

---

**INVESTIGATIONS ON THULIUM DOPED FIBER  
AMPLIFIERS FOR OPTICAL COMMUNICATION IN  
S AND NEAR-C BANDS**

---

A

*Thesis submitted  
in Partial Fulfilment of the Requirements  
for the Degree of*

**Doctor of Philosophy**

by

**Mohd Mansoor Khan**



Department of Electronics and Electrical Engineering  
Indian Institute of Technology Guwahati  
Guwahati - 781039, Assam, India  
November 2021



To

**Allah The Almighty**

*Whose mercy, love, and blessings thrived in me the path of righteousness*

**My Parents**

Mrs. Akhtar Khan and Mr. Mohd Tahir Khan

*For always being a source of endless inspiration to me*

**My Beloved Wife**

Sana

*For equally sharing the turmoils and elations of this journey*

and

**My Newborn Daughter**

Rumaisa

*For letting me truly understand the essence of love and care*





*your memories will always be cherished...*

Mother, Uncle, and Father-in-law





## Certificate

This is to certify that the thesis entitled “**Investigations on Thulium Doped Fiber Amplifiers for Optical Communication in S and near-C Bands**”, submitted by **Mohd Mansoor Khan** (136102025), a research scholar in the *Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The thesis has fulfilled all requirements as per the regulations of the institute and in my opinion has reached the standard needed for submission. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Date:

Place: Guwahati

**Ramesh Kumar Sonkar, Ph.D.**

Dept. of Electronics and Electrical Engg.,  
Indian Institute of Technology Guwahati,  
Guwahati - 781 039, Assam, India.



# Acknowledgements

In the first place, I would like to record my deepest and soulful gratitude to the Almighty for guiding me and granting me an opportunity to do something beneficial for the betterment of humanity through science as a launching pad.

This thesis was only possible with the continued and constant support of many individuals. First of all, I would like to express my most cordial and earnest gratitude to my supervisor Dr. Ramesh Kumar Sonkar for supporting and guiding me throughout this journey. The amount of patience Dr. Sonkar invested in me is beyond comparison. The dedication, enthusiasm, and energy with which he guided my thesis and the positive aura he created around me in the time of my lows is something I can never forget. My sincere thanks to him for extensively examining all the manuscripts which I presented to him including this thesis. Without his detailed critical comments, the publications through this work could not have been possible.

As far as my doctoral committee, I consider myself one of the luckiest scholars. I would like to extend my hearty thanks to all my doctoral committee members namely Prof. Ratnajit Bhattacharjee, Dr. Ashwini Kumar Sharma, Dr. Ramesh Kumar Sonkar, and Dr. Debabrata Sikdar for timely evaluating my progress, grilling on my wrongs, appreciating the rights, and overall contributing to this thesis at its finest level. Their invaluable suggestions and feedback helped me enormously in delivering this work.

Special thanks are worth mentioning to all the past and present Heads of the Department of Electronics and Electrical Engineering (EEE) for considering my requests at various levels during the span of my PhD work. I am also grateful to all the members of the research and technical staff of the department, especially Mr. Mukut and Mr. Dasharath, without whose help I could not have completed this thesis.

It's a pleasurable feeling for me to thank Prof. Gautam Barua, Director, Indian Institute of Information Technology Guwahati (IIITG), for granting me substantial time to carry out my PhD work while employed as Lecturer at IIITG under the Department of Electronics and Communication Engineering (ECE). My thanks also extend to Dr. Surajit Panja (Head of the

---

Department of ECE at IIITG), Dr. Ferdous Ahmed Barbhuiya (Associate Dean of Research and Development at IIITG), and Dr. Bidisha Dasgupta (Associate Dean of Academics Affairs at IIITG) for their support as and when required. My colleagues-cum-friends at IIITG Dr. Amarnath Yadav, Dr. Sanjay Moulik, and Ms. Gitimoni Saikia shared a special bond with me which helped to reach important conclusions on the discussions seemingly to research.

Worth mentioning is my friends-cum-labmates at the Indian Institute of Technology Guwahati (IITG) for their consistent ever helping attitude. Dr. Jitendra Prajapati, Dr. Darpan Mishra, and Mr. Manoranjan Minz always proved to be my material resource person as and when needed. The time shared in the lab with them, with all the lighter moments, definitely impacted my research and framed in me a positive attitude. I would also like to thank my friend Mr. Bhuvnesh Bansal for constantly dealing with my wrath in times of frustration.

My special thanks go to Prof. Majid Jamil (Department of Electrical Engineering, Jamia Millia Islamia-New Delhi) and Dr. Sunita Mishra (Head and Principal Scientist, CSIR-Central Scientific Instruments Organization, Chandigarh) for their unwavering support throughout the duration of this research period.

When it comes to my family members, I can proudly say they are the supporting frame of my life. I share my utmost love and affection to my parents (Mrs. Akhtar Khan and Mr. Mohd Tahir Khan) for upbringing me to an extent that I can hold a PhD degree. I would love to say my thanks to my uncle Late Mr. Mohd Tayyab Khan who was the fatherly figure of my life. To the beautiful, ever caring, and loving person my wife Sana, I owe the most of my thankfulness to you. Thank you my lovely daughter Rumaisha for being the bundle of joy and making me laugh by just seeing your face. My fatherly figured brother Mr. Mohd Shahid Khan and my loving sisters Ms. Sadaf Khan and Mrs. Nida Khan, I thank you all for being my strength especially when things were gloomy for me. I owe special thanks and respects to Mr. Kashif Khan for being a perfect brother-in-law. My lovely little gems Sania, Amira, Soha, Aizah, and Saquib thank you all for being the twinkle of my eye.

I would like to thank all the members of my extended family for believing in me. My mother and father-in-law (Mrs. Tabassum Khanam and Mr. Mohd Luqman Khan) proved to be

---

the reinforcement of my life. Muniza, Almas, and Qamar I thank you all for being wonderful sisters and brother-in-law.

I would also like to thank all the unmentioned hands who provided their much-needed service which contributed to the production of this thesis. It is this love, sacrifice, effort, and belief that all the mentioned persons have invested in me which resulted to accomplish and reach this proud stage of my life so far.

*(Mohd Mansoor Khan)*







# Abstract

Thulium doped fiber amplifiers (TDFAs) can provide high power optical amplification in the wavelength range of 1460 nm–1545 nm (S and near-C bands). They can be potentially employed for dense wavelength division multiplexing (DWDM) in optical fiber communication over a broad range, unlike the Erbium-doped fiber amplifiers (EDFAs), which are active only in the conventional “Erbium Window” of 1550 nm in the C-band. This research-work presents overmodulation of signal and gain dynamics on TDFAs using the EDFA’s Bononi and Rusch model, making it the first approach of its kind on TDFAs. It portrays the overmodulation of digital optical communication signal, of which, the amplitude is modulated by low-frequency ( $\sim 100$  kHz), for line-surveillance and management control of optical information in DWDM TDFA systems. Signal-to-signal and signal-to-amplified spontaneous emission transfer functions are derived to predict the system performance under high input signal power conditions and its variation on the input modulation index. Overmodulation sensitivity for various levels of input signal power is investigated to demonstrate the undesirable increment in the output modulation index at 8 dBm and 1490 nm signal wavelength respectively at the corner frequency. It also provides a methodical testbed to analyze the signal wavelength effect, using MatLab®-Simulink, resulting in the development of a simulator.

The thesis proposes the phenomenon of modulation instability (MI) in TDFAs operating at a calculated optimum wavelength of 1460 nm. It focuses on the loss parameter and non-linear effects when the continuous wave signal is allowed to amplify inside TDFAs and perturbed with weak modulation signals. Analytical model starting from the non-linear Schrödinger-wave equation for the integrated

gain including loss effects has been uniquely presented. The analysis is carried out to predict the frequency range for which MI could be invoked in TDFAs. The loss and non-linear factor analysis have been presented and a comparison of the frequency shift with and without losses has been done. Optimum TDFA length is also calculated and the parameters are compared to the existing state-of-the-art EDFAs. A special case is solved numerically as an example of a non-ideal case showing the MI's applicability as an active saturable absorber in building TDFA based femtosecond pulse-width lasers. Moreover, the pulse splitting effect through MI with variation in frequency chirp parameter of the input pulses and non-linear TDFA length is modeled, numerically solved, and simulated for various parameters. The input pulses considered are *sech*, *Gaussian*, and *super-Gaussian* type in a 1050 nm pumped heavily doped TDFA. The model is computationally solved on MatLab® and the results are verified by incorporating similar conditions and parameters on OptiSystem® simulation platform. The findings conclude the optimum non-linear length and the chirp parameter which has to be taken so as to obtain continuous-time domain pulse train as well as linearly spaced frequency combs for various applications.

The optical conversion efficiency of TDFAs is dependent on parameters like Thulium-ion concentration, pump power, fiber length, dopant area, signal wavelength, and ion-ion interaction mechanisms (IM). This thesis also focuses on the analytical formulation and simulation of IM effects involving homogeneous up-conversion and pair induced quenching on TDFA gain characteristics. The beneficial aspects of IM effects are perceived in the selection of optimum pump power and TDFA gain. The findings on optimum doping radius, TDFA length, and an added advantage of a single wavelength (1050 nm) pump further assist to evaluate and establish the performance of TDFAs for S and near-C band optical fiber networks for the future.

# Contents

|                                                                     |          |
|---------------------------------------------------------------------|----------|
| List of Figures                                                     | xxi      |
| List of Tables                                                      | xxxix    |
| List of Acronyms                                                    | xxxiii   |
| List of Symbols                                                     | xxxvi    |
| List of Publications                                                | xli      |
| <b>1 Introduction to the Optical Amplifiers</b>                     | <b>1</b> |
| 1.1 Optical Communication Wavelengths                               | 2        |
| 1.1.1 The O-band (Original band: 1260–1360 nm)                      | 2        |
| 1.1.2 The E-band (Extended band: 1360–1460 nm)                      | 3        |
| 1.1.3 The S-band (Short-Wavelengths band: 1460–1530 nm)             | 3        |
| 1.1.4 The C-band (Conventional band: 1530–1565 nm)                  | 3        |
| 1.1.5 The L-band (Long-Wavelengths band: 1565–1625 nm)              | 4        |
| 1.1.6 The U-band (Ultra Long-Wavelengths band: 1625–1675 nm)        | 4        |
| 1.2 Fiber-Optic Communication System                                | 4        |
| 1.2.1 Optical Transmitter                                           | 6        |
| 1.2.2 Communication Channel                                         | 7        |
| 1.2.3 Optical Receiver                                              | 18       |
| 1.3 Advantages and Applications of Fiber-Optic Communication System | 19       |
| 1.3.1 Large Band-width                                              | 20       |

## Contents

---

|          |                                                                  |           |
|----------|------------------------------------------------------------------|-----------|
| 1.3.2    | Electrically Isolated and Immune to Interference                 | 20        |
| 1.3.3    | Secure, Reliable, and Minimal Transmission losses                | 20        |
| 1.3.4    | Low in Cost and Easily Expandable                                | 21        |
| 1.3.5    | Ubiquitously Applicable                                          | 21        |
| 1.4      | Dopant based Classification of RE-DFAs                           | 21        |
| 1.4.1    | Neodymium-Doped Fiber Amplifiers (NDFAs)                         | 22        |
| 1.4.2    | Ytterbium-Doped Fiber Amplifiers (YDFAs)                         | 24        |
| 1.4.3    | Praseodymium-Doped Fiber Amplifiers (PDFAs)                      | 25        |
| 1.4.4    | Holmium-Doped Fiber Amplifiers (HDFAs)                           | 26        |
| 1.4.5    | Erbium-Doped Fiber Amplifiers (EDFAs)                            | 27        |
| 1.4.6    | Thulium-Doped Fiber Amplifiers (TDFAs)                           | 29        |
| 1.4.7    | Plastic Optical Fiber Amplifiers (POFAs)                         | 31        |
| 1.4.8    | Co-doped Fiber Amplifiers (CoDFAs)                               | 32        |
| 1.5      | Applications of TDFAs                                            | 35        |
| 1.5.1    | Bio-Medical Applications                                         | 35        |
| 1.5.2    | Spectroscopic and Remote Sensing Applications                    | 36        |
| 1.5.3    | Research, Industrial, and Defense Applications                   | 36        |
| 1.5.4    | Communication Applications                                       | 37        |
| 1.6      | Working Mechanism of TDFAs in S and near-C bands                 | 38        |
| 1.7      | Research Motivation and the Problem Formulation                  | 39        |
| 1.8      | Thesis Contribution                                              | 41        |
| 1.9      | Thesis Overview                                                  | 42        |
| <b>2</b> | <b>Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey</b> | <b>45</b> |
| 2.1      | Introduction                                                     | 46        |
| 2.2      | Main Components of S and near-C band TDFAs                       | 48        |
| 2.2.1    | The Active Fiber                                                 | 48        |
| 2.2.2    | The Constituent Components                                       | 49        |

|          |                                                                                                                            |            |
|----------|----------------------------------------------------------------------------------------------------------------------------|------------|
| 2.3      | Literature Survey                                                                                                          | 51         |
| 2.3.1    | Literature Review on the Overmodulation of Signal-Gain Dynamics (OSGD) in RE-DFAs                                          | 51         |
| 2.3.2    | Literature Review on the Modulation-Instability in TDFAs                                                                   | 58         |
| 2.3.3    | Literature Review on the Chirping Effects on Optical Pulses in TDFAs through MI                                            | 63         |
| 2.3.4    | Literature Review on the Ion-Ion Interaction Effects in TDFAs                                                              | 66         |
| 2.4      | Summary                                                                                                                    | 73         |
| <b>3</b> | <b>Overmodulation of Signal and Gain Dynamics in TDFAs</b>                                                                 | <b>75</b>  |
| 3.1      | Introduction                                                                                                               | 76         |
| 3.2      | Analytical Model                                                                                                           | 78         |
| 3.2.1    | The Population-Inversion Condition                                                                                         | 85         |
| 3.2.2    | Gain Modulation                                                                                                            | 86         |
| 3.2.3    | Signal Modulation                                                                                                          | 87         |
| 3.3      | Simulink Pedestal for TDFAs                                                                                                | 90         |
| 3.4      | Results and Discussions                                                                                                    | 93         |
| 3.4.1    | Input Signal Characteristics                                                                                               | 94         |
| 3.4.2    | Output Signal Characteristics                                                                                              | 95         |
| 3.4.3    | Signal-Gain and Noise-Figure Analysis                                                                                      | 97         |
| 3.4.4    | Overmodulation Sensitivity to the Mean Input Signal Power                                                                  | 99         |
| 3.4.5    | Overmodulation Sensitivity due to the Signal Wavelength                                                                    | 102        |
| 3.4.6    | Output-Signal modulation index response with respect to the input-signal power for signal overmodulation at $\omega_0 = 0$ | 103        |
| 3.5      | Summary                                                                                                                    | 105        |
| <b>4</b> | <b>Modulation Instability in Lossy and Non-linear TDFAs</b>                                                                | <b>107</b> |
| 4.1      | Introduction                                                                                                               | 108        |
| 4.2      | Analytical Model                                                                                                           | 110        |

## Contents

---

|       |                                                                                                              |            |
|-------|--------------------------------------------------------------------------------------------------------------|------------|
| 4.3   | Results and Discussions                                                                                      | 115        |
| 4.3.1 | TDFA's length effect on Integrated gain variation with respect to small-signal gain coefficient              | 115        |
| 4.3.2 | Integrated gain variation with respect to TDFA's Length for different input signal powers                    | 117        |
| 4.3.3 | Integrated gain variation with respect to small signal gain coefficient for different input signal powers    | 119        |
| 4.3.4 | Perturbation frequency and Loss-factor analysis on Integrated gain                                           | 120        |
| 4.3.5 | Perturbation frequency, nonlinear factor, and Loss-factor analysis on Integrated gain—A Comparative Approach | 122        |
| 4.3.6 | Numerical Approach to demonstrate the phenomenon of MI                                                       | 123        |
| 4.4   | Summary                                                                                                      | 124        |
| 5     | <b>Chirping Effects on Optical Pulses in TDFAs through MI</b>                                                | <b>125</b> |
| 5.1   | Introduction                                                                                                 | 126        |
| 5.2   | Mathematical Model                                                                                           | 127        |
| 5.3   | Simulation Setup                                                                                             | 129        |
| 5.4   | Results and Discussions                                                                                      | 131        |
| 5.4.1 | Non-linear parameter effect on various input-pulses                                                          | 131        |
| 5.4.2 | Chirp parameter effect on various input-pulses                                                               | 133        |
| 5.4.3 | TDFA length effect on various input-pulses                                                                   | 133        |
| 5.4.4 | Optimization of TDFA length to invoke MI                                                                     | 136        |
| 5.4.5 | Output-pulse splitting demonstration and its applications                                                    | 137        |
| 5.5   | Summary                                                                                                      | 138        |
| 6     | <b>Ion-Ion Interaction Analysis on TDFAs</b>                                                                 | <b>141</b> |
| 6.1   | Introduction                                                                                                 | 142        |
| 6.1.1 | The Ion-Ion Interaction Mechanisms                                                                           | 142        |
| 6.2   | Mathematical Model                                                                                           | 144        |

|          |                                                                 |            |
|----------|-----------------------------------------------------------------|------------|
| 6.3      | Simulation Setup                                                | 150        |
| 6.4      | Results and Discussions                                         | 150        |
| 6.4.1    | Optimum pump-power selection to maximize signal-gain            | 151        |
| 6.4.2    | Optimizing signal-wavelength and $\text{Tm}^{3+}$ doping radius | 152        |
| 6.4.3    | Optimizing signal-wavelength and $\text{Tm}^{3+}$ doping radius | 154        |
| 6.5      | Summary                                                         | 156        |
| <b>7</b> | <b>Conclusions and Future Scopes</b>                            | <b>157</b> |
| 7.1      | Summary of Conclusions and Discussions                          | 158        |
| 7.2      | Future Scopes                                                   | 162        |
| <b>A</b> | <b>Appendix</b>                                                 | <b>165</b> |
| A.1      | Numerical Methods                                               | 165        |
| A.2      | Split-Step Fourier Method                                       | 166        |
|          | <b>Bibliography</b>                                             | <b>168</b> |





## List of Figures

|     |                                                                                                                                                                                                                                                             |    |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.1 | The electromagnetic spectrum highlighting fiber-optic communication wavelengths.                                                                                                                                                                            | 2  |
| 1.2 | ITU-T based optical wavelength bands with arrow representing the wavelength increase to higher performance systems in general.                                                                                                                              | 4  |
| 1.3 | Illustration of <b>(a)</b> A generic optical communication system and <b>(b)</b> Essential elements of fiber-optics communication system showing components of optical transmitter, communication channel, and receiver respectively.                       | 5  |
| 1.4 | Illustration of <b>(a)</b> Lumped all-optical communication repeater with optical fiber amplifier as one of the most employed repeater shown in <b>(b)</b> .                                                                                                | 8  |
| 1.5 | Representation of general optical amplifier system functioning.                                                                                                                                                                                             | 9  |
| 1.6 | Gain–bandwidth characteristics of different optical amplifiers.                                                                                                                                                                                             | 10 |
| 1.7 | <b>(a)</b> Geometry of a typical <i>pn</i> -junction SOA and <b>(b)</b> The shape and characteristics of FPAs and TWAs.                                                                                                                                     | 11 |
| 1.8 | Schematics of the forward and backward pumping schemes associated with the Raman fiber amplifier.                                                                                                                                                           | 12 |
| 1.9 | <b>(a)</b> The spontaneous and stimulated Brillouin scattering mechanisms with later showing the stronger interference of input and reflected waves and <b>(b)</b> A representation of typical Brillouin fiber amplifier scheme in a passive optical fiber. | 14 |

## List of Figures

---

- 1.10 **(a)** Generic illustration of the parametric fiber amplifier and **(b)** Spectrum of single-pump and dual-pump PFA with respective signal idler waves. Under phase-match condition a perfect symmetry of spectra are observed around zero-dispersion wavelength  $\omega_0$ . 15
- 1.11 **(a)** Generic illustration of rare-earth doped fiber amplifier showing all essential components and **(b)** The usage and employment of RE-DFA in optical communication system as power, in-line, and pre-amplifiers respectively. 17
- 1.12 **(a)** Energy-level representation of  $\text{Nd}^{3+}$  with dotted lines showing phonon-transitions and **(b)** shows the absorption (left) and emission (right) CSA of  $\text{Nd}^{3+}$  for different host-glasses. 23
- 1.13 **(a)** Energy-level representation of  $\text{Yb}^{3+}$  with dotted lines showing phonon-transitions, **(b)** shows its absorption and emission CSA, and **(c)** schematic representation of cladding-pumped double-cladding YDFA. 24
- 1.14 **(a)** Energy-level representation of  $\text{Pr}^{3+}$  with dotted lines showing multi-phonon transitions and **(b)** Shows the absorption and emission CSA for  $\text{Pr}^{3+}$  doped in fluoride (left) and chalcogenide (right) host-glass respectively. 25
- 1.15 **(a)** Energy-level representation of  $\text{Ho}^{3+}$  with dotted lines showing up-conversion quenching (red) and phononic relaxation (orange) and **(b)** shows its absorption and emission CSA in mid-IR regime for silica host-glass. 26
- 1.16 **(a)** Energy-level representation of  $\text{Er}^{3+}$  with dotted lines showing the up-conversion, phononic transition, and excited-state absorption processes, **(b)** shows its absorption and emission CSA, and **(c)** schematic illustration of erbium-doped multi-core amplifier (ED-MCA) configuration. 28
- 1.17 **(a)** Energy-level representation of  $\text{Tm}^{3+}$  with possible pumping schemes where the dot-dash lines indicate the non-radiative decay and **(b)** Shows the absorption and emission CSA for  $\text{Tm}^{3+}$  doped in silica host-glass fiber highlighting the S and near-C bands as the region of interest. 29
- 1.18 Part-pumping strategy for up-conversion in TDFAs. 30

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 1.19 | (a) The refractive-index profile for POFs showing step-index (a1), graded-index (a2), and multi-step index (a3), (b) Typical examples of $\text{Eu}^{3+}$ and $\text{Er}^{3+}$ -chelate dopants, and (c) Energy-level representation of the $\text{Eu}^{3+}$ -chelate coordination complex with possible pumping from singlet-states $S_0 \rightarrow S_1 \rightarrow T_1$ (triplet-state via non-radiative decay). From $T_1$ , the intermolecular energy transfer takes schemes where the dot-dash lines indicate the non-radiative decay. | 31 |
| 1.20 | Different types of energy transfer (ET) mechanisms namely cross-relaxation, energy transfer up-conversion, fluorescence transfer, and energy migration indicated from Process-1 to 4 respectively.                                                                                                                                                                                                                                                                                                                                           | 33 |
| 1.21 | (a) The schematic level diagram of $\text{Er}^{3+}$ - $\text{Tm}^{3+}$ co-doped fiber amplifier system showing relevant ET-processes for near-IR emission and (b) shows the comparative effect of optimum $\text{Er}^{3+}$ - $\text{Tm}^{3+}$ doping combination with respect to sole $\text{Er}^{3+}$ (upper) and $\text{Tm}^{3+}$ (lower) respectively.                                                                                                                                                                                    | 34 |
| 1.22 | Various RE-DFAs including Eu-POFA doped in various glass-hosts with corresponding average power achieved.                                                                                                                                                                                                                                                                                                                                                                                                                                    | 35 |
| 1.23 | (a) The S and near-C bands TDFA energy level representation showing corresponding transitions and (b) shows the emission and absorption CSA for $\text{Tm}^{3+}$ particularly in S and near-C bands.                                                                                                                                                                                                                                                                                                                                         | 38 |
| 1.24 | Flow-diagram illustrating the organization of the thesis.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 42 |
| 2.1  | The comparative absorption and emission cross section areas for TDFA and EDFA.                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 47 |
| 2.2  | A basic structure of a TDFA.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 48 |
| 2.3  | Shows the power distribution of the output ports with 0.4% of return-loss with (a), (b) having a fiber core-to-core distance of $20\ \mu\text{m}$ and $16\ \mu\text{m}$ respectively. While (c) illustrating the effect on output power when the coupling-length is increased. The output-power percentage of the respective ports are mentioned on the right vertical-axis.                                                                                                                                                                 | 50 |

## List of Figures

---

- 2.4 Graphical summary of the work carried out in [219]. The three different wavelengths are considered for analysis from C-Band were 1530 nm, 1537 nm, and 1560 nm. 52
- 2.5 Graphical summary of the work carried out in [228]. It summarises and compares the results obtained through simulation on the Simulink with that of the experiment. 52
- 2.6 Graphical summary of the work carried out in [229]. The ASE effects were considered at the overmodulated signal transmission of 1530 nm. The developed “Matlab Simulink” model can help in analyzing a cascaded EDFA system in a single module. 53
- 2.7 Graphical summary of the work carried out in [230]. The significance of using the Gaussian-pulse signal with different duty-cycles is presented. The effect of the pump phase modulation has also been displayed through simulations which is further validated with experiments. 54
- 2.8 Graphical summary of the work carried out in [231]. The overmodulation effect on EDFAs and YDFAs have been shown analytically and experimentally. 54
- 2.9 Graphical summary of the work carried out in [221, 231]. The significance of ESA with 1064 nm pumping has also been displayed in this work. 55
- 2.10 Graphical summary of the work carried out in [233]. The perturbation gain-spectrum has been compared with the approximate method (WKB) to that of the exact analytical solution. 58
- 2.11 Graphical summary of the work carried out in [234]. The exact solution help in the prediction of perturbation frequency for maximum gain considerations. 59
- 2.12 Graphical summary of the work carried out in [235]. The exact solution help in the prediction of perturbation frequency for maximum gain considerations. It also display the perturbation phase behaviour on the MI. 60
- 2.13 Graphical summary of the work carried out in [236]. The analysis could help in the prediction of perturbation frequency to minimize RIN. 60

|      |                                                                                                                                                                                                                                                                        |    |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 2.14 | Graphical summary of the work carried out in [241]. The study emphasized on the upchirping effect on the input pulse evaluated inside a TDFA.                                                                                                                          | 63 |
| 2.15 | Graphical summary of the work carried out in [206]. The study emphasized on the production of the tunable laser using a thulium fluoride fiber in S/S <sup>+</sup> bands.                                                                                              | 64 |
| 2.16 | Graphical summary of the work carried out in [243]. The analysis could help in the selection of optimum pulse shape and chirping parameter.                                                                                                                            | 65 |
| 2.17 | Graphical summary of the work carried out in [244]. The study emphasized on the IM effects on EDFA performance with further optimization of parameters for the highest gain.                                                                                           | 67 |
| 2.18 | Graphical summary of the work carried out in [177,245]. The study emphasized the IM effects on EDFA's performance with respect to the numerical aperture and dopant concentrations. The IUC and HUC mechanisms have been compared with the achieved gain respectively. | 68 |
| 2.19 | Graphical summary of the work carried out in [247]. The simulation results performed by the authors on TDFAs helped to obtain optimum core CSA and doping concentration.                                                                                               | 69 |
| 2.20 | Graphical summary of the work carried out in [88]. The model and experimental results show the self-pulsing effect in TDFAs when the input pump-power has been increased gradually. The PIQ effect is also considered for 2 $\mu$ m systems.                           | 69 |
| 2.21 | Graphical summary of the work carried out in [249]. The simulation results helps in selection of the optimized TTDP parameters to maximize gain performance.                                                                                                           | 70 |
| 3.1  | Absorption and Emission CSA of Tm <sup>3+</sup> ions in silica glass matrix emphasizing the S and near-C bands spectra. Inset shows the respective comparative CSAs for Tm <sup>3+</sup> and Er <sup>3+</sup> ions.                                                    | 76 |

## List of Figures

---

|      |                                                                                                                                                                        |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 3.2  | Left-shows the up-conversion pumping scheme at $\sim 1420$ nm with the lasing transitions. Right-shows the ASE at 800 nm and 1800 nm with other radiative transitions. | 78  |
| 3.3  | Schematic representation for the signal-gain overmodulation dynamics studies on TDFAs.                                                                                 | 79  |
| 3.4  | Simulink test-bed for TDFA's signal-gain overmodulation.                                                                                                               | 92  |
| 3.5  | Details of input phase-shift subsection.                                                                                                                               | 93  |
| 3.6  | Parameters affecting the behaviour of the Gain, Noise-Figure, output modulation index and its phase.                                                                   | 94  |
| 3.7  | Effect of the modulation frequency on initial phase-shifts.                                                                                                            | 94  |
| 3.8  | Effect of the modulation frequency on input modulation indices of their respective energy levels.                                                                      | 95  |
| 3.9  | Effect of the applied modulation frequency sweep on the output modulation index.                                                                                       | 96  |
| 3.10 | Effect of applied modulation frequency sweep on output modulation index phase.                                                                                         | 96  |
| 3.11 | Output-signal time history of the modulated signal with input-signal power and signal-gain of 6 dBm and 58 dB respectively.                                            | 97  |
| 3.12 | Signal gain (dB) verses mean input-signal power (dBm) with (solid-lines) and without (dashed-lines) ASE.                                                               | 97  |
| 3.13 | Signal-gain (solid-lines) and noise-figure (dashed-lines), both in dB, verses fixed input signal power for four different wavelengths in S and near-C bands.           | 98  |
| 3.14 | Overmodulation sensitivity on the magnitude of the output-signal modulation index with respect to different input-signal powers at 1530 nm.                            | 99  |
| 3.15 | Overmodulation sensitivity on the magnitude of the output-signal modulation index with respect to different input-signal powers at 1490 nm.                            | 100 |
| 3.16 | Overmodulation sensitivity on the output-signal modulation index phase with respect to different input-signal powers at 1490 nm.                                       | 101 |



|      |                                                                                                                                                                                                                                                                          |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 3.17 | Overmodulation sensitivity on the output-signal modulation index magnitude with respect to the different input-signal wavelengths in S-Band at 8 dBm signal-power.                                                                                                       | 102 |
| 3.18 | Overmodulation sensitivity on the output-signal modulation index phase with respect to the different input-signal wavelengths in S-Band at 8 dBm signal-power.                                                                                                           | 103 |
| 3.19 | Output-Signal modulation index variation to the input-signal overmodulation at $\omega = 0$ verses mean input-signal power.                                                                                                                                              | 104 |
| 4.1  | Attenuation of optical signals in silica fibers showing the region of interest (S and near-C Bands)                                                                                                                                                                      | 108 |
| 4.2  | Schematic representation for the MI phenomenon in lossy and nonlinear TDFAs as the signal gain media.                                                                                                                                                                    | 111 |
| 4.3  | Parameters affecting the behaviour of the Integrated-Gain.                                                                                                                                                                                                               | 115 |
| 4.4  | Integrated gain ( $ F(\Omega) $ ) variation with respect to Second-Order dispersion ( $\beta_2$ ) for 100 m TDFA length ( $L$ ) for different input signal power ( $P_0$ ).                                                                                              | 116 |
| 4.5  | TDFA length ( $L$ ) effect on integrated gain ( $ F(\Omega) $ ) variation with respect to small-signal gain coefficient ( $g_0$ ) with inset showing the $ F(\Omega) $ built-up in low length TDFAs ( $L < 5$ m) at a comparative higher values of $g_0=4.46/\text{m}$ . | 117 |
| 4.6  | Integrated gain ( $ F(\Omega) $ ) variation with respect to TDFA length ( $L$ ) for different input signal powers ( $P_0$ ).                                                                                                                                             | 118 |
| 4.7  | Integrated gain ( $ F(\Omega) $ ) variation with respect to small signal gain coefficient to obtain optimum value as $g_0 = 0.21 / \text{m}$ for four different input signal powers.                                                                                     | 119 |
| 4.8  | Cut-off frequency ( $\Omega_0$ ) calculation at mentioned loss-factor ( $\alpha = 0.01/\text{m}$ ).                                                                                                                                                                      | 120 |
| 4.9  | (a) Reduction in maximum integrated gain under MI with corresponding perturbation frequency shift considering lossless (solid lines) and lossy (dashed lines) TDFA and (b) Loss-factor effect for fixed signal power of 150 mW and TDFA length of 100 m.                 | 121 |

## List of Figures

---

- 4.10 Comparison of nonlinear parameter ( $\gamma$ ) effect on integrated gain  $|F(\Omega)|$  for TDFA and EDFA. 122
- 4.11 Numerical solution for a particular case of (4.1) where amplitude of perturbations were comparable to that of CW input signal (1% of  $|P_0|$ ). 123
- 5.1 Schematic representation for the MI phenomenon in non-linear TDFAs with input signal as optical pulses. 127
- 5.2 Designed schematic of optical pulse evaluation in a non-linear TDFA. 130
- 5.3 Parameters affecting the behaviour of the the Output-Pulse. 131
- 5.4 Input optical pulses with  $L = 0.5L_D$  and  $C = 3$  showing (a) *Gaussian* input with (c), (e), (g) as *Gaussian*-output pulses with  $N_l = 1, 4, 12$  respectively. (b), (d) shows *sech*-input and output respectively for  $N_l = 12$  while (f), (h) shows *super-Gaussian*-input and output respectively for  $N_l = 12$ . 132
- 5.5 Input (blue line-markers) and spectra (red line-marker) with  $L = 0.5L_D$  and  $N_l = 12$  showing (a), (c), (e) as *Gaussian*, (b), (d), (f) as *sech*, and (g), (h), (i) as *super-Gaussian* with  $C = 0, 3, 12$  respectively. The corresponding output pulses and their spectra can be observed (solid black line) 134
- 5.6 Input (blue line-markers) and spectra (red line-marker) with  $C = 12$  and  $N_l = 12$  showing (a), (c), (e) as *Gaussian*, (b), (d), (f) as *sech*, and (g), (h), (i) as *super-Gaussian* with  $L = 0.5L_D, 0.8L_D, 1.0L_D$  respectively. The corresponding output pulses and spectra can be observed (solid black line) 135
- 5.7 The variation of signal gain with TDFA length and  $Tm^{3+}$  concentration in time and frequency domain is shown by (a) and (b) respectively. Optimum TDFA length can be seen as 375 m. 136
- 5.8 Input (left column) and Output (right column) pulse spectra for different values of chirp parameter  $C=0, 6, 12$  shown as (a)-(c) respectively. The increase in pulse splitting and spreading phenomenon can be observed in each case. 138



|      |                                                                                                                                                                                                                                                                                                                                                                                                   |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.9  | Time domain pulse (left column) and corresponding frequency spectrum (right column) of input optical <i>Gaussian</i> pulse at the TDFA input (a). At TDFA length 375 m the MI was initiated (b). Further splitting of pulse at TDFA length greater than 375 m (c).                                                                                                                                | 139 |
| 6.1  | HUC and PIQ clustering of $\text{Tm}^{3+}$ in uniform silica glass matrix                                                                                                                                                                                                                                                                                                                         | 143 |
| 6.2  | Quantum transition diagram for $\text{Tm}^{3+}$ highlighting the cooperative up-conversion through absorption (purple), stimulated emission in S and near-C bands (blue), other radiative transitions (dark-green), ASE transitions (orange), non-radiative transitions (red), donor-acceptor transitions (light-green), and ion-ion interaction due to cross-relaxation effect (black dash-dot). | 144 |
| 6.3  | Schematic representation of IM effects in heavily-doped TFAs.                                                                                                                                                                                                                                                                                                                                     | 145 |
| 6.4  | (a)–(c) $\text{Tm}^{3+}$ dopant profile with different dopant diameter $2a$ and fixed radial distance $r$                                                                                                                                                                                                                                                                                         | 146 |
| 6.5  | Schematic setup of TDFA system to study IM effects using OptiSystem pedestal.                                                                                                                                                                                                                                                                                                                     | 150 |
| 6.6  | Parameters affecting the behaviour of the the signal-gain and noise-figure.                                                                                                                                                                                                                                                                                                                       | 152 |
| 6.7  | Optimum pump power for non-IM effect (blue) and with IM effects (red)                                                                                                                                                                                                                                                                                                                             | 152 |
| 6.8  | IM effect on the signal-gain with respect to the doping radius for fixed $\text{Tm}^{3+}$ concentration showed as (a) input signal-wavelength variation and (b) shows the magnified portion concerning the S-band.                                                                                                                                                                                | 153 |
| 6.9  | IM effect on the noise-figure with respect to the doping radius for fixed $\text{Tm}^{3+}$ concentration showed as (a) input signal-wavelength variation and (b) shows the magnified portion concerning the S-band.                                                                                                                                                                               | 154 |
| 6.10 | (a) IM effect on doping concentration for the fixed $\text{Tm}^{3+}$ doping radius with respect to TDFA length and signal-gain. (b) shows the magnified portion to observe the optimum TDFA lengths.                                                                                                                                                                                              | 155 |
| 7.1  | Graphical summary of the work carried out during the analysis on overmodulation of signal and gain dynamics in TDFAs.                                                                                                                                                                                                                                                                             | 158 |

## List of Figures

---

- 7.2 Graphical summary of the analytical and simulation approach to study MI in the Lossy and Non-linear TDFAs. 159
- 7.3 Graphical summary of the analysis on the frequency chirp effects in non-linear TDFAs. 160
- 7.4 Graphical summary of the emphasizing on the beneficial aspects of IM effects in heavily doped TDFA systems. 161
- 7.5 The idea representation of the equivalent electrical circuit model of a TDFA system with its possible importance. 164
- A.1 Schematic illustration of the split-step Fourier method where  $\widehat{D}$  stands for the dispersion operator and  $\widehat{N}$  for the nonlinear operator. The dotted arrow represents the time to frequency conversion using FFT algorithm 166
- A.2 Schematic illustration of the symmetrized-SSFM. The initial and final half-steps are reduced 168
- A.3 A *Gaussian* pulse as an input inside a TDFA is evaluated by SSFM. The temporal and spectral splitting can be observed to this input pulse. 168

## List of Tables

|     |                                                                                                                                  |     |
|-----|----------------------------------------------------------------------------------------------------------------------------------|-----|
| 1.1 | Optical Communication Wavelength Bands                                                                                           | 3   |
| 1.2 | Commonly used Dopants in Host Glass with Absorption and Emission Wavelengths for RE-DFAs                                         | 17  |
| 1.3 | Commonly used host glasses for RE-DFAs with corresponding chemical composition ( $x, y$ representing the variable mol %).        | 22  |
| 2.1 | Summary of the OSGD studies in RE-DFAs                                                                                           | 56  |
| 2.2 | Summary of the MI studies in TDFAs                                                                                               | 61  |
| 2.3 | Summary of the frequency chirping effects on optical pulses in TDFAs                                                             | 65  |
| 2.4 | Summary of the IM studies on TDFAs                                                                                               | 71  |
| 3.1 | Wavelength-specific overlap-factor values                                                                                        | 81  |
| 3.2 | Parameters used in Analytical Model                                                                                              | 91  |
| 3.3 | Parameters used in Signal-Gain and Noise-Figure calculations                                                                     | 98  |
| 3.4 | Parameters used in the overmodulation sensitivity to input-signal power calculations at 1530 nm                                  | 99  |
| 3.5 | Parameters used in the overmodulation sensitivity to input-signal power calculations at 1490 nm                                  | 100 |
| 3.6 | Parameters used in the overmodulation sensitivity to input-signal wavelength calculations at 8 dBm power.                        | 102 |
| 3.7 | Parameters used to compute the output-signal modulation index as a response to the input-signal overmodulation at $\omega = 0$ . | 104 |

## List of Tables

---

|     |                             |     |
|-----|-----------------------------|-----|
| 4.1 | Model Parameters            | 114 |
| 4.2 | Correction Factor, $\eta$ . | 118 |
| 5.1 | Simulation Parameters       | 130 |
| 6.1 | Simulation Parameters       | 151 |



## List of Acronyms

|        |                                         |
|--------|-----------------------------------------|
| ASE    | Amplified Spontaneous Emission          |
| BER    | Bit Error Rate                          |
| BFAs   | Brillouin Fiber Amplifiers              |
| CoDFAs | Co-doped Fiber Amplifiers               |
| CR     | Cross Relaxation                        |
| CSA    | Cross Section Area                      |
| CW     | Contineous Wave                         |
| CWDM   | Coarse Wavelength Division Multiplexing |
| DRS    | Double Rayleigh Scattering              |
| DWDM   | Dense Wavelength Division Multiplexing  |
| EDFAs  | Erbium-Doped Fiber Amplifiers           |
| ED-MCF | Erbium-Doped Multi-Core Fiber           |
| EM     | Energy Migration                        |
| EMI    | Electro-Magnetic Interference           |
| ET     | Energy Transfer                         |
| ETU    | Energy Transfer Up-conversion           |
| FDM    | Finite Difference Method                |
| FPAAs  | Fabry–Pērot Amplifiers                  |
| FS     | Fluorescence Sensitization              |
| FTTP   | Fiber-to-the-Premises                   |

## List of Acronyms

---

|                  |                                                                                    |
|------------------|------------------------------------------------------------------------------------|
| FWHM             | Full Width at Half Maximum                                                         |
| GI               | Graded Index                                                                       |
| HDFAs            | Holmium-Doped Fiber Amplifiers                                                     |
| HUC              | Homogeneous Up-conversion                                                          |
| IM               | Ion-Ion Interaction Mechanism                                                      |
| IoT              | Internet-of-Things                                                                 |
| IR               | Infre-Red                                                                          |
| ITU-T            | International Telecommunication Union-<br>Telecommunication Standardization Sector |
| IM/DD            | Intensity Modulation with Direct Detection                                         |
| KKR              | Kramers-Kronig-Relations                                                           |
| LAN              | Local Area Network                                                                 |
| LIDAR            | Light Detection and Ranging                                                        |
| LP <sub>01</sub> | Linearly Polarized (Fundamental-Mode)                                              |
| LSA              | Linear Stability Analysis                                                          |
| MI               | Modulation Instability                                                             |
| NDFAs            | Neodymium-Doped Fiber Amplifiers                                                   |
| NLSE             | Non-linear Schrödinger-wave Equation                                               |
| NPE              | Nonlinear Polarization Evaluation                                                  |
| OEO              | Optical-Electrical-Optical                                                         |
| OGD              | Overmodulation Gain Dynamics                                                       |
| OSA              | Optical Spectrum Analyzer                                                          |
| OSGD             | Overmodulation of Signal-Gain Dynamics                                             |
| PDFAs            | Praseodymium-Doped Fiber Amplifiers                                                |
| PFA              | Parametric Fiber Amplifiers                                                        |
| PIQ              | Pair Induced Quenching                                                             |
| PMMA             | Poly (Methyl Metha-Acrylate)                                                       |
| PMMA-BZA         | PMMA-Benzyl Acrylate                                                               |

|                  |                                          |
|------------------|------------------------------------------|
| PMTs             | Photo Multiplier Tubes                   |
| POFAs            | Plastic Optical Fiber Amplifiers         |
| PSM              | Pseudo Spectral Method                   |
| QoS              | Quality of Service                       |
| RE <sup>3+</sup> | Rare-Earth Ion                           |
| RE-DFA           | Rare-Earth Doped Fiber Amplifiers        |
| RFAs             | Raman Fiber Amplifiers                   |
| RIN              | Relative Intensity Noise                 |
| RK               | Runga Kutta                              |
| SAM              | Semiconductor Saturable Absorber Mirror  |
| SBS              | Stimulated Brillouin Scattering          |
| SDM              | Space Division Multiplexing              |
| SMF              | Single Mode Fiber                        |
| SNR              | Signal-to-Noise Ratio                    |
| SOAs             | Semiconductor Optical Amplifiers         |
| SRS              | Stimulated Raman Scattering              |
| SSFM             | Split-Step Fourier Method                |
| TDFAs            | Thulium-Doped Fiber Amplifiers           |
| TDFL             | Thulium-Doped Fiber Lasers               |
| TFL              | Thulium Fiber Laser                      |
| THz              | Terra-Hertz                              |
| TTDPs            | Transverse Thulium Distribution Profiles |
| TTFA             | Thenoyl-Trifluoro-Acetyl-Acetone         |
| TWAs             | Travelling Wave Amplifiers               |
| UV               | Ultra-Violet                             |
| WAN              | Wide Area Network                        |
| WKB              | Wentzel-Brillouin-Kramers                |
| YDFAs            | Ytterbium-Doped Fiber Amplifiers         |





## List of Symbols

|                 |                                      |                       |                                                                |
|-----------------|--------------------------------------|-----------------------|----------------------------------------------------------------|
| $G_R$           | Raman signal gain                    | $u_p$                 | Transverse propagation constant of LP <sub>01</sub> mode       |
| $g_R$           | Raman power gain coefficient         | $N_i$                 | Tm <sup>3+</sup> population at the $i^{th}$ level              |
| $P_{P_R}$       | Raman pump power                     | $N_i^0$               | Steady-state Tm <sup>3+</sup> population at the $i^{th}$ level |
| $L_{R_{eff}}$   | Effective Raman fiber length         | $W_{pij}$             | Transition rates for 1420 nm pumping                           |
| $A_{R_{eff}}$   | Effective fiber cross section area   | $W_{sa,se}$           | Signal absorption and emission transition rates                |
| $k_R$           | Raman numerical factor               | $W_{8/18,a/e}$        | ASE transition rate at 800 nm, 1800 nm                         |
| $\alpha_{R_P}$  | Raman fiber loss factor              | $A_{ij}$              | Radiative rates                                                |
| $n_{B_{eff}}$   | Effective Brillouin refractive index | $\gamma_{21}^{nr}$    | Non-radiative transition rate                                  |
| $v_A$           | Acoustic velocity                    | $\lambda_s$           | Signal wavelength                                              |
| $\nu_P$         | Pump frequency                       | $\lambda_p$           | Pump wavelength                                                |
| $\nu_S$         | Signal frequency                     | $\lambda_{ASE}$       | Signal ASE wavelength                                          |
| $\Delta\nu_B$   | Acoustic phonon frequency            | $\lambda_{ASE\ 8,18}$ | ASE wavelength at 800 nm and 1800 nm                           |
| $\lambda_{B_P}$ | Brillouin pump wavelength            | $P_p$                 | Pump power                                                     |
| $\gamma$        | Non-linear parameter                 | $P_s$                 | Signal power                                                   |
| $G_p$           | Parametric gain                      | $P_{ASE\ 8,18}$       | ASE power at 800 nm and 1800 nm                                |

## List of Symbols

|                     |                                                                      |                 |                                                                   |
|---------------------|----------------------------------------------------------------------|-----------------|-------------------------------------------------------------------|
| $\omega_s$          | Optical signal frequency                                             | $A, B, C,$      | Coefficients in chapter 3                                         |
| $\omega_p$          | Optical pump frequency                                               | $D, E, F,$      |                                                                   |
| $\psi_{01}$         | Linearly-polarized mode                                              | $G, H, Q,$      |                                                                   |
| $K_0$               | Modified Bessel Function                                             | $R, S, T,$      |                                                                   |
| $J_0$               | Bessel Function                                                      | $U, V, U',$     |                                                                   |
| $\sigma_{pij}$      | Pump emission and absorption cross section area                      | $V'$            |                                                                   |
| $\sigma_{8/18,a/e}$ | ASE absorption and emission cross section area at 800 nm and 1800 nm | $P_s^0(0)$      | Mean input signal power at $z = 0$                                |
| $\sigma_{sa,se}$    | Signal absorption and emission cross section area                    | $m_s$           | Input modulation index of the signal                              |
| $h$                 | Planck's constant                                                    | $\delta_{1,3}$  | Modulation indices for steady-state population at levels 1 and 3  |
| $c$                 | Velocity of light in vacuum                                          | $\varphi_{1,3}$ | Initial phase-shifts of steady-state population in levels 1 and 3 |
| $\Delta\nu$         | Bandwidth of respective ASE frequency                                | $m'_s$          | Output modulation index of the signal                             |
| $\Gamma(\lambda_i)$ | Overlapping factor                                                   | $\omega_0$      | Spot size radius                                                  |
| $V$                 | Normalized frequency or the V-parameter of the fiber                 | $\theta_s$      | Output signal phase shift                                         |
| $NA$                | Numerical Aperture of the fiber                                      | $u(z, t)$       | Slowly varying envelope                                           |
| $G(dB)$             | Gain in decibel                                                      | $\beta_2$       | Mode propagation constant of order-2                              |
| $\mu$               | Scattering loss-factor of the fiber                                  | $g_0$           | Small signal gain                                                 |
| $P_{ASE}^{out}$     | Output signal ASE                                                    | $\alpha$        | Signal loss coefficient                                           |
| $\tau_{ij}$         | Level transition lifetime                                            | $T_2$           | Dipole relaxation time or finite gain bandwidth                   |

|                     |                                                    |                  |                                                                             |
|---------------------|----------------------------------------------------|------------------|-----------------------------------------------------------------------------|
| $\Delta\lambda$     | Gain-bandwidth                                     | $v_g$            | Pulse group velocity                                                        |
| $\overline{n_2}$    | Nonlinear Kerr refractive index                    | $t$              | Time variable                                                               |
| $\chi_{xxxx}^{(3)}$ | Third-order susceptibility with fourth-rank tensor | $z$              | Space variable                                                              |
| $n$                 | Linear refractive index                            | $U, \zeta, \tau$ | Dimensionless variables in chapter 5                                        |
| $a_{eff}$           | Effective mode area of the fiber core              | $T_0$            | Width of the input pulse                                                    |
| $a$                 | Fiber core diameter of TDFAs                       | $L_D$            | Dispersion length of TDFA                                                   |
| $P_0$               | Input signal power                                 | $N_l$            | Nonlinear parameter as a function of $L_D$ and $L_{NL}$                     |
| $a(z), b(z)$        | Weak modulation amplitude ( $\ll P_0$ )            | $\beta'_2$       | Modified mode propagation constant of order-2                               |
| $\Omega$            | Perturbation frequency                             | $\delta$         | Doping profile shape parameter                                              |
| $K(z)$              | Spatial Wave number                                | $\beta$          | Slope of the doping profile                                                 |
| $F(z)$              | Integrated gain                                    | $r$              | Radial distance from fiber axis                                             |
| $L$                 | TDFA length                                        | $k_{3011}$       | Cross-relaxation coefficient from $^3H_4 \leftrightarrow ^3H_6$ transitions |
| $\Omega_0$          | Cut-off perturbation frequency                     | $N_c$            | Clustered-ion population density of $Tm^{3+}$                               |
| $G$                 | Single-pass TDFA gain                              | $k$              | Relative number of ion clusters                                             |
| $P_{per}$           | Perturbation signal power                          | $mk$             | Percentage of ions in $Tm^{3+}$ cluster                                     |
| $f$                 | Normalized perturbation frequency                  | $N_s$            | Population of single $Tm^{3+}$ ion                                          |
| $L_{NL}$            | Nonlinear length of TDFA                           | $l_m$            | Effective interactive rate                                                  |
| $\eta$              | Correction factor                                  | $m$              | Number of $Tm^{3+}$ particles in a cluster                                  |
| $C$                 | Frequency chirp parameter                          | $H$              | Magnetic field                                                              |

## List of Symbols

---

|               |                                       |               |                                        |
|---------------|---------------------------------------|---------------|----------------------------------------|
| $A(z, t)$     | Slowly varying pulse envelope         | $\widehat{N}$ | Fiber nonlinearity handling operator   |
| $\beta_1$     | Mode propagation constant of order-1  | $\widehat{D}$ | Fiber dispersion handling operator     |
| $\widehat{U}$ | Nonlinear solution of NLSE using SSFM | $U$           | Dispersion solution of NLSE using SSFM |



## List of Publications

### Journal Publications

1. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Modulation Instability in Lossy and Non-linear Thulium Doped Fiber Amplifiers in S and near-C bands: Analytical and Numerical Approach,” *Optical Engineering*, SPIE, 59, no. 4, 046105, 2020.  
doi:10.1117/1.OE.59.4.046105
2. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Analytical model for Signal and Gain modulation on Thulium-doped fiber amplifiers in S and near-C bands including amplified spontaneous emission: Signal Power Analysis,” *Optical Engineering*, SPIE, 58, no. 2, 026103, 2019.  
doi: 10.1117/1.OE.58.2.026103
3. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Signal Wavelength Effect on Over-modulation in Thulium Doped Fiber Amplifiers with Amplified Spontaneous Emission: A Simulink Pedestal,” *Journal of Optical Communications*, de Gruyter, 43, no. 1, pp. 1-8, 2022.  
doi: <https://doi.org/10.1515/joc-2018-0192>

## Conference Publications

1. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Propagation Loss and Non-linear effects on Modulation Instability in Thulium Doped Fiber Amplifiers operating in S and near-C bands,” *2020 IEEE 8th International Conference on Photonics (ICP)*, Kota Bharu, Malaysia, pp. 1-2. IEEE 2020, doi: 10.1109/ICP46580.2020.9206421
2. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Performance estimation of Thulium doped fiber amplifiers in S-Band including Amplified Spontaneous Emission: Ion-Ion interaction analysis,” *TENCON 2019-2019 IEEE Region 10 Conference*, pp. 155-159. IEEE 2019. doi: 10.1109/TENCON.2019.8929580
3. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Numerical Modeling and Simulations on splitting of Chirped Optical Pulses in heavily doped Thulium Fiber Amplifiers through Modal Instability Analysis,” *Photonics Asia-2019*, pp. 1119510-1-11 SPIE, Hangzhou, China, 2019. doi: <https://doi.org/10.1117/12.2538902>
4. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Chirped Pulse Splitting in Heavily doped Thulium Fiber Amplifiers through Modal Instability: Numerical Modeling and Simulation,” *Progress In Electromagnetic Research Symposium-2019 (PIERS)*, Rome, 2A0-32, 2019.
5. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Overmodulation gain dynamics in thulium doped fiber amplifiers including amplified spontaneous emission,” *TENCON 2017-2017 IEEE Region 10 Conference*, pp. 2604-2608. IEEE, 2017. doi: 10.1109/TENCON.2017.8228301

6. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Analytical Model for gain modulation in Thulium doped fiber amplifiers (TDFA) operating in S-Band regime,” *OSI-International Conference on Light and Light Based Technologies (ICLLT)*, Tezpur University, Vol. 40, ICL2T/2016/082, 114, 2016.

## Other Publications

The following publications, authored/co-authored by the author of this thesis, are relevant but not included in the thesis:

1. Manoranjan Minz, Darpan Mishra, Ramesh Kumar Sonkar, and **Mohd Mansoor Khan** “Bandwidth optimization of germanium-doped silicon optical modulator for high-speed applications,” *Photonics Asia-2019*, pp. 111930T-1-6 SPIE, Hangzhou, China, 2019.  
doi: <https://doi.org/10.1117/12.2538873>
2. Darpan Mishra, Manoranjan Minz, Ramesh Kumar Sonkar, and **Mohd Mansoor Khan** “Grating-assisted MDM-PDM hybrid (de)multiplexer for optical interconnect applications,” *Photonics Asia-2019*, pp. 111930C-1-6 SPIE, Hangzhou, China, 2019.  
doi: <https://doi.org/10.1117/12.2538744>
3. **Mohd Mansoor Khan** and Ramesh Kumar Sonkar, “Design and proposal of dual line-of-defense perimeter watchdog incorporating optimally designed FBG based accelerometers and strain sensors using single optical fiber,” *7<sup>th</sup> International Conference on Optics and Photonics 2015*, vol. 9654, p. 965413 SPIE, Kolkata, India, 2015.  
doi: <https://doi.org/10.1117/12.2181626>





# 1

## Introduction to the Optical Amplifiers

### Contents

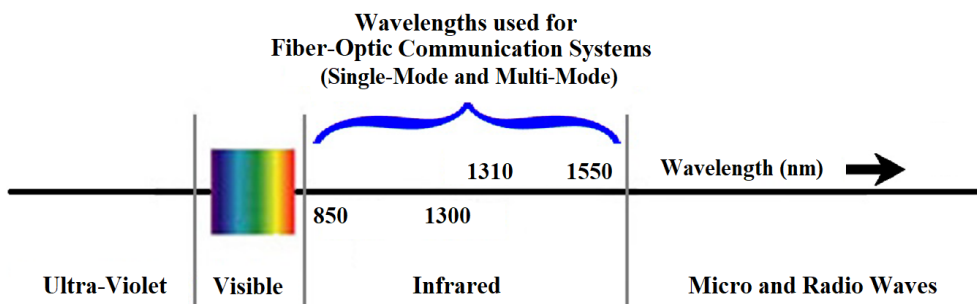
|     |                                                                 |    |
|-----|-----------------------------------------------------------------|----|
| 1.1 | Optical Communication Wavelengths                               | 2  |
| 1.2 | Fiber-Optic Communication System                                | 4  |
| 1.3 | Advantages and Applications of Fiber-Optic Communication System | 19 |
| 1.4 | Dopant based Classification of RE-DFAs                          | 21 |
| 1.5 | Applications of TDFAs                                           | 35 |
| 1.6 | Working Mechanism of TDFAs in S and near-C bands                | 38 |
| 1.7 | Research Motivation and the Problem Formulation                 | 39 |
| 1.8 | Thesis Contribution                                             | 41 |
| 1.9 | Thesis Overview                                                 | 42 |

### 1.1 Optical Communication Wavelengths

“Photonics - the electronics of 21<sup>st</sup> century” is the phrase that is being used with the advances in the technology of the optical-systems in today’s world. The present-day optical communication system utilizes substantially the fiber optics as its key component. The optical fiber communication system utilizes the low loss property of optical fibers as a waveguide. Broadly classifying, the wavelengths used for fiber-optic communication systems range from 800 nm to 1600 nm of the electromagnetic spectrum as shown in Fig. 1.1 [1–3]. The demand to push fiber-optic networks for higher speeds, larger distances, and high data capacity catered the need for new wavelength bands for the efficient operation of the system. With the advent of advanced technology in optical fiber fabrication, the material absorption of pure and “dry” silica (water-free) has been made negligible in the entire fiber-optic communication wavelength band [4]. Consequently, new transmission bands were identified, defined, and standardized based on the lowest transmission loss present in the optical fiber by the International Telecommunication Union-Telecommunication standardization Sector (ITU-T) as summarized in Table 1.1 [5–8]. The technological evolution of transmission from O-band to U-band and their relevance has been briefly summarised below.

#### 1.1.1 The O-band (Original band: 1260–1360 nm)

Fiber-optic transmission was responsible for the deployment of single-mode fibers with zero-dispersion regime in optical communication systems. The fibers produced in 1970s had the lowest loss near O-band due to minimum chromatic distortion of the signal. However, this wavelength window was not favoured for long-haul transmission due to increase in the effects



**Fig. 1.1:** The electromagnetic spectrum highlighting fiber-optic communication wavelengths.

**Table 1.1: Optical Communication Wavelength Bands**

| Band   | Description            | Wavelength Range |
|--------|------------------------|------------------|
| O-band | Original               | 1260–1360 nm     |
| E-band | Extended               | 1360–1460 nm     |
| S-band | Short-Wavelengths      | 1460–1530 nm     |
| C-band | Conventional           | 1530–1565 nm     |
| L-band | Long-Wavelengths       | 1565–1625 nm     |
| U-band | Ultra Long-Wavelengths | 1625–1675 nm     |

of optical non-linearities [9–13].

### 1.1.2 The E-band (Extended band: 1360–1460 nm)

It is generally referred as the “water-peak band” due to its high transmission loss regions owing to residual water (-OH group) impurity associated with the silica glass [9, 14]. However, the invention of dehydration technique in silica fiber fabrication, the attenuation of most commonly used optical fiber (ITU-T G.652.D) in the E-band has become lower than that in the O-band [5, 13]. Some research also reported the attenuation  $< 3$  dB/km but the use of E-band is still limited for long-haul communication due to fiber optic cables installed in 2000’s shows higher attenuation in E-band [15, 16].

### 1.1.3 The S-band (Short-Wavelengths band: 1460–1530 nm)

This band is utilized for many passive-optical network (PON) systems as the downstream wavelength [9, 13]. It has the lowest attenuation level except for the C and L-bands [17]. It however, owing to the facility of large bandwidth with comparatively lower attenuation, has been studied in recent past for signal amplification and communication which can be utilised in-situ with the existing state-of-the-art C-band optical communication [18].

### 1.1.4 The C-band (Conventional band: 1530–1565 nm)

It is the most exploited, commercialized, and viable band for the present day fiber optic communication system. Lowest attenuation of optical signal in the C-band motivated the optical scientists and engineers in the development of optical fiber operation in this band. It employs the 1550 nm “Erbium-Window” with narrow yet extensively exhausted gain-bandwidth of 70 nm [10]. Therefore, it is commonly employed in all-distance formats of fiber-optic communica-

## 1. Introduction to the Optical Amplifiers

| Name                  | O             | E               | S                 | C                                            | L         | U         |
|-----------------------|---------------|-----------------|-------------------|----------------------------------------------|-----------|-----------|
| Wavelength Range (nm) | 1260-1360     | 1360-1460       | 1460-1530         | 1530-1565                                    | 1565-1625 | 1625-1675 |
| Observation           | Original Band | Water-Peak Band | Short Wavelengths | Bands used by the higher performance systems |           | Not Used  |



**Fig. 1.2:** ITU-T based optical wavelength bands with arrow representing the wavelength increase to higher performance systems in general.

tion covering the metro, long-haul, ultra-long-haul (including transoceanic optical transmission system) with dense wavelength division multiplexing (DWDM) techniques [19]. Research efforts are being made in the development of new fiber amplifiers that promise to expand DWDM from S to L bands.

### 1.1.5 The L-band (Long-Wavelengths band: 1565–1625 nm)

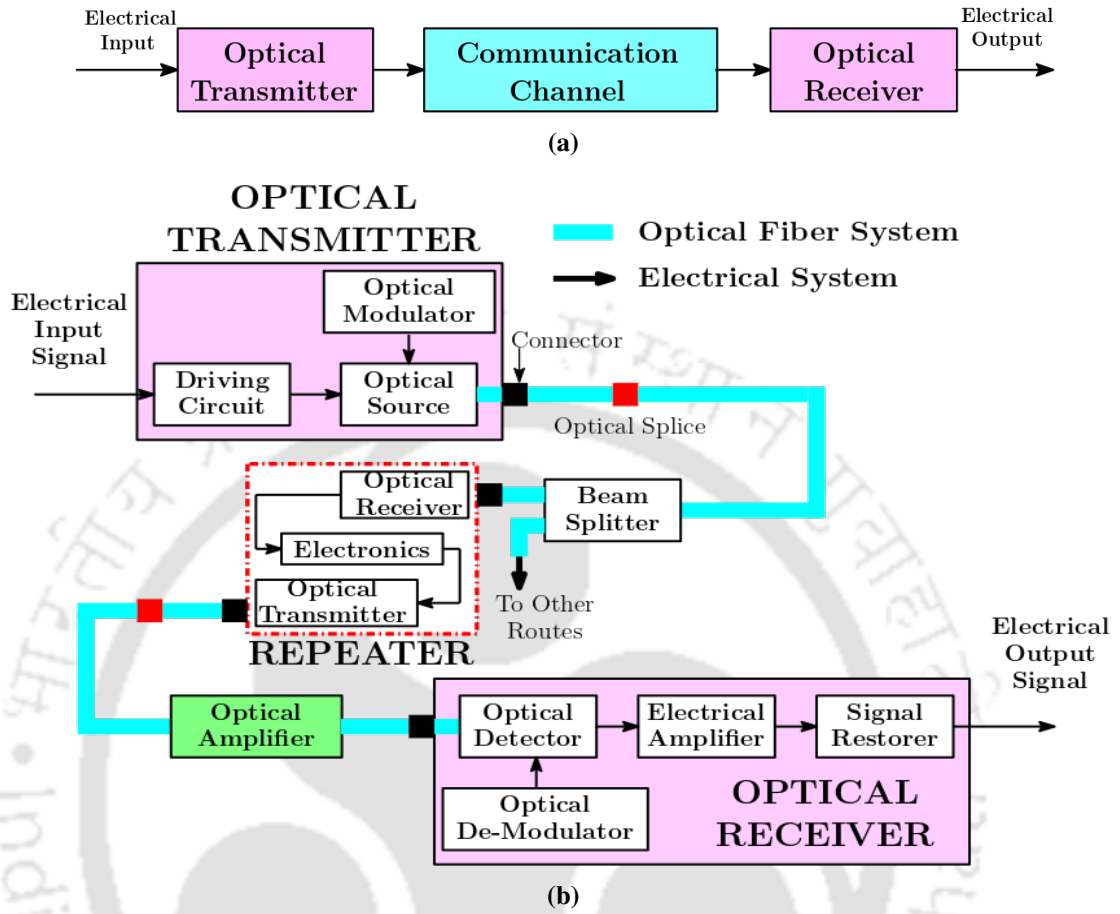
This band offers the second lowest attenuation with respect to the fiber-optics communication [17, 19]. The expansion of gain-bandwidth from the narrow C-band's "Erbium-Window" to L-band has been a subject of research in the recent past to cater the need of bandwidth demand. However, due to the use of Raman amplification to boost L-channel, the length requirements of the fiber often tend to maximize [20–23].

### 1.1.6 The U-band (Ultra Long-Wavelengths band: 1625–1675 nm)

It lies at the very end of the transmission allowance for silica fibers and carries considerable losses. It can be utilized for network monitoring purposes and is not suitable for long-haul communication system [5, 13, 24]. The above summary of the optical communication wavelength bands is shown in Fig. 1.2 as per the ITU-T definition [5, 8, 24].

## 1.2 Fiber-Optic Communication System

From the early civilizations to the modern-day world, "Light" has been in use in signaling and transferring information be it from fire, smoke signals, flashing of warship-torches, or the present-day free-space and fiber-optic communication system [12]. The higher carrier frequencies in optical-domain signal  $\sim 200$  THz compared to  $\sim 1$  GHz microwave carrier frequencies



**Fig. 1.3:** Illustration of (a) A generic optical communication system and (b) Essential elements of fiber-optics communication system showing components of optical transmitter, communication channel, and receiver respectively.

make them a high capacity information system [19]. Broadly classifying, the generic optical-communication system channel is categorized into guided and unguided using the optical-fibers and free-space mediums respectively which is connected to optical transmitter and receiver as shown in Fig. 1.3 (a). The fiber-optic in a communication system is used extensively in the present-day scenario and this thesis is focused on considering optical fibers as communication and amplifying media of the optical signals in a channel.

The communication channel of Fig. 1.3 (a) is when replaced by a guided media particularly an optical fiber results in a fiber-optic communication system as detailed in Fig. 1.3 (b). It shows the details of the building elements required for optical transmitter, optical fiber channel, and optical receiver [12, 19, 25–27]. The brief description of the corresponding blocks comprising of essential elements of Fig. 1.3 (b) are as follows:

## 1. Introduction to the Optical Amplifiers

---

### 1.2.1 Optical Transmitter

All naturally occurring signals are converted into electrical domain through sensors and transducers for its required further processing. Unlike the copper wire, the optical fiber cannot directly transmit the electrical signal without its conversion to the optical domain. Therefore, an optical transmitter is required to serve this purpose which comprises of three basic building blocks which are briefed as

#### 1.2.1.1 Optical Source

Light-emitting diodes (LEDs), semiconductor laser-diodes particularly vertical-cavity surface emitting laser (VCSEL), and fiber lasers are generally employed for the purpose of optical sources in a fiber-optic communication system [19, 26]. LEDs have comparatively broader spectral width than a semiconductor laser diode or a fiber laser [28–30]. LEDs are cost-effective optical sources that can be easily modulated and therefore proven to be apt for short distance fiber-optic communication and optical isolators. However, due to broad spectral width, the necessity of requirement for multi-mode optical fibers becomes its limitation.

VCSELs are laser diodes with a monolithic laser resonator where the emission of light takes place normal to the surface. They can be put into service with multi-mode fibers and free-space communication when modulated with frequencies in the giga-Hertz range. Various research has been done on the material selection and structure of VCSELs to increase the data rate up to 25–40 Gbit/s emitting at 850–1100 nm range [30–32].

Lasers from its early inception and development in the 1960s revolutionized the field of opto-electronics, particularly in communication. Therefore, it is apparent that solid-state and fiber lasers have been in utility by acting as an optical pump for population inversion in optical fiber amplifiers or generation of primary data pulses either in continuous wave (CW) or in pulsed form [33].

#### 1.2.1.2 Driving Circuit and Optical Modulator

A circuit which controls the output of another component output is known as a driving circuit for that component. Its basic purpose is to provide stable electrical power to the optical source



be it LED or semiconductor laser diodes [19]. The driver circuitry is commonly paired with the modulation scheme for the output current which is fed to the optical source and modulates the optical output (intensity modulation) as per requirement. The feedback mechanism in the driving circuit is used to control the temperature of the device by sensing the output current, consequently saving the optical source from catastrophic optical damage [34–36].

### 1.2.2 Communication Channel

The modulated optical signal generated from the optical transmitter is sent to desired distances through a guided channel of optical fiber spliced to optical source through a connector and fiber fly head as illustrated in Fig. 1.3 (b). The ideal channel should not distort the information, therefore, low-loss silica optical fibers with large light acceptance/cone angle are considered with loss limited to 0.2 dB/km [19]. However, to compensate for the  $\sim 99\%$  signal-loss in long-haul ( $> 100$  km) fiber-optic communication systems, the role of a repeater and optical amplifier are of utmost importance for the faithful detection of the true signal [19]. Fiber dispersion broadens the optical pulse traversing through it and is another factor which has to be considered and taken-care to avoid information distortion. In case of multi-mode fibers, different modes travel with different group velocities eventually broadening the pulse [1]. Consequently, single-mode fibers are mostly deployed in fiber-optic communication system. The fiber communication channel primarily comprises of beam-splitters, signal-repeaters, and fiber amplifiers which are spliced to optical detector through a connector as shown in Fig. 1.3 (b) and can be summarised below:

#### 1.2.2.1 Beam-Splitters

Optical fiber beam-splitters are essentially the fiber-couplers used in the reverse configuration for various purposes. For instance, they are required for fiber-optic interferometers or for the distribution of data from a single source to multiple users in a fiber-optic network [9]. It can be seen in Fig. 1.3 (b) that optical fiber beam-splitters are often used for optical power splitting in the desired ratio for various applications owing to their high-efficiency coupling property [37,38]. These devices can be manufactured by fusion-combining the fibers such that

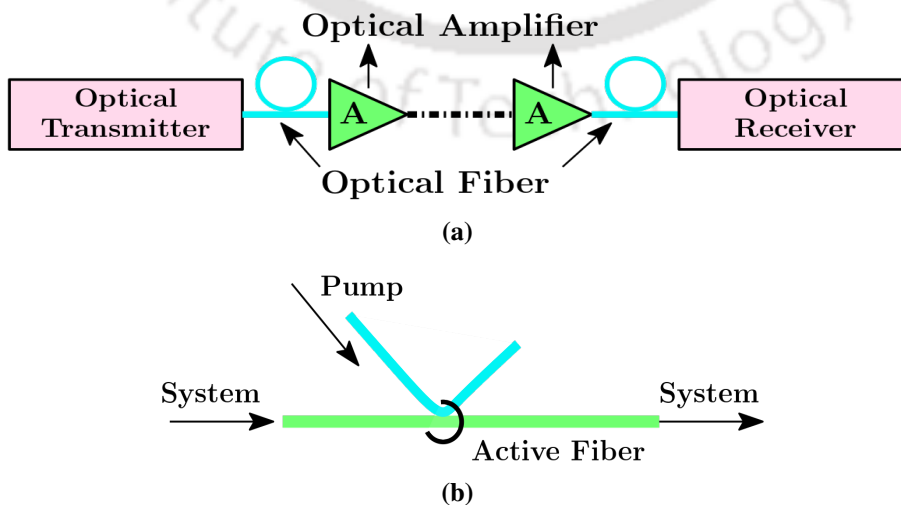
## 1. Introduction to the Optical Amplifiers

their core comes in close proximity and the physics of coupling is governed by coupled-mode theory [39,40]. Essentially, the fusion-losses during the splicing process has to be taken care-off for better system performance.

### 1.2.2.2 Signal-Repeaters

The optical losses incurred while propagating through the fiber were managed through opto-electronic repeaters until 1990. These repeaters, shown in dash-dot box of Fig. 1.3 (b), consist of receiver-transmitter pair with an optical-electrical-optical (OEO) mechanism with every 80 km of spacing [19]. However, with the advent of WDM/DWDM systems, the technology became expensive with respect to more complexity, lower bandwidth, and higher cost as each repeater would require individual de-multiplexing action. Therefore, a better alternative (red dash-dot block in Fig. 1.3 (b) denoting the replacement) to OEO type repeater is an optical fiber amplifier with the simultaneous advantage of amplifying multiple WDM channels.

The amplification scheme can be used as lumped and distributed amplifiers with the former shown in Fig. 1.4 (a). The fiber amplifiers (shown in Fig. 1.4 (b) with pumping mechanism) are employed as all-optical repeaters with a usual spacing of 60 to 100 km per repeater in a long-haul fiber-optic communication system. The later mentioned scheme uses the passive fiber itself for signal amplification employing the stimulated Raman scattering (SRS) as Raman amplifiers and Brillouin fiber amplifiers [41,42]. The all-optical repeaters are designed to carry



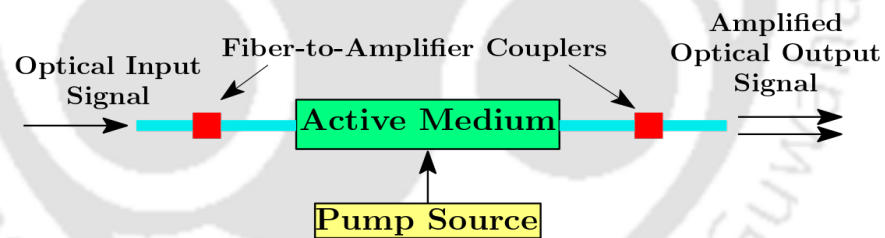
**Fig. 1.4:** Illustration of (a) Lumped all-optical communication repeater with optical fiber amplifier as one of the most employed repeater shown in (b).



out 3R-process (reamplification, reshaping, and retiming) of signal pulses utilizing the popular Mamyshev 2R regenerator scheme with additional regeneration stage [43–45].

### 1.2.2.3 Optical Amplifiers

Optical amplifiers boost the amplitude level of the modulated signal without requiring the OEO conversion which is otherwise required at repeated location in a network [46]. These devices can be operable in bidirectional mode with the most important feature of supporting the WDM action. In the case of single-mode fiber (SMF), the dispersive effect on signal is low which serves as an added advantage of amplifying the optical signal instead of full regeneration [1]. An optical amplifier may be considered simply as a laser without optical feedback as shown in Fig. 1.5 [47]. The active medium may comprise of a semiconductor optical amplifier (SOA), optical fiber amplifier, or distributed amplifiers consisting of Raman and Brillouin fiber amplifiers. Besides, it has been observed that optical amplifiers also serve the purpose of optical gates, pulse shapers, and routing switches when operated in a non-linear mode [48–52].

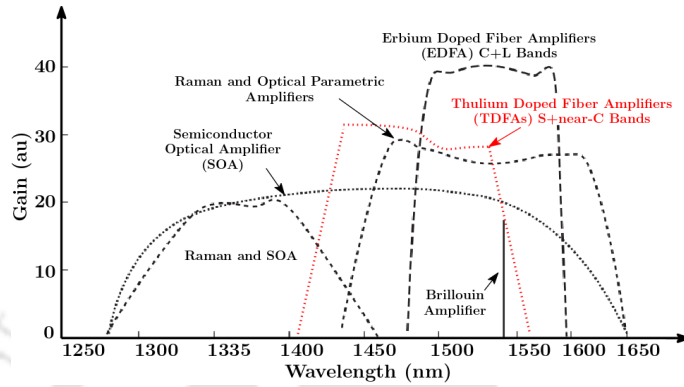


**Fig. 1.5:** Representation of general optical amplifier system functioning.

Categorically, the power-amplifier and pre-amplifier serves the purpose of boosting the signal power at the input and before the optical receiver respectively in the fiber-optic communication system. However, the line-amplifiers in a communication channel are located at strategic points to restore the signal strength as per the requirements making them the key component of the system. The pre-amplifiers should inculcate the properties of high gain with low noise figure. Broad classification of optical amplification schemes comprises of semiconductor optical amplifiers utilizing the stimulated emission from injected carriers and fiber amplifiers. Raman and Brillouin fiber amplifiers belong to the class of undoped fiber amplifiers while doped fiber amplifiers with rare-earth elements as the dopants. The later class which serve till date as the

## 1. Introduction to the Optical Amplifiers

foremost importance among optical amplifiers. For a quantitative impression, the comparative gain-profile and spectral-bandwidth characteristics of different classes of optical amplifiers can be observed in Fig. 1.6 [1, 53, 54].

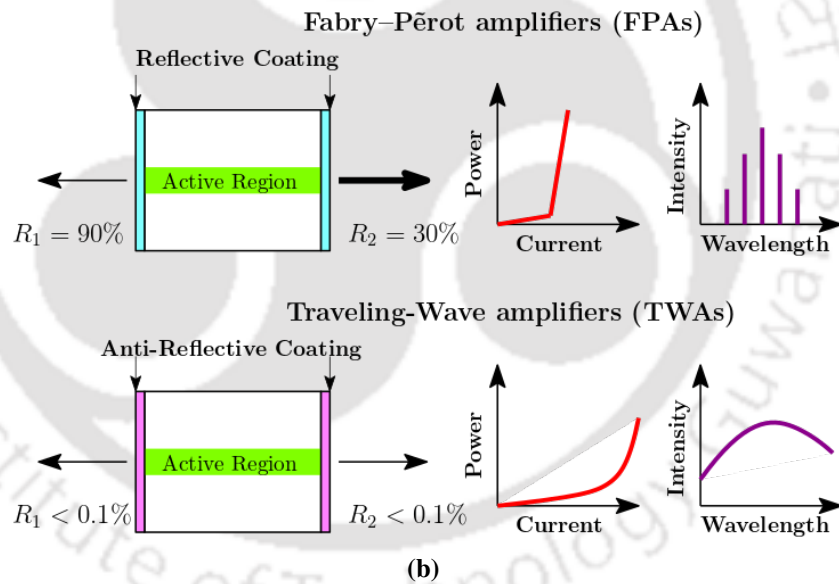
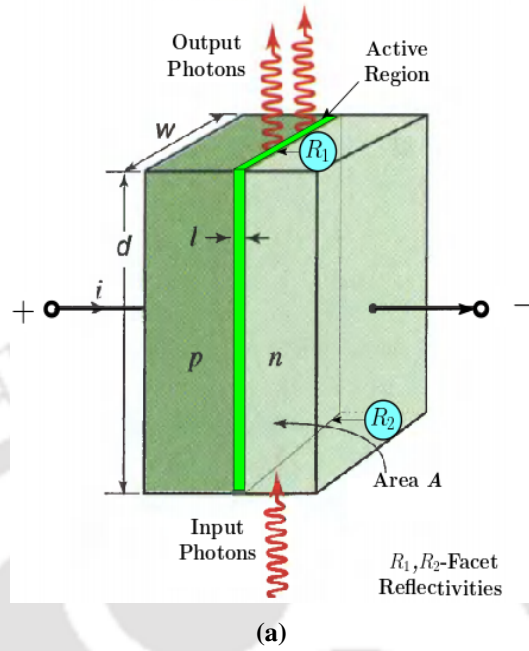


**Fig. 1.6:** Gain–bandwidth characteristics of different optical amplifiers.

The qualitative illustrations of the gain profiles of different optical amplifiers were not limited to the values mentioned in Fig. 1.6. Owing to continued research in this field, amplification is possible beyond these gain values. Therefore, basic categorization of optical amplifiers is needed to give an idea of the parameters on which the amplification is dependent. These are discussed as follows

### 1.2.2.3.1 Semiconductor Optical Amplifiers (SOAs)

It is essentially an optical amplifier operational in both the linear and non-linear modes with semiconductor gain medium using stimulated emission to amplify the optical signal. The active region of the semiconductor optical structure is similar to that of a typical laser diode, as shown in Fig. 1.7 (a), with dimensions of active region thickness  $l$ , height  $d$ , and width  $w$  [1, 47]. They can be broadly classified into two clusters namely the Fabry–Pérot amplifiers (FPAs) and traveling-wave amplifiers (TWAs) with respective facet reflectivities as the differentiating factor among the two [55–57]. Facet reflectivities ( $R_{1,2}$ ) with values around 0.3 give rise to FPA with high resonant peaks having very narrow passbands with trivial semiconductor laser action. However, the spectral bandwidth of an SOA can be increased by employing anti-reflection coatings to nullify the end reflectivities resulting in TWA. It has a benefit of the transmission being nearly independent of bias current fluctuations. The TWAs are single-pass amplification



**Fig. 1.7:** (a) Geometry of a typical  $pn$ -junction SOA and (b) The shape and characteristics of FPAs and TWAs.

process and provide advantages in terms of superior signal gain saturation and noise-figure with respect to FPA. The comparative structure and their respective characteristics are illustrated in Fig. 1.7 (b) [58].

Semiconductor optical amplifiers being smaller in size can be easily integrated in the optical-communication systems and networks as pre-amplifiers. They can offer an optical gain of 15 dB to 35 dB having low power consumption with tapered-tip single-mode fiber integration

## 1. Introduction to the Optical Amplifiers

advantage [1]. The full-width at half maximum (FWHM) or the 3 dB bandwidth provided by SOA can be extended more than 100 nm using quantum-dot SOA technology [59–62]. The SOA has extremely fast gain dynamics due to short carrier lifetime of sub-nano second range which in-turn is the cause of interchannel cross talks or noise. However, this disadvantage has also been used as a non-linear process to accomplish fast all-optical switches and cross-phase modulation mechanisms for different applications [59].

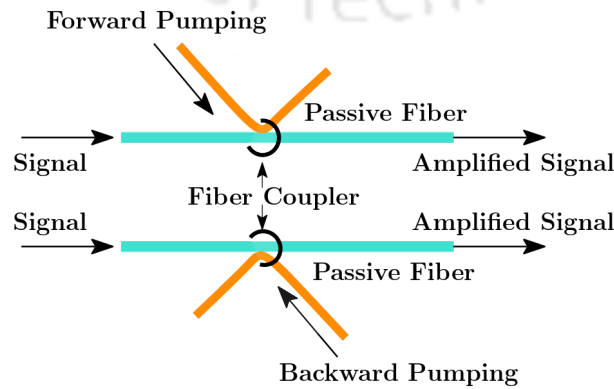
### 1.2.2.3.2 Raman Fiber Amplifiers (RFAs)

Stimulated Raman scattering (SRS) is a non-linear phenomenon responsible for the development of Raman fiber amplifiers in silica or fluoride fibers [19, 63]. During SRS, the pump-photon's energy is coupled to the thermal phonons and vibrational modes resulting in the wavelength shift towards longer wavelength. This shift in wavelength changes by the factor corresponding to the molecular vibration frequencies of the glass matrix [64].

It is a continuous pump-to-signal energy transfer process which is illustrated in Fig. 1.8 with forward and backward pumping scheme. The pump and signal self-phase matching with broad gain-bandwidth extending to 300 nm covering almost the entire optical-communication band as evident from Fig. 1.6 are the foremost advantages of RFA applicable in DWDM systems [1, 65].

The Raman signal-gain ( $G_R$ ) as high as 40 dB has been obtained with fluoride glass fibers which can be expressed as [1, 19]

$$G_R = \exp \left( \frac{g_R P_R L_{eff}}{A_{eff} k_R} \right) \quad (1.1)$$



**Fig. 1.8:** Schematics of the forward and backward pumping schemes associated with the Raman fiber amplifier.

where  $g_R$  is the power Raman gain coefficient,  $k_R$  is the Raman numerical factor,  $A_{R_{eff}} = \pi r_{R_{eff}}^2$  and  $L_{R_{eff}} = \{1 - \exp(-\alpha_{R_p} L)\} / \alpha_{R_p}$  are the effective Raman fiber core mode area and length respectively. The Raman fiber loss factor is represented by  $\alpha_{R_p}$ . It is evident from (1.1) that RFA gain is a strong function of pump power and fiber length. As the fiber length is increased the RFA gain also increases, however, at the cost of amplified spontaneous emission (ASE) as a major contributor to amplifier noise [66]. The backward pumping scheme is used to minimize the interaction time between pump and signal which helps in the reduction of interactive pump-signal relative intensity noise (RIN) [67]. In recent studies, it has been observed that by using hybrid versions of FRA with doped-fiber amplifiers, high power laser can be demonstrated with peak power as large as 1 kW [68, 69]. Also, the diverse usage impact of FRA in the field of long-haul optical communication is also observed with transmission distance over 6300 km [70]. However, major limitations associated with FRAs in the form of ASE and associated infrastructural costs should be taken into consideration.

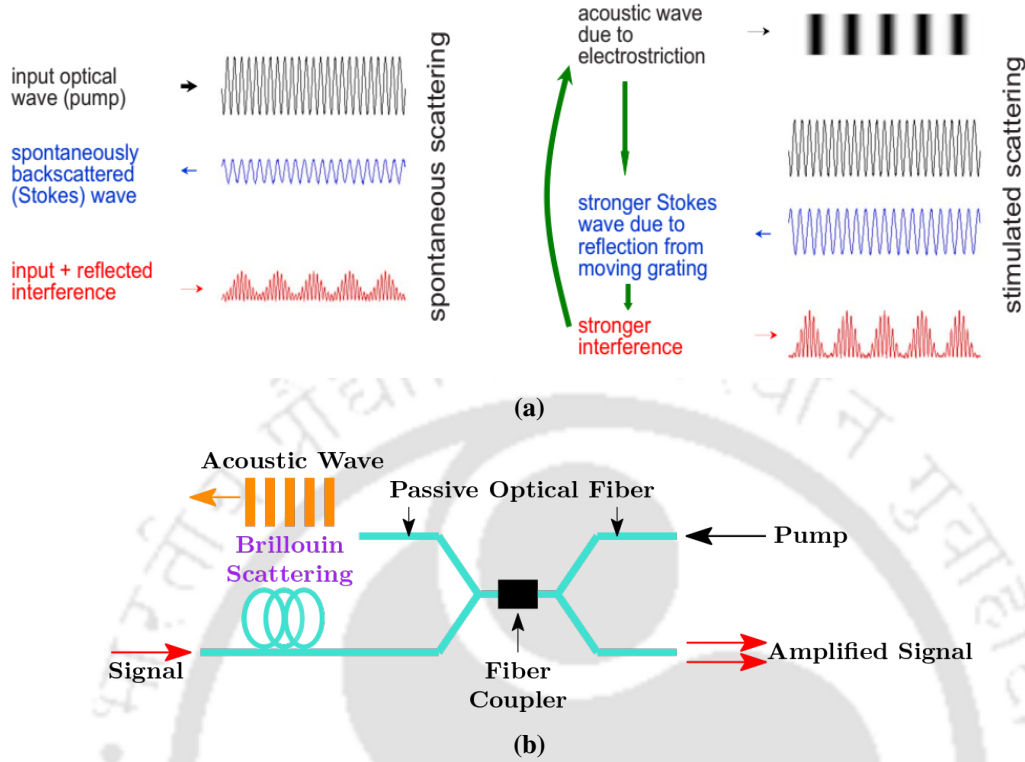
However, the major limitations of ASE and infrastructure costs for FRA have to be mitigated for extensive commercial usage.

#### **1.2.2.3.3 Brillouin Fiber Amplifiers (BFAs)**

The third-order susceptibility ( $\chi^{(3)}$ ) creates the non-linearity in a medium contributing to another scattering effect named after its first observer L  on Brillouin back in 1922 [71]. The phenomena deals with the interaction of light with acoustic phonons. The electrostriction process couple optical field and acoustic wave where an incident photon is converted into a lower frequency (Stokes wave) scattered photon, propagating in the backward direction, and a phonon [1, 72].

The Brillouin scattering is although a weak effect but in the case of optical fibers it is certainly a noticeable and undesirable effect under respective condition. At a certain threshold pump power, the Stokes wave traveling in the opposite direction becomes stimulated resulting in very efficient energy conversion from input pump to back-scattered photons and phonons with a process of stimulated Brillouin scattering (SBS). At this particular threshold pump power, the SBS can effectively reflect most of the incident power with a significant increase in the Stokes wave. In a way, the forward propagating acoustic wave acts as a refractive index grating or

## 1. Introduction to the Optical Amplifiers



**Fig. 1.9:** (a) The spontaneous and stimulated Brillouin scattering mechanisms with later showing the stronger interference of input and reflected waves and (b) A representation of typical Brillouin fiber amplifier scheme in a passive optical fiber.

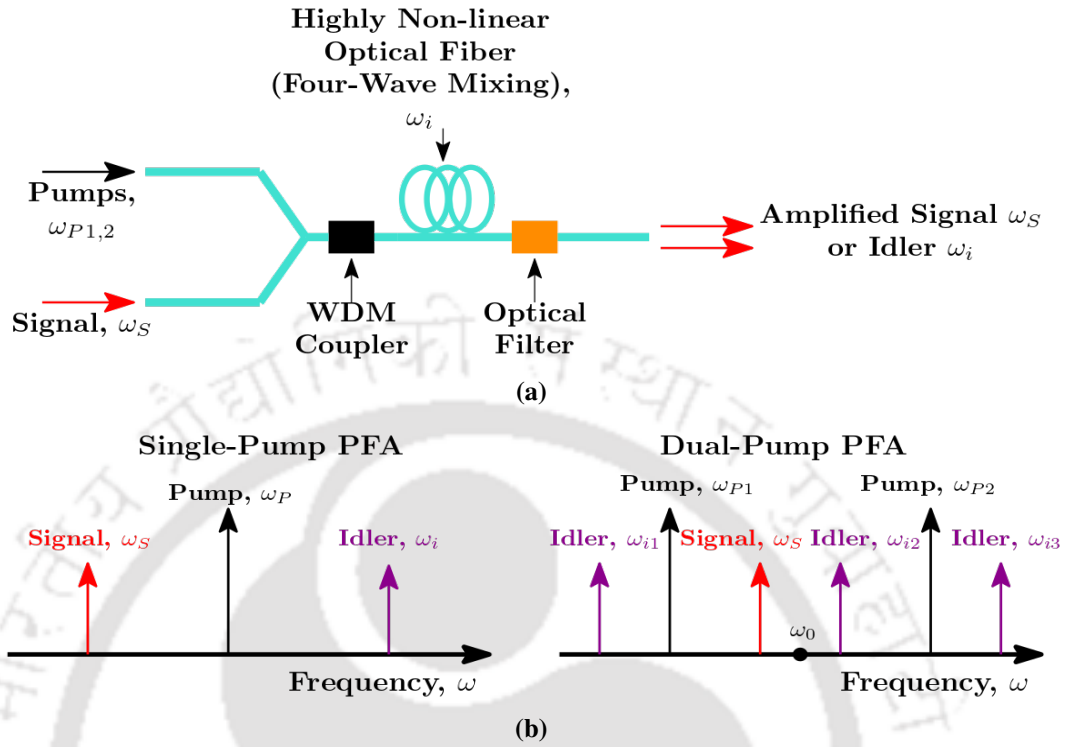
a Bragg grating which provides a non-linear optical gain for the back-scattered wave. The illustration of the Brillouin scattering mechanism is shown in Fig. 1.9 (a) [73].

The mechanism of Brillouin fiber amplification using SBS has been shown in Fig. 1.9 (b) [72]. The Brillouin shift inside the optical fiber with refractive index  $n_{B_{eff}}$ , acoustic velocity  $v_A$ , and the Brillouin pump wavelength  $\lambda_{B_p}$  can be given as [72]

$$\nu_P - \nu_S = \Delta\nu_B = \frac{2n_{B_{eff}}v_A}{\lambda_{B_p}} \quad (1.2)$$

where  $\nu_P$  and  $\nu_S$  are the pump and signal frequencies respectively. The frequency of acoustic phonons is represented as  $\Delta\nu_B$ . It can be observed from Fig. 1.2 that the Brillouin frequency shift depends on the effective refractive index of the optical fiber which in-turn is dependent on the temperature and pressure of the medium. This property can be effectively utilized in the development of fiber-optic sensors [1, 74]. As can be observed from Fig. 1.6, the SBS is a narrow-band process with (15–50) MHz gain-bandwidth for silica fiber near 1550 nm which significantly reduces the application of the BFA in high-speed communication systems [1].





**Fig. 1.10:** (a) Generic illustration of the parametric fiber amplifier and (b) Spectrum of single-pump and dual-pump PFA with respective signal idler waves. Under phase-match condition a perfect symmetry if spectra are observed around zero-dispersion wavelength  $\omega_0$ .

However, this limitation can be constructively utilized to develop tunable filters within WDM systems [75]. Due to its frequency selectiveness, the long-distance, > 500 km, frequency transfer has been achieved using BFA as an essential component [76, 77].

#### 1.2.2.3.4 Parametric Fiber Amplifiers (PFAs)

Optical fibers (passive, active, photonic crystals) offers a perfect environment for non-linearity due to its narrow cylindrical confinement of signal. The non-linear medium offers a scattering to the incoming strong signal and in-turn amplifying any other signal present in the medium using four-wave mixing (FWM) mechanism. The phenomenon of FWM is responsible for creating an optical-idler signal at frequency  $\omega_i = 2\omega_p - \omega_s$  with  $\omega_p$  and  $\omega_s$  being the optical pump and signal frequencies respectively [1, 19]. It can be observed from the illustration of Fig. 1.10 (a) that signal and pump waves are fed through a WDM-coupler to a highly non-linear optical fiber. Consequently, at the phase matching condition when the channel wavelength lie close to zero-dispersion wavelength, it triggers a process of FWM [19]. The pump signal power is transferred to the feeble input signal via FWM. Consequently, it results in a new signal with

## 1. Introduction to the Optical Amplifiers

---

frequency  $\omega_i$  with comparatively larger magnitude than signal which can be filtered out through optical filter as per the requirement.

The parametric gain from FWM can be written as an exponential function of pump-power ( $P_P$ ), non-linear parameter ( $\gamma$ ), and optical-fiber length ( $L$ ), given as [1, 19, 78]

$$G_P = \frac{1}{4} \exp(2\gamma P_P L) \quad (1.3)$$

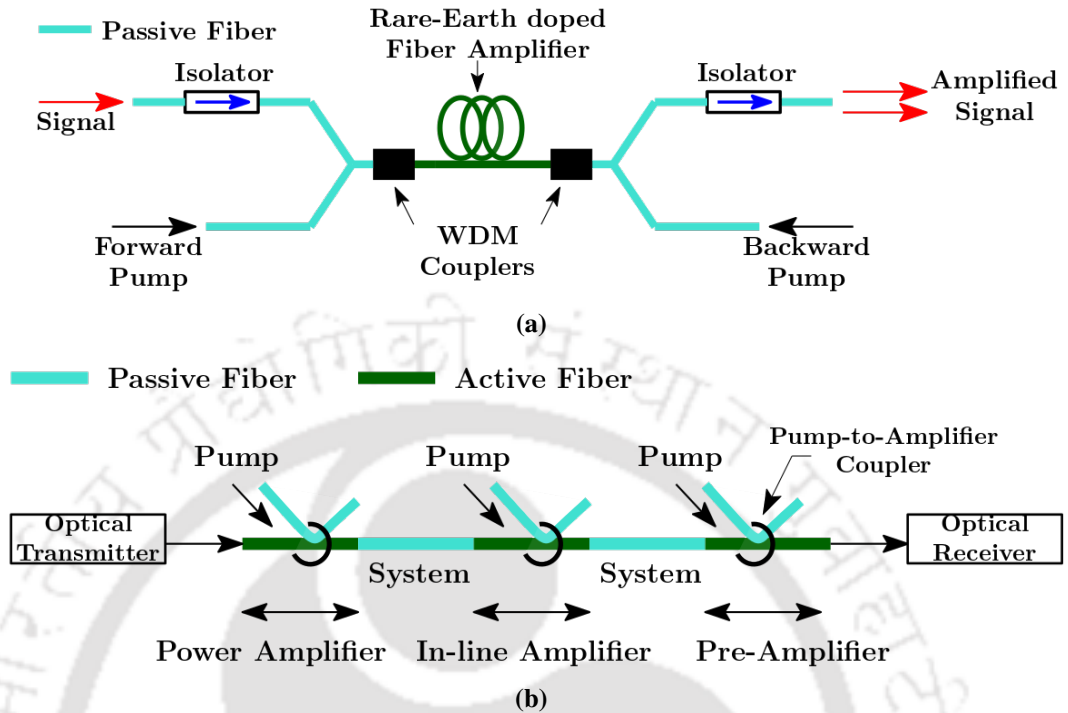
The non-linear parameter is related to the small effective cross-section area of fiber as  $\gamma \propto 1/A_{eff}$ , therefore, optical-fibers become the dominant reason for non-linearity. Single-pump or dual-pump may be employed for parametric gain, however, the later is used to increase the bandwidth by creating more idler signals as shown in Fig. 1.10 (b) [19, 79]. A parametric gain > 30 dB was observed for a 50 m long fiber at  $\gamma = 100 \text{ W}^{-1}\text{km}^{-1}$  with pumping power of 1 W [19]. A PFA can be used in a versatile manner such as a linear optical amplifier, wavelength converter, pulse generator, optical sampler, etc. [79]. However, a high noise factor is an alarming issue for such amplifiers.

### 1.2.2.3.5 Rare-Earth Doped Fiber Amplifiers (RE-DFAs)

Modern fiber-optic communication systems rely on rare-earth doped fiber amplifiers (RE-DFAs) for optical amplification and regeneration of signals. Besides having several advantages over SOA in terms of higher gain, lower inter-channel cross talks, and easy optical coupling, it can also serve as a non-linear medium for pulse shaping [19, 59, 80, 81]. As shown in Fig. 1.11 (a), a typical RE-DFA consists of pump and signal sources which are coupled through WDM couplers to avoid combinational losses. It is then passed through a rare-earth doped fiber of optimum length and the signal is amplified through population-inversion. This amplified signal is obtained at the output port via optical isolator to minimize the effect of oscillations. The pumping scheme employed may be categorized into forward, backward, or bi-directional modes as per the system's requirement [19].

The RE-DFAs can serve as a signal booster/power amplifier in case of a feeble input signal. The in-line and pre-amplifiers provide the functions of optical repeaters and pre-amplification respectively as illustrated in Fig. 1.11 (b). The most commonly used fibers with rare-earth-





**Fig. 1.11:** (a) Generic illustration of rare-earth doped fiber amplifier showing all essential components and (b) The usage and employment of RE-DFA in optical communication system as power, in-line, and pre-amplifiers respectively.

**Table 1.2:** Commonly used Dopants in Host Glass with Absorption and Emission Wavelengths for RE-DFA

| Dopant-Ion                        | Host Glass                       | Pump Wavelengths (nm)               | Emission Wavelengths (nm)      |
|-----------------------------------|----------------------------------|-------------------------------------|--------------------------------|
| Neodymium ( $\text{Nd}^{3+}$ )    | Silicate, Phosphate              | 808, 880                            | 900–950, 1030–1100, 1320–1350  |
| Ytterbium ( $\text{Yb}^{3+}$ )    | Silicate                         | 860, 920, 976                       | 976, 1000–1100                 |
| Erbium ( $\text{Er}^{3+}$ )       | Silicate, Phosphate, Fluoride    | 980, 1480, 1530                     | 1500–1600, 2700                |
| Thulium ( $\text{Tm}^{3+}$ )      | Silicate, Germanate, Fluoride    | 793                                 | 480, 800, 1450–1530, 1700–2100 |
| Praseodymium ( $\text{Pr}^{3+}$ ) | Silicate, Fluoride, Chalcogenide | 490, 520, 600, 635, 1300, 3500–7200 |                                |
| Holmium ( $\text{Ho}^{3+}$ )      | Silicate, Fluorozirconate        | 2051                                | 2100, 2900                     |

doped laser-active ions in host glasses with corresponding absorption pump and emission wavelengths have been summarised in Table 1.2 [1, 19, 82–87]. The chemical composition of host-glass plays a crucial role in describing the performance of the fiber amplifier. For example, it effectively plays a vital role in the selection of optimum Giles-parameters (doping concen-

## 1. Introduction to the Optical Amplifiers

---

tration, effective mode area, and effective transition cross-section areas) to characterize the RE-DFA [80]. A host-glass may affect the quenching effect and propagation losses by incorporating the maximum possible dopant concentration [88]. The silica as a host-glass material has amorphous nature which can broaden the energy levels into bands resulting in the possibility of multi-transition pumping [19].

Among different RE-DFAs, the most common considered for the discussion are doped with Neodymium ( $\text{Nd}^{3+}$ ), Ytterbium ( $\text{Yb}^{3+}$ ), Praseodymium ( $\text{Pr}^{3+}$ ), Erbium ( $\text{Er}^{3+}$ ), Thulium ( $\text{Tm}^{3+}$ ), and Holmium ( $\text{Ho}^{3+}$ ) as a sole dopant or co-doped with primary dopant ion. Additionally, basic working mechanism of plastic optical fiber amplifiers (POFA) is also included as the part of discussion. The short inclusion on types of RE-DFAs is highlighted in section 1.4.

### 1.2.3 Optical Receiver

Optical receiver converts the received optical signal to the electrical domain for further amplification and processing. It is one of the crucial blocks of a fiber-optic communication system to increase overall system performance. The infrastructure cost and maintenance in case of good performance optical receiver may result in fewer repeaters which eventually lowers the noise or increases the overall signal-to-noise ratio (SNR) [1]. As shown in Fig. 1.3 (b), it consists of an optical detector with a corresponding de-modulator, electrical amplifier, and signal restorer. These essential components are briefly described below:

#### 1.2.3.1 Optical Detector and De-modulator

After traversing along the channel, the optical signal is beamed and focused on the optical receiver via an optical coupler. The optical receivers, generally referred to as photo-detectors, are classified into different types based on their respective working mechanisms. A photo-multiplier tube (PMT) and vacuum photo-diodes uses an external photo-emission with high sensitivity, however, they are bulky and costly [1, 89]. On the other hand, the semiconductor photo-diodes with p-n, p-i-n, and avalanche configuration employing silicon, germanium, or compound semiconductor like GaAs, InGaAs, etc. uses internal photo-emission process. They provide advantages of high quantum efficiency, short response time, high compactness, and

cost-effectiveness besides others. Various research have been conducted on achieving high quantum efficiencies with the heralding values as high as 93% [90–92].

Depending on the type of modulation scheme, the de-modulation format is designed within the fiber-optic communication system. The FSK and PSK modulations require the most common homodyne or heterodyne de-modulation schemes [19]. However, an intensity modulation scheme referred to as intensity modulation with direct detection (IM/DD) is a fairly easy implementable scheme. The decision circuit demodulates by identifying the bits as ‘1’ or ‘0’ with direct detection of the signal amplitude. Along with SNR, the bit error rate (BER) is an important parameter that determines the system performance. It is defined as the average probability of incorrect bit identification during the de-modulation process [19]. Generally, an acceptable fiber-optic communication system has a BER of  $10^{-9} - 10^{-12}$ .

#### 1.2.3.2 Electrical Amplifier and Signal Restorer

The photo-detector within the optical receiver block of Fig. 1.3 (b) detects the distorted and weakened signal emerging at the end coupler. Therefore, for successful de-modulation and faithful re-coverage of the transmitted information, an electrical amplification and restoration of the original signal are required. During the course of an optical signal from transmitter to detector, it is interfered by various noises which tend to decrease the SNR and eventually increasing BER [1, 19, 93]. Hence, signal restoration is a key aspect for the optical system designers to manage the BER value to an acceptable limit of the fiber-optic communication system. Recently, many works have been carried out in designing of efficient signal restorers with BER value as low as  $10^{-21}$  [94, 95].

### 1.3 Advantages and Applications of Fiber-Optic Communication System

The advantages of optical fibers are self-evident especially in the area of optical communication. Optical fibers generally referred to as fibers, are relatively low in cost and offer flexibility for compact design systems. They have a large surface area to volume ratio for efficient heat dissipation and are less sensitive to gradual bend losses. An excellent feature of spatial beam quality makes them a perfect selection as a waveguide [89]. Apparently, some of the striking

## 1. Introduction to the Optical Amplifiers

---

features proven to be advantageous over conventional copper-wire electrical communication can be summarised below

### 1.3.1 Large Band-width

The optical fiber acts as an enormous amount of information carrier by considering there large band-width capability. The capacity which they lead by a gigantic figure of the orders of  $\sim 10^5$  over co-axial copper cables [1]. In fact, the present state-of-the-art EDFAs band-width has been recently increased in its communication window of 1550 nm by 50%, raising it to 6 THz [96]. Apparently, to overcome the bottleneck of EDFAs at 1550 nm “Erbium-Window”, search for new materials to further increase the band-width limits for DWDM fiber-optic communication is an on-going trend.

### 1.3.2 Electrically Isolated and Immune to Interference

Glass, the preform to the commercial optical-fibers, being the natural insulator and electrically isolated and can be used in hazardous environment like nuclear power-plants. Furthermore, the dielectric properties of optical fiber makes them immune to electromagnetic interference (EMI). The simultaneous cabling of optical-fibers and metal conductors for electrical supply do not interfere or cross-talk with each other [1]. Apparently, research has been carried out to check the stability of optical data with respect to temperature in a optical-fiber. It is demonstrated that a look-up table for a particular optical-fiber type can be obtained to fix the variation in polarization dispersion with respect to temperature to keep the information faithful [97, 98].

### 1.3.3 Secure, Reliable, and Minimal Transmission losses

Due to obvious low cladding losses, the leak of an optical signal carrying the information is negligible making it secure. However, tapping attacks are possible by physically removing the fiber cladding and splitting the signal to attain the information [99]. Extremely low transmission optical-fibers have resulted to curtail the losses to 0.15 dB/km. This maintains the faithfulness of transmitted information at the receiver [1]. However, strategies have been adopted to overcome any fiber-transmission distortion which may have taken place.

### **1.3.4 Low in Cost and Easily Expandable**

Particularly in long-haul communication systems, the comparative infrastructure cost of optical-fibers is significantly lower than conventional metallic wires [1]. Additionally, the low power requirements of the fiber-optic communication system further optimize the cost of operation in the long run. The system can be easily expandable for future demands compatible with the new types of optical-fibers and amplifiers.

### **1.3.5 Ubiquitously Applicable**

Various advantages of fiber-optic communications made them to be used in numerous different applications. In communication networks, they are employed from a wide area network (WAN) to optical-interconnects to scale computational speed and curb with the energy-bandwidth limitations of conventional copper wire [100–102]. The same can be effectively employed as a sensing agent to ensure the quality in the manufacturing industry including liquids such as milk, juices, power transformer oil quality [103–106]. Recently, an emergent field in the application of quantum encryption in existing fiber-optic communication paved new ways in network security [107].

## **1.4 Dopant based Classification of RE-DFAs**

The primary advantage of doping the host glass with rare-earth ( $\text{RE}^{3+}$ ) ion is the variation of energy position in their optical spectrum is minimal for different host glasses [85]. However, the spectroscopic parameters, namely the emission and absorption cross section areas (CSAs) or the Giles-parameters, may differ accordingly with the selected host glass type [80, 108–111].

Some of the common host glasses for RE-DFAs can be summarised in Table 1.3. All the mentioned host glasses possess the important properties required for the fabrication of optical-fibers. Consequently, the optical-fiber glass matrix is made prone to change its properties like thermal, spectral, mechanical, and non-linearity with doping [85]. The silica based optical-fibers have advantage of being drawn in long lengths with high grade quality of transmission required for long-haul fiber-optic communication. However, with high phonon energy of  $\sim 1100$

## 1. Introduction to the Optical Amplifiers

**Table 1.3:** Commonly used host glasses for RE-DFAs with corresponding chemical composition ( $x, y$  representing the variable mol %).

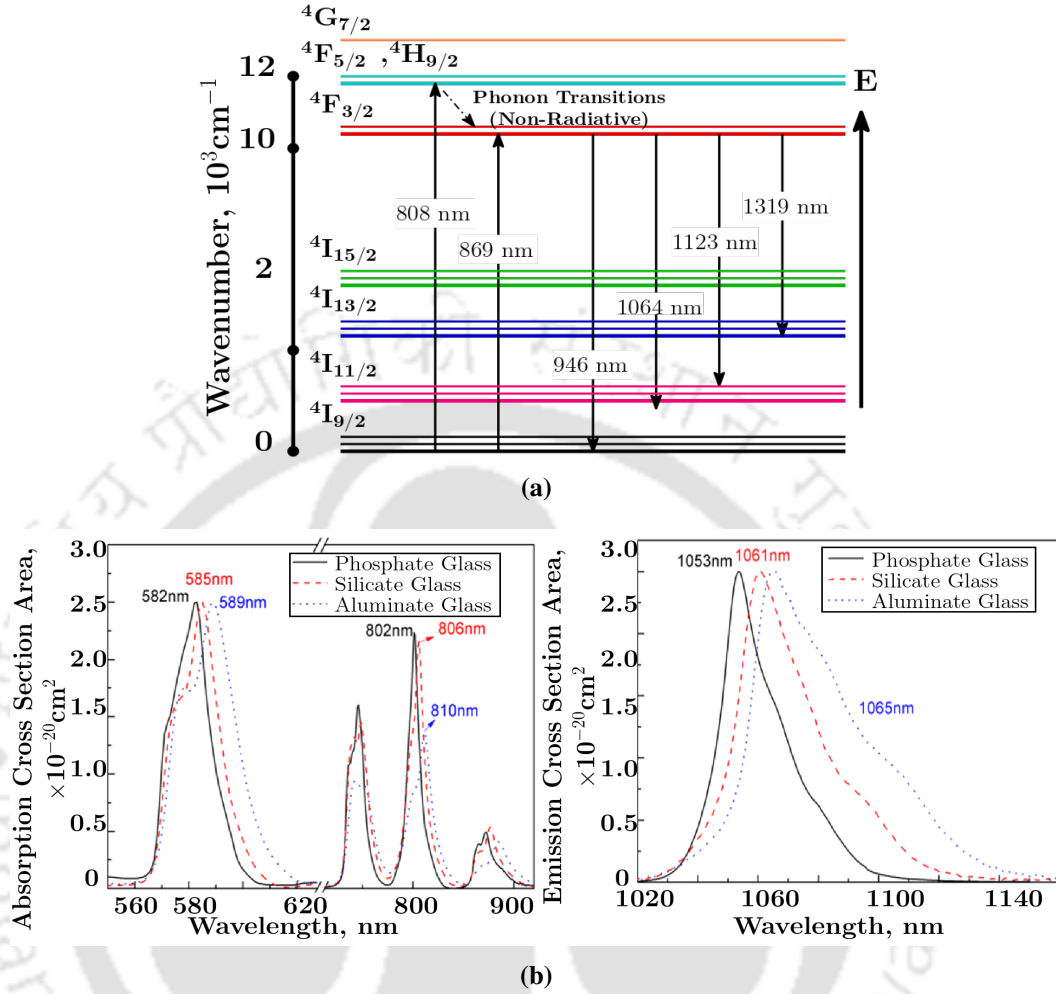
| Host Glass                            | Composition (mol %)                                                                                                                                                                                                                        | Reference       |
|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| Silicate<br>(Antimony-Silicate glass) | 45SiO <sub>2</sub> –5Al <sub>2</sub> O <sub>3</sub> –50Sb <sub>2</sub> O <sub>3</sub>                                                                                                                                                      | [112]           |
| Phosphate                             | 50P <sub>2</sub> O <sub>5</sub> –16.66MgO–33.34Li <sub>2</sub> O,<br>65P <sub>2</sub> O <sub>5</sub> –3Al <sub>2</sub> O <sub>3</sub> – $x$ Li <sub>2</sub> O<br>– $y$ BaO–4B <sub>2</sub> O <sub>3</sub> –6La <sub>2</sub> O <sub>3</sub> | [113–115]       |
| Germanate                             | 66GaO <sub>2</sub> –17MgO–17K <sub>2</sub> O,<br>56GeO <sub>2</sub> –31PbO–9Na <sub>2</sub> O–4Ga <sub>2</sub> O <sub>3</sub> ,<br>63GeO <sub>2</sub> –27PbO–10CaO                                                                         | [113, 116, 117] |
| Tellurite                             | 80TeO <sub>2</sub> –20Li <sub>2</sub> O,<br>75TeO <sub>2</sub> –15ZnO– $x$ Na <sub>2</sub> O                                                                                                                                               | [112, 118, 119] |
| ZBLAN<br>(Fluoride)                   | 57.35ZrF <sub>4</sub> –29.63BaF <sub>2</sub> –3.54LaF <sub>3</sub><br>–1.78NaF–5.16InF <sub>3</sub> –2.54AlF <sub>3</sub>                                                                                                                  | [112, 116, 120] |
| Chalcogenide                          | As <sub>2</sub> S <sub>3</sub> , As <sub>2</sub> Se <sub>3</sub> , As <sub>2</sub> Se <sub>1.5</sub> Te <sub>1.5</sub> ,<br>25Ge–10Sb–65S                                                                                                  | [121–123]       |
| Plastic                               | Polymers like PMMA, TTFA, CY-<br>TOP, PMMA-BzA, etc.                                                                                                                                                                                       | [124–126]       |

cm<sup>-1</sup> does limit the amount of dopant to be inculcated. While phosphate glasses have an advantage over silicate glasses with its matrix allowing significant dopants. Tellurite glasses are applied for a broad range of wavelengths from 400 nm to 6000 nm [85]. The ZBLAN (ZrF<sub>4</sub>–BaF<sub>2</sub>–LaF<sub>3</sub>–AlF<sub>3</sub>–NaF) glasses allow transmission from ultra-violet (UV) to mid-infrared (IR) with low phonon energy. The key RE-DFAs based on the energy-levels of relevant transitions, the emission/absorption CSAs, and some challenges associated with them have been discussed. The general configuration for RE-DFAs has been illustrated in Fig. 1.11 (a) and can be referred accordingly for all the mentioned RE-DFAs in this section.

### 1.4.1 Neodymium-Doped Fiber Amplifiers (NDFAs)

The Neodymium has been widely used in conventional bulk lasers in form of crystals as Nd:YAG, Nd:YAlO<sub>3</sub>, Nd:YVO<sub>4</sub>, and Nd:Y<sub>2</sub>GdVO<sub>4</sub> both in CW and pulsed operation [127, 128]. The trivalent Neodymium (Nd<sup>3+</sup>) ion has been rigorously employed in silica and phosphate glass matrices as doped-fiber amplifiers [85]. The wavelength in range of 900 nm to 1100 nm generates a lot of interest in producing the blue lasers [129]. As a result, the pump absorption and signal emission transitions involve the energy levels from <sup>4</sup>F<sub>3/2</sub> ↔ <sup>4</sup>I<sub>9/2, 11/2</sub> as shown in Fig.



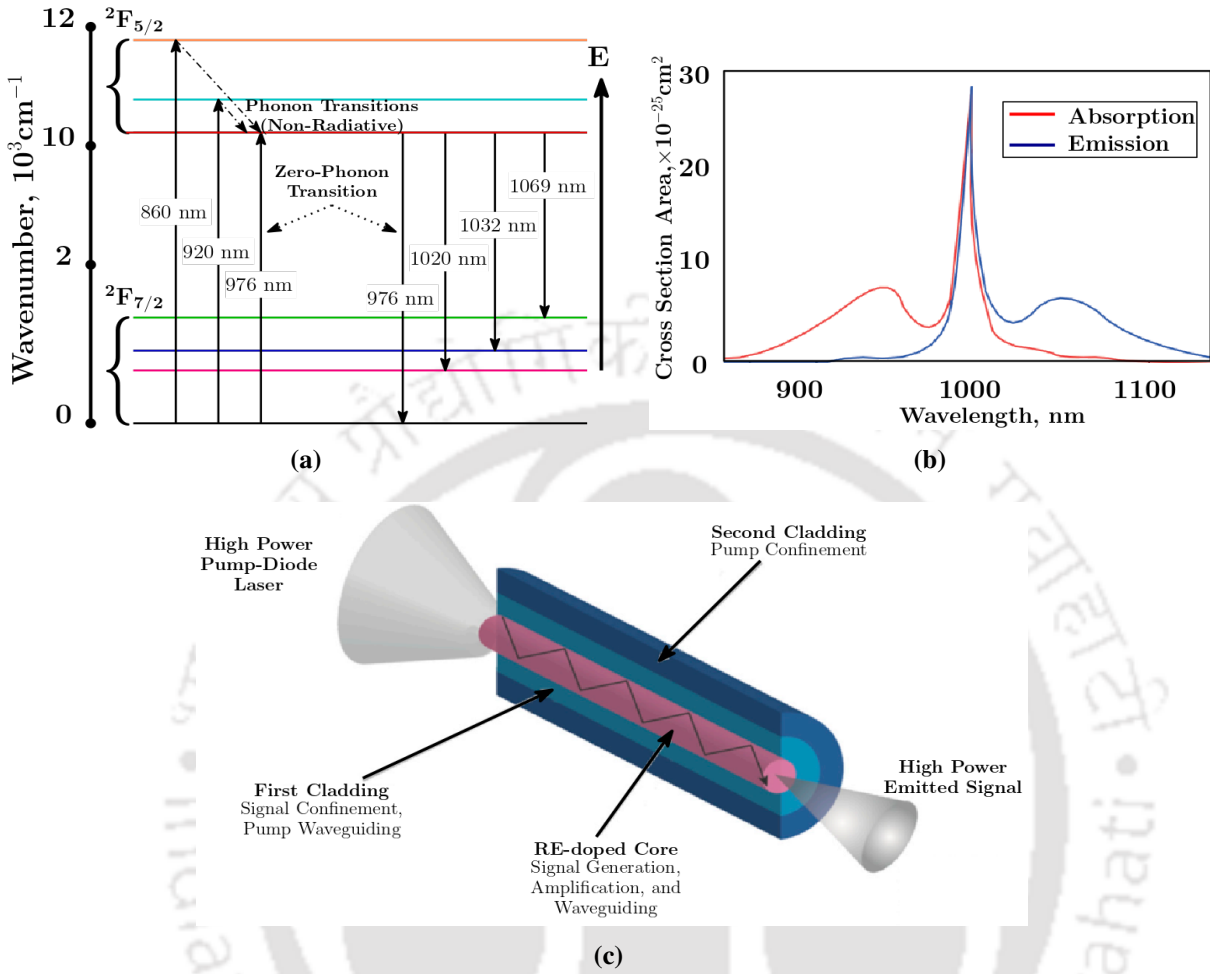


**Fig. 1.12:** (a) Energy-level representation of  $\text{Nd}^{3+}$  with dotted lines showing phonon-transitions and (b) shows the absorption (left) and emission (right) CSA of  $\text{Nd}^{3+}$  for different host-glasses.

1.12 (a) [130].

The four-level system, with lower-levels being aggregated, consists of the strongest lasing transition corresponding to a 1064 nm emission signal for all types of host-glasses [85]. It can be further observed from Fig. 1.12 (b) that the emission wavelength for three different host-glasses (phosphate, silicate, and aluminate) varies within the (8–12) nm range. Consequently, an option for mixed host-glass technique is possible for ultra-fast lasers [131]. The NDFAs have a variety of applications like in microsurgery, in industrial welding of metals, or acting as a pump laser for other RE-DFAs [132]. Other amplification wavelengths from the spectrum of Fig. 1.12 (a) are also possible, however, being weak in nature the dominating transition of 1064 nm should be suppressed by appropriate technique [130]. The other challenge is the low

## 1. Introduction to the Optical Amplifiers



**Fig. 1.13:** (a) Energy-level representation of  $\text{Yb}^{3+}$  with dotted lines showing phonon-transitions, (b) shows its absorption and emission CSA, and (c) schematic representation of cladding-pumped double-cladding YDFA.

concentration of  $\text{Nd}^{3+}$  in silica matrix which can be compensated by longer amplifier lengths.

### 1.4.2 Ytterbium-Doped Fiber Amplifiers (YDFAs)

The Ytterbium ( $\text{Yb}^{3+}$ ) ion is comprehensively used to fabricate DFAs and fiber-lasers in 1  $\mu\text{m}$  window along with ultra-short pulse amplifications [133]. The energy transitions involve the levels  $^2F_{5/2} \leftrightarrow ^2F_{7/2}$  in which further splitting of each level results into Stark sub-levels as shown in Fig. 1.13 (a) [85, 133]. Consequently, the pump and signal transitions between Stark sub-levels of the two energy levels result in the broad emission and absorption wavelengths. The absorption and emission CSA for  $\text{Yb}^{3+}$  as shown in Fig. 1.13 (b) corresponds to wavelength ranges of (850–1070) nm and (970–1200) nm respectively imparting YDFAs in a tunable operational range [133–136]. This broadband absorption CSA enables the opportunity for low-cost

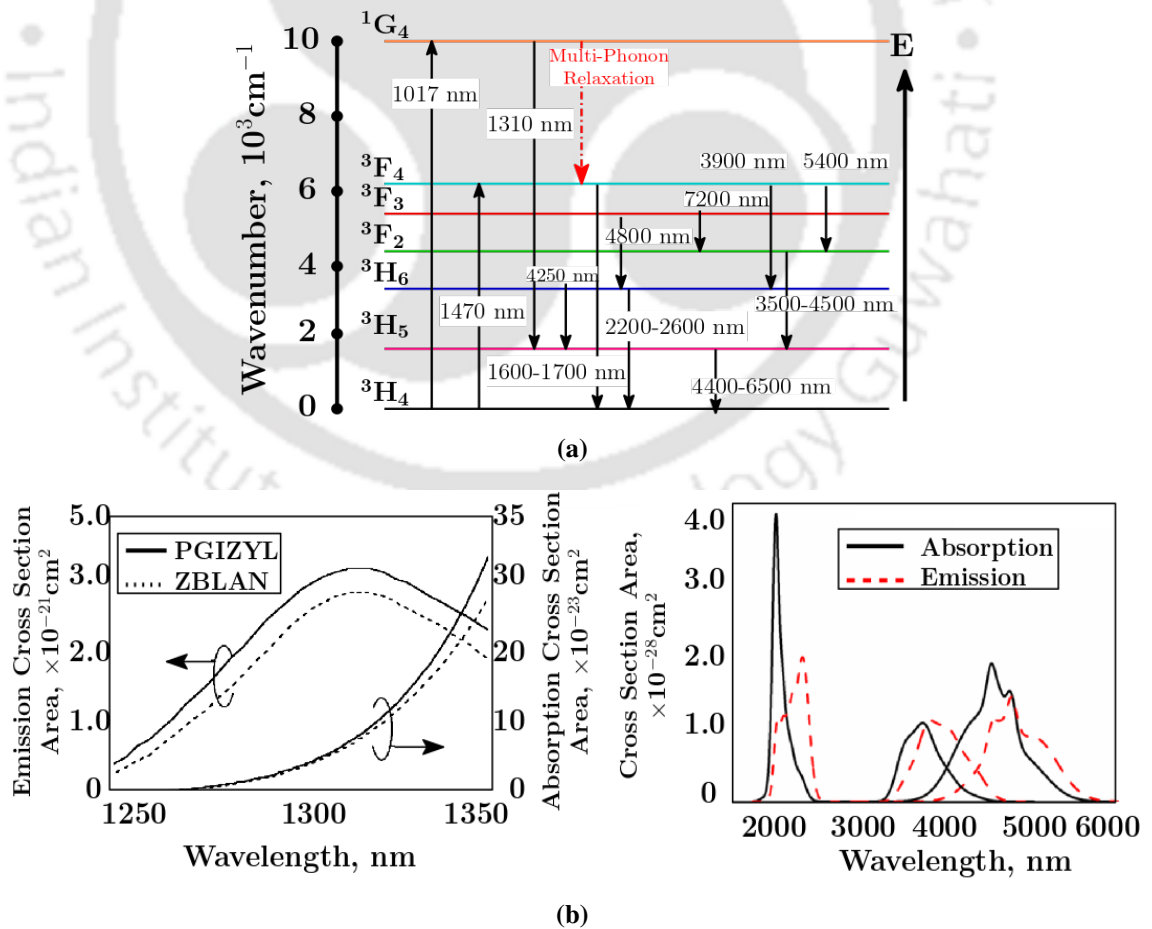


multi-wavelength pumping schemes proven to scale-up the power levels. The zero-phonon line transition also exists in YDFAs which is applicable in production of blue-lasers [137].

As a result of a fairly simple energy-level system, the YDFAs are generally immune to excited state absorption and the quenching effects. The low quantum defect also provides high power laser amplifications but sometimes at cost of quasi-three level characteristics which may decrease the power efficiency of lasing at 980 nm [85]. High-power YDFA to the level of 10 to 100 kW at  $\sim 1 \mu\text{m}$  window has been achieved by producing double-clad fibers with clad pumping operation as shown in Fig. 1.13 (c) [133, 134].

### 1.4.3 Praseodymium-Doped Fiber Amplifiers (PDFAs)

Fiber-optic operations particularly for the O-band (1260–1360) nm has been successfully carried by doping the fiber with RE-ion Praseodymium ( $\text{Pr}^{3+}$ ) [138, 139]. However, the process



**Fig. 1.14:** (a) Energy-level representation of  $\text{Pr}^{3+}$  with dotted lines showing multi-phonon transitions and (b) Shows the absorption and emission CSA for  $\text{Pr}^{3+}$  doped in fluoride (left) and chalcogenide (right) host-glass respectively.

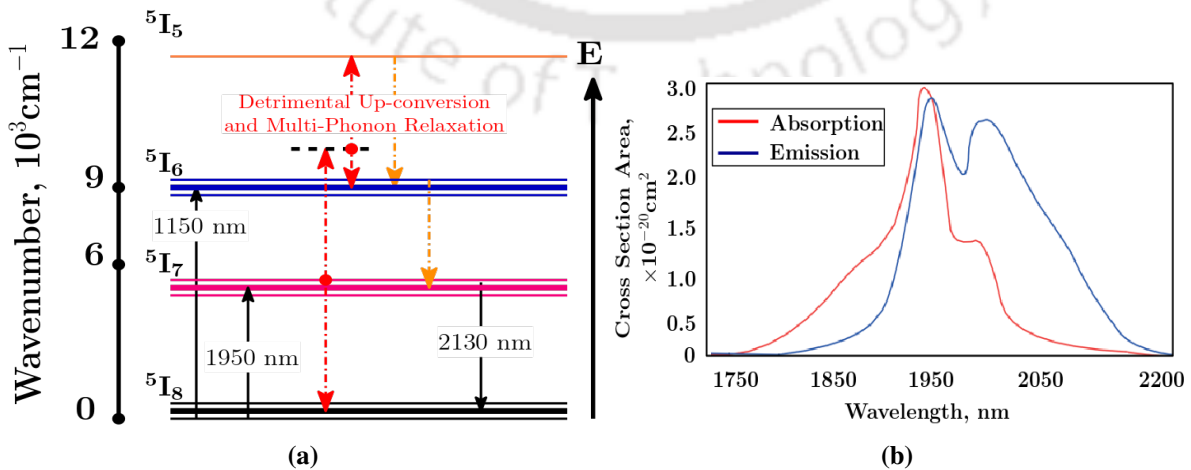
## 1. Introduction to the Optical Amplifiers

suffers with the drawback of low quantum-efficiency for 1310 nm emission for  $^1G_4 \rightarrow ^3H_5$  as shown in Fig. 1.14 (a) [138, 140]. The reason being the multi-phonon decay from  $^1G_4 \rightarrow ^3F_4$  when pumped with 1017 nm from  $^3H_4 \rightarrow ^1G_4$ . Consequently, large lengths of PDFAs are required to achieve desirable gains.

Depending on the host-glass, the electronic transitions results in the radiative or phononic decay. For example, in case of silica glass the  $^1G_4 \rightarrow ^3H_5$  transition is purely phononic while for fluoride glass it produces lasing at 1310 nm. Due to its multiple electronic transitions among different levels for respective host-glasses, PDFAs find application in producing mid-IR amplification [140]. It can be observed in Fig. 1.14 (b) that the absorption and emission CSA for fluoride and chalcogenide host-glasses have different spectra with respect to wavelength ranges [138, 141–143]. The mid-IR fiber-sources ranging from (2000–7200) nm are a hot topic of research due to its applications in biomedical sensing and environmental monitoring [141].

### 1.4.4 Holmium-Doped Fiber Amplifiers (HDFAs)

The excitation pump used for Holmium ( $\text{Ho}^{3+}$ ) ions doped in silica host-glass matrix is commonly carried by 1150 nm and 1950 nm wavelengths, as shown in Fig. 1.15 (a) [144–146]. The pumping wavelengths can be achieved using emissions from other RE-DFAs, for instance, in the case of YDFAs to generate 1150 nm wavelength. The lasing wavelengths for HDFAs have a window in the mid-IR region (2050–2850) nm transition from  $^5I_7 \rightarrow ^5I_8$  making them



**Fig. 1.15:** (a) Energy-level representation of  $\text{Ho}^{3+}$  with dotted lines showing up-conversion quenching (red) and phononic relaxation (orange) and (b) shows its absorption and emission CSA in mid-IR regime for silica host-glass.

an effective tool in biological tissue interactions for different applications [147]. However, for silica glass-host, an optimization is required to avoid the detrimental effects of up-conversion quenching and phononic radiations. Consequently, decreasing the quantum efficiency by a broad scale if mitigation schemes are not performed on the host-glass.

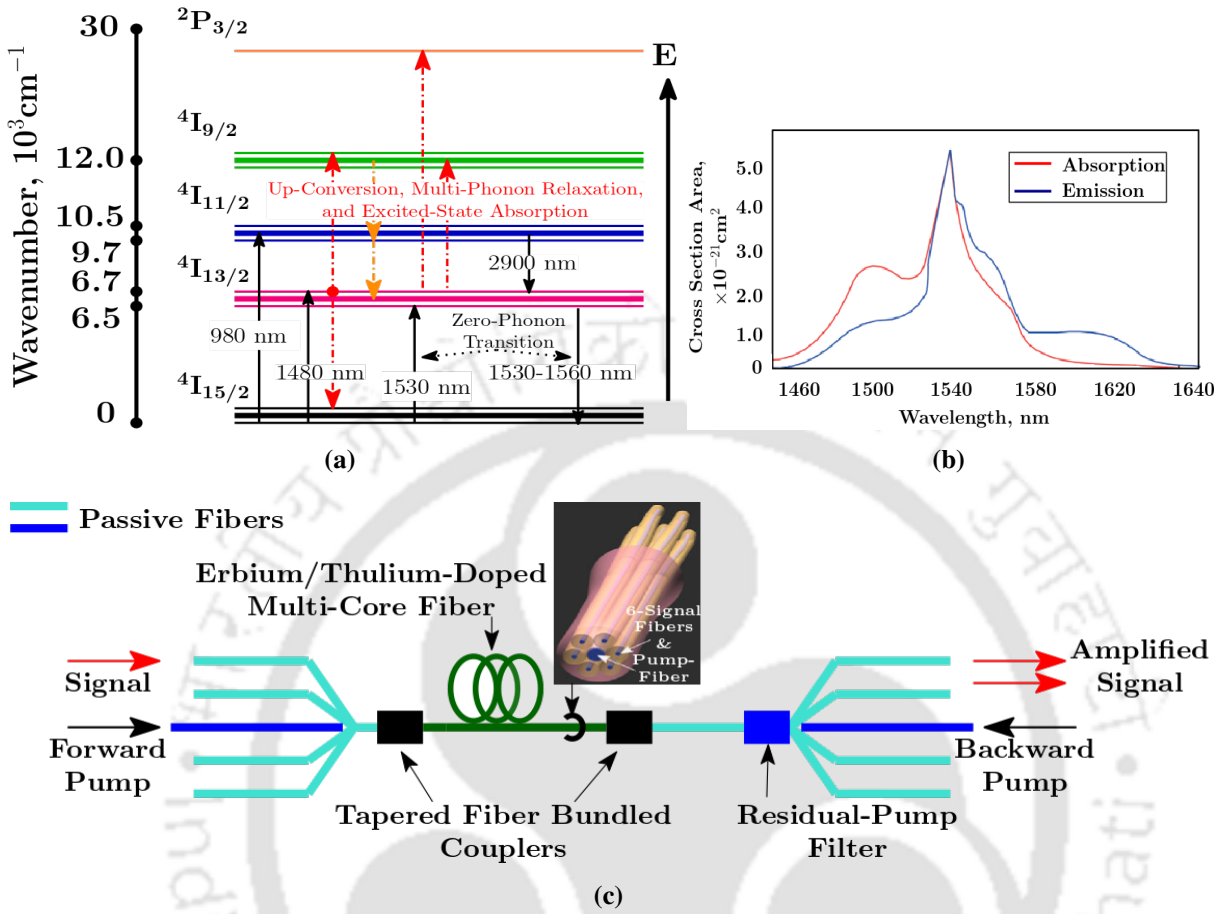
The emission CSA as shown in Fig. 1.15 (b) for  $\text{Ho}^{3+}$  in silica host also has peak around 2100 nm which is close to  $\text{OH}^-$  absorption overtone of 2200 nm in silica glass [147]. Consequently, a back-absorption may take place if water-less glasses are not used [148]. Recently, research work has been performed to achieve high power lasers based on  $\text{Ho}^{3+}$  in mid-IR regime with signal gain shooting to  $\sim 39$  dB [148–150].

#### **1.4.5 Erbium-Doped Fiber Amplifiers (EDFAs)**

The third-transmission window at 1550 nm of fiber-optic communication systems in the C-band with minimum attenuation makes Erbium ( $\text{Er}^{3+}$ ) ions the apt choice for waveguide communication [81]. Evidently, it can be observed in Fig. 1.16 (a) that 1480 nm and 980 nm provide lasing and amplification for 1530 nm to 1560 nm signal frame with transitions between  $^4\text{I}_{15/2} \leftrightarrow ^4\text{I}_{13/2}$  and  $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{11/2} \rightarrow ^4\text{I}_{13/2}$  (phononic relaxation)  $\rightarrow ^4\text{I}_{15/2}$  respectively [85, 147]. The 1480 nm pumping is less prone to excited state absorption (ESA) than 980 nm which can deplete the population in the meta-stable state  $^4\text{I}_{13/2}$  [151]. The zero-phonon transition line is also observed at 1530 nm between  $^4\text{I}_{15/2} \leftrightarrow ^4\text{I}_{13/2}$  due to the Stark-splitting of  $^4\text{I}_{13/2}$  level with energy  $6.5 \times 10^3 \text{ cm}^{-1}$  [85].

The EDFA system can also allow the efficient generation of (2900–3100) nm mid-IR emissions through homogeneous up-conversion (HUC) process [152]. However, the HUC process can only be initiated in case of heavily doped erbium fiber-amplifiers attaining a quantum-efficiency as high as 39.5% in the window of 3  $\mu\text{m}$  amplification [153]. The process also assists in obtaining the red and green fluorescence at 550 nm and 670 nm, respectively [154]. The absorption and emission CSA for  $\text{Er}^{3+}$  ion is shown in Fig. 1.16 (b) [147]. A peak in both the CSA can be observed in the 1500 nm window; consequently, high gains are observed in this range though with a very narrow bandwidth of  $\sim 30$  nm [1, 19, 155]. The evident benefit of lanthanides in the different host-glass matrix has been observed in the case of  $\text{Er}^{3+}$  ion too. The

## 1. Introduction to the Optical Amplifiers



**Fig. 1.16:** (a) Energy-level representation of  $\text{Er}^{3+}$  with dotted lines showing the up-conversion, phononic transition, and excited-state absorption processes, (b) shows its absorption and emission CSA, and (c) schematic illustration of erbium-doped multi-core amplifier (ED-MCA) configuration.

changes in the absorption and emission CSA for host-glass matrices such as meta-phosphate and silica glasses are minimal [85].

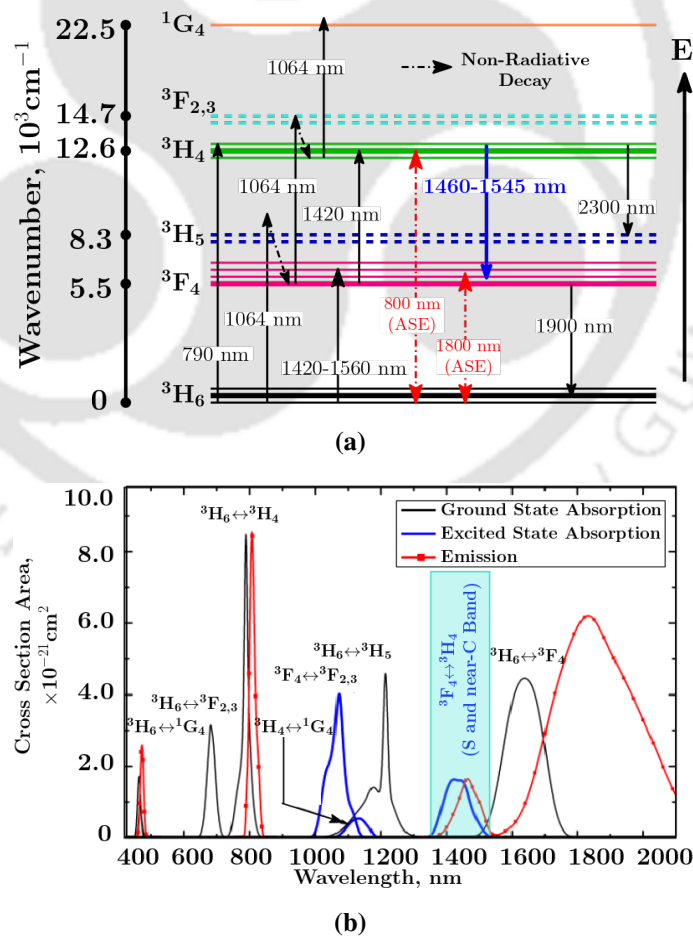
Owing to the crunch in low bandwidth because of narrow absorption and emission CSAs of EDFAs, remedies have been successfully proposed in terms of using multiple fiber-cores [156, 157]. The technique of space-division multiplexing (SDM) with multiple cores within single cladding is used to increase the amplification capacity and spectral efficiency to  $18 \text{ bits-sec}^{-1}/\text{Hz}$  of the system. The illustration of SDM has been shown in Fig. 1.16 (c) [157]. The multiple signal fibers are stacked, tapered, and coupled to the Erbium-doped multi-core fiber (ED-MCF) to obtain the desired amplification level. The pumping can be core or cladding, with former employing multiple pumps while the former has one common pump.

Mitigation schemes are required to overcome the low pumping efficiencies due to high ther-

mal losses amounting to 60%–70% of the total input power. Therefore, the long-wavelength pumping schemes have been in consideration for better quantum efficiency [85]. However, the laser diodes at 1500 nm are proven to be less efficient than the 980 nm (InGaAs) with respect to electrical-to-optical efficiency which further opens up the research in this field.

#### 1.4.6 Thulium-Doped Fiber Amplifiers (TDFAs)

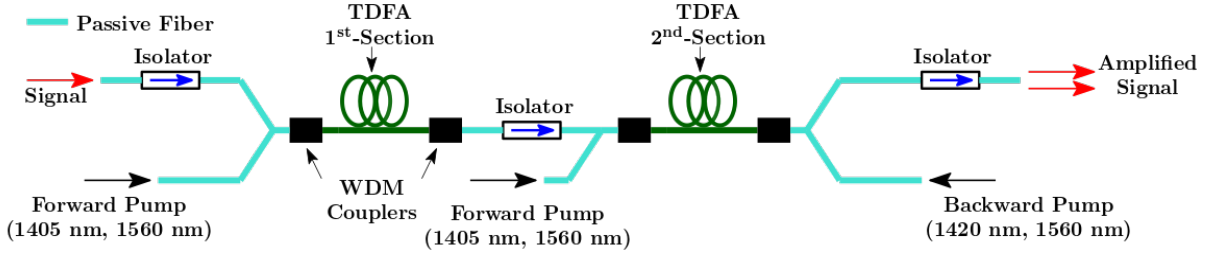
The speciality of Thulium ( $\text{Tm}^{3+}$ ) ions is that they are responsible for providing efficient amplification and lasing in “eye-safe” zone [85,147]. The reason being the emission range from 1400 nm to 2700 nm of mid-IR, which is absorbed by the water present in the cornea before reaching and probably damaging the highly photosensitive retina [158]. Of the broad range of transitions offered by TDFAs with respect to different glass-hosts, the two worth mentioning are



**Fig. 1.17:** (a) Energy-level representation of  $\text{Tm}^{3+}$  with possible pumping schemes where the dot-dash lines indicate the non-radiative decay and (b) Shows the absorption and emission CSA for  $\text{Tm}^{3+}$  doped in silica host-glass fiber highlighting the S and near-C bands as the region of interest.



## 1. Introduction to the Optical Amplifiers



**Fig. 1.18:** Part-pumping strategy for up-conversion in TDFAs.

(1460–1545) nm (S-Band with a part of C-Band) and (1800–2000) nm (mid-IR) windows [159]. The pumping schemes for the mentioned emissions can be carried out using either the direct or up-conversion approach.

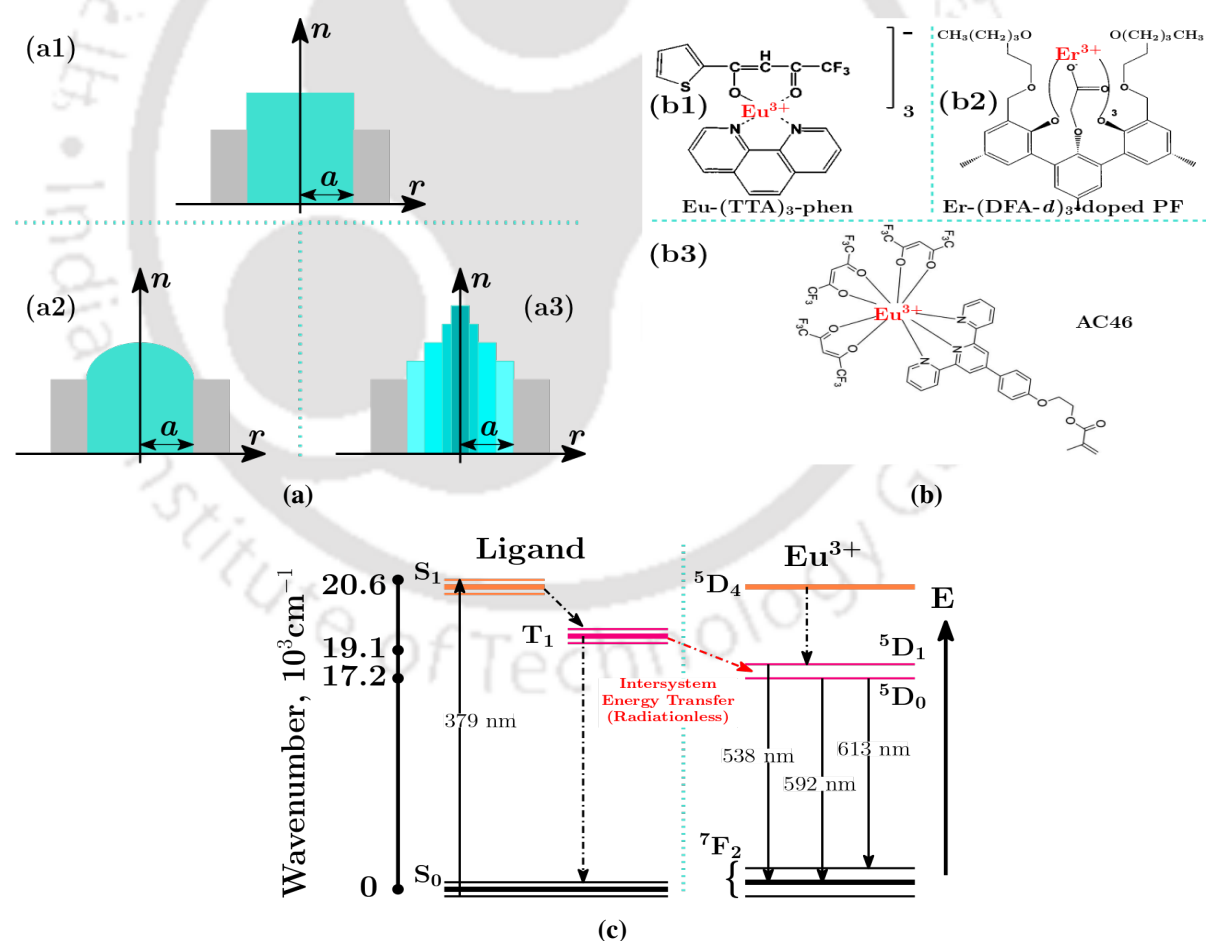
It can be observed in Fig. 1.17 (a) that for 1460-1545 nm emission, the energy level involved are  $^3H_4 \rightarrow ^3F_4$ . The corresponding direct pumping could be 790 nm wavelength transition as  $^3H_6 \rightarrow ^3H_4$ . The up-conversion process with a single pump of 1064 nm is required for one of the up-conversion pumping schemes with transitions  $^3H_6 \rightarrow ^3H_5 \rightarrow ^3H_4 \rightarrow ^1G_4$  as denoted in Fig. 1.17 (a). The other up-conversion pumping process involve (1420–1560) nm pump for the transitions  $^3H_6 \rightarrow ^3F_4 \rightarrow ^3H_4$ . The up-conversion pumping process is beneficial considering the shorter life-time of  $^3F_4$  energy-level [160]. Both the direct and up-conversion pumping processes involve the non-radiative phononic transitions to the meta-stable energy level  $^3H_4$ . Consequently, the host-glass for TDFAs should be associated with low-phonon energy transitions such as fluorides, tellurites, and chalcogenides ( $\sim 800 \text{ cm}^{-1}$ ) to reduce the multi-phonon relaxation rates [85,161]. However, silica based host-glass is considered to be significantly cost-effective and easy-to-fabricate.

The absorption and emission CSA of TDFAs in silica host-glass shown in Fig. 1.17 (b) highlights the S and near-C bands. Consequently, they can be effectively used to enhance the capacity of the present-day fiber-optic communication by a factor of  $\sim 75 \text{ nm}$  working in-tandem with the EDFAs [162]. The part-pumping strategy is often employed to achieve the up-conversion process by optimizing the sectional-lengths and corresponding pump powers of the TDFAs as shown in Fig. 1.18 [163]. The comparative low-gain in the S and near-C band for TDFAs can be compensated accordingly by using longer lengths or multi-core TDFAs as indicated in Fig. 1.16 (c). Furthermore, recent research shows that the unwanted ASEs at

800 nm and 1800 nm can be suppressed to further enhance the output power levels, SNR, pump slope-efficiency ( $\sim 73\%$ ) [164]. The other attractive wavelength-frame associated with TDFAs in tellurite host-glass are the mid-IR transitions with 1800 to 2300 nm amplification. The emission for this range are from  $^3F_4 \rightarrow ^3H_6$  and  $^3H_4 \rightarrow ^3H_5$  levels [159, 165, 166]. This wavelength range is particularly beneficial for atmospheric sensing like gas-trace detection and eye-safe laser systems.

### 1.4.7 Plastic Optical Fiber Amplifiers (POFAs)

The advantages of ease-of-handling, flexibility, large core diameter for easy coupling, and being economic with respect to manufacturing cost, makes plastic optical fiber (POFs) an apt



**Fig. 1.19:** (a) The refractive-index profile for POFs showing step-index (a1), graded-index (a2), and multi-step index (a3), (b) Typical examples of Eu<sup>3+</sup> and Er<sup>3+</sup>-chelate dopants, and (c) Energy-level representation of the Eu<sup>3+</sup>-chelate coordination complex with possible pumping from singlet-states  $S_0 \rightarrow S_1 \rightarrow T_1$  (triplet-state via non-radiative decay). From  $T_1$ , the intermolecular energy transfer takes schemes where the dot-dash lines indicate the non-radiative decay.



## 1. Introduction to the Optical Amplifiers

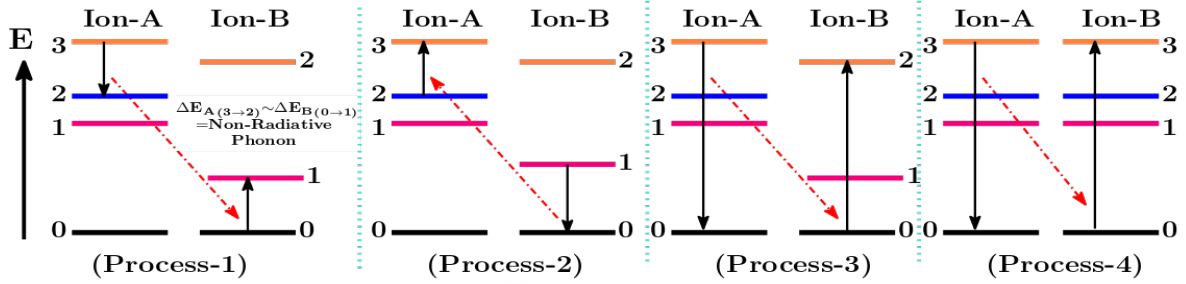
---

candidate for the short-haul fiber-optic communication. The limit in the communication distance is due to high attenuation of POFs relative to glass optical fibers [167–170]. The most common POF-material poly methyl methacrylate (PMMA) fiber-core is engineered to acquire relative low-loss giving better data-transfer rates. Consequently, it can be seen in Fig. 1.19 (a) that the step-index and graded-index (GI) POF can allow low attenuation (0.05 dB/m) and relatively high data transmission rates (1 Gb/s over 50 m and 100 Mb/s over 200 m) [167, 169]. This aspect makes them suitable in connecting the last mile especially in case of fiber-to-home-networks or local area network (LAN) where demand for bandwidth is ever increasing.

The low-attenuation POFs can compensate for the transmission and coupling losses by inserting short-lengths of POFAs in between a span [170, 171]. The dopant should be chosen so as to maximise absorption/emission CSA and should be readily incorporated in the POF's core. Organic dyes and rare-earth organic complexes serve the purpose of ideal dopants in POFAs with former having a problem of photodegradation due to continuous pump exposure [171–173]. Consequently, lanthanides-chelates are used as dopants in PMMA-POFs, some of them are structurally shown in Fig. 1.19 (b) [170, 171]. The Europium ( $\text{Eu}^{3+}$ )-chelate is readily dissolvable in PMMA-POFs in which efficient absorption of pump is carried. The process is conceded by inter-system energy transfer mechanism between ligand and Europium ( $\text{Eu}^{3+}$ )-chelate as shown in Fig. 1.19 (c). The pump and signal emission transitions involves 380 nm and (535–615) nm wavelengths respectively with maximum emission power of 0.76 W [171]. Besides  $\text{Eu}^{3+}$ -chelate doped POFs, the other dopants may include  $\text{Nd}^{3+}$ ,  $\text{Pr}^{3+}$ ,  $\text{Er}^{3+}$ ,  $\text{Tm}^{3+}$ , etc. with the corresponding major emission wavelengths.

### 1.4.8 Co-doped Fiber Amplifiers (CoDFAs)

The necessity of codoping the optical fiber is emerged due to the shortcomings of single dopant RE-DFAs as per the area of application. While EDFAs suffer from narrow absorption and emission CSA, other RE-DFAs like PDFAs or YDFAs feebly amplify the L, S, and C-bands of fiber-optic communication system. Consequently, to overcome these limitations the technology of co-doping of optical fiber with different ions came into existence. This process results in the interaction between them giving rise to different types of energy transfer (ET)



**Fig. 1.20:** Different types of energy transfer (ET) mechanisms namely cross-relaxation, energy transfer up-conversion, fluorescence transfer, and energy migration indicated from Process-1 to 4 respectively.

mechanisms as observed in Fig. 1.20 [174]. As a result, the processes 1 to 4 shows the ET-mechanism with initial and final energy states of the ions in the respective systems which can be described below.

**Process-1:** Ion-A (3), Ion B(0)  $\xrightarrow{\text{ET}}$  Ion-A (2), Ion B(1)

**Process-2:** Ion-A (2), Ion B(1)  $\xrightarrow{\text{ET}}$  Ion-A (3), Ion B(0)

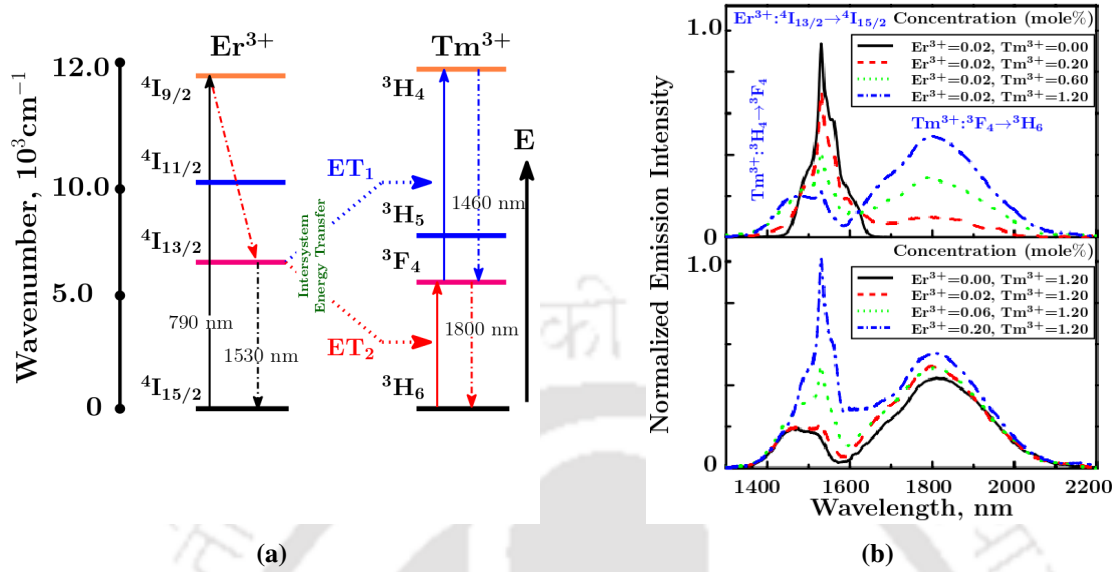
**Process-3:** Ion-A (3), Ion B(0)  $\xrightarrow{\text{ET}}$  Ion-A (0), Ion B(2)

**Process-4:** Ion-A (3), Ion B(0)  $\xrightarrow{\text{ET}}$  Ion-A (0), Ion B(3)

where A and B are the two systems with the respective ion-A and ion-B taking part in ET-mechanism. In the above expressions, the starting levels of both ions are written before the arrow. The final level after ET-mechanism but before the photon-emission process is written after the arrow. The energy level position of the respective ions has been mentioned within (·).

**Process-1** displays the generalized ET-mechanism of cross relaxation (CR). After the ET, both the ions are still in the excited state and the difference in their respective energy-gaps is compensated by the emission of a phonon. This process is observable in mono-doped as well as the co-doped system as presented in [175, 176]. In both the mentioned systems, the  $\text{Tm}^{3+}$ -ion populates  $^3\text{F}_4$  level as the ions depopulate  $^3\text{H}_4$  and  $^3\text{H}_6$  levels respectively with the “two-for-one” photon approach. **Process-2** implicates the opposite of the CR process known as energy transfer up-conversion (ETU). The ion-B loses its energy and transfers to ion-A which in-turn transits to a higher energy state. Both the mono-doped and co-doped systems experience the ETU process particularly as  $\text{Er}^{3+}$ - $\text{Er}^{3+}$  pair-induced quenching (PIQ) when heavily doped and  $\text{Tm}^{3+} (^3\text{H}_4) \rightarrow \text{Er}^{3+} (^4\text{I}_{13/2})$  respectively [177, 178].

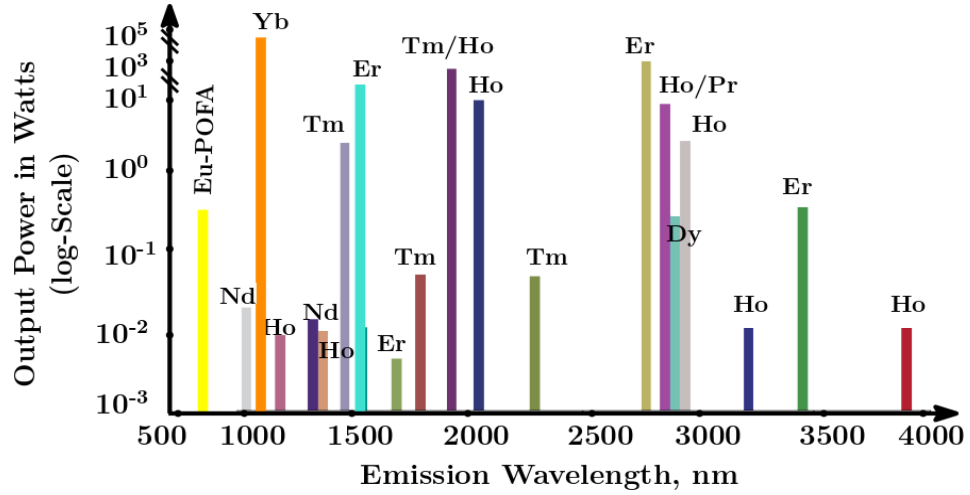
## 1. Introduction to the Optical Amplifiers



**Fig. 1.21:** (a) The schematic level diagram of  $\text{Er}^{3+}$ - $\text{Tm}^{3+}$  co-doped fiber amplifier system showing relevant ET-processes for near-IR emission and (b) shows the comparative effect of optimum  $\text{Er}^{3+}$ - $\text{Tm}^{3+}$  doping combination with respect to sole  $\text{Er}^{3+}$  (upper) and  $\text{Tm}^{3+}$  (lower) respectively.

In **Process-3** the generalized illustration of fluorescence sensitization (FS) is shown. The  $\text{Er}^{3+}$ - $\text{Yb}^{3+}$  CoDFA completes the typical example of FS energy transfer mechanism. The entire ET-mechanism follows  $\text{Yb}^{3+} ({}^2F_{5/2}) \xrightarrow{\text{ET}} \text{Er}^{3+} ({}^4I_{11/2}) \xrightarrow[\text{decay}]{\text{quick phonon}} \text{Er}^{3+} ({}^4I_{13/2})$  with  $\text{Yb}^{3+}$  transiting to its ground state [179, 180].

In **Process-4** energy migration (EM) takes place with a rapid energy exchange mechanism involving resonance between inter-system energy levels [152]. The process can be observed in  $\text{Er}^{3+}$ - $\text{Tm}^{3+}$  CoDFA where the resonance levels of  $\text{Er}^{3+}$  ( ${}^4I_{13/2}$ ) and  $\text{Tm}^{3+}$  ( ${}^3F_4$ ) differs in energy by  $\sim 0.05$  eV [181]. The process can be summarized as  $\text{Er}^{3+} ({}^4I_{13/2}) \xrightarrow[\text{decay}]{\text{Non-Radiative}} \text{Er}^{3+} ({}^4I_{15/2}) \xrightarrow{\text{ET}} \text{Tm}^{3+} ({}^3F_4) \rightarrow \text{Tm}^{3+} ({}^3H_4)$ . The process can be observed in Fig. 1.21 (a) with  $\text{ET}_1$  marked process. One of the evident advantages of co-doping of  $\text{Tm}^{3+}$  in  $\text{Er}^{3+}$  corresponding to aluminate host-glass matrix is the broadened emission CSA [181]. This expansion of emission CSA from the narrow C-band at 1550 nm to the S, C, L, and near-IR bands can be observed in Fig. 1.21 (b). The optimum concentration of the co-dopants is an important parameter for the desired broadening of emission CSA. However, co-doping often renders the system with limitations such as unwanted ASE, the extension of CoDFAs length, additive SBS, unwanted modal-instability in high power fiber lasers to name a few [182–184]. Consequently, mitigation



**Fig. 1.22:** Various RE-DFAs including Eu-POFA doped in various glass-hosts with corresponding average power achieved.

schemes to compensate these limitations should be incorporated within the system for better performance.

The RE-DFAs are used to amplify the incoming weak signal so as to render them strong with all the necessary information intact. These amplifiers can also be converted to build high-power fiber lasers for various applications. The improvement of output fiber laser power and efficiency of these systems continue to process with the evolution of new pumping mechanisms and dopant combinations. The graphical illustration with respect to the recent achievement power levels of fiber-optic lasers and amplifiers is shown in Fig. 1.22 [152, 171, 185–187].

## 1.5 Applications of TDFAs

The extensive coverage of absorption and emission CSA of  $\text{Tm}^{3+}$  ranging from visible to mid-IR wavelengths, allows TDFAs ubiquitous applications as per area specifics. Moreover, the development of new host-glasses helps TDFAs to mitigate some of its shortcomings in certainly required wavelength of operation [85]. Some of the explicit areas of applications in which TDFAs has been engaged are as follows:

### 1.5.1 Bio-Medical Applications

The applications of TDFAs in the field of medical technology has already been ubiquitous. The photo-medical applications as in the case of photodynamic therapy using TDFAs at an

## 1. Introduction to the Optical Amplifiers

---

emission wavelength if 1927 nm have helped in treating skin and lips disorders such as actinic cheilitis and melasma [188, 189]. The single pump source at 1064 nm along with SRS produces ASEs at 810 nm and blue emission at 480 nm. The ASE at 810 nm lies particularly in the “biological-window”, where its extinction through the human tissue is minimal thereby maximizing the penetration depth. Consequently, this emission can be effectively used in bio-imaging, fluorescence thermometers [190]. The development of TDFA based lithotripter could prove to be the future for the ablation of kidney stones. Using an efficient coupling of a high energy pulse (35 mJ) confined in a 50  $\mu\text{m}$  core diameter, a lithotripter has been successfully demonstrated [191]. The emission bands at  $\sim 2 \mu\text{m}$  and  $\sim 3 \mu\text{m}$  can be effectively utilized in human-tissue ablation and welding. The strong water absorption for  $\text{Tm}^{3+}$  in mid-IR region marks the emission at 1940 nm to be used as an all-optical scalpel for soft-tissue surgery while  $\sim 3 \mu\text{m}$  pulses are thought to be good for the treatment of bone and cutaneous surgery [147, 192].

### 1.5.2 Spectroscopic and Remote Sensing Applications

The spectroscopy added to microscopy has become one of the powerful tools in medical diagnostics. Optical frequency combs can be effectively used as a tool of high-precision spectroscopy for chemical and biological analysis. The “molecular fingerprinting” is often the term associated with spectroscopy in the mid-IR region containing unique spectral signatures of many chemical species [147]. For instance, the dual-comb emission at 1917 nm and 1981 nm can be used for chemical and atmospheric spectroscopy [193]. Furthermore, the emission spectrum of TDFAs overlaps with atmospheric gas molecules such as carbon dioxide ( $\text{CO}_2$ ), nitrogen dioxide ( $\text{NO}_2$ ), water ( $\text{H}_2\text{O}$ ), hydrogen bromide ( $\text{HBr}$ ), Helium ( $\text{He}$ ), etc. As a result, the cost-effective gas sensors can be built using TDFAs which can be effectively employed in atmospheric spectroscopy and remote sensing applications using light detection and ranging (LIDAR) set-ups [147, 194, 195].

### 1.5.3 Research, Industrial, and Defense Applications

The feature of  $\text{Tm}^{3+}$  emission spectra is that it covers the gaps which otherwise are not covered by emission bands of  $\text{Er}^{3+}$  or  $\text{Nd}^{3+}$  [147]. Therefore, this advantage opens up a lot of



application domains for TDFAs with respect to corresponding emission spectra. Particularly in the field of research, the emissions from TDFAs in S-band at 1480 nm can be employed to build an in-house, less complex, and cost-effective pumping solution in comparison to RFAs for the EDFAs [196]. Moreover, while using FRAs under high gain conditions a drawback of double Rayleigh scattering (DRS) may degrade the amplified signal through EDFAs. Furthermore, the TDFAs can be converted into nanosecond pulsed thulium fiber laser (TFL) for material processing. This aspect of TDFAs can be used as a tool for semiconductor wafer processing adding an application in the fields of research and industry. The emission wavelength of such pulsed-lasers are in mid-IR range ( $\sim 2 \mu\text{m}$ ) to tailor the silicon and gallium arsenide wafers [197,198].

The all-optical cutting and welding processes are one of the important industrial applications where pulsed TFLs can be of much use. Although, high power pumping ( $\sim 100 \text{ W}$ ) is a primary requirement for the process to be observed [199,200]. Direct laser writing is a technique that can be used to tailor the refractive index of the materials like glass ceramics with high absorption in near and mid-IR regions. Therefore, TFL fabricated out of TDFAs can be potentially used for this process in fiber-optic manufacturing industry [201]. The importance of TDFAs in the area of military-defense can be observed in the infrared-guided missile countermeasure applications. The amplitude-modulated multi-wavelength emission in the range of  $2\text{--}5 \mu\text{m}$  is desirable to lock the system with the thermal signatures of the incoming aircraft or missile [202]. The emission spectrum of  $\text{Tm}^{3+}$  shows the capability of lasing in the zone required for this type of application.

### 1.5.4 Communication Applications

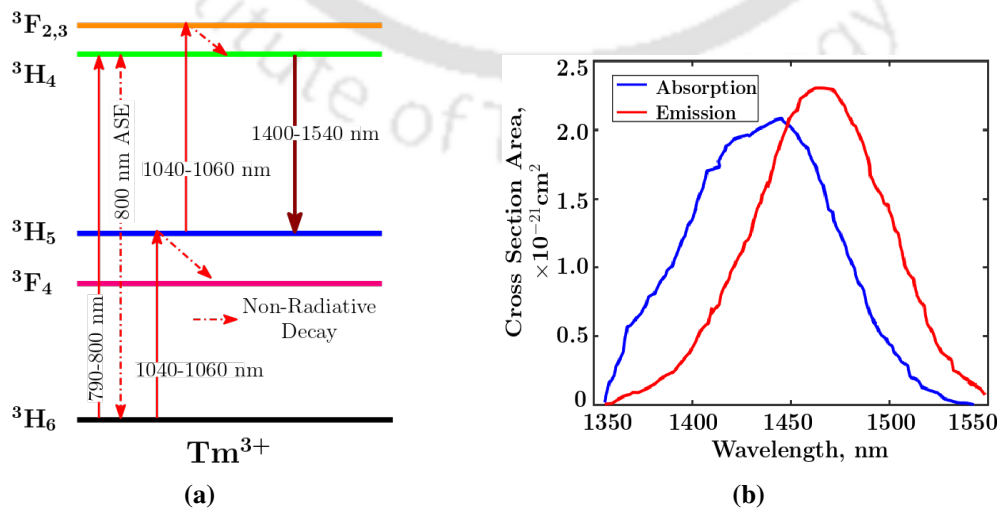
As today's world is leading towards the technologies requiring enormous information sharing, the internet speeds are cornered to their limits. The end-users of the internet have been growing exponentially in the recent past. Hence, with the introduction of internet-of-things (IoT) in domestic usage with fiber-to-the-premises (FTTP) concept, sensors in the industry, smart infrastructure, communication, etc. the demand for internet bandwidth has further increased [203–205]. As a result, the search for new resources to accommodate this bandwidth demand is the need of the hour. The  $\text{Tm}^{3+}$  emission spectrum shows that the near-IR (1460 nm to

## 1. Introduction to the Optical Amplifiers

1535 nm) and mid-IR ( $\sim 2 \mu\text{m}$ ) ranges have the potential to further the existing EDFA's communication at 1550 nm [206–208]. The extension of the bandwidth would be particularly important for DWDM and coarse wavelength division multiplexing (CWDM) systems for the long-haul as well as medium-haul ( $\sim 40 \text{ km}$ ) communication with used in-tandem with EDFAs [209]. The application of TDFAs have also been observed in sea under-water communication with blue-light emission at 479 nm where a  $\text{Tm}^{3+}\text{-Yb}^{3+}$  is used [210].

### 1.6 Working Mechanism of TDFAs in S and near-C bands

The near-IR ranges of wavelengths at 1460–1545 nm lie in the S and near-C bands of the optical communication system. It is a low-loss window for the conventional silica-based optical fiber, therefore, can be utilized for fiber-optic communication other than C-band [205]. Also, by using water-less or dry host-glasses, the water absorption peak in this band can be reduced considerably [4, 211, 212]. The other lesser attractive feature of TDFAs in S and near-C band is that the upper-level lifetime ( $^3\text{H}_4$ , 1.7 ms) is shorter than that of lower-level ( $^3\text{F}_4$ , 11 ms) which makes relatively difficult to accomplish population inversion. Therefore, to overcome this limitation, the  $\text{Tm}^{3+}$  should be depopulated from  $^3\text{F}_4$  using a co-doping strategy using  $\text{Ho}^{3+}$  [213]. This problem can also be mitigated using up-conversion pumping scheme in the wavelength range of (1040–1060) nm instead of using direct pumping in the range 790 nm to 800 nm as



**Fig. 1.23:** (a) The S and near-C bands TDEFA energy level representation showing corresponding transitions and (b) shows the emission and absorption CSA for  $\text{Tm}^{3+}$  particularly in S and near-C bands.



shown in Fig. 1.23 (a).

The other advantage of up-conversion pumping is that ASE at 800 nm remains small resulting in high gain, large output power, and better gain efficiency. The emission and absorption CSAs for the S and near-C bands can be observed from Fig. 1.23 (b) [54, 196]. However, research has been performed on shifting the S-band gain more towards the near-C band so as to achieve better sync with the existing 1550 nm EDFA's C-band amplification [163].

## **1.7 Research Motivation and the Problem Formulation**

High-speed data transmission is the backbone of today's technological world. EDFAs have been extensively employed for signal amplification in the DWDM system in the last couple of decades. Therefore, search for the new dopant material which can enhance the existing bandwidth in-situ with the existing infrastructure of C-Band is the need of the hour. Therefore, the TDFAs operating in S and near C-bands could potentially be the problem solver for this scenario. However, thorough performance evaluation should be carried out so as to consider TDFAs as potential optical amplifiers to extend the amplification band from the existing 1550 nm "Erbium-Window". Based on the evaluated TDFA parameters, the performance should be compared with that of the current state-of-the-art of EDFAs.

As discussed in the previous sections, very few studies have been carried out for TDFAs operating in S and near-band. A similar pattern of research work, however, has already been discussed for EDFAs. Employment of the techniques used for EDFA's performance characterization on TDFAs with its own novel uniqueness motivates us for the expectation of better results. Based on the literature survey, of which details are presented in chapter 2, the following problems have been identified for further investigations:

- (i) Management and surveillance of information in optical fibers can be done by low frequency ( $\sim 100$  kHz) amplitude modulation of the digital light-wave information signal, referred to as overmodulation in literature. The overmodulation of signal and gain dynamics is extensively researched for EDFAs as a method of line monitoring and surveillance of optical information in DWDM systems. It can predict the output modulation index when

## 1. Introduction to the Optical Amplifiers

---

the input signal is overmodulated with some perturbations. A similar analysis should be carried out for TDFAs operating in S and near-C bands so as to make sure its applicability in-situ with EDFAs for the increment of data rates. The signal wavelength and power should be analyzed using the dynamics involved to get optimum parameters.

- (ii) Modulation instability studies have been carried out on passive fibers and on EDFAs in the doped amplifier category. The study of perturbation frequency has been carried out for EDFAs, however, the loss effect has never been considered. Performing the MI phenomenon analysis on TDFAs with the cut-off frequency knowledge would definitely add to the credibility of using TDFAs in S and near-C bands. Exclusive analysis for loss factor and non-linear parameter effect have to be considered as an essential component and is planned to be carried out.
- (iii) The analysis is planned to examine the behavior of the input pulse type and chirping frequency effect for highly non-linear TDFAs. The motive behind this research is to find the optimum pulse type and TDFA parameters to generate a pulse train based on TDFAs.
- (iv) The performance estimation of TDFAs based on doping concentration levels has not been researched extensively. The IM mechanisms consisting of HUC and PIQ for TDFAs at (1460–1470) nm are planned to be analyzed. The result is expected to provide more information on the effects carried out by the IM phenomenon.

As a summary, the following are the objectives of this thesis:

- (i) To develop an analytical model for the overmodulation of the input signal-gain dynamics and to study its various features.
- (ii) To extend this developed model into a MatLab<sup>®</sup>-Simulink based simulator which exclusively studies the signal power and wavelength effects.
- (iii) To carry out modulation instability analysis on TDFAs particularly considering the loss factor and non-linear parameter variation effects.
- (iv) To propose and identify the optimum input pulse type and analyze its variation with respect to frequency chirping and non-linear parameter.
- (v) To analyze and simulate the ion-ion effects on TDFAs under heavy doping conditions.

## 1.8 Thesis Contribution

This thesis has endeavored to provide a platform to prove the potential utility of TDFAs in the S and near-C band of the optical communication system. The theoretical studies carried out and mathematical models developed for the various performance predictions and checks shall provide a significant effort to employ TDFAs in tandem with the EDFAs. The TDFA's geometric, material, and light interaction parameters have been calculated for various conditions to quantify the best possible choice out of them. This thesis

1. presents overmodulation of signal and gain dynamics on TDFAs using the EDFA's Bononi and Rusch (1998) model. It helps to portray the overmodulation of digital optical communication signal, of which, the amplitude is modulated by low-frequency ( $\sim 100$  kHz), for line-surveillance and management control of optical information in DWDM TDFA systems. Signal-to-signal and signal-to-amplified spontaneous emission transfer functions are derived to predict the system's performance under high input signal power conditions and its variation on the input modulation index. The difference of -10.3 dB (0.093 W) in output signal gain is observed at 1490 nm signal wavelength with ASE. The output modulation index of 15% having high pass signal characteristics as of a lead compensator is observed with the applied signal frequency sweep. Overmodulation sensitivity for various levels of input signal power demonstrates an undesirable 30% increment in the output modulation index at 8 dBm and 1490 nm signal wavelength respectively at the corner frequency.
2. provides a methodical test-bed analysis using the MatLab®-Simulink model with a different outlook in the respective field. The transfer functions for signal-to-signal and signal-to-amplified spontaneous emission are implemented to develop a simulator. An undesirable 30% increment in the output modulation index at 8 dBm and 1490 nm is obtained by simulating overmodulation sensitivity at different levels of mean input signal power and signal wavelength respectively at the corner frequency.
3. examines and compares with the EDFAs working at 1550 nm "Erbium-Window", exclusively the loss-factor and non-linear parameter effect on the modulation instability

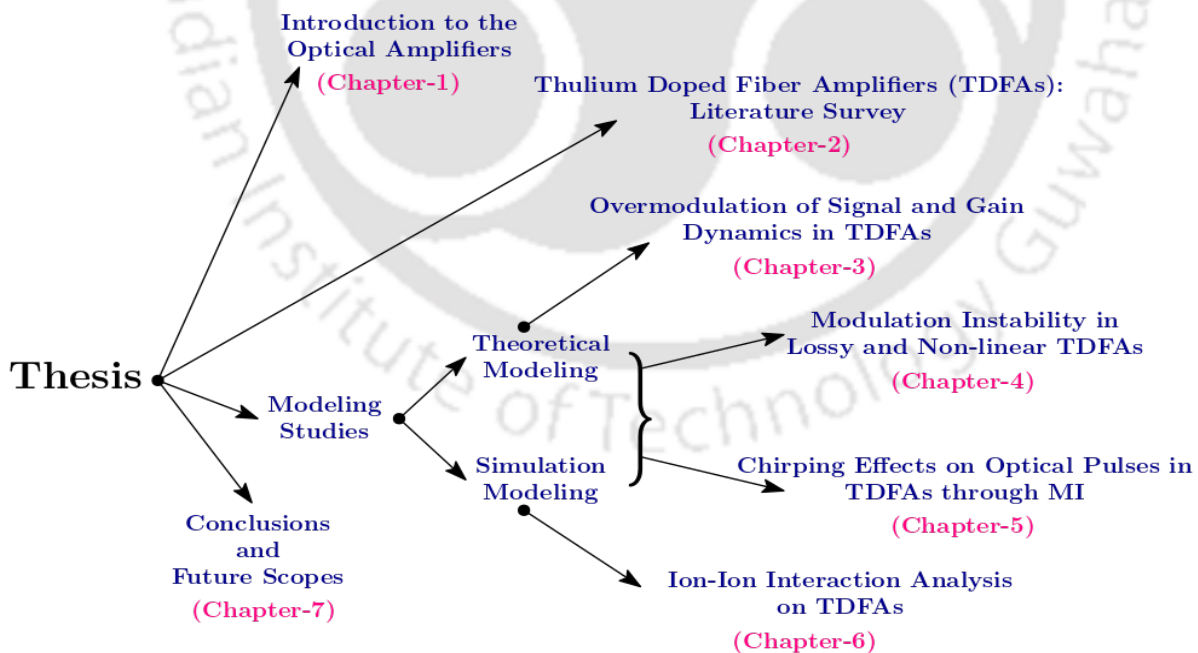
## 1. Introduction to the Optical Amplifiers

occurring in TDFAs at 1470 nm. The cut-off frequencies are estimated at different loss factor values up to which MI can trigger.

4. analyzes the frequency chirping and non-linear phenomenon for the various selected types of optical pulses. The feasibility of the optical pulse train is observed by simulation through the developed model on the OptiSystem® simulator.
5. delivers the results of performance estimation of TDFAs based on heavily doping the concentration levels which initiates the IM mechanisms in TDFAs. The HUC and PIQ effects are modeled and simulated on the OptiSystem® simulator.
6. includes the optimum calculation of TDFA's geometric, material, and light interaction parameters using analytical, numerical, and simulator-based on different conditions.

## 1.9 Thesis Overview

A structural organization of the thesis is shown in Fig. 1.24. The organization of this thesis is as follows:



**Fig. 1.24:** Flow-diagram illustrating the organization of the thesis.

➤ **Chapter 1** gives an introduction to the general process of fiber-optic communication, classifies different categories of optical amplifiers with their respective working principle, and describes various types of rare-earth doped fiber amplifiers. The importance and

application areas with respect to the electromagnetic spectrum are also presented. This chapter describes the problem statement and the motivation behind the work. Moreover, it also summarizes the thesis contribution and presents a brief outline of the thesis organization.

✍ **Chapter 2** starts with a brief introduction to the TDFA based systems. This chapter discusses the studies reported in the area of overmodulation dynamics, modulation instability, and ion-ion interaction mechanisms in fiber amplifiers mainly focusing on EDFAs and TDFAs for S and near-C band optical communication systems. Related mathematical modeling and simulation studies pertaining to the usability of TDFAs in current infrastructure as presented in the literature. Furthermore, it also elaborates on the issues related to these studies.

✍ **Chapter 3** presents the details of the analytical modeling of overmodulation signal and gain dynamics in TDFA systems for S and near-C bands. It presents the signal-to-signal and signal-to-amplified spontaneous emission transfer functions to predict the system performance under high gain conditions. Results in terms of output modulation index, signal gain, and noise-figure are also included to analyze the TDFA performance with respect to EDFAs.

✍ **Chapter 4** proposes the phenomenon of modulation instability in TDFAs. Starting from the NLSE, expressions for integrated gain for perturbation signals are formulated including the loss effects in TDFAs. The limit to the frequency of perturbation signals initiating MI effect is also presented. A comparison of loss effects and non-linear effects with respect to the lossless case corresponding to the integrated gain and perturbation frequency has been shown. A special case, considering the practical scenario, has been solved and presented numerically when perturbations becomes comparable to the input signal amplitude.

✍ **Chapter 5** includes the frequency chirping and non-linear effect on different types of input optical pulses traversing inside the TDFAs. Their evaluation is studied both mathematically and numerically which may result in the development of high energy optical

## 1. Introduction to the Optical Amplifiers

---

pulse trains. A brief introduction to OptiSystems simulator is also included in the chapter on which the simulations are carried out.

- ✍ **Chapter 6** includes the performance estimation of TDFAs based on ion-ion interaction effect. Various amplifier parameters such as length, fiber diameter, doping concentration, pump power, etc. are calculated optimally including the HUC and PIQ effects by simulating the model on OptiSystem simulator. Comparison studies are performed and presented with respect to signal gain, noise figure, and pump power with and without IM effects.
- ✍ **Chapter 7** presents the conclusions based on the work done in the previous chapters. All the objectives have been reviewed, and the findings/achievements have been highlighted. Further, it also includes the tracts for extending the work reported for the future.

# 2

## Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

### Contents

|     |                                            |    |
|-----|--------------------------------------------|----|
| 2.1 | Introduction                               | 46 |
| 2.2 | Main Components of S and near-C band TDFAs | 48 |
| 2.3 | Literature Survey                          | 51 |
| 2.4 | Summary                                    | 73 |

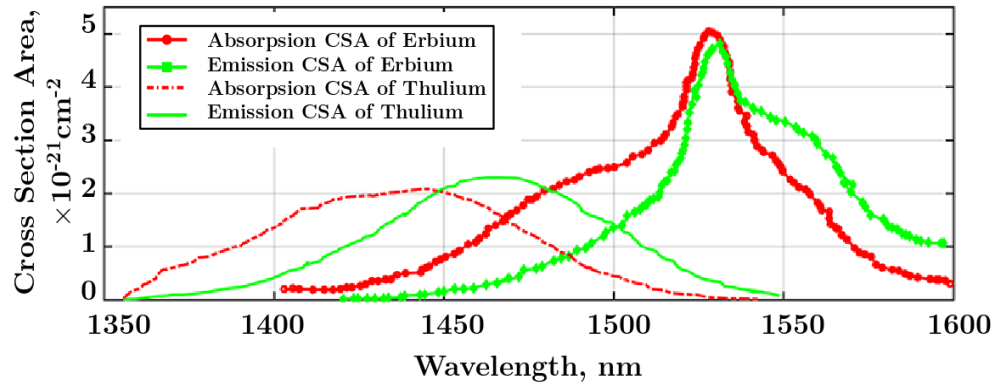


### 2.1 Introduction

The advent of EDFAs under the category of RE-DFAs has drastically enhanced the channel capacity of an optical fiber communication system [1]. It showed tremendous growth in the data transmission among all-fiber optical systems using CWDM and DWDM approaches [19]. The communication in the C-band at 1550 nm, commonly referred to as “Erbium-Window”, offers minimum attenuation to the optical signal owing to the lowest dispersion and water-loss in conventional silica fibers. However, this third transmission window with respect to EDFAs has a slender gain dependent bandwidth of meager 2.4 nm at maximum gain centered at 1536 nm [214]. The relatively low gain but with broader spectral bandwidth of 30 nm has been, however, observed at 1550 nm. This apparently has been utilized comprehensively for the current DWDM fiber-optic communication systems. Evidently, this gain-dependent band spectrum showing the narrow bandwidth at the maximum gain shifted focus of the researchers to slide the spectral characteristics towards the 1550 nm window.

Several mechanisms have been employed to mitigate these shortcomings of EDFAs which include replacements of host-glass, codoping, gain flattening methods, hybrid fiber configurations, etc. [215–217]. Although, these studies produced some promising results but to increase the complexity of the fabrication and working of the system. Therefore, new dopant material in various host-glasses to overcome the limitations of EDFAs and extend the existing transmission band is a prime requirement considering the exponential growth in information traffic in 1550 nm C-band.

TDFAs have managed to get accepted in the S and near-C bands of fiber-optic communication owing to its relatively broad absorption and emission CSAs as compared with EDFAs. The comparative absorption and emission CSAs of TDFAs and EDFAs in silica host-glass can be observed in Fig. 2.1 [54,159,163,218,219]. It can be seen in Fig. 2.1 that the bandwidth against peak emission CSA for EDFAs ( $5 \times 10^{-21} \text{ cm}^{-2}$ ) occurs at 1536 nm for a wavelength window less than 5 nm. However, comparing it with 1550 nm proximity, it spans to about 30 nm at emission CSA  $3.3 \times 10^{-21} \text{ cm}^{-2}$ . This emission CSA value of EDFAs is comparable to that of TDFAs



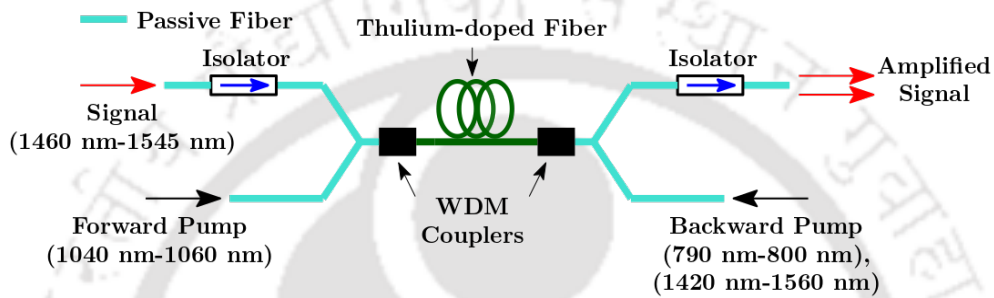
**Fig. 2.1:** The comparative absorption and emission cross section areas for TDFAs and EDFAs.

( $2.2 \times 10^{-21} \text{ cm}^{-2}$ ) in 1460 nm to 1545 nm (S and near-C bands) but with an advantage of  $\sim 75$  nm wavelength range with nearly-constant emission CSA. This spectral property of TDFAs avoid the use of gain flatteners which however is required for EDFAs. The S and near-C band operation of TDFAs can be used with the existing C-band EDFAs to enhance the capacity of the fiber optic system almost by a factor of four. Apparently, the lesser prone ESA wavelength at 1480 nm can act as a pumping scheme for EDFAs using the S and near-C band TDFAs tuned at 1480 nm emission. This can be an added application of TDFAs in the hybrid EDFA-TDFA optical-fiber communication systems apart from the regular S and near-C band communication.

Very few-to-none studies have been reported in the literature dealing with the aspects of TDFAs with respect to novel investigations such as overmodulation dynamics, the modulation instability incorporating loss-factor and non-linearity of fibers, the chirping effect of the traversing pulse within TDFAs, and the ion-ion interaction mechanisms or the cross-relaxation effects. These research act as an essential criterion to establish TDFAs for fiber-optic amplification and communication. This chapter gives a brief review on the main components of S and near-C band TDFAs followed by a discussion on the studies reported in the literature on the above-mentioned novel investigations. The comparison in most of the mentioned studies shall be with respect to the present state-of-the-art EDFAs.

### 2.2 Main Components of S and near-C band TDFAs

The TDFAs operating in the wavelength regimes of S and near-C bands have  $\text{Tm}^{3+}$  doped fiber as its main component along with the several constituent components spliced together resulting in a working and deployable TDFAs in the fiber-optic communication systems. The basic structure of an S and near-C band TDFA is shown in Fig. 2.2.



**Fig. 2.2:** A basic structure of a TDFA.

The schematic shown in the Fig. 2.2 is the most common configuration for most of the RE-DFAs including the TDFAs [163,220]. The essential details and characteristics of the components composing the structure are discussed as follows:

#### 2.2.1 The Active Fiber

Host-glass of the optical fiber doped with  $\text{Tm}^{3+}$  ions makes them active by enabling its amplifying property for the signals in S and near-C bands. This host-glass varies from silica to different glass-composites with respective advantages and limitations as mentioned in Table 1.3. It assist to determine the Giles parameters of each composition. Accordingly, the gain of the TDFAs can be expressed as a function of the dopant population of the respective energy-levels participating in the transitions, amplifier length, absorption and emission CSAs, overlapping-factor of the traveling mode, and the signal or pump wavelengths [221]. The optimum value of these parameters mentioned has to be obtained in order to attain an efficient working TDFA with respect to the gain it produces, the losses it incurs, and other non-linear phenomenon it encounters for the S and near-C bands fiber-optic communication system. Apparently, these parameters are also dependent on the wavelength and power of the optical-pump which is required to achieve the necessary condition of the population-inversion between the energy-levels.

The optical-signal strength inside the TDFA and in a passive fiber can result in triggering the non-linear phenomenons which , therefore, requires theoretical and experimental studies.

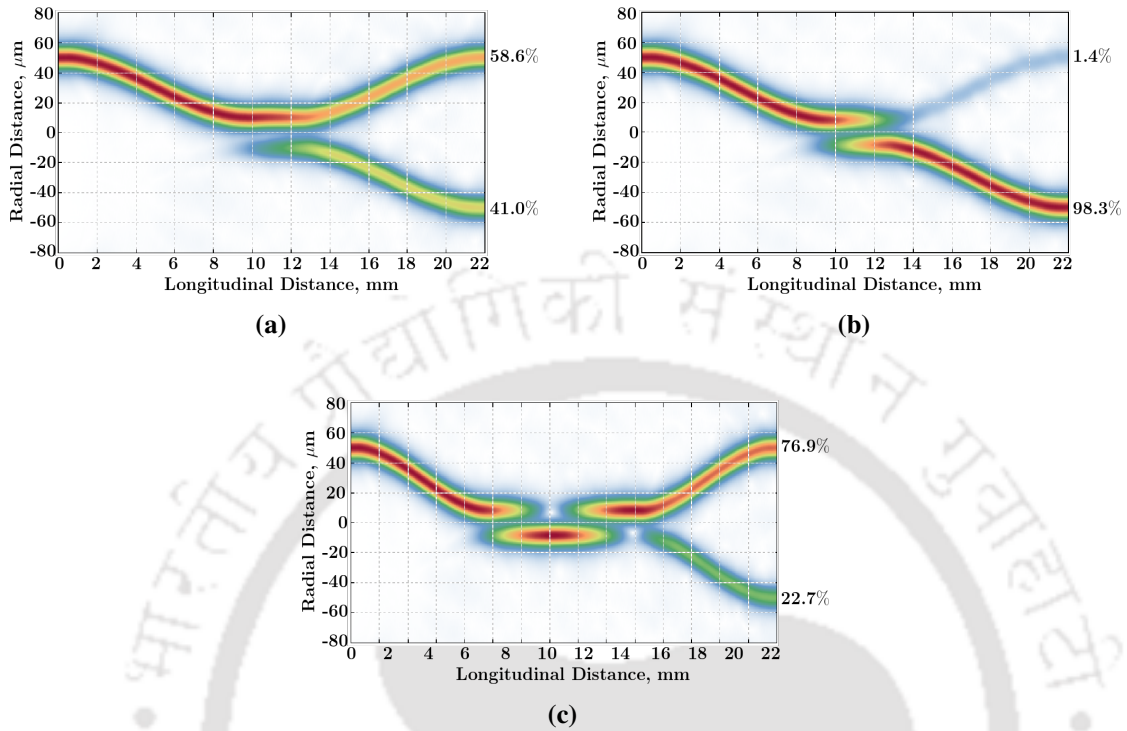
### 2.2.2 The Constituent Components

As illustrated in Fig. 2.2, showing the schematic diagram of TDFAs, the active-fiber is joined together with the other essential components mostly using arc-splicing technique. This is necessary to carry out the practical trials and experiments which can determine the integrity of the viable usage of TDFAs. Therefore, these important constituent components can be mentioned as follows:

- (i) **The Signal and Pump:** TDFA has a wide range of emission and absorption CSAs which can also be seen in Fig. 1.17 (b). Therefore, the wavelength range of signal and optical-pump should be compatible with the S and near-C band emissions. Also, the corresponding optical-power has to be considered to avoid the unnecessary development of other non-linear phenomenons like modal-instability at high optical powers [42]. The pumping can be achieved by optical sources like FRAs, RE-DFAs, and SOAs. Apparently, the pumping-scheme also plays an important role with respect to the reduction of inter-active noise between pump and signal, as seen in the backward pumping under Raman amplifiers to reduce RIN [67].
- (ii) **Optical-Isolators and WDM-Couplers:** Optical-fiber isolators are used to transmit the light in a definite direction while blocking it in others. One of the most important and commonly used isolators in the fiber-optic communication systems is the Faraday isolator [222,223]. A type of optical isolator variant is an optical-circulator. Often, when using isolators in fiber-optics, polarization-insensitive Faraday isolator is of wider interest as all optical-fibers may not have a “polarization-maintaining” feature. Apparently, the selection of low-loss optical-isolators should be a careful task with respect to the S and near-C band signals. If not, the system can get corrupted due to other non-linear phenomenons, such as FWMs, resulting in the unwanted additional wavelength in the system.

A WDM-coupler is essentially an optical device with multiple input fibers fused together to have several or single output fibers. The power distribution and the wavelength of the

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



**Fig. 2.3:** Shows the power distribution of the output ports with 0.4% of return-loss with (a), (b) having a fiber core-to-core distance of 20  $\mu\text{m}$  and 16  $\mu\text{m}$  respectively. While (c) illustrating the effect on output power when the coupling-length is increased. The output-power percentage of the respective ports are mentioned on the right vertical-axis.

output is determined using the coupled-mode theory. The return-loss of a WDM-Coupler should ideally be zero and all the input power should be divided among the output ports. The geometric parameters of the coupling region and the wavelength selection of the input-signal plays an important role in the ratio of the output power division as shown in Fig. 2.3 [224].

- (iii) **The Passive Fiber:** The input-output signal along with the optical-pump travels in the passive silica fiber which is spliced to the TDFA with other respective essential components. The signal generally travels in the fundamental mode as the fiber-optic communication system works with single-mode passive silica fibers. However, for other applications, multi-mode passive silica fibers can be considered with higher-order modes traveling through it.



## 2.3 Literature Survey

The literature survey in this section presents the theoretical and experimental studies carried out on the RE-DFAs with respect to overmodulation of signal-gain dynamics, modulation instability, chirped-pulse effects, and the ion-ion interaction mechanisms. These studies have been performed mostly on the state-of-the-art EDFAs as being the sole applicable RE-DFAs in the C-band communication at 1550 nm. Of the few findings pertaining to the mentioned aspects, some of them are also performed on TDFAs for which the summaries are presented. The reported studies in the literature considering the above-mentioned categories are as follows:

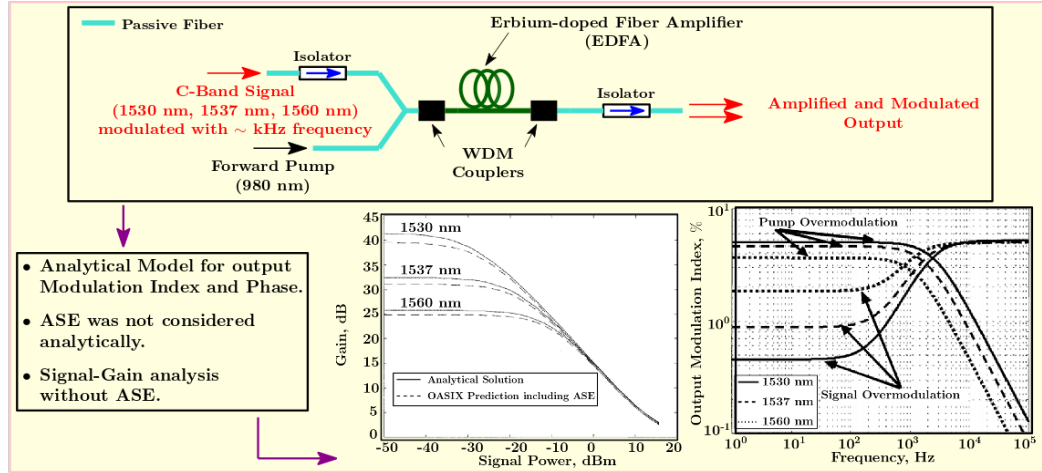
### 2.3.1 Literature Review on the Overmodulation of Signal-Gain Dynamics (OSGD) in RE-DFAs

Data accommodation, its management, and surveillance in the fiber-optic communication system are often done by amplitude-modulation of signals by low-frequencies in the ranges from few kHz to 100 kHz in DWDM systems. This process is generally referred as the overmodulation of signals in the literature. To analyze the effect of the overmodulation on the signal, pump, and gain, besides the changes it makes in the output modulation index, several theoretical and experimental studies have been performed on EDFAs. These studies find importance in establishing a mathematical-model of TDFAs with respect to the overmodulation, emphasizing on the inclusion of the effects of some of the earlier limitations. These studies provides a comprehensive knowledge on the overmodulation effects and are presented as follows:

- (i) Novak *et al.* [219] have presented the overmodulation of signal-gain dynamics in EDFAs.

The system is operational for a 1550 nm signal. It emphasizes the pattern of change at the output of fiber for the modulation index of perturbation signal with respect to the fed input. Analytical expressions for signal-to-signal and signal-to-pump have been developed to predict the overmodulation dynamics. The analysis is based on a model developed by Bononi and Rusch considering the transient gain behavior dynamics on EDFAs [225]. This approach has been in-turn fundamentally supported by [226, 227]. The analysis however excludes the effect of amplified spontaneous emission (ASE) waves. The graph-

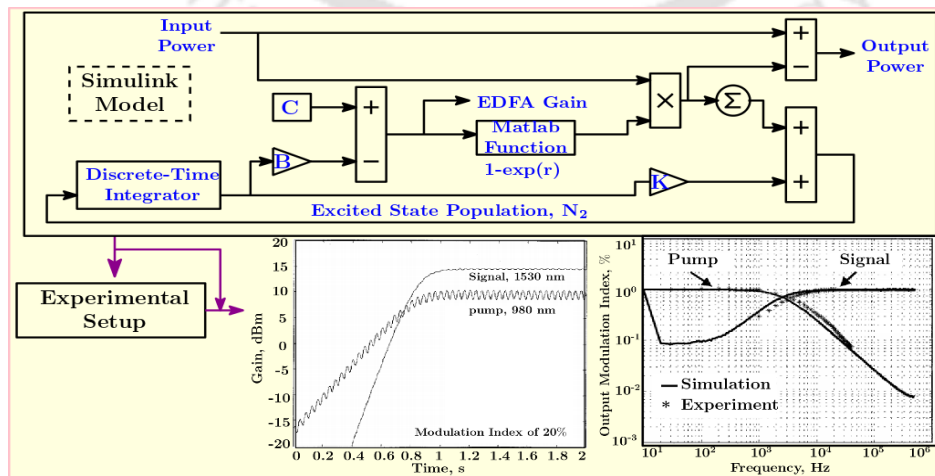
## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



**Fig. 2.4:** Graphical summary of the work carried out in [219]. The three different wavelengths are considered for analysis from C-Band were 1530 nm, 1537 nm, and 1560 nm.

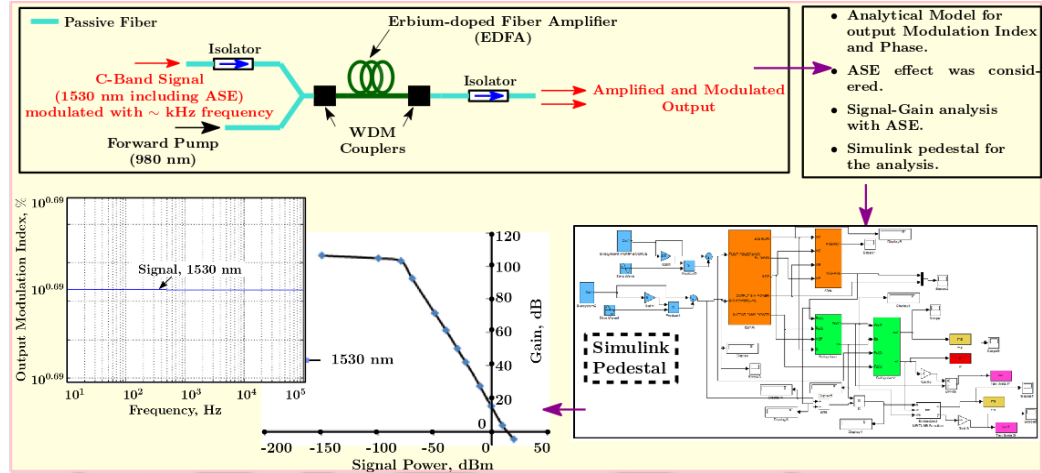
ical summary of this study is presented in Fig.2.4. The insets (counter-clockwise) shows a schematic of a TDFA system, the analytical model formed from the layout for overmodulation, and the respective gain with output modulation indices of pump and signal.

(ii) Novak *et al.* [228] have implemented the analytical model developed in [219] using the MatLab®-Simulink platform which can be seen in Fig.2.5 presenting its the graphical summary. The simulator developed can be used to predict the output modulation index of any overmodulated input signal. The signal and pump with respective wavelengths at 1530 nm and 980 nm are modulated by a 20% modulation index and the output power has been observed. It also reports the experimental demonstration of signal and pump output



**Fig. 2.5:** Graphical summary of the work carried out in [228]. It summarises and compares the results obtained through simulation on the Simulink with that of the experiment.





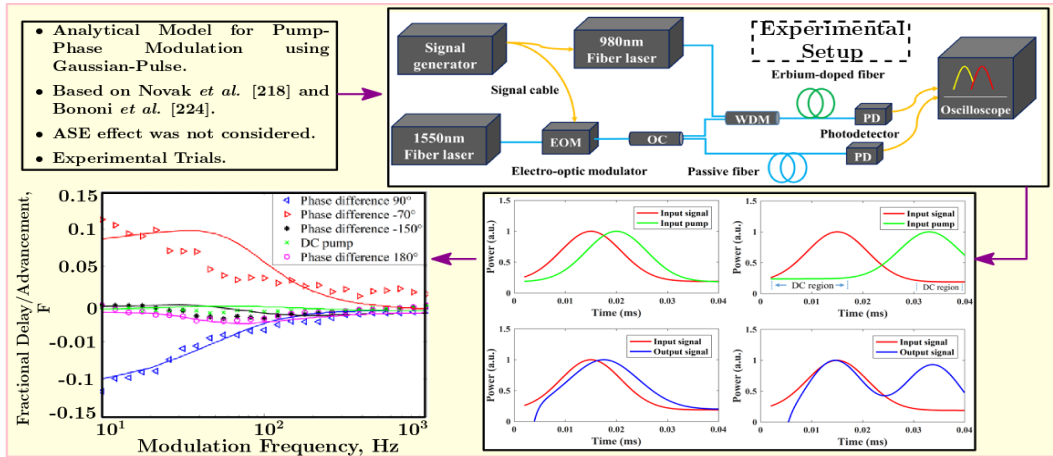
**Fig. 2.6:** Graphical summary of the work carried out in [229]. The ASE effects were considered at the overmodulated signal transmission of 1530 nm. The developed “Matlab Simulink” model can help in analyzing a cascaded EDFA system in a single module.

modulation index similar to high and low pass filter characteristics respectively. However, the analysis do not include the effects of the ASEs on the system’s performance. This study can be used on TDFA to determine its behavior to overmodulation dynamics.

(iii) Sharma *et al.* [229] have considered the analytical model by Novak *et al.* [219] but incorporating the effects of ASEs particularly in the high-gain systems as shown in the graphical summary of this study shown in Fig.2.6. The investigation is primarily focused on the impact of ASEs on the transmission quality of service (QoS) in ultra-high capacity fiber-optics systems. Based on the mathematical model for input overmodulation signal, the output modulation index and phase can be predicted including the ASE effects. A Matlab®-Simulink pedestal, acting as a test-bed, has been also constructed considering the derived governing equations of overmodulation dynamics. The results include the signal-gain build-up with respect to the input signal power and output modulation index. However, the model did not consider the directional ASEs separately and it is limited to a 2-level EDFA system.

(iv) Zhang *et al.* [230] have shown an important method of group velocity control of an input optical signal using pump-phase modulation technique. The optical signal considered is a Gaussian-pulse by adjusting its duty ratio which also served as an advantage over the sinusoidal signal. They performed and presented the simulation studies followed by

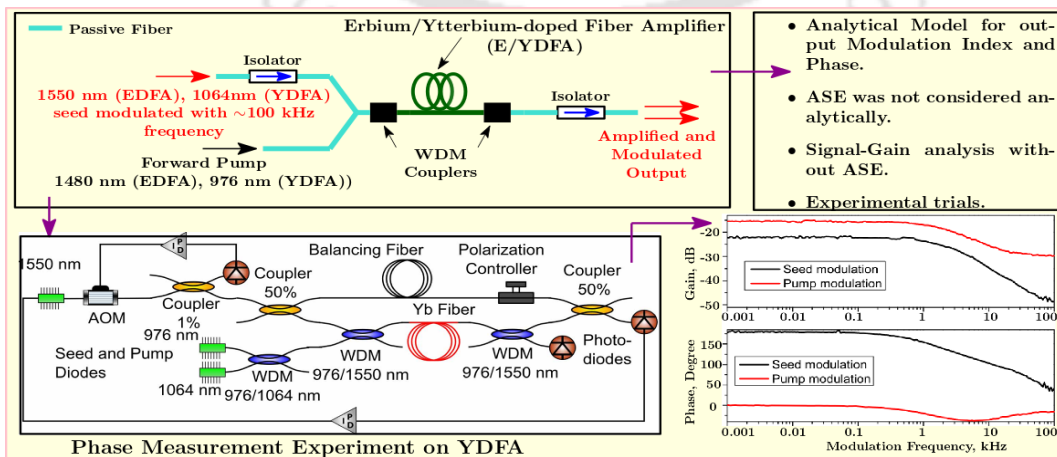
## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



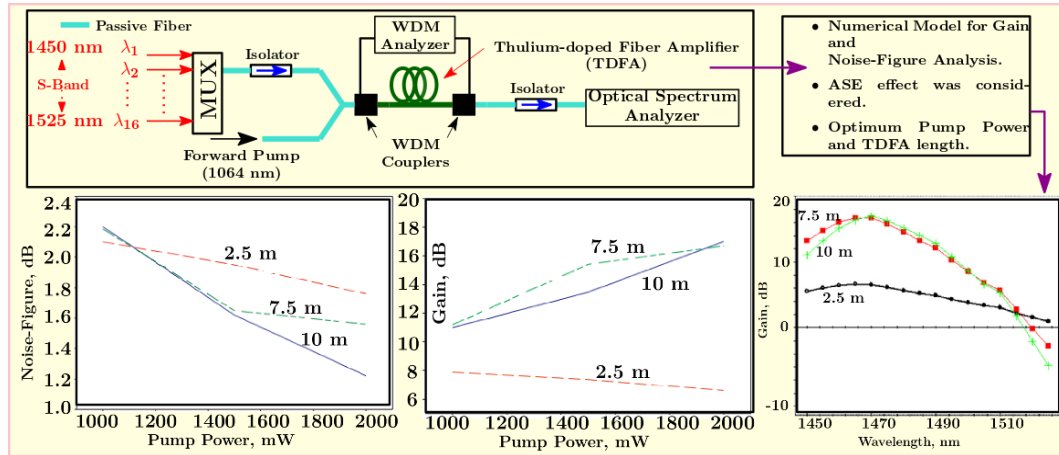
**Fig. 2.7:** Graphical summary of the work carried out in [230]. The significance of using the Gaussian-pulse signal with different duty-cycles is presented. The effect of the pump phase modulation has also been displayed through simulations which is further validated with experiments.

its experimental verification by controlling the phase difference between the pump and signal. The amount of delay in the output signal can be varied to the optimum as shown in graphical summary of Fig.2.7. The result showed in this study the significant application of Gaussian-pulse signals with respect to the fast and slow light changes. However, this study neither considered the ASE effects nor the significance of signal-phase modulation.

- (v) Tünnermann *et al.* [231] have taken the frequency domain approach to show the overmodulation gain dynamics and refractive index changes in EDFAs and YDFAs. The pump-power modulation effects have also been displayed by deriving the corresponding transfer function on the unabsorbed pump. This has been further been verified through



**Fig. 2.8:** Graphical summary of the work carried out in [231]. The overmodulation effect on EDFAs and YDFAs have been shown analytically and experimentally.



**Fig. 2.9:** Graphical summary of the work carried out in [221, 231]. The significance of ESA with 1064 nm pumping has also been displayed in this work.

experimental trials on EDFAs and YDFAs respectively as shown in the graphical summary of Fig.2.8. The developed model can predict the temporal behavior of the Kramers-Kronig-Relations (KKR) contribution to the refractive index. The analysis lacks the ASE effect contributions and is limited to the dynamics of two-level systems.

- (vi) Husein and Nahal [221, 232] have carried out studies on TDFAs with silica as host glass for WDM systems communicating in S-Band. The numerical model using the respective level rate-equations has been used to carry out gain and noise-figure analysis for the optimum performance as illustrated in the graphical summary shown in Fig.2.9. The choice of pump and signal wavelength selection with the appropriate value of TDFA length is also demonstrated. The importance of excited-state pump absorption with 1064 nm wavelength has been displayed in this work which is also observed in the results of [53, 163]. However, none of the mentioned reported studies analyzed the overmodulation behavior on TDFAs.

Although the above-reported studies are able to predict the effect overmodulation of signal and gain at the output modulation index and phase on a reduced 2-level EDFA systems, none of the studies were performed on the TDFA based fiber-optic systems. Therefore, an overmodulation of signal and gain dynamics study including the uncovered physics is required on TDFAs to analyze its behaviour on the S and near-C bands systems. A summary of the overmodulation of signal-gain dynamics in RE-DFAs discussed in this section is given in the Table 2.1.

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

Table 2.1: Summary of the OSGD studies in RE-DFAs

| Reference                  | Addressed Issues                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Unaddressed Issues                                                                                                                                                                                                                                                                                                                                                                           |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Novak <i>et al.</i> [219]  | <ul style="list-style-type: none"> <li>• Overmodulation of signal-gain dynamics in EDFAs.</li> <li>• Analytical model for output modulation index and phase.</li> <li>• Transfer functions for signal-to-signal and pump-to-signal derived.</li> <li>• Signal-Gain analysis without ASE.</li> </ul>                                                                                                                                                              | <ul style="list-style-type: none"> <li>• The effect of ASE on the Signal-Gain and NF analysis.</li> <li>• Application of the presented model on TDFAs for S and near-C bands amplification.</li> <li>• Transition dynamics of more than two energy levels.</li> </ul>                                                                                                                        |
| Novak <i>et al.</i> [228]  | <ul style="list-style-type: none"> <li>• Implementation of model presented in [219] on Matlab<sup>®</sup>-Simulink for EDFAs.</li> <li>• Experimental verification for the simulation results.</li> <li>• The developed simulator predicting the output modulation index and phase for modulated input signal.</li> <li>• Signal-Gain analysis without ASE.</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• The effect of ASE on the Signal-Gain analysis.</li> <li>• Application of the presented model on TDFAs for S and near-C bands.</li> <li>• Transition dynamics of more than two energy levels.</li> <li>• Matlab<sup>®</sup>-Simulink based simulator to predict TDFA performance under modulated signal input.</li> </ul>                            |
| Sharma <i>et al.</i> [229] | <ul style="list-style-type: none"> <li>• Analytical model for output modulation index and phase for over-modulated input in EDFAs.</li> <li>• The effect of ASEs in high-gain systems has been analyzed.</li> <li>• Implementation of the model on Matlab-Simulink platform.</li> <li>• The prediction of output modulation index and phase.</li> <li>• Disagreement with output modulation index of signal as a high-pass filter presented in [219].</li> </ul> | <ul style="list-style-type: none"> <li>• The effect of directional ASEs on the Signal-Gain analysis.</li> <li>• Application of the presented model on TDFAs for S and near-C bands amplification.</li> <li>• Transition dynamics of more than two energy levels.</li> <li>• Matlab<sup>®</sup>-Simulink based simulator to predict TDFA performance under modulated signal input.</li> </ul> |

continued ...

...continued

| Reference                      | Addressed Issues                                                                                                                                                                                                                                                                                                      | Unaddressed Issues                                                                                                                                                                                                                                                                                                 |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Zhang <i>et al.</i> [230]      | <ul style="list-style-type: none"> <li>Analytical model for pump phase modulation in EDFAs.</li> <li>Control of the signal group velocity using the pump phase modulation.</li> <li>Simulation verified through experimental trials of seeing Gaussian pulse input as an alternate to a sinusoidal signal.</li> </ul> | <ul style="list-style-type: none"> <li>Effect of ASE on output signal modulation index and phase.</li> <li>Effect of signal phase modulation effect.</li> <li>Transition dynamics of more than two energy levels.</li> <li>Pump-phase modulation in TDFAs to control the signal group velocity.</li> </ul>         |
| Tünnermann <i>et al.</i> [231] | <ul style="list-style-type: none"> <li>Analytical model for pump and signal modulation in EDFAs and YDFAs.</li> <li>Frequency-domain approach for finding refractive-index changes.</li> <li>Simulation verified through experimental trials on EDFAs and YDFAs to observe signal and pump gain and phase.</li> </ul> | <ul style="list-style-type: none"> <li>Effect of ASE on output signal modulation index and phase was not considered.</li> <li>Transition dynamics of more than two energy levels.</li> <li>Interesting to perform the refractive-Index change studies on TDFAs.</li> </ul>                                         |
| Husein and Nahal [221,232]     | <ul style="list-style-type: none"> <li>Numerical model to carry gain and NF analysis on TDFAs (silica host).</li> <li>Optimum selection of pump and signal wavelength for S-Band communication.</li> <li>Importance of 1064 nm pumping for ESA.</li> </ul>                                                            | <ul style="list-style-type: none"> <li>The overmodulation studies on signal, pump, and gain on S and near-C bands TDFAs.</li> <li>Optimization of TDFA's geometric parameters for the desired output modulation index and phase.</li> <li>Overmodulated Signal power effect on output modulation index.</li> </ul> |

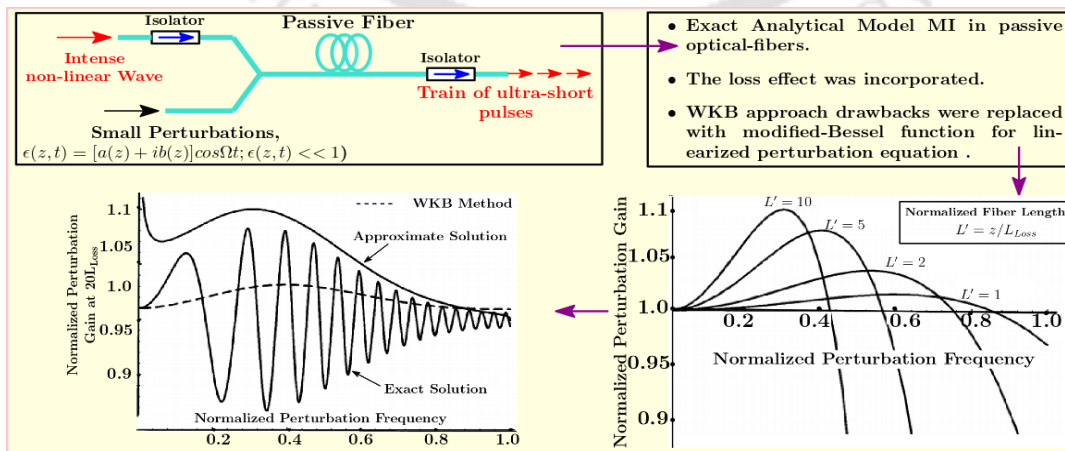


## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

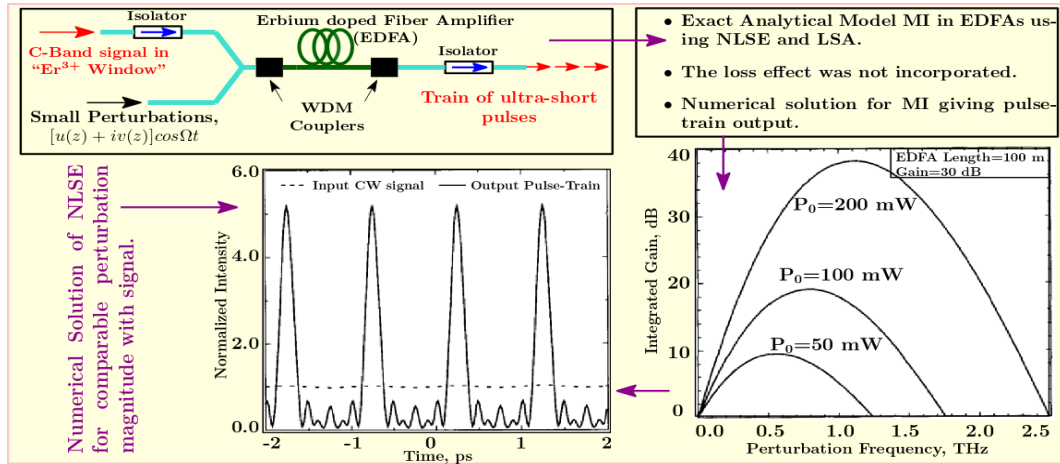
### 2.3.2 Literature Review on the Modulation-Instability in TDFAs

The phenomenon of modulation-instability (MI) in RE-DFAs, particularly on EDFAs, and on passive-fibers have been extensively researched. However, the analytical approach representations using linear stability analysis demonstrating the different effects of MI on the input signal has been sparsely shown in the literature. The necessity to analyze MI on TDFAs including the loss-factor effects would be worthy of research for S and near-C band fiber-optic communications. Therefore, some of the important related work on MI providing a comprehensive base to extend that knowledge on TDFAs are discussed as follows:

- (i) Karlsson [233] derived the exact analytical solution of MI in passive optical fibers. The analysis is based on stationary CW solution to the NLSE utilizing linear stability analysis. It emphasized the drawbacks of previous analytical approaches including that of the Wentzel-Kramers-Brillouin (WKB) method. Instead, an exact analytical solution has been developed in terms of modified Bessel functions giving the perturbation gain spectrum for different propagation distances including the losses. The summary of this study is shown in Fig.2.10 which displays the dependencies of perturbation frequencies with the gain leading to the MI phenomenon. In this work, the MI induced power-penalty on the received information has also been calculated. Although, the study is based on passive silica fibers the methodology presented became the framework for active fiber amplifiers.



**Fig. 2.10:** Graphical summary of the work carried out in [233]. The perturbation gain-spectrum has been compared with the approximate method (WKB) to that of the exact analytical solution.

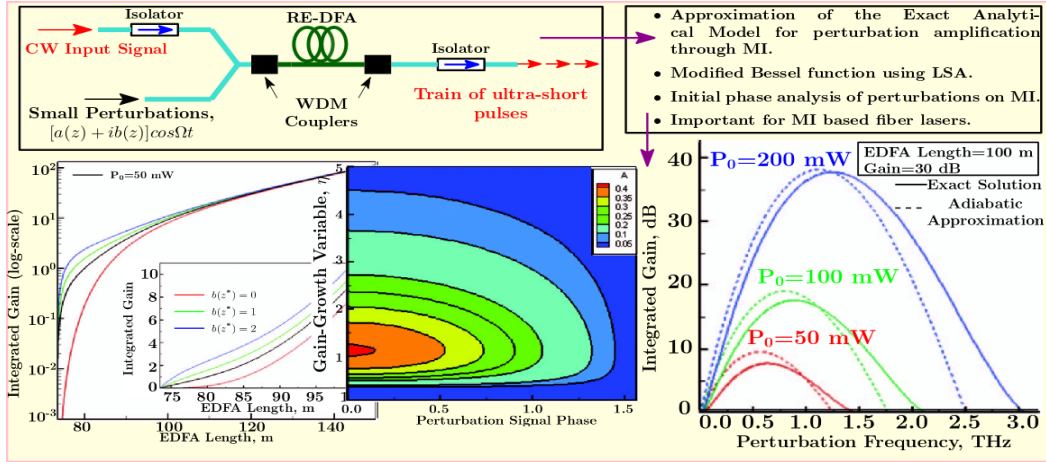


**Fig. 2.11:** Graphical summary of the work carried out in [234]. The exact solution help in the prediction of perturbation frequency for maximum gain considerations.

- (ii) Agrawal [234] mentioned the important aspect of MI in active-fibers (EDFAs) at much lower input-signal power. The study investigates the phenomenon of MI in EDFAs through solving NLSE considering linear stability analysis. The C-Band operation of EDFAs renders group-velocity dispersion in an anomalous regime which makes it susceptible to MI. The work also focused on the numerical solution to show MI when the amplitudes of input-signal perturbation and continuous-wave signal become comparable. This solution leads to the simulation results showing the pulse-train output from the amplifier implicated to the mode-locked fiber lasers as shown in graphical summary of Fig.2.11. However, the analysis was based on EDFAs operating in conventional C-band at 1550 nm. The effect of amplifier losses has not been considered in the analysis.
- (iii) Turitsyn *et al.* [235] showed the MI phenomenon, as a particular case taking EDFAs, by solving the NLSE to a set of non-linear coupled differential equations. The input power has been considered as growing adiabatically with the fiber distance instead of a constant value. The solution of the perturbation variables is presented through modified Bessel functions of the second kind. Further approximation, of which, leads to an analytical expression for integrated gain. A perturbation can pick this integrated gain if it lies below a defined threshold frequency as shown in the graphical summary of Fig.2.12. In addition, the study also presented the effect of the initial phase of the perturbations affecting the mechanism to invoke MI. The results obtained are in-tandem with the work presented



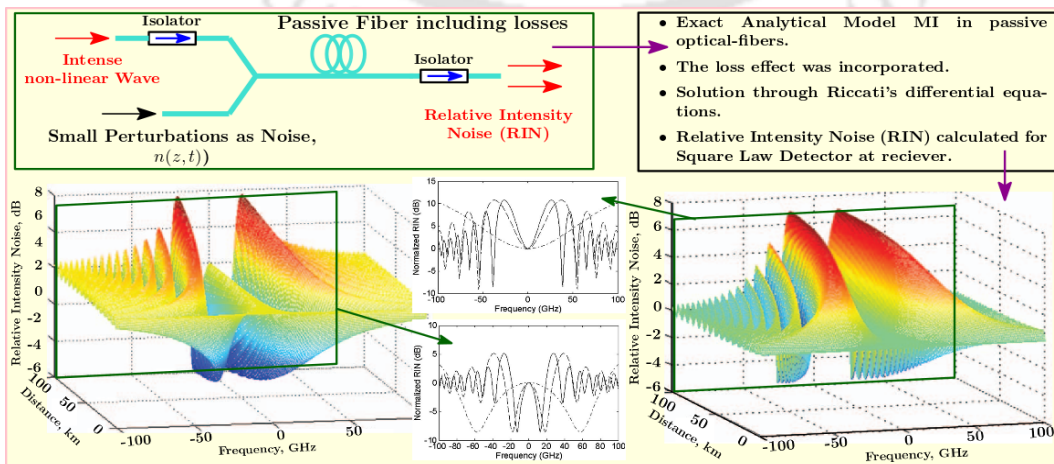
## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



**Fig. 2.12:** Graphical summary of the work carried out in [235]. The exact solution help in the prediction of perturbation frequency for maximum gain considerations. It also display the perturbation phase behaviour on the MI.

in [234]. The analysis proved to be crucial with respect to the mathematical methodology but the loss-factor effect was found to be missing.

- (iv) Aslam *et al.* [236] considered the demonstration of MI phenomenon in passive optical-fibers. They derived this method as an efficient computation of MI through the solution of Riccati's differential equations. The simulation further focused on the calculation of relative intensity noise (RIN) within the received signal through spectrum broadening owing to MI. The method displays the phenomenon in both the normal and anomalous regimes as shown in the graphical summary of Fig.2.13. As this method proved to be a powerful tool for MI prediction in passive optical-fibers, therefore, can be employed for



**Fig. 2.13:** Graphical summary of the work carried out in [236]. The analysis could help in the prediction of perturbation frequency to minimize RIN.

RE-DFAs too. More in-depth analysis of loss and non-linear factors could lead to new results relevant to MI.

Due to exceptionally high absorption and emission CSA of TDFAs in  $2\ \mu\text{m}$  regime, it is possible to achieve high power optical pulses ( $\sim\text{kW}$ ,  $\text{MW}$ ) using saturable absorber, mode-locking, Q-switching, and other non-linear amplification techniques [237, 238]. The thermal loading effect, arising due to modal instability, may be a potential source of perturbations that can invoke the MI effects in high power fiber-laser systems [239]. However, to achieve the same in S-band using MI technique still remains the area of research. Table 2.2 summarises the phenomenon of MI in RE-DFAs. It also suggests an idea to implement the possible techniques for MI investigations in TDFA systems for S and near-C bands fiber-optic communication systems.

Table 2.2: Summary of the MI studies in TDFAs

| Reference      | Addressed Issues                                                                                                                                                                                                                                                                                                                                                | Unaddressed Issues                                                                                                                                                                                                                                                                                                                              |
|----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Karlsson [233] | <ul style="list-style-type: none"> <li>Exact analytical solution of MI in lossy passive optical-fibers.</li> <li>Drawbacks of WKB-method with respect to accuracy.</li> <li>Modified-Bessel function has been used for linearized equations of perturbations.</li> <li>Initial nature of perturbations at the input has been considered as constant.</li> </ul> | <ul style="list-style-type: none"> <li>Initial nature of perturbations at input can be attributed to the ASEs from TDFAs.</li> <li>Application of the presented model on TDFAs for S and near-C bands amplification and to predict the frequency at which MI initiates.</li> <li>Transition dynamics of more than two energy levels.</li> </ul> |

continued ...

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

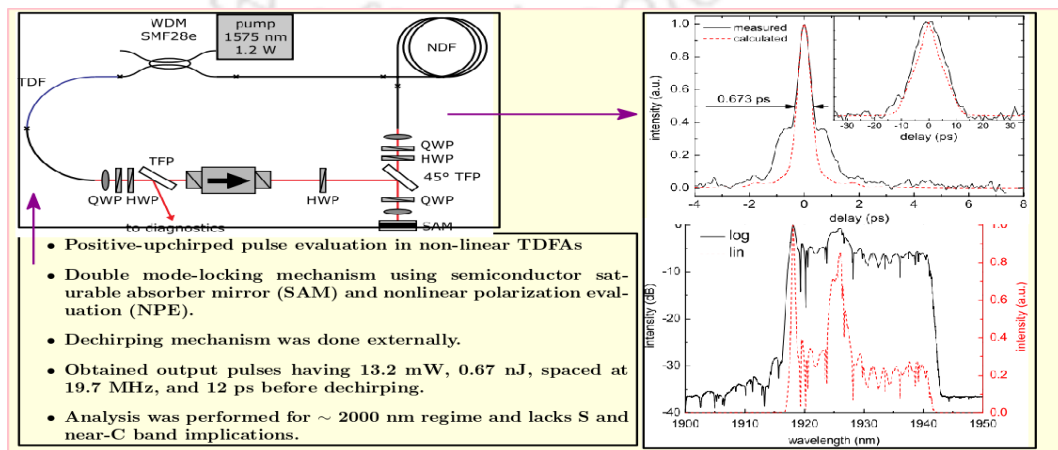
...continued

| Reference                    | Addressed Issues                                                                                                                                                                                                                                                                                                                                                                                | Unaddressed Issues                                                                                                                                                                                                                                                                                                                            |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Agrawal [234]                | <ul style="list-style-type: none"> <li>Analytical model to demonstrate MI in EDFAs.</li> <li>Study has been performed by solving NLSE through linear stability analysis.</li> <li>Numerical approach to demonstrate the breaking of the CW signal into a pulse-train.</li> <li>Finds application in the development of mode-locked fiber lasers</li> </ul>                                      | <ul style="list-style-type: none"> <li>The model did not considered the loss effects which may be attributed to possible ASEs in EDFAs.</li> <li>The non-linear factor analysis is not investigated.</li> <li>The approach has been displayed for C-Band signals and would be interesting to analyse for S-Band signals for TDFAs.</li> </ul> |
| Turitsyn <i>et al.</i> [235] | <ul style="list-style-type: none"> <li>Exact solution for the development of MI in EDFAs by solving NLSE.</li> <li>The solution is expressed as a modified Bessel functions which then reduced to approximated form to reduce complexity.</li> <li>The input-perturbation phase effect shows the evolution of MI.</li> <li>Utilization of the MI phenomenon in building fiber-lasers</li> </ul> | <ul style="list-style-type: none"> <li>The loss factor and non-linear factor variation effect on MI development.</li> <li>The analysis may be used in TDFA systems to provide the MI prediction and optimum frequency values.</li> <li>Transition dynamics of more than two energy levels.</li> </ul>                                         |
| Aslam <i>et al.</i> [236]    | <ul style="list-style-type: none"> <li>Analytical model for pump phase modulation in EDFAs.</li> <li>Control of the signal group velocity using the pump phase modulation.</li> <li>Simulation verified through experimental trials of establishing Gaussian pulse input as an alternate to a sinusoidal signal.</li> </ul>                                                                     | <ul style="list-style-type: none"> <li>Effect of ASE on output signal modulation index and phase.</li> <li>Effect of signal phase modulation effect.</li> <li>Transition dynamics of more than two energy levels.</li> <li>Pump-phase modulation in TDFAs to control the signal group velocity.</li> </ul>                                    |

### 2.3.3 Literature Review on the Chirping Effects on Optical Pulses in TDFAs through MI

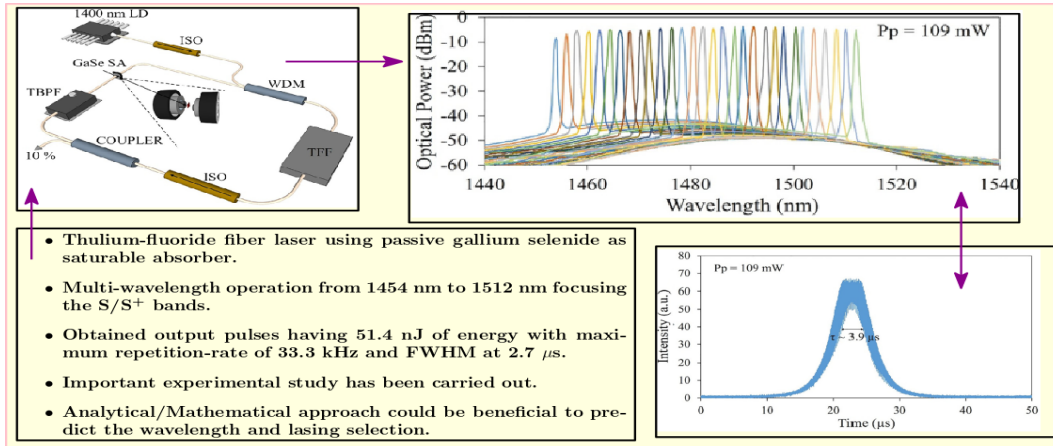
The phenomenon of MI may arise inside an optical amplifier when the pulse power due to amplification reaches to the level of threshold of keeping the pulse steady to perturbations. It has been found that the frequency chirping may cause the weak dispersive effect which act as a trigger to pulse splitting of which both group velocity distortion (GVD) and self phase modulation (SPM) are prime contributors [240]. High power time-domain optical pulses and tuneable frequency combs are of much interest in optical communication and medical technology. Numerous studies have been reported on MI due to chirping effects on EDFAs and TDFAs. However, the pulse propagation and its corresponding changes in its characteristics while traversing inside TDFAs have not been thoroughly investigated. Some of the relevant literature studies done in this domain are as follows:

- (i) Haxsen *et al.* [241] performed the experimental studies on the evaluation of up-chirped pulses inside the TDFA. The configuration of the setup is in a ring shape with double mode-locking mechanisms as shown in the graphical summary of Fig. 2.14. This dual mode-locked fiber laser has been assembled using a semiconductor saturable absorber mirror (SAM) along with non-linear polarization evaluation (NPE) for better dispersion management. The de-chirping mechanism has been carried out using an external grating compressor. The output pulse characteristics have been found with 13.2 mW of power and 0.67 nJ pulse energy. The pulses are having 19.7 MHz spacing with the upchirped



**Fig. 2.14:** Graphical summary of the work carried out in [241]. The study emphasized on the upchirping effect on the input pulse evaluated inside a TDFA.

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



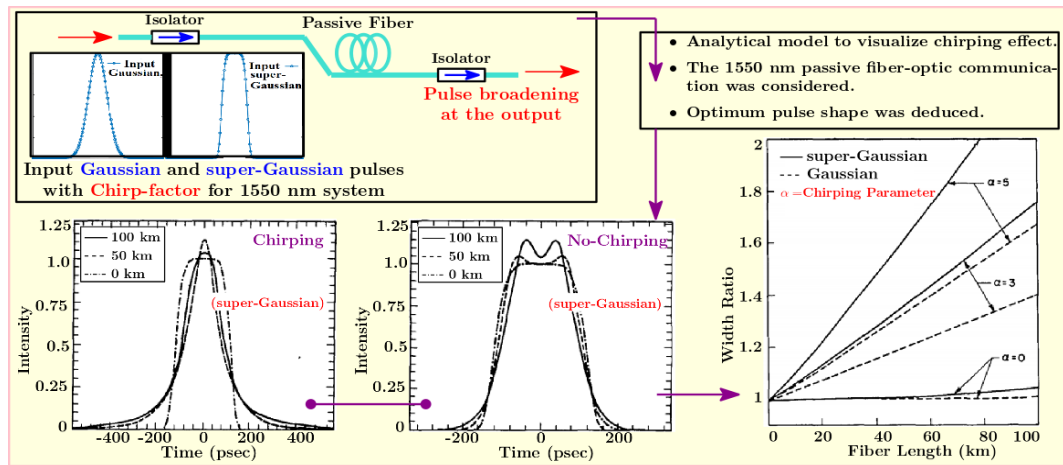
**Fig. 2.15:** Graphical summary of the work carried out in [206]. The study emphasized on the production of the tunable laser using a thulium fluoride fiber in S/S<sup>+</sup> bands.

FWHM as 150 ps. The entire analysis is based on  $\sim 2000 \text{ nm}$  wavelength regime and therefore lacks the S and near-C band implications.

(ii) Ahmad *et al.* [206] carried out experimental analysis on thulium-fluoride fibers. Although, the study did not involve the chirping effects but an insight has been given for S/S<sup>+</sup> bands lasing. Tunable wavelength TFFL has been displayed with 1454 nm to 1512 nm range of selection. The setup has been arranged in a ring configuration with passive saturable absorber from gallium selenide material. Obtained output pulses have energy of 51.4 nJ with maximum repetition-rate of 33.3 kHz and FWHM at 2.7  $\mu\text{s}$ . The analysis lack the mathematical approach which can be performed including the frequency chirping effects on silica based TDFAs. The graphical summary showing the experimental setup with tunable laser action can be seen in Fig. 2.15.

(iii) Agrawal *et al.* [234,242] showed the effect of frequency chirping in the input pulse for the 1550 nm system as a detrimental effect. The frequency chirp may cause the weak dispersive effects acting as a trigger to pulse splitting of which both group velocity distortion (GVD) and self-phase modulation (SPM) are prime contributors. This study deals with the behavior of frequency chirping effect on various types of optical input-pulses at 1550 nm. Apparently, it has been concluded that the rate of broadening of *super-Gaussian* pulse is faster than that of *Gaussian* pulse as shown in the graphical summary of Fig.2.16. Consequently, the results lead to the finding of optimum and best-suited pulse for fiber-





**Fig. 2.16:** Graphical summary of the work carried out in [243]. The analysis could help in the selection of optimum pulse shape and chirping parameter.

optic communication. The non-linearity factor is not considered in the analysis.

The above stated studies suggest the behaviour of the frequency chirped optical pulses in RE-DFAs. Apparently, assimilating the ideas reflected in these studies, it may be applied to the TDFAs with respect to S and near-C bands of fiber-optic communication. The summary of these studies are mentioned in Table 2.3 below

Table 2.3: Summary of the frequency chirping effects on optical pulses in TDFAs

| Reference                  | Addressed Issues                                                                                                                                                                                                                                                                                                                                                                  | Unaddressed Issues                                                                                                                                                                                                                                                        |
|----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Haxsen <i>et al.</i> [241] | <ul style="list-style-type: none"> <li>Positive-upchirped pulse evaluation in non-linear TDFAs is observed and analyzed experimentally.</li> <li>Double mode-locking mechanism using SAM NPE has been applied.</li> <li>Obtained output pulses having 13.2 mW, 0.67 nJ, spaced at 19.7 MHz, and 12 ps before dechirping.</li> <li>Dechirping has been done externally.</li> </ul> | <ul style="list-style-type: none"> <li>The non-linear and chirping analysis can be performed mathematically to predict the behaviour of the traversing pulse within TDFAs.</li> <li>The model can be derived for S and near-C bands amplification using TDFAs.</li> </ul> |

continued ...

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

...continued

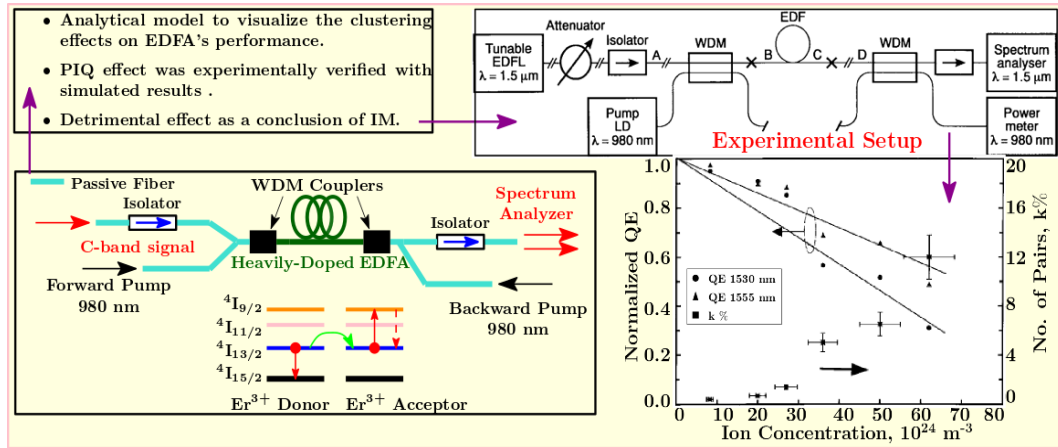
| Reference                       | Addressed Issues                                                                                                                                                                                                                                                                                                                                                               | Unaddressed Issues                                                                                                                                                                                                                                                      |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ahmad <i>et al.</i> [206]       | <ul style="list-style-type: none"> <li>• Experimental studies on the designed setup for tunable wavelength emission.</li> <li>• The S/S<sup>+</sup> band has been the region of interest.</li> <li>• Obtained output pulses having 51.4 nJ of energy with maximum repetition-rate of 33.3 kHz and FWHM at 2.7 <math>\mu</math>s.</li> </ul>                                    | <ul style="list-style-type: none"> <li>• Analytical and mathematical approach could be a beneficial aspect to predict the wavelength and lasing selection while designing the system.</li> <li>• The frequency chirping aspect can be included in the model.</li> </ul> |
| Agrawal <i>et al.</i> [234,242] | <ul style="list-style-type: none"> <li>• Analytical model for the chirping effect on passive fiber at 1550 nm systems.</li> <li>• Detrimental role of chirping may lead to MI.</li> <li>• Comparison of the best possible pulse shape in fiber-optic communication considering <i>super-Gaussian</i> and <i>Gaussian</i> pulses respectively with chirping effects.</li> </ul> | <ul style="list-style-type: none"> <li>• The non-linearity considerations in the analysis.</li> <li>• Transition dynamics of more than two energy levels.</li> <li>• Studies of the chirping effect on TDFA based systems including non-linearity.</li> </ul>           |

### 2.3.4 Literature Review on the Ion-Ion Interaction Effects in TDFAs

The optical conversion efficiency of RE-DFAs is dependent on parameters like dopant concentration, pump power, fiber length, dopant area, signal wavelength, and ion-ion interaction mechanisms (IM). The IM, also called cross-relaxation (CR) effects, give rise to two categories of CR effects known as homogeneous up-conversion (HUC) and clustering phenomenon called pair induced quenching (PIQ). At higher levels of pump powers and dopant concentration, PIQ effects become more dominant over HUC effects. Most of the studies on IM were performed on EDFAs through which we can extend the knowledge in this domain on TDFAs. Some of the comprehensive works performed on RE-DFAs on IM are as follows:

[TH-2662\\_136102025](#)

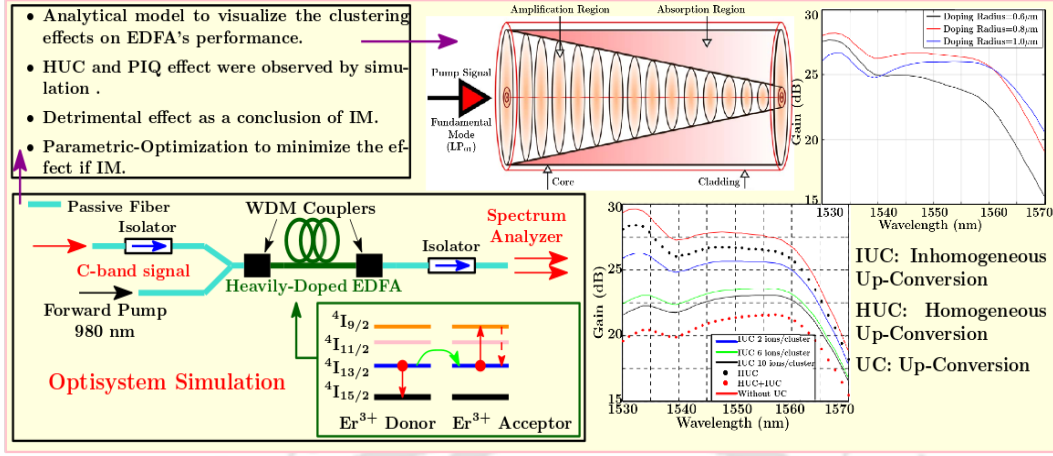




**Fig. 2.17:** Graphical summary of the work carried out in [244]. The study emphasized on the IM effects on EDFA performance with further optimization of parameters for the highest gain.

- (i) Myslinski *et al.* [244] carried out analytical modeling and experimental studies of clustering effects on EDFAs. The impact of the doping concentration of  $\text{Er}^{3+}$  ions on its performance has been analyzed. The amplifier's degraded recital has been owned by the upconversion mechanisms. The ion cluster effect i.e. PIQ is theoretically modeled and experimentally verified on aluminum co-doped EDFAs. The study is focused to reduce the detrimental effect of IM on the EDFA gain performance by optimizing the amplifier length, signal-wavelength selection in C-band,  $\text{Er}^{3+}$  ion concentration, and the relative direction of pumping scheme as shown in the graphical summary of Fig.2.17. It neglected the ASE effects by considering the amplifier to be strongly saturated. Although, the detrimental effect of IM has mostly been sighted, the constructive effects of the same with respect to early population-inversion is not presented. The analysis is limited to the two-level system which can be considered for TDFA systems too after valid transformations.
- (ii) Amin *et al.* [177, 245] performed the simulation studies on EDFAs where the emphasis has been given on doping concentration and amplifier-length optimization. The basic idea of the analysis is based on the studies performed in [244]. The EDFAs high-power level pumping may cause an increase in the dopant interaction resulting in detrimental IM effects. Therefore, for single-mode fibers with lower value of the core diameter, the problem of IM may escalate which has been demonstrated by varying the numerical-aperture in this analysis. The degraded performance of the EDFAs is accounted by the decrease

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey



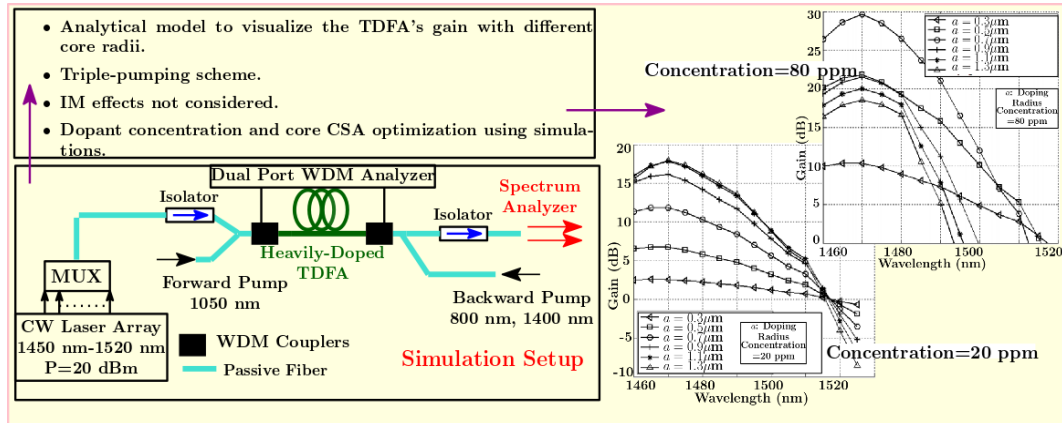
**Fig. 2.18:** Graphical summary of the work carried out in [177, 245]. The study emphasized the IM effects on EDFA's performance with respect to the numerical aperture and dopant concentrations. The IUC and HUC mechanisms have been compared with the achieved gain respectively.

in the effective fiber-core CSA due to the intensity distribution of the fundamental pump-mode in the core. The intensity envelope of this fundamental linearly polarized mode (LP<sub>01</sub>) has been considered as almost Gaussian while being actually represented as Eq. (2.1) [246]

$$\psi_{01}(\lambda_p, r) = \begin{cases} J_0^2\left(\frac{u_p r}{a}\right), & \text{for } r \leq a \\ \frac{J_0^2(u_p)}{K_0^2(w_p)} K_0^2\left(\frac{w_p r}{a}\right), & \text{for } r > a \end{cases} \quad (2.1)$$

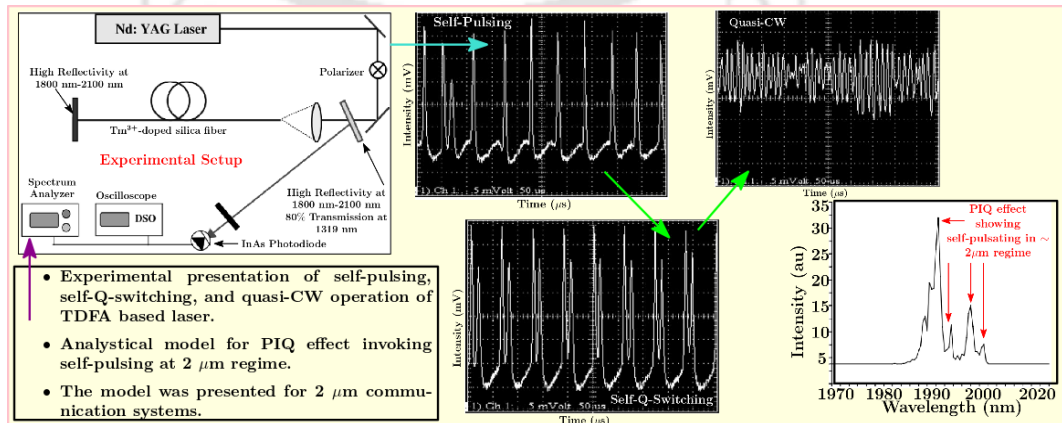
where  $J_0$  and  $K_0$  denotes the zeroth-order Bessel and modified Bessel functions respectively. The core-radius of step-index fiber is  $a$ ,  $u_p$  and  $w_p$  are the transverse propagation constants of the LP<sub>01</sub> mode. Consequently, the absorption region of the near-Gaussian shaped pump signal decreases at the core-cladding interface due to the tailing ends of the Gaussian intensity distribution profile. Consequently, the signal power at the fiber core axis may remain above the threshold while decreasing at the core-cladding interface resulting in absorption region rather than amplification. This may apparently result in inefficient use of the pump. The graphical summary of Fig.2.18 shows the pump-power, doping-radius, and the numerical aperture analysis. The harmful aspect of HUC and PIQ have been simulated and discussed on EDFAs. Although, the model showed the ASE term but the simulation parameters are considered without its effect.

(iii) Singh *et al.* [247, 248] selectively presented the doping concentration and core-radius ef-



**Fig. 2.19:** Graphical summary of the work carried out in [247]. The simulation results performed by the authors on TDFAs helped to obtain optimum core CSA and doping concentration.

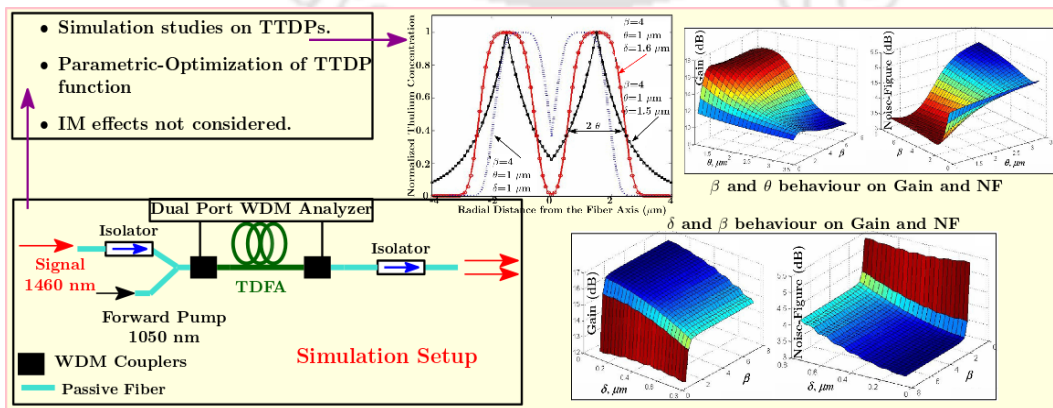
fects on the gain of TDFA in S-Band amplification system. The simulations have been based on the mathematical model consisting of  $\text{Tm}^{3+}$  ion energy-level rate equations considering the possible transactions from the levels  $^3\text{H}_6$  (level-0),  $^3\text{F}_4$  (level-1),  $^3\text{H}_5$  (level-2),  $^3\text{H}_4$  (level-3), and  $^1\text{G}_4$  (level-5) respectively. The triple-wavelength pumping mechanism with (1050 nm + 1400 nm + 800 nm) is considered resulting in increment of gain but may incur thermal-loading effects in the system leading to modal-instability. The analysis did not consider the impact of IM effects on TDFA gain which may arise in the system due to high-pumping power and low area of CSA of the core. The graphical summary shown in Fig.2.19 displays the simulation set-up followed by simulation-results for the triple-wavelength pumping mechanism.



**Fig. 2.20:** Graphical summary of the work carried out in [88]. The model and experimental results show the self-pulsing effect in TDFAs when the input pump-power has been increased gradually. The PIQ effect is also considered for  $2 \mu\text{m}$  systems.

## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

- (iv) El-Sherif *et al.* [88] presented the self-pulsing action of  $\text{Tm}^{3+}$  silica fiber laser at  $2\ \mu\text{m}$  regime pumped at  $1.319\ \mu\text{m}$ . The three-level energy system for TDFAs has been considered to show the PIQ effect under ESA. The graphical summary of Fig.2.20 shows the experimental setup to observe the self-pulsing effect. This further changes to self-Q-switching and quasi-CW operation on increasing the respective pump-power. The clustering effects consisting of PIQ have also demonstrated analytically which further being verified through experimental results. The study showed the absorption CSA of paired  $\text{Tm}^{3+}$  ions may become unstable by acting as an additional absorber which can eventually trigger self-pulsing. The entire analysis has been limited to  $^3\text{H}_4$  to  $^3\text{H}_6$  lasing transitions and therefore, S-band implications are lacking.
- (v) Emami *et al.* [249] relied on the fact that the  $\text{LP}_{01}$  mode of the pump effectively decreases the absorption CSA of TDFAs as shown in Fig. 2.18. Therefore, using appropriate numerical models, they performed optimization studies to maximize the gain using appropriate transverse thulium distribution profiles (TTDPs). Considering the S-Band amplification, the TTDP expression has been suggested as a function of dopant radius ( $\theta$ ), the roll-off factor ( $\beta$ ) of the profile, and the radial position of the profile peak ( $\delta$ ). This approach is based on the studies carried on EDFAs in [250, 251]. The graphical summary of Fig.2.21 displays the behavior of TTDP as the mentioned variables. The noise-figure analysis has also been carried out to observe the possible ASE effects in the S-Band. This work may



**Fig. 2.21:** Graphical summary of the work carried out in [249]. The simulation results helps in selection of the optimized TTDP parameters to maximize gain performance.

reduce the IM effects, considered to be detrimental to the gain performance of the TDFAs, however not presented in the analysis.

The above-mentioned studies provided comprehensive approaches to show IM effects through modeling, simulation, and experiments on RE-DFAs summarised in Table 2.4. However, the probable constructive aspect of early population inversion on low pump-power has been found to be missing. Moreover, for S and near-C bands communications, this analysis on TDFAs could further widen the path for them in commercial fiber-optic communications in-tandem with EDFAs.

Table 2.4: Summary of the IM studies on TDFAs

| Reference                        | Addressed Issues                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Unaddressed Issues                                                                                                                                                                                                                                                                                                                                          |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Myslinski<br><i>et al.</i> [244] | <ul style="list-style-type: none"> <li>• An analytical model to present the phenomenon of PIQ and HUC.</li> <li>• Optimization of parameters like <math>\text{Er}^{3+}</math> ion concentration, amplifier length, signal and pump power, signal wavelength, etc. for best possible amplifier gain.</li> <li>• The CR mechanisms have been shown as a detrimental factor on EDFA's performance.</li> <li>• Directional pumping-scheme analysed on EDFAs.</li> </ul> | <ul style="list-style-type: none"> <li>• The ASE effects are neglected by considering the amplifier to be saturated.</li> <li>• The analysis primarily deals with the two-level systems which can be further extended to TDFA systems.</li> <li>• The constructive effect of IM with respect to early population inversion at lesser pump-power.</li> </ul> |

continued ...



## 2. Thulium Doped Fiber Amplifiers (TDFAs): Literature Survey

... continued

| Reference                           | Addressed Issues                                                                                                                                                                                                                                                                                                                  | Unaddressed Issues                                                                                                                                                                                                                                                                                                                                              |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Amin<br><i>et al.</i><br>[177,245]  | <ul style="list-style-type: none"> <li>• Simulation studies on the clustering effects.</li> <li>• Optimization to minimize the detrimental effect of IM on the EDFA's gain performance.</li> <li>• Effective decrease in the fiber-core area considering the Gaussian-pump beam thereby increasing the IM probability.</li> </ul> | <ul style="list-style-type: none"> <li>• Simulation parameters did not consider ASE effects which are bound to occur in high power-pumping.</li> <li>• Only the detrimental effects of IM are presented.</li> <li>• Early population-inversion due to IM at lower pump-powers.</li> <li>• The methodology can be applied to TDFAs to demonstrate IM.</li> </ul> |
| Singh<br><i>et al.</i><br>[247,248] | <ul style="list-style-type: none"> <li>• TDFA's core CSA and doping concentration optimization.</li> <li>• Analytical model and Simulation setup.</li> <li>• Triple-pumping scheme.</li> </ul>                                                                                                                                    | <ul style="list-style-type: none"> <li>• The IM effects are not considered in the analysis.</li> <li>• Triple-pumping scheme may introduce thermal-loading.</li> <li>• Initiation of perturbations due to temperature increase leading to MI in high-gain conditions.</li> </ul>                                                                                |
| El-Sherif<br><i>et al.</i> [88]     | <ul style="list-style-type: none"> <li>• Self-Pulsing, Self-Q-Switching, and Quasi-CW operations in TDFAs with varying pump-power.</li> <li>• Experimental results on PIQ effect on self-pulsing initiation.</li> <li>• Analysis is performed for 2 <math>\mu\text{m}</math> fiber-optic communication systems.</li> </ul>        | <ul style="list-style-type: none"> <li>• The effect of ASE in the analytical model has not been considered.</li> <li>• The S-Band implications of the model presented is missing.</li> </ul>                                                                                                                                                                    |

continued ...

...continued

| Reference                 | Addressed Issues                                                                                                                                                                                                                                                                                                                                          | Unaddressed Issues                                                                                                                                                                                                              |
|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Emami <i>et al.</i> [249] | <ul style="list-style-type: none"> <li>• Performed optimization studies to maximize the gain using appropriate TTDPs for S-Band systems.</li> <li>• NF analysis to show the possible ASE effects.</li> <li>• TTDP represented as a function of dopant radius, the roll-off factor of the profile, and the radial position of the profile peak.</li> </ul> | <ul style="list-style-type: none"> <li>• Analysis on the possible decrease in the IM effects.</li> <li>• Intensity-based <math>\text{Tm}^{3+}</math> distribution in stepped layers as presented in [251] for EDFAs.</li> </ul> |

## 2.4 Summary

This chapter summarizes the various works published in the literature associated with the overmodulation of signal-gain dynamics, the modulation-instability and chirping effects, and the ion-ion interaction mechanisms in RE-DFAs. Furthermore, the comprehensive analytical approaches derived, simulation study performed, and experimental results obtained on EDFAs could provide a base to which TDFAs could be analyzed on these novel studies. Moreover, the discussions and the unaddressed issues discussed in this chapter also set the primary motivation for the analysis carried out in the subsequent chapters.





# 3

## Overmodulation of Signal and Gain Dynamics in TDFAs

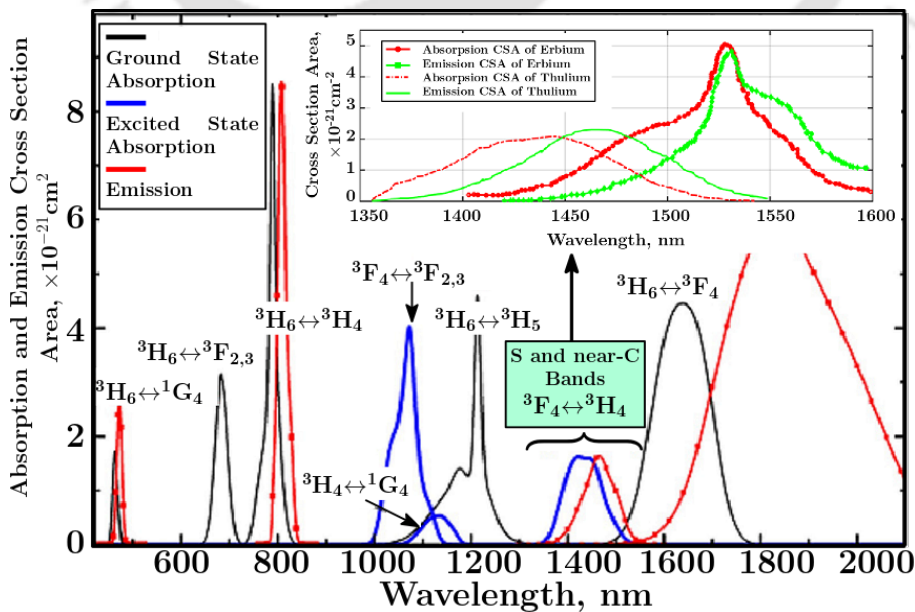
### Contents

|     |                             |     |
|-----|-----------------------------|-----|
| 3.1 | Introduction                | 76  |
| 3.2 | Analytical Model            | 78  |
| 3.3 | Simulink Pedestal for TDFAs | 90  |
| 3.4 | Results and Discussions     | 93  |
| 3.5 | Summary                     | 105 |

#### 3.1 Introduction

Over the past few decades, fiber-amplifiers have been typically fabricated with Erbium doping revolutionizing the optical communication in C-Band [89]. The ultrahigh capacity optical transmission, amplification, and switching networks are often vulnerable to perturbations and noises from different sources. As a result, it may bring the communication system down thereby breaking the backbone of today's technologically connected world. Therefore, information accommodation and data management have become a new challenge due to the recent phenomenal increase in data traffic owing to an effective and high-speed data network. In previous decades of EDFA-based communication, it is being the current state-of-the-art technology with DWDM system meeting the network demands with a channel rate of 40 Gbps. It further has reached the theoretical limit of saturation per fiber-core with spectral efficiency of  $0.8 \text{ bit s}^{-1}/\text{Hz}$  [163]. Consequently, the need for new methods and formulations to increase the data rate in the same existing band is the need of the hour.

Therefore, to fulfill this requirement, optical fibers doped with new materials have been in constant research. Thulium-doped fiber amplifiers have drawn researcher's attention due to its various potential applications as mentioned in Chapter 1. However, getting options for



**Fig. 3.1:** Absorption and Emission CSA of  $\text{Tm}^{3+}$  ions in silica glass matrix emphasizing the S and near-C bands spectra. Inset shows the respective comparative CSAs for  $\text{Tm}^{3+}$  and  $\text{Er}^{3+}$  ions.

existing C-band communication system infrastructure, the S and near-C band emission and absorption spectra of  $\text{Tm}^{3+}$  needs to be exhausted. The comparative absorption and emission CSA of TDFAs in S and near-C bands (1460 nm–1545 nm) with that of EDFAs communicating in the C-Band's "narrow-window"  $\sim (1550 \pm 8 \text{ nm})$  is shown in Fig. 3.1 [54, 218, 252]. It makes them an apt material for in-tandem communication amongst the two. Moreover, the requirements for gain flattening techniques would not be required for TDFAs owing to its flat spectral characteristics.

The exchange of status and information-management in the DWDM are currently implemented by overmodulating the amplitude of the information signal through pump. It can be effectively put to surveillance and monitoring using the technique of signal and gain modulation in EDFA systems. This in-fact can be represented as pump-to-signal and signal-to-signal transfer functions, as done for EDFAs in [219, 226, 228, 229]. Consequently, the gain characteristics of TDFAs have also been found to be substantially influenced by the dynamic modulation of the input signal [253]. Moreover, the portability of  $\text{Tm}^{3+}$  ions in its dopant form, as TDFAs, has been employed for S and near-C band communication [163, 221].

Therefore, the line surveillance and management of information can be done in TDFAs too using the overmodulation technique as mentioned above. This control-signal can be imposed as an overmodulated signal on the communication signal through low frequency ( $\sim 100 \text{ kHz}$ ) amplitude modulation. ASE-noise is also susceptible to channel add-drop in reconfigurable-DWDM networks. The optical filtering within different nodes of the network may dynamically reshape the ASE spectrum to irregular levels depending on the operating wavelength. As a consequence, the signal information may get corrupted if the ASE level becomes comparative to that of the signal. Therefore, for precise system monitoring and control in active networking systems exact behavior of noise becomes an important parameter [219, 227].

The primary focus of the presented study in this chapter is to analytically model the overmodulation of signal-gain dynamics in TDFA systems including the ASE effects. The transfer functions for signal-to-signal and signal-to-ASE have been derived to predict the system's performance under high-input signal power conditions and its variation on the input modula-

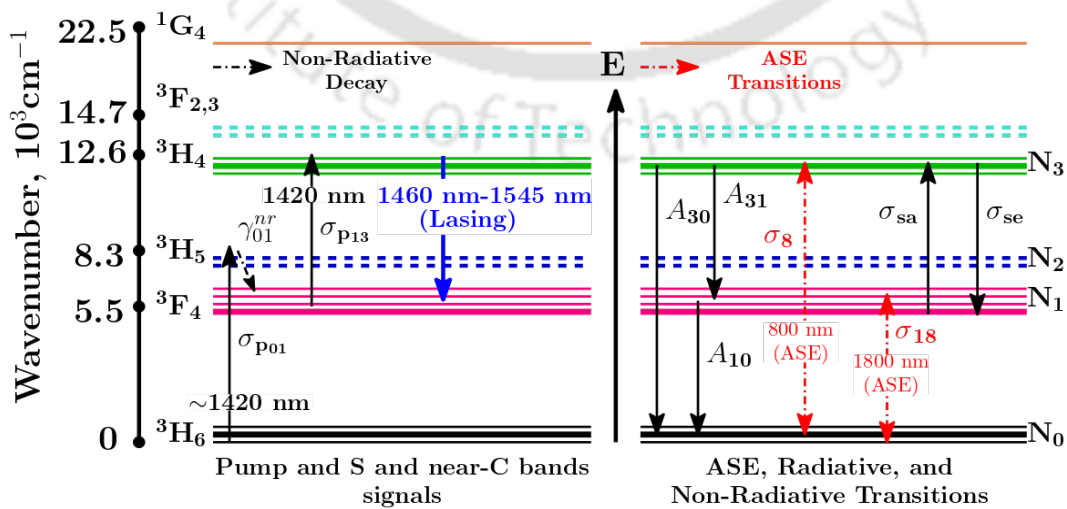
### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

tion index. The chapter further deals with the signal-wavelength variation effect on the output modulation-index and phase for which expressions are derived. The optimized signal power and wavelength in S and near-C bands have been determined from the simulation results to maximize the TDFA gain. The analytical model developed is also implemented on MatLab®-Simulink based test-bed resulting in a simulator. This can predict the system's performance in various conditions.

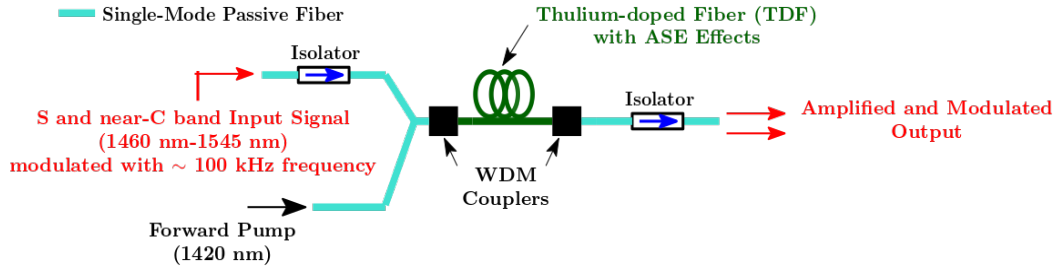
### 3.2 Analytical Model

The relatively shorter upper-level lifetime of  $^3H_4$  (1.7 ms) with respect to  $^3F_4$  (11 ms) make it difficult to achieve population inversion. Therefore, one of the strategies to overcome this constraint is an up-conversion pumping scheme at  $\sim 1420$  nm range. Moreover, at these pumping wavelengths, the ASEs at 800 nm remain at minimal levels and are less prone to ESA than 980 nm which can deplete the population in the meta-stable state  $^3H_4$  [151, 253]. Consequently the up-conversion pumping scheme for the TDFAs is shown in Fig. 3.2. The 1420 nm pumping along with S and near-C bands lasing transactions can be seen on the left-side of Fig. 3.2 while ASEs, radiative, and non-radiative are visible on the right.

The model includes the effects due to S and near-C band signal ASEs, 800 nm ASE, and 1800 nm ASE. It is assumed that the 800 nm and 1800 nm ASEs are homogeneous lightwaves



**Fig. 3.2:** Left-shows the up-conversion pumping scheme at  $\sim 1420$  nm with the lasing transitions. Right-shows the ASE at 800 nm and 1800 nm with other radiative transitions.



**Fig. 3.3:** Schematic representation for the signal-gain overmodulation dynamics studies on TDFAs.

to include the possible situations where population inversion persists among these levels [163]. Therefore, the consequent effects of ASEs can be observed pertaining to signal power and gain modulation. The implementation of signal overmodulation has been carried out using the Bononi and Rusch approach for the TDFA systems [225, 254]. It is used to analyze the output signal and gain variation with the input signal's modulation frequency and power of TDFAs. The analysis has been based considering the following assumptions:

- (i) A three-level TDFA transition system with emission level from  $^3H_4$  to  $^3F_4$ .
- (ii) The signal ASE is considered as unidirectional traversing from fiber's input to output, with no ASE at fiber input end.
- (iii) No loss of optical power in scattering process.
- (iv) Unidirectional pumping scheme as shown schematically in the Fig. 3.3.
- (v) Cross-relaxation processes have not been considered in this model. However, it is dealt with in chapter 5.

The transition dynamics for the concerned S and near-C bands levels should be taken into account. It can be seen from Fig. 3.2 that the energy-levels  $^3H_4$  and  $^3F_4$  are involved in population inversion and thus signal amplification. Level  $^3H_5$  has relatively short lifetime ( $\sim 6.03 \mu s$ ) for  $Tm^{3+}$  as a consequence the TDFA-system for S and near-C bands transitions has been effectually reduced to three levels [53]. The gain in the TDFAs is based on parameters such as the overlap factor of fiber, concentration of  $Tm^{3+}$  dopant, fiber length, and optical pump power. The pump power and fiber length has been considered as constant parameters in this model and the transformation of gain modulation as a function of steady-state concentrations of  $Tm^{3+}$  at  $^3F_4$  ( $N_1^0$ ) and  $^3H_4$  ( $N_3^0$ ) respectively has been presented. From the Fig. 3.2, the rate equations



### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

for population of ions  $N_i$  ( $i = 0, 1, 2, 3$ ), with  $i$  corresponding to each energy level, can be given as

$$\frac{\partial N_0}{\partial t} = (A_{10} + W_{18e})N_1 + (W_{8e} + A_{30})N_3 - (W_{18a} + W_{8a} + W_{p01})N_0 \quad (3.1)$$

$$\frac{\partial N_1}{\partial t} = (W_{18a} + W_{p01})N_0 - (A_{10} + W_{p13} + W_{sa} + W_{18e})N_1 + (W_{p31} + W_{se} + A_{31})N_3 \quad (3.2)$$

$$\frac{\partial N_3}{\partial t} = (W_{8a})N_0 + (W_{p13} + W_{sa})N_1 - (A_{30} + W_{p31} + W_{se} + A_{31} + W_{8e})N_3 \quad (3.3)$$

$$\sum_i^{\{0,1,3\}} N_i = N_t = \rho \quad (3.4)$$

where transition rates for 1420 nm pumping denoting the signal-stimulated absorption ( $a$ ) and emission ( $e$ ) rates respectively are  $W_{pij}$  and  $W_{sa,se}$ . The absorption/emission transition rates  $W_{8/18,a/e}$  are for the corresponding 800 nm and 1800 nm ASE respectively.  $A_{ij}$  represents the radiative rates, and  $\rho$  is the total  $\text{Tm}^{3+}$  density.  $\gamma_{21}^{nr}$  is the non-radiative transition rate between the energy levels  $^3\text{H}_5$  to  $^3\text{F}_4$  and can be disregarded as it represents multiphonon decay [221]. Other transitions pertaining to S and near-C bands amplification are ignored due to their non-participating nature. The transition rates are thus, defined as

$$W_{ij} = \lambda_p \sigma_{pij} (P_p / hcA_{\text{eff}}) \quad (3.5)$$

$$W_{8/18,a/e} = \lambda_{\text{ASE } 8,18} \sigma_{8/18,a/e} (P_{\text{ASE } 8,18} / hcA_{\text{eff}}) \quad (3.6)$$

$$W_{sa,se} = \lambda_p \sigma_{sa,se} (P_s / hcA_{\text{eff}}) + \lambda_s \sigma_{sa,se} (P_{\text{ASE}} / hcA_{\text{eff}}) \quad (3.7)$$

where the subscripts and superscripts of wavelengths  $\lambda_s$ ,  $\lambda_p$ ,  $\lambda_{\text{ASE}}$ , and  $\lambda_{\text{ASE } 8,18}$  represent the signal, pump, signal-ASE, ASE at 800 nm and 1800 nm wavelengths respectively. The pump and input-signal powers are defined as  $P_p$  and  $P_s$  respectively. Also, the various considered ASE powers can be represented as  $P_{\text{ASE } 8,18}$  (ASE power at 800 nm and 1800 nm) and  $P_{\text{ASE}}$  (signal ASE power).  $\sigma_{pij}$  are the pump emission and absorption CSAs,  $\sigma_{8/18,a/e}$  are the ASE absorption/emission CSAs at 800 nm/1800 nm, and  $\sigma_{sa,se}$  are the signal absorption and emission CSAs respectively. The Planck's constant and speed of light in vacuum are represented as  $h$  and

$c$  with  $A_{\text{eff}}$  being the effective CSA of the fiber respectively.

Ignoring the scattering losses, the photon progression in the fiber along its length can be defined as

$$\frac{\partial P_p}{\partial z} = -\Gamma(\lambda_p)[(\sigma_{p13}N_3 - \sigma_{p01}N_1)]P_p \quad (3.8)$$

$$\frac{\partial P_s}{\partial z} = \Gamma(\lambda_s)[\sigma_{se}(\lambda_s)N_3 - \sigma_{sa}(\lambda_s)N_1]P_s \quad (3.9)$$

$$\frac{\partial P_{\text{ASE}}}{\partial z} = \Gamma(\lambda_{\text{ASE}})[\sigma_{se}(\lambda_{\text{ASE}})N_3 - \sigma_{sa}(\lambda_{\text{ASE}})N_1]P_{\text{ASE}} + \Gamma(\lambda_{\text{ASE}})2h\nu\Delta\nu\sigma_{se}(\lambda_{\text{ASE}})N_3 \quad (3.10)$$

$$\frac{\partial P_{\text{ASE}_8}}{\partial z} = \Gamma(\lambda_8)[\sigma_{8e}(\lambda_8)N_3 - \sigma_{8a}(\lambda_8)N_0]P_{\text{ASE}_8} + \Gamma(\lambda_8)2h\nu\Delta\nu\sigma_{8e}(\lambda_8)N_3 \quad (3.11)$$

$$\frac{\partial P_{\text{ASE}_{18}}}{\partial z} = \Gamma(\lambda_{18})[\sigma_{18e}(\lambda_{18})N_1 - \sigma_{18a}(\lambda_{18})N_0]P_{\text{ASE}_{18}} + \Gamma(\lambda_{18})2h\nu\Delta\nu\sigma_{18e}(\lambda_{18})N_1 \quad (3.12)$$

where  $\Delta\nu$  is the bandwidth for each ASE frequency considered in this analysis. The overlapping factors between the respective fundamental and radiation modes are  $\Gamma(\lambda)$  as given as [53]

$$\Gamma(\lambda) = 1 - e^{\frac{-2b^2}{\omega_0^2}} \quad (3.13)$$

$$\omega_0 = a \left( 0.761 + \frac{1.237}{V^{1.5}} + \frac{1.429}{V^6} \right) \quad (3.14)$$

where the mode field radius is  $\omega_0$ , core radius of the fiber is  $a$ , and  $b$  is the dopant radius.  $V$  is the normalized frequency also known as  $V$ -parameter of fiber given as

$$V = \frac{2\pi}{\lambda}aNA \quad (3.15)$$

where  $NA$  is the numerical aperture of the fiber. Therefore, using (3.13)–(3.15), the wavelength-specific  $\Gamma(\lambda)$  to be used in this analysis was calculated and is given in Table 3.1. The expressions for the signal-gain ( $G$ ) and noise-figure ( $NF$ ), both in dB, are utilized in this study for TDFAs

**Table 3.1:** Wavelength-specific overlap-factor values

| Wavelength (nm) | Overlap Factor |
|-----------------|----------------|
| 1490            | 0.5            |
| 800             | 0.870          |
| 1800            | 0.280          |
| 1510            | 0.474          |
| 1520            | 0.452          |
| 1530            | 0.448          |

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

which are respectively denoted as

$$G \text{ (dB)} = 10 \log_{10} [\exp \{ \Gamma(\lambda_s) [\sigma_{se}(\lambda_s) N_3 - \sigma_{sa}(\lambda_s) N_1] L \} - \exp(\mu L)] \quad (3.16)$$

$$NF \text{ (dB)} = 10 \log_{10} \left[ \frac{1}{G} + \frac{P_{ASE}^{out}(\lambda_s)}{G h \nu \Delta \nu} \right] \quad (3.17)$$

where  $\mu$  is the scattering loss factor along the length of the fiber, which is neglected in the study to maintain the lucidity of the mathematics [221].  $P_{ASE}^{out}$  represents the output signal ASE at the end of the fiber. The pump propagation equation can be derived by substituting (3.5) in (3.8), given as

$$\frac{\partial P_p}{\partial z} = -\frac{\Gamma(\lambda_p) W_{p13} h c A_{eff} N_3}{\lambda_p} + \frac{\Gamma(\lambda_p) W_{p01} h c A_{eff} N_1}{\lambda_p} \quad (3.18)$$

Similarly, the propagation equations for the signal, signal-ASE, ASE at 800 nm and ASE at 1800 nm, respectively, can be obtained by substituting (3.7) in (3.9) and (3.10), and (3.6) in (3.11) and (3.12), as given as

$$\frac{\partial P_s}{\partial z} = \Gamma(\lambda_s) \left[ \frac{W_{se} h c A_{eff}}{\lambda_s} - \sigma_{se}(\lambda_s) P_{ASE} \right] N_3 - \Gamma(\lambda_s) \left[ \frac{W_{sa} h c A_{eff}}{\lambda_s} - \sigma_{sa}(\lambda_s) P_{ASE} \right] N_1 \quad (3.19)$$

$$\begin{aligned} \frac{\partial P_{ASE}}{\partial z} = & \Gamma(\lambda_{ASE}) \left[ \frac{W_{se} h c A_{eff}}{\lambda_s} - \sigma_{se}(\lambda_s) P_s \right] N_3 - \Gamma(\lambda_{ASE}) \left[ \frac{W_{sa} h c A_{eff}}{\lambda_s} - \sigma_{sa}(\lambda_s) P_s \right] N_1 \\ & + \Gamma(\lambda_{ASE}) 2 h \nu \Delta \nu \sigma_{se}(\lambda_s) N_3 \end{aligned} \quad (3.20)$$

$$\frac{\partial P_{ASE_8}}{\partial z} = \Gamma(\lambda_8) \left[ \frac{W_{8e} h c A_{eff}}{\lambda_{ASE_8}} \right] N_3 - \Gamma(\lambda_8) \left[ \frac{W_{8a} h c A_{eff}}{\lambda_{ASE_8}} \right] N_0 + \Gamma(\lambda_8) 2 h \nu \Delta \nu \sigma_8(\lambda_8) N_3 \quad (3.21)$$

$$\frac{\partial P_{ASE_{18}}}{\partial z} = \Gamma(\lambda_{18}) \left[ \frac{W_{18e} h c A_{eff}}{\lambda_{ASE_{18}}} \right] N_1 - \Gamma(\lambda_{18}) \left[ \frac{W_{18a} h c A_{eff}}{\lambda_{ASE_{18}}} \right] N_0 + \Gamma(\lambda_{18}) 2 h \nu \Delta \nu \sigma_{18}(\lambda_{18}) N_1 \quad (3.22)$$

From the governing rate equations (3.2) and (3.3), it is clear that levels 1 and 3 are involved in second stage pumping, and therefore, at steady-state when the system is in equilibrium lasing condition,  $W_{p13} N_1 = W_{p31} N_3$ . Hence, the modified rate equations obtained by ignoring the  $N_0$  to  $N_1$  pumping dynamics, which are non-lasing levels, can be given as

$$\frac{\partial N_3}{\partial t} = (W_{8a}) N_0 + (W_{sa}) N_1 - (A_{30} + W_{p31} + W_{se} + A_{31} + W_{8e}) N_3 \quad (3.23)$$

$$\frac{\partial N_1}{\partial t} = (W_{18a}) N_0 - (A_{10} + W_{sa} + W_{18e}) N_1 + (W_{se} + A_{31}) N_3 \quad (3.24)$$

The rate equations as a function of propagation equations and radiative-rates  $A_{ij}$  can be obtained by substituting (3.5)–(3.5) in (3.23) and (3.24), which are further expressed as the level transition lifetimes  $\tau_{ij}$  as

$$\begin{aligned} \frac{\partial N_3}{\partial t} = & \underbrace{\frac{-\lambda_{ASE8}}{\Gamma(\lambda_8)hcA_{eff}}}_{A} \frac{dP_{ASE8}}{dz} + \underbrace{\frac{\lambda_{ASE8}2h\nu\Delta\nu\sigma_8(\lambda_8)}{hcA_{eff}}}_{B} \frac{1}{2}N_3 - \underbrace{\frac{-\lambda_s}{\Gamma(\lambda_s)hcA_{eff}}}_{C} \frac{dP_s}{dz} \\ & + \underbrace{\frac{\sigma_{sa}(\lambda_s)P_{ASE}}{hcA_{eff}}}_{D} N_1 - \underbrace{\frac{\sigma_{se}(\lambda_s)P_{ASE}}{hcA_{eff}}}_{E} N_3 - \frac{N_3}{\tau_I} \end{aligned} \quad (3.25)$$

where

$$A_{ij} = 1/\tau_I = 1/\tau_{30} - 1/\tau_{31} \quad (3.26)$$

and

$$\begin{aligned} \frac{\partial N_1}{\partial t} = & \underbrace{\frac{-\lambda_{ASE18}}{\Gamma(\lambda_{18})hcA_{eff}}}_{H} \frac{dP_{ASE18}}{dz} + \underbrace{\frac{\lambda_{ASE18}2h\nu\Delta\nu\sigma_{18}(\lambda_{18})}{hcA_{eff}}}_{J} N_1 - \underbrace{\frac{-\lambda_s}{\Gamma(\lambda_s)hcA_{eff}}}_{C} \frac{dP_s}{dz} \\ & - \underbrace{\frac{\sigma_{sa}(\lambda_s)P_{ASE}}{hcA_{eff}}}_{D} N_1 + \underbrace{\frac{\sigma_{se}(\lambda_s)P_{ASE}}{hcA_{eff}}}_{-E} N_3 - \frac{N_1}{\tau_{10}} + \frac{N_3}{\tau_{31}} \end{aligned} \quad (3.27)$$

Equations (3.25) and (3.27) can be rewritten in the form of coupled differential equations in  $N_1$  and  $N_3$  with respect to time  $t$  shown as

$$\frac{\partial N_3}{\partial t} = A \frac{dP_{ASE8}}{dz} + \underbrace{\left(B - \frac{1}{\tau_I}\right)}_F N_3 + EP_{ASE}N_3 + DP_{ASE}N_1 + C \frac{dP_s}{dz} \quad (3.28)$$

$$\frac{\partial N_1}{\partial t} = H \frac{dP_{ASE18}}{dz} + \underbrace{\left(J - \frac{1}{\tau_{10}}\right)}_M N_1 - DP_{ASE}N_1 - EP_{ASE}N_3 + C \frac{dP_s}{dz} \quad (3.29)$$

The numerical values of coefficient parameters  $A, B, C, D, E, F, H, M$  have been calculated using their respective functions as defined in (3.25) and (3.27)–(3.29) and given in Table 3.2. The spontaneous-emission lifetimes,  $\tau_{30,31}$ , values are used to calculate the radiative-decays,  $A_{ij}$ , as given in (3.26) [53, 163]. The doping concentration is assumed to be constant along the length of the fiber and therefore,  $\tau_I$  and  $N_3$  are the functions of time while  $P_s, P_{ASE}, P_{ASE8}$ , and  $P_{ASE18}$  are the functions of both space and time. Signal power is thus, obtained by integrating (3.9)

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

with respect to  $z$  and is given as

$$P_s(L, t) = P_s(0, t) \exp \{ \Gamma(\lambda_s) [\sigma_{se}(\lambda_s) N_3 - \sigma_{sa}(\lambda_s) N_1] L \} \quad (3.30)$$

Equation (3.11) can be thus, be rewritten as

$$\frac{\partial P_{ASE_8}}{\partial z} + \Gamma(\lambda_8) [\sigma_{8a}(\lambda_8) N_0 - \sigma_{8e}(\lambda_8) N_3] P_{ASE_8} = \Gamma(\lambda_8) 2h\nu \Delta\nu \sigma_8(\lambda_8) N_3 \quad (3.31)$$

The space functionality of  $P_{ASE_8}$  is obtained by integrating (3.31) using integrating factor technique with respect to  $z$  along the length of fiber as

$$P_{ASE_8}(z) = 2h\nu \Delta\nu \Gamma(\lambda_8) \sigma_8(\lambda_8) N_3 z \quad (3.32)$$

Similar procedure has been followed to obtain the space functionality of  $P_{ASE_{18}}$  and  $P_{ASE}$ , which can be represented as

$$P_{ASE_{18}}(z) = 2h\nu \Delta\nu \Gamma(\lambda_{18}) \sigma_{18}(\lambda_{18}) N_1 z \quad (3.33)$$

$$P_{ASE}(z) = 2h\nu \Delta\nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_3 z \quad (3.34)$$

On substituting (3.30), (3.32)-(3.34) in (3.28) and integrating with respect to  $z$ , we get

$$\begin{aligned} \frac{\partial N_3}{\partial t} = A \left[ P_{ASE_8}(z, t) - \underbrace{P_{ASE_8}(0, t)}_{=0} \right] + FN_3 + E h\nu \Delta\nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_3^2 z^2 \\ + D h\nu \Delta\nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_1 N_3 z^2 + C [P_s(z, t) - P_s(0, t)] \end{aligned} \quad (3.35)$$

Equation (3.35) can be further simplified and written as

$$\begin{aligned} \frac{\partial N_3}{\partial t} = A P_{ASE_8}(L, t) + FN_3 + E h\nu \Delta\nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_3^2 L^2 + D h\nu \Delta\nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_1 N_3 L^2 \\ + C P_s(0, t) \exp \{ \Gamma(\lambda_s) [\sigma_{se}(\lambda_s) N_3 - \sigma_{sa}(\lambda_s) N_1] L \} - 1 \end{aligned} \quad (3.36)$$

Similarly, on substituting the same in (3.29), we get (3.37) as

$$\begin{aligned} \frac{\partial N_1}{\partial t} = & HP_{ASE_{18}}(L, t) + MN_1 - E h \nu \Delta \nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_3^2 L^2 - D h \nu \Delta \nu \Gamma(\lambda_{ASE}) \sigma_{se}(\lambda_{ASE}) N_1 N_3 L^2 \\ & + CP_s(0, t) \exp \{ \Gamma(\lambda_s) [\sigma_{se}(\lambda_s) N_3 - \sigma_{sa}(\lambda_s) N_1] L \} - 1 \end{aligned} \quad (3.37)$$

### 3.2.1 The Population-Inversion Condition

The obtained expressions given in (3.36) and (3.37) are the equations superseding the dynamics of  $N_3$  and  $N_1$  with respect to space and time. Under steady-state, the time derivative terms in (3.36) and (3.37) have been equated to zero to obtain the steady-state concentration of  $Tm^{3+}$  dopant. In the corresponding energy level-3 and level-1, they are denoted as  $N_3^0$  and  $N_1^0$  respectively. Therefore, adding (3.36) and (3.37) under steady-state condition and considering the first approximation in  $P_s(z, t)$  leads to

$$\begin{aligned} AP_{ASE^0_{8}} + HP_{ASE^0_{18}} + FN_3^0 + MN_1^0 + N_3^0/\tau_{31} \\ + 2CP_s^0(0) \Gamma(\lambda_s) [\sigma_{se}(\lambda_s) N_3^0 - \sigma_{sa}(\lambda_s) N_1^0] L = 0 \end{aligned} \quad (3.38)$$

where  $P_s^0(0)$  is the mean power of the input signal in the fiber and  $P_{ASE^0_{8,18}}$  being the steady-state ASE powers at 800 nm and 1800 nm respectively. On substituting the values of coefficient parameters in (3.38) from Table 3.2 and collecting the coefficients of  $N_3^0$  and  $N_1^0$ , we obtain the necessary condition of the population-inversion for this model, as given by

$$QN_3^0 + RN_1^0 + SP_s^0(0)N_3^0 + TP_s^0(0)N_1^0 = 0 \quad (3.39)$$

The coefficients  $Q, R, S$ , and  $T$  are obtained by putting the values of parameter coefficients in (3.38) as mentioned in the Table 3.2. Then, the population inversion under steady-state condition is given as

$$\frac{N_3^0}{N_1^0} = \frac{-[R + TP_s^0(0)]}{[Q + SP_s^0(0)]} \geq 1 \quad (3.40)$$

From (3.39), the mean signal power under steady-state condition can be defined as

$$P_s^0(0) \geq \frac{(Q + R)}{(T + S)} \quad (3.41)$$

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

---

On substituting the values of the coefficients,  $Q, R, S$ , and  $T$ , the theoretical values of input-signal power level is obtained to be  $P_s^0(0) \geq -0.0344$  W. Since, the input-signal power cannot be negative, it can thus, be concluded that a minimum positive seed input-signal power should be provided to get the amplification. For further analysis, this power was considered as the seed signal-input power of 2 mW at a wavelength of 1490 nm under the population-inversion condition  $N_3^0/N_1^0 = 2$ .

#### 3.2.2 Gain Modulation

Overmodulation is defined as a sinusoidal time-varying signal with relatively low modulation frequency ( $\sim 100$  kHz) as compared to optical communication signal data rate sampled at gigahertz or terahertz. Consequently, it can be assumed as an analog modulation on the mean input-signal power [219, 226, 229, 254], and can be represented as

$$P_s(0, t) = P_s^0(0)[1 + m_s \cos(\omega t)] \quad (3.42)$$

where  $P_s^0(0)$  is the mean input-signal power at  $z = 0$ ,  $m_s$  is the input modulation index of the signal, and  $\omega$  is the overmodulation frequency.

Dynamic population of  $\text{Tm}^{3+}$  ions in level-3 and level-1 are defined as  $N_3(t)$  and  $N_1(t)$  in terms of unmodulated steady-state solutions  $N_3^0$  and  $N_1^0$ . This is required in order to represent  $N_3(t)$  and  $N_1(t)$  about their respective mean (unmodulated) steady-state solutions which can be given as

$$N_3(t) = N_3^0[1 + \delta_3 \cos(\omega t + \varphi_3)] \quad (3.43)$$

$$N_1(t) = N_1^0[1 + \delta_1 \cos(\omega t + \varphi_1)] \quad (3.44)$$

where  $\delta_{3,1}$  are the modulation indices at input for steady-state populations  $N_{3,1}^0$  and  $\varphi_{3,1}$  are the initial phase shifts induced due to the first-order derivative resulting in phase-shifted outputs [219]. Therefore,  $\delta_{3,1}$  and  $\varphi_{3,1}$  needs to be calculated for further analysis. The mean steady-state population densities  $N_3^0$  and  $N_1^0$  are determined and estimated by keeping only the first-order terms in the expansion of the exponential part of these expressions under the population-inversion condition.



### 3.2.3 Signal Modulation

The overmodulation in input-signal with ASEs for TDFAs has been realized using the governing equations (3.36) and (3.37) as

$$\begin{aligned} \frac{\partial N_1}{\partial t} + \frac{\partial N_3}{\partial t} = & AP_{\text{ASE}_8}(L, t) + HP_{\text{ASE}_{18}}(L, t) + FN_3 + MN_1 + N_3/\tau_{31} \\ & + 2CP_s(0, t) (\exp \{ \Gamma(\lambda_s) [\sigma_{\text{se}}(\lambda_s)N_3 - \sigma_{\text{sa}}(\lambda_s)N_1]L \} - 2) \end{aligned} \quad (3.45)$$

Furthermore, on substituting (3.38) in (3.45), and taking the first approximation in the exponential term along with the substitution of the expressions (3.43) and (3.44) with respect to  $N_3(t)$  and  $N_1(t)$ , we get

$$\begin{aligned} & -N_3^0 \delta_3 \omega \sin(\omega t + \varphi_3) - N_1^0 \delta_1 \omega \sin(\omega t + \varphi_1) \\ & = \cos(\omega t + \varphi_3) [UN_3^0 \delta_3 + VN_3^0 \delta_3 m_s \cos(\omega t) + VN_3^0 m_s \cos(\varphi_3)] \\ & + \cos(\omega t + \varphi_1) [U'N_1^0 \delta_1 + V'N_1^0 \delta_1 m_s \cos(\omega t) + V'N_1^0 m_s \cos(\varphi_1)] \\ & + VN_3^0 m_s \sin(\varphi_3) \sin(\omega t + \varphi_3) + V'N_1^0 m_s \sin(\varphi_1) \sin(\omega t + \varphi_1) \end{aligned} \quad (3.46)$$

where  $U, V, U'$ , and  $V'$  are the coefficients obtained by substitution of respective terms in (3.46). These calculated values of  $U, V, U'$ , and  $V'$  are mentioned in Table 3.2. In order to observe the modulating behaviour of the population densities  $N_3(t)$  and  $N_1(t)$ , the values of  $\delta_{3,1}$  and  $\varphi_{3,1}$  should be calculated. Therefore, the coefficients of  $\cos(\omega t + \varphi_{1,3})$  and  $\sin(\omega t + \varphi_{1,3})$  from both sides of (3.46) were equated to give the following set of equations

$$-N_3^0 \delta_3 \omega = VN_3^0 m_s \sin(\varphi_3) \quad (3.47)$$

$$-N_1^0 \delta_1 \omega = V'N_1^0 m_s \sin(\varphi_1) \quad (3.48)$$

$$UN_3^0 \delta_3 + VN_3^0 \delta_3 m_s \cos(\omega t) + VN_3^0 m_s \cos(\varphi_3) = 0 \quad (3.49)$$

$$U'N_1^0 \delta_1 + V'N_1^0 \delta_1 m_s \cos(\omega t) + V'N_1^0 m_s \cos(\varphi_1) = 0 \quad (3.50)$$

While the study carried out in references [219, 221, 229] did not consider the second term of (3.49) and (3.50), it shall be evident from the results presented in the section 3.4 that these terms include very slight sinusoidal perturbations. Although, for deeper insight and analysis,

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

these terms are included this work.

The initial modulation indices  $\delta_{3,1}$  at the TDFAs-input and the input phase-shifts  $\varphi_{3,1}$  have been obtained from (3.47)–(3.50) and given as

$$\tan(\varphi_3) = \frac{-\omega}{\underbrace{-U - Vm_s \cos(\omega t)}_{\omega_{\text{eff}_3}}} \quad (3.51)$$

$$\tan(\varphi_1) = \frac{-\omega}{\underbrace{-U' - V'm_s \cos(\omega t)}_{\omega_{\text{eff}_1}}} \quad (3.52)$$

$$\delta_3 = \frac{-Vm_s}{\sqrt{\omega^2 + \omega_{\text{eff}_3}^2}} \quad (3.53)$$

$$\delta_1 = \frac{-V'm_s}{\sqrt{\omega^2 + \omega_{\text{eff}_1}^2}} \quad (3.54)$$

where  $\omega_{\text{eff}_{3,1}}$  are defined to be the denominators of (3.51) and (3.52) respectively. Subsequently, after obtaining the calculated values of  $\delta_{3,1}$  and  $\varphi_{3,1}$ , the relational expression linking the signal output to the signal input,  $N_3(t)$ , and  $N_3(t)$  is given as

$$P_s(L, t) = P_s^0(0, t) \exp \Gamma(\lambda_s) [\sigma_{\text{se}}(\lambda_s) N_3 - \sigma_{\text{sa}}(\lambda_s) N_1] L \quad (3.55)$$

On substitution of equations (3.42)–(3.44) in (3.55), to get

$$P_s(L, t) = P_s^0(0) [1 + m_s \cos(\omega t)] \times \exp \left[ \Gamma(\lambda_s) L \begin{pmatrix} \sigma_{\text{se}}(\lambda_s) N_3^0 \{1 + \delta_3 \cos(\omega t + \varphi_3)\} \\ -\sigma_{\text{sa}}(\lambda_s) N_1^0 \{1 + \delta_1 \cos(\omega t + \varphi_1)\} \end{pmatrix} \right] \quad (3.56)$$

Further using the steady-state expression of (3.38) in (3.56), the modified expression can be written as

$$P_s(L, t) = P_s^0(L) [1 + m_s \cos(\omega t)] \times \exp \left\{ \Gamma(\lambda_s) L \begin{pmatrix} \sigma_{\text{se}}(\lambda_s) N_3^0 \delta_3 \cos(\omega t + \varphi_3) \\ -\sigma_{\text{sa}}(\lambda_s) N_1^0 \delta_1 \cos(\omega t + \varphi_1) \end{pmatrix} \right\} \quad (3.57)$$

where the mean power output  $P_s^0(L)$  at the TDFA's end as a function of mean input power  $P_s^0(0)$

and the unmodulated population densities  $N_{3,1}^0$  is defined as

$$P_s^0(L) = P_s^0(0) \exp \{ \Gamma(\lambda_s) L [\sigma_{se}(\lambda_s) N_3^0 - \sigma_{sa}(\lambda_s) N_1^0] \} \quad (3.58)$$

On approximating the exponential term limited to the first order and putting the terms with the respective substitutions as  $\alpha = \Gamma(\lambda_s) L \sigma_{se}(\lambda_s) N_3^0 \delta_3$  and  $\beta = \Gamma(\lambda_s) L \sigma_{sa}(\lambda_s) N_1^0 \delta_1$ , we get the simplified expression for (3.57) written as

$$P_s(L, t) = P_s^0(L) \left\{ 1 + m_s \cos(\omega t) + \left[ \overbrace{1 + m_s \cos(\omega t)}^{\approx 1} \right] \alpha \cos(\omega t + \varphi_3) \right\} \\ - P_s^0(L) \left\{ \left[ \overbrace{1 + m_s \cos(\omega t)}^{\approx 1} \right] \beta \cos(\omega t + \varphi_1) \right\} \quad (3.59)$$

By taking the suitable approximation (as shown within equation as  $[1 + m_s \cos(\omega t)] \approx 1$  and expanding (3.58) in  $\cos(\omega t)$  and  $\sin(\omega t)$  and further collecting their respective coefficients we get

$$P_s(L, t) = P_s^0(L) \{ 1 + \cos(\omega t) [m_s + \alpha \cos(\varphi_3) - \beta \cos(\varphi_1)] \\ + \sin(\omega t) [-\alpha \sin(\varphi_3) + \beta \sin(\varphi_1)] \} \quad (3.60)$$

Therefore, equation (3.59) can be further expressed in a concise representation as

$$P_s(L, t) = P_s^0(L) [1 + m'_s \cos(\omega t + \theta_s)] \quad (3.61)$$

This is the expression for amplitude-modulation with a modified modulation index and phase. It represents the output modulation index  $m'_s$  of the signal and its corresponding phase-shift  $\theta_s$ , defined as

$$m'_s = \left\{ [m_s + \alpha \cos(\varphi_3) - \beta \cos(\varphi_1)]^2 + [\beta \sin(\varphi_1) - \alpha \sin(\varphi_3)]^2 \right\}^{1/2} \quad (3.62)$$

$$\tan(\theta_s) = \frac{\beta \sin(\varphi_1) - \alpha \sin(\varphi_3)}{m_s + \alpha \cos(\varphi_3) - \beta \cos(\varphi_1)} \quad (3.63)$$

The expressions shown in equations (3.62) and (3.63) shows expressions for output signal's modulation index and phase-shift. The first term in (3.62) represents the squared coefficient of

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

$\cos(\omega t)$  and the second term represents the squared coefficient of  $\sin(\omega t)$  term. On further substitution of the expressions for  $\alpha$ ,  $\beta$ , and equations (3.53)–(3.54) in (3.62) and (3.63), the following expressions were obtained for  $m'_s$  and  $\theta_s$

$$m'_s = \left[ \left( m_s + \frac{\alpha \omega_{\text{eff}_3}}{\sqrt{\omega^2 + \omega_{\text{eff}_3}^2}} - \frac{\beta \omega_{\text{eff}_1}}{\sqrt{\omega^2 + \omega_{\text{eff}_1}^2}} \right)^2 + \left( \frac{\beta \omega}{\sqrt{\omega^2 + \omega_{\text{eff}_1}^2}} - \frac{\alpha \omega}{\sqrt{\omega^2 + \omega_{\text{eff}_3}^2}} \right)^2 \right]^{1/2} \quad (3.64)$$

$$\tan(\theta_s) = \frac{-\omega \Gamma(\lambda_s) L \left[ \frac{-\sigma_{\text{se}}(\lambda_s) N_3^0 V}{\omega + \omega_{\text{eff}_3}^2} + \frac{\sigma_{\text{sa}}(\lambda_s) N_1^0 V'}{\omega + \omega_{\text{eff}_1}^2} \right]}{\left[ 1 + \frac{-\sigma_{\text{se}}(\lambda_s) N_3^0 V \omega_{\text{eff}_3}}{\omega + \omega_{\text{eff}_3}^2} + \frac{\sigma_{\text{sa}}(\lambda_s) N_1^0 V' \omega_{\text{eff}_1}}{\omega + \omega_{\text{eff}_1}^2} \right]} \quad (3.65)$$

Equations (3.64) and (3.65) are used to find the amplitude and phase characteristics of the output-signal represented by (3.61). These values are calculated by using the parameters given in Table 3.2. Furthermore, this developed model is implemented on MatLab®-Simulink to provide a methodical test-bed analysis platform as a graphic user interface (GUI) simulator presented in Section 3.3.

### 3.3 Simulink Pedestal for TDFAs

MatLab®-Simulink is a test-bed that can model non-linear equations and dynamic systems. It consists of signal processing modules primarily for electronic signal processing and has a wider population availability. Simulink based simulators have been already presented for EDFA overmodulation dynamics too but are limited to a single ordinary non-linear differential equation as the dynamics is limited to one level [228, 229]. The subsystems for the derived mathematical relations have been developed utilizing the graphical programming environment of Matlab®. The parameters are calculated using their respective relations, as mentioned in the analytical model of section 3.3, and are shown in Table 3.2. The simulator can act as a test bench to carry out overmodulation analysis of signal and gain. The simulator is constructed for a single TDFA unit where ASE effects have also been considered. Furthermore, it can be utilized to observe the cascaded effect of the different TDFA units in the fiber-optic communication system.

Table 3.2: Parameters used in Analytical Model

| Parameter                                 | Unit                         | Symbol                      | Value                   | Remark     |
|-------------------------------------------|------------------------------|-----------------------------|-------------------------|------------|
| <b>Thulium Concentration</b>              | $\text{m}^{-3}$              | $\rho$                      | $1.354 \times 10^{25}$  | Calculated |
| <b>TDF's Core-Diameter</b>                | m                            | $2a$                        | $1.9 \times 10^{-6}$    | [163]      |
| <b>TDF's Length</b>                       | m                            | $L$                         | 20                      | [163]      |
| <b>Signal Wavelength</b>                  | nm                           | $\lambda_s$                 | 1490                    | S-Band     |
| <b>ASE Wavelength</b>                     | nm                           | $\lambda_{\text{ASE}}$      | 1530                    | Estimated  |
| <b>ASE Bandwidth</b>                      | nm                           | $\Delta\nu$                 | 2                       | [163]      |
| <b>800 nm–ASE Bandwidth</b>               | nm                           | $\Delta\nu$                 | 10                      | [163]      |
| <b>1800 nm–ASE Bandwidth</b>              | nm                           | $\Delta\nu$                 | 100                     | [163]      |
| <b>Pump Wavelength</b>                    | nm                           | $\lambda_p$                 | 1420                    | [53, 163]  |
| <b>Numerical Aperture</b>                 |                              | $NA$                        | 0.3                     | [163]      |
| <b>Effective CSA</b>                      | $\text{m}^2$                 | $A_{\text{eff}}$            | $2.096 \times 10^{-12}$ | [53]       |
| <b>Mean SS Solution</b>                   | $\text{m}^{-3}$              | $N_3^0$                     | $9.05 \times 10^{24}$   | Calculated |
| <b>Mean SS Solution</b>                   | $\text{m}^{-3}$              | $N_1^0$                     | $4.51 \times 10^{24}$   | Calculated |
| <b>Signal Power at Input</b>              | mW                           | $P_s^0(0)$                  | 2                       | Estimated  |
| <b>Radiative Rate</b>                     | $\text{s}^{-1}$              | $A_{30}$                    | 702.8                   | [163]      |
| <b>Radiative Rate</b>                     | $\text{s}^{-1}$              | $A_{31}$                    | 73.3                    | [53]       |
| <b>Non-radiative Rate</b>                 | $\text{s}^{-1}$              | $A_{43}^{nr}$               | 52976                   | [53]       |
| <b>Stimulated Emission CSA at 1490 nm</b> | $\text{m}^2$                 | $\sigma_{\text{se}}^{1490}$ | $2.4 \times 10^{-25}$   | [163]      |
| <b>Stimulated Emission CSA at 1510 nm</b> | $\text{m}^2$                 | $\sigma_{\text{se}}^{1510}$ | $2.02 \times 10^{-25}$  | [163]      |
| <b>Stimulated Emission CSA at 1520 nm</b> | $\text{m}^2$                 | $\sigma_{\text{se}}^{1520}$ | $1.62 \times 10^{-25}$  | [163]      |
| <b>Stimulated Emission CSA at 1530 nm</b> | $\text{m}^2$                 | $\sigma_{\text{se}}^{1530}$ | $1.32 \times 10^{-25}$  | [163]      |
| <b>Absorption CSA at 1490 nm</b>          | $\text{m}^2$                 | $\sigma_{\text{sa}}^{1490}$ | $1.68 \times 10^{-25}$  | [163]      |
| <b>Absorption CSA at 1510 nm</b>          | $\text{m}^2$                 | $\sigma_{\text{sa}}^{1510}$ | $9.21 \times 10^{-26}$  | [163]      |
| <b>Absorption CSA at 1520 nm</b>          | $\text{m}^2$                 | $\sigma_{\text{sa}}^{1520}$ | $5.85 \times 10^{-26}$  | [163]      |
| <b>Absorption CSA at 1530 nm</b>          | $\text{m}^2$                 | $\sigma_{\text{sa}}^{1530}$ | $3.6 \times 10^{-26}$   | [163]      |
| <b>ASE Transition CSA at 800 nm</b>       | $\text{m}^2$                 | $\sigma_8$                  | $6.0 \times 10^{-25}$   | [163]      |
| <b>ASE Transition CSA at 1800 nm</b>      | $\text{m}^2$                 | $\sigma_{18}$               | $5.0 \times 10^{-25}$   | [163]      |
| <b>Coefficient Parameters</b>             | $\text{J}^{-1}\text{m}^{-2}$ | $A$                         | $-2.2 \times 10^{30}$   | Calculated |
|                                           | $\text{s}^{-1}$              | $B$                         | 17175.57                | Calculated |
|                                           | $\text{J}^{-1}\text{m}^{-2}$ | $C$                         | $-7.15 \times 10^{30}$  | Calculated |
|                                           | $\text{s}^{-1}\text{m}^{-1}$ | $D$                         | $4.03 \times 10^{11}$   | Calculated |
|                                           | $\text{s}^{-1}\text{m}^{-1}$ | $E$                         | $-5.76 \times 10^{11}$  | Calculated |
|                                           | $\text{s}^{-1}$              | $F$                         | 16399.42                | Calculated |
|                                           | $\text{J}^{-1}\text{m}^{-2}$ | $H$                         | $-1.542 \times 10^{31}$ | Calculated |

continued ...

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

...continued

| Parameter                                                        | Unit      | Symbol   | Value              | Remark     |
|------------------------------------------------------------------|-----------|----------|--------------------|------------|
|                                                                  | $s^{-1}$  | $J$      | 1431.29            | Calculated |
|                                                                  | $s^{-1}$  | $M$      | 1258.89            | Calculated |
| Coefficient Parameters under Population-Inversion condition      | $s^{-1}$  | $Q$      | -326936.43         | Calculated |
|                                                                  | $s^{-1}$  | $R$      | -27345.21          | Calculated |
|                                                                  | $J^{-1}m$ | $S$      | $3.43 \times 10^7$ | Calculated |
|                                                                  | $J^{-1}m$ | $T$      | $2.40 \times 10^7$ | Calculated |
| Coefficient Parameters for 1490 nm Signal Wavelength (Unit-less) |           | $U$      | -423792.96         | Calculated |
|                                                                  |           | $V$      | -68640             | Calculated |
|                                                                  |           | $U'$     | -236734.2          | Calculated |
|                                                                  |           | $V'$     | -48048             | Calculated |
|                                                                  |           | $\alpha$ | $21.672 \delta_3$  | Calculated |
|                                                                  |           | $\beta$  | $7.576 \delta_1$   | Calculated |

The dynamics of the energy levels with the corresponding population densities  $^3H_4 (N_3)$  and  $^3F_4 (N_1)$  have been implemented on a Simulink model using (3.36) and (3.36). Out of the cascaded network of TDFAs in a fiber-optic communication system, a single unit of TDFA's dynamics has been represented in Fig. 3.4. To make the design further compact, the calculation of various parameters is further divided into subsystems. These are shown by different

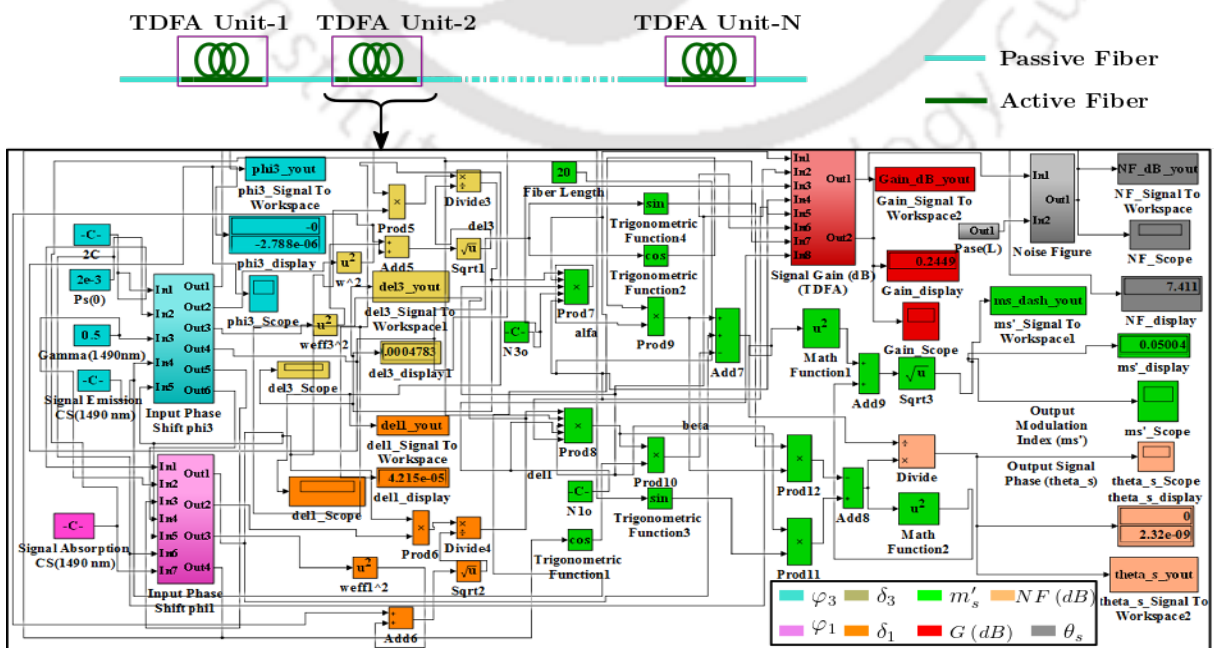
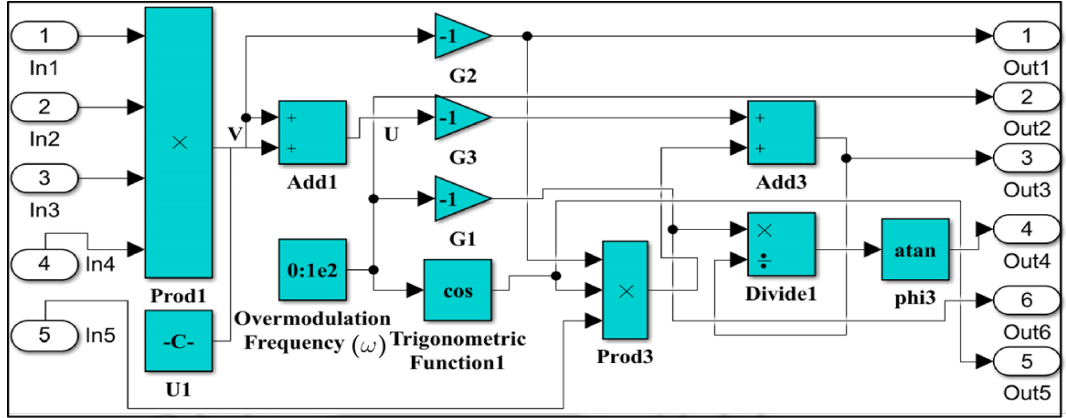


Fig. 3.4: Simulink test-bed for TDFA's signal-gain overmodulation.





**Fig. 3.5:** Details of input phase-shift subsection.

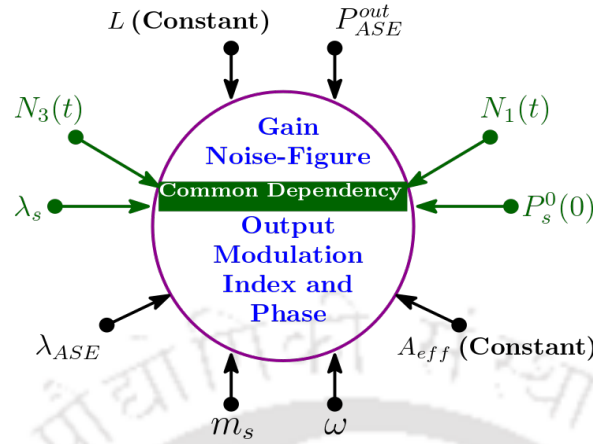
color representations of the respective parameter. For instance, the input phase shifts of levels 3–1 ( $\varphi_{3,1}$ ) have been represented by the blue and pink colored blocks in Fig. 3.4. As per the expressions of (3.51) and (3.52), the coefficient parameters  $U_1$  and  $V_1$  for the 1490 nm signal have been calculated using their respective mathematical definitions. The expanded view for the input phase shift operation ( $\varphi_3$ ) has been shown in Fig. 3.5. Furthermore, other subsystems representing input modulation indices ( $\delta_{3,1}$ ), output signal modulation index ( $m'_s$ ), signal gain ( $G$ ), noise figure ( $NF$ ), and output signal modulation index phase ( $\theta_s$ ) have also been developed using the parameters given in Table 3.2 and their respective expressions derived under the mathematical model. The gain and noise-figure analysis are also implemented in the simulator to calculate the TDFA's optimum working parameters. It can be utilized to check the overmodulation of signal and gain performance of the TDFA unit with various input combinations of parameters and optimize it as per the requirement.

### 3.4 Results and Discussions

From the developed analytical model for overmodulation of signal-gain dynamics along with signal-gain and noise-figure expressions, their respective parametric dependencies can be shown in Fig. 3.6. The central (green-zone) shows the common dependencies with respect to the concerned analysis. Therefore, this section includes the results obtained on the implementation of the analytical model developed in Section 3.2. The input and output characteristics of the signal, and overmodulation sensitivity to mean input signal power are discussed. It also includes



### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

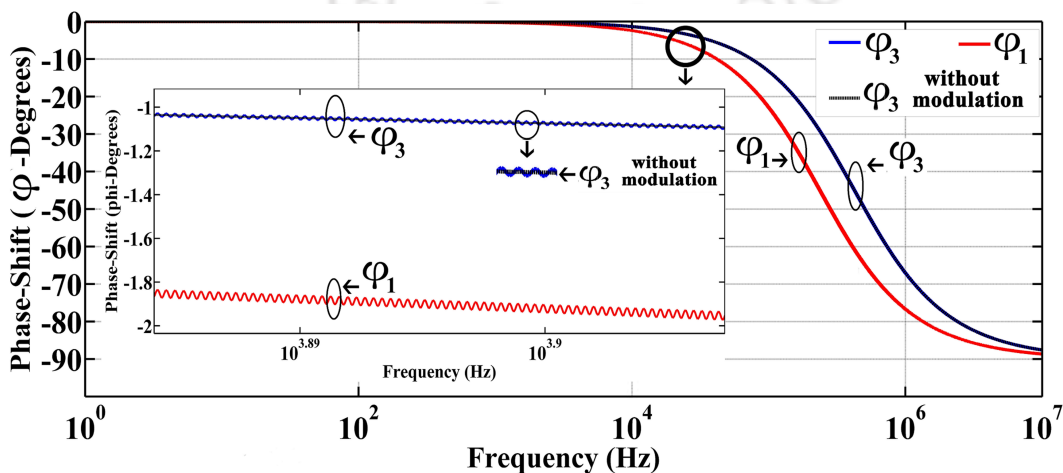


**Fig. 3.6:** Parameters affecting the behaviour of the Gain, Noise-Figure, output modulation index and its phase.

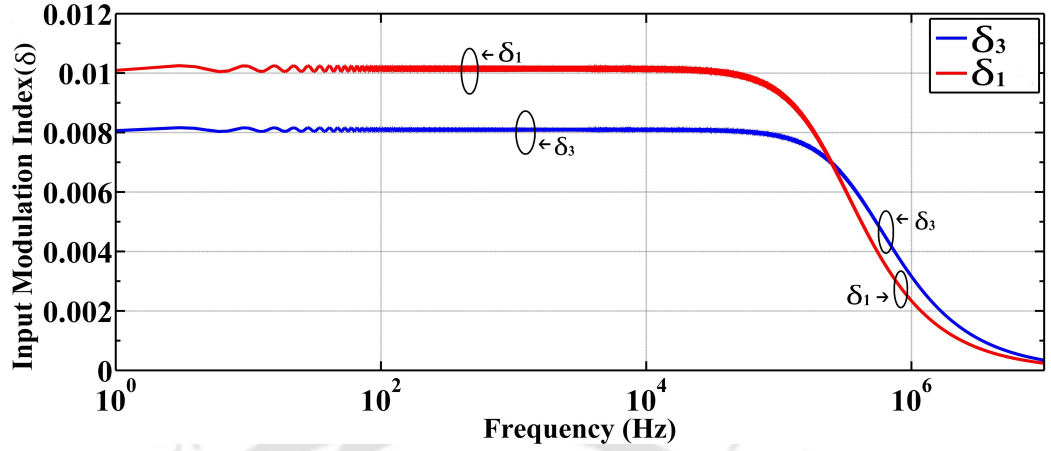
the results obtained from the Simulink implementation of the model developed in the section 3.3 with emphasis on the overmodulation sensitivity to signal wavelength. As a consequence of the assumptions, the results obtained based on analytical model are qualitatively presented and are comprehensively discussed in the following subsections.

#### 3.4.1 Input Signal Characteristics

In the expressions (3.43) and (3.44), the inclusion of initial phase shift is due to fact that the first derivative results in phase shifted solution [219, 229]. For input signal modulation index, the pattern for initial phase shift suggests some sinusoidal perturbation because of the term  $m_s \cos(\omega t)$  accompanying the expressions for  $\varphi_{3,1}$ , as in (3.51) and (3.52). However, for the stated time, the phase shift modulation is less than 0.73%. It has been observed from Fig. 3.7



**Fig. 3.7:** Effect of the modulation frequency on initial phase-shifts.



**Fig. 3.8:** Effect of the modulation frequency on input modulation indices of their respective energy levels.

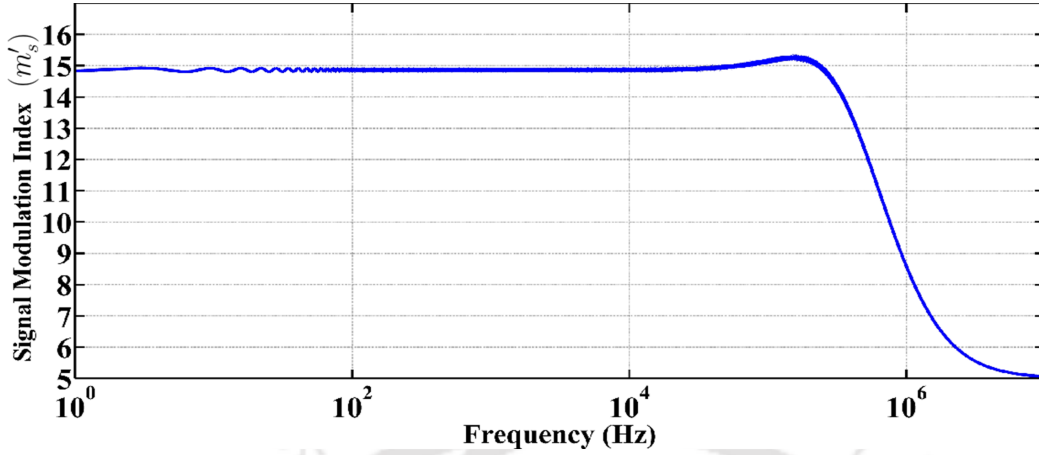
that  $N_1(t)$  has a phase lag referenced to  $N_3(t)$  and there is a slight modulation in the phase-shifts (Fig. 3.7 inset). This clearly indicates the case of population-inversion which is the necessary condition for optical amplification and lasing.

The variation of input modulation indices  $\delta_{3,1}$  with the modulation frequency has been obtained from the Simulink-pedestal and can be seen in Fig. 3.8. It is observed that the input modulation index associated with  $N_1^0$  is greater than that associated with  $N_3^0$  as per steady-state population inversion. Apparently, the depth of input modulation index is found to be decreasing at the corner-frequency of  $\sim 100$  kHz. As a result, the modulated population densities  $N_3^0$  and  $N_1^0$  have been found to be unaffected from the input modulation beyond  $\sim 10^4$  kHz. This behavior can be explained by the fact that at these mentioned high frequencies, the  $\text{Tm}^{3+}$  ions do not respond to fast dynamics as it exceeds the respective radiative rate  $A_{ij}$  values. Apparently, this result has been found in agreement with the experimental studies performed on YDFAs in [231], giving up a glance at refractive-index change behavior.

### 3.4.2 Output Signal Characteristics

The input-signal modulation index at the output has been varied with modulation frequency in the expression of (3.64). It can be observed from Fig. 3.9 that it follows a high-pass input-signal modulation characteristic beyond the corner-frequency. For the input-signal modulation index  $m_s = 5\%$ , the associated output signal has a 15% modulation depth for 3 dBm input signal power. The signal modulation index converges to the initial index after the corner frequency of

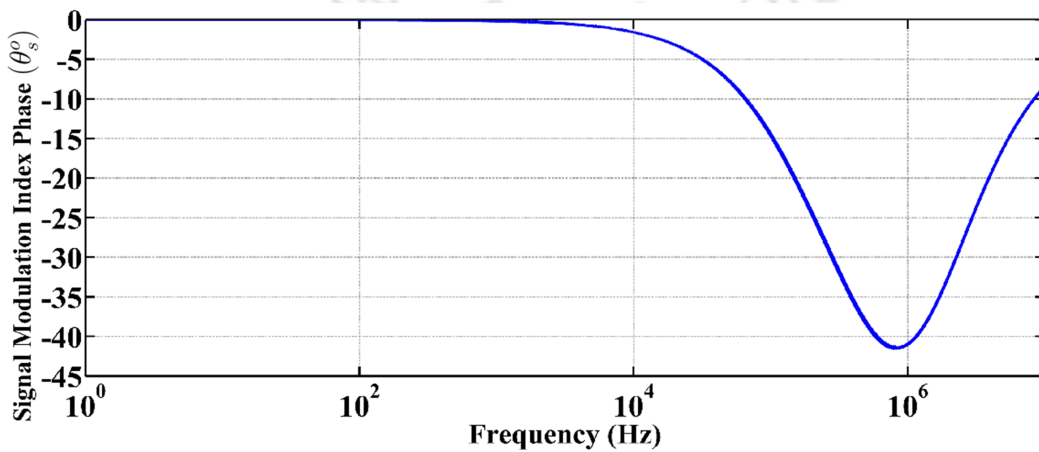
### 3. Overmodulation of Signal and Gain Dynamics in TDFAs



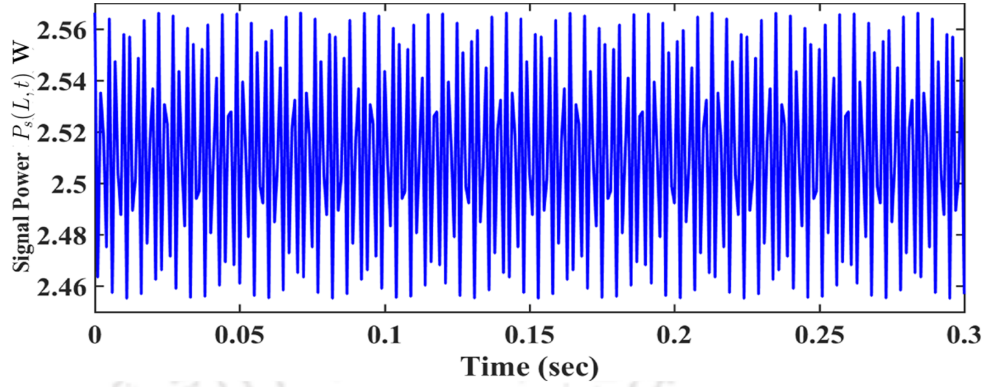
**Fig. 3.9:** Effect of the applied modulation frequency sweep on the output modulation index.

100 kHz. It further indicates that the TDFA-channel is not offering any modulation effect while traversing in the amplifier, which is desired for the successful recovery of the information signal in the DWDM system. For EDFAs, this effect had already been shown by Novak *et al.* in [219] and in this analysis, the results hold good for TDFAs too. The output-signal modulation index magnitude variation shows the property of a lead compensator i.e. having a zero followed by a pole which has also realized by Freeman *et al.* as well as Novak *et al.* for EDFAs [219, 226].

For the same set of parameters, the output-signal modulation index phase characteristics has been shown in Fig. 3.10. It can be observed that the phase lag occurs when the input signal is perturbed with modulation frequency. The importance of phase characteristics comes at the output port of the fiber where the signal will be demodulated and an appropriate phase corrector could be applied based on the phase lag value obtained from Fig. 3.10.



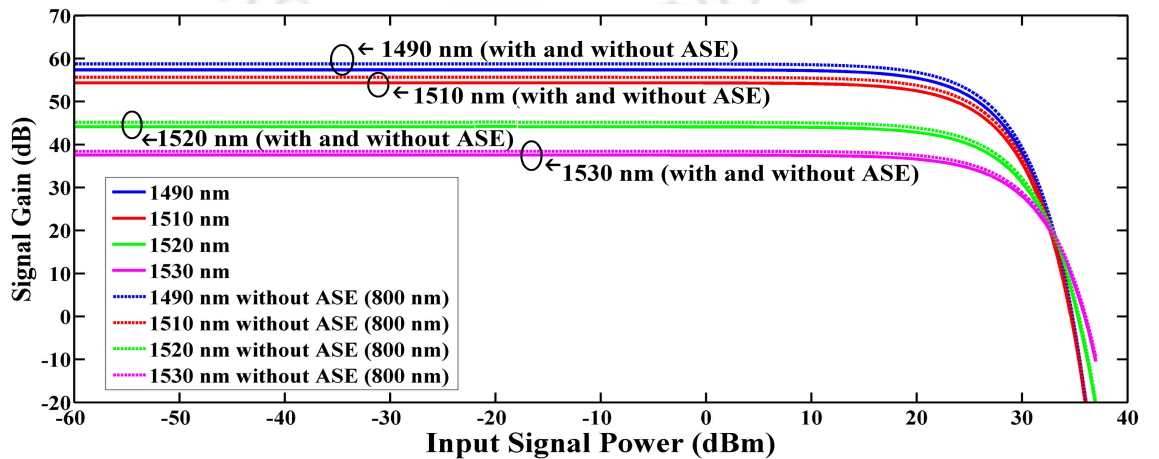
**Fig. 3.10:** Effect of applied modulation frequency sweep on output modulation index phase.



**Fig. 3.11:** Output-signal time history of the modulated signal with input-signal power and signal-gain of 6 dBm and 58 dB respectively.

### 3.4.3 Signal-Gain and Noise-Figure Analysis

To observe the modulation pattern of the output signal, the developed simulator has been fed at the wavelength in S-Band at 1490 nm. The input signal is kept at the power level of 6 dBm at a 5% modulation index. With the associated gain of 58 dB, the time history of the amplified output signal is shown in Fig. 3.11 having the output-signal modulation index of 30%. For enhanced insight, the signal gain is obtained using (3.16) for four different signal-wavelengths in S and near-C bands with values 1490, 1510, 1520, and 1530 nm. Correspondingly, the input signal power has been swept from  $-60$  dBm to  $+40$  dBm as shown in Fig. 3.12. It can be observed that the gain enters in a steady-saturation regime below 20 dBm of the signal power. On further increment of the signal-power, the gain starts to reduce. At a signal-power value of 31.5 dBm, the gain becomes almost negligible to a state of no-amplification due to the fact

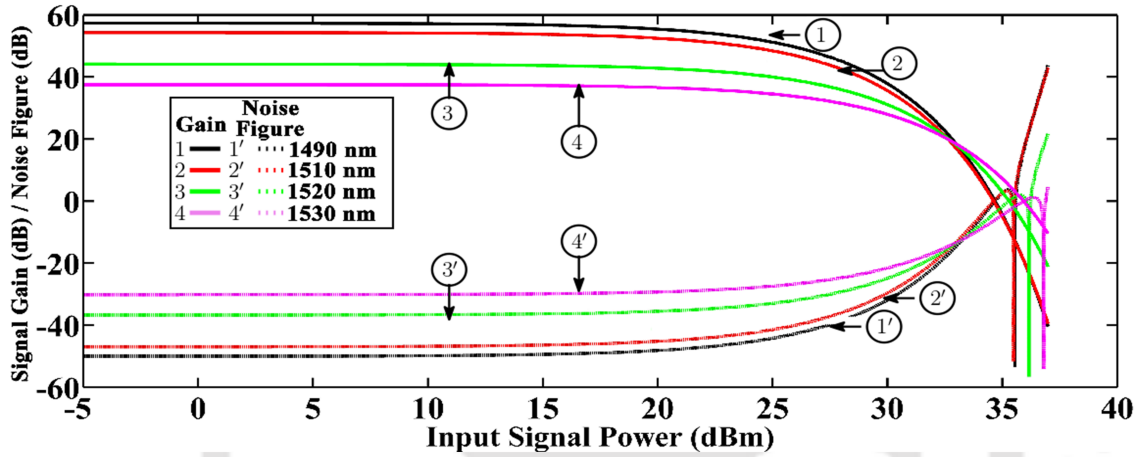


**Fig. 3.12:** Signal gain (dB) verses mean input-signal power (dBm) with (solid-lines) and without (dashed-lines) ASE.

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

**Table 3.3:** Parameters used in Signal-Gain and Noise-Figure calculations

| Case | Wavelength | $N_3^0$                                               | $C(\lambda)$            |
|------|------------|-------------------------------------------------------|-------------------------|
| 1    | 1490       | $8.47 \times 10^{24} - 2.885 \times 10^{24} P_s^0(0)$ | $-7.152 \times 10^{30}$ |
| 2    | 1510       | $8.47 \times 10^{24} - 2.924 \times 10^{24} P_s^0(0)$ | $-7.646 \times 10^{30}$ |
| 3    | 1520       | $8.47 \times 10^{24} - 2.505 \times 10^{24} P_s^0(0)$ | $-8.071 \times 10^{30}$ |
| 4    | 1530       | $8.47 \times 10^{24} - 2.165 \times 10^{24} P_s^0(0)$ | $-8.196 \times 10^{30}$ |



**Fig. 3.13:** Signal-gain (solid-lines) and noise-figure (dashed-lines), both in dB, verses fixed input signal power for four different wavelengths in S and near-C bands.

that the pump power is not sufficient enough to provide the population inversion. There is a progressive reduction in TDFA's gain saturation as the input signal power is increased which is also defined as "compression-level". The effect of ASE in the modeled system can be observed as a difference of  $-10.3$  dB or less in a low-compression regime while at a high-compression no difference is observed as highlighted in Fig. 3.12. It has also been seen that at input-signal wavelength of 1530 nm the gain is found to be 42 dB for TDFA which is comparable with that of EDFA in [219]. However, at 1490 nm for TDFA, the gain obtained is 58.6 dB as shown in Fig. 3.12.

For the same set of the parameters used for the gain calculations, the noise-figure (dB) analysis has been performed using (3.16). The variation of noise-figure analysis is shown in Fig. 3.13. It portrays the obtained minimum and maximum noise-figure values for 1490 nm and 1530 nm respectively. It is because due to its high emission CSA at 1490 nm where the pump at 1420 nm absorption CSA is comparable to signal emission CSA at 1490 nm giving



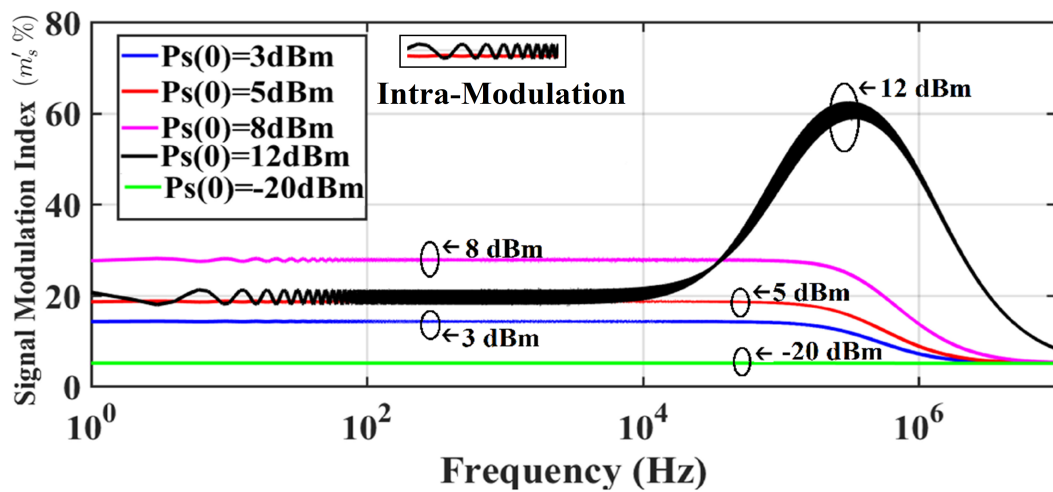
the optimum condition for signal amplification. The signal-gain and power obtained for four different wavelengths have been derived from the calculated four different sets of parameter coefficients as given in Table 3.3. Considering the values for the overlapping factors, emission cross-sections, and absorption cross-sections mentioned in Table 3.2 the above said coefficients have been calculated.

#### 3.4.4 Overmodulation Sensitivity to the Mean Input Signal Power

The effect of the steady-state input-signal power  $P_s^0(0)$  on the magnitude and phase of the output-modulation index has been investigated using the overmodulation transfer function expression given by (3.64). Keeping the input signal wavelength at 1530 nm (for the sake of comparison with that of the EDFA system given in [219]), the input-signal power levels are obtained for different power levels of 3, 5, 8, 12, and -20 dBm. Table 3.4 shows the calculated

**Table 3.4:** Parameters used in the overmodulation sensitivity to input-signal power calculations at 1530 nm

| Case | $P_s^0(0)$ in dBm | $U$        | $V$       | $U'$       | $V'$       |
|------|-------------------|------------|-----------|------------|------------|
| 1    | 3                 | -393927.25 | -38774.29 | -274208.21 | -10574.8   |
| 2    | 5                 | -416416.34 | -61263.38 | -268080.02 | -16702.19  |
| 3    | 8                 | -477291.98 | -122139.0 | -251471.57 | -333104.64 |
| 4    | 12                | -968174.52 | -613021.5 | -117594.52 | -167187.69 |
| 5    | -20               | -355346.83 | -193.87   | -284729.34 | -52.87     |



**Fig. 3.14:** Overmodulation sensitivity on the magnitude of the output-signal modulation index with respect to different input-signal powers at 1530 nm.



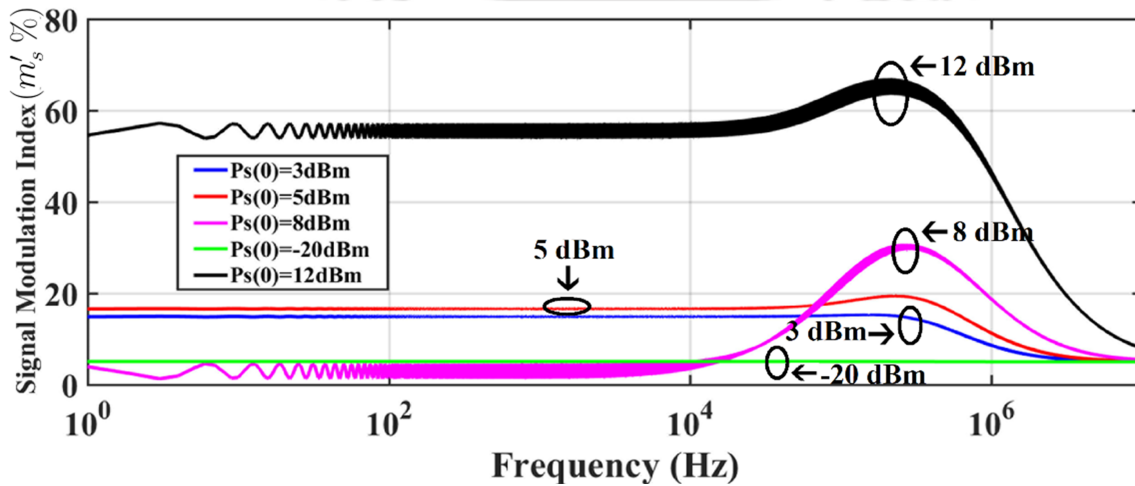
### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

values of the parameter coefficients for 1530 nm.

The variation of the output-signal modulation index at different power levels of the input-signal can be observed from Fig. 3.14. It can be seen that at 12 dBm of the input-signal power, the output-signal modulation index at corner-frequency is having an undesirable high value of 63%. Considering the S-Band signal wavelength at 1490 nm, the mean input-signal power is varied for five discrete values. The parameter coefficients for each case have been computed using (3.46) and are shown in Table 3.5. The behavior of the output-signal modulation index at five different signal power levels is shown in Fig. 3.15. The power levels are considered as 3, 5, 8, 12, and -20 dBm covering the range of variation of input signal power from a feeble to a comparatively high level. An ideal channel should not impose any amendments to the input-signal modulation index. This indeed has been observed for an input-signal power of -20 dBm as shown in Fig. 3.14 and Fig. 3.15. However, in practical systems, the input-signals

**Table 3.5:** Parameters used in the overmodulation sensitivity to input-signal power calculations at 1490 nm

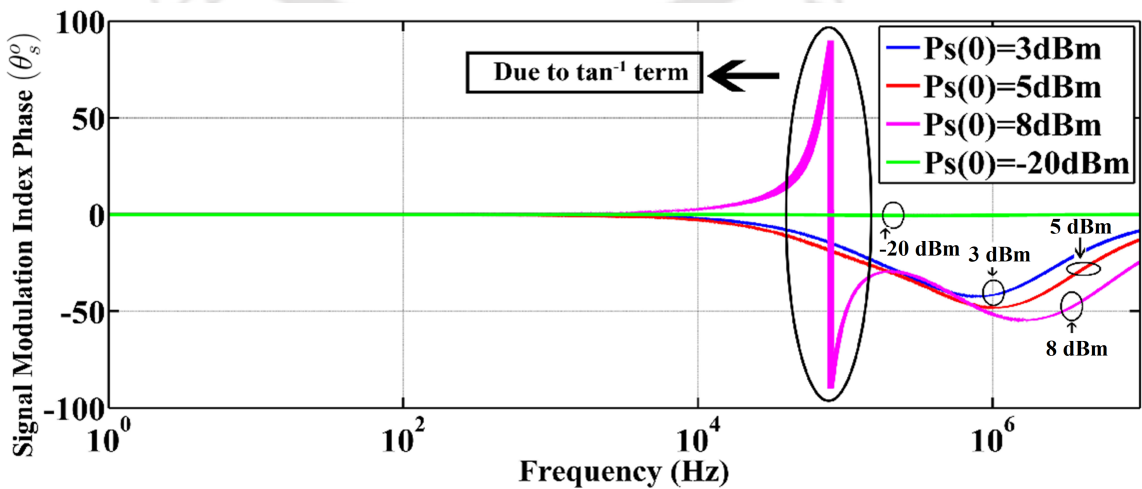
| Case | $P_s^0(0)$ in dBm | $U$        | $V$       | $U'$       | $V'$       |
|------|-------------------|------------|-----------|------------|------------|
| 1    | 3                 | -423792.96 | -68640.0  | -236734.2  | -48048.0   |
| 2    | 5                 | -463604.16 | -108451.2 | -208866.37 | -75915.84  |
| 3    | 8                 | -571368.96 | -216216.0 | -133456.21 | -151326.0  |
| 4    | 12                | -898781.76 | -543628.8 | -95757.95  | -380540.16 |
| 5    | -20               | -355496.16 | -343.2    | -284541.97 | -240.24    |



**Fig. 3.15:** Overmodulation sensitivity on the magnitude of the output-signal modulation index with respect to different input-signal powers at 1490 nm.

with such low strengths can fade out due to various loss mechanisms. Therefore, an optimum input-signal power, having significant magnitude, should be determined such that a minimum deviation is offered with respect to the input-signal modulation index. At the lower input-signal power levels, 3 and 5 dBm, the output modulation index increases at corner frequency but the rate remains low. However, as power is increased to 8 dBm, the modulation index shoots to a significantly high value of 30%, with an anomaly as an introduction of high intra-modulation which ranges from 1.3% to 4.5%. However, it is also observed that except at corner-frequency bandwidth ( $\sim 100$  kHz), the output modulation index remains constant with the input-signal modulation index having value of 5%.

Therefore, based on the stated analysis, 1490 nm has been qualitatively considered to be the optimal signal wavelength for TDFAs so as to obtain maximum gain and unperturbed modulation index. The overmodulation phase sensitivity on the output-signal's modulation index phase for various input-signal power is obtained using (3.65). The knowledge of phase change pattern also becomes an important criterion at the demodulation stage at fiber output for the successful recovery of the input modulated signal which can be predicted from Fig. 3.16 for different input-signal powers. Phase-reversal at an input-signal level of 8 dBm has been observed in the proximity of corner-frequency owing to the  $\tan^{-1}$  term in the expression of (3.65). This phase-reversal is associated with the respective input modulation indices  $\delta_{3,1}$  which in turn



**Fig. 3.16:** Overmodulation sensitivity on the output-signal modulation index phase with respect to different input-signal powers at 1490 nm.

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

have been modulating the population densities  $N_{3,1}$ . Consequently, it progressed to the condition of population-inversion at the corner-frequency. Henceforth, creating a phase-reversal at the outcome of amplified and modulated version of the input signal  $P_s^0(0)$  [231].

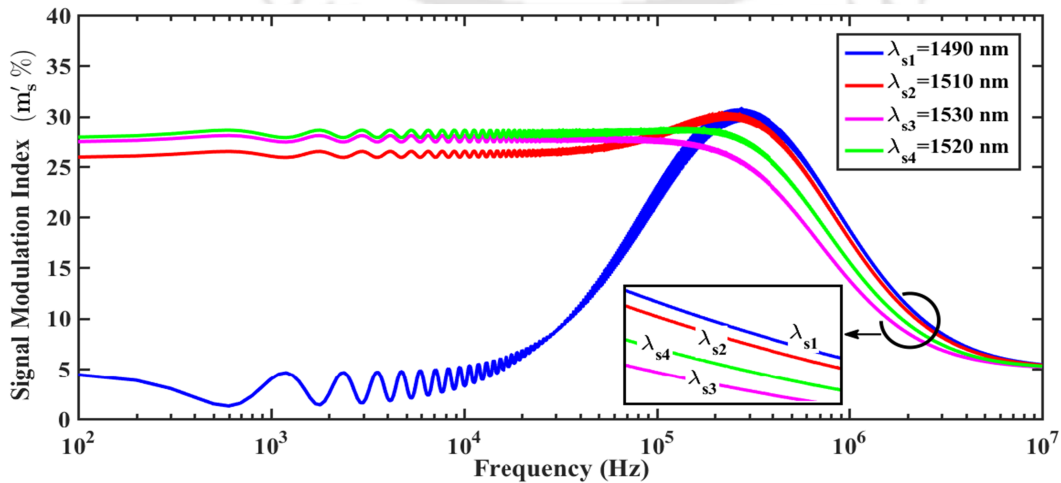
#### 3.4.5 Overmodulation Sensitivity due to the Signal Wavelength

Considering the magnitude and phase spectra of the overmodulation transfer-functions from the expressions (3.64) and (3.65), the sensitivity to the signal wavelength has been determined. The corresponding absorption and emission CSAs are calculated from Fig. 2.1 with respect to the different wavelengths, in the S-Band, fed into the designed TDFA system. The optimum input-signal power is taken to be 8 dBm from the signal-power analysis. The wavelengths considered for comparison are 1490, 1510, 1520, and 1530 nm. The corresponding coefficient-parameters have been calculated and are shown in Table 3.6.

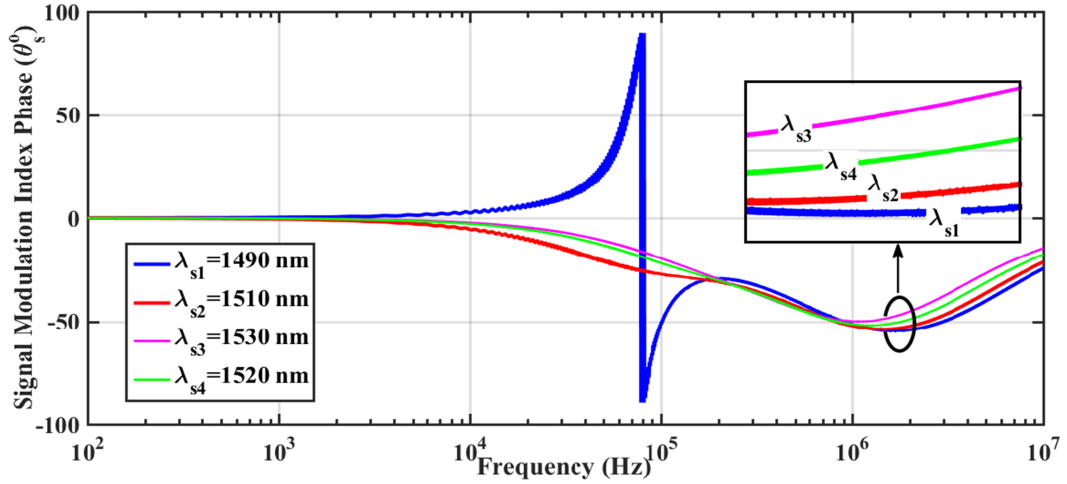
In reference to the the proximal bandwidth at the corner-frequency, the output-signal mod-

**Table 3.6:** Parameters used in the overmodulation sensitivity to input-signal wavelength calculations at 8 dBm power.

| Wavelength (nm) | $C(\lambda) \times 10^{30}$ | $U$        | $V$        | $U'$       | $V'$      |
|-----------------|-----------------------------|------------|------------|------------|-----------|
| 1490            | -7.152                      | -571368.96 | -216216    | -133456.21 | -151326   |
| 1510            | -7.646                      | -539639.42 | -184486.46 | -200668.21 | -84114    |
| 1520            | -8.071                      | -504082.66 | -148929.7  | -231002.04 | -53780.16 |
| 1530            | 8.196                       | -477291.97 | -122139.01 | -251471.57 | -33310.63 |



**Fig. 3.17:** Overmodulation sensitivity on the output-signal modulation index magnitude with respect to the different input-signal wavelengths in S-Band at 8 dBm signal-power.



**Fig. 3.18:** Overmodulation sensitivity on the output-signal modulation index phase with respect to the different input-signal wavelengths in S-Band at 8 dBm signal-power.

ulation index decreases at longer signal wavelengths as shown in Fig. 3.17. This increase also indicates an effective modulation coupling for the signal overmodulation [219, 231]. At the shortest considered signal wavelength of 1490 nm, the output modulation index rate of increment at the corner-frequency has been undesirably found to be maximum. However, the overall modulation index remained to be the lowest, making it the optimum operating wavelength except at the corner frequency. The output-signal modulation index phase characteristics for the identical set of parameters are shown in Fig. 3.18. It demonstrates that the output-signal modulation index phase decreases with increment in wavelengths at the corner-frequency. It is observed that approximately a constant rate of decrease in the phase has been maintained for all signal wavelengths with respect to the modulation frequency. The result also portrays the phenomenon of phase-reversal at 1490 nm with 8 dBm of input power. Therefore, this analysis indicates that modulation indices are less sensitive to the variation in the signal-level at 1490 nm in comparison with the higher wavelengths in S-Band except at the corner-frequency.

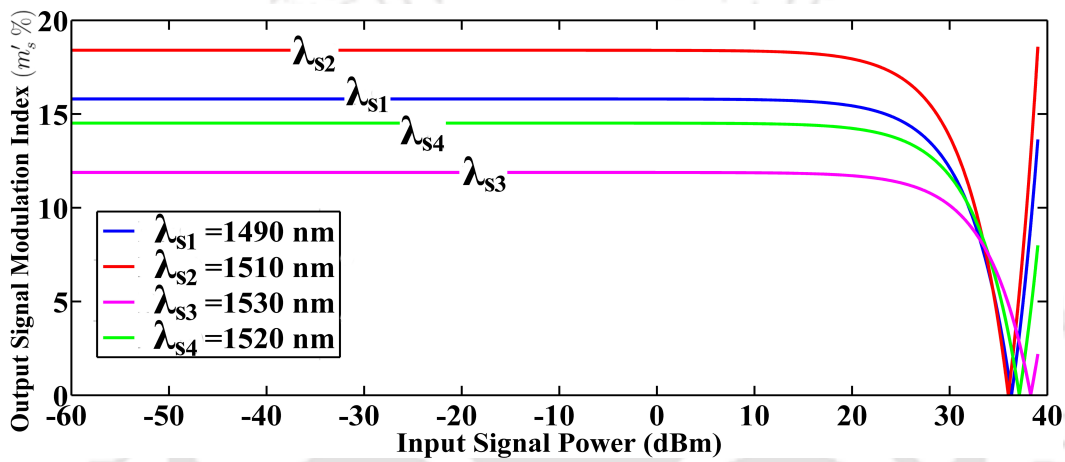
#### 3.4.6 Output-Signal modulation index response with respect to the input-signal power for signal overmodulation at $\omega_0 = 0$

Using the expressions for  $\alpha$  and  $\beta$  under the condition  $\omega = 0$  for the wavelengths considered in the subsection 3.4.5, the expressional values for  $\alpha$  and  $\beta$  have been obtained and are listed in Table 3.7. The expression for the output modulation index at  $\omega = 0$  is obtained using (3.64) and

### 3. Overmodulation of Signal and Gain Dynamics in TDFAs

**Table 3.7:** Parameters used to compute the output-signal modulation index as a response to the input-signal overmodulation at  $\omega = 0$ .

| Wavelength (nm) | $\alpha = f [P_s^0(0)]$             | $\beta = f [P_s^0(0)]$               |
|-----------------|-------------------------------------|--------------------------------------|
| 1490            | $[20.33 - 6.925 P_s^0(0)] \delta_3$ | $[7.115 - 2.423 P_s^0(0)] \delta_1$  |
| 1510            | $[16.22 - 5.596 P_s^0(0)] \delta_3$ | $[3.698 - 1.276 P_s^0(0)] \delta_1$  |
| 1520            | $[12.40 - 3.667 P_s^0(0)] \delta_3$ | $[2.239 - 0.6623 P_s^0(0)] \delta_1$ |
| 1530            | $[10.01 - 2.559 P_s^0(0)] \delta_3$ | $[1.366 - 0.348 P_s^0(0)] \delta_1$  |



**Fig. 3.19:** Output-Signal modulation index variation to the input-signal overmodulation at  $\omega = 0$  verses mean input-signal power.

has been plotted in Fig. 3.19. Values for  $N_3^0$  from Table 3.3 are utilized to get the dependency for input-signal power of the output modulation index. Figure 3.19 shows the trend of output-signal modulation index  $m'_s$  with the input-signal power at the considered S-Band wavelengths. It has been observed that the behavior of  $m'_s$  increases with the corresponding decrease in signal wavelength. However, an anomaly is observed at 1510 nm. Under the high compression zone, the output modulation index falls to the initial input index. On further increase of the input-signal power the output modulation index falls to zero which in-fact is apparent from Fig. 3.12. As the compression is increased, all the signal-wavelengths are seen to converge at one distinct signal-power, in this case, it is 32.5 dBm. The width of the transition region has been interestingly found to be the same for each considered wavelength. As a consequence, the crossover effect has been readily observed for all the considered wavelength uniformly which is unlike in EDFAs considered in Fig. 2.6.

### 3.5 Summary

In this chapter, a comprehensive analytical model of TDFA's overmodulation of gain and signal dynamics has been presented. The governing equations for the dynamics of TDFA based systems have been developed. This can be effectively utilized for the inline monitoring, surveillance, and information of the fiber-optic communication system for S and near-C bands. A mathematical model has been developed to obtain the plots of the variation of output modulation index, phase, and its variation with the input-signal power. Through this approach, estimation of the steady-state population of  $Tm^{3+}$  in the energy level-3 and level-1 has been presented. The inclusion of forward ASE and its effects on gain and signal-to-signal transfer function have also been presented. A difference of output-signal power with and without ASE has been observed as -10.3 dB while running the signal-gain and noise-figure analysis. Although small, can prove potentially disastrous in a long-haul and cascaded amplifier system. Apparently, it may lead to the phenomenon of modulation instability as discussed in the next chapter.

The work further presents the analytical and graphical explanation of the overmodulation sensitivity to the input-signal wavelength and power and compared it with the analogous EDFA wavelength of 1530 nm. It is inferred that the optimal input signal power is obtained at 8 dBm for 1490 nm for maximum gain and passes comparably unmodulated at an index of 5% except at corner frequency where it shoots to undesirable 30%. This study also resulted in the development of a simulator implemented through the MatLab<sup>®</sup>-Simulink pedestal using the analytical model. The probable effect of pump-signal crossover phenomenon has also been observed when output modulation index is simulated at  $\omega = 0$  under different sets of the signal wavelength at high compression regime.





# 4

## Modulation Instability in Lossy and Non-linear TDFAs

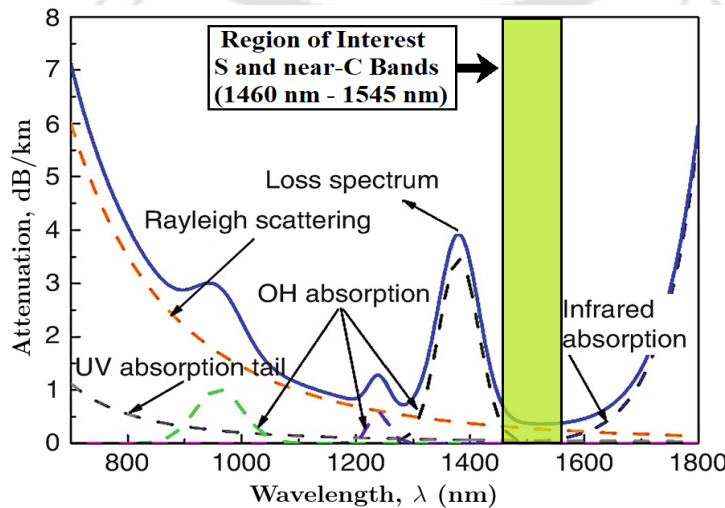
### Contents

|     |                         |     |
|-----|-------------------------|-----|
| 4.1 | Introduction            | 108 |
| 4.2 | Analytical Model        | 110 |
| 4.3 | Results and Discussions | 115 |
| 4.4 | Summary                 | 124 |

### 4.1 Introduction

DWDM optical fiber communication systems has already touched the theoretical limit for bandwidth saturation of  $0.8 \text{ bits s}^{-1}/\text{Hz}$  at a channel rate of 40 Gbps for EDFAs [163]. Therefore, the requirement for a new transmission band to increase the data capacity is the need of the hour. It can be seen from Fig. 4.1 that S and near-C bands (1460–1545) nm has the lowest loss level for silica fibers except for the C and L-bands [17]. However, S and near-C bands are selected over L-band considering the high absorption and emission CSAs for Thulium ( $\text{Tm}^{3+}$ ) as a doping material. These CSAs spectra in S and near-C bands for  $\text{Tm}^{3+}$  transiting from  $^3\text{H}_4$  to  $^3\text{F}_4$  levels are compared with that of EDFA and have been found that TDFA has  $2.2 \times 10^{-24} \text{ m}^{-2}$  covering comparatively larger bandwidth with constancy in (1460–1545) nm region [54, 219].

Fiber amplifiers create high energy confinement leading to the observation of nonlinear phenomena including modulation instability (MI). This well-versed phenomenon of MI showed its ubiquitous presence from water waves given by Benjamin-Feir instability to the nonlinear electric lines in electromagnetics [19, 255]. The phenomenon of MI in optical fibers is the splitting of the intense nonlinear continuous wave (CW) optical signal with high enough power into a train of ultrashort pulses when perturbed with low-intensity disturbances [233, 234, 256, 257]. Therefore, invoking MI in lossless TDFAs would be more probable than that of its practical counterpart (lossy) due to comparative reduction in amplified signal power in the latter case.



**Fig. 4.1:** Attenuation of optical signals in silica fibers showing the region of interest (S and near-C Bands)

The primary requirement for MI to get invoked is anomalous operation regime of group velocity dispersion (GVD) in the silica optical fiber (TDFAs) and instability render by the nonlinear phenomenon of self-phase modulation (SPM) [256, 257]. Consequently, loss analysis and its comparison with lossless amplifiers (TDFAs) become a crucial aspect to analyze the MI gain (with respect to perturbation frequency) in both the scenarios.

Primary reason behind MI is the interplay of dispersive and nonlinear effects simultaneously. Besides, the MI phenomenon can also be utilized to act as an active saturable absorber for fiber lasers [235, 258, 259]. Due to various dispersive, thermal, and scattering effects, a net loss factor of the optical fiber amplifier is generated [233]. The TDFAs operating in S and near C-band band holds the second-lowest loss factor of approximately 0.25 dB/km as compared to 1550 nm operational wavelength of EDFAs with 0.22 dB/km [260]. The conventional span-loss budget can be maintained in this band of communication with existing installed fiber links. The nonlinearity is caused by the doping concentration of ions in the optical fiber producing variations in the nonlinear refractive index. This deviation in nonlinear factor may incur changes in MI characteristics [261–263]. Consequently, loss and nonlinear analysis for TDFAs and its comparison with its lossless counterpart becomes an essential factor to consider the viability of commissioning it in the existing fiber optic communication network.

In this chapter, the loss and nonlinear factor effects are observed on the behaviour of MI in TDFAs operating in S and near-C bands. The loss factor effect is perceived as the gain reducer of MI as well as the perturbation frequency slider against the maximum integrated gain. The obtained results from the model determines the optimum small-signal gain coefficient and length for TDFAs to obtain maximum integrated gain so as to initiate the MI phenomenon. The nonlinear factor effect has been presented for TDFAs and compared with EDFAs. The cut-off perturbation frequency to invoke MI is determined for four input signal powers against a calculated small-signal attenuation coefficient of 0.01 /m. The analysis has been performed for the selected optimum TDFA parameters. A particular case is presented for a comparative perturbation magnitude to the CW signal by solving it numerically using the split-step Fourier method (SSFM). The results can prove to be crucial in the selection of optimum perturbation

frequency for TDFA based MI-lasers.

### 4.2 Analytical Model

Analysis of MI can be approached either by solving nonlinear Schrödinger equation (NLSE) or by investigating through four-wave mixing (FWM) approach [264,265]. The FWM technique may have a disadvantage of not possessing an analytical solution with additional terms (loss-factor) to NLSE [233]. Agrawal in [234] derived model for the MI in EDFAs by solving NLSE. The method of linear stability analysis (LSA) has been used to analyze the NLSE by introducing small perturbation modulating the stationary solution of the NLSE [257]. The evolution of the solution along the fiber length was determined by linearizing the nonlinear equation. Consequently, the analysis which has been performed on EDFAs gave the vital modeling approach which can be extended to TDFAs including the loss-factor effect.

Apparently, Karlsson in [233] emphasized on MI phenomenon in passive and lossy optical fibers. The model is based on the solution of NLSE through LSA using Wentzel-Kramers-Brillouin (WKB) and exact solution (ES) approaches. Though the WKB approach gives the approximate solution, it lacks accuracy around the turning points where solution diverges due to the attainment of a singularity in its term. Consequently, the ES approach has been considered in which the solution is stated as complex-valued orders of modified Bessel's function. While Turitsyn *etal* in [235] solved the NLSE based MI model through LSA using the basic formalism used in [234]. The analysis considers the solution using Stürmian theory under the obtained Sturm-Liouville problem form. However, the approach did not consider fiber loss information. Dinda *etal* in [266] demonstrated the behaviour of MI by considering the effects of second and fourth-order dispersion in the limitation of perturbation frequency for MI. In this case, the fiber was considered as a passive device and the loss-effect component was found to be missing.

Considering the above mentioned studies, a mathematical model has been developed with the following assumptions:

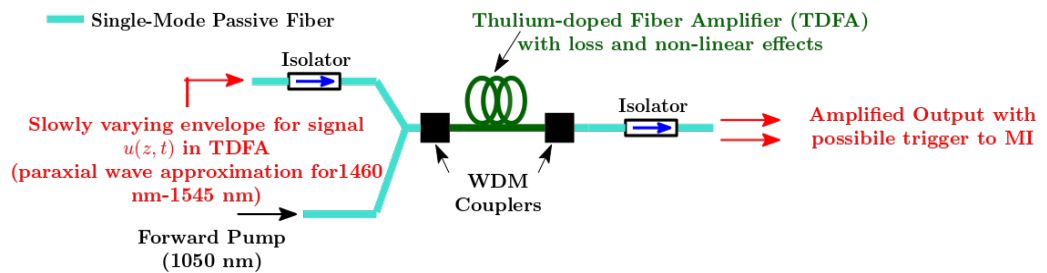
- (i) A three-level TDFA transition system with emission level from  $^3H_4$  to  $^3F_4$  for S and near-C bands emissions.

- (ii) The signal ASE is considered as unidirectional traversing from fiber's input to output, with no ASE at fiber input end.
- (iii) The slowly varying envelope for signal  $u(z, t)$  in TDFA is considered as paraxial wave approximation .
- (iv) Unidirectional pumping scheme as shown schematically in the Fig. 4.2.
- (v) The nonlinear factor has been considered in the analysis.

The longitudinal propagation of the field along the length of the fiber can be given by NLSE as in [256] to which the loss factor term  $\alpha$  was incorporated, given as (4.1)

$$i\frac{\partial u}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} + \gamma|u|^2u + \frac{ig_0T_2^2}{2}\frac{\partial^2 u}{\partial t^2} + i\frac{g_0u}{2} - i\frac{\alpha u}{2} \quad (4.1)$$

where,  $\beta_2$  is the GVD coefficient ( $< 0$  for the anomalous regime) and fiber nonlinearity is represented as  $\gamma$  responsible for SPM.  $g_0$  and  $\alpha$  are the small-signal gain and loss coefficients of TDFA respectively. The value for  $g_0$  is essentially zero for passive fibers and for the considered analysis it is calculated as 0.21 /m. The dipole relaxation time  $T_2$  was calculated as 318 fs for a gain bandwidth ( $\Delta\lambda$ ) of 30 nm at a signal wavelength of 1470 nm [19, 267]. Doping in the optical fiber induces a change in nonlinear refractive index ( $\bar{n}_2$ ) dependent on input pump power which populate  $\text{Tm}^{3+}$  to upper energy levels and alters the third-order susceptibility with fourth-rank tensor ( $\chi_{xxxx}^{(3)}$ ) of the fiber [255, 261]. The optical field is considered to be linearly polarized so as to make single component contribution of  $\chi_{xxxx}^{(3)}$  tensor to the nonlinear refractive index. Furthermore,  $\bar{n}_2$  is related with  $\chi_{xxxx}^{(3)}$  and linear refractive index ( $n$ ) [255, 261, 262], defined as



**Fig. 4.2:** Schematic representation for the MI phenomenon in lossy and nonlinear TDFAs as the signal gain media.



#### 4. Modulation Instability in Lossy and Non-linear TDFAs

---

$$\bar{n}_2 = \frac{3}{8n} \text{Re}(\chi_{xxxx}^{(3)}) \quad (4.2)$$

The nonlinear parameter ( $\gamma$ ) can be written as a function of  $\bar{n}_2$  given by (4.3). It is evident from (4.2) and (4.3) that  $\gamma$  can be represented in terms  $\chi_{xxxx}^{(3)}$  given by (4.4) below

$$\gamma = \frac{2\pi\bar{n}_2}{\lambda a_{eff}} \quad (4.3)$$

$$\gamma = \frac{3\pi}{4n\lambda a_{eff}} \text{Re}(\chi_{xxxx}^{(3)}) \quad (4.4)$$

where,  $a_{eff}$  is the effective mode area of the core which can be written as  $a_{eff} = \pi\omega_0^2$  with  $\omega_0$  being the spot size radius [255]. For a single mode fiber,  $\omega_0$  is defined as  $\omega_0 = a/\sqrt{\ln(V)}$ , where  $a, V$  are the core radius and fiber V-parameter respectively. The nonlinearity in TDFAs can be increased by heavily doping the fiber which in-turn increase the  $\chi_{xxxx}^{(3)}$  on steady-state pumping [255, 261, 262].

For any bounded input, linear systems produces bounded output and therefore considered to be stable. However, nonlinear systems such as NLSE may result in unbounded output rendering the system an unstable state. Therefore, thorough stability analysis becomes a critical factor while dealing with nonlinear systems. Adding small perturbations with respect to stationary solution in a nonlinear system results in a linearized system which can be solved through LSA. Consequently, stationary solution  $u(z, t)$  is time-independent during propagation inside TDFA, let the ansatz for the solution wave of (4.1) be given by [233, 234, 255, 268]

$$u(z) = \sqrt{P_0} \exp \left[ i\gamma \int_0^z P_0 \exp (g_0 z) dz + \frac{g_0 z}{2} - \frac{\alpha z}{2} \right] \quad (4.5)$$

where  $P_0$  is the input signal power with S and near C-band wavelengths. The term inside the  $[\cdot]$  depicts the nonlinear phase shift for TDFAs. By LSA, small perturbations can be introduced as the form of  $a + ib$  where  $a, b \ll \sqrt{P_0}$  corresponding to weak modulation of intense continuous wave background given by

$$u(z, t) = (\sqrt{P_0} + a + ib) \exp \left[ i\gamma \int_0^z P_0 \exp (g_0 z) dz + \frac{g_0 z}{2} - \frac{\alpha z}{2} \right] \quad (4.6)$$

Substituting (4.6) in (4.1), linearizing it in  $a$  and  $b$ , we obtain a set of coupled differential equations given as

$$\frac{\partial a}{\partial z} = \frac{\beta_2}{2} \frac{\partial^2 b}{\partial t^2} + \frac{g_0 T_2^2}{2} \frac{\partial^2 a}{\partial t^2} \quad (4.7)$$

$$\frac{\partial b}{\partial z} = -\frac{\beta_2}{2} \frac{\partial^2 a}{\partial t^2} + \frac{g_0 T_2^2}{2} \frac{\partial^2 b}{\partial t^2} + 2\gamma P_0 \exp[(g_0 - \alpha)z] \quad (4.8)$$

The coupled differential equations (4.7)–(4.8) for  $(a, b)$  assumes the solution of the form [234]

$$(a, b)(z) = (a_0, b_0)(z) \exp \left[ i \int K(z) dz - i\Omega t \right] \quad (4.9)$$

where  $(a_0, b_0)$  follows slowly varying envelope condition,  $\Omega$  is the perturbation frequency, and  $K(z)$  is the wave-number expressed as a function of space owing to the gain characteristics of the signal while traversing inside TDFA. Substituting (4.9) in (4.7)–(4.8) and solving for  $K(z)$ , we obtain the expression for space and perturbation frequency-dependent wave number given as

$$K(\Omega, z) = \frac{ig_0 T_2^2 \Omega^2}{2} \pm \frac{1}{2} |\beta_2| \Omega \left[ \Omega^2 + \left( \frac{4\gamma P_0}{\beta_2} \right) \exp \{(g_0 - \alpha)z\} \right]^{1/2} \quad (4.10)$$

The phenomenon of MI in TDFAs can only be triggered if the perturbation terms expressed in (4.9) grows exponentially. Consequently,  $K(z)$  should be assigned the value of the negative imaginary part. The total gain of the perturbations, also referred as integrated gain  $F(\Omega)$ , can then be obtained by integrating the imaginary part of (4.10) along the length of the TDFA  $L$ , given as

$$F(\Omega) = -2 \int_0^L \text{Im} [K(\Omega, z)] dz \quad (4.11)$$

here multiplicative factor of ‘2’ converts  $F(\Omega)$  to power gain [234, 269]. Under the anomalous regime of GVD ( $\beta_2 < 0$ ),  $F(\Omega)$  is positive for some frequencies and grows exponentially. The limit of allowable perturbation frequencies for MI to trigger is then can be expressed as

$$\Omega < \underbrace{\left( \frac{4\gamma P_0}{|\beta_2|} \right)^{1/2}}_{\Omega_0} \exp \{(g_0 - \alpha)z\} \quad (4.12)$$

#### 4. Modulation Instability in Lossy and Non-linear TDFAs

**Table 4.1:** Model Parameters

| Parameter                                      | Unit                             | Symbol        | Value                 | Remark               |
|------------------------------------------------|----------------------------------|---------------|-----------------------|----------------------|
| Signal wavelength                              | nm                               | $\lambda_s$   | 1470                  | S-Band               |
| Signal power                                   | mW                               | $P_s$         | 50, 100, 150, 250     | Estimated            |
| Perturbation power<br>(Numerical Analysis)     | mW                               | $P_{per}$     | 10                    | Estimated            |
| Perturbation frequency<br>(Numerical Analysis) | THz                              | $\Omega$      | 2                     | Calculated           |
| TDFA length                                    | m                                | $L$           | 100                   | Calculated           |
| Signal absorption CSA<br>at 1470 nm            | m <sup>2</sup>                   | $\sigma_{sa}$ | Fig. 2.1              | [54,163, 218,219]    |
| Signal emission CSA<br>at 1470 nm              | m <sup>2</sup>                   | $\sigma_{se}$ | Fig. 2.1              | [54,163, 218,219]    |
| Small signal attenuation                       | -                                | -             | 0.36                  | Estimated            |
| Small signal attenuation coefficient           | m <sup>-1</sup>                  | $\alpha$      | 0.01, 0.36            | Calculated           |
| Small signal gain coefficient                  | m <sup>-1</sup>                  | $g_0$         | 0.21                  | Calculated           |
| Dipole relaxation time                         | fs                               | $T_2$         | 318                   | Calculated, [19,267] |
| GVD coefficient                                | ps <sup>2</sup> km <sup>-1</sup> | $\beta_2$     | -13.74                | Calculated, [234]    |
| Nonlinear parameter (Tm <sup>3+</sup> )        | W <sup>-1</sup> m <sup>-1</sup>  | $\gamma$      | 0.0290,0.0257         | Calculated           |
| Nonlinear parameter (Er <sup>3+</sup> )        | W <sup>-1</sup> m <sup>-1</sup>  | $\gamma$      | 0.0133,0.010          | Calculated           |
| Nonlinear refractive index                     | m <sup>2</sup> W <sup>-1</sup>   | $\bar{n}_2$   | $2.4 \times 10^{-20}$ | [263]                |
| V-Parameter                                    | -                                | $V$           | 2.4                   | [256]                |
| Core radius                                    | $\mu\text{m}$                    | $a$           | 1.8                   | Estimated            |

Therefore, under the condition  $\beta_2 < 0$ , substituting the imaginary part of (4.10) in (4.11) and integrating over the TDFA length we get the governing expression for integrated gain given by

$$F(\Omega) = \frac{8fL}{\ln(G)L_{NL}} \left[ \sqrt{(G^2 - f^2)} + f \sin^{-1} \left( \frac{f}{\sqrt{G}} \right) - \sqrt{(G'^2 - f^2)} - f \sin^{-1} \left( \frac{f}{\sqrt{G'}} \right) - f^2 \Omega_0^2 T_2^2 \ln(G) \right] \quad (4.13)$$

where  $\Omega_0$  is the cut-off perturbation frequency beyond which the phenomenon of MI was not observable and defined as the limiting case of (4.12). The normalized perturbation frequency is expressed as  $f = \Omega/\Omega_0$ , nonlinear TDFA length as  $L_{NL} = 1/\gamma P_0$ , consolidated single-pass

amplifier gain as  $G = \exp \{(g_0 - \alpha)z\}$ , and  $G'$  takes value as

$$G' = \begin{cases} 1, & \Omega < \Omega_0 \\ f^2, & \Omega > \Omega_0 \end{cases} \quad (4.14)$$

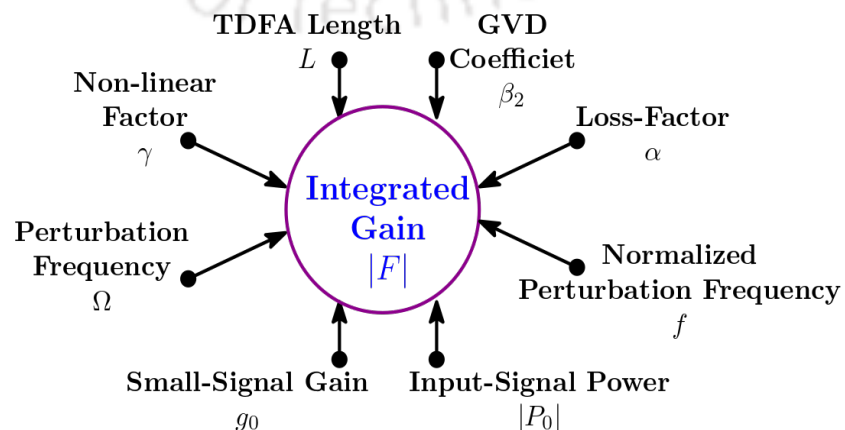
The model parameters have been calculated and are listed in Table 4.1. The results are obtained by substituting suitable parameters in the presented analytical model which have further being discussed in section 4.3.

### 4.3 Results and Discussions

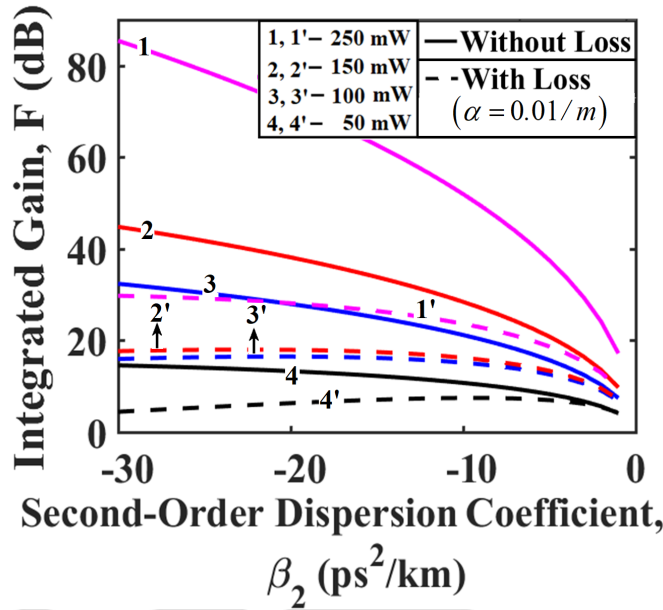
The analytical model developed in the section 4.2 for the integrated gain describes its parametric dependencies on multiple TDFA factors which is shown in Fig. 4.3. Consequently, this section includes the results obtained on the implementation of the analytical model. The results obtained based on the model are qualitatively presented due to the considered assumptions which have been comprehensively discussed in the following subsections.

#### 4.3.1 TDFA's length effect on Integrated gain variation with respect to small-signal gain coefficient

Variation of integrated gain  $F(\Omega)$  as a function of perturbation frequency  $\Omega$  highlights the effect of loss factor and nonlinearity in TDFAs. The observations are prominent with respect to the decrease in the magnitude of  $|F(\Omega)|$ . The relative slide in perturbation frequency has also been noted considering the comparison between lossless and lossy TDFAs. The simulations



**Fig. 4.3:** Parameters affecting the behaviour of the Integrated-Gain.

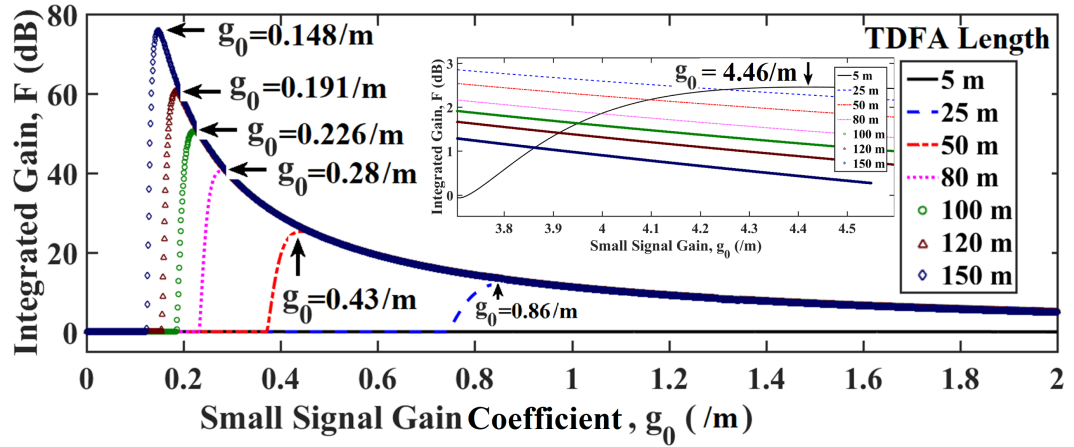


**Fig. 4.4:** Integrated gain ( $|F(\Omega)|$ ) variation with respect to Second-Order dispersion ( $\beta_2$ ) for 100 m TDFA length ( $L$ ) for different input signal power ( $P_0$ ).

have been performed by considering  $\beta_2 = -13.74 \text{ ps}^2/\text{km}$  for the S and near-C band fiber-optic communication [256].

Figure 4.4 highlights the effect of  $\beta_2$  variation on  $|F(\Omega)|$  with four different input signal powers (50, 100, 150, 250) mW and compared the lossy TDFA with that of the lossless for 100 m optimum TDFA length (justified in the later sections of this chapter). The graphical behaviour infers the increase in integrated gain with more dispersive regime and shows that mere inclusion of  $\alpha = 0.01/\text{m}$  can decrease  $|F(\Omega)|$  significantly. The nonlinearity too inculcated its effect on  $|F(\Omega)|$  for TDFAs which has been compared with EDFAs considering the similar conditions and parameter values. These observations are made by running simulations and calculating the optimum TDFA length and small-signal gain values for which the MI phenomenon is considerably visible.

The effect of small-signal gain coefficient ( $g_0$ ) on  $|F(\Omega)|$  for various TDFA lengths can be seen in Fig. 4.5. Considering 1 THz perturbation frequency, it has been observed that  $|F(\Omega)|$  at shorter TDFA lengths ( $L < 10$ ) m acquire zero value even for comparatively large small-signal gain coefficient values (up to  $g_0 < 3.73 \text{ m}^{-1}$ ) owing to inability of the system to reach population inversion state (shown in the inset of Fig.4.5). The smaller values of  $g_0$  assures undepleted pump approximation thereafter providing a closed-form solutions for integrated gain



**Fig. 4.5:** TDFA length ( $L$ ) effect on integrated gain ( $|F(\Omega)|$ ) variation with respect to small-signal gain coefficient ( $g_0$ ) with inset showing the  $|F(\Omega)|$  built-up in low length TDFA ( $L < 5$  m) at a comparative higher values of  $g_0 = 4.46/\text{m}$ .

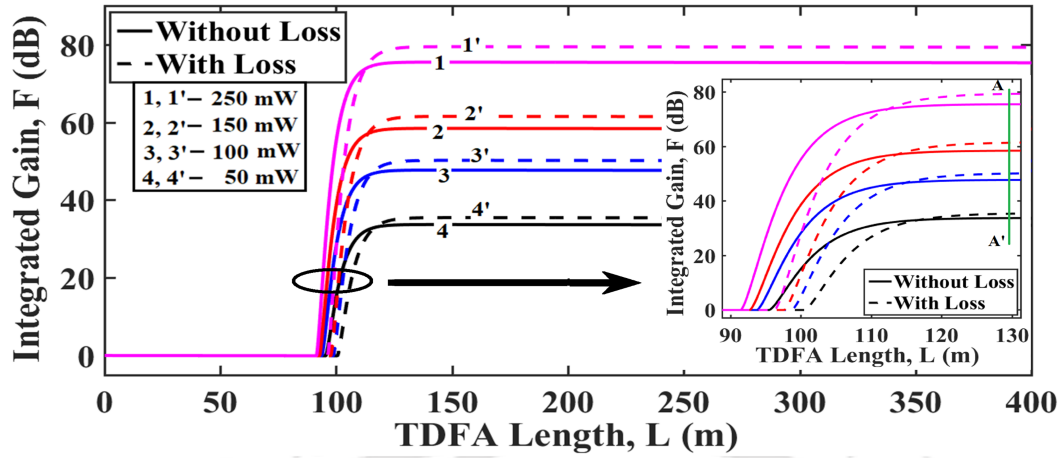
spectra [233, 256, 268]. However, as the TDFA lengths have been increased to considerable values ( $80 < L < 100$  m),  $|F(\Omega)|$  increases with corresponding decrease in  $g_0$ . For longer TDFA lengths ( $L > 100$  m),  $|F(\Omega)|$  is perceived to maximize at relatively less decrease in  $g_0$  values but at the cost of longer TDFA lengths which could add up to further maximize the loss-factor value. Therefore, the value for optimum TDFA length has been deduced to lie within the limit of 80 m to 100 m. As  $g_0$  was increased,  $|F(\Omega)|$  after attaining maximum value decreases due to advent to MI trigger leading to pulse breaking [256].

#### 4.3.2 Integrated gain variation with respect to TDFA's Length for different input signal powers

For a very weak estimation of small-signal attenuation value of 0.36, with corresponding small signal attenuation coefficient  $\alpha = 0.01/\text{m}$ , four input signal power were selected as (50, 100, 150, 250) mW. To find out optimum TDFA length at small signal  $g_0 = 0.21/\text{m}$ , it is observed from Fig.4.6 that the integrated gain starts to built-up in the vicinity of 100 m length mark. The higher signal power has been amplified at lower lengths as shown in the magnified portion of the image in the inset of Fig.4.6. The saturation region suggests that pump power is not sufficient enough to provide additional population inversion and has reached the equilibrium which can also be observed in [235]. The comparative effect of the lossy and lossless TDFA was seen following the desired pattern of lossy TDFA's integrated gain less than lossless till



#### 4. Modulation Instability in Lossy and Non-linear TDFAs



**Fig. 4.6:** Integrated gain ( $|F(\Omega)|$ ) variation with respect to TDFA length ( $L$ ) for different input signal powers ( $P_0$ ).

**Table 4.2:** Correction Factor,  $\eta$ .

| Input Signal Power<br>(mW) | $ F(\Omega) $ difference in dB<br>(Lossy-Lossless) | $\eta$ in dB |
|----------------------------|----------------------------------------------------|--------------|
| 250                        | 79.18 – 75.41                                      | 3.77         |
| 150                        | 61.25 – 58.37                                      | 2.88         |
| 100                        | 49.93 – 47.63                                      | 2.3          |
| 50                         | 35.19 – 33.63                                      | 1.56         |

lengths of 112 m for 250 mW signal power. Similarly, from Fig.4.6 the other TDFA threshold lengths ( $L_0$ ) are calculated for various signal powers for which the model has been following the desired results.

An anomaly is observed for the lossy TDFA case in the saturation region when an integrated gain of lossy TDFA exceeds the lossless. Evident reason for this anomaly has been analyzed from (4.13) wherein the denominator the value of  $\ln(G)$  term decreases for larger TDFA lengths. Consequently, the integrated gain increases for the lossy TDFA case in the saturation regime. Since this anomaly occurred in the saturation region, hence it is corrected by introducing a suitable correction factor  $\eta$  which needs to be subtracted from (4.13) when

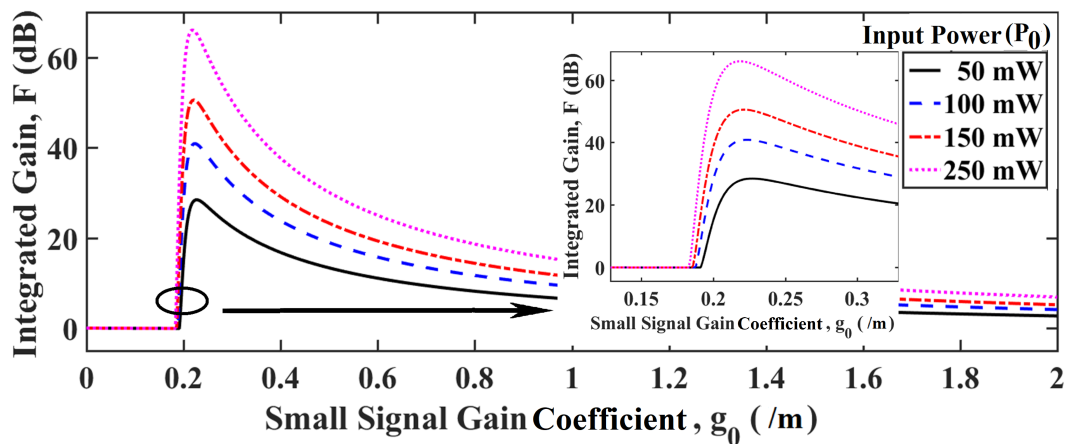
( $L > L_0$ ) to give (4.15), written as

$$F(\Omega) = \frac{8fL}{\ln(G)L_{NL}} \left[ \sqrt{(G^2 - f^2)} + f \sin^{-1} \left( \frac{f}{\sqrt{G}} \right) - \sqrt{(G'^2 - f^2)} - f \sin^{-1} \left( \frac{f}{\sqrt{G'}} \right) - f^2 \Omega_0^2 T_2^2 \ln(G) \right] - \eta \quad (4.15)$$

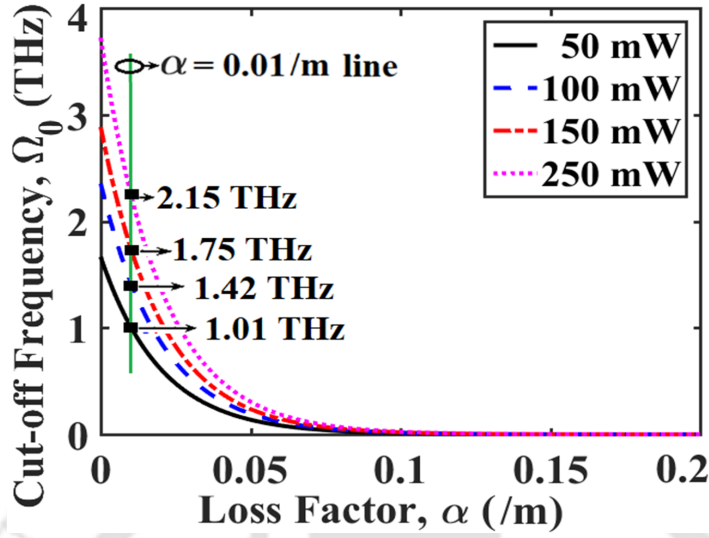
The optimum TDFA length is obtained as 100 m up to which there has been no requirement for the correction factor  $\eta$ . The lossy TDFA integrated gain eventually shall overcome the loss effect for longer lengths and is expected to acquire the saturation gain value of lossless TDFAs. For the sake of completeness of the solution, the values for  $\eta$  are calculated from the inset of Fig.4.6. The vertical line-segment AA' is made in the saturation zone and the difference of integrated gain values has been calculated leading to give  $\eta$  as summarized in Table 4.2.

#### 4.3.3 Integrated gain variation with respect to small signal gain coefficient for different input signal powers

Considering the calculated TDFA length of 100 m, the variation of  $|F(\Omega)|$  with respect to  $g_0$  for different input signal power is analyzed using Fig. 4.7. For initial low values of  $g_0$ , the TDFA acted as a passive fiber due to insufficient gain built-up. However,  $|F(\Omega)|$  attained maximum value for  $g_0$  in the vicinity of 0.2 /m with higher signal power initiating the integrated gain built-up first due to decrease in the nonlinear length ( $L_{NL}$ ) value as evident from relation  $L_{NL} = 1/\gamma P_0$  [256]. It has been inferred from the inset of Fig. 4.7, which highlights the magnified portion of  $g_0 = 0.2$  /m vicinity, that for  $g_0 = 0.21$  /m the integrated gain  $|F(\Omega)|$



**Fig. 4.7:** Integrated gain ( $|F(\Omega)|$ ) variation with respect to small signal gain coefficient to obtain optimum value as  $g_0 = 0.21$  /m for four different input signal powers.



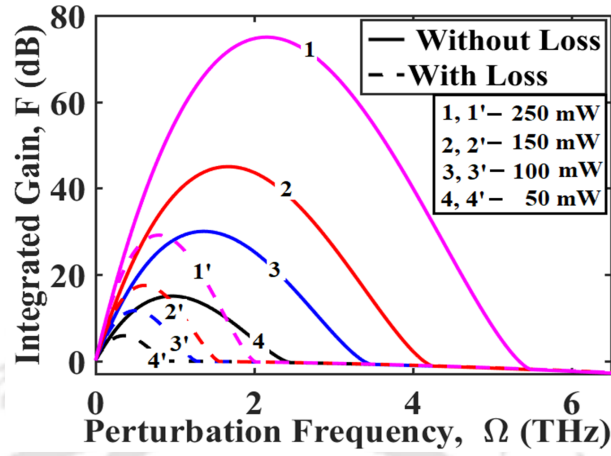
**Fig. 4.8:** Cut-off frequency ( $\Omega_0$ ) calculation at mentioned loss-factor ( $\alpha = 0.01/\text{m}$ ).

maximises hence acting as optimum small-signal gain coefficient value.

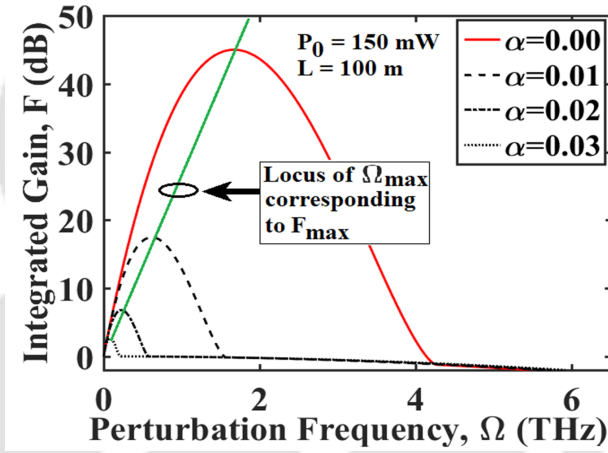
The cut-off perturbation frequency values have been obtained for four selected input signal powers as mentioned above. For  $\alpha = 0.01 /\text{m}$ , a vertical line segment is drawn in Fig. 4.8 to obtain the intersection point corresponding to the cut-off frequencies for desired signal power values. For example, considering  $P_0 = 150 \text{ mW}$  at  $g_0 = 0.21 /\text{m}$  and  $L = 100 \text{ m}$  the cut-off frequency ( $\Omega_0 \exp \{(g_0 - \alpha)z\}$ ) is obtained as 1.75 THz. Therefore, to invoke MI phenomenon at  $P_0 = 150 \text{ mW}$  signal power,  $\Omega < \Omega_0 \exp \{(g_0 - \alpha)z\}$  (1.75 THz) condition has to be satisfied. The optimum TDFA length obtained is comparable to the nonlinear length and dispersive length ( $L_D = T_2^2/|\beta_2|$ ) which ensures MI trigger due to the simultaneous interplay of GVD and SPM mechanisms [256].

#### 4.3.4 Perturbation frequency and Loss-factor analysis on Integrated gain

The effect of sweeping perturbation frequency ( $\Omega$ ) on integrated gain ( $|F(\Omega)|$ ) has been observed for the lossless and lossy fiber ( $\alpha = 0.01 /\text{m}$ ) scenarios shown in Fig. 4.9 (a). Considering parameter values from the Table 4.1 and four different input signal powers, obtained plots shows the gain spectrum focusing on the condition that it exists for  $\Omega < \Omega_0 \exp \{(g_0 - \alpha)z\}$ . The results obtained are in tandem to that of EDFAs in [234, 235] and to the growth rate of side-band amplitudes on frequency in [270]. For instance, at input signal power of 250 mW, a fall of 45 dB in maximum integrated gain has been observed when lossless and lossy TDFA



(a)



(b)

**Fig. 4.9:** (a) Reduction in maximum integrated gain under MI with corresponding perturbation frequency shift considering lossless (solid lines) and lossy (dashed lines) TDFA and (b) Loss-factor effect for fixed signal power of 150 mW and TDFA length of 100 m.

cases are compared. The corresponding perturbation frequency slide of 1.44 THz towards the low-frequency regime has also been observed. The early  $|F(\Omega)|$  gain at relatively lower TDFA lengths for larger values of input signal power can be correlated from Fig. 4.9 (a) and Fig.4.6. Similarly, the results of Fig. 4.8 and Fig. 4.9 (a) are in perfect relation with respect to cut-off frequencies.

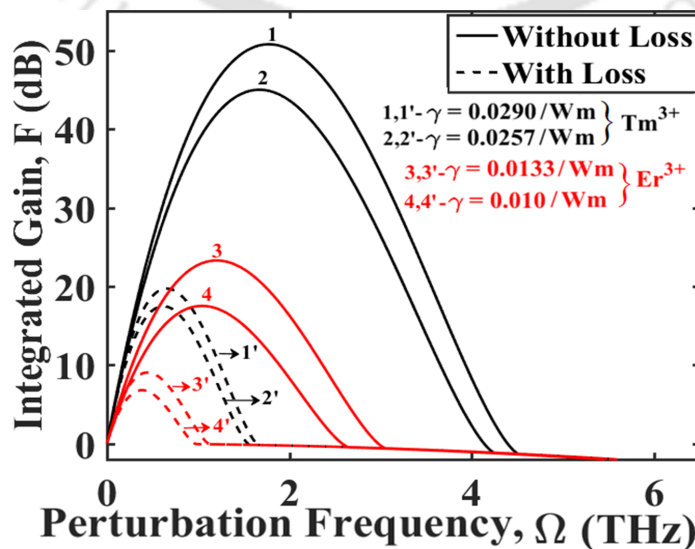
The loss-factor effect for the fixed input signal power ( $P_0 = 150$  mW) has been presented in Fig. 4.9 (b). The locus of  $|F(\Omega)|_{\max}$  and corresponding  $\Omega_{\max}$  is traced for four different loss-factors ( $\alpha = 0.00, 0.01, 0.02, 0.03$ ) /m. A slope of 26.69 dB/THz with a corresponding linear slide in  $\Omega_{\max} = -52.89$  THz (negative sign signifying the frequency slide towards the origin) is

#### 4. Modulation Instability in Lossy and Non-linear TDFAs

calculated as significant factors. This information can be utilized for the selection of optimum  $\Omega$  to construct TDFA lasers in which MI acts as an active saturable absorber [235].

##### 4.3.5 Perturbation frequency, nonlinear factor, and Loss-factor analysis on Integrated gain–A Comparative Approach

It can be observed from (4.4) and [256, 261, 262] that nonlinearity in fiber amplifiers are the function of doping concentration under undepleted steady-state pumping. Therefore, two values of the nonlinear parameter ( $\gamma$ ) are calculated with the same set of parameters for TDFA and EDFA respectively as mentioned in Table 4.1. The communication wavelength for EDFA has been taken as 1550 nm which returned lower value for  $\gamma$  as compared to TDFA. Consequently, the nonlinear effect seen in TDFAs is found to be more than EDFAs as shown in Fig. 4.10. The loss-factor effect along with nonlinearity can also be seen in Fig. 4.10 for  $\alpha = 0.01$  /m. The relative fall in  $|F(\Omega)|_{max}$  and corresponding  $\Omega_{max}$  slide for TDFA ( $\gamma = 0.0257$  W/m) and EDFA ( $\gamma = 0.010$  W/m) are calculated as (27.36 dB, 1.105 THz) and (10.75 dB, 0.664 THz) respectively. Although after consolidating the loss-factor and nonlinear effects, still it has been found that  $|F(\Omega)|_{max,TDFA} > |F(\Omega)|_{max,EDFA}$ . Apparently, the probability of MI-trigger increases substantially in TDFAs with respect to EDFAs. Therefore, it can be deduced that TDFA based saturable absorber with MI as the mechanism is better suited for fiber-laser production than its EDFA counterpart.



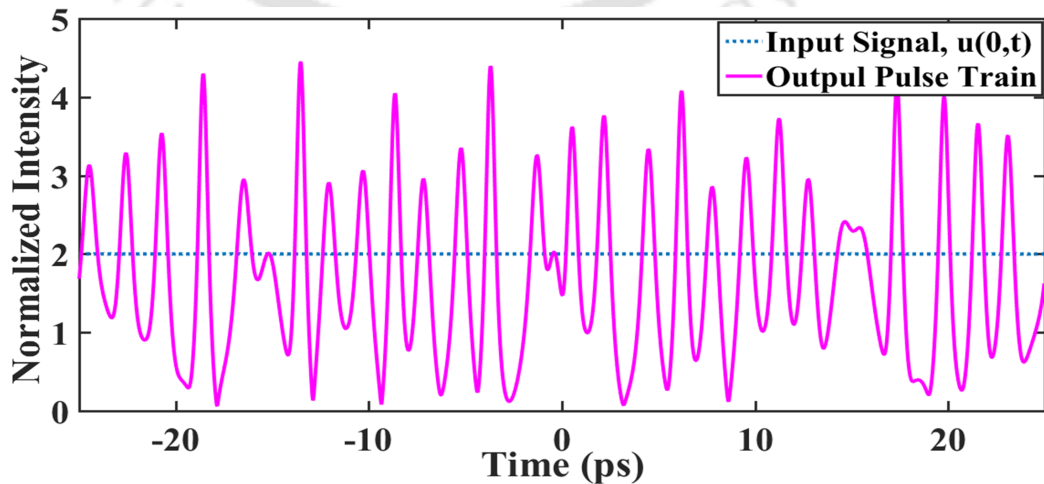
**Fig. 4.10:** Comparison of nonlinear parameter ( $\gamma$ ) effect on integrated gain  $|F(\Omega)|$  for TDFA and EDFA.

#### 4.3.6 Numerical Approach to demonstrate the phenomenon of MI

Practical conditions may alter ideal conditions and the analytical solution may no longer hold good. One of the non-ideality condition may occur when perturbation amplitude becomes comparable to the CW signal (1% of  $|P_0|$ ) [234]. Consequently, LSA could no longer be applied to solve (4.1) analytically leaving us for a numerical approach to obtain the solution. For the time and frequency domain, NLSE's solution is known considering pure nonlinear and pure dispersive medium in the respective domains [234]. Therefore, split-step Fourier's method (SSFM) can be used as numerical tool to find solution of (4.1) under non-ideal conditions. The detailed formalism of SSFM can be accessed from Appendix A.1 of this thesis. For  $\Omega = 2$  THz, the input signal to TDFA in time ( $t$ ) domain can be written as [256]

$$u(0, t) = P_0[1 + 0.01P_0 \sin(2\pi\Omega t)] \quad (4.16)$$

It can be observed from Fig. 4.11 that a quasi-CW signal has been perturbed by relatively large magnitude disturbances with frequency within the limits of  $\Omega_0$ . MI phenomenon converts the quasi-CW signal input into the amplified pulses and the obtained quasi-periodic spatio-temporal dynamics is found to follow the approximate similar behaviour for EDFAs in [256] and in general [271]. The FWHM pulse width has been observed as 450 fs and is found to be comparable in the magnitude-order against the dipole relaxation time ( $T_2$ ) for  $\text{Tm}^{3+}$  which is



**Fig. 4.11:** Numerical solution for a particular case of (4.1) where amplitude of perturbations were comparable to that of CW input signal (1% of  $|P_0|$ ).



#### 4. Modulation Instability in Lossy and Non-linear TDFAs

---

calculated as 318 fs. The unequal magnitude of pulses with quasi-periodic nature observed in Fig. 4.11 can also be seen in [256,271, 272] and MI is the probable responsible phenomenon for this behaviour. Moreover, the phenomenon of MI often lead to the route to chaos and rogue waves which indeed is an important aspect and can be discussed as a separate research article [240,273].

#### 4.4 Summary

In this chapter, a detailed analysis on loss and nonlinear factor effects on MI in TDFAs operating in S and near-C band has been presented. An analytical model has been derived through NLSE and solved through the LSA technique considering the slowly varying envelope for signal traversing within TDFA. To trigger the MI phenomenon, optimum values for small-signal gain coefficient and TDFA length are obtained as 0.21 /m and 100 m respectively. The results obtained show the massive reduction in integrated gains for a small-signal attenuation of a mere 0.36 (corresponding to  $\alpha = 0.01$  /m), thereby reducing the probability of MI trigger in TDFAs. nonlinear factor analysis on TDFA has been compared with that of the EDFA. The result projected better performance of the former with larger integrated gains for the same set of fiber amplifier parameters. Considering lossless and lossy cases simultaneously, the deteriorating effect of loss factor has also been observed in the nonlinear factor analysis.

The perturbation frequency selection in lossy TDFAs is a crucial aspect to trigger MI, which can be predicted from the presented analysis. The solution to a special case with non-ideal conditions with respect to the large amplitudes of input perturbations is solved numerically and presented. The observation of the generation of quasi-periodic pulses through MI has also been observed. The digital communication aspect through optical-pulses inside the TDFAs has been dealt in the next chapter considering the chirping effects. All the observations and results produced in this chapter could provide an important platform for the development of S and near-C band TDFA lasers in which the MI phenomenon acts as an active saturable absorber.

# 5

## Chirping Effects on Optical Pulses in TDFAs through MI

### Contents

|     |                         |     |
|-----|-------------------------|-----|
| 5.1 | Introduction            | 126 |
| 5.2 | Mathematical Model      | 127 |
| 5.3 | Simulation Setup        | 129 |
| 5.4 | Results and Discussions | 131 |
| 5.5 | Summary                 | 138 |

### 5.1 Introduction

Phenomenon of modulation instability (MI) in optical fibers can be defined as the splitting of the continuous wave (CW) optical pulses into a train of ultra short pulses [256]. The figurative reason behind MI is the employment of dispersive and non-linear effects simultaneously. Recently, studies have been performed on Thulium ( $\text{Tm}^{3+}$ ) doped fiber amplifiers (TDFAs) emphasizing on its potential as a defining alternative to existing Erbium doped fiber amplifiers (EDFAs) for fiber optic communication systems [53, 163, 221, 232, 247, 249, 274–276]. Multiple quantum levels of  $\text{Tm}^{3+}$  makes them fit to transit and lase in S and near-C (1460 nm–1545 nm) band of optical spectrum [163]. Hence, proving them a suitable substitute for existing narrow C-band (centered at 1550 nm) EDFAs to S and near-C band ultra short pulse ( $\sim$  pico and femto second) amplification [206, 242, 256, 277].

The phenomenon of MI may arise inside an optical amplifier when the pulse power due to amplification reaches to the level of threshold of keeping the pulse steady to perturbations. The frequency chirp may cause the weak dispersive effects acting as a trigger to pulse splitting of which both group velocity distortion (GVD) and self phase modulation (SPM) are prime contributors [256]. High power time-domain optical pulses and tuneable frequency combs are of much interest in optical communication and medical technology [278]. Numerous studies have been reported on MI on EDFAs and TDFAs which have been discussed already in Chapters 2 and 4. However, the pulse propagation and its corresponding changes in its characteristics while traversing inside TDFAs have not been thoroughly investigated as per the literature studies. Due to exceptionally high absorption and emission CSAs of TDFAs in 2  $\mu\text{m}$  regime, it is possible to achieve high power optical pulses ( $\sim$  kW, MW) using saturable absorber, mode-locking, Q-switching, and non-linear amplification techniques [176, 218, 237, 238, 279]. However, to achieve the same in S-band using MI technique still remains the area of research.

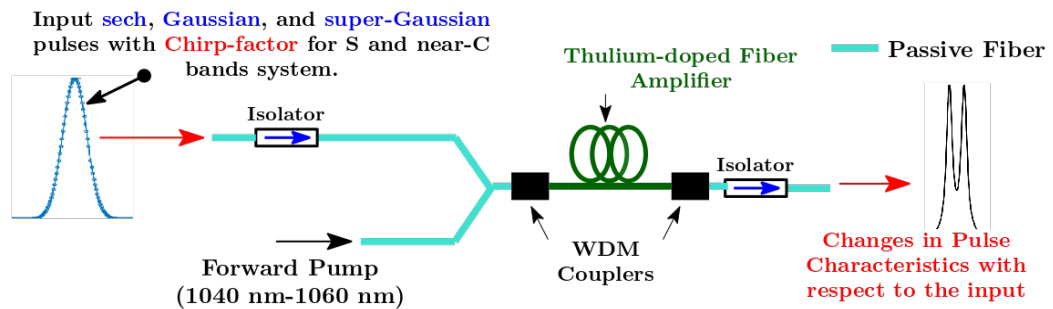
This chapter utilizes the fact of doping concentration effect on non-linear refractive index change in TDFAs, thereof creating a condition of non-linearity [261–263, 280]. It presents mathematical model for MI effect in 1050 nm pumped heavily doped  $\text{Tm}^{3+}$  fiber amplifier. It

quantitatively displays the pulse splitting characteristics with respect to frequency chirp parameter ( $C$ ) for the input pulse. The influence of chirp parameter on input pulses i.e. *sech*, *Gaussian*, and *super-Gaussian* are considered and their evaluation inside the corresponding TDFA is examined with respect to pulse splitting. The impact of non-linear fiber length is also reflected in the results of the model. Governing equations have been solved numerically on MatLab® and the results are verified by incorporating similar conditions on OptiSystem® simulation test bench. Results conclude the findings on the optimum non-linear length ( $L_{NL}$ ) and the pulse-chirp parameter ( $C$ ).

## 5.2 Mathematical Model

As mentioned and discussed in Chapter 4, analysis of MI can be approached by solving non-linear Schrödinger equation (NLSE). The model presented in this chapter considers the following assumptions:

- A three-level TDFA transition system with emission level from  $^3H_4$  to  $^3F_4$  for S and near-C bands emissions.
- The slowly varying envelope,  $A(z, t)$ , for signal in TDFA is considered as paraxial wave approximation. For the pulse-propagation analysis, this  $A(z, t)$  was taken as *sech*, *Gaussian*, and *super-Gaussian* at the TDFA's input shown schematically in the Fig. 5.1.
- Unidirectional pumping scheme as shown schematically in the Fig. 5.1.
- The loss-factor ( $\alpha$ ) of the TDFA is considered to be negligible to dilute the complexity of mathematics.



**Fig. 5.1:** Schematic representation for the MI phenomenon in non-linear TDFAs with input signal as optical pulses.

## 5. Chirping Effects on Optical Pulses in TDFAs through MI

The optical pulse propagation in a single mode heavily-doped  $\text{Tm}^{3+}$  fiber amplifier can be described by non-linear Schrödinger equation (NLSE) obeyed by slowly varying envelope [234]. In this analysis, the pulse envelope is represented as  $A(z, t)$ , given as

$$i\frac{\partial A}{\partial z} + i\beta_1\frac{\partial A}{\partial t} - \frac{(\beta_2 + ig_0T_2^2)}{2}\frac{\partial^2 A}{\partial t^2} + i\frac{\alpha A}{2} + \gamma|A|^2A = 0 \quad (5.1)$$

The first and second order mode propagation constants represented as  $\beta_1$  and  $\beta_2$  (also called GVD coefficient which is  $< 0$  for the anomalous regime). The non-linear parameter ( $\gamma$ ) mentioned in (5.1) can be written as  $\gamma = 2\pi\bar{n}_2/\lambda a_{eff}$  with  $a_{eff}$  and  $\lambda$  as the effective mode area of the TDFA's core and signal wavelength (1460 nm) respectively.  $\bar{n}_2$  is the non-linear Kerr refractive index which changes by  $\pm 5\%$  in the signal wavelength variation from 1300 nm to 1550 nm and its wavelength dependence is  $< 2\%$  [263]. The dependence of  $\bar{n}_2$  is directly correlated with the third-order susceptibility of fourth order ( $\chi_{xxxx}^{(3)}$ ) which is further dependent on the population density of the excited state  $\text{Tm}^{3+}$  concentration [261, 262]. The small signal gain ( $g_0$ ) of the amplifier is calculated as 30 mW for the TDFA length of 375 m (justified in later sections of this chapter) and the total amplifier gain ( $G$ ) having the value of 40 dB. The finite gain bandwidth of TDFA ( $T_2$ ) which can be defined as the dipole relaxation time of  $\text{Tm}^{3+}$  dopant has been calculated as 318 fs using [242, 267].

For the initial brief period, the pulse envelope has been moving with group velocity  $v_g = 1/\beta_1$ , however, quickly over-driven by  $\beta_2$ . Considering the anomalous dispersion regime for which  $\beta_2 < 0$ , let the frame of reference moves with the pulse at group velocity  $v_g = 1/\beta_1$ . Consequently, a transformation is made as  $T = t - z/v_g = t - \beta_1 z$  thereby shaping the expression of (5.1) as

$$i\frac{\partial A}{\partial z} - \frac{\overbrace{(\beta_2 + ig_0T_2^2)}^{\beta'_2}}{2}\frac{\partial^2 A}{\partial t^2} + \gamma|A|^2A = 0 \quad (5.2)$$

where  $\beta'_2$  is the modified mode propagation constant of order 2. Equation (5.2) is further normalized by introducing the dimensionless variables ( $U, \zeta, \tau$ ) given as

$$U = \frac{A}{\sqrt{P_0}}; \quad \zeta = \frac{z}{L_D}; \quad \tau = \frac{T}{T_0} \quad (5.3)$$

where  $P_0$  and  $T_0$  are the peak power and width of input pulse respectively. The corresponding dispersion and non-linear lengths of the TDFA are defined as  $L_D$  and  $L_{NL}$  which have been given below as

$$L_D = \frac{T_0^2}{|\beta_2 + ig_0 T_0^2|}; \quad L_{NL} = \frac{1}{\gamma P_0}; \quad (5.4)$$

Consequently, (5.2) can be modified and rewritten as

$$i \frac{\partial U}{\partial \zeta} - \text{sgn}(\text{Re}(\beta'_2)) \frac{1}{2} \frac{\partial^2 U}{\partial \tau^2} + N_l^2 |U|^2 U = 0 \quad (5.5)$$

where we have defined  $N_l$  as a non-linear parameter related to fiber and pulse parameters as

$$N_l = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2 + ig_0 T_0^2|}} = \sqrt{\frac{L_D}{L_{NL}}} \quad (5.6)$$

For the non-linear regime to be prevailing, the necessary condition is  $L_D/L_{NL} > 1$ , TDFA's length  $L < L_D$ , and  $L \sim L_{NL}$  [256]. Equation (5.5) gives the pulse propagation governing expression, through which *sech*, *Gaussian*, and *super-Gaussian* optical pulses are evaluated while traversing along the length of the fiber amplifier. The shapes of these input pulses can be defined as in [242]

$$U(0, \tau) = \exp [-(1 + iC)\tau^{2m}/2] \quad (5.7)$$

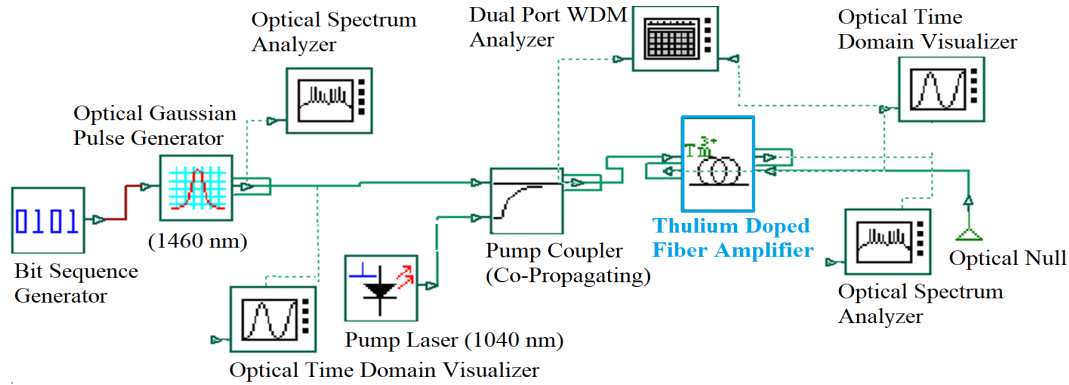
where,  $C$  is the initial frequency chirp as mentioned earlier,  $m$  is the pulse shaping factor which takes the value '0' for *sech*, '1' for *Gaussian*, and  $>1$  (taken as '3' in this study) for *super-Gaussian* type of pulses respectively. Equations (5.5)–(5.7) are solved on MatLab® platform numerically employing SSFM. The numerical results of this model have been presented in Section 5.4.

### 5.3 Simulation Setup

Corresponding to the non-linear pulse propagation in the developed mathematical model presented in Section 5.2, a simulation set-up has been designed on the OptiSystem® pedestal which is essentially an optical communication system design software. It basically designs, analyzes, and optimizes virtually multiple types of broad spectrum of optical networks in the



## 5. Chirping Effects on Optical Pulses in TDFAs through MI



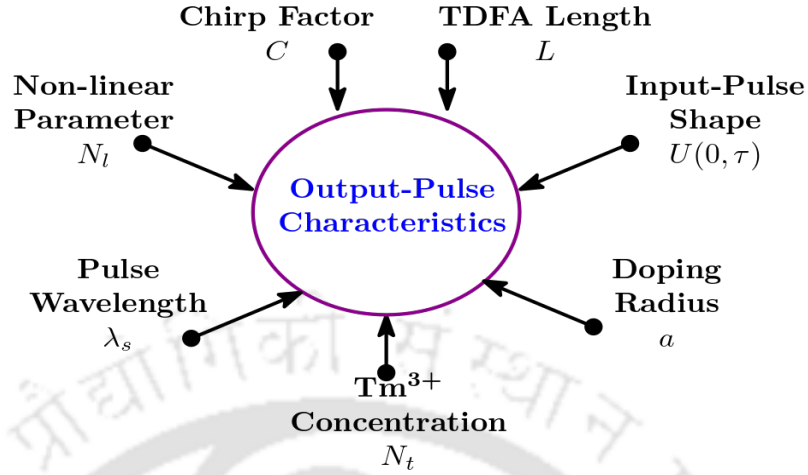
**Fig. 5.2:** Designed schematic of optical pulse evaluation in a non-linear TDFA.

**Table 5.1:** Simulation Parameters

| Parameter                      | Value                | Unit            | Symbol           | Remark                       |
|--------------------------------|----------------------|-----------------|------------------|------------------------------|
| Pulse Wavelength, Power        | 1460, -20            | nm, dBm         | $\lambda_s, P_s$ | S-Band (Variable), Estimated |
| Pump Wavelength, Power         | 1040, 10             | nm, W           | $\lambda_p, P_p$ | [163], Calculated            |
| TDFA Length                    | 375                  | m               | $L$              | Calculated                   |
| TDFA core radius               | 1.8                  | $\mu\text{m}$   | $r$              | [53]                         |
| TDFA doping radius             | 1.0                  | $\mu\text{m}$   | $a$              | Calculated                   |
| TDFA Numerical Aperture        | 0.3                  | –               | $NA$             | Estimated (SMF)              |
| Tm <sup>3+</sup> concentration | $2.2 \times 10^{27}$ | m <sup>-3</sup> | $N_t$            | Calculated                   |
| Chirp Parameter                | 12                   | rad/s           | $C$              | Calculated                   |
| Non-linear Parameter           | 12                   | au              | $N_l$            | Calculated                   |
| All CSAs for TDFAs             |                      | m <sup>2</sup>  | $\sigma$         | [163, 249], Table 3.2        |

physical layer. Its graphical user interface (GUI) controls the layout of the optical components from its extensive and comprehensive library. Optimization can be carried out easily by sweeping the parametric variables of the designed system [281].

Consequently, to this simulation setup as shown in Fig.5.2 the system parameters are assigned which are given in Table 5.1. The signal input is considered as *Gaussian*-pulse using optical Gaussian pulse generator which is combined with a 1040 nm pump-signal of 10 W using a pump coupler as shown in Fig.5.2. The power of this pump-signal is selected, through simulation, at the advent of MI process in the 375 m TDFA. The output power is monitored using optical time domain visualizer, and an optical spectrum analyzer (OSA). Dual port Wavelength division multiplexer (WDM) analyzer is utilized to observe the signal gain.



**Fig. 5.3:** Parameters affecting the behaviour of the the Output-Pulse.

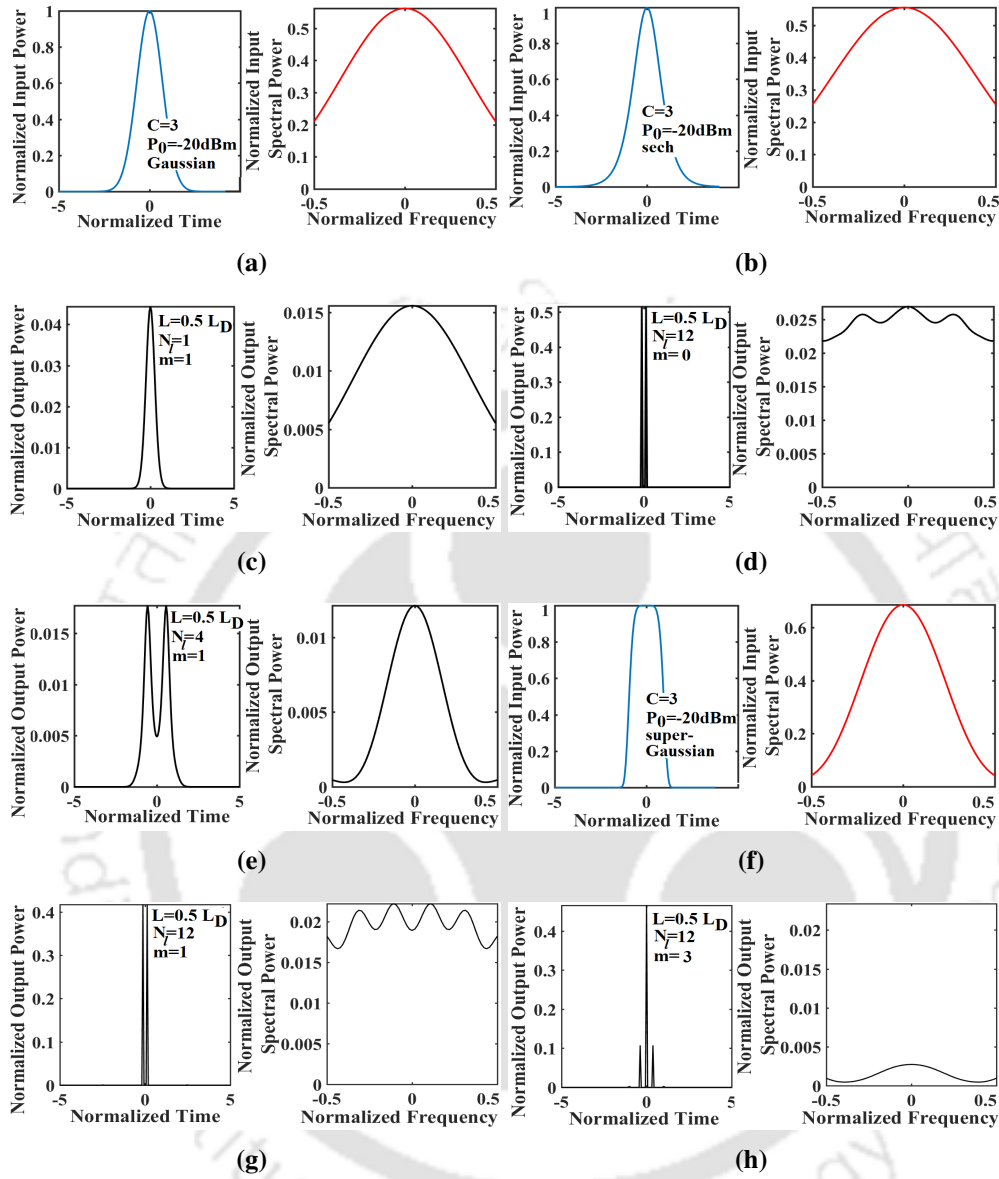
## 5.4 Results and Discussions

From the developed mathematical model, it has been found that the factors on which output pulse characteristics depends can be seen in Fig. 5.3. Aforementioned optical pulses are fed to the TDFA's input end of Fig. 5.1 to analyze the evaluated pulses at the fiber output. The governing factors considered while solving the model numerically on MatLab<sup>®</sup> are  $N_l$ ,  $C$ , and  $L_D$ . A simple and straight forward approach of split-step Fourier method is employed to solve (5.5) computationally. The fiber length  $L$  is selected in terms of fiber dispersion length  $L = 0.5L_D$ , to maintain the propagation in non-linear regime. Optimization is performed by varying one governing factor with the other two remaining constant. Furthermore, chirping effect has also been demonstrated by running the simulations on the OptiSystem<sup>®</sup> testbed as shown in Fig. 5.2.

### 5.4.1 Non-linear parameter effect on various input-pulses

Figure 5.4 shows an image matrix displaying the variation of  $N_l$  in a heavily doped  $\text{Tm}^{3+}$  fiber amplifier. Through doping concentrations in the order of ( $\sim 10^{27}/\text{m}^3$ ), the corresponding value for  $N_l$  is estimated to be comparatively large (calculated as 12) to invoke the phenomenon of MI due to the increment in non-linear refractive index [261–263, 280]. It can be observed from Fig. 5.4 that for *Gaussian* input pulse shown in (a) an order of  $\sim$  pico, femto second output optical pulse train (g) is obtained at corresponding  $N_l = 12$  which could be further amplified as

## 5. Chirping Effects on Optical Pulses in TDFAs through MI



**Fig. 5.4:** Input optical pulses with  $L = 0.5L_D$  and  $C = 3$  showing (a) *Gaussian* input with (c), (e), (g) as *Gaussian*-output pulses with  $N_l = 1, 4, 12$  respectively. (b), (d) shows *sech*-input and output respectively for  $N_l = 12$  while (f), (h) shows *super-Gaussian*-input and output respectively for  $N_l = 12$ .

per the application domain. The input and output frequency spectrum for *Gaussian* pulse can also be observed in Fig. 5.4 (a), (c), (e), (g) respectively showing a spread with broad frequency combs owing to GVD effects. The MI phenomenon is seen to be invoked at  $N_l = 4$ , however for higher values i.e.  $N_l = 12$  the effect could be seen in the frequency spectrum too with evenly spaced frequency combs.

Employing similar methodology as used for *Gaussian* input pulse, *sech* and *super-Gaussian* pulses are treated too inside T DFA for their respective evaluation as shown in Fig. 5.4 (b), (f)

for  $N_l = 12$ . The spreading of spectrum in *super-Gaussian* pulse is way too high than *sech* due to sharper leading and trailing edges which broaden the spectrum which can be seen in Fig. 5.4 (h) with the side lobes due to MI. The broadening of spectrum also limits the propagation of pulses to very large lengths making them unsuitable for long-haul optical communication system [242].

#### 5.4.2 Chirp parameter effect on various input-pulses

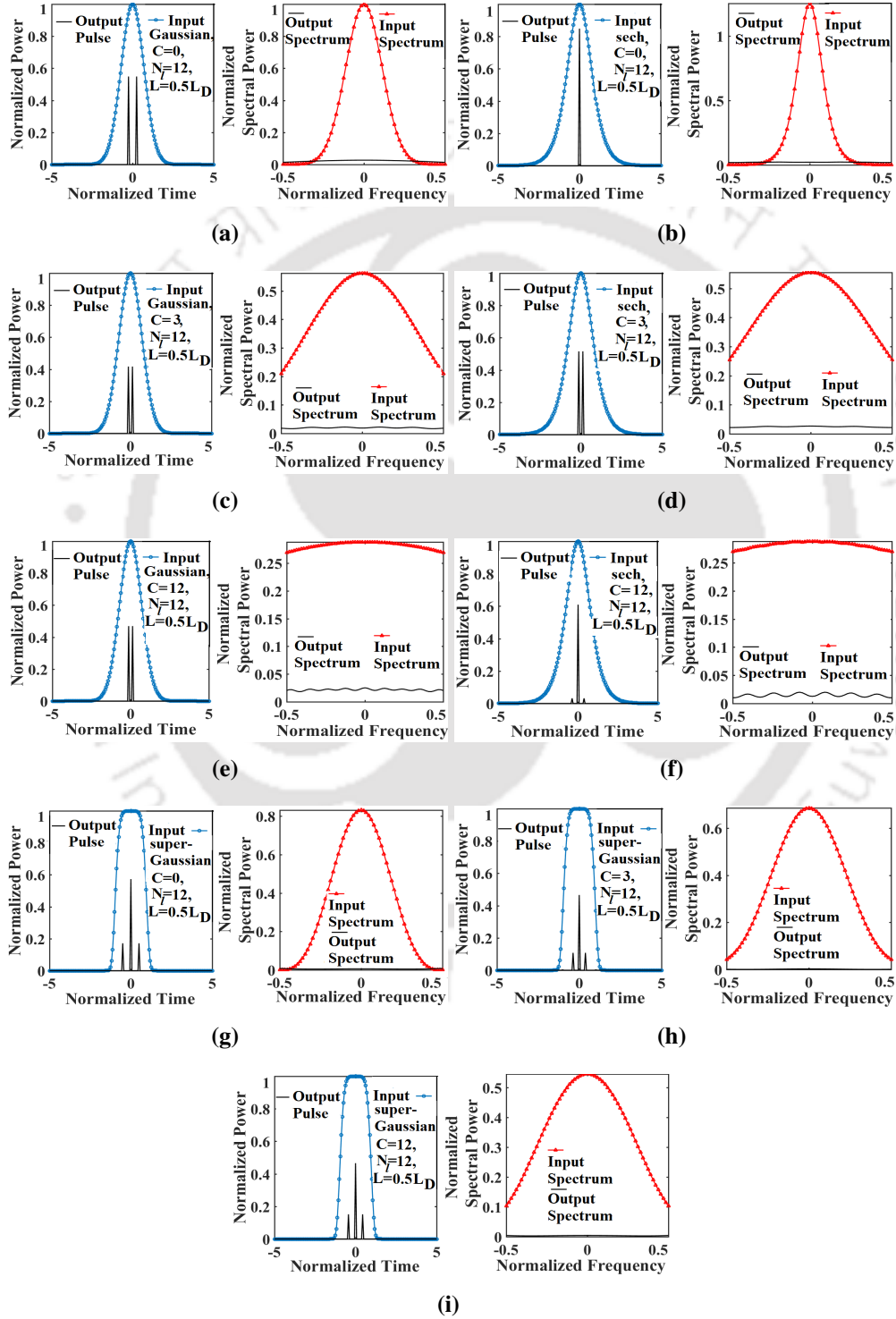
The non-linear parameter for TDFA is kept high by maintaining heavy doping. Therefore, keeping  $N_l = 12$  and  $L = 0.5L_D$ , the chirping parameter  $C$  has been varied with values '0' (unchirped), '3' (moderately chirped), and '12' (heavily chirped) in the input optical pulse (5.7). The variation is applied to all types of considered input pulses and the results are analyzed using image matrix of Fig.5.5. It is deduced that for each *Gaussian*, *sech*, and *super-Gaussian* pulses, it is the effect of linear chirping parameter that compresses the respective pulses by traversing through the non-linear fiber (TDFA) through SPM. For instance at  $C = 12$  the pulse compression in time domain for *Gaussian* and *sech* pulses are observed to maximize as shown in Fig.5.5 (e)–(f). The corresponding frequency spectrum also displays the formation of frequency combs at  $C = 12$ . Apparently, the GVD effect in the spreading of frequency spectrum is observed dominantly in *super-Gaussian* pulses as shown in Fig.5.5 (g)–(i) hence making it unfit for long-haul fiber-optic communication systems.

#### 5.4.3 TDFA length effect on various input-pulses

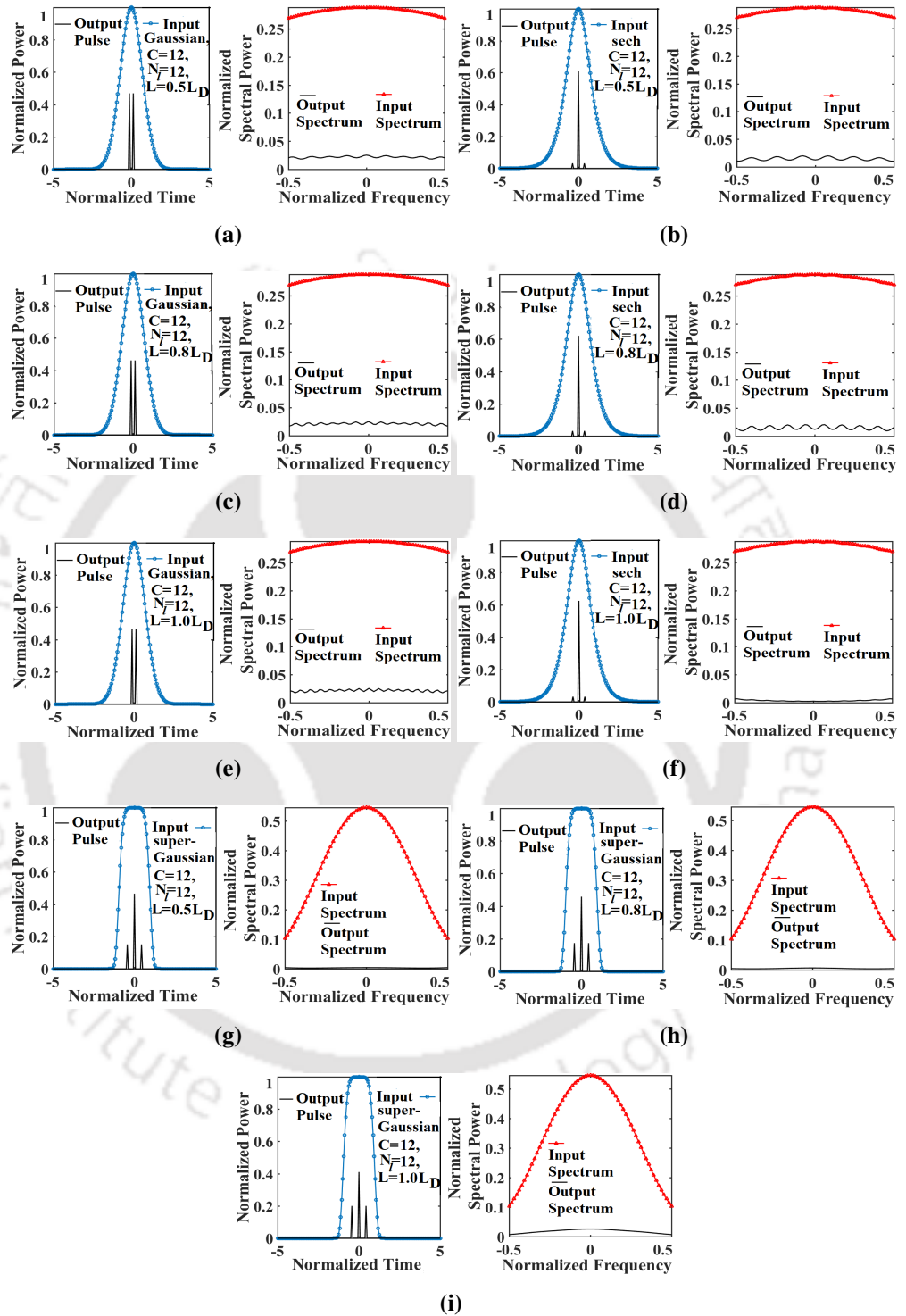
The results obtained from Fig.5.4 and Fig.5.5 gives the optimum values of  $N_l$  and  $C$  for heavily doped  $\text{Tm}^{3+}$  fiber amplifiers to invoke MI phenomenon and hence pulse compression. However, varying the fiber length within the non-linear regime of operation i.e.  $L < L_D$ , and  $\beta_2 < 0$  should give the dependence of pulse evaluation on fiber length and hence its optimum value. The image matrix presented in Fig.5.6 shows the variation of optical pulses with respect to non-linear fiber lengths ( $L = 0.5L_D$ ,  $0.8L_D$ , and  $1.0L_D$ ) keeping  $N_l = 12$  and  $C = 12$  as fixed parameters. For *sech* pulse,  $L = 0.8L_D$  has been found to be optimum length for frequency comb spectrum as shown in Fig.5.6 (d). However, for *Gaussian* pulse maximum frequency

## 5. Chirping Effects on Optical Pulses in TDFAs through MI

perturbations could be seen for  $L = 1.0L_D$  as shown in Fig.5.6 (e). The *super-Gaussian* pulse suffers very large spectrum spread due to the reason mentioned previously.



**Fig. 5.5:** Input (blue line-markers) and spectra (red line-marker) with  $L = 0.5L_D$  and  $N_l = 12$  showing (a), (c), (e) as *Gaussian*, (b), (d), (f) as *sech*, and (g), (h), (i) as *super-Gaussian* with  $C = 0, 3, 12$  respectively. The corresponding output pulses and their spectra can be observed (solid black line)



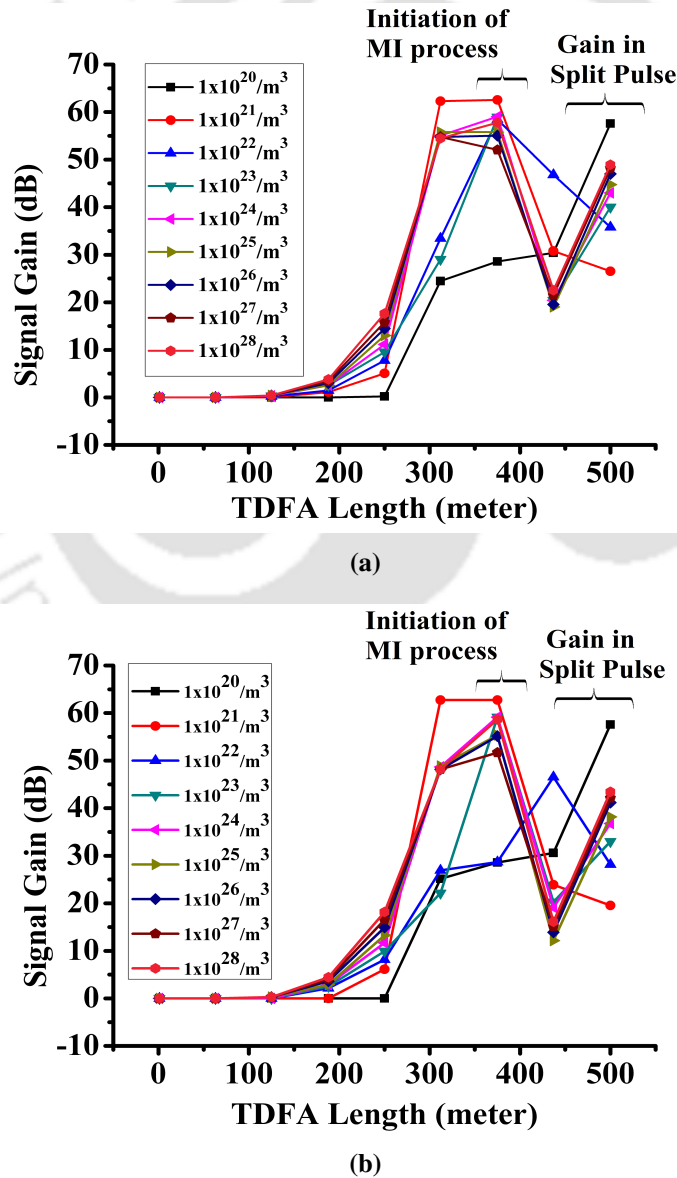
**Fig. 5.6:** Input (blue line-markers) and spectra (red line-marker) with  $C = 12$  and  $N_l = 12$  showing (a), (c), (e) as *Gaussian*, (b), (d), (f) as *sech*, and (g), (h), (i) as *super-Gaussian* with  $L = 0.5L_D, 0.8L_D, 1.0L_D$  respectively. The corresponding output pulses and spectra can be observed (solid black line)



## 5. Chirping Effects on Optical Pulses in TDFAs through MI

### 5.4.4 Optimization of TDFA length to invoke MI

The numerical results obtained through the model are applied to the designed set-up and the simulations are performed on Optisystem<sup>®</sup> test bench. The setup of the system has been shown in the schematic of Fig.5.2. The first analysis performed on the considered system is to find the optimum TDFA length and  $Tm^{3+}$  concentration value at which the MI phenomenon was invoked. The chirp parameter in this analysis is having a considerably large value (taken as '12') based on the results of numerical model. This estimation of  $C$  is verified later with



**Fig. 5.7:** The variation of signal gain with TDFA length and  $Tm^{3+}$  concentration in time and frequency domain is shown by (a) and (b) respectively. Optimum TDFA length can be seen as 375 m.

optimum TDFA length and concentration values. The pump-power is taken as 10 W so as to affirm the MI effect to get invoked. Figure 5.7 (a)–(b) shows the variation of length and  $\text{Tm}^{3+}$  concentration with respect to signal gain with signal power being taken as -20 dBm.

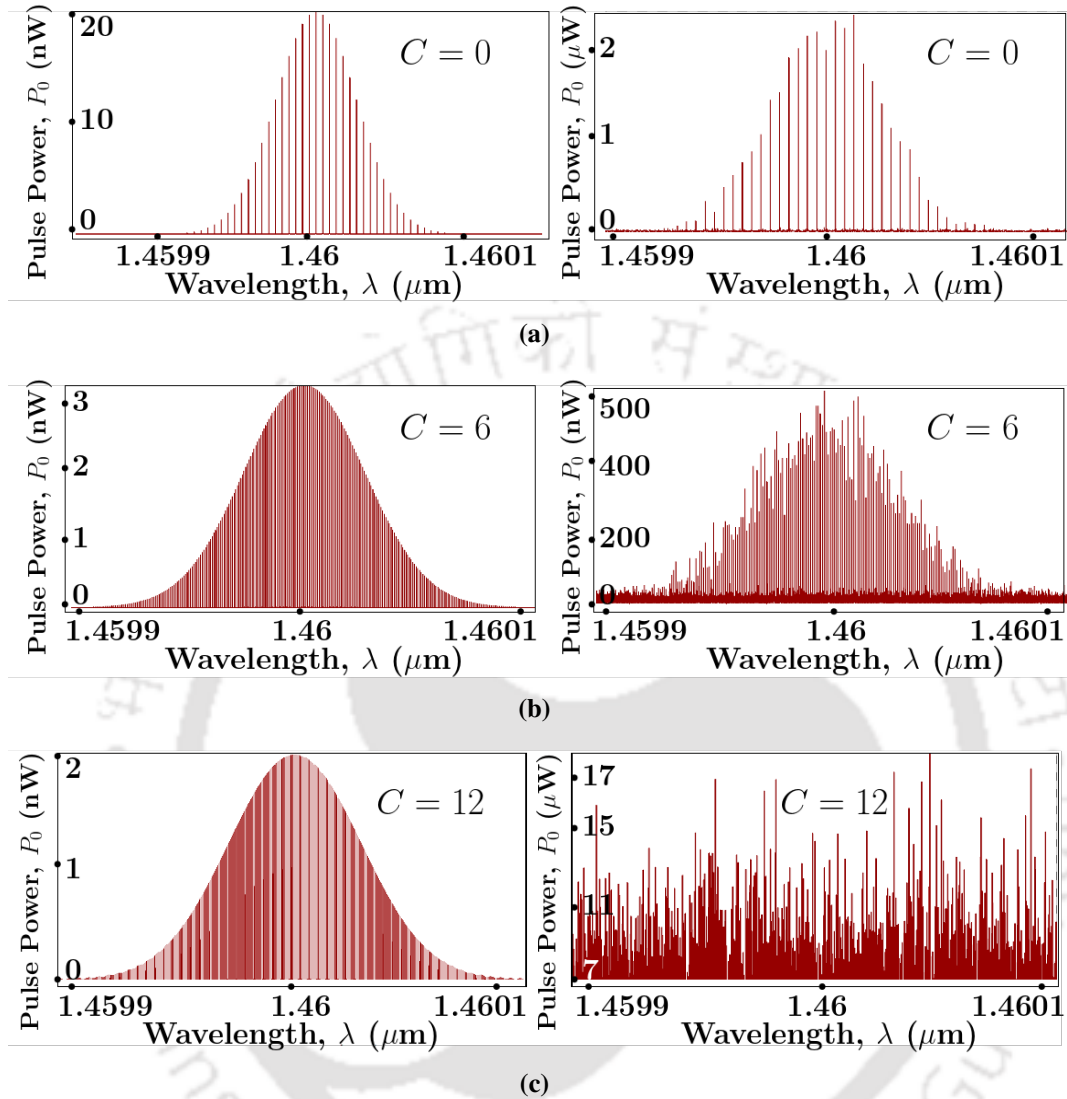
It can be observed from the time-domain as well as frequency-domain signal-gain that at lower  $\text{Tm}^{3+}$  concentration values, the MI effect is initiated at large gain values. However, when the  $\text{Tm}^{3+}$  concentration has been increased, the thresholds to invoke MI are floored to lower gains which are rather trivial due to change in non-linear refractive index for the reason of fast build-up of population-inversion at  $^3\text{F}_4$  level [163]. The MI effect can be seen to get initiated when the TDFA length is 375 m with rapid decrease in signal gain due to the pulse-splitting. As the TDFA length has been further increased, it is observed that the split pulses are regaining the power through amplification which can be visualized in Fig.5.7 (a)–(b). The optimum doping-concentration of  $\text{Tm}^{3+}$  has been calculated through simulation as  $2.2 \times 10^{27} \text{ m}^{-3}$ . It can be observed from Fig. 5.7 (a)–(b) that when the  $\text{Tm}^{3+}$  concentration exceeds  $2.2 \times 10^{27} \text{ m}^{-3}$ , the threshold for MI increases due to the probable up-conversion effect which deplete the  $^3\text{F}_4$  level [177,244].

#### 5.4.5 Output-pulse splitting demonstration and its applications

To demonstrate the combined effect of MI and chirp factor, its values have been varied for  $C = 0, 6, 12$  and fed to the input *Gaussian* pulse generated from optical Gaussian pulse generator operating at 1460 nm wavelength. The input pulse spectrum and the corresponding evaluated output spectrum is analyzed for these mentioned values of chirp parameters. It is observed from Fig. 5.8 (a)–(c) that as the value of chirp parameter increases, the splitting and spreading of the spectrum take place which is expected as per the numerical results. This pulse-splitting characteristics can be utilized to produce an all-fiber multi-frequency pulsed laser for various industrial, scientific, and medical applications.

It is certain that for relatively larger chirp parameter this splitting is proportionate. With  $C = 12$ ,  $N_l = 12$ ,  $N_t = 2.2 \times 10^{27} \text{ m}^{-3}$ , optimum TDFA length is calculated as 375 m to invoke MI effect. Consequently, the pulse evaluation at different TDFA length has been examined to observe the pattern of pulse splitting in both the time and frequency domains. Figure 5.9 (a)

## 5. Chirping Effects on Optical Pulses in TDFAs through MI

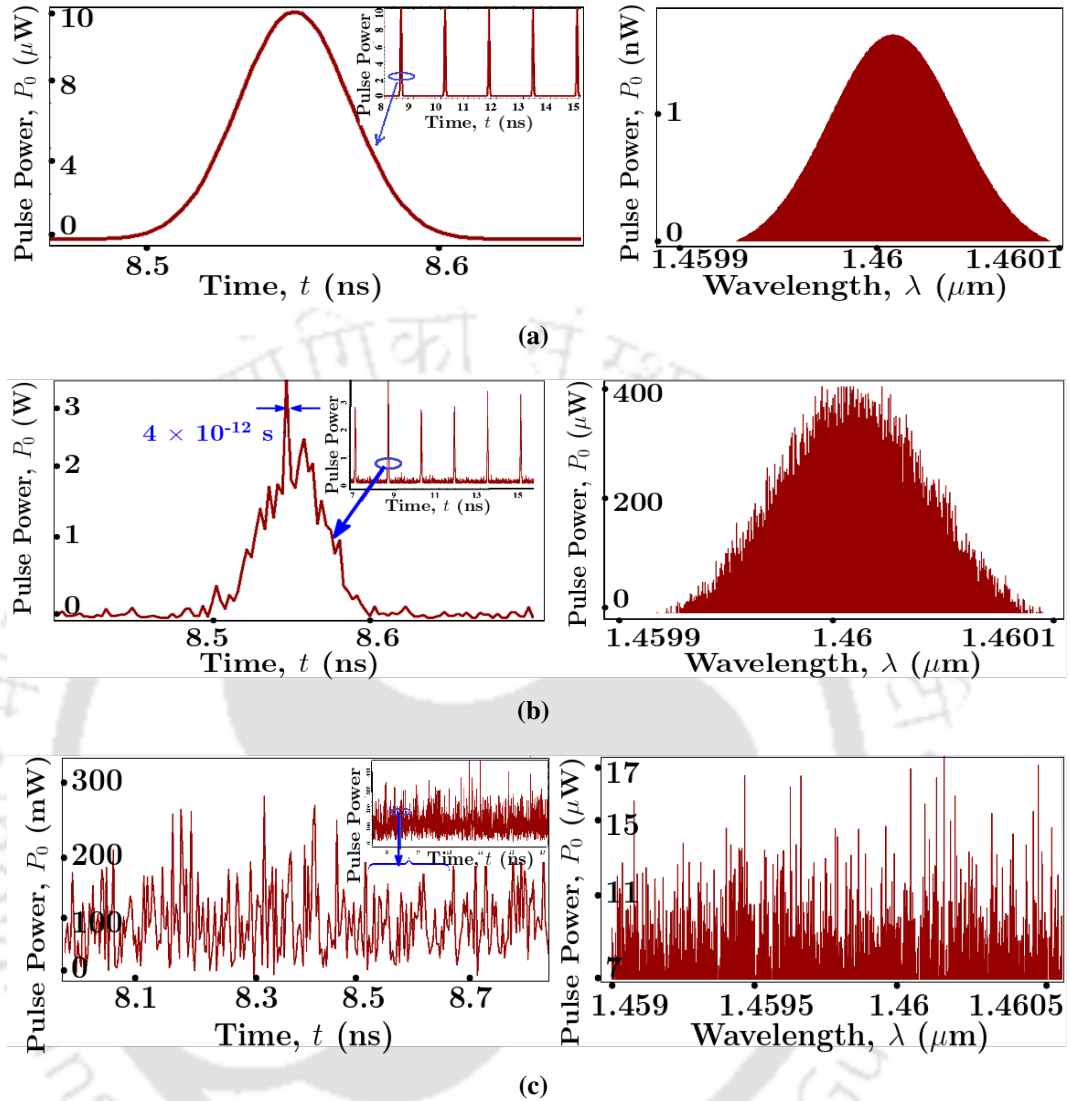


**Fig. 5.8:** Input (left column) and Output (right column) pulse spectra for different values of chirp parameter  $C=0, 6, 12$  shown as (a)-(c) respectively. The increase in pulse splitting and spreading phenomenon can be observed in each case.

shows the input *Gaussian* pulse train (inset) with corresponding input spectrum. At 375 m of TDFA length from the input end, the MI effect was initiated to produce a 4 ps, 500 MHz spaced pulse-train each having 8 nJ of energy at 1460 nm wavelength.

## 5.5 Summary

$\text{Tm}^{3+}$  doped fiber amplifiers can be employed to expand the data carrying capacity for future dense wavelength division multiplexing systems by employing the S and near-C bands (1460–1545) nm of fiber-optic communication system. For this the optical pulse propagation and evaluation along its length has been studied in this chapter. A mathematical model has been



**Fig. 5.9:** Time domain pulse (left column) and corresponding frequency spectrum (right column) of input optical *Gaussian* pulse at the TDFA input (a). At TDFA length 375 m the MI was initiated (b). Further splitting of pulse at TDFA length greater than 375 m (c).

developed and solved numerically to obtain the optimum results for various input-pulse shapes. The effect of MI was put in considerations to obtain 4 ps, 500 MHz spaced pulses with each having 8 nJ of energy in the pulse train at 1460 nm wavelength. The entire analysis concluded the optimum TDFA length as 375 m. In particular, the non-linear factor and frequency chirp factors have been studied simultaneously.

Based on the qualitative presentation of the results owing to some presumed assumptions, it is concluded that for area of specific applications the pulse-type and the propagation governing factors should be selected. The mathematical model is also validated by simulating the

## 5. Chirping Effects on Optical Pulses in TDFAs through MI

---

similar conditions on OptiSystem® software. As this analysis dealt with heavily-doped TDFAs, therefore, other ion-ion interaction effects may also occur which has to be taken care for deeper analysis as presented in the next chapter of this thesis.



# 6

## Ion-Ion Interaction Analysis on TDFAs

### Contents

|     |                         |     |
|-----|-------------------------|-----|
| 6.1 | Introduction            | 142 |
| 6.2 | Mathematical Model      | 144 |
| 6.3 | Simulation Setup        | 150 |
| 6.4 | Results and Discussions | 150 |
| 6.5 | Summary                 | 156 |



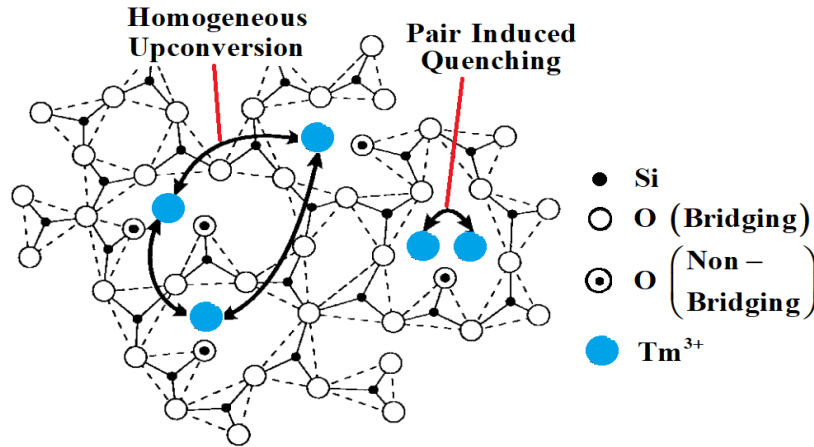
### 6.1 Introduction

In an era of Internet-of-Things (IoT), a push to achieve high speed data transmission rates against the domestic, strategic, and industrial demand is a foremost challenge for optical communication engineers and researchers. Building smart cities and urban planning based on big data analytic requires high speed of data transmission and computation [282]. While, big data in healthcare with medical-IoT further spread the requirement for high data transmission rates. The dynamic monitoring of the patient, quantifying the medical condition, and delivering the drugs remotely using IoT devices prerequisite fast internet [283]. From the previous chapters of this thesis, substantial established studies has been done across the globe to prove the utility of TDFAs in S and near-C bands. It has been also compared with the present state-of-the-art EDFAs. The efficacy of comparatively broad and uniform absorption and emission CSAs of  $\text{Tm}^{3+}$  provides uniform gain in S and near-C bands. Consequently, it has been found that TDFAs can be employed in existing fiber optic communication infrastructure along with EDFAs [196].

#### 6.1.1 The Ion-Ion Interaction Mechanisms

Previous studies reveal that when the dopant concentration density in the fiber amplifier core is increased then the deteriorating effects were observed on its efficiency [177, 244, 245]. Therefore, the ion-ion interaction mechanism (IM) has been identified as an apparent reason for this degrading effect owing to reduction of the excited-state population density. These IM effects can be classified into two categories as:

- (i) **Homogeneous Upconversion (HUC)**– In this category, the dopant-ions are homogeneously distributed within the fiber amplifier core. The relative energy transfer may take place between the neighboring dopants resulting in the depopulation of the excited state.
- (ii) **Inhomogeneous Upconversion (IUC)**– This category of IM dominates when the inter-ionic distance between the dopants reduces significantly and is comparable to the dopant ion diameter [244]. It results in the formation of residual interactions creating ion clusters. This clustering effect can cause rapid transactions through cross-relaxation (CR) process, thereby decreasing the excited state population density. This deteriorating effect is often

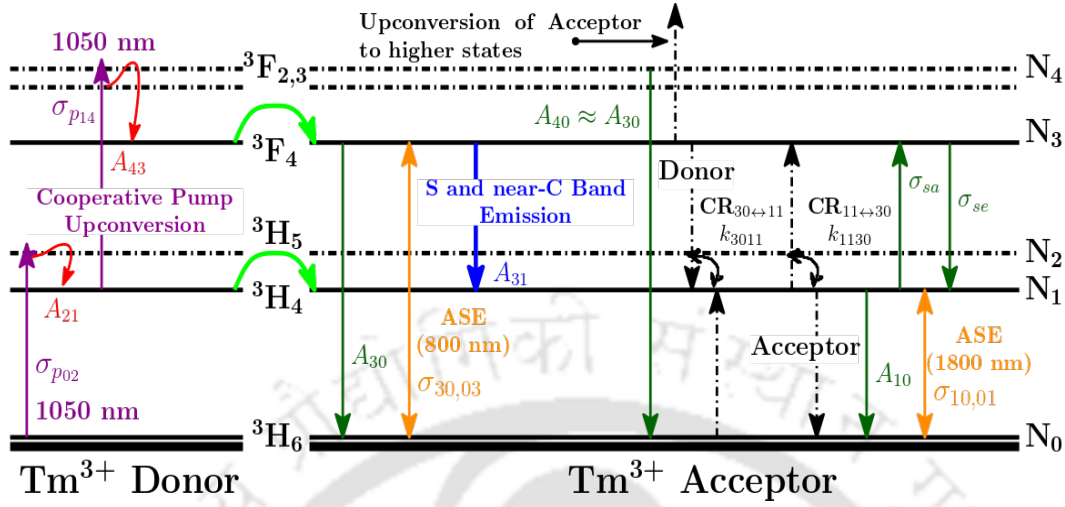


**Fig. 6.1:** HUC and PIQ clustering of  $\text{Tm}^{3+}$  in uniform silica glass matrix

known as pair induced quenching (PIQ).

These inter-ionic interaction rates are strongly dependent on the distance between them and therefore the PIQ effect is more dominant over HUC. Considering the case of EDFAs, the timescale of relaxation of IUC is  $\sim \mu\text{s}$  while for the HUC it is  $\sim \text{ms}$  [244]. These effects can be seen in Fig. 6.1 with silica glass-host shown in two-dimensional representation. In between the silica tetrahedron  $(\text{SiO}_4)^{2-}$  shown are the  $\text{Tm}^{3+}$  dopant ions with the corresponding two interaction mechanisms.

As cited in chapter 2, studies based on PIQ and HUC effects have been extensively done on EDFAs, however on TDFAs the topic still remains naive. The detrimental effect of cross-relaxation processes including the clustering effects in EDFAs leading to signal gain reduction has been mathematically studied and experimentally demonstrated [177, 244, 245]. El-Sherif *et al.* considered the PIQ effect in TDFAs limited to  $^3\text{H}_4$  to  $^3\text{H}_6$  lasing transitions [88], however, this model can be utilized as the basic formulation of PIQ effect in S and near-C bands transactions. In this chapter, the constructive aspect of IM effect with HUC and PIQ is studied on TDFAs. Design parameters of TDFA are studied by carrying out the simulations based upon the implementation of the mathematical model on MatLab® and OptiSystem® platforms. The obtained results infer the constructive nature of the IM effects. Performance estimation of TDFA with respect to parameters such as amplifier length, pump power, doping radius, and dopant concentration are also evaluated optimally. Noise-figure analysis is performed to select

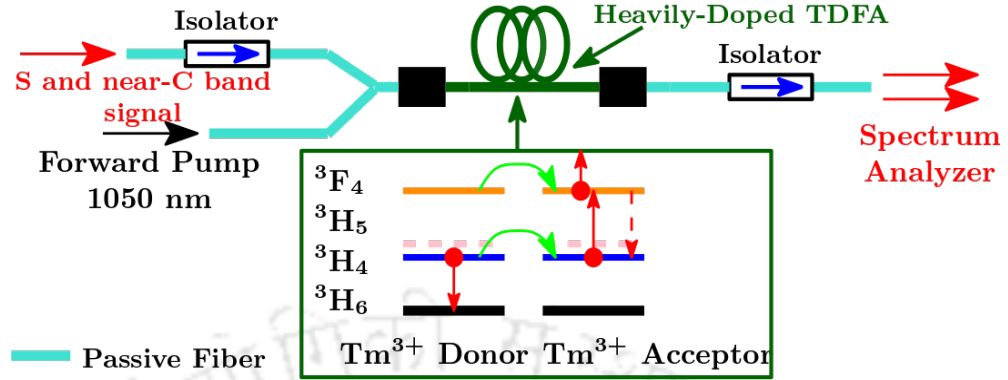


**Fig. 6.2:** Quantum transition diagram for  $\text{Tm}^{3+}$  highlighting the cooperative up-conversion through absorption (purple), stimulated emission in S and near-C bands (blue), other radiative transitions (dark-green), ASE transitions (orange), non-radiative transitions (red), donor-acceptor transitions (light-green), and ion-ion interaction due to cross-relaxation effect (black dash-dot).

the optimum working wavelength in S and near-C band regime.

## 6.2 Mathematical Model

The four level energy system for TDFA's quantum transition has been effectively reduced to three level system as shown in Fig. 6.2 [163, 229, 284]. It is evident that the modified energy level diagram can be potentially utilized for S and near-C band amplification [249]. This energy level diagram also shows that the level  $^3\text{F}_4$  with population density  $N_3$  of  $\text{Tm}^{3+}$  can be population-inverted through wavelength pump of 1050 nm. It explains the process of cross-relaxation effect in which the donor-pump ion from the level  $^3\text{F}_4$  may transfer its energy to the acceptor at  $^3\text{F}_4$ , which inturn transit to higher levels through HUC process. The donor pump ion may then decay to  $^3\text{H}_4$  (as shown by the dash-dot line of Fig. 6.2). During this process, the acceptor ion can decay back from higher levels to  $^3\text{F}_4$  and simultaneously one more pump-donor from  $^3\text{H}_4$  shall repeat this process for acceptor at  $^3\text{H}_4$ . Therefore, the metastable state  $^3\text{F}_4$  is now populated with two photons, and hence HUC could rather help in building the population inversion condition more rapidly while still at lower pumping levels. The IM effects are generally denoted as  $\text{CR}_{30 \leftrightarrow 11}$  which can be read as the transition of  $\text{Tm}^{3+}$  from level-3 to level-1 and from level-0 to level-1 respectively.



**Fig. 6.3:** Schematic representation of IM effects in heavily-doped TFAs.

The added advantage of the proposed scheme as shown in Fig. 6.3 is the utilization of only single wavelength pump (1050 nm) unlike the work presented in [247, 248] in which three different pumps (1050 nm + 1400 nm + 800 nm) were employed. Consequently, the schematic designed in this work is more efficient in terms of overall heat loading and cost effectiveness. The mathematical model is based on the model presented in [88, 244] for EDFA and TDFA system respectively and considers the following assumptions:

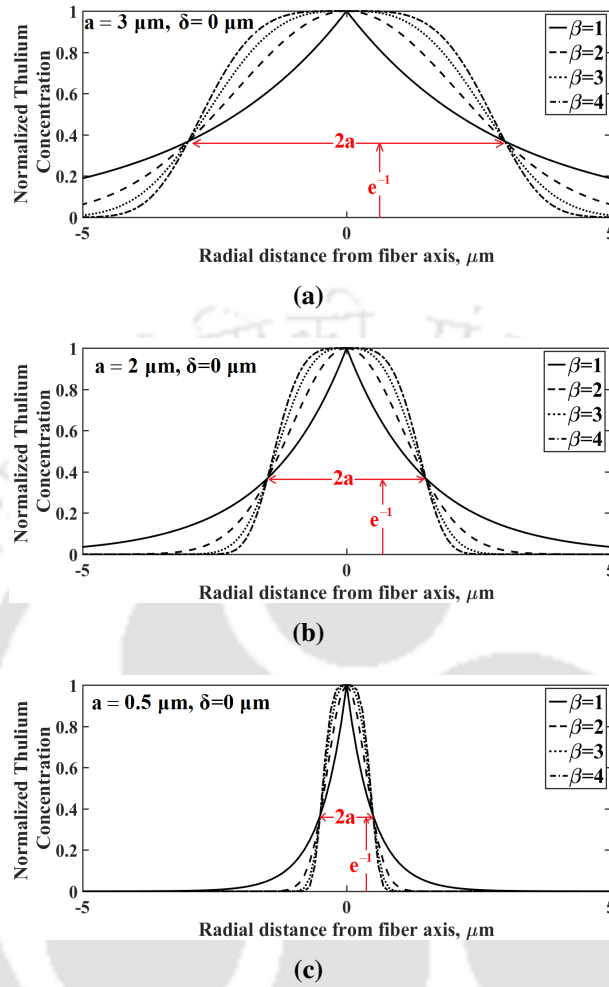
- (i) Quasi three level TDFA system with emission level from  $^3H_4$  to  $^3F_4$  (1470 nm) in S-band.  $^3H_4$  has relatively much shorter lifetime (6.03  $\mu$ s) therefore, it only participates in phonon decay [53].
- (ii) Unidirectional pumping scheme with forward ASE.
- (iii) Other scattering process and loss factors are neglected.
- (iv) The cluster size of  $Tm^{3+}$  ions and number of ions per cluster are kept constant [244].
- (v) The absorption and emission CSAs to be same for the clustered and single ion.

The doping profile plays a crucial role in determining the odds of occurrence of the IM effects. The profile of transverse doping distribution of  $Tm^{3+}$  in fiber core can be obtained from (6.1) [249, 285]. It is utilized to generate maximum types of doping profile scenarios including the step and Gaussian distribution.

$$n_t(r) = N_t \exp \left[ - \left( \frac{|r - \delta|}{a} \right)^\beta \right] \quad (6.1)$$

where the  $Tm^{3+}$  concentration in fiber core having radius  $a$  is represented by  $N_t$ . The doping profile shape stating its relative shift from the fiber axis and the slope of the profile are defined

## 6. Ion-Ion Interaction Analysis on TDFAs



**Fig. 6.4:** (a)–(c)  $\text{Tm}^{3+}$  dopant profile with different dopant diameter  $2a$  and fixed radial distance  $r$

as  $\delta$  and  $\beta$  respectively [249]. With no shift in the doping profile i.e. for  $\delta = 0$  condition, the parameter  $\beta$  was varied for values 1–4 and the dopant profile shapes are obtained as shown in Fig. 6.4 (a)–(c). The overlap factor, described as the intersection of the fiber core and the doping profile, plays a key role when it comes to doping radius with concentration of the dopant being kept fixed.

Figure 6.4 shows that  $\text{Tm}^{3+}$  density towards the fiber core axis increases with the reduction of doping radius keeping the concentration constant. The dopant radius is taken as the distance from the fiber core axis when normalized  $\text{Tm}^{3+}$  concentration reaches  $e^{-1}$  times the total concentration [249, 285]. The profile shape did not affect this increment of  $\text{Tm}^{3+}$  at the fiber axis. Consequently, due to the overlap factor, signal-gain should ideally maximize for the least dopant radius. However, if the dopant radius is decreased below a certain value, an avalanche

of the detrimental effect in the form of IM shall come into play which is comparatively lower and constructive when the radius is at near-optimum value.

Incorporating the CR processes, the rate equations for  $\text{Tm}^{3+}$  density in there corresponding energy levels can be written from Fig. 6.2 as

$$\begin{aligned} \frac{\partial N_0}{\partial t} = & (A_{10} + W_{18e})N_1 + (W_{8e} + A_{30})N_3 \\ & - (W_{18a} + W_{8a} + W_{p01})N_0 - CR_{30 \leftrightarrow 11} \end{aligned} \quad (6.2)$$

$$\begin{aligned} \frac{\partial N_1}{\partial t} = & (W_{18a} + W_{p01})N_0 - (A_{10} + W_{p13} + W_{sa} + W_{18e})N_1 \\ & + (W_{p31} + W_{se} + A_{31})N_3 + 2CR_{30 \leftrightarrow 11} \end{aligned} \quad (6.3)$$

$$\frac{\partial N_3}{\partial t} = (W_{8a})N_0 + (W_{p13} + W_{sa})N_1 + (W_{p31} + W_{se} + A_{31})N_3 - CR_{30 \leftrightarrow 11} \quad (6.4)$$

$$\sum_i^{\{0,1,3\}} N_i = N_t \quad (6.5)$$

$$CR_{30 \leftrightarrow 11} = k_{3011} N_3 N_0 \quad (6.6)$$

where  $W_{pij}$  are the transition rates for 1050 nm pump.  $W_{sa,se}$  are the rates for signal absorption and emission respectively. The 800 nm, 1800 nm, and S-band signal-ASE rates are defined as  $W_{8/18,a/e}$ .  $A_{i,j}$  represents the radiative rates with  $A_{21,43}$  being non-radiative which do not participate in the S-band amplification.  $CR_{30 \leftrightarrow 11}$  is the cross relaxation term with  $k_{3011}$  being the cross-relaxation coefficient from the transition  ${}^3\text{H}_4 \rightarrow {}^3\text{H}_6$ . Under the condition of population inversion between  ${}^3\text{F}_4$  and  ${}^3\text{H}_4$  levels  $N_3/N_1 \geq 1$ . Assuming  $N_0$  acts as an ion-pool, it is inferred that  $N_0/N_3 \geq 0$  and for limiting case when at least half of the ions are excited to state  $N_3$  gives  $N_3 = N_0$  leading to  $CR_{30 \leftrightarrow 11} = k_{3011} N_3^2$  which is the expression analogous to that of EDFA's cross-relaxation process in [244]. All the transition rates mentioned above are defined as

$$W_{ij} = \lambda_p \sigma_{pij} (P_p / hc A_{eff}) \quad (6.7)$$

$$W_{8/18,a/e} = \lambda_{ASE}^{8,18} \sigma_{8/18,a/e} (P_{ASE}^{8,18} / hc A_{eff}) \quad (6.8)$$

$$W_{sa,se} = \lambda_p \sigma_{sa,se} (P_s / hc A_{eff}) + \lambda_s \sigma_{sa,se} (P_{ASE} / hc A_{eff}) \quad (6.9)$$

where  $\lambda_{s,p,ASE,8,18}$  represent signal, pump, signal-ASE, 800 nm ASE, and 1800 nm ASE wave-



## 6. Ion-Ion Interaction Analysis on TDFAs

lengths respectively. The corresponding powers and CSAs given as  $P_{s,p,ASE_{8,18}}$  and  $\sigma_{pij}$ ,  $\sigma_{8/18,a/e}$ ,  $\sigma_{sa,se}$  have been extensively defined in Chapter 3. Vacuum light velocity  $c$  and Plank's constant  $h$  values are considered accordingly. The signal, pump, and ASE quantum propagation can thus be defined by assimilating  $\Delta\nu$  as the ASE band-width as

$$\begin{aligned} \frac{\partial P(\lambda)}{\partial z} = & \Gamma(\lambda)P(\lambda) \sum_{ij} \begin{pmatrix} 10, \\ 30, \\ 31 \end{pmatrix} [N_i\sigma_{ij}(\lambda) - N_j\sigma_{ji}(\lambda)] \\ & + \Gamma(\lambda)P(\lambda) \sum_{ijkl} \begin{pmatrix} se & sa & 3 & 1, \\ 8e & 8a & 3 & 0, \\ 18e & 18a & 1 & 0 \end{pmatrix} [\sigma_i(\lambda)N_k - N_j\sigma_j(\lambda)N_l] \\ & + \Gamma(\lambda)P(\lambda)2h\nu\Delta\nu \sum_{ij} \begin{pmatrix} se & 3, \\ 8 & 3, \\ 18 & 1 \end{pmatrix} [\sigma_i(\lambda)N_j] \end{aligned} \quad (6.10)$$

Under the population-inversion condition at steady-state, the population of  $Tm^{3+}$  at different energy levels are calculated by equating (6.2)–(6.4) to zero. Ion-Ion interactions have been discussed with respect to transmission saturation properties of EDFAs and it is applied to model its performance [286–288]. Therefore, similar strategy on TDFAs can be applied and utilized to observe IM effects. The  $Tm^{3+}$  ions can be classified as single ion and clustered ions [244]. Therefore, under steady-state, the ion in each of the cluster may occupy level-1 ( $^3H_4$ ) or level-3 ( $^3F_4$ ) under first and second upconversion processes as shown in Fig. 6.2. The upconversion

process is continued by the rapid transfer of energies between the clustered ions until one ion remains at  $^3F_4$  which is regarded as the metastable energy state. For IUC when the ions are in the close proximity to form clusters due to local charge compensation, PIQ comes in scenario. Therefore, for the total concentration of  $Tm^{3+}$  ions  $N_t$ , the concentration of clustered ions can be denoted as

$$N_c = mkN_t \quad (6.11)$$

where  $k$  is the relative number of clusters inside the TDFA photon cavity and  $mk$  is percentage of ions in a cluster. Under the steady-state condition it is assumed that the absorption and emission CSAs to be same for the clustered and single ion. Eventually, the clustered ions will also follow the same dynamics as that of the single ion given by (6.2)–(6.4) [244]. The single ion concentration can thus be written as

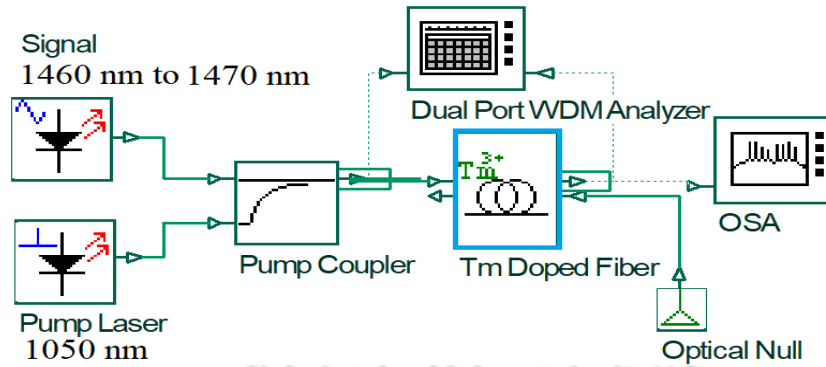
$$N_s = (1 - mk)N_t \quad (6.12)$$

Consequently, the  $Tm^{3+}$  ion population at level-3 and level-1 would be  $N_3 = N_{s3} + N_{c3}$  and  $N_1 = N_{s1} + N_{c1}$  respectively. Here,  $N_{s3,1}$  and  $N_{c3,1}$  denotes the population of single ions and clustered ions in the level-3 and level-1 respectively which can be seen in Fig. 6.2. As the spontaneous emission rates along with absorption and emission CSAs of single and clustered ions are assumed to be same, the steady-state population for clustered ions can be calculated as [244]

$$N_c = N_{c1} + N_{c3} \quad (6.13)$$

The lesser dominant IM effect out of the two under heavy  $Tm^{3+}$  ion concentrations is the HUC. This cooperative interaction between the homogeneously distributed dopant ions can be described by the single ion dynamics obtained by substituting  $N_{s3,1}$  in (6.2)–(6.4) with  $k = 0$  from (6.12). Similarly, for  $m$ -particle homogeneous upconversion the term  $T$  given by (6.14) may be added to the above discussed cluster ion dynamics [244].

$$T = -I_m(N_{s3,1})^m \quad (6.14)$$



**Fig. 6.5:** Schematic setup of TDEFA system to study IM effects using OptiSystem pedestal.

where  $m$  is the size of particle cluster and  $l_m$  is the effective interaction rate that can be calculated through the interaction averaged over all possible distances between the ions. For  $m = 2$  and step-function doping profile of  $\text{Tm}^{3+}$  dopants the value of  $l_m = 1$  [244]. Moreover, the energy transfer in this clustered HUC takes place homogeneously as these clusters are distributed at larger distances with respect to the PIQ effect. As  $m > 3$ , the process becomes less probable than the single ion and two-particle cluster.

### 6.3 Simulation Setup

This mathematical model was analyzed by designing a system in OptiSystem<sup>®</sup> platform as demonstrated in Fig.6.5. The signal at 1470 nm and pump at 1050 nm laser sources are fed to the heavily doped TDEFA through a pump coupler. The output is observed through dual port WDM analyzer. The simulation parameters of Table 6.1 are calculated and is fed to the model to obtain the optimum TDEFA performance with respect to the signal gain, TDEFA length, and IM effects.

### 6.4 Results and Discussions

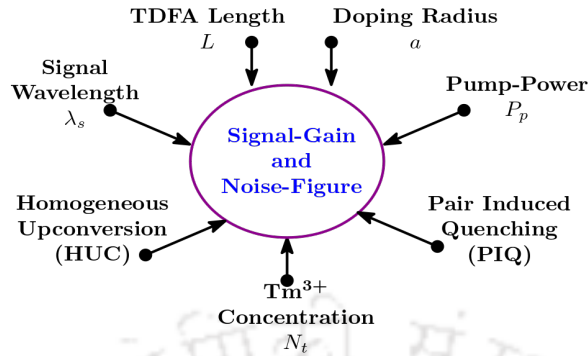
The stated mathematical model demonstrates the dependencies of the signal-gain and noise-figure on various parameters which can be seen in Fig. 6.6. The impact of IM effects can be observed when comparative simulations are performed considering similar parameters but with two different scenarios. The cases contemplate firstly without the IM effects and then with HUC and PIQ effects collectively.

**Table 6.1:** Simulation Parameters

| Parameter            | Unit            | Symbol         | Value                  | Remark     |
|----------------------|-----------------|----------------|------------------------|------------|
| Signal wavelength    | nm              | $\lambda_s$    | 1470                   | S-Band     |
| Pump wavelength      | nm              | $\lambda_p$    | 1050                   | [249]      |
| Signal power         | dBm             | $P_s$          | -20                    | Estimated  |
| Pump power           | mW              | $P_p$          | 450                    | Calculated |
| TDFA length          | m               | $L$            | 100                    | Calculated |
| Fiber core radius    | $\mu\text{m}$   | $r$            | 1.8                    | [245]      |
| Doping radius        | $\mu\text{m}$   | $a$            | 1                      | Calculated |
| Doping concentration | $\text{m}^{-3}$ | $N_t$          | $2.2 \times 10^{27}$   | Calculated |
| Numerical aperture   | –               | NA             | 0.3                    | [249]      |
| CR coefficient       | $\text{m}^{-3}$ | $k_{3011}$     | $1.8 \times 10^{-24}$  | [289]      |
| CR coefficient       | $\text{m}^{-3}$ | $k_{1130}$     | $5.12 \times 10^{-26}$ | Calculated |
| Signal absorption    |                 |                |                        |            |
| CSA at 1470 nm       | $\text{m}^2$    | $\sigma_{sa}$  | Fig.1.23 (b)           | [249]      |
| Signal emission      |                 |                |                        |            |
| CSA at 1470 nm       | $\text{m}^2$    | $\sigma_{se}$  | Fig.1.23 (b)           | [249]      |
| Radiative decay rate | $\text{s}^{-1}$ | $A_{10}$       | 285.7                  | [163]      |
| Radiative decay rate | $\text{s}^{-1}$ | $A_{30}$       | 702.8                  | [163]      |
| Radiative decay rate | $\text{s}^{-1}$ | $A_{31}$       | 73.3                   | [163]      |
| Pump Absorption      |                 |                |                        |            |
| CSA at 1050 nm       | $\text{m}^2$    | $\sigma_{p02}$ | $1.1 \times 10^{-27}$  | [249]      |
| Pump Absorption      |                 |                |                        |            |
| CSA at 1050 nm       | $\text{m}^2$    | $\sigma_{p14}$ | $1.1 \times 10^{-27}$  | [249]      |
| Non-radiative rate   | $\text{s}^{-1}$ | $A_{43}$       | 52976                  | [249]      |
| Non-radiative rate   | $\text{s}^{-1}$ | $A_{21}$       | $2.22 \times 10^5$     | Estimated  |

#### 6.4.1 Optimum pump-power selection to maximize signal-gain

Apparently, the constructive effect of IM has been observed with respect to optimum pump-power corresponding to maximum gain conditions. Consequently, the signal gain for each scenario is calculated as 20.91 dB and 20.32 dB respectively as shown in Fig.6.7. The noise-figure with respect to maximum gain conditions for both the cases have been found towards the

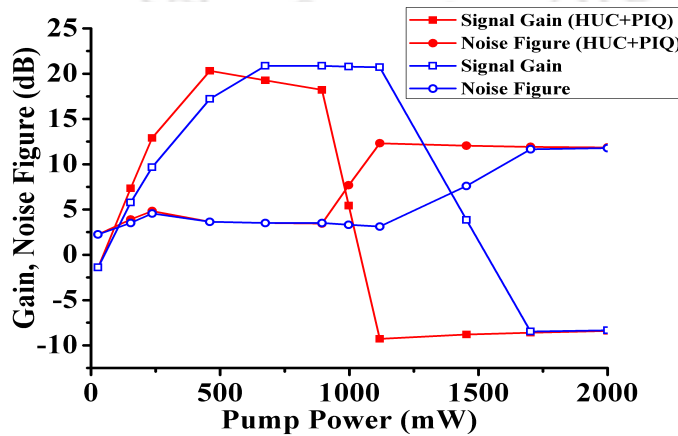


**Fig. 6.6:** Parameters affecting the behaviour of the the signal-gain and noise-figure.

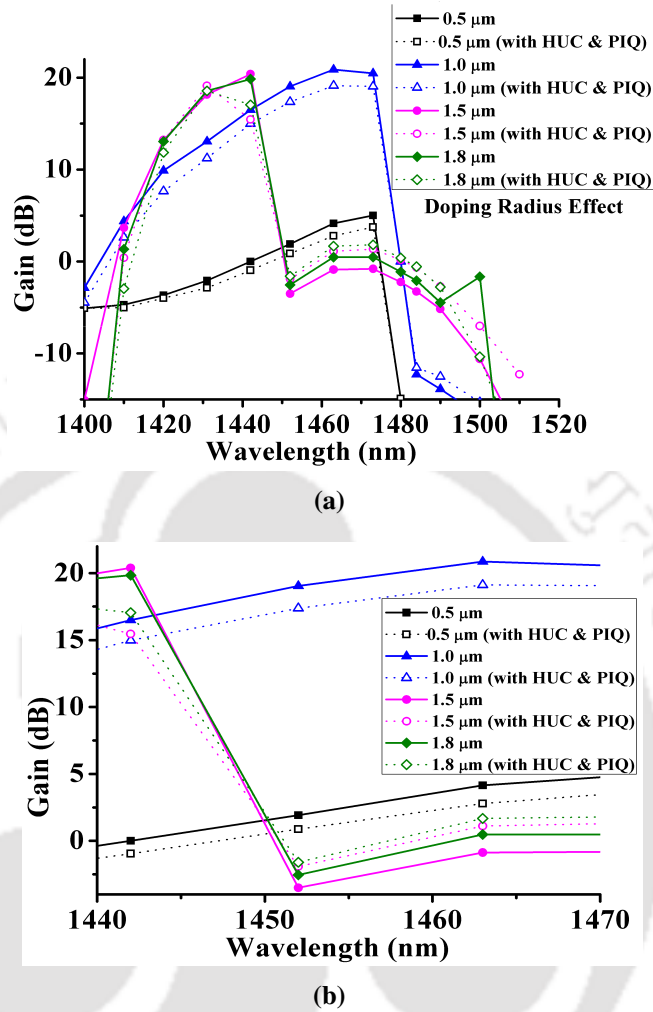
minimum. The corresponding pump powers are noted as 450 mW and 680 mW respectively, highlighting the fact that population-inversion has occurred at relatively lower pump-power in the case with IM effects. This constructive nature of the IM effect can be effectively utilized to achieve early population-inversion in a TDFA based fiber laser.

### 6.4.2 Optimizing signal-wavelength and $\text{Tm}^{3+}$ doping radius

For the calculated value of optimum pump power (450 mW), the doping radius variation effect for  $\text{Tm}^{3+}$  dopant is carried out for S-band wavelength sweep. The signal power has been considered as -20 dBm and the doping radii are varied for  $a = (0.5, 1, 1.5, 1.8) \mu\text{m}$ . Figure 6.8 (a) and (b) shows the signal-wavelength dependency on the gain and in-particular the S-band which is the region of interest. It can be seen that for  $a = 0.5 \mu\text{m}$ , the inter-ionic distance between  $\text{Tm}^{3+}$  dopants decreases. This in-turn creates the PIQ effect much intense which dominates over HUC thereby resulting in deterioration of the signal-gain. On increasing the dopant radius



**Fig. 6.7:** Optimum pump power for non-IM effect (blue) and with IM effects (red)

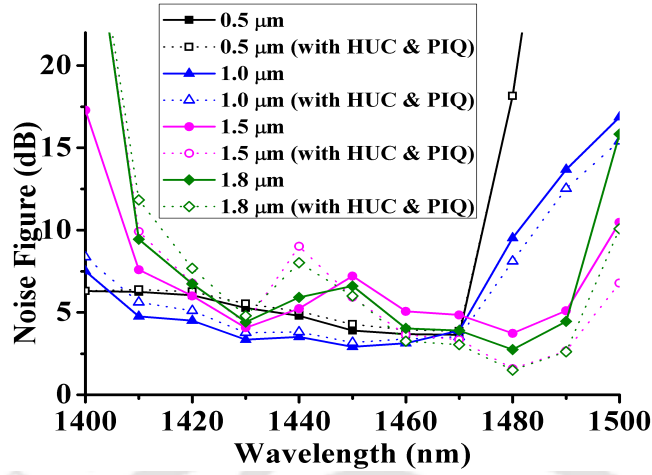


**Fig. 6.8:** IM effect on the signal-gain with respect to the doping radius for fixed  $\text{Tm}^{3+}$  concentration showed as (a) input signal-wavelength variation and (b) shows the magnified portion concerning the S-band.

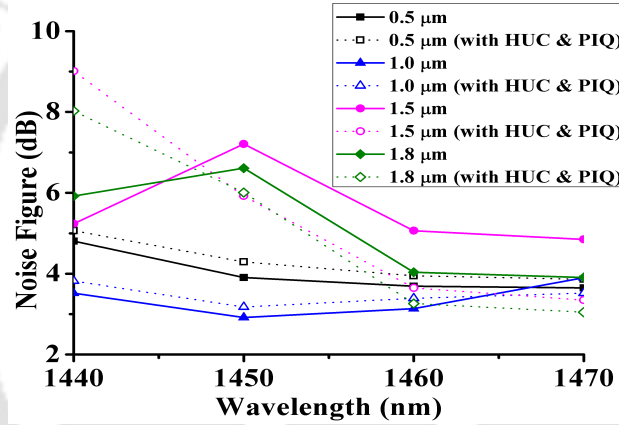
accordingly as  $a = (1, 1.5, 1.8) \mu\text{m}$ , the gain starts to build-up as a consequence that the PIQ effect decreases while HUC continue to populate  $^3\text{H}_4$  level. The gain values obtained for the radii  $a = (1, 1.5, 1.8) \mu\text{m}$  have been almost constant, however, for 1460 nm the bandwidth is about 1.5 times more than that at 1430 nm making it an optimal wavelength for S-band amplification.

Figure 6.9 (a) and (b) shows the noise-figure (NF) variation with its zoomed counterpart for dopant the radii  $a = (0.5, 1, 1.5, 1.8) \mu\text{m}$  respectively. Therefore, the assimilated inference can be obtained from Fig. 6.8 and Fig. 6.9 that for  $a = 1.0 \mu\text{m}$  and signal-wavelength of 1460 nm traversing through this TDFA, the gain maximises and NF minimises which makes them the optimum TDFA parameters for the S-band.





(a)

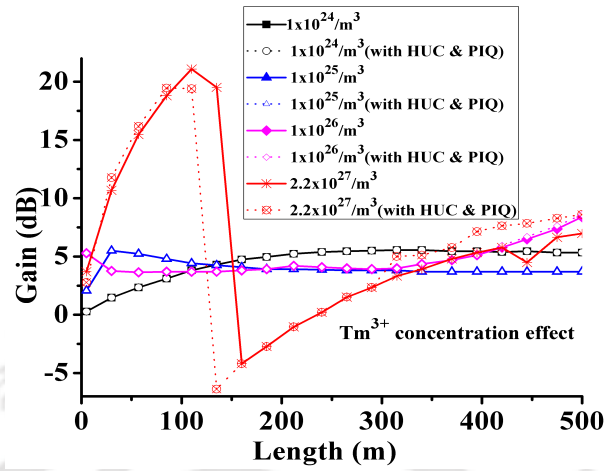


(b)

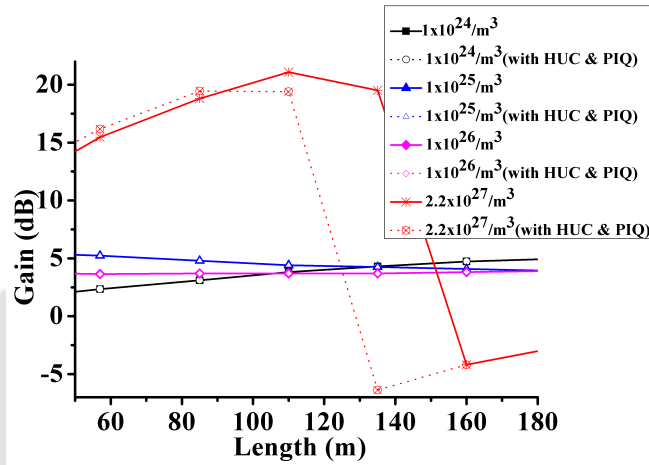
**Fig. 6.9:** IM effect on the noise-figure with respect to the doping radius for fixed  $\text{Tm}^{3+}$  concentration showed as (a) input signal-wavelength variation and (b) shows the magnified portion concerning the S-band.

### 6.4.3 Optimizing signal-wavelength and $\text{Tm}^{3+}$ doping radius

As according to the optimum calculated values for the dopant radius  $a = 1.0 \mu\text{m}$  and pump-power of 450 mW, the dopant concentration effect is simulated with the intention of finding the optimum  $\text{Tm}^{3+}$  concentration. The variation has been performed with respect amplifier length with four different concentrations as shown in the Fig. 6.10 (a) and (b). At the lower concentration values of  $\text{Tm}^{3+}$  dopant i.e. when  $N_t = (1 \times 10^{24}, 1 \times 10^{25}, 1 \times 10^{26}) \text{ m}^{-3}$ , it has been observed that the signal-gain obtained is small owing to the insufficient built-up of  $\text{Tm}^{3+}$  ion concentration in the metastable state  $^3\text{F}_4$ . However, as the dopant concentration is increased to  $N_t = 2.2 \times 10^{27} \text{ m}^{-3}$ , the signal-gain shoots up to the value of 20.92 dB at 130 m of TDFA length.



(a)



(b)

**Fig. 6.10:** (a) IM effect on doping concentration for the fixed  $\text{Tm}^{3+}$  doping radius with respect to TDFA length and signal-gain. (b) shows the magnified portion to observe the optimum TDFA lengths.

When the  $\text{Tm}^{3+}$  ion concentration has been increased to this high value, it is observed that for the optimum dopant radius ( $a = 1.0 \mu\text{m}$ ) and signal wavelength (1460 nm) respectively, the IM effect dominance has been observed. The comparable signal-gains have been obtained as 20.32 dB against 20.92 dB when IM effects are not considered. Apparently, the signal-gain obtained with IM effects is at significantly smaller TDFA length of 100 m against the 130 m when these effects have not been considered under simulation environment. Therefore, the constructive nature of IM effects can be appreciated while selecting the length of the TDFAs.

### 6.5 Summary

TDFAs could be the potential candidates to be employed in the present fiber optic communication system to accommodate the data-carrying traffic. The system could be beneficial as it is compatible to work with the EDFA architecture, however utilizing the S-band of optical communication. This chapter focused on the beneficial aspect of the IM effect while optimum parameters for the TDFAs have to be selected. Performance of TDFAs have been evaluated with respect to HUC and PIQ processes and it is inferred that they can act as helping mechanisms for early population-inversion at relatively lower pump-power and smaller TDFA length rather than its detrimental behavior on signal-gain.

The performance parameters have been optimized by implementing the mathematical model and simulating it on OptiSystem® platform. The optimum TDFA length is determined as 100 m with  $\text{Tm}^{3+}$  dopant radius of  $1\ \mu\text{m}$ . Due to the interplay of the IM effect the optimum pump-power is determined as 450 mW with a signal-gain of 20.32 dB. This determination of the TDFA parameters is also supplemented with the noise-figure analysis which further strengthens the optimization scenarios. Importantly, the entire analysis uses only a single wavelength pump of 1050 nm which rather prove to lessen the heat-load and economical cost factor of the designed system.

# 7

## Conclusions and Future Scopes

### Contents

|     |                                        |     |
|-----|----------------------------------------|-----|
| 7.1 | Summary of Conclusions and Discussions | 158 |
| 7.2 | Future Scopes                          | 162 |

## 7. Conclusions and Future Scopes

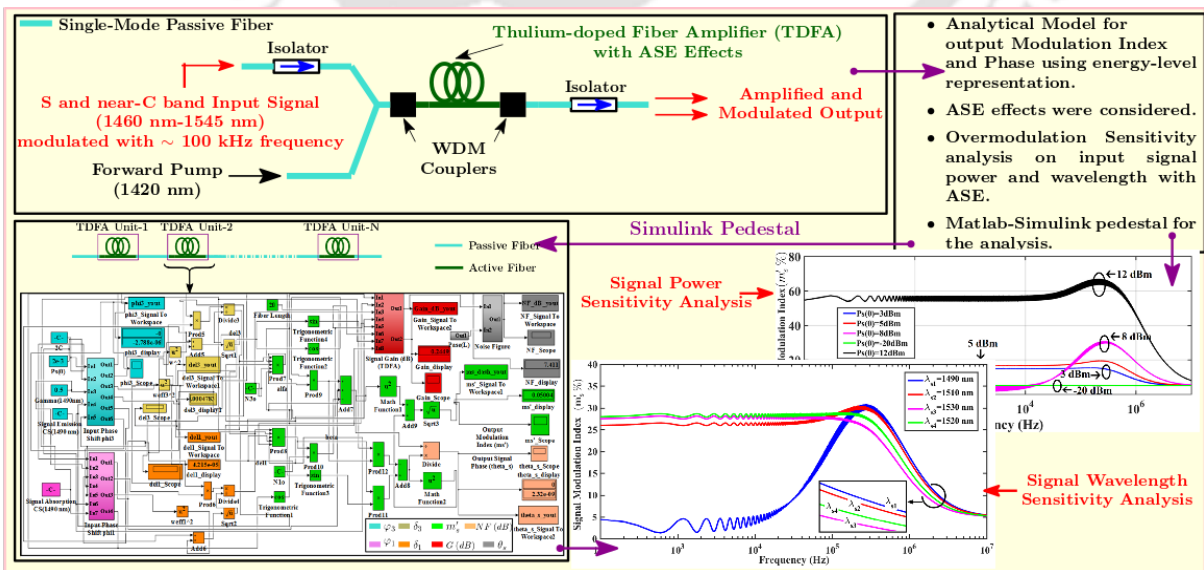
In this thesis, we have investigated TDFAs for their potential application in S and near-C bands of fiber-optic communication systems. Assimilating various analytical and simulation approaches carried out in this thesis, efforts have been made to consider TDFAs in commissioning vis-a-vis to the existing state-of-the-art EDFAs which are operational at a 1550 nm window. The studies which have been carried out in this thesis can increase the data capacity of the existing system using TDFAs. In this chapter, the main contributions of the work presented in this thesis are summarized in section 7.1, and possible future extension of the work are outlined in section 7.2.

### 7.1 Summary of Conclusions and Discussions

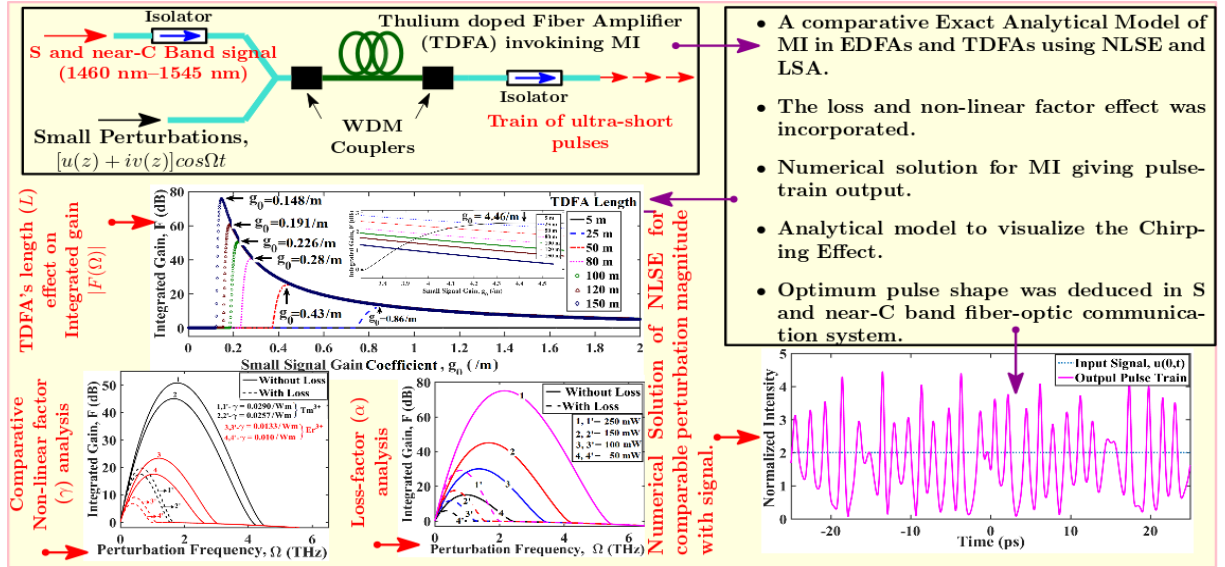
In this section, a summary and the review of the findings during this thesis work are presented. This thesis presents:

#### ✓ Analysis on the Overmodulation of Signal and Gain dynamics in TDFAs :

In this study, a comprehensive analytical model of TDFA's overmodulation of gain and signal dynamics has been presented. The governing equations for the dynamics of TDFA based systems have been developed. This can be effectively utilized inline monitoring, surveillance, and information of the fiber-optic communication system for S and near-C



**Fig. 7.1:** Graphical summary of the work carried out during the analysis on overmodulation of signal and gain dynamics in TDFAs.



**Fig. 7.2:** Graphical summary of the analytical and simulation approach to study MI in the Lossy and Non-linear TDFAs.

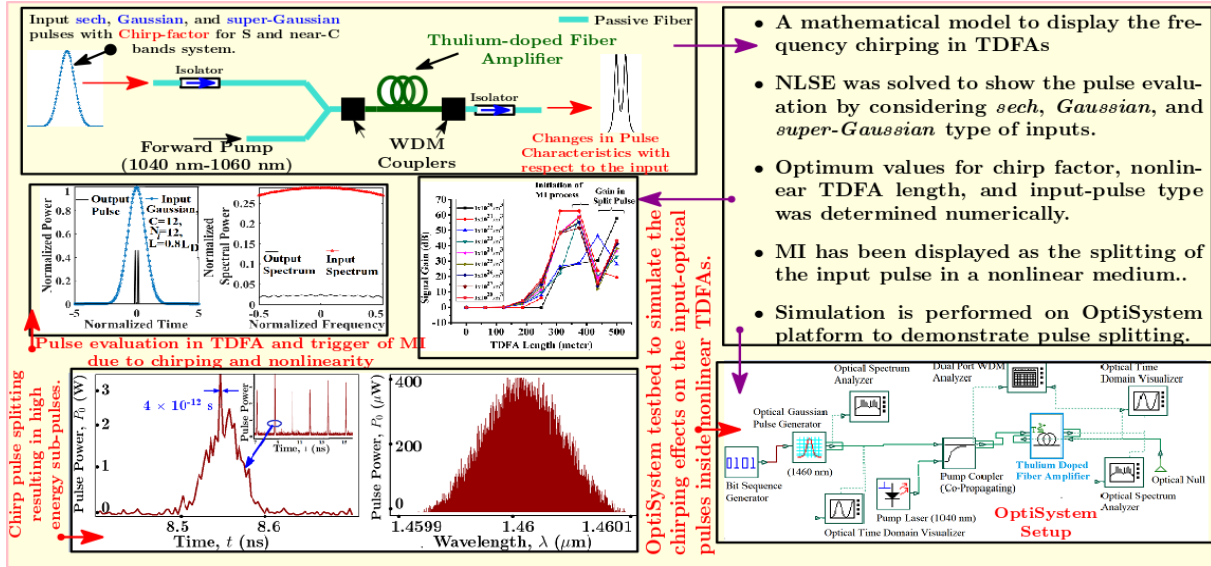
bands. The inclusion of ASE and its effects on gain and signal-to-signal transfer function have also been presented. A comparative study, considering EDFA and TDFA systems, has been projected displaying the signal power and wavelength effect on overmodulation sensitivity. The optimum operating wavelength, input-modulation index, input-signal power have been determined. This study also resulted in the development of a simulator implemented through the MatLab®-Simulink pedestal using the analytical model. The probable sighting of crossover effects was also observed in the analysis. The graphical summary of this work can be seen in Fig. 7.1.

#### ✓ Analytical and Simulation studies on the Modulation Instability in Lossy and Non-linear TDFAs :

This study proposed a detailed analysis on loss and non-linear factor effects on MI in TDFAs operating in S and near-C bands. An analytical model has been derived through NLSE and solved through the LSA technique. To trigger the MI phenomenon, optimum values for small-signal gain coefficient and TDFFA length has been obtained . The results obtained show the massive reduction in the integrated gains for small-signal attenuation values. Non-linear factor analysis on TDFFA has been compared with that of the EDFA. The result projected better performance of the former with larger integrated gains for the



## 7. Conclusions and Future Scopes



**Fig. 7.3:** Graphical summary of the analysis on the frequency chirp effects in non-linear TDFAs.

same set of fiber amplifier parameters. Considering the lossless and lossy cases simultaneously, the deteriorating effect of the loss factor has also been observed in the non-linear factor analysis. The perturbation frequency selection in lossy TDFAs is a crucial aspect to trigger MI, which can be predicted from the presented analysis. The real situation scenario has been solved numerically using SSFM with respect to the large amplitudes of input perturbations. The observation of the generation of quasi-periodic pulses through MI has been also observed as can be seen in the graphical summary of Fig. 7.2.

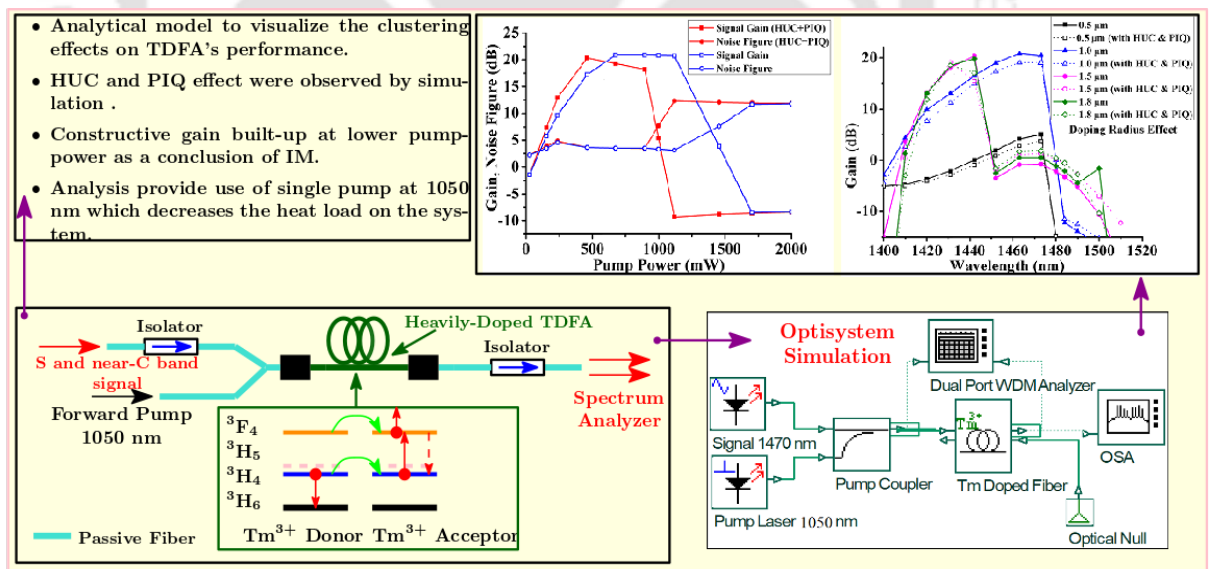
### ✓ Analysis on the Chirping Effects on Optical-Pulses traversing in nonlinear TDFAs through MI :

In digital fiber-optic communications, data is sent via pulse operation. Therefore, observing the progression of the pulses through TDFAs would be an interesting aspect to study. Consequently, the optical pulse propagation and its evaluation along the TDFFA's length have been mathematically analyzed in this thesis. The model has been developed and solved numerically to obtain the optimum results for various input-pulse shapes. The effect of MI was put in considerations to obtain high-energy optical pulses. Furthermore, optimum TDFFA length has been calculated considering the non-linear and frequency chirp factors respectively. The mathematical model was also validated by simulating the similar conditions on OptiSystem® software as presented in the graphical summary of

Fig. 7.3.

✓ **Analysis on the Ion-Ion Interaction Mechanisms in TDFAs through simulations :**

The analysis performed in this thesis with respect to heavily-doped TDFAs has been focused on the IM effects. Apparently, the beneficial aspect of the IM effect has been considered thereby obtaining the optimum parameters. Performance of TDFAs have been evaluated with respect to HUC and PIQ processes and it is inferred that they can act as helping mechanisms for early population-inversion at relatively lower pump-power and smaller TDFA length rather than its detrimental behavior on the signal gain. The performance parameters have been optimized by implementing the mathematical model and simulating it on the OptiSystem<sup>®</sup> platform. The importance of a singly pumped TDFA system has also been emphasized in the analysis as shown in the graphical summary of Fig. 7.4.



**Fig. 7.4:** Graphical summary of the emphasizing on the beneficial aspects of IM effects in heavily doped TDFA systems.

### 7.2 Future Scopes

In this thesis, several investigations associated with the modeling and the performance of the TDFAs have been studied. The main motif of this study is to establish TDFAs in-situ with EDFAs with respect to practical commissioning. However, these studies are based on certain assumptions which reduce the accuracy of the results. Therefore, we propose some possible directions in which the present work can be extended to make these models more reliable and accurate.

- ➡ The simulation studies based on the analytical model developed for overmodulation of signal and gain dynamics in TDFAs consider the ASEs. However, it would be interesting to analyze the behavior of the overmodulation results including the backward ASEs too. The cross-relaxation processes can be included in the governing equations so as to observe their effects. Apparently, the inclusion of pump overmodulation and its coupling aspect with the signal in TDFA systems can give a better insight into cross-over effects.
- ➡ It would be interesting to know the behaviour of the overmodulated system under backward pumping scheme. It may lead to the finding of more efficient and optimized parameters. The model can further include more energy level transitions and therefore would require a numerical approach. The analysis on overmodulation studies on various co-doped fiber amplifier can open the domains for new material in the field of fiber-optic communication and amplification.
- ➡ The MI studies performed in this thesis assume that no ASE contributes its effect on the results. However, considering its impact would give better insight into the MO studies relating to TDFAs. Furthermore, the slowly varying envelope approximation is not always true in the practical scenario. Although, it has been solved numerically using SSFM other methodology can also be employed to compare the computational time and accuracy of the results.
- ➡ The frequency chirping effects considered in this thesis do not handle the loss factor of the TDFAs. Therefore, it would be beneficial to know the outcomes of the chirping effects including the loss factor. Furthermore, the simulation on the OptiSystem® platform

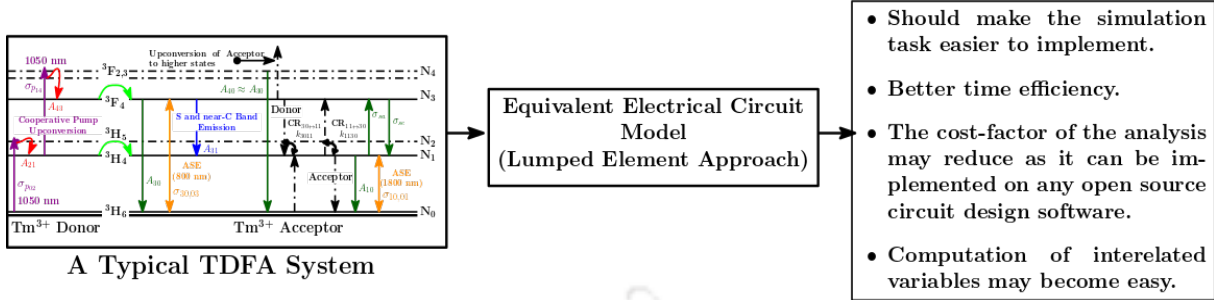
only considered *Gaussian* pulse behavior. It would be interesting to perform the comparative analysis via the inclusion of *sech* and *super-Gaussian* pulse type in these simulation studies.

- ➡ The study based on the IM effects assumed absorption and emission CSAs to be the same for the clustered and single ion. Therefore, performing this analysis through mathematical and simulation approaches but including the loss factor as well as different CSAs of the clustered and single ions should give more accurate and efficient results.
- ➡ At high pump powers such as 680 mW confined to the fiber core may encourage the excitation of Raman stokes signal through stimulated Raman scattering (SRS) which may enhance the overall gain of the system. This Raman gain is dependent on the pump wavelength and pump power [53]. Also, due to Rayleigh scattering, this gain may limit the performance of Raman amplification due to an increase in noise figure contributing to the net ASE of the system. It also may be noted that Brillouin backscattered wave may also get triggered in case of high pump power in fiber core which may create instability in the system leading to pulse splitting [88]. However, these aspects have not been considered in the presented theses and it would be an important aspect include these studies in the future prospects which could provide more accurate results.

Furthermore, investigations can also be performed on TDFAs through which we can get more knowledge with respect to its feasibility in the fiber-optic communication system. Some of these are mentioned below

- ➡ The analysis and studies performed in this thesis can be given an alternative approach through an equivalent electrical circuit model as shown in the idea given in Fig. 7.5. This may be done by mapping the energy level diagram and the governing differential equations in its equivalent electrical circuit lumped elements. They can be connected and simulated in the electrical domain. The importance of this type of analysis may give better time and cost efficiency as compared to its original form. The variable behavior can be represented in closed-form electrical expressions which could not have been possible in its present form.

## 7. Conclusions and Future Scopes



**Fig. 7.5:** The idea representation of the equivalent electrical circuit model of a TDFA system with its possible importance.

- ➡ To overcome the last mile problem in the FTTH systems, to avoid unnecessary high maintenance and cost factors, the usability of POFA with  $\text{Tm}^{3+}$  could be of great significance. The analysis can be carried out with respect to TDFAs as a pre-amplifier in a plastic matrix.
- ➡ It would be interesting to carry out the analysis performed in this thesis but in the  $\sim 2\mu\text{m}$  regime with TDFAs owing to its large absorption and emission CSAs.

# A

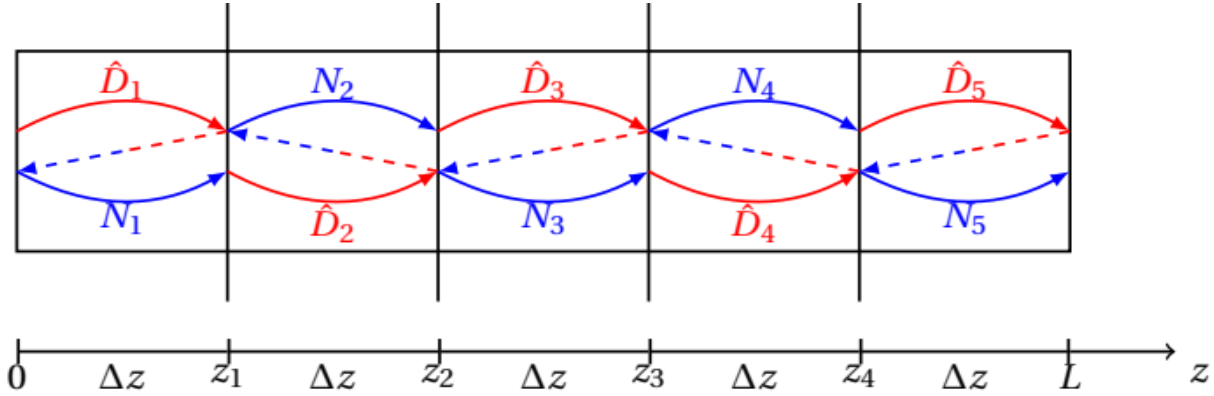
## Appendix

### A.1 Numerical Methods

Often analytical and approximate solutions are not available for the nonlinear Schrödinger equation owing to the practical conditions making the system too complicated. The solution of these equations are often beyond the reach by classical methods and a closed form solution is normally not possible. Therefore, numerical methods are employed for the simulation of optical system operating in real scenarios including the nonlinear effects in the optical fibers and RE-DFAs. These numerical techniques have been classified under finite-difference methods (FDM) and pseudo-spectral methods (PSM) [256]. While the former is applicable in DWM systems where temporal resolution is usually small fraction of the spectral bandwidth (BW). Consequently, for large number of channels the the total BW may reach  $\sim 100$  THz and temporal resolution of  $\sim 1$  fs. Therefore, to achieve such demands, the requirement of FDM is proposed. Many FDM methods are used to solve NLSE and may be applied according to the conditions. For instance, fourth-order Runge-Kutta (RK) method can be used to solve NLSE and generate supercontinuum inside optical fibers [256].

One of the most popular scheme under PSM is the split-step Fourier method (SSFM). It is





**Fig. A.1:** Schematic illustration of the split-step Fourier method where  $\widehat{D}$  stands for the dispersion operator and  $\widehat{N}$  for the nonlinear operator. The dotted arrow represents the time to frequency conversion using FFT algorithm

used to solve the pulse-propagation and its evaluation in a non-linear dispersive optical fibers. Specially, in the case of slowly varying envelope approximation of the input-pulse, this method is remarkably fast as it involves fast-Fourier transform in its algorithm [290]. The details involving the SSFM is discussed in section A.2.

## A.2 Split-Step Fourier Method

The methodology this algorithm employ is that it consider the solution as the form expressed as [256]

$$\frac{\partial U}{\partial z} = (\widehat{D} + \widehat{N})U \quad (\text{A.1})$$

where the dispersion, including the loss effects, is accounted by  $\widehat{D}$  and fiber non-linearities are handled by  $\widehat{N}$  operators while representing NLSE. The pulse envelope can be represented by  $U(z, t \text{ or } \omega)$ . The simulation inside the fiber, particularly TDFAs, takes place by considering the solution in segment form which when cascaded together forms the total solution. Therefore, the fiber is either dispersive with linearity in the frequency domain or non-dispersive with non-linearities in the time domain. This shifting from time to frequency domain is due to the fact that the solution of NLSE exists individually for the above-said cases [268]. Considering the optical fiber segmented into large number of segments each having width  $\Delta z$  as shown the Fig. A.1.

During the propagation of the pulse in the element- $n$  from  $z_n$  to  $z_{n+1}$ , the nonlinearity acts

alone with  $\widehat{D} = 0$  and then dispersion acts independently with  $\widehat{N} = 0$ . Therefore, mathematically it can be written as

$$U(z_{n+1}, t) \approx \exp(\Delta z \widehat{D}) \exp(\Delta z \widehat{N}) U(z_n, t) \quad (\text{A.2})$$

where the exponential term with operator  $\widehat{D}$  can be evaluated using FFT and then can be reconverted into time domain using inverse FFT. Therefore, the dispersion and nonlinearity terms of the NLSE can be solved using the pair of expressions as

$$\textbf{Dispersion: } \widehat{U}(z_{n+1}, \omega) = \widehat{U}(z_n, \omega) \exp \left[ i(z_{n+1} - z_n) \sum_{m=1}^{\infty} \frac{\beta_m}{m!} \omega^m \right] \quad (\text{A.3})$$

$$\textbf{Nonlinearity: } U(z_{n+1}, t) = \widehat{U}(z_n, t) \exp \left[ i\gamma P_0 |U|^2 \frac{e^{-\alpha z_n} - e^{-\alpha z_{n+1}}}{\alpha} \right] \quad (\text{A.4})$$

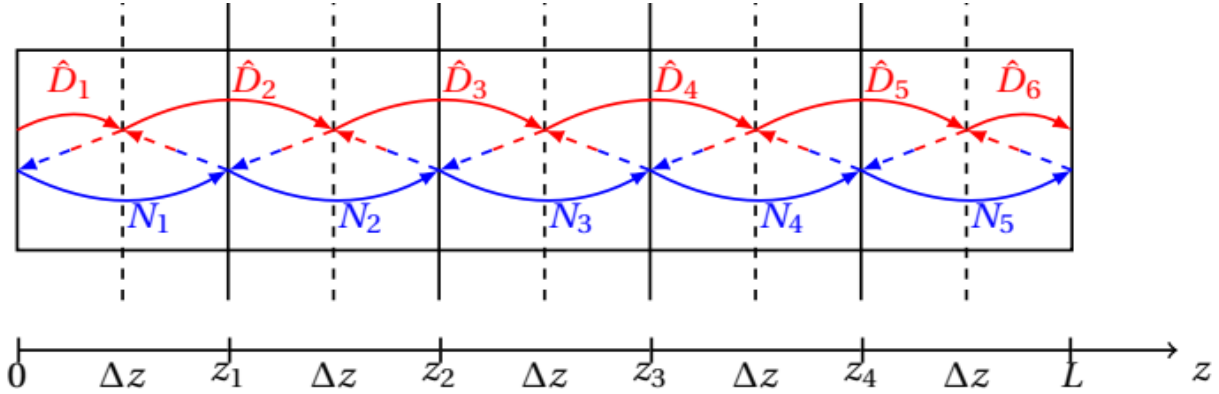
where  $\widehat{U}(\cdot)$  and  $U(\cdot)$  are the solutions defining the dispersion and nonlinearity of the input pulse. The equations (A.3) and (A.4) are obtained using the Baker-Hausdroff formula for the two non-commuting operators such as  $\widehat{D}$  and  $\widehat{N}$  [256]. It has been seen that an error term proportional to  $(\Delta z)^2$  is associated with the above expansion. Consequently, the accuracy of SSFM is limited to the second-order term of the step-size.

The accuracy can be increased to third-order i.e.  $(\Delta z)^3$  by using the symmetric initial and the final half steps with nonlinearity term sandwiched in between the two. Therefore, (A.2) can be written as [256]

$$U(z_{n+1}, t) \approx \exp \left[ \frac{\Delta z}{2} \widehat{D} \right] \exp \left[ \int_{z_n}^{z_{n+1}} \widehat{N}(z') dz' \right] \exp \left[ \frac{\Delta z}{2} \widehat{D} \right] U(z_n, t) \quad (\text{A.5})$$

here in the above expression the nonlinearity term is included in the middle which can be expressed as  $\sim \exp(\Delta z \widehat{N})$  for significantly smaller step-size. Owing to the symmetric terms in (A.5), this method is called symmetrized-SSFM as shown in Fig. A.2. However, at a smaller step-size the computation time is more and therefore a trade-off exists between these two.

Different scenarios has been presented in Chapter 5 of this thesis of using simple SSFM to observe the pulse evaluation in a nonlinear TDFA. As an example, a 100m long TDFA with the following parameters has been considered

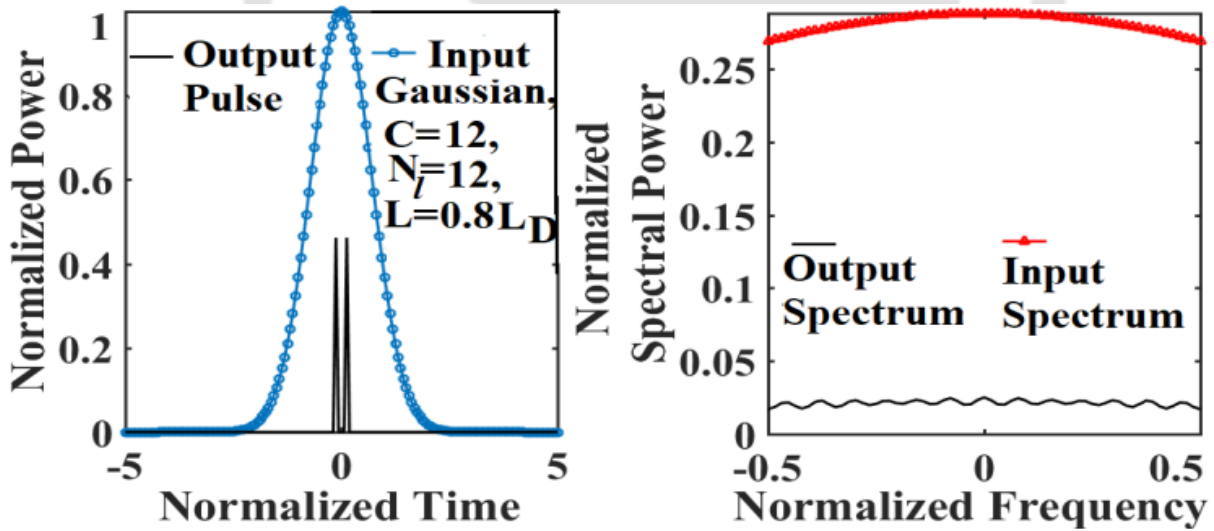


**Fig. A.2:** Schematic illustration of the symmetrized-SSFM. The initial and final half-steps are reduced

$\beta_2 = -13.74 \text{ ps}^2/\text{km}$ ,  $L = 100 \text{ m}$ ,  $\gamma = 0.0133 \text{ /Wm}$ ,  $\alpha = 0.36$  corresponding to  $0.1 \text{ /m}$ ,

input-pulse power  $P_s = 50 \text{ mW}$ ,  $\lambda_s = 1470 \text{ nm}$  with *Gaussian* pulse shape.

This pulse is launched into the TDFA and the output is evaluated by the SSFM algorithm on MatLab. The time and frequency domain plots can be observed in Fig. A.3. Evidently, the dispersion and nonlinear components can respectively alter the shape of the frequency and time domain spectra respectively.



**Fig. A.3:** A *Gaussian* pulse as an input inside a TDFA is evaluated by SSFM. The temporal and spectral splitting can be observed to this input pulse.

## Bibliography

- [1] J. M. Senior and M. Y. Jamro, *Optical fiber communications: Principles and Practice*. Pearson Education, 2009.
- [2] R. Ramaswami, K. Sivarajan, and G. Sasaki, "Propagation of signals in optical fiber," in *Optical Networks*. San Francisco: Morgan Kaufmann, 2002, pp. 49–106.
- [3] B. Ferguson and X.-C. Zhang, "Materials for terahertz science and technology," *Nature materials*, vol. 1, no. 1, pp. 26–33, 2002.
- [4] Y. Luo, J. Wen, J. Zhang, J. Canning, and G.-D. Peng, "Bismuth and Erbium codoped optical fiber with ultrabroadband luminescence across O-, E-, S-, C-, and L-bands," *Optics letters*, vol. 37, no. 16, pp. 3447–3449, 2012.
- [5] "ITU - telecommunication standardization sector," <https://www.itu.int>.
- [6] M. Bredol, D. Leers, L. Bosselaar, and M. Hutjens, "Improved model for OH absorption in optical fibers," *Journal of lightwave technology*, vol. 8, no. 10, pp. 1536–1540, 1990.
- [7] T. Izawa, N. Shibata, and A. Takeda, "Optical attenuation in pure and doped fused silica in the IR wavelength region," *Applied Physics Letters*, vol. 31, no. 1, pp. 33–35, 1977.
- [8] M. I. Ahamed and K. S. Kumar, "Studies on Cu<sub>2</sub>SnS<sub>3</sub> quantum dots for O-band wavelength detection," *Materials Science-Poland*, vol. 37, no. 2, pp. 225–229, 2019.
- [9] J. Hayes, *The FOA Reference Guide to Fiber Optics and Study Guide to FOA Certification*. Fiber Optic Association, 2009.
- [10] Y.-S. Seo, Y. Fujimoto, and M. Nakatsuka, "Optical amplification in a Bismuth-doped silica glass at 1300 nm telecommunications window," *Optics communications*, vol. 266, no. 1, pp. 169–171, 2006.
- [11] P. J. Winzer, D. T. Neilson, and A. R. Chraplyvy, "Fiber-optic transmission and networking: the previous 20 and the next 20 years," *Optics express*, vol. 26, no. 18, pp. 24 190–24 239, 2018.
- [12] H. J. Dutton, *Understanding optical communications*. Prentice Hall PTR Durham, North Carolina, USA, 1998, vol. 1.
- [13] "Fiberlabs inc." <https://www.fiberlabs.com/glossary/about-optical-communication-band/>.
- [14] S. V. Kartalopoulos, "Elastic bandwidth [optical-fiber communication]," *IEEE Circuits and Devices Magazine*, vol. 18, no. 1, pp. 8–13, 2002.
- [15] J. W. Dawson, L. S. Kiani, P. H. Pax, G. S. Allen, D. R. Drachenberg, V. V. Khitrov, D. Chen, N. Schenkel, M. J. Cook, R. P. Crist *et al.*, "E-band Nd<sup>3+</sup> amplifier based on wavelength selection in an all-solid micro-structured fiber," *Optics express*, vol. 25, no. 6, pp. 6524–6538, 2017.

- [16] Y. Yamamoto, T. Sasaki, T. Taru, M. Hirano, S. Ishikawa, M. Onishi, E. Sasaoka, and Y. Chigusa, "Water-free pure-silica-core fibre and its stability against hydrogen ageing," *Electronics Letters*, vol. 40, no. 22, pp. 1401–1403, 2004.
- [17] M. Ding, D. Fan, W. Wang, Y. Luo, and G.-D. Peng, *Basics of Optical Fiber Measurements*. Singapore: Springer Singapore, 2018, pp. 1–39.
- [18] J. B. Rosolem, A. A. Juriollo, R. Arradi, A. D. Coral, J. C. R. F. Oliveira, and M. A. Romero, "All silica S-band double-pass Erbium-doped fiber amplifier," *IEEE Photonics Technology Letters*, vol. 17, no. 7, pp. 1399–1401, 2005.
- [19] G. P. Agrawal, *Fiber-optic communication systems*. John Wiley & Sons, 2012, vol. 222.
- [20] H. Chen, M. Leblanc, and G. Schinn, "Gain enhanced L-band optical fiber amplifiers and tunable fiber lasers with Erbium-doped fibers," *Optics communications*, vol. 216, no. 1-3, pp. 119–125, 2003.
- [21] C. F. Lam, H. Liu, B. Koley, X. Zhao, V. Kamalov, and V. Gill, "Fiber optic communication technologies: What's needed for datacenter network operations," *IEEE Communications Magazine*, vol. 48, no. 7, pp. 32–39, 2010.
- [22] A. Ghazisaeidi, I. F. de Jauregui Ruiz, R. Rios-Müller, L. Schmalen, P. Tran, P. Brindel, A. C. Meseguer, Q. Hu, F. Buchali, G. Charlet *et al.*, "Advanced C+L-band transoceanic transmission systems based on probabilistically shaped PDM-64QAM," *Journal of Lightwave Technology*, vol. 35, no. 7, pp. 1291–1299, 2017.
- [23] H. Choi, J. Oh, D. Lee, S. Ahn, B. Park, and S. Lee, "Simple and efficient L-band Erbium-doped fiber amplifiers for WDM networks," *Optics Communications*, vol. 213, no. 1-3, pp. 63–66, 2002.
- [24] O. Bands, B. Laurent, and G. Draka, "From O to L: The future of optical-wavelength bands," *Broadband properties*, pp. 83–85, 2008.
- [25] N. Massa, "Fiber optic telecommunication," *Fundamentals of photonics*, p. 298, 2000.
- [26] M. Curran and B. Shirk, "Basics of fiber optics," 2015.
- [27] G. Keiser, *Optical fiber communications*. Wiley Online Library, 2003.
- [28] M. H. Crawford, "LEDs for solid-state lighting: performance challenges and recent advances," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 15, no. 4, pp. 1028–1040, 2009.
- [29] R. Michalzik, "VCSELs: fundamentals, technology and applications of vertical-cavity surface-emitting lasers," vol. 166, 2012.
- [30] P. Westbergh, J. S. Gustavsson, A. Haglund, H. Sunnerud, and A. Larsson, "Large aperture 850 nm VCSELs operating at bit rates up to 25 gbit/s," *Electronics Letters*, vol. 44, no. 15, pp. 907–908, 2008.
- [31] T. Anan, N. Suzuki, K. Yashiki, K. Fukatsu, H. Hatakeyama, T. Akagawa, K. Tokutome, and M. Tsuji, "High-speed 1.1  $\mu\text{m}$  range InGaAs VCSELs," in *OFC/NFOEC 2008-2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*. IEEE, 2008, pp. 1–3.
- [32] Y.-C. Chang, C. Wang, and L. Coldren, "High-efficiency, high-speed VCSELs with 35 gbits error-free operation," *Electronics Letters*, vol. 43, no. 19, pp. 1022–1023, 2007.



- [33] S. Parker, "Introduction, history of lasers and laser light production," *British dental journal*, vol. 202, no. 1, pp. 21–31, 2007.
- [34] W. Koechner, *Solid-state laser engineering*. Springer, 2013, vol. 1.
- [35] C. J. Erickson, M. Van Zijl, G. Doermann, and D. S. Durfee, "An ultrahigh stability, low-noise laser current driver with digital control," *Review of Scientific Instruments*, vol. 79, no. 7, p. 073107, 2008.
- [36] I. P. Kaminow and T. L. Koch, *Optical fiber telecommunications III*. Academic press, 1997.
- [37] T. Zhong, X. Hu, F. N. Wong, K. K. Berggren, T. D. Roberts, and P. Battle, "High-quality fiber-optic polarization entanglement distribution at 1.3  $\mu\text{m}$  telecom wavelength," *Optics letters*, vol. 35, no. 9, pp. 1392–1394, 2010.
- [38] L. Fang and J. Wang, "All-fiber polarization-manageable directional couplers," *arXiv preprint arXiv:1912.02020*, 2019.
- [39] A. W. Snyder and Y. Chen, "Nonlinear fiber couplers: switches and polarization beam splitters," *Optics letters*, vol. 14, no. 10, pp. 517–519, 1989.
- [40] A. W. Snyder and J. Love, *Optical waveguide theory*. Springer Science & Business Media, 2012.
- [41] E. Desurvire, D. Bayart, B. Desthieux, and S. Bigo, *Erbium-doped fiber amplifiers: Device and System Developments*. Wiley-Interscience New York, NY, 2002, vol. 2.
- [42] G. P. Agrawal, *Applications of nonlinear fiber optics*. Elsevier, 2001.
- [43] P. Westbrook, T. Her, B. Eggleton, S. Hunsche, and G. Raybon, "Measurement of pulse degradation using all-optical 2R regenerator," *Electronics Letters*, vol. 38, no. 20, pp. 1193–1194, 2002.
- [44] H. Murai, Y. Kanda, M. Kagawa, and S. Arahira, "Regenerative SPM-based wavelength conversion and field demonstration of 160-gb/s all-optical 3R operation," *Journal of Lightwave Technology*, vol. 28, no. 6, pp. 910–921, 2010.
- [45] M. Daikoku, N. Yoshikane, T. Otani, and H. Tanaka, "Optical 40-gb/s 3R regenerator with a combination of the SPM and XAM effects for all-optical networks," *Journal of lightwave technology*, vol. 24, no. 3, p. 1142, 2006.
- [46] D. Large and J. Farmer, *Broadband cable access networks: the HFC plant*. Morgan Kaufmann, 2008.
- [47] B. E. Saleh and M. C. Teich, *Fundamentals of photonics*. John Wiley & sons, 2019.
- [48] F.-S. Choa, X. Zhao, X. Yu, J. Lin, J. Zhang, Y. Gu, G. Ru, G. Zhang, L. Li, H. Xiang *et al.*, "An optical packet switch based on WDM technologies," *Journal of lightwave technology*, vol. 23, no. 3, pp. 994–1014, 2005.
- [49] Y. Ye, X. Xi, C. Shi, B. Yang, X. Wang, H. Zhang, P. Zhou, and X. Xu, "Comparative study on transverse mode instability of fiber amplifiers based on long tapered fiber and conventional uniform fiber," *Laser Physics Letters*, vol. 16, no. 8, p. 085109, 2019.
- [50] P. Sidorenko, W. Fu, and F. Wise, "Nonlinear ultrafast fiber amplifiers beyond the gain-narrowing limit," *Optica*, vol. 6, no. 10, pp. 1328–1333, 2019.



- [51] S. M. Kobtsev and B. Nyushkov, "Hybrid SOA/fibre topology for actively mode-locked laser with extended pulse-shaping capability," in *Solid State Lasers XXVIII: Technology and Devices*, vol. 10896. International Society for Optics and Photonics, 2019, p. 1089620.
- [52] A. D. McAulay, "Novel all-optical flip-flop using semiconductor optical amplifiers in innovative frequency-shifting inverse-threshold pairs," *Optical Engineering*, vol. 43, no. 5, pp. 1115–1121, 2004.
- [53] S. D. Emami, P. Hajireza, F. Abd-Rahman, H. A. Abdul-Rashid, H. Ahmad, and S. W. Harun, "Wide-band hybrid amplifier operating in S-band region," *Progress In Electromagnetics Research*, vol. 102, pp. 301–313, 2010.
- [54] S. D. Emami, S. W. Harun, F. Abd-Rahman, H. A. Abdul-Rashid, S. A. Daud, and H. Ahmad, "Optimization of the 1050 nm pump power and fiber length in single-pass and double-pass thulium doped fiber amplifiers," *Progress In Electromagnetics Research*, vol. 14, pp. 431–448, 2009.
- [55] M. Adams, J. Collins, and I. Henning, "Analysis of semiconductor laser optical amplifiers," *IEE Proceedings J (Optoelectronics)*, vol. 132, no. 1, pp. 58–63, 1985.
- [56] P. Royo, R. Koda, and L. Coldren, "Vertical cavity semiconductor optical amplifiers: comparison of Fabry-Perot and rate equation approaches," *IEEE journal of quantum electronics*, vol. 38, no. 3, pp. 279–284, 2002.
- [57] M. J. O'Mahony, "Semiconductor laser optical amplifiers for use in future fiber systems," *Journal of lightwave technology*, vol. 6, no. 4, pp. 531–544, 1988.
- [58] R. E. Camacho-Aguilera, "Ge-on-Si laser for silicon photonics," Ph.D. dissertation, Massachusetts Institute of Technology, 2013.
- [59] R. Hui, *Introduction to Fiber-Optic Communications*. Academic Press, 2020.
- [60] T. Akiyama, M. Ekawa, M. Sugawara, K. Kawaguchi, H. Sudo, A. Kuramata, H. Ebe, and Y. Arakawa, "An ultrawide-band semiconductor optical amplifier having an extremely high penalty-free output power of 23 dBm achieved with quantum dots," *IEEE Photonics Technology Letters*, vol. 17, no. 8, pp. 1614–1616, 2005.
- [61] A. Fardi, H. Baghban, and M. Razaghi, "Dynamics of pulse amplification in tapered-waveguide quantum-dot semiconductor optical amplifiers," *Optik*, vol. 207, p. 164396, 2020.
- [62] S. M. Izadyar, M. Razaghi, and A. Hassanzadeh, "Quantum dot semiconductor optical amplifier: Investigation of ultra-fast cross gain modulation in the presence of second excited state," *Journal of Physics D: Applied Physics*, 2020.
- [63] C. Headley and G. P. Agrawal, *Raman amplification in fiber optical communication systems*. Academic press, 2005.
- [64] A. Girard, "Measuring fiber characteristics," *Encyclopedia of Modern Optics*, p. 308, 2018.
- [65] M. N. Islam, "Raman amplifiers for telecommunications," *IEEE journal of selected topics in quantum electronics*, vol. 8, no. 3, pp. 548–559, 2002.
- [66] S. Lewis, S. Chernikov, and J. Taylor, "Characterization of double Rayleigh scatter noise in Raman amplifiers," *IEEE Photonics Technology Letters*, vol. 12, no. 5, pp. 528–530, 2000.

- [67] M. Mermelstein, K. Brar, and C. Headley, "RIN transfer measurement and modeling in dual-order Raman fiber amplifiers," *Journal of lightwave technology*, vol. 21, no. 6, p. 1518, 2003.
- [68] Y. Chen, J. Leng, H. Xiao, T. Yao, and P. Zhou, "Pure passive fiber enabled highly efficient Raman fiber amplifier with record kilowatt power," *IEEE Access*, vol. 7, pp. 28 334–28 339, 2019.
- [69] Y. Chen, J. Song, J. Ye, T. Yao, J. Xu, H. Xiao, J. Leng, and P. Zhou, "Power scaling of Raman fiber amplifier based on the optimization of temporal and spectral characteristics," *Optics Express*, vol. 28, no. 8, pp. 12 395–12 404, 2020.
- [70] M. Ionescu, D. Lavery, A. Edwards, E. Sillekens, L. Galdino, D. Semrau, R. Killey, W. Pelouch, S. Barnes, and P. Bayvel, "74.38 Tb/s transmission over 6300 km single mode fiber with hybrid EDFA/Raman amplifiers," in *2019 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2019, pp. 1–3.
- [71] L. de la Brillouin, "Diffusion of light and X-rays by a homogeneous transparent body – the influence of thermal agitation," in *Annals of Physics*, vol. 9, no. 17. EDP Sciences, 1922, pp. 88–122.
- [72] C. T. Troy, "Sound helps make a better optical clock," *Photonics Spectra*, 2010.
- [73] A. Kobayakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin scattering in optical fibers," *Advances in optics and photonics*, vol. 2, no. 1, pp. 1–59, 2010.
- [74] F. Ravet, X. Bao, J. Snoddy, Y. Li, and L. Chen, "Characterization of Brillouin fiber generator and amplifier for optimized working condition of distributed sensors," *Optical Fiber Technology*, vol. 15, no. 3, pp. 304 – 309, 2009.
- [75] A. R. Chraplyvy and R. W. Tkach, "Narrow band tunable optical filter for channel selection in densely packed WDM systems," *Electronics Letters*, vol. 22, no. 20, pp. 1084–1085, 1986.
- [76] O. Terra, G. Grosche, and H. Schnatz, "Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber," *Opt. Express*, vol. 18, no. 15, pp. 16 102–16 111, Jul 2010.
- [77] S. M. F. Raupach, A. Koczwar, and G. Grosche, "Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier," *Opt. Express*, vol. 22, no. 22, pp. 26 537–26 547, Nov 2014.
- [78] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li, and P.-O. Hedekvist, "Fiber-based optical parametric amplifiers and their applications," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 8, no. 3, pp. 506–520, 2002.
- [79] M. E. Marhic, P. A. Andrekson, P. Petropoulos, S. Radic, C. Peucheret, and M. Jazayerifar, "Fiber optical parametric amplifiers in optical communication systems," *Laser & photonics reviews*, vol. 9, no. 1, pp. 50–74, 2015.
- [80] C. R. Giles and E. Desurvire, "Propagation of signal and noise in concatenated erbium-doped fiber optical amplifiers," *Journal of lightwave technology*, vol. 9, no. 2, pp. 147–154, 1991.
- [81] E. Desurvire and M. N. Zervas, "Erbium-doped fiber amplifiers: principles and applications," *Physics Today*, vol. 48, p. 56, 1995.
- [82] M. J. Digonnet, *Rare-earth-doped fiber lasers and amplifiers, revised and expanded*. CRC press, 2001.

- [83] R. Paschotta, "Rare-earth-doped fibers," *RP Photonics Encyclopedia*,. URL [http://www. rp-photonics. com/rare\\_earth\\_doped\\_fibers. html](http://www.rp-photonics.com/rare_earth_doped_fibers.html), 2012.
- [84] D. N. Messias, M. V. D. Vermelho, M. T. de Araujo, A. S. Gouveia-Neto, and J. S. Aitchison, "Blue energy upconversion emission in thulium-doped-SiO/sub 2/-P/sub 2/O/sub 5/ channel waveguides excited at 1.064  $\mu\text{m}$ ," *IEEE Journal of Quantum Electronics*, vol. 38, no. 12, pp. 1647–1650, 2002.
- [85] V. Ter-Mikirtychev, "Fundamentals of fiber lasers and fiber amplifiers," 2014.
- [86] M. Malinowski, Z. Frukacz, M. Szuflińska, A. Wnuk, and M. Kaczkan, "Optical transitions of  $\text{Ho}^{3+}$  in YAG," *Journal of alloys and compounds*, vol. 300, pp. 389–394, 2000.
- [87] A. Guhur and S. Jackson, "Efficient Holmium-doped fluoride fiber laser emitting 2.1  $\mu\text{m}$  and blue upconversion fluorescence upon excitation at 2  $\mu\text{m}$ ," *Optics express*, vol. 18, no. 19, pp. 20 164–20 169, 2010.
- [88] A. F. El-Sherif and T. A. King, "Dynamics and self-pulsing effects in  $\text{Tm}^{3+}$ -doped silica fibre lasers," *Optics communications*, vol. 208, no. 4-6, pp. 381–389, 2002.
- [89] A. Ghatak and K. Thyagarajan, *An introduction to fiber optics*. Cambridge University Press, 1998.
- [90] I. Esmaeil Zadeh, J. W. Los, R. B. Gourgues, V. Steinmetz, G. Bulgarini, S. M. Dobrovolskiy, V. Zwiller, and S. N. Dorenbos, "Single-photon detectors combining high efficiency, high detection rates, and ultra-high timing resolution," *Apl Photonics*, vol. 2, no. 11, p. 111301, 2017.
- [91] H. Le Jeannic, V. B. Verma, A. Cavaillès, F. Marsili, M. D. Shaw, K. Huang, O. Morin, S. W. Nam, and J. Laurat, "High-efficiency WSi superconducting nanowire single-photon detectors for quantum state engineering in the near infrared," *Optics letters*, vol. 41, no. 22, pp. 5341–5344, 2016.
- [92] S. Miki, M. Yabuno, T. Yamashita, and H. Terai, "Stable, high-performance operation of a fiber-coupled superconducting nanowire avalanche photon detector," *Optics express*, vol. 25, no. 6, pp. 6796–6804, 2017.
- [93] G. Keiser, *Optical communications essentials*. McGraw Hill Professional, 2003.
- [94] B. Das, M. Abdullah, and N. S. M. Shah, "All optical signal restoration for 10G DPSK system," in *Advanced computer and communication engineering technology*. Springer, 2016, pp. 545–556.
- [95] B. Das, M. F. L. Abdullah, B. Pandey, and D. A. Hussain, "Design and implementation of optical signal reinstatement technique for high DPSK RZ transceiver scheme," *Wireless Personal Communications*, vol. 106, no. 4, pp. 1767–1786, 2019.
- [96] X. Liu, "Evolution of Fiber-Optic Transmission and Networking Towards the 5G Era," *Iscience*, 2019.
- [97] A. K. Ermakov, A. S. Podstrigaev, and N. V. Povarenkin, "Temperature impact on the parameters of the fiber-optic communication line," in *2019 Wave Electronics and its Application in Information and Telecommunication Systems (WECONF)*, 2019, pp. 1–5.
- [98] M. S. Ahmed and I. Glesk, "Mitigation of Temperature-Induced Dispersion in Optical Fiber on OCDMA Auto-Correlation," *IEEE Photonics Technology Letters*, vol. 29, no. 22, pp. 1979–1982, 2017.

- [99] N. Skorin-Kapov, M. Furdek, S. Zsigmond, and L. Wosinska, "Physical-layer security in evolving optical networks," *IEEE Communications Magazine*, vol. 54, no. 8, pp. 110–117, 2016.
- [100] S. Rumley, M. Bahadori, R. Polster, S. D. Hammond, D. M. Calhoun, K. Wen, A. Rodrigues, and K. Bergman, "Optical interconnects for extreme scale computing systems," *Parallel Computing*, vol. 64, pp. 65–80, 2017.
- [101] A. V. Krishnamoorthy, H. D. Thacker, O. Torudbakken, S. Müller, A. Srinivasan, P. J. Decker, H. Opheim, J. E. Cunningham, I. Shubin, X. Zheng *et al.*, "From chip to cloud: Optical interconnects in engineered systems," *Journal of Lightwave Technology*, vol. 35, no. 15, pp. 3103–3115, 2017.
- [102] J. Bashir, E. Peter, and S. R. Sarangi, "A survey of on-chip optical interconnects," *ACM Computing Surveys (CSUR)*, vol. 51, no. 6, pp. 1–34, 2019.
- [103] N. Grebenikova, V. Davydov, A. Moroz, M. Bylina, and M. Kuzmin, "Remote control of the quality and safety of the production of liquid products with using fiber-optic communication lines of the internet," in *IOP Conference Series: Materials Science and Engineering*, vol. 497, no. 1. IOP Publishing, 2019, p. 012109.
- [104] A. Gowri, A. S. Rajamani, B. Ramakrishna, and V. Sai, "U-bent plastic optical fiber probes as refractive index based fat sensor for milk quality monitoring," *Optical Fiber Technology*, vol. 47, pp. 15–20, 2019.
- [105] S. Abasi, S. Minaei, B. Jamshidi, and D. Fathi, "Dedicated non-destructive devices for food quality measurement: A review," *Trends in food science & technology*, vol. 78, pp. 197–205, 2018.
- [106] D. K. Mahanta and S. Laskar, "Water quantity-based quality measurement of transformer oil using polymer optical fiber as sensor," *IEEE Sensors Journal*, vol. 18, no. 4, pp. 1506–1512, 2017.
- [107] J. F. Dynes, W. W. Tam, A. Plews, B. Fröhlich, A. W. Sharpe, M. Lucamarini, Z. Yuan, C. Radig, A. Straw, T. Edwards *et al.*, "Ultra-high bandwidth quantum secured data transmission," *Scientific reports*, vol. 6, p. 35149, 2016.
- [108] S. Tanabe, "Rare-earth-doped glasses for fiber amplifiers in broadband telecommunication," *Comptes Rendus Chimie*, vol. 5, no. 12, pp. 815–824, 2002.
- [109] N. K. Dutta, *Fiber amplifiers and fiber lasers*. World Scientific, 2015.
- [110] S. Tanabe, "Optical properties and local structure of rare-earth-doped amplifier for broadband telecommunication," *Journal of alloys and compounds*, vol. 408, pp. 675–679, 2006.
- [111] A. Zakery and S. Elliott, "Optical properties and applications of chalcogenide glasses: a review," *Journal of Non-Crystalline Solids*, vol. 330, no. 1-3, pp. 1–12, 2003.
- [112] D. Dorosz, J. Zmojda, and M. Kochanowicz, "Investigation on broadband near-infrared emission in  $\text{Yb}^{3+}/\text{Ho}^{3+}$  co-doped antimony–silicate glass and optical fiber," *Optical Materials*, vol. 35, no. 12, pp. 2577–2580, 2013.
- [113] F. Pellé, N. Gardant, and F. Auzel, "Effect of excited-state population density on nonradiative multiphonon relaxation rates of rare-earth ions," *JOSA B*, vol. 15, no. 2, pp. 667–679, 1998.
- [114] E. Mura, J. Lousteau, D. Milanese, S. Abrate, and V. M. Sglavo, "Phosphate glasses for optical fibers: Synthesis, characterization and mechanical properties," *Journal of non-crystalline solids*, vol. 362, pp. 147–151, 2013.



- [115] E. Ceci-Ginistrelli, D. Pugliese, N. G. Boetti, G. Novajra, A. Ambrosone, J. Lousteau, C. Vitale-Brovarone, S. Abrate, and D. Milanese, "Novel biocompatible and resorbable UV-transparent phosphate glass based optical fiber," *Optical Materials Express*, vol. 6, no. 6, pp. 2040–2051, 2016.
- [116] H. Li, J. Lousteau, W. N. MacPherson, X. Jiang, H. T. Bookey, J. S. Barton, A. Jha, and A. K. Kar, "Thermal sensitivity of tellurite and germanate optical fibers," *Optics express*, vol. 15, no. 14, pp. 8857–8863, 2007.
- [117] J. Wang, J. Lincoln, W. Brocklesby, R. Deol, C. Mackechnie, A. Pearson, A. Tropper, D. Hanna, and D. Payne, "Fabrication and optical properties of lead-germanate glasses and a new class of optical fibers doped with  $\text{Tm}^{3+}$ ," *Journal of applied physics*, vol. 73, no. 12, pp. 8066–8075, 1993.
- [118] A. Mori, H. Masuda, K. Shikano, and M. Shimizu, "Ultra-wide-band tellurite-based fiber Raman amplifier," *Journal of Lightwave Technology*, vol. 21, no. 5, p. 1300, 2003.
- [119] J. Lousteau, N. Boetti, A. Chiasera, M. Ferrari, S. Abrate, G. Scarciglia, A. Venturello, and D. Milanese, " $\text{Er}^{3+}$  and  $\text{Ce}^{3+}$  codoped tellurite optical fiber for lasers and amplifiers in the near-infrared wavelength region: Fabrication, optical characterization, and prospects," *IEEE Photonics Journal*, vol. 4, no. 1, pp. 194–204, 2012.
- [120] S. D. Jackson, F. Bugge, and G. Erbert, "Directly diode-pumped holmium fiber lasers," *Optics letters*, vol. 32, no. 17, pp. 2496–2498, 2007.
- [121] G. Tao, H. Ebendorff-Heidepriem, A. M. Stolyarov, S. Danto, J. V. Badding, Y. Fink, J. Ballato, and A. F. Abouraddy, "Infrared fibers," *Advances in Optics and Photonics*, vol. 7, no. 2, pp. 379–458, 2015.
- [122] G. Snopatin, V. Shiryaev, V. Plotnichenko, E. Dianov, and M. Churbanov, "High-purity chalcogenide glasses for fiber optics," *Inorganic materials*, vol. 45, no. 13, p. 1439, 2009.
- [123] M. Churbanov, G. Snopatin, V. Shiryaev, V. Plotnichenko, and E. Dianov, "Recent advances in preparation of high-purity glasses based on arsenic chalcogenides for fiber optics," *Journal of non-crystalline solids*, vol. 357, no. 11-13, pp. 2352–2357, 2011.
- [124] K. Kuriki, Y. Koike, and Y. Okamoto, "Plastic optical fiber lasers and amplifiers containing lanthanide complexes," *Chemical Reviews*, vol. 102, no. 6, pp. 2347–2356, 2002.
- [125] J. Zubia and J. Arrue, "Plastic optical fibers: An introduction to their technological processes and applications," *Optical fiber technology*, vol. 7, no. 2, pp. 101–140, 2001.
- [126] Y. Koike and M. Asai, "The future of plastic optical fiber," *NPG Asia Materials*, vol. 1, no. 1, pp. 22–28, 2009.
- [127] D. Krennrich, R. Knappe, B. Henrich, R. Wallenstein, and J. L'huillier, "A comprehensive study of Nd: YAG, Nd:  $\text{YAlO}_3$ , Nd:  $\text{YVO}_4$  and Nd:  $\text{YGdVO}_4$  lasers operating at wavelengths of 0.9 and 1.3  $\mu\text{m}$ . part 1: cw-operation," *Applied Physics B*, vol. 92, no. 2, p. 165, 2008.
- [128] —, "A comprehensive study of Nd: YAG, Nd:  $\text{YAlO}_3$ , Nd:  $\text{YVO}_4$  and Nd:  $\text{YGdVO}_4$  lasers operating at wavelengths of 0.9 and 1.3  $\mu\text{m}$ . part 2: passively mode locked-operation," *Applied Physics B*, vol. 92, no. 2, p. 175, 2008.
- [129] Y. Wang, Y. Zhang, J. Cao, L. Wang, X. Peng, J. Zhong, C. Yang, S. Xu, Z. Yang, and M. Peng, "915 nm all-fiber laser based on novel Nd-doped high alumina and yttria glass@ silica glass hybrid fiber for the pure blue fiber laser," *Optics letters*, vol. 44, no. 9, pp. 2153–2156, 2019.

- [130] C. D. Boley, J. W. Dawson, L. S. Kiani, and P. H. Pax, "E-band Neodymium-doped fiber amplifier: model and application," *Applied optics*, vol. 58, no. 9, pp. 2320–2327, 2019.
- [131] D. He, S. Kang, L. Zhang, L. Chen, Y. Ding, Q. Yin, and L. Hu, "Research and development of new Neodymium laser glasses," *High Power Laser Science and Engineering*, vol. 5, 2017.
- [132] J. Szela, M. Napierala, E. Beres-Pawlik, and K. Jedrzejewski, "Neodymium doped fiber laser," in *2008 2nd ICTON Mediterranean Winter*, 2008, pp. 1–3.
- [133] N. G. Boetti, D. Pugliese, E. Ceci-Ginistrelli, J. Lousteau, D. Janner, and D. Milanese, "Highly doped phosphate glass fibers for compact lasers and amplifiers: A Review," *Applied Sciences*, vol. 7, no. 12, p. 1295, 2017.
- [134] M. N. Zervas and C. A. Codemard, "High power fiber lasers: A Review," *IEEE Journal of selected topics in Quantum Electronics*, vol. 20, no. 5, pp. 219–241, 2014.
- [135] R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," *IEEE Journal of quantum electronics*, vol. 33, no. 7, pp. 1049–1056, 1997.
- [136] R. Royon, J. Lhermite, L. Sarger, and E. Cormier, "High power, continuous-wave Ytterbium-doped fiber laser tunable from 976 to 1120 nm," *Optics express*, vol. 21, no. 11, pp. 13 818–13 823, 2013.
- [137] W. F. Krupke, S. A. Payne, and C. D. Marshall, "Blue diode-pumped solid-state-laser based on Ytterbium doped laser crystals operating on the resonance zero-phonon transition," Oct. 16 2001, uS Patent 6,304,584.
- [138] Y. Nishida, M. Yamada, T. Kanamori, K. Kobayashi, J. Temmyo, S. Sudo, and Y. Ohishi, "Development of an efficient Praseodymium-doped fiber amplifier," *IEEE journal of quantum electronics*, vol. 34, no. 8, pp. 1332–1339, 1998.
- [139] P. Urquhart, "Praseodymium-doped fiber amplifiers: Theory of 1.3  $\mu\text{m}$  operation," *IEEE journal of quantum electronics*, vol. 28, no. 10, pp. 1962–1965, 1992.
- [140] L. Sojka, Z. Tang, D. Jayasuriya, M. Shen, J. Nunes, D. Furniss, M. Farries, T. M. Benson, A. B. Seddon, and S. Sujecki, "Milliwatt-level spontaneous emission across the 3.5–8  $\mu\text{m}$  spectral region from  $\text{Pr}^{3+}$  doped selenide chalcogenide fiber pumped with a laser diode," *Applied Sciences*, vol. 10, no. 2, p. 539, 2020.
- [141] Z. Tang, H. Zhu, E. Bereś-Pawlik, D. Furniss, A. Seddon, T. Benson, S. Sujecki *et al.*, "Study of mid-infrared laser action in chalcogenide rare earth doped glass with  $\text{Dy}^{3+}$ ,  $\text{Pr}^{3+}$  and  $\text{Tb}^{3+}$ ," *Optical Materials Express*, vol. 2, no. 11, pp. 1632–1640, 2012.
- [142] D. D. Hudson, A. Fuerbach, and S. Jackson, "Progress in mid-infrared fiber source development," in *Handbook of optical fibers*. Springer, Springer Nature, 2018, pp. 1–34.
- [143] E. A. Anashkina and A. V. Kim, "Numerical simulation of ultrashort Mid-IR pulse amplification in Praseodymium-doped chalcogenide fibers," *Journal of Lightwave Technology*, vol. 35, no. 24, pp. 5397–5403, 2017.
- [144] A. Hemming, N. Simakov, J. Haub, and A. Carter, "A review of recent progress in Holmium-doped silica fibre sources," *Optical Fiber Technology*, vol. 20, no. 6, pp. 621–630, 2014.



- [145] B. Samson, G. Oulundsen, A. Carter, and S. R. Bowman, "Optical fiber fabrication-Holmium-doped silica fiber designs extend fiber lasers beyond 2  $\mu\text{m}$ ," *Laser Focus World*, vol. 48, no. 8, p. 47, 2012.
- [146] N. Simakov, Z. Li, Y. Jung, J. M. Daniel, P. Barua, P. C. Shardlow, S. Liang, J. K. Sahu, A. Hemming, W. A. Clarkson *et al.*, "High gain Holmium-doped fibre amplifiers," *Optics Express*, vol. 24, no. 13, pp. 13 946–13 956, 2016.
- [147] A. T. Gursel, "Fiber lasers and their medical applications," *Optical Amplifiers-A Few Different Dimensions*, 2018.
- [148] N. Simakov, Z. Li, S. Alam, P. Shardlow, J. Daniel, D. Jain, J. Sahu, A. Hemming, W. Clarkson, and D. Richardson, "Holmium-doped fiber amplifier for optical communications at 2.05–2.13  $\mu\text{m}$ ," in *2015 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2015, pp. 1–3.
- [149] N. Simakov, Z. Li, Y. Jung, J. M. Daniel, P. Barua, P. C. Shardlow, S. Liang, J. K. Sahu, A. Hemming, W. A. Clarkson *et al.*, "High gain Holmium-doped fibre amplifiers," *Optics Express*, vol. 24, no. 13, pp. 13 946–13 956, 2016.
- [150] S. Antipov and A. Kurkov, "A Holmium-doped fiber amplifier at 2.1  $\mu\text{m}$ ," *Laser Physics Letters*, vol. 10, no. 12, p. 125106, 2013.
- [151] J. A. Bebawi, I. Kandas, M. A. El-Osairy, and M. H. Aly, "A comprehensive study on EDFA characteristics: Temperature Impact," *Applied Sciences*, vol. 8, no. 9, p. 1640, 2018.
- [152] T. Hu, "Ultrafast Mid-Infrared fibre lasers," 2015.
- [153] D. Faucher, M. Bernier, G. Androz, N. Caron, and R. Vallée, "20 W passively cooled single-mode all-fiber laser at 2.8  $\mu\text{m}$ ," *Optics letters*, vol. 36, no. 7, pp. 1104–1106, 2011.
- [154] P. Babu, H. J. Seo, K. H. Jang, K. U. Kumar, and C. Jayasankar, "1.55  $\mu\text{m}$  emission and upconversion properties of  $\text{Er}^{3+}$ -doped Oxyfluorotellurite glasses," *Chemical Physics Letters*, vol. 445, no. 4-6, pp. 162–166, 2007.
- [155] M. J. Dignonnet, *Rare-earth-doped fiber lasers and amplifiers, revised and expanded*. CRC press, 2001.
- [156] H. Chen, N. K. Fontaine, R. Ryf, C. Jin, B. Huang, K. Shang, R.-J. Essiambre, L. Wang, T. Hayashi, T. Nagashima *et al.*, "Demonstration of cladding-pumped six-core Erbium-doped fiber amplifier," *Journal of Lightwave Technology*, vol. 34, no. 8, pp. 1654–1660, 2016.
- [157] S. LaRochelle, C. Jin, C. Matte-Breton, and Y. Messaddeq, "Cladding pumped multi-core fiber amplifiers for space division multiplexing," in *2018 IEEE Canadian Conference on Electrical & Computer Engineering (CCECE)*. IEEE, 2018, pp. 1–5.
- [158] J. Cajzl, P. Peterka, M. Kowalczyk, J. Tarka, G. Sobon, J. Sotor, J. Aubrecht, P. Honzátko, and I. Kašík, "Thulium-doped silica fibers with enhanced fluorescence lifetime and their application in ultrafast fiber lasers," *Fibers*, vol. 6, no. 3, p. 66, 2018.
- [159] P. Peterka, B. Faure, W. Blanc, M. Karasek, and B. Dussardier, "Theoretical modelling of S-band Thulium-doped silica fibre amplifiers," *Optical and Quantum Electronics*, vol. 36, no. 1-3, pp. 201–212, 2004.

- [160] B. Dussardier, W. Blanc, P. Peterka *et al.*, “Tailoring of the local environment of active ions in rare-earth-and transition-metal-doped optical fibres, and potential applications,” *Selected Topics on Optical Fiber Technology*, pp. 97–120, 2012.
- [161] R. Balda, J. Fernández, S. García-Revilla, and J. M. Fernández-Navarro, “Spectroscopy and concentration quenching of the infrared emissions in  $\text{Tm}^{3+}$ -doped  $\text{TeO}_2$ - $\text{TiO}_2$ - $\text{Nb}_2\text{O}_5$  glass,” *Optics express*, vol. 15, no. 11, pp. 6750–6761, 2007.
- [162] S. Singh and R. S. Kaler, “Review on recent developments in hybrid optical amplifier for dense wavelength division multiplexed system,” *Optical Engineering*, vol. 54, no. 10, p. 100901, 2015.
- [163] T. Kasamatsu, Y. Yano, and T. Ono, “1.49- $\mu\text{m}$ -band gain-shifted thulium-doped fiber amplifier for WDM transmission systems,” *Journal of Lightwave Technology*, vol. 20, no. 10, p. 1826, 2002.
- [164] A. Muhammad, S. D. Emami, J. Hmood, K. Sayar, R. Penny, H. Abdul-Rashid, H. Ahmad, and S. Harun, “Enhanced performance of an S-band fiber laser using a thulium-doped photonic crystal fiber,” *Laser Physics*, vol. 24, no. 11, p. 115201, 2014.
- [165] S. Muravyev, E. Anashkina, A. Andrianov, V. Dorofeev, S. Motorin, M. Y. Koptev, and A. Kim, “Dual-band  $\text{Tm}^{3+}$ -doped tellurite fiber amplifier and laser at 1.9  $\mu\text{m}$  and 2.3  $\mu\text{m}$ ,” *Scientific reports*, vol. 8, no. 1, pp. 1–13, 2018.
- [166] J. Xu, Y. Tang, Y. Yang, and Y. Hang, “High power tunable  $\text{Tm}^{3+}$ -fiber lasers and its application in pumping  $\text{Cr}^{2+}$ : ZnSe lasers,” in *2008 Conference on Lasers and Electro-Optics and 2008 Conference on Quantum Electronics and Laser Science*. IEEE, 2008, pp. 1–2.
- [167] J. Zubia and J. Arrue, “Plastic optical fibers: An introduction to their technological processes and applications,” *Optical fiber technology*, vol. 7, no. 2, pp. 101–140, 2001.
- [168] J. Clark, L. Bazzana, D. D. Bradley, J. Cabanillas-Gonzalez, G. Lanzani, D. G. Lidzey, J. M. Morgado, A. Nocivelli, W. C. Tsoi, T. Virgili *et al.*, “Blue polymer optical fiber amplifiers based on conjugated fluorene oligomers,” *Journal of Nanophotonics*, vol. 2, no. 1, p. 023504, 2008.
- [169] I. Mollers, D. Jager, R. Gaudino, A. Nocivelli, H. Kragl, O. Ziemann, N. Weber, T. Koonen, C. Lezzi, A. Bluschke *et al.*, “Plastic optical fiber technology for reliable home networking: Overview and results of the EU project POF-ALL,” *IEEE Communications Magazine*, vol. 47, no. 8, pp. 58–68, 2009.
- [170] K. Kuriki, Y. Koike, and Y. Okamoto, “Plastic optical fiber lasers and amplifiers containing lanthanide complexes,” *Chemical Reviews*, vol. 102, no. 6, pp. 2347–2356, 2002.
- [171] J. Arrue, B. García-Ramiro, F. Jiménez, M. Illarramendi, I. Ayesta, J. Zubia, R. Evert, and D. Zarembo, “Gain in europium-chelate-doped polymer-optical-fiber amplifiers,” *JOSA B*, vol. 35, no. 11, pp. 2770–2779, 2018.
- [172] C. Jiang, M. G. Kuzyk, J.-L. Ding, W. E. Johns, and D. J. Welker, “Fabrication and mechanical behavior of dye-doped polymer optical fiber,” *Journal of applied physics*, vol. 92, no. 1, pp. 4–12, 2002.
- [173] P. Miluski, M. Kochanowicz, J. Zmojda, and D. Dorosz, “Properties of  $\text{Eu}^{3+}$  doped poly (methyl methacrylate) optical fiber,” *Optical Engineering*, vol. 56, no. 2, p. 027106, 2017.
- [174] S. D. Jackson, “The spectroscopic and energy transfer characteristics of the rare earth ions used for silicate glass fibre lasers operating in the shortwave infrared,” *Laser & Photonics Reviews*, vol. 3, no. 5, pp. 466–482, 2009.

- [175] S. D. Jackson, A. Sabella, and D. G. Lancaster, "Application and development of high-power and highly efficient silica-based fiber lasers operating at 2  $\mu\text{m}$ ," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 3, pp. 567–572, 2007.
- [176] J. Zhang, N. Wang, Y. Guo, M. Cai, Y. Tian, F. Huang, and S. Xu, "Tm<sup>3+</sup>-doped lead silicate glass sensitized by Er<sup>3+</sup> for efficient 2  $\mu\text{m}$  mid-infrared laser material," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 199, pp. 65–70, 2018.
- [177] M. Z. Amin, K. K. Qureshi, and M. M. Hossain, "Doping radius effects on an erbium-doped fiber amplifier," *Chinese Optics Letters*, vol. 17, no. 1, p. 010602, 2019.
- [178] C. Jiang and L. Jin, "Modeling erbium–thulium-co-doped fiber amplifier for 1400–1650 nm band," *Applied Physics B*, vol. 94, no. 4, p. 609, 2009.
- [179] A. H. M. Husein, A. H. El-Astal, and F. I. El-Nahal, "The gain and noise figure of Yb-Er-codoped fiber amplifiers based on the temperature-dependent model," *Optical Materials*, vol. 33, no. 3, pp. 543–548, 2011.
- [180] S. W. Harun, H. A. Abdul-Rashid, S. Z. Muhd-Yassin, M. K. Abd-Rahman, K. K. Jayapalan, and H. Ahmad, "37.2 dB small-signal gain from Er/Yb co-doped fiber amplifier with 20 mW pump power," *Optics & Laser Technology*, vol. 40, no. 1, pp. 88–91, 2008.
- [181] F. Xu, R. Serna, M. J. De Castro, J. F. Navarro, and Z. Xiao, "Broadband infrared emission of erbium–thulium-codoped calcium borosilicate glasses," *Applied Physics B*, vol. 99, no. 1-2, pp. 263–270, 2010.
- [182] A. J. Miskowiec and T. M. Roberts, "Limitations on gain in rare-earth doped fiber amplifiers due to amplified spontaneous emission," 2009.
- [183] Q. Han, W. Yan, Y. Yao, Y. Chen, and T. Liu, "Optimal design of Er/Yb co-doped fiber amplifiers with an Yb-band fiber Bragg grating," *Photonics Research*, vol. 4, no. 2, pp. 53–56, 2016.
- [184] G. Sobon, P. Kaczmarek, A. Antonczak, J. Sotor, and K. M. Abramski, "Controlling the 1  $\mu\text{m}$  spontaneous emission in Er/Yb co-doped fiber amplifiers," *Optics express*, vol. 19, no. 20, pp. 19 104–19 113, 2011.
- [185] Z. Li, "Thulium-doped fiber sources for novel applications," Ph.D. dissertation, University of Southampton, 2015.
- [186] M. Saad, "Heavy metal fluoride glass fibers and their applications," in *2011 Asia Communications and Photonics Conference and Exhibition (ACP)*. IEEE, 2011, pp. 1–16.
- [187] S. D. Jackson, "Towards high-power mid-infrared emission from a fibre laser," *Nature photonics*, vol. 6, no. 7, pp. 423–431, 2012.
- [188] K. Hendel, M. Mogensen, E. Wenande, C. Dierickx, M. Haedersdal, and K. Togsverd-Bo, "Fractional 1,927 nm thulium laser plus photodynamic therapy compared and combined for photodamaged décolleté skin: A side-by-side randomized controlled trial," *Lasers in surgery and medicine*, vol. 52, no. 1, pp. 44–52, 2020.
- [189] G. Kurmuş, A. Tatlıparmak, B. Aksoy, E. Koç, Z. Aşiran Serdar, and C. Ergin, "Efficacy and safety of 1927 nm fractional thulium fiber laser for the treatment of melasma: a retrospective study of 100 patients," *Journal of Cosmetic and Laser Therapy*, vol. 21, no. 7-8, pp. 408–411, 2019.

- [190] A. S. Gouveia-Neto, J. F. Silva, M. V. D. Vermelho, A. S. L. Gomes, and C. Jacinto, "Generation of multiwavelength light in the region of the biological windows in  $\text{Tm}^{3+}$ -doped fiber excited at 1.064 $\mu\text{m}$ ," *Applied Physics Letters*, vol. 109, no. 26, p. 261108, 2016.
- [191] R. L. Blackmon, T. C. Hutchens, L. A. Hardy, C. R. Wilson, P. B. Irby, and N. M. Fried, "Thulium fiber laser ablation of kidney stones using a 50- $\mu\text{m}$ -core silica optical fiber," *Optical Engineering*, vol. 54, no. 1, p. 011004, 2014.
- [192] A. Pal, D. Pal, S. D. Chowdhury, and R. Sen, "All-fiber laser at 1.94  $\mu\text{m}$ : effect on soft tissue," in *Optical Interactions with Tissue and Cells XXVIII*, vol. 10062. International Society for Optics and Photonics, 2017, p. 100620A.
- [193] R. Liao, Y. Song, W. Liu, H. Shi, L. Chai, and M. Hu, "Dual-comb spectroscopy with a single free-running thulium-doped fiber laser," *Optics express*, vol. 26, no. 8, pp. 11 046–11 054, 2018.
- [194] G. Sobon, J. Sotor, I. Pasternak, A. Krajewska, W. Strupinski, and K. M. Abramski, "Thulium-doped all-fiber laser mode-locked by CVD-graphene/PMMA saturable absorber," *Optics express*, vol. 21, no. 10, pp. 12 797–12 802, 2013.
- [195] R. Currey, A. Khademian, and D. Shiner, "Development of a thulium fiber laser for an atomic spectroscopy experiment," *Fibers*, vol. 8, no. 2, p. 12, 2020.
- [196] T. Sakamoto, S.-i. Aozasa, M. Yamada, and M. Shimizu, "Hybrid fiber amplifiers consisting of cascaded TDFA and EDFA for WDM signals," *Journal of lightwave technology*, vol. 24, no. 6, pp. 2287–2295, 2006.
- [197] L. Shah, T. Bonhoff, T. Ferhat, A. F. El-Sherif, M. Ramme, C. C. Willis, M. Baudelet, P. Kadwani, C. Gaida, M. Gebhardt *et al.*, "Silicon backside machining using a nanosecond 2- $\mu\text{m}$  Tm: fiber laser," in *Micromachining and Microfabrication Process Technology XVIII*, vol. 8612. International Society for Optics and Photonics, 2013, p. 861207.
- [198] I. Mingareev, N. Gehlich, T. Bonhoff, A. Abdulfattah, A. M. Sincore, P. Kadwani, L. Shah, and M. Richardson, "Principles and applications of trans-wafer processing using a 2- $\mu\text{m}$  thulium fiber laser," *The International Journal of Advanced Manufacturing Technology*, vol. 84, no. 9-12, pp. 2567–2578, 2016.
- [199] I. Mingareev, F. Weirauch, A. Olowinsky, L. Shah, P. Kadwani, and M. Richardson, "Welding of polymers using a 2  $\mu\text{m}$  thulium fiber laser," *Optics & Laser Technology*, vol. 44, no. 7, pp. 2095–2099, 2012.
- [200] K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, "2  $\mu\text{m}$  laser sources and their possible applications," in *Frontiers in guided wave optics and optoelectronics*. IntechOpen, 2010.
- [201] I. Mingareev, M. Kang, M. Truman, J. Qin, G. Yin, J. Hu, C. M. Schwarz, I. B. Murray, M. C. Richardson, and K. A. Richardson, "Spatial tailoring of the refractive index in infrared glass-ceramic films enabled by direct laser writing," *Optics & Laser Technology*, vol. 126, p. 106058, 2020.
- [202] S. D. Jackson, A. Sabella, and D. G. Lancaster, "Application and development of high-power and highly efficient silica-based fiber lasers operating at 2  $\mu\text{m}$ ," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 3, pp. 567–572, 2007.
- [203] L. Yu, J. Wu, and P. Fan, "Energy efficient designs of ultra-dense iot networks with nonideal optical front-hauls," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 7934–7945, 2019.



- [204] S. Aleksic, “A survey on optical technologies for IoT, smart industry, and smart infrastructures,” *Journal of Sensor and Actuator Networks*, vol. 8, no. 3, p. 47, 2019.
- [205] S. Meng, G. Zhao, J. Hou, Y. Liu, Y. Guo, Y. Fang, Y. Zhou, and J. Zou, “High performance of near-infrared emission for S-band amplifier from  $\text{Tm}^{3+}$ -doped bismuth glass incorporated with Ag nanoparticles,” *Journal of Luminescence*, p. 117313, 2020.
- [206] H. Ahmad and S. A. Reduan, “S<sup>+</sup>/S band passively Q-switched thulium-fluoride fiber laser based on using gallium selenide saturable absorber,” *Optics & Laser Technology*, vol. 107, pp. 116–121, 2018.
- [207] G. Lakshminarayana, U. Caldino, A. Meza-Rocha, A. Lira, P. V. Rao, V. Singh, A. Dahshan, I. Kityk, D.-E. Lee, J. Yoon *et al.*, “Fluorescence features of  $\text{Tm}^{3+}$ -doped multicomponent borosilicate and borotellurite glasses for blue laser and s-band optical amplifier applications,” *Optical Materials*, vol. 96, p. 109354, 2019.
- [208] S. Aozasa, H. Masuda, H. Ono, T. Sakamoto, T. Kanamori, Y. Ohishi, and M. Shimizu, “1480-1510 nm-band Tm doped fiber amplifier (TDFA) with a high power conversion efficiency of 42%,” in *Optical Fiber Communication Conference*. Optical Society of America, 2001, p. PD1.
- [209] J. Rosolem, A. Juriollo, R. Arradi, and M. A. Romero, “Triple band double pass EDFA/TDFA with an embedded DCF for DWDM and CWDM applications,” in *SBMO/IEEE MTT-S International Conference on Microwave and Optoelectronics, 2005*. IEEE, 2005, pp. 542–545.
- [210] Y. Yang, Y. Chu, Z. Chen, Y. Ma, L. Liao, H. Li, J. Peng, N. Dai, J. Li, and L. Yang, “Blue upconversion luminescence for  $\text{Yb}^{3+}/\text{Tm}^{3+}$  co-doped borosilicate glasses,” *Journal of Luminescence*, vol. 195, pp. 247–251, 2018.
- [211] Y. Cheng, W. Zhongqing, H. Xi, W. Tengyan, and Z. Weiwei, “Thermal stability and optical properties of a novel  $\text{Tm}^{3+}$  doped fluorotellurite glass,” *Journal of Rare Earths*, vol. 32, no. 12, pp. 1154–1161, 2014.
- [212] H. Ebendorff-Heidepriem, K. Kuan, M. R. Oermann, K. Knight, and T. M. Monro, “Extruded tellurite glass and fibers with low oh content for mid-infrared applications,” *Optical Materials Express*, vol. 2, no. 4, pp. 432–442, 2012.
- [213] T. Sakamoto, M. Yamada, T. Kanamori, M. Shimizu, Y. Ohishi, Y. Terunuma, and S. Sudo, “Thulium-doped fluoride fiber amplifiers for 1.4  $\mu\text{m}$  and 1.6  $\mu\text{m}$  operation,” in *Optical Amplifiers and Their Applications*. Optical Society of America, 1996, p. FAW14.
- [214] R. J. Mears, L. Reekie, I. Jauncey, and D. N. Payne, “Low-noise erbium-doped fibre amplifier operating at 1.54  $\mu\text{m}$ ,” *Electronics Letters*, vol. 23, no. 19, pp. 1026–1028, 1987.
- [215] U.-C. Ryu, K. Oh, W. Shin, and U. Paek, “Inherent enhancement of gain flatness and achievement of broad gain bandwidth in erbium-doped silica fiber amplifiers,” *IEEE journal of quantum electronics*, vol. 38, no. 2, pp. 149–161, 2002.
- [216] F. E. Durak and A. Altuncu, “All-optical gain clamping and flattening in L-band EDFAs using lasing-controlled structure with fbg,” *Optical Fiber Technology*, vol. 45, pp. 217–222, 2018.
- [217] C.-H. Yeh, C.-C. Lee, and S. Chi, “120-nm bandwidth erbium-doped fiber amplifier in parallel configuration,” *IEEE Photonics Technology Letters*, vol. 16, no. 7, pp. 1637–1639, 2004.

- [218] P. Peterka, I. Kasik, A. Dhar, B. Dussardier, and W. Blanc, "Theoretical modeling of fiber laser at 810 nm based on thulium-doped silica fibers with enhanced  $^3\text{H}_4$  level lifetime," *Optics express*, vol. 19, no. 3, pp. 2773–2781, 2011.
- [219] S. Novak and A. Moesle, "Analytic model for gain modulation in EDFAs," *Journal of Lightwave Technology*, vol. 20, no. 6, p. 975, 2002.
- [220] B. Cole and M. L. Dennis, "S-band amplification in a thulium doped silicate fiber," in *OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171)*, vol. 2. IEEE, 2001, pp. TuQ3–TuQ3.
- [221] A. H. M. Husein and F. I. El-Nahal, "Optimizing the thulium doped fiber amplifier (TDFA) gain and noise figure for S-band  $16 \times 10$  gb/s WDM systems," *Optik*, vol. 124, no. 19, pp. 4052–4057, 2013.
- [222] D. Jalas, A. Petrov, M. Eich, W. Freude, S. Fan, Z. Yu, R. Baets, M. Popović, A. Melloni, J. D. Joannopoulos *et al.*, "What is—and what is not—an optical isolator," *Nature Photonics*, vol. 7, no. 8, pp. 579–582, 2013.
- [223] L. Sun, S. Jiang, and J. Marciante, "Compact all-fiber optical faraday components using 65-wt%-terbium-doped fiber with a record Verdet constant of- 32 rad/(Tm)," *Optics express*, vol. 18, no. 12, pp. 12 191–12 196, 2010.
- [224] R. Paschotta, "tutorial on" passive fiber optics," *Encyclopedia of Laser Physics and Technology*, 2008.
- [225] A. Bononi and L. A. Rusch, "Doped-fiber amplifier dynamics: A system perspective," *Journal of Lightwave Technology*, vol. 16, no. 5, p. 945, 1998.
- [226] J. Freeman and J. Conradi, "Gain modulation response of erbium-doped fiber amplifiers," *IEEE photonics technology letters*, vol. 5, no. 2, pp. 224–226, 1993.
- [227] M. Murakami, T. Imai, and M. Aoyama, "A remote supervisory system based on subcarrier over-modulation for submarine optical amplifier systems," *Journal of lightwave technology*, vol. 14, no. 5, pp. 671–677, 1996.
- [228] S. Novak and R. Gieske, "Simulink model for EDFA dynamics applied to gain modulation," *Journal of lightwave technology*, vol. 20, no. 6, p. 986, 2002.
- [229] R. Sharma and S. K. Raghuwanshi, "Modeling and analysis of overmodulation in erbium-doped fiber amplifiers including amplified spontaneous emission," *Optical Engineering*, vol. 56, no. 2, p. 026105, 2017.
- [230] Z. Zhang, X. Liu, W. Wei, Z. Yang, S. Lu, L. Tang, L. Ding, and Y. Li, "Group velocity control of gaussian pulse signal with pump phase modulation," *IEEE Photonics Technology Letters*, vol. 32, no. 11, pp. 647–650, 2020.
- [231] H. Tünnermann, J. Neumann, D. Kracht, and P. Weßels, "Gain dynamics and refractive index changes in fiber amplifiers: a frequency domain approach," *Optics express*, vol. 20, no. 12, pp. 13 539–13 550, 2012.
- [232] F. I. El-Nahal and A. H. M. Husein, "Thulium doped fiber amplifier (TDFA) for S-band WDM systems," *Open Journal of Applied Sciences*, vol. 2, no. 04, 2013.



- [233] M. Karlsson, “Modulational instability in lossy optical fibers,” *JOSA B*, vol. 12, no. 11, pp. 2071–2077, 1995.
- [234] G. P. Agrawal, “Modulation instability in erbium-doped fiber amplifiers,” *IEEE photonics technology letters*, vol. 4, no. 6, pp. 562–564, 1992.
- [235] S. K. Turitsyn, A. M. Rubenchik, and M. P. Fedoruk, “On the theory of the modulation instability in optical fiber amplifiers,” *Optics letters*, vol. 35, no. 16, pp. 2684–2686, 2010.
- [236] M. S. Aslam, M. Y. Hamza, and N. Sarwar, “Analytical analysis of modulation instability in fiber optics,” *AIP Advances*, vol. 2, no. 2, p. 022168, 2012.
- [237] Z. Li, A. Heidt, J. Daniel, Y. Jung, S. Alam, and D. J. Richardson, “Thulium-doped fiber amplifier for optical communications at 2  $\mu\text{m}$ ,” *Optics Express*, vol. 21, no. 8, pp. 9289–9297, 2013.
- [238] T. Heuermann, C. Gaida, M. Gebhardt, and J. Limpert, “Thulium-doped nonlinear fiber amplifier delivering 50 fs pulses at 20 W of average power,” *Optics letters*, vol. 43, no. 18, pp. 4441–4444, 2018.
- [239] A. V. Smith and J. J. Smith, “Mode instability in high power fiber amplifiers,” *Optics express*, vol. 19, no. 11, pp. 10 180–10 192, 2011.
- [240] S. Toenger, T. Godin, C. Billet, F. Dias, M. Erkintalo, G. Genty, and J. M. Dudley, “Emergent rogue wave structures and statistics in spontaneous modulation instability,” *Scientific reports*, vol. 5, p. 10380, 2015.
- [241] F. Haxsen, D. Wandt, U. Morgner, J. Neumann, and D. Kracht, “Monotonically chirped pulse evolution in an ultrashort pulse thulium-doped fiber laser,” *Optics letters*, vol. 37, no. 6, pp. 1014–1016, 2012.
- [242] G. P. Agrawal and M. Potasek, “Effect of frequency chirping on the performance of optical communication systems,” *Optics letters*, vol. 11, no. 5, pp. 318–320, 1986.
- [243] Y. Bu, X.-y. Zhang, and X.-z. Wang, “Effects of frequency chirping on the performance of optic communication system using midway optical phase conjugation,” *JOURNAL OF OPTOELECTRONICS LASER*, vol. 15, no. 6, pp. 683–687, 2004.
- [244] P. Myslinski, D. Nguyen, and J. Chrostowski, “Effects of concentration on the performance of erbium-doped fiber amplifiers,” *Journal of lightwave technology*, vol. 15, no. 1, pp. 112–120, 1997.
- [245] M. Z. Amin and K. K. Qureshi, “Er<sup>3+</sup>-Er<sup>3+</sup> interaction effects and performance evaluation of erbium doped fiber amplifiers,” in *2015 IEEE 28th Canadian Conference on Electrical and Computer Engineering (CCECE)*. IEEE, 2015, pp. 1383–1386.
- [246] A. W. Snyder and J. Love, *Optical waveguide theory*. Springer Science & Business Media, 2012.
- [247] R. Singh and M. L. Singh, “Evaluating the effect of doping concentration and doping radius on the gain of silica based thulium doped fiber amplifier,” in *2016 International Conference on Recent Advances and Innovations in Engineering (ICRAIE)*. IEEE, 2016, pp. 1–5.
- [248] —, “Investigation of the effect of change in doping parameters on the gain of a thulium doped fiber amplifier,” *Journal of Optical Technology*, vol. 88, no. 4, pp. 215–226, 2021.

- [249] S. D. Emami, H. A. Abdul-Rashid, H. Ahmad, A. Ahmadi, and S. W. Harun, "Effect of transverse distribution profile of thulium on the performance of thulium-doped fibre amplifiers," *Ukrainian journal of physical optics*, no. 13, № 2, pp. 74–81, 2012.
- [250] J. Martín, "Erbium transversal distribution influence on the effectiveness of a doped fiber: optimization of its performance," *Optics communications*, vol. 194, no. 4-6, pp. 331–339, 2001.
- [251] A. Hassani, E. Arzi, and F. E. Seraji, "Intensity based erbium distribution for erbium doped fiber amplifiers," *Optical and quantum electronics*, vol. 39, no. 1, pp. 35–50, 2007.
- [252] B. Vjaceslavs, S. Spolitis, I. Girts *et al.*, "Extended reach spectrum-sliced passive optical access network," *International Journal of Physical Sciences*, vol. 8, no. 13, pp. 537–548, 2013.
- [253] S.-H. Yam and J. Kim, "Ground state absorption in thulium-doped fiber amplifier: experiment and modeling," *IEEE journal of selected topics in quantum electronics*, vol. 12, no. 4, pp. 797–803, 2006.
- [254] Y. Sun, G. Luo, J. Zyskind, A. Saleh, A. Srivastava, and J. Sulhoff, "Model for gain dynamics in erbium-doped fibre amplifiers," *Electronics letters*, vol. 32, no. 16, pp. 1490–1491, 1996.
- [255] T. B. Benjamin and J. E. Feir, "The disintegration of wave trains on deep water part 1. theory," *Journal of Fluid Mechanics*, vol. 27, no. 3, pp. 417–430, 1967.
- [256] G. P. Agrawal, "Nonlinear fiber optics," in *Nonlinear Science at the Dawn of the 21st Century*. Springer, 2000, pp. 195–211.
- [257] K. Tai, A. Hasegawa, and A. Tomita, "Observation of modulational instability in optical fibers," *Physical review letters*, vol. 56, no. 2, p. 135, 1986.
- [258] S. Pan, C. Lou, and Y. Gao, "Multiwavelength erbium-doped fiber laser based on inhomogeneous loss mechanism by use of a highly nonlinear fiber and a Fabry-Perot filter," *Opt. Express*, vol. 14, no. 3, pp. 1113–1118, Feb 2006.
- [259] Y. Tao, Z. Xu, and S. Chen, "High-energy wavelength-tunable picosecond all-fiber laser based on active mode-locking," in *17th International Conference on Optical Communications and Networks (ICOON2018)*, Z. Li, Ed., vol. 11048, International Society for Optics and Photonics. SPIE, 2019, pp. 826 – 831. [Online]. Available: <https://doi.org/10.1117/12.2522582>
- [260] T. Kasamatsu, Y. Yano, and H. Sekita, "1.50- $\mu$ m-band gain-shifted thulium-doped fiber amplifier with 1.05 and 1.56- $\mu$ m dual-wavelength pumping," *Optics letters*, vol. 24, no. 23, pp. 1684–1686, 1999.
- [261] H. Garcia, A. M. Johnson, F. A. Oguama, and S. Trivedi, "Pump-induced nonlinear refractive-index change in erbium-and ytterbium-doped fibers: theory and experiment," *Optics letters*, vol. 30, no. 11, pp. 1261–1263, 2005.
- [262] Y. O. Barmenkov, A. Kir'yanov, and M. Andres, "Resonant and thermal changes of refractive index in a heavily doped erbium fiber pumped at wavelength 980 nm," *Applied physics letters*, vol. 85, no. 13, pp. 2466–2468, 2004.
- [263] K. Kim, R. Stolen, W. Reed, and K. Quoi, "Measurement of the nonlinear index of silica-core and dispersion-shifted fibers," *Optics letters*, vol. 19, no. 4, pp. 257–259, 1994.
- [264] G. Cappellini and S. Trillo, "Third-order three-wave mixing in single-mode fibers: exact solutions and spatial instability effects," *JOSA B*, vol. 8, no. 4, pp. 824–838, 1991.

- [265] S. Trillo and S. Wabnitz, "Dynamics of the nonlinear modulational instability in optical fibers," *Opt. Lett.*, vol. 16, no. 13, pp. 986–988, Jul 1991.
- [266] P. T. Dinda and K. Porsezian, "Impact of fourth-order dispersion in the modulational instability spectra of wave propagation in glass fibers with saturable nonlinearity," *JOSA B*, vol. 27, no. 6, pp. 1143–1152, 2010.
- [267] S. Aozasa, T. Sakamoto, T. Kanamori, K. Hoshino, K. Kobayashi, and M. Shimizu, "Tm-doped fiber amplifiers for 1470-nm-band WDM signals," *IEEE Photonics Technology Letters*, vol. 12, no. 10, pp. 1331–1333, 2000.
- [268] M. Alem, M. A. Soto, and L. Thévenaz, "Analytical model and experimental verification of the critical power for modulation instability in optical fibers," *Optics express*, vol. 23, no. 23, pp. 29 514–29 532, 2015.
- [269] M. N. Zervas, "Transverse mode instability analysis in fiber amplifiers," in *Fiber Lasers XIV: Technology and Systems*, vol. 10083. International Society for Optics and Photonics, 2017, p. 100830M.
- [270] V. E. Zakharov and L. Ostrovsky, "Modulation instability: the beginning," *Physica D: Nonlinear Phenomena*, vol. 238, no. 5, pp. 540–548, 2009.
- [271] A. Balyakin and N. Ryskin, "A change in the character of modulation instability in the vicinity of a critical frequency," *Technical Physics Letters*, vol. 30, no. 3, pp. 175–177, 2004.
- [272] D. Richardson, R. Laming, and D. Payne, "Pulse repetition-rates in a passive, self-starting, femtosecond soliton fibre laser," *Electronics Letters*, vol. 27, pp. 1451–1453, 1991.
- [273] M. A. Sharif, "Modulation instability of optical nonlinear media, a route to chaos," in *2011 Asia Communications and Photonics Conference and Exhibition (ACP)*. IEEE, 2011, pp. 1–8.
- [274] A. Zarifi, S. Emami, F. Zahedi, H. Fatehi, S. Mirnia, H. Ahmad, and S. Harun, "Quantitative analysis of energy transfer processes in Thulium–Bismuth germanate co-doped fiber amplifier," *Optical Materials*, vol. 35, no. 2, pp. 231–239, 2012.
- [275] S. D. Jackson and T. A. King, "Efficient gain-switched operation of a Tm-doped silica fiber laser," *IEEE journal of quantum electronics*, vol. 34, no. 5, pp. 779–789, 1998.
- [276] A. V. Smith and J. J. Smith, "Mode instability thresholds for Tm-doped fiber amplifiers pumped at 790 nm," *Optics Express*, vol. 24, no. 2, pp. 975–992, 2016.
- [277] S. Aozasa, H. Masuda, and M. Shimizu, "S-band thulium-doped fiber amplifier employing high thulium concentration doping technique," *Journal of lightwave technology*, vol. 24, no. 10, pp. 3842–3848, 2006.
- [278] S. Naderi, I. Dajani, J. Grosek, T. Madden, and T.-N. Dinh, "Theoretical analysis of effect of pump and signal wavelengths on modal instabilities in Yb-doped fiber amplifiers," in *Nonlinear Frequency Generation and Conversion: Materials, Devices, and Applications XIII*, vol. 8964. International Society for Optics and Photonics, 2014, p. 89641W.
- [279] J. Liu, C. Liu, H. Shi, and P. Wang, "High-power linearly-polarized picosecond thulium-doped all-fiber master-oscillator power-amplifier," *Optics express*, vol. 24, no. 13, pp. 15 005–15 011, 2016.

- [280] M. Montagna, S. Selleri, and M. Zoboli, “Nonlinear refractive index in erbium-doped optical amplifiers,” *Optical and quantum electronics*, vol. 27, no. 10, pp. 871–880, 1995.
- [281] O. G. Started, “Optical communication system design software,” 2003.
- [282] M. M. Rathore, A. Ahmad, A. Paul, and S. Rho, “Urban planning and building smart cities based on the internet of things using big data analytics,” *Computer Networks*, vol. 101, pp. 63–80, 2016.
- [283] D. V. Dimitrov, “Medical internet of things and big data in healthcare,” *Healthcare informatics research*, vol. 22, no. 3, pp. 156–163, 2016.
- [284] S. D. Agger and J. H. Povlsen, “Emission and absorption cross section of thulium doped silica fibers,” *Opt. Express*, vol. 14, no. 1, pp. 50–57, Jan 2006.
- [285] J. Martin, “Erbium transversal distribution influence on the effectiveness of a doped fiber: optimization of its performance,” *Optics Communications*, vol. 194, no. 4, pp. 331 – 339, 2001.
- [286] P. F. Wysocki, J. L. Wagener, M. J. Digonnet, and H. J. Shaw, “Evidence and modeling of paired ions and other loss mechanisms in erbium-doped silica fibers,” in *Fiber laser sources and amplifiers IV*, vol. 1789. International Society for Optics and Photonics, 1993, pp. 66–79.
- [287] J. Nilsson, B. Jaskorzynska, and P. Blixt, “Implications of pair-induced quenching for erbium-doped fiber amplifiers,” in *Optical Amplifiers and Their Applications*. Optical Society of America, 1993, p. MD19.
- [288] E. Delevaque, T. Georges, M. Monerie, P. Lamouler, and J.-F. Bayon, “Modeling of pair-induced quenching in erbium-doped silicate fibers,” *IEEE Photonics Technology Letters*, vol. 5, no. 1, pp. 73–75, 1993.
- [289] M. Tao, Q. Huang, T. Yu, P. Yang, W. Chen, and X. Ye, “Cross relaxation in Tm-doped fiber lasers,” in *2<sup>nd</sup> International Symposium on Laser Interaction with Matter (LIMIS 2012)*, vol. 8796. International Society for Optics and Photonics, 2013, p. 87961W.
- [290] J. W. Cooley and J. W. Tukey, “An algorithm for the machine calculation of complex Fourier series,” *Mathematics of computation*, vol. 19, no. 90, pp. 297–301, 1965.