Analysis and Design of Matched Feeds for Offset Parabolic Reflector Antennas using Analytical and Numerical Techniques

A Synopsis report

submitted by

Rajib Jana
(Roll No. 09610210)

in partial fulfillment for the award of the degree of

DOCTOR OF PHILOSOPHY

Under the supervision of

Prof. R. Bhattacharjee

DEPARTMENT OF ELECTRONICS AND ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
GUWAHATI - 781 039, ASSAM, INDIA

Abstract

This research deals with the analysis and design of few novel matched feed structures for offset parabolic reflector antenna systems. An effective hybrid numerical technique is developed to evaluate the performance of a complete system of feed and reflector which reduces of computation time and memory requirement at the same time maintain appropriate level of accuracy. The hybrid technique is formed by using the combination of mode matching (MM) and 2-D finite element method (FEM) for interior field analysis of horn; method of moment (MoM) solution for Kirchoff Huygen's equation using Rao, Wilton and Gilsson (RWG) basis functions for open ended waveguide problem; physical optics (PO) to evaluate the far field radiation pattern of the reflector. The performance of this technique is compared with simulated results of HFSS and close match is obtained. Further, particle swarm optimization (PSO) technique and analytical or computed semi-analytical far field pattern of feed aperture using the available analytical or 2-D FEM based solution of Helmholtz equation respectively, are incorporated for conjugate matching to estimate the mode coefficients and relative phases in the matched feed design. In this thesis, the details of conjugate matching and matched feed design is investigated and also, few novel matched feed configurations are introduced. The proposed matched feed structures reported in this thesis have the ability to achieve the wide bandwidth for both return loss and conjugate matching.

1 Introduction

Offset reflector antennas offer features such as reduced aperture blockage, low side lobe levels, and isolation between feed and reflector as compared to their axisymmetric counterpart. Such features have been made use of in various applications like satellite communication, telemetry, remote sensing and mono-pulse tracking radar, etc [1]. In spite of these advantages, such reflector antennas often have limitations in exploiting the benefit of frequency reuse and effect the accuracy of the signal tracking by exhibiting high cross-polarization level when illuminated with linearly polarized feed. On the other hand, it also suffers from beam squinting when illuminated by a circularly polarized feed. Several remedial measures to reduce the depolarization effect of such antenna which have been reported in literature are as follows:

- Maintaining large focal-length-to-diameter ratio (F/D) and small tilt angle (α) helps in solving such problem [2]. However, large F/D results in a bulky and heavy structure.
- Use of the polarization selective grid has been proposed for offset reflector, so that it discriminates the cross-polar level in the secondary pattern [3]. Such solution may add complexity and increase system cost.
- Use of conventional dielectric lens in front of the horn is a way of reducing cross-polar power of an offset reflector antenna [4]. However, presence of dielectric increases the noise temperature as well as reduces the system gain.
- Rudge and Adatia proposed the conjugate matching technique which combines appropriate amount of desired higher order modes with dominant mode to reduce the cross-polar power of secondary pattern [1]. This technique is widely used nowadays for the design of feed as a multi-mode horn or antenna array. Such feeds are called matched feed.

With the increase in number of satellites on orbits, reducing the possibility of interference with other satellites is becoming increasingly important now a days. To minimize this interference, the amount of side lobe and cross-polarization energy should be as low as possible in the principal plane of transmitting and receiving antenna; and a narrow main beam is also preferable for satellite communication. Taking those considerations into account, offset parabolic reflector antennas are often preferred over other narrow beam antennas, such as center feed parabolic antenna which suffers due to aperture blockage, dual reflector system which has drawback of noise temperature and low efficiency, and antenna array which has narrow bandwidth and high power loss etc [1]. Offset parabolic reflector antenna, which is a variant of parabolic reflector antenna, is extensively used in satellite communication systems like remote sensing, telemetric and TV broadcasting.

Design of compact offset reflector antenna system requires low values of F/D (F: focal length, D: diameter of the offset paraboloid antenna). Further, small F/D reduces the side lobe energy and creates very narrow pencil beam [1]. However, it increases cross polarization for a linear polarized feed. As mentioned earlier, literature provides the conjugate matching techniques to suppress the cross polar power with the use of multi-mode horns [1, 5, 6]. Also, it is mentioned in [1] that the performance of offset parabolic reflector antennas is strongly dependent on the feed characteristics. Although the concept of matched feed is known to the research community for a long time, it may be mentioned that the design methodologies of

such feeds have not been dealt comprehensively in literature. The design of such feeds is quite involved and simulation of the entire system using CAD-tool is often very time-consuming. Matched feed design for offset reflector is still an active area of research as apparent from recent publications in this field. A tri-mode $(\mathrm{TE}_{11}^1, \mathrm{TM}_{11}^1, \mathrm{TE}_{21}^1)$ circular matched feed [7] has been used to feed the gravitationally balanced back-to-back reflector antenna, a rectangular matched feed has been proposed for mono-pulse radar using TE_{01} and TE_{11} modes [6], and a corrugated circular matched feed using HE_{11}^1 and HE_{21}^1 hybrid modes have also been developed [8]. A simplified analytical study on the dual-mode circular matched feed using TE_{11}^1 and TE_{21}^1 modes has been presented in [9] and a ring choke excited compact dual-mode circular waveguide feed using similar type of modes has also been proposed in [10]. A novel dual-mode dual-polarized circular waveguide feed excited by concentrically shorted ring patch is presented in [11]. A new kind of feed having symmetrical cascaded discontinuities which are created using intersection of three off-centered junctions of circular waveguide placed symmetrically with angular spacing of 120^0 operated with TE_{11}^1 and TE_{21}^1 modes, is proposed in circular waveguide for broadband operation of conjugate matched feed [12]. Several other literature related to conjugated matching are also available [13–15]. Such recent works motivates us to investigate the various aspects of the design of multi-mode matched feed.

There has been considerable development in solving the electromagnetic (EM) problems using numerical techniques such as finite-element method (FEM), method of moment (MoM), finite difference time domain method (FDTD) etc. Such techniques can be applied along with geometric optics (GO), physical optics (PO), geometric theory of diffraction (GTD) and physical theory of diffraction (PTD) for calculation of radiated fields. However, solving practical problem using such techniques are quite involved. Instead of using a single technique, combination of techniques are preferable. A combination of these techniques can be applied keeping in view the accuracy of solution, requirement of computation resources and time. Therefor, the objective of this research is also to develop hybrid techniques for analysis and design of multi-mode feed horn structures and investigate the performance of the complete system including the offset reflector. Literature which have mostly inspired or motivated us to develop the hybrid technique to analyze the entire system of offset reflector antenna, are mentioned in [16–19].

2 Objectives

From the discussions presented in the earlier section, it can be seen that a feed antenna has a critical role in determining the overall performance of the offset parabolic antenna system. Moreover, performance evaluation of the complete system involving the offset reflector and the feed is quite involved. The objective of the thesis work is to investigate and propose new matched feed structures and implement the hybrid technique to investigate the entire system of offset reflector antenna. In order to meet the thesis objective, following majors tasks are to be carried out:

- Pattern calculation in case of an offset parabolic reflector for a given feed excitation.
- Development of an efficient hybrid numerical computing technique to analyze the feed antenna.

- Design of matched feed for a given specification of parabolic reflector.
- Development of analytical/numerical technique for synthesizing the feed and reflector.

3 Thesis Organization

The organization of this thesis is presented as follows:

Chapter 1: Introduction

This chapter presents the introduction and basic theory of an offset reflector antenna. The motivation of the work and summary of the contributions of the thesis are reported in this chapter. A flow chart is also presented which highlights the individual chapter's work.

Chapter 2: Interior Field Analysis using MM Technique

In this chapter, analysis of scattering parameters of regular shape horn (like rectangular and circular) using mode matching (MM) technique is reported. In case of tapered junction of regular horn structure, the closed-form expression of reaction matrix which aids in efficient implementation of the codes for junction analysis is formulated. Also, the convergence issue of MM technique is discussed. In addition, the theory of generalize scattering parameter (GSP) is presented in this chapter. To evaluate the performance of this technique, several horn structures having smooth, stepped and corrugated walls are studied and for such horn structures, results computed using our developed code in MATLAB are compared with simulated results of HFSS.

Chapter 3: A Hybrid MM/FE Technique to Analyze Horn having Discontinuities

This chapter presents the solution of Helmholtz equation using 2-D finite element method (FEM) to calculate the fields and their cutoff wave-numbers for non-regular surfaces. Delaunay triangulations are used to develop the FEM solution. The related theory for accurate prediction of eigenvalue and eigenvector for the solution of Helmholtz equation is discussed. The issues related to the calculation of reaction matrix for non-regular junction employing MM technique are elaborately discussed. The performance of this hybrid technique which is a combination of MM and 2-D FEM is evaluated in case of stepped cylindrical horn containing inner posts.

Chapter 4: Analysis of Open Ended Waveguide using MoM Technique

This chapter discusses the theory based on which the aperture problem related to multi-mode horn is modeled using the method of moment (MOM). The Rao-Willton-Gillson function (RWG) and Delaunay triangulations are used for 2D MOM solution to model for cases of horn having aperture on finite and infinite ground plane. Kirchhoff-Huygen's principle has been applied to model the horn aperture on a finite ground plane. The singular problem of the solution of scattering electric and magnetic field equation (EFIE, MFIE) is also described in

this modeling. The performance of several horn structures are investigated using those techniques and the results are also compared with the simulated results obtained using HFSS-15. The theory behind the calculation of approximate far field pattern of multi-mode feed using Chu's model (analytical model) is also elaborately explained.

Chapter 5: **An Analytical/Semi-analytical and Proposed Hybrid Technique for Reflector-Feed Model**

In this chapter, the far field pattern calculation of an offset reflector antenna using physical optics (PO) is reported. A brief discussion on particle swarm optimization technique (PSO) is presented as PSO has been used as a tool for optimization. Matched feed design using this optimization technique along with analytical or semi-analytical model of feed and reflector is also presented. For the rest of this chapter, the performance of our proposed hybrid technique comprising of MM, FEM, MoM and PO is evaluated for a proposed new kind of circular matched feed structure. The matched feed design involves TE_{11}^1, TM_{11}^1 and TE_{21}^1 modes as the operating modes.

Chapter 6: **Design of Novel Matched Feed Structures**

In this chapter, several matched feed structures are designed using PSO optimization technique along with analytical or semi-analytical model of feed and reflector. The first design is a rectangular matched feed based on TE_{01} and TM_{11} operating modes. In the next design, a non-regular type of matched feed structure for wide-band application is presented in this chapter. This is followed by a wide-band diagonal matched feed which is introduced to suppress the cross-polar power of the asymmetric-plane of an offset reflector antenna. A feed structure utilizing the conjugate field radiated from a rectangular choke excited by two slots on a diagonal horn to suppress the wide-band cross-polar power of an offset reflector antenna is also proposed. Design techniques for all the horn structures are explained in details.

Chapter 7: **Summary and Future Work**

In this chapter, the summary of the works is presented and conclusions are drawn. Possible directions of extending some of these works are also discussed in the chapter.

4 Thesis Contribution

Various factors which influence the cross-polar performance of a conjugately matched feed have been investigated in detail.

Novel matched feed configurations have been proposed for obtaining wideband cross polar performance. Rectangular matched feed employing TE_{01} and TM_{11} modes have been designed and its cross polar performance has been investigated. Circular matched feed structure involving TE_{11}^1, TM_{11}^1 and TE_{21}^1 modes has been developed. Matched feed design involving non-regular geometries and waveguide modes have also been introduced. A diagonal matched

feed has been investigated for the application of horizontal-polarization. A rectangle choke excited by two slots on a diagonal waveguide has been proposed for the wide-band application.

Hybrid methods along with numerical codes have also been developed to investigate the performance of the proposed horn geometries. The proposed methods are reasonably accurate with comparatively lower computation complexity. For the adopted hybrid technique, the major points are outlined below::

(a) Formulation of closed form expressions of reaction matrix for waveguide junctions for application of mode matching technique.

(b) Investigation of discontinuities using combination of MM and 2D-FEM techniques.

(c) Use of Kirchhoff-Huygen's principle to solve problems related to horn aperture in a finite ground plane and computation of field quantities employing RWG functions and 2D MOM.

(d) Development of PO technique for evaluation of reflector pattern.

5 List of Publications

Journal Publications:

- R. Jana and R. Bhattacharjee, "Matched feed design employing TE_{01} and TM_{11} modes in a smooth walled rectangular waveguide for cross-polar reduction in offset reflector antenna systems," *AEÜ International Journal of Electronics and Communications*, vol-69, pp. 873 - 877, 2015.

- R. Jana and R. Bhattacharjee, "A Novel Matched Feed Structure for Achieving Wide Cross-polar Bandwidth for an Offset Parabolic Reflector Antenna System," *IEEE Antenna and Wireless Propagation Letters*, vol-14, pp. 1590-1593, 2015.

Conference Publications:

- R. Jana and R. Bhattacharjee, "Analysis of waveguide junctions using mode matching technique," *in IEEE Applied Electromagnetics Conference (AEMC)*, pp.1-4, 18-22 Dec., 2011.

- R. Jana and R. Bhattacharjee, "Analysis of horn antennas including the horn transition into half space employing a full wave hybrid technique," *in IET International Radar Conference*, pp.1-4, 14-16 April, 2013.

- R. Jana and R. Bhattacharjee, "Analysis of Scattering Parameters of a Stepped Cylindrical Horn containing inner Posts using MM and 2-D FEM," *in Twentieth National Conference communications (NCC)*, pp.1-6, Feb. 28-March 2, 2014.

- R. Jana and R. Bhattacharjee, "A Tri-mode Low Cross-polarized Circular Matched Feed for Offset Reflector Antenna System," *in Twenty First National Conference communications (NCC)*, pp.1-6, Feb. 27-March 1, 2015.

- R. Jana and R. Bhattacharjee, "A Hybrid Numerical Technique to Investigate the Performances of Offset Reflector and Matched Feed," *in IEEE Applied Electromagnetics Conference (AEMC)*, 18-21 Dec., 2015.

Manuscripts Under Preparation:

- R. Jana and R. Bhattacharjee, "Design of a novel dual-mode diagonal matched feed to achieve wide cross-polar bandwidth for an offset reflector antenna," *under preparation*.

- R. Jana and R. Bhattacharjee, " Wide-band matched feed design employing conjugate field radiated from a square choke excited by two slots on a diagonal waveguide," *under preparation*.

- R. Jana and R. Bhattacharjee, " A Matched feed design using the combined of 2-D full wave hybrid numerical technique and a hybrid probabilistic optimization technique," *under preparation*.

References

[1] A. Rudge and N. Adatia, "Offset-parabolic-reflector antennas: A review," *Proceedings of the IEEE*, vol. 66, no. 12, pp. 1592–1618, Dec. 1978.

[2] W. Stutzman and M. Terada, "Design of offset-parabolic-reflector antennas for low cross-pol and low sidelobes," *Antennas and Propagation Magazine, IEEE*, vol. 35, no. 6, pp. 46–49, Dec 1993.

[3] T. S. Chu, "Cancellation of polarization rotation in an offset paraboloid by a polarization grid," *The Bell Sys. Tech., J.*,, vol. 56, no. 6, pp. 977 – 986, July 1977.

[4] E. Lier and S. Skyttemyr, "A shaped single reflector offset antenna with low cross-polarization fed by a lens horn," *Antennas and Propagation, IEEE Transactions on*, vol. 42, no. 4, pp. 478–483, Apr 1994.

[5] Z. Pour and L. Shafai, "A novel impedance matched mode generator for excitation of the {TE21} mode in compact dual-mode circular waveguide feeds," *Antennas and Wireless Propagation Letters, IEEE*, vol. 10, pp. 427–430, 2011.

[6] S. Sharma, D. Pujara, S. Chakrabarty, and V. Singh, "Improving the cross-polar performance of an offset parabolic reflector antenna using a rectangular matched feed," *Antennas and Wireless Propagation Letters, IEEE*, vol. 8, pp. 513 –516, 2009.

[7] K. Bahadori and Y. Rahmat-Samii, "Tri-mode horn feeds revisited: Cross-pol reduction in compact offset reflector antennas," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 9, pp. 2771–2775, Sept. 2009.

[8] S. Sharma, D. Pujara, S. Chakrabarty, and R. Dey, "Cross-polarization cancellation in an offset parabolic reflector antenna using a corrugated matched feed," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 861–864, 2009.

[9] Z. Pour and L. Shafai, "A simplified feed model for investigating the cross polarization reduction in circular- and elliptical-rim offset reflector antennas," *Antennas and Propagation, IEEE Transactions on*, vol. 60, no. 3, pp. 1261–1268, March 2012.

[10] ——, "A ring choke excited compact dual-mode circular waveguide feed for offset reflector antennas," *Antennas and Propagation, IEEE Transactions on*, vol. 60, no. 6, pp. 3011–3015, June 2012.

[11] ——, "A novel dual-mode dual-polarized circular waveguide feed excited by concentrically shorted ring patches," *Antennas and Propagation, IEEE Transactions on*, vol. 61, no. 10, pp. 4917–4925, Oct 2013.

[12] R. Dey, S. Chakrabarty, and R. Sharma, "Broadband conjugate matched feed horn- a novel concept," *Antennas and Wireless Propagation Letters, IEEE*, vol. PP, no. 99, pp. 1–1, 2015.

[13] Z. Pour and L. Shafai, "Improved cross-polarization performance of a multi-phase-center parabolic reflector antenna," *Antennas and Wireless Propagation Letters, IEEE*, vol. 13, pp. 540–543, 2014.

[14] Z. Pour, L. Shafai, and B. Tabachnick, "A practical approach to locate offset reflector focal point and antenna misalignment using vectorial representation of far-field radiation patterns," *Antennas and Propagation, IEEE Transactions on*, vol. 62, no. 2, pp. 991–996, Feb 2014.

[15] Z. Pour and L. Shafai, "Investigation of asymmetric phase errors of an optimized dual-mode primary feed on the cross polarization of offset reflector antennas," *Antennas and Wireless Propagation Letters, IEEE*, vol. 9, pp. 872–875, 2010.

[16] R. Bunger and F. Arndt, "Moment-method analysis of arbitrary 3-d metallic n-port waveguide structures," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 48, no. 4, pp. 531–537, Apr 2000.

[17] F. Arndt, J. Brandt, V. Catina, J. Ritter, I. Rullhusen, J. Dauelsberg, U. Hilgefort, and W. Wessel, "Fast cad and optimization of waveguide components and aperture antennas by hybrid mm/fe/mom/fd methods-state-of-the-art and recent advances," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 1, pp. 292–305, 2004.

[18] R. Beyer and F. Arndt, "Efficient modal analysis of waveguide filters including the orthogonal mode coupling elements by an mm/fe method," *Microwave and Guided Wave Letters, IEEE*, vol. 5, no. 1, pp. 9 –11, jan 1995.

[19] Y. Rahmat-Samii, D.-W. Duan, D. Giri, and L. Libelo, "Canonical examples of reflector antennas for high-power microwave applications," *Electromagnetic Compatibility, IEEE Transactions on*, vol. 34, no. 3, pp. 197 –205, aug 1992.