INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
PhD-17 SHORT ABSTRACT OF THESIS

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SHORT ABSTRACT

This thesis investigates the coherent manipulation of light–matter interactions using scalar and vector beams to achieve controlled enhancement of spatial resolution in atomic and quantum-dot systems. By exploring both linear and nonlinear optical regimes, the work demonstrates how structured light can be harnessed to engineer susceptibility, beam dynamics, and super-resolution imaging. A semiclassical framework is adopted to describe light–matter interaction, beginning with Maxwell's equations and wave propagation in linear and nonlinear media under the paraxial approximation. The atom–field interaction Hamiltonian is developed within the electric-dipole approximation, and the density-matrix formalism is introduced to analyze quantum coherence effects. Fundamental concepts including exciton–phonon interactions in quantum dots, multi-level atomic systems, vector beam generation, and the resolution limit of stimulated emission depletion (STED) microscopy are also discussed.

The first study examines phase-dependent susceptibility in a nondegenerate four-level closed-loop atomic system interacting with cylindrical vector beams. The relative phase between probe and control fields enables controlled gain and absorption through distinct quantum pathways. Phase-induced modulation leads to polarization rotation over one Rayleigh length. In the nonlinear regime, increased probe intensity and atomic density produce quasi-periodic self-focusing and self-defocusing patterns for radial, azimuthal, and spiral vector beams, resulting in beam narrowing and enhanced gain, indicating potential resolution improvement.

The second study compares scalar and vector beam focusing in a four-level active-Raman-gain medium. Analytical expressions for linear and third-order nonlinear susceptibilities reveal significant enhancement of cross-Kerr nonlinearity under appropriate detuning conditions. For scalar beams, strong cross-Kerr effects drive substantial beam waist reduction, while vector beams exhibit gain-assisted narrowing dominated by energy transfer from the control field. Distinct polarization dynamics are observed at the minimum beam waist, highlighting fundamental

differences in focusing mechanisms between scalar and vector beams.

The final study extends structured-light control to a two-level quantum dot system for super-resolution imaging. Using chirped and time-delayed spatiotemporal beams within a rapid adiabatic passage protocol, robust population transfer is achieved to generate a super-resolved spot. Temperature-dependent phonon-induced decoherence is analyzed via the variational master equation approach. An unwanted low-intensity ring arising from beam-tail dominance is suppressed using Bessel-modulated truncated structured beams. Numerical results show that exciton–phonon interactions degrade resolution at low pulse areas but enter a decoupling regime at higher pulse areas, restoring image quality.