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Linear and nonlinear propagation of cylindrical vector beams through a nondegenerate four-level atomic system

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In this work, we consider a nondegenerate four-level closed-loop system where the relative phase shift between various applied fields can effectively modulate the response for the probe field. This configuration can be realized in the $^6\text{Li } D_1$ line transition hyperfine structure. Due to the closed-loop structure, the phase difference between the control and the probe field gives rise to different excitation pathways. The interference between different paths affects the linear response of the medium. Also, at higher densities, the nonlinear effect introduces self-focusing and defocusing of the probe vector beam (PVB) as it propagates through the medium. In our work, self-focusing with cylindrical vector (CV) beams controls the polarization, a feature that is limited in scalar beams. To validate the linear response of PVB, we present the atomic coherences numerically which align precisely with our analytical findings. The analysis of susceptibilities affords important insights into the physics underlying phase-dependent interference. We demonstrate that at two-photon resonance, transitioning phase shift from 0 to $\pi/2$ can convert an absorber into an amplifier. Further, we investigate the state of polarization (SOP) of the PVB at the input and a distance of one Rayleigh length inside the medium for all three kinds of CV beams (radial, azimuthal, and spiral). We find, for a phase shift of zero, the polarization ellipse rotates $\pi/2$ at each point in the transverse plane after traversing a distance of one Rayleigh length. However, for a phase shift of $\pi/2$, the polarization rotation is smaller than in the previous scenario, albeit accompanied by variations in ellipticity. At strong probe intensities, a phenomenon known as “self-focusing” emerges, attributed to the dominant effects of the medium’s third-order nonlinearity. The implementation of self-focusing has resulted in a reduction in the spot size of the beams, which could prove beneficial in enhancing resolution.

Author: DAS, Partha (Indian Institute of Technology Guwahati)

Co-author: Prof. DEY, Tarak Nath (Indian Institute of Technology Guwahati)

Presenter: DAS, Partha (Indian Institute of Technology Guwahati)

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