Theory of electromagnetically induced waveguides

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We use a full density matrix framework and the propagation equation to study the electromagnetic field induced waveguide in an atomic vapor. We explain the experimental results of Truscott et al. [Phys. Rev. Lett. 82, 1438 (1999)] for waveguiding in Rb vapor.

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In recent years considerable progress has been made in achieving control of the optical properties of a medium [1]. In particular the control of the dispersive properties of a medium is especially significant in several contexts. Scully and co-workers proposed enhancement of refractive index and its subsequent usage in enhancing the sensitivity of magnetometers [2]. Harris et al. [3] recognized the possibility of slowing the group velocity [4] of light and this has been demonstrated in recent experiments of Hau et al. [5] and Scully et al. [6]. In early works Tewari and Agarwal [7] and Harris et al. [8] had demonstrated the enhancement of the efficiency of VUV generation by the modifications in the absorptive and dispersive properties of a medium. These ideas have been extended to other nonlinear processes [9].

In a recent experiment Truscott et al. [10] demonstrated yet another important application of the modified dispersive properties of a medium. They produced an optically written waveguide in an atomic vapor. In their experiment a weak Gaussian probe beam was tuned close to the rubidium D₂ line (780 nm, 5 S₁/₂ → 2 P₃/₂), while a strong donut shaped pump beam [11] was tuned close to the rubidium D₁ resonance (795 nm, 5 S₁/₂ → 2 P₁/₂). The two beams interact because the two transitions share a common ground state. They used a simplified model for the susceptibilities to argue how the waveguiding can be produced.

In this paper we develop an explanation based on full density matrix equations and propagation equations in slowly varying envelop approximation. Our work includes all coherence effects. Our simulations for Doppler broadened systems produce results in excellent agreement with the work of Truscott et al. Our simulations also show guiding behavior at different positions inside the cell.

We now present a theoretical model for guiding of one optical beam with another optical beam. We consider the example of the relevant energy levels of Rb. The transitions are shown in Fig. 1. We ignore the hyperfine structure of the levels for a variety of reasons [12]. The D₁ and D₂ transition of Rb can be described as a V-type atomic system. The 2 γ’s represent the rate of spontaneous decay. The field on the D₂ transition |1⟩→|3⟩ is the probe field E₂ while the field on D₁ transition |2⟩→|3⟩ is the pump field E₁. Δ’s represent various detunings: Δ₁ = ω₁₃ − ω₁ and Δ₂ = ω₂₃ − ω₂, and 2G’s denote the Rabi frequencies. G₁ = d₁₃ E₁ /ℏ, G₂ = d₂₃ E₂ /ℏ with d_{αβ}’s representing the dipole matrix elements. This type of atomic system can be described by the following set of density matrix equations

\[ \dot{\rho}_{11} = -2 \gamma_1 \rho_{11} + i G_1 \rho_{31} - i G_1^* \rho_{13}, \]

\[ \dot{\rho}_{12} = -\left[ \gamma_1 + \gamma_2 + i (\Delta_1 - \Delta_2) \right] \rho_{12} + i G_1 \rho_{32} - i G_2 \rho_{13}, \]

\[ \dot{\rho}_{13} = -(\gamma_1 + i \Delta_1) \rho_{13} - i G_2 \rho_{23} - i G_1 \rho_{11} - \rho_{33}, \]

\[ \dot{\rho}_{22} = -2 \gamma_2 \rho_{22} + i G_2 \rho_{32} - i G_2^* \rho_{23}, \]

\[ \dot{\rho}_{23} = -(\gamma_2 + i \Delta_2) \rho_{23} - i G_1 \rho_{21} - i G_2 \rho_{22} - \rho_{33}, \]

\[ \dot{\rho}_{33} = 2 \gamma_1 \rho_{11} + 2 \gamma_2 \rho_{22} - i G_1 \rho_{31} + i G_1^* \rho_{13} - i G_2 \rho_{32} + i G_2^* \rho_{23}. \]

All the fast dependences of ρ_{αβ} have been removed by canonical transformation. Thus ρ₁₃ in the Schrödinger picture will be obtained by multiplying the solution of Eq. (1) by \( e^{-i\omega_{13} t} \). A Gaussian probe beam is tuned near to D₂ transition and a donut shaped Laguerre-Gaussian [11] pump beam of charge 3 is tuned near to D₁ transition. Thus the Rabi frequencies for pump and probe beams are given by

\[ G_1 = \left( \frac{G_{01}}{w_1} (z) \right) \frac{2}{\pi} \exp \left( -\frac{ikr^2}{2q_1} \right) e^{ikz - i\omega_{13}t}, \]

\[ G_2 = \left[ G_{02} / \sqrt{\frac{3\pi w_2}{r}} (z) \right] \left( \frac{\sqrt{2} r}{w_2 (z)} \right)^3 \times \exp \left( -\frac{ikr^2}{2q_2} - 3i \theta \right) e^{ikz - i\omega_{23}t}. \]

FIG. 1. A typical V system corresponding to the studies in Ref. [10].