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Photon drag enhancement by a slow-light moving medium via electromagnetically-induced transparency amplification

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ABSTRACT

Recently, a considerable enhancement has been observed in the celebrated Fresnel–Fizeau light drag by innovative experimental and theoretical approaches because of its fundamental and practical interest in the emerging technology of quantum optics and photonics. We present a semiclassical density matrix approach on the demonstration of light drag in a slow-light moving medium comprising five-level single tripod atomic configuration. To accomplish this, we introduce Kerr-type nonlinearity that leads to electromagnetically-induced transparency amplification under resonance conditions. By switching ON Kerr-type nonlinearity effect, we observe a prominent transparency window in probe field's absorption spectrum whose width and amplitude can be controlled further by the intensity of Kerr field and control field. The incorporation of Kerr field also switches light propagation from superluminal to subluminal domain. We predict a significant enhancement both in the lateral and the rotary photon drag owing to drag of light linear polarization state subjected to translation and rotation of the host medium, respectively. Consistent with earlier results, light drag considerably depends on both transverse and angular velocity of the host medium. In regime of subluminal propagation, light polarization state drags along the medium motion while in the superluminal propagation region it drags opposite to the medium motion.

1. Introduction

Frensel predicted that light propagating through a moving medium is subject to a drag effect [1]. On account of its fundamental and practical interest, Fresnel's drag has attracted a considerable attention over the years. Fresnel's predictions were verified experimentally for the longitudinal case by Fizeau [2]. Afterwards, experimental confirmation of the lateral photon drag was carried out by Jones [3]. He observed that a light beam propagating through a moving dielectric medium with transverse velocity v experienced a lateral displacement given by

$$\Delta x = \left(n_g - \frac{1}{n_r}\right)\frac{v_s L}{c}\,, \tag{1}$$

where n_g and n_r are the group and phase refractive indexes, v is the transverse velocity of moving medium, L is the length of the medium, and c is the speed of light.

For an accurate measurement of the light drag, Zeeman et al. [4] have carried out a series of experiments, which turned out to be consistent with the theoretical predictions of the light drag effect in a dispersive media. Subsequently, Jones [5] confirmed the existence of the rotary photon drag in a rotating dielectric medium. He observed angular displacement (rotation) of linear polarization state of light by a small angle θ_r given by

$$\theta_r = \left(n_g - \frac{1}{n_r}\right)\frac{\omega_s L}{c}\,, \tag{2}$$

where ω_s is the spin angular velocity of the medium.

Here the angular drag of light polarization arises from the phase difference between the right- and left-handed circular polarization states, which corresponds to the spin angular momentum of light [6]. It was observed that the optical spin and the orbital angular momentum separately account for the rotation of the polarization state of light and the transmitted image, respectively [7–10].

In this Letter, we demonstrate both the lateral (or transverse) and the rotary photon drag occurring due to translation and rotation of a slow-light optical medium, respectively. We exploit

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a five-level generic tripod atomic system. The Kerr-type nonlinearity in this system can, under resonance conditions, result in electromagnetically-induced transparency. We observe a prominent transparency window in the probe field's absorption spectrum. The width and amplitude of this spectral feature can be controlled by changing the intensities of the Kerr and the control fields. We can also tune the group velocity of the probe beam and make it either superluminal or subluminal. We predict a significant enhancement both in the lateral and the rotary photon drag. We find that, consistently with the earlier results, the light drag depends on both linear and angular velocities of the host medium. In the case of subluminal probe beam propagation, its polarization state is dragged in the same angular direction as the rotation of the medium while in the superluminal propagation regime it is dragged in the opposite direction.

As is well established, the law of dispersion of electromagnetic waves propagating through media exhibiting electromagnetically-induced transparency can be rather extreme. This results in slow light and light drag effects [11–14]. Demonstrations of ultraslow light in optical media can be found in Refs. [15–19]. Propagation of slow light in such media gives rise to many phenomena of fundamental and practical interest [20]. Recently, several experimental demonstrations of light drag in slow-light ruby medium have been performed [6,21–24]. Arnold et al. [6] have observed a considerable light drag enhancement (light polarization rotation) in rotating ruby medium. However, the mechanism of slow light in ruby medium has been a matter of debate [23,24]. Light pulse propagating in highly dispersive atomic media such as hot Rubidium vapor can experience ultrasmall group velocities leading to significant light drag. It was Lorentz who first predicted the impact of dispersion on the light drag effect [25]. Unfortunately, the light drag enhancement in dispersive atomic media is often accompanied by strong light absorption at the resonance frequency. However, Safari et al. [26] have presented experimental demonstration of the longitudinal light drag effect enhancement in highly dispersive Rubidium vapors. Instead of creating electromagnetically-induced transparency by kerr-type nonlinearity so as to control light propagation in cold atomic systems, the authors have exploited the dispersive nature of a hot atomic medium. This induces strong Doppler shifts and, hence, slow-light effects. The scheme has applications regarding highly-sensitive measurements of relative linear motion. Consequently, Kuan et al. [27] have observed further improvement in light drag using three-level cold Rubidium-85 atomic medium with the scheme of electromagnetically-induced transparency for the practical realization of a sensitive motion sensor. The authors have controlled the dispersive property of the medium by changing its refractive index so as to acquire the desired results of longitudinal light drag.

Both experimental studies in Refs. [26,27] have demonstrated only the longitudinal light drag enhancement by manipulating the drag of phase velocity of light without introducing Kerr-type nonlinearity that we introduced in this study. Recently one of the authors with collaborators [28] has studied rotary photon drag in a chiral medium with four-level cascade atomic configuration by manipulating the drag of group velocity of the probe field. In contrast, the current study demonstrates both lateral and rotary photon drag enhancement exploiting the scheme of electromagnetically-induced transparency amplification under Kerr-type nonlinearity in a single proposed experimental scheme. Moreover, we have used non-chiral five-level tripod atomic configuration, which has not been exploited for this purpose so far.

2. Model and its dynamics

For the practical realization of our theoretical model, we exploit a five-level tripod atomic configuration as shown in Fig. 1.

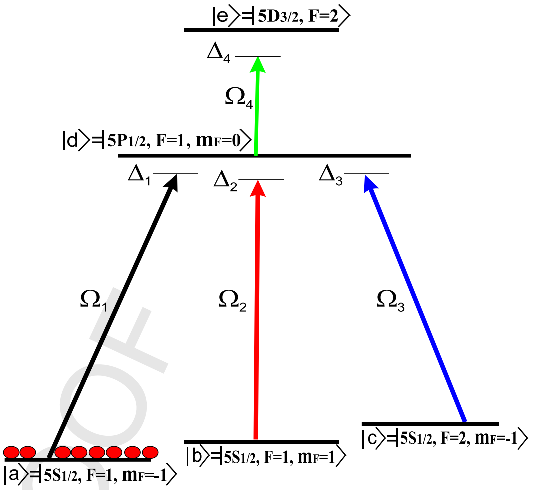

Fig. 1. The proposed laser-coupling energy level configuration of five-level tripod-type atomic system [30] employed for electromagnetically induced transparency amplification in conjunction with Kerr nonlinearity.

Previously, the same atomic system has been used for the study of giant Kerr nonlinearity for the practical implementation of 3-qubit phase gate in [30]. The authors predicted a significant reduction in group velocity that leads to slow light propagation. This motivates us to consider this novel five-level atom with peculiar optical properties as a slow light medium for the enhancement of photon drag coefficient by deploying Kerr-type nonlinearity. To the best of our knowledge, this scheme has not been previously employed on this unique tripod atomic configuration for photon drag enhancement. Nevertheless, previously, four-level tripod atomic systems have been studied extensively for various applications [29, 31–34]. Besides, five-level double tripod and N-tripod atomic systems have also attracted some research interest for slow light applications [18,35–37]. The study of five-level tripod atomic system may be more challenging for experimentalists, especially because of larger laser fields applied between various energy levels. At the same time, however, these systems have opened many new physical mechanisms of fundamental and practical interests. These include quantum more prominent interference and coherence effects which may drastically alter absorption, dispersion and optical nonlinearity of the system as is the case in our model.

In the proposed atomic configuration the states $|a\rangle$, $|b\rangle$ and $|c\rangle$, $|d\rangle$ and $|e\rangle$ are the eigenstates of the unperturbed Hamiltonian. The electric dipole transitions $|a\rangle \to |d\rangle$, $|b\rangle \to |d\rangle$ and $|c\rangle \to |d\rangle$ are coupled by a weak probe, Kerr, and coherent pump fields with Rabi frequencies $\Omega_1 = E_1\wp_{da}/2\hbar$, $\Omega_2 = E_2\wp_{db}/2\hbar$, $\Omega_3 = E_3\wp_{dc}/2\hbar$ respectively. The transition $|d\rangle \to |e\rangle$ is driven by a control field with Rabi frequency $\Omega_4 = E_4\wp_{ed}/2\hbar$. The detunings for these transitions are $\Delta_1 = \omega_{da} - \omega_a$, $\Delta_2 = \omega_{db} - \omega_b$, $\Delta_3 = \omega_{dc} - \omega_c$, $\Delta_4 = \omega_{ed} - \omega_d$, respectively. The proposed model could be experimentally realized in Rubidium-87 atomic configuration confined in a magneto-optical trap or in vapor cell [30]. The three ground states of the system namely, $|a\rangle$, $|b\rangle$, $|c\rangle$ can be represented by $\left|5S_{1/2}, F=1, m_F=-1\right\rangle$, $\left|5S_{1/2}, F=1, m_F=1\right\rangle$, $\left|5S_{1/2}, F=2, m_F=-1\right\rangle$, respectively. The lower and upper excited states $|d\rangle$ and $|e\rangle$ can be represented by $\left|5P_{1/2}, F=1, m_F=0\right\rangle$, and $\left|5D_{3/2}, F=2\right\rangle$, respectively (Fig. 1).

The self Hamiltonian of the system is given by

$$H_0 = \hbar\omega_e \left|e\right\rangle \left\langle e\right| + \hbar\omega_d \left|d\right\rangle \left\langle d\right| + \hbar\omega_c \left|c\right\rangle \left\langle c\right| \\ + \hbar\omega_b \left|b\right\rangle \left\langle b\right| + \hbar\omega_a \left|a\right\rangle \left\langle a\right| \qquad (3)$$

The Hamiltonian of the system interacting with the laser fields under dipole and rotating wave approximation is given as

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