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Microwave-controlled airy beam propagation in multilevel atomic vapors

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ABSTRACT

The propagation of two-dimensional Airy beams through an atomic system in closed-Λ configuration is theoretically investigated in which the hyperfine levels are coupled by a microwave pulse. Based on the generalized Huygens-Fresnel integral, the analytical expression for Airy beam through three-level atomic vapor is presented. By utilizing the S-matrix, the susceptibility determined by the microwave field, can play an important role to control Airy beam properties such as acceleration, self-bending and the intensity distribution, in the multi-level atomic systems. The mechanism of efficient manipulation of an Airy beam may have important applications in signal processing and optical communication.

1. Introduction

Due to the remarkable and interesting properties including transverse acceleration [1], self-healing [2], and nondiffraction over many Rayleigh lengths [3], investigations on Airy beams have been abundant and have undergone rapid development over the past decade. Such optical beams were extensively studied in optically linear media, nonlinear dielectrics, fibers, Bose–Einstein condensates, and so on. In particular, Zhang et al. have considered the dynamics of one–and two–dimensional finite–energy Airy beams in media with a harmonic potential [4,5], exhibiting periodic inversion and anharmonic oscillation properties. Moreover, it has been demonstrated that the propagation dynamics of self-accelerating beams can be considerably affected by the boundary conditions of a strongly nonlocal medium [6]. The propagation of an Airy beam in a strongly nonlocal nonlinear medium (SNNM) was theoretically studied by Zhou et al. [7]. Shen et al. have studied the anomalous interaction of Airy beams in nonlocal nonlinear media [8].

Besides, atomic vapor is a good platform for studying the generation, propagation and manipulation of optical beams as its optical properties are well known for us. When electromagnetically induced transparency (EIT) generated in atomic vapor, with the strong dispersion and free-absorption properties, now it is broadly used in investigating the propagation of Airy beams in this medium. However, those pioneering studies are only limited to the open EIT system, because of which can be easily implemented in theory and experiment. For instance, Zhuang et al. [9] and Hang and Huang [10] individually studied the propagation properties of an Airy beam through a four- and open three-level EIT atomic vapor. Hang and Huang [11] investigated the possibility of guiding stable ultraslow weak-light bullets by using Airy beams in a four-level atomic system via EIT and they also investigated the storage and retrieval of Airy light wave packets in a three-level atomic gas via EIT [12]. Compared to that, propagation of Airy beam in a close-Λ three-level system have attracted little attention. Although

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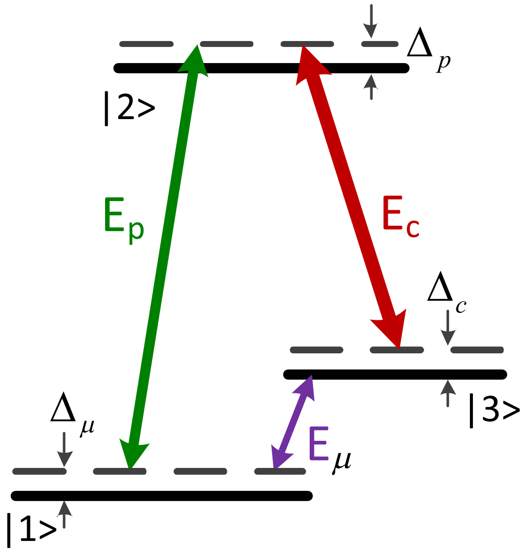

Fig. 1. The schematic of the close-Λ EIT system. Probe, control and microwave field are denoted asE_p, E_c and E_μ individually and these three fields are coupled with the atomic levels as shown above. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

the introduction of an microwave field to the Raman trapped states can bring a relative phase between the microwave field and the double optical fields, and the Raman trapped states will varies depending on the relative phase [13], the close-Λ EIT system manipulating the propagation of Airy beam has not been studied much.

In this paper, we have theoretically studied the propagation of Airy beams in a close-Λ EIT system. The susceptibility and refractive index of the medium are calculated and analyzed. Because of the role of the microwave field, the refractive index of the medium varies periodically along the propagation direction of the optical field, which further lead to acceleration of Airy beams propagating in a wavy parabolic way. Then on the basis of the extended Huygens-Fresnel integral principle, the propagation properties of two-dimensional Airy beam can be modulated by multiple variables of the microwave field. This offers us a powerful tool for controlling the propagation of Airy beams.

2. Theoretical model

The relevant energy levels for our scheme are shown in Fig. 1. The levels $\left|1\right\rangle$, $\left|2\right\rangle$ and $\left|3\right\rangle$ form a close-Λ three-level atomic system. The probing beam E_p (the wavevector $\boldsymbol{k}_p$and frequency ω_p) connects the transition $\left|1\right\rangle$ to $\left|2\right\rangle$ with the atomic resonant frequency ω_{21}. The coupling beam E_c ($\boldsymbol{k}_c$and ω_c) characterized by resonant frequency ω_{23} drives the transition $\left|2\right\rangle$ to $\left|3\right\rangle$. In addition, a microwave field E_μ ($\boldsymbol{k}_\mu$and ω_μ) is also introduced to couple the two ground levels $\left|1\right\rangle$ to $\left|3\right\rangle$ with the atomic resonant frequency ω_{31}. We define the frequency detuning as $\Delta_p = \omega_{21} - \omega_p$, $\Delta_c = \omega_{23} - \omega_c$ and $\Delta_\mu = \omega_{31} - \omega_\mu$, respectively. This is a typical closed-Λ system and has been intensively studied. However, in the following analysis, we show that with multiple variables such system can be used to theoretically analyzed the propagation of Airy beam.

In our scheme, the atomic cell is placed inside a magnetic-shielding cavity and a microwave resonator. The control and probe light are phase-locked to ensure the following coherent interaction process. The corresponding fields can be expressed as

$$E_p = \varepsilon_p \cos\left(\nu_p t - k_p z + \phi_p\right) \tag{1a}$$

$$E_c = \varepsilon_c \cos\left(\nu_c t - k_c z + \phi_c\right) \tag{1b}$$

$$E_\mu = \varepsilon_\mu \cos\left(\nu_\mu t + \phi_\mu\right) \tag{1c}$$

Where ε, ν and ϕ are the amplitude, angular frequency and initial phase, respectively. Now we begin our analysis by considering that Airy beam propagates in the close-Λ three-level atomic system, being described by the density-matrix equation of motion $\dot{\rho} = -\frac{i}{\hbar}[H, \rho] - \frac{1}{2}\left\{\Gamma, \rho\right\}$, with $H = \hbar\left(\Omega_{21}\left|1\right\rangle\left\langle 1\right| + \Omega_{23}\left|2\right\rangle\left\langle 2\right| + \Omega_{13}\left|3\right\rangle\left\langle 3\right|\right) + \left(\mu_{21}E_p\left|1\right\rangle\left\langle 2\right| + \mu_{23}E_c\left|2\right\rangle\left\langle 3\right| + \mu_{13}E_\mu\left|3\right\rangle\left\langle 1\right| + H.c.\right)$is the Hamiltonian of the microwave modified EIT system. Using a perturbation expansion and rotating wave approximation, we can obtain a series of density matrix equations as follows [14,15]:

$$\frac{\partial}{\partial t}\sigma_{21} = -(i\Delta_p + \Gamma_{21} + k_p u)\sigma_{21} - i\Omega_p(\sigma_{22} - \sigma_{11}) + i\Omega c_\sigma - i\Omega_\mu^* e^{i\Delta kz}\sigma_{23} \tag{2a}$$