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The localization of light in a 2D quasi-periodic coherently prepared atomic medium

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ABSTRACT

We study the localization of light in two-dimensional (2D) atomic systems. The system proposed in this paper is a resonant cold atomic ensemble with N configuration, which is coherently prepared by four pairs of control fields. Under the condition of the electromagnetically induced transparency, the propagation of the signal field is modelled as a system that is uniform along the propagating direction (z) but shows quasi-periodic structure on the transverse plane (x–y plane). Through numerical simulations, we find that the 2D quasi-periodic coherently prepared atomic medium can make the signal field anisotropic localized transversely during the propagation, and the localization direction can be manipulated by the phase of the control field.

1. Introduction

The localization of wave in disordered media is a universal phenomenon, occurring in a variety of different quantum and classical systems. The most interesting phenomenon of the wave localization in disordered structure is the Anderson model [1], which is a key concept, formulated to explain the spatial confinement due to disorder of quantum mechanical wave functions that would spread over the entire system [2–4]. Although Anderson localization (AL) was studied experimentally, the underlying phenomena were rarely observed directly due to the existence of complicated many-body interaction and other uncontrollable effects [5,6]. Instead, in recent years, various engineered systems have been proposed in which transportation of particles or propagation of waves can be significantly manipulated by controllable disorder. The typical examples include sound and light wave in disordered structures [5,7–11], quantum chaotic systems [12–14], and Bose–Einstein condensates (BECs) in optical potential [15,16].

In the original Ankderson model, investigations show that a localization phase transition is expected to occur only in three dimensions (3Ds) as the strength of disorder crosses a critical value [2]. It has been shown that for the lower dimensional system, only a crossover from extended to localized phases can be observed [7–9]. However, other kinds of delocalization–localization could occur in some one-dimensional (1D) models. The successful example is the Aubry–Andre model, in which a 1D quasi-periodic potential is introduced and a localization transition appears [17]. In recent years there has been renewed interest in wave propagation in quasi-periodic systems [18–20], in which the localization behavior can also be presented similar as in the disorder system.

EIT is a result of coherent preparation, by which the optical properties of the medium can be modified [22] dramatically. In the EIT medium, if the control field is designed to have various transverse distributions, the signal field may experience refractive index modulation, and consequently lead to many interesting transverse effects, such as electromagnetically induced focusing [23], electromagnetically induced gratings [24], electromagnetically induced waveguides [25], and electromagnetically induced selfimaging [23,26,27]. Ref. [21] has recently reported an EIT study in a quasi-periodic 1D medium. Considering the practicability, in our proposal, we coherently prepared a 2D quasi-periodic atomic structure with N configuration, which is driven by four pairs of control fields with different and small cross angles. Under the condition of the electromagnetically induced transparency, the propagation of the signal light field is modelled as a system that is uniform along the propagating direction (z) but shows

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quasi-periodic structure on the transverse plane (x–y plane), which makes the signal field anisotropic localized transversely during the propagation. Additionally, by appropriately tuning the related parameters, the transverse structure of the medium can be modulated, and the localization direction can also be manipulated.

2. The coherent preparation of a 2D quasi-periodic medium via EIT

Take the cold ^{87}Rb atoms for example, and assume that there is a magnetic field along z direction to separate the magnetic sublevels, we choose the N-type four-level EIT system as depicted in Fig. 1(a) [28], in which the two low-energy states $|1\rangle$ (F=1, m_F=−1) and $|2\rangle$ (F=2, m_F=−1) are taken from $5^2S_{1/2}$, and the two excited states $|3\rangle$ and $|4\rangle$ correspond to $5^2P_{1/2}$ ($F'=1$, m_F=0) and $5^2P_{3/2}$ ($F'=3$, m_F=0). $\delta=\omega_p-\omega_{13}$ is the signal detuning, and $\Delta=\omega_c-\omega_{24}$ is the controlling detuning. There are three fields to drive the transitions, the pump field driving the $|2\rangle$ to $|3\rangle$ transition with Rabi frequencies Ω_p, the control field driving $|2\rangle$ to $|4\rangle$ transition with Rabi frequencies Ω_c, and the signal field connecting $|1\rangle$ to $|3\rangle$ transition with Rabi frequencies Ω_s.

Owing to the selection rules of the excited atomic transitions, all three fields should have right circularly polarized components. Thus, we assume that the signal E_s incidents in the medium along z direction and is right circularly polarized, the pump field E_p comes from the negative direction $-z$ (see Fig. 1(b)) and is also right circularly polarized. The control field consists of four pairs of laser beams. Two pairs ($E^{\pm}_{xc1}$ and $E^{\pm}_{xc2}$, green beams) with different cross angles θ_1 and θ_2 along z direction are x linearly polarized, and the other two pairs ($E^{\pm}_{yc1}$ and $E^{\pm}_{yc2}$, blue beams) with cross angles α_1 and α_2 are y linearly polarized. Because linear polarization can be decomposed into the superposition of right and left polarization, such a kind of configuration can be used to generate a spatially modulated Rabi frequency for the control field to drive the $|2\rangle$ to $|4\rangle$ transition. Then, *an induced angle-tuned optical lattice is obtained* [29]. The system is assumed to have the population in the atomic ground state $|1\rangle$, the signal light is weak and travels along z direction, the pump field is strong enough so that it will not be depleted, the control fields are a little weak but much stronger than the signal field.

Assuming that the control fields shown in Fig. 1 have the Rabi frequency:

$$\Omega^{\pm}_{xc1}=\tfrac{1}{2}\Omega_{xc1}\exp[ik_c(\mp x\sin\theta_1-z\cos\theta_1)\mp i\psi_1],$$
$$\Omega^{\pm}_{xc2}=\tfrac{1}{2}\Omega_{xc2}\exp[ik_c(\mp x\sin\theta_2-z\cos\theta_2)\mp i\psi_2],$$
$$\Omega^{\pm}_{yc1}=\tfrac{1}{2}\Omega_{yc1}\exp[ik_c(\mp y\sin\alpha_1-z\cos\alpha_1)\mp i\varphi_1],$$
$$\Omega^{\pm}_{yc2}=\tfrac{1}{2}\Omega_{yc2}\exp[ik_c(\mp y\sin\alpha_2-z\cos\alpha_2)\mp i\varphi_2].$$

where k_c is the wave vector of the control fields, Ω_{xci}, $\psi_i(i=1,2)$ are the amplitudes and the phases of the ith component of the control field on the x–z plane, respectively and Ω_{ycj}, $\varphi_j(j=1,2)$ are the amplitudes and the phases of the jth component of the control field on the y–z plane, respectively.

In the circumstance of small cross angles, and suppose that $\psi_1=\psi_2=\psi_x$, $\varphi_1=\varphi_2=\varphi_y$, $\Omega_{x0}=\Omega_{xc1}$, $\eta_x=\Omega_{xc2}/\Omega_{xc1}$, $\beta_x=\sin\theta_2/\sin\theta_1$, $d_x=(k_c\sin\theta_1)^{-1}$; and on the y–z plane, $\Omega_{y0}=\Omega_{yc1}$, $\eta_y=\Omega_{yc2}/\Omega_{yc1}$, $\beta_y=\sin\alpha_2/\sin\alpha_1$, $d_y=(k_c\sin\alpha_1)^{-1}$. Then the transverse distribution of the control field can be written as the standard formula [21]:

$$\Omega_c(x,y)=\Omega_{x0}\left[\cos\left(\frac{x}{d_x}+\psi_x\right)+\eta_x\cos\left(\beta_x\frac{x}{d_x}+\psi_x\right)\right]+\Omega_{y0}\left[\cos\left(\frac{y}{d_y}+\varphi_y\right)+\eta_y\cos\left(\beta_y\frac{y}{d_y}+\varphi_y\right)\right],\qquad(1)$$

where β_n and η_n ($n=x,y$) are the incommensurate rate and the relative modulation strength in the x or y direction, respectively.

With the Maxwell–Bloch equation, and making rotating-wave and slowly varying envelope approximations, the equation for the envelope E of the signal field in steady state can be written as

$$2ik_s\frac{\partial E}{\partial z}+\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)E+k_s^2\chi(x,y)E=0,\qquad(2)$$

where k_s is the wave vector of the signal field. The expression of the susceptibility χ under the EIT condition has been given in Ref. [28]. Making the scaling transform $x\to x/(N\lambda/2\pi)$, $y\to y/(N\lambda/2\pi)$, $z\to z/(N^2\lambda/2\pi)$ (N is a constant), Eq. (2) reduces to the standard form:

$$i\frac{\partial E}{\partial z}=-\frac{1}{2}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)E+V(x,y)E,\qquad(3)$$

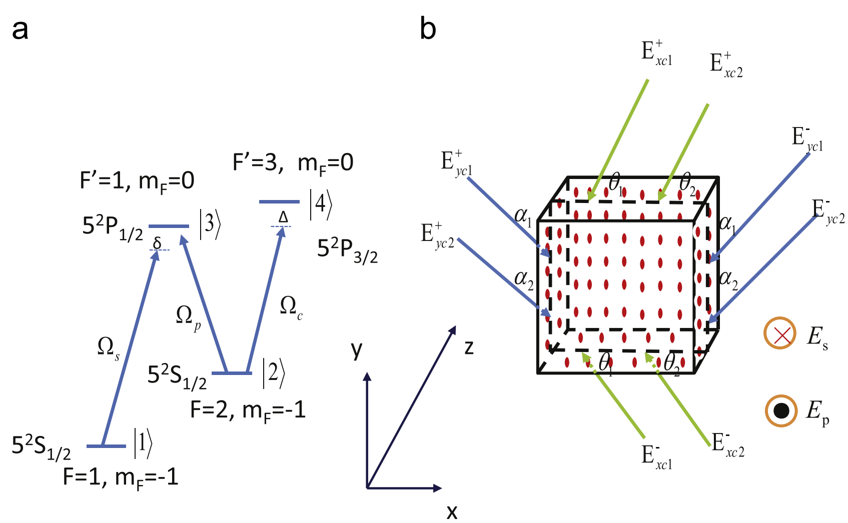

Fig. 1. Schematic of the system for realizing EIQPW. The left side is the atomic energy-level configuration, in which Ω_s, Ω_p and Ω_c are the Rabi frequencies of signal, pump and control fields, respectively. δ and Δ are the detunings for the transition from the state $|1\rangle$ to the state $|3\rangle$, and from the state $|2\rangle$ to the state $|4\rangle$, respectively. The signal E_s and the pump field E_p are incident in the medium from ahead and from behind. The control field consists of four pairs of laser beams, two pairs ($E^{\pm}_{xc1}$ and $E^{\pm}_{xc2}$, green beams) with different cross angles θ_1 and θ_2 (the angles between the control fields and x–z plane), the other two pairs ($E^{\pm}_{yc1}$ and $E^{\pm}_{yc2}$, blue beams) with cross angles α_1 and α_2 (the angles between the control fields and y–z plane), which are used to produce an electromagnetically induced quasi-periodically waveguide (EIQPW) medium on the transverse plane x–y, for the signal field to travel in the z direction. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)