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Electromagnetically induced two-dimensional grating assisted by incoherent pump

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ABSTRACT

We propose a scheme for realizing electromagnetically induced two-dimensional grating in a double-Λ system driven simultaneously by a coherent field and an incoherent pump field. In such an atomic configuration, the absorption is suppressed owing to the incoherent pumping process and the probe can be even amplified, while the refractivity is mainly attributed to the dynamically induced coherence. With the help of a standing-wave pattern coherent field, we obtain periodically modulated refractive index without or with gain, and therefore phase grating or gain-phase grating which diffracts a probe light into high-order direction efficiently can be formed in the medium via appropriate manipulation of the system parameters. The diffraction efficiency attainable by the present gratings can be controlled by tuning the coherent field intensity or the interaction length. Hence, the two-dimensional grating can be utilized as all-optical splitter or router in optical networking and communication.

1. Introduction

Electromagnetically induced transparency (EIT) [1,2], which plays an important role in the manipulation of optical properties of atomic medium, has been extensively investigated in the past two decades due to its enormous promising applications, such as slow light [3], optical storage [4], enhanced nonlinear optical processes at low light levels [5,6] and optical switching [7]. By replacing the traveling-wave field in EIT with an intensity dependent standing-wave field, a type of all-optical device called electromagnetically induced grating (EIG) [8–26] is formed as a result of the periodic variation of absorption and refractive index experienced by the probe field. And then, it acts as a Bragg grating or a diffraction grating according to the propagation direction of probe beam relative to the standing-wave. Based on that, EIG has many potential applications in optical communication, such as coherently induced photonic band gaps [12–14], beam splitter [15], optical switching and routing [16], optical bistability [17].

As a diffraction grating, the EIG is usually a hybrid grating with synchronous modulations on amplitude and phase, and then the diffraction efficiency in first-order directions is quite limited. To overcome the absorption, much attention was paid to create a medium that is transparent to the probe field, but can induce a deep phase modulation. Araujo proposed electromagnetically induced phase grating (EIPG) based on nonlinear modulation in a four-level N-type atomic system [18]. Due to the enhancement of nonlinearity accompanied by nearly vanishing linear absorption, the diffracting power of grating is improved. Later, spontaneously generated coherence (SGC) was utilized to realize EIPG and the attainable diffraction efficiency is also enhanced via quantum interference [19,20]. To improve the high-order diffraction efficiencies further, electromagnetically induced gain-phase grating based on active Raman gain (ARG) was presented by Kuang et al. [21]. Moreover, multi-level atomic systems and other quantum systems were utilized to enhance the diffraction efficiency [22–26]. Recently, by using two orthogonal standing-wave fields, electromagnetically induced cross gratings, which can diffract the probe into two-dimensional directions, were proposed [27–29].

The phase modulation, which plays an important role in EIG, corresponds to the refractive index experienced by probe field. Therefore, attention must be paid to obtain enhanced refractive index with vanishing absorption which can significantly improve the diffraction efficiency. The most straightforward way is to tuning the light frequency close to an atomic resonance, however such enhancement is accompanied with inevitable absorption which prevents the usage of obtained refractive index. In order to overcome this disadvantage, several schemes on resonantly enhancing refractive index with zero-absorption have been proposed [30,31]. The refractive index enhancement has many potential applications, such as high sensitivity magnetometer [32], phase shifter [33], enhanced Kerr nonlinearity [34]. Most recently, a scheme for uniform phase modulation without paraxial diffractions via control of re-

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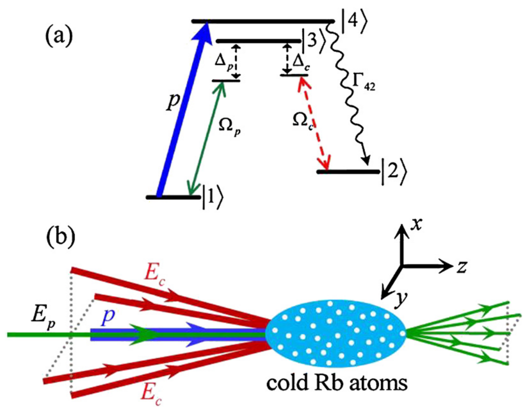

Fig. 1. (a) The schematic diagram of a four-level double-Λ systems. The atomic system interacts with the weak probe, coherent and a two-way incoherent pump field. (b) The sketch of the spatial configuration of the probe, coherent and incoherent pump field.

fractive index was proposed in a four-level double-Λ system driven by a coherent field and an incoherent pump field [35]. In such atomic system, amplification can be induced owing to the incoherent pumping, thus compensating the absorption. Meanwhile, a linear constant dispersion appears for the probe field. Therefore it is not difficult to find that such a system is in favor of realizing EIG with high diffracting power.

In this paper, we theoretically present a scheme for electromagnetically induced two-dimensional grating which is formed in a four-level double-Λ system driven by a coherent field and an incoherent pump field. With the help of a coherent field with two-dimensional standing-wave pattern, a probe light, which propagates along a direction normal to the standing-wave, can be diffracted into high-order directions. We investigate the effect of interaction length and coherent field intensity on the diffraction efficiency of the grating. The results show that, high diffraction intensity can be obtained via proper manipulation of the system parameters. The grating here is created with the help of an incoherent pump field, and the absorption of the probe beam is eliminated. Then the resulted diffraction efficiency can be improved as comparing with other schemes for two-dimensional gratings. Consequently, the present grating is more suitable for beam splitting and fanning in optical communication and networking.

This paper is organized as follows: In Sec. 2 the atomic model and relevant equations are presented. In Sec. 3 we investigate the phase and gain-phase grating assisted by incoherent pump field. In Sec. 4 we show the conclusions of this paper.

2. Atomic model and relevant equations

The four-level double-Λ atomic system is shown in Fig. 1(a). A weak probe field E_p with Rabi frequency Ω_p and detuning $\Delta_p = \omega_p - \omega_{13}$ couples the transition $|1\rangle \leftrightarrow |3\rangle$. The transition $|2\rangle \leftrightarrow |3\rangle$ is resonantly driven by a coherent field E_c with Rabi frequency Ω_c and detuning $\Delta_c = \omega_c - \omega_{32}$. Simultaneously, an incoherent field with pumping rate p is imposed to the transition $|1\rangle \leftrightarrow |4\rangle$. The Rabi frequencies of the corresponding laser fields are $\Omega_p = \mu_{13}E_p/2\hbar$ and $\Omega_c = \mu_{23}E_c/2\hbar$, respectively. Here, E_p (E_c) represents the amplitude of the probe (coupling) field and μ_{13} (μ_{23}) is the electric-dipole moment of the transition $|1\rangle \leftrightarrow |3\rangle$ ($|2\rangle \leftrightarrow |3\rangle$). For simplicity, we take these Rabi frequencies as real. The level structure can be realized in the D_1 line of cold Rb^{87} for the reason that it can effectively reduce the impact of undesired effects such as AC Stark shifts, collisional broadening and power broadening of Raman transition. We choose the magnetic sublevels $5S_{1/2} : |1\rangle = |F = 1, m_F = 0\rangle$, $|2\rangle = |F = 2, m_F = 2\rangle$ and $5P_{1/2} : |3\rangle = |F = 2, m_F = 1\rangle$, $|4\rangle = |F = 1, m_F = 1\rangle$ as the four considering atomic states. Therefore, the light fields should be circular polarized and propagate in the same directions. Fig. 1(b) shows the geometry of beams clearly. In order to form standing-wave, the coupling fields should propagate nearly parallel to the probe field with a small angle, and then they interfere with each other. As a result, we obtain the standing-wave pattern, of which the amplitude varies perpendicular to the propagating direction of probe field and coupling fields.

In the framework of the semiclassical theory, using the dipole approximation and the rotating wave approximation, we can obtain the Hamiltonian of the system in the interaction picture as follows

$$H = \hbar(\Delta_c - \Delta_p)|2\rangle\langle 2| - \hbar\Delta_p|3\rangle\langle 3| - \hbar\big[\Omega_p|1\rangle\langle 3| + \Omega_c|2\rangle\langle 3| + \text{H.c}\big]. \quad (1)$$

Considering the relaxation process, the motion equations for the density matrix of the atomic system are given by

$$\dot\rho_{11} = -i(-\Omega_p\rho_{31} + \Omega_p\rho_{13}) + \Gamma_{31}\rho_{33} - p(\rho_{11} - \rho_{44}) + \Gamma_{41}\rho_{44}, \quad (2a)$$

$$\dot\rho_{21} = -i(-\Delta_p\rho_{21} - \Omega_c\rho_{31} + \Omega_p\rho_{23}) - \gamma_{21}\rho_{21} - \frac{p}{2}\rho_{21}, \quad (2b)$$

$$\dot\rho_{22} = -i(-\Delta_p\rho_{22} - \Omega_c\rho_{32} + \Delta_p\rho_{22} + \Omega_c\rho_{23}) + \Gamma_{32}\rho_{33} + \Gamma_{42}\rho_{44}, \quad (2c)$$

$$\dot\rho_{31} = -i(-\Omega_p\rho_{11} - \Omega_c\rho_{21} - \Delta_p\rho_{31} + \Omega_p\rho_{33}) - \gamma_{31}\rho_{31} - \frac{p}{2}\rho_{31}, \quad (2d)$$

$$\dot\rho_{32} = -i(-\Omega_p\rho_{12} - \Omega_c\rho_{22} - \Delta_p\rho_{32} + \Delta_p\rho_{32} + \Omega_c\rho_{33}) - \gamma_{32}\rho_{32}, \quad (2e)$$

$$\dot\rho_{33} = -i(-\Omega_p\rho_{13} - \Omega_c\rho_{23} - \Delta_p\rho_{33} + \Omega_p\rho_{31} + \Omega_c\rho_{32} + \Delta_p\rho_{33}) - \Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33}, \quad (2f)$$

$$\dot\rho_{41} = -i\Omega_p\rho_{43} - \gamma_{41}\rho_{41} - p\rho_{41}, \quad (2g)$$

$$\dot\rho_{42} = -i(\Delta_p\rho_{42} + \Omega_c\rho_{43}) - \gamma_{42}\rho_{42} - \frac{p}{2}\rho_{42}, \quad (2h)$$

$$\dot\rho_{43} = -i(\Omega_p\rho_{41} + \Omega_c\rho_{42} + \Delta_p\rho_{43}) - \gamma_{43}\rho_{43} - \frac{p}{2}\rho_{43}, \quad (2i)$$

$$\dot\rho_{44} = -\Gamma_{42}\rho_{44} - \Gamma_{41}\rho_{44} + p(\rho_{11} - \rho_{44}), \quad (2j)$$

where $\gamma_{jk} = \frac{\Gamma_j + \Gamma_k}{2}$ $(j, k = 1, 2, 3, 4)$ are the dephasing rates of the relevant transitions and Γ_{mn} $(m = 3, 4;\ n = 1, 2)$ denote the spontaneous decay rates from $|m\rangle$ to $|n\rangle$, $\Gamma_3 = \Gamma_{31} + \Gamma_{32}$ and $\Gamma_4 = \Gamma_{41} + \Gamma_{42}$ represent the spontaneous decay rates of the upper levels while $\Gamma_1 \approx 0$ and $\Gamma_2 \approx 0$ are those of the lower levels. In the presence of the incoherent pump field, the steady-state solutions of density matrix elements in zeroth order of Ω_p are given by

$$\rho_{11}^{(0)} = 4\Gamma_{31}(p + \Gamma_4)\Omega_c^2/w, \quad (3a)$$

$$\rho_{33}^{(0)} = 4p\Gamma_{42}\Omega_c^2/w, \quad (3b)$$

$$\rho_{23}^{(0)} = -i2p\Gamma_3\Gamma_{42}\Omega_c/w, \quad (3c)$$