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Optical processes in different types of photonic band gap structures

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ABSTRACT

For the first time, we investigate the photonic band gap (PBG) structure in the static and moving electromagnetically induced grating (EIG) through scanning the frequency detunings of the probe field, dressing field and coupling field. Especially, the suppression and enhancement of the four wave mixing band gap signal (FWM BGS) and the probe transmission signal (PTS) can be observed when we scan the dressing field frequency detuning in the FWM BGS system. It is worth noting that the PBG structure and FWM BGS appear at the right of the electromagnetically induced transparency (EIT) position in the case of scanning the frequency detuning of the coupling field in the FWM BGS system, while the PBG structure and FWM BGS appears at the left of the EIT position on the condition of scanning the probe field frequency detuning. Moreover, in the moving PBG structure, we can obtain the nonreciprocity of FWM BGS. Furthermore, we can modulate the intensity, width, location of the FWM BGS and PTS through changing the frequency detunings and intensities of the probe field, dressing field and coupling field, sample length and the frequency difference of coupling fields in EIG. Such scheme could have potential applications in optical diodes, amplifiers and quantum information processing.

1. Introduction

Electromagnetically induced transparency (EIT) [1] in atoms attracts a lot of attentions from all over the world in the past decades. It is well-known that the nonlinear optical effect four wave mixing (FWM) [2] which can be enhanced or suppressed [3–5] in an EIT medium. A variety of interesting research results [6–9] are reported, including the electromagnetically induced grating (EIG) [10,11] that result from two counter propagating coupling fields [12–14]. And the EIG possesses photonic band gap (PBG) structure, has a potential application in all optical switch, manipulation of light propagation to create a tunable photonic band gap [15,16].

Many research results have reported that the optical nonreciprocity has been achieved in parity-time symmetric media [17,18], media with magneto-optical effects [19] or acousto-optical effects [20], non-symmetric photonic crystals [21], etc. Recently, researchers found that in the moving photonic crystal [22] may appear the phenomenon optical nonreciprocal transmission. The result is got in an EIT spatially uniform distributed atomic medium where the standing wave also called moving EIG is formed by two counter propagating coupling fields with different frequencies through mutual interference [23].

In this paper, in a reverted-Y type energy system, we investigate the PBG structure in the static and moving EIG through scanning the frequency detunings of the probe field, dressing field and coupling field for the first time. For the static PBG structure, the EIG is resulted from two counter propagating coupling fields with same frequencies. However, the two counter propagating coupling fields with different frequencies form a moving EIG. We observe that the suppression and enhancement of the four wave mixing band gap signal (FWM BGS) and the probe transmission signal (PTS) when we scan the dressing field frequency detuning in the FWM BGS system. The difference in the position of PBG structure and FWM BGS will be researched on the condition of scanning the probe and coupling field frequency detuning, respectively. Moreover, the nonreciprocity of FWM BGS will be achieved in the moving PBG structure. Through changing the frequency detuning, intensity of different laser beam field, sample length and the frequency difference of coupling fields in EIG, the position, width and intensity of the FWM BGS, PTS and PBG structure can be modulated flexibly.

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2. Basic theory

In this paper we use a reverted-Y type four-level atomic system composed by $5S_{1/2}$ ($F = 3$) ($|0\rangle$), $5S_{1/2}$ ($F = 2$) ($|3\rangle$), $5P_{3/2}$ ($|1\rangle$), and $5D_{5/2}$ ($|2\rangle$) of ^{85}Rb as shown in Fig. 1(a). Probe laser beam E_1 (frequency ω_1 and wave vector $\mathbf{k_1}$) probes the transition $|0\rangle$ to $|1\rangle$. A pair of coupling laser beams E_3 (ω_3, $\mathbf{k_3}$) and E'_3 (ω'_3, $\mathbf{k'_3}$) connect the transition $|3\rangle$ to $|1\rangle$, and another laser beam E_2 (ω_2, $\mathbf{k_2}$) drive an upper transition $|1\rangle$ to $|2\rangle$. The coupling field E_3 and E'_3 propagate through medium in the opposite direction, generate a standing wave $E_c = \hat{y}[E_3\cos(\omega_3 t - k_3 x) + E'_3\cos(\omega'_3 t + k'_3 x)]$, i.e. EIG. When $\omega_3 = \omega'_3$, the generating EIG is static. While $\omega'_3 \neq \omega_3$, the moving EIG will form. Furthermore static (or moving) EIG will lead to a static (or moving) PBG structure. The probe field E_1 propagates in the same direction of E'_3 through the medium with a small angle between them. The dressing field E_2 propagates in the opposite direction of E'_3 with a small angle between them. When the probe field E_1 incidences from left, in the system, the generated FWM BGS satisfies the phase-matching condition $\mathbf{k_F} = \mathbf{k_1} + \mathbf{k_3} - \mathbf{k'_3}$ as shown in Fig. 1(b).

2.1. Static PBG Theory

According to the energy system and Liouville pathways [24], we can obtain the static first-order and third-order density matrix elements as follows:

$$\rho_{s10}^{(1)} = \frac{iG_1}{d_{s10} + |G_{3s}|^2/d_{s30} + |G_2|^2/d_{s20}} \tag{1}$$

$$\rho_{s10}^{(3)} = \frac{-iG_1G_3G'_3}{(d_{s10} + |G_{3s}|^2/d_{s30} + |G_2|^2/d_{s20})^2 d_{s30}} \tag{2}$$

where $|G_{3s}|^2 = |G_3|^2 + |G'_3|^2 + 2G_3G'_3\cos(2k_3x)$, $G_i = \mu_i E_i/\hbar$ is the Rabi frequency with transition dipole moment μ_i, $d_{s10} = \Gamma_{10} + i\Delta_1$, $d_{s30} = \Gamma_{10} + i\Delta_1 - i\Delta_3$, $d_{s20} = \Gamma_{10} + i\Delta_1 + i\Delta_2$, frequency detuning $\Delta_i = \Omega_i - \omega_i$ (Ω_i is the resonance frequency of the transition driven by E_i) and Γ_{ij} is transverse relaxation rate between $|i\rangle$ and $|j\rangle$.

According to the relation $\varepsilon_0\chi E = N\mu\rho$, in which N, ε_0 are the atom density and dielectric constant respectively, so the formulations of the susceptibility can be obtained as follows:

$$\chi_s^{(1)} = \frac{iN\mu^2}{\hbar\varepsilon_0}\frac{1}{d_{s10} + |G_{3s}|^2/d_{s30} + |G_2|^2/d_{s20}} \tag{3}$$

$$\chi_s^{(3)} = -\frac{iN\mu^2}{\hbar\varepsilon_0}\frac{1}{(d_{s10} + |G_{3s}|^2/d_{s30} + |G_2|^2/d_{s20})^2 d_{s30}} \tag{4}$$

The condition of generating PBG structure is that the medium should have a periodic refractive index. According the relation of the refractive index with the susceptibility, i.e. $n = \sqrt{1 + Re(\chi)}$, in order to get the periodic refractive index, the susceptibility should also be periodic. Further we should generate the periodic energy level structure for getting the periodic susceptibility. Hence, by introducing periodic standing wave field, we can obtain the periodic energy levels as shown in Fig. 2. In Fig. 2(a1)–(a3), the level $|1\rangle$ will be split into two dressed states $|G_{3s}\pm\rangle$ depending on Δ_3 and $|G_{3s}|^2$. The two dressed states $|G_{3s}\pm\rangle$ have the eigenvalues $\lambda_{|G_{3s}\pm\rangle} = -\Delta_3/2 \pm \sqrt{\Delta_3^2/4 + |G_{3s}|^2}$. Since $|G_{3s}|^2$ is periodic along x-axis, so $\lambda_{|G_{3s}\pm|}$ values are also periodic along x. Thus we can obtain the periodic energy levels as shown in Fig. 2(b1)–(b3). When the probe reaches two-photon resonance $\Delta_1 - \Delta_3 = 0$, absorption will be suppressed, i.e. the PTS becomes strong. At the same time, the FWM BGS will be suppressed correspondingly. Thus, we define $\Delta_1 - \Delta_3 = 0$ as the suppression condition. When E_2 is turn on, $|G_{3s}+\rangle$ is further split into two dressed states $|G_{3s} + G_2\pm\rangle$ due to the second level dressing effect of E_2, moreover $|G_{3s} + G_2\pm\rangle$ move with changing Δ_2 as shown in Fig. 2(c1) and (c2). The two dressed states $|G_{3s} + G_2\pm\rangle$ have the Eigenvalues $\lambda_{|G_{3s}+G_2\pm\rangle} = \frac{-\Delta_3 + \sqrt{\Delta_3^2 + 4|G_{3s}|^2}}{2} + \frac{\Delta''_2 \pm \sqrt{\Delta''^2_2 + 4|G_2|^2}}{2}$ with $\Delta''_2 = \Delta_2 - \left\{-\Delta_3 + \sqrt{\Delta_3^2 + 4|G_{3s}|^2}\right\}\Big/2$. The same way $|G_{3s}-\rangle$ is further dressed into two second level dressed states $|G_{3s} - G_2\pm\rangle$ as shown in Fig. 2(c4) and (c5), the Eigenvalues of which are $\lambda_{|G_{3s}-G_2\pm\rangle} = \frac{-\Delta_3 - \sqrt{\Delta_3^2 + 4|G_{3s}|^2}}{2} + \frac{\Delta'_2 \pm \sqrt{\Delta'^2_2 + 4|G_2|^2}}{2}$, where $\Delta'_2 = \Delta_2 - \left\{-\Delta_3 - \sqrt{\Delta_3^2 + 4|G_{3s}|^2}\right\}\Big/2$. In Fig. 2(c3), because of three photon resonance with $\Delta_1 = -\Delta_2 = \Delta_3$ only two dressed states appear. Thus we also obtain the double dressed periodic energy levels as shown in Fig. 2(d1)–(d5).

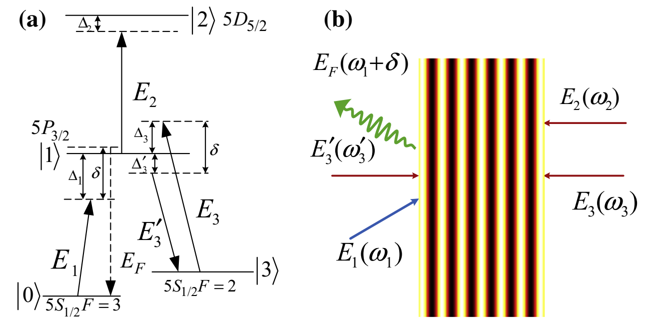

Fig. 1. (a) Reverted-Y type energy system. (b) Schematic of a moving EIG formed by two coupling beams E_3 and E'_3.

For the FWM BGS system, the normalized total susceptibility is $\chi_{Fs} = \chi_s^{(1)} + \chi_s^{(3)}|E_3|^2 + \chi_s^{(3)}|E'_3|^2$. We present the real part of χ_{Fs} versus x and Δ_1 in Fig. 3, which determine the refractive index of the system according to $n = \sqrt{1 + Re(\chi)}$. For the systems generating the FWM BGS, the real part of susceptibility are both periodic along with x.

As to the PBG of the EIG, we can obtain it by adopting the plane-wave expansion method [25]. Expending χ as Fourier series and considering two-mode approximation, we obtain the expression of the Bragg wave vector as follows:

$$q_s \approx \pm\frac{1}{2k_3}\sqrt{[k_1^2(1 + \chi_{s0}) - k_3^2]^2 - k_1^4\chi_{s1}^2} \tag{5}$$

For the FWM BGS system, χ_{s0}, χ_{s1} is the zero-order Fourier coefficient of the susceptibility $\chi_s^{(1)}$ and $\chi_s^{(3)}$, respectively.

In order to estimate the reflection efficiency of FWM BGS, we start from the nonlinear coupled wave equations [15],

$$\partial E_1(x)/\partial x = -\alpha E_1(x) + ke^{-i\Delta k_x x}E_r(x)$$
$$-\partial E_r(x)/\partial x = -\alpha E_r(x) + ke^{i\Delta k_x x}E_1(x)$$

where $E_1(x)$ and $E_r(x)$ represent the PTS and FWM BGS, respectively. $\alpha = (\omega_1/c)\mathrm{Im}\chi'^{(1)}/2$ is the attenuation of the field due to the absorption of the medium and k is the gain due to the nonlinear susceptibility. Especially, for the FWM BGS system, $E_r(x)$ stands for the FWM BGS, $k = i(\omega_1/c)\chi'^{(3)}/2$. $\chi'^{(1)}$ and $\chi'^{(3)}$ are the zero order coefficients from Fourier expansion of $\chi_s^{(1)}$ and $\chi_s^{(3)}$, respectively. $\Delta k_x = \{2(\omega_1\cos\theta - \omega_3) + Re[\chi'^{(1)}]\omega_1\cos\theta\}/c$ is the phase mismatch magnitude, in which θ is the angle between probe E_1 and E'_3. If length of the sample in x direction is d_x, then by solving above equations, the reflected FWM BGS (R_s) and PTS (T_s) are given as