Modulated photonic band gaps generated by high-order wave mixing

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Received September 23, 2014; revised November 6, 2014; accepted November 20, 2014; posted November 20, 2014 (Doc. ID 223519); published December 24, 2014

For the first time, to the best of our knowledge, we investigate the photonic band gap (PBG) structure through scanning the frequency detunings of the probe field, the dressing field, and the coupling field in the static and moving electromagnetically induced grating (EIG) field. When we scan the frequency detuning of the coupling field, the PBG structure and six-wave-mixing band gap signal (SWM BGS) appear at the right of the electromagnetically induced transparency (EIT) position. But the PBG structure and SWM BGS appear at the left of the EIT position in the case of scanning the probe field frequency detuning. Also, on the condition of scanning the probe field frequency detuning, the SWM BGS appears in two frequency ranges. Moreover, in the moving PBG structure, nonreciprocity of the SWM BGS can be obtained. Furthermore, the intensity, width, and location of the SWM BGS can be modulated through changing the frequency detunings and intensities of the probe field, the dressing field, and the coupling field; the sample length; and the frequency difference of coupling fields in EIG. Such a scheme could have potential applications in optical diodes, amplifiers, and quantum information processing. © 2014 Optical Society of America

OCIS codes: (190.4830) Nonlinear optics, four-wave mixing; (190.4180) Multiphoton processes; (300.2570) Four-wave mixing; (270.1670) Coherent optical effects.
http://dx.doi.org/10.1364/JOSAB.32.000179

1. INTRODUCTION

Over the past few decades, a lot of attention has been paid to the electromagnetically induced transparency (EIT) [1,2] in atoms. The nonlinear optical effect, four-wave mixing (FWM) [3], which can be enhanced or suppressed [4–6] in an EIT medium, is well known. The electromagnetically induced grating (EIG) [7,8,9] that results from two counterpropagating coupling fields [10,11] is reported in a variety of interesting research results [12–14]. And the EIG possesses a photonic band gap (PBG) structure that has potential application in all-optical switches, and the manipulation of light propagation to create a tunable PBG [15,16].

Optical nonreciprocity has been achieved in parity-time symmetric media [17,18], media with magneto-optical effects [19] or acousto-optical effects [20], nonsymmetric photonic crystals [21], etc., in many research results. Recently, the phenomenon of optical nonreciprocal transmission has appeared in the moving photonic crystal [22] found by researchers. The result is obtained in an EIT spatially uniform distributed atomic medium, where the standing wave, also called a moving EIG, is formed by two counterpropagating coupling fields with different frequencies through mutual interference [23]. Also related to the moving and static atomic Bragg mirrors, the enhancement mechanisms have been demonstrated in cold atoms pumped by auxiliary near-resonant beams [24], two-color photonic crystal lasing in cold atoms [25], or around a narrow stop-band opening up in the cold confined 87Rb atoms [26]. In addition, peculiar nonlinearities related to static or moving atomic Bragg mirrors have been reported by many researchers, such as dynamically controlled PBGs via balanced FWM interaction [27], non-Doppler contributions to radiation pressure experienced by a moving dielectric [28], and complete unidirectional reflectionless light propagation [29].

In this paper, through scanning the frequency detunings of the probe field, the dressing field, and the coupling field, the PBG structure in the static and moving EIG is investigated for the first time, to the best of our knowledge, in a reverted-Y type energy system. For the static PBG structure, two counterpropagating coupling fields with the same frequencies can form an EIG. However, a moving EIG resulted from the two counterpropagating coupling fields with different frequencies. The difference in the position of the PBG structure and the six-wave-mixing band gap signal (SWM BGS) will be researched on the condition of scanning the probe and coupling field frequency detuning, respectively. Moreover, in the moving PBG structure nonreciprocity of the SWM BGS will be achieved. Through changing the frequency detuning, the intensity of different laser beam fields, the sample length, and the frequency difference of coupling fields in EIG, the position, width, and intensity of the SWM BGS 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 $S_{1/2}(F = 3)$ ($|0\rangle$), $S_{1/2}(F = 2)$ ($|3\rangle$), $P_{3/2}$ ($|1\rangle$), and $5D_{5/2}$ ($|2\rangle$) of $^{87}$Rb as shown in Fig. 1(a). Probe laser beam $E_1$ (frequency $\omega_1$ and wave vector $k_1$) probes the transition $|0\rangle \to |1\rangle$. A pair of coupling laser beams $E_3$ ($\omega_3, k_3$) and $E_3'$ ($\omega_3', k_3'$) connect the transition $|3\rangle \to |1\rangle$, and another laser beam $E_2$ ($\omega_2, k_2$) drives an upper transition $|1\rangle \to |2\rangle$. The coupling fields $E_2$ and $E_3$ propagate through the medium in the opposite direction, generating a standing wave $E_r = \hat{E}_r E_3 \cos(\omega_3 t - k_3 x) + E_3' \cos(\omega_3' t + k_3' x)$, i.e., EIG. When $\omega_3 = \omega_3'$, the generating EIG is static. While $\omega_2 \neq \omega_3$, a moving EIG will form. Furthermore a static (or moving) EIG will lead to a static (or moving) PBG structure. The probe field $E_1$ propagates in the same direction of $E_1'$ through the medium with a small angle between them. The dressing field $E_2$ propagates in the opposite direction of $E_1'$ with a small angle between them. When the probe field $E_1$ incidences from the left, in the system, the SWM BGS satisfies the phase-matching condition $k_s = k_1 + k_2 - k_3 - k_4$, as shown in Fig. 1(b).

A. Static PBG Theory

According to the energy system and Liouville pathways [30], we can obtain the static first-order, fifth-order density matrix elements as follows:

$$\rho^{(1)} = \frac{-iG_1}{d_{s10} + |G_{s3}|^2/d_{s30} + |G_{s2}|^2/d_{s20}},$$

(1)

$$\rho^{(5)} = \frac{iG_1 G_3 G_3 G_3 G_2}{(d_{s10} + |G_{s3}|^2/d_{s30} + |G_{s2}|^2/d_{s20})^3 d_{s30} d_{s20}},$$

(2)

where $|G_{s3}|^2 = |G_3|^2 + |G_3|^2 + 2G_3 G_3' \cos(2k_3 x)$, $G_1 = \mu_i E_1 / h$ is the Rabi frequency with transition dipole moment $\mu_i$, $d_{s10} = 1 + i\Delta_i, d_{s30} = 1 - i\Delta_3$, $d_{s20} = 1 + i\Delta_2$, frequency detuning $\Delta_i = \Omega_i - \omega_i$ ($\Omega_i$ is the resonance frequency of the transition driven by $E_i$), and $\Gamma_i$ is inverse relaxation rate between $|i\rangle$ and $|j\rangle$.

According to the relation $\epsilon_{32} E = N \mu \rho$, in which $N, \epsilon_0$ are the atom density and dielectric constant, respectively, the formulations of the susceptibility can be obtained as follows:

$$\chi^{(3)} = \frac{iN \mu^2}{\hbar \epsilon_0} \frac{1}{d_{s10} + |G_{s3}|^2/d_{s30} + |G_{s2}|^2/d_{s20}},$$

(3)

$$\chi^{(5)} = \frac{iN \mu^2}{\hbar \epsilon_0} \frac{1}{d_{s10} + |G_{s3}|^2/d_{s30} + |G_{s2}|^2/d_{s20}}.$$  

(4)

The condition of generating the PBG structure is that the medium should have a periodic refractive index. According to the relation of the refractive index with the susceptibility, i.e., $n = \sqrt{1 + \text{Re}(\chi)}$, in order to get the periodic refractive index, the susceptibility should also be periodic. Further we should generate a periodic energy level structure for obtaining the periodic susceptibility. Hence, by introducing periodic standing wave field, we can obtain the periodic energy levels as shown in Fig. 2. In Figs. 2(a1–2a3), the level $|1\rangle$ will be split into two dressed states $|G_{s3} s\rangle$ depending on $\Delta_3$ and $|G_{s3} f\rangle$. The two dressed states $|G_{s3} f\rangle$ have the eigenvalues $\lambda_{G_{s3} f} = -\Delta_3/2 + \sqrt{\Delta_3^2/4 + |G_{s3}|^2}$. Since $|G_{s3}|^2$ is periodic along the $x$ axis, the $\lambda_{G_{s3} |s\rangle}$ values are also periodic along $x$. Thus we can obtain the periodic energy levels as shown in Figs. 2(b1–2b3). When the probe reaches two-photon resonance $\Delta_1 - \Delta_2 = 0$, absorption will be suppressed; i.e., the PTS becomes strong. Thus, we define $\Delta_1 - \Delta_2 = 0$ as the suppression condition. When $E_2$ is turned on, $|G_{s3} f\rangle$ is further split into two dressed states $|G_{s3} f s\rangle$, $|G_{s3} f f\rangle$ due to the second level dressing effect of $E_2$; moreover $|G_{s3} f s\rangle$, $|G_{s3} f f\rangle$ moves with changing $\Delta_2$ as shown in Figs. 2(c1) and 2(c2). The two dressed states $|G_{s3} f s\rangle$, $|G_{s3} f f\rangle$ have the eigenvalues $\lambda_{G_{s3} f |s\rangle} = -\Delta_2/2 - \sqrt{\Delta_2^2/4 + |G_{s3}|^2}$ with $\Delta_2 = 2 - \sqrt{\Delta_3^2/4 + |G_{s3}|^2}$. The two states $|G_{s3} f f\rangle$ are the second level dressed states $|G_{s3} f f\rangle$ as shown in Figs. 2(c3) as $|G_{s3} f f\rangle$, $|G_{s3} f f\rangle$ are the eigenvalues of which are $\lambda_{G_{s3} f |f\rangle} = -\Delta_2/2 - \sqrt{\Delta_2^2/4 + |G_{s3}|^2}$, where $\Delta_2 = 2 - \sqrt{\Delta_3^2/4 + |G_{s3}|^2}$. In Fig. 2(c3), since 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 Figs. 2(d1–2d5).

For the SWM BGS system, the normalized total susceptibility is $\chi_s^{(3)} = \chi^{(3)} + \chi^{(5)} |E_{\delta1}|^4 + \chi^{(3)} |E_{\delta2}|^4 + \chi^{(5)} |E_{\delta2}|^2 |E_{\delta1}|^2$. We present the real part of $\chi_s^{(3)}$ versus $\chi$ in Fig. 3, which determines the refractive index of the system according to $n = \sqrt{1 + \text{Re}(\chi)}$ for the systems generating the SWM BGS, the real parts of susceptibility are both periodic along with $x$.

As for the PBG of the EIG, we can obtain it by adopting the plane-wave expansion method [31]. Expanding $\chi$ as a Fourier series and considering the two-mode approximation, we obtain the expression of the Bragg wave vector as follows:

$$q_s \approx \frac{1}{2 |k_0|} \sqrt{|k_0^2(1 + \chi_{\text{eff}}) - k_3^2|^2 + k_4^2|\lambda_{\text{eff}}|^2}.$$  

(5)

For the SWM BGS system, $\chi_s^{(3)}$, $\chi_s^{(5)}$ is the zero-order Fourier coefficient of the susceptibility $\chi_s^{(3)}$, $\chi_s^{(5)}$, respectively. To estimate the PBG structure, we set $k_s = k_3 \pm q_s$. One can use the real part of the expression $k_s / k_3 - 1$ to examine the Bloch wave-vector modes $k_s$ near the Brillouin zone band edge, i.e., the PBG structure.

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

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Fig. 1. (a) Reverted-Y type energy system. (b) Schematic of a moving EIG formed by two coupling beams $E_3$ and $E_3'$.
Γ is the angle between probes and \( d \) stands for the SWM BGS, and Δ are the zero-order coefficients from Fourier expansion of \( \chi^{(2)} \) and \( \chi^{(3)} \), respectively. \( \Delta \) is the phase mismatch magnitude, in which \( \theta \) is the angle between probes \( E_1 \) and \( E_2 \). If the length of the sample in the \( x \) direction is \( d_x \), then by solving the above equations, the reflected SWM BGS (\( R_x \)) and PTS (\( T_x \)) are given as

\[
R_x = \frac{1}{k} \left| \frac{e^{-i\lambda_1 dx}}{(\lambda_1 + \alpha)^{-1} - e^{-i\lambda_2 dx}(\lambda_1 + \alpha)^{-1}} \right|^2,
\]

\[
T_x = \left| \frac{e^{i\lambda_1 dx}(\lambda_1 - \lambda_2^+)}{(\lambda_1 + \alpha)e^{i\lambda_1 dx} - (\lambda_1 + \alpha)e^{i\lambda_2 dx}} \right|^2,
\]

where \( \lambda_1^+ = -i\Delta_k/2 - (\alpha - i\Delta_k/2)^2 k_2 \) and \( \lambda_2^+ = \lambda_1^+ + i\Delta_k \).

**B. Moving PBG Theory**

When the coupling field frequency \( \omega_3 \neq \omega_3' \), according to the energy system and Liouville pathways, the moving first-order and fifth-order density matrix elements are as follows:

\[
\rho^{(1)}_{m10} = \frac{iG_1}{d_{x10} + |G_2|^2/d_{220} + |G_3|^2/d_{330}},
\]

\[
\rho^{(5)}_{m10} = \frac{iG_1^* G_3 G_2^* |G_2|^2}{(d_{x10} + |G_2|^2/d_{220} + |G_3|^2/d_{330})(d_{x10} + |G_2|^2/d_{220} + |G_3|^2/d_{330})d_{m20} + |G_3|^2/d_{m20} + |G_3|^2/d_{m30})d_{m30}d_{m20}},
\]

where \( |G_3| = |G_3|^2 + |G_3'|^2 + 2G_3G_3' \cos(\delta t + 2k_2x) \), \( \delta = \omega_3 - \omega_3' \), and \( k_2 = (\omega_3' + \omega_3)/2c \) with \( c \) the vacuum light speed. \( d_{x10} = i(\Delta_1 - \delta) + \Gamma_{x0}, \) \( d_{m20} = i(\Delta_1 + \Delta_2 - \delta) + \Gamma_{x0}, \) \( d_{m30} = i(\Delta_1 - \Delta_3 - \delta) + \Gamma_{x0}. \)
Also according to the relation \( \epsilon_0 E = N \mu \rho \), the moving susceptibility can be obtained as follows:

\[
\chi_m^{(1)} = \frac{iN\mu^2}{\varepsilon_0 c d_{10}} \left( G_2^2/d_{20} + G_{3m}^2/d_{3m0} \right),
\]

\[
\chi_m^{(5)} = \frac{iN\mu^2}{\varepsilon_0 c d_{10}} \left( G_2^2/d_{20} + G_{3m}^2/d_{3m0} \right) (d_{m10} + G_2^2/d_{m20} + G_{3m}^2/d_{m30})^2 d_{m20}.
\]

The moving speed of the EIG is \( v = -\Delta/2k_0 \). If we fix \( \omega_0 \) and change \( \omega \) to detune the moving direction and speed, we can obtain the effective period of the moving EIG as \( D = \pi/[k_0 + \Delta/(2c)] \), from which we can see that \( D \) is larger for \( \delta < 0 \) than that for \( \delta > 0 \). Here, we would like to emphasize that the effective period \( D \) results from the Doppler effect. For the same probe incidence, \( D \) is different when the moving velocity of EIG is different. And this would lead to different SWM BGS and PTS. We display the real part of susceptibility of the SWM BGS system \((\chi_{Sm})\) for the different values of \( \delta \) in Fig. 4; it is worth noting that the period of the real part of susceptibility is not same for the different \( \delta \).

As for the PBG structure of the moving EIG, the expression of the Bragg wave vector is given as

\[
q_m \approx \pm \frac{1}{2k_0} \sqrt{k_2^2(1 + \chi_{m0}) - k_c^2} \left( k_2^2 - k_1^2 \right).
\]

For the SWM BGS system, \( \chi_{m0}, \chi_{m1}^{(1)} \) is the zero-order Fourier coefficient of the susceptibility \( \chi_m^{(1)} \) and \( \chi_m^{(5)} \), respectively.

In the moving EIG system, the equations of the reflected SWM BGS \((R_m)\) and PTS \((T_m)\) are as follows:

\[
R_m = \frac{1}{\lambda_1^+ e^{i\lambda_1^+ d_1} - e^{i\lambda_1^- d_1}},
\]

\[
T_m = \frac{e^{i\lambda_1^+ d_1} (\lambda_1^+ - \lambda_1^-)}{(\lambda_1^+ + \alpha) e^{i\lambda_1^+ d_1} - (\lambda_1^+ + \alpha) e^{i\lambda_1^- d_1}}^2,
\]

where \( \lambda_1^\pm = \pm k_{max}/2 \) and \( \lambda_1^\pm = \pm k_{max}/2 \pm [(\alpha - \Delta k_{max}/2)^2 - k_c^2]^{1/2} \) and \( \lambda_2^\pm = \lambda_1^\pm + i\Delta k_{max} \). \( \Delta k_{max} = 2(k_0 \cos \theta_0 - k_1) + (\sin \theta_0/\alpha) \epsilon(\alpha_1/c) \chi^{(1)} / 2 \).

3. RESULTS AND DISCUSSION

A. Static SWM BGS, PTS, and PBG Structure

Now we observe the static SWM BGS, PTS, and static PBG structure on the condition of scanning the probe frequency detuning \( \Delta_1 \) in the static SWM BGS system. It is worth noting that the SWM BGS (PTS) and PBG structure appears in two different frequency ranges as shown in Figs. 5(a1)–5(d1). One (left SWM BGS) is located at the left of the EIT position \( \Delta_1 = \Delta_3 = -1 \text{ MHz} \) due to the term \( |G_{3m}|^2/d_{3m0} \) in \( \rho_{11}^{(1)} \), and the other (right SWM BGS) appears at the left of the right EIT location \( \Delta_1 = -\Delta_3 = 8 \text{ MHz} \) according to the term \( |G_2|^2/d_{20} \) in \( \rho_{11}^{(1)} \) and \( \rho_{11}^{(1)} \). When we change \( \Delta_3 \) from -1 to 0 MHz in Figs. 5(a2)–5(d2), it is clear to see that the left SWM BGS (or PBG) moves to the left of \( \Delta_1 = \Delta_3 = 0 \text{ MHz} \) and the right SWM BGS moves to the right of \( \Delta_1 = -\Delta_3 = 6 \text{ MHz} \) and the two SWM BGSs are higher than those in Figs. 5(a2)–5(d2). So one can conclude that along with the left and right SWM BGS approaching, the intensities of the left SWM BGS and right SWM BGS become obviously stronger.

When we set the \( \Delta_3 = -\Delta_2 = 0 \text{ MHz} \) in Figs. 5(a4)–5(d4), the two SWM BGSs (or the two PBGs) overlap at the left of the position \( \Delta_1 = -\Delta_2 = \Delta_3 \), and the intensity of the SWM BGS reaches above 90% because of \( \Delta_3 = -\Delta_2 \). Through changing the value of \( G_2 \), we find that the intensity of the SWM BGS shows the maximum value near \( G_2 = 30 \text{ MHz} \). The intensity of the SWM BGS decreases with \( G_2 \) reducing \( G_2 = 30 \text{ MHz} \) or rising \( G_2 = 90 \text{ MHz} \) as shown in Figs. 5(a5)–5(c5) and Figs. 5(a6)–5(c6). However, the width of the SWM BGS always becomes broad when \( G_2 \) increases.

Similarly, when we change \( G_3 \) in Figs. 5(a7)–5(c7) and Figs. 5(a8)–5(c8), the SWM BGS has a max value near \( G_3 = 50 \text{ MHz} \). But the width of the SWM BGS always increases with \( G_3 \) rising. So we can modulate the intensity of SWM BGS flexibly through changing the frequency detuning of the dressing field or the coupling field or the value of \( G_2 \) and \( G_3 \), which will have potential application in amplifiers.

To make a comparison, we display the static reflection and transmission signals versus \( \Delta_3 \) and L. First, when the \( E_2 \) laser beam is blocked, according to the expressions of \( R_3 \) and \( T_3 \) in Eqs. (6) and (7), we can obtain the SWM BGS, PTS, and PBG structure as shown in Figs. 6(a1)–6(d1).

Compared with the case of scanning \( \Delta_1 \) in Fig. 5, the SWM BGS, PTS, and PBG structure only appears at one frequency.
range, which locates at the right of the EIT position $\Delta_1 = \Delta_2$. When we change $\Delta_1$ in Figs. 6(a2)–6(d2), the SWM BGS, PTS, and PBG structure will move with $\Delta_1$ changing, but it always locates at the right of EIT. Also the intensity of the SWM BGS decreases from 0.8 to 0.2. The reason is that $\Delta_1$ is away from the position of $\Delta_1 = -\Delta_2$ according to the term $|G_2|^2/d_{2\alpha}$ in $\rho_{s10}^{(5)}$ and $\rho_{s10}^{(1)}$. When we change $\Delta_2$ in Figs. 6(a3)–6(d3), the intensity of the SWM BGS decreases sharply for the same reason as for changing $\Delta_1$. But the location of the SWM BGS, PTS, and PBG structure will not move with $\Delta_2$ changing. Next, we open the laser beam $E_2$ to observe the influence of the dressing field $E_2$ on the static SWM BGS and PTS as shown in Figs. 6(a4)–6(d4). The intensity of the SWM BGS and the width of the PBG structure will decrease due to the dressing effect of $G_2$.

On the condition of scanning $\Delta_{1,2}$ and $L$, the SWM BGS, PTS, and PBG structure are shown in Fig. 7. First, we open the laser beam $E_2$ in Figs. 7(a1)–7(d1); it is clear to see that the largest reflection (smallest transmission) and PBG structure only locate one frequency range to the left of the position $\Delta_2 = -\Delta_1$ compared with the case of scanning $\Delta_1$. When we change the $\Delta_1$ in Figs. 7(a2)–7(d2), the SWM BGS, PTS, and PBG structure will move when changing $\Delta_1$, and the intensity of the SWM BGS decreases obviously because $\Delta_1$ is away from the position of $\Delta_1 = \Delta_2$ according to the term $|G_2|^2/d_{2\alpha}$ in $\rho_{s10}^{(5)}$ and $\rho_{s10}^{(1)}$. Now we change $\Delta_3$ from 5 to 12 MHz in Figs. 7(a3)–7(d3); the intensity of the SWM BGS decreases sharply for the same reason as for changing $\Delta_1$. But the location of the SWM BGS (or PTS) and PBG structure will not move with $\Delta_3$ changing.
B. Moving SWM BGS, PTS, and PBG Structure

In the moving SWM BGS system, in the case of scanning the probe frequency detuning and the frequency difference of the coupling field, we have researched the SWM BGS, PTS, and PBG structure adequately through changing the relative parameters, and the corresponding calculation results are shown in Fig. 8. First, when we set $\Delta_2 = -9$ MHz and $\Delta_3 = -1$ MHz, the corresponding simulation results are...
displayed in Figs. 8(a1) and 8(c1). There exit two frequency ranges where the PBG structure appears. One (left SWM BGS) is located at the right of the position \( \Delta_1 = -\Delta_2 + \delta \), which results from the term \( |G_{32}|^2/d_{m20} \) in \( \rho_{m10}^{(6)} \). The other (right SWM BGS) is located at the right of \( \Delta_1 = \Delta_3 + \delta \). In Figs. 8(a2) and 8(c2), we change \( \Delta_3 \) from 1 to 0 MHz. According to the term \( |G_{32m}|^2/d_{m30} \) in the equation \( \rho_{m10}^{(6)} \), the location of the right SWM BGS moves with \( \Delta_3 \) changing. It is worth noting that the intensities of the left SWM BGS and right SWM BGS decrease when the value of \( -\Delta_3 \) is close to \( \Delta_3 \). When we change \( \Delta_3 \) from \(-9 \) to \(-8 \) MHz in Figs. 8(a3) and 8(c3), the intensities of the two SWM BGSs are stronger than those in Figs. 8(a2)–8(d2) and the location of the left SWM BGS moves caused by the dressing term \( |G_{32}|^2/d_{m20} \). In Figs. 8(a4)–8(d4), we set \( \Delta_3 = -\Delta_3 = 0 \) MHz. It can be seen clearly that the left and right SWM BGSs are overlapped at the location of \( \Delta_1 = \Delta_3 + \delta \) (or \( \Delta_1 = -\Delta_3 + \delta \)). Then we increase the power of the laser beam \( E_2 \) to 90 MHz in Figs. 8(a5)–8(d5). It can be seen clearly that the width of the SWM BGS becomes broader and the intensity of the reflection signal decreases due to the dressing effect of \( G_2 \). When we change \( G_3 \) from 50 to 100 MHz, the width of the SWM BGS increases and the intensity of the reflection signal (the area of the PBG region) becomes smaller, caused by the dressing effect \( G_3 \).

On the condition of scanning \( \Delta_3 \) and \( \delta \) in the moving PBG structure, we have researched the SWM BGS, PTS, and PBG structure carefully through inputting different parameters, and the corresponding SWM BGS, PTS, and PBG are displayed in Fig. 9. When the \( E_2 \) laser beam is blocked in Figs. 9(a1)–9(d1), we can find that the SWM BGS, PTS, and PBG only exits at one frequency range when \( \delta \) is fixed compared with the case scanning \( \Delta_1 \) and \( \delta \) as shown in Fig. 9. And when \( \delta > 0 \) (probe incidences from right), the SWM BGS, PTS, and PBG locate at the left of the EIT \( \Delta_3 = \Delta_1 + \delta \). The EIT position is decided by the term \( |G_{32m}|^2/d_{m30} \) in the equation \( \rho_{m10}^{(6)} \). When \( \delta < 0 \) (probe incidences from left), the SWM BGS, PTS, and PBG locate at the right of the EIT \( \Delta_3 = \Delta_1 + \delta \). It is seen clearly that the reflected SWM BGS (or PTS) is at different frequencies for the left and right incidence probes when \( \delta \) is fixed since the position of the PBG structure has changed. Optical nonreciprocity can be obtained, and it has potential application in optical diodes. When we change \( \Delta_1 \) from \(-10 \) to \(-5 \) MHz in Figs. 9(a2)–9(d2), the intensity of the SWM BGS decreases from 0.95 to 0.8 because \( \Delta_1 = -5 \) MHz is away from \( \Delta_1 = -\Delta_2 \); here \( \Delta_2 \) is set as \(-15 \) MHz according to the term \( |G_{32m}|^2/d_{m20} \) in \( \rho_{m10}^{(6)} \). Also the positions of the SWM BGS, PTS, and PBG move with \( \Delta_1 \) changing comparing Fig. 9(c2) with Fig. 9(c1). In Figs. 9(a3)–9(d3), we change \( \Delta_3 \) from 15 to 25 MHz. The intensity of the SWM BGS (or PTS) decreases (increases) obviously for the same reason as for the case of changing \( \Delta_1 \). Then, we open the laser beam \( E_2 \) to observe the influence of the dressing field \( E_2 \) on the SWM BGS as shown in Figs. 9(a4)–9(d4). We can find that the intensity of the SWM BGS decreases from 0.95 to 0.9 and the area of the PBG decreases obviously due to the dressing effect of \( E_2 \).

In the case of scanning \( \Delta_3 \) and \( \delta \) in the moving PBG structure, the SWM BGS, PTS, and PBG structure is illustrated in
Fig. 9. (a) Moving SWM BGS, (b) PTS, and (d) PBG structure versus $\Delta_3$ and $\delta$. (c) Moving SWM BGS with fixed $\delta$ versus $\Delta_3$. For (a1)–(d1), the corresponding parameters for the simulation results are $G_2 = 0.01$ MHz, $G_2^2 + G_3^2 = 2000$ MHz, $\Delta_1 = -10$ MHz, and $\Delta_2 = 15$ MHz. In (a2)–(d2), the simulation results correspond to (a1)–(d1), only changing $\Delta_1$ to $-5$ MHz. In (a3)–(d3), the simulation results correspond to (a1)–(d1), only changing $\Delta_2$ to $25$ MHz. In (a4)–(d4), the simulation results correspond to (a1)–(d1), only changing $G_2$ to $20$ MHz. The values of the other parameters are the same as those in Fig. 5.

Fig. 10. (a) Moving SWM BGS, (b) PTS, and (d) PBG structure versus $\Delta_2$ and $\delta$. (c) Moving SWM BGS with fixed $\delta$ versus $\Delta_2$. For (a1)–(d1), the corresponding parameters for the simulation results are $G_2 = 80$ MHz, $G_2^2 + G_3^2 = 2500$ MHz, $\Delta_1 = -10$ MHz, and $\Delta_3 = 10$ MHz. In (a2)–(d2), the simulation results correspond to (a1)–(d1), only changing $\Delta_1$ to $-10$ MHz. In (a3)–(d3), the simulation results correspond to (a1)–(d1), only changing $\Delta_3$ to $20$ MHz. The values of the other parameters are the same as those in Fig. 5.

Fig. 10. When one opens the laser beam $E_2$ in Figs. 10(a1)–10(d1), we can find that the SWM BGS, PTS, and PBG structure only exits on one frequency range. When we fixed $\delta < 0$ in Fig. 10(c1), the position of the largest intensity of the SWM BGS was at the left of the EIT $\Delta_1 = -\Delta_2 + \delta$. The EIT position is decided by the term $|G_2|^2/d_{m20}$ in the equation $\rho_{m10}^{(5)}$. When we change $\Delta_1$ from $-5$ to $-10$ MHz in Figs. 10(a2)–10(d2), the intensity of the SWM BGS decreases from about 0.92 to about 0.85 because $\Delta_1 = -10$ MHz is away from $\Delta_1 = \Delta_3$; here $\Delta_3$ is set as $10$ MHz, according to the term $|G_{3m}|^2/d_{m30}$ in $\rho_{m10}^{(5)}$ and
Also the position of the SWM BGS (or PTS) moves with \( \Delta_1 \) changing comparing Fig. 10(c2) with Fig. 10(c1). In Figs. 10(a2)–10(d2), we change \( \Delta_1 \) from 10 to 20 MHz; the intensity of the SWM BGS (or PTS) decreases (or increases) sharply for the same reason as in the condition of changing \( \Delta_1 \).

4. CONCLUSION

In summary, we have researched the static and moving PBG structure in the SWM BGS system for the first time, to the best of our knowledge. Through changing the frequency detuning of the probe field, the dressing field, and the coupling field. Also, it is verified that the positions of the PBG structure SWM BGS are different when scanning the frequency detuning of the coupling field and the probe field, respectively. Furthermore, nonreciprocal generation of SWM BGS has been demonstrated in moving EIG. Moreover, the intensity, width, and location of the SWM BGS and PTS have been modulated through changing the frequency detunings and intensities of the probe field, the dressing field, and the coupling field; the sample length; and the frequency difference of coupling fields in EIG. This research could find applications in optical amplifiers and quantum information processing.

ACKNOWLEDGMENTS

This work was supported by the 973 Program (2012CB921804), the NSFC (61108017, 11474228, 61308015, 11104214, 11104216, and 61205112), KSTIT of Shaanxi Province (2014JZ020), the NSFC (61108017, 11474228, 61308015, 1104214, 11104216, and 61205112), KSTIT of Shaanxi Province (2012CB921804), the NSFC (61108017, 11474228, 61308015, 1104214, 11104216, and 61205112), KSTIT of Shaanxi Province (2014JZ020), and CPSF (2014M560779).

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