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Effect of spontaneously generated coherence in controlling the optical bistability and multistability in a left-handed four-level atomic system

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Abstract In this paper, we theoretically investigated the influence of spontaneously generated coherence (SGC) on electromagnetic characteristics, and optical bistability (OB) and optical multistability (OM) of dense four-level atomic system. In the absence of the SGC effect, this atomic system exhibits left-handed property in one frequency detuning band of the probe field, while in the presence of the SGC effect it exhibits left-handed property in two frequency detuning bands of the probe field. The real and imaginary parts of the refractive index have negative values in the same frequency band. We can use this atomic system as an active medium for amplification of electromagnetic fields. In the absence of the SGC effect, we can easily control the transition between the OB and the OM effects by modifying the sign of the refractive index. In the presence of the SGC effect, we observe the OM behavior in this system such that the threshold of the OM in the negative refractive index band is less than the positive refractive index band. In this system, the negative refractive index, the OB and the OM behaviors can be controlled based on the effect of quantum coherence.

Keywords Left-handed · Optical bistability · Spontaneously generated coherence

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1 Introduction

Over the last several decades, quantum and nonlinear optical phenomena such as the OB and the OM in multi-level atomic systems confined inside an optical cavity have been extensively studied. For a certain input state, if more than one stable output state is observed for a nonlinear atomic system, it is said that the optical system displays the OB or the OM behavior. Such systems can be used for optical switching (Antn 2006), optical transistors (Antn and Carreo 2009) and logic circuits (Gibbs et al. 1976) which exhibit interesting dynamic behaviors. The OB and the OM behaviors have been studied in many atomic systems such as; controlling the optical bistability and transmission coefficient in a four-level atomic medium (Asadpour and Eslami-Majd 2012), three-level rubidium atoms (Joshi and Xiao 2003; Joshi et al. 2003a), a microwave-driven four-level atomic system (Xiao and Kim 2010), an open Λ-type three-level atomic system (Wang et al. 2012), the influence of spin coherence on the optical bistability (OB) and multistability in four-level atomic system (Asadpour et al. 2013). The basic mechanisms for changing the output of a multi-level atomic system are, quantum coherence and quantum interference. Spontaneous generated coherence (SGC) is a mechanism in which atomic coherence is created in two closely lying atomic levels. The influence of SGC on the OB has been investigated in many papers; for example studying the influence of SGC on the OB in a three-level Λ-type (Joshi et al. 2003b) and V-type (Joshi et al. 2003c), changing the range of the OB hysteresis due to the SGC effect (Cheng et al. 2004), studying the gain of probe field with the SGC (Xu et al. 2004), the effect of incoherent pumping field and SGC on optical bistability for different values of exit rates (Asadpour et al. 2013), investigation of the OB and the OM with the SGC and the quantum interference of incoherent pumping (Sahrai et al. 2011), the effect of SGC on phase control of the OB and OM (Hamedi et al. 2013). Insignificant research has been done in the field of the OB in a left-handed medium (negative refractive index). The left-handed mediums have permittivity and permeability negative values, simultaneously (Shen et al. 2004; Shen 2006; Krowne and Shen 2009; Zhao et al. 2010; Yang and Jiang 2012; Shen 2013). The studies are shown that the atomic vapors are good candidates for achieving negative refractive index at visible and infrared wavelengths (Shen 2013). Analyzation of the OB effect in the periodic structure with positive and negative refractive index consists of two materials, in which the OB is demonstrated by a vanishing average refractive index (Feise et al. 2004). Investigation of the OB behavior in a nonlinear optical coupler with a negative index channel, in which the negative index material channel is an effective feedback mechanism for occurring the OB effect (Litchinitse et al. 2007). Recently, the OB behavior induced by quantum coherence in a V-type level atomic system with a negative refractive index has been studied (Zhang et al. 2013). It is shown that the OB occurs in the negative refractive index frequency bands and also that the OB can be switched to the OM from a negative index frequency band to a positive index frequency band.

In this paper, we intend to study the role of SGC's effect on the OB and the OM behaviors in a left-handed four-level atomic system located in a ring optical cavity. The our atomic systems can be found in atomic vapors. We apply a pulse laser, a probe field and a controlling field to control the quantum coherence and to create the SGC effect. At first, based on the effect of quantum coherence by the laser pulse and the controlling fields the atomic system displays left-handed property. Afterward, despite of absorption very low of the probe field in the negative refractive index frequency bands, we observe the OM behavior in the presence of the SGC effect. The main reason for this phenomenon is quantum coherence generated by the laser pulse and the controlling fields.

2 Theoretical model

The configuration of a four-level atomic system is shown in Fig. 1. In this system, a laser pulse field Ω_S (with frequency ω_S and phase φ_S) is used $|1\rangle \to |3\rangle$ and $|1\rangle \to |4\rangle$, in which $\Delta\omega_S \gg |\Delta\omega_{34}|$. $\Delta\omega_S$ is the spectral width of the laser pulse envelop and $\Delta\omega_{34} = \omega_3 - \omega_4$. The transitions $|2\rangle \to |3\rangle$ and $|3\rangle \to |4\rangle$ are driven by a weak probe field Ω_P (with frequency ω_P and phase φ_P) and a controlling field Ω_C (with frequency ω_C and phase φ_C), respectively. The two levels $|2\rangle$ and $|3\rangle$ have opposite parity with transition electric dipole moment $d_{23} = \langle 2|\widehat{d}|3\rangle$, where $\widehat{d}$ is the electric dipole operator. Also, levels $|1\rangle$ and $|2\rangle$ have equal parity with transition magnetic dipole moment $\mu_{21} = \langle 2|\widehat{\mu}|1\rangle$, where $\widehat{\mu}$ is the magnetic dipole operator. The spontaneous decay rates from level $|4\rangle$ to the levels $|2\rangle$ and $|3\rangle$ and from level $|3\rangle$ to the level $|2\rangle$ are γ_{42}, γ_{43} and γ_{32}, respectively.

The density matrix equations for our atomic system can be described by using the dipole and rotation wave approximations as

$$
\begin{aligned}
\dot{\rho}_{12} &= -i\Delta_P\rho_{12} + i\Omega_S e^{i\varphi_S}(\rho_{32}+\rho_{42}) - i\Omega_P\rho_{13} \\
\dot{\rho}_{13} &= -\gamma_{32}\rho_{13} + i\Omega_S e^{i\varphi_S}(\rho_{33}-\rho_{11}) - i\Omega_P\rho_{12} + i\Omega_S e^{i\varphi_S}\rho_{43} \\
&\quad - P\sqrt{\gamma_{32}\gamma_{42}}\rho_{14} - i\Omega_C\rho_{14} \\
\dot{\rho}_{14} &= -(-i\Delta_S + \gamma_{42} + \gamma_{43})\rho_{14} + i\Omega_S e^{i\varphi_S}(\rho_{44}-\rho_{11}) - i\Omega_C\rho_{13} \\
&\quad + i\Omega_S e^{i\varphi_S}\rho_{34} - P\sqrt{\gamma_{32}\gamma_{42}}\rho_{13} \\
\dot{\rho}_{23} &= -(-i\Delta_P + \gamma_{32})\rho_{23} - i\Omega_S e^{i\varphi_S}\rho_{21} + i\Omega_P(\rho_{33}-\rho_{22}) \\
&\quad + \Omega_C\rho_{24} - P\sqrt{\gamma_{32}\gamma_{42}}\rho_{24} \\
\dot{\rho}_{24} &= -((-i\Delta_P + \Delta_S) + \gamma_{42} + \gamma_{43})\rho_{24} - i\Omega_S e^{i\varphi_S}\rho_{21} + i\Omega_P\rho_{34} \\
&\quad - i\Omega_C\rho_{23} - P\sqrt{\gamma_{32}\gamma_{42}}\rho_{23} \\
\dot{\rho}_{34} &= -(-i\Delta_C + (\gamma_{32}+\gamma_{42}+\gamma_{43}))\rho_{34} + i\Omega_S e^{-i\varphi_S}\rho_{14} + i\Omega_S e^{i\varphi_S}\rho_{31} \\
&\quad + i\Omega_P\rho_{24} + i\Omega_C(\rho_{44}-\rho_{33}) \\
\dot{\rho}_{11} &= i\Omega_S e^{i\varphi_S}(\rho_{31}+\rho_{41}) - i\Omega_S e^{-i\varphi_S}(\rho_{13}+\rho_{14}) \\
\dot{\rho}_{22} &= i\Omega_P(\rho_{32}-\rho_{23}) + \gamma_{32}\rho_{33} + \gamma_{42}\rho_{44} + 2P\sqrt{\gamma_{32}\gamma_{42}}(\rho_{34}+\rho_{43}) \\
\dot{\rho}_{33} &= -i\Omega_S e^{i\varphi_S}\rho_{31} + i\Omega_S e^{-i\varphi_S}\rho_{13} - i\Omega_P(\rho_{32}-\rho_{23}) - \gamma_{32}\rho_{33} \\
&\quad + \gamma_{43}\rho_{44} - P\sqrt{\gamma_{32}\gamma_{42}}(\rho_{34}+\rho_{43}) + i\Omega_C(\rho_{43}-\rho_{34})
\end{aligned}
\tag{1}
$$

where, $\Delta_S = \omega_S - \omega_{41}, \Delta_C = \omega_C - \omega_{43}$ and $\Delta_P = \omega_P - \omega_{32}$ are the frequency detuning of the laser pulse field, the controlling field and the probe field, respectively. φ_S is the phase of the laser pulse and for simplicity, we assumed the real values for Rabi frequency of the controlling field and the probe field. $\omega_{ij} = \omega_i - \omega_j$ exhibit the transition frequency from level i to level j (i, j $= 1, 2, 3, 4$). The equations of the density matrix follow the conditions $\rho_{ij} = \rho_{ji}^*$ and $\sum_{i=1}^{4} \rho_{ii} = 1$. Also, $P\sqrt{\gamma_{42}\gamma_{32}}$ is the result of the quantum interference between spontaneous emissions of nearly spaced upper levels, in which $P = \widehat{d}_{42}.\widehat{d}_{32}/|d_{42}||d_{32}| = cos\theta$ represent the arrangement of the dipole moment matrix elements. Where, the angle between d_{42} and d_{32} is given by θ.

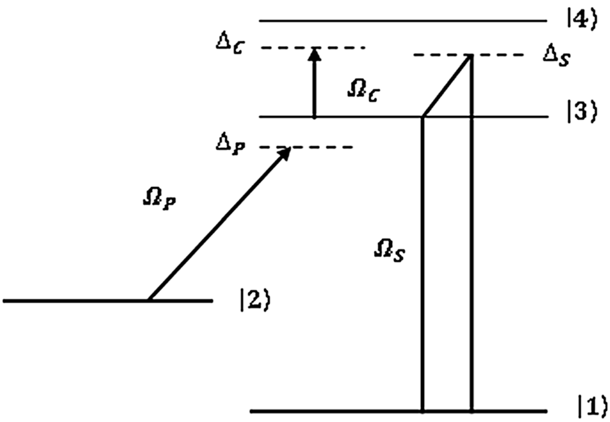

Fig. 1 The scheme of a four-level atomic system interacting with the pulse laser Ω_S, the controlling field Ω_C and the probe field Ω_P

At first, we investigate how we can achieve a negative refractive index in this atomic system. Left-handed materials are characterized by simultaneous negative real parts of the relative dielectric permittivity ε_r and magnetic permeability μ_r. Mathematically, the relation between the negative refractive index n, ε_r and μ_r is given by $n = -\sqrt{\varepsilon_r \mu_r}$. The negative refractive index can be obtained based on the effect of quantum coherence in such a system. To evaluate the electric and magnetic responses of the medium to the applied probe field, we need to have calculated the ρ_{32} and the ρ_{12}. According to the classical electromagnetic theory, the classical electric polarization of the medium is given by $\vec{P}(\omega_P) = \varepsilon_0 \alpha_e(\omega_P)\vec{E}_P(\omega_P)$, where, α_e is the complex atomic polarizability tensor. Furthermore, the induced electric dipole moment of the atom can be also given, according to the quantum coherence, by $\vec{P}(\omega_P) = Tr(\widehat{\rho}\widehat{d}) = d_{23}\rho_{32} + C.C.$ In the following, we assume that $\vec{E}_P$ is parallel to the atomic dipole d_{23}, therefore the electric polarizability α_e will be a scalar quantity and can be expressed by,

$$\alpha_e = \frac{d_{23}\rho_{32}}{\varepsilon_0 \vec{E}_P} \tag{2}$$

Similarly, the classical magnetic polarization of the medium is given by $\vec{M}(\omega_P) = \frac{1}{\mu_0}\alpha_m(\omega_P)\vec{B}_P(\omega_P)$, where, α_m is the complex atomic magnetizability tensor. Furthermore, according to the quantum coherence, the induced magnetic dipole moment of the atom can be also given by $\vec{M}(\omega_P) = Tr(\widehat{\rho}\widehat{\mu}) = \mu_{21}\rho_{12} + C.C.$ Based on Maxwells relation $\vec{B}_P = \vec{K}_P \times \frac{\vec{E}_P}{\omega_P}$, the magnetic field is proportional to the electric field, where, $\vec{K}_P$ is the wavevector of the probe field. Assuming that $\vec{B}_P$ is parallel to μ_{21} , the magnetizability will also be a scalar quantity and is given by,

$$\alpha_m = \frac{\mu_0 c \mu_{21}\rho_{12}}{\eta E_P} \tag{3}$$

where, η is a unitary complex number depending on the polarization of the probe field, μ_0 is permeability of vacuum and c is speed of the light in vacuum. We consider a dense medium, with density N, and take into account the local-field effects (Boyd 2008); therefore, the relative permittivity and relative permeability (Oktel 2004) is expressed as

$$\varepsilon_r = 1 + \chi_e \tag{4}$$

$$\mu_r = \frac{1}{1 - N\alpha_m(1 + \chi_e/3)} \tag{5}$$

where, χ_e is susceptibility of the medium and is determined by the Clausius–Mossotti relation Oktel (2004) as

$$\chi_e = N\alpha_e(1 - N\alpha_e/3)^{-1} \tag{6}$$

The next aim of this paper is to investigate of the OB and the OM in the present atomic system. For this purpose, we consider a unidirectional ring cavity with length of L that consists of the ensemble of N homogeneously broadened four-level atoms (Fig. 2). To simplify, we select mirrors 3 and 4 with perfect reflectivity, and mirrors 1 and 2 with the reflection and transmission powers R and T $(R + T = 1)$, respectively. The total electromagnetic field inside the cavity will be as

$$\vec{E} = \vec{E}_P e^{-i\omega_P t} + \vec{E}_S e^{-i\omega_S t} + \vec{E}_C e^{-i\omega_C t} + C.C. \tag{7}$$

where, $\vec{E}_P$ is the probe field that can circulate in the ring cavity. $\vec{E}_S$ and $\vec{E}_C$ are the laser pulse and the controlling fields, respectively, which they are non- circulating in the cavity. According to slowly varying envelope approximation, the Maxwells equation for the probe field reduces to

$$\frac{\partial \vec{E}_P}{\partial t} + c\frac{\partial \vec{E}_P}{\partial z} = i\frac{\omega_P}{2\varepsilon_0}\vec{P}(\omega_P) \tag{8}$$

where, the induced polarization in the transition $|3\rangle \to |2\rangle$ is $\vec{P}(\omega_P) = Nd_{23}\rho_{32}$ and N is the number density of the atoms. In the mean-field limit, by solving Eq. (8) in the steady-state and applying the boundary conditions between the incident and the transmitted fields as

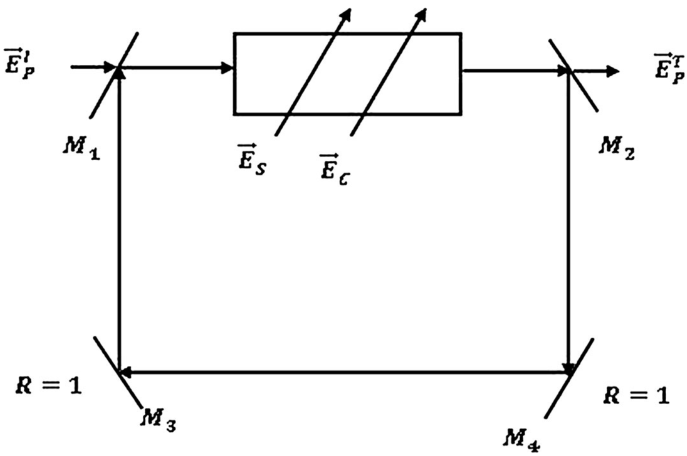

Fig. 2 Schematic setup of a unidirectional ring cavity with length of L that consists of the ensemble of N homogeneously broadened four-level atoms

$$\vec{E_P}(L) = \frac{\vec{E_P^T}}{\sqrt{T}} \tag{9}$$

$$\vec{E_P}(0) = \sqrt{T}\vec{E_P^I} + R\vec{E_P}(L) \tag{10}$$

The relation between incident and transmitted fields can be obtained as,

$$y = x - iC\gamma_{32}\rho_{32} \tag{11}$$

The second term in the right-hand of Eq. (10), describes the feedback mechanism of the mirror that is necessary to acquire optical bistability. $x = \frac{d_{23}\vec{E_P^T}}{\hbar\sqrt{T}}$ and $y = \frac{d_{23}\vec{E_P^I}}{\hbar\sqrt{T}}$, in Eq. (11), are the normalizing of the input-output fields. In the right-hand side of Eq. (11), the steady-state value of ρ_{32} is obtained by setting the time derivatives of the density matrix in Eqs. (1) to zero. The electronic cooperation parameter is given by,

$$C = \frac{\omega_P NL|d_{23}|^2}{2\hbar\varepsilon_0 cT} \tag{12}$$

3 Results

In first step, we numerically solve the density matrix equations (1) to obtain the negative refractive index of the atomic system. Appropriate typical parameters are selected as Yang and Jiang (2012):

- Atomic density; $N = 10^{20}\,\mathrm{m}^{-3}$.
- Electric transition dipole moment; $d_{23} = 2.5 \times 10^{-32}\,\mathrm{C\,m}$.
- Magnetic transition dipole moment; $\mu_{21} = 0.927 \times 10^{-23}\,\mathrm{A\,m}^2$.

The other parameters are scaled as; $\gamma = 10^8\,\mathrm{s}^{-1}$. $\gamma_{42} = \gamma_{32} = \gamma, \gamma_{43} = 0.5\gamma$ and $\varphi_S = \pi$. The frequency detuning is $\Delta_S = -1$ for the laser pulse and $\Delta_C = 1$ for the controlling field. In Fig. 3, we plot the real parts of the permittivity ε_r and permeability μ_r as a function of

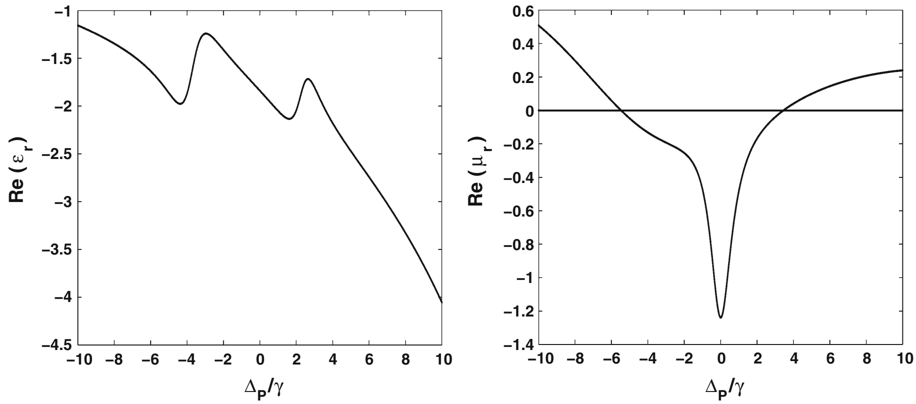

Fig. 3 The real parts of the permittivity ε_r and permeability μ_r as a function of Δ_P/γ for $P = 0$. $\Omega_S = 3\gamma, \Omega_C = 1\gamma, \gamma_{42} = \gamma_{32} = \gamma, \gamma_{43} = 0.5\gamma, \Delta_S = -1$ and $\Delta_C = 1$

Δ_P/γ (probe detuning frequency) for $P = 0$. This atomic system exhibits left-handed properties, with simultaneously negative permittivity and permeability, in the frequency detuning band of $-5.3 < \Delta_P/\gamma < 3.6$. Figure 4 show the real and imaginary parts of refractive index in this the frequency detuning band. As can be see from Fig. 4, the real part of refractive index has negative values in the frequency detuning band of $-5.3 < \Delta_P/\gamma < 3.6$, while the imaginary part of refractive index has both negative and positive values in this frequency band. Figure 5 show the real parts of the permittivity and permeability as a function of Δ_P/γ for $P = 0.8$ (the reason of this selection will be explained later). Other parameters are similar to the case of Fig. 3. The real part of the permittivity is perfect negative in the selection band of Δ_P/γ, as $P = 0$. However, the real part of the permeability has negative values in two bands, $-5.8 < \Delta_P/\gamma < -1.27$ and $0.47 < \Delta_P/\gamma < 3.92$. Consequently, the atomic system can show left-handed material characteristics in these two frequency detuning bands for $P = 0.8$. The real and imaginary parts of the refractive index for $P = 0.8$ were plotted in Fig. 6 for two frequency detuning bands. The real part of the refractive index has negative values in the frequency detuning bands of Fig. 5, in which the system has shown left-handed property while the imaginary part of refractive index has both negative and positive values in these frequency bands. Figure 7 shows the absorption of probe field that it is proportional to the imaginary part of the ρ_{32}. Based on the effect of quantum coherence by the laser pulse and the controlling field, the absorption property of atomic system decrease in the negative refractive index frequency bands. So, system can be stores an amount of energy that related to magnetic response. This feature is important reason to obtain the negative values for real part of the refractive index and the absorption of atomic system. As a result, the atomic system becomes an active medium in the bands of $-2.96 < \Delta_P/\gamma < 0.1$ and $2.2 < \Delta_P/\gamma < 3.59$ for $P = 0$ and in the bands of $-3.23 < \Delta_P/\gamma < -1.27$ and $2.43 < \Delta_P/\gamma < 3.92$ for $P = 0.8$, and this can be applied to amplification of electromagnetic fields.

In the next step, we investigate the OB and the OM behaviors in this atomic system in the negative refractive band. The input-output curves are plotted in Fig. 8 for $P = 0$ according to the values of Fig. 3, for $C = 400$. For $\Delta_P/\gamma > 0$, we select $\Delta_P/\gamma = 1$ within the negative refractive index band and $\Delta_P/\gamma = 4$ outside of the negative refractive index band. For $\Delta_P/\gamma < 0$, we select $\Delta_P/\gamma = -6$ outside of the negative refractive index band and

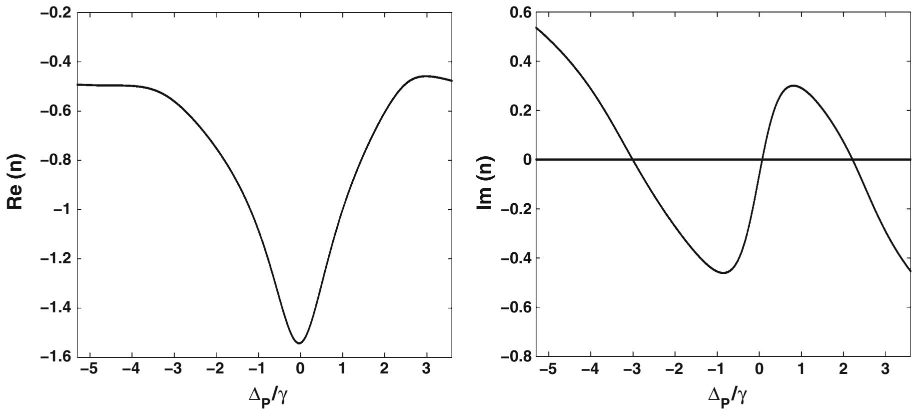

Fig. 4 The real and imaginary parts of the refractive index as a function of Δ_P/γ for $P = 0$. Other parameters are the same as Fig. 3

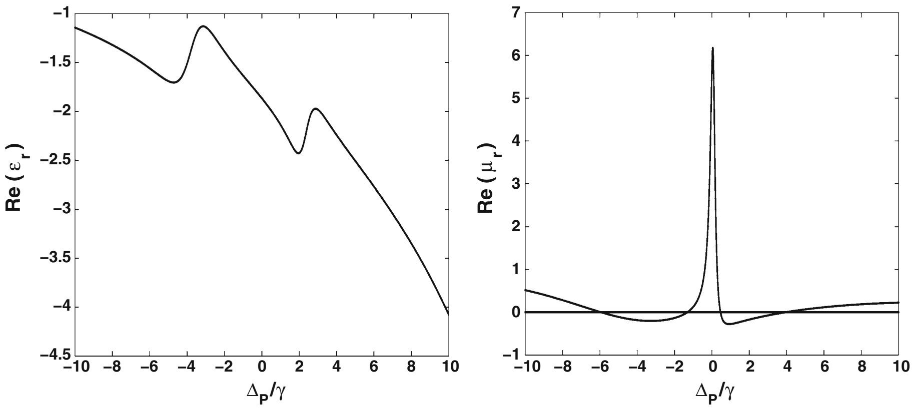

Fig. 5 The real parts of the permittivity ε_r and permeability μ_r as a function of Δ_P/γ for $P = 0.8$. Other parameters are the same as Fig. 3

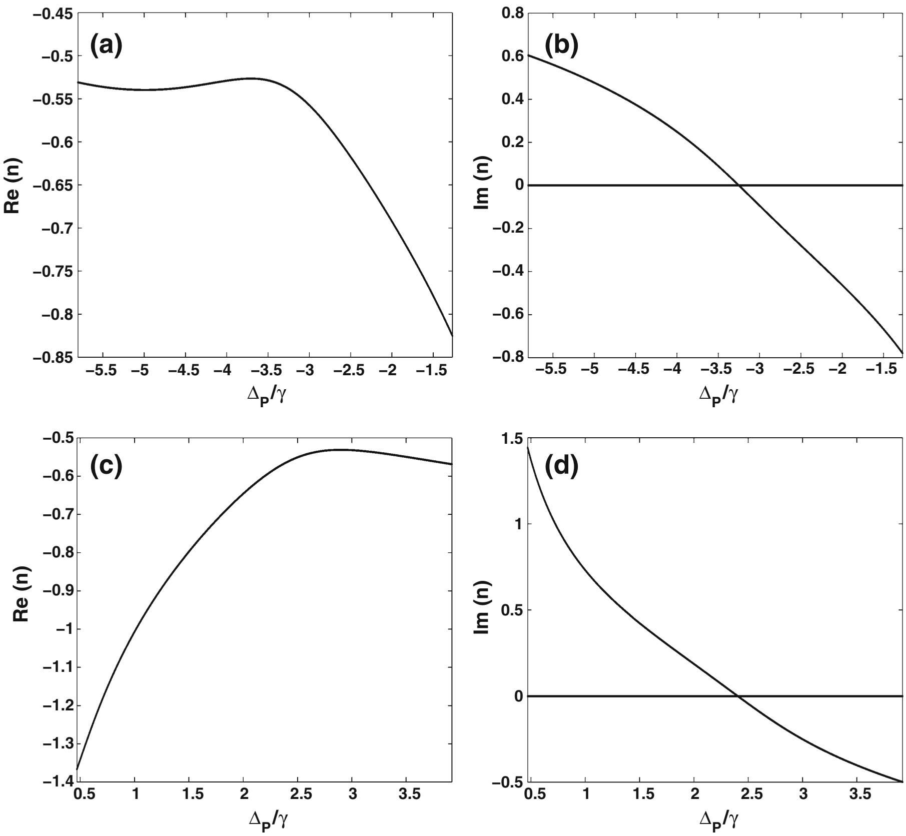

Fig. 6 **a**, **b** The real and imaginary parts of the refractive index for $-5.8 < \Delta_P/\gamma < -1.27$; **c**, **d** the real and imaginary parts of the refractive index for $0.47 < \Delta_P/\gamma < 3.92$ as a function of refractive Δ_P/γ for $P = 0.8$. Other parameters are the same as Fig. 3

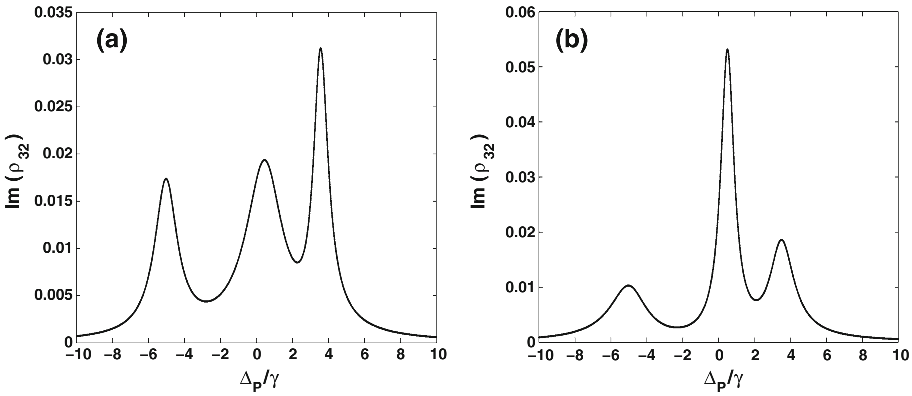

Fig. 7 The absorption of probe field as a function of Δ_P/γ, **a** for $P = 0$ and **b** for $P = 0.8$. Other parameters are the same as Fig. 3

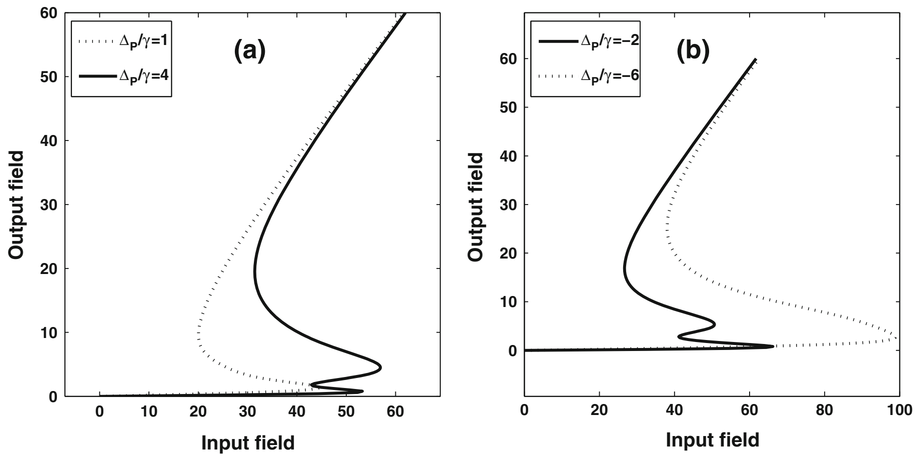

Fig. 8 Output field versus input field curves for $P = 0$, **a** $\Delta_P/\gamma = 1$ in the negative refractive index band and $\Delta_P/\gamma = 4$ in the positive refractive index band for $\Delta_P/\gamma > 0$ and **b** in $\Delta_P/\gamma = -2$ in the negative refractive index band and $\Delta_P/\gamma = -6$ in the positive refractive index band for $\Delta_P/\gamma < 0, \mathrm{C} = 400$. Other parameters are the same as Fig. 3

$\Delta_P/\gamma = -2$ within the negative refractive index band. For $\Delta_P/\gamma > 0$, we see that the atomic system is switched from the OB to the OM when the system has a transition from the negative refractive index band to the positive refractive index band. While, for $\Delta_P/\gamma < 0$ the system goes from the OM to the OB when it has a transition from the positive refractive index band to the negative refractive index band. Thus, we can easily control the transition between the OB and the OM effects by modifying the sign of the refractive index. This is to say, switching from the OM to the OB and vice versa can be controlled very effectively by tuning the negative refractive index to the positive refractive index. In Fig. 9 the input-output curves are shown for $P = 0.8$ and $C = 400$, other parameters are fixed as Fig. 3. The results are similar to each other in both $\Delta_P/\gamma > 0$ and $\Delta_P/\gamma < 0$ bands, and we can see the OM behavior in this system when the SGC effect is considered. The

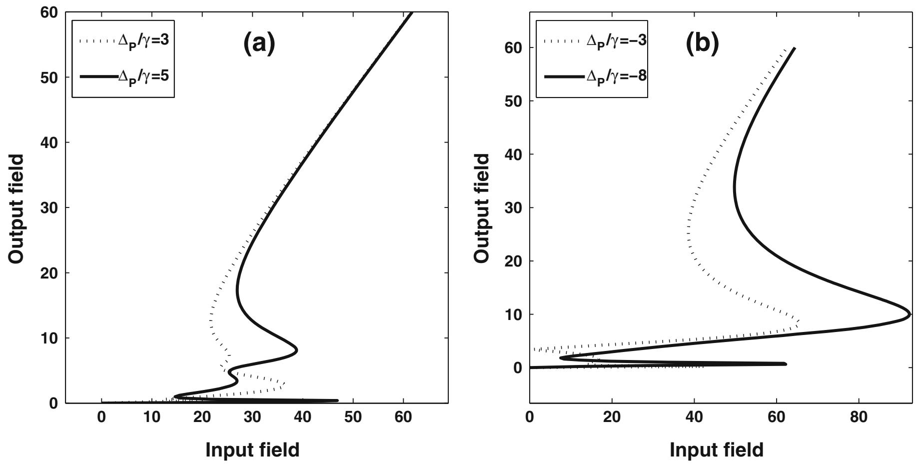

Fig. 9 Output field versus input field curves for $P = 0.8$, **a** $\Delta_P/\gamma = 3$ in the negative refractive index band and $\Delta_P/\gamma = 5$ in the positive refractive index band for $\Delta_P/\gamma > 0$ and **b** in $\Delta_P/\gamma = -3$ in the negative refractive index band and $\Delta_P/\gamma = -8$ in the positive refractive index band for $\Delta_P/\gamma < 0$, C = 400. Other parameters are the same as Fig. 3

threshold of the OM in the negative refractive index band is less than that of the positive refractive index band. For $\Delta_P/\gamma < 0$, we select $\Delta_P/\gamma = -8$ outside of the negative band and $\Delta_P/\gamma = -3$ within the negative band. Also for $\Delta_P/\gamma > 0$, we select $\Delta_P/\gamma = 5$ outside of the negative band and $\Delta_P/\gamma = 3$ within the negative band. It is found that with absorption very low or even close to zero of the probe field in the negative refractive index frequency bands, the OB and the OM behaviors can appear in these bands of atomic system. The main reason for this phenomenon is quantum coherence generated by the laser pulse and the controlling fields. Furthermore, absorption of the probe field in left-handed material will manipulate by the laser pulse and the controlling fields. For $P > 0.8$ the threshold of the OM effect will occurr in very high input fields, hence we select $P = 0.8$ for studying of the SGC effect. The frequency bands will be in the range GHz because of $\gamma = 10^8\ \mathrm{s}^{-1}$.

4 Conclusion

In conclusion, we theoretically investigated electromagnetic characteristics and the OB and the OM effects of dense four-level atomic system. We introduced three electromagnetic fields to couple the four states of the system; a pulse laser, a controlling field and a weak probe field. In the absence of the SGC effect, this atomic system exhibits left-handed property in one frequency detuning band of the probe field. In the presence of the SGC effect, the real part of the permittivity ε_r is perfect negative in the selection frequency detuning band while the real part of the permeability μ_r has the negative value in two bands of the selection frequency detuning band. Hence, the atomic system can obtain a negative refractive index, in one probe detuning frequency band in the absence of the SGC effect and in two probe detuning frequency bands in the presence of the SGC effect. In both cases, the imaginary part of the refractive index has both negative and positive values in the frequency bands. Therefore, the real and imaginary parts of refractive index can have negative values in the same frequency band due to of quantum coherence by the laser pulse and the controlling field and reduce of absorption property of atomic system. Consequently, we can use this atomic system as an active medium for amplification of electromagnetic fields. In the absence of the SGC effect, we can easily control the transition between the OB and the OM effects by changing the sign of the refractive index. In the presence of the SGC effect, we can see the OM behavior in this system that the threshold of the OM in the negative refractive index band is less than of positive refractive index band. The reason of this phenomenon can be the quantum coherence generated by the laser pulse and the controlling fields. The quantum coherence reduces the probe field absorption, therefore enhances the Kerr nonlinearity in the negative refractive index band.

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