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Polarization dependence of optical bistability in the presence of external magnetic field

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ABSTRACT

In this paper, a four-level inverted Y type atomic system for controlling the optical bistability and multistability is proposed. An elliptically polarized probe field and a coherent coupling field in the presence of external magnetic field are interacted by this medium. It is shown that the external magnetic field and relative phase between two electric field components of the probe field can influence the threshold of optical bistability. Moreover, it is found that optical bistability can be converted to the optical multistability by external magnetic field and relative phase.

1. Introduction

It is known that controlling light by light is one of the important and interestable research topics in the quantum and nonlinear optics. In such case, quantum coherence and quantum interference are the basic mechanisms for modifying the optical response of the medium: for example, electromagnetically induced transparency (EIT) [1–3], lasing without inversion [4], four wave mixing [5–7], optical solitons [8], enhancing Kerr nonlinearity [9,10], superluminal light propagation [11–13] and optical bistability [14–16]. For developing all optical communication and quantum communication networks, all optical switching, optical transistors and logic circuits are required. Therefore, optical bistability is developed due to its potential application in all optical switching and optical transistors. Optical bistability has extensively studied both experimentally and theoretically in various atomic media [17–20]. For example, in a three-level Λ-type atomic system inside an optical cavity, Wang et al. [21] have experimentally demonstrated the bistability and instability. Gong et al. [22] have showed that the large bistable hysteresis cycle can be obtained if the initial coherence of the three level atomic system increases. Also, the bistable and multistable behaviors of a three-level V-type [23], open three-level Λ-type [24], four-level N-type [25] and even semiconductor structures [26–28] have been discussed. Moreover, the effect of the phase fluctuation [29], squeezed vacuum field [30] and vacuum induced coherence [31] on OB has also been studied. Recently, a double two-level atomic system for realizing optical bistability and optical multistability [32] was proposed. In this study, it is shown that the relative phase between applied fields can influence the optical bistability and optical multistability and transition from optical bistability to optical multistability or vice versa is possible. In our recent studies, we shown that spontaneously generated coherence (SGC) makes the medium phase dependent and thus the bistability behaviors can be controlled by relative phase between applied fields [33].

In this paper, the behaviors of OB and OM in a four-level inverted Y-type atomic system driven by an elliptically polarized probe field and a coupling laser field in the presence of external magnetic field are investigated. To the best of our knowledge, the bistable and multistable behaviors of the four-level atomic system with this configuration are not reported theoretically or experimentally. It is shown that by adjusting the frequency detuning of the probe field, intensity of coupling filed and external magnetic field one can control the bistable and multistable behaviors of the media by changing the phase deference between two circularly polarized components of the probe field.

2. Model and equations

We consider a four-level atomic system as depicted in Fig. 1. The two lower states $|1\rangle$ and $|2\rangle$ are the degenerate Zeeman sublevels corresponding respectively to the magnetic quantum numbers $m=1$ and $m=-1$ of a ground-state hyperfine level $F=1$. The two upper states $|3\rangle$, $|4\rangle$, are all the $m=0$ Zeeman sublevels, respectively, of different excited states and belong to hyperfine

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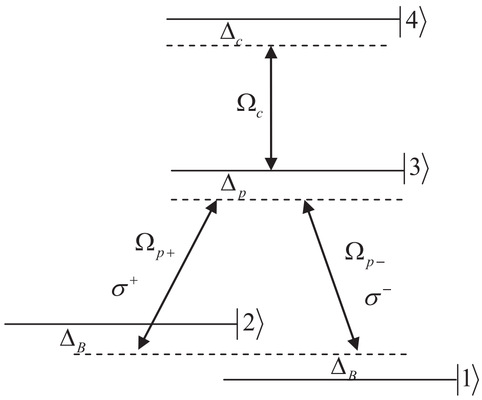

Fig. 1. Schematic of four-level inverted Y-type atomic system.

levels between which the electric dipole transitions are allowed. The medium is subject to a longitudinal magnetic field B that removes the degeneracy of the ground-state sublevels, where the magnetic field B shifts $m = \pm 1$ levels by $\pm\Delta_B$. All the atoms are assumed to be optically pumped to the two ground-state levels $|1\rangle$ and $|2\rangle$, which therefore have the same incoherent populations equal to 1/2, i.e. $\rho_{11} = \rho_{22} \simeq 1/2$. An elliptically polarized control field with frequency ω_p and wave vector k_p is used to create electric dipole transitions from the exited state $|3\rangle$ to the ground states $|1\rangle$ and $|2\rangle$ simultaneously. A probe beam with electric field amplitude E_0 after passing through the QWP that has been rotated by angleθ becomes elliptically polarized. Thus the polarized probe beam can be decomposed into $E_p = E^+\sigma^+ + E^-\sigma^-$, where $E^+ = E_0/\sqrt{2}(\cos\theta + \sin\theta)e^{i\theta}$ and $E^- = E_0/\sqrt{2}(\cos\theta - \sin\theta)e^{-i\theta}$. Here, σ^+ and σ^- are the unit vectors of the right-hand circularly and the left-hand circularly polarized basis, respectively. The strength and phase difference of the two electric field components can be changed by QWP. Thus, the Rabi frequencies of the probe field become $\Omega_{p^+} = \Omega_p(\cos\theta + \sin\theta)e^{i\theta}$ and $\Omega_{p^-} = \Omega_p(\cos\theta - \sin\theta)e^{-i\theta}$. It is assumed that $\mu_{13} = \mu_{23} = \mu$ and $\Omega_p = \mu E_0/\sqrt{2}\hbar$. Electric dipole transition between states $|3\rangle$ and $|4\rangle$ is coupled by a control beam with carrier frequency ω_c and wave vector k_c.

In the interaction picture, the resulting 4×4 interaction Hamiltonian describing the atom–field interaction for the system under study can be written as:

$$H_{\text{int}} = 2\Delta_B|2\rangle\langle2| + (\Delta_B + \Delta_P)|3\rangle\langle3| + (\Delta_B + \Delta_P + \Delta_c)|4\rangle\langle4| + (\Omega_{P-}|3\rangle\langle1| + \Omega_{P+}3\rangle\langle2| + \Omega_c|4\rangle\langle3|) + hc \tag{1}$$

Here the detuning parameters are defined as:$\Delta_p = \omega_{31} - \Delta_B - \omega_p = \omega_{32} + \Delta_B - \omega_p$, $\Delta_c = \omega_{43} - \omega_c$, where ω_{ij} is the frequency deference between level $|i\rangle$ and level $|j\rangle$. Δ_B is the Zeeman shift of levels $|1\rangle$ and $|2\rangle$ in the presence of the magnetic field and Δ_B is taken to zero for zero magnetic field. The density matrix equations of motion under the rotating wave approximation and in the rotating frame are:

$$\frac{\partial\rho_{11}}{\partial t} = \gamma_{31}\rho_{33} + i\Omega_{p-}\rho_{31} - i\Omega_{p-}\rho_{13},$$
$$\frac{\partial\rho_{22}}{\partial t} = \gamma_{32}\rho_{33} + i\Omega_{p+}\rho_{32} - i\Omega_{p+}\rho_{23},$$
$$\frac{\partial\rho_{33}}{\partial t} = -(\gamma_{31} + \gamma_{32})\rho_{33} + \gamma_{43}\rho_{44} + i\Omega_{p-}\rho_{13} - i\Omega_{p-}\rho_{31} + i\Omega_{p+}\rho_{23} - i\Omega_{p+}\rho_{32} + i\Omega_c\rho_{43} - i\Omega_c\rho_{34},$$
$$\frac{\partial\rho_{44}}{\partial t} = -\gamma_{43}\rho_{44} + i\Omega_c\rho_{34} - i\Omega_c\rho_{43},$$
$$\frac{\partial\rho_{21}}{\partial t} = -2i\Delta_B\rho_{21} + i\Omega_{p+}\rho_{31} - i\Omega_{p-}\rho_{23},$$
$$\frac{\partial\rho_{31}}{\partial t} = -\left[i(\Delta_B + \Delta_p) + \frac{\gamma_{31} + \gamma_{32}}{2}\right]\rho_{31} + i\Omega_{p-}(\rho_{11} - \rho_{33}) + i\Omega_{p+}\rho_{21} + i\Omega_c\rho_{41},$$
$$\frac{\partial\rho_{41}}{\partial t} = -\left[i(\Delta_B + \Delta_p + \Delta_c) + \frac{\gamma_{43}}{2}\right]\rho_{41} + i\Omega_c\rho_{31} - i\Omega_{p-}\rho_{43},$$
$$\frac{\partial\rho_{32}}{\partial t} = -\left[i(-\Delta_B + \Delta_p) + \frac{\gamma_{31} + \gamma_{32}}{2}\right]\rho_{32} + i\Omega_{p+}(\rho_{22} - \rho_{33}) + i\Omega_{p-}\rho_{12} + i\Omega_c\rho_{42},$$
$$\frac{\partial\rho_{42}}{\partial t} = -\left[i(-\Delta_B + \Delta_p + \Delta_c) + \frac{\gamma_{43}}{2}\right]\rho_{42} + i\Omega_c\rho_{32} - i\Omega_{p+}\rho_{43},$$
$$\frac{\partial\rho_{43}}{\partial t} = -\left[i\Delta_c + \frac{\gamma_{31} + \gamma_{32} + \gamma_{43}}{2}\right]\rho_{43} + i\Omega_c(\rho_{33} - \rho_{44}) - i\Omega_{p-}\rho_{41} - i\Omega_{p+}\rho_{42}. \tag{2}$$

In the above equations, if we assume the cold atomic gas, the relaxation rates of coherence between the ground states $|1\rangle$ and $|2\rangle$ by collision and etc are negligible thus can be safely omitted. The set of Eq. (2) can be solved numerically to obtain the steady state response of the medium. In fact, response of the medium to the applied field is determined by the susceptibility χ_p, corresponding to two components of opposite circular polarization, for the $|3\rangle \leftrightarrow |1\rangle$ and $|3\rangle \leftrightarrow |2\rangle$ transitions, respectively, which are define as:

$$\chi_p = \frac{N|\mu|^2(\rho_{31} + \rho_{32})}{2\hbar\varepsilon_0\Omega_p} \propto (\rho_{31} + \rho_{32}) \tag{3}$$

where N is the atomic density number in the medium. Note that, the all parameters used in this paper are scaled by γ_{31}, which should be in the order of MHz for rubidium or sodium atoms. In this approach, when the Zeeman shift Δ_B is scaled by γ_{31}, then the magnetic field strength B should be in units of the combined constant $\gamma_c = \hbar g_F^{-1}\mu_B^{-1}\gamma_{31}$, where g_F is gyromagnetic factor and μ_B is the Bohr magneton. In the following numerical calculations we assume $\gamma_{31} = \gamma_{32} = \gamma, \gamma_{43} = 0.25\gamma$ and all the used parameters are scaled with γ.

Now, we consider a medium of length L composed of the above described atomic system immersed in unidirectional ring cavity as shown in Fig. 2. The intensity reflection and transmission coefficients of mirrors 1 and 2 are R and T (with R+T=1), respectively. We assume that both the mirrors 3 and 4 are prefect reflectors. The total electromagnetic field for the elliptically polarized probe beam and control beam in the cavity can be written as:

$$E_p e^{-i(\omega_p t - k_p z)} + E_c e^{-i(\omega_c t - k_c z)} + cc \tag{4}$$

Where E_p is the amplitude of elliptically polarized probe field, which circulate in the ring cavity and E_c is a control field and is not circulate in the cavity. Under slowly varying envelop approximation, the dynamics response of the elliptically polarized probe beam is governed by Maxwell's equations:

$$\frac{\partial E_p}{\partial t} + c\frac{\partial E_p}{\partial z} = \frac{i\omega_p}{2\varepsilon_0}P(\omega_p) \tag{5}$$

where $P(\omega_p)$ is the induced polarization, $P(\omega_p) = N\mu(\rho_{31} + \rho_{32})$. For a perfectly tuned cavity, the boundary conditions in the steady-state limit between the incident field E_p^I and transmitted

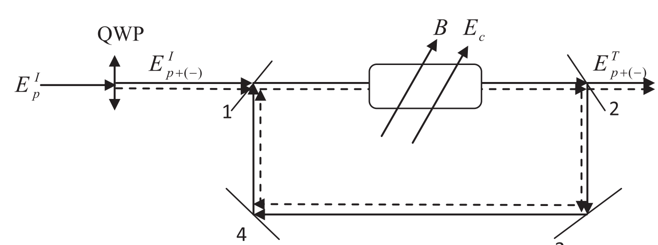

Fig. 2. Unidirectional ring cavity with sample of length L. $E^I_{p+(-)}$and $E^T_{p+(-)}$are the incident and transmitted fields, respectively. A uniform magnetic field B is applied to the sample to the direction of light propagation. E_c is the coherent coupling field.