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Optical multistability generation via cavity series

Rasool Doostkam *, Mohammad Mahmoudi

Department of Physics, University of Zanjan, University Blvd, Zanjan 45371-38791, Iran

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ABSTRACT

We investigated a different approach to establish an optical multistability (OM) in quantum atomic systems. It is demonstrated that using two cavities in series configuration leads to a more flexible OM. The number of output intensities can be further than usual and each branch of OM diagram is controllable. In addition, we have specified necessary conditions to achieve this flexible OM. It is shown that the OM threshold and even the lengths of branches are adjustable.

1. Introduction

Optical Bistability (OB) and Multistability (OM) are one of the attractive and practical aspects of nonlinear Optics. Recently, these phenomena have received much attention because of their numerous applications such as all-optical switching, optical transistors, optical memories, and logical gates [1–3]. OB in atomic systems has been extensively studied both theoretically and experimentally [4]. An optical bistable system has two possible output intensities for an input intensity [5]. Many approaches have been introduced to control OB in atomic systems. The effects of intensity and the frequency detuning of the coupling field, electromagnetically induced transparency (EIT) and quantum interferences on OB have been studied [6,7]. In addition, OM has been studied theoretically and experimentally in different atomic systems and some approaches have been proposed to control of its features [8–10]. OM feature in a silicon-core silica-cladding fiber has been observed by using the power and wavelength modulation [11]. Kerr effect and establishment of OM in a four-level Y-type atomic system has been investigated [12]. Tunneling-induced and incoherent pumping field in a quantum dots are other methods in order to control OM [13]. The study of OM in N-type atomic system and the effect of quantum interference on OM have been reported [14]. In this letter, we suggest completely different method to constructing and controlling the OM. People has been used a single cavity in ordinary OM setup while alternative proposition is using two cavities in series configuration that leads to an OM with intriguing characteristics. In our proposed configuration, the OB switches to OM with controllable possible outputs.

The output field of first cavity is practically considered as an input field for second cavity. There are some conditions in order to achieve favorable OM features that are determined and clarified. It is worth noting that the OB behaviors of cavities must appear in the same region of the intensity. In addition, it is demonstrated that changing the relative phase of the applied fields, has a significant effect on the thresholds of OM branches.

2. Model and equations

We consider two cavities in series configuration as shown in Fig. 1(a). In this scheme the output field from the first cavity is considered as an input field for second one. Different atomic systems are included inside of each cavity and interact with probe and control fields. Therefore, we consider two atomic systems as shown in Fig. 2. System (I) has a lower level$|1\rangle$ and excited states$|2\rangle$ and $|3\rangle$ [15]. The transitions $|1\rangle-|3\rangle, |1\rangle-|2\rangle$, and $|2\rangle-|3\rangle$ are driven by coherent laser fields with Rabi frequencies Ω_p, Ω_c, and Ω_d respectively (for example $\Omega_p = E_p\mu_{31}/2\hbar$ [15]), to establish a V-type atomic system. Decay rates form excited states $|3\rangle$ and $|2\rangle$ to the lower state are denoted by γ_{31} and γ_{21}. The Hamiltonian of system in the interaction picture, and dipole and rotating-wave approximations, can be written as

$$H = -\hbar(\Omega_p|3\rangle\langle 1|e^{-i\Delta_p t} + \Omega_d|3\rangle\langle 2|e^{-i\Delta_d t} + \Omega_c|2\rangle\langle 1|e^{-i\Delta_c t} + h.c), \quad (1)$$

where $\Delta_p = \omega_{31} - \omega_p$ and $\Delta_c = \omega_{21} - \omega_c$ are frequency detunings between fields and the central frequency of transitions. The related phase between fields is denoted by φ.

By adopting the standard procedures ($\dot{\rho}(t) = [H,\rho]/i\hbar + \Lambda\rho$) [16] and assuming $\Delta_d = 0$ and $\Delta_p = \Delta_c = \Delta$ the density matrix equations can be written as

$$\dot{\rho}_{11} = \gamma_{31}\rho_{33} + \gamma_{21}\rho_{22} + i\Omega_c(\rho_{21} - \rho_{12}) + i\Omega_p(\rho_{31} - \rho_{13})$$
$$\dot{\rho}_{22} = -\gamma_{21}\rho_{22} + i\Omega_c(\rho_{12} - \rho_{21}) + i\Omega_d(e^{-i\varphi}\rho_{32} - e^{i\varphi}\rho_{23}),$$

* Corresponding author.
E-mail address: mahmoudi@znu.ac.ir (R. Doostkam).

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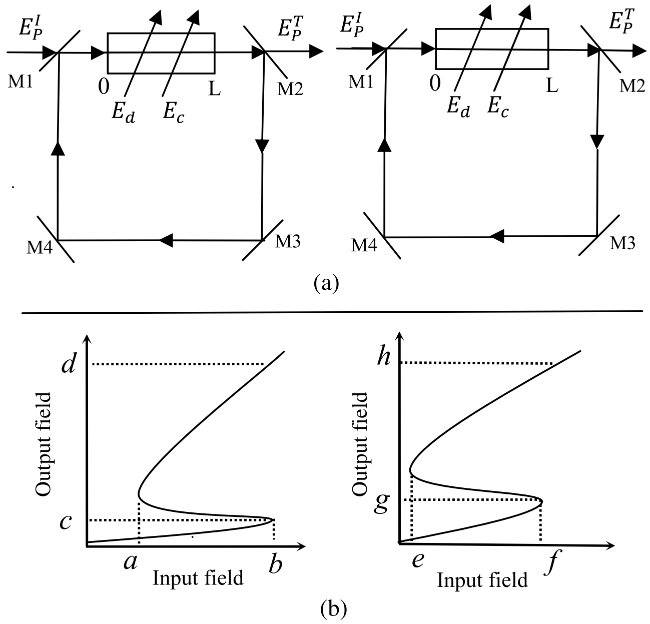

Fig. 1. (a) Unidirectional ring cavities beside together with their atomic samples of length L. E_p^I and E_p^T are the incident and transmitted fields while E_c and E_d are the coupling and microwave coherent laser fields, respectively. For mirrors 1 and 2 it is assumed $\bar{R}+\bar{T}=1$ and mirrors 3 and 4 have perfect reflectivity. (b) The schematic diagram of individual OB feature for each system.

$$\dot{\rho}_{33}=-\gamma_{31}\rho_{33}+i\Omega_p(\rho_{13}-\rho_{31})+i\Omega_d(e^{i\varphi}\rho_{23}-e^{-i\varphi}\rho_{32}),$$
$$\dot{\rho}_{12}=\left(i\Delta-\frac{\gamma_{21}}{2}\right)\rho_{12}+i\Omega_p\rho_{32}+i\Omega_c(\rho_{22}-\rho_{11})-i\Omega_d e^{i\varphi}\rho_{13}, \quad (2)$$
$$\dot{\rho}_{13}=\left(i\Delta-\frac{\gamma_{31}}{2}\right)\rho_{13}+i\Omega_p(\rho_{33}-\rho_{11})+i\Omega_c\rho_{23}-i\Omega_d e^{-i\varphi}\rho_{12},$$
$$\dot{\rho}_{23}=\left(-\frac{\gamma_{21}+\gamma_{31}}{2}\right)\rho_{23}+i\Omega_c\rho_{13}-i\Omega_p\rho_{21}+i\Omega_d e^{-i\varphi}(\rho_{33}-\rho_{22}),$$

In contrast, system (II) has an upper level $|3\rangle$ and lower levels $|1\rangle$ and $|2\rangle$ (lambda-type system) [17]. The probe field with Rabi frequency Ω_p is applied to the transition $|1\rangle-|3\rangle$ while coupling and microwave fields with their Rabi frequencies Ω_c and Ω_d are applied to transitions $|2\rangle-|3\rangle$, and $|1\rangle-|2\rangle$. In system (II) we use the Rabi frequency relations used in [17] (for example $\Omega_p=E_p\mu_{31}/\hbar$) that differs from system (I) by the factor of two and decay rates from level $|3\rangle$ to levels $|1\rangle$ and $|2\rangle$ are $2\Gamma_{31}$ and $2\Gamma_{32}$. Similarly, in the interaction picture, and dipole and rotating-wave approximations Hamiltonian of system (II) will be as follows

$$H=-\hbar(\Omega_p|3\rangle\langle 1|e^{-i\Delta_p t}+\Omega_c|3\rangle\langle 2|e^{-i\Delta_c t}+\Omega_d|2\rangle\langle 1|e^{-i\Delta_d t}+h.c), \quad (3)$$

where $\Delta_p=\omega_{31}-\omega_p, \Delta_c=\omega_{32}-\omega_c, \Delta_d=\omega_{21}-\omega_d=0$, present atom–field detunings and ϕ is the related phase of applied fields.

Using this Hamiltonian, The density matrix equations can be achieved as

$$\dot{\rho}_{11}=2\Gamma_{31}\rho_{33}+i\Omega_p(\rho_{31}-\rho_{13})+i\Omega_d(e^{i\phi}\rho_{21}-e^{-i\phi}\rho_{12}),$$
$$\dot{\rho}_{22}=2\Gamma_{32}\rho_{33}+i\Omega_c(\rho_{32}-\rho_{23})+i\Omega_d(e^{-i\phi}\rho_{12}-e^{i\phi}\rho_{21}),$$
$$\dot{\rho}_{33}=-2\Gamma_{31}\rho_{33}-2\Gamma_{32}\rho_{33}+i\Omega_p(\rho_{13}-\rho_{31})+i\Omega_c(\rho_{23}-\rho_{32}),$$
$$\dot{\rho}_{23}=\left(-\Gamma_{31}-\Gamma_{32}-i\Delta_c\right)\rho_{23}+i\Omega_c(\rho_{33}-\rho_{22})-i\Omega_p\rho_{21}+i\Omega_d e^{-i\phi}\rho_{13}, \quad (4)$$
$$\dot{\rho}_{12}=i\left(\Delta_p-\Delta_c\right)\rho_{12}-i\Omega_c\rho_{13}+i\Omega_p\rho_{32}+i\Omega_d(\rho_{22}-\rho_{11})e^{i\phi},$$
$$\dot{\rho}_{13}=\left(-\Gamma_{31}-\Gamma_{32}+i\Delta_p\right)\rho_{13}+i\Omega_p\left(\rho_{33}-\rho_{11}\right)-i\Omega_c\rho_{12}+i\Omega_d e^{i\phi}\rho_{23},$$

One aspect of the nonlinear optics is observing the bistable behavior for light during the optical cavity interacting with saturable medium.

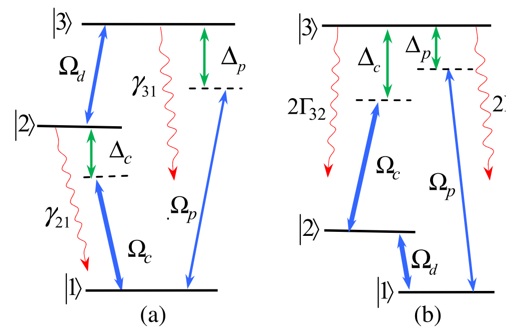

Fig. 2. Schematic diagrams of the three level (a) V-type atomic system and (b) Λ-type atomic system. Coherent laser fields with Rabi frequencies Ω_p, Ω_c, Ω_d and atom–field detunings $\Delta_p=\omega_{31}-\omega_p$, and $\Delta_c=\omega_{32}-\omega_c$ are applied to transitions. Decay rates of levels $|3\rangle$ and $|2\rangle$ are denoted by γ_{31} and γ_{21} in system (I) and $2\Gamma_{31}$ and $2\Gamma_{32}$ are decay rates of level$|3\rangle$ in system (II).

Taking into account the mean-field limit and using the boundary conditions, the steady state input–output relation for probe field is given by

$$y=x-iC\gamma_{31}\rho_{31}(x), \quad (5)$$

where $x=\frac{\mu_{31}E_p^T}{\hbar\sqrt{T}}$, $y=\frac{\mu_{31}E_p^I}{\hbar\sqrt{T}}$, and cooperation parameter is denoted by$C=\frac{N\omega_p L\mu_{31}^2}{2\hbar\varepsilon_0 cT\gamma_{31}}$ [15]. Similarly, we write Eq. (5) for both cavities

$$y_1=x_1-iC_1\gamma_{31}\rho_{31}(x), \quad (6)$$
$$y_2=x_2-iC_2 2\Gamma_{31}\rho_{31}(x), \quad (7)$$

In cavity series, the first output field is input light for second system ($y_2=x_1$). Therefore, we use Eqs. (6) and (7) to take output–input relation between initial and final fields of setup.

3. Results and discussion

We propose a suitable setup to achieve OM via two cavities. Fig. 1(a) shows the suggested setup which can be used with two different or similar atomic systems inside the cavities, however, there are some conditions to get favorite OM. Firstly, it is obvious that both systems must show OB behavior individually. Secondly, since the first output light plays input-light role for second cavity, the OB behavior in both cavities should be appear in a same region of intensities (the c–d interval must become similar to e–f in Fig. 1(b)).

In the steady state condition, we numerically solve Eqs. (2) and (4) and substitute its result in Eqs. (6) and (7). Note that the output of first cavity is considered as the input of second cavity. For simplicity, all parameters are reduced to dimensionless units through scaling by $\gamma_{31}=\Gamma_{31}=\gamma$ and all figures are plotted in the unit of γ.

Fig. 3(a) shows the input–output relation for system (I) (solid) and system (II) (dashed) while (b) is related to overall two cavities setup. For system (I) the parameters are $\gamma_{31}=\gamma_{21}=1$, $\Delta_c=\Delta_p=\Delta=2$, $\Omega_c=6, \Omega_d=0.5$, $\varphi=\pi/2$, $C_1=400$, while for system (II) are $\Gamma_{31}=1$, $\Gamma_{32}=2$, $\Delta_c=0, \Delta_p=1, \Omega_c=5, \Omega_d=0.01, \phi=\pi/3, C_2=200$. According to Fig. 3, in the OB area of system (I), output intensities approximately are $5\gamma-35\gamma$ and system (II) shows OB behavior for input intensities from 15γ to 25γ. Therefore, these intensities satisfy the necessary conditions for observation of overall OM and two OB behaviors results in OM as shown in Fig. 3(b).

If one uses two systems in the cavities that show OM behaviors individually the branches of overall OM will increase dramatically that is not reachable in an ordinary OM.

After producing OM, we try to control the OM feature via different methods. In Fig. 4, we control the branches of OM via changing the