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Controlling the optical bistability in a quantum-well nanostructure via indirect incoherent pump field

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ABSTRACT

We investigate the optical bistability (OB) behavior in an asymmetric two-coupled quantum well structure inside a unidirectional ring cavity. By controlling the assisting coherent driven field and frequency detuning of the driven laser field, the threshold of OB can be controlled, and even OB converted to optical multistability (OM) by adjust driven pump field detuning. In addition, when we apply an incoherent indirect pump field, we find that the appearance and disappearance of OB and its threshold can easily be controlled by incoherent indirect pump rate.

1. Introduction

Control of light by light is essential in all-optical communication and optical computing. In the past three decades, optical transistors, all-optical switching, and all-optical storage devices based on optical bistability (OB) in two-level atomic systems have extensively been studied both experimentally and theoretically [1,2]. The OB in three-level atomic system confined in an optical ring cavity has theoretically [3] and experimentally [4] been studied. It has been shown that the field-induced transparency and quantum interference effects could significantly decrease the threshold of OB [5]. The effects of phase fluctuation [6] and squeezed state fields [7] on the OB have subsequently been studied. It has been found that the OB could appear for small cooperation parameters due to the present of squeezed vacuum field [8].

On the other hand, many kinds of nonlinear quantum optical phenomena based on the quantum interference and quantum coherence in the semiconductor quantum wells (SQWs) have extensively been studied in recent years [9–11]. These investigations are include gain without inversion [12], electromagnetically induced transparency [13], coherent population trapping [14], enhanced index of refraction without absorption [15], ultrafast all optical switching [16], optical bistability [17], Kerr nonlinearity [18], optical soliton [19], ac stark splitting [20], and so on. The fundamental reason for this studies is the potentially applications in optoelectronics and solid-state quantum information science. Otherwise, the devices based on intersubband transitions in the SQWs have many inherent advantages that the atomic systems do not have; such as the large electric dipole moments due to the small effective electron mass, the great flexibilities in devices design by choosing the materials and structure dimensions, the high nonlinear optical coefficients. In addition, the transition energies and the dipoles as well as the symmetries can also be engineered as desired. The implementation of EIT in semiconductor-based devices is very attractive from an application view-point. It is worth pointing out that the bistable behaviors in a semiconductor QW that interacts with a strong driving electromagnetic field under two-photon resonant condition are recently analyzed, and the results show that the threshold for switching to upper branch of the bistable curve can be reduced due to the presence of quantum interference [21]. The bistable behaviors via tunable Fano-type interference in asymmetric semiconductor quantum well with three-subband V-configuration are also studied [22].

In this work, we investigate the optical bistability, optical multistability, and absorption properties in a three-level asymmetric semiconductor quantum well system. We find that these properties can be efficiently controlled by changing the rate of incoherent indirect pump field. An important advantage of our scheme is that the optical bistability can be converted to optical multistability in our quantum well system. The control of the optical bistability and generate multistability are achieved by applying a coherent driven field and its adjustable parameters. It is well known that the OM also plays a crucial role in nonlinear quantum optics, which will have more advantages than the OB in some applications where more than two states are needed. We are mainly interested in studying the controllability of the optical bistability and absorption properties via the rate of indirect incoherent pumping field, which have never been investigated to our best knowledge. Note

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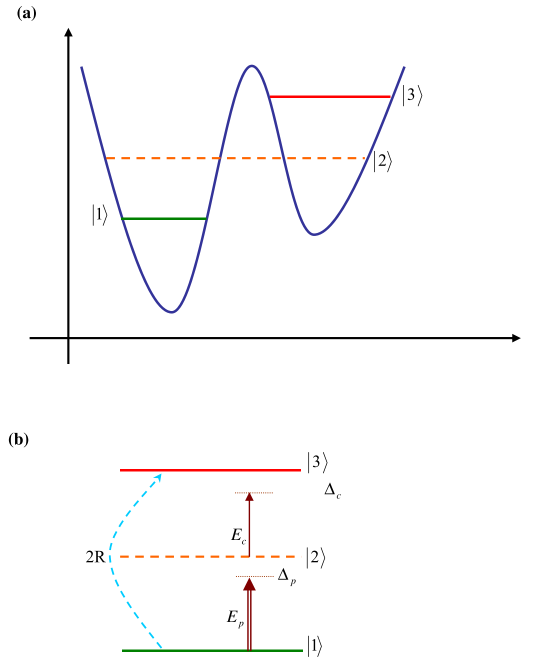

Fig. 1. (a) Schematic diagram of the three-level ladder-type quantum well system. (b) Schematic diagram of the energy level arrangement for the three-level ladder type quantum well under study.

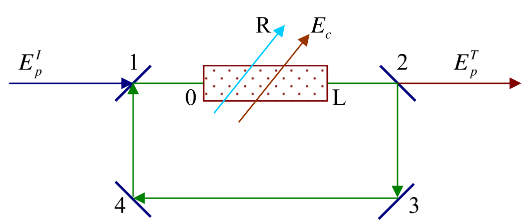

Fig. 2. Unidirectional ring cavity containing a QW sample of length L; E_p^I and E_p^T are the incident and the transmitted field, respectively. E_c represents the coupling field which is noncirculating in the cavity.

that this scheme is much more practical than its atomic counterpart due to its flexible design, controllable interference intensity, and the wide tunable parameters. These may provide the possibility for obtaining potential applications on solid-state quantum computation, quantum communication. The remainder of our paper is organized into three parts as follows: in Section 2, we present the theoretical model and establish the corresponding equations. Our numerical results and physical analysis are shown in Section 3. In Section 4, some simple conclusions are given.

2. The model and equations

We consider a three-level ladder-type quantum well system as shown in Fig. 1(a) [17]. Two laser fields and an indirect incoherent field are applied to drive the medium. A weak probe field with amplitude E_p, angular frequency ω_p, and Rabi-frequency $\Omega_p = \frac{\mu_{12}E_p}{\hbar}$ is applied to $|1\rangle \rightarrow |2\rangle$ transition. Another control laser field with amplitude E_c, angular frequency ω_c, and Rabi-frequency $\Omega_c = \frac{\mu_{23}E_c}{\hbar}$ is applied to the $|2\rangle \rightarrow |3\rangle$ transition. Here $\mu_{ij}(i,j=1,2,3)$ are the corresponding atomic dipole moments. Therefore the total electromagnetic fields can be written as $E = E_p e^{-i\omega_p t} + E_c e^{-i\omega_c t} + c.c.$ In order to reduce the absorption at the probe field transition frequency, an incoherent pumping field with suitable polarization is applied to the transition $|1\rangle \leftrightarrow |3\rangle$ of a double QW system. By adopting the standard density matrix equations of motion in dipole

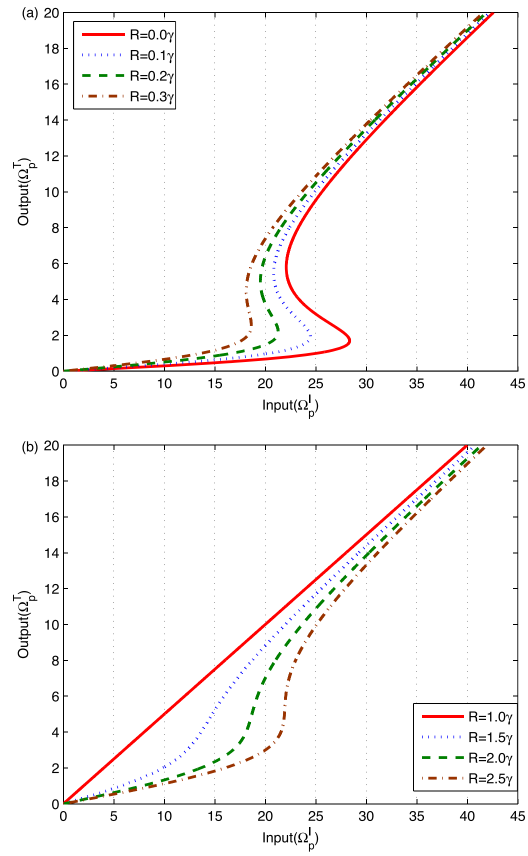

Fig. 3. (a) Behavior of output-input field intensity for $R = 0.0, 0.1\gamma, 0.2\gamma, 0.3\gamma$, (b) for $R = 1, 1.5\gamma, 2\gamma, 2.5\gamma$. Other parameters are $\gamma_{21} = \gamma_{31} = \gamma_{32} = \gamma$, $\Gamma_{12} = \Gamma_{13} = \Gamma_{23} = 5\gamma$, $\Omega_c = 3\gamma$, $\Delta_c = 0.0$, $\Delta_p = 0.0$.

and rotating-wave approximations for this system can be written as follows:

$$\begin{aligned}
\dot{\rho}_{21} &= -(i\Delta_p + \frac{\Gamma_{12}}{2} + R)\rho_{21} - i\Omega_p(\rho_{22} - \rho_{11}) + i\Omega_c\rho_{31}, \\
\dot{\rho}_{32} &= -(i\Delta_c + \frac{\Gamma_{23}}{2})\rho_{32} - i\Omega_c(\rho_{33} - \rho_{22}) - i\Omega_p\rho_{31}, \\
\dot{\rho}_{31} &= -[i(\Delta_p + \Delta_c) + \frac{\Gamma_{13}}{2} + R]\rho_{31} - i\Omega_p\rho_{32} + i\Omega_c\rho_{21}, \\
\dot{\rho}_{22} &= -\gamma_{21}\rho_{22} + \gamma_{32}\rho_{33} - i\Omega_c(\rho_{23} - \rho_{32}) - i\Omega_p(\rho_{21} - \rho_{12}), \\
\dot{\rho}_{33} &= -(\gamma_{31} + \gamma_{32})\rho_{33} + i\Omega_c(\rho_{23} - \rho_{32}) + 2R\rho_{11}.
\end{aligned} \tag{1}$$

where $\rho_{ij} = \rho_{ji}^*(i,j = 1,2,3)$, and constrained by $\rho_{11} + \rho_{22} + \rho_{33} = 1$. The $\Delta_p = \omega_{12} - \omega_p$ and $\Delta_c = \omega_{23} - \omega_c$ are detuning frequencies of probe and control fields, respectively. Also, ω_{12} and ω_{23} are resonant frequencies, which associates with the corresponding optical transitions $|1\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |3\rangle$. Here R is an indirect incoherent pump rate that applied between $|1\rangle$ and $|3\rangle$ transition according to Fig. 1(b). The population decay rates and dephasing decay rates are added phenomenologically in the above density matrix equations [20], which are comprised of a population decay contribution as well as a dephasing contribution. The population decay rates from subband $|i\rangle$ to subband $|j\rangle$ denoted by $\gamma_{ij}(i \neq j)$ is mainly due to longitudinal optical (LO) photon emission at low temperature. The total decay rates $\Gamma_{ij}(i \neq j)$ are given by $\Gamma_{12} = \gamma_{12} + \gamma_{13} + \gamma_{23} + \gamma_{12}^{dph}$; $\Gamma_{23} = \gamma_{23} + \gamma_{23}^{dph}$ and $\Gamma_{13} = \gamma_{12} + \gamma_{13} + \gamma_{13}^{dph}$, where $\gamma_{ij}^{dph}(i \neq j)$ determined by electron–electron, interface roughness, and phonon scattering