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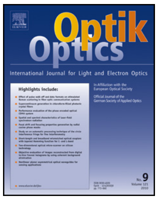

Original research article

Impact of the incoherent pump fields on the optical bistability of a dielectric slab doped with semiconductor quantum wells

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ABSTRACT

The behavior of the optical bistability (OB) and optical multi-stability (OM) is investigated in an optical system which consists of a dielectric slab doped with a three-level asymmetric semiconductor quantum well system. It is found that the optical bistability can be converted to optical multi-stability (or vice versa) by adjusting different physical parameters such as the strength of Fano interference and the rate of incoherent pump field. Moreover, we find that the OB converts to OM by increasing the slab thickness. This optical system may provide some new possibilities for test the switching process.

1. Introduction

It is well known that many kinds of optical phenomena based on the quantum coherence and quantum interference are the basic mechanisms in the semiconductor quantum wells (SQWs), investigated extensively in recent years. There has been much interest in a variety of new optical phenomena based on the quantum interference effect such as coherent population trapping [1], enhanced index of refraction [2], electromagnetically induced transparency [3], lasing without population inversion [4], ultra-slow [5] and ultra-fast [6]. EIT and similar phenomena have been extensively investigated in dense atomic gases [7–11]. Propagation of light in solid-state material, such as a slab system or photonic crystal (PC) is also important due to their potential applications. Propagation of an electromagnetic field in one-dimensional PCs (1DPCs) has attracted a lot of attention in recent years. In fact, periodic media called PCs are an important material for the optical properties of a light pulse [12,13]. A multi-layered medium is considered as a simple example of the 1DPCs. OB processes were done in hot atoms rather than in cold atomic media theoretically and experimentally in recent years [14–16]. It is worth pointing out that, Joshi and Xiao recently analyzed the OB behavior in a semiconductor quantum well that interacts with two electromagnetic fields, a strong field and a weak field, and show that the threshold for switching to upper branch of the bistable curve can be reduced due to the presence of quantum interference [17]. Optical bistability (OB) behavior based on intersubband transitions in an asymmetric coupled-quantum well (CQW) driven by laser fields in the unidirectional ring cavity is analyzed in Ref. [18]. Devices which take advantage of intersubband transitions in quantum wells (QWs) have inherent advantages that the atomic systems do not have, such as large electric dipole moments due to the small effective electron mass, and a great flexibility in the device design by a proper selection of the materials and their sizes.

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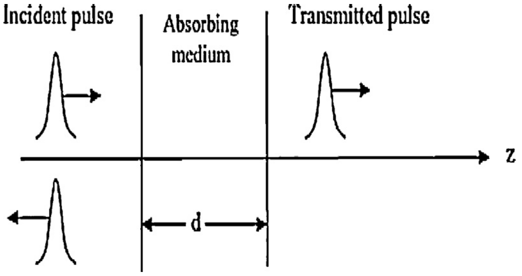

Fig. 1. Schematic of the weakly absorbing dielectric slab.

In this paper, we investigate the optical bistability or multi-stability in three-level asymmetric QWs which doped into the dielectric slab. It is realized that the OB converted to OM only in the presence of Fano type interference (decay processes) and also demonstrates role the rates of incoherent pump in the switching the bistable behavior from OB to OM or vice versa. Note that our study and the system are mainly based on the Ref [19,20], but, it is a major difference with those works. Especially, we are interested in investigating controllability bistable behavior via Fano type interference and incoherent pump field in a slab which is doped by semiconductor quantum well. Moreover, the effect of the slab thickness on the bistable is studied and we find that the OB converts to OM by increasing the thickness of the slab.

2. Model and equations

2.1. Pulse propagation in a slab

We consider a weakly absorbing and nonmagnetic slap which is extended from $z = 0$ to $z = d$ in the z direction with the complex relative permittivity $\varepsilon(\omega_p) = \varepsilon_r + i\varepsilon_i$ where ε_r and ε_i represent the dispersion and the absorption parts, respectively as depicted in Fig. 1. Both sides of slab are vacuums and a light pulse with Gaussian form at the surface of slab in plane $z = 0$, incident on it. The transfer matrix of a normally incident monochromatic wave with frequency ω_p is given by [21]

$$\begin{pmatrix} \cos[kd] & i\dfrac{1}{n(\omega_p)}\sin[kd] \\ in(\omega_p)\sin[kd] & \cos[kd] \end{pmatrix}, \tag{1}$$

where $n(\omega_p) = \sqrt{\varepsilon(\omega_p)}$ is the refractive index of the slab. We assume that the slab is doped by QD nanostructure, so the dielectric function, i.e., (ω_p), can be divided into two parts,

$$\varepsilon(\omega_p) = \varepsilon_b + \chi(\omega_p), \tag{2}$$

where $\varepsilon_b = n_b^2$ is the background dielectric function and $\chi(\omega_p)$ represents the susceptibility of the medium doped in the dielectric slab. Using the transfer-matrix method, the reflection and transmission coefficients of the monochromatic wave can be described as [22]

$$r(\omega_p) = \frac{-(\frac{i}{2})(\frac{1}{\sqrt{\varepsilon}} - \sqrt{\varepsilon})\sin(kd)}{\cos(kd) - (\frac{i}{2})(\frac{1}{\sqrt{\varepsilon}} + \sqrt{\varepsilon})\sin(kd)} \tag{3}$$

$$t(\omega_p) = \frac{1}{\cos(kd) - (\frac{i}{2})(\frac{1}{\sqrt{\varepsilon}} + \sqrt{\varepsilon})\sin(kd)} \tag{4}$$

These equations show that the susceptibility of the doped elements has a major role in determination of reflectivity and transmission of a light pulse through the slab. Moreover, these coefficients depend on the thickness and the refractive index of the slab. For the resonance condition, the thickness of the slab is employed as $d = 2m(\lambda_0/4\sqrt{\varepsilon_b})$.

2.2. Quantum well system

We consider an asymmetric double semiconductor QW structure consisting of subband in the shallow well $|a\rangle$ and the subband in the deep well $|b\rangle$, which are separated by a narrow barrier as shown in Fig. 2a. The sample was grown as a 6.8 nm thick $Al_{0.15}Ga_{0.85}As$ shallow well and a 7 nm thick $GaAs$ deep well separated by a 2 nm thick $Al_{0.3}Ga_{0.7}As$ tunnel barrier, which due to the mixing of the states $|a\rangle$ and $|b\rangle$, and under the exactly resonant conditions $|1\rangle = (|a\rangle - |b\rangle)/\sqrt{2}$ and $|2\rangle = (|a\rangle + |b\rangle)/\sqrt{2}$. The splitting ω_s on resonance is given by the coupling strength and can be controlled by adjusting the height and width of the tunneling barrier with applied bias voltage [23]. Therefore, $\Omega_{p_i} = \wp_{i0}E_p/2\hbar$ $(i = 1, 2)$ are the corresponding Rabi-frequencies of the probe laser field to transitions $|0\rangle \leftrightarrow |i\rangle$ $(i = 1, 2)$, where E_p is the amplitude of probe laser field with frequency ω_p, and $\wp_{i0}$ are the relevant intersubband dipole moments. Two broadband incoherent pump