Optica Applicata, Vol. XLIX, No. 1, 2019
DOI: 10.5277/oa190109

Output-input properties of incident light on a defect dielectric slab with quantum dot nanostructure

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We demonstrate output-input properties of incident light in a defect slab doped by three-level quantum dot nanostructure via quantum coherence and Fano-interference phenomena. Here, we will show that the output-input properties of the system can be adjusted by the Fano-interference strength, amplitude and the relative phase of the driving fields, respectively. Also, we consider the thickness effect of defect medium on controlling the output-input behaviors of probe light. Moreover, we realize that it is possible to switch between optical bistability and optical multistability by optimizing the conditions which are more practical in all-optical switching based nanoscale devices.

Keywords: quantum dot nanostructure, optical bistability and multistability.

1. Introduction

Controlling of light by light is one of the most intriguing and interesting fields of research in quantum and nonlinear optics. There can be a large number of potential applications in optical sciences and related fields, such as all-optical switches in optical communication and signal processing [1, 2]. Optical bistability (OB) is a rapidly expanding field of current research because of its potential application in the all-optical logic and because of the interesting phenomena it encompasses. The theoretical prediction of OB was first given by Szöke *et al*. [3] and the first experimental observation was made by Gibbs *et al*. [4] using a sodium-filled Fabry–Pérot (FP) interferometer. According to the theories and experiments [5–8], the OB behaviors are very sensitive to the absorption, dispersion and nonlinear properties of the medium. Therefore, studies of OB in various nonlinear optical systems, especially those displaying electromagnetically induced transparency (EIT), are very important from the point of view of implementing devices of practical uses. By using changes in linear and nonlinear optical properties around resonance, due to the EIT, it is easy to manipulate and control nonlinear optical processes in the multilevel systems [8]. These EIT systems have also displayed several other interesting effects such as the group velocity reduction of light to a few meters per second [9–11], lasing without inversion (LWI) [12], optical properties of graphene [13], generation of entangled photons [14], enhanced index of refraction [15], waveguides written optically in atomic vapor [16], and storage of photon [17] and so on [18–37].

Optical bistability (OB) and optical multistability (OM) behaviors of weak probe light in an optical ring cavity nanostructure confined with quantum wells (QWs) and quantum dots (QDs) and three-level system have been studied by many research groups [38–42]. As an illustration, ZHEN WANG *et al*. [41] analyzed the hybrid absorptive-dispersive OB behavior in an open Λ-type three-level atomic system by using a microwave field to drive the hyperfine transition between two lower states, along with the consideration of incoherent pumping and spontaneously generated coherence. The substantial changes in optical properties of three-level systems, including enormous reduction in absorption of the probe (cavity) laser field, enhanced sharp linear dispersion, as well as enhanced Kerr nonlinearity dispersion resulted in further explorations of OB [43]. Such OB behaviors in composite system of three-level inside optical cavities were studied theoretically [44] in three-level systems in ladder-type and Λ-type configurations of their levels. Recently, a full controllability of OB in its shape, width, threshold, and direction (rotation of hysteresis loop) has been experimentally demonstrated in a three-level atomic EIT system inside an optical ring cavity [45–49].

Due to strong electron–electron interactions, the semiconductor quantum dots (SQDs) behave effectively with atomic-like intersubband transition (ISBT) responses. Owing to the small effective electron mass, they have the advantages of high nonlinear optical coefficients and large electric dipole moments of ISBT. Quantum interference which arises between absorption paths to two states coupled to a common continuum by tunneling has been observed. This kind of interference is called Fano interference which will lead to nonreciprocal absorptive and dispersive profiles [50, 51]. Some similar phenomena involving quantum coherence can also appear in QDs and QWs [52, 53]. In recent years, many proposals have been suggested for controlling the OB and OM in quantum wells and quantum dot nanostructures [54–59].

2. Model and equations

We consider a dielectric slab doped by a QD nanostructure with three-level configuration as shown in Fig. 1**a**. The three-level system interacts with an additional external laser field called coupling field, which can be utilized to control the switching of probe field. In fact, one can obtain the energy states of the QD by solving the Schrödinger–Poisson equations self-consistently for carriers in InAs/GaAs QD conduction bands. The physical features of the three-level QD nanostructure can be found in [60]. We assume that the incident probe light is propagated into a slab with length d in the z direction and

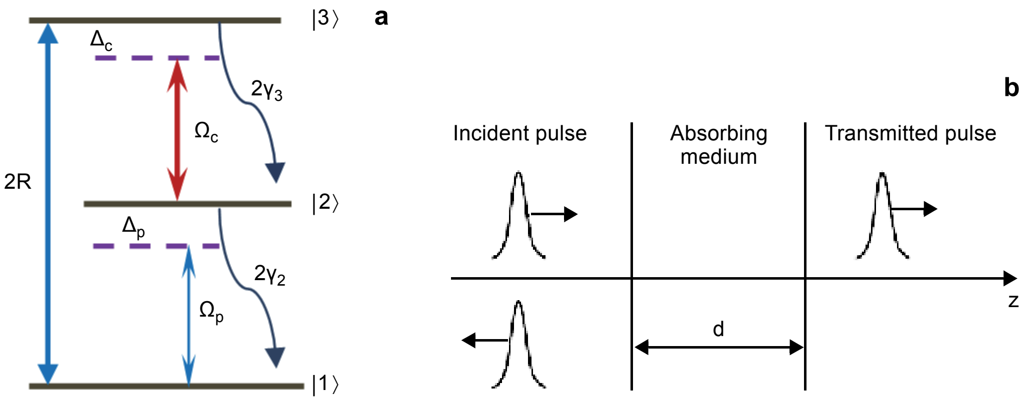

Fig. 1. Schematic of the energy levels and transitions in the defect slab doped three-level quantum dot nanostructure system interacting with coupling field, incoherent pump field and weak probe field (**a**). The defect slab medium (**b**).

outside of the slab is a vacuum (Fig. 1**b**). The transfer matrix for the incident light with frequency ω_p through the slab can be given as [61]

$$\begin{pmatrix} \cos\left[\frac{\omega_p}{c} n(\omega_p) d\right] & \frac{1}{n(\omega_p)} \sin\left[\frac{\omega_p}{c} n(\omega_p) d\right] \\ -n(\omega_p) \sin\left[\frac{\omega_p}{c} n(\omega_p) d\right] & \cos\left[\frac{\omega_p}{c} n(\omega_p) d\right] \end{pmatrix} \tag{1}$$

where c is the speed of light in vacuum and $n(\omega_p) = \sqrt{\varepsilon(\omega_p)}$ corresponds to the refractive index of the slab and $\varepsilon(\omega_p)$ is dielectric function.

Under the transform matrix method, the reflection and transmission coefficients can be expressed as [61]:

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

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

where d is the optical thickness of the slab and is given by $d = 4\sqrt{\varepsilon_b}\,\lambda_0/2m$ or the resonance condition and $d = 4\sqrt{\varepsilon_b}\,\lambda_0/(2m+1)$ for the off-resonance condition [62, 63]. Here, m is an integer and by changing it, we can adjust the thickness of the slab. In other words, the integer m is a controllable parameter which can influence the slab's thickness. The $\varepsilon(\omega_p)$ is the dielectric function of the slab medium and can be divided into two parts:

$$\varepsilon(\omega_p) = \varepsilon_b + \chi(\omega_p) \tag{3}$$

where $\varepsilon_b = 1$ is the background dielectric function and $\chi(\omega_p)$ represents the susceptibility of the three-level QD nanostructure doped inside the dielectric slab. A coupling field with frequency ω_c and wave vector k_c is used to create electric dipole transitions from the exited state $|3\rangle \leftrightarrow |2\rangle$ simultaneously. It is assumed that $\mu_{23} = \mu$ and $\Omega_c = \mu E_c/\sqrt{2}\hbar$. Here, Ω_c is the Rabi frequency of the coupling field. Additionally, an incoherent pump with a pumping rate $2R$ is applied between levels $|1\rangle$ and $|3\rangle$. Electric dipole transition between states $|2\rangle$ and $|1\rangle$ is coupled by a probe beam with carrier frequency ω_p and wave vector k_p.

As a result, the matrix elements of the atomic density operator ρ obey the following equation:

$$\dot{\rho}_{11}(t) = -2R\rho_{11} + 2\gamma_2\rho_{22} + i\Omega_p^*\rho_{21} - i\Omega_p\rho_{12} \tag{4a}$$

$$\dot{\rho}_{22}(t) = 2\gamma_3\rho_{33} - 2\gamma_2\rho_{22} - i\Omega_p^*\rho_{21} + i\Omega_p\rho_{12} - i\Omega_c\rho_{23} + i\Omega_c^*\rho_{32} \tag{4b}$$

$$\dot{\rho}_{33}(t) = 2R\rho_{11} - 2\gamma_3\rho_{33} + i\Omega_c\rho_{23} - i\Omega_c^*\rho_{32} \tag{4c}$$

$$\dot{\rho}_{23}(t) = -(\gamma_2 + \gamma_3 + i\Delta_c)\rho_{23} + i\Omega_c^*(\rho_{33} - \rho_{22}) + i\Omega_p\rho_{13} \tag{4d}$$

$$\begin{aligned}\dot{\rho}_{12}(t) = {} & -(R + \gamma_2 + i\Delta_p)\rho_{12} + 2\eta\exp(i\Phi)\sqrt{\gamma_2\gamma_3}\,\rho_{23} \\ & + i\Omega_p^*(\rho_{22} - \rho_{11}) - i\Omega_c\rho_{13}\end{aligned} \tag{4e}$$

$$\dot{\rho}_{13}(t) = -\left[\gamma_3 + R + i(\Delta_p + \Delta_c)\right]\rho_{13} - i\Omega_c^*\rho_{12} + i\Omega_p^*\rho_{23} \tag{4f}$$

The above density matrix elements additionally obey the normalization and Hermitian condition $\sum_{i=1}^{3}\rho_{ii} = 1$ and $\rho_{ij} = \rho_{ji}^*$. The detuning of the probe and coupling fields are defined as: $\Delta_p = \omega_p - \omega_{21}$, $\Delta_c = \omega_c - \omega_{32}$, where ω_{ij} is the frequency difference between level $|i\rangle$ and level $|j\rangle$, $2\gamma_j$ corresponds to the decay rate of the state $|j\rangle$ ($j = 2, 3$). In SQDs, $2\gamma_j = 2\gamma_{jm} + 2\gamma_{jn}$ depicts the corresponding total decay rate of level $|j\rangle$, where $2\gamma_{jm}$ is the population decay rate of level $|j\rangle$. Mainly due to longitudinal-optical (LO) phonon emission events at low temperature, $2\gamma_{jn}$ is the dephasing broadening linewidth, which may originate from electron–electron scattering and electron–phonon scattering, as well as inhomogeneous broadening due to scattering on interface roughness [64, 65]. The parameter $k = (2\gamma_{3m}2\gamma_{2m})^{1/2}$ represents the cross-coupling of state $|2\rangle$ and $|3\rangle$, describing the process in which a phonon is emitted by state $|2\rangle$ and recaptured by state $|3\rangle$ via LO phonon relaxation. The strength of the Fano-interference is defined by $\eta = k(2\gamma_3 2\gamma_2)^{-1/2}$, and the values $\eta = 0$ and $\eta = 1$ corresponds to no interference and perfect interference (no dephasing), respectively. Due to the presence of the Fano-interference, the system becomes quite sensitive to the relative phase between the probe and the coupling fields. In other words, if all the fields had been phase dependent, only the collection phase would be important and no individual phase-dependent term would occur, where $\Phi = \varphi_c - \varphi_p$ is the relative phase of the applied fields by repeating the coherence term calculation ρ_{21} and noting that the Rabi-frequencies are complex in general. Here φ_i is the phase of the complex Rabi-frequency Ω_i of the driving fields.

The set of Eqs. (4) can be solved numerically to obtain the steady state response of the medium. In fact, the response of the medium to the applied fields is determined by the susceptibility χ, which defines as:

$$\chi(\omega_p) = \frac{2N\boldsymbol{\mu}_{12}}{\varepsilon_r E_p}\rho_{12} \tag{5}$$

To investigate the OB behavior of the slab, we should calculate the transmitted intensity U_t *vs.* the incident intensity U_{in}, which can be obtained as follows:

$$U_{in} = \frac{U_t}{T} \tag{6}$$

Here, T denotes the transmission coefficient of probe light in a defect slab and can be obtained via Eq. (2).

3. Results and discussion

In the following, we will show the results of numerical simulation in Figs. 2–6. We can take a reasonable value for the decay rate $2\gamma_3 = 2\gamma = 4 \times 10^{13}$ s^{-1} according to a numerical

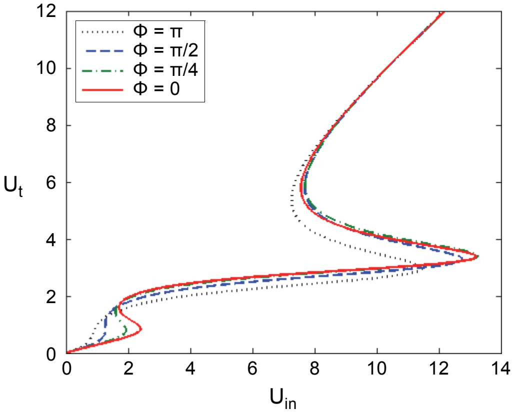

Fig. 2. Behavior of output field as a function of input field intensity with $\Omega_c = \gamma$ and $2R = 0.3\gamma$ for relative phase $\Phi = 0$ (solid line), $\Phi = \pi/2$ (dashed line), $\Phi = \pi/4$ (dotted-dashed line) and $\Phi = \pi$ (dotted line). The selected parameters are = 1/2, $\gamma_2 = \gamma_3 = \gamma = 2 \times 10^{13}$ s^{-1}, $\Delta_p = \Delta_c = 0.01\gamma$ and $m = 90$.

estimate based on [66, 67], and assuming, $\gamma_2 = \gamma_3$, these values depend on the sample quality and the substrate used in the experiment [68, 69]. The transmitted intensity of the probe field U_t *vs*. the incident intensity U_{in} with different relative phase is investigated in Fig. 2. It is realized that, by reducing relative phase from $\Phi = \pi$ (dotted line) to $\Phi = 0$ (solid line), the transition conversion from OB to OM occurs. That is to say that, the multistable to bistable behavior can be controlled very easily by tuning the relative phase of the driving fields. In Fig. 3 the effect of Rabi frequencies of coupling field with specific relative phase Φ on the transmitted intensity of the probe field U_t *vs*. the incident intensity U_{in} is investigated. It is shown that the threshold of OM is reduced in the presence of the coupling field and also by increasing the intensity of the coupling field. Physically, enhancing the Rabi frequencies of coupling field leads to a decrease in the amplitude of transmission coefficient and makes the intensity of multistability for transmitted light decrease. It can be found that adjusting the transmission coefficient has an essential role in controlling the stability of the transmitted

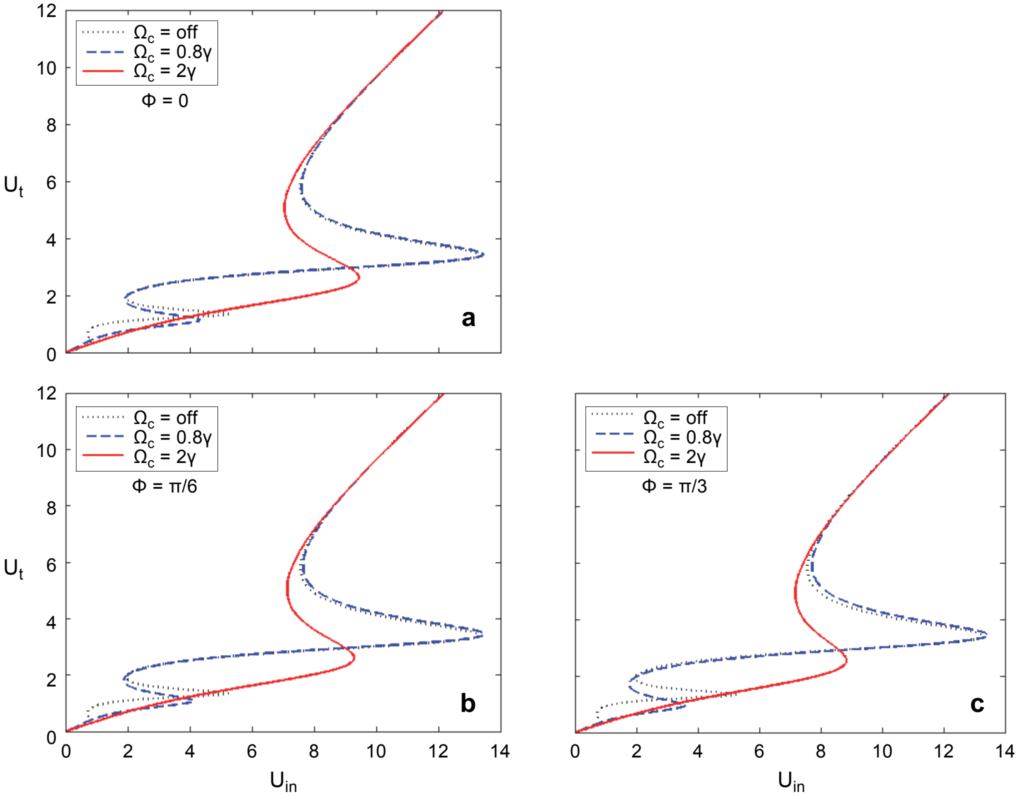

Fig. 3. The transmitted intensity of the probe field U_t *vs*. the incident intensity U_{in} in the absence (dotted line) and in the presence ($\Omega_c = 0.8\gamma$ – dashed line, and $\Omega_c = 2\gamma$ – solid line) of coupling field for $\Phi = 0$ (**a**), $\Phi = \pi/6$ (**b**) and $\Phi = \pi/3$ (**c**). The other parameters are the same as in Fig. 2.

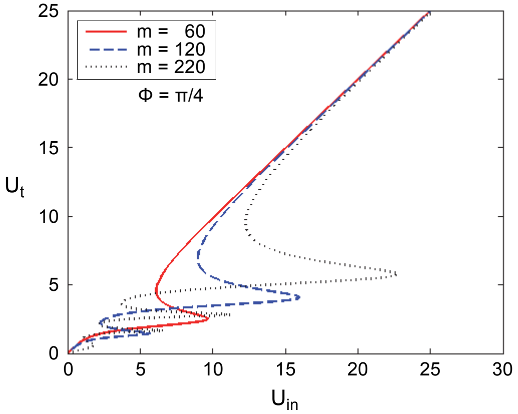

Fig. 4. The transmitted intensity of the probe field U_t *vs*. the incident intensity U_{in} for different thicknesses of the slab according to $m = 60$ (solid line), $m = 120$ (dashed line) and $m = 220$ (dotted line). The selected parameter is $\Phi = \pi/4$, and the other parameters are the same as in Fig. 2.

field. In addition, OM threshold converts to OB threshold, and under these conditions, with increasing relative phase from $\Phi = 0$ to $\Phi = \pi/3$, the threshold of OM and OB is reduced. Physically, by adjusting the relative phase between applied fields, the absorption and Kerr nonlinearity of the medium can be modified. Therefore, controlling the threshold of OB and OM can be possible. In our future work, we will discuss about absorption and Kerr nonlinearity of the defect medium via relative phase between applied fields. In the following, we study the effect of the thickness of the slab on the OB behavior of the probe field. It can be seen that by enhancing the parameter m, the OB threshold first increases and then for $m = 220$ (dotted line) converts to OM. Therefore, we find

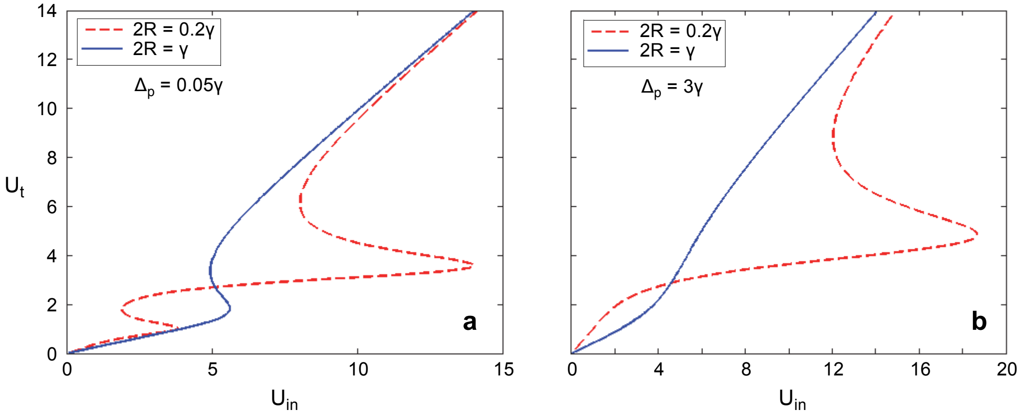

Fig. 5. Behavior of output–input field intensity for incoherent pump with a pumping rate $2R = 0.2\gamma$ (dashed line) and $2R = \gamma$ (solid line), probe-field detuning $\Delta_p = 0.05\gamma$ (**a**) and $\Delta_p = 3\gamma$ (**b**). The selected parameter is $\Phi = \pi/4$, and the other parameters are the same as in Fig. 2.

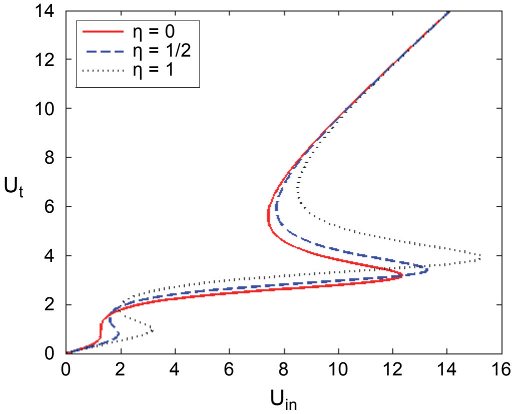

Fig. 6. The transmitted intensity of the probe field U_t *vs*. the incident intensity U_{in} at different values of Fano-interference strength. The selected parameter is $\Phi = 7\pi/4$, and the other parameters are the same as in Fig. 2.

that the transition from OB to OM or *vice versa* can be made possible by changing the thickness of the slab. Figure 5 shows the effect of incoherent pump with a pumping rate $2R$ on the OB behavior of the probe field in probe-field detuning $\Delta_p = 0.05\gamma$ (**a**) and $\Delta_p = 3\gamma$ (**b**). It is realized that, by increasing the rate of incoherent pumping field, the OM converts to OB and in addition in these conditions, by enhancement of probe -field detuning, OB threshold first decreases progressively and then disappears. The main reason for the above phenomena is that the changed frequency detuning of the coupling field will modify the absorption and the Kerr nonlinearity of the medium, which makes the multistable behavior disappear. Finally, we are interested in studying the effect of the strength of Fano-interference η on the OM behavior of probe light in the slab in Fig. 6. By attention to Fig. 6, one can find that for $\eta = 0$ (solid line), OM phenomena appear weakly and then by enhancement of the strength of Fano-interference to $\eta = 1/2$ (dashed line) and $\eta = 1$ (dotted line), OM threshold increases. That is to say, the reflection and transmission coefficients of the defect slab doped InGaN/GaN quantum dot nanostructure on altering the total decay rate of levels change dramatically. Therefore, the intensity threshold of OM can be manipulated by changing the dephasing broadening linewidth which may originate from electron–electron scattering and electron–phonon scattering, as well as inhomogeneous broadening due to scattering on interface roughness. The values $\eta = 0$ and $\eta = 1$, correspond to no interference and perfect interference (no dephasing). In fact, the strength of the Fano interference between the bounding and unbounding states can be manipulated by dephasing rates which are realized by changing the temperature appropriately. It is well known that OM also plays an important role in nonlinear quantum optics, and will have advantages over OB in some applications where more than two states are needed. As an illustration, the efficiency and bandwidth of optical communications can be increased dramatically if all the devices for optical signal processing and networks can be designed to perform all optically.

4. Conclusion

In summary, we have proposed a new scheme for realizing OB or OM in a defect slab doped InGaN/GaN quantum dot nanostructure controlled by a coupling field and an incoherent pump field. We find that due to quantum coherence and Fano-interference in our proposal of QD nanostructure, by properly choosing the parameters of the system such as relative phase, thickness of the slab medium, Fano-interference strength and amplitude of coupling field, the bistable behaviors can be easily controlled and one can switch between bistability and multistability. These results may be helpful for experimental studies of amplitude and phase control of OB in a defect slab and can be applied in all-optical switching or coding elements and in technology based nanoscale devices.

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Received February 7, 2018
in revised form March 30, 2018