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Optical bistability and multistability in a four-level quantum system in the presence of plasmonic nanostructure

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ABSTRACT

In this paper, the effect of plasmonic nanostructure on behavior of optical bistability and multistability in a four-level quantum system embedded in a unidirectional ring cavity has been studied. It is found that the distance between plasmonic nanostructures and a four-level quantum system is varied from 4.4 nm to 14.4 nm and has an essential role for controlling the threshold of optical bistability and multistability. Moreover, obtained results show that the group velocity of pulse propagation through the medium is strongly depended on the distance between the plasmonic nanostructure and the four-level quantum system.

1. Introduction

Atomic coherence due to the coherent laser field has essential roles for modifying the optical properties of atomic systems such as electromagnetically induced transparency (EIT) [1], optical solitons [2], electron localization [3], four-wave mixing (FWM) [4,5] and so on [6–10]. Optical bistability (OB) in multilevel atoms confined in an optical ring cavity, due to its potential wide applications in all-optical switches, memories, transistors, and logic circuits has been the subject of many recent studies [11–13]. Many different mechanisms, such as quantum interference, the squeezed state field, spontaneously generated coherence and etc have been discussed [14–26] for controlling OB. The OB behavior in semiconductor nanoparticles has also been extensively studied recently. The OB behavior in a four-subband quantum well system driven coherently by the control and probe fields inside the unidirectional ring cavity have been discussed by Li [27]. He found that the energy splitting of the two upper excited states, the coupling strength of the tunneling, the Fano-type interference, the driving field intensity, as well as the frequency detuning can affect OB behavior dramatically, which can be used to manipulate the bistable threshold intensity and the hysteresis loop efficiently. Wang studied OB and optical multistability (OM) in a coupled semiconductor double-quantum-dot nanostructure inside an optical ring cavity. It was found that the transition from OB to OM or vice versa could be easily controlled by properly adjusting the corresponding parameters of the system [28]. In our recent work, we discussed the role of spin coherence on the optical bistability and multistability. It was shown that OB and OM are very sensitive to the relative phase between applied fields [29].

The aim of the present work is to study optical bistability in a four-level quantum system near a plasmonic nanostructure. It has been realized that the spontaneous emission of quantum emitters, such as atoms, molecules and quantum dots, can be strongly influenced by the presence of nanostructures [30–34]. An important effect in such systems is the significantly modified spontaneous decay rate in different emitter dipole moment directions, for example, for orthogonal dipole directions. It has been recently shown [30], by using a rigorous electromagnetic (EM) Green's tensor technique [35–37], that the placement of a three-level V-type quantum emitter in the closeness of simple, or complex, the degree of quantum interference in spontaneous emission can be boosted by metallic nanostructures. The effects of spontaneous emission interference in absorption and dispersion in metallic photonic crystals doped with quantum dots in the V-type configuration have been studied [38]. In addition, the study of spontaneous emission and resonance fluorescence of quantum emitters near various plasmonic structures has attracted significant attention recently [39–46]. The effects of a plasmonic nanostructure on the linear absorption and dispersion spectrum of a four-level double- V-type quantum system have also been discussed theoretically [47]. It was assumed that one V-type transition is influenced by the interaction with surface plasmons while the other V-type transition interacted with free-space vacuum. Therefore, due to the presence of the plasmonic nanostructure, effects of optical transparency had been created. A two-dimensional array of metal-coated dielectric nano spheres has been considered as a

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plasmonic nanostructure. The relevant decay rates can be obtained by a rigorous electromagnetic Green's tensor technique [48]. In a recent study, it has been shown that induced transparency can be occurred in the energy absorption spectra of quantum dots in the V-type configuration interacting with a probe and coupling laser field near metallic nanoparticles [49,50]. In this paper, we follow the results of Ref. [48], and study the behavior of optical bistability and multistability in such system. Here, the medium interacts with a linearly polarized laser field, which couples the lowest state with the upper states in the free-space transitions. It is found that in presence of plasmonic nanostructures the threshold intensity of optical bistability and multistability can be controlled. Moreover, the controlling of OB and OM are accompanied by existence of slow light. In addition, it is explored that the OB and OM are completely dependent on the distance of the quantum system from the plasmonic nanostructure.

2. Model and equations

The four-level quantum system shown in Fig. 1 consists of two closely lying upper states $|2\rangle$ and $|3\rangle$, and two lower states $|0\rangle$ and $|1\rangle$. The dipole moment operator is taken as $\vec{\mu} = \mu'(|2\rangle\langle 0|\hat{\varepsilon}_- + |3\rangle\langle 0|\hat{\varepsilon}_+) + \mu(|2\rangle\langle 1|\hat{\varepsilon}_- + |3\rangle\langle 1|\hat{\varepsilon}_+) + H.c$, Where $\hat{\varepsilon}_\pm = (e_z \pm ie_x)/\sqrt{2}$ describe the right-rotating ($\hat{\varepsilon}_+$) and left-rotating ($\hat{\varepsilon}_-$) unit vectors and μ, $\mu'$are taken to be real. The system is located in vacuum at distance d from the surface of the plasmonic nanostructure. A linearly polarized continuous-wave electromagnetic field with electric field $\vec{E}(t) = \hat{z}E_0\cos(\omega t)$, where E_0 is the electric field amplitude and ω is angular frequency interacting with the system. In the rotating-wave approximations, the Hamiltonian describing the interaction of the electromagnetic field with quantum dot system is written as:

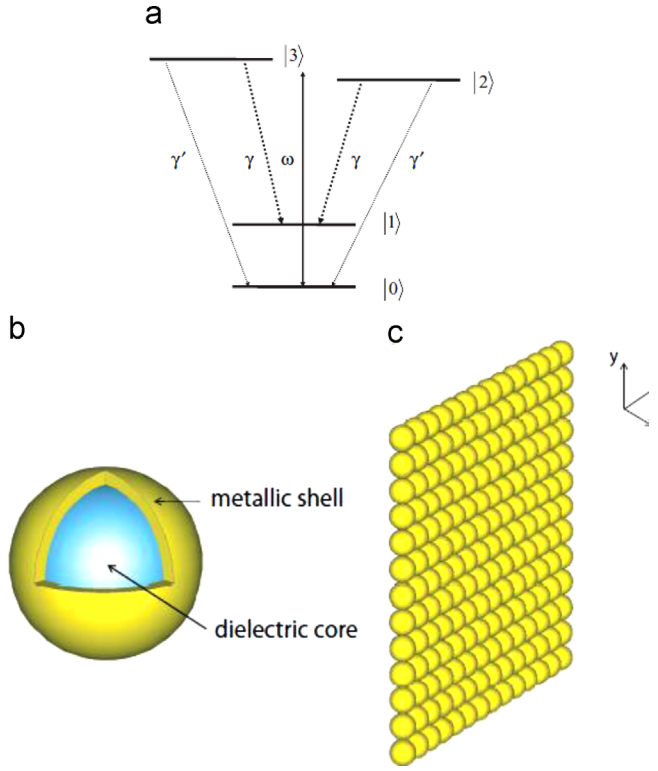

Fig. 1. (a) a four-level quantum system. The two upper states $|2\rangle$ and $|3\rangle$, decay with spontaneous emission to the two lower states $|0\rangle$ and $|1\rangle$. (b) A metal-coated dielectric nanosphere and (c) a 2D array of such spheres used in this work [32].

$$H = \hbar(-\delta - \frac{\omega_{32}}{2})|2\rangle\langle 2| + \hbar(-\delta + \frac{\omega_{32}}{2})|3\rangle\langle 3| - \frac{\hbar\Omega}{2}(|0\rangle\langle 2| + |0\rangle\langle 3| + H.c) \quad (1)$$

Here, $\delta = \omega - \tilde{\omega}$ is the detuning from resonance with the average transition energies of states $|2\rangle$ and $|3\rangle$ from state $|0\rangle$, with $\tilde{\omega} = (\omega_3 + \omega_2)/2 - \omega_0$, $\omega_{32} = (\omega_3 - \omega_2)/2$, and Ω is the Rabi frequency defined as $\Omega = \mu' E_0/(\sqrt{2}\hbar)$. Here, we assumed that the magnitudes of dipole moments between levels $|0\rangle$ to $|2\rangle$ and $|3\rangle$ are equal, i.e. $\mu_{20} = \mu_{30} = \mu'$. Also, $\hbar\omega_n$ with $n = 0 - 3$, is the energy of state $|n\rangle$. Both excited states $|2\rangle$ and $|3\rangle$ decay spontaneously to state $|0\rangle$ with decay rates $2\gamma'_2$ and $2\gamma'_3$, respectively, and to state $|1\rangle$ with decay rates $2\gamma_2$ and $2\gamma_3$, respectively. It is assumed that transitions from $|2\rangle$ and $|3\rangle$ to $|1\rangle$ lie within the surface-plasmon bands of the plasmonic nanostructure, whereas transitions from $|2\rangle$ and $|3\rangle$ to $|0\rangle$ are spectrally distant from the surface-plasmon bands and are not influenced by the plasmonic nanostructure. Therefore, in transitions from $|2\rangle$ and $|3\rangle$ to $|0\rangle$, the spontaneous decay occurs due to the interaction of the quantum system with free-space vacuum modes. The energy difference of states $|2\rangle$ and $|3\rangle$ is chosen to be small, i.e., ω_{32} is considered to be just a few Γ_0, where Γ_0 is the decay rate of states $|2\rangle$ and $|3\rangle$ to state $|1\rangle$ in the vacuum. For both states, the latter is taken to be the same. Therefore, it is assumed that $\gamma_2 = \gamma_3 = \gamma$ and $\gamma'_2 = \gamma'_3 = \gamma'$[47,48]. By using the Hamiltonian of Eq. (2), the equations related to the density matrix elements of the system are obtained as follows:

$$\begin{aligned}
\dot{\rho}_{00}(t) &= 2\gamma'[\rho_{22}(t) + \rho_{33}(t)] - i\Omega/2[\rho_{02}(t) - \rho_{20}(t)] \\
&\quad - i\Omega/2[\rho_{03}(t) - \rho_{30}(t)] \\
\dot{\rho}_{22}(t) &= -2(\gamma + \gamma')\rho_{22}(t) + i\Omega/2[\rho_{02}(t) - \rho_{20}(t)] \\
&\quad - k[\rho_{23}(t) + \rho_{32}(t)], \\
\dot{\rho}_{33}(t) &= -2(\gamma + \gamma')\rho_{33}(t) + i\Omega/2[\rho_{03}(t) - \rho_{30}(t)] \\
&\quad - k[\rho_{23}(t) + \rho_{32}(t)], \\
\dot{\rho}_{20}(t) &= (i\delta + i\omega_{32}/2 - \gamma - \gamma')\rho_{20}(t) + i\Omega/2[\rho_{00}(t) - \rho_{22}(t)] \\
&\quad - i\Omega/2\rho_{23}(t) - k\rho_{30}(t), \\
\dot{\rho}_{30}(t) &= (i\delta - i\omega_{32}/2 - \gamma - \gamma')\rho_{30}(t) + i\Omega/2[\rho_{00}(t) - \rho_{33}(t)] \\
&\quad - i\Omega/2\rho_{32}(t) - k\rho_{20}(t), \\
\dot{\rho}_{23}(t) &= (i\omega_{32} - 2\gamma - 2\gamma')\rho_{23}(t) + i\Omega/2\rho_{03}(t) \\
&\quad - i\Omega/2\rho_{20}(t) - k[\rho_{22}(t) + \rho_{33}(t)],
\end{aligned} \quad (2)$$

With $\rho_{00}(t) + \rho_{11}(t) + \rho_{22}(t) + \rho_{33}(t) = 1$, and $\rho_{nm}(t) = \rho^*_{mn}(t)$. The coupling coefficient between states $|2\rangle$ and $|3\rangle$ due to spontaneous emission in a modified anisotropic vacuum is shown by k. Moreover, it is responsible for the appearance of quantum interference. The values of γ and k are obtained by [47,48].

$$\gamma = \frac{\mu_0\mu^2\bar{\omega}^2}{\hbar}\hat{\varepsilon}_-.\,\mathrm{Im}\,G(r, r; \bar{\omega}).\,\hat{\varepsilon}_+ \quad (3)$$

$$k = \frac{\mu_0\mu^2\bar{\omega}^2}{\hbar}\hat{\varepsilon}_+.\,\mathrm{Im}\,G(r, r; \bar{\omega}).\,\hat{\varepsilon}_+ \quad (4)$$

The dyadic electromagnetic Green's tensor is shown by $G(r, r; \omega)$, where r and μ_0 are the position of the quantum emitter and the permeability of vacuum, respectively. The values of $\gamma$and k based on Refs. [47,48], can be obtained as follows:

$$\gamma = \frac{\mu_0\mu^2\bar{\omega}^2}{\hbar}\mathrm{Im}[G_\perp(r, r; \bar{\omega}) + G_\parallel(r, r; \bar{\omega})] = \frac{1}{2}(\Gamma_\perp + \Gamma_\parallel), \quad (5)$$

$$k = \frac{\mu_0\mu^2\bar{\omega}^2}{\hbar}\mathrm{Im}[G_\perp(r, r; \bar{\omega}) - G_\parallel(r, r; \bar{\omega})] = \frac{1}{2}(\Gamma_\perp - \Gamma_\parallel), \quad (6)$$