Laser Physics Letters

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To cite this article: Surendar Aravindhan *et al* 2023 *Laser Phys. Lett.* **20** 066001

IOP Publishing | Astro Ltd Laser Physics Letters

Laser Phys. Lett. **20** (2023) 066001 (5pp) https://doi.org/10.1088/1612-202X/accce1

Letter

All-optical control of optical bistability in a hybrid system

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Received 14 February 2023
Accepted for publication 6 April 2023
Published 2 May 2023

Abstract

In this paper, we study the tunneling induced optical bistability (OB) in a quantum dot (QD)-metallic nanoparticle (MNP) hybrid system via surface plasmon effects. We realized that in the presence of the tunneling effect, OB arises when the probe light is parallel to the major axis of the hybrid system. We realized the threshold of OB can be controlled by controlling the distance parameter between the QD and MNP. For appropriate distance between the QD and MNP, we find that optical multistability (OM) appears in the system. We find that the threshold of OM can be adjusted when we consider the radius effect of the MNP, respectively.

Keywords: optical bistability, tunneling effect, metallic nanoparticle

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical bistability (OB) is a major nonlinear optical phenomenon that has been investigated for a number of years and may have uses in optoelectronics and photonics. Numerous atomic media have been the subject of substantial experimental and theoretical research on OB [1–7]. In this situation, the fundamental methods for changing the medium's optical response are quantum coherence and quantum interference [8, 9]. Two-level atoms in an optical resonator have received the majority of attention in both experimental and theoretical OB research [10, 11]. To examine the bistable and multi-stable behavior of the multi-level atomic system and semiconductor nanostructures have also been proposed [12–20].

More of these researches localized the multi-level atomic or quantum dot (QD) systems in free space. As a result, in this study, we will use the assumption that the quantum system is localized close to the metallic nanoparticle (MNP) [6, 21–25] and talk about the OB and optical multistability

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(OM) by varying the distance between the quantum system and MNP. Recent research has demonstrated that when the quantum system localizes close to the MNP, a number of intriguing optical features can manifest. In fact, a variety of intriguing optical effects can be observed in a quantum system when the resonance of the plasmon in the MNP is matched with the excitonic transition of the QD [26–33]. In a QD-MNP hybrid system, Hatef *et al* studied plasmonic electromagnetically induced transparency (EIT) [34]. It has been discovered that the surface plasmon effect in the MNP can alter the energy level of absorption in hybrid systems. In a different study, Hatef and Singh looked at how the interaction between their dipole–dipole interactions affected the absorption spectrum of a metallic photonic crystal doped with a group of three-level QDs [35]. By changing the plasma's energy, the position of the transparent peaks can be changed. As a result, it may be possible to transition to an absorbent or transparent material. Surface plasmon effect in the graphene nanodisk was used by Cox *et al* [31] to study nonlinear two-photon absorption in a QD-graphene nanoflake nanocomposite system. It has been discovered that the strong local field of the graphene plasmons makes it possible to control nonlinear optical processes in QD. In a unidirectional ring cavity, Bao *et al* [36] recently investigated the OB of a coupled exciton-plasmon hybrid system. It is demonstrated that altering the distance between the QD and MNP as well as the radius of the MNP can change the threshold of the OB. The Goos–Hanchen (GH) shifts of the transmitted and reflected light beams from a fixed cavity structure doped by a QD-MNP hybrid structure have been discussed by Asadpour group [37]. They have found that by changing the distance between QD an MNP, the GH shifts in reflected and transmitted light beams can be controlled. In this paper, we will discuss the OB and OM properties of the transmitted light beam from a ring cavity with a QD-MNP. The QD molecule consists of an asymmetry double QD system coupled by tunneling. In this design, the two exciton states are coupled to produce quantum coherence using tunneling phenomena. We may achieve the controllability of OB and OM by appropriately changing the tunneling effect, distance between QD an MNP, and radius of the QD.

2. Theoretical model and formulations

A QD molecule with three energy levels (figure 1) and radius a is located at distance d from the MNP (figure 2). The QD and MNP interacts together via surface plasmon effect in the MNP [37]. A weak probe light with frequency ω_{p} and amplitude E_{p} acts on transition $|0\rangle \leftrightarrow |1\rangle$. The coherent tunneling coupling with coefficient T_{e} acts on transition $|1\rangle \leftrightarrow |2\rangle$ which can be tuned experimentally by the applied bias voltage. The exciton transition frequency ω_{10} lies near to the plasmon resonance energy ω_{pr} of MNP. We can write the Hamiltonian of the hybrid system in interaction picture as follows:

$$H_{\mathrm{QD}} = \begin{bmatrix} \frac{1}{2}\Delta_{\mathrm{p}} & \Omega_{\mathrm{p}} + D_{\mathrm{p}}\rho_{10} & 0 \\ \Omega_{\mathrm{p}} + D_{\mathrm{p}}\rho_{01} & -\frac{1}{2}\Delta_{\mathrm{p}} & T_{\mathrm{e}} \\ 0 & T_{\mathrm{e}} & -\frac{1}{2}\Delta_{\mathrm{p}} - \omega_{12} \end{bmatrix}. \quad (1)$$

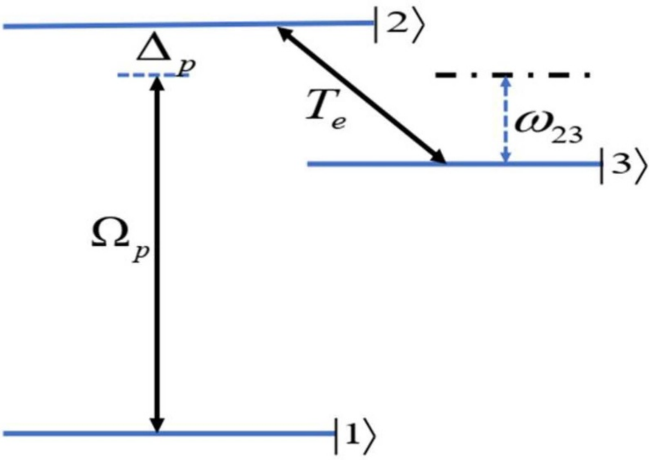

Figure 1. Three-level quantum dot nanostructure with electron tunneling effect.

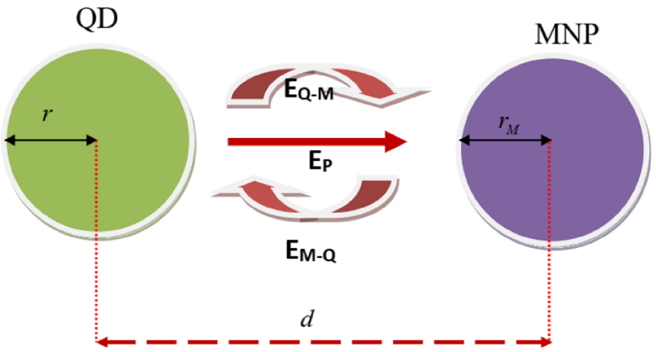

Figure 2. The hybrid system consists of a quantum dot nanostructure located at distance d from nanoparticle with radius r_M.

The parameters in above equations are given as follows:

$$\Omega_{\mathrm{p}} = \frac{\mu_{10}E_{\mathrm{p}}}{2\hbar\varepsilon_{\mathrm{dr}}} + \frac{\mu_{10}E_{\mathrm{p}}}{2\hbar\varepsilon_{\mathrm{dr}}}\frac{kgr_M^2}{d^3} \quad (2a)$$

$$D_{\mathrm{p}} = \frac{kg^2\mu_{10}^2}{(4\pi\,\varepsilon_B\varepsilon_0)\hbar\varepsilon_{\mathrm{dr}}^2}\frac{r_M^2}{d^6} \quad (2b)$$

$$\Delta_{\mathrm{p}} = \omega_{\mathrm{p}} - \omega_{10} \quad (2c)$$

where parameter Ω_{p} is the normalized Rabi frequency corresponds to the external probe light and field produced by MNP. The D_{p} denotes the self-interaction factor between QD and MNP. The factor g shows the polarization parameter and has values of $g = 2(-1)$ when the external fields are parallel (perpendicular) to the major axis of the hybrid system. Parameters μ_{10} is the dipole moments for associated transitions. Parameter $\varepsilon_{\mathrm{dr}} = (2\varepsilon_B + \varepsilon_s)/3\varepsilon_B$ and ε_B, ε_s ε_0 are the dielectric constant of the QD and permittivity of free space. Factor k has the form $k = (\varepsilon_m(\omega) - \varepsilon_B)/(2\varepsilon_B + \varepsilon_m(\omega))$ and $\varepsilon_m(\omega) = \varepsilon_{IB}(\omega) + \varepsilon_{\mathrm{D}}(\omega)$ is a combination of d electrons $\varepsilon_{IB}(\omega)$ and s electrons $\varepsilon_{\mathrm{D}}(\omega)$ in the MNP. For a small, spherical, gold MNP,

$\varepsilon_{IB}(\omega) = 1.15 + i105$ at $\omega = 2.5\,\text{eV}$. The dielectric function $\varepsilon_{\text{D}}(\omega)$ is given by the Drude model as [34]:

$$\varepsilon_{\text{D}}(\omega) = 1 - \frac{\omega_{\text{p}}^2}{\omega^2 + i\omega\left(\gamma_{\text{bulk}} + \frac{A v_{\text{F}}}{d}\right)}. \tag{3}$$

In the above equations parameter $\gamma_{\text{bulk}} = 0.1$ eV and $v_{\text{F}} = 1.40 \times 10^6\,\text{m}\,\text{s}^{-1}$ are the bulk damping and velocity of electrons at Fermi energy and $A = 1$ is a model dependent parameter. We can obtain the density matrix equation of hybrid system under the rotating wave approximation as follow:

$$\begin{aligned}
\dot{\rho}_{11} &= -\gamma_{10}\rho_{11} + iT_{\text{e}}(\rho_{12} - \rho_{21}) + i(\Omega_{\text{p}} + D_{\text{p}}\rho_{10})\rho_{10} \\
&\quad - i(\Omega_{\text{p}} + D_{\text{p}}\rho_{01})\rho_{01} \\
\dot{\rho}_{22} &= -\gamma_{20}\rho_{22} + iT_{\text{e}}(\rho_{21} - \rho_{12}) \\
\dot{\rho}_{10} &= (i\Delta_{\text{p}} - \Gamma_{10})\rho_{10} - iT_{\text{e}}\rho_{20} - i(\rho_{00} - \rho_{11})(D_{\text{p}}\rho_{10} + \Omega_{\text{p}}) \\
\dot{\rho}_{20} &= [i(\Delta_{\text{p}} + \omega_{12}) - \Gamma_{20}]\rho_{20} - iT_{\text{e}}\rho_{10} + i\rho_{21}(D_{\text{p}}\rho_{10} + \Omega_{\text{p}}) \\
\dot{\rho}_{12} &= -(i\omega_{12} + \Gamma_{12})\rho_{12} - iT_{\text{e}}(\rho_{22} - \rho_{11}) - i(\Omega_{\text{p}} + D_{\text{p}}\rho_{01})\rho_{02}.
\end{aligned} \tag{4}$$

We now doped the mention hybrid system in a unidirectional ring cavity. The properties of unidirectional ring cavity are well described in the previous published works [1, 10, 38]. The propagation of probe light in unidirectional cavity can be obtained by using the Maxwell's equation under slowly varying envelope approximation [10]:

$$\frac{\partial E_{\text{p}}}{\partial t} + c\frac{\partial E_{\text{p}}}{\partial z} = i\frac{\omega_{\text{p}}}{2\varepsilon_{\text{dr}}}P(\omega_{\text{p}}). \tag{5}$$

Parameter c corresponds to the velocity of light and $P(\omega_{\text{p}}) = N\mu_{10}\rho_{10}$ is the polarization in transition $|0\rangle \to |1\rangle$. In the steady-state limit, we have:

$$\frac{\partial E_{\text{p}}}{\partial z} = i\frac{N\omega_{\text{p}}\mu_{10}}{2c\varepsilon_{\text{dr}}}\rho_{10}. \tag{6}$$

The boundary conditions for the perfectly tuned cavity for the incident E_{P}^{I} and transmitted E_{P}^{T} fields are as:

$$E_{\text{p}}(L) = \frac{E_{\text{p}}^{\text{T}}}{\sqrt{T}},\, E_{\text{p}}(0) = \sqrt{T}E_{\text{p}}^{\text{I}} + RE_{\text{p}}(L). \tag{7}$$

Parameters R and T are the reflection and transmission coefficients of mirrors 1 and 2, respectively. By using the above boundary condition, we can obtain the following equation as follows: $\frac{\mu_{10}E_{\text{P}}^{\text{I}}}{\hbar\sqrt{T}} = \frac{\mu_{10}E_{\text{P}}^{\text{T}}}{\hbar\sqrt{T}} + \frac{\alpha L\Gamma_{10}}{2T}\text{Im}(\rho_{10}) - i\frac{\alpha L\Gamma_{10}}{2T}\text{Re}(\rho_{10})$, where $\alpha = \frac{N\omega_{\text{p}}\mu_{10}^2}{\hbar c\Gamma_{10}}$ and ρ_{10} is the coherence term which can be obtained via equation (4) in steady-state limit. By replacing $A = \frac{\mu_{10}E_{\text{P}}^{\text{I}}}{\hbar\sqrt{T}}$, $B = \frac{\mu_{10}E_{\text{P}}^{\text{T}}}{\hbar\sqrt{T}}$ and $C = \frac{\alpha L}{2T}$. We can obtain the input-output relationship in the mean field limit as:

$$A = B + C\Gamma_{10}Im(\rho_{10}) - iC\Gamma_{10}\text{Re}(\rho_{10}). \tag{8}$$

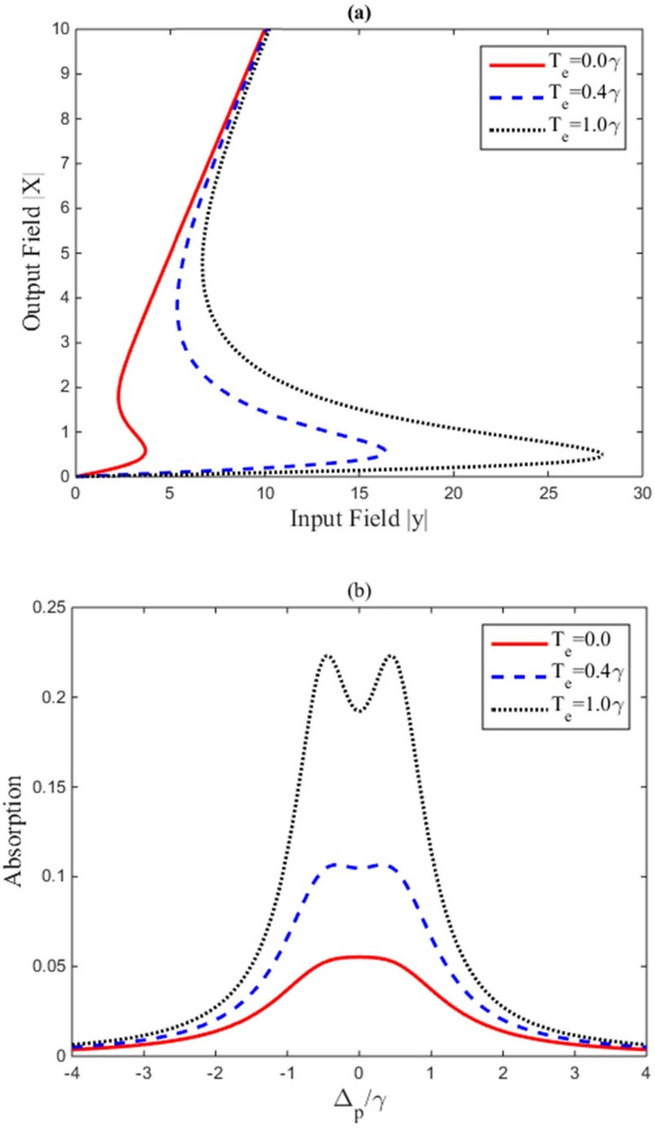

Figure 3. Input-output (a) and absorption (b) spectrums of the propagated probe light through ring cavity consists of hybrid system. Solid line corresponds to $T_{\text{e}} = 0$, dashed line corresponds to $T_{\text{e}} = 0.5\gamma$ and dotted line corresponds to $T_{\text{e}} = 1\gamma$. The selected parameters are $\Delta_{\text{p}} = 0$, $\omega_{12} = 0.4\gamma$, $g = 2$, $C = 100$, $r_M = 4\,\text{nm}$, $d = 9\,\text{nm}$.

3. Results and discussion

In this section, we investigate the behavior of OB and OM for different interaction parameters of the studied system. Here we will show that the threshold intensity of bistable and multistable can be adjusted using control parameters. An important phenomenon that was not considered in previous studies will be discussed in this article. In fact, tunneling effect with the help of dipole-dipole interaction phenomenon plays an important role to control the bistable characteristics in this hybrid system. In figure 3, we show the behavior of OB (a) and absorption (b) of the probe field for the case where the nanostructure of the QD is located at the distance $d = 9$ nm from the nanoparticle. We observe that by increasing the tunneling effect, the intensity of the bistable threshold increases and

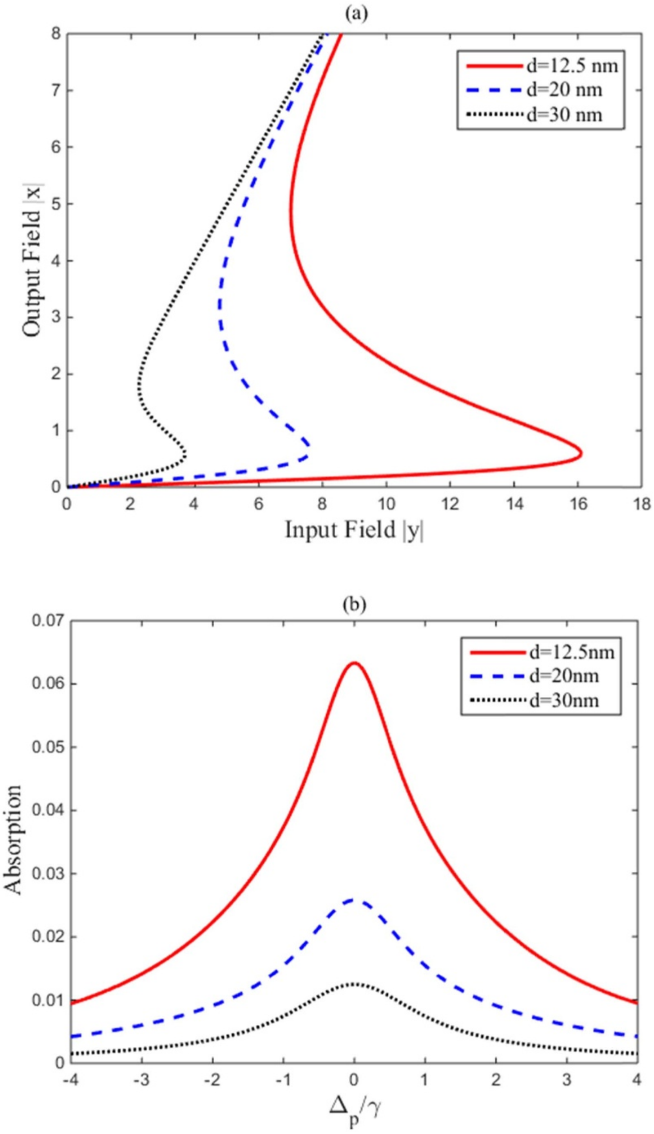

Figure 4. Input-output (a) and absorption (b) spectrums of the propagated probe light through ring cavity consists of hybrid system. Solid line corresponds to $d = 12.5\,\text{nm}$, dashed line corresponds to $d = 20\,\text{nm}$ and dotted line corresponds to $d = 30\,\text{nm}$. The tunneling parameter is $T_\text{e} = 0.5\gamma$ and others are same as figure 3.

reaches to the maximum value for $T_\text{e} = 1.0\gamma$. Examining the absorption behavior also shows that the amount of absorption increases by increasing the tunneling effect. In fact, these two results are completely different from the state where the quantum system is placed in free space. In systems that are in vacuum, by increasing of the tunneling effect or the Rabi frequency for a three-level Λ-type system, the intensity of the bistable threshold and absorption of the probe field decreases. But in this hybrid system, due to the presence of nanoparticle that is placed at the distance $d = 9$ nm, the opposite result is obtained. That is, the intensity of the bistable threshold and absorption of the probe field increase, respectively. In figure 4, we show the bistable (a) and absorption (b) diagram of the probe field for the case where the tunneling effect has the value of $T_\text{e} = 1.0\gamma$ for different distance between QD and nanoparticle. Here, we can see that by increasing of the distance between the QD and the nanoparticle, the threshold intensity decreases and reaches the minimum value for the distance $d = 30$ nm (dotted line). The absorption graph also shows that its value decreases by increasing the distance between QD and nanoparticle. Hence, it can be concluded that, as the distance increases, the amount of interaction between the QD and the nanoparticle decreases, and the probe field easily reaches the saturation state, and as a result, the intensity of OB decreases. Next and in figure 5, we examine the effect of the radius of the nanoparticle for the case where the distance between the QD and the nanoparticle is $d = 30$ nm. It can be seen that by enhancing of the nanoparticle radius, the intensity of the bistable threshold increases. This result shows that for a larger radius of the nanoparticle, the probe field is harder to reach the saturation state, and therefore, the intensity of the bistable threshold increases. At the end and in figure 6, we show the OB diagram for the case where the value of the radius of the nanoparticle and the distance between it and the QD is the smallest. In this figure, we examine the effect of tunneling on the bistable diagram. We observe that compared to the previous figure, by slightly increasing the amount of tunneling $T_\text{e} = 0.75\gamma$ (solid line), the intensity threshold of OB increases at the beginning. Then, by further increasing the tunneling value to $T_e = 2.5\gamma$ (dashed line), the OB converts to OM. As we know, OM has wide applications in the field of quantum gates, which is one of the basic required for quantum information technologies.

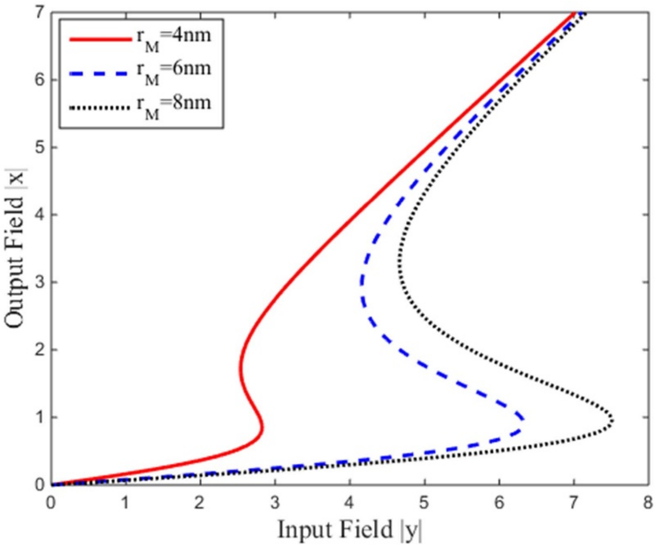

Figure 5. Input-output properties of the propagated probe light through ring cavity consists of hybrid system. Solid line corresponds to $r_M = 4\,\text{nm}$, dashed line corresponds to $r_M = 6\,\text{nm}$ and dotted line corresponds to $r_M = 8\,\text{nm}$. The tunneling parameters and distance are $T_\text{e} = 0.5\gamma$ and $d = 30\,\text{nm}$. The others are same as figure 3.

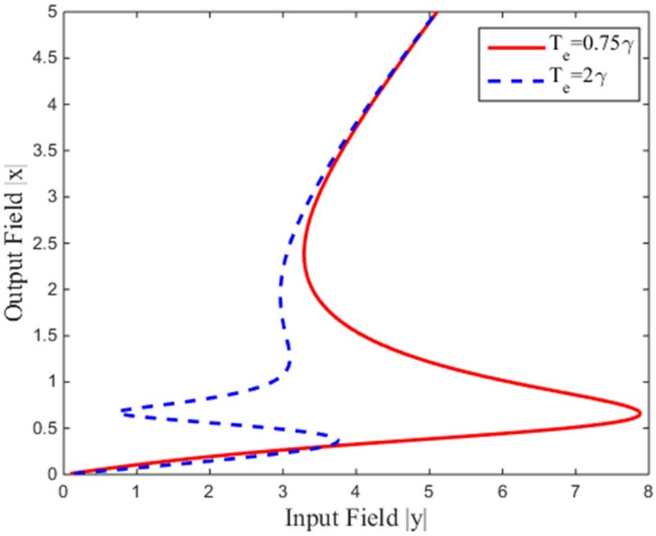

Figure 6. Input-output properties of the propagated probe light through ring cavity consists of hybrid system. Solid line corresponds to $T_e = 0.75\gamma$, dashed line corresponds to $T_e = 2.5\gamma$. The selected parameters are $r_M = 4\,\mathrm{nm}$, $d = 9\,\mathrm{nm}$ and others are same as figure 3.

4. Conclusion

In this article, we investigated the OB in a hybrid system including a QD and a nanoparticle. We have shown that by controlling the distance between the QD and the nanoparticle, the radius of the nanoparticle as well as the tunneling effect in the QD can be controlled. Here, we have found that due to the presence of nanoparticles, the intensity of the bistable threshold is different from the case when the QD is placed in free space. In addition, we showed that it is possible to convert OB to OM by controlling the nanoparticle radius, the distance between them, and the tunneling effect.

Conflict of interest

The authors declare no conflict of interest.

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