COL **12**(4), 042601(2014) CHINESE OPTICS LETTERS April 10, 2014

Voltage-controlled transmission through a dielectric slab doped with quantum dot molecules

Lida Ebrahimi Zohravi and Mohammad Mahmoudi*

Department of Physics, University of Zanjan, University Blvd, 45371-38791, Zanjan, Iran

**Corresponding author: mahmoudi@znu.ac.ir*

Received Decemebr 12, 2013; accepted January 22, 2014; posted online March 12, 2014

Transmission and reflection of an electromagnetic pulse through a dielectric slab doped with the quantum dot molecules are investigated. It is shown that the transmission and reflection coefficients depend on the inter-dot tunneling effect and can be simply controlled by applying a gate voltage without any changing in the refractive index or thickness of the slab. Such simple controlling prepares an active beam splitter which can be used in all optical switching, optical limiting, and other optical systems.

OCIS codes: 260.2110, 250.5590, 020.1670, 310.6860.
doi: 10.3788/COL201412.042601.

In recent years, optical interconnects have been developed because of its potential replacement for metallic interconnects[1]. Optical transmission has a major role in optical communications and different various systems have been introduced for controlling the optical transmission of the systems[2−5].

The optical properties of the reflected and transmitted light pulses from a weakly absorbing dielectric slab were investigated[6]. Recently the phase control of the group velocity of reflected and transmitted light pulse was studied in a dielectric slab doped with three-level ladder-type atoms[7]. Moreover, the coherent control of transmission and group velocity in one-dimensional photonic crystal were also introduced[8].

On the other hand, the interesting tunable electronic and optical properties of the quantum dots (QDs) have been studied. A QD is a semiconductor nanostructure that confines the motion of conduction band electrons in all three spatial directions and then electrons and holes can occupy only set of discrete energies. Theory of quantum coherence phenomena in the semiconductor QD has been investigated[9] and coherent phenomena in ensembles of QDs have also been observed[10−12].

A QD molecule is an aggregate of two coupled QDs (the left and right one), leading to the formation of coherent electronic states via inter-dot tunneling effect. The inter-dot tunneling effect can be controlled by a gate voltage[13]. The QD molecules have been extensively studied and it is shown that the optical properties of the system depend on the inter-dot tunneling effect[14,15]. Recently the voltage-controlled inter-dot tunneling effect has been used for controlling the optical bistability[14], entanglement[16], and light propagation[15].

In this letter, we consider a dielectric slab doped with the QD molecules and investigate the optical properties of reflected and transmitted pulses through the dielectric slab. It is shown that the transmission and reflection of the electromagnetic pulse can be controlled via a gate voltage. Moreover, the controllable transmission with a zero reflectivity is obtained for the slab.

We consider a weakly absorbing and nonmagnetic slap which is extended from $z = 0$ to $z = d$ as depicted in Fig. 1, which is located in vacuum. A light pulse normally incident on the slap with complex relative permittivity $\varepsilon(\omega_p) = \varepsilon_r + \mathrm{i}\varepsilon_i$ where ε_r and ε_i represent the dispersion and absorption properties of the slab, respectively. The transfer matrix for electric and magnetic components of a monochromatic wave with frequency ω_p through the slab can be written as[6,17]

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

where $n(\omega_p) = \sqrt{\varepsilon(\omega_p)}$ shows the refractive index of the slab. We assume a dielectric slab is doped with QD molecules and the complex relative permittivity is given by 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 QD molecules. Using the transfer matrix method, the reflection and transmission coefficients of the monochromatic wave can be written as[17]

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

$$t(\omega_p) = \frac{1}{\cos(kd) - \frac{\mathrm{i}}{2}\left(\frac{1}{\sqrt{\varepsilon}} + \sqrt{\varepsilon}\right)\sin(kd)}. \tag{3b}$$

These equation shows 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 of the

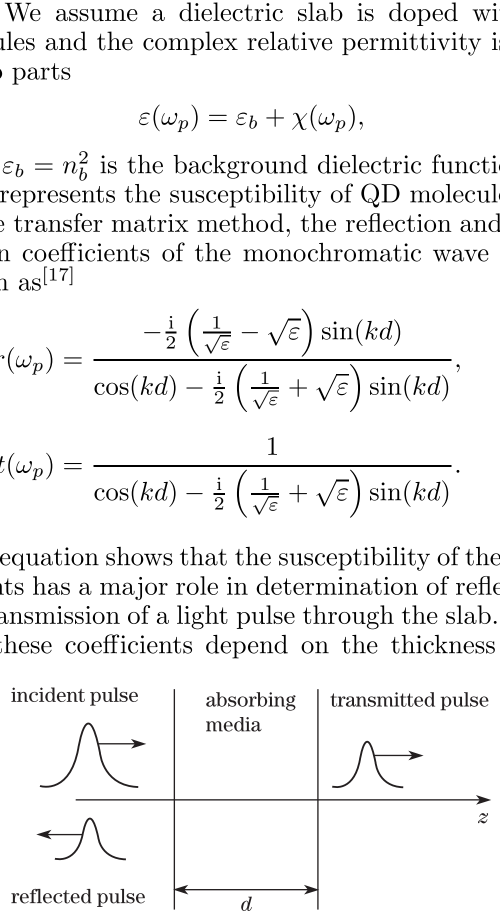

Fig. 1. Schematic of the weakly absorbing dielectric slab.

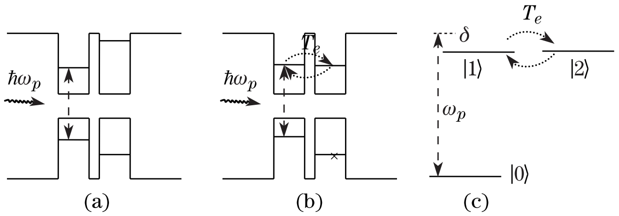

Fig. 2. Band diagram of QD molecule interacting with a tunable weak probe field (a) before and (b) after applying the gate voltage. The dashed arrow shows the probe field. (c) Proposed energy levels scheme.

slab. The resonance condition in a passive slab happens at $d = 2m(\lambda_0/4\sqrt{\varepsilon_b})$ while the off-resonance condition is established at $d = (2m+1)(\lambda_0/4\sqrt{\varepsilon_b})$.

Let us consider a QD molecule consisting of a two-QD (the left and right one) system coupled by inter-dot tunneling. Such a QD molecule can be fabricated using self-assembled dot growth technology[13]. As a realistic example, the asymmetric QD molecules have been detected in double layer InAs/GaAs structures[18]. Two levels $|0\rangle$ and $|1\rangle$ are the lower valance and upper conducting band levels of the left QD, respectively. Level $|2\rangle$ is the excited conducting level of the second QD, as shown in Fig. 2(a). It is assumed that, the energy difference of two lower levels as well as two excited states is large, and then their tunneling couplings can be ignored. By applying a gate voltage, the level $|2\rangle$ gets closer to the level $|1\rangle$ while the valance band levels have still a high energy difference. The system configuration after applying the gate voltage is shown in Fig. 2(b). A weak probe field of frequency ω_p with Rabi-frequency Ω_p applies to the transition $|1\rangle \rightarrow |0\rangle$ (Fig. 2(c)). The Hamiltonian of the system is given by

$$\mathbf{H}_{\text{int}} = \begin{pmatrix} \frac{1}{2}\delta & \Omega_p & 0 \\ \Omega_p & -\frac{1}{2}\delta & T_e \\ 0 & T_e & -\frac{1}{2}\delta - \omega_{12} \end{pmatrix}, \qquad (4)$$

where $\delta = \omega_p - \omega_{10}$ is the probe detuning from the exact resonance, and ω_{1j} $(j = 0, 2)$ is the central frequency of transition $|1\rangle - |j\rangle$. The parameter T_e is the electron tunneling matrix element. The probe field excites one electron from valance to conducting band in left QD that can tunnel to the right one.

In weak probe field approximation, i. e., $\Omega_p \ll \Gamma_{10}$, the probe susceptibility is given by[10]

$$\chi(\omega_p) \propto \frac{\rho_{10}}{\Omega_p} = \frac{(\delta + \mathrm{i}\Gamma_{20})}{[(\Gamma_{10} - \mathrm{i}\,\delta)(\Gamma_{20} - \mathrm{i}\,\delta) + T_e^2]}, \qquad (5)$$

where Γ_{10} and Γ_{20} are dephasing broadening of the corresponding transitions.

Equation (6) shows that the imaginary part is strictly positive doublet absorption and the maximums of the doublet absorption are located at $\delta_{\min} \approx \pm T_e$.

The imaginary parts of $\chi(\omega_p)$ around $\delta = 0$ is given by

$$\mathrm{Im}[\chi(\omega_p)] = \frac{\Gamma_{20}}{T_e^2 + \Gamma_{10}\Gamma_{20}}, \qquad (6)$$

which introduce a tunneling induced transparency like window for different values of inter-dot tunneling matrix element. The maximum value of absorption ($\approx 1/\Gamma_{10}$) is obtained for $T_e \ll \Gamma_{20}$ and the minimum value (Γ_{20}/T_e^2) is obtained for $T_e \gg \Gamma_{20}$.

The half width of the central dip around $\delta = 0$, for T_e , $\Gamma_{10} \gg \Gamma_{20}$ is determined by

$$w \approx \sqrt{\frac{1}{2}\left(2\,T_e^2 + \Gamma_{10}^2 - \Gamma_{10}\sqrt{4\,T_e^2 + \Gamma_{10}^2}\right)}, \qquad (7)$$

which introduce a inter-dot tunneling broadening in absorption spectrum.

Now we consider a dielectric slab doped with the QD molecules. Such a system can be prepared similar to the embedding technique of the single lateral InGaAs QD molecules into a planar microcavity[19,20]. We investigate the transmission and reflection of light pulse through the slab. In our calculation, times are given in units of the Planck constant, so that the energy of 1 meV corresponds to a frequency 242 GHz. In Fig. 3, we plot the transmission and reflection of light pulse versus detuning for different values of inter-dot tunneling parameters. Using parameters are Γ_{10}=5.54 meV, Γ_{20}=0.005 meV, ω_{12}=0.0, Ω_p=0.001 meV, m=50 and T_e=0.1 meV (thin-solid), 0.5 meV (dashed), 1 meV (dotted), 2 meV (dashed-dotted), 2.5 meV (thick-solid).

An investigation on Fig. 3(a) shows that the maximum transmission depends on the inter-dot tunneling parameter. For the small values of T_e, the magnitude of maximum transmission around zero probe detuning is negligible. However, by increasing the inter-dot tunneling via an applied gate voltage, the transmission increase and even the slab becomes transparent. Then the inter-dot tunneling effect induces a wide range of transmission for a slab doped by QD molecules. Note that the width of transparent window ($\approx$ 1 meV) is approximately equal to the transparent width of the free QD molecules which is given by Eq. (8). The results of Fig. 3(b) show that increasing the inter-dot tunneling parameter applies a zero reflection for the slab and it can be used as an anti-reflected device; however it does not induce a wide range of variation for reflectivity of the slab.

Another important parameter is the thickness of the slab. Figure 4 displays the behavior of maximum values of transmission versus the inter-dot tunneling parameter for different thickness of the slab. It can be found that the thin slab, i.e. $m = 10$, cannot cover all possible values of transmission, but the problem is solved by choosing the thicker slab, i.e. $m = 50$ or $m = 100$.

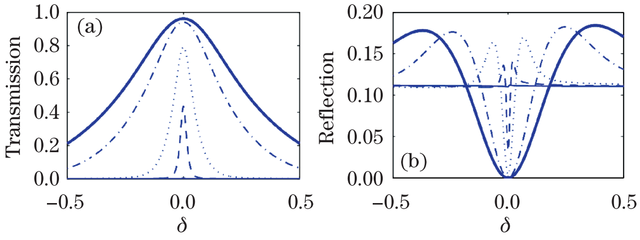

Fig. 3. (a) Transmission and (b) reflection of light pulse versus detuning for different values of inter-dot tunneling parameters. m=50, ω_{12}=0.0, Γ_{10}=5.54 meV, Γ_{20}=0.005 meV, Ω_p=0.001 meV, and T_e=0.1 meV (thin-solid), 0.5 meV (dashed), 1 meV (dotted), 2 meV (dashed-dotted), 2.5 meV (thick-solid).

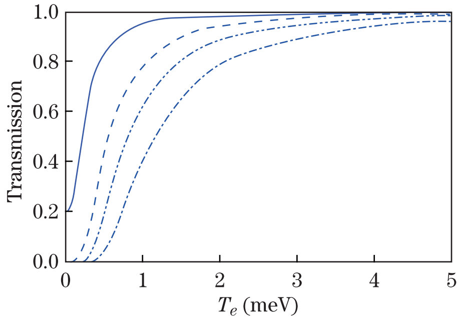

Fig. 4. Behavior of maximum values of transmission versus the inter-dot tunneling parameter for different thicknesses of the slab. $\delta = 0$, $m = 10$ (solid), 50 (dashed), 100 (dotted), and 200 (dash-dotted). Other parameters are the same as Fig. 3.

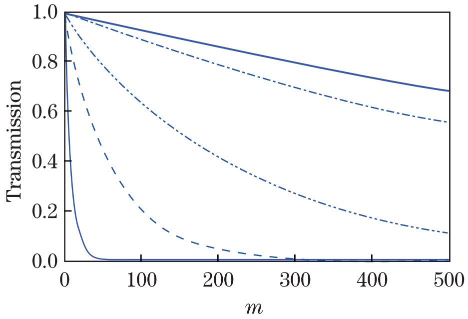

Fig. 5. Transmission versus thickness of the slab for different values of inter-dot tunneling. $T_e = 0.1$ (thin-solid), 0.5 (dashed), 1 (dotted), 2 (dashed-dotted), and 2.5 meV (thick-solid). Other parameters are the same as Fig. 3.

Finally, we plot the transmission versus thickness of the slab for different values of inter-dot tunneling in Fig. 5. It can be seen that the transmission reduces by increasing the slab thickness, however the slope of reduction is steep for small values of inter-dot tunneling parameters.

In conclusion, we show that the optical properties of the QD molecules inside the slab are completely different from the gas systems. It is demonstrated that by changing the applied gate voltage, the different values of transmission and reflection coefficients can be generated in a dielectric slab doped with the QD molecules, without any changing in the refractive index, thickness of the slab, or intensity of applied fields.

References

1. D. A. B. Miller, Proc. IEEE **97,** 1166 (2009).
2. J. Li and R. Yu, Opt. Express **19,** 20991 (2011).
3. Y. Shen, G. Yu, J. Fu, and L. Zou, Chin. Opt. Lett. **10,** 021301 (2012).
4. H. Xu, H. Li, and G. Xiao, Chin. Opt. Lett. **11,** 042401 (2013).
5. S. Relaix, M. Pevnyi, W. Cao, and P. Palffy-Muhoray, Photon. Res. **1,** 58 (2013).
6. L. G. Wang and S. Y. Zhu, Opt. Lett. **31,** 2223 (2006).
7. D. Jafari, M. Sahrai, H. Motavalli, and M. Mahmoudi, Phys. Rev. A **84,** 063811 (2011)
8. H. Sattari and M. Sahrai, Opt. Commun. **311,** 83 (2013)
9. W. W. Chow, H. C. Schneider, and M. C. Phillips, Phys. Rev. A **68,** 053802 (2003).
10. J. Kim, O. Benson, H. Kan, and Y. Yamamoto, Nature **397,** 500 (1999).
11. P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, Science **290,** 2282 (2000)
12. M. Pelton, C. Santori, J. Vuckovic, B. Zhang, G. S. Solomon, J. Plant, and Y. Yamamoto, Phys. Rev. Lett. **89,** 233602 (2002).
13. J. M. Villas-Boas, A. O. Govorov, and S. E. Ulloa, Phys. Rev. B **69,** 125342 (2004).
14. J. Li, R. Yu, J. Liu, P. Huang, and X. Yang, Phys. E **41,** 70 (2008).
15. M. Mahmoudi and M. Sahrai, Phys. E **41,** 1772 (2009).
16. X. Y. Lu, J. Wu, L. R. Zheng, and Z. Zhan, Phys. Rev. A **83,** 042302 (2011).
17. L. G. Wang, H. Chen, and S. Y. Zhu, Phys. Rev. E **70,** 066602 (2004).
18. G. G. Tarasov, Z. Y. Zhuchenko, M. P. Lisitsa,Y. I. Mazur, Z. M. Wang , G. J. Salamo, T. Warming, D. Bimberg, and H. Kissel, Semiconductors **40,** 79 (2006).
19. C. Hermannstädter, M. Witzany, G. J. Beirne, W.-M. Schulz, M. Eichfelder, R. Rossbach, M. Jetter, P. Michler, L. Wang, A. Rastelli, and O. G. Schmidt, J. Appl. Phys. **105,** 122408 (2009).
20. P. M. Petroff, A. Lorke, and A. Imamoglu, Phys. Today **54,** 46 (2001).