

ALL-OPTICAL TUNABLE MIRROR DESIGN USING ELECTROMAGNETICALLY INDUCED TRANSPARENCY

K. Abbasian, A. Rostami, and Z. D. Koozehkanani[†]

Photonics and Nanocrystal Research Lab. (PNRL)
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz 51664, Iran

Abstract—A new and efficient proposal for all-optical tunable devices and systems using electromagnetically induced transparency (EIT) is proposed. For this purpose a slab doped with quantum dots for realization of three-level atomic system is considered. Density matrix formulation for evaluation of the proposed structure is used. The reflection and transmission coefficients of the considered slab are calculated and the related amplitude and phase quantities studied versus parameters of the structure. We show that some nanometer tuning with application of the control field is obtained. So, the proposed idea can open a new realization method of all-optical tunable devices and systems towards all-optical systems.

1. INTRODUCTION

High-speed communication and computing are basic industrial and academic research demand recently. Optical engineering is one of the best alternatives for realization of these purposes. One of key operation in developing of complete optical engineering domain is suitable proposal for tunable device design. In conventional optical engineering there aren't all-optical tunable devices and systems. So, in this paper, we try to propose this operation for the first time from our point of view.

In this part some of presented papers in this field are reviewed.

Basic principles of EIT and applications of this phenomenon were discussed in [1–5]. In these papers applications of EIT in optical filter

[†] The second author is also with School of Engineering Emerging Technologies, University of Tabriz, Tabriz, Iran

design was considered too. Also, a nonlinear optical property in slow light regime was studied.

Application of the EIT in design of high resolution (sub-nanometer) displacement optical sensor was discussed in [6]. In this paper the authors have been shown that using 3-level atoms doped into ring resonator the sensitivity of the optical displacement sensor can be increased.

For description of the quantum optical nature of light propagation through media including 3-level atoms density matrix method incorporating classical light and quantum mechanical particles are needed which was discussed in [7–14].

Optimal control of light propagation through 3-level atoms was discussed in [15]. In this paper interference between the control and probe fields were used for group velocity control of the probe field.

Finally optical mirror design for vertical cavity surface emitting laser diodes was discussed in [16, 17]. Finally, selective optical pumping for introducing selective reflection spectrum was discussed in [18]. It should mention that some papers published by one of authors recently illustrate that considering shape of quantum dots, nonlinear coefficients and dipole moments can be increased several order of magnitudes, which can be used for easy all-optical device design [19–21].

In [22] high precision displacement sensor based on electromagnetically induced transparency (EIT) was presented. In this paper using EIT ultra-high-precision was reported. In [23] transparency in Meta materials was considered. Finally transparency in optical sensor design was applied in [24].

Thus there isn't a practical method for implementation of tunable devices and systems. So, we decided to propose a new design for mirror using electromagnetically induced transparency. We considered a slab doped with quantum dots implemented 3-level artificial atoms. Density matrix method is used for theoretical evaluation of the optical properties of the proposed slab as mirror. Using developed mathematical method the reflection coefficient (amplitude and phase) is calculated. Considering the obtained result it is observed that both amplitude and phase of the reflection coefficient can be controlled that is used for realization of all-optical devices and systems.

Organization of the paper is as follows:

In Section 2 mathematical background for simulation of the proposed all-optical tunable mirror is presented. Simulation results and discussions are presented in Section 3. Finally the paper ends with a short conclusion.

2. MATHEMATICAL BACKGROUND

The proposed structure for all-optical tunable mirror is illustrated in Fig. 1. It is shown that the proposed structure includes a slab doped with 3-level nanocrystals which is operates as optical mirror applicable for optical devices and systems. As an example one can consider Si-nanocrystals doped in silica matrix. Schematically the probe field is applied to the slab horizontally from the left side and a control field is applied from the bottom. Now, in the following, with doping of 3-level particles (as an example in this work, other discrete energy structures can be considered too) such as suitable quantum dots inside slab, we obtain the reflection and transmission coefficients based on the Maxwell's equations. Also, the light propagation through the proposed slab is modeled. First, we consider normal (without EIT) slab inserted between air layers in the following structure for simplicity. The presented relation generally manages the system parametrically and can be applied to EIT case with considering the refractive index of the slab with calculated real part of the optical susceptibility. For calculation of optical susceptibility of slab, quantum optical density matrix method is used. In the following, we review some basic relation illustrating the reflection and transmission coefficients of single layer homogeneous and isotropic media.

According to basic concepts in classical optics and relations in homogeneous, linear and isotropic media the following relations are presented for the reflected and transmitted parts of incident light. First, we introduce two basic relations defining the phase difference of light wave propagating through the media and conservation of the reflection and transmission coefficients as follows:

$$\delta = 2\pi \frac{n_r L}{\lambda}, \quad (1)$$

$$\begin{cases} r' = -r \\ r^2 + tt' + \alpha = 1 \end{cases}, \quad (2)$$

where δ , n_r , L , λ , r , r' , α , t , t' and $R = |r|^2$ are the phase difference of probe light (incident light), the real part of refractive index for proposed slab, medium length, incident wavelength, the reflection coefficient of interfaces from left, the reflection coefficient of interfaces from right hand side, optical loss coefficient in the interface, the transmission coefficient of interfaces from right hand side and intensity reflection coefficient of the slab interface respectively.

Using the basic relation in the wave optics the following relations can be derived for the reflected and transmitted field amplitudes and

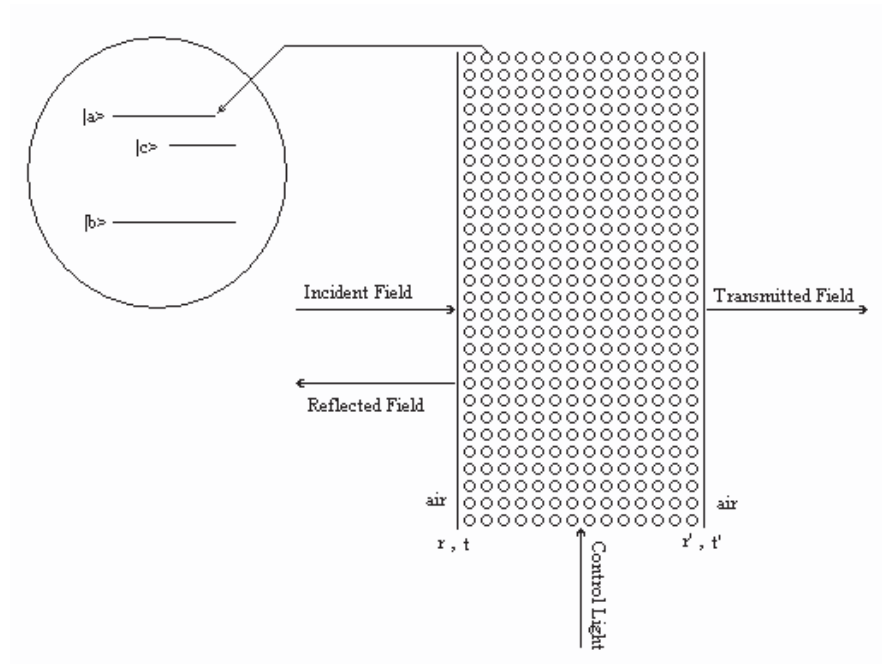


Figure 1. Schematic of the proposed all-optical tunable mirror (medium with quantum dot dopants).

phases.

$$E_R = E_I \frac{r(1 - e^{i2\delta})}{1 - R e^{i2\delta}}, \quad (3)$$

$$E_T = E_I \frac{tt'}{1 - R e^{i2\delta}}, \quad (4)$$

where E_R , E_T , E_I and δ are the reflected, transmitted, incident electric fields and the gained phase delay during propagation in the slab length respectively. So, absolute value of the transmission coefficient and phase can be extracted as follows:

$$|t_E| = \left| \frac{E_T}{E_I} \right| = \frac{(1 - R - \alpha) \sqrt{[(1 - R \cos 2\delta)^2 + (R \sin 2\delta)^2]}}{(1 - R \cos 2\delta)^2 + R^2 \sin^2 2\delta}, \quad (5)$$

$$\varphi_{\frac{E_T}{E_I}} = \tan^{-1} \frac{R \sin 2\delta}{1 - R \cos 2\delta}, \quad (6)$$

where $R = |r|^2$. For the reflection coefficient the similar method can be used and the following results are obtained.

$$|r_E| = \left| \frac{E_R}{E_I} \right| = \frac{\sqrt{[(1+R)(1-\cos 2\delta)]^2 + (R-1)\sin^2 2\delta}}{(1-R\cos 2\delta)^2 + R^2\sin^2 2\delta}, \quad (7)$$

$$\varphi_{\frac{E_R}{E_I}} = \tan^{-1} \left[\left(\frac{R-1}{1+R} \right) \cot \delta \right], \quad (8)$$

Now, we develop the mathematical method to describe effect of parameters of 3-level particles added in the considered slab on optical characteristics of the designed device (mirror). Fig. 2 shows the model of 3-level particles including the probe and control fields and decay rates. In this figure the control and probe fields applied between c, a and b, a levels respectively. Due to applied control field the optical characteristic is changed and in the following, theoretical calculation for description of the proposed system is presented.

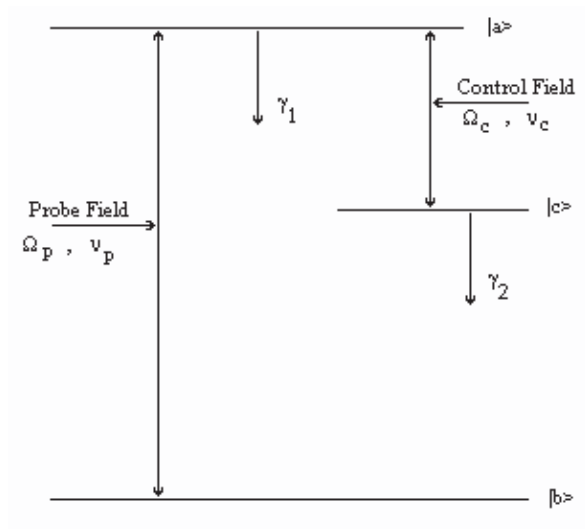


Figure 2. Schematic of 3-level Λ type atom doped in slab waveguide.

After some mathematical manipulation, which is well known in the quantum optics research field, the following matrix form of the

Hamiltonian and density matrix are given as follows.

$$H = \hbar \begin{bmatrix} \omega_b & 0 & -\frac{\wp_{ab}\varepsilon}{2\hbar}e^{iv_p t} \\ 0 & \omega_c & -\frac{1}{2}\Omega_c e^{i\varphi_c} e^{iv_c t} \\ -\frac{\wp_{ab}\varepsilon}{2\hbar}e^{-iv_p t} & -\frac{1}{2}\Omega_c e^{-i\varphi_c} e^{-iv_c t} & \omega_a \end{bmatrix}, \quad (9)$$

$$\rho = \begin{bmatrix} \rho_{bb} & \tilde{\rho}_{cb}^* e^{i\omega_{cb} t} & \tilde{\rho}_{ab}^* e^{i\omega_{ab} t} \\ \tilde{\rho}_{cb}^* e^{-i\omega_{cb} t} & \rho_{cc} & \tilde{\rho}_{ac}^* e^{i\omega_{ac} t} \\ \tilde{\rho}_{ab}^* e^{-i\omega_{ab} t} & \tilde{\rho}_{ac}^* e^{-i\omega_{ac} t} & \rho_{aa} \end{bmatrix}, \quad (10)$$

where ω_a , ω_b , ω_c , γ_{ab} , ε , v_p , v_c , ϕ_c and $\Omega_c = \wp_{ac}\varepsilon_c/\hbar$ are frequencies corresponding to three levels, decay rate between levels a and b , amplitude of the probe field (V/m), probe field frequency, control field frequency, control field phase and Rabi frequency of the control field respectively. ω_{cb} , ω_{ab} and ω_{ac} are frequencies corresponding to energies between levels in the presented model. Based on the time development equation of density matrix [6] with differential motion equations and assuming appropriate boundary conditions the following matrix form of equations can be obtained [7].

$$\dot{R}' = -MR' + A \quad (11)$$

with

$$R' = \begin{bmatrix} \tilde{\rho}_{ab} \\ \tilde{\rho}_{cd} \end{bmatrix}, \quad (12)$$

$$M = \begin{bmatrix} i\Delta + \gamma_1 & -\frac{i}{2}\Omega_c e^{-i\varphi_c} \\ -\frac{i}{2}\Omega_c e^{i\varphi_c} & i\Delta + \gamma_2 \end{bmatrix}, \quad (13)$$

$$A = \begin{bmatrix} i\wp_{ab}\varepsilon/2\hbar \\ 0 \end{bmatrix}, \quad (14)$$

where γ_1 and γ_2 are decay rate of density matrix elements of ρ_{ab} and ρ_{cb} . Also, Ω_c , \wp_{ab} and Δ are the Rabi frequency of the control field, dipole moment element between a and b levels and detuning of the probe field from resonance frequency, respectively.

So, optical susceptibility can be obtained with manipulation of the relationship between polarization and dipole moment element as follows.

$$\chi = \frac{P}{\varepsilon_0 E} = \frac{2N_a \wp^2 \rho_{ab}}{\varepsilon_0 \Omega_p \hbar}, \quad (15)$$

where Ω_p and N_a are the Rabi frequency of the probe field and the density of 3-level atoms respectively. According to basic concepts the

optical loss or gain and induced index of refraction using from the real and imaginary parts of the susceptibility can be found as follows.

$$\alpha = \frac{\kappa}{2}\chi'', \quad (16)$$

$$\delta n = n\frac{\chi'}{2}, \quad (17)$$

where χ' , χ'' , κ and n are the real and imaginary parts of the optical susceptibility, wave number and refractive index respectively.

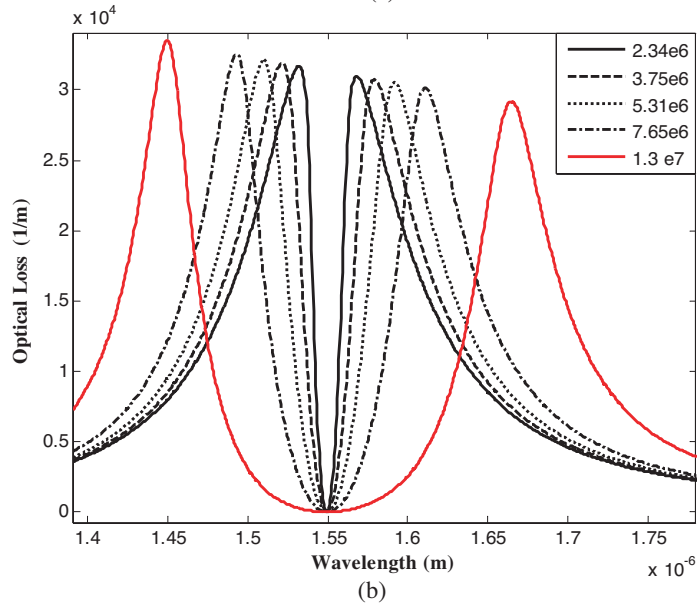
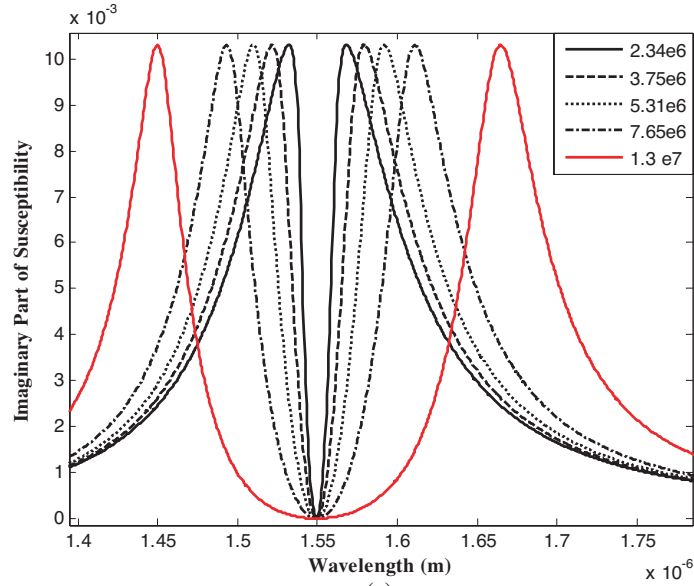
3. SIMULATION RESULTS

In this section numerical investigation of the proposed structure including the reflection and transmission coefficients and spectral behavior of the proposed device are done. First, we consider effect of the applied control field on optical susceptibility, refractive index and optical loss which is shown in Fig. 3, and then investigate effect on magnitude and phase of the reflection coefficient which is illustrated in Fig. 4. It is well known that with increasing the control field EIT window is broadened where optical loss coefficient goes to zero and slope of refractive index decreases. We show that with change of control field (illustrated in the figure legend) the magnitude and phase of the reflection coefficient are changed at given wavelength. So, with applying the control light, optically tunable capability of the proposed mirror is obtained and illustrated in both below and above regions of EIT window.

Figure 4 shows that with increasing magnitude of the control field, the reflection profile is shifted to long wavelengths. This effect can be described in terms of upper level splitting more with increasing the control field. On the other hand with increasing the control field upper energy level splits more and the probe field with smaller energy can be absorbed. Thus the resonant wavelength shifts to long wavelengths. The magnitude and phase profiles of the reflection coefficient for different magnitudes of the control field are shown in Fig. 5. It is shown that with change of the magnitude of control field the magnitude and phase of reflection coefficient of the probe field is changed that is excellent for realization of all optical tunable devices and systems.

Figure 6 shows the tuning range of designed mirror versus Rabi frequency of control field. It is shown that with given structure and considered parameters well about 4 nanometer tuning range can be obtained. We should mention that according to Fig. 3, EIT window broadens from 2.6 nm to 40 nm (from wavelength 1.53 to 1.57 micron) where loss coefficient remains less than 300 m^{-1} which is negligible.

In Fig. 5, we observed that with increasing magnitude of the control field, the magnitude and phase of the reflection coefficient increase in below region of resonant wavelength (wavelengths smaller



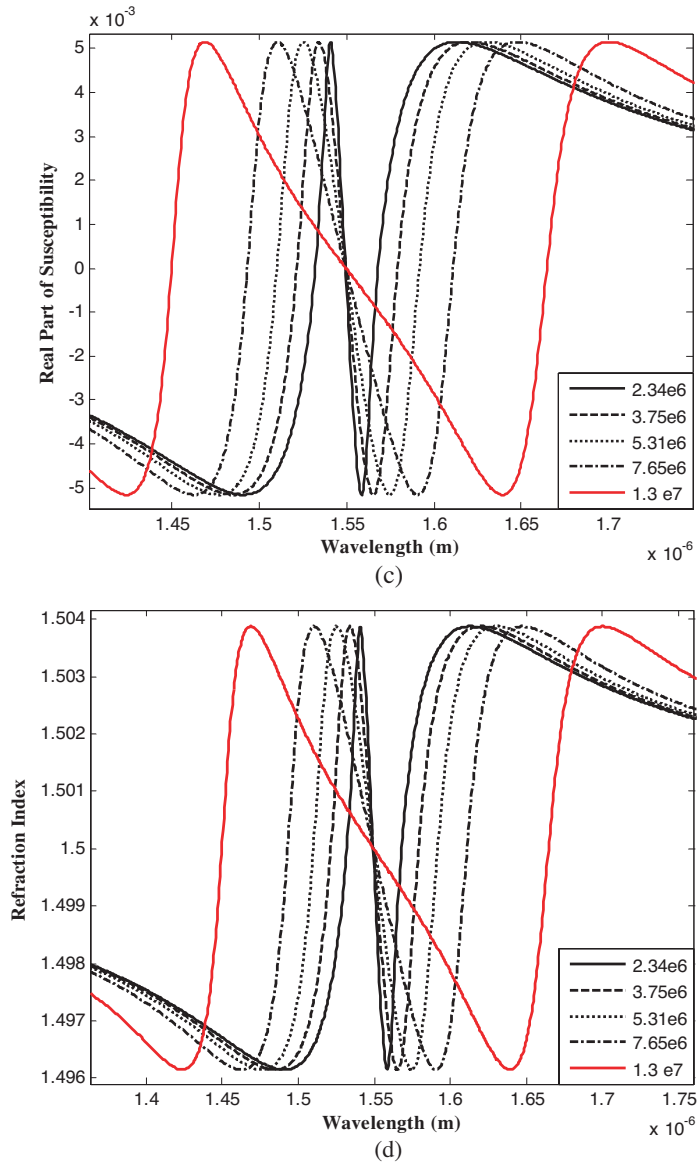
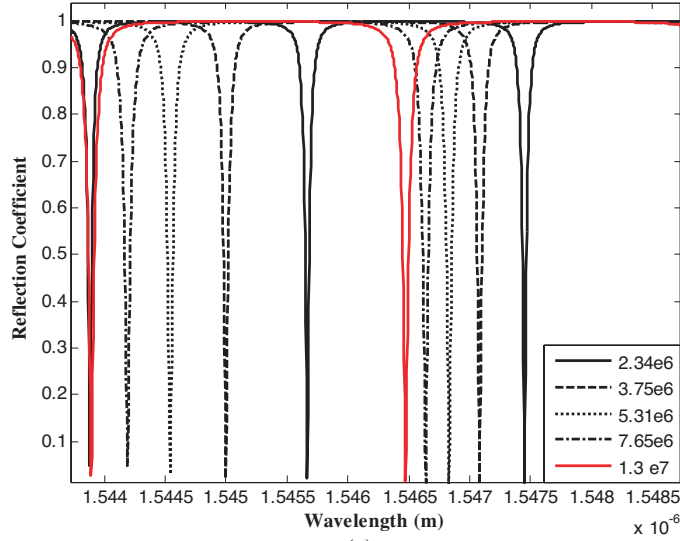
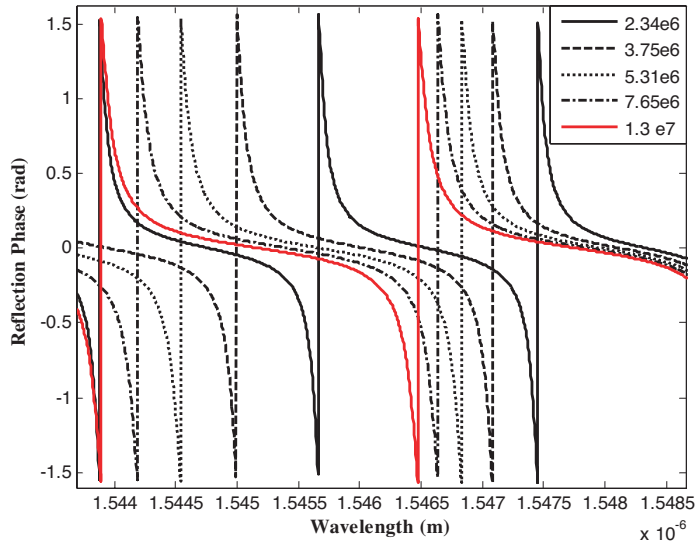


Figure 3. Optical susceptibility, refractive index and loss vs. wavelength and control field amplitude as a parameter. (a) Imaginary part of optical susceptibility, (b) optical loss, (c) real part of optical susceptibility and (d) refractive index. $E_p = 10$ V/m, $N_a = 7.5 \times 10^{16}$ cm $^{-3}$, $\gamma_1 = 5 \times 10^{11}$ s $^{-1}$, $\gamma_2 = \gamma_3 = 10^7$ s $^{-1}$, $\wp_{ab} = 5 \times 10^{-9}$ e-cm.

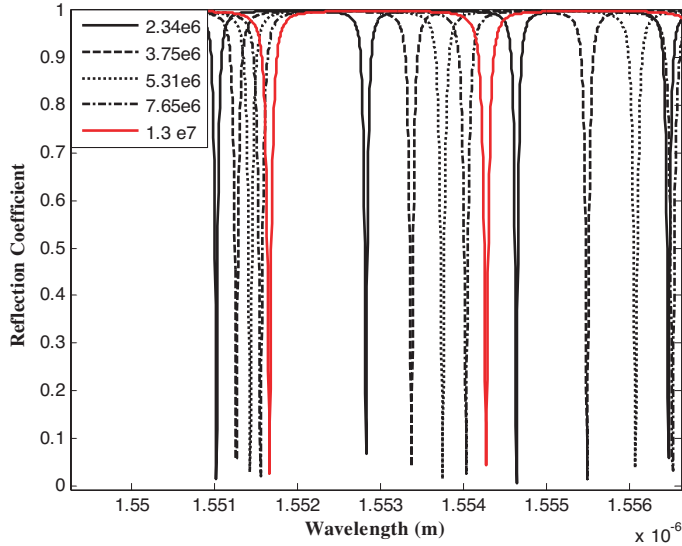
than resonant wavelength) while those quantities decrease in above region (wavelengths larger than resonant wavelength). So, wavelength tuning ranges for below and above regions are shown in Fig. 6. Two parts of Fig. 6 shows wavelength tuning ranges with slab lengths of 100, 200, 300 and 400 microns versus control field amplitude. In the



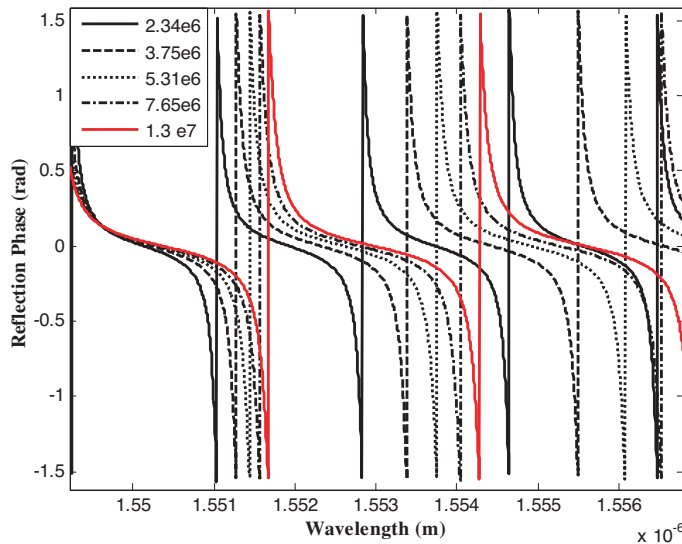
(a)



(b)



(c)

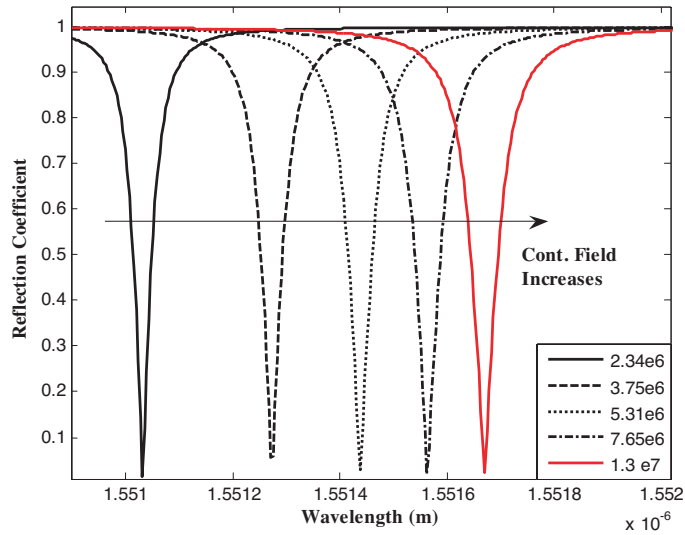


(d)

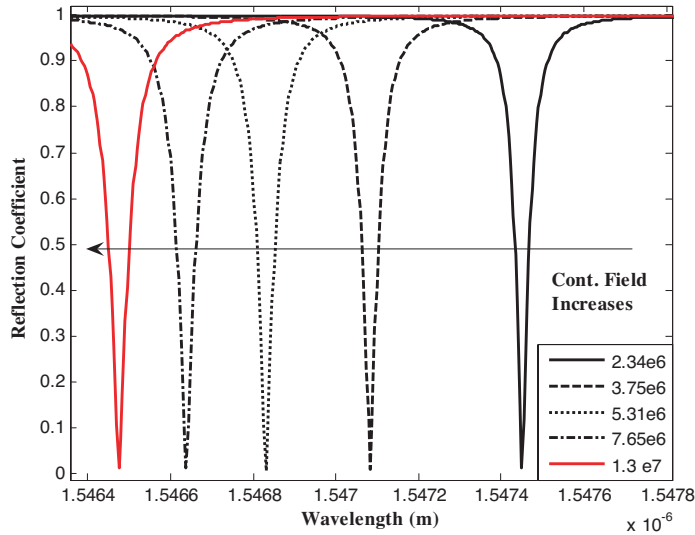
Figure 4. Reflection coefficient (magnitude and phase of probe field) vs. wavelength and the control field amplitude as a parameter. (a) magnitude, (b) phase (radian) in below and (c) magnitude, (d) phase (radian) in above regions of resonant wavelength. $E_p = 10 \text{ V/m}$, $N_a = 7.5 \times 10^{16} \text{ cm}^{-3}$, $\gamma_1 = 5 \times 10^{11} \text{ s}^{-1}$, $\gamma_2 = \gamma_3 = 10^7 \text{ s}^{-1}$, $\wp_{ab} = 5 \times 10^{-9} \text{ e-cm}$, $R = 0.75$, $L = 3 \times 10^{-4} \text{ m}$.

following effect of atomic density on maximum obtainable tuning range of the proposed mirror is studied and result is illustrated in Fig. 7. It is observed that with increasing the atomic density the maximum wavelength tuning range is increased proportional, which is measured in outside of EIT window.

Also, Fig. 7 shows the wavelength tuning range of the magnitude



(a)



(b)

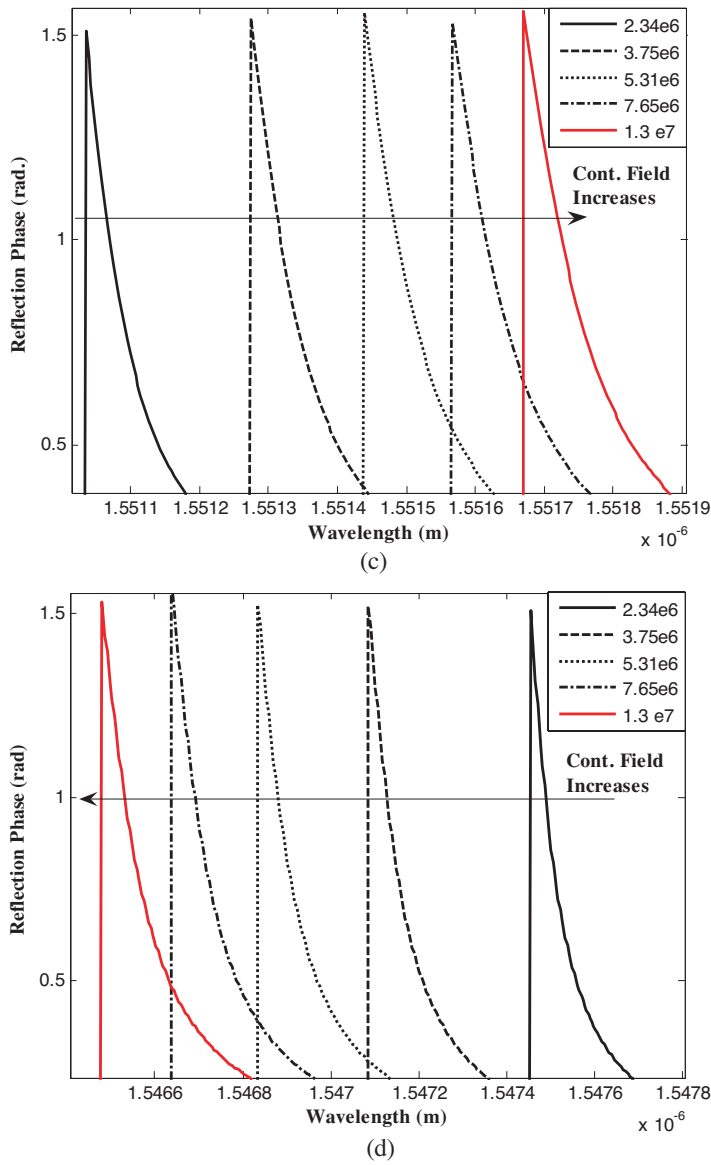


Figure 5. Magnitude and phase of the reflection coefficient of probe field vs. wavelength. (a) and (b) in below region of resonant wavelength, (c) and (d) in above region of resonant wavelength. $E_p = 10 \text{ V/m}$, $N_a = 7.5 \times 10^{16} \text{ cm}^{-3}$, $\gamma_1 = 5 \times 10^{11} \text{ s}^{-1}$, $\gamma_2 = \gamma_3 = 10^7 \text{ s}^{-1}$, $\wp_{ab} = 5 \times 10^{-9} \text{ e-cm}$, $R = 0.75$, $L = 3 \times 10^{-4} \text{ m}$.

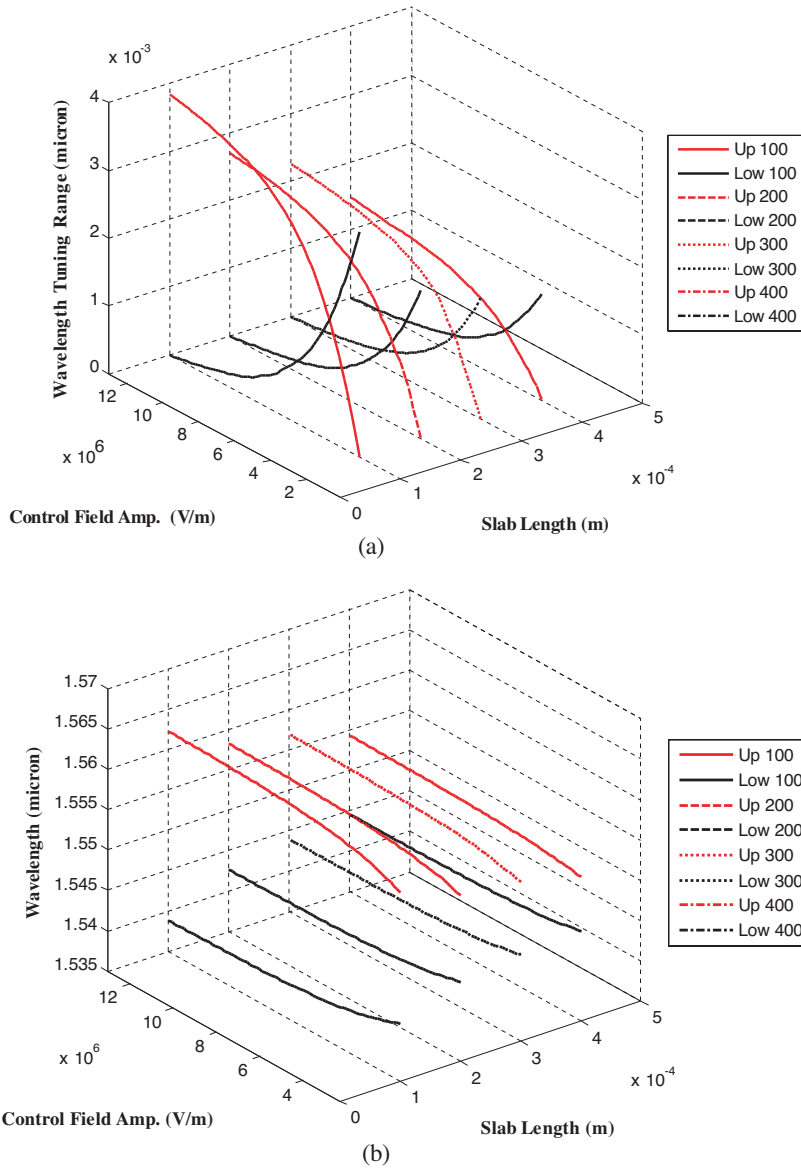


Figure 6. (a) Wavelength tuning range of the reflection coefficient vs. control field with different slab lengths (micrometer), (b) wavelength tuning position of the reflection coefficient vs. control field with different slab lengths. $E_p = 10$ V/m, $N_a = 7.5 \times 10^{16}$ cm $^{-3}$, $\gamma_1 = 5 \times 10^{11}$ s $^{-1}$, $\gamma_2 = \gamma_3 = 10^7$ s $^{-1}$, $\wp_{ab} = 5 \times 10^{-9}$ e-cm, $R = 0.75$.

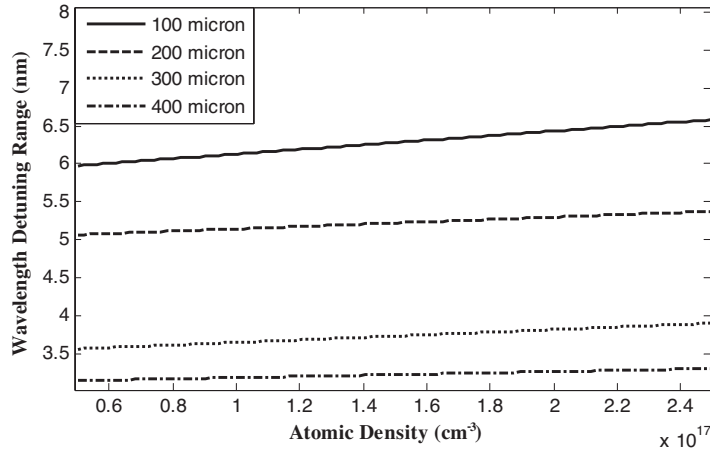


Figure 7. Tuning range of the reflection coefficient vs. control field and slab length. $E_p = 10$ V/m, $N_a = 7.5 \times 10^{16}$ cm $^{-3}$, $\gamma_1 = 5 \times 10^{11}$ s $^{-1}$, $\gamma_2 = \gamma_3 = 10^7$ s $^{-1}$, $\wp_{ab} = 5 \times 10^{-9}$ e-cm, $R = 0.75$, $L = 3 \times 10^{-4}$ m.

and phase of the reflection coefficient for different slab lengths. It is observed that for atomic density variation from 5×10^{16} to 2.5×10^{17} cm $^{-3}$ the wavelength tuning range changes about %5 from 5.98, 5.066, 3.56, 3.14 to 6.585, 5.37, 3.899, 3.21 nanometer for slab lengths of 100, 200, 300, 400 microns, respectively.

4. CONCLUSION

In this paper all-optical tunable device and system operation principle based on the EIT phenomenon has been proposed for first time. In this case as an example optical mirror which has applications in semiconductor lasers is considered. We have shown that with change of the control field the reflection coefficient including amplitude and phase are changed. In this paper, we considered a slab including three-level quantum dots for realization of Λ -type atoms for EIT process and find about 4 nm tuning range in EIT window where optical loss is negligible.

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