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Role of Terahertz Radiation on Optical Properties of Laser Pulse in a Double Coupled Quantum Well Nanostructure

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Abstract

The transient and steady-state behavior of the absorption and the dispersion of a probe pulse laser field propagating through an InGaAs\InP double coupled quantum well are studied. The effect of terahertz radiation excitation, electron tunnelling and incoherent pumping on the optical properties of the probe field is discussed. In the terahertz (30~300 μm or 1~10 THz) intersubband transition, the incoming photon energy is (4~41 mev) and maybe in the order of electron thermal broadening (KT~6 meV-25 meV for 77 K-300 K). Therefore in the conventional structure, the incoming photon can directly excite the ground state electrons to higher energy levels and this process inhabits the correct optical switching in terahertz applications. We show that the group velocity of a light pulse can be controlled from superluminal to subluminal or vice versa by controlling the rates of incoherent pumping field and tunnelling between the quantum wells. The required switching time is calculated and we find it between 3 to 26 picoseconds.

Keywords: Electro-optical switching; Dispersion and absorption; Group velocity; Terahertz radiation; Tunnelling effects; Incoherent pumping field

Introduction

It is known that the absorption and the dispersion properties of a weak probe field can be modified effectively by atomic coherence and quantum interference [1-6]. Atomic coherence can be achieved by the strong coupling fields, the spontaneous emission and incoherent pumping fields. It is known that atomic coherence due to the coherent laser field has essential roles for modifying the optical properties of atomic systems such as spontaneously generated coherence (SGC) [2], lasing without inversion [3], modifying spontaneous emission [4], coherent population trapping (CPT) [6], optical bistability [7-11] and so on [12-17]. Furthermore, it has been shown that quantum interference arising from SGC [8] and incoherent pumping field [18] can be used for analyse of some interesting phenomena such as lasing without population inversion [5], optical bistability [18], and superluminal/subluminal light propagation [19]. Similar phenomena involving quantum coherence in solid state systems such as semiconductor quantum wells (QWs) and quantum dots (QDs) [20], can also be occurred [21,22]. In the past decade, there has been an increasing interest in optical properties of quantum dot molecules (QDMs) and quantum wells (QWs), due to important role in optoelectronic devices. Recently, investigators have examined the effects of an external field and inter-dot tunnel coupling on the optical properties of QDs and QWs [23-29]. Quantum well semiconductors were chosen because of their advantage in flexible design, controllable interference strength, long dephasing times [30,31] large dephasing rates [~10ps-1] [32] and large electric dipole moment which make them suitable for application in the optoelectronic devices. Quantum coherence in a QW structure can be induced by electron tunnelling or applying a laser field [33,34]. Coherence induced by incoherent field and tunnel coupling in the QW system plays an important role in light-matter interaction and has found numerous implementations in semiconductor optics. On the other hand, coherent control [35-38] over the dispersive and absorptive properties of solid-state media such as photonic crystals and semiconductors has recently attracted a lot of attention [39-43]. Several proposals for quantum coherence and interference in QWs have been performed and analyzed. To utilize the tunnelling effect, an electron is excited by a laser field, then tunnels to the second QW by controlling the external voltage between the wells [44]. An interesting application of QWs is modification of light pulse to make a fast electro-optical switch by controlling the propagation of a weak light pulse in a semiconductor system, which depends on the dispersive properties of the medium.

In this paper, we introduce a compact four level quantum wells system composed of two QWs. Then, we investigate effect of terahertz radiation, incoherent pumping field and tunnelling between QWs on the absorption, dispersion and the group velocity of a weak probe field. The required switching time when propagation of light changes from subluminal to superluminal and vice versa is also discussed. We find that the dispersion/absorption spectra of the probe pulse can be changed via the effect of terahertz radiation, incoherent pumping field and tunnelling effect.

Model and Equations of Motion

In Figure 1, we consider a compact double coupled quantum well nanostructure which is fabricated using InGaAs/InP nanostructures in material grown by an attractive growth technique i.e., organometallic vapor phase epitaxy (OMVPE). The QWs consist of two periods of alternating InGaAs and InP layers .An incoherent pumping field and weak probe field are applied to first quantum well (QW_1). The quantum well is designed so that its width is narrower in comparison to the other quantum well (QW_2) and provides larger energy difference between the levels. For controlling of the tunnelling rate between QWs, the system is placed between two connected electrodes, as electrodes

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are in contact to this system. By applying independently tunable gate voltages, electron tunnelling can easily be accomplished between QW_1 and QW_2. Figure 1 shows the detailed band structure and energy levels of the system. Lower level $|0\rangle$ and upper level $|1\rangle$ are conducting band levels of QW_1. Level $|2\rangle$ and level $|3\rangle$ are the excited conducting levels of the QW_2 of the right of QW_1. It is assumed that the energy difference of three excited levels and the lower level is large, so their tunneling couplings can be ignored. By applying a gate voltage the level $|2\rangle$ and the level $|3\rangle$ get closer to the level $|1\rangle$. A weak tunable probe field of the frequency ω_p with Rabi frequency $\Omega_p = \vec{E}.\vec{\wp}/2\hbar$ and an incoherent pumping field Λ are applied to the transition $|0\rangle \to |1\rangle$. Here, $\vec{\wp}$ is electric dipole moment and E is amplitude of the probe field laser. By forming the resonant coupling of the probe field with the QW_1, an electron is excited from the $|0\rangle$ band to the $|1\rangle$ band of the QW_1. By providing the tunnelling conditions the electron can be transferred to level $|2\rangle$ in QW2 and the terahertz radiation of frequency ω_{THz} with Rabi frequency Ω_{THz} prompt the electron from the level $|2\rangle$ to the level $|3\rangle$. The total Hamiltonian in the rotating-wave approximation method [45,46] which represents the interaction of the probe laser field, terahertz radiation and incoherent pumping field with the double coupled QWs system, can be expressed in the form of

$$H = \sum_{j=0}^{5} E_j |j\rangle\langle j| + \left[(\Omega_p e^{-i\omega_p t} |0\rangle\langle 1| + \wp\varepsilon |0\rangle\langle 1| + T_{12}|1\rangle\langle 2| + \Omega_{THz} e^{-i\omega_{THz} t} |2\rangle\langle 3| + H.C. \right] \quad (1)$$

Where $E_j = \hbar\omega_j$ denotes the energy of state $|i\rangle$. $\wp$ Is the dipole moment of the atomic transition corresponding to the pumping of the electrons from level $|0\rangle$ to level $|1\rangle$, and the electric field ε implies the electrical amplitude of the incoherent pumping field. T_{12} Correspond to tunnelling between "QW_1" and "QW_2". The tunnelling can be described by perturbation theory which can be given by Bardeen's approach [47]. The density-matrix approach given by

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H,\rho], \quad (2)$$

Can be used to obtaining the density operator in an arbitrary multilevel QWs system. Substituting eqn. (1) in eqn. (2), the density matrix equations of motion can be expressed as

$$\dot{\rho}_{01} = (i\delta_p - \Gamma_{01} - \Lambda)\rho_{01} + iT_{12}\rho_{02} - i\Omega_p(\rho_{00} - \rho_{11}),$$

$$\dot{\rho}_{02} = iT_{12}\rho_{01} + (i(\delta_p + \omega_{12}) - \Gamma_{02} - \Lambda/2)\rho_{02} + i\Omega_{THz}\rho_{03} + i\Omega_p\rho_{12},$$

$$\dot{\rho}_{03} = i\Omega_{THz}\rho_{02} + (i(\delta_p + \omega_{12} + \omega_{23}) - \Gamma_{03} - \Lambda/2)\rho_{03} + i\Omega_p\rho_{13},$$

$$\dot{\rho}_{12} = i\Omega_p\rho_{02} - (i\omega_{12} + \Gamma_{12} + \Lambda/2)\rho_{12} + i\Omega_{THz}\rho_{13} + iT_{12}(\rho_{11} - \rho_{22}),$$

$$\dot{\rho}_{13} = i\Omega_p\rho_{03} + i\Omega_{THz}\rho_{12} - (i(\omega_{12} + \omega_{23}) + \Gamma_{13} + \Lambda/2)\rho_{13} - iT_{12}\rho_{23},$$

$$\dot{\rho}_{23} = -iT_{12}\rho_{13} - i(\omega_{23} + \Omega_{THz})\rho_{23} + i\Omega_{THz}(\rho_{22} - \rho_{33}),$$

$$\dot{\rho}_{00} = -i\Omega_p(\rho_{01} - \rho_{10}) - \Lambda\rho_{00} + (\gamma_{10} + \Lambda)\rho_{11} + \gamma_{20}\rho_{22} + \gamma_{30}\rho_{33},$$

$$\dot{\rho}_{11} = i\Omega_p(\rho_{01} - \rho_{10}) + \Lambda\rho_{00} - (\gamma_{10} + \Lambda)\rho_{11} + iT_{12}(\rho_{12} - \rho_{21}),$$

$$\dot{\rho}_{22} = -iT_{12}(\rho_{12} - \rho_{21}) + i\Omega_{THz}(\rho_{23} - \rho_{32}) - \gamma_{20}\rho_{22},$$

$$\dot{\rho}_{33} = -i\Omega_{THz}(\rho_{23} - \rho_{32}) - \gamma_{30}\rho_{33}, \quad (3)$$

Where $\rho_{mn} = |m\rangle\langle n| (m,n = 0,1,2,3)$ and $\rho_{mm} = |m\rangle\langle m| (m = 0,1,2,3)$ represent the coherent terms and the population operators for the QWs, respectively. We get $\omega_{12} = \omega_{10} - \omega_{20}$ and $\omega_{23} = \omega_{20} - \omega_{30}$. The probe field detuning with respect to the QW transition frequencies is $\delta_p = \omega_{10} - \omega_p$. The term $\Lambda = 2(\wp^2/\hbar^2)\Gamma_P$ is the incoherent pumping rate. The spontaneous emission rates for sub-band $|i\rangle$, denoted by γ_{10}, are due primarily to longitudinal optical (LO) phonon emission events at low temperature. The total decay rates $\Gamma_{ij}(i \neq j)$ are given by $\Gamma_{0n} = \gamma_{n0}/2 + \gamma_{n0}^{dph}$, $\Gamma_{mn} = (\gamma_{n0} + \gamma_{m0})/2 + \gamma_{mn}^{dph}$, $m,n = 1,2,3$ and $m \neq n$, here $|i\rangle \leftrightarrow |j\rangle$, are the dephasing rates of the quantum coherence of the $|i\rangle \leftrightarrow |j\rangle$ pathway and determined by electron–electron, interface roughness, and phonon scattering processes. Usually, γ_{mn}^{dph} is the dominant mechanism in a semiconductor solid-state system. Eqn. (3) can be solved to obtain the steady state response of the medium. The susceptibility of the compact double QWs to the weak probe field is determined by coherence term ρ_{01}

$$\chi = \frac{2N\wp}{E\varepsilon_0}\rho_{01}, \quad (4)$$

Where N is the carrier density in the proposed QWs system. Ssusceptibility comprise two parts, real and imaginary ($\chi = \chi' + i\chi''$). Note that the real part of the susceptibility χ' correspond to the dispersion and imaginary part χ'' correspond to absorption. The dispersion slope of the probe field has a major role in the group velocity. The group velocity v_g of the light, which is propagates in the medium, given by Bardeen [48]:

$$v_g = \frac{c}{1 + 2\pi\chi'(\omega_p) + 2\pi\omega_p(\partial\chi'(\omega_p)/\partial\omega_p)}, \quad (5)$$

Eqn. (5) implies that for a negligible real part of susceptibility, the light propagation can be superluminal as a negative slope of dispersion, on the other hand, for positive dispersion slope, the light propagation in the medium can be subluminal.

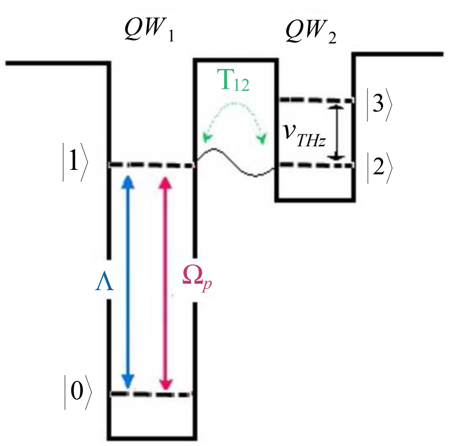

Figure 1: Schematic of system, which shows the detailed band structure and quantized energy levels for proposed double coupled QW.

Results and Discussion

Now, we analyze the numerical results of the above equations and discuss the transient and the steady-state behavior of the absorption and the dispersion. It is assumed that the system is initially in the ground state, i.e., $\tilde{\rho}_{00}(0) = 1$ and $\tilde{\rho}_{ij}(0) = 0$ (i, j=0, 1, 2, 3). We take typically slow dephasing rates $\Gamma_{01} = \gamma = 1\,THz$ and spontaneous emission $\gamma_{10} = 0.6\,THz$ and other relevant parameters by the factor of these rates. Introduced rates are equivalent to dephasing times in the order of picoseconds. Here the according to the equation (5), the positive and negative dispersion slope are representing the propagation

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of light subluminal and superluminal respectively.

Figure 2(a) shows the dispersion (dashed) and absorption (solid) properties of a probe field *vs.* probe field detuning δ_p, in the absence of incoherent pumping field $\Lambda$and tunnelling effect. We observe that the absorption peak accompanies by a negative dispersion. Thus, superluminal light with large absorption propagates through the medium. In Figure 2(b), we show at the steady state behavior of the probe dispersion (dashed) and absorption (solid) in the presence of the first tunnelling effect T_{12} and absence of an incoherent pumping field. It can easily be seen that the absorption of the probe field reduced around zeros detuning probe field just by applying tunnelling rate $T_{12} = 1\gamma$. We find that the slope of dispersion is very sensitive to the tunnelling effect. When we increase T_{12} from 0 to 1γ, slope of dispersion changes from negative to positive. Figure 2(c) shows the effect of the terahertz radiation on the system, when keeping all other parameters fixed in Figure 2(b), and with applying the terahertz signal, the dispersion slope does not change, but tow windows transparency created that is accompanied by three absorption peaks.

In Figure 3, we investigate the incoherent pumping field effect on the system. In Figure 2(a), we applied an incoherent pumping filed to condition of Figure 2(a) with values $\Lambda = 8\gamma$. By increasing the incoherent pumping field Λ from 0 to 8γ, the absorption peak of the probe field becomes broaden, while the slope of the dispersion is still negative around the probe field detuning. Physically, by increasing the incoherent pump rate, the upper levels are populated, for this condition the probe absorption will reduce in transition $|0\rangle \to |1\rangle$, thus the peak maximum of the probe field absorption gets reduce. In Figure 3(b), by applying the tunnelling rate T_{12} mid incoherent pumping field, one absorption peak of the probe field is crated around zeros detuning probe field. By applying the incoherent pumping field, when keeping all other parameters fixed in Figure 2(b), the slope of dispersion changes from positive to negative that is shown in Figure 2(b) and 3(b). This indicates that group velocity of light propagates, increasing from subluminal to superluminal through the medium. In Figure 3(c), we simultaneously apply the tunnelling rate T_{12} between QW_1 and QW_2 and the terahertz signal, while the incoherent pump rate is still Λ=8γ. We observe that the probe field absorption convert to probe gain, which is accompanied by positive dispersion slope i.e. the probe field propagation changes from superluminal to subluminal in medium by applying the incoherent field as shown in Figures 2(c) and 3(c). This is an important mechanism in which the probe field absorption and dispersion can be controlled by the incoherent pump field in the quantum well.

Now, we are interested in the dynamical behaviour of the dispersion slope due to this properties can be used as an electro-optical switch of group velocity from subluminal to superluminal or vice versa. We are interested in the required switching time for change of the light propagation from subluminal to superluminal or vice versa. Switching time for subluminal/superluminal light propagation is defined as the time to reach a steady-state from the superluminal state to the subluminal state and vice versa. Figure 4(a) shows the transition

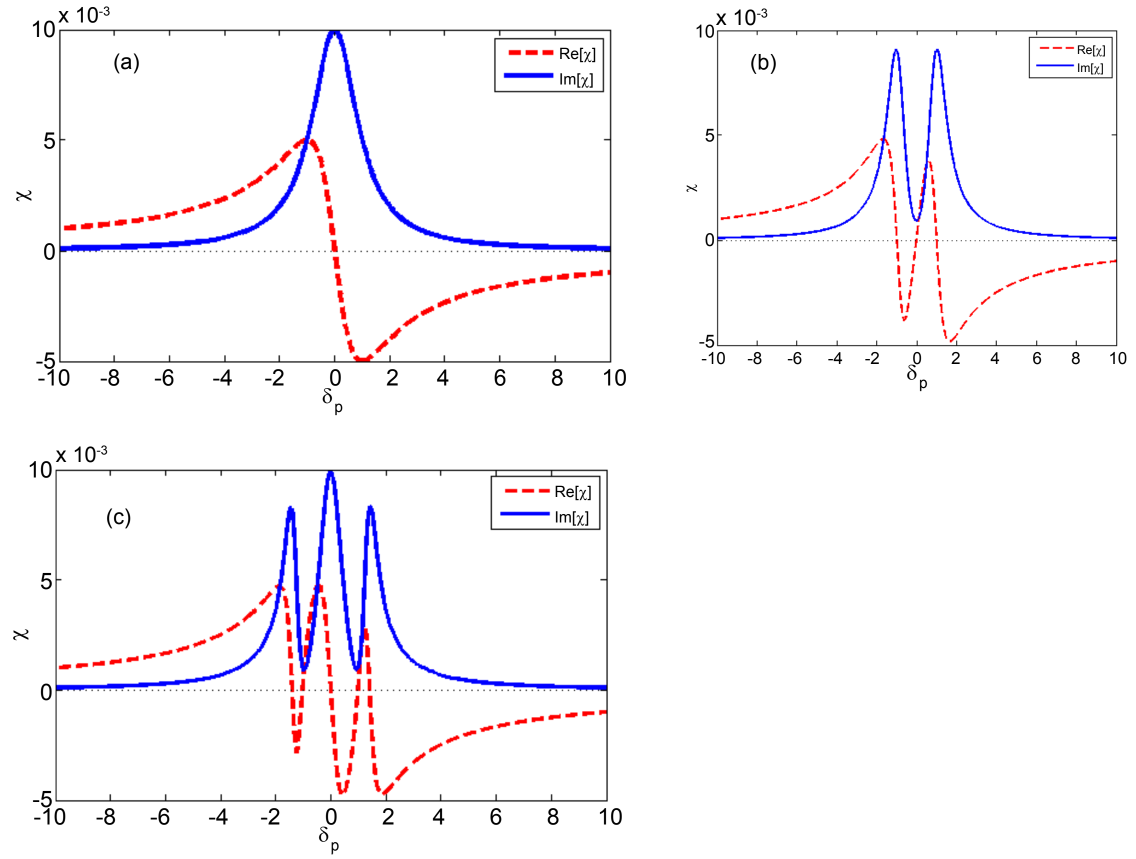

Figure 2: Real (dashed) and imaginary (solid) parts of susceptibility as a probe field wavelength for (a) T_{12}=0, TH_z *signal=off*, Λ=0, (b) T_{12}=1γ, TH_z *signal=of*, Λ=0, (c), T_{12}=1γ, $\Lambda = 0$, TH_z *signal=on* Other parameters are, $\omega_{12}=\omega_{23}$=0.01γ, Γ_{01}=γ=1TH_z, Γ_{02}=0.1Γ_{01}, Γ_{03}=0.01Γ_{01}, Γ_{12}=0.05Γ_{01}, Γ_{13}=0.025Γ_{01}, Γ_{23}=0.05Γ_{01}, γ_{10}=0.6TH_z, γ_{20}=0.1 γ_{10}, γ_{30}=0.1γ_{10}, Ω_P=0.01γ.

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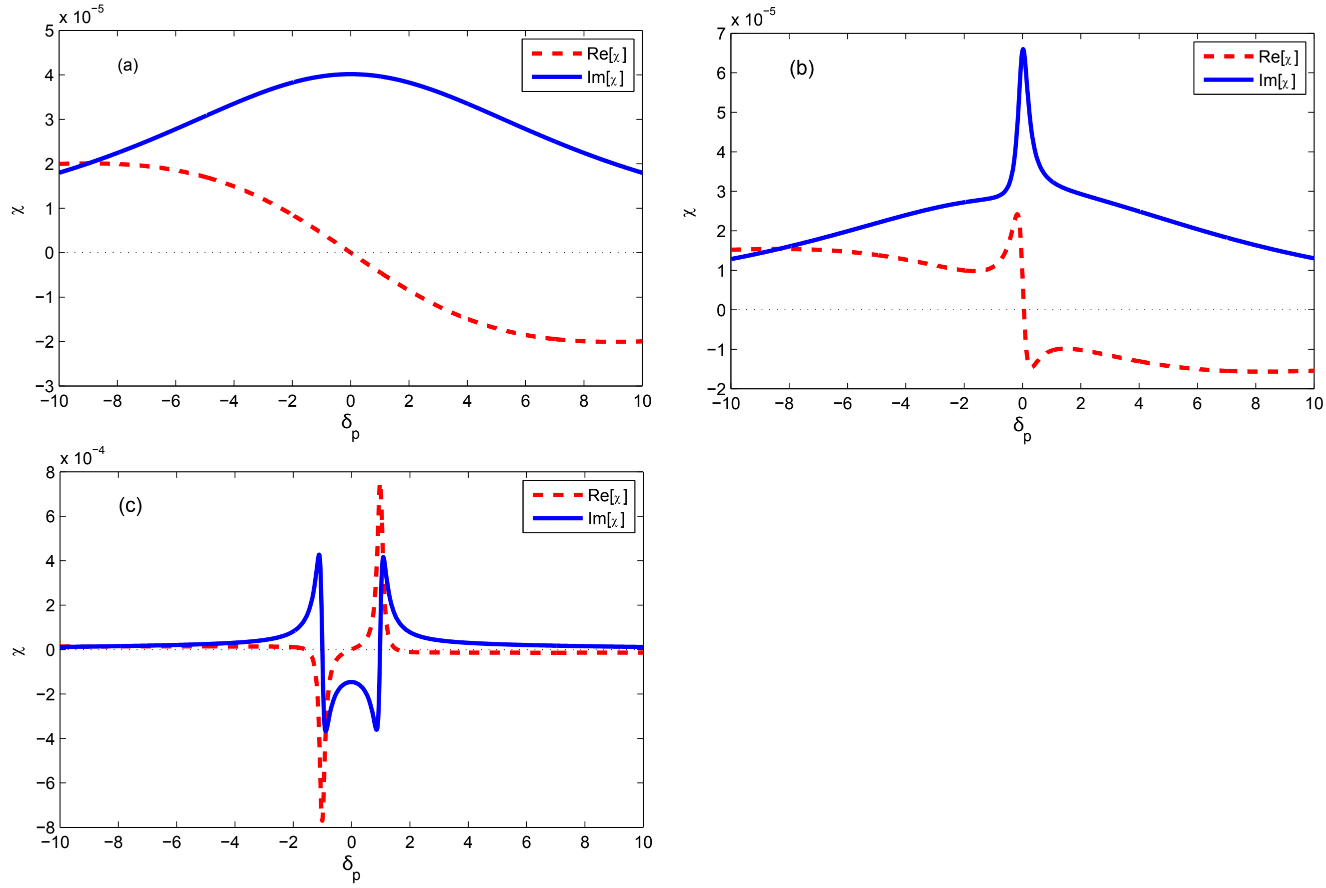

Figure 3: Real (dashed) and imaginary (solid) parts of susceptibility as a probe field wavelength for (a) T_{12}=0, TH_z *signal=off*, Λ=8γ, (b) T_{12}=1γ, TH_z *signal=off*, Λ=8γ, (c) T_{12}=1γ, Λ=8γ, TH_z *signal=on* (d) Other parameters are as in Figure 2.

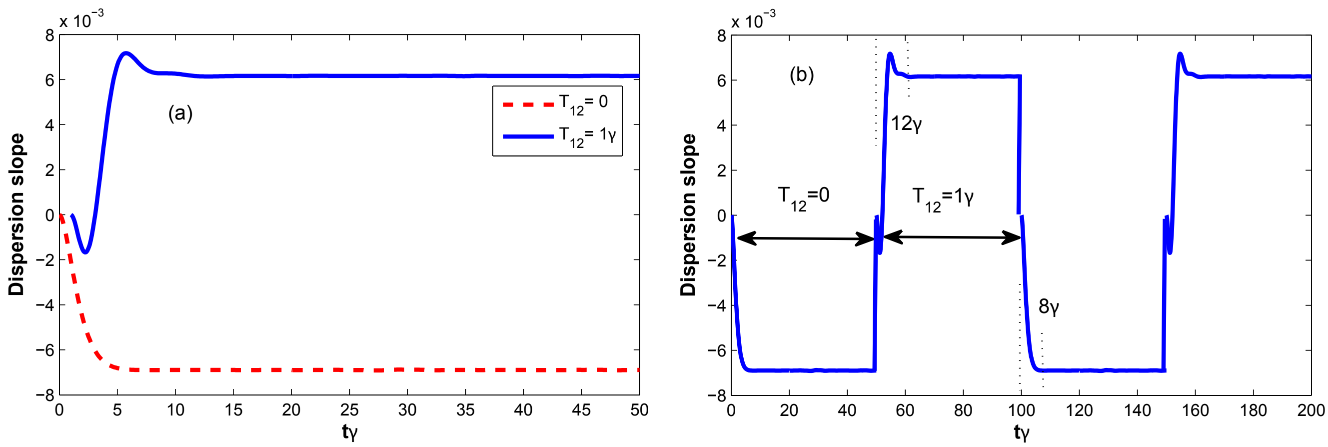

Figure 4: Dynamical behaviour (a) and switching process (b) of dispersion slope for T_{12}=(0, 1γ), TH_z *signal=off*, Λ=0.Other parameters are as in Figure 2.

behaviour of the dispersion slope by consecutively switching the tunnelling rate from $T_{12}=0$ to $T_{12}=1\gamma$ and vice versa. By increasing the normalized time $t\gamma$ ($\gamma=\Gamma_{10}=1THz$), the dispersion slope takes a steady negative values for $T_{12}=0$ corresponding to superluminal light propagation, while it changed to negative on applying the terahertz signal which is corresponding to subluminal light propagation. In Figure 4(b), we plot the switching diagram of the dispersion slope for two different values of T_{12}. The required switching time for propagation of the light from subluminal to superluminal is about 8ps and from superluminal to subluminal is about 12ps. Now, we investigate the effect of the incoherent pumping rate by consecutively switching incoherent pumping rate from $\Lambda=0$ to $\Lambda=8\gamma$ and vice versa, while the tunnelling rate $\Lambda=0$ is fixed (Figure 5(a)). It is clearly find that the slope of the dispersion changes from positive to negative by adjusting

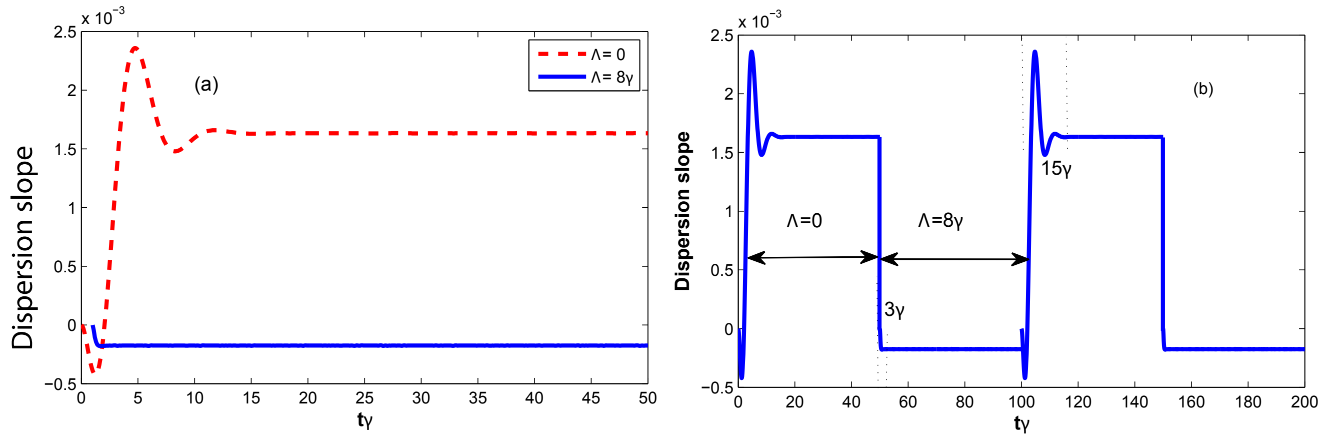

Figure 5: Dynamical behaviour (a) and switching process (b) of dispersion slope for T_{12}=1γ, *TH_z signal=off*, Λ=(0, 8γ). Other parameters are as in Figure 2.

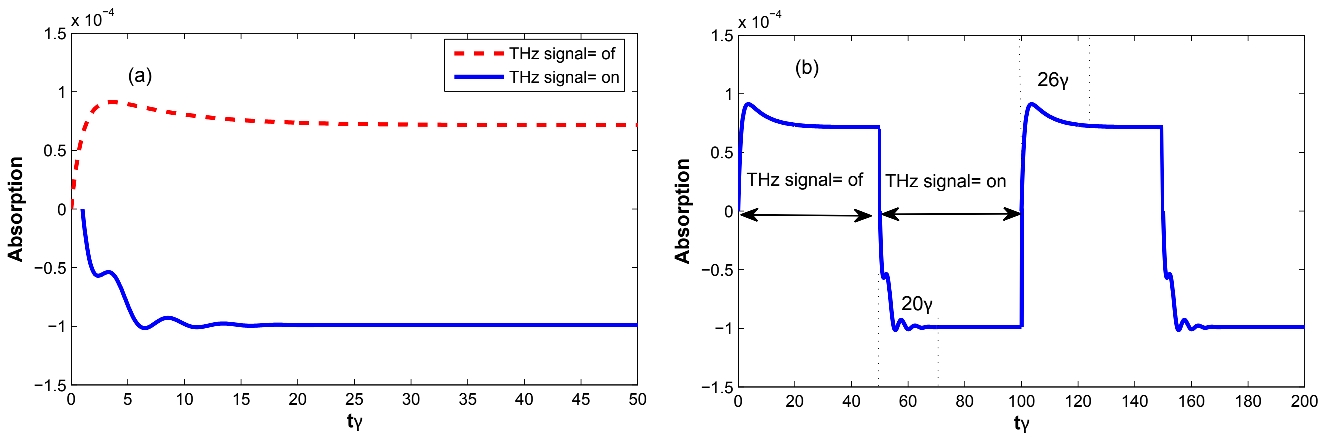

Figure 6: Dynamical behaviour (a) and switching process (b) of absorption for *TH_z signal (off*, on) T_{12}=1, Λ=0. Other parameters are as in Figure 2.

the incoherent field. For $\Lambda = 0$ the slope of the dispersion is positive corresponding to subluminal light propagation, while it changes to negative as the incoherent pumping changes from $\Lambda = 0$ to $\Lambda = 8\gamma$ corresponding to superluminal light propagation. The required switching time for change of the propagation light from subluminal to superluminal is about 3ps, and vice versa is 15ps (Figure 5(b)). This approach can be utilized to produce a switch operating only by controlling the tunnelling rate T_{12} and incoherent rate Λ. The transient behaviour of the probe absorption is displayed for two various rate of terahertz signal, while keeping $T_{12} = 1\gamma$ and $\Lambda = 8\gamma$ fixed in Figure 6. We are looking for the required switching time for changing the light absorption case to the probe gain or vice versa by proper manipulating the tunnelling rate T_{12} and terahertz signal. Effect of the terahertz signal leads to a significant probe amplification of steady state probe absorption. Figure 6(a,b) shows that the required switching time from large absorption to probe gain case or vice versa is about 20γ.

Conclusion

We investigated the transient and the steady-state behavior of a weak probe field in a compact double coupled QWs system with applying the tunnelling between QWs, terahertz signal and one incoherent pumping field. It is shown that the absorption and the dispersion of the probe field can be controlled by applying the tunnelling between QWs, terahertz radiation and incoherent pumping fields. It has also been shown that the medium can be used as an optical switch in which the propagation of the laser pulse can be controlled with tunnelling between QWs and the incoherent pumping field. We obtained the switching time; between 3 to 26 picosecond as a high speed optical switch is an important technique for quantum information, networks and communication.

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