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# High-temperature all-optical intersubband quantum well Terahertz switch

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ABSTRACT

In this article an asymmetric intersubband quantum well structure as a high temperature terahertz (THz) optical switch is proposed. In our proposed structure the incoming low power energy photon (THz control signal) causes an optical switching. In this structure we introduce an optical terahertz switch based on coherent population trapping (CPT) phenomena. In the presence of electromagnetic THz field, quantum interference between the terahertz control field and short-wavelength probe field under appropriate condition, the medium becomes transparent (zero absorption) for the probe field. So the absorption and refraction characteristic of optical probe field can be modified with THz radiation. Therefore this idea is suitable for all – optical terahertz switching.



## 1. Introduction

In telecommunication, an optical switch is a switch that enables signals in optical fibers or integrated optical circuits (IOCs) to be selectively switched from one circuit to another. An optical switch may operate by mechanical means, such as physically shifting an optical fiber to drive one or more alternative fibers, or by electro-optic effects, magneto-optic effects, or other methods [1,2].

In optical switches that use the electro-optic effect, there is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light. The electro-optic effect could be done by a change in the absorption or change in the refractive index. In quantum well structures a change in the absorption index is called the quantum-confined Stark effect (QCSE) which is described by the effect of an external electric field upon the light absorption spectrum of a quantum well (QW) [3,4]. In the absence of an external electric field, electrons and holes within the quantum well may only occupy states within a discrete set of energy subbands. Consequently, only a discrete set of frequencies of light may be absorbed by the system. When an external electric field is applied, the electron states shift to lower energies, while the hole states shift to higher energies. This reduces the permitted light absorption frequencies.

In the terahertz (30–300 $\mu$m or 1–10 THz) intersubband transition quantum-well structures [5,6], the incoming photon energy is (4–41 mev) and maybe in the order of electron thermal broadening (KT $\sim$ 6–25 meV for 77–300 K) [5–7]. Therefore in conventional electro-optic absorption structure, both the incoming photon and the environment temperature can directly excite the ground state electrons to higher energy levels and this problem inhibits the correct optical switching in high temperature and terahertz frequencies applications.

In our proposed CPT [8–10] based optical THz switch, the incoming electromagnetic THz switch control field, according to perturbation theory and atom-field interaction Hamiltonian [8] in Schrodinger equation, interacts with the short-wavelength (1–2 $\mu$m) electromagnetic probe field and causes like quantum-confined Stark effect phenomena. The coherent modification of the atomic spectrum in the electric field of a light field resembles the Stark splitting and shifting in a static electric field. It is therefore called optical Stark effect [11]. As a result there is a change in the optical properties of material such as absorption and refractive index of short wavelength electromagnetic probe field. Under appropriate condition, the medium becomes transparent (zero absorption) for the probe field.

The absorption and refraction characteristic of optical probe field could be modified with THz radiation. So the electromagnetic THz field can create sharp absorption peak where there was a transparency or sharp transparency peak where there was absorption in the transmission coefficient of probe field. The wavelength and intensity of this absorption or transparency peak can be controlled by the THz frequency and THz intensity.

In the THz range we are not dealing with electron transport problems. The incoming terahertz light and the environment temperature do not directly excite electrons, but affect the absorption characteristics of short-wavelength probe optical field. In fact we convert the incoming Terahertz signal to short-wavelength optical field through CPT phenomena, where such problems are not critical in this rang of switching.

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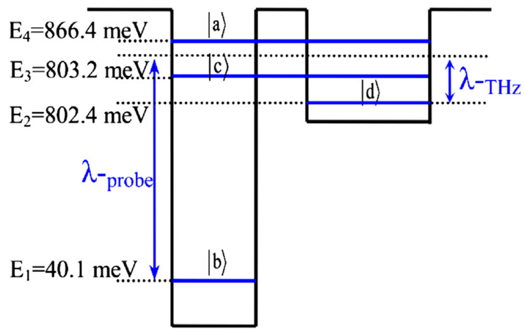


**Fig. 1.** Asymmetric double barrier intersubband quantum well structure as a THz switch.

## 2. Model derivation

Our proposed intersubband quantum well structure as an all-optical THz switch is shown in Fig. 1. In this structure the electromagnetic short wavelength probe filed and the electromagnetic THz control filed are applied respectively. In quantum well structures the stark-like effect can be created with the coupling two wells [8–11]. The barrier potential between two wells is thin (coupled wells) and the eigen-states are in the same energy or in the range of electron–LO phonon scattering or electron–electron scattering and other scattering processes. So the wave functions of two wells can see each other through thin barrier (resonant-mode). Thus the two new states $|a\rangle$,$|c\rangle$ are created. This effect is like optical stark effect [11] in an atomic system which is introduced by strong pump field.

In many aspects the eigen-states in quantum well are like atomic systems, therefore the wave-function and total Hamiltonian (non-interaction and interaction terms) as follows respectively [8–12]:

$$\Psi(t)\rangle = c_b(t)|b\rangle + c_a(t)|a\rangle + c_c(t)|c\rangle + c_d(t)|d\rangle \tag{1}$$

$$H_0 = \hbar\omega_b|b\rangle\langle b| + \hbar\omega_a|a\rangle\langle a| + \hbar\omega_c|c\rangle\langle c| + \hbar\omega_d|d\rangle\langle d| \tag{2}$$

$$H_1 = \hbar q\Omega_p|b\rangle\langle a| + \hbar\Omega_p|b\rangle\langle c| + \hbar k\Omega_{\mathrm{THz}}|d\rangle\langle a| + \hbar\Omega_{\mathrm{THz}}|d\rangle\langle c| \tag{3}$$

$$H = H_0 + H_1 \tag{4}$$

$$H = h\begin{pmatrix} \nu_b & 0 & -\Omega_p e^{i\nu_p t} & -q\Omega_p e^{i\nu_p t} \\ 0 & \nu_d & -\Omega_{\mathrm{THz}} e^{i\nu_{\mathrm{THz}} t} & -k\Omega_{\mathrm{THz}} e^{i\nu_{\mathrm{THz}} t} \\ -\Omega_p e^{-i\nu_p t} & -\Omega_{\mathrm{THz}} e^{-i\nu_{\mathrm{THz}} t} & \nu_c & 0 \\ -q\Omega_p e^{-i\nu_p t} & -k\Omega_{\mathrm{THz}} e^{-i\nu_{\mathrm{THz}} t} & 0 & \nu_a \end{pmatrix} \tag{5}$$

In the above equations $\Psi(t)$, $c_b(t)$, $c_a(t)$, $c_c(t)$, $c_d(t)$ are the wave function and the probability amplitude of finding the atom in states $|b\rangle$,$|a\rangle$,$|c\rangle$,$|d\rangle$, respectively. $\Omega_p$,$\Omega_{\mathrm{THz}}$ are the Rabi frequencies of probe signal and terahertz signal. Where $H_0$, $H_1$, $H$ represent the unperturbed and the interaction and the total Hamiltonian respectively.

In the structure in Fig. 1 the probe field could interact with both the subband transitions $|b\rangle\leftrightarrow|c\rangle$ and $|b\rangle\leftrightarrow|a\rangle$ simultaneously with the Rabi frequencies $\Omega_p$ and $q\Omega_p$ where $q = \mu_{ab}/\mu_{cb}$ is the ratio of dipole moment of relevant transition). On the other hand the terahertz-infrared field could interact with both $|d\rangle\leftrightarrow|c\rangle$ and $|d\rangle\leftrightarrow|a\rangle$ with the Rabi frequencies $\Omega_{\mathrm{THz}}$ and K$\Omega_{\mathrm{THz}}$. Where $K = \mu_{ad}/\mu_{cd}$ is the ratio of dipole moment of relevant transition).

The dynamic response of the proposed quantum well THz switch is described by using the density matrix formalism [13–15], under the electro-dipole and rotating-wave approximations, [8,16,17].

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] \tag{6}$$

$$\dot{\rho}_{ab} = -[i(\Delta_p + \frac{\omega_S}{2}) + \Gamma_{ab}]\rho_{ab} + iq\Omega_p\rho_{bb} - iq\Omega_p\rho_{aa} + ik\Omega_{IR}\rho_{db} - i\Omega_p\rho_{ac} \tag{7}$$

$$\dot{\rho}_{cb} = -[i(\Delta_p - \frac{\omega_S}{2}) + \Gamma_{cb}]\rho_{cb} + i\Omega_p\rho_{bb} + i\Omega_{IR}\rho_{db} - iq\Omega_p\rho_{ca} - i\Omega_p\rho_{cc} \tag{8}$$

$$\dot{\rho}_{dc} = -[i(\Delta_{IR} + \frac{\omega_S}{2}) + \Gamma_{dc}]\rho_{dc} - i\Omega_p\rho_{db} - i\Omega_{IR}\rho_{dd} + i\Omega_{IR}\rho_{cc} + ik\Omega_{IR}\rho_{ac} \tag{9}$$

$$\dot{\rho}_{db} = -i(\Delta_p + \Delta_{IR} + \Gamma_{db})\rho_{db} + i\Omega_{IR}\rho_{cb} + ik\Omega_{IR}\rho_{ab} - i\Omega_p\rho_{dc} - iq\Omega_p\rho_{da} \tag{10}$$

$$\dot{\rho}_{da} = -[i(\Delta_{IR} - \frac{\omega_S}{2}) + \Gamma_{da}]\rho_{da} - iq\Omega_p\rho_{db} - ik\Omega_{IR}\rho_{dd} + ik\Omega_{IR}\rho_{aa} + i\Omega_{IR}\rho_{ca} \tag{11}$$

$$\dot{\rho}_{ac} = -[i\omega_S + \Gamma_{ac}]\rho_{ac} - i\Omega_p\rho_{ab} + iq\Omega_p\rho_{bc} - i\Omega_{IR}\rho_{ad} + ik\Omega_{IR}\rho_{dc} \tag{12}$$

where $\omega_s = \nu_{ab} - \nu_{cb}$, $\nu_0 = (\nu_{ab} + \nu_{cb})/2$, $\nu'_0 = (\nu_{ad} + \nu_{cd})/2$ and $\Delta_p = \nu_0 - \upsilon_p$, $\Delta_{IR} = \nu'_0 - \upsilon_{IR}$. The population and dephasing decay rates are added phenomenologically in the above density matrix equations. The population decay rate for subband $|j\rangle$ (due to LO-phonon emission events) is denoted by $\gamma_j$. The total decay rates are given by: $\Gamma_{cb} = \gamma_c + \gamma_{cb}^{dph}$, $\Gamma_{ab} = \gamma_a + \gamma_{ab}^{dph}$, $\Gamma_{db} = \gamma_d + \gamma_{db}^{dph}(\gamma_d = \gamma_{cd} + \gamma_{ad})$, $\Gamma_{ac} = \gamma_a + \gamma_c + \gamma_{ac}^{dph}$, $\Gamma_{cd} = \gamma_c + \gamma_d + \gamma_{cd}^{dph}$ and $\Gamma_{ad} = \gamma_a + \gamma_d + \gamma_{ad}^{dph}$. In these expressions $\gamma_{ij}$ (determined by electron–electron, interfaces roughness, and phonon scattering process) is the dephasing decay rate of the $|i\rangle\leftrightarrow|j\rangle$ transition.

In terms of the density matrix notation, we have [8]:

$$P(z, t) = [\wp_{ab}(\rho_{ab_{(z,t)}} + c.c) + \wp_{cb}(\rho_{cb_{(z,t)}} + c.c)] \tag{13}$$

where $P(z, t)$, $\wp_{ij}$ is the optical polarization and dipole moment matrix element between sates $|i\rangle$,$|j\rangle$ respectively. The optical polarization can be calculated as follows [8]:

$$P(z, t) = \varepsilon_0\chi E(z, t) \tag{14}$$

where $\chi$,$E(z,t)$ are the linear susceptibility and the electric filed respectively.

We can write the linear susceptibility as[]:

$$\chi = \frac{P}{\varepsilon_0 E} = \frac{2N_a(\wp_{ab}^2\rho_{ab} + q\wp_{cb}^2\rho_{cb})}{\varepsilon_0\Omega_p\hbar} \tag{15}$$

where $\Omega_p$ and $N_a$ are the Rabi frequency of the probe field and the carrier density respectively.

By using analytical solution the optical susceptibility is obtained as [8]:

$$\chi_p^{(1)} = \frac{(2N/\varepsilon_0\hbar)[\wp_{ab}^2(L_1L_2 + \Omega_{\mathrm{THz}}^2) + \wp_{cb}^2(-K\Omega_{\mathrm{THz}}\Omega_{\mathrm{THz}} + qL_3L_2 + qK\Omega_{\mathrm{THz}}^2)]}{L_1L_2L_3 + L_3\Omega_{\mathrm{THz}}^2 + L_1 + K^2\Omega_{\mathrm{THz}}^2} \tag{16}$$

where $L_1 = [i(\Delta_p - (\omega_s/2)) + \Gamma_{cb}]$, $L_2 = [i(\Delta_p + \Delta_{IR}) + \Gamma_{db}]$, $L_3 = [i(\Delta_p + (\omega_s/2)) + \Gamma_{ab}]$, $K = \mu_{da}/\mu_{dc}$, $q = \mu_{ab}/\mu_{cb}$.

In the terahertz (30–300 μm) intersubband transition quantum-well structures, the incoming photon energy is (4–41 mev) and maybe in the order of electron thermal broadening (KT ∼ 6–25 meV