Quantum Well Terahertz Switch Based On Electromagnetically Induced Transparency

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Abstract: We propose a new asymmetric quantum well structure as a high temperature long wavelength (THz) optical switch based on electromagnetically induced transparency (EIT). In this structure the electromagnetic field of terahertz-infrared radiation interfere with the electromagnetic field of short-wavelength probe field and this effect changes the absorption and refraction characteristic of probe field. Therefore this idea is suitable for terahertz optical switching.In the terahertz (30~300µm or 1~10THz) intersubband transition quantum-well structures, the incoming photon energy is (4~ 41mev) and maybe in the order of electron thermal broadening (KT~ 6meV-25meV for 77K - 300K)[1]. Therefore in the conventional structure, both the incoming photon and the environment temperature can directly excite the ground state electrons to higher energy levels and this problem inhabits the correct optical switching in high temperature and terahertz applications. In our proposed EIT [2,3] based optical switch, the incoming Terahertz IR signal interacts with the short-wavelength (1~2µm) probe field (does not directly excite the ground state electrons) and causes a sharp absorption or transparency in this visible optical probe.
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Key Words: Terahertz signal, Asymmetric quantum well, Coherent population trapping (CPT), Optical switch, Quantum interference, Electromagnetically Induced Transparency.

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.

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

2. Model derivation

In quantum well structures the stark –like effect can be created with the coupling two wells and the EIT like condition may be appeared [4,5]. The barrier potential between two well is thin (coupled wells) and the eigen-states be 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). And the two new states $|a>, |c>$ are created. This effect is like to stark effect [2] in an atomic system which is introduced by strong pump field.

Our proposed quantum well structure as an optical switch is inset into Fig.1. With using the density matrix formalism, under the electro-dipole and rotating-wave approximations, [2,4]we describe the dynamic response of the proposed quantum well structure. The real and imagery part of susceptibility $\chi = \chi' + \chi''$ lead to dispersion and absorption respectively. The absorption and dispersion coefficient are given by $\alpha = \omega_p n_0 \chi''/c$ and $\beta = \omega_p n_0 \chi'/2c$ respectively. By using analytical solution the optical susceptibility is obtained as [2]:

$$\chi_P^{(1)} = \frac{2N/_{\epsilon_0\hbar}\,[\wp_{ab}^2(L_1L_2+\Omega_{IR}^2)+\wp_{cb}^2(-K\Omega_{IR}\Omega_{IR}+qL_2L_3+qK\Omega_{IR}^2)]}{L_1L_2L_3+L_3\Omega_{IR}^2+L_1+K^2\Omega_{IR}^2}$$

Where $L_1 = \left[i\left(\Delta_p - \frac{\omega_s}{2}\right) + \Gamma_{cb}\right]$, $q = \frac{\mu_{ab}}{\mu_{cb}}$,$K = \frac{\mu_{da}}{\mu_{dc}}$

$L_2 = [i(\Delta_p - \Delta_{IR}) + \Gamma_{db}]$, $L_3 = \left[i\left(\Delta_p + \frac{\omega_s}{2}\right) + \Gamma_{ab}\right]$

As shown in Fig.1 in the absence of THz signal, we see two sharp absorption peaks in two different wavelengths which are related to $|b> \leftrightarrow |a>$ and $|b>\leftrightarrow |c>$ transitions.

Fig.2. shows the transmission coefficient of probe field in the presence of THz signal. In this case we see two sharp transparencies in two different wavelengths where there was absorption. These transparencies are related to the THz signal coupling to $|d> \leftrightarrow |a>$ $|d> \leftrightarrow |c>$ transitions.

Therefore THz signal changes the complete absorption to transparency and this can be a base for optical switching.

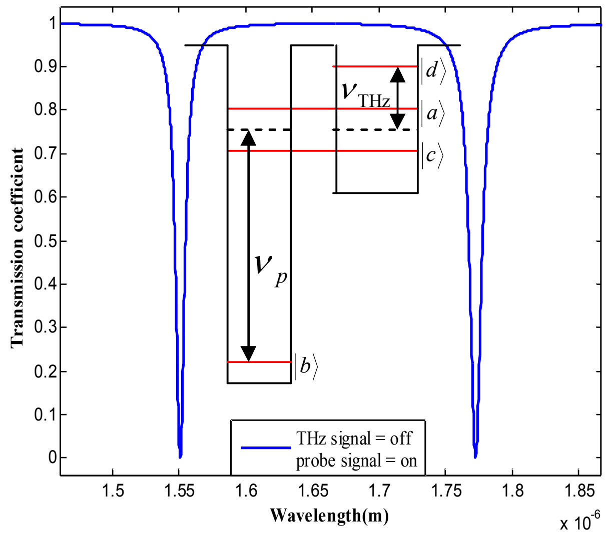

Fig.1. Schematic of asymmetric double barrier quantum well structure and the transmission coefficient without infrared (THz) field.

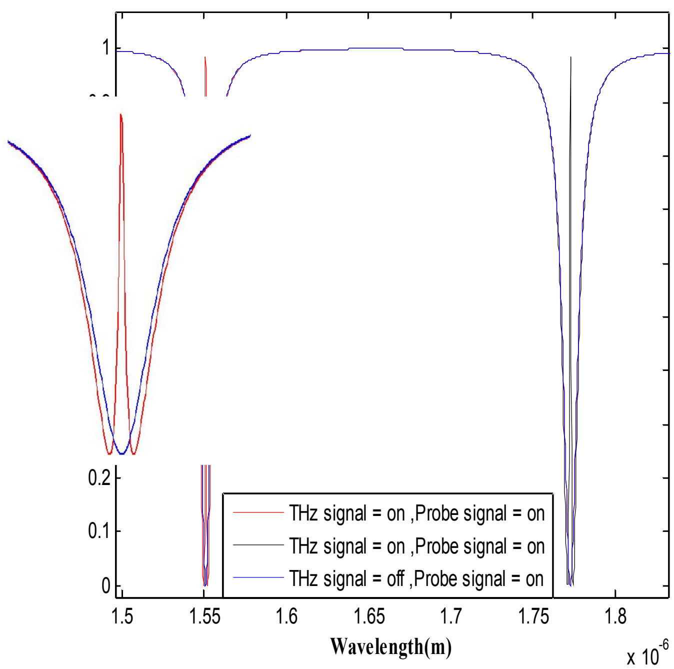

Fig.2. Transmission coefficient of probe fieldin the presence of THz signal (resonant to $|d\rangle \leftrightarrow |a\rangle, |d\rangle \leftrightarrow |c\rangle$ allowed transition)

Another case is also happening in the presence of THz signal. Fig.3. shows the transmission coefficient of probe field when the THz signal is coupled between the states $|a\rangle, |c\rangle$ where there are not any allowed state. In this case we see an absorption in a certain wavelength where there was transparency. So the effect of THz signal is creating absorption and this can be also a base for an optical switch operation.

In our proposed structure, the environment average thermal energy may be added to the IR-signal energy as follow:

$$E_{total} = E_{signal} + E_{thermal}$$

Although the effect of thermal energy is shifting the wavelength of absorption or transmission, in a fix temperature, the fluctuation of wavelength will be negligible. Therefore our proposed quantum well structure based on electromagnetically induced transparency is suitable for high temperature and long wavelength optical switch.

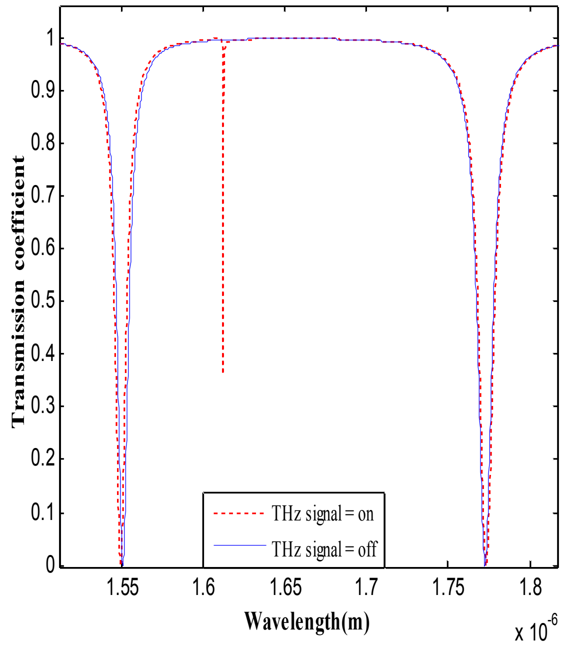

Fig.3. Transmission coefficient of probe field in the presence of THz signal (THz signal is applied between states $|a\rangle, |c\rangle$)

3. Conclusion

In this article we proposed a novel high temperature all optical Intersubband Quantum well THz Switch based on CPT phenomena. The incoming THz switch control signal (low power energy photon) causes an optical switching in the short wavelength frequency. The results of simulations show that in the proposed structure the quantum interference of a short-wavelength probe signal and the terahertz signal modifies the absorption coefficient of the probe filed and a sharp absorption peak or transparency peak (an interferential state) appears. 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 (short wavelength) field. The wavelength and intensity of THz signal created absorption or transparency peaks could be controlled by the THz frequency and THz intensity. Therefore this idea is suitable for all - optical terahertz switching.

3/17/2013

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