ELECTROMAGNETIC INDUCED TRANSPARENCY EFFECTS IN SEMICINDUCTOR QUANTUM WELL WITH V CONFIGURATION

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Abstract. From the density matrix equation, the paper has presented the interaction between the electromagnetic field and electron in the semiconductor quantum well with V configuration. We study the change of absorption coefficient in a semiconductor and frequency of probe laser and coupling laser. From the research results, we determine the values of Ω_p, Ω_c, Δ_p, Δ_c for the appearance of the electromagnetically induced transparency effect.

Keywords: *Semiconductor quantum well, absorption coefficient, electromagnetically induced transparency.*

I. INTRODUCTION

The manipulation of subluminal and superluminal light propagation in optical medium has attracted many attentions due to its potential applications during the last decades, such as controllable optical delay lines, optical switching, telecommunication, interferometry, optical data storage and optical memories quantum information processing, and so on [1]. The most important key to manipulate subluminal and superluminal light propagations lies in its ability to control the absorption and dispersion properties of a medium by a laser field.

As we know that coherent interaction between atom and light field can lead to interesting quantum interference effects such as electromagnetically induced transparency (EIT) [2]. The EIT is a quantum interference effect between the probability amplitudes that leads to a reduction of resonant absorption for a weak probe light field propagating through a medium induced by a strong coupling light field [4]. Basic configurations of the EIT effect are three-level atomic systems including the Λ-Ladder and V-type configurations. In each configuration, the EIT efficiency is different, in which the Λ-type configuration is the best, whereas the V-type configuration is the worst [5-7], therefore, the manipulation of light in each configuration are also different. To increase the applicability of this effect, scientists have paid attention to creating many transparent windows. One proposed option is to add coupling laser fields to further stimulate the states involved in the interference process. This suggests that we choose to use the analytical model to determine the dispersion coefficient for the V configuration of the semiconductor quantum well.

In the present study, the model used to realize electromagnetically induced transparency consists of a single quantum well in which InAs is embedded in a GaAs barrier material [4]. We study a confined electron considered in GaAs/InAs/GaAs cylindrical quantum well with the presence of internal laser field. The potential energy hole is limited to zero inside the well and V_0 outside. The associated parameters used in the calculations are shown in Table 1.

Table 1. *Associated parameters used in the the calculations.*

Parameter	Value
N (m^{-3})	3.0×10^{21}
$\gamma_{22}, \gamma_{33}, \gamma_{23}$ (Hz)	10^{10}
μ_{12} (nm)	0.67
μ_{12} (nm)	2.93
ω_{21} (s^{-1})	8.05×10^{14}
ω_{32} (s^{-1})	1.4×10^{14}
Ω (s^{-1})	2.0×10^{11}
n_b	3.6

II. THE DENSITY MATRIX EQUATION

We first consider a V-configuration of the semiconductor quantum well as shown in Fig. 1. Level $|2\rangle$ is the ground states of the valence band. The levels $|1\rangle$ and $|3\rangle$ are excited states of the conduction region.

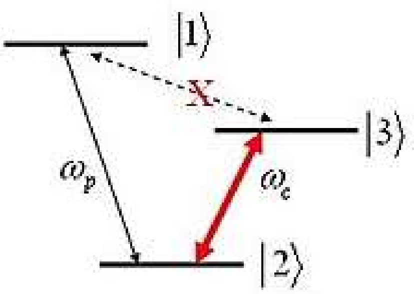

Fig. 1. *Three-level excitation of the V- configuration in the semiconductor quantum well.*

A weak probe laser L_p has intensity E_p with frequency $\omega_1 = \omega_p$ and the frequency detuning of $\boldsymbol{\Delta_P = \omega_{12} - \omega_1}$ create displacement $|2\rangle \rightarrow |1\rangle$, strong coupling laser L_c with has intensity E_p with frequency $\omega_2 = \omega_c$ and the frequency detuning of $\boldsymbol{\Delta_C = \omega_{32} - \omega_3}$ whereas the transition $|2\rangle \rightarrow |3\rangle$, excited energy levels $|1\rangle$ and $|3\rangle$ can be strongly excited in different ways down to the ground state level $|2\rangle$. Here, Wij is the spontaneous emission rate of the level $|i\rangle$ to level $|j\rangle$, W_i is the natural decay rate of the level $|i\rangle$. The decay rate of the ground state level $|2\rangle$ is negligible. The Rabi frequencies of the probe and coupling fields are denoted, respectively $\Omega_p = \frac{\mu_{21}E_p}{\hbar}$ and $\Omega_c = \frac{\mu_{32}E_c}{\hbar}$ Ω_c, w_t is the rate of escape product in the quantum hole at levels due to different causes, where μ_{ij} is the electric dipole matrix element $|i\rangle \leftrightarrow |j\rangle$.

The evolution of the system, which is represented via the density operator ρ is determined by the following Liouville equation [2]:

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}\left[H,\rho\right] + \Lambda\rho \qquad (1)$$

where, H represents the total Hamiltonian and $\Lambda\rho$ represents the decay part. Hamilton of the systerm can be written by matrix form:

$$H = H_0 + H_I \tag{2.1}$$

$$H_0 = \hbar\omega_1 |1\rangle\langle 1| + \hbar\omega_2 |2\rangle\langle 2| + \hbar\omega_3 |3\rangle\langle 3| \tag{2.2}$$

$$H_I = \frac{\hbar\Omega_p}{2}\left(|1\rangle\langle 2| e^{i\omega_p t} + |2\rangle\langle 1| e^{-i\omega_p t}\right) + \frac{\hbar\Omega_c}{2}\left(|2\rangle\langle 3| e^{i\omega_c t} + |3\rangle\langle 2| e^{-i\omega_c t}\right) \tag{2.3}$$

In the framework of the semiclassical theory, the density matrix equations can be written as:

$$[\dot{\rho}]_{11} = i.\Omega_p(\rho_{12} - \rho_{21}) - W_1\rho_{11} \tag{3.1}$$

$$[\dot{\rho}]_{12} = i\Omega_p(\rho_{11} - \rho_{22}) - d_1\rho_{12} + i\Omega_c\rho_{13} \tag{3.2}$$

$$[\dot{\rho}]_{13} = i\Omega_c\rho_{12} - d_2\rho_{13} - i\Omega_p\rho_{23} \tag{3.3}$$

$$[\dot{\rho}]_{22} = -i\Omega_p(\rho_{12} - \rho_{21}) + i\Omega_C(\rho_{23} - \rho_{32}) + W_{12}\rho_{11} + W_{32}\rho_{33} \tag{3.4}$$

$$[\dot{\rho}]_{23} = -i\Omega_p\rho_{13} + i\Omega_C(\rho_{22} - \rho_{33}) - d_3\rho_{23} \tag{3.5}$$

$$[\dot{\rho}]_{33} = -i.\Omega_C(\rho_{23} - \rho_{32}) - W_3\rho_{33} \tag{3.6}$$

with $d_1 = i\Delta_p + \gamma_{12}$, $d_2 = i\Delta_p - i\Delta_c + \gamma_{13}$, và $d_3 = -i\Delta_C + \gamma_{23}$

In addition, suppose the initial atomic system is at a level $|2\rangle$ therefore, $\rho_{11} \approx \rho_{33} \approx 0, \rho_{22} = 1$. We analytically solve the density matrix equations under the steady-state condition by setting the time derivatives to zero:

$$\frac{d\rho}{dt} = 0 \tag{4}$$

Therefore, the equation system from (3.1) to (3.6), we have:

$$i.\Omega_p(\rho_{12} - \rho_{21}) - W_1\rho_{11} = 0 \tag{5.1}$$

$$i\Omega_p(\rho_{11} - \rho_{22}) - d_1\rho_{12} + i\Omega_c\rho_{13} = 0 \tag{5.2}$$

$$i\Omega_c\rho_{12} - d_2\rho_{13} - i\Omega_p\rho_{23} = 0 \tag{5.3}$$

$$-i\Omega_p(\rho_{12} - \rho_{21}) + i\Omega_C(\rho_{23} - \rho_{32}) + W_{12}\rho_{11} + W_{32}\rho_{33} = 0 \tag{5.4}$$

$$-i\Omega_p\rho_{13} + i\Omega_C(\rho_{22} - \rho_{33}) - d_3.\rho_{23} = 0, \tag{5.5}$$

$$i.\Omega_C(\rho_{23} - \rho_{32}) + W_3.\rho_{33} = 0. \tag{5.6}$$

where, the frequency detuning of the probe and L$_c$ coupling laser from the relevant transitions are respectively determined by $\Delta_p = \omega_p - \omega_{21}$, $\Delta_c = \omega_c - \omega_{23}$.

We slove the systerm of equations from (5.1) to (5.6) and get the result:

$$\rho_{12} = \frac{i[\Omega_p\Omega_c^2 - \Omega_p d_2 d_3)}{\Omega_c^2 d_3 + d_1 d_2 d_3} = \frac{K + iL}{P + Qi} \tag{6}$$

with

$$K = \Omega_p[\Delta_c\gamma_{13} - \gamma_{23}(\Delta_p - \Delta_c)] \tag{6.1}$$

$$L = \Omega_p[(\Delta_p - \Delta_c)\Delta_c - \Omega_c^2 - \gamma_{13}\gamma_{23}] \tag{6.2}$$

$$P = \gamma_{23}\Omega_c{}^2 + \gamma_{12}\,[(\Delta_p - \Delta_c)\Delta_c + \gamma_{13}\gamma_{23}] \text{-}\Delta_p[\gamma_{23}(\Delta_p - \Delta_c) - \Delta_c\gamma_{13}] \tag{6.3}$$

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$$Q = \Delta_p[(\Delta_p - \Delta_c)\Delta_c + \gamma_{13}\gamma_{23}] + \gamma_{12}(\Delta_p\gamma_{23} - \Delta_c\gamma_{23} - \Delta_c\gamma_{13}) - \Delta_c{\Omega_c}^2 \qquad (6.4)$$

III. ABSORPTION COEFFICIENT

We start from the susceptibility of the medium for the probe light that is determined by the following relation:

$$\chi = -2\frac{Nd_{12}}{\varepsilon_0 E_p}\rho_{12} = \chi' + i\chi'' \qquad (7)$$

The absorption coefficient α of the medium for the probe beam is determined through the real part of the linear susceptibility (7):

$$\alpha = \frac{\omega_p}{c}.\frac{2Nd^2{}_{12}}{\hbar\varepsilon_0\Omega_p}.\frac{LP-KQ}{P^2+Q^2} \qquad (8)$$

We investigate the absorption coefficient α for the quantum hole of the GaAs/InAs/GaAs structure when changing the parameters respectively as follows: $\gamma_{22} = \gamma_{33} = = \gamma_{23} = \gamma_{13} = 10^{10}$ Hz, the density of three level system $N = 3.10^{21}/\text{m}^3$, dielectric coefficient $\varepsilon_0 = 8{,}86.10^{-12}$ F/m, $\hbar = 1{,}05.10^{-34}$ *J.s*, and frequency of probe beam $\omega_p = 3{,}84.10^{14}$ Hz.

Investigation of the absorption of the probe beam according to the intensity of the coupling beam Ω_c and the deviation of the probe beam Δ_p:

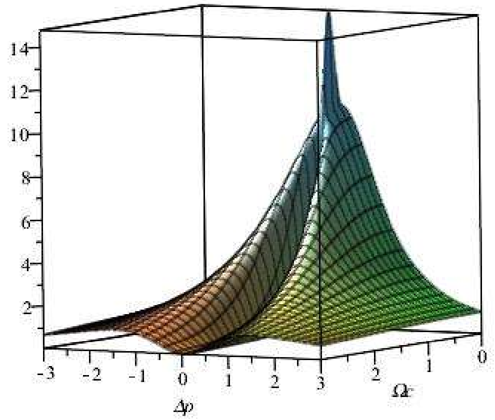


Fig. 2. *Three-dimensional graph of the absortion coefficient α according to Δp and Ωc with Δc= 0 MHz.*

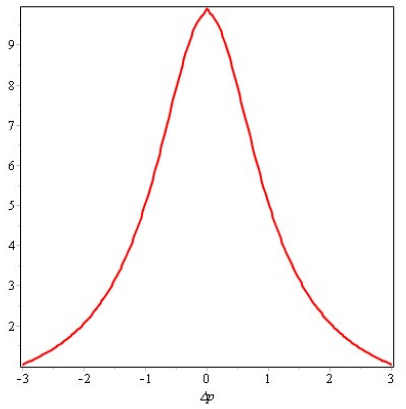


Fig. 3. *Two-dimensional graph of the absorption coefficient according to Δp with Ωc = 0.35 MHz, Δc = 0.*

From Fig. 2, when the value of Δc = 0 MHz is fixed, gradually increasing the intensity of the control beam (ie gradually increasing Ω_c), the absorption coefficient of the medium with the probe beam decreases at position Δp = 0. When the value of Ω_c increases from 0 to 0.35 MHz, but the EIT spur has not yet appeared.

In Fig. 3, due to the large decay rate, when the Ω_c value of about 0.35 MHz ,3 MHz begins to appear EIT effect, the center of the transparent window is at the value $\Delta_p = 0$, that is, the frequency is number of the probe beam resonating with the transition frequency $|2\rangle$ and $|1\rangle$. When Ω_c is gradually increased then EIT window gradually increases in depth relative to the maximum absorption. Investigate the absorption of the probe beam according to the frequency detuning probe beam $\boldsymbol{\Delta_p}$ and the frequency of the coupling beam $\boldsymbol{\Delta_c}$.

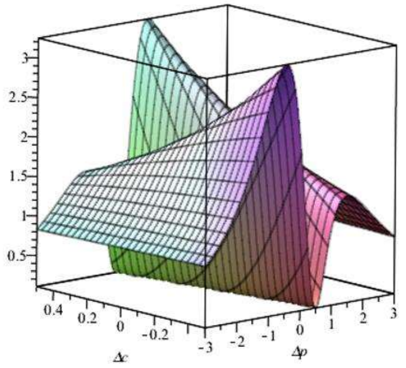
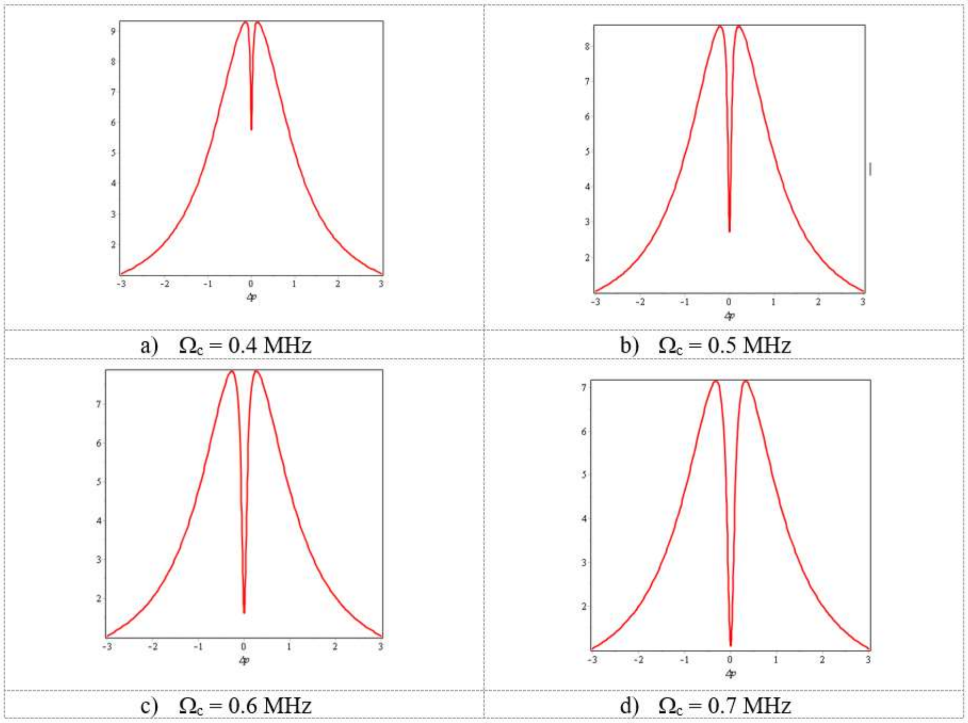


Fig. 4. *Three-dimensional graph of the absortion coefficient* α *according to* Δ_p *and* Δ_c *with* Ω_p*= 0.01 MHz,* Ω_c *= 2MHz.*



a) $\Omega_c = 0.4$ MHz

b) $\Omega_c = 0.5$ MHz

c) $\Omega_c = 0.6$ MHz

d) $\Omega_c = 0.7$ MHz

Fig. 5. *Two-dimensional graph of the absorption coefficient according to* Δ_p *with* Ω_c *= 0.4 MHz (Fig. a),* Ω_c *= 0.5 MHz (Fig. b),* Ω_c *= 0.6 MHz (Fig. c),* Ω_c *= 0.7 MHz (Fig. d).*

To investigate the absorption of the probe beam of the environment, we fixed the values Ω_p=0.01 MHz, Ω_c=2 MHz, changing the frequency of the probe beam in the range from -30 MHz to 30 MHz, the absorption of the medium for the probe beam varies symmetrically around the value $\Delta_c = 0$ MHz (Fig. 5).

The center of the EIT slit is centered with the value $\Delta_c = 0$, $\Delta_p = 0$ which means that then both the probe and control beam have a resonant frequency with the transition frequency $|2\rangle$ and $|1\rangle$ of the medium (Fig. 6c). In addition to the value $\Delta_c = 0$, the depth of the EIT window

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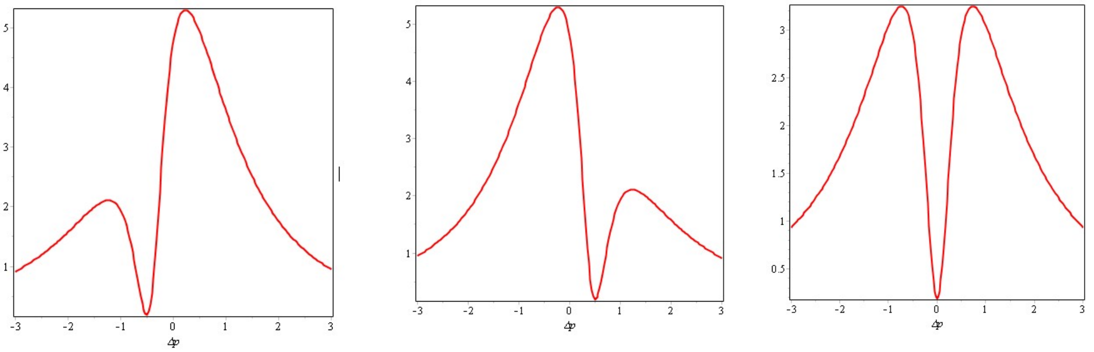
does not reach the minimum and the center of the window will be skewed to a negative value of Δ_p when Δ_c is negative (Fig. 6b) and the center of the window will be skewed about the positive value of Δ_p when Δ_c is positive (Fig. 6c).



a) $\Delta_c = 0{,}5$ MHz b) $\Delta_c = -\ 0{,}5$ MHz c) $\Delta_c = 0$

Fig. 6. *Two-dimensional graph of the absorption coefficient versus frequency of the control beam with* $\Omega_p=0.01$ *MHz,* $\Omega_c = 2$ *MHz in the case of* $\Delta_c = 0.5$ *MHz (Fig. a),* $\Delta_c = -0.5$ *MHz (Fig. b),* $\Delta_c = 0$ *MHz (Fig. c).*

IV. CONCLUSIONS

In the framework of the semi-classical theory, we have cited the density matrix equation for the semiconductor quantum well in the V-configuration under the simultaneous effects of two laser probe and coupling beams. Using approximate rotational waves and approximate electric dipoles, we have found solutions in the form of analytic for the dispersion coefficient of atoms when the probe beam has a small intensity compared to the coupling beams. We study the change of absorption coefficient in a semiconductor and frequency of probe laser and coupling laser. From the research results, we determine the values of Ω_p , Ω_c, Δ_p, Δ_c for the appearance of the electromagnetically induced transparency effect. The results show that a V-configuration appears a transparent window for the probe laser beam. The depth and width or position of these windows can be altered by changing the intensity or frequency detuning of the coupling laser fields.

However, the survey problem here is new considering the case of 3 levels in a V-configuration semiconductor quantum well without considering other configurations, without side effects. Therefore, our recommendation is to apply the results of this topic, expand it to other effects such as: Dopler effect, group velocity dispersion, Kerr-type nonlinear coefficient control... or consider for the 3-level case in other configurations in the semiconductor quantum well.

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