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Electromagnetically induced transparency in semiconductors based on the quantum well structures with a three levels Lambda configuration

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Abstract. In this paper, we study the interaction between the electromagnetic fields and electron in semiconductors based on the GaAs/InAs/GaAs quantum well structures with a three levels Lambda configuration. The Lambda configuration includes two lower levels in the valence band and an upper level in the conduction band. We calculate the absorption coefficient in the semiconductor quantum well in the presence of two laser fields of different frequencies, one is called the probe field, the other is called the coupling field. From the obtained results, we determine the values of the Rabi frequencies, frequency detuning of the probe field and the coupling field. The results show that with an energy spectrum of the Lambda-configuration appears a transparent window for the probe laser beam. The depth and width or position of the window can be altered by changing the intensity of the coupling laser field.

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

1. Introduction

In 1989, Harris and colleagues investigated a new effect of light-matter interactions in three level systems, called electromagnetically induced transparency (EIT) [1]. The EIT effect was experimentally verified in 1991 [2]. This effect is accompanied by significantly enhanced nonlinear susceptibility. Furthermore, this gives rise to many other effects, for example: the slowing and stopping of light [3]. This is due to quantum interference between the probability amplitudes of displacement under coherent excitation of laser beams. This interference, under the control of a strong laser beam (coupling field), the medium will become transparent to a weak laser beam (probe field) and cause eliminating the spectral shift probability amplitude leads to eliminating the absorption of the environment for the detector laser field and forming a transparent window on the absorption curve, so it is called the EIT window [3].

Recently, EIT has been demonstrated by experiments and theoretical calculations in low-dimensional materials [4-8]. Most recently, the work of Joseph Jayarubi studied the EIT phenomenon in a three-energy level V configuration in a semiconductor quantum well (QW) [8]. Joseph Jayarubi and his colleagues used density matrix formalisms, perturbation methods, and plotting the absorption curve with a probe field in a semiconductor quantum cavity. The new research results stop at V-configuration. This has suggested to us the choice of using analytical models to study the EIT phenomenon of the three-level Lambda (Λ)-configuration system, within the framework of this article. From there we can determine the analytical expression of the absorption coefficient for the probe beam. This expression is the basis for us to study nonlinear Kerr effects, slowing down the speed of light groups, optical bistability, all-optical switching [9-12].

In the present study, the model used to realize EIT consists of semiconductor based on a QW in which InAs is embedded in a GaAs barrier material [8]. We study a confined electron considered in GaAs/InAs/GaAs cylindrical QW with the presence of internal laser field. The potential energy is limited to zero inside the well and V_0 outside (Fig.1).

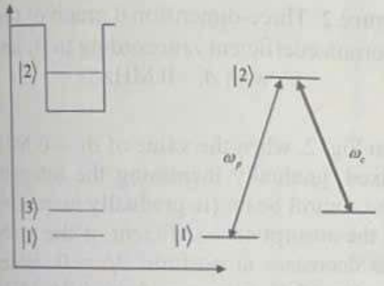


Figure 1. Three-level excitation of the Λ - configuration in the semiconductor based on a quantum well.

2. Density matrix equation

We first consider a Λ-configuration of the semiconductor based on a quantum well as shown in Fig. 1. The levels $|1>$ and $|3>$ are the ground states of the valence band. The level $|2>$ is excited state of the conduction region.

A weak probe laser L_p has intensity E_p with frequency $\omega_1=\omega_p$ and the frequency detuning of $\Delta_p = \omega_{12} - \omega_1$ create displacement $|1>\rightarrow|2>$, strong coupling laser L_c with has intensity E_p with frequency $\omega_2=\omega_c$ and the frequency detuning of $\Delta_c = \omega_{32} - \omega_3$ whereas the transition $|3>\rightarrow|2>$, excited energy level $|2>$ can be strongly excited in different ways down to the ground state levels $|1>$ and $|3>$. Here, $\gamma_{ij} = (\Gamma_i+\Gamma_j)/2$ is the spontaneous emission rate of the level $|i>$ to the level $|j>$, Γ_i is the natural decay rate of the level $|i>$. The Rabi frequencies of the probe and coupling fields are denoted, respectively $\Omega_p = 2\mu_{12}E_p/\hbar$ and $\Omega_c = 2\mu_{23}E_c/\hbar$ where μ_{ij} is the electric dipole matrix element $|i> \leftrightarrow |j>$.

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

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H,\rho] + \Lambda\rho \tag{1}$$

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

$$H = H_0 + H_I \tag{2}$$

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

$$\begin{aligned} H_I = {} & \frac{\hbar\Omega_p}{2}\left(|1\rangle\langle 2|e^{i\omega_p t} + |2\rangle\langle 1|e^{-i\omega_p t}\right) + \\ & + \frac{\hbar\Omega_c}{2}\left(|3\rangle\langle 2|e^{i\omega_c t} + |2\rangle\langle 3|e^{-i\omega_c t}\right) \end{aligned} \tag{4}$$

In the framework of the semiclassical theory, the density matrix equations can be written for $\dot{\rho}_{11}$, $\dot{\rho}_{12}$, $\dot{\rho}_{13}$, $\dot{\rho}_{21}$, $\dot{\rho}_{22}$, $\dot{\rho}_{23}$, $\dot{\rho}_{31}$, $\dot{\rho}_{32}$, and $\dot{\rho}_{33}$, where, the frequency detuning of the probe and L_c coupling laser from the relevant transitions are respectively determined by $\Delta_p = \omega_p - \omega_{12}$, $\Delta_c = \omega_c - \omega_{32}$.

We analytically solve the density matrix equations under the steady-state condition by setting the time derivatives to zero ($d\rho/dt = 0$) and noted that the probe field amplitude is very small compared to the coupling field amplitude, and the level $|3>$ and $|2>$ residences are very small compared to the basic level $|1>$ residence, ρ_{31} expression can be approximated and rewritten:

$$\rho_{31} \approx \frac{1}{2}\frac{i\Omega_c\rho_{21}}{\gamma_{32}-i(\Delta_p-\Delta_c)}. \qquad (5)$$

$$\rho_{21} = \frac{i(\Omega_p/2)(\rho_{11}-\rho_{22})}{\gamma_{21}-i\Delta_1+\dfrac{|\Omega_c|^2/4}{\gamma_{32}-i(\Delta_p-\Delta_c)}}. \qquad (6)$$

We use the law of conservation of density $Tr(\rho)=\rho_{11}+\rho_{22}+\rho_{33}=1$. In addition, we suppose the initial system is at a level $|1>$, therefore, $\rho_{22}\approx\rho_{33}\approx 0, \rho_{11}=1$.

$$\rho_{21} = \frac{i\Omega_p/2}{\gamma_{21}-i\Delta_1+\dfrac{|\Omega_c|^2/4}{\gamma_{32}-i(\Delta_p-\Delta_c)}}. \qquad (7)$$

3. Absorption coefficient

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

$$\chi = -2\frac{Nd_{12}}{\varepsilon_0 E_p}\rho_{12} = \chi' + i\chi'', \qquad (8)$$

here, ρ_{12} is decomposed into real and imaginary parts:

$$\rho_{21} = \frac{(\Omega_p/2)(\gamma_{32}^2\Delta_p+\Delta_p(\Delta_p-\Delta_c)^2-(\Delta_p-\Delta_c)\Omega_c^2/4)}{(\gamma_{21}\gamma_{32}-\Delta_p(\Delta_p-\Delta_c)+\Omega_c^2/4)^2+(\Delta_p\gamma_{32}+(\Delta_p-\Delta_c)\gamma_{21})^2}+$$
$$+i\frac{(\Omega_p/2)\left[-\gamma_{21}\gamma_{32}^2-\gamma_{32}\Omega_c^2/4-(\Delta_p-\Delta_c)^2\gamma_{21}\right]}{(\gamma_{21}\gamma_{32}-\Delta_p(\Delta_p-\Delta_c)+\Omega_c^2/4)^2+(\Delta_p\gamma_{32}+(\Delta_p-\Delta_c)\gamma_{21})^2} \qquad (9)$$

The absorption coefficient α of the medium for the probe beam (between states $|2>$ and $|1>$ for the Λ-configuration in a semiconductor based on the QW) is determined through the real part of the linear susceptibility:

$$\alpha(\omega_p)=\frac{4\pi\omega_p N\hbar\Omega_p^2\left[\gamma_{21}\gamma_{32}^2+\gamma_{32}\Omega_c^2/4+(\Delta_p-\Delta_c)^2\gamma_{21}\right]}{\varepsilon_0 E_p^2 c\left[(\gamma_{21}\gamma_{32}-\Delta_p(\Delta_p-\Delta_c)+\Omega_c^2/4)^2+(\Delta_p\gamma_{32}+(\Delta_p-\Delta_c)\gamma_{21})^2\right]} \qquad (10)$$

From this absorption coefficient expression, we can investigate the influence of pump beam intensity parameters, frequency deviation...

For numerical conculations for the GaAs/InAs/GaAs QW structure, the parameters used in the calculations as follows: μ_{12} = 0.67 nm, μ_{23} = 2.93 nm, γ_{21} = γ_{32} = 10^{10} Hz, n_b = 3.6, the density of three level system N = 3.0 x 10^{21}/m^3, dielectric coefficient ε_0 = 8.86.10^{-12} F/m, $\hbar$ = 1.05 x 10^{-34} $J.s$, ω_{21} = 8.05×10^{14} s^{-1}n, ω_{32} = 1.4×10^{14}s^{-1} and frequency of probe beam ω_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:

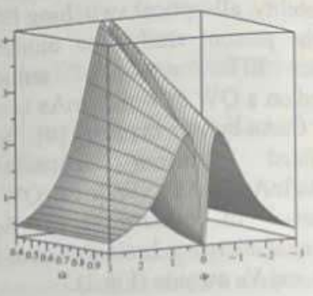


Figure 2. Three-dimensional graph of the absorption coefficient α according to Δ_p and Ω_c with Δ_c= 0 MHz.

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 probe beam decreases at position Δp = 0. When the value of Ω_c increases from 0.36 MHz, the EIT window begins to appear. As the value of A continues to increase, the width and depth of the EIT window increase (Fig. 4). This means that we can control the width and depth of the EIT window through the parameters in the analytical expression of the absorption coefficient $\alpha(\omega_p)$.

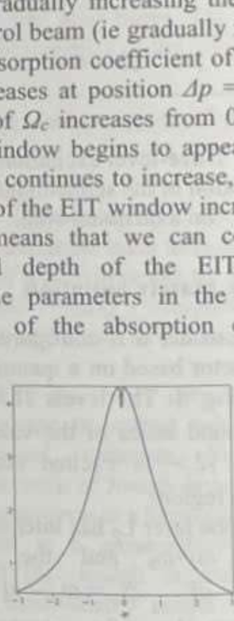
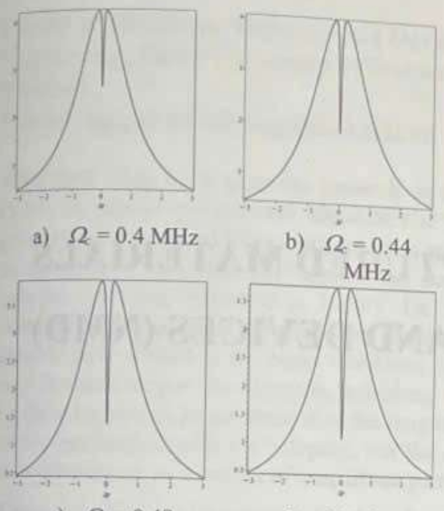


Figure 3. Two-dimensional graph of the absorption coefficient according to Δ_p with Ω_c = 0.36 MHz, Δ_c = 0.

In Fig. 3, due to the large decay rate, when the Ω_c value of about 0.36 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 $|1>$ and $|2>$. When Ω_c is gradually increased then EIT window gradually increases in depth relative to the maximum absorption.



a) $\Omega_c = 0.4$ MHz b) $\Omega_c = 0.44$ MHz

c) $\Omega_c = 0.48$ MHz d) $\Omega_c = 0.52$ MHz

Figure 4. Two-dimensional graph of the absorption coefficient according to $\Delta_p = 0$ with $\Omega_c = 0.4$ MHz (a), $\Omega_c = 0.44$ MHz (b), $\Omega_c = 0.48$ MHz (c), $\Omega_c = 0.52$ MHz (d).

4. Conclusion

Using a semiclassical theoretical model for a semiconductor based on a QW in the Λ-configuration under the simultaneous action of two laser beams (probe beam and coupling beam), we have found analytical solutions for the dispersion coefficient of the system when the probe beam has a small intensity compared to the coupling beam. This is the general analytical expression of the absorption coefficient between two states $|2>$ and $|1>$ for the Λ-configuration for the three-level configuration in semiconductors based on a QW.

From the analytical expressions of the absorption coefficient, we can investigate the influence of different parameters of the QW and characteristic parameters for external laser fields.

We numerically calculate the absorption coefficient in InAs is embedded in a GaAs barrier material in the case of the simultaneous presence of the probe laser and coupling laser. From the research results, we determine the values of Ω_c, Δ_p for the appearance of the EIT effect. The results show that a Λ-configuration appears a transparent window for the probe laser beam. The depth and width or position of this window can be altered by changing the intensity of the coupling laser fields.

However, the survey problem here only stops at considering the three-level case in the Λ-configuration semiconductor QW. Therefore, we recommend applying the results of this topic, expanding to study other effects such as: Kerr nonlinear effect, slowing down the speed of light groups, optical bistable, all-optical switching or considering the three-level case in other configurations in semiconductor quantum wells taking into account other effects.

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