Design and Analysis of Slow Light Device based on Double Quantum Dots Tunneling Induced Transparency

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Abstract- **Slow light Transparency window can be achieved with the help of Electromagnetically Induced Transparency (EIT) method and Tunneling Induced Transparency (TIT) method accompanied by observing tunneling effect between InAs quantum dot structure with energy gap of 0.35ev and a thin layer of GaAs potential barrier with energy gap of 1.42ev. By investigating different parameters such as group velocity and Slow Down Factor (SDF) coefficient at different detuning frequencies, we have obtained an improved design in tunneling and identifying some better conditions. Under TIT condition, the SDF parameter has improved to the amount of 3.2×10⁶.**

Keywords component- **quantum dots, slow light devices, Rabi frequency, detuning parameter, susceptibility**

I. Introduction

Moore's law is said to be out of date by 2022, so technological innovations will shift from electronic devices to optics and Photonics [1]. Therefore, with optimization of logic devices and gates, the issue of Slow light and its applications will be raised. Slow light can also be used in all-optical buffers [4], beam splitter construction, quantum computing, optical storage and quantum telecommunications [5]. In this paper, we will examine the Tunneling Induced Transparency (TIT) method, in which electrons in the conductivity of the Quantum Dot (QD) structure can tunnel through the barrier, thus creating the conditions for the Lambda (Λ) system. We use electron tunneling between quantum structures instead of a control laser, and achieve the Tunneling Induced Transparency method in producing slow light.

In this method, as shown in figure1, by applying an external electric field, the electron energy level in QD is tilted and through this, we can control the detuning parameter ω_{21}. If the ratio of T_e/Γ_1 is less than half, the condition of TIT and if it is more than half, the condition of Autler-Townes splitting (ATS) will be fulfilled.

II. Theory And Performed Researches

The selected quantum structure includes quantum dot. So that the InAs molecules form dot structures and the middle space is covered by GaAs. The fabrication process is based on the Molecular Beam Epitaxy (MBE) method. Reference [9] illustrates the overall structure of this process. The dimensions of the QDs are set to 2nm and 4nm with the height of about 20nanometers. To obtain the value of susceptibility, the density matrix must be used. Due to the triple state of the system, density appeared in 3 by 3 argument, and the required element of density matrix (ρ_{10}), which related to probe laser states or signal laser is given from equation (1):

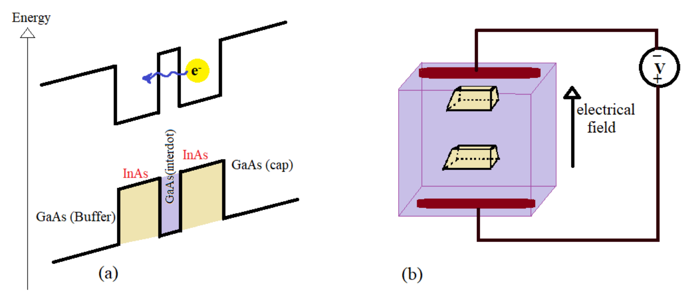

Fig. 1. (a)The direction of the electric force caused by the applied electric field will lead to the energy level of the electric carrier tilt in the quantum structure. (b) The cross-section of our QD structure.

$$\rho_{10} = \frac{(\delta_1+\delta_2)+2j\Gamma_2}{(j\delta_1-\Gamma_1)(j(\delta_1+\delta_2)-2\Gamma_2)+2T_e^2}. \quad (1)$$

Susceptibility is proportional to this component and can be expressed in the form of equation (2):

$$\chi = \frac{\Gamma_{opt}|\mu_{10}|^2}{V\varepsilon_0\hbar\Omega}\rho_{10}. \quad (2)$$

Where Γ_{opt} is the optical confinement parameter that shows the amount of light passing through the waveguide channel relative to the channel environment. Here δ_1 is the detuning parameter and δ_2 also comes from the δ_2=δ_1+2ω_{21} relation. As well as V is the volume of QD from which the electrons want to start tunneling, and ε_0 is the dielectric constant in a vacuum. μ shows the transition element from $|0\rangle$ to $|1\rangle$[8]. Naturally, the higher the tunneling strength, the wider the transparency window in the frequency range. In the following, we calculate the ratio of the speed of light (C) to the group velocity (V_g) when $\delta_1$and ω_{21} are symmetrical and plot it in figure2. The reason for examining this ratio at such a point is that Re[χ] has the highest slope and also has the largest C/V_g ratio at the vicinity of this point.

III. Parameter Optimization

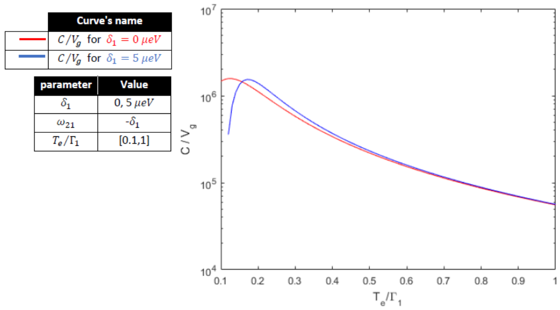

Fig. 2. Group speed Miniaturization up to 6 order of magnitude compared to normal light speed in logarithmic diagram.

To find the maximum SDF from the three variables δ_1, ω_{21} and T_e/Γ_1, we first consider two parameters as constant and draw the graph according to the third variable. In figure3, we have considered the parameter δ_1 as variable. Before calculating, it should be mentioned that the value of SDF in the reference [3] was equal to 1.5×10^6. In our simulation results, we have estimated up to doubled value of this parameter and improved it to 3.2×10^6. When δ_1 is variable, the maximum of graph occurs at point (ω_{21}=-3×10^{-7}, SDF =2.26×10^5). In order to better observation of the relation between 3 variables and better investigation, several 3-Dimensional (3D) diagrams are drawn in figures 4 and 5 each of which has two variable parameters and one fixed parameter. The parameters T_e/Γ_1 and δ_1 are fixed in these figures, respectively. As shown in the density diagram of figure4, the brighter points are seen around the line $\delta_1+\omega_{21}=0$. In figure4, the maximum occurs at the $\omega_{21}=-\delta_1=2\times10^{-5}$ and the value of SDF at this peak is equal to 3.2×10^6. In figure5, the maximum SDF stands at the vertices $\omega_{21}=-4\times10^{-8}$, $T_e/\Gamma_1=0.1$ and the value of SDF at this peak is equal to 3.2×10^6.

IV. CONCLUSION

In this paper, we've investigated the maximum SDF value by changing the available parameters such as T_e, which depends on the tunneling power of electrons in the TIT method for the GaAs/InAs device and the quantum dot structure. The value of T_e should be chosen around $0.1\Gamma_1$ and symmetric on δ_1 and ω_{21}. Therefore, by performing the necessary simulations, we will be able to reach 3.2×10^6 for the slow down factor which will increase by about one hundred percent compared to the work done in reference 3.

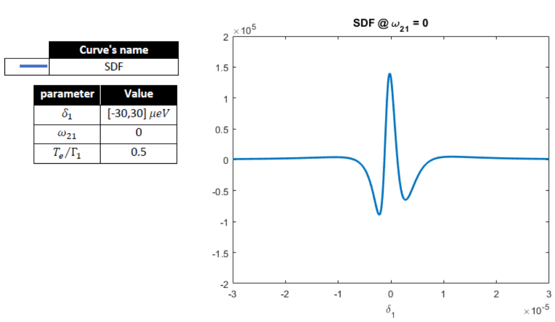

Fig. 3. SDF at ω_{21}=0 and T_e =Γ_1/2.

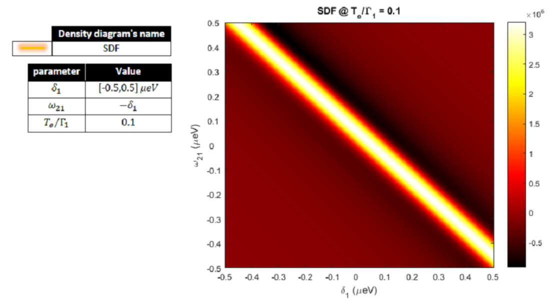

Fig. 4. SDF at T_e=Γ_1/10.

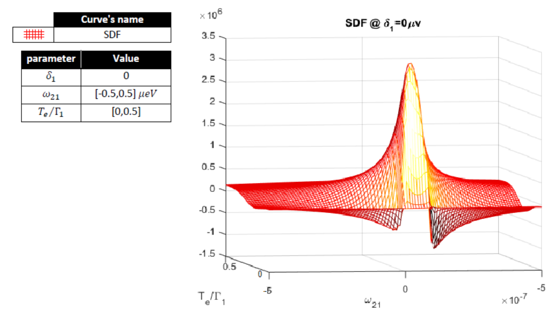

Fig. 5. SDF at δ_1=0.

V. REFERENCES

[1] Mike Fritze, Patrick Cheetham, Jennifer Lato, and Paul Syers. The Death of Moore's Law.

[2] Bahram Choupanzadeh, Hassan Kaatuzian. Performance Improvement of Quantum Dots Slowlight Devices Based on Tunneling Induced Transparency Method. 2017 25th Iranian Conference on Electrical Engineering (ICEE).

[3] H.S. Borges, L. Sanz, J.M. Villas-Boas, O.O. Diniz Neto and A.M. Alcalde. Tunneling induced transparency and slow light in quantum dot molecules. PHYSICAL REVIEW B 85, 115425 (2012).

[4] C. J. Chang-Hasnain, P. C. Ku, J. Kim, and S. L. Chuang, "Variable optical buffer using slow light in semiconductor nanostructures," Proc. IEEE 91, 1884 (2003).

[5] S. E. Harris, "Electromagnetically induced transparency," Phys. Today 50, 36 (1997).

[6] Z. Ficek and S. Swain, "Quantum interference in optical fields and atomic radiation," J. Mod. Opt. 49, 3 (2002).

[7] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, "Electromagnetically induced transparency: Optics in coherent media," Rev. Mod. Phys. 77, 633 (2005).

[8] Chunchao Yu, Hai Huang, Liang Zhang, Dahai Xu. Double Tunneling Induced Transparency in The Asymmetry Quantum Dot Molecules. Optica Applicata, Vol. Xlvi, No. 3, 2016.

[9] A. S. Bracker, M. Scheibner, M. F. Doty, E. A. Stinaff, I. V. Ponomarev, J. C. Kim, L. J. Whitman, T. L. Reinecke, and D. Gammon. "Engineering electron and hole tunneling with asymmetric InAs quantum dot molecules". Naval Research Laboratory, Washington, DC 20375.