Optical Response of a Strongly Driven Asymmetric Quantum Dot Molecule

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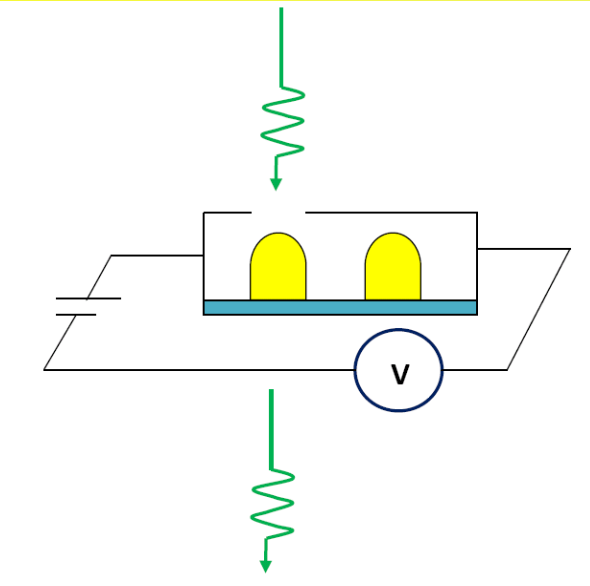
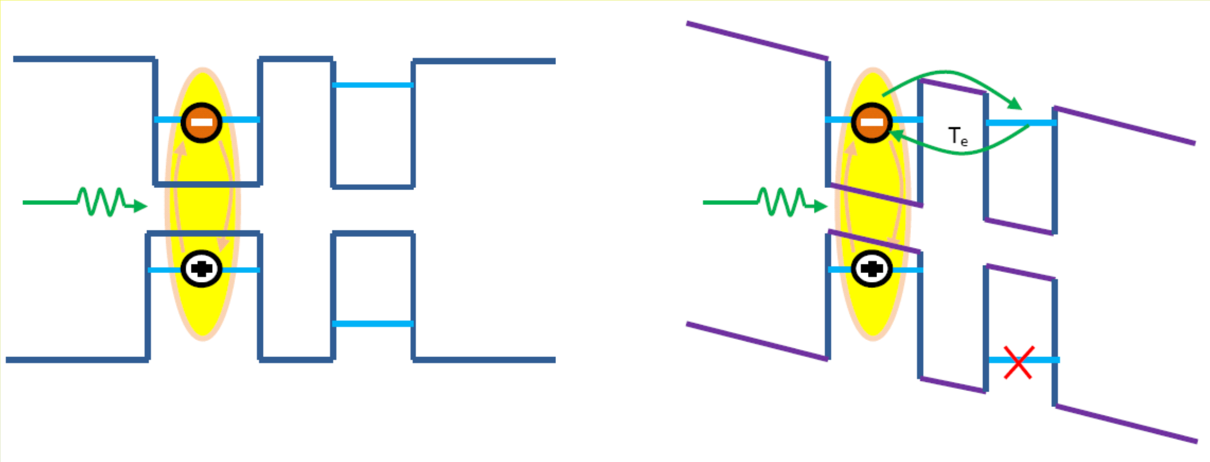
Optical Properties of an Asymmetric Quantum Dot Molecule

- The optical properties of an asymmetric double semiconductor quantum dot molecule that interacts with electromagnetic fields have attracted some attention in recent years.
- Particular interest has been given to controlled absorption and dispersion of an electromagnetic field that interacts with the quantum dot molecule, where phenomena such as tunneling induced transparency [1,2], slow light [1,2] and transient gain without inversion [3] have been identified.
- These phenomena have also been proposed for various applications in optoelectronics and quantum information processing in asymmetric double quantum dot molecules that are coupled with optical cavities or plasmonic circuits.

1. C.-H. Yuan and K.-D. Zhu, Appl. Phys. Lett. 89, 052115 (2006).
2. H. S. Borges, L. Sanz, J.-M. Villas-Boas, O. O. Diniz Neto, and A. M. Alcalde, Phys. Rev. B 85, 115425 (2012).
3. M. Ioannou, J. Boviatsis, and E. Paspalakis, Physica E 40, 2010 (2008).

Asymmetric Quantum Dot Molecule





Upper: Schematic of the setup. An electromagnetic field drives strongly the left quantum dot. V is a bias voltage.

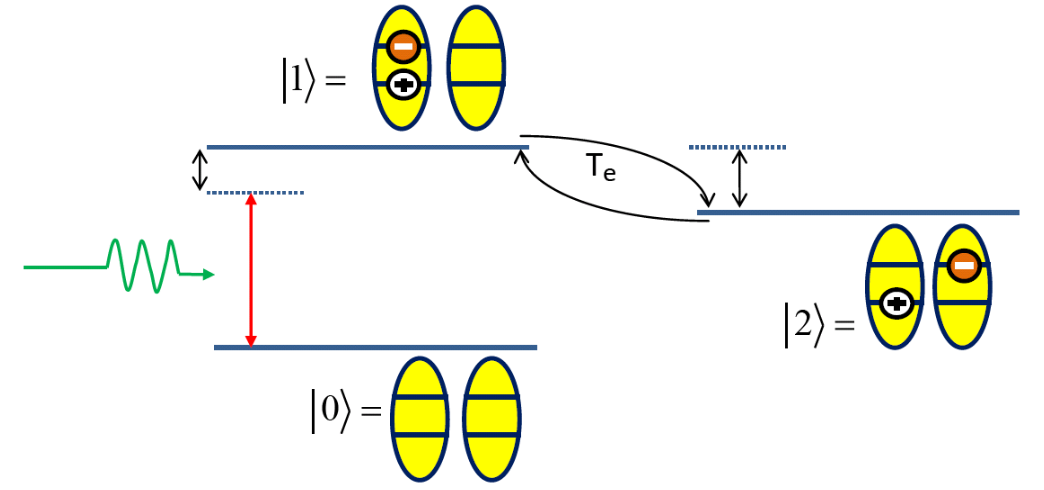
Upper: Schematic of the band structure. Left: without a gate voltage, electron tunneling is weak. Right: with applied gate voltage, conduction band levels get into resonance, increasing their coupling, while valence-band levels become even more off-resonance, resulting in effective decoupling of those levels.

Effects Presented in this Talk

- Here, we consider an asymmetric double semiconductor quantum dot molecule that interacts simultaneously with a weak probe field and a strong pump field.
- For the theoretical analysis of the optical properties of the system under pump and probe excitation we use a density matrix approach where we assume that the pump field is strong and should be treated to all the orders, while the probe field is weak and should be treated to first order [1].
- We present results for different electron tunneling coupling coefficients, and different values of frequency and intensity of the pump field.
- We show that the absorption and dispersion of the probe field can be controlled by the gate voltage and the pump field. For example, we find that the application of the pump field leads to controlled probe absorption and gain for weak tunneling rates, while for stronger tunneling rates optical gain disappears.

1. S. G. Kosionis, A. F. Terzis, and E. Paspalakis, Appl. Phys. B 104, 33 (2011).

Theoretical Model (1)



Left: Schematic level configuration of the double quantum dot system [1]. T_e is the electron tunneling coupling coefficient between the two quantum dots.

$$H = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1| + E_2|2\rangle\langle 2| + \frac{\hbar\Omega_a}{2}\left(e^{-i\omega_\alpha t}|1\rangle\langle 0| + e^{i\omega_\alpha t}|0\rangle\langle 1|\right)$$

$$+\frac{\hbar\Omega_b}{2}\left(e^{-i\omega_b t}|1\rangle\langle 0| + e^{i\omega_b t}|0\rangle\langle 1|\right) + \hbar T_e\left(|1\rangle\langle 2| + |2\rangle\langle 1|\right).$$

E_n is the energy of state $|n>$, $n = 0,1,2$.

$\Omega_a = -\mu E_a/\hbar$ is Rabi frequency of the pump field.

$\Omega_b = -\mu E_b/\hbar$ is Rabi frequency of the probe field.

1. J. M. Villas-Boas, A. O. Govorov, and S. E. Ulloa, Phys. Rev. B 69, 125342 (2004).

Theoretical Model (2)

• We use a density matrix approach including decay and dephasing effects. We take that the Rabi frequency of the pump field is much larger than the Rabi frequency of the probe field, i.e. $\Omega_a \gg \Omega_b$.

• We proceed to the expansion of the density matrix elements, according to the first order approximation to the probe field

$$\rho_{nm} = \rho_{nm}^{(0)} + \rho_{nm}^{(+)} e^{i\delta t} + \rho_{nm}^{(-)} e^{-i\delta t}$$

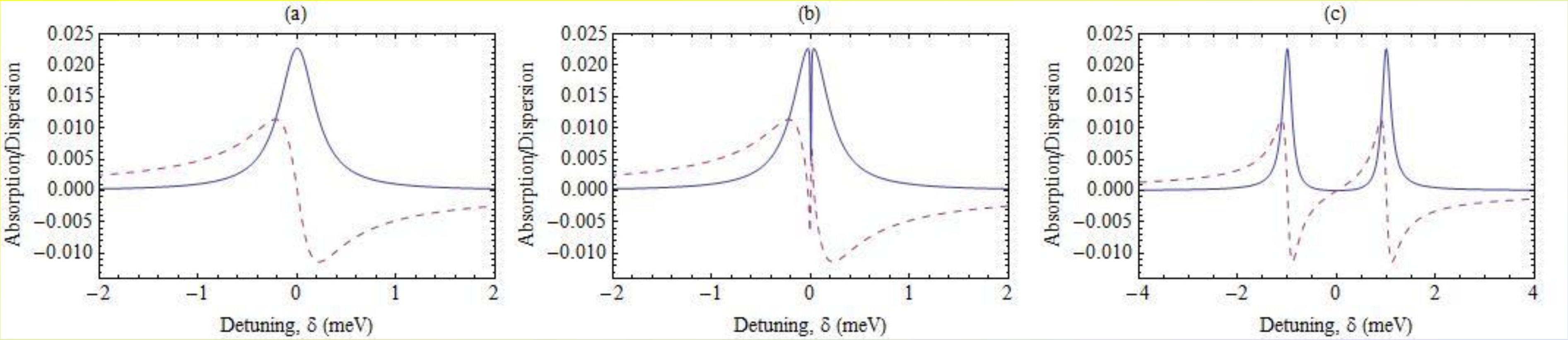
with $|\rho_{nm}^{(0)}| >> |\rho_{nm}^{(+)}|, |\rho_{nm}^{(-)}|$ and obtain the differential equations for the various density matrix elements. Here, δ is the detuning between the two applied fields: $\delta = \omega_b - \omega_a$.

• The absorption and dispersion properties of the probe field in first order, under the presence of a strong pump field, are determined, respectively, by the imaginary and real parts of the density matrix element $\rho_{01}^{(+)}$.

• Additional basic parameters: $\omega_{12} = (E_1 - E_2)/\hbar$.

Detuning of the pump field from resonance: $\Delta = (E_1 - E_0)/\hbar - \omega_a$.

No Pump Field – Effects of Electron Tunneling



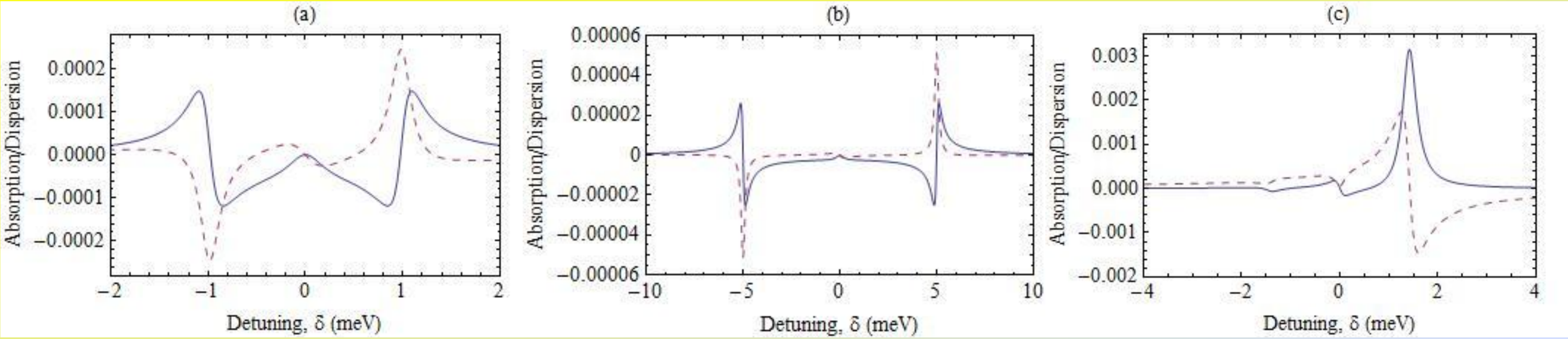
The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, with no pump field (Rabi frequency of the pump field $\Omega_a = 0$) and (a) no tunneling ($T_e = 0$), (b) very weak tunneling ($\hbar T_e = 0.03$ meV) and (c) stronger tunneling ($\hbar T_e = 1$ meV). In (b) and (c) $\omega_{12} = 0$.

Here and in all other figures typical values for InAs/GaAs quantum dots are used in the calculations [1].

- In (a) a typical Lorentzian absorption spectrum is observed. Also a typical dispersion spectrum is obtained.
- In (b) and (c) tunneling induced transparency [1,2] occurs at $\delta = 0$. In this case the absorption peaks are separated by $2T_e$.

1. H. S. Borges, L. Sanz, J.-M. Villas-Boas, O. O. Diniz Neto, and A. M. Alcalde, Phys. Rev. B 85, 115425 (2012).
2. C.-H. Yuan and K.-D. Zhu, Appl. Phys. Lett. 89, 052115 (2006) .

No Electron Tunneling – Effects of Pump Field

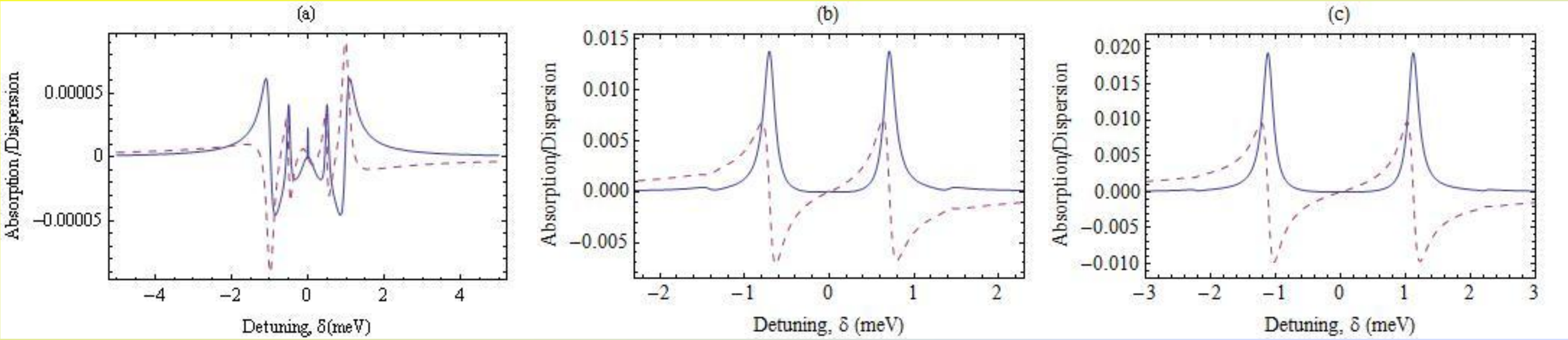


The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, with no electron tunneling (T_e = 0, which is similar to a single strongly-driven quantum dot system [1]) under the influence of the pump field. In (a) $\hbar\Omega_a$ = 1 meV, Δ = 0, (b) $\hbar\Omega_a$ = 5 meV, Δ = 0 and (c) $\hbar\Omega_a$ = 1 meV, $\hbar\Delta$ = 1 meV.

- In (a) and (b) typical Mollow-type absorption/dispersion spectra [1,2] are observed. The absorption is zero at δ = -Ω_a , 0, Ω_a . Between -Ω_a and Ω_a optical gain is obtained. At $\delta = \Omega_a$ the maximum dispersion is obtained that leads to enhanced index of refraction without absorption [3].
- For the off-resonance driving case strongly asymmetric spectra occurs, with strong enhancement for positive δ, as Δ is taken positive.

1. X.-D. Xu *et al*., Phys. Rev. Lett. 101, 227401 (2008).
2. B. R. Mollow, Phys. Rev. A 5, 1522 (1972); *ibid* 5, 2217 (1972).
3. M. Fleischhauer *et al*., Phys. Rev. A 46, 1468 (1992).

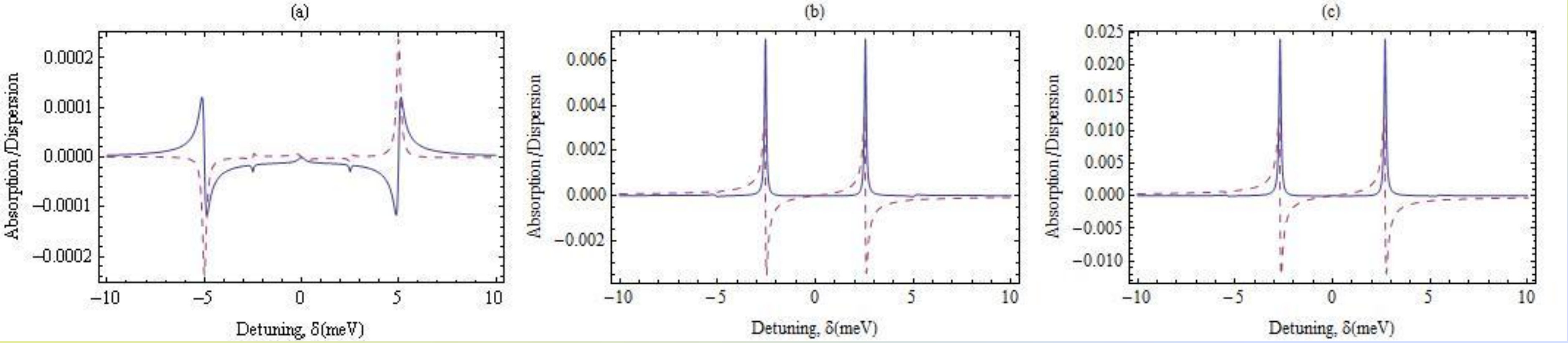
Combined Electron Tunneling and Pump Field Effects



The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\omega_{12} = 0$, $\hbar\Omega_a = 1$ meV, $\Delta = 0$. In (a) $\hbar T_e = 0.03$ meV, (b) $\hbar T_e = 0.5$ meV and (c) $\hbar T_e = 1$ meV.

- In (a) that is for very weak tunneling a significant structure is created in the region of δ between -Ω_a and Ω_a. This structure shows both gain and absorption, with specific zeroes in absorption as well. In addition, a pronounced absorption peak is created at $\delta = 0$.
- For larger values of the tunneling coupling coefficient, as can be seen in (b) and (c), the structure between the two strong absorption peaks essentially dissapears and strong suppression of absorption occurs in this region. The suppression of absorption also becomes more pronounced and the gain essentially dissappers, as the tunneling becomes stronger.

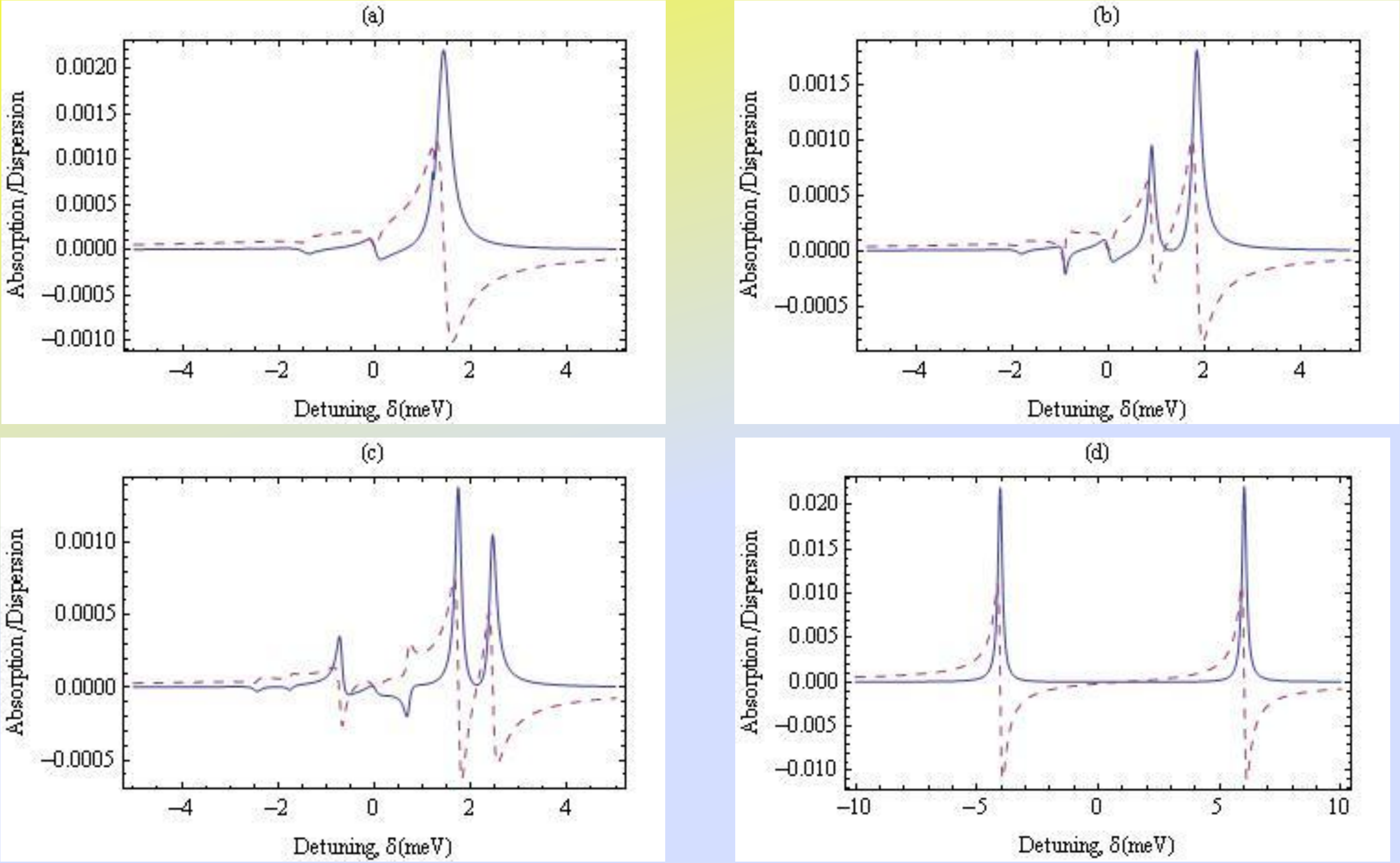
Combined Electron Tunneling and Pump Field Effects – Stronger Pump Field



The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\omega_{12} = 0$, $\hbar\Omega_a = 5$ meV, $\Delta = 0$. In (a) $\hbar T_e = 0.03$ meV, (b) $\hbar T_e = 0.5$ meV and (c) $\hbar T_e = 1$ meV.

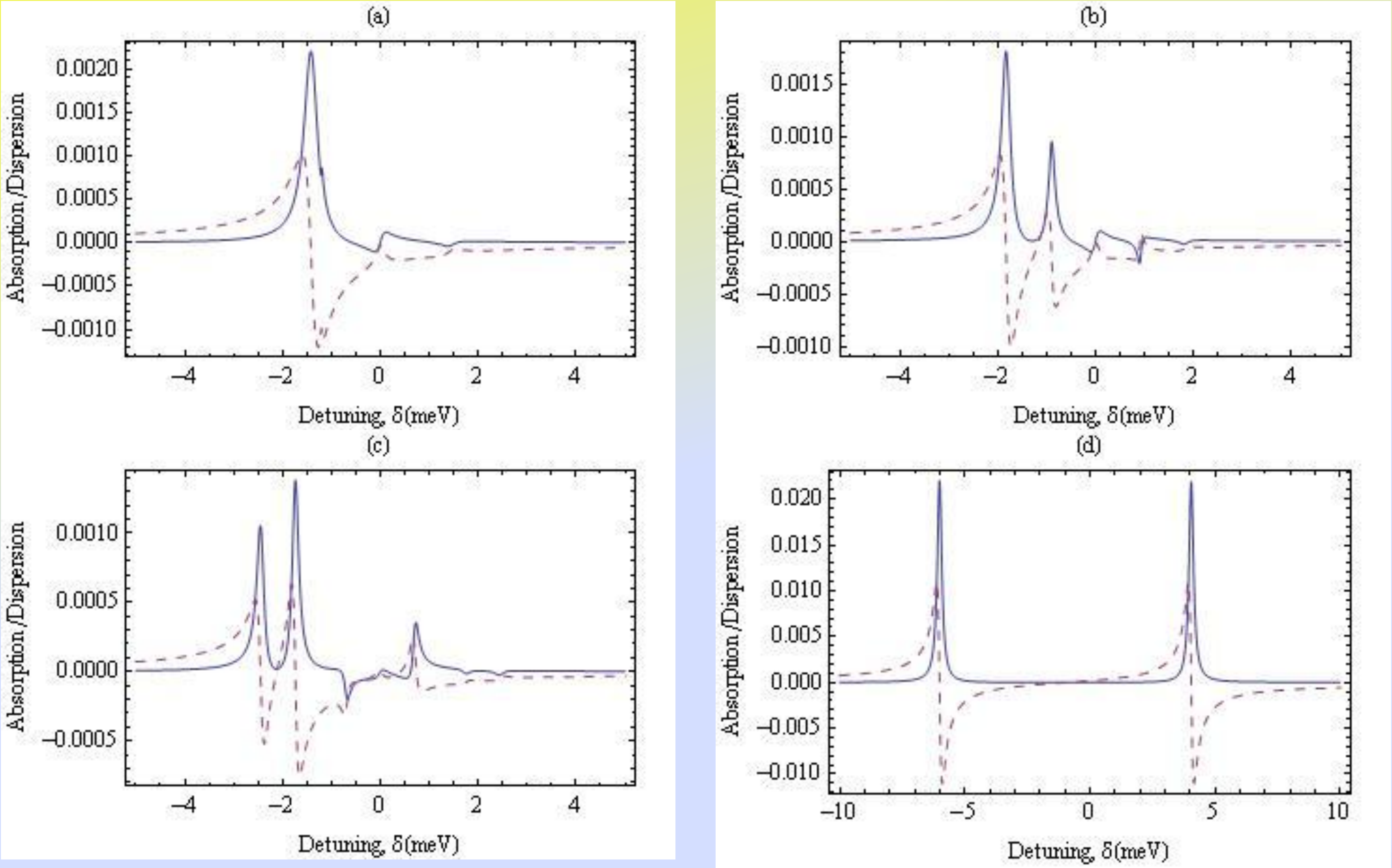
- In (a) that is for very weak tunneling Mollow-type absorption/dispersion spectra are obtained with very weak structure of δ between $-\Omega_a$ and Ω_a. Also, the pronounced absorption peak at $\delta = 0$ disappears.
- For larger values of the tunneling coupling coefficient, as can be seen in (b) and (c), there are two strong absorption peaks and plateau of essentially zero absorption (transparency) between these peaks. The position of the two absorption peaks in this case is given by $\pm\sqrt{4T_e^2 + \Omega_a^2}/2$.

Combined Electron Tunneling and Pump Field Effects – Detuned Pump Field



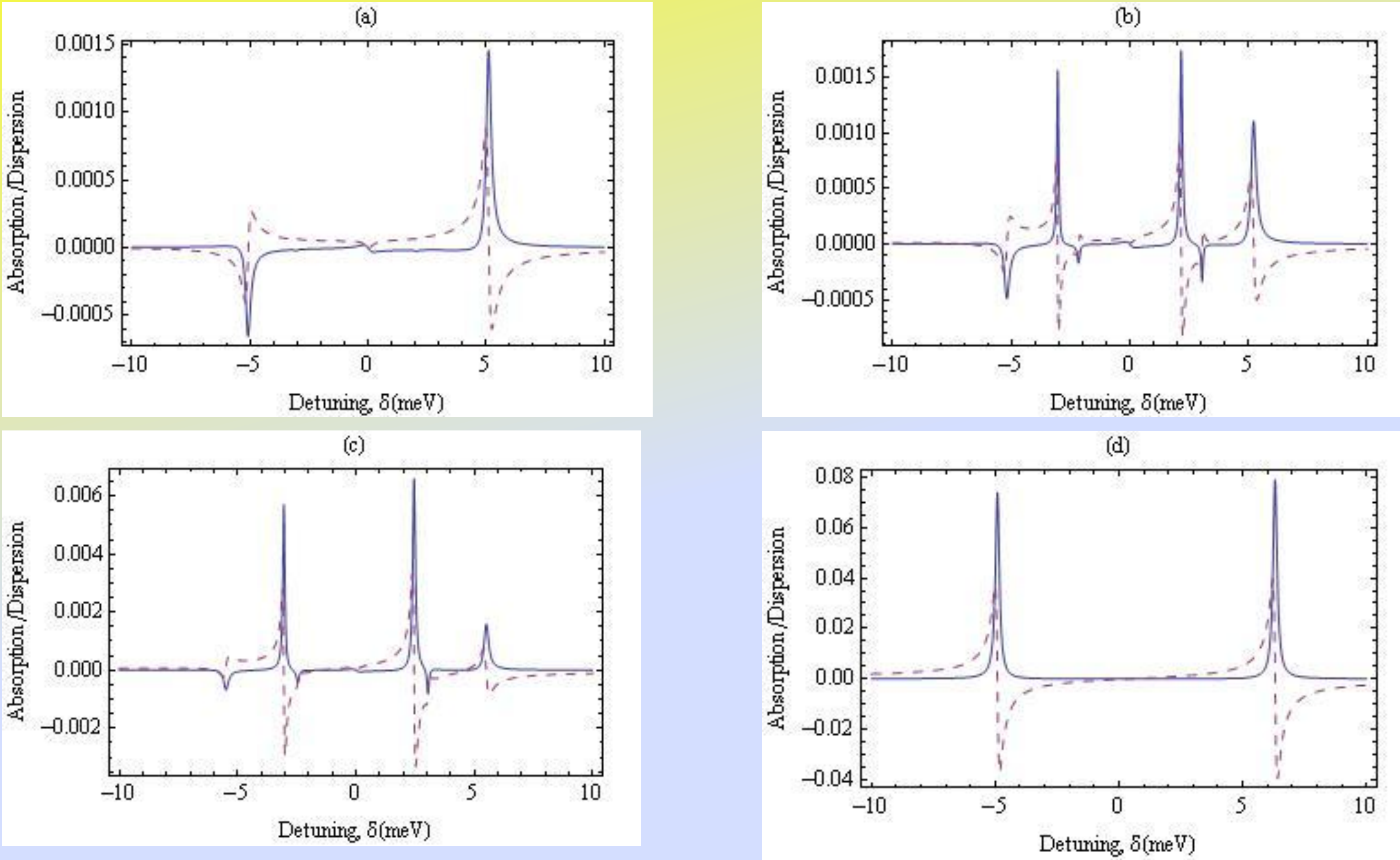
The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\omega_{12} = 0$, $\hbar\Omega_a = 1$ meV, $\hbar\Delta = 1$ meV. In (a) $\hbar T_e = 0.03$ meV, (b) $\hbar T_e = 0.5$ meV, (c) $\hbar T_e = 1$ meV and (d) $\hbar T_e = 5$ meV.

Combined Electron Tunneling and Pump Field Effects – Detuned Pump Field with Negative Detuning



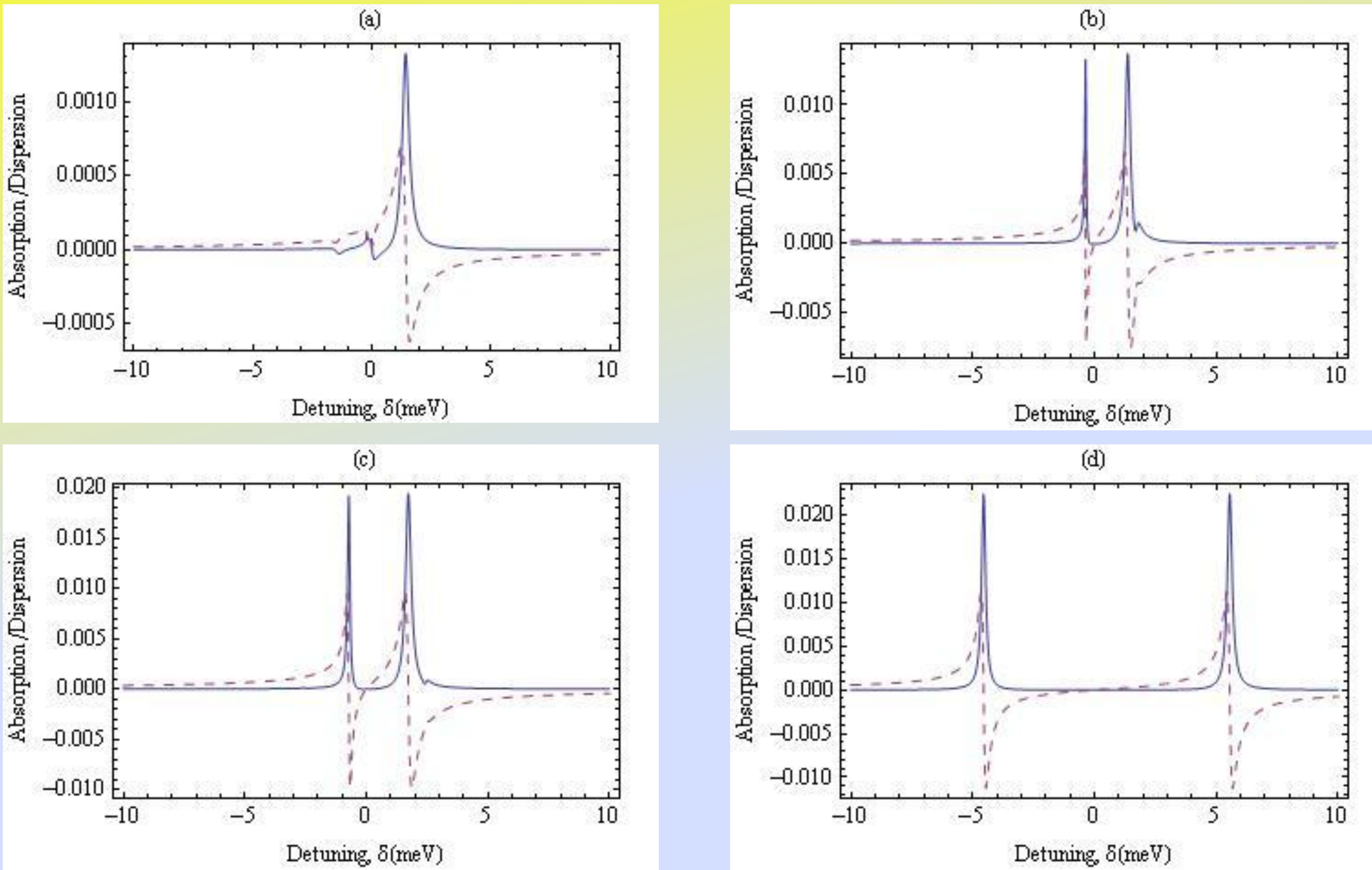
The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\omega_{12} = 0$, $\hbar\Omega_a = 1$ meV, $\hbar\Delta = -1$ meV. In (a) $\hbar T_e = 0.03$ meV, (b) $\hbar T_e = 0.5$ meV, (c) $\hbar T_e = 1$ meV and (d) $\hbar T_e = 5$ meV.

Combined Electron Tunneling and Pump Field Effects – Stronger and Detuned Pump Field



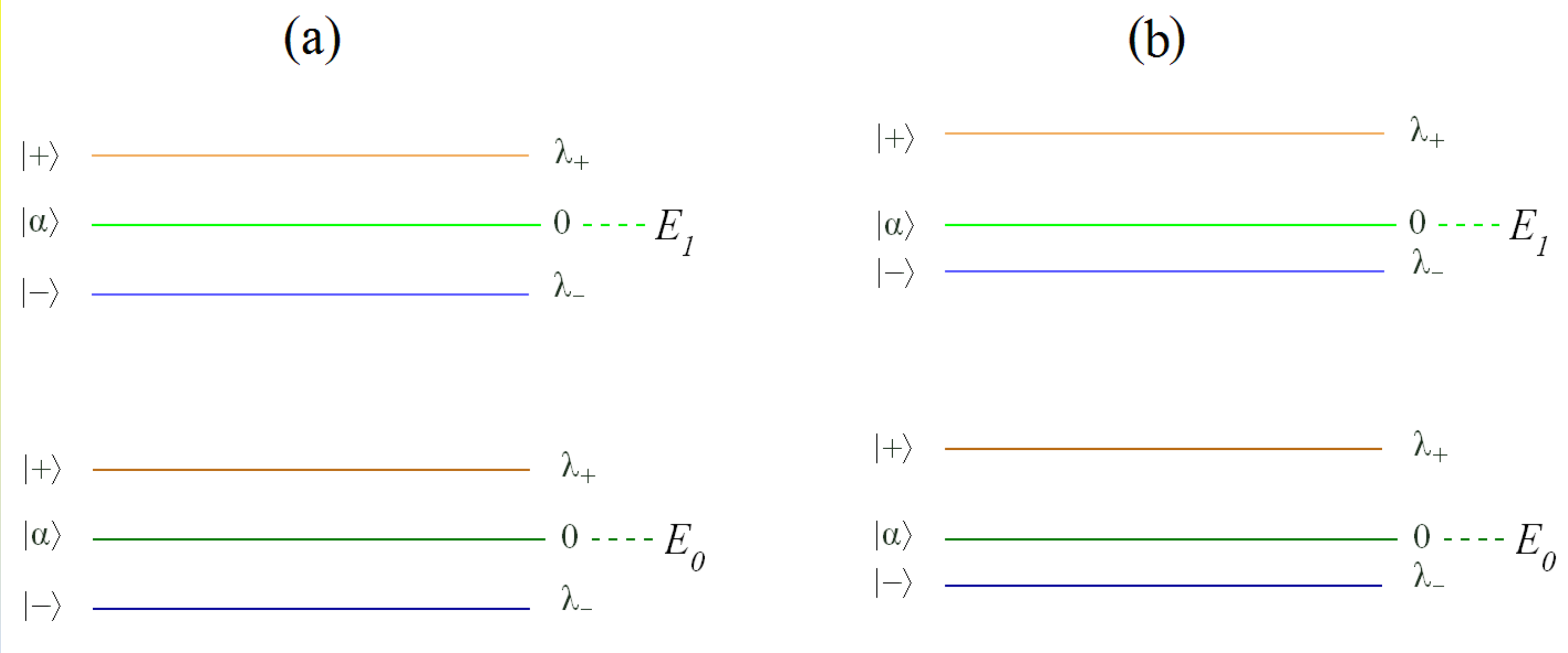
The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\omega_{12} = 0$, $\hbar\Omega_a = 5$ meV, $\hbar\Delta = 1$ meV. In (a) $\hbar T_e = 0.03$ meV, (b) $\hbar T_e = 0.5$ meV, (c) $\hbar T_e = 1$ meV and (d) $\hbar T_e = 5$ meV.

Combined Electron Tunneling and Pump Field Effects – Detuned Pump Field with $\Delta = \omega_{12} \neq 0$



The absorption (solid curve) and the dispersion (dashed curve) spectrum, in arbitrary units, for $\hbar\omega_{12}$ = 1 meV, $\hbar\Omega_a$ = 1 meV, $\hbar\Delta$ = 1 meV. In (a) $\hbar T_e$ = 0.03 meV, (b) $\hbar T_e$ = 0.5 meV, (c) $\hbar T_e$ = 1 meV and (d) $\hbar T_e$ = 5 meV.

Explanation for Stronger Tunneling Coupling Coefficients with Dressed States



In the presence of the strong pump field, the lower and upper levels split into doublets. Here, we present the possible excitation pathways that may be followed. Capture (a) refers to the case where $\omega_{12} = \Delta = 0$, while (b) corresponds to the case where $\omega_{12} = \Delta \neq 0$, where the distance of the energy levels presented above and below the initial energy level is no longer equal to each other.

Summary

- We considered an asymmetric double semiconductor quantum dot molecule that interacts with a weak probe field and a strong pump field. The nanostructure consists of two quantum dots with different band structures controlled by a gate voltage.
- We have shown that the optical response of the system can be controlled by the gate voltage that leads to tunneling and the pump field electric field amplitude and frequency.
- We have found that the application of the pump field leads to various forms of the absorption and dispersion spectra for very weak tunneling coupling coefficient, exhibiting, for example, both absorption and gain for the absorption spectrum.
- For stronger tunneling coupling coefficients optical gain disappears and two strong absorption peaks appear, for certain values of the pump-probe field detuning.

Acknowledgements

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