Slow light and voltage control of group velocity in resonantly coupled quantum wells

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Abstract: We analyze slow light propagation in a coupled semiconductor quantum wells system exhibiting tunneling induced transparency. A group index as high as 85, for simple applicable GaAs/AlGaAs quantum wells structures, is predicted. Using DC voltage, the resonant tunneling rate can be altered and the related group index can be controlled over a broad range.

OCIS codes: (999.9999) Slow light; (270.1670) Coherent optical effects; (230.1150) All-optical devices;

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1. Introduction

In recent years intense research effort was exerted towards the realization of controllable slow light propagation [1]. Any medium or device exhibiting steep chromatic dispersion may lead to significant light slowing. Consequently, variety of implementations were proposed – both theoretically and experimentally including quantum interference phenomena – the most prominent is the Electromagnetically Induced Transparency (EIT) [2], nonlinear phenomena in optical fibers [3], nonlinear phenomena in semiconductors[4], linear dispersive waveguides, microcavities[5] and photonic crystals [6] exploiting near band edge dispersion. The atomic EIT exhibits the record low group velocity - 8 m/sec [7], however for realizable technology, providing chip-scale slow-light devices, different EIT related schemes in solids were proposed and demonstrated [8,9,10].

The generic EIT system is doubly driven and controlled by external electromagnetic fields. The slow light control (as well as the transparency window) is accomplished by changing the amplitude of the pump electromagnetic field [2]. In order to realize an autonomous system that reduces the group velocity of a primary light field without a pump one, we employ here an alternative coupling mechanism to replace the pump light field. This scheme, namely tunneling induced transparency was previously proposed by Imamoglu group in relations to implementation of inversionless lasers and Fano interference [11]. It is based on two resonant quantum wells exhibiting a periodic Rabi oscillation of the electron due to the resonant tunneling effect – thus can serve as the 'second' arm in the V or Λ configurations of the EIT scheme. It should be emphasized that the tunneling scheme is not a time varying perturbation (such as the pump field) but a stationary ingredient of the quantum structure.

We propose and analyze the exploitation of the tunneling configuration for slow light generation and the application of a DC voltage to control the group velocity magnitude - a scheme that is favorable for implementation in semiconductor materials. Tunneling control by voltage is a phenomenon exploited in devices such as resonant tunneling diodes [12] - but here, it is proposed for a very efficient and simple control of the group propagation velocities of slow light. Reports on slow light in solid state media (by coherent population trapping or by unique nonlinearities [13]) all required a second electromagnetic field and thus are substantially different from our proposed scheme.

2. Anomalous dispersion of double quantum well configuration

The tunneling induced transparency system proposed for inversionless lasers in Ref. [14] is comprised of two different quantum wells – one supporting two energy states and the second a single state, resonant with the excited state of the first well. For many material systems, the well supporting the one state must be very narrow, thus is usually inapplicable in a realizable practical scheme. In our case we used two identical coupled quantum wells [Fig. 1(a)], each one is supporting two quantum states, ground $|1\rangle$, $|3\rangle$ and exited $|2\rangle$, $|4\rangle$. The potential wells are designed such that under zero applied voltage – state $|2\rangle$ ($|1\rangle$) is resonant (equal-energy) with state $|4\rangle$ ($|3\rangle$). We exploited the much larger localization of the ground state, such that the inter-well coupling efficiency of the excited states is dominant and the ground states coupling can be ignored (the ratio of the coupling constants is about an order of magnitude). Thus the four (effectively three) levels scheme of the EIT is achieved in a simple, established structure of identical coupled wells. We denote the coupling coefficients by α's and depict the in-plane wave functions in Fig. 1(b). We assume that the incident light polarization is in the direction of the epitaxial growth, enabling only the intraband transitions. Note that we used the intraband electronic transitions only as the most basic demonstration of the concept, while similar results in the visible – near IR regime, using interband transitions will be detailed in a forthcoming publication [15].

We employ here the density matrix formalism [16], for a system described by a Hamiltonian expressed by the eigen functions of the separated wells. This different approach for solving this quantum system is more transparent to the similarity between the tunneling and external field.

$$H_0 = \hbar \begin{pmatrix} \omega_1 & 0 & 0 & 0 \\ 0 & \omega_2 & 0 & 0 \\ 0 & 0 & \omega_3 & 0 \\ 0 & 0 & 0 & \omega_4 \end{pmatrix} \qquad V_{pert} = \begin{pmatrix} 0 & -\mu_{12}E & 0 & 0 \\ -\mu_{12}^* E^* & 0 & \alpha & 0 \\ 0 & \alpha^* & 0 & -\mu_{43}E \\ 0 & 0 & -\mu_{43}^* E & 0 \end{pmatrix} \tag{1}$$

where $\hbar\omega_i$ is the self energy of the i-th QW level, μ_{ij} is the dipole moment of the i-j transition, E is light field and α_1, α_2 are the tunneling constants, depicted on Fig. 1(a) and discussed further.

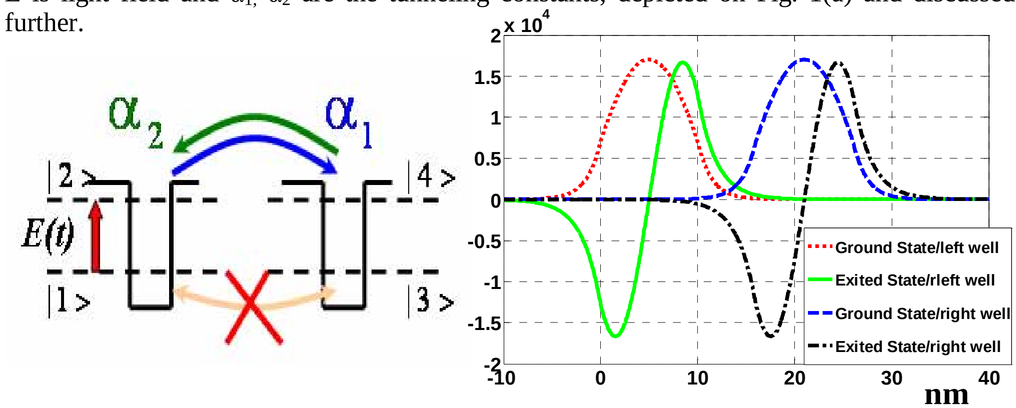

Fig. 1. The coupled quantum wells configuration (a) Energy-level diagram. (b) In plane electronic wave functions

The total Hamiltonian of the system ($H=H_0+V_{pert}$) is generally asymmetrical due to our selection of nonorthogonal basis set. This small asymmetry comes into effect when applying voltage for tilting the potential wells as explained in the next section. We assume that the perturbation is small enough; hence, any bound electron wave function may be written in this basis, additionally, we neglect the excitonic effects [17] and Colomb interactions [18], which are of significance only in final engineering optimization without changing the basic physical phenomena.

Applying the rotating-wave and electric-dipole approximations and phenomenology introducing the dephasing rates (γ's) we obtain for the slowly varying density matrix [1]:

$$\begin{pmatrix} i(\omega-\omega_{21})-\gamma_{21} & -i\alpha_2/\hbar & 0 & 0 \\ -i\alpha_1/\hbar & i(\omega-\omega_{41})-\gamma_{41} & 0 & 0 \\ 0 & 0 & i(\omega-\omega_{23})-\gamma_{23} & -i\alpha_2/\hbar \\ 0 & 0 & -i\alpha_1/\hbar & i(\omega-\omega_{43})-\gamma_{43} \end{pmatrix} \times \begin{pmatrix} \sigma_{12} \\ \sigma_{14} \\ \sigma_{32} \\ \sigma_{34} \end{pmatrix} = -\frac{i}{\hbar} \begin{pmatrix} \mu_{12}E(\rho_{11}-\rho_{22}) \\ 0 \\ 0 \\ \mu_{34}E(\rho_{33}-\rho_{44}) \end{pmatrix} \tag{2}$$

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Solving Eq. (2) easily may be obtained, that the four level system decouples to the pair of inverse λ tunneling-EIT schemes. For the harmonic solution, we get the complex material susceptibility:

$$\chi = \chi_{bac} - iN\left(\frac{|\mu_{12}|^2(\rho_{11}-\rho_{22})}{\hbar}\frac{1}{\frac{\alpha_1\alpha_2}{\hbar^2\left(i(\omega-\omega_{41})-\gamma_{41}\right)}+i(\omega-\omega_{21})-\gamma_{21}} + \frac{|\mu_{34}|^2(\rho_{44}-\rho_{33})}{\hbar}\frac{1}{\frac{\alpha_1\alpha_2}{\hbar^2\left(i(\omega-\omega_{23})-\gamma_{23}\right)}+i(\omega-\omega_{43})-\gamma_{43}} \right) \quad (3)$$

where $\omega_{ij}=\omega_i-\omega_j$, ω is the central frequency of the input light, ρ_{ii} is the electron occupation density of the i-th level, later would be assuming to reduce to the ground states and N is the number of the ground state electrons and χ_{bac} is the susceptibility of the background material. The tunneling related constants are defined by the perturbation theory formula and the well known α_1=<2| left well perturbation|4>, α_2=<4|right well perturbation|2> [19]. The complex permeability is shown in Fig. 2(a) for an actual semiconductor heterostructre (detailed in section III) along with the calculated group velocity index defined by:

$$n_{group}(\omega_s) = n_r(\omega_s) + \omega_s\left(\frac{dn_r}{d\omega}\right)_{\omega=\omega_s} \qquad v_{group} = \frac{c}{n_{group}} \quad (4)$$

These results replicate the outcome of conventional EIT configuration. The excited states coupling to the resonant neighboring well – splits the upper level, thus opening a transmission window which is characterized by a substantially large group index.

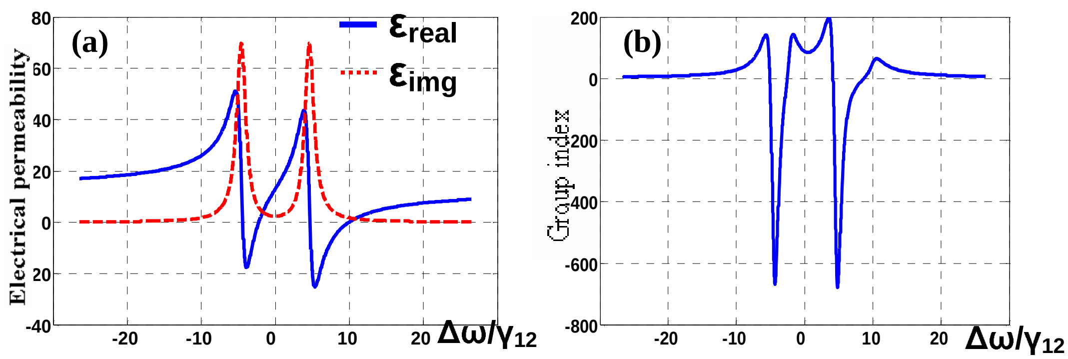

Fig. 2. The permeability (0 bias voltage) (a) Dispersion curve (b) Group index

3. Results for GaAs–$Al_{0.3}Ga_{0.7}As$ coupled wells

We explored a well known heterostructure GaAs–$Al_{0.3}Ga_{0.7}As$ as a simple example to demonstrate a medium exhibiting significant light slowing. Many other variants of material families and coupled structures exhibit the same phenomena and can be optimally engineered for applicable devices. The parameters were taken from experimental data in Ref. [19]: well depth - ΔEc = 230meV, width 10nm, barrier width 6nm, effective masses – $m_a = 0.067m_0$ and $m_b = 0.097m_0$, the volume density of charge $3\cdot10^{23}m^{-3}$. Dephasing rates of the dipolar transitions were chosen to be $\gamma_{12} = \gamma_{34} = 10^{12}$ rad/sec and $2\cdot\gamma_{14} = 2\cdot\gamma_{23} = \gamma_{12}$ [20]. χ_{bac} is the average between the constituents and its value is ~13 and it should be noted that it is significantly different compared to atomic EIT, where the background susceptibility is 1 – due to the differences in the media density. This results in the asymmetry of the group index curve [Fig. 2(b)], which is absent in atomic vapor EIT.

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When applying a field on the system the very well known tilting of the heterostructure band diagram [19] occurs. While explicit analytical solutions for infinite triangular well are the Airy functions [19]; the tilted finite quantum well wave function solutions are much more complex. We treated the applied DC field in terms of a first order perturbation theory to find corrections for energy levels and electron wave functions. The validity of the perturbative approach is manifested in Fig. 3 – exhibiting the results of numerical calculations of the specific system under study. Both the small energy shift and especially the very small modification of the wavefunctions validate the first order perturbation calculation.

Figures 4-5 depict the real and imaginary parts of permeability for two levels of a DC applied field, along with the derived group velocity index. The applied electric field tilts the energy levels of the structure such that |2> and |4> move out of resonance reducing the coupling efficiency. For high voltage – the two wells are tilted enough such that virtually no coupling occurs – regressing to isolated two-level absorption in the quantum wells.

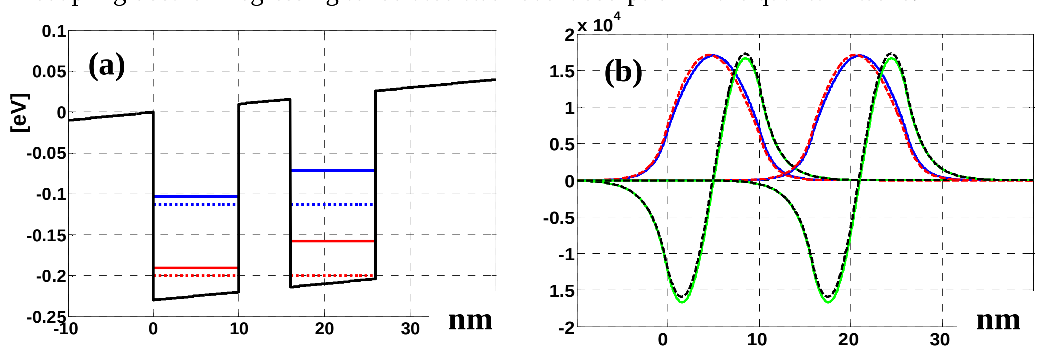

Fig. 3. Applying 10^6 eV DC field (a) Energy-level diagram tilting (dashed line: original energy levels) (b) In plane electronic wave functions tilting (dashed line: original wavefunctions)

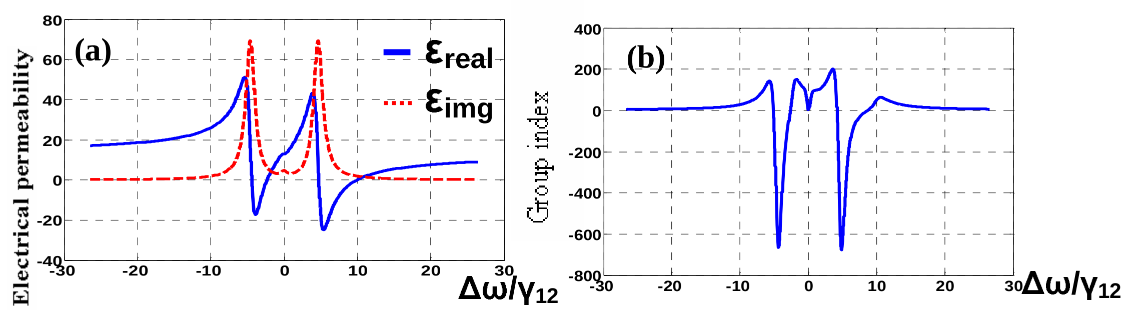

Fig. 4. Applying 10^4 eV DC field (a) Dispersion curve (b) Group index

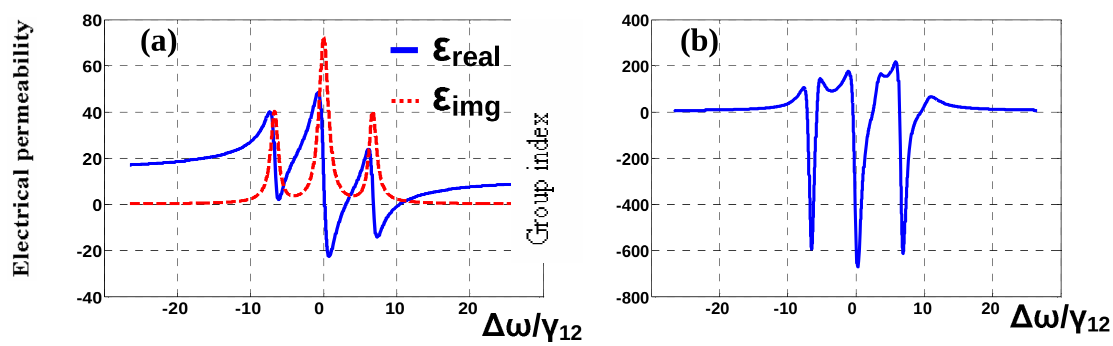

Fig. 5. Applying 10^5 eV DC field (a) Dispersion curve (b) Group index

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4. Electrostatically controllable slowing down factor

The effect of the applied electric field on the slowing down factor (group index) is evident from the previous figures. The highest group index is usually achieved for the frequencies of maximum absorption which makes these regions to be less important for applications. At a zero detuning frequency, significant cancellation of absorption is exhibited (at resonance condition), making it is the frequency of choice for light slowing scheme. In Fig. 6 we show the group index at the zero detuning frequency as a function of applied electric field. It is shown that control over group velocity index from 85 down to 1 can be achieved by a relatively small DC voltage with a figure of merit (at 0 bias) of n_{grop}/n_{imag} = 264 (loss of 0.3μm^{-1}). This residual loss can be potentially lowered significantly for optimized selection of working temperature, material, and coupling coefficients or mitigated by gain material. Under our conditions the workable spectral window is tens of GHz wide (~0.5nm). It can be seen that by exploiting further the anomalous dispersion [Fig. 6(b)] fast light could be achieved as well as backward propagation, however it is accompanied by a shrinking of the transparency window and a very high propagation loss.

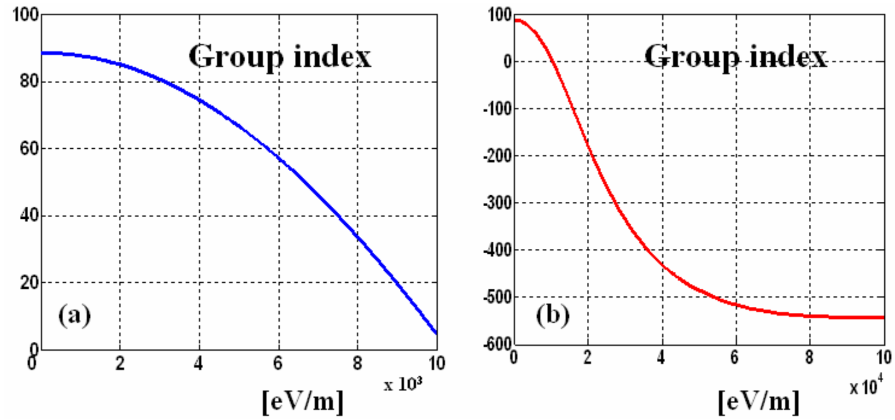

Fig. 6. Group index as a function of applied DC field (a) Zoomed at positive group indices (b) Extended voltage region

5. Conclusion

We proposed a realizable semiconductor based scheme for slowing and controlling the light group velocity – the latter is achieved by an applied electrostatic field. Instead of the cumbersome employment of external light control for slow light generation, the resonant tunneling induced transparency was used. The structure is easily controllable (tunable), because employment of external voltage tilts the wells potential - reducing their coupling strength and modifies the group velocity. About two orders of magnitude in the slow down factor are achievable and controlled. In addition, the large dephasing in solids flattens the group velocity frequency dependence [Fig. 2(b)] permitting many GHz bandwidth of information modulation.

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