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Hansen, Per Lunnemann; Mørk, Jesper

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Reducing the impact of inhomogeneous broadening on quantum dot based electromagnetically induced transparency

Per Lunemann\(^{ab}\) and Jesper Mørk\(^{b}\)

\(^a\)DTU Fotonik, Technical University of Denmark, DK-2800 Kgs Lyngby, Denmark
\(^b\)Department of Photonics Engineering, Technical University of Denmark, DK-2800 Kgs Lyngby, Denmark

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Slow light based on electromagnetically induced transparency in an inhomogeneously broadened quantum dot medium is investigated theoretically. Three schemes, \(\Xi\), \(V\), and \(\Lambda\), are compared and it is shown that the \(V\)-scheme gives a group velocity that is more than three orders of magnitude smaller compared to the \(\Xi\)- and \(\Lambda\)-schemes. The physical mechanisms that make the \(V\)-scheme less vulnerable to inhomogeneous broadening are analyzed and discussed. © 2009 American Institute of Physics. [DOI: 10.1063/1.3079676]

Electromagnetically induced transparency (EIT) was in 1999 proven effective at drastically reducing the speed of light in an ultracold atomic gas.\(^1\) The result has since then given rise to a number of impressive experiments based on EIT.\(^2\) Quantum dots (QDs) are excellent candidates for EIT in semiconductor material due to their quantized energy levels and relatively low dephasing rates,\(^3\) as well as the possibility for monolithic integration. In order to obtain a significant slowdown, it is necessary to interact with an ensemble of QDs. However, self-assembled QDs exhibit inhomogeneous broadening (IHB), mainly caused by size fluctuations of the QD. At cryogenic temperatures, IHB is several orders of magnitude wider than the transition linewidth.\(^4\) The broadening causes the probe and coupling laser fields to experience different detunings depending on the individual QD size and, as a result, the overall EIT features are smeared out. EIT was previously demonstrated in quantum well structures by exploiting excitonic effects\(^\text{5}\) and, in Ref.\(^6\), a similar scheme was previously demonstrated in quantum well structures by and, as a result, the overall EIT features are smeared out. EIT causes a change in the group index and we shall in the following investigate the possible reduction in the group velocity of the three schemes in an inhomogeneously broadened QD medium.

Calculations of the slowdown factor, defined as the group index relative to the background index \(n_{\text{bg}}/n_{\text{bg}}\), were based on a density matrix approach similar to Ref.\(^7\). For the calculations we use \(1/\Gamma_{21}=1/\Gamma_{31}=500\) ps, \(1/\Gamma_{32}=8\) ns, and \(1/\gamma_{21}=1/\gamma_{31}=1/\gamma_{32}=600\) ps, where \(\Gamma_{ij}\) and \(\gamma_{ij}\) denote the population decay and dephasing rate, respectively, between state \(|i\rangle\) and \(|j\rangle\). To date, no measurement has been published, giving the measured population decay and dephasing rates on the same QD sample for transitions related to those depicted in Fig. 1. Thus, the used population decay rates are similar to those measured in Ref.\(^4\), while the dephasing rate \(\gamma_{21}\) is similar to Ref.\(^8\) at \(T=7\) K. We tentatively set \(\gamma_{31}\) and \(\gamma_{32}\) equal to \(\gamma_{21}\). The chosen relaxation time, \(1/\Gamma_{32}\), is long compared to typical values reported \((\sim 1-10)\) ps). As will be discussed, a low intraband relaxation time is required to achieve EIT for the \(V\)-scheme. However, QDs with such long intraband relaxation time can in fact be fabricated, as demonstrated in Ref.\(^4\). For comparison, we also calculate the slowdown factor of the \(V\)-scheme with a short intraband relaxation time \(1/\Gamma_{32}=10\) ps and with a population decay limited dephasing time. For the dipole moments \(\mu_{ij}\), we use \(\mu_{12}/e=7\) Å, \(\mu_{13}/e=1\) Å, and \(\mu_{23}/e=47\) Å, where \(e\) is the electron charge. For ease of notation, we shall denote the dephasing and population decay related to the optically coupled transitions as \(\gamma_{p}\) and \(\Gamma_{p}\), for the probe and \(\gamma_{c}\) and \(\Gamma_{c}\) for the coupling transition, respectively. For the transition between terminal states that are not coupled, dephasing and population decay is denoted as \(\gamma_{g}\) and \(\Gamma_{g}\), respectively. A similar notation is used for the dipole moments, i.e., \(\mu_{pp}\), \(\mu_{pc}\), and \(\mu_{cp}\). The laser detunings are measured relative to the peak of the inhomogeneous distribution and we use a confinement factor \(\Gamma=6\times10^{-3}\). Finally, the inhomogeneous dis-

FIG. 1. Illustration of the three different excitation schemes considered in the QD. \(\Omega_{p}\) and \(\Omega_{c}\) denote the Rabi frequency of the probe and coupling laser field, respectively.
trubution function is assumed to be Gaussian and for the purpose of illustration we choose a full width at half maximum of $\sigma_p = 200 \gamma_p \approx 0.44$ meV, where we recognize this value to be somewhat smaller than typical QD samples ($\approx 10$ meV).

The slowdown factor is shown in Fig. 2 as a function of the coupling laser intensity for all three schemes. Looking at the results without IHB taken into account (dashed lines), it is seen that the V-schemes require a higher coupling intensity due to the much lower dipole moment of the coupling transition. However, when looking at the results including IHB (solid lines), it is seen that the V-scheme is vastly superior, with a maximum slowdown of $\approx 4 \times 10^3$ at 20 W/cm$^2$.

For the other schemes, signs of slowdown are almost completely washed out. Increasing the IHB to realistic values ($\approx 10$ meV), it was observed that the maximum slowdown factor decreases to $\approx 200$ for the V-scheme, while for the other schemes all slowdown is lost. To understand what causes this notable difference, we need to analyze the mechanisms behind EIT a little closer.

It can be shown$^2$ that transparency occurs when the probe and coupling detunings fulfill the two-photon resonance condition $\delta = \Delta_p + \Delta_c = 0$, where the sum is for the $\Sigma$-scheme and the difference for the $V$- and $\Lambda$-schemes and $\Delta_p$ ($\Delta_c$) is the probe (coupling) laser detuning with respect to the probe (coupling) transition. In case the pump is detuned far away from resonance, only the probe pathway contributes and as a result, normal absorption occurs. We shall denote this as the primary absorption resonance.$^9$ Consider instead both lasers far detuned, but on two-photon resonance. As mentioned, here the absorption terms from the single- and two-photon pathways exactly cancel. If the probe frequency is now slightly further detuned, transition amplitudes from the single- and two-photon paths no longer cancel, and as a result absorption occurs with the dominant contribution arising from the two-photon pathway. We denote this as the secondary absorption resonance.

The absorption and refractive index of the probe for a given class of QDs are found from the imaginary and real part of the electric susceptibility $\chi_p(\Delta_p, \Delta_c)$ that in turn is calculated from the density matrix equations.$^1$ Here we explicitly write the effective detuning of $\chi_p$, where $\tilde{\Delta}_p = \Delta_p - \Delta_{p,0}$, with $\Delta_p$ being the probe detuning and $\Delta_{p,0}$ the fre-

![FIG. 2. (Color online) Calculations of the slowdown factor for the three schemes V (black and gray), $\Lambda$ (green), and $\Sigma$ (red). Solid/dashed lines are with/without IHB taken into account. All plots are for long intraband relaxation time, $\Gamma_2 = 8$ ps, except for the gray plots where $\Gamma_2 = 10$ ps.](Image 49x589 to 283x743)

quency shift of the probe transition for a particular class of QDs. Both terms are measured relative to the center frequency of the inhomogeneous distribution of the probe transition. Similarly, $\tilde{\Delta}_c = \Delta_c - \Delta_{c,0}$ for the coupling transition. The total material response is found by integrating $\chi_p(\tilde{\Delta}_p, \tilde{\Delta}_c)$ over $\Delta_{p,0}$ and $\Delta_{c,0}$ weighted by the inhomogeneous distribution functions of the two transitions. Modeling the QDs as disk shaped infinite potentials with radius $a$ and height $\ell$, we can explicitly derive the relation between $\Delta_{c,0}$ and $\Delta_{p,0}$.$^3$ Considering only fluctuations of $a$, a small change $\delta a$ in size implies a shift of the two lowest eigenenergies given by $\delta E_l = -\hbar^2 Z_{1l} / (a m^* \delta a)$, where we assumed $\ell < a$ (Ref. 3) and $l = 0, 1$. Here, $m^*$ is the electron effective mass and $Z_{1l}$ denotes the first root of the $l$th Bessel function. Due to the large hole mass we shall in the following neglect shifts in the valence band. The change in eigenenergies causes a shift of both the probe ($\delta E_p$) and the coupling ($\delta E_c$) transition energies that depend on the chosen scheme. Defining $\kappa = \delta E_c / \delta E_p$, the effective detuning of the pump and probe for a single QD is reduced to $\Delta_p = \Delta_p - \Delta_{p,0}$ and $\tilde{\Delta}_c = \Delta_c - \kappa \Delta_p$, respectively, where $\Delta_{p,0} = \Delta_{p,0}$. A plot of the normalized electric susceptibility as a function of $\Delta_p$ and $\Delta_{p,0}$ is seen in Fig. 3 with $\Omega_p = 5 \Gamma_p$, $\Delta_0 = 0$, $1/13 = 1/\Gamma_{32} = 500$ ps, $1/13 = 8$ ns, and pure dephasing is neglected (dephasing is population decay limited).

The two-photon resonance condition for a QD class spectrally shifted by $\Delta_0$ can then be put in the form $\Delta_{p,0} = (1/ \kappa + \kappa) \Delta_p = \alpha \Delta_p$, with the sum being for the $\Sigma$-scheme and the difference for the $V$- and $\Lambda$-schemes. This relation is indicated on Fig. 3 as dashed white lines.

![FIG. 3. (Color online) Real (top row) and imaginary (bottom row) parts of the electric susceptibility in units of $2\hbar \mu^2 / (\hbar e A)$ for the $\Sigma$- (left), $V$- (middle), and $\Lambda$-schemes (right). Dashed white lines indicate the two-photon resonance ($\delta = 0$). Primary and secondary absorption peaks are indicated by I and II, respectively.](Image 345x646 to 512x743)
the considered V-scheme, while $\alpha \geq 0$ for the $\Xi$- and $\Lambda$-scheme; we therefore stress that this observed difference remains valid in the case of using a more realistic model of the QD. Furthermore, it is seen from the figure that the V-scheme lacks clear signatures of the secondary absorption resonance. This stems from the fact that in the V-scheme the coupling transition involves carrier excitations as opposed to the other two schemes. For those QDs where the coupling laser is far off resonance (i.e., $|\Delta_{ih}| \gg 0$) carriers from $|1\rangle$ are no longer excited to $|3\rangle$ and as a result absorption from the two-photon pathway vanishes. Of course, this also implies a reduction in the number of QDs contributing to the slowdown factor of the V-scheme in the framework of QUEST as well as by the EU through the IST project QPHOTON.

In conclusion, we theoretically investigated the three schemes, $\Xi$, $\Lambda$, and $V$, for realizing EIT in an inhomogeneously broadened QD medium. IHB was shown to be detrimental for the $\Xi$- and $\Lambda$-scheme, whereas for the V-scheme this was effectively eluded. This arises from two effects. First, the V-scheme has a two-photon resonance condition with a negative slope between the probe detuning and inhomogeneous spectral shift ($\Delta_{ih}$). Second, the V-scheme relies on excitation of carriers, which thereby diminishes the influence from QDs off resonance.

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