Slow light in semiconductor quantum wells

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We demonstrate slow light via population oscillation in semiconductor quantum-well structures for the first time. A group velocity as low as 9600 m/s is inferred from the experimentally measured dispersive characteristics. The transparency window exhibits a bandwidth as large as 2 GHz. © 2004 Optical Society of America

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Recently, there has been wide interest in the physics and applications of slow light, i.e., light propagating at a very low group velocity. Controllably varied group velocity can make possible device applications such as all-optical buffers,[1,2] ultralow V_π optical modulators,[3] and variable true time delay. To design such a device on a semiconductor platform is not only of scientific interest but also essential for future system integration. Slow light has been observed in dilute atomic systems via electromagnetically induced transparency[4] and population oscillation (PO).[5] The underlying principle in these experiments is to coherently induce a sharp and pronounced absorption dip in an optically thick medium to generate a steep dispersion in the index of refraction over a narrow spectral range[6] [Kramers–Kronig (KK) relation]. The resulting reduction of the group velocity scales inversely with the spectral linewidth of the induced transparency window. Observations of group velocities lower than the speed of sound have been reported. In semiconductors, however, rapid decoherence of optical excitations has severely limited the amount of group-velocity reduction reported in earlier experiments.[7–9] Advances of atomlike semiconductor nanostructures such as quantum dots make it possible to achieve a large slowdown factor.[1,10] However, experimental demonstration is still lacking, mainly because of the nonuniform distribution of quantum dot size and energy resonances that wipe out the slowdown effect.[6] Slow light via PO, on the other hand, depends only on the lifetime of the population grating induced by two coherent beams. This lifetime has been shown to be ~1 ns in a high-quality quantum-well (QW) structure.[11] In this Letter we report that a narrow transparency window can be induced via PO in a multiple-QW structure with an associated steep refractive-index change over a narrow spectral range (hence slow light).

PO arises from a process of coherent wave mixing. A pump of frequency v_p and a probe of frequency v_s with a frequency detuning $\delta = v_s - v_p$ intersecting in a sample at a small angle $\Delta\theta$ with respect to each other can induce a population grating (PG) that oscillates at frequency δ. In addition to the temporal modulation, the PG also has a spatial modulation pattern with a period given by $\Lambda = \lambda/2 \sin(\Delta\theta/2)$, where λ denotes the optical wavelength in the sample. The complex amplitude of the PG scales as $1/(\delta + i\Gamma)$, where Γ is the decay rate of the PG. Note that, for excitons in a QW, $\Gamma = \Gamma_{\mathrm{rad}} + 4\pi^2 D/\Lambda^2$, where D is the exciton diffusion coefficient, includes contributions from radiative recombination of thermalized excitons as well as from spatial diffusion of these excitons.[11] Interactions between the PG and the pump induce a dipole that oscillates at v_s and propagates along the direction of the probe beam. This dipole interferes destructively with the dipole induced by the probe alone, leading to a reduction in the absorption of the probe, more specifically, a dip in the probe absorption spectrum. In the limit that Γ is small compared with the decoherence rate, the spectral width of the dip is determined by Γ rather than the much greater homogeneous linewidth of the underlying optical transition, since the PO occurs only when δ is small compared with Γ. This narrow spectral dip induced by the PO can circumvent the difficulty of rapid decoherence processes and lead to slow light in semiconductors.

Figure 1 shows the experimental setup. The sample consists of 15 GaAs (13.5 nm)/$Al_{0.3}Ga_{0.7}As$ (15.0 nm) QWs grown by molecular beam epitaxy and is mounted on a sapphire disk with the substrate removed. A single-mode Ti:sapphire laser and a tunable diode laser are used to provide the pump and the probe beam, respectively. A fast photodetector (D4) is used with a rf spectrum analyzer to monitor detuning δ. The pump and the probe are collinearly polarized. The two beams are focused onto the same spot of the sample. The probe is split into two beams before the sample, traveling through a Mach–Zehnder

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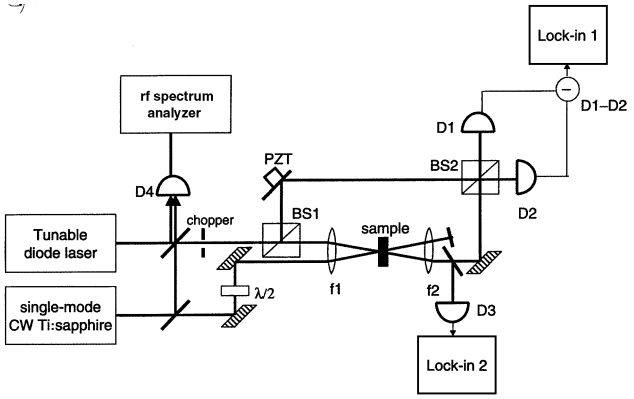

Fig. 1. Experimental setup: BS1, BS2, nonpolarizing 50/50 beam splitters; D1, D2, identical photodetectors; D3, detector measuring probe transmission; D4, fast photodetector. Lock-in detection is used in combination with a mechanical chopper placed in the probe beam path. A half-wave plate ($\lambda/2$) allows for control of the pump polarization. CW, continuous wave; PZT, piezotranslator; f1, f2, focal lengths of plano–convex lenses.

interferometer (MZI) with the sample in one arm. Detector D3 measures the probe transmission. To obtain the absorption spectra we normalize the transmission spectra obtained from D3 to the transmission spectrum with the probe beam detuned to the lower-energy edge of the heavy-hole (HH) resonance. A homodyne detection scheme (detectors D1 and D2) at the output of the MZI is used to measure the dispersive characteristics. This setup, similar to one used to measure electromagnetically induced transparency dispersion,[12] allows us to measure both the real and the imaginary parts of the complex refractive index simultaneously.

Figure 2(a) shows absorption spectra as a function of detuning. In the figure L is the total thickness of the 15 QWs. The absorption αL is defined by $I_{\text{out}} = I_{\text{in}} \exp(-\alpha L)$. The sample is kept at a temperature of 10 K. The spectra were obtained at various pump intensities near the HH exciton resonance. The excitons are resonantly excited well within the homogeneous linewidth with energies at or slightly above the HH line center. The absorption spectra feature a sharp dip centered at zero detuning. The spectral linewidth of the dip is much smaller than the exciton's homogeneous linewidth. The depth of the absorption dip increases with increasing pump intensity. The overall HH exciton absorption resonance also saturates with increasing pump intensity (not shown here). The spectral width of the dip depends on the relative angle between the pump and the probe, reflecting the effects of exciton spatial diffusion. The sharp absorption dip arises from the PO induced by the pump and the probe. At low excitation levels the linewidth of the dip corresponds to grating lifetimes of 0.51 and 0.33 ns for $\Delta\theta = 2.5°$ and 5°, respectively, which are quantitatively consistent with a previous four-wave mixing study for delocalized excitons.[9] Note that, in addition to saturation, the HH absorption resonance also features many-body effects, including a blueshift that is due to exchange repulsion and a broadening of the absorption resonance that is due to excitation-induced dephasing.[13] Details of these nonlinear optical processes have been extensively investigated in earlier studies and will not be discussed here.

To single out the PO effects we define relative depth d of the absorption dip as the ratio between the magnitude of the absorption dip and the magnitude of the reduced absorption background (i.e., absorption at large detuning):

$$d \equiv \Delta\alpha/\alpha_{\text{bac}}\,. \tag{1}$$

Figure 2(b) shows the pump intensity dependence of d at two different relative angles, $\Delta\theta = 2.5°$ and 5°. For a two-level system the dependence of d on the pump intensity is given by

$$d \propto \frac{I}{1 + I/I_0}, \tag{2}$$

where I is the pump intensity and I_0 is the characteristic saturation intensity proportional to both the population decay rate and the decoherence rate for the relevant optical transition.[5] Despite the many-body effects inherent in semiconductors, the relative depth obtained can still be described by expression (2) but now with I_0 as the phenomenological saturation intensity. Note that I_0 depends on the relative angle between the pump and the probe following decay of the population grating as a result of exciton spatial diffusion. The saturation intensity I_0 obtained from the numerical fit shown in Fig. 2(b) is 2.5 kW/cm^2 for $\Delta\theta = 2.5°$ and 1.6 kW/cm^2 for $\Delta\theta = 5°$.

The group velocity, v_g, can be obtained directly from the dispersion of the refractive index. The homodyne signal, D1 − D2, is proportional to the cosine of the phase delay, $\Delta\beta(v_s)L$, of the probe beam propagating

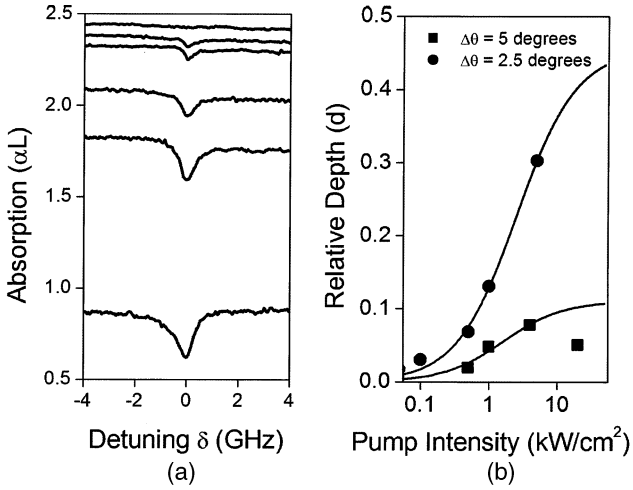

Fig. 2. (a) Absorption spectra obtained at different pump intensities. From top to bottom the curves are $I = 0.01, 0.05, 0.1, 0.5, 1, 5$ kW/cm^2. $\Delta\theta = 5°$. The probe intensity is 1.5 W/cm^2. (b) Pump intensity dependence of the relative depth of absorption dip d. The probe intensities are 1.5 W/cm^2 for $\Delta\theta = 2.5°$ and 6 W/cm^2 for $\Delta\theta = 5°$. The solid curves are best fits to expression (2).

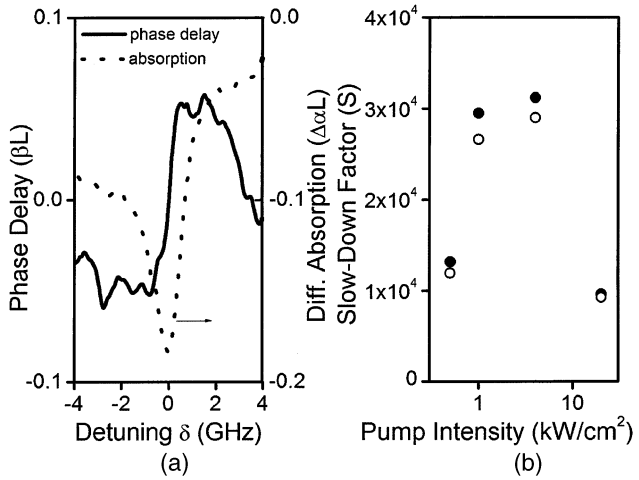

Fig. 3. (a) Phase delay and absorption experienced by the probe. The slope of the phase delay gives the group velocity. The pump and probe intensities are 1 and 0.09 kW/cm^2, respectively. (b) Pump intensity dependence of the slowdown factor of the group velocity as obtained from dispersion (filled circles) and absorption measurements (open circles). The probe intensity is 6 W/cm^2.

through the sample:

$$\mathrm{D1} - \mathrm{D2} \propto \exp[-\alpha(v_s)L/2]\cos[\Delta\beta(v_s)L + \phi_{\mathrm{LO}}(v_s, \Delta l)]. \tag{3}$$

The local oscillator phase $\phi_{\mathrm{LO}}(v_s, \Delta l)$ arises from unbalanced optical paths Δl in the MZI and a background phase delay in the absence of the pump. As shown in Fig. 1, we can adjust the local oscillator by controlling the path difference Δl in the MZI, using a piezotranslator. Before each scan the piezotranslator is adjusted such that $\phi_{\mathrm{LO}}(v_s, \Delta l) = \pi/2 + 2m\pi$, with m being an integer number at $\delta = 0$. For small variations of the phase delay induced by the pump, the cosine can then be approximated by $\Delta\beta(v_s)L$. The phase delay of the probe beam through the sample is obtained after normalization of the homodyne signal with respect to the absorption $\exp[-\alpha(v_s)L/2]$ measured by D3.

Figure 3(a) shows the dispersion and absorption spectra for pump and probe intensities of 1 and 0.09 kW/cm^2, respectively. The slope of the dispersion at zero detuning reveals a slowdown factor of $S = 31{,}200$, where $S \equiv c/v_g$, demonstrating a group velocity as small as 9600 m/s. Figure 3(b) shows the pump intensity dependence of S. S initially increases with increasing pump intensity and peaks before decreasing above 4 kW/cm^2. This behavior is in agreement with the pump intensity dependence of the associated absorption dip, which first shows emergence of the absorption dip, then saturation and broadening as the pump intensity increases.

For a more quantitative comparison, we note that for an absorption dip with a Lorentzian line shape there is a simple relation among S at $\delta = 0$, the spectral width (Δv), and the depth ($\Delta\alpha$) of the dip (c is the velocity of light in vacuum):

$$S = c\,\frac{\Delta\alpha}{\Delta v}\,. \tag{4}$$

This result, which arises directly from KK relations, shows how the absorption dip relates to the group-velocity reduction. Using Eq. (4), we can calculate S by extracting $\Delta\alpha$ and Δv from the absorption spectra as shown, for example, in Fig. 2(a). The results are plotted in Fig. 3(b) as open circles. As shown in Fig. 3(b), S obtained from the dispersion measurement agrees well with that obtained from absorption measurement with Eq. (4), although S from the absorption measurement tends to underestimate the result, possibly because of slight deviations of the absorption dip from an ideal Lorentzian line shape.

In summary, we have demonstrated slow light in semiconductor quantum wells, using population oscillation for what is believed to be the first time. Our experiments exploit the relatively long population grating lifetime in semiconductor QWs to attain a sharp and pronounced absorption dip that leads to a group velocity as low as 9600 m/s. A bandwidth of 2 GHz (FWHM) was obtained, demonstrating the broad bandwidth advantage of using semiconductors for communication applications.

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