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Tunable slow light in Bragg-spaced quantum wells

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The group velocity of light is continuously varied in the intermediate band of a Bragg-spaced quantum well structure by tuning the pulse frequency. Delays of 0–0.4 bit, without significant pulse distortion, are measured. The high group index is found to lead to large Fresnel reflection coupling losses and Fabry-Pérot fringing. Antireflection (AR) coatings deposited on both sides of the Bragg-spaced quantum well structure are shown to improve coupling of light into the intermediate band but to be sensitive to small errors ($\sim 1\%$) in the AR coating layer thicknesses. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2403927]

Materials that can be engineered to have large, tunable group velocities ($v_g = d\omega/dk = c/n_{\text{group}}$, $n_{\text{group}} = n + \omega_0 dn/d\omega$) are attractive for applications that require pulses or pulse packets to be spatially compressed and stored for a continuously variable time. Here, we demonstrate that $In_{0.025}Ga_{0.975}As/GaAs$ Bragg-spaced quantum wells (BSQWs) can be used to produce tunable slow light delays and that antireflection coatings are necessary for improving the coupling of light into such structures. BSQWs are attractive for slow light applications because they can be fabricated from technologically important semiconductor materials,[1] making them compact and potentially integrable with optoelectronic systems. Schemes have been proposed for stopping, storing, and releasing light pulses using BSQWs,[2,3] which have shown promise as materials for all-optical switching.[4,5]

BSQWs are structures that are characterized by two frequencies: the 1s-heavy-hole quantum well excitonic resonance (ω_X) and the fundamental Bragg frequency ($\omega_B = \pi c/n_b a$, where n_b is the background index and a is the periodic spacing of the quantum wells). The presence of two characteristic frequencies breaks the photonic band structure into three bands, as illustrated in Fig. 1(a) for $\omega_X \sim \omega_B$. The intermediate transmission band [centered near 1.4925 in Fig. 1(a)] has been shown to have the analytic form[2]

$$\cos(Ka) = \cos(qa) + \frac{\Gamma}{(\omega + i\gamma) - \omega_X}\left(\frac{\omega}{\omega_X}\right)\sin(qa), \qquad (1)$$

where ω (K) is the polariton angular frequency (wave vector), c the speed of light in vacuum, $q = n_b\omega/c$, and Γ (γ) the radiative decay (dephasing) rate. The simulation in Fig. 1 uses material parameters appropriate for an $In_{0.025}Ga_{0.975}As/GaAs$ BSQW:[1] $\hbar\omega_B = 1.491$ eV, $\hbar\omega_X = 1.494$ eV, $\hbar\Gamma = 30$ μeV, and $n_b = 3.61$.

The width of the intermediate band (IB), $\Delta\omega_{\text{IB}}$, and the v_g associated with it are each proportional to the relative detuning $|\omega_B - \omega_X|$.[2,3] Thus, the speed of light in a BSQW can be varied and controlled by shifting ω_B and/or ω_X externally following growth. Figure 1(b) shows v_g as a function of photon energy for two $\Delta\omega_{\text{IB}}$: -3.0 meV [corresponding to the IB in Fig. 1(a)] and -1.25 meV. The inset shows the variation of the maximum v_g vs $\Delta\omega_{\text{IB}}$. Clearly, the group velocity can be made arbitrarily small by narrowing the IB. In fact, when $\Delta\omega_{\text{IB}} = 0$, the IB is flat, $v_g = 0$, and no propagation is allowed. Of course, if the IB is narrowed to a bandwidth less than that of the incident pulse, spectral narrowing (temporal broadening) of the transmitted pulse will occur. The time delay τ_{delay} that is possible without spectrally narrowing the input pulse can be readily estimated using the approximate expression given for the maximum v_g in Ref. 3:

$$\tau_{\text{bit}} \equiv \tau_{\text{delay}}/\tau_{\text{pulse}} \cong (8/9)[3(\Gamma/\omega_X)/2\pi]^{1/2}N, \qquad (2)$$

where N is the number of quantum wells in the BSQW and where we have assumed that the full width at half maximum spectral width $\Delta\nu$ of the input pulse is equal to the intermediate bandwidth ($\Delta\omega_{\text{IB}} = 2\pi\Delta\nu$). Thus, the bit delay depends only on the oscillator strength and number of wells. Using

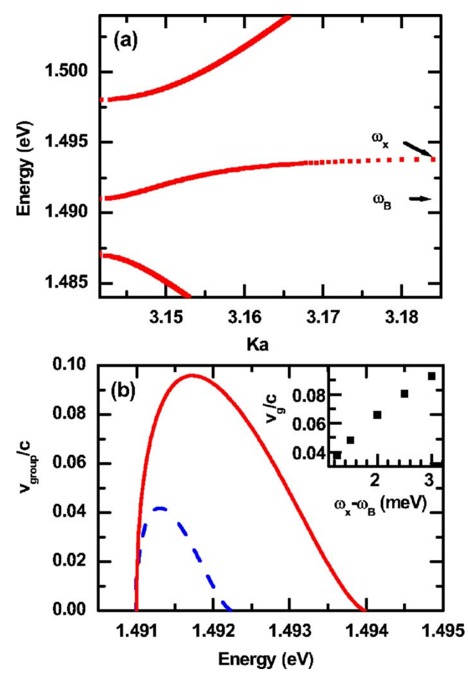

FIG. 1. (a) Simulated band structure of a detuned ($\Delta\omega = \omega_B - \omega_X = -3.0$ meV) BSQW structure with unit cell parameters chosen to match those of $In_{0.025}Ga_{0.975}As/GaAs$ quantum wells: $\hbar\omega_B = 1.491$ eV, $\hbar\omega_X = 1.494$ eV, $\hbar\Gamma = 30$ μeV the radiative damping rate, and $n_b = 3.61$. (b) Simulated group velocity of a BSQW structure at two detunings, $\Delta\omega = \omega_B - \omega_X = -3.0$ meV (red, solid) and $\Delta\omega = -1.25$ meV (blue, dashed). By varying the detuning $\Delta\omega$, the group velocity of the pulse is continuously tunable (inset).

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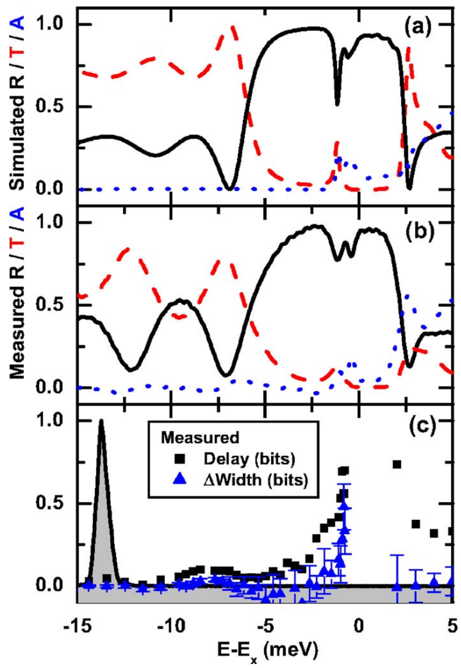

FIG. 2. (a) Simulated reflection (black, solid) from, transmission (red, dashed) through, and absorption (blue, dotted) by an $N=210$ Bragg-spaced $In_{0.025}Ga_{0.975}As/GaAs$ quantum well structure. (b) Low temperature measurements (10 K) on the corresponding experimental structure. (c) Measured relative delay (black, square) and pulse broadening (blue, triangle) of a 0.67 meV (3.5 ps) pulse, shown for reference in black/gray fill.

parameters appropriate for GaAs ($\Gamma/\omega_X \sim 2\times 10^{-5}$) and the number of wells in the samples described below ($N=210$), one would expect $\tau_{\text{bit}} \approx 0.6$.

To illustrate the slowing of light in BSQWs, we use an $N=210$ $In_{0.025}Ga_{0.975}As/GaAs$ BSQW grown by molecular beam epitaxy. The low In content ensures no significant difference between the background indices of the quantum well and the barrier, and the strain introduced by the In ensures that the light-hole exciton is energetically located far above the heavy-hole exciton. The layer thicknesses were systematically wedged by not spinning the sample during growth, allowing the relative detuning $\omega_B - \omega_X$ to be selected simply by changing the position of the optical pulse on the surface of the sample.

Figures 2(a) and 2(b) show, respectively, the simulated and measured reflection (R), transmission (T), and absorption ($A=1-R-T$) of the BSQW for a detuning $\Delta\omega = -3.3$ meV. Experimentally, detuning is determined by mapping layer thicknesses, measured directly by x-ray diffraction, as a function of position on the sample surface, and confirmed with numerical simulations of the spectra. Measurements are performed with the sample mounted in a cryostat cooled to 10 K. Simulations are performed using a transfer matrix method (see Ref. 1 for details). Good quantitative agreement can be seen in Figs. 2(a) and 2(b) between simulation and experiment. Deviations can be explained by the disorder in the quantum well periodicity.[1]

Both experiment [Fig. 2(b)] and simulation [Fig. 2(a)] show an ~8-meV-wide high-reflection on stop band associated with the forbidden photonic band gap. The IB is visible in the middle of the stop band and has a bandwidth approximately equal to the detuning $\Delta\omega = -3.3$ meV. However, the reflection (transmission) decrease (increase) is small, and oscillations in the reflection appear within the IB. These non-

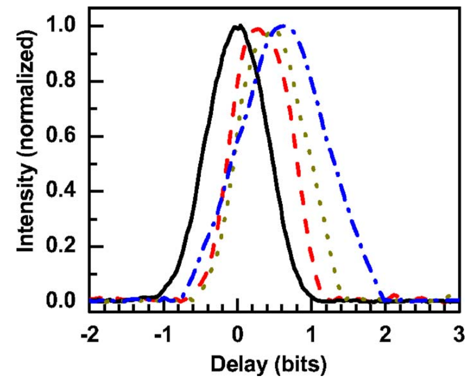

FIG. 3. Measured temporally resolved 0.67 meV, 3.5 ps pulses transmitted through the experimental structure of Fig. 2(c). Pulses were centered on $E-E_x = -0.79$, -1.08, -2.26, and -11.51 meV for the blue dash-dot line, the dark yellow dotted line, the red dashed line, and the black solid line, respectively. Delays are relative to the transmitted pulse at -11.51 meV.

ideal features are caused by the large effective index of refraction associated with the BSQW.[2] Fresnel reflections at the front surface associated with this large index cause poor coupling efficiency of the light into the IB rather than a well-defined allowed transmission window. In addition, Fresnel reflections at the air/BSQW and BSQW/substrate interfaces lead to Fabry-Pérot fringing and account for the reflectivity oscillations seen within the IB.

The group velocity and group velocity dispersion of pulses propagating through the BSQW shown in Fig. 2(a) are investigated by measuring the delay and broadening of a weak ($88\ \text{nJ/cm}^2$) 3.5 ps transmitted pulse. The incident pulses are obtained by attenuating and using a pulse shaper to spectrally narrow (to 0.67 meV) pulses from a mode-locked Ti:sapphire laser. The time delay and width of each transmitted pulse are measured by cross correlating the transmitted pulse with an 80 fs reference pulse using second harmonic generation in a beta barium borate crystal.

The relative delay and broadening of each transmitted pulse are shown in Fig. 2(c). Near the low energy edge of the IB, time delays dramatically and continuously increase to ~0.4 bit (1 bit=3.5 ps), corresponding to $v_g \sim 0.067c$, with little pulse broadening and ~10% transmission. In this regime, the pulse delay can be continuously tuned either by tuning the wavelength of the incident pulse or actively changing the width of the IB by external tuning of the exciton resonance (e.g., quantum confined Stark effect). From measurements in this region, we estimate the pulse time delay-bandwidth product to be ~0.2. This time delay-bandwidth product compares favorably with slow light reports in semiconductors based on other mechanisms such as coherent population oscillations (~0.04).[6,7] As the pulse is tuned closer to the excitonic resonance, the group velocity is further reduced, the transmission goes to zero, and the pulse broadening sharply increases. A maximum of 0.7 bit delay, corresponding to a group velocity $\sim 0.038c$, is observed in the region near the upper edge of the IB band, but the pulse is broadened by ~0.5 bit. The continuous tuning of the delay near the band edge and the onset of broadening as the excitonic resonance is approached are illustrated in Fig. 3, which shows selected temporally resolved transmitted pulses centered at different photon energies in the IB.

The less than ideal performance of the BSQW used for the measurements shown in Figs. 2 and 3 can be attributed to

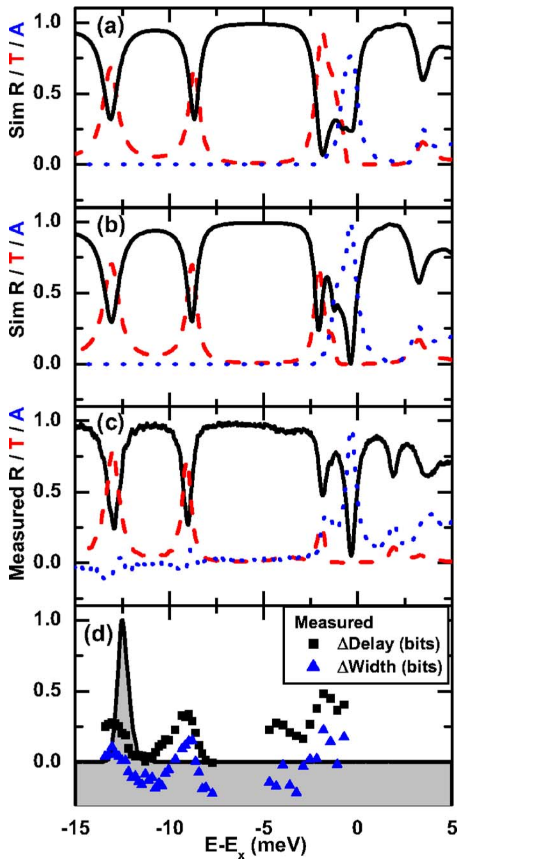

FIG. 4. Simulation of a BSQW identical to Fig. 2 except with AR coatings on the front and exit interfaces designed for (a) $\Delta\omega=-3.3$ meV and (b) $\Delta\omega=22$ meV, including reflection (black, solid), transmission (red, dashed), and absorption (blue, dotted). (c) Measurement of an experimental sample with target structure of (a), but actual structure closer to (b). The percentage error in AR coating layer thicknesses equals 1.5%. (d) Measured relative delay (black, square) and pulse broadening (blue, triangle) of a 0.67 meV (3.5 ps) pulse, shown for reference in black/gray fill.

the Fresnel reflections and Fabry-Pérot fringing discussed earlier.[2] In an attempt to reduce these adverse effects, we grew an identical sample, except that an antireflection (AR) coating was grown on both incident and exit sides. On the incident side (air/BSQW interface), the AR coating consists of 7.5 periods of quarter wave layers ($\lambda_{design}/4n_b$ thick) of $GaAs/Al_{0.33}Ga_{0.67}As$, two available (but nonoptimal) materials, designed according to Ref. 2. On the exit side (BSQW/substrate interface), an identical AR coating was used (but was nonoptimal due to GaAs rather than air as the exit medium). The design wavelength (λ_{design}) was chosen to be close to λ_B $(=2\pi n_b c/\omega_B)$, where the group velocity (and group index) is fairly flat (e.g., see Fig. 1). Figure 4(a) shows simulations of R, T, and A of the target BSQW detuned to $\Delta\omega=\omega_B-\omega_X=-3.3$ meV. The simulation shows reduced Fabry-Pérot fringing and improved coupling to the IB, i.e., less reflection across the IB. Figure 4(c) (solid lines) shows measurements of R, T, and A of the corresponding experimental structure performed at low temperature (10 K). The coupling of light clearly is improved in the AR coated BSQW compared to the non-AR coated structure (Fig. 2), with minimum reflection close to zero; however, Fabry-Pérot fringing is more pronounced than in the simulated target structure in Fig. 4(a). We speculate that the difference between the simulated and grown AR coated BSQWs may be due to small errors in the thicknesses of the layers in the AR coating. This sensitivity to errors in the layer thickness is illustrated by the simulation shown in Fig. 4(b), where an error in the layer thicknesses of 1.5% has been assumed and which produces significantly better agreement with the experimental result. Improved designs that are less sensitive to small errors in the layer thicknesses can be constructed from materials with more optimal indices of refraction.

The delay and broadening of a 3.5 ps pulse transmitted through the AR coated BSQW using the same procedure as that used to obtain Fig. 2(c) are shown in Fig. 4(d). The AR coating improved the coupling and reduced the fringing of the BSQW. Near the lower edge of the IB, there is a spectral region where the delay is significant (~0.25 bit) and broadening is negligible. Closer to the excitonic resonance, a maximum bit delay of 0.5 is observed, but at the expense of increased broadening of the pulse width (~0.2 bit) and reduced transmission (~1%).

Slow light features are observed in the AR coated BSQW that are not present in the uncoated sample. Below the reflectivity stop band, the AR coating acts like an ordinary Fabry-Pérot cavity, i.e., two mirrors separated by the thickness of BSQW structure. Regularly spaced modes of the cavity can be seen at the low energy side of the high reflectivity photonic stop band in Fig. 4(d). As expected, the laser pulses are also slowed and broadened by the dispersion associated with the bare cavity modes.

The negative changes in pulse width shown in Fig. 4(d) suggest that the pulse is temporally compressed at some photon energies (e.g., midway between cavity modes). This compression of the nearly transform-limited pulses is reproduced by linear transfer matrix calculations, which show that the compression is due to a spectral reshaping of the pulse. When positioned midway between cavity modes, the spectral tails of the pulse are enhanced, while the center of the pulse is attenuated, resulting in a pulse with a spectrally broader and temporally narrower width.

In summary, we have measured the slowing and broadening by group velocity dispersion of picosecond pulses propagating in the IB of two $In_{0.025}Ga_{0.975}As/GaAs$ BSQWs: one non-AR coated and the other AR coated. Continuously tunable delays from 0 to ~0.4 bit were measured with negligible broadening for the non-AR BSQW. Unoptimized AR coatings were shown to improve the coupling of light into the structure. AR coatings fabricated from GaAs and AlGaAs were also found to be sensitive to small errors (1.5%) in the AR coating layer thicknesses.

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