

Electromagnetically-induced transparency and slow light in GaAs/AlGaAs multiple quantum wells in a transient regime

Seong-Min Ma, Hua Xu, and Byoung Seung Ham*

Center for Photon Information Processing, and the Graduate School of Information and Telecommunications,
Inha University, Incheon 402-751, South Korea

*bham@inha.ac.kr

Abstract: Electromagnetically-induced transparency (EIT) is observed and analyzed for the group velocity of a femtosecond light pulse interacting with GaAs/AlGaAs multiple quantum wells (MQWs) in a transient regime. The calculated slowdown factor of the group velocity inside the medium due to the dynamic refractive index change is $\sim 2.10 \times 10^3$. We discuss the potential of EIT-induced slow light in GaAs/AlGaAs MQWs for ultrafast (~ 210 GHz) all-optical information processing such as photon routing.

©2009 Optical Society of America

OCIS codes: (270.1670) Coherent optical effects; (300.6470) Spectroscopy, semiconductors; (320.7130) Ultrafast processes in condensed matter, including semiconductors.

References and links

1. R. S. Tucker, P. C. Ku, and C. J. Chang-Hasnain, "Delay-bandwidth product and storage density in slow-light optical buffers," *Electron. Lett.* **41**(4), 208–209 (2005).
2. B. S. Ham, "Investigation of quantum coherence excitation and coherence transfer in an inhomogeneously broadened rare-earth doped solid," *Opt. Express* **16**(8), 5350–5361 (2008).
3. L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, "Light speed reduction to 17 metres per second in an ultracold atomic gas," *Nature* **397**(6720), 594–598 (1999).
4. M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, "Superluminal and slow light propagation in a room-temperature solid," *Science* **301**(5630), 200–202 (2003).
5. Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, "Tunable all-optical delays via Brillouin slow light in an optical fiber," *Phys. Rev. Lett.* **94**(15), 153902 (2005).
6. J. E. Sharping, Y. Okawachi, and A. L. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," *Opt. Express* **13**(16), 6092–6098 (2005).
7. P. C. Ku, F. Sedgwick, C. J. Chang-Hasnain, P. Palinginis, T. Li, H. Wang, S. W. Chang, and S. L. Chuang, "Slow light in semiconductor quantum wells," *Opt. Lett.* **29**(19), 2291–2293 (2004).
8. S. E. Harris, "Electromagnetically induced transparency," *Phys. Today* **50**(7), 36–42 (1997).
9. M. C. Phillips, and H. Wang, "Spin coherence and electromagnetically induced transparency via exciton correlations," *Phys. Rev. Lett.* **89**(18), 186401 (2002).
10. M. C. Phillips, and H. Wang, "Exciton spin coherence and electromagnetically induced transparency in the transient optical response of GaAs quantum wells," *Phys. Rev. B* **69**(11), 115337 (2004).
11. M. C. Phillips, H. Wang, I. Rumyantsev, N. H. Kwong, R. Takayama, and R. Binder, "Electromagnetically induced transparency in semiconductors via biexciton coherence," *Phys. Rev. Lett.* **91**(18), 183602 (2003).
12. R. Binder, and M. Lindberg, "Ultrafast adiabatic population transfer in p-doped semiconductor quantum wells," *Phys. Rev. Lett.* **81**(7), 1477–1480 (1998).
13. R. A. Ganeev, A. I. Rysanyanskiy, and T. Usmanov, "Optical and nonlinear optical characteristics of the Ge and GaAs nanoparticle suspensions prepared by laser ablation," *Opt. Commun.* **272**(1), 242–246 (2007).
14. K. Bott, O. Heller, D. Bennhardt, S. T. Cundiff, P. Thomas, E. J. Mayer, G. O. Smith, R. Eccleston, J. Kuhl, and K. Poog, "Influence of exciton-exciton interactions on the coherent optical response in GaAs quantum wells," *Phys. Rev. B* **48**(23), 17418–17426 (1993).
15. R. A. Taylor, C. W. W. Bradley, N. Mayhew, T. N. Thomas, and J. F. Ryan, "Femtosecond hole burning measurements in semiconductors," *J. Lumin.* **53**(1-6), 321–326 (1992).
16. N. H. Kwong, I. Rumyantsev, R. Binder, and A. L. Smirl, "Relation between phenomenological few-level models and microscopic theories of the nonlinear optical response of semiconductor quantum wells," *Phys. Rev. B* **72**, 235312 (2005).
17. R. W. Boyd, *Nonlinear Optics* (Academic Press, New York, 2003).
18. A. Yariv, *Quantum Electronics* (John Wiley & Sons, New York, 1989).
19. H. Nickolaus, H.-J. Wünsche, and F. Henneberger, "Exciton spin relaxation in semiconductor quantum wells: the role of disorder," *Phys. Rev. Lett.* **81**(12), 2586–2589 (1998).

20. T. C. Damen, L. Via, J. E. Cunningham, J. Shah, and L. J. Sham, "Subpicosecond spin relaxation dynamics of excitons and free carriers in GaAs quantum wells," *Phys. Rev. Lett.* **67**(24), 3432–3435 (1991).
 21. B. S. Ham, "Observations of delayed all-optical routing in a slow-light regime," *Phys. Rev. A* **78**(1), 011808 (2008); For a nonslow light regime, see B. S. Ham, "Potential applications of dark resonance to subpicosecond optical switches in hyper-terahertz repetition rate," *Appl. Phys. Lett.* **78**(22), 3382–3384 (2001)
-

1. Introduction

Controlling the speed of light in solid state materials has drawn significant attention because of its potential application to photonic devices such as all optical buffer memories and quantum information processing [1,2]. Several techniques to control the speed of light have been demonstrated, including electromagnetically-induced transparency (EIT), population oscillation (PO), stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS) [3–6]. Recently, Ku *et al.* reported slow light via PO, which is mainly influenced by the lifetime of excitons, using a process of coherent wave mixing with continuous wave (CW) lasers in GaAs/AlGaAs MQWs [7]. In a three-level system for EIT, destructive quantum interference between two absorption pathways renders an opaque medium transparent even in a resonant light field [8]. Phillips *et al.* reported EIT via exciton correlation to control exciton absorption processes with femtosecond excitation in GaAs/AlGaAs MQWs at 10 K, which is due to the rapid decay and the fragile nature of the quantum coherence in semiconductors [9–11]. However, in GaAs/AlGaAs MQWs, slow light via EIT has not been reported in a transient regime. Modification of an absorption spectrum in a narrow spectral region via EIT induces a very steep change of refraction as a function of frequency, and results in slowing the group velocity of light in the medium [3].

In this paper, we report an observation of EIT with an ultrafast (fs) light pulse resonantly interacting with GaAs/AlGaAs multiple quantum wells (MQWs) for exciton transitions, and analysis of the slowdown factor of the light using a fourth-order Runge-Kutta method in a transient regime. The calculated group velocity is $\sim 1.44 \times 10^5$ m/s, where the slowdown factor due to EIT is $\sim 2.10 \times 10^3$. The observed bandwidth of the EIT transparency window is as wide as ~ 210 GHz, where the corresponding pulse duration is as short as ~ 3 ps.

2. Experimental details

The GaAs/Al_{0.35}Ga_{0.65}As MQW sample was grown on a GaAs substrate by molecular beam epitaxy. Figure 1(a) shows the GaAs/Al_{0.35}Ga_{0.65}As MQW sample configuration containing twenty periods of wells (GaAs) and barriers (AlGaAs) with a thickness of 9 nm and 20 nm, respectively. To measure transmission, the topside of the MQW sample was mounted on a sapphire disk, and the GaAs substrate was removed using mechanical polishing and chemical etching techniques. The GaAs MQW sample was placed in a helium cryostat, keeping the temperature at 10 K to reduce phonon scattering. The light pulse of Ti:Sapphire laser (KM Labs Inc., Chinook) has a 25 fs pulse duration at an 82 MHz repetition rate and a temporally Gaussian shape. The wavelength of the laser is 800 nm to excite excitons in GaAs MQWs. The output beam from the laser is split into two to create a strong coupling (or pump) beam and a weak probe beam. Each beam's polarization is controlled by using a combination of half- and quarter-wave plates. The coupling beam is passed through a pulse shaper so that the pulse duration is stretched approximately 100 times longer than the probe pulse duration and a much narrower spectral linewidth (~ 0.5 nm) is obtained for a central wavelength of ~ 790 nm. A temporal overlap between the coupling and probe pulses inside the sample is controlled by using a homemade probe pulse time-delay system. The coupling and probe pulses are focused onto the sample by a 5 cm focal length lens. A beta-barium borate (BBO) crystal is employed to measure the temporal overlap as well as the spatial overlap between the coupling and probe pulses. The coupling laser intensity is ~ 0.24 MW/cm² in the sample. The coupling and probe pulses are right circularly (σ^+) and left circularly (σ^-) polarized to excite doubly degenerated heavy hole (HH) excitons with opposite spins, respectively.

Figure 1(b) shows the absorption spectrum of the probe interacting with the GaAs MQWs at ~ 10 K. The observed 1s HH and 1s light hole (LH) exciton peaks are ~ 790.02 nm and ~ 782.40 nm, respectively. The well thickness (9 nm) of the sample is much thinner than that

of the bulk exciton Bohr radius of GaAs (13.5 nm) [12]. Since the strong quantum confinement of excitons is satisfied in the quantum wells, a large energy splitting (~ 7.62 nm) occurs between the 1s HH and the 1s LH; the peaks are blue-shifted from the absorption edge of a bulk state (~ 870 nm) [13]. Figure 1(c) shows the electron transitions from the doubly degenerated ground states (or HH states), $| -3/2 \rangle$ and $| +3/2 \rangle$, to the excited states, $| -1/2 \rangle$ and $| +1/2 \rangle$, by right circularly polarized light σ^+ and left circularly polarized light σ^- , corresponding to the excitation of the spin up ($|X^+\rangle$) and spin down ($|X^-\rangle$) HH excitons, respectively [14]. The pair of opposite circularly polarized coupling and probe pulses in the MQW sample with a nearly zero time delay induces an unbound two-exciton continuum state (or unbound biexciton state, $|X^+X^-\rangle_{unb}$) and an interacting bound two-exciton state (or bound biexciton state, $|X^+X^-\rangle_{bou}$) via Coulomb correlations between the HH excitons with opposite spins, resulting in the exciton spin coherence for EIT in GaAs MQWs [9,14]. The two symmetric pathways of the exciton transitions of a four-level system are formed by exciton interactions. The exciton transition processes between the single exciton states and the two-exciton states are depicted with the opposite circularly polarized laser beams as shown in Fig. 1(d).

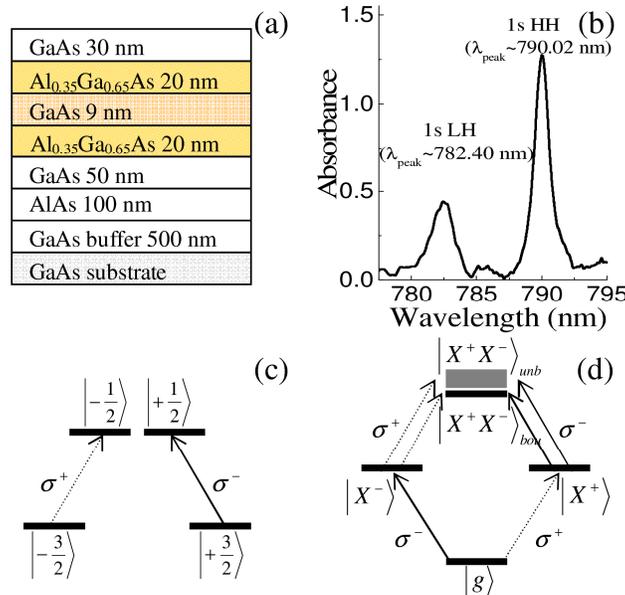


Fig. 1. (a) GaAs MQW sample configuration; (b) absorption spectrum of the sample with 1s HH and 1s LH absorption peaks; (c) electron transitions between the HH bands and the conduction bands; and (d) HH exciton transitions between the single-exciton states and two-exciton states.

3. Results and discussion

The thicker solid (blue) lines of Figs. 2(a) ~2(c) show the experimental results of femtosecond EIT via the unbound two-exciton state with a satisfaction of two-photon resonance in GaAs MQWs at $\lambda_c = \sim 789.92, 790.02,$ and 790.12 nm for the coupling laser wavelengths, respectively, with a nearly zero time delay ($\tau = 0$) at 10 K. Even though the probe pulse is as wide as ~ 28 THz (~ 25 fs) in bandwidth, only a limited portion of the bandwidth is used for EIT. As shown in Fig. 2(b), a typical EIT phenomenon of absorption reduction at line center is observed and the EIT transparency window is as large as ~ 210 GHz, which is obtained by the full width at half maximum (FWHM) of the absorption dip. The window is relatively broad compared with that reported by Phillips *et al.*: ~ 90 GHz of the EIT transparency window using a 150 fs probe pulse and a 6 ps coupling pulse [9–11]. The broad window is caused

mainly by the relatively shorter coupling pulse duration. However, the FWHM of the coupling spectral width is narrower than that of the HH absorption width. At slightly off-resonance transitions of the coupling, an asymmetrical EIT dip is also observed in Figs. 2(a) and 2(c) as a proof of EIT. The broadened HH exciton absorption linewidth is due mainly to the light absorption to both unbound and bound biexcitons around 790 nm and 791.4 nm, respectively.

Figures 2(b) and 2(d) ~2(f) show the time-resolved pump-probe EIT with a delay τ in GaAs MQWs for $\tau = \sim 0$ ps, +3 ps, -2 ps, and -3 ps, respectively, at a fixed coupling wavelength: $\lambda_c = 790.02$ nm, where τ defines the delay time of the probe pulse peak to the coupling pulse peak as shown in the inset in Fig. 2. The delay τ -dependent experimental results reveal that the modified absorption spectra result from a coherent process and are not due to spectral hole burning [10] because the hole burning persists for longer than 1 ns in GaAs MQWs [15]. Thus, the transparency increase in Fig. 2 is due to EIT.

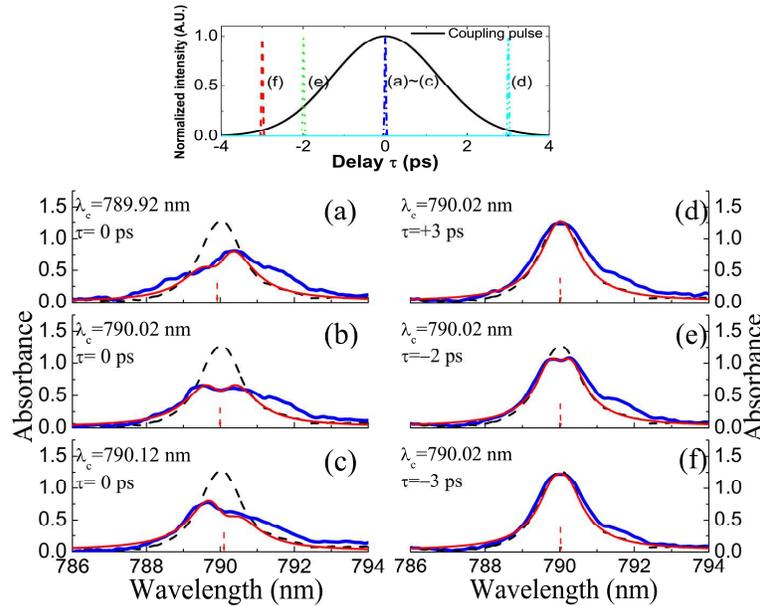


Fig. 2. EIT in GaAs MQWs in a transient regime for a 25 fs probe light at (a) the coupling laser wavelength $\lambda_c = 789.92$ nm; (b) 790.02 nm; (c) 790.12 nm at the pump-probe delay $\tau = 0$; and at $\lambda_c = 790.02$ nm at the pump-probe delays (d) $\tau = +3$ ps; (e) -2 ps; and (f) -3 ps. The dashed lines, thicker solid (blue) lines, and thinner solid (red) lines indicate the experimental results without, with the coupling laser, and the best fitting results obtained by the optical Bloch equations (OBEs) with the coupling laser, respectively. The inset shows the pulse shapes and delay τ between the coupling and probe pulses. The dashed arrow indicates the spectral position of the coupling laser pulse.

For simplification, we denote the two single-exciton states ($|X^+\rangle$ and $|X^-\rangle$) by $|1\rangle$ and $|2\rangle$, respectively, and treat the unbound two-exciton continuum states ($|X^+X^-_{unb}\rangle$) as a single level by $|3\rangle$ [10,16]. In the excitation region, the states $|1\rangle$, $|2\rangle$, and $|3\rangle$ form a Λ -type three-level system via Coulomb correlations and the destructive quantum interference between two absorption pathways ($|1\rangle$ to $|3\rangle$ and $|2\rangle$ to $|3\rangle$) causes EIT with a two-photon resonance. As mentioned above, since the pulse duration of coupling is much longer than that of probe and zero time delay between the pulses, we can assume that the state $|1\rangle$ is initially populated before the probe pulse arrives under the coupling field with longer pulse duration, and is treated as a ground state in the Λ -type three-level system. In the transition configuration, as shown in Figs. 1(c) and 1(d), a V-type system via transitions from $|g\rangle$ to $|1\rangle$ and from $|g\rangle$ to $|2\rangle$ does not create EIT because no common state is shared. In the case of a ladder-type system in GaAs/AlGaAs MQWs, the absorption dip shifts must be opposite the present experimental

results to satisfy the two-photon resonance condition for EIT, which indicates that EIT for the ladder-type model $\{|3\rangle - |1\rangle$ (or $|2\rangle) - |g\rangle\}$ is either not present or very weak to be neglected [10,11].

To analyze the experimental results of Fig. 2, we employ optical Bloch equations (OBEs) for a Λ -type three-level system with first-order perturbation in a weak probe field [10]:

$$\dot{\sigma}_{31}(t) = (i\Delta_p - \gamma_{31})\sigma_{31}(t) + \frac{i}{\hbar}\mu_{31}E_p(t) + \frac{i}{\hbar}\mu_{32}E_c(t)\sigma_{21}(t) \quad (1)$$

$$\dot{\sigma}_{21}(t) = (i(\Delta_p - \Delta_c) - \gamma_{21})\sigma_{21}(t) + \frac{i}{\hbar}\mu_{32}^*E_c^*\sigma_{31}(t) \quad (2)$$

where $\rho_{31}(t) = \sigma_{31}(t)\exp[-i\omega_p t]$ and $\rho_{21}(t) = \sigma_{21}(t)\exp[-i(\omega_p - \omega_c)t]$ are the off-diagonal terms of the density matrix elements, and σ_{31} (σ_{21}) is the slowly varying quantity of $\rho_{31}(t)$ ($\rho_{21}(t)$). The initial population is set: $\rho_{11} = 1$; $\rho_{22} = \rho_{33} = 0$. The ω_p and ω_c are the angular frequencies of the probe and coupling, respectively. The γ_{31} (γ_{21}) is the decay rate of coherence between the state $|3\rangle$ ($|2\rangle$) and the state $|1\rangle$. The μ_{ij} and $\hbar\omega_{ij}$ are the dipole matrix elements and energy differences between states $|i\rangle$ and $|j\rangle$, ($i = j = 1, 2, 3, i \neq j$); Δ_p ($= \omega_{31} - \omega_p$) and Δ_c ($= \omega_{32} - \omega_c$) are the frequency detuning parameters of the probe and coupling pulses; and E_p and E_c are the pulse envelopes of the applied probe and coupling electric fields, respectively. The coupled differential equations are solved using a fourth-order Runge-Kutta method.

The absorbance of the GaAs MQWs is expressed by $A \cong 0.43L\alpha(\omega)$, where L is the total thickness of the GaAs MQWs, and $\alpha(\omega)$ is the absorption coefficient [17]:

$$\alpha(\omega) \cong \frac{\omega}{c\sqrt{\epsilon_{bac}}} \text{Im}[\chi(\omega)] = \frac{2N|\mu_{31}|^2\omega}{\hbar\epsilon_0\sqrt{\epsilon_{bac}}c} \text{Im}\left[\frac{\sigma_{31}(\omega)}{\Omega_p(\omega)}\right] \quad (3)$$

where $\chi(\omega)$ is the susceptibility; N is the number density of carriers; ϵ_0 is the electric permittivity of free space ($\cong 8.85 \times 10^{-12}$ C/V.m); c is the speed of light in vacuum; and $\Omega_p(\omega) = 2\mu_{31}E_p/\hbar$ is the Rabi frequency of the probe. In a resonant region, the dielectric constant can be expressed by $\epsilon_r = \epsilon_{bac} + \chi$, where ϵ_r is the relative dielectric constant of the material and ϵ_{bac} ($\cong 12.7$) is the background dielectric constant far away from the resonant region [12,18]. The red (thinner solid) lines in Figs. 2(a) through 2(f) show the best-fit theoretical data obtained from Eq. (3) via Fourier transformation of Eqs. (1) and (2) for the experimental results of EIT. From the FWHM of 1s HH exciton transition linewidth (~ 1.25 nm) without the coupling pulse, the depth of the absorption dip and the width of EIT are used to calculate both the dipole decoherence rate ($\gamma_{31} \sim 2.0 \times 10^{12}$ Hz) and the nonradiative decoherence rate ($\gamma_{21} \sim 0.8 \times 10^{12}$ Hz). From the analysis for Fig. 2(b) we can calculate the Rabi frequency of the applied coupling field to be ~ 0.38 THz. From this analysis we can conclude that the probe absorption is half reduced by EIT, where the bandwidth is ~ 210 GHz.

Figures 3(a) and 3(b) show the calculation results of the normalized absorption as a function of coupling laser intensity for different values of coherence decay times T_{31} ($= 1/\gamma_{31}$) and T_{21} ($= 1/\gamma_{21}$), respectively, at a zero time delay $\tau = 0$ with zero coupling detuning $\Delta_c = 0$. The absorption reduction via EIT becomes larger as the coupling laser intensity and coherence decay times increase. The decay of nonradiative coherence γ_{21} in semiconductor materials for EIT depends much on the decay of hole spin coherence, which is strongly influenced by the sample quality including alloy fluctuations, surface roughness [19] or defects [20] of each layer.

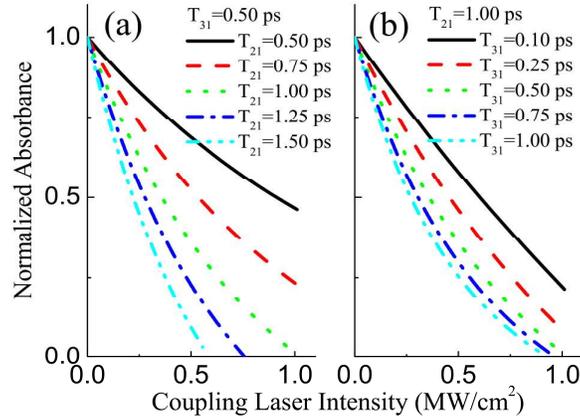


Fig. 3. Calculations for the change of absorption with (a) fixed T_{31} ($= 1/\gamma_{31}$) and various T_{21} ($= 1/\gamma_{21}$), and (b) with fixed T_{21} and various T_{31} as a function of the coupling laser intensity at a zero time delay with a zero coupling laser frequency detuning.

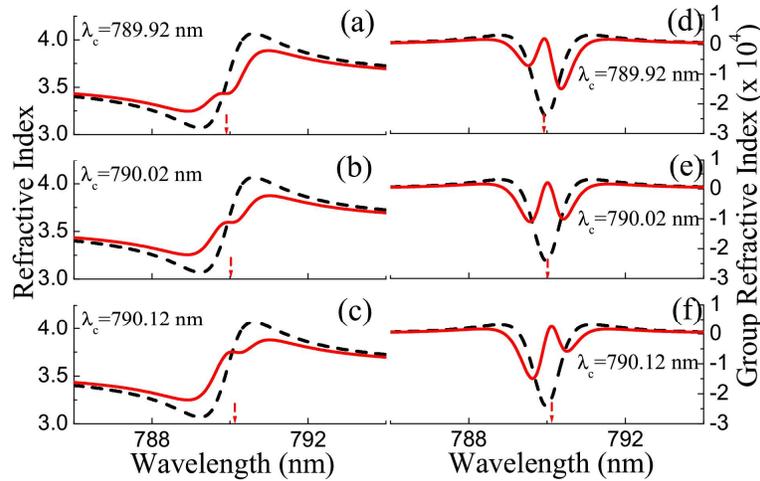


Fig. 4. Calculations (a) ~ (c) for the change of the refractive index and (d) ~ (f) for the group refractive index of GaAs MQWs as a function of wavelength at $\tau = 0$ ps. The dashed lines and solid lines indicate the calculation results without and with coupling laser, respectively. For (a) and (d) $\lambda_c = 789.92$ nm; for (b) and (e) $\lambda_c = 790.02$ nm; and for (c) and (f) $\lambda_c = 790.12$ nm. The dashed arrow indicates the spectral position of the coupling laser pulse.

Since the reduction of the probe absorption via EIT is related to the refractive index change of the medium, this reduction causes group refractive index change as a function of frequency: $n_g(\omega) = (n + \omega dn/d\omega)$, where n is the refractive index. The group refractive index (n_g) represents the ratio of the speed of light in vacuum to the group velocity (v_g) of light in the medium as a slowdown factor: $S = c/v_g$. Using the Kramers–Kronig relation, the slowdown factor S is redefined by the speed of light multiplied by the ratio of depth to width of the EIT dip: $S \approx c\Delta\alpha/(2\pi\Delta\nu_{FWHM})$, where $\Delta\alpha$ and $\Delta\nu_{FWHM}$ are $\sim 9.16 \times 10^6$ m⁻¹ and ~ 210 GHz, respectively [7]. The bandwidth of 210 GHz is far beyond the all-optical switching bandwidth limited by carrier relaxation time determined by exciton recombination processes.

Figure 4 shows the calculation results for the refractive index (n) and the group refractive index (n_g) with and without the coupling laser using the OBEs based on the same parameters obtained from the EIT experiments as shown in Figs. 2 at $\tau = 0$ ps. In the calculations for the line center (coupling laser at $\lambda_c = 790.02$ nm), the change of the refractive index (Δn) is extracted to be ~ 0.11 , and the group refractive index and group velocity are $\sim 2.10 \times 10^3$ and

$\sim 1.44 \times 10^5$ m/s, respectively. Although the group refractive index is relatively small (or group velocity is relatively large) compared with that obtained by PO in Ref. 7, the broader optical bandwidth has benefit for ultrafast active photonic device applications such as photon routing based on slow light phenomena [21].

4. Summary

EIT and slow light in GaAs/AlGaAs MQWs have been investigated via an unbound biexciton state in a transient regime using femtosecond laser light. The changes of refraction, group refractive index, and group velocity of light have been obtained indirectly by calculating the OBEs with the slowdown factor calculated from the EIT experimental results. The results of EIT and slow light of a femtosecond laser pulse show promise for ultrawide bandwidth all-optical information processing such as ultrafast photon routing, where the obtained bandwidth (210 GHz) is beyond the conventional limitation (≤ 100 GHz) of subnanoseconds determined by exciton recombination processes.

Acknowledgment

This work was supported by the CRI program (Center for Photon Information Processing) of the Korean Ministry of Education, Science, and Technology (MEST) via Korea Science and Engineering Foundation (KOSEF), South Korea. BSH acknowledges helpful discussions with Prof. H. Wang of the University of Oregon, USA.