Ultrahigh-bandwidth electrically tunable fast and slow light in semiconductor optical amplifiers [Invited]

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Slow and fast light enables key functionality in various rf applications and all-optical networks. Semiconductor-based schemes offer electrical control of velocity at very high bandwidths in an extremely compact device. Furthermore, they operate at room temperature and can be easily integrated into various optical systems. Ultrafast nonlinear processes in semiconductor optical amplifiers (SOAs) have been used to achieve tunable slow and fast light in the terahertz bandwidth. For a 700 fs pulse, we show an electrically and optically controllable advance of 1.9 ps corresponding to an advance–bandwidth product (ABP) of 2.5. Furthermore, by leveraging self-phase modulation in these devices, we extend the performance to an ABP of 3.7. We develop comprehensive theory using a density matrix approach to explain the experimental results. Our results show that an ultrashort pulse propagating through the SOA experiences nonlinear index change due to spectral-hole burning and wave mixing between different spectral components. We derive analytical expressions for the nonlinear index induced by these ultrafast processes and numerically solve the propagation of an ultrashort pulse through the SOA. Our theoretical predictions agree very well with our experimental results. Finally, we show fast light for two ultrashort pulses separated by 7.2 ps, which demonstrates the feasibility of this scheme at high bit rates. © 2008 Optical Society of America

1. INTRODUCTION

Ability to control the velocity of light has attracted significant attention in recent times due to numerous applications in nonlinear science, rf systems, and optical communication networks [1–3]. Slow and fast light can be used to control the phase of a rf modulated wave at high bandwidths, giving rise to true-time delays (TTD). TTD can be used to effectively steer a rf beam in different directions in a phased-array antenna system and to avoid the squinting problem [4]. In an all-optical network, tunable delays enable a myriad of functionalities including synchronization [5], time-division multiplexing [6], and contention resolution in an optical buffer [1,3]. In a dispersive medium, the group velocity of light (to the first-order approximation) can be expressed as

\[ v_g = \frac{c}{n_g}, \]

where \( n_g = n(\omega) + \frac{\partial n(\omega)}{\partial \omega} \) is the group index and \( n(\omega) \) is the frequency-dependant refractive index of the medium. The group velocity (1) can be significantly altered by changing the group index \( n_g \), in particular by using the dispersion of the refractive index \( n(\omega) \). A large group index can be obtained near the center of a resonance line where there is a large gain–loss variation in a narrow frequency band [2]. Similarly, high-Q resonators can give a large group index due to their narrow linewidths [3]. Several schemes in various media have been realized to slow down the velocity of light significantly [7–9]. Even negative group velocities have been demonstrated using erbium-doped fiber amplifiers (EDFAs) [10].

For several applications including fast radars and all-optical communication networks, control of delays at high bandwidths is extremely desired. A useful metric to characterize the performance of a scheme is the advance/delay–bandwidth product (A/DBP), which is equivalent to normalizing the advance or delay with respect to the pulse duration. Using stimulated Raman scattering in an 8 mm long silicon waveguide, a time shift of 4 ps is demonstrated for a 3 ps pulse [11]. Wavelength conversion and the use of dispersive fiber yield a large controllable delay of 44 ns in a 10 Gbits/s non-return-to-zero (NRZ) system [12]. Schemes based on semiconductor systems have the advantage of providing electrically tunable delays at large bandwidths in an extremely compact device. Coherent population oscillations (CPO) have been used to achieve both slow and fast light at a 13 GHz bandwidth in a quantum-dot semiconductor optical amplifier (SOA) [13]. When a strong pump beam and a weak signal beam (at a different wavelength) propagate in a SOA, beating between the two beams causes oscillations of carrier density. This creates dynamical gain and index gratings in the device. Interaction of the signal with the dynamical gratings results in a group index change for the pulse.
The group index can be controlled either electrically (by changing the bias current of the SOA) or optically (by changing the pump power). Using this method, a group index reduction of 10% is demonstrated in a compact 2 mm device. Tunable delays using exciton resonance take advantage of strong Coulomb interaction between free carriers and excitons in GaAs semiconductor quantum wells [14]. Optical injection of free carriers changes the exciton resonance spectrum; hence the group velocity of a pulse can be controlled optically. A DBP greater than 2 is achieved for an 8 ps pulse using heavy-hole exciton resonance. Gain saturation in quantum dots has also been used to achieve a DBP of 0.4 for an ultrashort 170 fs pulse [15]. In this paper, we review our previous theoretical and experimental work toward achieving a large A/DBP in the terahertz (THz) bandwidth in an extremely compact device (<1 mm). Using ultrafast nonlinear processes in quantum-well semiconductor optical amplifiers, we demonstrate electrically and optically controllable fast light with an ABP of 2.5 for a 700 fs pulse [16]. Here the term fast light refers to the situation where the group velocity is greater than the velocity of light in the medium \( v_g > c/n \). We propose a scheme to extend the ABP to 3.7 using self-phase modulation in these devices.

2. ULTRAFAST NONLINEAR PROCESSES IN SEMICONDUCTORS

An ultrashort pulse propagating through a semiconductor optical amplifier (biased in a gain region) removes the cold electrons and holes via stimulated emission [17]. This creates a spectral hole in the carrier distribution [Fig. 1(a)]. Carriers then relax to equilibrium carrier distribution at the lattice temperature via ultrafast processes: carrier–carrier scattering and carrier–phonon scattering. Carrier–carrier scattering [Fig. 1(b)] involves relaxation of electrons near the spectral hole to thermal equilibrium [Fig. 1(c)] at a temperature higher than the lattice temperature. Then, carriers relax to lattice temperature by the carrier–phonon scattering process [Fig. 1(d)]. Eventually, the density of electrons and holes recovers through carrier injection [Fig. 1(e)]. The typical time scale of carrier–carrier scattering and carrier–phonon scattering is dependent on material systems, device design, and the operating wavelength. In our devices, we measured a relaxation time of 830 fs and 3.3 ps for carrier–carrier scattering and carrier–phonon scattering, respectively [16]. The spectral hole created by an ultrashort pulse propagating through the SOA is sustained over the carrier–carrier scattering time. This spectral hole in carrier distribution is equivalent to a spectral hole in gain distribution. Through Kramers–Kronig relations, a frequency-dependant gain caused by the spectral hole translates to a frequency-dependant index change and correspondingly to a change of the group index for the pulse. In this case, a dip in the gain spectrum results in fast light for the pulse. Furthermore, for an ultrashort pulse, beating between several frequency components results in intraband population oscillations [18] similar to CPO described earlier [8,13]. This finally leads to an additional change of the group index for the pulse. Recently, we showed that this additional contribution results in a larger advance for the pulse [19]. Similarly, a SOA biased in a loss region experiences a delay due to these nonlinear processes. Index change induced by these processes depends on the gain in the device. Hence, pulse delay and advance can be tuned electrically by changing the applied bias to the SOA.

3. EXPERIMENTAL DEMONSTRATION OF SLOW AND FAST LIGHT

Figure 2 shows the schematic of the setup to realize fast light in semiconductor optical amplifiers [16]. A mode-locked fiber laser operating in the C-band acts as a sub-

![Fig. 1. (Color online) Schematic showing the response of a semiconductor medium biased in a gain region to an ultrashort pulse. (a) An ultrashort pulse burns a hole in the carrier distribution. (b) Carrier–carrier scattering and carrier–phonon scattering are ultrafast processes that restore the carriers to intraband equilibrium on a picosecond time scale. (c) Carrier–carrier scattering causes carriers to reach intraband equilibrium at a temperature higher than the lattice temperature. (d) Carrier–phonon scattering then relaxes the carriers to lattice temperature. (e) Electrons and holes eventually reach equilibrium through carrier injection.](image1)

![Fig. 2. (Color online) Experimental setup to realize fast light in semiconductor optical amplifiers. Output from the mode-locked laser is split into a reference (99%) and a signal (1%). The time shift of the signal is controlled by changing the SOA bias. As the SOA gain is increased by increasing the bias, the pulse experiences an advance. Similarly, when the SOA bias is decreased below transparency, the pulse experiences a delay.](image2)
picosecond pulse source. The pulses have a FWHM of 700 fs with a repetition rate of 25 MHz. The output of the fiber laser is split into two branches. The 99% branch acts as a reference and goes through a delay line before entering the cross correlator. The power of the signal (1% branch) entering the SOA is controlled using a variable attenuator. Polarization of the signal is adjusted to align with the principal gain axis of the optical amplifier. The SOA used in this experiment is a quantum-well device from JDSU operating at 1550 nm with a small signal gain of 20 dB at a bias current of 200 mA. The output of the SOA goes through an EDFA before entering the cross correlator. Cross correlation with the reference enables the pulse amplitude and advance to be recorded as the SOA current is increased.

The energy of the 700 fs pulses at the input of the SOA is \( \sim 1 \text{ pJ} \). Figure 3 shows normalized cross-correlation traces as the SOA current is increased from near transparency (50 mA) to maximum gain (200 mA). It should be noted that cross-correlation traces appear broader than the actual pulse due to the finite width of the reference. We see a large advance \( \tau \) of 1.9 ps with increasing current. This corresponds to a normalized advance \( \tau/\Delta \tau_{\text{in}} \) where \( \Delta \tau \) is the FWHM of the pulse) or ABP of 2.5. A larger advance with an increasing SOA current can be explained by the theory described earlier. As the SOA gain increases, the depth of the spectral hole created by the pulse and the strength of the intraband population oscillations increase. Both of these effects contribute to a larger index change for the pulse. A tunable advance of 1.9 ps in a 1 mm long device corresponds to a significant nonlinear index change of \( -0.6 \) at THz bandwidth. Here it is worth mentioning that even though the pulse experiences fast light, the index change is less than the refractive index \( n \sim 3.5 \) of the medium. Hence causality is not violated in this scheme because the pulse still propagates with a positive group velocity in the medium. Figure 4 shows the amplitude change as a function of the SOA current. The amplitude change as the SOA current is increased from 50 to 200 mA is less than 11 dB. The amplitude variation is much less than the linear gain (20 dB) because the pulses saturate the amplifier at a current of 100 mA. Pulses at the output are broader due to dispersion in various fiber-based components. However, pulse broadening variation due to the fast-light effect is less than 50%.

Fig. 3. (Color online) Cross-correlation traces as the SOA current is varied. Cross-correlation traces appear broader than the actual pulses due to the finite width of the reference (700 fs). A large advance of 1.9 ps is observed for a 700 fs pulse as the SOA current is increased from transparency (50 mA) to maximum gain (200 mA). This corresponds to an ABP of 2.5.

Fig. 4. (Color online) Amplitude change and pulse broadening as the SOA current is varied. Amplitude change as the current is increased from 50 to 200 mA is less than 11 dB. The amplitude variation is much less than the linear gain (20 dB) because the pulses saturate the amplifier at a current of 100 mA. Pulses at the output appear broader due to dispersion in various fiber-based components. However, pulse broadening due to the fast-light effect varies by only 50% as the SOA current is varied. The pulse peak amplitude decreases as the current is increased beyond 100 mA as a result of pulse broadening due to the fast-light effect.

By operating the SOA in a loss region, we expect to see a large delay. Figure 5 shows normalized cross-correlation traces for a 600 fs input pulse, as the current is decreased from near transparency (50 mA) to the loss region extremely large, impractical gain of 6200 dB [20]. By using nonlinear processes in SOAs, we can achieve the same ABP with a gain change of less than 11 dB. Pulse broadening \( \Delta \tau_{\text{out}} - \Delta \tau_{\text{in}} / \Delta \tau_{\text{in}} \) is also plotted as a function of the SOA current. Pulses at the output appear broader due to the large amount of fiber present in various fiber-based components, including the SOA and EDFA. However, pulse broadening due to the fast-light effect varies by only 50% as the SOA current is varied. The pulse peak amplitude decreases as the current is increased beyond 100 mA as a result of pulse broadening due to the fast-light effect.

Fig. 5. (Color online) Cross-correlation traces for a 600 fs input pulse. A large delay of 0.75 ps is observed as the SOA current is decreased from transparency (50 mA) to the loss region (20 mA). As the SOA current is increased from transparency (50 mA) to the gain region (100 mA), a large advance of 0.77 ps is observed. A total time shift of 1.52 ps corresponds to an ABP of 2.5.
(20 mA). We see a large delay of 0.75 ps. As expected, increasing the current from 50 to 100 mA gives an advance of 0.77 ps. Combining the results of advance and delay, we achieve a continuous tunable shift of 1.52 ps, corresponding to an ABP of 2.5. In this case, we used a higher input power so that we can detect the signal in the loss region. As a result, the pulse is broadened for large currents. A more sensitive cross correlator would enable us to achieve the same ABP without increased broadening.

The pulse advance can also be optically controlled by varying the input power. Since the depth of the spectral hole is proportional to the pulse power, we expect to see an advance with increasing input power. A constant SOA bias of 100 mA is used in this experiment. Figure 6 shows the time traces as the pulse energy of a 700 fs pulse is increased by 3 orders of magnitude from 1 fJ to 1 pJ. A large ABP of 1.3 is observed in this case. An EDFA at the output of the SOA can be used to maintain a constant output power as the input power is varied.

4. FAST LIGHT USING CASCADED SEMICONDUCTOR OPTICAL AMPLIFIERS

In this section, we investigate the possibility of increasing the advance for an ultrashort pulse by cascading two SOAs. The experimental setup is similar to the one shown in Fig. 2 except isolators are added to prevent amplified spontaneous emission (ASE) from the second SOA entering the first SOA. The current of each of the SOAs is controlled independently. Figure 7 shows the cross-correlation traces for a 600 fs pulse with increasing SOA current. From the time traces it is evident that, as the current of the first SOA is increased keeping the other approximately constant, a large advance for the pulse is observed. By increasing the current of the second SOA, we obtain additional advance. A total advance of 2 ps for a 600 fs pulse corresponds to an ABP of 3.3. When we increased the current to higher values than shown in the figure (>100 mA), we observed pulse distortion and the appearance of the pedestal. This distortion could be a result of the high peak power of the pulse entering the second SOA. As mentioned earlier, as the SOA gain increases, the depth of the spectral hole created by the pulse increases. A deeper spectral hole results in a large index change and hence an advance for the pulse. However, the maximum depth of the spectral hole saturates when the peak power of the pulse is large enough to drive the local carrier concentration to transparency. Increasing the current beyond this value causes significant distortion for the pulse and results in a pedestal.

Comparing the ABP of 3.3 for two SOAs with the earlier result of 2.5 for a single SOA shows that cascading multiple SOAs results in a higher ABP. However, as the number of SOAs is increased, the incremental benefit of adding additional SOAs diminishes. This is mainly due to the coupling of amplified spontaneous noise from one SOA to the other, which reduces the available gain in the second SOA and also adds noise to the signal. Furthermore, pulse broadening from each of the SOAs contributes to deterioration of performance. These problems can be mitigated by adding attenuators, optical filters, and dispersion compensators after each SOA. By adding a variable attenuator after each SOA, the input power of the pulse entering the SOA can be controlled, which helps in reducing the distortion at high SOA currents. An optical filter aids in removing the unnecessary spontaneous emission contribution from one SOA entering the next SOA, whereas dispersion elements compensate for the broadening induced by the fast-light effect. To understand the potential and limitations of cascading multiple SOAs, we propose a scheme based on a SOA in a loop configuration that uses a single SOA to mimic the effect of cascading multiple SOAs.

The experimental setup for this scheme is shown in Fig. 8. The output of the fiber laser is split into reference and signal. The signal pulse enters the 10% branch of the input 90:10 splitter and passes through the SOA. The output of the SOA is further split using a second 90:10 splitter. The 90% branch goes through the EDFA before enter-
ing to cross correlator while the 10% branch goes through a variable attenuator before entering the 90% branch of the input splitter. The two splitters combined with the SOA form a loop configuration. Hence, the signal pulse goes through the SOA multiple times. In this case, the variable attenuator is adjusted so that there is a net loss in the loop, which prevents lasing in the loop due to ASE. Hence, the amplitude of the pulse going through the SOA multiple times diminishes. By adjusting the fixed delay arm of the reference, we can selectively observe the advance of the pulse that has gone through the SOA multiple times. Figure 9 shows the cross-correlation traces for a single-pass pulse and a double-pass pulse. For a single-pass pulse, increasing the current from transparency to 100 mA gives an advance of 0.64 ps. However, the advance for a double-pass pulse is increased to 1.17 ps, which is roughly double the advance for a single-pass pulse, which clearly demonstrates the improvement in performance. However, the pulse broadening for this case is also roughly twice that of the single-pass case. Increasing the current beyond 100 mA causes lasing in the loop due to ASE. By inserting an optical filter to remove the ASE, higher SOA currents can be used, which will give more advance for the pulse. By adding a dispersion compensator in the loop, pulse broadening and distortion can be significantly reduced.

5. THEORY AND SIMULATION RESULTS

Propagation of an ultrashort pulse through a semiconductor optical amplifier can be modeled using the density matrix equations for a semiconductor and the propagation equation for the pulse [18, 21]. Numerically solving the full density matrix equations, which describe detailed population and polarization dynamics for each carrier state and optical transition in a semiconductor, is computationally intensive and does not yield considerable insight into the physics of the problem. For these reasons, we solve the equations analytically using adiabatic approximation with the first-order correction over the parameter $\tau_2/\tau_{\text{pulse}}$ ($\tau_2$ is the dephasing time, $\tau_{\text{pulse}}$ is the pulse duration) in order to include nonadiabaticity [21]. Finally, we obtain the analytical expressions for nonlinear group indices due to ultrafast processes [19] described earlier (Section 2). The contribution to the group index due to optical transitions in a semiconductor can be expressed as

$$\Delta n_g = \Delta n_g^{\text{lin}} + \Delta n_g^{\text{SHB}} + \Delta n_g^{\text{CH}},$$

where $\Delta n_g^{\text{lin}}(N)$ is the linear contribution to the group index related to the dependence of linear gain $g_{\text{lin}}(N, \omega)$ on the photon frequency $\omega$, where $N$ is the carrier density. $\Delta n_g^{\text{SHB}}$ and $\Delta n_g^{\text{CH}}$ are the nonlinear contribu-
tions to the group index due to spectral-hole burning (SHB) and carrier heating (CH) respectively. Assuming that the SOA gain bandwidth is much larger than $1/\tau_g$, the contribution from SHB can be written as

$$\Delta n_g^{\text{SHB}} = \Delta n_g^{\text{SHB-DIP}} + \Delta n_g^{\text{SHB-FWM}},$$

$$\Delta n_g^{\text{SHB-DIP}} = -\tau_c g_{\text{lin}}^* n_{\text{SHB}} S/4,$$

$$\Delta n_g^{\text{SHB-FWM}} = -3\tau_c g_{\text{lin}}^* n_{\text{SHB}} S/4,$$

(3)

where $\Delta n_g^{\text{SHB-DIP}}$ is the contribution from the creation of a spectral hole in an otherwise broad gain spectrum. $g_{\text{SHB}}$ is the gain suppression factor due to SHB and $S$ is the photon density. $\Delta n_g^{\text{SHB-FWM}}$ is the contribution from wave mixing between different components of the pulse that leads to intraband population oscillations. These oscillations in turn lead to oscillation of the depth of the spectral hole, which gives a group index change for the pulse similar to CPO [8,13]. Contribution from carrier heating can be expressed as

$$\Delta n_g^{\text{CH}} = -\tau_c g_{\text{lin}}^* n_{\text{CH}} S,$$

(4)

where $\tau_c$ is the carrier heating time. Using group indices (2) and (3), we solved the propagation equation for the pulse. Results of the simulation shown in Fig. 10 elucidate the importance of nonlinear effects. Input into the SOA is a hyperbolic secant with a FWHM of 700 fs. Using a simple gain saturation model by neglecting the contributions from SHB and CH [22] shows an advance of 0.5 ps. However, for an ultrashort pulse, gain suppression due to nonlinear effects is extremely important. Taking into account the nonzero gain suppression ($g_{\text{SHB}} \neq 0$, $n_{\text{CH}} \neq 0$) while neglecting the contribution due to nonlinear group index ($\Delta n_g = 0$) leads to an advance of only 0.2 ps. However, including the index change due to nonlinear effects yields a large advance of 1.4 ps corresponding to an ABP of 2.0. Pulse shape at this condition shows strong self-steepening due to the nonlinear group indices. This strong self-steepening is because of the first-order correction to the pure adiabatic consideration of intraband carrier dynamics [19]. Solving the pulse propagation equation with higher-order corrections yields a better pulse shape as we will show at the end of Section 6.

6. ENHANCING THE ABP USING SHORTER PULSES

As the pulse width decreases, the spectral hole created by the pulse does not relax significantly during the pulse transit time. Hence, the pulse experiences significant fast light due to the spectral hole, which contributes to a larger advance. Furthermore, changes in carrier density and carrier temperatures result in a refractive index change and correspondingly in a phase change for the pulse, which is usually referred to as self-phase modulation (SPM) [22,23]. Large linewidth enhancement factors due to carrier density ($\alpha_N$) and carrier temperature ($\alpha_T$) [21] in SOAs contribute to large SPM. In a SOA biased in the gain region, a reduction in the local carrier density due to pulse propagation causes a redshift (longer wavelengths) for the pulse. Figure 11 shows the wavelength shift caused by SPM for different SOA currents. As expected, the redshift increases with increasing SOA current [20]. At a SOA current of 100 mA, we see a redshift of 6 nm. By adding dispersive elements after the SOA, we can leverage the SPM to achieve a larger advance. Here the term dispersive element is used to emphasize the fact that the group delay through the element is a function of frequency. Hence, a change in frequency due to SPM with increasing SOA current translates to a time shift for the pulse. In this experiment, we use a grating-based chirper that introduces a time shift that changes linearly with frequency. Hence, we refer to this as a linear chirper. The chirper in this case also helps in obtaining a better pulse shape by compensating for SOA-induced chirp. The total advance through the system can be mathematically expressed as

![Fig. 10. (Color online) Results of the simulation for a 700 fs pulse propagating through a SOA with a linear gain of 30 dB. A dephasing time of 100 fs and a carrier heating time of 650 fs is used in this simulation. When we neglect the contribution due to nonlinear effects, we see an advance of 0.5 ps corresponding to an ABP of only 0.7. Modification of the model to include nonlinear gain decreases the advance to 0.2 ps due to nonlinear gain suppression. However, including the gain and index change due to SHB and CH gives a large advance of 1.4 ps (ABP 2).](image-url)

![Fig. 11. (Color online) Spectra for a 370 fs pulse for various SOA currents at an input pulse energy of 4 pJ. An increasing SOA current causes a redshift for the pulse due to self-phase modulation. At a SOA current of 100 mA, a redshift of 6 nm is observed. The oscillatory structure observed in the spectrum at high currents is typical of nonlinear processes.](image-url)
\[ T_{\text{adv}} = T_{\text{NL}} + T_{\text{SPM}}, \]  

where \( T_{\text{NL}} \) is the advance due to nonlinear effects (SHB and CH) and \( T_{\text{SPM}} \) is the advance due to SPM. Both of these time shifts are a function of SOA current and hence can be controlled electrically.

The experimental setup is similar to the one described earlier, except a chirper is added after the SOA to leverage SPM. Figure 12 shows the cross-correlation traces as a function of the SOA current for a 190 fs input pulse. A total advance of 0.71 ps is observed as the current is increased from transparency (50 mA) to maximum gain (300 mA), corresponding to a large ABP of 3.7. The amplitude variation is less than 10 dB as the current is varied. The value of the chirp is chosen so as to obtain an optimized pulse shape and is fixed at a particular value as the current is varied. The pulse broadening for this case is less than 100%.

Figure 13 shows the advance and ABP as the pulse width is swept from 1 ps to 86 fs. The peak power is maintained constant as the pulse width is varied because the nonlinear index change is dependent on the peak power. The advance increases almost linearly with increasing pulse width. However, the ABP increases as the pulse width decreases. A maximum ABP of 6.5 is achieved for the lowest pulse width of 86 fs. However, for this case the maximum broadening is close to 250%. This broadening is a result of the large amount of fiber in our EDFA and is due to the fact that the linear chirper employed in this experiment cannot exactly compensate for the nonlinear chirp induced by the SOA. Pulse broadening can be reduced by employing tailored chirpers.

We simulate pulse propagation in a SOA using the density matrix approach described earlier and propagation through the chirper by adding a quadratic phase as described in [24]. Figure 14 shows the simulation results for a 190 fs pulse as the linear gain is increased from 0 to 30 dB, corresponding to a SOA current of 50 and 300 mA, respectively. From the simulation, we observe an advance of 0.71 ps, which agrees very well with our experimental results. Furthermore, time traces at higher currents do not show self-steepening compared with the earlier case (Fig. 10) because of the inclusion of higher-order terms.

7. FAST LIGHT FOR TWO PULSES IN SUCCESSION

For applications related to optical networks, it is desirable to achieve a large ABP for a train of pulses. Experimental results presented here so far have been focused on achieving a large ABP for a single pulse. Here, we present experimental results for two pulses successively entering the SOA. A large ABP for both the pulses can be achieved if the carriers depleted by the first pulse relax quickly enough before the second pulse enters the SOA. The SOAs used in this study have an extremely fast gain recovery time of 25 ps. Hence, we expect to see a large ad-
8. CONCLUSION

Ultrahigh bandwidth slow and fast light is extremely useful in various rf systems and future-generation all-optical networks. Using ultrafast nonlinear processes including spectral-hole burning and carrier heating, we demonstrate a large ABP of 2.5 for a 700 fs pulse. This advance can be either controlled electrically by changing the SOA bias or optically by changing the input power. Our theoretical results show that the index change is mainly due to two effects: a spectral hole created by an ultrashort pulse and wave mixing between different spectral components of the pulse. Self-phase modulation in SOAs can be leveraged to achieve a larger advance by employing a chirper after the SOA. Using this scheme, we demonstrate a tunable advance of 0.71 ps for a 190 fs pulse corresponding to an ABP of 3.7. The theory developed using the density matrix approach is used to accurately simulate the ultrashort pulse propagation in our optical amplifiers. Finally, we demonstrate significant fast light for two 630 fs pulses separated by 7.2 ps.

REFERENCES


