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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. Further they operate at room temperature and can be easily integrated into various optical systems. Ultra-fast non-linear processes in semiconductor optical amplifiers (SOAs) have been used to achieve tunable advance and delay at THz bandwidth. For a 700fs pulse, we show electrically and optically controllable advance of 1.9 ps corresponding to an advance-bandwidth product (ABP) of 2.5. Further, by leveraging self-phase modulation in these devices we extend the performance to an ABP of 3.7. We develop comprehensive theory using density matrix approach to explain the experimental results. Our results show that an ultra-short pulse propagating through the SOA experiences non-linear index change due to spectral-hole burning and wave mixing between different spectral components. We derive analytical expressions for non-linear index induced by these ultra-fast processes and numerically solve the propagation of an ultra-short pulse through the SOA. Our theoretical predictions agree very well with our experimental results. Finally, we show fast light for two ultra-short pulses separated by 7.2ps which demonstrates the feasibility of this scheme at high bit-rates.

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Final Report

Ultrabroad Bandwidth Slow Light in Semiconductor Nanostructures

Supported by DARPA Slow Light Program Contract N00014-06-1-0920

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Abstract

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. Further they operate at room temperature and can be easily integrated into various optical systems. Ultra-fast non-linear processes in semiconductor optical amplifiers (SOAs) have been used to achieve tunable advance and delay at THz bandwidth. For a 700 fs pulse, we show electrically and optically controllable advance of 1.9 ps corresponding to an advance-bandwidth product (ABP) of 2.5. Further, by leveraging self-phase modulation in these devices we extend the performance to an ABP of 3.7. We develop comprehensive theory using density matrix approach to explain the experimental results. Our results show that an ultra-short pulse propagating through the SOA experiences non-linear index change due to spectral-hole burning and wave mixing between different spectral components. We derive analytical expressions for non-linear index induced by these ultra-fast processes and numerically solve the propagation of an ultra-short pulse through the SOA. Our theoretical predictions agree very well with our experimental results. Finally, we show fast light for two ultra-short pulses separated by 7.2 ps which demonstrates the feasibility of this scheme at high bit-rates.

I. AWARDS AND HONORS BY CONNIE CHANG-HASNAIN

Nick Holonyak Jr. Award, Optical Society of America, 2007.

Citation: for significant contributions to vertical cavity surface emitting laser arrays, injection locking and slow light

II. AWARDS RECEIVED BY MENTORED STUDENTS

1. Forrest Sedgwich received the 2008-09 **Leon Chua Award.** This award is presented to a graduate student or undergraduate student or recent alumnus for outstanding research in the area of nonlinear science.
2. Bala Pesala, **Demetri Angelakos Award,** EECS, University of California, Berkeley 2009
3. **Best Paper of Topical Meeting,** OSA Slow and Fast Light Topical Meeting, 2007.

   Bala Pesala, Forrest G. Sedgwick, Alexander V. Uskov, Connie Chang-Hasnain, Tony H. Lin, "THz Tunable Slow Light and Fast Light of Ultrashort Pulses in Semiconductor Optical Amplifiers"

4. P. C. Ku, **Ross Tucker Award, AIME Electronic Materials Awards**, 2004

III. PUBLICATIONS

A. PLENARY TALKS

1. C. J. Chang-Hasnain, "Slowing and Stopping Light", SPIE Photonics West, Optoelectronics Symposium, January 2005.
2. C. J. Chang-Hasnain, "Slow Light in Semiconductors", Conference on Nanostructures: Physics and Technology, St. Petersburg, Russia, June 21-25, 2004
3. C. J. Chang-Hasnain, "Progress in Tunable VCSELs for WDM Applications", International Semiconductor Lasers Conference, Garmisch, Germany, September 30, 2002

B. INVITED REFERRED JOURNAL PUBLICATIONS

1. Bala Pesala, Forrest Sedgwick, Alexander Uskov, and Connie Chang-Hasnain, "Ultrahigh-bandwidth electrically tunable fast and slow light in semiconductor optical amplifiers", JOSA B, Vol. 25, Issue 12, pp. C46-C54 (2008)
2. P.C. Ku, C. J. Chang-Hasnain and S.L. Chuang, "Slow light in semiconductor heterostructures", J. Phys. D, January 2007.
3. C. J. Chang-Hasnain and S.L. Chuang, "Slow and Fast Light in Semiconductor Quantum-well and Quantum-dot Devices", IEEE Journal of Lightwave Communications, Special Issue on Optoelectronics, 24, 12, pp. 4642-4654, December 2006.

C. REFERRED JOURNAL PUBLICATIONS

4. Bala Pesala, Forrest G. Sedgwick, Alexander V. Uskov, and Connie Chang-Hasnain, "Greatly enhanced slow and fast light in chirped pulse semiconductor optical amplifiers: Theory and experiments," Optics Express Vol. 17, No. 4, pp. 2188-2197, February 2009.
5. Bala Pesala, Forrest Sedgwick, Alexander Uskov, and Connie Chang-Hasnain, "Ultrahigh-bandwidth electrically tunable fast and slow light in semiconductor optical amplifiers [Invited]," Journal of Optics Society American B, Vol. 25, No. 12, pp.C46-C54, September 2008.
6. F. G. Sedgwick, Bala Pesala, Alexander V Uskov and C. J. Chang-Hasnain, "Chirp-enhanced fast light in semiconductor optical amplifiers " Optics Express, Vol. 15 Issue 26, pp.17631-17638 (2007)
7. Bala Pesala, F. G. Sedgwick, Alexander V Uskov and C. J. Chang-Hasnain, "Electrically tunable fast light at THz bandwidth using cascaded semiconductor optical amplifiers", Optics Express, Vol. 15 Issue 24, pp.15863-15867 (2007)
8. Xiaoxue Zhao, Devang Parekh, Erwin K. Lau, Hyuk-Kee Sung, Ming C. Wu and Connie J. Chang-Hasnain, Werner Hofmann and Markus C. Amann, "Novel cascaded injection-locked 1.55-μm VCSELs with 66 GHz modulation bandwidth", Optics Express, 15, 22, 14810, Oct. 29, 2007
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10. F. G. Sedgwick, Bala Pesala, Jui-Yen Lin, Wai Son Ko, Xiaoxue Zhao, and C. J. Chang-Hasnain, "THz-bandwidth tunable slow light in semiconductor optical amplifiers", Vol. 15, No. 2, OPTICS EXPRESS 747, 22 January 2007
11. Bala Pesala, Zhangyuan Chen, Alexander V. Uskov and Connie Chang-Hasnain, "Experimental Demonstration of Slow and Superluminal Light in Semiconductor Optical Amplifiers", Vol. 14, No. 26, OPTICS EXPRESS 12968, 25 December 2006

12. A. Uskov, Forrest Sedgwick, and Constance J. Chang-Hasnain, "Delay Limit of Slow Light in Semiconductor Optical Amplifiers", IEEE Photonics Technology Letters, Vol. 18, 6, pp. 731 – 733, March 2006.
13. Rodney S. Tucker, Pei-Cheng Ku, and Constance J. Chang-Hasnain, "Slow-Light Optical Buffers: Capabilities and Fundamental Limitations", Journal of Lightwave Communications, Vol. 23, 12, pp. 4046 – 4066, Dec. 2005
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D. REFERRED CONFERENCE PROCEEDINGS

26. Bala Pesala, Forrest G. Sedgwick, Alexander Uskov and Connie Chang-Hasnain, "Theory and Experiment of chirped-pulse THz slow and fast light in semiconductor optical amplifiers", Frontier in Optics (FiO '08)/Laser Science XXIV (LS) Conference, New York, U.S.A, October 19-23, 2008.
27. Bala Pesala, Forrest G. Sedgwick, Waison Ko and Connie Chang-Hasnain, "Electrically tunable fast light of 86fs pulses in Semiconductor Optical Amplifiers", OSA topical meeting, Boston MA, USA 13-16 July 2008.
28. Forrest G. Sedgwick, Bala Pesala and Connie J. Chang-Hasnain, "Chirped-Pulse Slow and Fast Light in SOA with a Record Delay-Bandwidth Product of 10.7," Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 4-9 May 2008

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31. Forrest G. Sedgwick, Bala Pesala, Jui-Yen Lin, Connie J. Chang-Hasnain and Tony Lin, "Increase of Fractional Advance in THz-Bandwidth Fast Light by Pulse Chirping in an SOA," OSA topical meeting on slow and fast light, Salt Lake City, Utah, USA, 8-11 July 2007.
32. Bala Pesala, Forrest G. Sedgwick, Alexander V. Uskov, Connie Chang-Hasnain and Tony H. Lin, "THz Tunable Slow Light and Fast Light of Ultrashort Pulses in Semiconductor Optical Amplifiers", OSA topical meeting on slow and fast light, Salt Lake City, Utah, 8-11 July 2007.
33. Bala Pesala, F.G. Sedgwick and Connie Chang-Hasnain, "Ultra High Bandwidth THz Tunable Delays using Cascaded Semiconductor Optical Amplifiers", CLEO, Baltimore, MD, 7-11 May 2007
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44. SHU-WEI CHANG, SHUN-LIEN CHUANG, University of Illinois at Urbana-Champaign, CONNIE J. CHANG-HASNAIN, University of California at Berkeley, HAILIN WANG, "Slow Light Using Electromagnetically Induced Transparency from Spin Coherence in [110] Strained Quantum Wells", APS Annual Meeting, March 2005

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49. P. C. Ku, C. J. Chang-Hasnain, J. Kim, and S. L. Chuang, "Novel Semiconductor Mach-Zehnder Modulators with Low Drive Voltage V_π", OSA Annual Meeting, Tucson, AZ, Oct. 2003
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IV. TECHNICAL REPORT

1. INTRODUCTION

Ability to control the velocity of light has attracted significant attention in recent times due to numerous applications in non-linear science, RF systems and optical communication networks [1-3]. Slow and fast light can be used to control the phase of an RF modulated wave at high bandwidths giving rise to true-time delays (TTD). TTD can be used to effectively steer an 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, group velocity of light (to the first-order approximation) can be expressed as

$$v_g = \frac{c}{n_g} \qquad (1)$$

where $n_g = n(\omega) + \omega \frac{\partial n}{\partial \omega}$ is the group index, $n(\omega)$ 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 line-widths [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 [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 A/DBP (Advance/delay bandwidth product), which is equivalent to normalizing 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 Gb/sec 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 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. 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 takes 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. 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 ultra-short 170 fs pulse [15]. In this paper, we review our previous theoretical and experimental work towards achieving a large A/DBP at THz bandwidth in an extremely compact device (< 1 mm). Using ultra-fast non-linear process in quantum-well semiconductor optical amplifiers we demonstrated electrically and optically controllable ABP of 2.5 for a 700 fs pulse [16]. We propose a novel scheme to extend the ABP to 3.7 using self-phase modulation in these devices.

2. ULTRA-FAST NON-LINEAR PROCESSES IN SEMICONDUCTORS

An ultra-short 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. 1a). Carriers then relax to equilibrium carrier distribution at the lattice temperature via ultra-fast processes: carrier-carrier scattering and carrier-phonon scattering. Carrier-carrier scattering (Fig. 1b) involves relaxation of electrons near the spectral hole to thermal equilibrium (Fig. 1c) at a temperature higher than the lattice temperature. Then, carriers relax to lattice temperature by carrier-phonon scattering process (Fig. 1d). Eventually, the density of electrons and holes recovers through carrier injection (Fig. 1e). 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 [15]. The spectral hole created by an ultra-short pulse propagating through the SOA is sustained over 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 gain spectrum results in fast light for the pulse. Further for an ultra-short pulse, beating between several frequency components results in intra-band 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, an SOA biased in a loss region experiences a delay due to these non-linear 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 set-up to realize fast light in semiconductor optical amplifiers [16]. A mode-locked fiber laser operating in C-band acts as a sub-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 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 recording of pulse amplitude and advance as the SOA current is increased.

The energy of the 700 fs pulses at the input of SOA is ~ 1pJ. Fig. 3 shows normalized cross-correlation traces as 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 finite width of the reference. We see a large advance (τ) of 1.9 ps with increasing current. This corresponds to a normalized advance ($\tau/\Delta\tau_{in}$, where $\Delta\tau$ is the FWHM of the pulse) or ABP of 2.5. Larger advance with increasing SOA current can be explained by the theory described earlier. As SOA gain increases, depth of the spectral hole created by the pulse and the strength of intra-band population oscillations increases. Both of these effects contribute to a larger index change for the pulse. Tunable advance of 1.9 ps in a 1 mm long device corresponds to a significant non-linear index change of -0.6 at THz bandwidth. Here it's worth mentioning that even though the pulse experiences fast light, the index change is less than the refractive index (n ~ 3.5) of the medium. Hence causality is not violated in this scheme as the pulse still propagates with a positive group velocity in the medium. Fig. 4 shows the amplitude change as a function of SOA current. The amplitude change as the SOA current is increased from 50 mA to 200 mA is less than 11 dB. The amplitude variation is much less than the variation of the small signal gain with bias current (20 dB) because the device is operating under the saturation regime due to the large peak power of the pulse. It is interesting to note that achieving an ABP of 2.5 using a slow light scheme based on group index change over a resonance line requires an extremely large impractical gain of 6200 dB [21]. By using non-linear processes in SOAs, we can achieve the same ABP with gain change of less than 11 dB. Pulse broadening (defined as $(\Delta\tau_{out}-\Delta\tau_{in})/\Delta\tau_{in}$) is also plotted as a function of SOA current. Pulses at the output appear broader due to the large amount of fiber present in various fiber based components including SOA and EDFA. However, pulse broadening due to fast light effect varies only by 50% as the SOA current is varied. Pulse peak amplitude decreases as current is increased beyond 100 mA as a result of pulse broadening due to fast light effect.

By operating the SOA in loss region, we expect to see a large delay. Fig. 5 shows normalized cross-correlation traces for a 600 fs input pulse, as the current is decreased from near transparency (50 mA) to loss region (20 mA). We see a large delay of 0.75 ps. As expected, increasing the current from 50 mA 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 loss region. As a result, pulse is broadened at large currents. A more sensitive cross-correlator would enable us to achieve the same ABP without increased broadening.

Pulse advance can also be optically controlled by varying the input power. Since the depth of the spectral hole is proportional to pulse power, we expect to see an advance with increasing input power. A constant SOA bias of 100 mA is used in this experiment. Fig. 6 shows the time traces as the pulse energy of a 700 fs pulse is increased by three orders of magnitude from 1fJ to 1pJ. A large ABP of 1.5 is observed in this case. An EDFA at the output of SOA can be used to maintain a constant output power as the input power is varied.

4. FAST LIGHT USING CASCADED SOAs

In this section, we investigate the possibility of increasing the advance for an ultra-short pulse by cascading two SOAs. Experimental set-up is similar to the one shown in fig. 2 except isolators are added to prevent ASE from 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's 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 high peak power of the pulse entering the second SOA. As mentioned earlier, as the SOA gain increases, 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 higher ABP. However, as the number of SOAs is increased, the incremental benefit of adding additional SOA 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. Further, 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 variable attenuator after each SOA, input power of the pulse entering the SOA can be controlled which helps in reducing the distortion at high SOA currents. 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 limitation of cascading multiple SOAs, we propose a novel scheme based on an SOA in a loop configuration that uses a single SOA to mimic the effect of cascading multiple SOAs.

The experimental set-up for this scheme is shown in fig. 8. The output of the fiber laser is split into reference and signal. 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 entering 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, variable attenuator is adjusted so that there is a net loss in the loop which prevents lasing in the loop due to ASE. Hence, 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, pulse broadening for this case is also roughly twice compared to single-pass case. Increasing the current beyond 100 mA causes lasing in the loop due to ASE. By inserting an optical filter to remove 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 ultra-short 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, 20]. Numerically solving the full density matrix equations, which describe detailed population and polarization dynamics for each carrier state and optical transition in semiconductor is computationally intensive and doesn't 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 τ_2/τ_{pulse} (τ_2 is the dephasing time, τ_{pulse} is the pulse duration) in order to include non-adiabaticity [20]. Finally, we obtain the analytical expressions for non-linear group indices due to ultra-fast processes [19] described earlier [Sec. 2]. The contribution to the group index due to optical transitions in semiconductor can be expressed as

$$\Delta n_g = \Delta n_g^{lin} + \Delta n_g^{SHB} + \Delta n_g^{CH} \quad (2)$$

where $\Delta n_g^{lin} = \Delta n_g^{lin}(N)$ is the "linear" contribution to the group index related to the dependence of "linear" gain $g_{lin} = g_{lin}(N,\omega)$ on the photon frequency ω, where N is carrier density. Δn_g^{SHB}, Δn_g^{CH} are the non-linear contributions to the group index due to spectral-hole burning and carrier heating respectively. Assuming that the SOA gain bandwidth is much larger than $1/\tau_2$, the contribution from SHB can be written as

$$\begin{aligned} \Delta n_g^{SHB} &= \Delta n_g^{SHB-DIP} + \Delta n_g^{SHB-FWM}, \\ \Delta n_g^{SHB-DIP} &= -\tau_2 c g_{lin}.\varepsilon_{SHB} S/4 \\ \Delta n_g^{SHB-FWM} &= -3\tau_2 c g_{lin}.\varepsilon_{SHB} S/4 \end{aligned} \quad (3)$$

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

$$\Delta n_g^{CH} = -\tau_h c g_{lin}.\varepsilon_{CH} S \quad (4)$$

where τ_h is the carrier heating time. Using the group indices (2, 3), we solved the propagation equation for the pulse. Results of the simulation shown in Fig. 10 elucidate the importance of non-linear 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 ultra-short pulse gain suppression due to non-linear effects is extremely important. Taking into account the nonzero gain suppression ($\varepsilon_{SHB} \neq 0, \varepsilon_{CH} \neq 0$) while neglecting the contribution due to nonlinear group index ($\Delta n_g \rightarrow 0$) leads to an advance of only 0.2 ps. However, including the index change due to non-linear 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 intra-band carrier dynamics [19]. Solving the pulse propagation equation with higher order corrections yields a better pulse shape as we will show in the latter part of this paper.

6. ENHANCING ABP USING SHORTER PULSES

As the pulse-width decreases, spectral hole created by the pulse doesn't relax significantly during the pulse transit time. Hence, the pulse experiences significant fast light due to the spectral hole which contributes to larger advance. Further, 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) [20, 21]. Large line-width enhancement factors due to carrier density (α_N) and carrier temperature (α_T) [21] in SOAs contribute to large SPM. In an SOA biased in gain region, a reduction in local carrier density due to pulse propagation causes a red shift (longer wavelengths) for the pulse. Figure 11 shows the wavelength shift caused by SPM for different SOA currents. As expected, red shift increases with increasing SOA current [20]. At an SOA current of 100 mA, we see a red shift of 6 nm. By adding dispersive elements after the SOA, we can leverage SPM to achieve larger advance. Here the term "dispersive element" is used 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 which changes linearly with frequency. Hence, we refer to this as linear chirper. Chirper in this case also helps in obtaining a better pulse shape by compensating for SOA induced chirp. Total advance through the system can be mathematically expressed as

$$T_{adv} = T_{NL} + T_{SPM} \qquad (5)$$

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

Experimental set-up is similar to the one described earlier except a chirper is added after the SOA to leverage SPM. Fig. 12 shows the cross-correlation traces as a function of 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. Amplitude variation is less than 10 dB as the current is varied. Value of chirp is chosen so as to obtain an optimized pulse shape and fixed a particular value as the current is varied. Pulse broadening for this case is less than 100%.

Figure 13 shows the advance and ABP as pulse-width is swept from 1 ps to 86 fs. Peak power is maintained constant as the pulse-width is varied because the non-linear index change is dependent on peak power. Advance increases almost linearly with increasing pulse-width. However, 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 large amount of fiber in our EDFA and due to the fact that the linear chirper employed in this experiment cannot exactly compensate for non-linear chirp induced by the SOA. Tailored chirpers can be employed to obtain a better compensation.

We simulate pulse propagation in SOA using density matrix approach described earlier and propagation through the chirper by adding a quadratic phase as described in [22]. Figure 14 shows the simulation results for a 190 fs pulse as the linear gain is increased from 0 dB to 30 dB corresponding to an SOA current of 50 mA and 300 mA respectively. From the simulation, we observe an advance of 0.71 ps which agrees very well with our experimental results. Further, time traces at higher current doesn't show self-steepening compared to 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 advance for both the pulses. Output of our fiber laser shows a pre-pulse before the main pulse. The pulses are separated by 7.2 ps as shown in fig. 15. As the current is increased, we observe a large advance for both the pulses. For the pre-pulse, an advance of 1.16 ps is observed as the SOA current is increased from transparency to maximum gain corresponding to an ABP of 1.84. Even in the presence of pre-pulse, an advance of 1.72 ps is observed for the main pulse as shown in fig. 16. This corresponds to a large ABP of 2.72. Advance for the pre-pulse is smaller than for the main pulse because the lower input power. As explained earlier, a low input power results in a smaller advance because the spectral hole created by the pulse is not very deep. Varying the pre-pulse amplitude and the distance between the pre-pulse and main pulse will provide further insight regarding the potential of this scheme at high bit-rates.

8. CONCLUSION

Ultra-high bandwidth slow and fast light is extremely useful in various RF systems and future generation all-optical networks. Using ultra-fast non-linear 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: spectral hole created by an ultra-short pulse and wave mixing between different spectral components of the pulse. Self-phase modulation in SOAs can be leveraged to achieve 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. Theory developed using density matrix approach is used to accurately simulate the ultra-short pulse propagation in our optical amplifiers. Finally, we demonstrate significant fast light for two 630 fs pulses separated by 7.2 ps.

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Figures

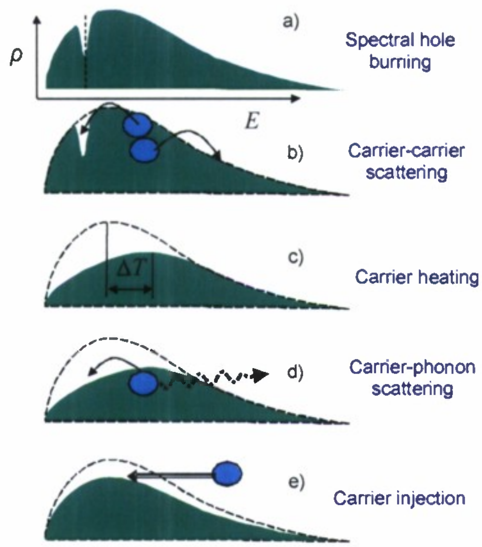


Fig. 1. Schematic showing the response of semiconductor medium biased in a gain region to an ultra-short pulse. An ultra-short pulse burns a hole in carrier distribution (a). Carrier-carrier scattering and carrier-phonon scattering are ultra-fast processes that restore the carriers to intra-band equilibrium in a pico-second time scale. Carrier-carrier scattering causes carriers to reach intra-band equilibrium at a temperature higher than lattice temperature (b,c). Carrier-phonon scattering then relaxes the carriers to lattice temperature (d). Electrons and holes eventually reach equilibrium through carrier injection (e).

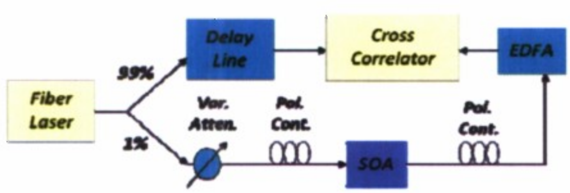


Fig. 2. Experimental set-up to realize fast light in semiconductor optical amplifiers. Output from the mode-locked laser is split into reference (99%) and signal (1%). Time shift of the signal is controlled by changing the SOA bias. As the SOA gain is increased by increasing the bias, the pulse experiences an advance. Similarly, when the SOA bias is decreased below transparency, the pulse experiences a delay.

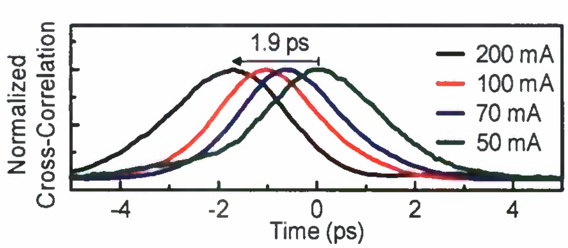


Fig. 3. Cross-correlation traces as the SOA current is varied. Cross-correlation traces appear broader than the actual pulses due to finite width of reference (700 fs). A large advance of 1.9 ps is observed for a 700 fs pulse as the SOA current is increased from transparency (50 mA) to maximum gain (200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

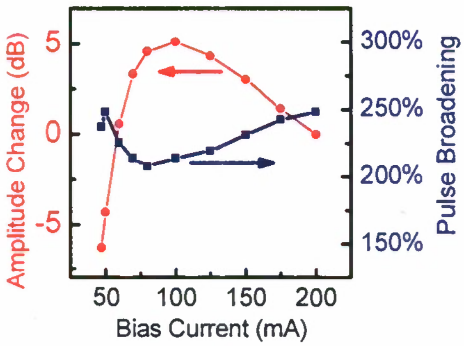


Fig. 4. Amplitude change and pulse broadening as the SOA current is varied. Amplitude change as the current is increased from 50 to 200 mA is less than 11 dB. The amplitude variation is much less than the linear gain (20 dB) because the pulses saturate the amplifier at a current of 100 mA. Pulses at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

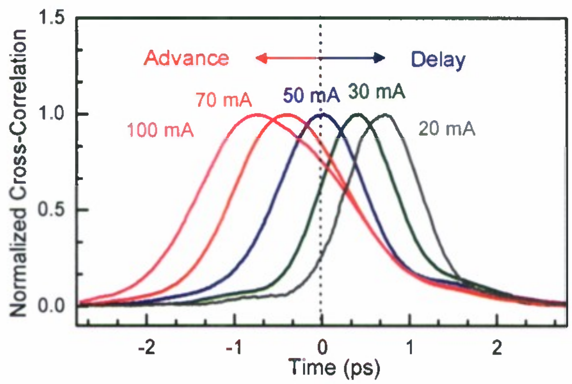


Fig. 5. Cross-correlation traces for a 600 fs input pulse. A large delay of 0.75 ps is observed as the SOA current is decreased from transparency (50 mA) to loss region (20 mA). As the SOA current is increased from transparency (50 mA) to gain region (100 mA), a large advance of 0.77 ps is observed. A total time shift of 1.52 ps corresponds to an ABP of 2.5.

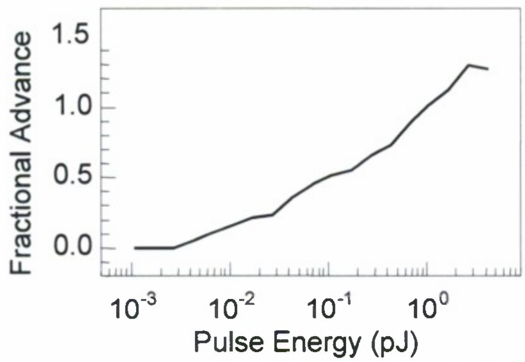


Fig. 6. Time traces for a 700 fs input pulse at a SOA bias of 100 mA as the input power is increased. An ABP of 1.3 is achieved as the pulse energy is increased from 1 fJ to 1 pJ demonstrating the feasibility of optical tuning.

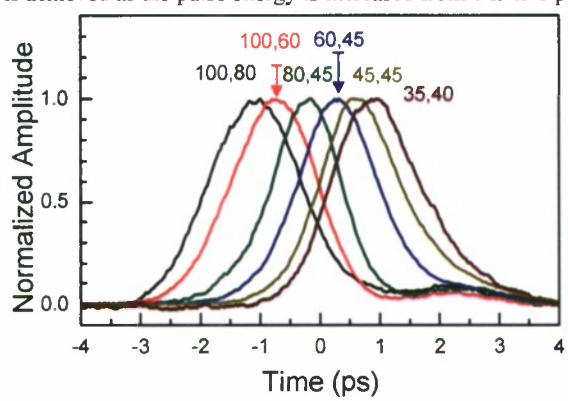


Fig. 7. Cross-correlation traces for a 600 fs pulse passing through two cascaded SOAs. The numbers indicate the bias current of each SOA in mA. An advance of 2 ps is observed as the bias current is varied continuously corresponding to an ABP of 3.3. Comparing this result with the earlier reported ABP of 2.5 for a single SOA demonstrates the scalability of this scheme. Increasing the current of the SOAs to larger values (>100 mA) results in pulse distortion due to high power of the signal pulse at the input of second SOA.

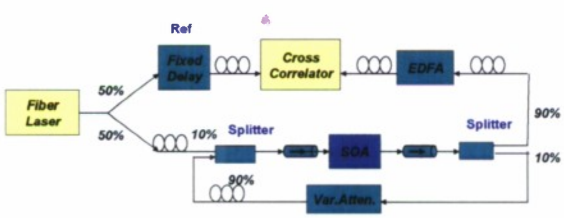
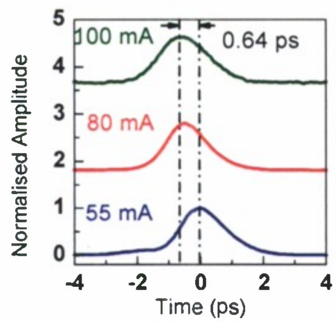
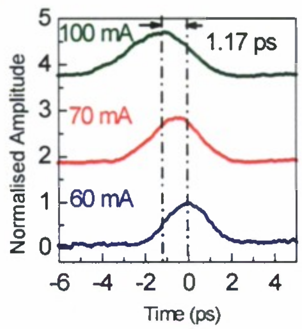


Fig. 8. Experimental set-up to investigate the scalability of this scheme using cascaded SOAs to achieve larger pulse advance. By using 90:10 splitters before and after the SOA, the signal pulse can be made to go through SOA multiple times. By adjusting the delay line in the reference arm, we can selectively measure the advance of a pulse that has gone through multiple times. Attenuation of the variable attenuator is adjusted so as to prevent lasing in the loop.

a)



a)



b)

Fig. 9a. Time traces for a pulse propagating through the SOA once (single-pass) as the SOA current is increased. A maximum advance of 0.64 ps is observed. Fig. 9b. Advance for a pulse propagating through the SOA twice (double-pass). An advance of 1.17 ps for this case is roughly twice that of a single-pass pulse. However, pulse broadening is also roughly twice that of a single pass pulse. Increasing the current beyond 100 mA causes lasing in the loop due to ASE. By adding optical filters and dispersion compensators in the loop pulse advance can be increased while reducing the pulse broadening.

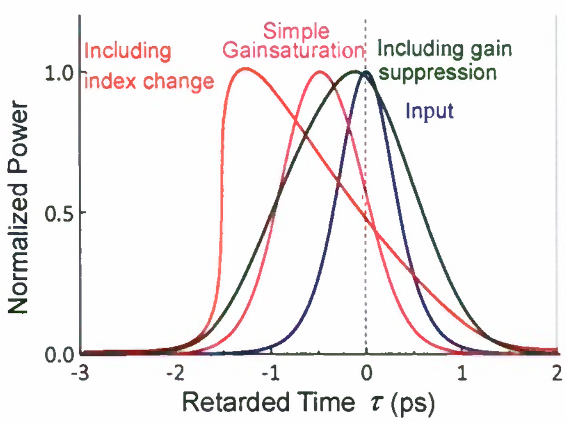


Fig. 10. Results of the simulation for a 700 fs pulse (blue curve) propagating through an SOA with a linear gain of 30 dB. A dephasing time of 100 fs and a carrier heating time of 650 fs is used in this simulation. When we neglect the contribution due to non-linear effects, we see an advance of 0.5 ps (magenta curve) corresponding to an ABP of only 0.7. Modification of the model to include non-linear gain decreases the advance to 0.2 ps (green curve) due to

non-linear gain suppression. However, including the gain and index change due to SHB and CH gives a large advance of 1.4 ps (ABP 2).

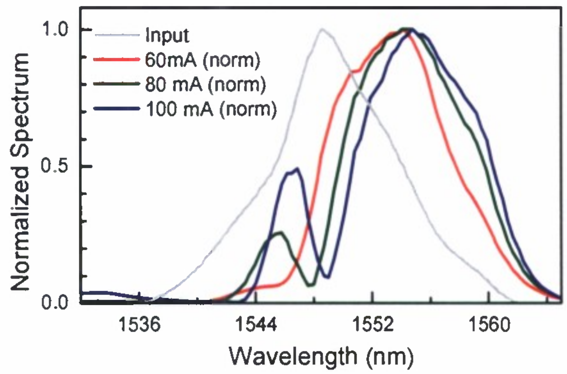


Fig. 11. Spectra for a 370 fs pulse for various SOA currents at an input pulse energy of 4 pJ. An increasing SOA current causes a red shift for the pulse due to self-phase modulation. At an SOA current of 100 mA, a red shift of 6nm is observed. Oscillatory structure observed in the spectrum at high currents is typical of non-linear processes.

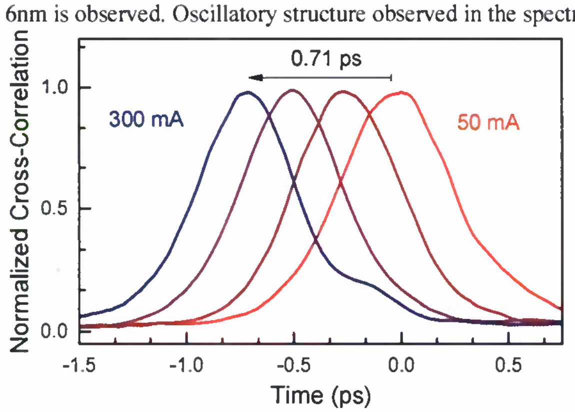


Fig. 12. Cross-correlation traces for a 190 fs pulse as a function of SOA current. We observed a large tunable advance of 0.71 ps corresponding to an ABP of 3.7. Amplitude variation is less than 10 dB and pulse broadening is less than 100% as the current is varied.

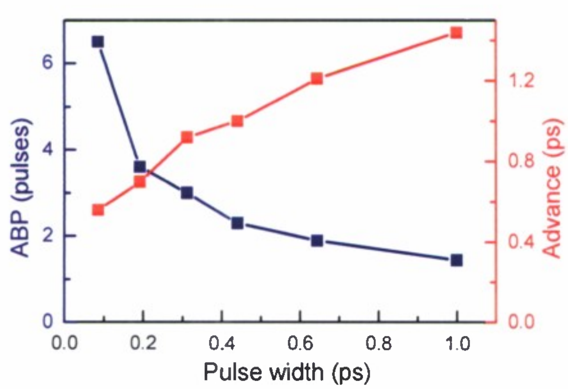


Fig. 13. Advance and ABP as the pulse-width is varied by an order of magnitude (86 fs to 1 ps). Peak power of the pulse is kept constant as the pulse-width is varied. As expected, ABP increases with decreasing pulse-width. For an 86 fs pulse, we observe an ABP of 6.5. However, maximum pulse broadening for this case is 250% due to large amount of fiber in our EDFA. Further, linear chirpers employed in this scheme cannot exactly compensate for the non-linear chirp induced by the SOA. Pulse broadening can be reduced by employing tailored chirpers.

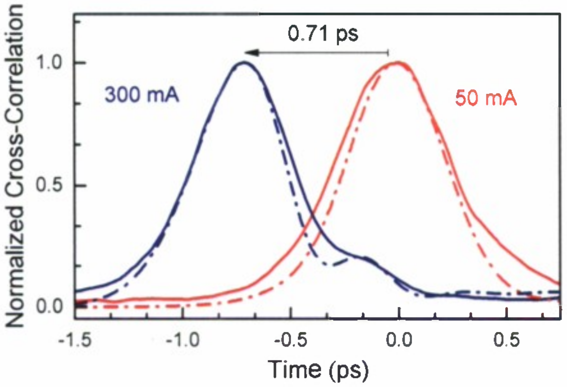


Fig. 14. Results of the simulation (dotted curves) for a 190 fs pulse as the SOA current is increased from transparency (50 mA) to maximum gain (300 mA). A tunable advance of 0.71 ps is obtained corresponding to an ABP of 3.7 which agrees very well with our experimental results (solid curves).

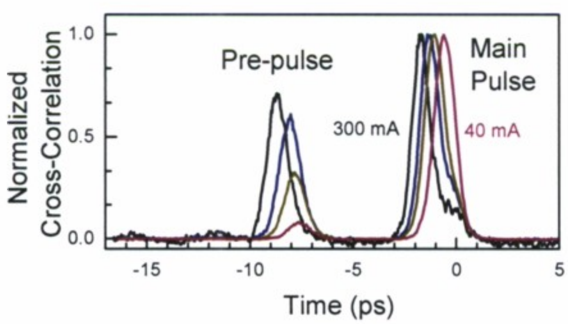


Fig. 15. Cross-correlation traces for two pulses entering the SOA. The pre-pulse is separated from the main pulse by 7.2 ps. As the SOA current is increased, we observe a large advance for both the pulses.

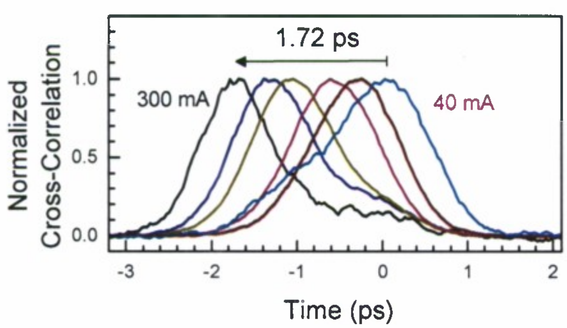


Fig. 16. Cross-correlation traces for the main pulse with increasing current. Even in the presence of a pre-pulse, a large advance of 1.72 ps corresponding to an ABP of 2.72 is observed.