Chirp-enhanced fast light in semiconductor optical amplifiers

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Abstract: We present a novel scheme to increase the THz-bandwidth fast light effect in semiconductor optical amplifiers and increase the number of advanced pulses. By introducing a linear chirp to the input pulses before the SOA and recompressing at the output with an opposite chirp, the advance-bandwidth product reached 3.5 at room temperature, 1.55 μm wavelength. This is the largest number reported, to the best of our knowledge, for a semiconductor slow/fast light device.

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OCIS codes: (999.9999) Slow Light; (250.5980) Semiconductor Optical Amplifiers.

References and links
16. SOA-NL-OED-1550 nonlinear SOA from CI Photonics.
1. Introduction

The ability to delay or advance optical pulses enables key functionalities of an all-optical packet switched network such as packet synchronization and buffering [1]. There are also important applications in RF photonics, such as antenna remoting and beam forming. Slow and fast light techniques allow realization of large time shifts in compact devices. Currently there has been substantial research targeted at increasing the bandwidth and the delay or advance normalized to the input pulse duration (also called delay-bandwidth product, DBP, or advance-bandwidth product, ABP). Semiconductor material systems offer compact size, ease of integration, and the potential for operation at communications wavelengths and at room temperature. Sarkar et al. [2] have used the bleaching of an exciton absorption resonance in a GaAs/AlGaAs multiple quantum well (MQW) to demonstrate a DBP of 2 for 8 ps input pulses.

Semiconductor optical amplifiers (SOA) can be used to produce both delay and advance, depending upon whether the SOA is biased in the absorption or gain regime [3]. Our recent work [3, 4] has focused on the use of spectral hole burning and carrier heating effects, i.e. intraband effects, in SOAs to produce ABP of 2.5 for 700 fs pulses at a 1.55 μm wavelength and at room temperature. As the input pulse introduces a spectral hole in the SOA gain spectrum, it experiences the resulting group index increase. In addition, a preliminary study showing the suitability of this technique for high bit rate pulses was reported [5]. In that work, we reported the cross correlation traces for two pulses in rapid succession of 7 ps. We showed both pulses experienced an advance of 1.8-2.7 pulses. The ABP using intraband effects is shown to increase by increasing the SOA current, but eventually saturates at a value dependent upon the input pulse power [4]. In this work, we overcome this saturation effect by introducing a novel technique we call time-wavelength division multiplexing. We demonstrate an increase of ABP to 3.5 by introducing a linear chirp to the input pulse, such that different wavelength components of the pulse enter the SOA at different times to avoid gain depletion. The output pulse is subsequently recompressed and a large ABP is achieved with little distortion.

2. Background

Prior efforts at slow and fast light in SOAs relied on saturation of gain [5] or on carrier density pulsations (CDP), also known as coherent population oscillations (CPO) [7 - 10]. These effects are based on interband process and can be understood by approximating the semiconductor as a two level system. The bandwidth of these schemes is limited by the carrier lifetime to hundreds of MHz. For larger bandwidth, we must use faster time-scale, intraband effects, such as spectral hole burning and carrier heating [11, 12].

When a fast optical impulse is applied to a semiconductor, carriers are removed from a specific band of energies within the gain spectrum, producing a spectral hole. This spectral hole burning (SHB) effect lasts until carrier-carrier scattering causes the carriers to reach a Fermi-Dirac distribution. The resulting carrier temperature will be higher than the original lattice temperature, this is the phenomenon known as carrier heating (CH). The carrier distribution cools to the lattice temperature by carrier-phonon scattering. CH recovery occurs on a time scale from sub-picosecond to 3 ps, while SHB recovery occurs in the 100~800 femtosecond range [3, 11 - 13].

To explain propagation of pulses with durations where these effects become significant, we have formulated a semi-phenomenological model based on the density matrix equations, which are solved without the adiabatic approximation [13]. This treatment leads to terms in the polarization which are proportional to the time derivative of the electric field envelope, and which, in turn, gives, in particular, “nonlinear group index” terms in the propagation equation. There are two such nonlinear group index terms: there is a term due to pulsations of
the carrier temperature, which are very analogous to the nonlinear group index CDP [7] but with much higher bandwidth; and there is a term due to the dip in gain of the spectral hole, which can be heuristically considered as the change in refractive index which must accompany a change in transmission for a causal system under the Kramers-Kronig relations. It should be noted, however, that the system described is nonlinear, and the Kramers-Kronig relations cannot rigorously be considered to apply in this circumstance. We emphasize that the system we discuss here is causal and although the effective group velocity is faster than the \( cn \) where \( n \) is the material index, and hence the term fast light, it is still slower than \( c \).

Calculations and experiments indicate that SHB and CH can be present when the SOA is operated as an amplifier and as an absorber. As an absorber, a hole is burned in the absorption spectrum and the nonlinear group index produces slow light, while as an amplifier fast light is produced. An advantage to working in the fast light regime is that pulse amplitude increases with propagation and so do the above effects. However, a limit is reached when the pulse is amplified along the amplifier path and has depleted enough carriers to burn a hole down to transparency. After this point, further advance is not possible and the pulse distorts. This saturation of ABP is discussed later in Section 4.2. In this paper, we report our investigation of the use of chirped input pulses as a way to circumvent this limitation. Conceptually, different spectral components of the pulse will enter the SOA at different times and will burn holes in different parts of the gain spectrum, hence we call this technique time-wavelength division multiplexing (TWDM). Thus, the saturation effect of ABP can be significantly reduced, leading to a larger ABP. The stretching of short pulses to improve performance of slow and fast light systems has been suggested before ([14] and references therein), but with these linear systems the channelization schemes serve only to trade off delay for bandwidth. Our work presented here is based on nonlinear group index, and is not subject to the limitations of channelization.

3. Experiment and results

In this work we present two series of experiments. For all the experiments, the bias current of the SOA is swept from near transparency up to maximum and the advance of the pulse due to fast light effects is recorded. In the first series of experiments we sweep the duration of nearly transform-limited input pulses from 600 fs to 2.8 ps and study the effect of pulse duration on advance and ABP. In the second series of experiments we demonstrate the saturation of advance with increasing bias current and we present experimental results of the TWDM technique as a way to increase the value at which the ABP saturates. All experiments are conducted at room temperature and 1550 nm wavelength.

![Experimental setup to measure advance and ABP as a function of SOA bias current.](image)

Figure 1 shows our experimental setup for measuring ABP as a function of pulse duration. The pulses originate from a Calmar-Optcom mode-locked fiber laser with adjustable transform-limited pulse width, 20 MHz repetition rate, and up to 500 pJ of pulse energy (only a small fraction of which is required for the fast light effect). The pulse train is split into two arms, the signal and the reference. The reference traverses a distance equal to that of the signal and then enters one arm of an optical cross correlation device. The signal pulses pass through a variable attenuator, then through a polarization controller and into the SOA. The output of the SOA then enters the EDFA and then into the cross correlator. The output of the cross correlator is then recorded.

Received 13 Sep 2007; revised 9 Nov 2007; accepted 26 Nov 2007; published 12 Dec 2007

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through a variable attenuator to regulate power into the SOA. The SOA is fiber coupled, and fiber polarization controllers are used to optimize the fast light effect. An EDFA is used to amplify the signal, which finally arrives at the other arm of the cross-correlation device. As the SOA bias is swept the temporal shift of the signal relative to the reference is measured. This experiment is repeated for each value of pulse duration.

Representative cross-correlation traces are shown in Fig. 2 for pulse duration of 780 fs [Fig. 2(a)] and 2.6 ps [Fig. 2(b)]. Note that, because the cross-correlation signal is a convolution of the reference and signal, the actual pulses are considerably narrower than the traces shown. For the 780 fs pulse [Fig. 2(a)] the ABP is 1.34 pulses, whereas for the 2.6 ps pulse [Fig. 2(b)] the ABP has dropped to 0.44 ps. This follows a general trend of slightly increasing advance and sharply decreasing ABP with increasing pulse width. Figure 3 summarizes these results. The very small increase in advance due to a lower bandwidth pulse [Fig. 3(a)] is less than the increase in pulse duration, so the ABP decreases [Fig. 3(b)]. For this SOA, the SHB and CH recovery times have been measured to be 0.83 ps and 3.3 ps, respectively [4]. The ABP drops as pulse duration increases beyond these times and intraband effects no longer efficiently contribute to pulse advance.

Figure 4 shows our experimental setup for TWDM. The chirper and compensator consist of grating pairs which add or remove a linear chirp to the pulse while leaving its spectrum unaltered [15]; which means the pulses are stretched or compressed in the time. After stretching or “chirping out” the pulses are no longer transform limited since they retain their original bandwidth. The chirpers can be switched into or out of the optical path at will.

Fig. 2. Normalized cross-correlation traces of the output pulses of the SOA in system shown in Fig. 1, as SOA bias is swept from near transparency (black curve) to high gain (red curve), for two different pulse durations. Pulse durations were swept by tuning the mode-locked laser, producing nearly transform-limited pulses. Note that actual pulses are narrower than cross-correlation traces. Figure 2(a): input pulse has a full-width half-maximum (FWHM) of 780 fs, and shows an advance of 1.04 ps (ABP = 1.34 pulses). Figure 2(b): input pulse has a duration of 2.6 ps (note change in time scale!) and shows advance of 1.16 ps (ABP = 0.44).

Fig. 3. (a). Effect of pulse duration on net advance achieved by sweeping SOA current from transparency to maximum. As the pulse bandwidth decreases, net advance increases very slightly. Figure 3(b). ABP vs. pulse duration. For this SOA, the measured spectral hole burning and carrier heating recovery time are 0.83 ps and 3.3 ps, respectively. Despite the slight increase in net advance, the ABP drops as pulse duration increases beyond these times and intraband effects no longer efficiently contribute to pulse advance.

Figure 4 shows our experimental setup for TWDM. The chirper and compensator consist of grating pairs which add or remove a linear chirp to the pulse while leaving its spectrum unaltered [15]; which means the pulses are stretched or compressed in the time. After stretching or “chirping out” the pulses are no longer transform limited since they retain their original bandwidth. The chirpers can be switched into or out of the optical path at will. For
these experiments a new, free-space coupled SOA [16] is used, allowing a reduction in fiber and larger pulse energies without concern for fiber nonlinearities. The maximum small signal gain is approximately 30 dB, the output saturation power is 6 dBm. The laser wavelength sits slightly on the blue side of the SOA gain peak at all bias currents. The length of the SOA is 2.0 mm; so a 3 ps pulse is completely contained within the device as it propagates through. After the split between the signal and reference arms, the signal pulses are coupled to free space and then pass through a variable attenuator to maintain the same pulse energy at the SOA input throughout all these experiments, approximately 0.23 pJ. Despite the polarization independent small signal gain, we find that there is a polarization dependence of the fast light effect [17] and we add waveplates to ensure light is coupled into the TE mode of the SOA for maximum fast light effect. For precise polarization control before the SOA. After the SOA and some more polarization control the signal is coupled back into fiber, where the remainder of the signal path is identical to that described in the previous section.

Fig. 4. Experimental setup for TWDM. Similar to that shown in Fig. 1, except that i) the SOA is free-space coupled and ii) grating-based chirpers at the SOA input and output can be switched into and out of the optical path. Grating-based chirpers preserve the pulse bandwidth and stretch or compress the pulse in time. The input grating delays red components while the output grating is opposite.

Four basic experiments were performed. First, both the chirpers were bypassed and cross-correlation measurements were taken with a nearly transform-limited pulse of 700 fs duration. An advance of 1.3 ps and ABP of 1.86 were measured. This value is smaller than the previously reported ABP of 2.5 [4] because the pulse energy is attenuated. This is done to allow fair comparison with the chirped pulses, which suffer from 10 dB of attenuation after propagation through the grating chirper. The pulse duration was then increased at the fiber laser to 2.68 ps (still transform-limited), and advance and ABP were again measured. The advance increases from 1.3 ps to 2 ps, but as discussed in the previous section the ABP drops from 1.86 to 0.75, which is consistent with the previous experimental results shown in Fig. 3. Next, the 700 fs pulse was chirped out to 2.68 ps, but was not recompressed at the output. The chirper causes blue spectral components to enter the SOA first. Figure 5(a) shows the cross-correlation trace. The pulse is obviously distorted, but the peak has shifted forward by 2.6 ps.
Fig. 5. Normalized cross-correlation traces of the output pulses of the SOA in system shown in Fig. 4, as SOA bias is swept from near transparency (black curve) to high gain (red curve), for two different chirper configurations. Figure 5(a): input pulse has been chirped out from 700 fs to 2.68 ps while the bandwidth remains equivalent to the original pulse (390 GHz). The “peak” advances by 2.6 ps (ABP = 1) Fig. 5(b): the input pulse is the same chirped pulse from Fig. 5(a), but the output has passed through the counter-chirper stage as well. The distortion is removed and the pulse has advanced by 2.2 ps (ABP = 3.14).

Finally both the chirper and counter-chirper were used in the complete TWDM scheme. The 700 fs transform-limited pulse was chirped out to 2.68 ps, advanced with the SOA, and then recompressed at the SOA output with the counter-chirper. The counter-chirper delays the blue spectral components, effectively recompressing the pulse and largely removing the distortion. Figure 5(b) shows the resulting cross-correlation (note the change in time scale). The peak has advanced 2.2 ps, giving an ABP of 3.14. This represents a factor of 1.7 increase in ABP over that of the 700 fs transformed-limited input pulses. On the other hand, the increase of ABP is as large as 7.0 times that of the 2.68 ps transform-limited input pulse.

The study presented above illustrates the benefits of the TWDM technique. However, Fig. 5(b) shows some distortion of the pulse in the form of a pedestal. Also, the pulses have broadened in comparison with the original, unchirped pulses shown on Fig. 2(a). This is due to mismatch between the chirper and counter-chirper. Because the pulse shape changes somewhat between the input and output, the broadening of the pulse must be quantified by taking the pulse duration as the root-mean-square (RMS), rather than FWHM. Additionally, the RMS width of an auto- or cross-correlation signal is determined by the RMS widths of the constituent pulses by [18]

\[ \sigma_{\text{corr}}^2 = \sqrt{\sigma_1^2 + \sigma_2^2} \]  

After the RMS width of the reference pulse is determined by auto-correlation, the RMS of the signal pulse can be determined from the cross-correlation measurements by inserting the RMS of the reference pulse into Eq. (1). Note that the RMS width is an appropriate metric for calculating pulse broadening when the shape of the pulse has changed as well [19], but the FWHM remains a more appropriate (and generally accepted) metric for pulse duration when calculating the ABP. Another important point is that cross-correlation cannot detect distortions of the pulse which may occur on timescales short compared with the width of the reference pulse.

Further optimization of the chirper – counter-chirper pair allowed the use of faster input pulses, larger amounts of chirp, and the elimination of pulse broadening. Figure 6 shows the result of such an effort. Figure 6(a) shows the auto-correlation at the input of the chirper. The FWHM is 500 fs while the RMS width is 320 fs. The chirper expands the pulse nearly 10 times to 4.7 ps. Figure 6(b) shows the cross correlation traces after the SOA and counter-chirper. The advance in this case is 1.76 ps, or 3.5 pulses. The RMS width of the output pulses is maximum near the lowest bias (434 fs, 33% broadening). The cross-correlation traces in Fig. 6(b) still exhibit a small pedestal, the height of which is always less than 28% of the peak. The height and position of the pedestal relative to the peak are strongly affected by the polarization controls before and after the SOA. Because the peak power is very high in such a short pulse (about 1.4 W) even a small fraction of pulse...
energy coupled into the orthogonal TM mode of the SOA can be easily amplified to a point where carrier dynamics are significantly affected. Additionally this orthogonally polarized pulse will experience different waveguide dispersion, propagating either ahead of or behind the main pulse, and will interact with the carrier population differently due to general anisotropy of a quantum well structure. Hence, the pedestal is attributed to an artifact of imperfect polarization control and can be corrected in future experiments.

![Normalized Cross-Correlation Time](image)

**Fig. 6.** (a). Auto correlation of incident pulse, RMS width is 320 fs, FWHM is 500 fs (assuming sech squared pulse shape). Figure 6(b). Cross-correlation of output pulse as SOA bias is increased from near transparency to maximum. Pulse advances by 1.76 ps (3.5 pulse widths). RMS width of pulses, calculated by measuring RMS of reference pulses, is less that 1.15 times the original pulse.

Figure 7 summarizes the results of this work. Figure 7(a) plots ABP vs. SOA bias for the 700 fs unchirped, chirped, and TWDM cases. In this figure, the saturation of ABP with increasing SOA bias current (proportional to small signal gain) is readily apparent. The increase in the ABP saturation value for the TWDM is clearly visible, demonstrating the advantages of TWDM. Furthermore, if faster original pulses can be used, ABP may be increased by an even larger amount. We expect considerable improvement if a 200 fs pulse is chirped out to 700 fs, where the ABP of the transform-limited pulses is higher. Figure 7(b) summarizes the results from the 500 fs pulse TWDM scheme. Here, the pulse broadening, calculated from RMS pulse widths, is overlaid on top of the ABP. The ABP reaches 3.5 at maximum SOA current. The broadening is less than 9% for the majority of the operating regime.

![ABP vs. SOA Current](image)

**Fig. 7.** (a). ABP vs. SOA bias for 700 fs (black) and 2.68 ps (blue) transform-limited pulses and for chirped. Also shown is the chirped and compensated TWDM pulse (red). ABP saturates with increasing SOA current. The ABP of the 2.68 ps pulse saturates at a much lower value because it is longer than the spectral hole burning and carrier heating recovery times. Different spectral components of the TWDM pulse enter the SOA at different times, allowing more efficient use of the SOA gain spectrum, and an ABP of 3.14. Fig. 7(b). ABP and broadening (relative to the input pulse) of 500 fs TWDM. Chirper and counter-chirper have been optimized for minimal broadening and ABP of 3.5. Average broadening is 8% and never exceeds 33%.

4. Summary and conclusion

In this work, we present a novel technique called time-wavelength division multiplexing (TWDM) for increasing the ABP of intraband fast light in an SOA. First we study the
variation in ABP for transform-limited pulses of various durations. We show that as the duration becomes longer than the SHB and CH recovery times, the ABP drops. However, with TWDM, a linear chirp is imposed upon the input pulses to stretch them in time, allowing different spectral components of the pulse to interact with the carrier distribution within the SOA at different times. At the output of the SOA, the chirp is removed by a counter-chirper and the pulse is recompressed. This technique increases the ABP from 1.86 to 3.14, a factor of 170%. Further experiments with 500 fs pulses chirped out over a longer duration (4.8 ps) results in an advance of 3.5 pulses. This is, to the best of our knowledge, the largest ABP (DBP) reported in a single semiconductor fast (slow) light device. In future work, we will study the TWDM scheme for ultrafast pulses at high repetition rates. We also expect improvement by decreasing the duration of the original pulse such that the chirped pulse is still fast enough to efficiently use both SHB and CH effects.

Acknowledgments

We gratefully acknowledge the support of DARPA grant N00014-06-1-090 and Air Force contract FA 9550-04-1-0196, and Steve Kane at Horiba Jobin Yvon for helpful discussions regarding grating-based chirpers.