**THz-bandwidth tunable slow light in semiconductor optical amplifiers**

**F. G. Sedgwick, Bala Pesala, Jui-Yen Lin, Wai Son Ko, Xiaoxue Zhao, and C. J. Chang-Hasnain**

*Department of Electrical Engineering and Computer Science, University of California, Berkeley, California 94720*  
sedgwick@eecs.berkeley.edu

**Abstract:** We report tunable fractional delays of 250% for 700 fs pulses propagating in a 1.55 μm semiconductor optical amplifier at room temperature. This large fractional delay is attributed to a spectral hole created by the propagating pulses for pulses with duration shorter than the carrier heating relaxation time. Delay can be tuned electrically by adjusting the current with low amplitude variation across the tuning range.

© 2007 Optical Society of America

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

**References and links**

1. Introduction

Variable all-optical delay lines using slow light effects continue to attract increasing interest due to their potential applications in optical buffering, packet synchronization, phased-array antennas and optical signal processing [1]. Semiconductor material systems have been shown to offer these effects at bandwidths greater than GHz, making them attractive for communications systems [2-8]. In addition, they may be operated in both absorption and gain regimes, making future cascade designs possible. Recently, Sarkar et al. [2] demonstrated a fractional delay of 200% for 8 ps input pulses by bleaching an exciton absorption resonance in a GaAs/AlGaAs multiple quantum well (QW) sample at 20 K and 850-nm wavelength. Semiconductor optical amplifiers (SOA) are desirable because they are compact, compatible with telecommunications wavelengths (1.55 um), and operate at room temperature. Further, they can produce both fast and slow light [4, 5]. In particular, coherent population oscillations and four-wave mixing effects have been explored as mechanisms to produce slow and fast light with bandwidths on the order of GHz [4-7], ultimately limited by the carrier lifetime. Coherent population oscillations (also called population pulsations) have produced 290° RF phase shifts at 0.5 GHz [4] and 3% fractional delays with over 15 GHz of bandwidth [7]. Gain saturation in quantum dot (QD) SOA has offered tunable delays of 40% with 2.6 THz bandwidth at room temperature [8].

In this paper we explore the influence of high-bandwidth intraband effects on short pulse propagation in an SOA. Specifically we demonstrate large fractional delays due to spectral hole burning (SHB) for pulses with duration shorter than the carrier heating (CH) relaxation time. We demonstrate tunable delays up to 1.9 ps for 0.7 ps input pulses (880 GHz bandwidth) at room temperature. The tuning can be continuously controlled electrically. This is the largest fractional delay reported for a room-temperature slow light device reported to date, to the best of our knowledge.

2. SOA gain dynamics

As we are interested in exploring the group delay experienced by an ultrashort pulse due to the spectral hole created by the pulse itself, it is essential to measure the SOA gain dynamics and establish a time regime within which the spectral hole can be sustained. In this section, we present our experimental results. There are two ultrafast gain dynamic effects which could play a role in the time-dependent gain experienced by ultrashort pulses: spectral hole burning and carrier heating. We conducted time-domain pump-probe measurements to characterize the gain dynamics of our SOA [9,10]. The experimental setup is shown in Fig. 1.

A mode-locked fiber laser produces pulses of 500 fs duration and approximately 4 W of peak power. The 25 MHz repetition rate allows 40 ns for the SOA gain to recover before the next pulse arrives. The pulses are split into a pump (90%) branch and probe (10%). The probe propagates through a half waveplate, a polarizer, a variable attenuator, and a mechanical chopper for lock-in detection. The free-space propagation distance of the probe is varied with a precision linear stage. The polarization state of the pump is adjusted with a fiber polarization controller and matched to that of the probe. Both are polarized along the slow axis of the PM 50/50 splitter. A final fiber polarization controller adjusts the polarization state of the SOA input.

Fig. 1. Experimental setup for measurement of gain dynamics. The pulses are split into two branches, the pump (90%) and probe (10%). The probe propagates through a half waveplate, a polarizer, a variable attenuator, and a mechanical chopper for lock-in detection. The free-space propagation distance of the probe is varied with a precision linear stage. The polarization state of the pump is adjusted with a fiber polarization controller and matched to that of the probe. Both are polarized along the slow axis of the PM 50/50 splitter. A final fiber polarization controller adjusts the polarization state of the SOA input.

A mode-locked fiber laser produces pulses of 500 fs duration and approximately 4 W of peak power. The 25 MHz repetition rate allows 40 ns for the SOA gain to recover before the next pulse arrives. The pulses are split into a pump (90%) branch and probe (10%). The pump pulse removes large numbers of carriers from the conduction band in a short amount of
time via stimulated emission. The probe is delayed by a variable amount $t_0$ before entering the SOA. Measuring the probe transmission as a function of $t_0$ maps out the transient gain response with a temporal resolution on the order of the pump and probe pulse width. To distinguish between the pump and probe at the detector, the probe is mechanically chopped at 2.5 kHz and lock-in detection is used. The 50/50 combiner is made with polarization maintaining fiber, assuring that the pump and probe are co-polarized. The SOA is a fiber-coupled commercial device designed for operation at 1550 nm with a small signal gain up to 28 dB and a saturation power of 13 dBm. It is polarization insensitive with less than 2 dB polarization dependent gain.

Assuming that the gain saturation response is linear in pump power, the average probe transmission as a function of delay $t_0$ can be expressed as [11]

$$I_{\text{probe}}(t_0) = \int h(t' + t_0)F(t')dt'$$  \hspace{1cm} (1)

where $h$ is the impulse response of the medium and $F$ is the cross-correlation between pump and the probe. The impulse response function is assumed to be of the form [10]

$$h(t) = u(t)\left\{a_0 + a_{\text{SHB}}e^{\frac{-t}{\tau_{\text{SHB}}}} + a_{\text{CH}}e^{\frac{-t}{\tau_{\text{CH}}}}\right\}$$  \hspace{1cm} (2)

where $u(t)$ is the unit step function and $\tau_{\text{CH}}$ and $\tau_{\text{SHB}}$ are relaxation time constants for the gain saturation effects under consideration. The purpose of these measurements is to calculate the relaxation times. Experimentally, we measure $I_{\text{probe}}(t_0)$ and $F(t)$ at various SOA bias currents. At each bias current we fit the $I_{\text{probe}}(t_0)$ data by varying $a_0$, $a_{\text{SHB}}$, and $a_{\text{CH}}$ in Eq. (2) and then numerically integrating Eq. (1). We recursively search for values of $\tau_{\text{CH}}$ and $\tau_{\text{SHB}}$ which produce the best fits at all bias currents. This process is similar to those used in references [9, 10].

Figure 2 shows the pump-probe cross-correlation at the input and output of the SOA. The resolution of these experiments is limited to 2 ps by the resolution of the variable delay stage and by the FWHM of the pump-probe cross-correlation. For our setup the pulse widths are the limiting factor. Unfortunately, as can be seen in Fig. 2, the pulses are broadened significantly as they propagate through the SOA. We find that the best fits are obtained when we use the output cross-correlation traces in Eq. (1).

![Fig. 2. Broadening and distortion of pump-probe cross-correlation after propagation through the SOA at various currents. Note that cross-correlation traces shown above are broader than the actual pulses.](image-url)
Figure 3 shows the data and fits at three different SOA currents: 20 mA, 50 mA, and 100 mA corresponding to absorption, near transparency, and gain. At absorption bias, the probe absorption will be first reduced due to SHB by the pump, and subsequently increased due to the CH effect. On the other hand, with the SOA biased in the gain region, SHB and CH both are expected to reduce the gain. At transparency the contribution of SHB to the impulse response should be zero, while CH will decrease the probe transmission. Note that in all three cases the effect of CH is to attenuate the probe, whereas SHB will amplify or attenuate depending on the bias [10]. The time constants which best fit the data in all three regions are 0.83 ps and 3.3 ps. The corresponding coefficients $a_{\text{SHB}}$ and $a_{\text{CH}}$ at the different bias points are given in Table 1. The signs of the coefficients are as expected, switching from positive to negative for SHB and remaining negative for CH. The best-fit time constant for spectral hole burning is at the limit of our resolution. Prior measurements on InGaAsP strained layer multiple quantum well amplifiers place the carrier-carrier scattering time for SHB relaxation at approximately 100 fs and the carrier-phonon scattering time for CH relaxation at approximately 1 ps [10, 14]. The time constants we obtained here are well within the acceptable range, given the effects under consideration are strongly dependent on wavelength, material composition, and QW structure. Hence, we conclude that pulses having a sub-picosecond width should be well within the time scale where the carriers depleted by a pulse have not completely relaxed to a Fermi-Dirac distribution. In this case the pulse would travel within a spectral hole created by itself and experience a group delay.

Table 1. Time constants and coefficients from Eq. (2) for intraband gain or absorption saturation effects. A negative coefficient corresponds to an initial decrease in probe transmission relaxing upward with the specified time constant.

<table>
<thead>
<tr>
<th>Transient Effect</th>
<th>Relaxation Time</th>
<th>Coefficients ($a_{\text{SHB}}$ or $a_{\text{CH}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Heating</td>
<td>3.3 ps</td>
<td>Absorption: -14.2 Near Transparency: -0.61 Gain: -0.61</td>
</tr>
<tr>
<td>Spectral Hole Burning</td>
<td>0.83 ps</td>
<td>Absorption: 7.47 Near Transparency: -1.62 Gain: -2.37</td>
</tr>
</tbody>
</table>

3. Experimental setup

Figure 4 shows our slow light experimental setup based on the same mode-locked fiber laser that is used above. A small amount of pulse energy, about 1%, is tapped off for use as a signal (< 40 mW peak pulse power). The remainder is used as a fixed reference for the cross-correlation measurements and does not enter the SOA. The signal passes through a variable attenuator, a polarization controller, and the SOA with isolators at both the input and output. After the SOA the signal passes through a second polarization controller and an EDFA before arriving at the cross correlator. The polarization controller is required because this is a
polarization-maintaining EDFA with over 20 dB difference in gain between polarization modes. For the high gain polarization the EDFA has a small signal gain up to 30 dB. The EDFA is necessary to amplify the signal before cross-correlation measurements. The cross correlator allows us to measure delay, pulse broadening, and amplitude changes. The nominal resolution of the cross correlator is 1 fs.

![Diagram](image)

**Fig. 4.** Experimental setup for slow light measurements. Pulses are split into reference (99%) branch and signal (1%) branch. A cross correlator is used to measure optical delay as a function of SOA current.

### 4. Tunable delay results

Figure 5(a) shows an auto-correlation trace of the pulse at the SOA input. Assuming a sech^2 pulse shape, the pulse width can be obtained by multiplying the FWHM of the cross-correlation traces by a deconvolution factor of 0.65. The input pulse has broadened to 0.72 ps due to fiber dispersion between the laser and SOA input. Also shown is a typical pulse after propagation through the SOA; for a bias current of 70 mA the pulse width is 1.5 ps.

![Graphs](image)

**Fig. 5.** (a). Normalized auto correlation at the SOA input and signal-reference cross-correlation at the SOA output (70 mA, no pump). FWHM, assuming sech^2 pulse shape, is labeled on the figure. Figure 5(b). Normalized cross-correlation at the SOA output showing delay of pulses as current is varied (no pump). Note that the cross-correlation traces are broader than the actual pulses.

A continuously tunable delay of up to 1.9 ps is observed, corresponding to a fractional delay of 250% of the input pulse, as the SOA bias current is varied from 200 mA to 50 mA. Figure 5(b) shows normalized cross-correlation traces. It should be noted that the actual pulses are approximately 1.5 times narrower than the cross-correlation traces of Fig. 5. Given the effect is a hole in the gain spectrum, \( \frac{\partial n}{\partial \omega} \) is negative and hence fast light is observed. As the SOA current is increased, the gain is increased. Hence, the input pulse experiences a deeper spectral hole due to SHB, which leads to a larger (but still negative) \( \frac{\partial n}{\partial \omega} \) and to faster light. The result on Fig. 5(b) shows pulse advances with increasing SOA current. The fractional delay vs. bias current is also shown in Fig. 6.
The variation of pulse amplitude as delay is tuned is shown in Fig. 7. There is less than 11 dB amplitude variation over the entire tuning range. Also shown in Fig. 7 is the variation in pulse broadening, defined as the ratio between output pulse width and input pulse width, as the current is changed. Pulse broadening in slow light schemes can lead to problems in communications applications. Pre- and post-propagation dispersion compensation techniques may be used to reduce the effect [15, 16]. At all currents pulse widths are roughly doubled by propagation through the SOA, and the width varies by about 50% as the current is varied. The broadening is inversely correlated to the amplitude change; the pulse width decreases with increasing amplification. A preliminary assessment of the importance of input power was also made. After attenuating the input by 3 dB, the bias current was swept and the tunable range of delay remained unchanged. Measurements at lower input powers were infeasible due to low signal to noise ratio at the lower bias currents.

5. Discussion of slow light results

The typical slow light system consists of a steep change in refractive index over a narrow region of the optical spectrum, resulting in an extremely low group velocity. The Kramers-Kronig relations predict such a change when the absorption or gain changes rapidly within a narrow spectral window. A sharp decrease in gain, such as that caused by SHB, will result in a large negative group velocity, corresponding to superluminal pulse propagation or “fast light.” For pulses with support far in advance of the pulse peak (e.g. Gaussian or sech² pulses) causality is not an issue and the temporal advance of fast light can be treated similarly to the temporal retardation of slow light [17]. Hence our measured “delay” at lower currents can more accurately be understood as a temporal advance at higher currents, where the spectral hole is deeper.

Note that our experiments demonstrate delays in excess of that predicted by the Kramers-Kronig relations alone. For a Lorentzian spectral hole of depth $\Delta g$ and FWHM $\Delta \omega$ the Kramers-Kronig relations predict a group velocity $v_g$ at the center

$$v_g^{-1} = \frac{\omega}{c} \frac{dn}{d\omega} = \frac{1}{2\pi} \frac{\Delta g}{\Delta \omega}. \quad (3)$$

For a device of length $L$, the pulse advance $T_{adv}$ is

$$T_{adv} = L/v_g = \frac{\Delta g L}{\Delta \omega}. \quad (4)$$

Assuming $\Delta \omega$ corresponds to the spectral width of a transform-limited $sech^2$ pulse, an advance of 1.9 ps corresponds to a spectral hole depth $\Delta g L$ of 5.2 and implies an SOA gain of 23 dB, which is larger than our measured small-signal gain of 20 dB at 200 mA. Also, the pulse experiences more than 10 dB of gain at 200 mA, implying that a spectral hole has not been completely burned to transparency. A similar analysis can be used to show that the SOA gain
peak, with a FWHM greater than 4 THz at all bias currents, see Fig. 8(b), cannot be responsible for the observed fractional advance; the gain peak would need to be over 200 dB. These analyses fail because the Kramers-Kronig relations are strictly valid only for a medium with a linear response, which SHB is most certainly not.

Pulse reshaping via gain saturation is an example of one way a nonlinear response may induce a temporal shift. A simple analysis in Ref. [8] demonstrates a shift in pulse peak due to the amplification of the leading edge relative to the trailing edge. However, as the authors pointed out, their basic model cannot account for a fractional delay of more than 50%, as no amount of pulse reshaping can cause the peak to shift outside of the original pulse. That model is based on the assumption that pulse duration is much shorter than the carrier lifetime, but much longer than carrier-carrier scattering times. Their approximation neglects any pulse-induced change in the carrier distribution which may give rise to a spectral hole and subsequent group velocity effects. A final subtlety in analyzing our results arises when the amplifier is biased in the gain region. Here pulse propagation can be further influenced by wave-mixing effects [12, 13]. Unlike the interband effects of [5-7], the bandwidth of intraband wave-mixing is on the order of THz [14]. A complete theoretical model of our results will need to take dynamic carrier distribution into account, which is beyond the scope of this paper and is under investigation.

Finally we note that pulses in a bit stream will not allow the same recovery time as pulses from a 25 MHz source. A higher repetition rate will lower the average carrier concentration in the SOA, so we expect that delay of a bit stream would require an increase in bias current to produce the same delay. Because carrier recovery operates on a time scale much longer than our pulses, we do not expect any appreciable pattern dependence for data. The present experiment repetition rate is limited by our instrumentation.

6. Summary and conclusion

We report a tunable fractional delay of 250% for sub-picosecond pulses (THz bandwidth) in semiconductor optical amplifiers at room temperature. This fractional delay and bandwidth are the highest reported to date, to the best of our knowledge. The SOA spectral hole burning and carrier heating time constants are measured. The large tunable group delay is attributed to the spectral hole created by the short pulse itself. Future work will address the issues of pulse broadening and input power requirements – both important considerations for communications applications. Further development of theory is necessary to understand the full potential of this mechanism.

Acknowledgments

We thank the support of DARPA grant N00014-06-1-090 and Airforce contract FA 9550-04-1-0196. We also thank Dr. Zafer Yasa for helpful discussions and advice.