Electrically tunable fast light at THz bandwidth using cascaded semiconductor optical amplifiers

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Abstract: Ultra fast non-linear processes are used to achieve an advance of 2 ps for a 600 fs pulse propagating through two SOAs in series. This corresponding 3.3-pulse advance is tuned continuously by changing the current applied to the devices. We propose an experimental scheme that uses a single SOA in a loop to emulate the propagation of pulse through multiple cascaded SOAs.

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OCIS codes: (230.1150) All-optical devices; (230.4320) Nonlinear optical devices

References and Links

1. Introduction

Slow and fast light research has several important applications in future generation all optical networks [1, 2]. Such networks may potentially operate at THz bandwidths. Hence a scheme that can achieve time shifts at high bandwidth is very essential. For this purpose, several schemes have been proposed using stimulated Raman scattering [3], stimulated Brillouin scattering [4, 5] and optical parametric amplification assisted by SRS [6].

Tunable delays using semiconductor based devices offer an additional advantage of compactness and electrical tunability. Exciton resonance [7], VCSEL resonance [8] and coherent population oscillations [9-11] in semiconductors have been used to achieve tunable delays. Using ultra-fast non-linearities in Quantum dot SOAs, an advance of 68 fs is obtained for a 170 fs pulse [12]. Recently, we demonstrated that spectral hole burning and carrier heating in Quantum well SOAs can be used to achieve an advance of 2.5 pulses at THz bandwidths [13]. In this paper we show that by cascading two SOAs the total advance can be increased from 2.5 pulses to 3.3 pulses. We also propose a novel experimental scheme that uses a single SOA in loop configuration to demonstrate the feasibility of cascading multiple SOAs.

2. Physical principle

Fast light at very high bandwidths can be obtained by using ultra-fast non-linearities in SOAs. When an optical pulse enters the SOA biased in gain region, it depletes carriers via stimulated emission and leaves a hole in the carrier distribution. The SOA undergoes a series of steps to restore the equilibrium carrier distribution. Electron-electron scattering process, usually referred to as spectral hole burning (SHB), with a measured life time of ~800 fs [13] fills the hole. Due to the energy conserving nature of this process, the average temperature of carriers in this quasi equilibrium state is higher than the lattice temperature. Electron-phonon process, usually referred to as carrier heating (CH), relaxes the carrier temperature to the lattice temperature. The carriers finally reach steady state through carrier injection. As mentioned earlier, the spectral hole created by an ultra-fast pulse is sustained over the SHB lifetime. Hence, the pulse experiences self advance due to the index change associated with the dip in gain spectrum. Using this mechanism, we have demonstrated an advance of 2.5 pulses for a 600 fs propagating through a quantum well SOA [13]. This is similar to the self advance reported in [12] with quantum dots as active material. In this paper, we investigate the feasibility of increasing the total advance by cascading two SOAs.

3. Experimental set-up

The experimental set-up used to obtain fast light is shown in Fig. 1. Calmar Optcom fiber laser is used to generate 600 fs pulses. The output from the fiber laser is split into two branches. One of the branches is used as reference for performing cross correlation measurements. Other branch goes through a variable attenuator and the polarization controller before it enters the optical amplifier. This enables control of the input power and polarization. The SOAs are quantum-well devices from JDS Uniphase Corporation operating in the C-band regime with a small signal gain of 28dB. The current of both the SOAs is controlled independently.
Fig. 1. Experimental set-up to realize fast light of 600 fs pulses in a SOA. The output of fiber laser is split into two branches. The signal branch goes through two concatenated SOAs and experiences fast light. The advance of the pulse is measured by performing cross correlation measurements using the reference.

4. Results and discussion

First we performed auto correlation measurements to characterize the pulse after it goes through the optical amplifier. Figure 2(a) shows the auto correlation traces at the input and output of the SOA. It can be seen that the auto correlation at the output is broadened by two times. This broadening is due to the large amount of fiber that is inherently present in various fiber based components including the fiber pigtailed SOAs, polarization controller and EDFA. This contribution can be eliminated in future by employing a free space set-up.

Previously, we reported an advance of 2.5 pulses using a single SOA as the current is varied from 50 mA to 200 mA [13]. Figure 2(b) shows the cross correlation traces when two SOAs are used in conjunction. It should be noted that the cross correlations are much wider than the actual pulse widths. To obtain real pulse width one has to subtract the contribution from the reference. For a current of around 100 mA for both SOAs, a maximum advance of 2 ps is obtained. This corresponds to an advancement of 3.3 pulses. These results are consistent with the physical explanation discussed earlier. As the SOA bias is increased, the depth of the spectral hole increases. This increases the group index which results in pulse advance. Recently, we showed that the wave mixing between different frequency components results in the oscillations of spectral hole depth and carrier temperature. This results in additional advance [14]. From the cross correlation traces, one can also see that the pulse width does not change significantly with increasing SOA current. As pointed earlier, this shows that most of the broadening is due to large amount of fiber present in various components. Increasing the current to higher values (>100 mA) causes significant distortion in the pulse shape due to self-steepening effect [14]. From the time traces in fig. 2(b), a small pedestal in
the pulse shape is seen at high currents. In general, fast light leads to spectral broadening of the pulse [15]. This is because frequency components at the center of gain hole experience less gain than frequency components away from the hole. This results in change of pulse shape which could explain the pedestal. We also observed that pedestal can be reduced by adjusting the input polarization into the SOA. Since the amount of advance depends on input polarization (TE/TM) as shown in [16], precise control of polarization is critical to achieving a good pulse shape. In our experiments, it’s hard to precisely control polarization due to large amount of fiber. We believe the pedestal can be minimized by using a free space set-up.

Comparing the total time advance of 3.3 pulses with the earlier mentioned value of only 2.5 pulses for a single SOA shows that cascading technique is scalable and results in higher advance as the number of SOAs is increased. However, as we increase the number of SOAs in the chain, the additional advance we get decreases due to spontaneous emission noise, spectral broadening and reshaping. These problems can be partially mitigated by including optical filters, attenuators and dispersion compensators between each optical amplifier. In order to better understand these limitations, we propose a novel scheme that uses a single SOA in a loop configuration that simulates the effect of cascading multiple SOAs.

![Fig. 3. Novel experimental scheme to study the effect of cascading multiple SOAs. By adjusting the time delay in the reference arm, we can selectively look at the pulses that have gone through the SOA multiple times.](image)

The experimental set-up for this scheme is shown in Fig. 3. Similar to earlier set-up, the output from the fiber laser is split into reference and signal. The signal arm goes through a 90/10 splitter before it enters the SOA. The output of the SOA is also connected to a 90/10 splitter. The 10% branch is fed back into the SOA while the rest of the power is used to monitor the output. Using this scheme, we can measure the time delay of the pulses passing through the SOA multiple times.

The time advance for a 700 fs pulse propagating through the SOA once is shown in Fig. 4(a). As expected, increasing the current of the SOA increases the advance. An advance of 0.64 ps is measured for a maximum current of 100 mA. For a pulse propagating through the SOA twice, total advance is increased to 1.17 ps as seen from Fig. 4(b). This advance is roughly twice that of a single pass pulse. This increased performance is consistent with the earlier measurement done using two cascaded SOAs. In this experiment, increasing the current beyond 100 mA causes the pulse to distort significantly as the SOA is at the threshold of lasing. Amplified spontaneous emission at high currents also contributes to pulse distortion. For the double pass case, pulse broadening is roughly 1.5 times compared to a single pass pulse. Currently experiments are underway to include an optical filter and a dispersion compensator in the loop to avoid these limitations.

4. Summary

We have demonstrated fast light at THz bandwidths using two SOAs in series. An advance of 2 ps is achieved for a 600 fs pulse by using ultra fast non-linear processes including spectral hole burning and carrier heating. This corresponds to an advance of 3.3 pulses. We also proposed an experimental scheme that uses a single SOA in a loop to study the effect of cascading multiple SOAs. The results show that the advance of a pulse propagating through
the SOA is roughly doubled compared to a single pass pulse. Using this scheme, we can also better understand the limitations caused by the ASE noise and the spectral reshaping of the pulse.

![Graph](image)

Fig. 4 (a) Electrical tuning of advance for a pulse propagating through the SOA once. A maximum advance of 0.64 ps is observed.

Fig. 4 (b) Electrical tuning of advance for a pulse propagating through the SOA twice. Observed advance of 1.17 ps is roughly twice that of a single pass pulse.

Acknowledgements

The authors would like to thank the support of DARPA grants F30602-02-2-0096 and Airforce contract FA 9550-04-1-0196.