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Executive Summary:

In this work, we will show the demonstration of a new effect that can enable all-optical logic at ultrafast speeds using semiconductor optical amplifier (SOA) technology. The name of this effect is the gain-dependent-time-shift. We believe there are many opportunities for growth in optical information processing systems using this effect and technology. Our modeling results were used to predict the existence of this effect. The experimental demonstration confirmed the existence of the gain-dependent-time-shift. Based on these experimental results, we predict that an ultrafast all-optical switch with switching energies of several femtojoules, switching times of sub-100 fsec, low power, and monolithically integrable is possible.

A. Theory:

The nonlinear pulse propagation equation used to model the pulse compression and gain dependent time shift effects is given by [1]

$$\begin{aligned} \frac{\partial A}{\partial z} + \beta'(\Omega) \frac{\partial A}{\partial t} + \frac{i}{2} \beta''(\Omega) \frac{\partial^2 A}{\partial t^2} - i \frac{\Omega}{c} n_{2_{\text{inst}}} |A|^2 A \\ = \frac{g_0}{2} A + \left[\left(-\frac{g_0 a}{2} + i \frac{\Omega}{c} n_{2_{\text{integ}}} \right) \int_{-\infty}^{t-\beta'z} |A|^2 dt \right] A \end{aligned}$$

A represents the field, β the propagation constant, g_0 the unsaturated gain,

$n_{2_{\text{inst}}}$ the instantaneous Kerr effect, and $n_{2_{\text{integ}}}$ the delayed Kerr effect. The first four terms in the equation represents the standard soliton effects. The terms in the square brackets represent the effects of the real and imaginary parts of gain saturation. The experimental verification of the above equation would be an important contribution to the field of semiconductor nonlinear optics.

Qualitatively, the pulse compression arises from the increase in linear chirp provided by the down-swept portions of the gain saturated chirp. The time shift occurs because the gain saturation chirp essentially lowers the frequencies of the existent soliton pulse; and thus, in a positive dispersive medium (as is the case near the bandedge of the semiconductor material) the pulse is advanced in time. The gain saturation also decreases the relative amplitude of the trailing edge of the soliton pulse making for a cleaner advance of the soliton in time.

B. Modeling Results:

Figure 1 shows the effects of both the pulse compression and the gain dependent time shift in the semiconductor traveling wave amplifier. The input pulse width and energy were 100 fsec and 500 fJ, respectively. The g_0 was varied from 40 cm^{-1} to 55 cm^{-1} and the length of the amplifier was $580 \text{ }\mu\text{m}$ (one soliton period). The time scale in fig. 1 is retarded time, $t-\beta'z$; thus without the gain saturation effects, the output pulse time shift is zero. From fig. 1 it is evident that the pulse compressed to 11 fsec and was time

advanced by 90 to 240 fsec with increasing gain. Thus, a gain change in g_0 of 15 cm^{-1} results in a pulse advancement of 150 fsec. This small gain change, approximately equivalent to 10 milliamps of pumping current, shifted the output pulse arrival time by about 10 pulse widths. The gain change can also be induced by another optical pulse, thus allowing for a new class of very sensitive and compact all-optical switches.

Figure 1. Pulse output from the SOA as function of retarded time.

C. Experimental set-up and data:

Figure 2. Cross-correlation set-up used to measure the gain-dependent time shift in SOAs.

The experiment encompasses measuring the time of flight through the SOA as depicted in figure 2. The current of the SOA is then varied so that the initial gain of the gain of the SOA, g_0 , can be varied by changing the carrier density of the SOA gain medium. By measuring the time shift of the pulse through the SOA versus applied current to the SOA we can verify the gain dependent time of flight. The optical pulses were generated by a modelocked Ti:sapphire laser. The laser outputs 100 fsec pulses at a repetition rate of 100 MHz with peak powers on the order of 10^5 watts. The pulses are beam split into two branches. One branch is sent to the SOA and then time delayed by a movable speaker upon which a retroreflector is mounted and then sent to the LiIO3 crystal. The movable speaker arrangement allowed for real time observation of the gain dependent time of flight. The other branch was equally time delayed and sent to the LiIO3 crystal. The LiIO3 crystal was operated in a frequency doubling mode whereby the light from both branches must be present in order that the doubles frequency light is generated. The photomultiplier tube (PMT) is used to observe the doubled light and is displayed on the vertical axis of an oscilloscope. Lock-in detection was used for the vertical channel and the horizontal axis of the oscilloscope displayed the voltage applied to the movable speaker. The LiIO3 crystal is functioning as a cross-correlator or time coincidence detector with response times on the order of 150 fsec. Thus, the relative time delay of the SOA pulses could be measured with respect to the other branch whose distance is fixed during the measurement.

Figure 3 a. SOA output pulse versus negative time for $I = 40$ mA applied to the SOA. The horizontal scale is 80 fs/cm.

Figure 3 b. SOA output pulse versus negative time for $I = 90$ mA applied to the SOA. The horizontal scale is 80 fs/cm.

Shown in figure 3a and 3b are the cross-correlation traces taken with the experimental apparatus of figure 2 at pumping currents of 40 mA and 90 mA respectively. The wavelength of the Ti:Sapphire laser was centered at 880 nm. The gain peak of the SOA was approximately at 890 nm with a bandwidth of 30 nm. Note the horizontal axis is as a function of negative time delay i.e. decreasing time delay. Thus, we see as the initial gain is increased in the SOA, the pulse advances in time. The amount of shift is significant and is approximately 160 fsec. Note that there are two traces in figures 3a and 3b. The two traces were a result of the retrace on the movable speaker. To properly compare the figures just compare either the rightmost or leftmost traces. The average pulse power in figure 3a was 2 microwatts (peak power ~ 0.2 watts) and in figure 3 b it was 6.4 microwatts (peak power ~ 0.64 watts). This coupled power into the SOA was limited by back reflection instabilities induced into the modelocked Ti:sapphire laser. \

Using computer modeling of the nonlinear Schrodinger equation (and appropriate perturbations for the SOA), a simple formula predicting the amount of time shift is given by (cf. figure 1)

$$\Delta\tau = -15 \text{ fsec/mA} * I \quad (1),$$

where I is the applied current to the SOA. This effect is much larger than simple index changes due to band filling of the semiconductor under pumped conditions. The time shift due simple index changes is estimated to be

$$\Delta\tau = -0.05 \text{ fsec/mA} * I \quad (2) .$$

The gain dependent time shift effect is almost two orders of magnitude larger and thus adds to the usefulness of this effect. At a wavelength of 880 nm, we measured a time shift in the SOA of (cf. figures 3a and 3b)

$$\Delta\tau = -3.2 \text{ fsec/mA} * I \quad (3) .$$

This amount of shift cannot be explained by simple index changes with current (cf. (2), (3)). Thus, we feel the only plausible explanation is the gain dependent time shift.

D. Gain dependent time shift application:

Ultimately, as time progresses, we hope to demonstrate an ultrafast optical switch based on this effect. Shown in figure 4 is a Mach-Zhender interferometer based all-optical switch fabricated with each branch made of the nonlinear SOAs such that the gain dependent time shift is operating. The electrical analog of such a switch would be the transistor.

Figure 4. All-optical switch based on the gain-dependent-time-shift in a SOA

The operation of the all-optical switch is as follows: L_{bias} represents a pump beam that excites the nonlinear mode, the gain dependent time shift in each branch containing a SOA. The energy of this pulse would be approximately a few femtojoules. Each SOA would amplify this energy to the required 50 to 100 femtojoules. I_{bias} to each SOA would be adjusted so that destructive interference occurs at the output L_{out} . The all-optical switching beam, L_{in} , would change the initial gain in one of the SOAs such that the gain dependent time shift would cause one of the pulses to not completely interfere with the other pulse. Thus, the switching beam will destroy the destructive interference and thus allow light to be present at the output L_{out} . Based on our experimental demonstration of the amount of time shift in the SOA, we can estimate the switching energy required for the switching beam to be approximately, several femtojoules. This switching energy is quite small indeed and if demonstrated would represent a breakthrough in the field of integrated nonlinear optics. Further small amounts of funding (and mostly time) would be needed to accomplish this task.

E. Conclusions and Future work:

In this work, we have demonstrated a novel and far-reaching nonlinear and ultrafast effect in SOAs. We believe effects such as this will enable completely new type of systems in optical information applications. Our modeling results confirm the effect. However, in the experiment, we did not observe the pulse compression as predicted by the model. The parameter that is the largest in discrepancy is the peak power of the pulse and we feel by increasing the peak power we should be able to observe the pulse compression. Indeed as can be seen in figure 3b, a second peak is starting to occur as the output power of the pulse is being increased. In the experiment, this power was ultimately limited by the susceptibility of the Ti:Sapphire laser to back reflections and resultant instabilities. We believe that the back reflection was the one that occurred at the output fiber of the SOA and was amplified by the SOA itself. In future experiments, we will free-space couple the output and increase the input peak power to the SOA. If we can perform this increase in power and demonstrate the pulse compression, then we should be able to decrease the required switching energy by a factor ten to the sub-femto joule level. We feel the experimental and theoretical results, as they stand, are publishable in a refereed scientific journal. However, we feel that before this is done, a sincere attempt to observe the pulse compression, as described above, should be taken. We look forward to updating these results.

F. Acknowledgments:

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G. References:

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