Ultrafast all-optical switching using a semiconductor optical amplifier

Harm J.S. Dorren, Daan Lenstra* and G. Djan Khoe

COBRA Research Institue, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands (H.J.S.Dorren@tue.nl)

* also with Vrije Universiteit, FEW, Division of Physics and Astronomy, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands (lenstra@nat.vu.nl)

On the basis of numerical experiments, we discuss how a semiconductor optical amplifier in a Sagnac interferometric arrangement can be used for switching 200 fs pulses. The switching principle is based on gain and index saturation dynamics on a sub-picosecond timescale. The model accounts for bi-directional propagation of ultrashort optical pulses through the amplifier as well as free-carrier and two-photon absorption.

Introduction

Semiconductor optical amplifiers (SOA's) constitute important building stones in optical communication networks. In the near future they may become even more crucial in their role of providing the nonlinearity required for ultra-fast all-optical signal processing. It is therefore of great importance to study the nonlinear dynamical characteristics of these devices under circumstances involving sub-picosecond or even femtosecond optical pulses [1]. An interesting application of a SOA for ultrafast optical switching is in the Sagnac interferometric configuration sketched in Fig.1. A data pulse is split by an optical splitter in two equal parts, one pulse propagating in the clockwise (cw) and the other pulse propagating in the counter clockwise (ccw) direction in the optical loop. The SOA is positioned asymmetrically in the loop, so that the cw pulse experiences a different gain (and thus refractive index) than the ccw pulse. Only if the phase difference equals an odd multiple of π, will the incoming pulse be directed into the output port. There can also be injected a control pulse, which should arrive in the SOA in between the arrivals of the ccw and the cw data pulses. With the control pulse, the amplitude and phase difference between the co-propagating data pulses can be manipulated further.

The configuration of Fig.1 is referred to as SLALOM if there is no control pulse [2], but with control pulse it is known as TOAD [1]. Until present, these and similar devices were operated on the principle of carrier depletion with pulses not shorter than 30 ps, which are spatially much longer than the SOA. However, in case of the 200 fs pulses that we have in mind, the SOA length of 250 μm is much longer than the pulse length of 20 μm and other, i.e. faster, physical processes have to be considered.

A recent experiment by Romstad *et al* [3] involves 175 fs pulses propagating in a bulk gain SOA operating at 1.53 μm. The pulse energies were varied from far below to well beyond the saturation value. Among other observations they found for saturating pulses substantial narrowing around transparency or under absorption conditions, while break-up of the pulse occurred in the high-gain regime. Clearly, they have demonstrated the presence of strong nonlinear effects that, on the one hand, pose severe restrictions as to the applicability of SOA's as short-pulse amplifiers, but on the other hand indicate their potential for new all-optical signal processing applications.

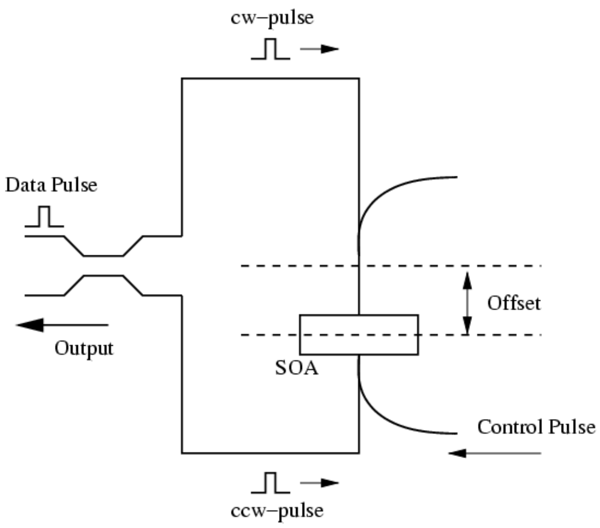


Figure 1: Configuration of a SOA in a Sagnac interferometer

Model

For our simulations we have used a model similar to the one by Mark and Moerk [4], which takes account of carriers that are involved in the optical transitions, the total number of e-h pairs, carrier-carrier scattering, carrier-phonon scattering, energy relaxations and local chemical potentials and temperatures. We also include two-photon absorption (TPA) and free-carrier absorption (FCA) in the conduction band, because these are the basic mechanisms for nonlinearity on the picosecond or shorter timescales. Finally, we extend the model with phase modulation and bi-directional propagation of optical pulses.

A more detailed description of our model can be found in [5]. Let us mention here that the total carrier density and the energy densities in conduction and valence band must be tracked since they are needed to self-consistently calculate in each time step of integration the quasi Fermi-levels and temperatures of electrons and holes, which in turn are needed to find quasi-equilibrium values for the densities of electrons, holes and corresponding energies. Thus a closed set of 11 equations is obtained that is solved using standard methods.

We have chosen the length of our optical pulses such that an optimal effect was expected from the ultrafast relaxation processes that typically occur on the 50 – 100 fs timescale. The parameter values we used are: e-h recombination time 250 ps; e-e scattering time 100 fs and h-h scattering time 50 fs; two-photon absorption coefficient 35 cm/GW; hole-phonon scattering time 0.25 ps; electron-phonon scattering time 0.7 ps; free-electron absorption 19 per cm; confinement factors 0.023 for stimulated emission and 0.09 for two-photon absorption and the bandgap energy 0.77 eV (1.53 μm). The SOA length is 250 μm and the active volume is 50 μm^3 while pump currents were considered of 120 and 300 mA. Finally the remaining parameters were chosen so as to reach a small-signal gain of 15.4 dB. These parameter settings lead to results that are in quantitative agreement with most of the experimental results reported in [3].

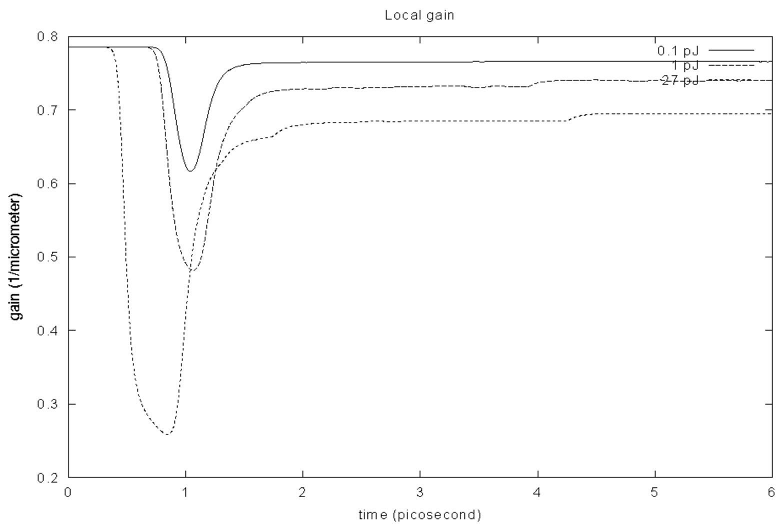


Figure 2: Local gain dynamics at a depth of 50 μm for pulse energies of 0.1, 1.0 and 27 pJ, as indicated.

Results

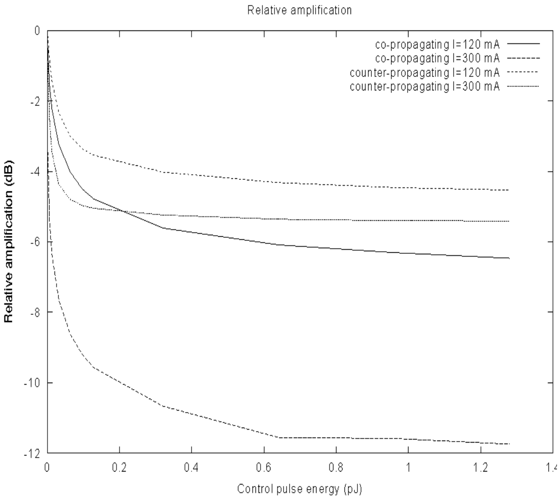
In Figure 2 the local gain at a depth of 50 μm is shown for a 200 fs optical pulse with incident energies of 0.1, 1.0 and 27 pJ. The gain in the SOA temporarily decreases after the stimulated emission caused by the passing pulse. The gain partially recovers after 200 to 500 fs, depending on the pulse energy. Full recovery of the gain takes place on a much longer timescale set by the e-h recombination time (~1 ns, not shown in Fig.2). A 1 pJ pulse typically introduces a local gain decrease of about 30%. This can be used for optical switching.

In the following numerical experiment, a data pulse with incident energy of 0.13 fJ propagates through the SOA while tailing a control pulse in such a manner that it stays in the gain minimum burned by the control pulse. Thus, the data pulse receives substantially less amplification than in the absence of the control pulse. We also investigate the case that the data pulse and the control pulse are counter-propagating, which in view of the much shorter interaction time gives rise to smaller differences in amplification. All results are shown in Figure 3, where relative amplifications of the 0.13 fJ data pulse are given versus the control pulse energy, for both co- and counter-propagating cases and for both 120 and 300 mA pump bias. In the co-propagating tailing case, a gain difference of 6 to12 dB can be obtained. For the counter-propagating case the gain difference is less spectacular, but 4 to 5 dB is still possible if the control pulse energy is not too small.

The corresponding phase differences (taken at the pulse maximum) are shown in Figure 4. Phase differences larger than π can easily be obtained in the co-propagating case with the data pulse tailing the control pulse. For the counter-propagating case much smaller phase differences are obtained. These results are obtained for a value of the self-phase modulation parameter α=5. It was verified that all curves in Fig.4 scale linearly with α. This imples that for α-values not smaller than 10 it is still possible to obtain a phase difference value of π, required for interferometric switching.

Acknowledgments

This research was supported by the Netherlands Organization for Scientific Research (NWO) through the “NRC Photonics” grant.



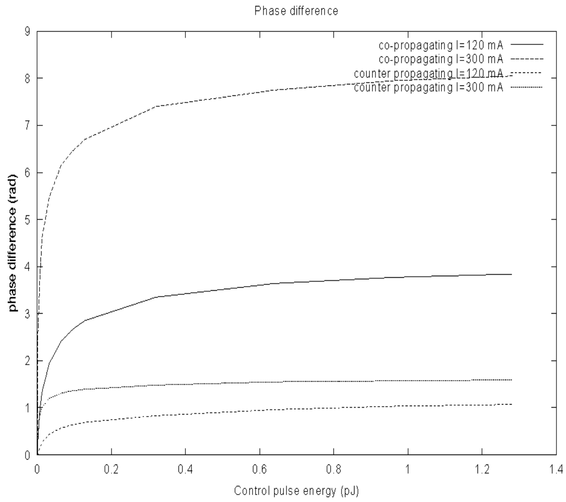


Figure 3: Amplification of a 0.13 fJ data pulse in the presence of a control pulse as function of the control pulse energy and relative to the situation without control pulse. Curves labelled co-propagating are for the data pulse tailing the control pulse in the gain minimum as described in the text. Curves labelled counter-propagating are for colliding data pulse and control pulse. Two different pump currents *I*=120 and 300 mA are considered.

Figure 4: Phase differences corresponding to the four cases of Fig.3 for α=5. The curves scale linearly with α.

References

[1] D. Cotter, R.J. Manning, K.J. Blow, A.D. Ellis, A.E. Kelly, D. Nesset, I.D. Philips, A.J. Poustie and D.C. Rogers, "Nonlinear optics for high-speed digital information processing", Science 286, 1999, pp.1523-1528.

[2] M. Eiselt, W. Pieper and H.G. Weber, "SLALOM: Semiconductor optical amplifier in a loop mirror", J. Lightwave Techn. 13, 1995, pp. 2099-2112.

[3] F. Romstad, P. Borri, W. Langbein, J. Moerk, J.M. Hvam, "Measurement of pulse amplitude and phase distortion in a semiconductor optical amplifier: from pulse compression to break-up", IEEE Photonics Techn. Lett. 12, 2000, pp. 1674-1676.

[4] J. Mark and J. Moerk, "Subpicosecond gain dynamics in InGaAsP optical amplifiers: Experiment and theory", Applied Phys. Lett. 61, 1992, pp. 2281-2283.

[5] H.J.S. Dorren, G.D. Khoe and D. Lenstra, "Ultrafast all-optical switching using a semiconductor optical amplifier in a Sagnac interferometric arrangement", submitted for publication in Optics Commun., 2001.