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All-optical switching of an ultrashort pulse using a semiconductor optical amplifier in a Sagnac-interferometric arrangement

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Abstract

On the basis of numerical experiments, we explain how a semiconductor optical amplifier in a Sagnac-interferometric arrangement can be used for switching of 200 fs optical pulses. The switching principles are 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 absorption and two-photon absorption. The results indicate that the system can operate as an ultrafast optical “and”-gate. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

Telecommunication systems based on femtosecond optical pulses for ultrahigh bit-rate optical transmission require new concepts to be developed for ultrafast all-optical switching [1]. An interesting all-optical switch that allows ultrafast operation consists of a semiconductor optical amplifier (SOA) in an interferometric environment. An example is the configuration depicted in Fig. 1. A data-pulse is split in two equal parts by an optical splitter. Half of the optical power then propagates in clock-wise (cw) direction through the optical loop, while the other half propagates in the counter-clock-wise (ccw) direction. The SOA is placed out of the center of the loop. This creates an asymmetry causing the cw-pulse to experience a gain (and thus refractive index) in the SOA different from the ccw-pulse. Only if the phase-difference between the pulses equals an odd-multiple of $\pi$ is the incident pulse directed to the output port. For historical reasons, this configuration is referred to as Terahertz Optical Asymmetric Demultiplexer (TOAD), if there is also an additional control-pulse injected to sweep some additional gain out of the SOA [2]. Otherwise the configuration is called a Semiconductor Laser Amplifier in a Loop Optical Mirror (SLALOM) [3]. In this letter, we discuss how a SOA can be used for switching of 200 fs
holes, which are much shorter than the SOA length.

2. Model

Mark and Mørk [4] have carried out pump-probe experiments in order to measure ultrafast gain dynamics in bulk SOAs. Their results confirmed the relevance of carrier heating as a result of two-photon absorption (TPA) and free-carrier absorption (FCA). Moreover, they formulated a theoretical model in which all these effects are accounted for. The model that we use is in the spirit of the one that is presented in [4] but extended with self-phase modulation, and bi-directional propagation of optical pulses. Thus, we take into account, TPA, FCA, carrier heating and spectral-hole burning [4,5].

The total electromagnetic field $E(z,t)$ in the SOA is represented as

$$E(z,t) = [A_-(z,t)e^{ik_0z} + A_+(z,t)e^{-ik_0z}]e^{i\omega_0t} + \text{c.c.},$$

(1)

where the wavenumber $k_0 = (n(\omega_0)/c)\omega_0$ with $n(\omega_0)$ is the refractive index taken at the central frequency of the pulses $\omega_0$ and $c$ is the light velocity in vacuum. The frequency $\omega_0$ has been chosen such that the complex pulse amplitudes $A_{\pm}(z,t)$ are slowly varying functions of $z$ and $t$. These complex amplitudes satisfy:

$$\left( \frac{1}{v_g} \frac{\partial}{\partial t} \pm \frac{\partial}{\partial z} \right) A_{\pm}(z,t)$$

$$= \left[ \frac{1}{2} \Gamma (1 + i\zeta) g(z,t) - \frac{1}{2} \alpha_{\text{int}} - \frac{1}{2} \beta_2 (1 + i\rho) S(z,t) - \frac{1}{2} \Gamma \beta_n n_e(z,t) - \frac{1}{2} \Gamma \beta_v n_v(z,t) \right] A_{\pm}(z,t),$$

(2)

where $v_g$ is the group-velocity at $\omega_0$, $\Gamma$ is the confinement factor, $\zeta$ is the phase modulation parameter (in a laser context also known as linewidth enhancement factor), $\rho$ accounts for the index change induced by the TPA. Corresponding phase modulation parameters for the FCA should not be considered here as they are already accounted for in $\rho$. The local gain $g(z,t)$ is defined by

$$g(z,t) = \frac{1}{v_g} a_n(\omega_0)[n_e(z,t) + n_v(z,t) - N_0],$$

(3)

where $a_n(\omega_0)$ is the gain coefficient at $\omega_0$, $N_0$ is the total density of electronic states involved in the optical transition, $n_e(z,t)$ is the corresponding density of the electrons in the conduction and $n_v(z,t)$ the density of the holes in the valence band. $\alpha_{\text{int}}$ represents the internal mode losses in the waveguide. The last three terms in the RHS of (2) describe TPA and FCA, with corresponding coefficients $\beta_2$ (TPA), and $\beta_n$ and $\beta_v$ (FCA) taken real. The pulse amplitudes are written as

$$A_{\pm}(z,t) = \sqrt{S_{\pm}(z,t)} e^{i\phi_{\pm}(z,t)}$$

(4)

introducing the right and left traveling intensities $S_{\pm}(z,t)$ and phases $\phi_{\pm}(z,t)$. In the total intensity $S(z,t)$, we neglect the grating induced by the interference of the overlapping counter propagating pulses, that is we put $S(z,t) = S_+(z,t) + S_-(z,t)$. This is probably a good approximation since both numerical and analytical estimates indicate that the index variations of the grating induced by TPA remain smaller than $10^{-4}$.

The SOA model is completed by formulating the remaining equations. For the subset of carriers directly involved in the stimulated emission and FCA we have

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**Fig. 1. Configuration of a SOA in a Sagnac interferometer.**
\[
\frac{\partial n_e(z,t)}{\partial t} = -n_e(z,t) - \overline{n}_e(z,t) - \left[ v_g g(z,t) + n_e \beta_1 S(z,t) \right] \quad (v \in \{c, v\}).
\] (5)

The total electron–hole pair density \(N(z,t)\) satisfies:
\[
\frac{\partial N(z,t)}{\partial t} = \frac{I}{eV} - \frac{N(z,t)}{\tau_s} - v_g g S(z,t) + \frac{\Gamma_2}{\Gamma} v_g \beta_2 S^2(z,t),
\] (6)

where it is noted that \(N(z,t)\) counts all electron–hole pairs including those that are not directly available for stimulated emission. The energy densities \(U_v(z,t)\) satisfy:
\[
\frac{\partial U_v(z,t)}{\partial t} = \left[ \beta \hbar \omega_0 n_v(z,t) - E_v g(z,t) \right] v_g S(z,t) - \frac{\Gamma_2}{\Gamma} v_g \beta_2 E_2 S^2(z,t) - \frac{U_v(z,t) - \overline{U}_v(z,t)}{\tau_{h,v}}.
\] (7)

The quantities in these equations have the following meanings. The confinement factor \(\Gamma_2\), takes account of the fact that in TPA only photons absorbed in the active layer will produce a recyclable carrier-pair. \(\tau_{1,v}\) are the carrier–carrier scattering times and \(\overline{n}_v\) are the quasi-equilibrium values for the carriers. \(I\) is the bias current, \(e\) is the unit charge, \(V\) is the active volume, and \(\tau_s\) is the electron–hole lifetime for spontaneous recombination (both radiative and non-radiative). \(E_v\) and \(E_{2,v} (>0)\) are energies with respect to the corresponding band edges. \(\tau_{h,v}\) are the carrier–phonon interaction times and \(\overline{U}_v(z,t)\) are the quasi-equilibrium energies. The total carrier density \(N(z,t)\) and the energy densities \(U_v(z,t)\) are needed to self-consistently calculate in each time-step the quasi-Fermi-levels and temperatures of electrons and holes, which in turn are needed to find the quasi-equilibrium quantities \(\overline{n}_v(z,t)\) and \(\overline{U}_v(z,t)\). For the energy relaxation, the temperature must be taken equal to the lattice temperature \(T_L\) (300 K). Carrier diffusion (in the \(z\)-direction) is not taken into

![Fig. 2. Local gain at a depth of 50 μm for pulse energies of 0.1, 1, and 27 pJ, respectively.](image-url)
account because its effect is very weak on the picosecond timescale.

3. Numerical experiments

We now have a closed set of equations that can be solved using standard methods. In our simulations, we use the parameter values $\tau_s = 250$ ps, $\tau_{1s} = 50$ fs, $\tau_{1c} = 100$ fs, $\tau_c = 250$ ps, $\beta_2 = 35$ cm/GW, $\tau_{h,s} = 0.25$ ps, $\tau_{h,c} = 0.7$ ps, $\beta_s = 0$, $\beta_c = 19$ cm$^{-1}$, $\Gamma_1 = 0.023$, $\Gamma_2 = 0.09$ and the bandgap $E_g = 0.77$ eV [4]. The phase modulation parameters $a$ and $a_2$ were both given the value 5 [6,7]. Moreover, we consider a SOA length of 250 $\mu$m, an active volume of 50 $\mu$m$^3$ and pump currents of 120 and 300 mA, respectively. The transparency current was 30 mA. The remaining parameters have been chosen in order to reach a small-signal gain of 14.4 dB (at 120 mA), i.e., $a(\omega_0) = 2.5 \times 10^{-4}$ $\mu$m/ps and $g_{\text{int}} = 0.0027$ $\mu$m$^{-1}$.

These parameter settings lead to results that are in good agreement with measured gains, as presented in Fig. 2(b) of [8]. Small variations, i.e., within 10%, in the parameter values did not lead to qualitatively different results or conclusions.

In Fig. 2, the local gain at a depth of 50 $\mu$m is presented for a 200 fs optical pulse with incident pulse energies of 0.1, 1 and 27 pJ and a pumping current of 120 mA. The gain in the SOA temporarily decreases after the stimulated emission caused by the optical pulse passing by. The gain partially recovers at a timescale of about 200 fs. Full recovery of the gain takes place on a much longer timescale $\tau_s$ (~1 ns, not shown in Fig. 2). A 1 pJ optical pulse typically introduces a local gain decrease of about 30%. This can be employed for optical switching. In the following numerical experiment, a data-pulse with incident pulse energy of 0.2 fJ propagates through a SOA in the gain-minimum that is introduced by a control-pulse. Hence, the data-pulse receives less amplification.

![Relative amplification graph](image)

Fig. 3. Amplification of a 0.2 fJ data-pulse co-propagating in the local gain-minimum of a control-pulse relative to the amplification without a control-pulse for $I$ is 120 mA and $I$ is 300 mA, respectively. The control-pulse energy is plotted on the horizontal axis. Also the cases where the data-pulse and the control-pulse propagate in opposite directions are presented.
compared to the same data-pulse propagating through the SOA in the absence of the control-pulse. In Fig. 3 the control-pulse energy is plotted versus the relative amplification for different values of the pump current \( I \). It follows from Fig. 3, that a data-pulse propagating through a SOA \( (I = 120 \text{ mA}) \) in the gain-minimum of a control-pulse with a pulse energy of 0.6 pJ or more, receives at least 6 dB less gain compared to the same data-pulse propagating through the SOA in the absence of the control-pulse. If the pumping current is increased to 300 mA, the gain difference nearly reaches 11 dB. Also shown in Fig. 3 is the difference in amplification of a 0.2 fJ data-pulse while the control-pulse is propagating in opposite direction through the SOA. Due to the short interaction time, the attenuation is substantially less than 1.5 dB \( (I = 120 \text{ mA}) \) compared to the case of the data-pulse propagating in the gain-minimum of a control-pulse.

The corresponding phase-differences (taken at the maximum pulse energy) are plotted in Fig. 4. Phase-differences larger than \( \pi \) can be obtained if the data-pulse and the control-pulse propagate in the same direction. If the data-pulse and the control-pulse propagate in opposite direction, phase differences larger than \( \pi \) cannot be obtained.

4. Conclusions

According to these results a data-pulse co-propagating in the gain-minimum of a control-pulse is undergoing adequate gain and phase differences required for switching. The effects can be enlarged by using a longer SOA, so that the data-pulse remains longer in the gain-minimum that is introduced by the control-pulse. In the case where the data-pulse counter propagates with the control-pulse, the phase difference is not adequate.
for switching. If longer optical pulses are used, the interaction time between the pulses is longer and hence a larger phase difference could be expected. These numerical results indicate that a SOA placed in a Sagnac interferometer can be employed as an optical “and’’-gate if the system is operated in a TOAD configuration and the control-pulse co-propagates with the data-pulse. If the additional control-pulse is missing (SLALOM operation), the phase-differences are not sufficient for optical switching.

Our results indicate that all-optical switching of low energy femtosecond optical pulses is possible but two comments should be made. First of all, after studying the literature [6,7,9–11], one can doubt whether we have taken the correct sign for \( \varepsilon_2 \). Our choice is consistent with [6,7], but we note that if \( \varepsilon_2 \) has the opposite sign even larger phase-shifts would occur. So with respect to optical switching our results are conservative. Second, in optical communications applications it would be essential to operate systems at ultrahigh repetition rates. In this case, the main restriction is the ultrafast recovery time of the gain. According to Fig. 2, a repetition rate of 1 THz would not be a problem, since in that case the background gain will settle at a value that can easily be controlled by adjusting the operating current. Preliminary simulations on the basis of five subsequent optical pulses at a repetition rate of 1 THz support this conclusion.

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