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Sub-picosecond all-optical switch using a multi-quantum-well semiconductor optical amplifier

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Abstract

We investigate an all-optical switch that is operated by the nonlinear phase-shift introduced by optical pulses with duration of 200 fs in a semiconductor optical amplifier (SOAs). The gate is made out of a commercially available InGaAsP–InGaAs multi-quantum-well (MQW) SOA placed in a Mach–Zehnder interferometer. We have measured the nonlinear phase-shift as a function of the injection current and we show that the largest effect takes place at zero current. We show that the gate has a contrast ratio better than 11 dB and that the switching time is less than 1 ps. The gate is operated with pulse energies of 800 fJ.

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1. Introduction

The need for ultrafast all-optical logic has been well documented [1]. Semiconductor optical amplifiers (SOAs) are attractive as nonlinear elements

in all-optical logic gates since they provide a high gain, have a strong refractive-index change and allow photonic integration [1–7]. In conventional applications the switching speed of optical logic based on SOA nonlinearities is limited to 250 GHz due to the slow SOA recovery (typically in the order of 1 ns) [1]. Higher switching speeds can be realized by employing two-photon absorption (TPA) and free carrier absorption (FCA) in combination with ultrafast carrier cooling for the SOA recovery [6–10]. In this case, SOA recovery is limited by the electron–electron or the hole–hole scattering time (typically in the order of 50–100 fs)

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and the carrier-phonon scattering time (less than 1 ps) [9]. Recent experiments for a multi-quantum-well (MQW) SOA indicate that nonlinear phase shifts introduced by 200 fs pump pulses can be larger than π radians, while the recovery time is shorter than 1 ps [7].

An interesting optical logic gate consists of a SOA that is placed in a Mach–Zehnder interferometer (see Fig. 1). A beam splitter splits the power of a data pulse that inputs the interferometer into two parts. The first part forms the reference pulse, which is sent directly to the interferometer output. The second pulse forms the probe pulse, which passes through the SOA before being sent to the interferometer output, where the probe and reference pulses interfere. The interferometer output power depends on the power and the relative phases of probe and reference pulses. By injecting a pump pulse into the SOA, both power and phase of the probe pulse can be modified due to the SOA saturation [1]. Thus the power of the interferometer output can be controlled by injection of a saturating control pulse. Such a configuration forms a universal optical logic gate since it can act not only as an optical AND gate but also as an optical XOR gate [1].

Switching experiments, employing femtosecond pulses in an ultrafast nonlinear interferometer were reported in [6]. The nonlinear phase shift induced by femtosecond optical pulses in SOAs was investigated in [5–7,11–15]. However, in these

papers no systematic investigation is given of the nonlinear phase-shift in the SOA, in the context of ultrafast optical logic. The present paper shows the four important new results. Firstly, we present the maximum nonlinear phase-shift induced in the SOA by 200 fs optical pulses as a function of the injection current and show that the nonlinear phase-shift increases with decreasing injection current. This result is essentially different from those cases in which the nonlinear phase-shift is introduced by picosecond optical pulses, since in the latter cases the effect of TPA is irrelevant. Secondly, we show that the nonlinear phase-shift recovers in approximately 1 ps. The third new result is that the largest nonlinear phase-shift in semiconductor optical amplifiers is obtained for zero injection current. This result might be relevant for researchers in the OTDM community since it suggests that it is beneficial to employ optically pumped passive waveguides for ultrafast optical time domain demultiplexing instead of active waveguides. Finally, we present for the first time experimental results on the contrast ratio for switching of 200 fs pulses based on the above-mentioned phase shift.

We demonstrate all-optical AND gate operation by using a single MQW SOA that is placed in an asymmetric Mach–Zehnder interferometer. In contrast to [6], the pump–probe and reference beams have the same wavelength but are at different polarizations. We show that the gate can be operated with optical pulses with duration of 200 fs while having a contrast ratio larger than 11 dB.

2. Experimental setup

A schematic of our all-optical logic AND gate is shown in Fig. 1. An optical parametric oscillator (OPO) pumped with a mode-locked Ti:Sapphire laser is used to produce optical pulses that were 200 fs (FWHM) in duration at a repetition rate of 75 MHz. The central wavelength of the pulses was 1520 nm. The OPO output is firstly attenuated using a half-wave plate and a polarizer. A second half-wave plate is used to set the polarization of the laser beam to linear under

Fig. 1. Schematic of the experimental set-up, where the symbols of optical components are defined as: OPO: optical parametric oscillator; HW: half-wave plate; P is polarizer; M: mirror; PBS: polarizing beam-splitter; BS: beam-splitter; PR: prism; A: attenuator; L: lens.

45°. A polarizing beam splitter is used to create a transverse electric (TE) polarized laser beam and a transverse magnetic (TM) polarized laser beam. The TM polarized laser beam forms the pump light and is fed into a variable delay line. A beam splitter divides the TE polarized laser beam into a probe beam and a reference beam. The pump and probe beams are coupled into the SOA through microscope objectives. The coupling losses are estimated to be 6 dB. The pump–probe delay is controlled by the variable delay stage. The SOA used in our experiments is an InGaAsP–InGaAs MQW SOA with a central length of 750 μm and a taper zone with a length of 400 μm on each sides of the central part. Neutral density filters are used to control the power of the probe and reference beams. A translatable end mirror controls the delay between the reference beam and the probe beam. When the pump and probe beams have passed through the SOA, the pump light is removed by using another polarizing beam-splitter. The probe and reference beams firstly interfere in the beam-splitter. The interfered light is then collimated into an optical fiber that is connected to a detector. The whole set-up is placed in a box to shield the interferometer from thermal and mechanical disturbances. An automated measurement system is employed to obtain stable measurements without any active control.

3. Results

In our first experiment, the interferometer output power is measured for zero pump–probe delay. The power of the probe beam was equal to the power of the reference beam but the pump power was ten times larger. We have observed that our SOA converts about 1% of the TM polarized pump light into TE polarized light, which also interferes with the probe- and reference beams. First, we measured the maximum interferometer output (i.e. with zero time delay between probe and reference pulse) as a function of the injection current. The interferometer output power can be related to the nonlinear phase-shift through the following relationship:

$$S_{\text{det}}(\tau) = \frac{1}{T} \int_{-T/2}^{T/2} \left\{ P_p(t+\tau) + P_{\text{pr}}(t) + P_r(t) \right. \\ + 2\sqrt{P_r(t)P_p(t+\tau)} \cos[\phi_{r,p} - aI] \\ + 2\sqrt{P_p(t+\tau)P_{\text{pr}}(t)} \cos[\phi_{p,\text{pr}} - \Delta\phi_{\text{NL}}(\tau)] \\ \left. + 2\sqrt{P_r(t)P_{\text{pr}}(t)} \cos[aI + \Delta\phi_{\text{NL}}(\tau)] \right\} dt, \quad (1)$$

where $S_{\text{det}}(\tau)$ is the detector signal, τ the pump–probe delay, $P_p(t+\tau)$ is the power of the polarization converted pump pulse, $P_{\text{pr}}(t)$ is the power of the probe pulse and $P_r(t)$ is the power of the reference pulse. The pump-induced nonlinear phase shift $\Delta\phi_{\text{NL}}(\tau)$ is the phase difference of the probe pulse between the cases in presence and absence of a pump pulse. $\phi_{r,p}$ is the phase-shift introduced by the optical path length difference between the reference pulse and the polarization converted pump pulse. Similarly, $\phi_{p,\text{pr}}$ represents the phase shift introduced by the path length difference between the polarization converted pump pulse and the probe. Finally, we have observed the phase-shift induced by the SOA injection current I equals aI , and we measured the value $a = \pi/100$ rad/mA. The detector response time T in Eq. (1) is much larger than the pulse duration.

The solid curve in Fig. 2 shows a typical measured data trace. The dotted curve shows a fit of the measured data using Eq. (1). For this specific example, the pump pulse energy is 3.2 pJ, the probe pulse energy is 0.3 pJ and the reference pulse energy is 0.3 pJ, while $I = 0$ mA. The maximum pump–probe delay is 5 ps (not shown in Fig. 2). $\phi_{r,p}$ and $\phi_{p,\text{pr}}$ do not depend on the pump–probe delay time τ and can be treated as constant phase factors. Their values are determined for $\tau = 0$, by using three separate measurements, one with the probe beam blocked, one with the reference beam blocked and one with all three beams present simultaneously. By properly combining all these data, one can find the values for $\phi_{r,p}$ and $\phi_{p,\text{pr}}$. After substitution of these values in Eq. (1), we can numerically solve for $\Delta\phi_{\text{NL}}(\tau)$.

The dotted line in Fig. 3 shows the nonlinear phase-shift as a function of the pump–probe delay τ without injection current. The pump and probe

Fig. 2. Typical measured data-trace (solid curve) and a fit of the data (dotted curve), where the pump pulse energy is 3.2 pJ and the probe (or reference) pulse energy is 0.3 pJ, $I = 0$ mA.

Fig. 3. Nonlinear phase shifts as a function of the pump-probe delay time, for $I = 0$ mA (dotted curve) and $I = 180$ mA (solid curve). The pump pulse energy is 3.2 pJ and the probe (or reference) pulse energy is 0.3 pJ.

energies were 3.2 and 0.3 pJ, respectively. The solid line in Fig. 3 shows the same result but now for an injection current of 180 mA. Also, Fig. 3 shows that the nonlinear phase-shift comes up and disappears within 1 ps. The pump and probe results are in good qualitative agreement with the result published in [7]. Similarly as in [7], but in contrast to [5], we do not observe a long-lived tail in the recovery of the phase shift.

Fig. 4, shows the maximum nonlinear phase-shift as a function of the injection current. The

Fig. 4. Nonlinear phase shifts as a function of the injection current for various pump and probe energies when the pump-probe delay is zero.

maximum phase-shifts observed in Fig. 4 are in agreement with the data presented in Fig. 3. It follows that for small injection currents large positive phase shifts can be obtained. These results are in qualitative agreement with the results published in [7], where it is shown that the phase-shift due to TPA opposes the phase shift introduced by the gain. It should be remarked however, that if the SOA is pumped with injection currents higher than 200 mA, also larger nonlinear phase-shifts in the absorption regime could be expected.

The nonlinear phase-shift per SOA unit length can be expressed as $2(\partial\Delta\phi_{NL}(\tau))/(\partial z) = \alpha[g_p(\tau) - g_0] - \alpha_2\beta_2S(\tau)$ [7]. Here, α is the linewidth enhancement factor, β_2 the TPA coefficient, α_2 the linewidth enhancement factor associated with TPA, $S(\tau)$ the photon number of the injected light, $g_p(\tau)$ the gain in presence of a pump pulse and g_0 is the gain in absence of the pump light. The gain difference in the first contribution describes the well-known gain depletion and ultrafast recovery due to carrier cooling versus pump-probe delay time [9,10]. This term has an overall proportionality to the injection current I . For sufficiently small currents, the first contribution is positive due to dominating absorption. For a certain current, which depends on the pump pulse energy, this term turns negative due to depletion. The second term is proportional to, and has the same shape as

the pump pulse. It was already concluded from the measurements in [7] that α_2 has a negative sign. Therefore the contribution of the second term to the phase-shift is always positive. Hence, at zero current we predict the highest phase-shifts, while for higher currents the phase-shift decreases due to the smaller contribution of the first term.

If an ultrashort optical pump pulse is fed into an SOA that is operated at zero injection current, it will generate carriers, not only directly by absorption but also by TPA. These latter carriers are hot, but will cool down on a sub-picosecond time scale and will already lead to an extra increase of the gain within the carrier–carrier scattering time (50–100 fs), all of which leads to a positive phase shift. On the other hand, if the injection current is increased to a value above transparency, a reservoir of carriers is available in the conduction and valence bands. As soon as the optical pump pulse passes by, these carriers recombine due to stimulated emission followed by a recovery of the carrier number due to TPA and cooling. In this case, the negative gain induced contribution to the phase-shift counteracts the positive instantaneous TPA induced contribution. For a specific injection current, the value of which depends on the pump pulse energy, the net phase-shift vanishes. For this injection current, the phase-shift due to the stimulated emission is precisely compensated by the phase-shift due to TPA [7]. If the injection current is increased further the net phase shift is dominated by the stimulated emission and saturates for high injection currents.

Finally, we have measured the contrast ratio of the optical gate using pump pulses of 800 fJ energy. The result is shown in Fig. 5, where also the output power of the gate is plotted in the presence and absence of a pump pulse. According to Fig. 4, the best result with 800 fJ pump pulses is expected for $I = 0$. Therefore, the set up was calibrated at $I = 0$ to achieve a minimum output without pump light. We measure for $I = 0$ a contrast ratio of –11 dB. This value is limited by the residual noise in the output without pump pulse, as well as by the polarization converted pump pulse residue as discussed below (1). It can be derived from (1) that, given the observed noise level, if the pump pulse residue could be suppressed, the ideal contrast

Fig. 5. Average output powers of the AND gate as a function of the injection current in presence and absence of pump light. Also shown is the contrast ratio. The pump-pulse energy is 800 fJ while the probe (or reference) pulse energy is 80 fJ. The “ideal” curve shows the calculated contrast ratio that could be achieved if the polarization converted pump pulse residue could be removed.

ratio can be as small as –26 dB, increasing slowly with I . This is indicated by the curve labeled “ideal” in Fig. 5. In this latter curve it is assumed that for each value of I the system is calibrated to the minimum noise floor level in the output without pump pulse (which has not been done in the experiment). The contrast ratio can be further improved by optimizing the delay between the pump and probe pulses, the probe and reference pulse, as well as by lowering the noise floor in the output without pump pulse.

In addition, we observed from the optical spectra that the output pulse did not significantly broaden after passing through the gate.

4. Conclusions

An ultrafast all-optical logic AND gate has been demonstrated that is operated by optical pulses with duration of 200 fs (FWHM). We observed a contrast ratio larger than 11 dB for control pulse energies as low as 800 fJ. We observed that the nonlinear phase-shift recovers within 1 ps, which implies that optical switches operated by SOA nonlinearities can handle ultrahigh bit-rates. The absence of a long-lived tail in the recovery of the refractive index suggests that such optical

switches will not be sensitive for pattern effects. The largest nonlinear phase-shifts were obtained for an injection current of 0 mA. Considerable nonlinear phase-shifts in the absorption regime have also been reported by others. In [16,17] wavelength conversion results in InGaAsP/InP MQW electro-absorption modulators have been presented. The authors show that in a 100 μm long device phase-shifts up to 0.25π rads can be realized using 2 ps pulses with energy of 2.8 pJ. Our device is eight times longer compared to electro-absorption modulators used in [15,16], thus larger nonlinear phase-shifts can be expected.

The greatest technological challenge on the road towards the implementation of ultrafast optical switches based on SOA nonlinearities, is undoubtedly related to the power consumption of these devices. A data signal consisting of optical pulses with energy of 800 fJ at a repetition rate of 1 THz has an average power of 400 mW (here it is assumed that half of the transmitted data are zeros). Taking into account that the maximum input power that can be handled by an SOA is 50 mW, it is essential to realize switches that operate at lower power.

A reduction of the electronic power could be realized by operating the SOA based switch in the absorption regime. Our experiments indicate that sufficiently large phase shifts can be obtained for low injection currents. This observation is relevant for OTDM demultiplexing at ultrahigh bit-rate. It suggests that it may be favorable to employ SOAs at low or vanishing currents (or even to use passive nonlinear waveguides) for ultrafast optical switching. This may turn out to be an important property for OTDM systems that are operated at ultrahigh bit rate, where reducing the power consumption is a crucial issue. It should be noted however, that for zero injection current, the losses in the waveguides are approximately 10 dB (measured using a 30 fJ optical pulse), which implies that in optical switches operated by nonlinearities in passive optical waveguides, re-amplification is essential. It should be noted however, that in the absorption regime TPA decreases the pulse attenuation.

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