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Ultrafast Refractive-Index Dynamics in a Multiquantum-Well Semiconductor Optical Amplifier

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***Abstract*—We investigate ultrafast refractive index dynamics in a multiquantum-well InGaAsP–InGaAs semiconductor optical amplifier that is operated in the gain regime by using a pump-and-probe approach. The pump-and-probe pulses are cross-linearly polarized. We observe a phase shift of 200° if the amplifier is pumped with 120 mA of current, but find that the phase shift vanishes if the injection current is increased to 160 mA. Our results indicate a contribution of two-photon absorption to the nonlinear phase shift that opposes the phase shift introduced by the gain. Finally, we observe that the phase shift comes up and disappears within a picosecond.**

***Index Terms*—Optical signal processing, optical switching, semiconductor optical amplifiers (SOAs), ultrafast optics.**

I. Introduction

THE TELECOMMUNICATION employing of femtosecond optical pulses for optical transmission at terahertz speed requires ultrafast all-optical switching technology for demultiplexing and routing [1]. Semiconductor optical amplifiers (SOAs) are attractive as nonlinear element in future all-optical (packet) switches, since they provide a high gain and exhibit a strong refractive-index change [2], [3]. Moreover, switching systems based on SOAs allow photonic integration.

The application of SOAs in all-optical signal processing systems appears to be limited to bit rates lower than 160 Gb/s due to the electron-hole recombination time [2]. Recent results based on colinearly polarized pump-and-probe pulses indicate that femtosecond optical pulses introduce ultrafast gain and refractive-index changes in bulk SOAs that are suitable for optical switching [4]. In this letter, we investigate ultrafast refractive-index changes in a multiquantum-well SOA introduced by cross-linearly polarized pump-and-probe pulses.

II. Experimental Method

The experimental method we used is referred to as spectral interferometry [6]. A sequence of two optical pulses, a probe pulse, and a reference pulse, with well-defined phases enter the SOA. The pump-induced refractive-index change causes a phase shift of the probe pulse that is measured by interfering the probe pulse with the reference pulse. Measuring the probe phase shift as a function of the pump–probe delay enables the time-resolved measurement of ultrafast refractive-index changes. The optical spectrum of the probe-and-reference pulses has a modulation that is proportional to $\cos[(\omega-\omega_0)T+\phi]$, where ω is the optical frequency and ω_0 is the central optical frequency of the pulses [6]. T is the time between the pulses and ϕ is their relative phase. The modulation of the spectrum is inversely proportional to the time between the pulses and the modulation depth is proportional to the amplitude difference of the pulses [6]. The relative phase determines the positions of the minima and maxima of the fringes in spectrum. The (low intensity) reference pulse is fully amplified since the SOA is in equilibrium, but the (high intensity) pump pulse is timed in such a way that it arrives at the SOA just before the probe pulse. Thus, the probe pulse will receive less amplification and undergo a phase shift, which is different from the reference pulse due to the gain saturation introduced by the pump pulse [4].

Fig. 1 is a schematic of the experimental setup. An optical parametric oscillator (OPO) pumped with a mode-locked Ti : Sapphire laser is used to produce optical pulses that were 140 fs (at full-width at half-maximum) in duration and at a repetition rate of 80 MHz. The central wavelength of the pulses was 1550 nm. The OPO output power is divided by a half mirror into two parts. The first half of the optical power is collimated into a single-mode optical fiber after passing trough a polarization controller and an attenuator. A variable attenuator is employed to precisely control the pulse power. A Mach–Zehnder interferometer with unequal arms is utilized as fiber delay system to create the probe-and-reference pulse. The reference pulse is advancing the probe pulse by 100.4 ps. The second half of the OPO output forms the pump pulse. The pump pulse is subsequently sent through a polarization controller, an attenuator, and a variable delay line, and finally also fed into a single-mode optical fiber. The pump pulse and the probe-and-reference pulses are cross-linearly polarized to distinguish the pump light from the probe-and-reference pulse. The pulses are then combined by using an optical coupler

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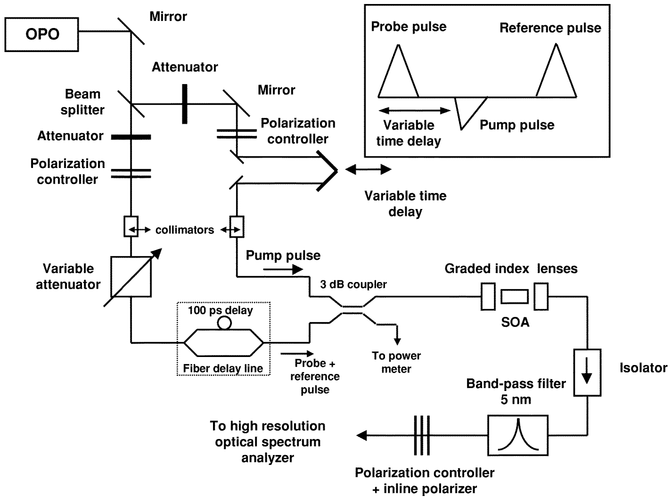

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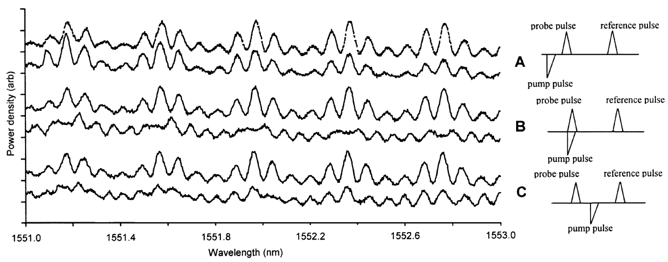

Fig. 2. Optical spectra of a probe-and-reference pulse in the case that the pump pulse A: arrives after the probe-and-reference pulse. B: The pump pulse arrives almost simultaneously with the probe pulse. C: The pump pulse arrives 1.3 ps before the probe pulse. The injection current is 120 mA. The upper trace in the series "A," "B," and "C" represents the interference spectrum in absence of pump light. The 50-GHz modulation that is visible in the spectra is an instrumental artifact related to "aliasing."

and fed into the SOA by using a set of graded-index lenses. The SOA used in our experiments is an InGaAsP–InGaAs multiquantum-well SOA with a central length of 750 μm. On both sides of the central part is a taper zone with a length of 400 μm. In the fiber system, the pulses are broadened to 300 fs due to dispersion. The total coupling losses are estimated to be 10 dB. Measured at the coupler, the optical power of the pump signal was 705 μW while the optical power of the combined probe-and-reference pulses was 61 μW. The SOA output is fed into an inline polarizer after passing through an isolator, an optical bandpass filter (5 nm), and a polarization controller. The inline polarizer is used to separate the pump light from the probe-and-reference pulse. After passing through the inline polarizer, the power ratio between the pump pulse, and the probe-and-reference pulse was $1:14$. Finally, the optical spectrum of the probe-and-reference pulses are analyzed by using an optical spectrum analyzer (ANDO AQ6317B) with a resolution of 0.010 nm. The relative phase is stable over several minutes without using active control since the interferometer is made of fiber couplers and shielded in a box from thermal and mechanical disturbances.

III. Results

In the first experiment, the SOA is pumped with 120 mA of current. Fig. 2 shows three traces of measured optical spectra

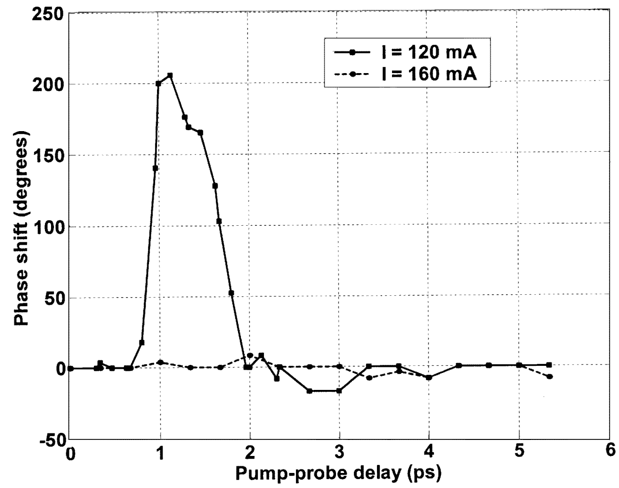

Fig. 3. Phase change as a function of the pump–probe delay for injection currents of 120 mA (solid line) and 160 mA (dashed line). The error margin is 10°.

of the probe-and-reference pulse in the presence and absence of pump light. The upper trace in series "A" is the optical spectrum of the probe-and-reference pulses in absence of pump light. The lower trace in series "A" is the measured optical spectrum if the pump pulse arrives after the probe-and-reference pulse. Consequently, the pump light does not affect the probe-and-reference pulses and thus no phase changes are visible. The two traces in series "B" are the optical spectra in the case that the pump pulse arrives at the SOA simultaneously with the probe pulse. The upper trace in series "B" is the spectrum of the probe-and-reference pulses in absence of pump light. First, a decrease of the modulation depth of the spectrum is visible. This is due to the reduced amplification of the probe pulse in the presence of the pump light [5]. It is estimated that the probe pulse has received 2.7 dB less amplification compared with the reference pulse. Second, a phase shift of approximately 200° is visible. This is due to the refractive index change introduced by the pump pulse. The two traces in series "C" represent the case that the pump pulse arrives 1.3 ps before the probe pulse at the SOA. Again, the upper trace in series "C" is the spectrum of the probe-and-reference pulses in absence of pump light. From the reduced modulation depth, it can be concluded that the probe pulse has received less gain, but no phase difference is visible. The solid line in Fig. 3 shows the phase change as a function of the pump–probe delay for $I = 120$ mA. It follows from Fig. 3 that the phase change recovers within a picosecond. In contrast to results for an InGaAsP–InP bulk SOA that are published in [4], we do not observe additional phase recovery effects on a time scale of a few picoseconds. In the second experiment, the SOA current was increased to 160 mA while all the other conditions were kept the same. The dashed line in Fig. 3 shows the phase change as a function of the pump–probe delay for $I = 160$ mA. It follows that no phase-change is visible. However, the reduced modulation depth of the optical spectrum reveals a maximum difference in amplification between the reference pulse and the probe pulse of 3.2 dB.

Our results concerning the ultrafast phase change in the SOA can be explained by using the formula [5]

$$\frac{\partial \phi}{\partial z} = \frac{1}{2}\alpha g - \frac{1}{2}\beta \alpha_2 S \tag{1}$$

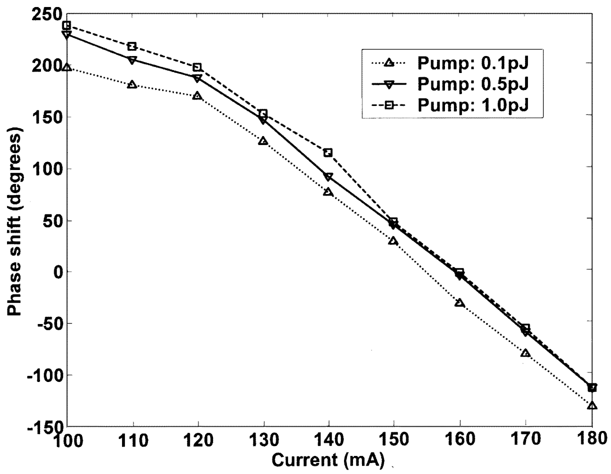

Fig. 4. Simulation of the phase change of a 20-fJ probe pulse as a function of the injection current for various pump-pulse energies.

where α is the linewidth enhancement factor, g is the SOA gain, β the two-photon absorption (TPA) coefficient, α_2 the linewidth enhancement factor due to TPA, and S the photon number. The first term on the right-hand side of (1) describes the phase change due to the change in gain. The second term on the right-hand side describes the phase change due to TPA. In the presence of a pump pulse, the first term will always lead to a negative phase-shift contribution with respect to the situation without pump pulse. This contribution increases in magnitude with increasing bias current. The second term is only nonzero in the presence of a pump pulse. Clearly, the observed compensating effect for higher current can only be explained when $\alpha_2 < 0$.

In Fig. 4, a simulation result is presented in which the phase shift of a 200-fs probe pulse in the presence of a pump pulse relative to the situation without pump pulse is plotted as a function of the bias current. The numerical model used in the simulation is in the fashion of the model presented in [5], but extended with polarization-dependent gain, as shown in [7]. The probe-pulse energy was 20 fJ and it was used that $\alpha = 2$ and that $\alpha = -4(\beta = 3.5\ 10^{-7}\ \mu\text{m}^2)$. The pump pulse energies used in Fig. 4 are in the same order as in the experiment. Our numerical results reveal that for $I = 120$ mA, a phase change of at least 180° can be obtained while the phase change almost vanishes for $I = 160$ mA. This result also clarifies inconsistent results that are reported in the literature about the sign of α_2 [8]–[11]. We can only explain our experimental results if α and α_2 have opposite signs, so that the phase change due to TPA opposes the phase change due to the SOA gain. Moreover, Fig. 4 indicates that similar phase changes can be obtained for pulses energies between 0.1 and 1 pJ. Finally, experimental results based on colinearly pump-and-probe pulses in a bulk SOA show a long-lived tail in the refractive index recovery due to electron-hole recombination [4]. Our experiments on a multiquantum-well amplifier give no clear evidence for such a long-lived tail. Numerical simulations reveal that the strength of the tail depends on the pump-pulse energy. For certain pulse energies the tail could even vanish. Simulation results suggest that for the pulse energies used in our experiments, the tail is so weak that it cannot be observed by our experimental method.

IV. Conclusion

Our results show that a data pulse propagating in the gain minimum of a cross-linearly polarized control pulse is undergoing adequate gain and phase differences required for optical switching. These results also indicate that optical signal processing systems based on SOAs placed in interferometers can be operated by ultrashort cross-linearly polarized pulses.

We have also observed that the refractive index recovers on the time scale of 1 ps. We did not observe recovery effects on a time scale of a few picoseconds. The ultrafast recovery effects are associated with carrier heating driven by TPA and free carrier absorption. Finally, our results show that the phase change due to TPA opposes the phase change introduced by the gain. Our results can be explained by a similar model as presented in [5].

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