Ultrafast refractive-index dynamics in a multi-quantum well semiconductor optical amplifier

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We investigate ultrafast refractive index dynamics in a multi-quantum well InGaAsP-InGaAs semiconductor optical amplifier that is operated in the gain regime by using pump and probe pulses that are cross-linearly polarized. We observe a phase shift of 200 degrees 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. We observe that the phase shift comes up and disappears within a picosecond.

1. Introduction

Telecommunication employing 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 optical switches since they provide a high gain, exhibit a strong refractive-index change and allow photonic integration [2, 3]. The application of SOAs in all-optical signal processing systems are limited to bit-rates lower than 160 Gbit/sec due to the electron-hole recombination time [2]. In this letter, we investigate ultrafast refractive-index changes in a multi-quantum-well SOA introduced by cross-linearly polarized pump and probe pulses.

The SOA used in our experiments is an InGaAsP-InGaAs multi-quantum 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. We have investigated the SOA ultrafast index dynamics in the gain regime. If the SOA is pumped with 120 mA of current, we observe a maximum phase change of 200 degrees. However, for an injection current of 160 mA and all other conditions the same, we do not detect any phase change. We also observe that the amplifier fully recovers within one picosecond.

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2. Experimental method

The nonlinear phase change in measured by injecting 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 [4]. 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 [4]. 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 [5].

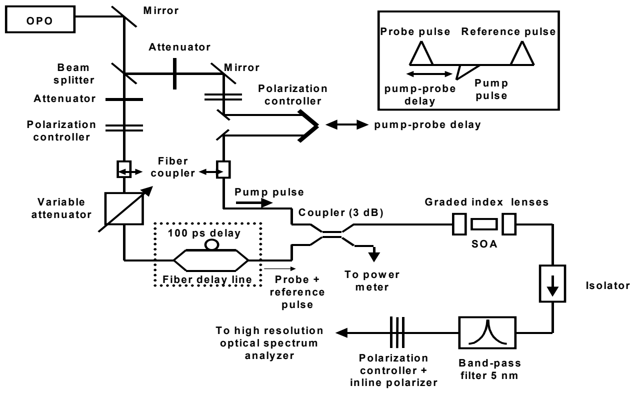

Figure 1: Schematic of the experimental set-up.

Figure 1 is a schematic of the experimental set-up. An Optical Parametric Oscillator (OPO) pumped with a mode-locked Ti:Sapphire laser is used to produce optical pulses that were 140 fs (at FWHM) 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 and fed into the SOA by using a set of graded-index lenses. 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 band-pass 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 with a resolution of 0.01 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.

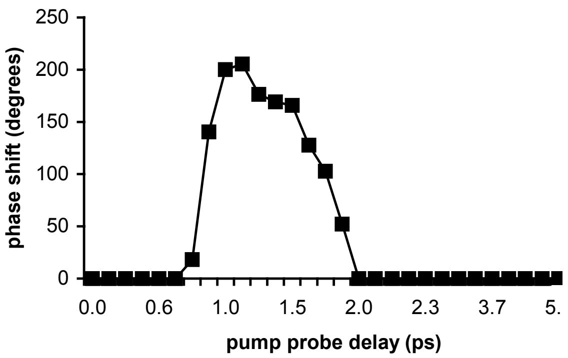

Figure 2: Phase change as a function of the pump-probe delay. The SOA current is 120 mA.

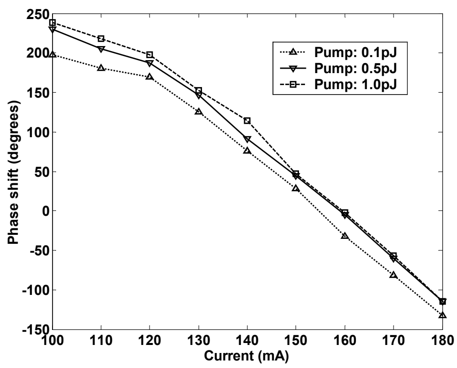

Figure 3: Simulation of the phase change of a 20 fJ probe pulse as a function of the injection current for various pump pulse energies.

3. Results

Figure 2 shows the phase change as a function of the pump-probe delay if the amplifier is pumped with 120 mA of current. It follows from Figure 2 that a maximum phase change of over 200 degrees can be obtained and that the phase change recovers within one a picosecond. In contrast to results for an InGaAsP-InP bulk SOA that are published in [5], we do not observe phase recovery effects on a time scale of a few pico-seconds that can be associated with carrier-heating. When the SOA current was increased to 160 mA while all the other conditions were kept the same, no phase-change is visible. Our results concerning the ultrafast phase change in the SOA can be explained by using the formula [6]:

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

where α is the linewidth enhancement factor, g is the SOA gain, β the two-photon absorption parameter, α_2 the linewidth enhancement factor due to TPA, and S the photon number, i.e. proportional to the optical pulse energy. The first term on the right-hand-side of (1) describes the phase change due to the SOA gain that depends on the injection current. 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 Figure 3, 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 [6], 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 $\alpha_2 = -4$. The pump pulse energies used in Figure 3 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 degrees 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 [6]. 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.

4. Conclusions

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 TOADs and Mach-Zehnder interferometers can be operated by ultrashort cross-linearly polarized control and data pulses.

We also have also observed that the refractive index recovers on the time scale of one pico-second. We did not observe recovery effects on a time scale of a few pico-seconds that can be associated with carrier heating. Finally, our results show that the phase change due to two-photon absorption opposes the phase change introduced by the gain. Our results can be explained by a similar model as presented in [6].

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