Ultrafast all-optical switching induced by nonlinear polarization rotation in a multi-quantum well semiconductor optical amplifier

H. Ju, S. Zhang, H. de Waardt, Giok-Djan Khoe, and H.J.S. Dorren

COBRA Research Institute, Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.

We investigate the ultrafast refractive index dynamics in a multi-quantum well semiconductor optical amplifier (SOA) with a focus on nonlinear polarization switching. A pump-probe technique is utilized to examine ultrafast carrier dynamics of the SOA in conjunction with nonlinear birefringence. Nonlinear optical effects such as two-photon absorption describe the pump-induced birefringence on the sub-picosecond time scales which introduce a significant temporal window for ultrafast applications of nonlinear polarization switching.

Introduction

Ultrafast all-optical switches are one of the key elements for ultrahigh speed communication technologies. Focus has been placed on nonlinear optical interaction since it can allow device response fast enough to overcome the electronic bottleneck [1].
Recently, optical polarization switches with semiconductor optical amplifiers (SOA) have been recognized to deserve much research interests since they can operate for high nonlinearity in a compact scheme, allowing integration into a single chip. SOA polarization switches find various applications such as optical time domain demultiplexing [2, 3], all-optical logic gates [4, 5, 6] and optical flip-flip memories [7].
In addition, much efforts have been devoted to understanding ultrafast dynamics of photo-generated carriers in a SOA for efficient operation of ultrafast optical signal processing. Two-photon absorption (TPA) and carrier heating/cooling effects are reported to be significant in explaining ultrafast dynamics of refractive indices [8, 9]. In this work, we report the measurement of nonlinear polarization rotation of femtosecond optical pulses in a multi-quantum well SOA with a discussion in conjunction with the ultrafast carrier dynamics .

Experimental apparatus and techniques

Figure 1 shows schematic of the experimental setup for nonlinear polarization rotation. About 200 fs optical pulses were launched at a wavelength of $\sim$ 1515 nm by an optical parametric oscillator (Coherent OPO Basic CTA) pumped by a Ti:sapphire laser (Coherent Mira 900-F) of $\sim$ 76 MHz repetition rate. We used an InGaAsP/InP multi-quantum well SOA (GEC Marconi) of 250 μm length for nonlinear interaction.
A polarizing beam splitter (PBS) split pulsed light into two beams , i.e. pump and probe. Adjustment of an angle of each quarter-wave plate in each arm allowed two orthogonal polarizations, i.e. TE (pump) and TM (probe) modes between PBS and HP2, as shown

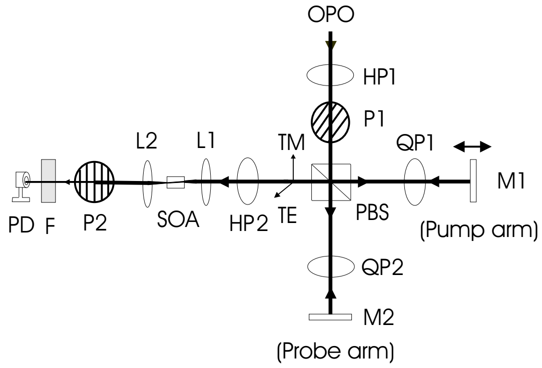

Figure 1: Schematic of the setup for nonlinear polarization switching. OPO : optical parametric oscillator, HP1-2 :half-wave plates, P1-2 : Polarizers, PBS : polarizing beam splitter, QP1-2 : quater-wave plates, M1-2: Mirrors, L1-2 : Microscope objective lenses, SOA : semiconductor optical amplifier, F: attenuation filter, PD : photodiode

in Fig. 1. We used a half-wave plate (HP2) to change polarizations of pump and probe at the SOA input. Light was focused into the SOA by a microscope objective lens of 4.6 mm focal length (NA= 0.65) while collimated out of the SOA by another microscope objective lens of numerical aperture 0.45.
The use of orthogonal polarizations of input light benefit achievement of efficient blocking of pump light by a polarizer (P2). The transmission through P2 reflected the output probe light whose polarization remained the same as input probe. This scheme could alow pump-induced birefringence to reduce the transmission.

Results and discussion

We measured optical power transmission through the SOA whereby the coupling loss could be estimated to be $\sim$ 7dB. Scattering and absorption during the propagation can account for the loss as well as the focusing limitation and imperfect AR-coating of the SOA facets. The limited dimension of the collimated optics also reduced the measurement efficiency.
Figure 2 shows the probe energy transmitted through P2 as the pump-probe delay time scanned. Not only the SOA spontaneous emission but also the SOA-characteristic birefringence of pump light were subtracted before the normalization to the averaged background level.
Figure 2 $\{A\}$ and $\{B\}$ correspond to input pulse energies of $\sim$ 2.9 pJ and $\sim$ 1.7 pJ, respectively in the SOA. The SOA bias current was 200 mA for A while 0 mA for B. Pump-induced polarization rotation caused blocking of up to 21% (16%) probe power for $\{A\}(\{B\})$. This resulted in a transmission profile of the drastic decrease followed by the fast recovery. The decreased transmission could be distinguished from the background noise by up to $\sim$ 16.5 dB ($\sim$ 16.8 dB). $\{A\}$ shows a significant tail of the transmission on a scale of $\sim$ 1 ps. This tail could occur due to the carrier cooling process while preventing the full recovery of the transmission on a sub-picosecond scale. We can estimate stimulated emission and free-carrier absorption could cause substantial carrier heating which played a major role in the induced birefringence.

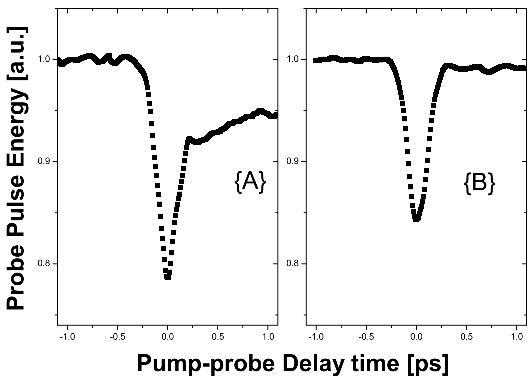

Figure 2: Pump-induced nonlinear polarization rotation. {A} corresponds to a pulse energy of 2.9 pJ while {B} to 1.7 pJ in the SOA

In {B}, no long-lived tail occurred significantly. This reflects the dominance of TPA over carrier heating in the SOA for the nonlinear birefringence since TPA-caused carrier distribution change is believed to occur on a sub-picosecond time scale.
For the application of ultrafast all-optical switching, the slow recovery of nonlinear birefringence can be minimized by tuning device parameters such as optical pump powers and bias current.

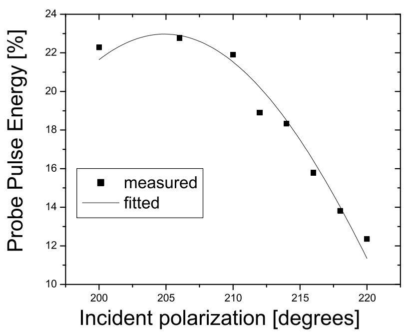

Figure 3: Pump-induced polarization rotation versus an input polarization relative to the SOA

We also measured pump-induced birefringence as a function of an input polarization, as given by figure 3. The x-axis denotes the angles of an input polarization relative to the SOA while y-axis representing the portion of probe light blocked by P2. The solid line fits the measured data, based on the birefringence (x) formula given by

$$x = |\sin(\gamma/2)\sin(2\theta)|. \tag{1}$$

Here θ is the angle of a probe polarization relative to the ordinary (or extraordinary) axis of the SOA and γ is the phase retardation between the ordinary and extraordinary axes of the SOA. The fitting gives an estimate of γ of 0.46. This indicates pump-induced index change lead to the elliptical polarization of output probe light and the probe transmission through P2 could be optimized by tuning an input polarization with respect to the SOA.

Summary

We demonstrated with pump-probe technique that the SOA nonlinearity drove the nonlinear polarization rotation in a femtosecond regime for ultrafast all-optical switching. This rotation lead to a transmission profile of the drastic decrease followed by the fast recovery. The slow recovery of the transmission could be avoided by optimizing the system whereby carrier cooling was minimized. This indicates that SOA nonlinearities could be employed in optical signal processing system operated at ultrahigh repetition rate.
The ultrafast polarization rotation depended not only on an optical pump power but also a polarization incident to the SOA. We estimated the phase retardation of pump-induced birefringence to result from TPA and carrier heating effects. The numerical modelling is underway for much details.

Acknowledgements

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