All-optical wavelength conversion based on nonlinear polarization rotation driven by 120 fs optical pulses in a semiconductor optical amplifier

A.K. Mishra, X. Yang, D. Lenstra, G.D. Khoe and H.J.S. Dorren

COBRA Research Institute, Eindhoven University of Technology,

P.O. Box 513, 5600 MB, Eindhoven, the Netherlands

Abstract

We demonstrate ultrafast wavelength conversion utilizing nonlinear polarization rotation an InGaAsP-InGaAs multi-quantum-well semiconductor optical amplifier. In this paper we describes the principles of wavelength conversion using a control pulse of duration 120 fs with an emphasis of two-photon absorption and ultrafast carrier relaxation for applications to high-speed communications and information processing. We have investigated wavelength conversion efficiency for different injection currents and for different control pulse energies. We show that a conversion efficiency of 12 dB can be obtained for control pulse energies of 10 picojoule.

I. INTRODUCTION

All optical wavelength converters are expected to play an important role in future high-speed optical switching applications. In this paper, we concentrate on wavelength conversion using nonlinear polarization rotation driven by femtosecond optical pulses in semiconductor optical amplifiers [1-8]. In brief, wavelength conversion in a nonlinear polarization switch is based on nonlinear polarization rotation caused by polarization dependent gain saturation in the SOA that is introduced by pump light [7]. This concept has been described in [1] using optical pulses with duration 47 picoseconds. Nonlinear gain and index dynamics of SOA on femtosecond timescales differs from nonlinear index dynamics on picosecond timescales on a few essential points i.e. carrier relaxation driven by TPA and FCA plays a dominant role and allows the amplifier to recover on sub-picoseconds timescales [8-11]. Employing these ultrafast effects for wavelength conversion is beneficial since the SOA recovery time can be reduced to sub-picoseconds timescales. In the present paper, we employ the model presented in [8] to achieve wavelength conversion employing a nonlinear polarization switch as presented in [7]. Our experimental results show that the model presented in [8] is capable of describing wavelength conversion driven by 120 fs optical pulses in a nonlinear polarization switch. We studied wavelength conversion efficiency as a function of the injection current and the control pulse energies at different probe powers and a conversion efficiency of 12 dB was obtained.

II. EXPERIMENTS AND RESULTS

The scheme of our wavelength converter is shown in Figure 1. The wavelength converter is made out of an SOA, two polarization controllers (PC-1, PC-2), two beam splitters (BS-1, BS-2), an optical band-pass filter (BPF), and a polarizing beam splitter (PBS). The amplifier used in this experiment is a multi-quantum well InGaAsP-InGaAs SOA with a central length of 750 μm and at both sides a taper zone of 400 mm. A beam of optical pulses with duration of 120 fs at a repetition rate of 75.82 MHz and with a central wavelength of 1520 nm was generated by an optical parametric oscillator that was pumped by a Ti:Sapphire laser. The OPO output is firstly attenuated using a half-wave plate (HW-1) and a polarizer. A second half-wave plate (HW-2) is used to set the polarization of the laser beam to the TE mode. A tunable laser emits a continuous wave (CW) probe beam at wavelength 1555 nm. The power of the probe beam is controlled by the variable attenuator (A-1) and the polarization is controlled by polarization controller PC-1. The pump and probe beam were combined by beamsplitter BS-1 and fed into the SOA by using microscope objectives. At the SOA output, after passing through PC-2, the pump and probe light were separated by a bandpass filter (BPF). The BPF with a bandwidth of 1 nm was used to remove the pump light and to suppress the amplified spontaneous emission generated by the SOA.

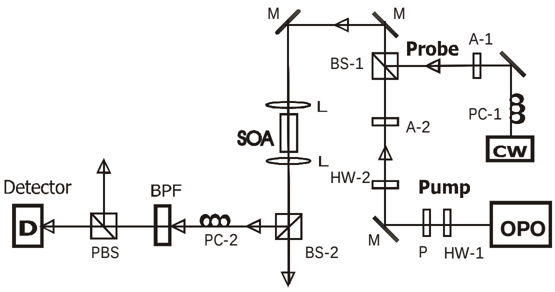

Figure1: Experimental setup for ultrafast wavelength conversion, where the symbols of optical components are defined as: OPO: optical parametric oscillator, HW: half-wave plate, P: polarizer, M: mirror, PBS: polarizing beam-splitter, BS: beam-splitter, L: lens, A: attenuator, BPF: band pass filter, PC: polarization controller, CW: Continuous wave tunable laser.

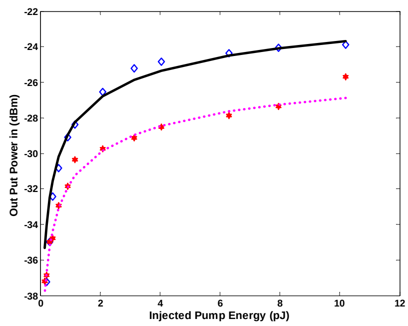

Figure 2: Measured and computed output power of the nonlinear polarization switch as a function of pump pulse energy. The diamond shaped points show the result if the CW input power was 0 dBm and the star shaped points represents the results if the CW power was 3 dBm. The SOA injection current was 200 mA.

In the wavelength conversion experiment, PC-1 was adjusted so that the polarization of the input signal is approximately 45 degree with respect to the orientation of the SOA layers. PC-2 was adjusted in such a way that the probe beam that outputs the SOA cannot pass through the PBS. The whole set-up was placed in a box to shield the polarization switch from thermal and mechanical disturbances. When a pump pulse is injected in the SOA, polarization dependent gain saturation will lead to polarization dependent index changes and thus to pump induced birefringence. The pump induced birefringence makes that the TE component of the probe beam experiences a different refractive index compared to the TM component of the probe beam, which causes a rotation of the polarization state of the probe beam. As a consequence, the power meter could detect some probe light passed through the PBS. The discrete points in Figure 2 show the observed PBS output for various pump pulse energies while the SOA injection current was 200 mA and the power of the cw probe beam was 3 dBm. The solid and dashed lines represent computed results, based on the model in Section 2 and the parameters in Table1. We found a conversion efficiency larger than 12 dB for pulses with an energy of 10 pJ. It is clearly visible that our SOA model leads to results that are in good agreement with the experimental data. This experiment was repeated for the case of a probe power of 0 dBm and we found similar results.

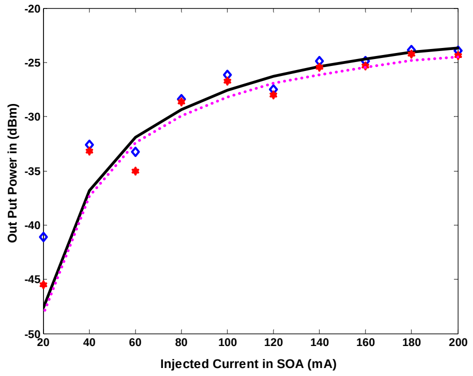

Figure 3: Measured and computed output power of the nonlinear polarization switch as a function of the SOA injection current. The diamond shaped points shows the result if the pump pulse energy was 10 pJ and the star shaped points represents the results if the pump pulse energy was 6.3 pJ. The CW power was 3 dBm.

We have also investigated wavelength conversion as a function of the injection current for different pump pulse energies. The power of the cw probe beam was 3 dBm. The result is shown in Figure 3. The diamond shaped points represent the results for pump energies of 10 pJ and the star shaped points represent the results for pump pulse energies of 6.3 pJ. The solid and dashed lines represent computed results for pump pulses of 10 pJ and 6.3 pJ respectively, based on the model and the parameters in Table1. It is observed that the averaged converted power of the light that passes through the PBS increases as a function of current. We find that our experimental results are in good agreement with the computational results at least for the current above transparency current (50mA).

Our experimental set-up did not allow time-resolved measurements of the converted pulse. We therefore investigate the converted pulse numerically. The expression for the average output power detected by the power meter due to polarization rotation can be written as:

$$P_{out}^{Average} = \frac{1}{T}\int_{-T/2}^{T/2}\{S_{CW}^{TE}(t) + S_{CW}^{TM}(t) + 2\sqrt{S_{CW}^{TE}(t)\cdot S_{CW}^{TM}(t)}\cos(\Delta\phi_{NL}(t)+\pi)\}dt \qquad (1)$$

Where, T is detector response time, $S_{CW}^{TE}(t)$ and $S_{CW}^{TM}(t)$ are the intensities of TE and TM components of the light that passes through the PBS and $\Delta\phi_{NL}(t)$ is the pump induced nonlinear phase difference between the TE and TM modes per unit length which can be expressed as

$$\frac{\partial \Delta\phi_{NL}(t)}{\partial z} = \alpha[g_{CW}^{TE}(t) - g_{CW}^{TM}(t)] \qquad (2)$$

Here, α is the linewidth enhancement factor and $g_{CW}^{TE}(t)$ and $g_{CW}^{TM}(t)$ represent the gain that accounts for TPA and FCA. Note that Eq. (2) differs from its counterpart in [12] since in (2) is no direct contribution due to TPA. Since both modes propagate through the same SOA, the contribution to the nonlinear phase shift due to TPA is canceled out. As a result of this, the operation of a nonlinear polarization switch operated by femtosecond optical pulses differs fundamentally from a similar functionality based on nonlinear gain and index dynamics of a SOA placed in a Mach-Zehnder interferometer [9]. In Figure 2, we observe that an increase of the pump pulse energy leads to an increase in the transmission of the probe light through the PBS. Moreover, it is clearly visible from Figures 2 and 3 that the output power saturates for both high pump energy and high injection current. This is because SOA gain saturates for both high injection currents as well as for high pulse energies. In the latter case the saturation of the SOA gain can be explained by TPA and FCA. Also, it is clearly visible in Figure 2 and Figure 3 that the wavelength converted output power was very low, which is due to the low repetition rate of the pump light. We observed a static extinction ratio larger than 12 dB with pump pulses having energy of 10 pJ. This value for the energy is much higher than desired in telecommunication systems. However, it can be substantially lowered by optimizing the bandwidth of the band pass filter that is used to suppress spontaneous noise and pump pulses. Thus, it should be possible to achieve wavelength conversion operating at high repetition rates.

III. CONCLUSIONS

We have discussed wavelength conversion using a nonlinear polarization switch that is driven with optical pulses with duration of 120 fs and demonstrated a static conversion efficiency larger than 12 dB. It was argued in [12] that the nonlinear phase shift contains two contributions, one due to the phase shift introduced by the carrier depletion and the other due to the direct nonlinear phase shift introduced by TPA. Since in a nonlinear polarization switch both the TE and TM modes propagate through the same SOA, our model reveals that there is a direct effect of the modulated TE polarized pump light on the cw probe beam due to cross TPA modulation. Which means TPA cross coupling may occur between probe and pump beam even when they are in different polarization states that we call cross polarization cross TPA coupling. Due to a precise cancellation, this effect plays no role in our present switching configuration. On the other hand, there is an indirect and much slower effect due to ultrafast nonlinear index and carriers dynamics that is driven by TPA and cross TPA, which does play an important role to realize the ultrafast wavelength conversion here demonstrated. This implies that the width of the pulse that outputs the nonlinear polarization switch only depends on the nonlinear carrier dynamics in the SOA.

Acknowledgement

This work was supported by the Netherlands Organisation for Scientific Research (NWO), the Technology Foundation STW and the Ministry of Economic Affairs through respectively the NRC Photonics grant and the Innovational Research Incentives Scheme programme.

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