

Ultrafast all-optical wavelength conversion by 160 fs pulses in a multi-quantum-well SOA

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***Abstract-** We demonstrate wavelength conversion based on nonlinear polarization rotation driven by ultrafast carrier relaxation in an InGaAsP-InGaAs multi-quantum-well semiconductor optical amplifier. We used a continuous wave (CW) probe beam of 1555 nm, and a control pulse of duration of 160 fs at a center wavelength of 1520 nm. We studied wavelength conversion for different control pulse energies and obtained a conversion efficiency of 12 dB with pulse energies of 10 picojoule.*

I. INTRODUCTION

Nonlinear phenomena in semiconductor optical amplifiers such as cross-gain, cross-phase, four-wave mixing (FWM), and nonlinear-polarization rotation have been widely utilized for wavelength conversion and optical switching by a number of research groups. Wavelength conversion based on nonlinear polarization rotation in semiconductor optical amplifiers (SOAs) is presented in [1-8]. In conventional applications the speed of wavelength converters based on SOA nonlinearities is limited to 250 GHz due to the slow SOA recovery by carrier injection (typically in the order of 1 ns) [9]. In this paper, we present a new concept that employs ultrafast nonlinear effects in SOAs such as ultrafast carrier relaxation driven by two-photon absorption and free carrier absorption for ultrafast wavelength conversion. A model that describes polarization dependent nonlinear gain and index dynamics in SOAs on sub-picosecond timescales is presented in [20]. In this paper, we employ the ultrafast effects presented in [20] to achieve wavelength conversion employing a nonlinear polarization switch as presented in [8]. We show that ultrafast nonlinearities introduced by a pulse with duration of 160 fs can be employed to achieve ultrafast wavelength conversion. We studied wavelength conversion for different control pulse energies at different probe powers. We found a conversion efficiency of 12 dB.

II. EXPERIMENTS AND RESULTS

A scheme of our wavelength converter is shown in Fig 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 SOA employs a MQW active region with a length of 750 μ m. A beam of optical pulses with duration of 160 fs at a repetition rate of 75.82 MHz and with a central wavelength of 1520 nm is generated by an optical parametric oscillator that is 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 TE mode. A tunable laser emits a continuous wave (CW) probe beam at wavelength 1555 nm that is fed into the MQW SOA via attenuator (A-1). A-1 is a neutral density filters that is used to control the intensity of the probe beam so that the SOA is operated in the linear gain regime. The transmission of the probe beam through

polarizing beam splitter (PBS) followed by and a polarization controller (PC-2) and one beam splitter (BS-2) was measured by using a power meter. The system contains two polarization controllers.

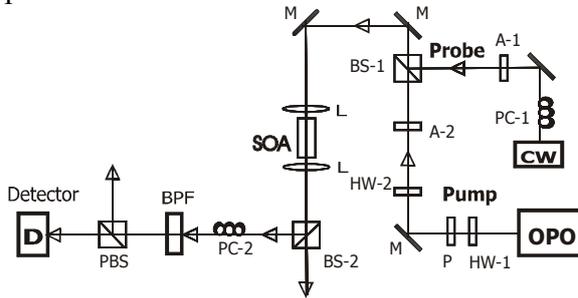


Figure 1: Experimental setup for ultrafast wavelength conversion, where the symbols of optical components are defined as: OPO: optical parametric oscillator, HW: half-wave plate, P: polarizer, M: mirror, PBS: polarizing beam-splitter, BS: beam-splitter, L: lens, A: attenuator, BPF: band pass filter, PC: polarization controller, CW: Continuous wave tunable laser.

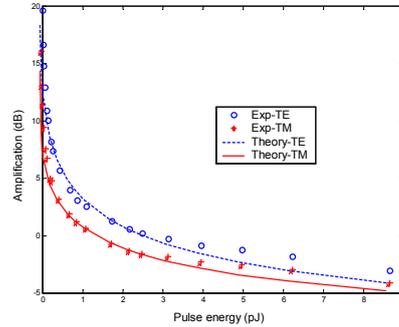


Figure 2: Measured and computed polarization dependent gain vs. injected energy of TE (dotted line) and TM (solid line) modes for ultrashort saturating pump pulses at SOA injection current $I=200$ mA.

The first polarization controller (PC-1) is used to adjust polarization of the input signal to be approximately 45° to the orientation of the SOA layers, while the second polarization controller (PC-2) is used to adjust the polarization of the amplified SOA output with the orientation of the PBS. At the PBS, the two modes coherently combine. The polarization controllers are set in such a way that the probe beam cannot pass through the PBS when only the probe beam is present. A fixed band pass filter with a bandwidth of 1 nm is used to remove pump light and also to suppress the amplified spontaneous emission generated by the SOA. The whole set-up is placed in a box to shield the polarization switch from thermal and mechanical disturbances.

In the first experiment, we measured the polarization dependent gain of the SOA for ultrashort pulses as a function of pump pulse energy at a SOA injection current of 200 mA. The results are shown in Fig 2, in which the amplification for TE and TM modes are plotted as a function of the injected pulse energy and the curve with the maximum amplification is attributed to the TE mode and the curve with the minimum amplification is attributed to the TM mode. The solid (dashed) line in Fig 2 represents the computed amplification for TM (TE) and the points represents the measured amplification for TE and TM modes [20]. If we correct for the coupling and component losses, estimated to be 12.0 dB (this includes two times 3.0-dB facet losses and 5.0 dB for the components used in the experimental setup), it follows from Fig 2 that for a current of 200 mA, the gain of the TE mode equals to 19.6 dB and that of the TM mode 16.3 dB for very small injection pulse energy of 13 fJ. As we increase the pulse energy to 8.6 pJ, the gain of the corresponding modes drops down to -3.1dB and -4.1 dB. This is mainly due two-photon-absorption and FCA, which dominates at high pulse energies. We find that the experimental results are in good agreement with the theoretical results.

In the second experiment, the polarization-dependent gain of the probe beam is measured as a function of the injected current I in the absence of the ultrashort pump pulses. The results are shown in Fig 3. If we correct for the component and coupling losses in the experimental setup, the amplification for TE and TM modes of CW light at

injection 200mA, are 23 dB and 18 dB respectively. The computed amplifications for the two orthogonal polarization fields are in agreement with the experimental data at least for the current above threshold current (50 mA). We believe, the disagreement below threshold current is mainly due to current dependency on population imbalance factor [7, 20]. It should be remarked, however, that from an experimental point of view, it is difficult to control the intensities of the light that is injected in each mode.

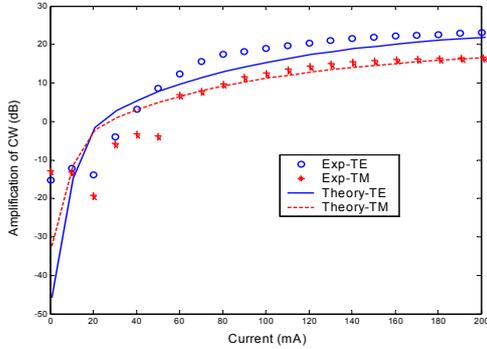


Figure 3: Measured and computed polarizations dependent gain vs. injected current for TE (solid line) and TM (dotted line) modes of CW beam of av. power 0.1 mW.

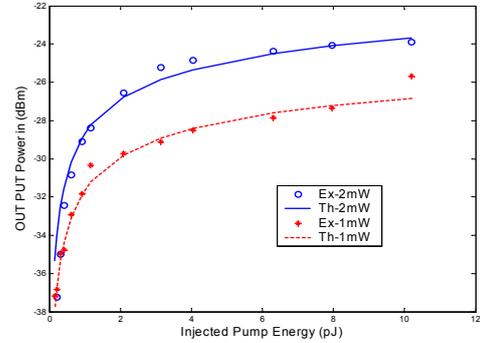


Figure 4: Measured and computed out put power of probe light (1555 nm) vs. injected pulse energy of the ultrashort pump beam at SOA injection current 200 mA for CW light of av. power of 2mW (solid line) and 1mW (dotted line) respectively.

In the wavelength conversion experiment, the polarization direction of the input probe light of average power of 2mW is kept approximately at 45° to the layers of the SOA with the injection current 200 mA. This is because our SOA had a polarization sensitivity of almost 5 dB at 1550 nm, implying a difference in the saturation properties of TE and TM modes as well. The input angle is carefully adjusted to compensate for this. If saturating pump pulses at a center wavelength of 1520 nm, are coupled into the SOA, the ultrafast dynamics including the intrinsic nonlinearities in the SOA leads to a phase difference between the TE and TM modes of the probe signal, causing the polarization of the probe light to be rotated [1,3]. As a consequence, the power meter can detect some probe light passed through the PBS. The discrete points in Fig 4 show the experimental PBS output for different pulse energies in the TE mode, thus achieving more than 12dB conversion contrast ratio for the pulses energies of 10 pJ. It is clearly visible that our SOA model leads to results that are in good agreement with the experimental data.

The expression for the output power detected by the power meter due to polarization rotation is presented in [7]. The nonlinear phase difference between TE and TM modes of CW light per SOA unit length can be expressed as $\frac{\partial \Delta \phi_{NL}(t)}{\partial z} = \alpha [g_{CW}^{TE}(t) - g_{CW}^{TM}(t)] - \alpha_2 \beta_2 S_{CW}^{TE}(t) + \alpha_2 \beta_2 S_{CW}^{TM}(t)$. Here, α is the linewidth enhancement factor, β_2 the TPA coefficient, α_2 the linewidth enhancement factor associated with TPA, $S_{CW}^{TE}(t)$ and $S_{CW}^{TM}(t)$ the photon number of injected TE and TM modes of CW light, $g_{CW}^{TE}(t)$ and $g_{CW}^{TM}(t)$ are the corresponding gain in presence of a pump pulse. The gain difference between TE and TM modes in the first contribution describes the well-known gain depletion. The second and third term are nonlinear phase induced by pump due to two-photon-absorption for TE and TM modes respectively. In Fig 4, we observed that

an increase in the intensity of the pump light leads to an increase in the intensity of the probe light that outputs through the PBS. For higher pump pulse energies, the nonlinear polarization rotation is dominated by two photon and free carrier absorption. Also, the result was consistent for different input probe average power of 1mW. It is clearly visible in Fig 4 that the wavelength converted output power is very low that is brought by low repetition rate of pump pulses. Also, the conversion contrast ratio can be further improved by optimizing the bandwidth of band pass filter that is used to suppress spontaneous noise and pump pulses or by some innovative detection methods.

III. CONCLUSIONS

We have successfully demonstrated for the first time a new type of wavelength converter operating at ultra high speed based on nonlinear polarization rotation in a multi-quantum-well SOA. The wavelength converter operates based on nonlinear polarization rotation caused by the difference in intensity dependent phase shift accumulated by two orthogonal polarized (TE and TM) field components that interact with each other. We have shown that wavelength conversion can be obtained by using a single SOA. We obtained the static extinction ratio of the converted signal is more than 12 dB. The effect of tensile strain is accounted for by a population imbalance factor, small differences in gain coefficients and a small difference in confinement factors for TE and TM modes respectively.

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