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Wavelength Conversion Employing 120-fs Optical Pulses in an SOA-Based Nonlinear Polarization Switch

A. K. Mishra, X. Yang, D. Lenstra, *Member, IEEE*, G.-D. Khoe, *Fellow, IEEE*, and H. J. S. Dorren

Abstract—We demonstrate wavelength conversion based on nonlinear polarization rotation driven by ultrafast carrier relaxation in an InGaAsP–InGaAs multiquantum-well semiconductor optical amplifier. We use a continuous-wave (CW) probe beam at a center wavelength of 1555 nm, and a control pulse of duration of 120 fs at a center wavelength of 1520 nm. We have investigated wavelength conversion 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 pJ.

Index Terms—Nonlinear polarization rotation, semiconductor optical amplifier, ultrafast carrier relaxation, wavelength conversion.

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. Wavelength conversion based on nonlinear polarization rotation in semiconductor optical amplifiers (SOAs) is presented in [1]–[7]. 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) [7].

In this paper, we investigate wavelength conversion driven by femtosecond optical pulses in a nonlinear polarization switch as described in [1] using optical pulses with duration 47 ps. 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]. Suppose that a continuous-wave (CW) probe signal and a modulated pump signal, both at different wavelengths, are simultaneously injected into the SOA. The modulated pump signal will saturate the SOA. Since the SOA gain saturation is polarization dependent, a polarization-dependent nonlinear index change also is introduced in the SOA by the pump light. Thus,

the pump beam creates additional birefringence in the SOA, which makes the polarization angle of the probe light rotated while propagating through the SOA. It has been shown in [7] that this concept can lead to error-free inverted and noninverted wavelength conversion at a bit rate of 10 Gb/s.

A model that describes polarization-dependent nonlinear gain and index dynamics in SOAs on subpicosecond timescales is presented in [8]. The rate-equation model of [8] takes into consideration carrier dynamics on femtosecond timescales driven by two-photon absorption (TPA) and free-carrier absorption (FCA). The model accounts for self- and cross-phase modulation, carrier heating, and spectral and spatial hole burning, as well as self- and cross-polarization modulation. The polarization-dependent gain saturation is taken into account by assuming that the polarized optical field can be decomposed into a TE and TM component. These modes propagate "independently" through the SOA although they have indirect interaction with each other through the carriers. The model accounts different TE and TM gains by assuming that these polarizations couple to different hole reservoirs. This assumption is justified by the fact that in zinc-blende structures such as GaAs and InP the optical transitions occur between an $l = 0$ type conduction band state and a (degenerate) $l = 1$ type valence band state. Two out of the three possible transition types are selected by the TE and TM polarizations with the two corresponding inversions. In the isotropic bulk situation, these two transitions will occur in a fully symmetric manner, but we are now interested in the case where tensile strain is built into the active medium, and this will cause an asymmetry between the two transition types such that TM will be favored over TE transitions.

In this paper, we present experimental results which 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 investigated the wavelength conversion efficiency as a function of the injection current and the control pulse energy for different probe powers. We found a conversion efficiency of 12 dB and the performance of this switch is compared to switching in a Mach–Zehnder interferometer. Moreover, we investigate the converted pulsewidth numerically. Our numerical results indicate that the converted pulse broadens while propagating through the switch, but the recovery of the nonlinear polarization switch remains below 1 ps.

The paper is organized as follows. In Section II, we describe a wavelength conversion experiment based on nonlinear polarization rotation driven by 120-fs optical pulses. We present experimental results and show that the model presented in [8] can explain the experimental data. In Section III, conclusions are given.
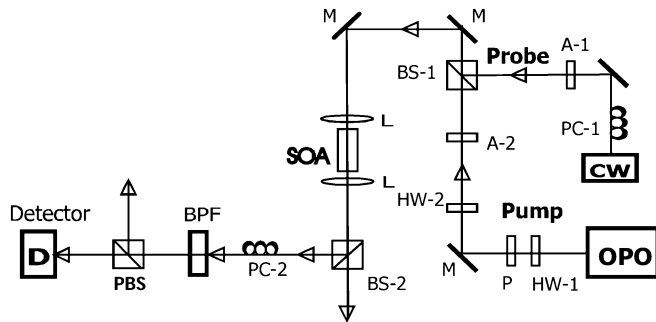
Fig. 1. Experimental implementation of the nonlinear polarization switch. OPO: optical parametric oscillator, HW: half-wave plate, P: polarizer, M: mirror, PBS: polarizing beam-splitter, BS: beam-splitter, L: lens, A: attenuator, BPF: band pass filter, PC: polarization controller, CW: CW tunable laser.

II. EXPERIMENTS AND RESULTS

The 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 bandpass filter (BPF), and a polarizing beam splitter (PBS). The amplifier used in this experiment is a multiquantum well InGaAsP–InGaAs SOA with a central length of 750 μm and at both sides a taper zone of 400 μm. 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 first 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 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 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.

Wavelength conversion can be realized in this setup by setting the linear polarization of the probe beam by approximately 45° with respect to the SOA layers. 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 it so 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. The rotation of the polarization is observed by measuring the transmission through the PBS. PC-2 was adjusted so that initially no light can pass through the PBS. However, if a pump pulse is injected in the SOA, the pump-induced rotation of the polarization angle of the probe light makes it so that some probe light can pass through the PBS. This means that at the PBS output, the pump pulse is converted to the wavelength of the probe light.

In the first experiment, the polarization-dependent SOA gain was measured as a function of pump pulse energy. The SOA injection current was 200 mA. The results are shown in Fig. 2, in
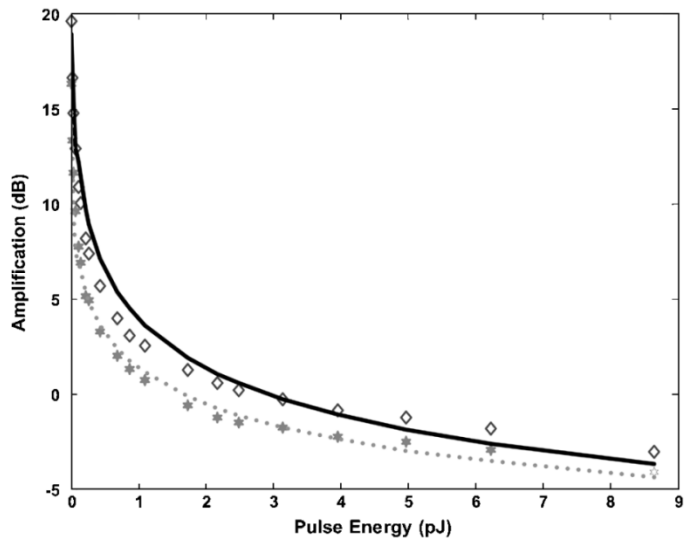

Fig. 2. Measured and computed polarization-dependent gain for the TE and TM modes as a function of the pump pulse energy. The diamond-shaped points and the star-shaped points represent the measured data for both modes. The solid line represents the computed result for the TE mode, and the dashed line represents the computed result for the TM mode. The SOA injection current was 200 mA.

which the amplification for TE and TM modes are plotted as a function of the injected pulse energy. 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 line in Fig. 2 represents the computed amplification for the TE mode, while the diamond-shaped points represent the measured data. Similarly, the dashed line in Fig. 2 represents the computed amplification for the TM mode, while the star-shaped points represent the observations [8]. The SOA parameters used in the simulations can be found in Table I. We corrected for the coupling and component losses that were estimated to be 12.0 dB (this includes two times 3.0-dB facet losses and 6.0 dB for the components used in the experimental setup); it follows from Fig. 2 that for a current of 200 mA, the small signal gain (measured for pulses with a pulse energy of 13 fJ) equals 19.6 dB for the TE mode and 16.3 dB for the TM mode. If we increase the pulse energy to 8.6 pJ, the gain of the corresponding modes dropped down to −3.1 dB for the TE mode and −4.1 dB for the TM mode. This is due to TPA and FCA, which dominate at high pulse energies. It follows from Fig. 2 that the experimental and numerical results are in good agreement.

In the second experiment, the polarization-dependent gain of the probe beam was measured as a function of the injected current I in the absence of pump light. The probe power was −10.0 dBm. The results are shown in Fig. 3. If the SOA is pumped with 200 mA of current, after correction for the component and coupling losses, the amplification for the TE and TM modes of the CW beam was 23 and 18 dB, respectively. We found that the small signal gain for the pump light differs from the small signal gain for the CW beam. The main reason for this is that we have different coupling losses for the pump light and probe light in our experiment. Similarly, as in Fig. 2, the discrete points represent the observations and the solid and dashed lines represent the computed results for the TE and TM modes of the CW beam. The computed amplifications for the

TABLE I
SOA PARAMETER DEFINITIONS AND THEIR VALUES

| Parameter	Symbol	Value	Units
Active volume	$V = L \times W \times D$	750×2×0.1	μm^3
Confinement factor	$\Gamma_{TE}, \Gamma_{TM}, \Gamma_2$	0.032, 0.021, 0.09	
Phase modulation coefficients	α, α_2	1.2, -1.5	
FCA coefficients	β_c, β_v	1×10^{-10}, 0	μm^{-1}
Electron-hole pair lifetime	τ_s	1.3	ns
Gain coefficient	a_{TE}, a_{TM}	7.0×10^{-5}, 5.5×10^{-5}	$\mu m^3 / ps$
Group velocity	v_g	100	$\mu m / ps$
Internal loss	α_{int}	0.00175	μm^{-1}
Optical transition energies (Valence band)	E_c, E_{2c}	0.03, 0.7	eV
Optical transition energies (Conduction band)	E_v, E_{2v}	0.003, 0.07	eV
Carrier-carrier scattering times	$\tau_{l,c}, \tau_{l,v}$	0.1, 0.05	ps
Carrier-phonon relaxation times	$\tau_{h,c}, \tau_{h,v}$	0.7, 0.25	ps
TPA coefficient	β_2	2.5×10^{-9}	μm^2
Optical transition state density	N_0	1.25×10^6	μm^{-3}
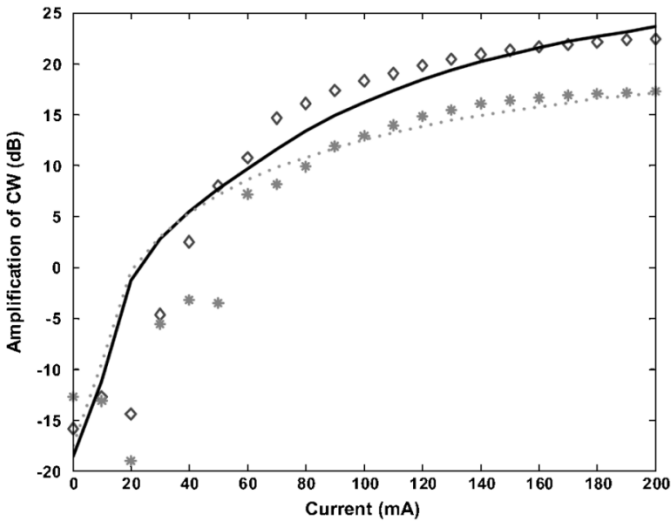
Fig. 3. Measured and computed polarization-dependent gain for the TE and TM modes as a function of the SOA injection current. The diamond-shaped points and the star-shaped points represent the measured data for both modes. The solid line represents the computed result for the TE mode, and the dashed line represents the computed result for the TM mode. The CW input power was −10.0 dBm and the injection current was 200 mA.

two modes are in agreement with the experimental data for currents above transparency point (50 mA). It should be remarked, however, that from an experimental point of view, it is increasingly more difficult to control the intensities of injected light in each mode while reducing the current below transparency.

In the wavelength conversion experiment, PC-1 was adjusted so that the polarization of the input signal is approximately 45° 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 setup was placed in a box to shield the polarization switch from thermal and mechanical disturbances. When saturating pump pulses were coupled into the SOA, the gain saturation led 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 could detect some probe light passed through the PBS. The discrete points in Fig. 4 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 using the model of [8]. 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.
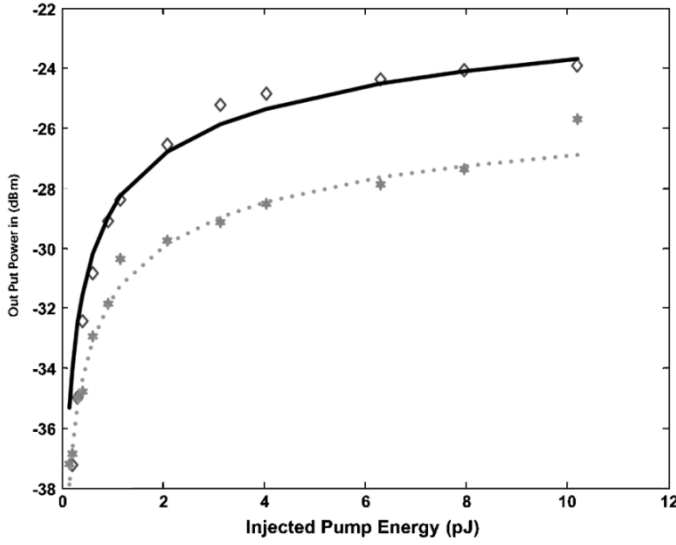
Fig. 4. Measured and computed output power of the nonlinear polarization switch as a function of pump pulse energy. The diamond-shaped points show the result if the CW input power was 0 dBm, and the star-shaped points represents the results if the CW power was 3 dBm. The SOA injection current was 200 mA. The central wavelength of the CW light was 1555 nm and the central wavelength of the pump light was 1520 nm.
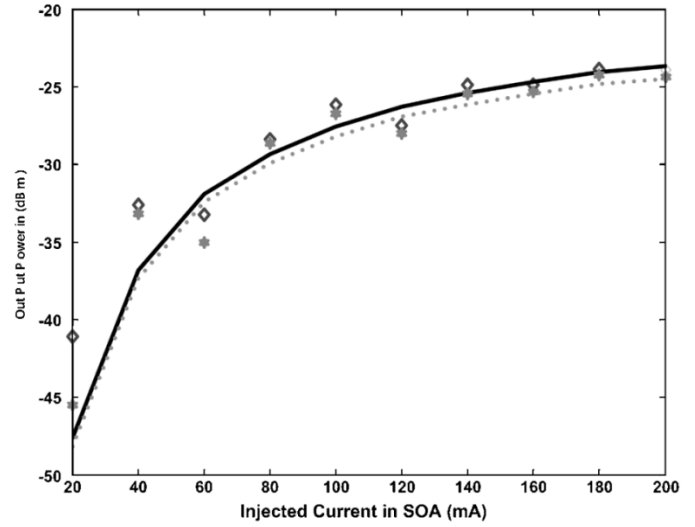
Fig. 5. Measured and computed output power of the nonlinear polarization switch as a function of the SOA injection current. The diamond-shaped points shows the result if the pump pulse energy was 10 pJ and the star-shaped points represents the results if the pump pulse energy was 6.3 pJ. The central wavelength of the CW light was 1555 nm, the central wavelength of the pump light was 1520 nm, and 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 Fig. 5. 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 and 6.3 pJ, respectively, based on the model and the parameters in Table I. 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 (50 mA).

Our experimental setup 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

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

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

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

Here, α is the linewidth enhancement factor and $g_{\text{CW}}^{\text{TE}}(t)$ and $g_{\text{CW}}^{\text{TM}}(t)$ represent the gain that accounts for TPA and FCA. Note

that (2) differs from its counterpart in [12], since in (2) there 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 an SOA placed in a Mach–Zehnder interferometer [9]. Fig. 6(a) shows a simulation of the nonlinear phase shift as a function of the time. It follows from Fig. 6 that the nonlinear phase shift $\Delta\phi_{\text{NL}}(t)$ has a long-lived tail that is much smaller than 0.1 rad. However, since the PBS output power is proportional to the cosine of the nonlinear phase shift, the effect of the long-lived tail has vanished in the PBS output power. This is visible in Fig. 6(b), which shows a simulation of the pulse that outputs the nonlinear polarization switch. Fig. 6 also shows that the nonlinear phase shift recovers in 500 fs so that the duration of the pulse that outputs the nonlinear polarization switch is also approximately 500 fs (at full-width at half-maximum). Fig. 6(b) also indicates that the converted pulse has considerably broadened with respect to the input pulse.

In Fig. 4, 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 Figs. 4 and 5 that the output power saturates for both high pump energy and high injection current. This behavior can be explained by using the results shown in Figs. 2 and 3, in which it is shown that the SOA 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 Figs. 4 and 5 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
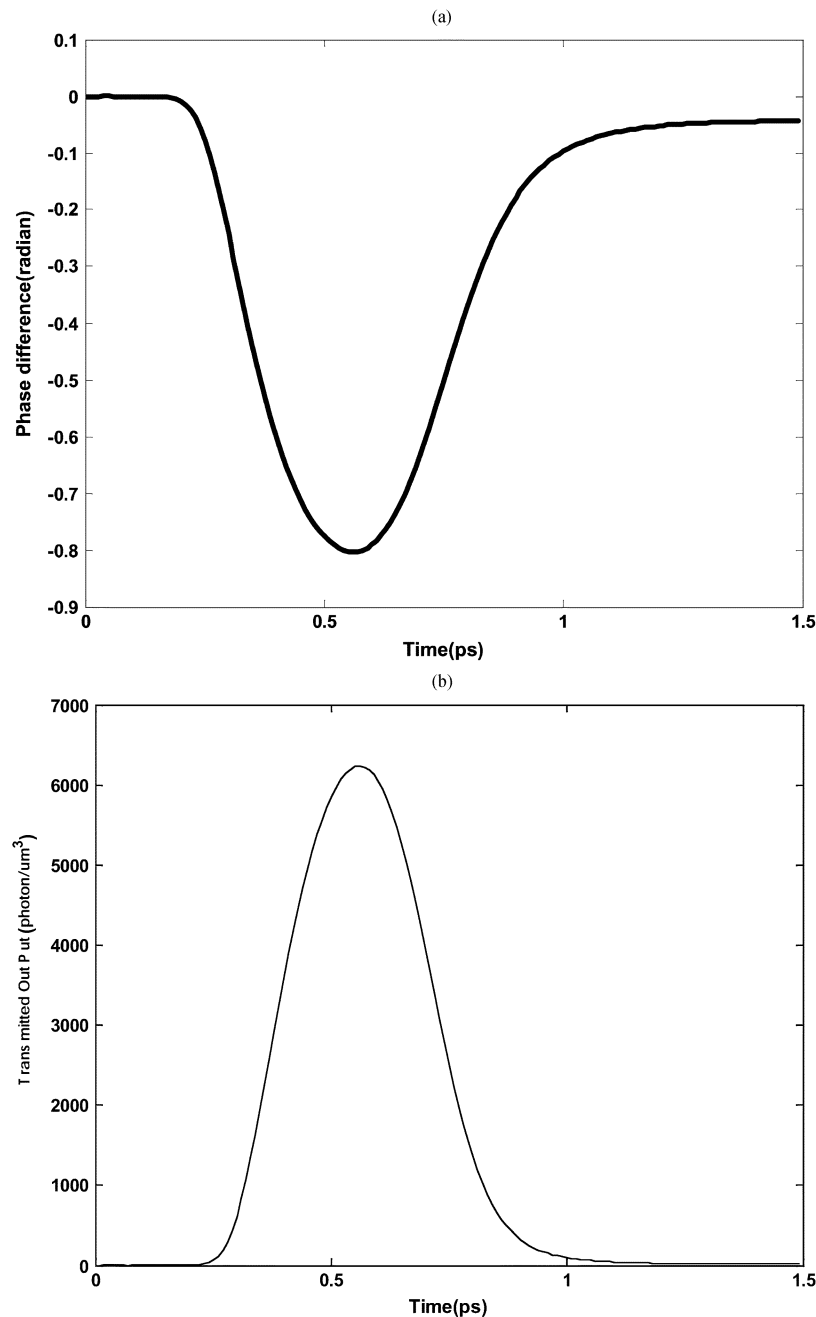
Fig. 6.   (a) Computed nonlinear phase shift $\Delta\phi_{NL}(t)$ as a function of time using (2). (b) Computed pulse transmission through the PBS as a function of time. In both cases, the pump pulse energy was 10 pJ and the power of the CW probe light was 3 dBm. The SOA injection current was 200 mA.

is much higher than desired in telecommunication systems. However, it can be substantially lowered by optimizing the bandwidth of the BPF 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. CONCLUSION

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.

We have also shown that the operation of a nonlinear polarization switch differs on an essential point from the operation of a nonlinear optical switch based on an SOA placed in a Mach–Zehnder interferometer. This is due to the fact that both the TE and TM modes propagate through the SOA (this is in contrast to a Mach–Zehnder interferometer, where only TE modes of the probe beam propagates through the SOA [9]). 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, the direct contribution due to TPA was canceled out. This implies that the width of the pulse that outputs the nonlinear polarization switch only depends on the nonlinear carrier dynamics in the SOA.

Our results indicate that there are two major challenges on the road toward system applications of wavelength conversion in SOAs employing subpicosecond pulses. First, the pump pulses that were used in our experiment had energy of 10 pJ, which is two orders too high to allow system applications at high repetition rates. We believe, though, that the pulse energy can be substantially lowered by optimizing the experiment. Second, numerical simulations indicate that the converted pulse has significantly broadened with respect to the input pulse. This is undesirable in system applications in which the output pulse typically has the same duration as the input pulse.

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Prof. Khoe received the MOC/GRIN award in 1997. His professional activities include many conferences, where he has served on technical committees, management committees, and advisory committees as a Member or Chairman. Recently, he was General Cochair of the ECOC 2001. In Europe, he is closely involved in research programs of the European Community and in Dutch national research programs, as Participant, Evaluator, Auditor, and Program Committee Member. He is one of the founders of the Dutch COBRA University Research Institute and one of the three recipients of the prestigious "Top Research Institute Photonics" grant that is awarded to COBRA in 1998 by the Netherlands Ministry of Education, Culture, and Science. In 2001, he brought four groups together to start a new international alliance called the European Institute on Telecommunication Technologies (eiTT). He is Associate Editor of the IEEE JOURNAL OF QUANTUM ELECTRONICS. His has served in the IEEE Lasers and Electro-Optics Society (LEOS) organization as European Representative of the Board of Governors, Vice President of Finance and Administration, Board of Governors Elected Member, and Member of the Executive Committee of the IEEE Benelux Section. He was Founder of the LEOS Benelux Chapter. He is currently the Junior Past President of LEOS.

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