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# Wavelength Conversion Using Nonlinear Polarization Rotation in a Single Semiconductor Optical Amplifier

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**Abstract**—We discuss an all-optical wavelength converter based on nonlinear polarization rotation in a single semiconductor optical amplifier. We show that inverted and noninverted wavelength conversion can be realized. We also demonstrate this wavelength-conversion concept can operate over a large wavelength range. Experiments show that error-free wavelength conversion can be obtained at a bit rate of 10 Gb/s.

**Index Terms**—All-optical wavelength converter, birefringence, nonlinear polarization rotation, semiconductor optical amplifier (SOA).

## I. INTRODUCTION

ALL-OPTICAL wavelength converters based on nonlinearities in semiconductor optical amplifiers (SOAs) are considered as important building blocks for wavelength-division-multiplexed (WDM) networks [1], [2]. Several SOA-based wavelength-conversion techniques have been demonstrated. Wavelength conversion utilizing four-wave mixing in an SOA is independent of the modulation format but it has low conversion efficiency and also the input light needs to be polarization matched [1]. Inverted wavelength conversion based on cross-gain modulation (XGM) in a single SOA has been demonstrated at 100 Gb/s, but this approach also leads to a degradation of the extinction ratio [2], [3]. Interferometric wavelength converters based on cross-phase modulation in combination with XGM in SOAs lead to an improved extinction ratio and can also be used to realize inverted and noninverted conversion. Furthermore, this concept can be utilized for signal reshaping [1], [2].

In this letter, we focus on wavelength conversion based on nonlinear polarization rotation in a single SOA. Although the principle of wavelength conversion based on nonlinear polarization rotation has already been demonstrated by others [4], [5], we present new results that clearly demonstrate the potential of this concept within a telecommunication systems context. We demonstrate that error-free inverted and noninverted wavelength conversion at data rates up to 10 Gb/s can be realized in a single SOA. The stable operation is obtained by using a commercially available pigtailed SOA. We note that there is

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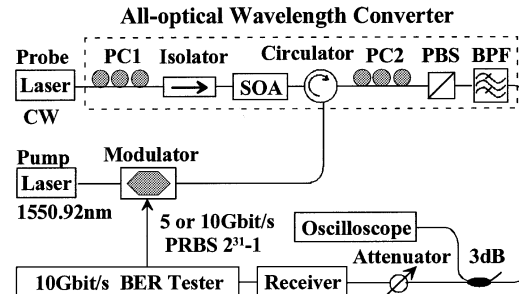


Fig. 1. The configuration of the all-optical wavelength converter based on nonlinear polarization rotation. BPF: optical bandpass filter.

a remarkable similarity between the characteristics of a wavelength converter based on nonlinear polarization rotation in a single SOA and Mach-Zehnder interferometric (MZI) wavelength converters. This similarity can be explained by the fact that wavelength converters based on nonlinear polarization rotation operate by interferometric principles, since the transverse electric (TE) and transverse magnetic (TM) modes that independently propagate through the SOA play the roles of the different light paths in the MZI. Hence, important properties of interferometric wavelength converters also apply to this concept. A clear advantage of this wavelength converter is that it allows inverted and noninverted wavelength conversion as well as reshaping using a single SOA. A similar approach has already been used for demultiplexing from 40 to 10 Gb/s [6].

## II. SYSTEM CONCEPT

The all-optical wavelength converter is depicted in Fig. 1. As shown in the dashed box of Fig. 1, the wavelength converter is made from an SOA, two polarization controllers (PCs), an optical isolator, an optical circulator, an optical bandpass filter and a polarization beam splitter (PBS). A laser emits a continuous wave (CW) probe beam at wavelength  $\lambda_{\text{probe}}$  that is fed into an SOA. The SOA output is sent into a PBS. The system contains two polarization controllers. The first polarization controller is used to adjust polarization of the input signal to be approximately  $45^\circ$  to the orientation of the SOA layers, while the second polarization controller is used to adjust the polarization of the amplified SOA output with the orientation of the PBS. The SOA can be saturated by injecting a high-intensity pump signal at a different wavelength ( $\lambda_{\text{pump}}$ ). The injected pump light introduces additional birefringence in the SOA [7], which causes

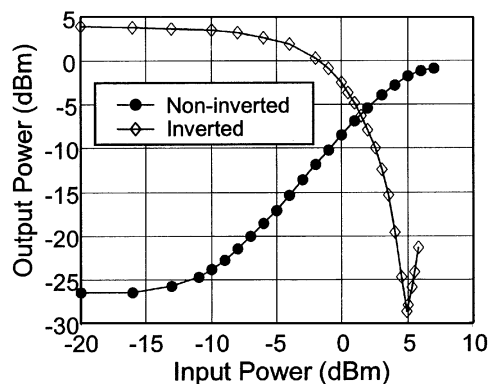


Fig. 2. Measured static output power of probe light (1552.52 nm) versus the input power of the pump light (1550.92 nm).

the TE and the TM modes of the probe beam to experience a different refractive index. At the PBS, the two modes coherently combine.

In the first case, 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. If a saturating pump beam is coupled into the SOA, the additional birefringence 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 [4], [5]. As a consequence, some probe light can pass through the PBS. Hence, 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. Thus, noninverted wavelength conversion is obtained.

Conversely, the polarization controllers can also be adjusted so that initially a maximum amount of probe light can pass through the PBS. If a saturating pump beam is applied, the phase change between the TE and TM modes leads to a lower intensity at the PBS output. Thus, an increase in the pump intensity leads to a decrease in the probe intensity at the PBS output. Thus, inverted wavelength conversion is realized.

### III. EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 1. The CW probe light is sent into the SOA via PC1 and an optical isolator. The SOA (manufactured by JDS Uniphase) has an active length of 800  $\mu\text{m}$  and employs a strained bulk active region. The pump beam (1550.92 nm) is first modulated by a 10-Gb/s external modulator, and then coupled into the SOA via a circulator. The bit patterns have a data format of a  $2^{31} - 1$  nonreturn-to-zero pseudorandom bit stream. The PBS has an extinction ratio of 30 dB. A bandpass filter (1 nm bandwidth) is used to suppress the spontaneous emission noise of the SOA.

The static operation of the wavelength converter is measured by an optical power meter, as presented in Fig. 2. In Fig. 2, the (measured) power of the probe light that outputs the PBS is plotted versus the power of the pump light, for both the inverted and the noninverted case. The intensity of the probe light that enters the SOA is 2 dBm. The SOA is pumped with 237 mA of current. However, it is not essential to drive the SOA at this current. By adjusting the setting of the two polarization controllers (PC1 and PC2), similar curves can be obtained when the

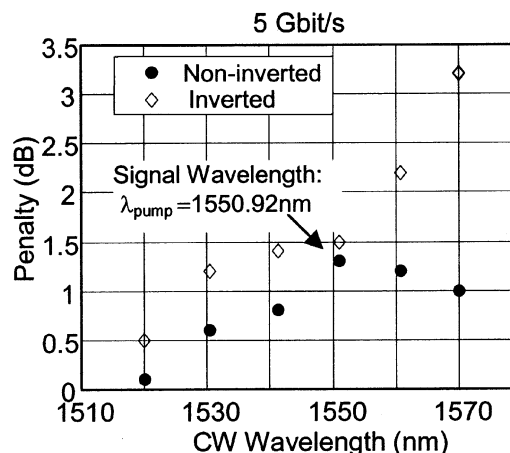


Fig. 3. The measured penalty after wavelength conversion versus the CW wavelength of probe light at a bit rate of 5 Gb/s.

SOA is biased at a higher current (for example 392 or 399 mA, as used in later experiments). It can be seen from Fig. 2 that the extinction ratio of the converted signal can be over 20 dB. In the wavelength converter, high-intensity pump light is required to saturate the SOA. Therefore, XGM takes place simultaneously with nonlinear polarization rotation. XGM opposes the effect of noninverted wavelength conversion, but enlarges the effect of inverted wavelength conversion. As a consequence, the slope of the curve for the inverted case is sharper than the one for the noninverted case.

Fig. 3 shows the measured penalty for conversion from 1520 to 1570 nm at a bit rate of 4.976 64 Gb/s. The wavelength of modulated pump light is 1550.92 nm. The intensity of the input CW probe light is 1.58 dBm and the average power of the pump light is 0.53 dBm. The SOA is biased with 392 mA of current. It can be observed from Fig. 3 that this wavelength-conversion concept can operate over a large wavelength range (50 nm) with a small penalty. Fig. 3 shows that the penalty for non-inverted conversion reaches a maximum when the pump and probe light have the same wavelength. This is due to the reflected pump light at the SOA facet, which has the same wavelength as the probe light. For inverted wavelength conversion effects of nonlinear polarization rotation and XGM enlarge each other. XGM, however, has a larger penalty for up-conversion than for down-conversion, so the total penalty for inverted conversion increases if the probe wavelength is increased. Finally, we mention that this wavelength converter can also convert information to the same wavelength, which is important for applications in WDM switching blocks [8].

Fig. 4(a) shows the bit-error-rate (BER) curves of the converted signal for both inverted and noninverted operation, together with back-to-back measurement at a bit rate of 9.953 28 Gb/s. The input power of the CW probe light (1552.52 nm) is 3.82 dBm and the average power of modulated pump light (1550.92 nm) is 3.80 dBm. The SOA is pumped with 399 mA of current. The BER measurements are optimized for an input power that corresponds to a BER of  $10^{-9}$ . It can be seen in Fig. 4(a) that noninverted conversion leads to a penalty of 3 dB at a BER of  $10^{-9}$ . Moreover, it is visible that no BER floor is observed up to BERs as low as  $10^{-12}$ , which indicates excellent

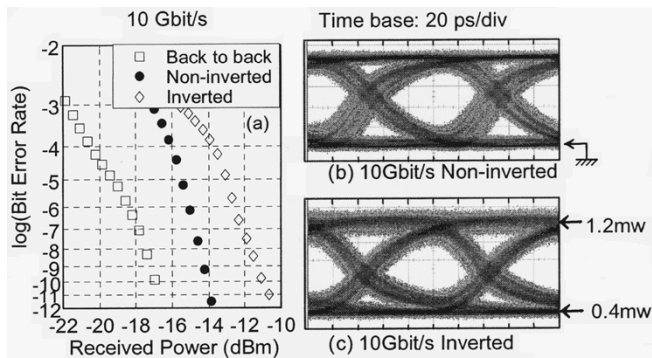


Fig. 4. (a) BER curves for wavelength conversion at 10 Gb/s and related eye diagrams. (b) Noninverted and (c) inverted signal.

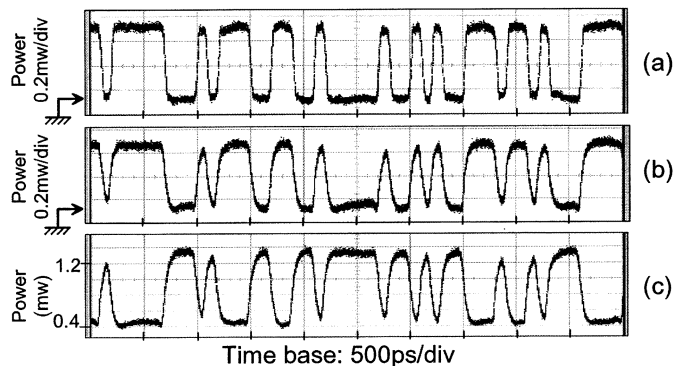


Fig. 5. Oscilloscope traces of the 10-Gb/s input and converted signals. (a) Input pump signal, (b) noninverted, and (c) inverted signal.

performance of the wavelength converter. The eye diagram is presented in Fig. 4(b), having an extinction ratio of 12.3 dB and a  $Q$  factor of 11.1. The eye pattern for an inverted conversion is presented in Fig. 4(c), having an extinction ratio of 4.7 dB and a  $Q$  factor of 7.3. The eye diagram for the inverted conversion has a fast fall time but slow rise time, which can be explained by the nonlinear slope in the transfer curve (see Fig. 2) in combination with the slow carrier recovery time of the SOA. The oscilloscope traces of 10 Gb/s input pump signal as well as converted signals (noninverted and inverted) are shown in Fig. 5. The eye diagrams are measured on an HP 83480A Digital Communication Analyzer with a 30-GHz O/E converter (83482A).

The extinction ratio of the converted signal is degraded from 20 dB in the static measurement to 12 dB in the dynamic measurement. There are two reasons for the degradation. Firstly, the SOA carrier number can reach a steady-state value in the static tests, leading to a small output value in the "0" level. However, in dynamic operation, the SOA carrier number does not reach this steady-state value due to the finite carrier lifetime, hence, the small output value in the "0" level is not reached. Secondly, noise in the O/E converter (30 GHz bandwidth) and the oscilloscope limits the smallest signal that can be seen, thus further degrading the extinction ratio. In the dynamic measurement, a higher current is applied to the SOA in order to reduce the carrier lifetime of the SOA, so that a better extinction ratio of converted signal can be obtained.

Finally, we have investigated the reshaping functionality of the wavelength converter. We have found that for noninverted

conversion at a data rate of 5 Gb/s, a modulated pump signal with an extinction ratio of 6.6 dB leads to a converted signal with an extinction ratio of 12.1 dB. As in other interferometric wavelength converters, the reshaping capability of the wavelength converter is based on the input-to-output transfer curve (Fig. 2). The shape of the transfer curve in this system is determined by the drive current of the SOA and the setting of the two polarization controllers (PC1 and PC2).

#### IV. CONCLUSION

We have investigated wavelength conversion based on nonlinear polarization rotation in an SOA. We have shown that inverted and noninverted wavelength conversion can be obtained by using a single SOA. The selection for inverted or noninverted operation is achieved by using PCs. The static extinction ratio of the converted signal is more than 20 dB. It is demonstrated that this approach can convert signals over a large wavelength range (50 nm) with a small conversion penalty. Error-free wavelength conversion at 10 Gb/s is obtained. No error floors are observed. Moreover, the reshaping ability is investigated.

Our results indicate that the operation of the wavelength converter based on nonlinear polarization rotation in an SOA is comparable with the operation of MZI wavelength converters. In fact, the wavelength conversion based on nonlinear polarization rotation operates as an MZI since the independently propagating TE and TM modes in an SOA play the roles of the different paths in the MZI.

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