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A novel approach to all-optical wavelength conversion by utilizing a reflective semiconductor optical amplifier in a co-propagation scheme

L.Q. Guo [a,b,*], M.J. Connelly [a]

[a] Optical Communications Research Group, Department of Electronic and Computer Engineering, University of Limerick, Co. Limerick, Ireland
[b] Photonics Research Group, Department of Electrical and Computer Engineering, University of Toronto, Toronto, Ontario, Canada

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ABSTRACT

Nonlinear optical gain modulation in an InGaAsP/InP bulk reflective semiconductor optical amplifier (RSOA) is studied. The differences of the optical properties between RSOAs and conventional SOAs are initially investigated. All-optical wavelength conversion based on nonlinear gain modulation in RSOAs is demonstrated at a bit rate of 2.488 Gbit/s. It is shown that a bit-error-rate of $<10^{-9}$ can be achieved and an extinction ratio of >9 dB can be obtained at a bit rate of 2.488 Gbit/s with a $2^{31}-1$ non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS). In comparison with conventional SOAs, wavelength conversion by RSOAs shows much improved performances in high-speed all-optical wavelength conversions.

1. Introduction

The semiconductor optical amplifier (SOA), utilized as an active nonlinear optical medium, has demonstrated its feasibilities in all-optical functional applications, such as optical switching, wavelength conversion, pulse generation and optical logic gate [1,2]. Cross gain modulation (XGM), which is based on intensity-modulated optical gain in the SOA, is a promising approach to all-optical wavelength conversion [3–5]. The attractions of XGM wavelength conversion devices lie in their simplicity, high conversion efficiency, polarization independence, and insensitivity to the wavelength of the input data (provided it is within the SOA gain bandwidth). Polarization independence is ensured if the SOA gain is designed to be polarization independent [6].

Reflective semiconductor optical amplifiers (RSOAs) utilize a high reflective (HR) coating on one facet and an anti-reflective (AR) coating on the other facet to produce a highly versatile gain medium. Although its waveguide structure is similar to a conventional SOA [7], the RSOA features a lot of different optical properties. RSOAs offer low noise figure and high optical gain at low drive current. Recently RSOAs have drawn a lot of research interest and found increasing applications in wavelength division multiplexing passive optical network (WDM-PON) [8–10]. In this paper, we report a new approach to realize all-optical wavelength conversions by putting a RSOA in a co-propagation scheme. Both up and down wavelength conversion are demonstrated. The mechanism of optical gain saturation in RSOAs and its applications are initially studied, in comparison with that of conventional SOAs.

2. Reflective semiconductor optical amplifier

The RSOA used in this work is a commercially available pigtailed RSOA (Kamelian, OPA series). It employs a tensile-strained bulk InGaAsP/InP active region, which is similar to the SOAs used in our previous works [11–13]. The active layer consists of a rectangle active region and taper region at the end. Very low reflectivity ($<10^{-5}$) is obtained by combining buried windows with AR-coated tilted facets.

However the RSOA in this work utilizes HR coating on one of its facets, and maintains a similar structure on the other facet as the conventional SOA. This structure provides high optical gain at low bias current. The polarization sensitivity is less than 1.0 dB, and the gain ripple is less than 0.5 dB around 1.5 μm. The optical gain as a function of input power at different wavelengths is depicted in Fig. 1. The RSOA bias current and temperature are maintained at 120 mA and 20 °C, respectively. Compared with conventional SOAs [14], the RSOA provides high optical gain at low bias current. Meanwhile it can be easily saturated at low optical power, which is advantageous to implement wavelength conversion based on XGM.

3. Principle of operation

The all-optical wavelength conversion in this work is based on XGM in RSOAs. In this approach, an intensity-modulated signal, re-

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* Corresponding author. Address: Optical Communications Research Group, Department of Electronic and Computer Engineering, University of Limerick, Co. Limerick, Ireland.
E-mail address: lq.guo@utoronto.ca (L.Q. Guo).

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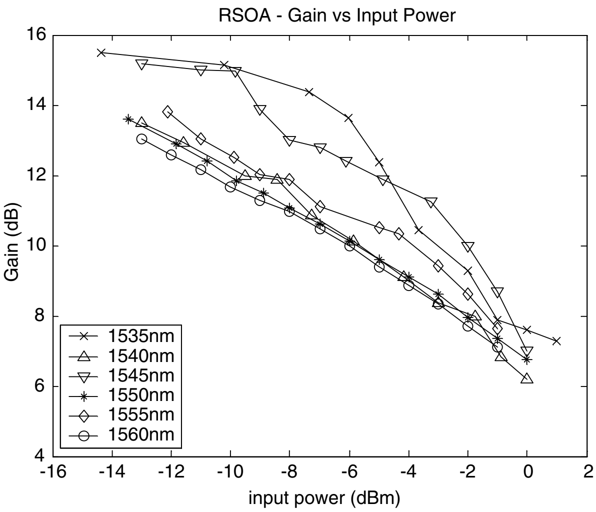

Fig. 1. The optical gain as a function of input power at different wavelength for a RSOA.

ferred to as the pump beam, propagates through a RSOA and is intense enough to compress significantly the gain of the RSOA. The induced gain variations are impressed on a second input to the RSOA, a CW beam at a different wavelength called the probe. In this case, the wavelength-converted data is the complementary copy of the original data signal. The schematic operation is depicted in Fig. 2. HR and AR coatings are indicated. An optical filter at the RSOA output is used to separate the converted signal from the pump signal.

4. Experiments

In this work, a co-propagation scheme is used, and the experimental setup of the wavelength conversion by RSOA is shown in Fig. 3. Because of the highly reflective nature of one facet of the RSOA, only the co-propagation scheme can be used. This is contradicted to the conventional SOA, which can be operated in either co- or counter-propagation scheme [13,14].

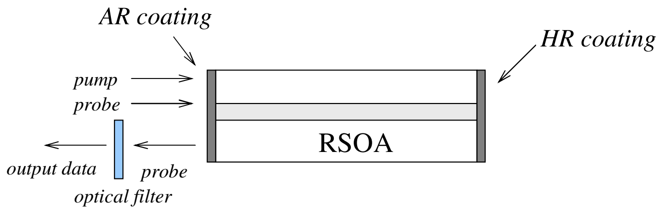

Fig. 2. Principle of wavelength conversion by XGM in RSOA.

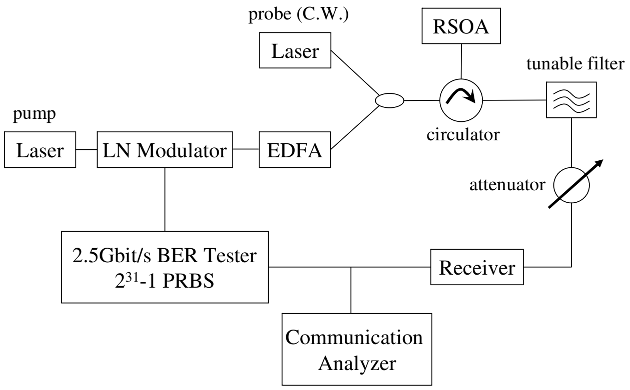

Fig. 3. Experimental setup for wavelength conversion by XPM in RSOA.

During the operation, the RSOA bias current and temperature are maintained at 120 mA and 20 °C, respectively. The pump light is externally modulated at 2.488 Gbit/s by a non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS) of length $2^{31}-1$ via a LiNbO$_3$ Mach–Zehnder modulator, and coupled into the RSOA by a circulator together with a probe light. The modulated pump light therefore modulates the optical gain of the RSOA. The probe light experiences this gain variation and transfers the data information from the pump light. Therefore wavelength conversion is realized.

The eye diagrams are measured on an HP83480A digital communication analyzer with a 20 GHz O/E plug-in module (HP83485 A), and are demonstrated in Fig. 4. The wavelength of pump light is 1550 nm; the wavelength of probe light for up and down conversion is 1555.3 nm and 1543.2 nm, respectively. The eye diagrams are measured under the conditions that bit-error-rate (BER) is optimized around 10^{-9} after introducing a considerable amount of attenuation into the system. An HP8156A optical attenuator in Fig. 3 attenuates the converted signal before the BER tester to simulate a telecommunication system in practice. The eye diagram of up-conversion presented in Fig. 4a shows an extinction ratio of 6.3 and a Q factor of 7.08; and the eye diagram of down conversion is presented in Fig. 4b, having an extinction ratio of 5.8 and a Q factor of 7.00. The open eyes suggest the operation can be operated at even higher bit rates.

The BER measurements of up and down wavelength conversion together with back-to-back measurements are presented in Fig. 5. It can be seen that down conversion leads to a penalty of ~4.0 dB at a BER of 10^{-9}. Up-conversion leads to an additional 0.9 dB penalty compared with the down-converted case. This is because of the band-filling effects at the presence of an intense pump signal [13,14]. Because of this asymmetrical gain compression in RSOA gain medium, the extinction ratio for wavelength conversion by XGM is always better in down conversion. This agrees with the operations in conventional SOAs [6,13]. One consequence of this nonlinear gain compression is better BER performance for down conversion, which can be clearly seen in Fig. 5. Meanwhile, no error floor is found up to BER as low as 10^{-14}, which indicates excellent

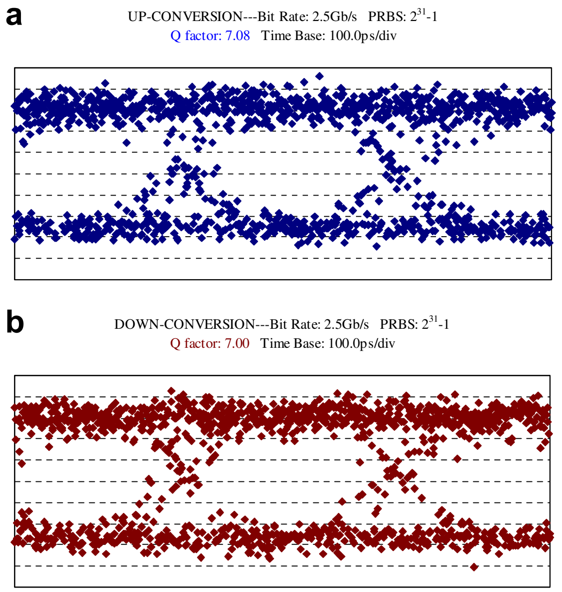

Fig. 4. Eye diagrams for up and down wavelength conversions by XGM in RSOA.

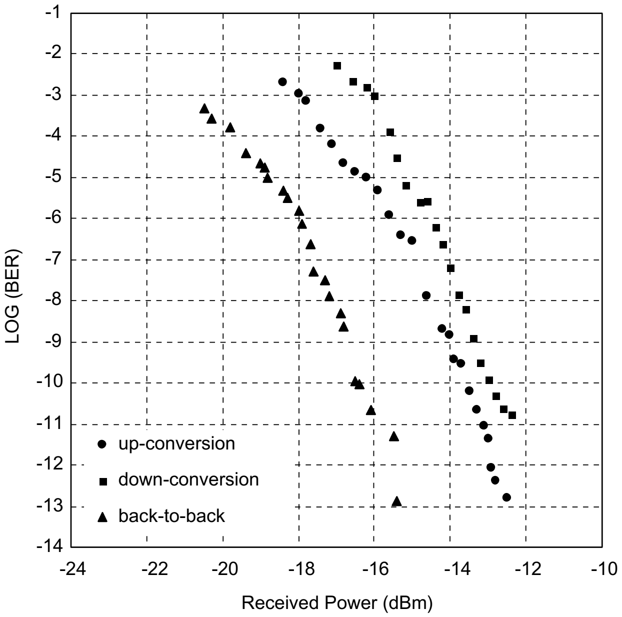

Fig. 5. Plot of 2.488 Gbit/s BER measurement for up and down wavelength conversions by XGM in RSOA, together with back-to-back measurement.

conversion performance by utilizing the RSOA in the co-propagation scheme.

5. Discussions

RSOAs feature high optical gain and low saturation power compared with conventional SOAs. These unique properties result in much improved performances in wavelength conversion based on XGM compared with that of conventional SOAs. Meanwhile its wideband gain provides the feasibility of wavelength conversion over a wide wavelength range.

The *Q* factors for the wavelength converter by RSOA and SOA at different probe power levels are depicted and compared in Fig. 6. The experimental setup using RSOA is shown in Fig. 3. For SOA-based wavelength converter, we use our previous setup which is described in [6,13]. From Fig. 6 one can see that, at very low probe power level (less than −4 dBm), SOA fails to perform any wavelength conversion, while RSOA can deliver a good performance at power level as low as −8 dBm. This is mainly due to the high optical gain nature of the RSOA and the double pass of the probe beam in the RSOA [15]. At high probe power, the *Q* factor for the devices by RSOA and SOA are almost identical. From practical point of view, it is always advantageous to operate the wavelength converter at low probe power level over a wide power range. Fig. 6 suggests that the RSOA offers this desirable operation.

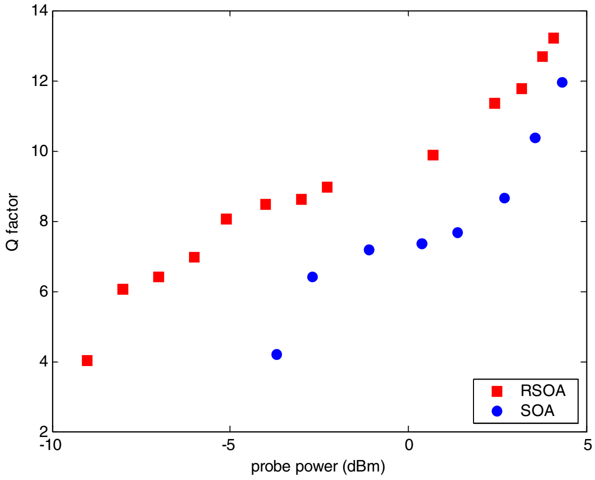

Fig. 6. The *Q* factor for the operation of wavelength conversion by RSOA and SOA versus probe power levels.

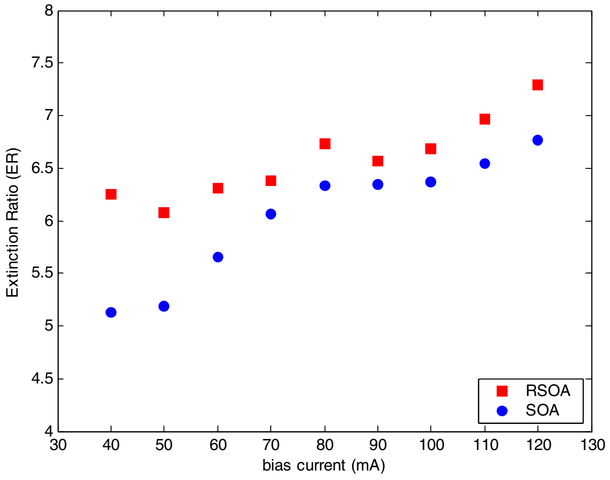

Fig. 7. The ER for the operation of wavelength conversion by RSOA and SOA at different bias current level.

The measurements of extinction ratio (ER) for wavelength converter by RSOA and SOA at different bias current are depicted in Fig. 7. The pump and probe powers are maintained at 8 dBm and −2 dBm, respectively. Fig. 7 shows that ER for RSOA-based converter is always better than that of SOA-based converter. This is a direct result of superior gain performance and relatively low saturation power of the RSOA. It worth note that, at low bias current, the ER achieved in RSOAs is much higher than that by SOAs, which is a desired feature in all-optical signal processing and applications.

6. Conclusion

Wavelength conversion by nonlinear gain modulation in RSOAs is demonstrated at a bit rate of 2.5 Gbit/s in both up and down wavelength conversion schemes. While shorter and longer wavelength conversion can be realized, the extinction ratio of a signal converted to shorter wavelength is always better, since the pump light reduces the carrier density and the optical gain is compressed asymmetrically as a result of band-filling effects [13]. Because of this asymmetrical gain compression, the extinction ratio is always better in down conversion. Wavelength conversion using a RSOA and conventional SOA are demonstrated and compared. RSOAs show many superiorities, such as low probe power operation with wide power range, exceptional ER at different bias currents.

Acknowledgments

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