Application of Semiconductor Optical Amplifiers in High-Speed All-Optical NRZ to RZ Format Conversion

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ABSTRACT
We present two types of 42.6 Gbit/s all-optical non-return-zero (NRZ) to return-zero (RZ) format converters using semiconductor optical amplifiers (SOAs). The converters are based on cross-phase modulation (XPM) and cross-polarisation modulation (XPolM) in SOAs. Both format converters produce a correctly-coded, polarity-preserved RZ signal at the output and have the flexibility of variable NRZ input data wavelength. Error-free operation was achieved for both converters with switching energy below 50 fJ/pulse. The format converter based on XPM has the additional advantage of variable duty-cycle of the RZ signal and exhibited negative power penalties.
Keywords: Semiconductor optical amplifier, All-optical signal processing, NRZ to RZ Format conversion.

1. INTRODUCTION

Current optical telecommunications networks rely on digital electronic signal processing, leading to networks which lack transparency and have high power consumption, high cost and the complexity of optical-to-electrical-to-optical conversion. All-optical signal processing functions such as wavelength conversion, regeneration and logic gates, all of which may be implemented using semiconductor optical amplifiers (SOAs), are potentially practical alternatives to electronics in high-speed optical networks. A particularly useful function is all-optical data format conversion between non-return-zero (NRZ) and return-zero (RZ) to make use of flexible NRZ/RZ formats at different stages of network. Conversion to RZ format also enables other all-optical signal processing operations to be performed using SOAs.

NRZ to RZ format conversion using cross-gain modulation (XGM) [1] or cross-phase modulation (XPM) [2,3] in SOAs has been reported; however these reports have been limited to bit rates of ~ 10 Gbit/s. Devices based on cross-polarisation modulation (XPolM) are also attractive because of their much simpler structure [4]. XPolM does not lend itself so readily to differential switching, and hitherto has been limited to maximum rates of ~10 Gbit/s. However, a 40 Gbit/s wavelength converter using XPolM was demonstrated recently with an SOA-based turbo-switch [4, 5]. 40Gbit/s NRZ to RZ conversion has also been reported using an SOA-based Mach-Zehnder delay interferometer [6]; however it required a complex pre-coder because the converted RZ signal was a modified duo-binary signal or alternate mark inversion signal.

In this paper, firstly we report an SOA-based all-optical 42.6 Gbit/s NRZ to RZ converter using XPM in a single SOA. The converter employs a single SOA followed by an asymmetric Mach-Zehnder filter. Secondly, we demonstrate 42.6 Gbit/s all-optical NRZ to RZ format conversion by XPolM incorporating an SOA-based turbo-switch as switching element [4]. In this case, the four-fold increase in operating speed over previous format converters is achieved by using the turbo-switch configuration, whilst for the XPM device the rate increase is attributed to the clock driven configuration employed. For both format converters, the output is a correctly coded RZ signal with the input polarity preserved. Both approaches exhibit low patterning. The switching pulse energies required are low (15 ~ 50 fJ) and the input data wavelength may be varied. Moreover, the format converter based on XPM allows controllable pulsewidth of the RZ output data.

2. PRINCIPLES

2.1 NRZ to RZ format conversion based on XPM in SOA

We use the delay-interferometer-signal wavelength conversion (DISC) configuration, in which a single SOA is followed by an asymmetric Mach-Zehnder filter [7], as shown in Fig. 1*a*. The Mach-Zehnder filter was formed by using a piece of polarisation-maintaining (PM) fibre with a time of flight delay Δt between its fast and slow axes, this delay being dependent on the PM fibre length. The NRZ data probe beam is input into the SOA after synchronisation with the clock beam. A pump consisting of clock pulses introduces periodic phase-shifts to the following NRZ data via XPM in the SOA. This phase modulation is converted into amplitude modulation in the delay interferometer, which results in a RZ output signal with a pulsewidth mainly determined by the offset delay (Δt) of the Mach-Zehnder filter and is limited by the clock pulsewidth. Thus in the case of NRZ data, if the input is '0', the output is '0'; whereas when the NRZ data input is '1', an RZ optical data pulse with a pulsewidth of Δt is obtained at the output port. Since the phase modulation is dominated by the stronger clock

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signal which is always present in every bit period, this leads to the absence of patterning effects. Thus this approach should enable the device to be operated at even higher bit-rates beyond 40 Gbit/s.

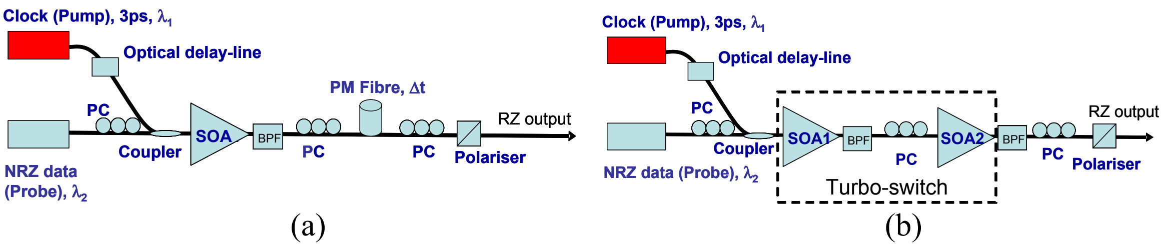

Figure 1. Experimental setup for NRZ to RZ format conversion based on: (a) XPM in SOA; (b) XPolM in SOA, where PC: polarisation controller, BPF: band-pass filter.

2.2 NRZ to RZ format conversion based on XPolM in SOA

The schematic setup of an XPolM format converter is shown in Fig. 1*b*. The inputs to the SOA are strong clock pulses (pump) and NRZ input data (probe) synchronised to the pump. When a strong clock pulse is present in the SOA, it induces different phase-shifts for the TE and TM components of the NRZ input data. The two components therefore acquire a net phase difference, which causes a rotation of the resultant polarisation, and results in an output pulse after the polarizer. The polarisation of the input data is set to balance the amplitudes of TE and TM components and optimise the output pulse intensity. Thus if the NRZ data input is '0', the output is '0'; when the NRZ data input is '1', this phase-shift difference will result in an RZ optical data pulse at the output port. In this way, NRZ input data is converted into RZ output.

In order to increase the effective switching speed beyond 10 Gbit/s, we adopted a turbo-switch configuration [4,5] instead of a single SOA. The turbo-switch consists of a pair of SOAs separated by a wide band-pass filter (BPF), which prevents the pump pulses from entering the second SOA. The authors demonstrated a 40 Gbit/s wavelength conversion based on XPolM [4], moreover showed an error-free wavelength conversion based on XPM at 170.4 Gbit/s [5], both using a turbo-switch. Measurements showed that the overall response time of a turbo-switch was about four-fold faster than a single SOA [8].

3. EXPERIMENT AND RESULTS

3.1 NRZ to RZ format conversion based on XPM in SOA

The small-signal gain of the SOA was 24 dB at 1550 nm at the operating current of 400 mA. The input beams to the SOA were a 42.6 Gbit/s NRZ probe at 1550 nm, and a 42.6 GHz RZ pump beam, consisting of 3 ps (full width at half maximum, FWHM) pulses at 1545 nm. The probe and pump signals were synchronized by using an optical delay-line before the SOA. The input data sequences were programmed with pseudo-random binary sequences (PRBS) of lengths 2^7-1 to 2^{31}-1. A wide band-pass 5 nm (FWHM) filter was placed after the SOA which blocked the pump pulse and allowed only the NRZ data to pass through. The pulsewidth of the RZ output signal was determined by the differential delay Δt of the PM fibre, which we varied in order to characterise the device at different output duty-cycles.

The RZ output of the format converter was detected by a receiver with a dual stage EDFA pre-amplifier, incorporating two 5 nm filters to suppress amplified spontaneous emission (ASE) whilst passing the RZ signal spectrum. A typical set of bit error rate (BER) measurements is plotted in Fig. 2*a*. These measurements were taken for a differential delay Δt of 11.5 ps. Error-free operation was achieved for all pattern lengths used. The 42.6 Gbit/s converted RZ and NRZ (unconverted) eye diagrams for a PRBS length of 2^7-1 are shown in the inserts in Fig. 2*a*. As shown in Fig. 2*a*, the power penalties were -1.9, -0.6 and -0.4 dB for pattern lengths of 2^7-1, 2^{15}-1 and 2^{31}-1 respectively, where the PRBS length of the back-to-back NRZ signal was 2^7-1. No error floor was observed for any of the different PRBS lengths used.

For these results, the average input power to the SOA was -10 dBm for the NRZ data signal, and -2 dBm for the clock pulses, which indicates that the switching energy was 15 fJ/pulse. The average output power of the converted RZ signal after the Mach-Zehnder filter was -4 dBm, which indicated a 6 dB net gain after conversion, including shaping losses. This offers a significant advantage over format conversion using electro-optic modulators which suffer from both insertion loss (4 dB) and shaping losses [9].

Similarly, the BER measurements of the converted RZ signal were taken at different wavelengths of the input NRZ signal, as shown in Fig. 2*b* for a pattern length of 2^7-1. Error-free format conversions were obtained for all these cases using a differential delay of 11.5 ps. Again, improvements in receiver sensitivity of RZ pulses were observed, with penalties varying from -1.0 dB to -1.9 dB over the wavelength range studied.

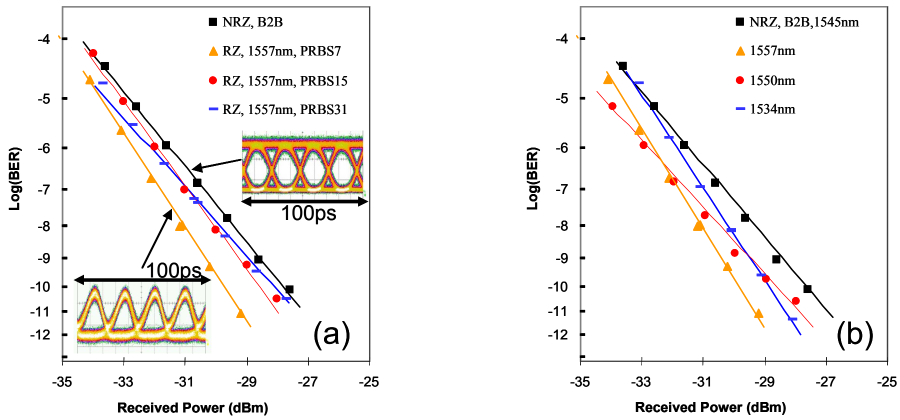

Figure 2. BER measurement of 42.6Gbit/s NRZ to RZ conversion, showing the input NRZ back-to-back (B2B) signal (black), and the output RZ signals. (a). BER measurement for various PRBS lengths of 2^7-1, 2^{15}-1 and 2^{31}-1, for a differential delay of 11.5ps and input wavelength of 1557 nm. The inserts are the corresponding eye diagrams of B2B NRZ signal and RZ signal when the PRBS length is 2^7-1. (b). BER measurement for various input NRZ wavelengths, for a differential delay of 11.5ps and a PRBS length of 2^7-1.

In Fig. 3, we show the receiver sensitivities with variable pulsewidths (duty-cycles) of the output RZ signal at 1557 nm for the 42.6 Gbit/s NRZ input data of PRBS length of 2^{31}-1, where the differential delay Δt was set at 1.9, 5.7 and 11.5 ps. For all these three output pulsewidths, we obtained negative power penalties of -1.0 dB, -0.9 dB and -0.4 dB respectively. The pulsewidth of the RZ output signals was 12 ps when $\Delta t = 11.5$ ps, as measured using an autocorrelator, assuming a square pulse shape.

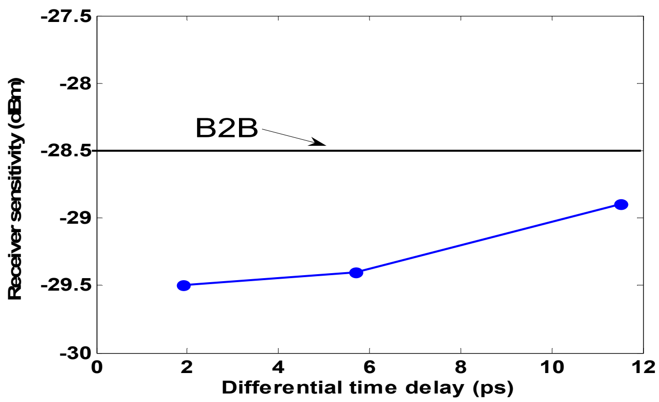

Figure 3. Receiver sensitivity of the BER measurement of 42.6 Gbit/s NRZ to RZ conversion, compared to that for a back-to-back (B2B) NRZ signal.

3.2 NRZ to RZ format conversion based on XPolM in SOA

The input beams to the SOA were a 42.6 Gbit/s PRBS length of 2^{31}-1, NRZ probe at 1557 nm, and a 42.6 GHz RZ clock pump beam, consisting of 3 ps pulses at 1545 nm. The probe and pump signals were synchronized by using an optical delay-line before they entered SOA1. To form a turbo-switch configuration, a 5 nm wide BPF was placed after SOA1 to block the pump pulses and allow only the NRZ probe to reach SOA2. Both of the SOAs used in the setup had a peak small-signal gain of 24 dB at 400 mA. Another BPF with a bandwidth of 5 nm (FWHM) was used to filter out the ASE noise from SOA2.

The average powers of the NRZ data before SOA1 and SOA2 were -7 dBm and -3 dBm respectively. The average power of the clock pulse beam was 3 dBm, corresponding to a switching energy of 50 fJ/pulse. A typical set of BER measurements is plotted in Fig. 4. Error-free operation was achieved with a PRBS length of 2^{31}-1. The 42.6 Gbit/s converted RZ and NRZ (unconverted) eye diagrams are shown in the inserts in Fig. 4. The power penalty was 3 dB at the BER of 10^{-9}, as shown in Fig. 4. No evidence for an error floor was observed down to 8×10^{-11}. The power penalty was mainly due to inter-symbol interference caused by the larger than optimum pulse-width of the converted RZ signal, which implies that the overall full recovery time of the turbo-switch by XPolM was still slightly longer than one bit period.

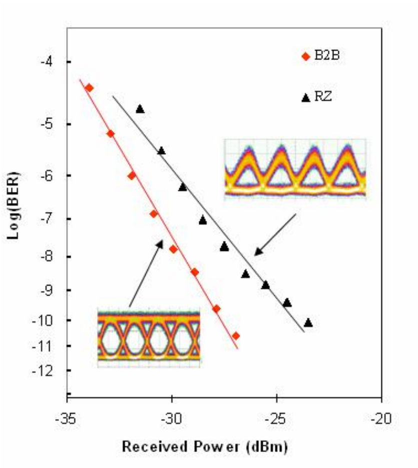

Figure 4. BER of 42.6 Gbit/s NRZ to RZ format conversion by XPolM. B2B: input NRZ signal, RZ: converted output RZ signal. The insets are the corresponding eye diagrams of NRZ and RZ signals.

4. CONCLUSIONS

We have compared two schemes to increase the effective recovery time of SOA's for clock-driven NRZ to RZ conversion. Whilst both schemes offer advantages over electro-optic modulators, such as net gain and low switching energies, we have shown that the differential XPM configuration exhibits the better performance, requiring a lower switching energy (15 fJ) and allowing pulse width tunability.

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