# All-optical 42.6 Gbit/s NRZ to RZ format conversion by cross-phase modulation in single SOA

X. Yang, A.K. Mishra, R.J. Manning, R.P. Webb and A.D. Ellis

A 42.6 Gbit/s all-optical non-return-to-zero (NRZ) to return-to-zero (RZ) format converter using a single SOA followed by an asymmetrical Mach-Zehnder interferometer is presented. The format converter generates a correctly-coded RZ signal with a controllable duty-cycle. It has the advantages of flexible input NRZ wavelength, preserved input polarity, negative bit error rate power penalty and low switching pulse energy (15fJ).

*Introduction:* Current optical telecommunications networks rely on digital electronic signal processing, leading to networks which have high power consumption, high cost and complexity in optical-to-electrical-to-optical conversion. All-optical signal processing functions, such as wavelength conversion, regeneration and logic gates, all employing semiconductor optical amplifiers (SOAs), are potential practical alternatives to electronics for certain line-rate operations in high-speed optical networks. The data format most commonly used for demonstrations of all-optical processing is return-to-zero (RZ), because bit-serial data can be easily processed in RZ format using SOAs [1]. All-optical processing is generally realised by SOA-based logic gates such as AND, XOR., etc. Since the non-return-to-zero (NRZ) data format is widely used for transmission, it is desirable to be able to convert to RZ format for the purpose of all-optical signal processing. NRZ to RZ format converters using cross-gain modulation (XGM) [2, 3] or cross-phase modulation (XPM) [4, 5] in SOAs have been reported; however, these schemes are limited to bit rates of ~10 Gbit/s. Reference [6] demonstrated the first 40 Gbit/s NRZ to RZ converter using an SOA-based Mach-Zehnder delayed interferometer; however, it required a complex pre-coder because the converted RZ signal was a modified duo-binary signal or alternate mark inversion signal. We demonstrated another 40 Gbit/s all-optical NRZ to RZ format converter by cross-polarisation modulation incorporating an SOA-based turbo-switch as the switching element [7], which was the first to produce a correctly-coded 40 Gbit/s RZ signal without the need for a pre-coder. However, the pulse width of the RZ signal was not controllable.

In this Letter, we demonstrate, for the first time to our knowledge, a 42.6 Gbit/s all-optical NRZ to RZ converter using XPM in a single SOA. Compared with the 42.6 Gbit/s format conversion used in [7], this scheme gives us the advantages of flexible pulse width of the RZ output data (variable duty-cycle), absence of patterning effects (making higher bit-rate operation possible), negative power penalties in the bit error rate (BER) measurement and 6 dB net gain after the conversion. The converter employs a single SOA followed by an asymmetric Mach-Zehnder filter. The converted output is an RZ signal with the flexibility of input data wavelength, polarity preserved, and no requirement for a pre-coder as used in [6]. Moreover, the converter requires a low signal input pulse energy (15fJ).

*Operation principle:* We use the delay-interferometer-signal wavelength conversion (DISC) configuration, in which an SOA is placed in front of an asymmetrical Mach-Zehnder filter [1]. The Mach-Zehnder filter was realised using a piece of polarisation-maintaining (PM) fibre with a time-of-flight delay $\Delta t$ between its fast and slow axes, this delay being dependent on the PM fibre length. The inputs to the SOA are an RZ clock-pulse stream (pump) and, at a lower power, the NRZ input data (probe), which were synchronised by using an optical delay-line. The pump clock pulses introduce periodic phase shifts to the following NRZ data via XPM in the SOA. This phase modulation is converted into amplitude modulation in the Mach-Zehnder filter, which results in an RZ output signal with a controllable pulsewidth (duty-cycle) determined mainly by the offset delay ($\Delta t$) of the Mach-Zehnder filter. The difference between this approach and DISC-based wavelength conversion is that in this setup the CW probe beam is replaced by the NRZ data beam. 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 pulse width of $\Delta t$ is obtained at the output port. Because the Mach-Zehnder interferometer responds to the phase difference between the probe and the delayed probe, the effective response time of the converter is much shorter than the SOA recovery time, which enables the device to operate at 40 Gbit/s [6]. Since the XPM is dominated by the stronger clock signal, which is always present in every bit period, this leads to the absence of patterning effects that result from the SOA recovery time when the SOA is switched by a data signal. Thus, this approach also should allow the device to be operated at even higher bit-rates beyond 40 Gbit/s.

*Experimental setup and results:* The schematic experimental setup is shown in Fig. 1. 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 3ps (full width at half maximum (FWHM)) pulses at 1545 nm. The input data sequences were programmed with pseudorandom binary sequences (PRBS) of lengths $2^7-1$ to $2^{31}-1$. A wide bandpass 5 nm (FWHM) filter was placed after the SOA which blocked the pump pulse and allowed only the NRZ data to pass through. A piece of PM fibre with a differential delay $\Delta t$ was used along with two polarisation controllers and a polariser to form an asymmetrical Mach-Zehnder interferometer. The differential delay $\Delta t$ was variable in order to characterise the device at different output duty-cycles.

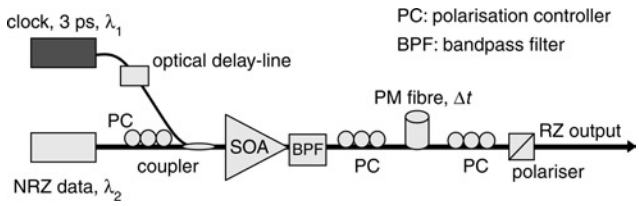


**Fig. 1** *Experimental setup of NRZ to RZ format conversion*

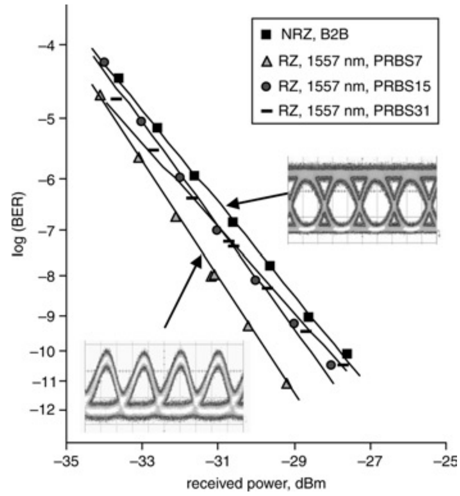


**Fig. 2** *BER measurement of 42.6 Gbit/s NRZ to RZ conversion, showing receiver sensitivity of RZ signal against PRBS lengths of $2^7-1$, $2^{15}-1$, $2^{31}-1$, for differential delay of 11.5 ps and input wavelength of 1557 nm*

Insets: Corresponding eye diagrams of back-to-back (B2B) NRZ signal and output RZ signal, PRBS length $2^7-1$

The receiver comprised a dual-stage preamplifier, incorporating a 5 nm filter to suppress amplified spontaneous emission (ASE) while passing the RZ signal spectrum. A typical set of bit error rate (BER) measurements is plotted in Fig. 2. These measurements were taken for a differential delay $\Delta t$ of 11.5 ps. Error-free operation was achieved for all pattern lengths used. Eye diagrams of the 42.6 Gbit/s RZ (converted) and NRZ (unconverted) signals for a PRBS length of $2^7-1$ are shown in the insets in Fig. 2. The power penalties were −1.9, −0.6 and −0.4 dB, corresponding to the pattern lengths of $2^7-1$, $2^{15}-1$ and $2^{31}-1$, respectively, while the pattern length of the back-to-back (B2B) 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 15fJ/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 [8].

Similarly, the BER measurements of the converted RZ signal were taken at different wavelengths of the input NRZ signal, as shown in Fig. 3 for a pattern length of $2^7-1$. Error-free format conversion was realised for each wavelength using a differential delay of 11.5 ps. Again, improvements in receiver sensitivity of RZ pulses were observed, with penalties varying from −1.0 to −1.9 dB over the wavelength range studied.

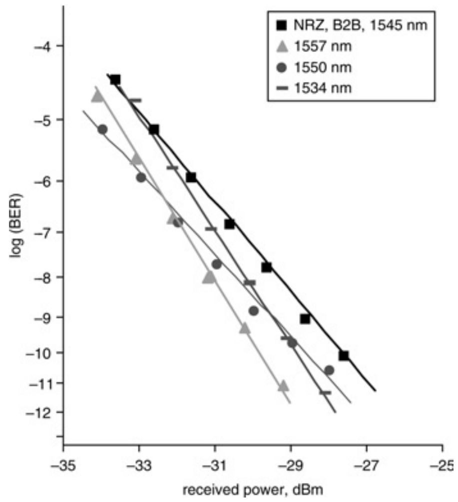


**Fig. 3** *BER measurement of 42.6 Gbit/s NRZ to RZ conversion, showing receiver sensitivity at various input NRZ wavelengths, for differential delay of 11.5 ps and PRBS length of* $2^7-1$

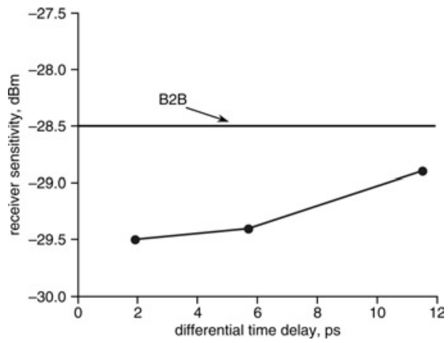


**Fig. 4** *Receiver sensitivity of BER measurement of 42.6 Gbit/s NRZ to RZ conversion for various differential delays, compared to that for back-to-back (B2B) NRZ signal*

Fig. 4 shows 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 $\Delta t$ was set at 1.9, 5.7 and 11.5 ps. For these three output pulsewidths, we obtained negative power penalties of −1.0, −0.9 and −0.4 dB, respectively. The pulse width of the RZ output depends mainly on the applied differential delay, with a lower limit set by the clock pulse width. The pulse width of the RZ output signals was 12 ps when $\Delta t = 11.5$ ps, as measured using an autocorrelator, assuming a square pulse shape after the Mach-Zehnder filter.

*Conclusions:* We have demonstrated error-free 42.6 Gbit/s all-optical NRZ to RZ format conversion using a single SOA followed by an asymmetrical Mach-Zehnder interferometer. This format conversion scheme is insensitive both to the wavelength and to the PRBS length of NRZ input signal. The output converted RZ signal has the flexibility of variable pulse widths (duty-cycles) depending on the applied differential delay and can offer up to 6 dB net gain in average power. In addition, this scheme also exhibited negative BER power penalties referred to the NRZ input data and requires a low switching energy of 15fJ/pulse.

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