# All-optical 40 Gbit/s NRZ to RZ format conversion by nonlinear polarisation rotation in SOAs

X. Yang, A.K. Mishra, R.J. Manning and R. Giller

Error-free all-optical 40 Gbit/s non-return-to-zero (NRZ) to return-to-zero (RZ) format conversion using nonlinear polarisation rotation in semiconductor optical amplifiers (SOAs) is demonstrated. The high bit rate operation of the devices is achieved by incorporating an SOA-based turbo-switch.

*Introduction:* The high-speed all-optical switch is expected to become a key technique in high bit rate optical time division multiplexed (OTDM) communication networks [1]. Among the various methods available, the techniques using the nonlinear behaviour of semiconductor optical amplifiers (SOAs) are attractive because of the SOA characteristics of high gain, low switching power, wide gain bandwidth, small footprint and the potential for integration with other photonic devices. However, SOA-based switches suffer from the patterning effect associated with the slow full carrier recovery time, which is of the order of 100 ps. This, in principle, should limit the operation speed to <10 Gbit/s. However, interferometric schemes incorporating SOAs and using differential switching have enabled much faster rates. In addition to cross-gain (XGM) and cross-phase modulation (XPM) in an SOA, devices based on cross-polarisation modulation (XPolM) are attractive because of their much simpler structure [2]. XPolM does not lend itself so readily to differential switching, and has hitherto been limited to maximum rates of ~10 Gbit/s. However, a 40 Gbit/s wavelength converter by XPolM was demonstrated in non-return-to-zero (NRZ) format with a fast SOA [2]. The authors demonstrated the first 40 Gbit/s wavelength converter by XPolM in return-to-zero (RZ) format by an SOA-based turbo-switch [3].

Apart from wavelength conversion, another particularly useful application of the all-optical switch, which facilitates transparent interfacing between different sectors of the network, is format conversion between NRZ to RZ. It is also desirable to convert NRZ data to RZ format for the purpose of all-optical signal processing using SOAs. Such NRZ to RZ format conversions using XGM [4] or XPM [5, 6] in SOAs have been reported, however these schemes are limited to bit rates of ~10 Gbit/s. Reference [7] demonstrated a 40 Gbit/s NRZ to RZ conversion approach using an SOA-based Mach-Zehnder delay interferometer, however it required a complex pro-coder because the converted RZ signal was a modified duo-binary signal or alternate mark inversion (AMI) signal.

In this Letter, we demonstrate for the first time a 42.6 Gbit/s all-optical NRZ to RZ format conversion by XPolM incorporating an SOA-based turbo-switch. The fourfold increase in operating speed of the format converter is achieved with a turbo-switch configuration which cancels the patterning effects associated with the SOA slow carrier recovery dynamics [1]. The format conversion at 42.6 Gbit/s was shown to operate at low pulse switching energy (100 fJ) and with good extinction ratio (>12 dB). Furthermore, the output is a correctly coded sequence of RZ signal with the input data wavelength and polarity preserved, and so there is no requirement for a pro-coder.

*Operation principles:* The switch structure of an XpolM format converter using an SOA as the nonlinear element is shown in Fig. 1. In the case of the wavelength converter [3], both continuous-wave (CW) and data-modulated control pulse beams are injected into the SOA, as shown in Fig. 2. The CW beam decomposes equally into transverse electric (TE) and transverse magnetic (TM) polarised components which recombine coherently at the polariser. The polarisation controller (PC) after the SOA is adjusted to minimise the output after the polariser, in the absence of the control pulse (OFF state). When a control data pulse is present in the SOA, it induces polarisation-dependent refractive index changes in the active layer owing to carrier depletion, which result in differing phase-shifts for the TE and TM components of the CW beam. The two components therefore acquire a net phase difference, which causes a rotation of the resultant polarisation, and an increase in the output after the polariser (ON state).

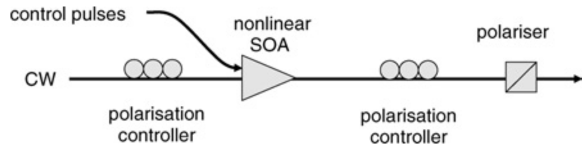


**Fig. 1** *Schematic of all-optical switch using nonlinear polarisation rotation in SOA*

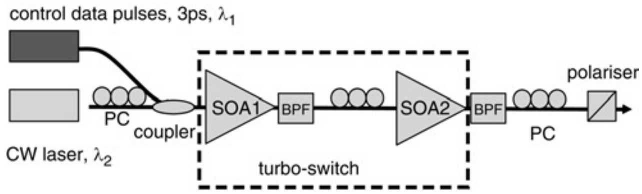


**Fig. 2** *Experimental setup of 40 Gbit/s wavelength converter using polarisation rotation*

PC: polarisation controller; BPF: bandpass filter

The modifications of the format conversion from wavelength conversion [3] are as follows. The CW probe beam was replaced by the NRZ data, while the pump pulses were replaced by RZ clock pump pulses. In this way, the inputs to the SOA are replaced by strong clock pulses (pump) and an NRZ input data (probe). 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. Thus, if the input of NRZ data 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. The NRZ and clock signals have to be synchronised using an optical delay-line.

To increase the effective switching speed beyond 10 Gbit/s, we adopted a turbo-switch configuration [1], which we used in place of the single SOA in Fig. 1. The turbo-switch consists of a pair of SOAs separated by a wide bandpass filter (BPF), which prevents the control pulses from entering the second SOA. As a switch, it has been shown to operate error free at 170.4 Gbit/s [1]. As well as the enhancement of the high-speed response of the constituent SOAs, its excellent performance is in part explained by the presence of a large overshoot in the gain response of the device. This offsets the saturating effect of successive high-power control pulses, thus helping to ameliorate nonlinear patterning effects. As evidence of the fast response of a turbo-switch, the probe beam responses to a single control pulse shot after a single SOA and after the turbo-switch were measured and plotted (see Fig. 3) using time-resolved spectroscopy [8]. These two curves were measured directly after the filters following the SOA1 and SOA2 in the setup of Fig. 2. They show that the full recovery time is ~70 ps for the single SOA switch, and ~15 ps for the turbo-switch.

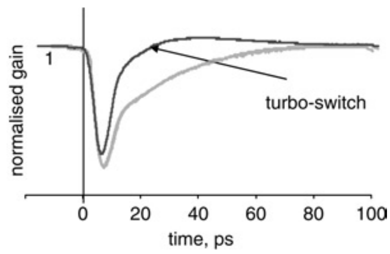


**Fig. 3** *Normalised gain measurement of CW beam modulated by one single 3ps control pulse shot*

The two curves compare responses of single SOA and of turbo-switch

*NRZ to RZ format conversion:* The schematic experimental setup is shown in Fig. 4. The input beams to the SOA were a 42.6 Gbit/s pseudorandom bit sequence (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 synchronised using an optical delay-line before they enter into SOA1. A 5 nm-wide BPF was placed after SOA1 which blocked the pump pulses and allowed only the NRZ probe to pass through SOA2, which forms a turbo-switch configuration. Both of the SOAs (Kamelian) used in the setup had a small-signal gain of 32 dB at 400 mA. Another BPF with a bandwidth of 5 nm (FWHM) was used after SOA2 to filter out the amplified spontaneous emission (ASE) noise.

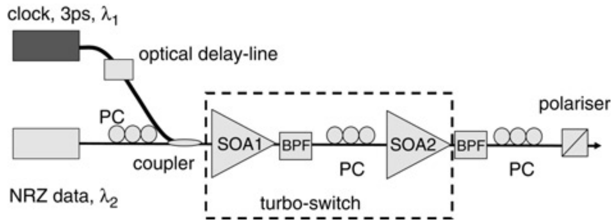


**Fig. 4** *Experimental setup of NRZ to RZ format conversion*
PC: polarisation controller; BPF: bandpass filter

The RZ output of the format converter was detected by a receiver with a dual-stage preamplifier, incorporating a 5 nm filter to suppress ASE while passing the RZ signal spectrum. The average powers of the NRZ data before SOA1 and SOA2 were −7 and −3 dBm respectively. The average power of the clock pulse beam was 3 dBm, corresponding to a switching energy of 100fJ/pulse.

A typical set of BER measurements is plotted in Fig. 5. 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 plotted as the insets in Fig. 5. The power penalty was 3 dB at the BER of $10^{-9}$, as shown in Fig. 5. No evidence for an error floor was observed down to $8\times10^{-11}$. The extinction ratio of the format converted signal was measured more than 12 dB. The power penalty was mainly due to intersymbol interference caused by the larger than ideal pulse-width of the converted RZ signal.

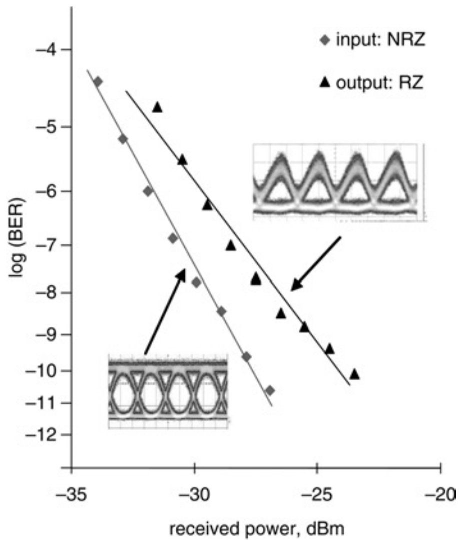


**Fig. 5** *BER of 42.6 Gbit/s NRZ to RZ format conversion by XPolM*
NRZ: input NRZ signal; RZ: converted output RZ signal
Insets: Corresponding eye diagrams of NRZ and RZ signals

*Conclusions:* We have demonstrated for the first time both error-free 42.6 Gbit/s all-optical NRZ to RZ format conversion, based on XpolM in SOAs using the turbo-switch approach. For the 42.6 Gbit/s format conversion, the correctly coded RZ sequence was generated from the NRZ input. An advantage of the XpolM scheme is that it requires very low switching pulse energy, which was in the order of 100fJ.

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