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Abstract: We report the first demonstration of polarisation insensitive all-optical wavelength conversion (AOWC) for single wavelength channel 640 Gbit/s return-to-zero differential-phase-shift-keying (RZ-DPSK) signal and 1.28 Tbit/s polarisation multiplexed (Pol-Mux) RZ-DPSK signals using a 100-m polarisation-maintaining highly nonlinear fiber (PM-HNLF) in a polarisation diversity loop configuration. The AOWC is based on four-wave mixing in PM-HNLF. Error free performance is achieved for the wavelength converted signals. Less than 0.5 dB polarisation sensitivity is obtained.

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1. Introduction

The concept of 1 Tbit/s Ethernet envisioned to carry the future Internet traffic has been proposed recently [1], spurred on by the continuous growth of the Internet. With the introduction of the 1 Tbit/s Ethernet, all the network techniques such as switching and routing on such high bit rates become quite challenging. Currently, the 107 Gbit/s electronic signal processing technique based on electrical time division multiplexing (ETDM) is state-of-the-art [2], and it will be very difficult to realize electronic signal processing approaching 1 Tbit/s in the near future. On the other hand, all-optical signal processing techniques based on optical time division multiplexing (OTDM) have shown the potential for high-speed signal processing on 640 Gbit/s and beyond [3–6].

Wavelength conversion is a key network functionality in future high-speed optical network, which can resolve the packet contention by transmitting at an alternate wavelength through the same route, resulting in identical latency and packet sequence. A number of wavelength conversion technologies have been proposed, and among them all-optical wavelength conversion (AOWC) offers advantages over optical-electrical-optical (O/E/O) schemes such as high signal bandwidth (far beyond 100 Gbit/s), potential low power consumption, simultaneous conversion of several WDM or TDM channels as well as transparency to data rate and modulation format.

AOWC has been demonstrated using different nonlinear media such as semiconductor optical amplifiers (SOA), periodically poled Lithium Niobate (PPLN) waveguides, or highly nonlinear fibers (HNLF). The AOWC using a SOA has been demonstrated up to 320 Gbit/s, based on a filtered cross phase modulation (XPM) induced chirp [7]. The AOWC using PPLN waveguides has been demonstrated up to 320 Gbit/s based on either cascaded second harmonic and difference frequency generation (cSHG/DFG) [8] or cascaded sum frequency generation (SFG) and DFG [9]. AOWC using a HNLF has been shown to work at 640 Gbit/s and 1.28 Tbit/s, either using filtered XPM-induced chirp [10] or four wave mixing (FWM) [11–13].

Polarisation insensitivity is also an important feature for AOWC in system applications. Although most of the nonlinear media are inherently polarisation dependent, polarisation insensitive AOWC can be achieved with polarisation diversity operation. Most recently, polarisation insensitive 320 Gbit/s AOWC based on a Ti:PPLN waveguide has been demonstrated using the polarisation diversity scheme [8].

In this paper, we report the first demonstration of polarisation insensitive AOWC for a 640 Gbit/s return-to-zero differential-phase-shift-keying (RZ-DPSK) signal and a 1.28 Tbit/s polarisation multiplexed (Pol-Mux) RZ-DPSK signal, using a 100-m polarisation-maintaining HNLF (PM-HNLF) in a polarisation diversity loop configuration. The AOWC is based on FWM in PM-HNLF. Error free performance is achieved for the wavelength converted signals. Less than 0.5 dB polarisation sensitivity is also obtained. To the best of our knowledge, this is the highest operation speed of a polarisation insensitive wavelength converter reported to date.
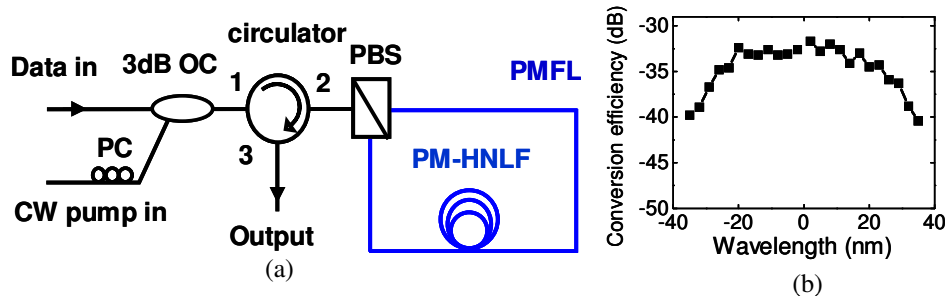
2. Operation principle

Fig. 1. (a) Polarisation-maintaining fibre loop (blue lines indicate the PMF), (b) FWM conversion efficiency dependence on wavelength detuning

A polarisation-maintaining fibre loop (PMFL) with bi-directional operation is used for the polarisation insensitive AOWC, as shown in Fig. 1(a). The loop provides a polarisation diversity scheme with loop configuration [8], and it consists of a PM-HNLF, a polarisation beam splitter (PBS), a circulator and a coupler. A data signal and a continuous wave (CW) pump are coupled together and launched into the PBS through a 3-dB optical coupler (OC) and a circulator. In the PMFL, the data signal is split into two components that counter-propagate through the fibre loop and together with the wavelength converted signal are recombined by the PBS and sent out at port 3 of the circulator. The pump polarisation state is adjusted and launched into the PBS with equal intensity in both directions of the loop; therefore, the FWM conversion efficiencies (proportional to the square of the pump intensity) of both directions are the same. When the pump wavelength is set at 1545 nm, the FWM conversion efficiencies (defined as the ratio between the FWM product power and the power of the original data signal measured at the output of the circulator, not including the 4.5-dB passive losses of the PMFL) under CW characterization show a 50-nm conversion bandwidth [Fig. 1(b)], covering the entire C-band.
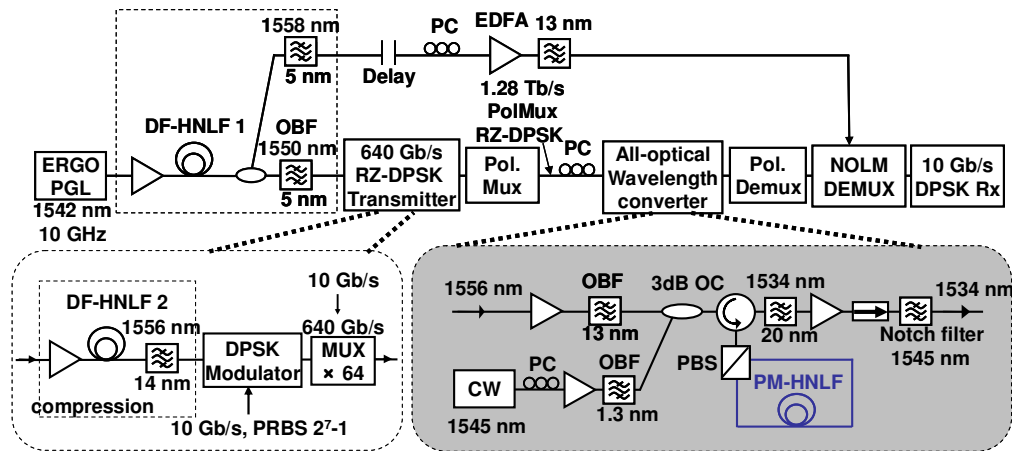
3. Experimental setup and results

Fig. 2. Experimental setup for the polarisation insensitive AOWC of a 640 Gbit/s RZ-DPSK signal (without Pol. Mux and Pol. Demux) or a 1.28 Tbit/s Pol-Mux RZ-DPSK signal

The experimental setup for the polarisation insensitive AOWC of a 640 Gbit/s RZ-DPSK signal or a 1.28 Tbit/s Pol-Mux RZ-DPSK signal is shown in Fig. 2. It mainly includes a 640 Gbit/s or 1.28 Tbit/s OTDM transmitter, an all-optical wavelength converter, a non-linear optical loop mirror (NOLM) demultiplexer and a 10 Gbit/s DPSK receiver. The erbium glass oscillating pulse-generating laser (ERGO-PGL) produces 10 GHz pulses at 1542 nm with a 1.5-ps full-width at half-maximum (FWHM) pulse width. The spectrum of the pulses is broadened in the 400-m dispersion-flattened highly nonlinear fibre DF-HNLF 1 (dispersion coefficient D = −0.45 ps/nm/km and dispersion slope S = 0.006 ps/nm^2/km at 1550 nm, nonlinear coefficient γ = 10.5 W^{-1}km^{-1}) due to self-phase modulation (SPM). The broadened spectrum is filtered at 1550 nm with a 5-nm optical bandpass filter (OBF) to generate the 10 GHz pulses for data signal and is also filtered at 1558 nm using another 5-nm OBF to obtain the 10 GHz control pulses for the NOLM demultiplexer. The 10 GHz pulses at 1550 nm are further compressed and regenerated in the 100-m DF-HNLF 2 (D = −1.07 ps/nm/km and S = 0.004 ps/nm^2/km at 1560 nm, γ = 10.5 W^{-1}km^{-1}) based on SPM, and subsequent offset filtering with a 14 nm BPF at 1556 nm. The compressed pulses are then encoded by DPSK with a 10 Gbit/s PRBS (2^7-1) signal in a Mach-Zehnder modulator. The modulated 10 Gbit/s DPSK signal is multiplexed in time using a passive fibre-delay multiplexer (MUX × 64) to generate the 640 Gbit/s RZ-DPSK signal. The multiplexers used in the experiment are PRBS

(2^7-1) maintaining and polarisation maintaining. The FWHM of the data and DEMUX control pulses are 560 fs and 920 fs, respectively. For the generation of a single wavelength 1.28 Tbit/s Pol-Mux RZ-DPSK signal, the 640 Gbit/s DPSK signals are polarisation-multiplexed using a polarisation-maintaining 3-dB coupler and a polarisation beam combiner.

In the AOWC the generated 640 Gbit/s RZ-DPSK signal or the 1.28 Tbit/s Pol-Mux RZ-DPSK signal is amplified by an EDFA, then filtered by a 13 nm OBF and finally launched into the PMFL through a 3 dB optical coupler (OC). The average signal power is 22.9 dBm at the input of the circulator. The CW pump light at 1545 nm is amplified by an EDFA, filtered by a 1.3 nm OBF and launched into the PMFL through the second input of the 3 dB coupler. The pump power is 21.8 dBm at the input of circulator. The pump polarisation is adjusted for equal power in both directions of the loop; therefore, the pump power at the input of the PM-HNLF for each direction is only 18 dBm which is below the Stimulated Brillouin Scattering (SBS) threshold of 21 dBm. The wavelength converted signal together with the original signal and the CW pump are sent out at port 3 of the circulator and then launched into a filter subsystem, which consisted of a 20-nm OBF, a fiber Bragg grating (FBG) based notch filter and an EDFA in between. The notch filter is used to block the pump light, and the OBF is used to separate the converted signal at 1534 nm from the original data signal.

The wavelength converted 640 Gbit/s RZ-DPSK signal or 1.28 Tbit/s Pol-Mux RZ-DPSK signal is detected by the receiver which consists of a polarisation demultiplexer (Pol. Demux), a NOLM demultiplexer and a 10 Gbit/s DPSK receiver. The 1.28 Tbit/s Pol-Mux RZ-DPSK signal is separated by the Pol. Demux (polarisation beam splitter) into two 640 Gbit/s polarisation components (TM mode and TE mode). The following NOLM is then used to OTDM demultiplex the single polarisation 640 Gbit/s data down to a 10 Gbit/s data signal. The NOLM operation is based on cross-phase modulation (XPM) in a 15-m HNLF. Finally, the demultiplexed 10 Gbit/s RZ-DPSK signal is demodulated and detected using a delay interferometer and a balanced photodetector in the 10 Gbit/s DPSK receiver.
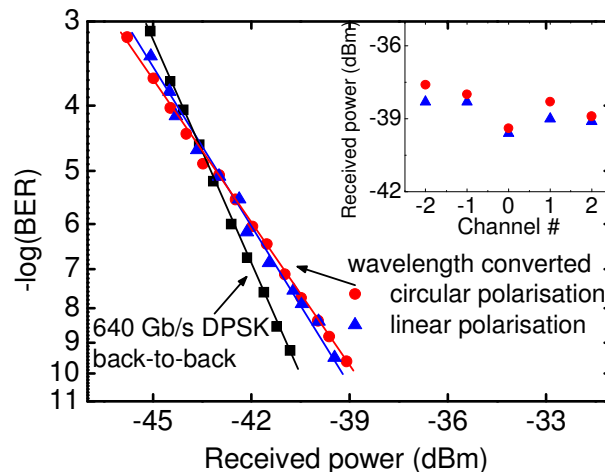

Fig. 3. BER measurements for the 640 Gbit/s RZ-DPSK signal back-to-back, and for the wavelength converted 640 Gbit/s RZ-DPSK signal with input SOP being circular polarisation or linear polarisation.

The AOWC for the 640 Gbit/s RZ-DPSK signal is obtained by skipping the Pol. Mux and Pol. Demux stages. The state of polarisation (SOP) of the 640 Gbit/s RZ-DPSK signal is monitored by a polarisation analyzer at the input of the AOWC. Figure 3 shows the results of the bit error rate (BER) measurements for the 10 Gbit/s DPSK channels demultiplexed from the wavelength converted 640 Gbit/s RZ-DPSK signals with input SOP being circular polarisation or 90° linear polarisation, together with the 640 Gbit/s RZ-DPSK back-to-back case. The AOWC causes about 1.5-dB power penalty at the BER of 10^{-9} compared with the

back-to-back case, which is mainly due to the different receiver sensitivities at 1534 nm and 1556 nm. The different slopes of the two BER curves also mainly come from the wavelength difference. In order to demonstrate the polarisation insensitive characteristics of the AOWC, we vary the SOP at the input of the AOWC and observed the BER performance for the different input SOPs. The results indicate that for the input SOP being circular or linear the difference in the receiver sensitivity is almost negligible (less than 0.5 dB). The inset shows the receiver sensitivity at BER of 10^{-9} for five adjacent channels with circular or linear polarisation. Error free performance is achieved for all the channels with a spread of ~2 dB. To characterize the residual polarisation sensitivity, we measured the power of the wavelength converted signal versus time (1 s) while scrambling the polarisation in front of the AOWC with a scan rate of 5 Hz. The maximum fluctuations for both single polarisation 640 Gbit/s signal [Fig. 4 (a)] and Pol. Mux 1.28 Tbit/s signal [Fig. 4 (b)] are less than 0.5 dB.
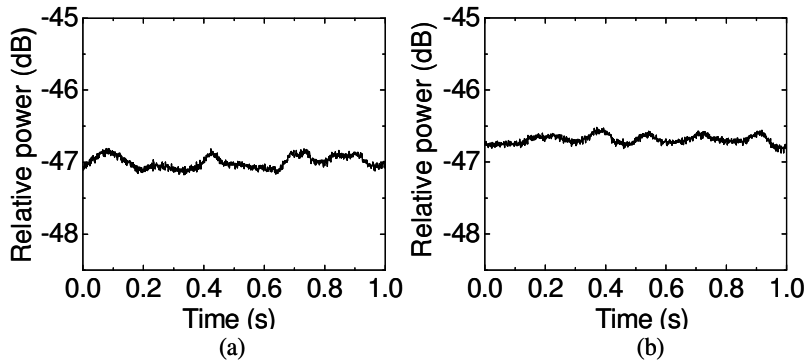

Fig. 4. (a) and (b): Power fluctuations of the wavelength converted single polarisation 640 Gbit/s signal and the Pol. Mux 1.28 Tbit/s signal with polarisation scrambling.
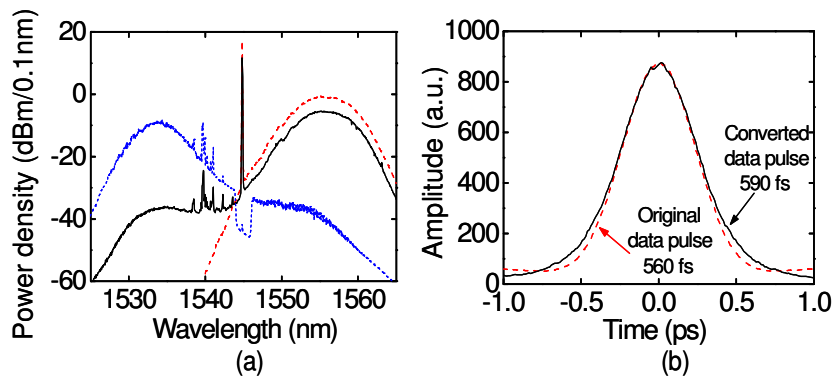

Fig. 5. (a) Spectra at input (red dash) and output (black solid) of the PMFL, and the wavelength converted 1.28 Tbit/s Pol-Mux RZ-DPSK signal (blue short dash); (b) Autocorrelations of original data pulse (dashed) and converted data pulse (solid line).

In the experiment with the 1.28 Tbit/s AOWC, the spectrum at the input and output of the PMFL is shown in Fig. 5(a). The FWM conversion efficiency is –31 dB and it could be improved by using higher CW pump power. If the pump power is higher than SBS threshold, a simple scheme with phase modulation of the pump can suppress the SBS but will also distort the phase of the wavelength converted signal. In this case, an advanced phase modulation scheme might be necessary. The spectrum of the wavelength converted 1.28-Tbit/s Pol-Mux RZ-DPSK signal is also shown in Fig. 5(a). The residual peaks are due to the XPM on the CW pump from the original data signal. The autocorrelation traces of the original data pulse and the wavelength converted data pulse are shown in Fig. 5(b). Compared with

original data pulse (FWHM of 560 fs) the wavelength converted data pulse is slightly broadened to a FWHM of 590 fs, which is mainly due to filtering effect in the filter subsystem. The BER measurements are shown in Fig. 6(a) as a function of the received power. BER curves are plotted for the 10 Gbit/s DPSK channels demultiplexed from the 1.28 Tbit/s Pol-Mux RZ-DPSK signals back to back (TM and TE), and the converted 1.28 Tbit/s Pol-Mux RZ-DPSK signals (TM and TE). The wavelength conversion causes about 1 dB power penalty at the BER of 10^{-9} compared with the back to back case (unconverted signal). The inset shows the receiver sensitivity at BER of 10^{-9} for five adjacent channels. Error free performance is achieved for all the channels (TM and TE) with a spread of ~3 dB. The 10 Gbit/s eye-diagrams of the converted, demultiplexed and demodulated signals in TM and TE polarisation are shown in Fig. 6(b). The eye-diagrams indicate that the wavelength converted signals of TM and TE have almost identical performance.
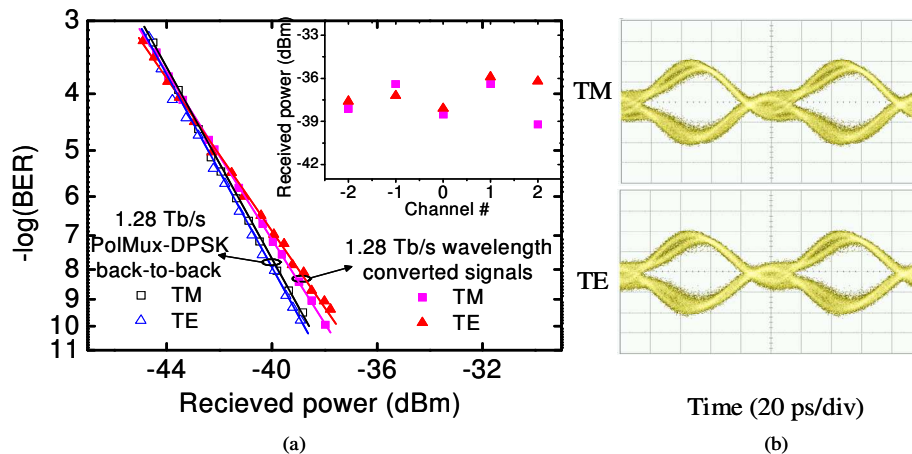

(a)   (b)

Fig. 6. (a) BER measurements for the 10 Gbit/s DPSK channels demultiplexed from the 1.28-Tbit/s Pol-Mux RZ-DPSK signals back to back, and the wavelength converted 1.28-Tbit/s Pol-Mux RZ-DPSK signals (TM and TE). (b) 10 Gbit/s eye-diagrams of the converted, demultiplexed and demodulated signals in TM and TE polarisation.

4. Conclusion

We have demonstrated polarisation insensitive wavelength conversion for a single wavelength channel 640 Gbit/s RZ-DPSK signal and a 1.28 Tbit/s Pol-Mux RZ-DPSK signal using a 100-m PM-HNLF in a polarisation diversity scheme. Less than 0.5 dB polarisation sensitivity is obtained. Error free operations for both the wavelength converted 640 Gbit/s RZ-DPSK signal and the wavelength converted 1.28 Tbit/s Pol-Mux RZ-DPSK signal are achieved. We also investigated the characteristics of the polarisation insensitive AOWC. The results show that a FWM conversion efficiency of –31 dB is obtained with a CW pump power of 18 dBm and the 3-dB conversion bandwidth is 50 nm. The BER measurements and eye-diagrams show that the TM and TE polarisations of the wavelength converted 1.28 Tbit/s Pol-Mux RZ-DPSK signal have almost identical performance.

Acknowledgments