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160-Gb/s Polarization-Insensitive Demultiplexer Based on a Fiber-Optical Parametric Amplifier

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Abstract—We report the experimental demonstration of a 160-Gb/s polarization-insensitive demultiplexer based on a pulsed-pump fiber-optical parametric amplifier. Switching window and 12-dB conversion gain are measured with polarization scrambled signal. No more than 1.5-dB power penalty is achieved for 16 demultiplexed 10-Gb/s tributaries.

Index Terms—Demultiplexing, optical parametric amplifiers (OPAs), polarization diversity.

I. INTRODUCTION

W

ITH increasing information capacity demand, all-optical signal processing techniques are promising core solutions for future high-speed optical communication networks. All-optical demultiplexing utilizing optical fiber [1]–[4] in time-division multiplexing (OTDM) is attractive compared with the approaches of using semiconductor optical amplifiers (SOAs) [5] and electroabsorption modulators (EAMs) [6] which are dependent on electric bandwidth. The advantage of using optical fiber is its inherent femtosecond response time, governed by the $\chi^{(3)}$ nonlinear susceptibility of an optical fiber [7]. Recently, several demonstrations of 160-Gb/s or higher bit-rate demultiplexing based on four wave mixing (FWM) in highly-nonlinear fiber (HNLF) have been reported. Polarization-insensitive demultiplexer using FWM was demonstrated with $\sim$6-dB conversion efficiency [3], but compensation for the low efficiency is required to expand transmission length. Fiber optical parametric amplifiers (FOPAs) are of particular interest owing to their high conversion efficiency [8], 40-Gb/s demultiplexing using a 10-GHz sinusoidal pump [4], and 160-Gb/s demultiplexing using a pulsed pump [9] have been demonstrated with parametric gain. However, the two schemes are not practical as they require accurate control of the states of polarization (SOP) of signal.

In this letter, to take advantage of high efficiency of FOPA and polarization diversity technology, we further improve our previous scheme [9] for polarization-insensitive operation [10]. This approach can overcome subtle alignment of the SOP of the signal. The polarization scrambled signal is used to quantify the performance of the polarization-insensitive demultiplexer. No more than 1.5-dB power penalties are observed for the sixteen 10-Gb/s tributaries demultiplexed from the 160-Gb/s input data; while the conversion gains are stable even if the SOP of signal fluctuates.

II. OPERATING PRINCIPLE

The polarization-insensitive demultiplexer is based on the polarization-diversity technique described in Fig. 1 [9]. Different from conventional FOPA configuration, polarization-diversity FOPA is constructed by a fiber loop which consists of a polarizing beam splitter (PBS), a polarization controller (PC2), and a spool of highly-nonlinear dispersion-shifted fiber (HNLF-DSF). By adjusting PC1, the pump is linearly polarized and launched at 45$^\circ$ with respect to the axis of the PBS. Then the pump is divided into two orthogonal components with identical power and out of port1 ($P_1$) and port2 ($P_2$). $P_1$ travels in the clockwise direction, while $P_2$ travels in the opposite direction. Likewise, the signal is also split into two orthogonal components $S_1$ and $S_2$, regardless of its SOP. PC2 is used to maintain the original SOPs of $P_1$, $P_2$, $S_1$, and $S_2$ along the fiber loop. After exiting at port $R$, the four components combine and construct the pump and signal again. In this circumstance, $S_1$ and $S_2$ experience the same parametric gain dependent only on pump power, while $P_1$ and $P_2$ are identical. The total signal output power is independent on the signal input power distribution in the two orthogonal polarizations. This means the signal can obtain the same gain regardless of its SOP. Therefore, a polarization-insensitive demultiplexer can be realized.

III. EXPERIMENT

The experimental setup is shown in Fig. 2. Fig. 2(a) shows the pump branch. A 10-GHz pulsed pump with 2-ps pulsewidth at 1558.0 nm generated by a mode-locked laser diode (MLLD) was amplified by two stage erbium-doped fiber amplifiers.
Two 1.0-nm bandwidth tunable bandpass filters (TBPF1 and TBPF2) were used to suppress amplified spontaneous emission (ASE) noise from EDFAs. In the Fig. 2(b), the input 160-Gb/s OTDM signal branch was generated by time-multiplexing an intensity-modulated 2-ps 10-GHz pulse train from a mode-locked fiber laser (MLFL) with a Mach–Zehnder modulator which was driven by a 10-Gb/s 2^7 - 1 pseudorandom binary sequence (PRBS). EDFA3 was used before the bit-rate multiplier to compensate for its loss. This 160-Gb/s signal was then amplified by EDFA4. Channel selection was carried out by aligning the pulsed pump with the bit slot of the target channel using an optical delay line (ODL). The pump and the 160-Gb/s signal were then combined by a 90/10 coupler and launched 10% of the signal and 90% of the pump into the fiber loop shown in Fig. 2(c). This loop was made up of a PBS, PC7 and a 150-m spool of HNL-DSF with nonlinearity coefficient $\gamma \approx 30 \text{W}^{-1}\text{km}^{-1}$, zero-dispersion wavelength $\lambda_0 \approx 1554$ nm and dispersion slope $dD/d\lambda = 0.03 \text{ps/nm}^2\text{km}$. Note that both the pump and signal were coupled into the loop by port 1 and extracted from port $R$. The clockwise (from port 1 to 2) and counterclockwise (from port 2 to 1) pump power were set to be equal by adjusting PC4. Polarization scrambler (PS) on signal branch scrambled the SOP of signal and was used to test the performance dependent on the signal SOP. After wavelength conversion, the original 160-Gb/s signal and the demultiplexed 10-Gb/s idler were filtered using a variable-bandwidth tunable filter, TBPF3. The output from TBPF3 was monitored by the digital communication analyzer (DCA) or optical sampling oscilloscope (OSO) for the waveform, and by the bit-error rate tester (BERT) for the BER measurement.

Fig. 3(a) shows the 10-GHz pump pulse. Its pulse width was broadened to 3.5 ps by TBPF1 and TBPF2. The pulse width of the 160-Gb/s signal was measured to be 2.2 ps, as shown in Fig. 3(b). Fig. 3(c) shows the demultiplexed 10-Gb/s idler after the OPA. A clear and wide-open eye diagram was obtained. The broadened pulse width observed in the demultiplexed signal was mainly due to the limited bandwidth (30 GHz) of the photo-detector (the idler wavelength was out of the range of our C-band OSO). Here the walk-off effect was reduced significantly by setting the signal and pump wavelength symmetrically with respect to $\lambda_0$. Otherwise, the asymmetric allocation of signal and pump wavelength will decrease the conversion efficiency and broaden the pulsewidth of demultiplexed tributaries.

Fig. 4(a) shows the switching window of this demultiplexer. We measured the switching window by time-shifting control pulse (i.e., pulse pump) across the 160-Gb/s RZ signal and recorded the corresponding output power after filter centered at the idler wavelength. The full-width at half-maximum (FWHM) of the measured window was 4.2 ps, which was wide enough to transfer a 10-Gb/s tributary of 2-ps 160-Gb/s OTDM signal to demultiplexed channel. To investigate the sensitivity of the demultiplexed channels to the SOP of the input signal, conversion gain was measured as the input signal SOP was changed. A
From Fig. 4(b), we can find that the conversion gain of the polarization-insensitive case remained constant while the polarization-sensitive case (i.e., conventional scheme) had as much as 13.5-dB variation.

To quantify the polarization-insensitive demultiplexer, BER of the demultiplexed signals was measured with the polarization scrambler switched on and off. Both were compared to the back-to-back (B-to-B) 10-Gb/s RZ signal as shown in Fig. 5. The circles and triangles show the BERs obtained when the polarization scrambler was off and on, respectively. 0.4-dB penalty between them indicates that the demultiplexed tributaries independent on SOP of signal can be achieved with reasonable performance. Inset shows the power penalties for all 16 demultiplexed channels with scrambler on. Compared to the B-to-B curve, the power penalties ranged from 0.9 dB to 1.5 dB at 10^{-9} BER. The variation of the power penalties among different tributaries is believed to be introduced by the amplitude unbalance which is 18 dB higher than that of the FWM process as shown in [3]. This high conversion efficiency of demultiplexed tributaries can expand the transmission length, and also be used as a high-sensitivity optical preamplifier, which is another important application as in the optical receiver [11].

IV. CONCLUSION

A pulsed-pump polarization-insensitive FOPA has been demonstrated for high-speed all-optical time demultiplexing. A 160-Gb/s OTDM signal has been successfully demultiplexed into 16 individual 10-Gb/s signals with 12-dB conversion gain. No more than 1.5-dB power penalty at 10^{-9} BER can be achieved regardless of the OTDM signal SOP. The proposed FOPA-based polarization-insensitive demultiplexer is promising for high-performance simultaneous demultiplexing and power amplification of OTDM signals.

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REFERENCES


Fig. 5. Bit-error-rate plots of demultiplexing.

Fig. 6. Input and output spectra of the FOPA. FOPA: Fiber-optical parametric amplifier.