

# All-optical time-division demultiplexing with polarization-diversity nonlinear loop interferometer

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**Abstract:** We demonstrate a polarization insensitive time-division demultiplexer using semiconductor optical amplifier based nonlinear interferometer in a polarization-diversity loop. The demultiplexer had a very low switching energy (<100 femtojoules) and error-free operation in demultiplexing a 40 Gb/s input was achieved. The residual polarization dependence of the incident signal was found to be only 0.3 dB. Capability of demultiplexing at higher bit rates was proved by the ultrafast switching of 160 Gb/s pulses.

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## 1. Introduction

All-optical time-division demultiplexers are key elements in realizing future high bit rate optical time-division multiplexed (OTDM) systems. Semiconductor optical amplifiers (SOAs) based all-optical demultiplexers are attractive because of their compact size, potential for integration with other elements, low switching energy and high-speed operation. Time-division demultiplexers based on the SOAs have been demonstrated in ultrafast nonlinear interferometer (UNI) [1], nonlinear polarization rotation [2], and four-wave mixing (FWM) [3]. For practical deployment in OTDM transmission systems, all-optical demultiplexers should be insensitive to signal polarizations. However, polarization dependence is inherent in those demultiplexers. Several research groups have proposed different polarization insensitive OTDM demultiplexers based on fiber nonlinearity [4-7]. In such demultiplexers, long fibers (kilometers) and high peak power pulses are needed to induce sufficient nonlinear phase shift for demultiplexing.

In this letter, we propose and demonstrate a novel SOA-based polarization-insensitive OTDM demultiplexer which uses a polarization diversity nonlinear loop interferometer. The configuration is similar to [7] but using a SOA instead of long dispersion-shifted fiber as the nonlinear phase shifter. Compared to other fiber-based polarization insensitive demultiplexers, our proposed demultiplexer is more compact and has a very low switching energy ( $<0.1$  pJ), because of the relatively high nonlinearity in the SOA. We experimentally verified that there is no unforeseen interaction between the counter-propagating pulses in the SOA when it is used in a polarization diversity loop. We also discuss the integration feasibility of the proposed demultiplexer at the end of this letter.

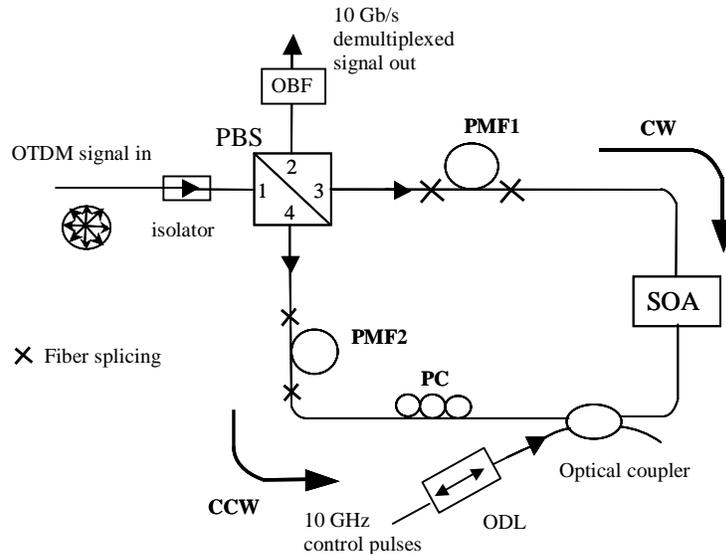


Fig. 1. Basic configuration of polarization diversity loop demultiplexer: PBS=Polarization Beam Splitter; ODL=optical delay line; SOA=semiconductor optical amplifier; PMF=Polarization maintaining fiber.

## 2. Principle of polarization-insensitive operation

The basic configuration of polarization-diversity loop demultiplexer is shown in Fig. 1. The incoming OTDM signal from port 1 of polarization beam splitter (PBS) was split into two orthogonally polarized components, and propagated inside the loop in clockwise (CW) and counter-clockwise (CCW) directions respectively. Two polarization-maintaining fibers

(PMFs) with the same length were put inside the loop as the birefringence elements to temporally separate the signal pulses. For CW propagation, the principal optical axes of PMF was aligned such that the signal pulse was temporally split into two orthogonal components ( $+45^\circ$  and  $-45^\circ$ ) and separated in time by  $\tau$ , where  $\tau$  depended on the birefringence and the length of PMF1. After the SOA and 3-dB coupler, the polarization states of two orthogonal components were appropriately aligned by a polarization controller (PC) such that the polarization of the faster pulse was matched with the slow axis of PMF2. The delay between the two pulses was thus reversed and the two pulses were recombined before entering port 4 of PBS. Without the control pulse, the two orthogonal components experienced the same phase shifts inside the loop and leave the PBS via port 1. However, if a control pulse was introduced to the SOA, the slower pulse would experience an additional phase shift and the polarization of the recombined signal was rotated. As a result, the recombined signal pulse can be switched out at port 2 of the PBS.

In our experimental setup, due to the limited availability of components which have PMF as pigtails, all fibers inside the polarization diversity loop were standard single-mode fibers (SMF) except for the two lengths of PMFs. In this case, additional PCs were needed at appropriate locations to maintain the polarization states. However, once the polarization states were correctly aligned, the demultiplexer remained stable over extended durations (many hours). In principle, the whole loop can be made of PMFs, with two section of PMFs (for pulse splitting purpose) being spliced  $45^\circ$  with respect to the fast axis of other PMFs. In this case no PCs would be needed within the loop, thus easing the initial setting up of the demultiplexer and further enhancing the stability of the demultiplexer.

Although the orthogonally polarized signals after the PBS can have different optical path lengths before reaching the SOA without affecting the overall length in the loop, the CW and CCW signals should arrive at the SOA well within the time delay  $\tau$  introduced by the birefringence of PMFs, in order to ensure that the control pulse can switch out the counterpropagating signals. The relative arrival times of the signal traveling in opposite directions must therefore be precisely adjusted before polarization independent operation can be achieved.

### 3. Experiments

The 40 Gb/s OTDM input signal was generated from a 10-GHz mode-locked fiber ring laser, while the control pulses were generated from a 10 GHz gain-switched distributed feedback (DFB) laser. Both the signal and the control pulses were driven by the clock source from the 10 Gb/s bit-error-rate tester (BERT) for synchronization. The 3-ps fullwidth at half-maximum (FWHM) signal pulses at 1559 nm were externally modulated with a  $2^{23}-1$  pseudorandom bit sequence (PRBS) by a LiNbO<sub>3</sub> modulator. The 10 Gb/s signal was passively multiplexed up to 40 Gb/s through a fiber multiplexer. The 40 Gb/s data stream was then fed into the polarization diversity loop via an isolator. A polarization controller was put before the loop to adjust the input signal polarizations. The control pulses at 1549 nm were firstly compressed to 8 ps FWHM pulsewidth with 500-m dispersion-compensating fiber (DCF) and then fed into the loop through a 3-dB coupler. The average power of control pulses was -2 dBm before entering the SOA. The switching energy was estimated to be 0.06 pJ. An optical delay line was used to select the demultiplexed channel of incoming OTDM signals. An isolator blocked the 40 Gb/s signal coming out from the loop via the 3-dB coupler. Inside the loop, two 11m-length PMFs were used to introduce 12 ps time delay between the orthogonally polarized signals.

The SOA (Alcatel 1901) employed in the experiment had a peak gain at 1555 nm and was biased at 120 mA. The SOA had a 0.3dB higher gain for the transverse-electric (TE) mode. A 1-nm bandwidth tunable optical filter was put at port-2 of the PBS to block the control pulses. Finally, a 10-Gb/s bandwidth receiver with sensitivity of around -21 dBm was used for measuring the BER of the demultiplexed signal.

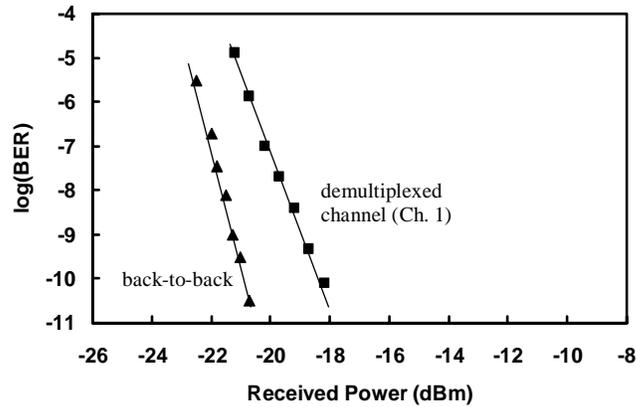


Fig. 2. BER measurements of the back-to-back signal and one of the demultiplexed channels.

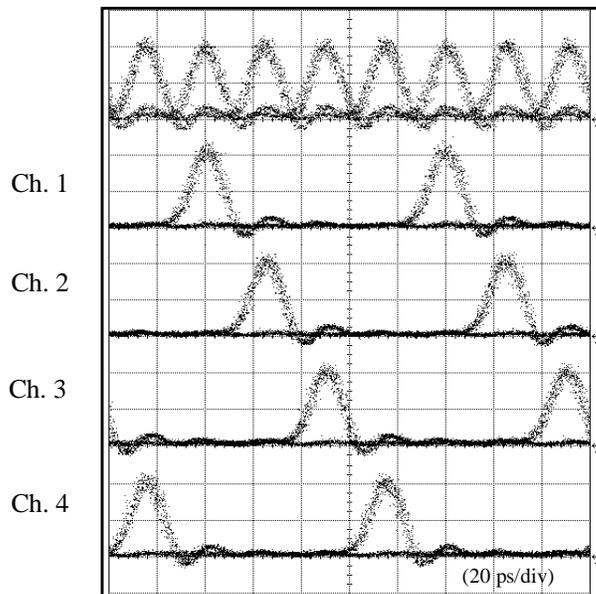


Fig. 3. The eye diagrams of 40 Gb/s OTDM signal and four demultiplexed 10 Gb/s channels at the same power levels measured by 45 GHz bandwidth photodetector.

#### 4. Results and discussion

Figure 2 shows the bit error rate (BER) of back-to-back and one of the demultiplexed channels at 10 Gb/s. The received optical power was the power in front of the optical receiver. The power penalty at a BER of  $10^{-9}$  for channel 1 was 2.3 dB. Figure 3 shows the eye diagrams of input 40-Gb/s signal and the four demultiplexed 10-Gb/s channels at the same power levels measured by a 45-GHz bandwidth photodetector. All channels have almost the same clearly opened eye patterns and extinction ratio in the diagram and thus had similar BER performance. The demultiplexed channels have good extinction ratio of over 15 dB.

To measure the polarization sensitivity of the demultiplexer, we varied the polarization states of the incident OTDM signals and measured the output power fluctuations. The polarization sensitivity was defined as the ratio of minimum and maximum output power at all input polarization states. The polarization sensitivity thus measured was only 0.3 dB. In the experiment, we found that the polarization sensitivity was strongly dependent on the arrival

times of the CW and CCW signals to the SOA. The polarization dependence on the mismatch of arrival times arisen from the different phase shifts that the CW and CCW signals experienced. This can change the polarization rotation and thus reduced the demultiplexed output power. For a mismatch larger than time delay  $\tau$  introduced by the birefringence of PMFs, the control pulse may switched out only one direction of signals at port-2 of the PBS, because either CW or CCW signal maybe out of the switching windows (switching window is related to polarization mode dispersion of PMF). Therefore, it was essential that the arrival times be carefully adjusted to minimize the polarization dependence of the demultiplexer. We observed a 0.3 dB polarization sensitivity which can be accounted for by the polarization dependent gain of the SOA.

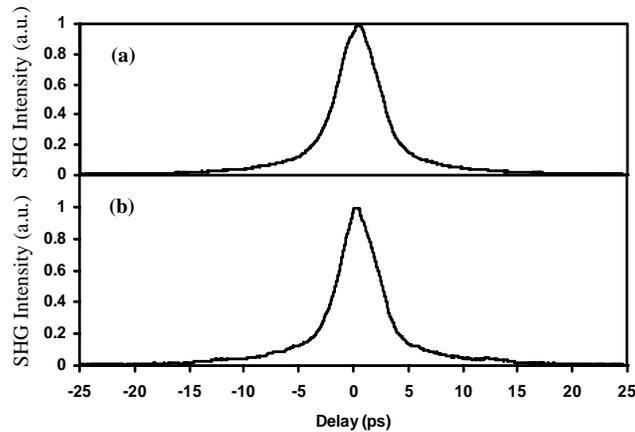


Fig. 4. The autocorrelation traces of (a) input and (b) output ultrashort pulses.

To demonstrate that this demultiplexer could work at higher bit rates ( $>160$  Gb/s), two independent experiments were carried out. Firstly, an ultrashort pulse train was injected into the polarization diversity loop and measured the output pulsewidth. In this measurement, a 10-m length of DCF ( $-91$  ps/nm/km) was added at the output to compensate the linear dispersion of the loop. Figure 4 shows that the output pulse had almost the same pulsewidth ( $\sim 3$  ps FWHM) as the input pulse from the autocorrelation measurements. The result showed that the pulse broadening inside the loop was insignificant.

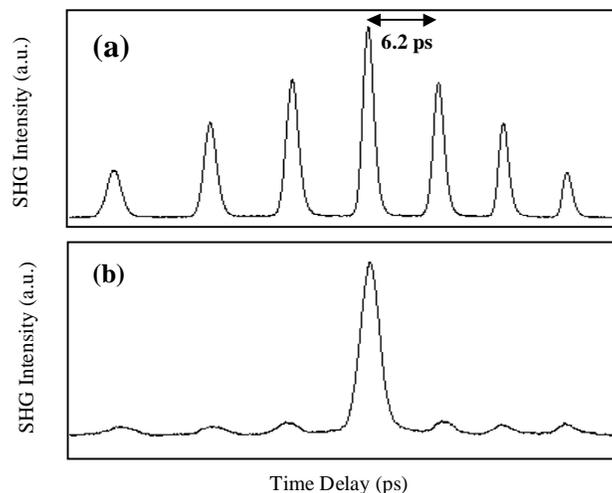


Fig. 5. The autocorrelation traces of (a) 160 Gb/s signal and (b) demultiplexed pulses.

The second experiment was pulse train demultiplexing at high bit rates by using the same switching mechanism. A passively mode-locked fiber ring laser generated 0.9 ps (FWHM) pulses at a repetition rate of 19 MHz at 1560 nm. The pulses were then passively multiplexed to a series of four pulses at an interval of 6.2 ps, corresponding to 160 Gb/s. Figure 5(a) shows the autocorrelation traces of the incident signal pulses. The triangular pulse train envelope and the appearance of seven peaks on the traces were the results of four-pulse series autocorrelation. The asymmetric traces (pulsewidth and interval) on two sides of central peak were due to the non-uniform real-time scanning of the autocorrelator [8]. Figure 5(b) shows the autocorrelation traces after injecting the control pulses into the SOA with proper delay line adjustment. The observed traces clearly indicate that the only one signal pulses was switched out. The extinction ratio between the switched and non-switched signal pulses was greater than 13 dB. The slight pulsewidth broadening on the switched pulses was due to the uncompensated linear dispersion.

Due to the insignificant broadening of the pulses and the ultrafast switching, it can be concluded that the demultiplexer can handle over 160 Gb/s multiplexed signal streams. However, at bit rates of 160 Gb/s it may be necessary to send control pulses in both directions within the polarization diversity loop (by injecting the control pulses at the same port as the signal) to ensure the switching characteristics of co-propagating and counter-propagating pulses within the SOA are identical. Typically, the lengths of the SOAs are of the order of hundreds of microns and the difference in overlap for the co-propagating and counter-propagating case within the SOA is not significant for 40 Gb/s signal demultiplexing.

The polarization diversity demultiplexer has three main elements: the PBS, the birefringence element (i.e. PMF), and the SOA. There is good potential for hybrid integration of these elements since integrated polarization splitters (or TE/TM mode splitter) are available in polymer [9], InGaAsP-InP [10] or silicon [11]. It may be possible to monolithically integrate the InGaAsP-InP polarization splitter with the SOA. Otherwise, the SOA need to be attached to polymer or silicon substrate together with hybrid integration of a birefringent element and passive waveguides. The (hybrid) integration approach is attractive because it simplifies the setup, since no polarization controllers would be needed and it should help the long term stability of the demultiplexer.

## 5. Conclusion

We have demonstrated a SOA-based polarization insensitive OTDM demultiplexer in a polarization diversity loop configuration. The polarization sensitivity was measured to be only 0.3 dB. The demultiplexer operated at a BER of  $10^{-9}$  with a power penalty of 2.3 dB and an extinction ratio of over 15 dB was achieved. Ultrafast switching at 160 Gb/s was successfully demonstrated. A hybrid integrated waveguide demultiplexer based on the same configuration was also proposed.

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