All-Optical Demultiplexing of 640 Gbit/s OTDM-DPSK Signal Using a Semiconductor SMZ Switch

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Abstract *The all-optical demultiplexing of a 640 Gbit/s OTDM signal is successfully demonstrated using a symmetric Mach-Zehnder switch incorporating SOAs. An ultrafast switching gate as narrow as 1.4 ps is realised, which facilitates low-penalty demultiplexing.*

Introduction

Optical time division multiplexing (OTDM) enables us to achieve ultrahigh-speed transmission at a single wavelength with a bit rate beyond the limit of electrical signal processing. Single-channel 1.28 to 2.56 Tbit/s transmission has already been demonstrated at a 640 Gbaud symbol rate per polarisation [1,2]. For demultiplexing OTDM signals at such a high data rate, fibre-based all-optical switches such as a nonlinear optical loop mirror (NOLM) [3] and Kerr switching with parametric amplification [4] have been demonstrated. Fibre-based switches have potential for ultrafast operation owing to the femtosecond response time of Kerr nonlinearity. However, because of its intrinsically low nonlinearity, a fibre with a length of a few tens or hundreds of metres is generally needed. In addition, the switching efficiency depends on the dispersion profile as it causes walk-off between the data and control pulses.

A semiconductor optical amplifier (SOA) is also an attractive switching device because of its compactness, high stability, and low switching power. One difficulty with SOA is the operating speed, which is limited by the slow gain recovery time of about 100 ps. It has been found that the SOA response can be improved by installing a detuned optical filter at the SOA output so that the slow gain recovery components can be removed. This scheme has been applied to 640 to 40 Gbit/s demultiplexing [5]. However, the switching performance includes a large penalty because of the distortions in the switching gate induced by residual slow recovery components and the excessive loss caused by the optical filtering.

Another promising scheme for SOA-based ultrafast switching involves introducing an interferometric configuration such as a symmetric Mach-Zehnder (SMZ) structure, in which two SOAs are installed in each arm of a Mach-Zehnder interferometer [6]. This scheme has a simple configuration, low optical power for switching, and an ultranarrow flat-top switching gate, which are very important for improving the demultiplexing performance. The SMZ switch has a hybrid-integrated form, and a switching operation as fast as 320 Gbit/s has already been achieved [7].

In this paper, we present the first experimental demonstration of 640 Gbit/s all-optical demultiplexing with the SMZ switch. The duration of the optical control pulse is reduced to 720 fs, which enables us to obtain a switching gate sufficiently narrow for 640 Gbit/s demultiplexing.

Experimental set-up for 640 Gbit/s demultiplexing

The basic configuration of the SMZ switch is shown in Fig. 1. In the SMZ switch, OTDM data and control pulses are injected into each SOA, where a π phase shift is introduced into the data signal through cross phase modulation with the control pulse. By introducing a first phase shift ϕ_1 in SOA1 followed by a second phase shift ϕ_2 in SOA2 with a time delay of $\Delta\tau$, it is possible to cancel the slow relaxation of the two phase shifts. This allows us to realise an ultranarrow switching gate [6].

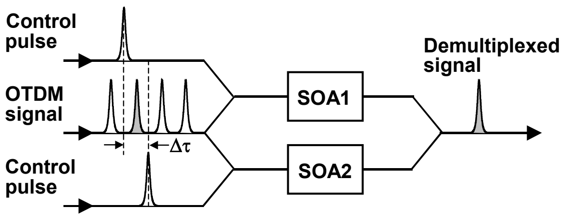

Fig. 1 Basic configuration of ultrafast SMZ switch.

We undertook a 640 Gbit/s OTDM demultiplexing experiment with the SMZ switch, whose set-up is shown in Fig. 2. To generate an ultrashort pulse for 640 Gbit/s data, we used a 40 GHz mode-locked fibre laser (MLFL) that generates a 1.6 ps pulse train at 1540 nm and employed external pulse compression based on spectral broadening using self-phase modulation (SPM) in a fibre with normal dispersion. The MLFL output pulse was amplified to 23.5 dBm and launched into a 2 km normal dispersion-flattened fibre (DFF) with a dispersion of – 0.2 ps/nm/km, a dispersion slope of only 0.002 ps/nm^2/km and a nonlinear coefficient γ = 5 W^{-1}km^{-1}. The spectrum was broadened to 12 nm via the interplay between SPM and the normal dispersion. After compensating for the chirp with a 38 m single-mode fibre (SMF) and optical filtering, the pulse was compressed to 380 fs and the time-bandwidth product was 0.49. The compressed

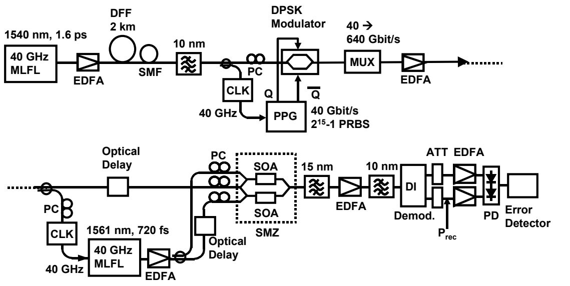

Fig. 2 Experimental set-up for all-optical 640 to 40 Gbit/s OTDM demultiplexing using an SMZ switch.

pulse was DPSK modulated with a 40 Gbit/s, 2^{15}-1 PRBS, where the pulse pattern generator (PPG) was synchronized to the 40 GHz clock that was extracted after the pulse compression. The DPSK signal was then optically multiplexed to 640 Gbit/s with a single polarisation using a fibre delay-line multiplexer.

On the receiver side, the 640 Gbit/s OTDM signal and 40 GHz control pulses were combined and coupled to the SMZ switch. For demultiplexing at 640 Gbit/s, the switching gate has to be as narrow as 1.5 ps, which corresponds to a bit interval of 640 Gbit/s. To realise such a narrow gate, a low-jitter, subpicosecond control pulse is required. As a control pulse source, we used a 40 GHz MLFL operated by FM mode-locking [8], which can directly emit a 720 fs pulse train. The control pulse wavelength was set at 1561 nm. The MLFL was PLL-operated with a 40 GHz clock extracted from the 640 Gbit/s data using an electro-optical PLL clock recovery unit [9]. The control pulse was divided by a 3 dB coupler and one part was delayed by $\Delta\tau$ = 1.5 ps for the switching. The optical power of the data and control pulse were set at 13 and 11 dBm, respectively. Under these conditions, we obtained a 1.4 ps wide switching window, which we evaluated by injecting CW light at the data wavelength instead of the OTDM signal. At the SMZ output, the demultiplexed signal was separated from the control pulse with 15 and 10 nm optical filters. The demultiplexed 40 Gbit/s DPSK signal was finally converted to an OOK signal with a one-bit delay interferometer (DI), and the bit error rate (BER) was measured after detection with a balanced photo-detector (PD).

Experimental results

Figure 3 shows the auto-correlation traces of the 640 Gbit/s OTDM signal and the demultiplexed pulse. The OTDM signal was successfully demultiplexed to 40 Gbit/s with an extinction ratio of more than 15 dB. After the demultiplexing, the pulse width was broadened to 570 fs. This was caused by the optical filters at the output of the SMZ switch used for removing the control pulses. Figure 4 shows the BER measurement result for the demultiplexed signal, where error-free operation with a BER down to 10^{-11} was achieved. The received power required for a BER of 10^{-9} was measured for all sixteen OTDM

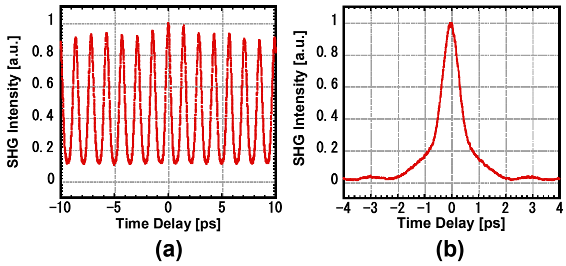

Fig. 3 Auto-correlation traces of 640 Gbit/s OTDM signal (a) and demultiplexed 40 Gbit/s pulse (b).

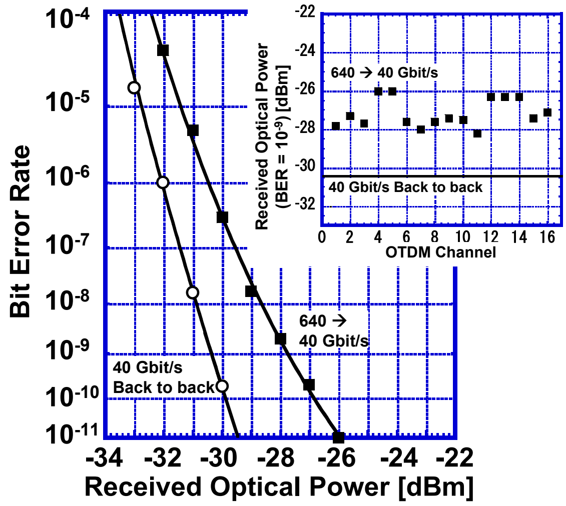

Fig. 4 BER performance of 640 to 40 Gbit/s demultiplexing. The inset shows the received power at BER = 10^{-9} for all sixteen OTDM channels.

tributaries, and the result is shown in the inset of Fig. 4. The power penalty with respect to the 40 Gbit/s back-to-back baseline was 2~4 dB and error-free operation was achieved for all channels. The variations in the received power are attributed to the difference between the channel amplitudes caused at the OTDM.

Conclusion

We have demonstrated all-optical 640 to 40 Gbit/s OTDM-DPSK signal demultiplexing by using SOAs in an SMZ configuration. As a result of ultrafast switching with a gate width as narrow as 1.4 ps, low power-penalty demultiplexing was successfully achieved. The SMZ switch allows us to realise ultrafast demultiplexing characteristics with a simple configuration and low optical power for switching.

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