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Ultrafast Demultiplexing and Bit-Wise Logic Operation Using Symmetric Mach-Zehnder All-Optical Switches

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1. Introduction

Ultrafast semiconductor all-optical switches are expected to play important roles in future optical communication networks, where applications of such switches include ultrafast demultiplexing, pulse regeneration, wavelength conversion and other time-domain manipulations of pico-second pulses. To realize these functions, the authors proposed a Symmetric Mach-Zehnder (SMZ) all-optical switch [1,2] and its variants, a Polarization-Discriminating SMZ (PD-SMZ) [3] and a Delayed Interference Signal-wavelength Converter (DISC) [4]. We have achieved a fastest switching speed of 200 fs and a fastest demulti-plexing operation corresponding to 1.5Tbps [5]. We also predicted [1] and verified [6] a high repetition capability of these devices in the SMZ family. We recently realized a Hybrid-Integrated SMZ (HI-SMZ) [7] and with the HI-SMZ we achieved 168 to 10.5 Gbps error-free demultiplexing [8]. Here, we report on improvements in the demultiplexing experiment, and 84 Gbps error free all-optical pulse regeneration and wavelength conversion.

2. HI-SMZ and 168 to 10.5 Gbps error-free demultiplexing

Figure 1 shows the HI-SMZ. The Mach-Zehnder inter-ferometer was fabricated on the PLC platform by the AP-CVD technique. A semiconductor optical amplifier (SOA) array chip (used as nonlinear phase shifters) and pig-tail fibers were assembled onto it by using self-aligning techniques [7,8]. The static extinction ratio of this device was approximately 25 dB and the dynamic extinction ratio was better than 18 dB in the 168Gbps demux experiment. In this experiment, two actively mode-locked fiber lasers (MLFLs) were used for control and signal pulse sources at 1545 and 1560 nm, respectively. A switching window of 6 ps at 10.5 GHz was realized by the HI-SMZ driven by the 2.5 ps control pulses, to demultiplex the signal pulses. The signal light was formed by modulating the 10.5 GHz, 1.4 ps pulses at 1560 nm by a Ti:LiNbO$_3$ modulator driven by a pulse pattern generator (PPG). Then it was multiplexed to 168 Gbps by delay lines. The coded pulse stream at 168 Gbps was input into the signal port of HI-SMZ to be demultiplexed back to 10.5 Gbps. The demultiplexed signal light was then lead to the detection system. Details of this experimental setup can be found in Ref. 8.

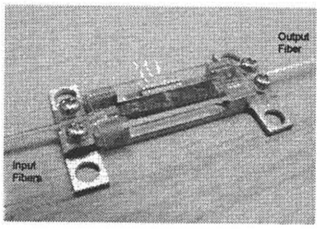

Fig. 1 Hybrid-Integrated SMZ.

Figure 2 is the result of bit-error-rate (BER) assessment of 168 to 10.5 Gbps demultiplexing. The received power was measured at the input of an EDFA in front of the photodetector. Error-free operation where the BER was less than 10^{-10} was achieved even with a pseudorandom bit sequence (PRBS) of 2^{31}-1. An increase in power penalty over 2^7-1 was mostly attributable to the receiver, not the demultiplexer, as seen from the difference between the baselines. These results are better than those reported in ref. 7, owing to further optimizations applied to the experimental setup.

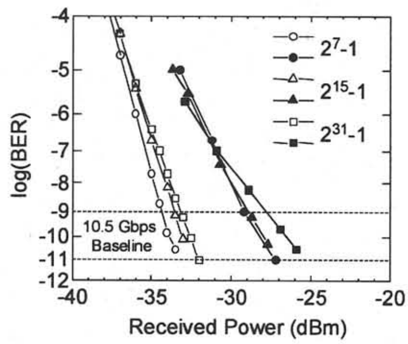

Fig. 2 Bit-error rates of 168 Gbps demultiplexing.

3. Error-free pulse regeneration at 84 Gbps

Figure 3 shows the experimental setup for pulse regeneration, where the PD-SMZ [3,5] for pulse regene-ration was added to the mux/demux apparatus. The wavelength and pulse width of the 84 Gbps coded signal pulses were 1560 nm and 2.0 ps, respectively. The 84 GHz clock pulses were 1545 nm and 2.5 ps. The input signal and clock light powers to an SOA in the PD-SMZ were 0 dBm and 1 dBm, indicating a very low switching energy of ~5 fJ [9]. The output of the PD-SMZ was demultiplexed to 10.5 Gbps by the HI-SMZ to evaluate the BER.

The results of BER measurements are shown in Fig. 4. The power penalty (PP) of 84 Gbps pulse regeneration (which

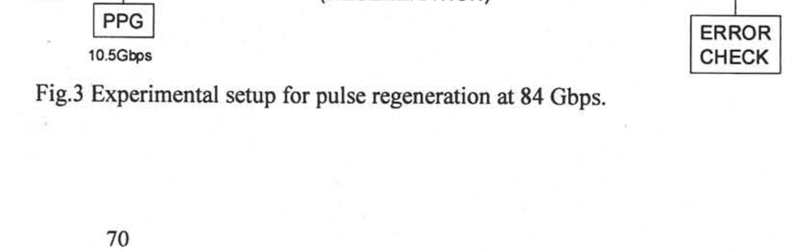

Fig.3 Experimental setup for pulse regeneration at 84 Gbps.

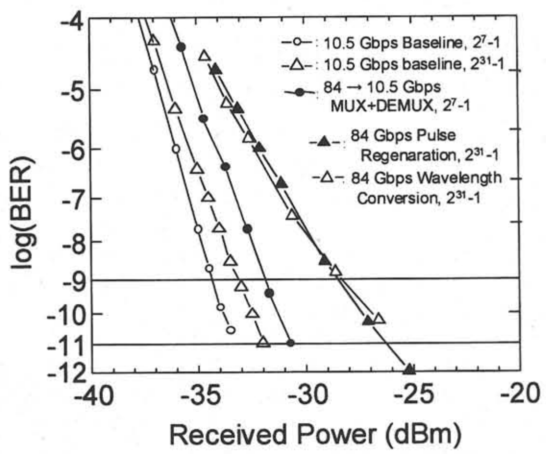

Fig. 4 Results of bit-error-rate measurements.

involves mux, regeneration, and demux) should be measured against the PP of mux+demux from 10.5 to 84 and again to 10.5 Gbps. Unfortunately, that data is available only with a PRBS of 2^7-1, because 168 Gbps mux+demux characteristics were of interest in the above experiment. But it is possible to estimate the PP due to pulse regeneration alone with a PRBS 2^{31}-1 at a BER of 10^{-9} as PP(mux+regeneration+demux, 2^{31}-1) -PP(mux+demux, 2^7-1) - (the PP difference between 2^{31}-1 and 2^7-1 of the 10.5 Gbps baseline) = ~2dB. So the power penalty of pulse regeneration is estimated to be ~2dB, but it is stressed that ~200 consecutive "0"s and "1"s occured in the 84 Gbps pulse stream used in this experiment. This is because it was generated by optically multiplexing the 10.5 Gbps PRBS 2^{31}-1 pulses eight times with a longest delay of only ~150 ps (3T/2). Unlike the case of demultiplexing, this was a very severe situation for the PD-SMZ which was driven by this bit stream. In fact, we observed that the PP became very low when the PPG was switched to 2^7-1 in the same experiment, where the number of consecutive zeros and ones was reduced to ~ 40. Thus we believe that the power penalty due to the pulse regeneration is much lower than 2dB, if a correct PRBS 2^{31}-1 at 84 Gbps is used. The eye diagram shown in Fig. 5 should be observed with these discussions in mind.

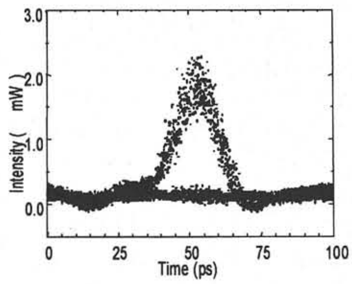

Fig.5 Eye diagram of 84 Gbps pulse regeneration after demultiplexing to 10.5 Gbps.

We also evaluated the pulse retiming capability of such a scheme. The result showed that the jitter-tolerant-window-width was better than ~2.25 ps (~3.2 ps) where a BER degradation was kept less than 10 dB (20 dB). So if the possibility of 2.25/2 (3.2/2) ps jitter occurring is 10 % (1%), then the total BER would remain in the same level. This retiming capability was a result of the square-like modulation characteristic of the SMZs [1] that enabled quasi-digital operation.

4. Error-free wavelength conversion at 84 Gbps

We also performed all-optical wavelength conversion at 84 Gbps. The experimental setup was similar to the case of pulse regeneration, but the PD-SMZ was replaced with the DISC [4], which is a simplified PD-SMZ for wavelength conversion. The clock pulse source was also replaced with an unmodulated CW diode laser (1560 nm, 4.5 dBm). The signal pulses were 1547 nm and 5.3 dBm. The BER performance was similar to the case of pulse regeneration as shown in Fig. 4. The discussion on the PP with ~200 consecutive "1"s and "0"s equally applies to this experiment.

5. Conclusion

In conclusion, we have achieved error-free 168 to 10.5 Gbps demultiplexing. This is the fastest experiment using an integrated device. A BER of better than 10^{-10} was achieved with a power penalty of ~6dB which was partially due to the excess signal loss in the device. We have also achieved error-free all-optical pulse regeneration and wavelength conversion at 84Gbps. This is only slightly faster than the previously reported record of 80 Gbps [10,11], but the switching energy was drastically reduced from 0.2 pJ to 0.005 pJ. We also showed that the power penalty was ~2dB even with a bit sequence that contained ~200 consecutive "1"s and "0"s, implying a much lower power penalty if a correct PRBS 2^{31}-1 was employed. Furthermore, this is the first quantitative demonstration of the retiming function. The result was +/-1.1 ps (+/-1.6 ps) for a BER increase of 10 dB (20 dB), showing that the quasi-square modulation characteristic, a unique feature of the SMZs, was still apparent at a highest random switching rate of 84 Gbps reported to date.

Acknowledgement

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[11] A device called "UNI" was used in ref.9. The principle of operation of the UNI is identical to the PD-SMZ. Thus it is a different implementation of the PD-SMZ, using optical fibers.