160-Gb/s OTDM Transmission Using Integrated All-Optical MUX/DEMUX With All-Channel Modulation and Demultiplexing

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***Abstract*—This letter provides the first report of 160-Gb/s optical time-division-multiplexed transmission with all-channel independent modulation and all-channel simultaneous demultiplexing. By using a multiplexer and a demultiplexer based on periodically poled lithium niobate and semiconductor optical amplifier hybrid integrated planar lightwave circuits, 160-km transmission is successfully demonstrated.**

***Index Terms*—Integrated optics, nonlinear optics, optical communication, optical signal processing, optical waveguide components, time-division multiplexing.**

I. INTRODUCTION

OPTICAL time-division multiplexed (OTDM) transmission systems require an all-channel independent modulation multiplexer (MUX) [1] and an all-channel simultaneous demultiplexer (DEMUX) [2]. In previous experiments on over 100-Gb/s OTDM transmission [3]–[5], partly modulated or folded OTDM signals were used. At the receiver end, only one channel was demultiplexed. To further this field, we have been developing an all-channel independent modulation MUX [6], realized as periodically poled lithium niobate (PPLN) waveguides hybrid integrated on a planar lightwave circuit (PLC), and an all-channel simultaneous DEMUX [7], fabricated as a semiconductor optical amplifier (SOA) array, hybrid integrated on another PLC. This letter provides the first report of 160-Gb/s OTDM transmission using the MUX and DEMUX with all-channel independent modulation and all-channel simultaneous demultiplexing.

II. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental setup. The OTDM-MUX generates a 160-Gb/s OTDM signal from four independent 40-Gb/s signals that share the same clock. 10-Gb/s electrical signals (pseudorandom bit sequence (PRBS) of $2^{31}-1$) were multiplexed to 40 Gb/s by an electrical MUX. A 40-GHz optical clock was generated by using a mode-locked laser diode (MLLD) [8] and supercontinuum (SC) techniques [9]. The wavelength and pulsewidth (full-width at half-maximum) of the MLLD were 1560 nm and 4.7 ps (near Gaussian profile), respectively. The 40-GHz pulse train was converted into an appropriate wavelength and pulsewidth by filtering the SC spectrum. Four 40-Gb/s nonreturn-to-zero format optical modulation signals [Fig. 2(a)] and a 40-GHz optical clock [Fig. 2(b)] were input into OTDM-MUX. The optical clock was split into four optical clocks by the 1×4 coupler in the PLC of OTDM-MUX. Each optical clock was combined with an optical modulation signal by a 2×1 coupler and both were then input into a PPLN waveguide to generate a cascaded $\chi^{(2)}$ component. The PPLN waveguides exhibit polarization dependence, so we adopted an all-polarization-maintaining configuration in the OTDM-MUX. The cascaded $\chi^{(2)}$ processes are similar to four-wave mixing (FWM) from the viewpoint of the relationship between input and output wavelengths. Therefore, the optical clock is modulated by the optical modulation signal. The four optically modulated signals were then combined with the same polarization state in the 4×1 coupler in the PLC. Since the path-length difference between subsequent waveguides was set to one time-slot at 160 Gb/s (6.3 ps), the four optically modulated signals were time-division multiplexed into a 160-Gb/s OTDM signal [Fig. 2(c)]. The optical spectrum of OTDM-MUX output is shown in Fig. 1(b). In this experiment, the bit sequences of the four optically modulated signals were not shifted in generating the PRBS pattern, so the 160-Gb/s OTDM signal was not a PRBS pattern. Compared to the previous OTDM-MUX [6], the output power of OTDM-MUX is improved by the use of about two times higher efficiency PPLN waveguides (second harmonic generation efficiency of 1000%/W) and reduced excess losses by the simplification of the MUX due to the increase of the base bit rate from 20 to 40 Gb/s. As a result, the output OTDM signal power of −4 dBm was obtained when the input optical power of the modulation signal and optical clock power were 19 dBm/ch and 21 dBm, respectively. The clear eye opening of the measured OTDM signal waveform shown in Fig. 2(c) confirms its high signal-to-noise ratio (SNR). The signal quality (Q factor at 10 Gb/s) of each channel was over 19 dB.

The 160-Gb/s OTDM signal was boosted by an erbium-doped fiber amplifier and launched into 160-km (80 km × 2) transmission line. The input optical power to transmission line was 5 dBm. The transmission span consisted of 60-km single-mode

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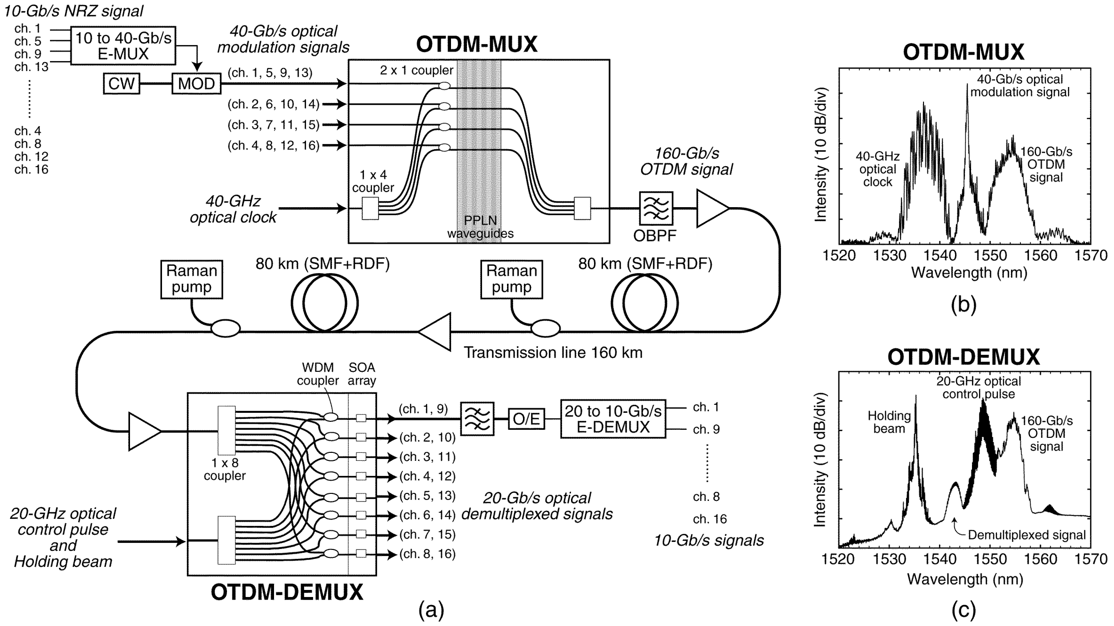

Fig. 1. (a) Experimental setup of 160-Gb/s transmission with all-channel independent modulation MUX and all-channel simultaneous DEMUX. E-MUX: electrical MUX. CW: continuous-wave laser source. MOD: $LiNbO_3$ intensity modulator. OBPF: optical bandpass filter. SMF: single-mode fiber. RDF: reverse dispersion fiber. O/E: optoelectronic converter. E-DEMUX: electrical DEMUX. Measured optical spectra of (b) OTDM-MUX output and (c) OTDM-DEMUX output.

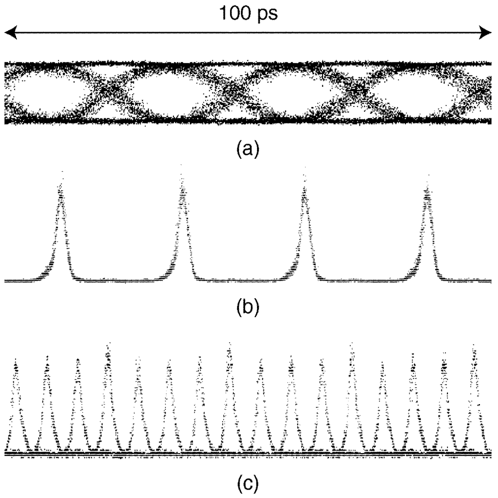

Fig. 2. Measured waveforms of OTDM-MUX. (a) 40-Gb/s optical modulation signal, (b) 40-GHz optical clock, and (c) 160-Gb/s OTDM signal.

fiber and 20-km reverse-dispersion fiber with backward Raman pumping to suppress nonlinear effects. The total optical power of the Raman pump LDs was 23 dBm. We also transmitted a 10-GHz optical clock ($\lambda = 1535$ nm) with 160-Gb/s OTDM signal for clock recovery at the receiver. The recovered 10-GHz clock was doubled to generate 20-GHz optical control pulses for the OTDM-DEMUX and to provide a 20-GHz clock for the electrical DEMUX.

The OTDM-DEMUX accepted the 160-Gb/s OTDM signal [Fig. 3(a)] and 20-GHz optical control pulse [Fig. 3(b)] and output 8×20 Gb/s demultiplexed signals [Fig. 3(c)]. We used an SOA as the gate device. The FWM of the SOA yielded all-optical demultiplexing. We used a linear polarized pump beam and a polarization controller to demultiplex the OTDM signal. Demultiplexing via the SOA can potentially achieve polarization independent operation [10] if a pump beam with both transverse-electric and transverse-magnetic polarization is injected into the SOA. Polarization dependence of the SOA used was less than 0.6 dB. Because of the SOAs relaxation time, the base bit rate of the OTDM-DEMUX was 20 Gb/s. Injected 160-Gb/s OTDM signal and 20-GHz optical control pulse train were split into eight OTDM signals and control pulse trains by the 1×8 couplers. Each control pulse train was combined with the OTDM signal by a wavelength-division-multiplexing coupler, and both were then input into an SOA to generate an FWM light (20-Gb/s demultiplexed signal). The path length of each channel was set to demultiplex a different channel. In order to realize all-channel simultaneous demultiplexing, all that is necessary is to adjust the timing difference at the two input ports, because timing phase is decided in the PLC. The optical spectrum of OTDM-DEMUX output is shown in Fig. 1(c). The optical power of injected OTDM signal, control pulse, and 20-Gb/s demultiplexed signal were 16 dBm, 22 dBm, and -23 dBm/ch, respectively. We launched a holding beam into OTDM-DEMUX to suppress the pattern effect of the SOA. The wavelength and power of the holding beam were 1536 nm and 19 dBm, respectively. Eight 20-Gb/s signals were electrically demultiplexed to 2×10 Gb/s. We measured the bit-error rates (BERs) of the 16×10 Gb/s signals after 160-km fiber transmission. Fig. 4 shows the BER curves of the best and worst channel, and Fig. 4 shows the minimum received optical power at BER $= 10^{-9}$. Error-free operation (BER $< 10^{-9}$) was achieved in all channels. The difference of minimum received optical power between channels was within 2.7 dB. The difference is mainly due to the nonuniformities of the PPLN waveguides in the OTDM-MUX and the SOA array in the OTDM-DEMUX.

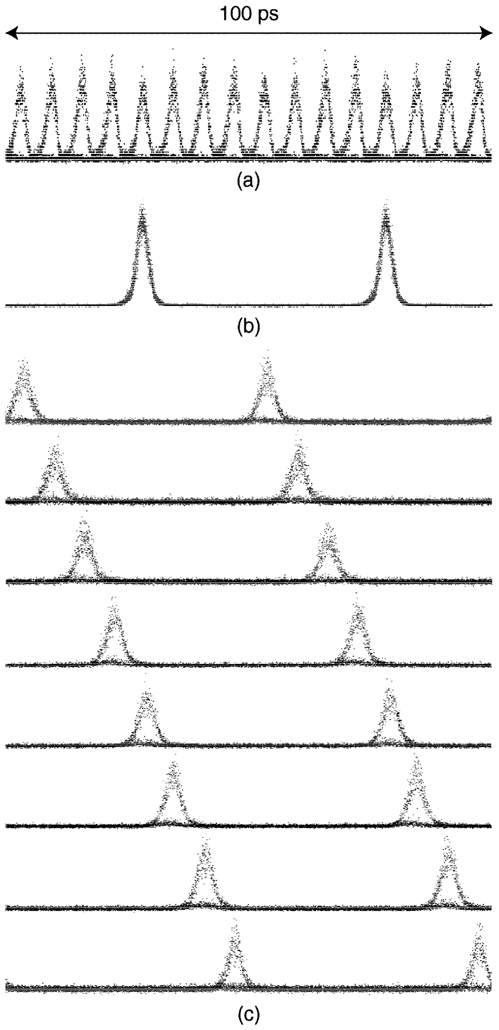

Fig. 3. Measured waveforms of OTDM-DEMUX. (a) 160-Gb/s OTDM signal after 160-km transmission, (b) 20-GHz optical control pulse, and (c) eight demultiplexed 20-Gb/s signals.

The OTDM-MUX and DEMUX occupy about 16×4 cm^2 and 14×4 cm^2, respectively. Their small size enables precise temperature control in a simple manner, so OTDM transmission with high stability was successfully demonstrated.

III. Conclusion

A 160-Gb/s OTDM transmission with all-channel modulation and all-channel simultaneous demultiplexing has been successfully demonstrated for the first time. The MUX and DEMUX strictly maintain the delay time between adjacent channels and offer high-temperature stability because they are hybrid integrated on PLCs; they will, therefore, be the keys to future OTDM transmission systems.

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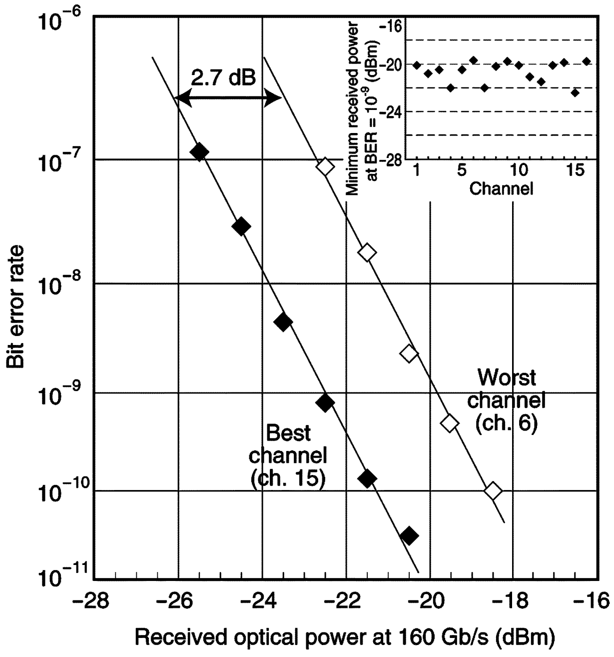

Fig. 4. Measured BER of 16×10 Gb/s after 160-km fiber transmission. Inset shows the minimum received optical power at BER $= 10^{-9}$.

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