160-Gb/s Optical-Time-Division Multiplexing With PPLN Hybrid Integrated Planar Lightwave Circuit

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***Abstract*—160-Gb/s (20 Gb/s × 8) optical time-division-multiplexing is demonstrated using a multiplexer based on periodically poled lithium niobate hybrid integrated planar lightwave circuits. With this multiplexer, eight 20-Gb/s signals are independently modulated and time division multiplexed all-optically. To confirm the quality of the multiplexed signal, it was demultiplexed and bit error rates were measured. The measured power penalties are less than 2.2 dB.**

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

I. Introduction

FUTURE optical time-division-multiplexed (OTDM) transmission systems [1] will require stable time-division-multiplexing of optical signals without fluctuations in pulse separation to suppress the influence of the crosstalk from adjacent pulses on demultiplexing and to minimize the jitter in timing extraction. All-optical modulation combined with an optical clock is one approach to this problem [2]. Another solution is to integrate the optical components into a compact circuit [3]–[5]. The integrated multiplexer makes the optical path lengths very short and makes temperature control easier. We previously proposed integrated multiplexers (MUXs) that use a semiconductor optical amplifier (SOA) integrated into a hybrid planar lightwave circuit (PLC) and 80-Gb/s (20 Gb/s $\times$ 4) multiplexing operation was successfully demonstrated as a result of all-optical modulation and the integration of optical components [6]. Our all-optical modulation scheme eliminates the microwave crosstalk between adjacent channels which occurs in conventional electrooptic modulation schemes. The combination of PLC-based integration and all-optical modulation realizes stable, ultrahigh-speed OTDM signal generation. Recently, periodically poled lithium niobate (PPLN) devices are attracting attention because of their compact size, high-efficiency ultrahigh-speed nonlinear processes and low noise. The low noise characteristic originates from absence of amplified spontaneous emission noise and the pattern effect unlike SOA. The external (fiber-to-fiber) conversion efficiency of -7 dB has been reported [7].

Manuscript received July 26, 2002; revised November 5, 2002.

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Digital Object Identifier 10.1109/LPT.2002.806889

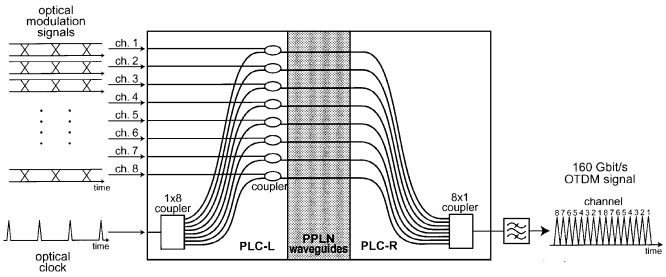


Fig. 1. Fundamental configuration of PLC-OTDM-MUX. Injected 20 GHz optical clock was divided into eight optical clocks and each optical clock was independently modulated using the cascaded $\chi^{(2)}$ processes in the PPLN waveguide. The eight modulated optical clocks were multiplexed into a 160-Gb/s OTDM signal.

This letter reports optical time-division multiplexing by a hybrid PLC-based OTDM-MUX. The PLC-OTDM-MUX utilizes mixing in PPLN waveguides to modulate the optical signals all-optically. With this device, eight 20-Gb/s optical signals were multiplexed into a 160-Gb/s OTDM signal in a stable manner.

II. PLC-OTDM-MUX

Fig. 1 shows the fundamental configuration of the proposed PLC-OTDM-MUX. The device consists of two PLCs (PLC-L, PLC-R) and a set of PPLN waveguides. Each PLC has a 1×8 coupler and eight different-path-length waveguides. In addition, PLC-L has eight 2×1 couplers. The eight PPLN waveguides are connected to the PLCs waveguides by a conventional technique [8]. The waveguides were fabricated using annealed and reverse proton exchange in PPLN [9]. The length and the quasi-phase-matching period of the PPLN waveguide are 4 cm and 15.5 μm, respectively. The PPLN waveguide employs a simple integrated mode filter and taper for efficient coupling and does not require electrodes, hence its fabrication is simpler than that of the SOA. The details of the PLC-OTDM-MUX such as optical characterisitics and fabrication will be reported elsewhere [10].

An input optical clock (repetition rate 20 GHz, wavelength λ_0) is split into eight optical clocks by the 1×8 coupler in the PLC-L. Each optical clock is combined with an nonreturn-to-zero (NRZ) optical modulation signal (bitrate 20-Gb/s, wavelength $\lambda_{\rm pump}$) by a 2×1 coupler and both are then input into a PPLN waveguide to generate a cascaded $\chi^{(2)}$ conversion component as the RZ optically modulated signal (bitrate 20

Gb/s, wavelength $\lambda_{\rm conv}$). The cascaded $\chi^{(2)}$ processes consist of two second-order nonlinear processes. The 1st process is second-harmonic generation (SHG) of the optical modulation signal and produces second-harmonic component at wavelength $\lambda_{\rm pump}/2$. The 2nd process is difference-frequency generation (DFG) between the second-harmonic component and the optical clock and produces difference-frequency component at wavelength $\lambda_{\rm conv}$. These processes occur simultaneously in the PPLN waveguides and are similar to four-wave mixing (FWM) from the viewpoint of relationship between input and output wavelengths. Therefore, the optical clock is modulated by the optical modulation signal. The eight optically modulated signals are combined in the 8×1 coupler in PLC-R. Since the path-length difference between subsequent waveguides is set to one time-slot at 160 Gb/s (6.3 ps), the eight optically modulated signals are time-division multiplexed into a 160-Gb/s OTDM signal. Since each optical clock is modulated all-optically by the cascaded $\chi^{(2)}$ processes, all channels are independently modulated without microwave crosstalk [3]–[5], so multiplexing yields an ultrahigh-speed OTDM signal.

III. Experiments

The normalized conversion efficiencies of the PPLN waveguides used in this device ranged from 450 %/W to 750 %/W as measured using a continuous-wave (CW) optical source. The normalized conversion efficiency η is defined as

$$\eta(\%/\mathrm{W}) = 100 \times \sqrt{\frac{P_{\rm conv}}{P_{\rm pump}^2 P_0}}$$

where $P_{\rm conv}$, $P_{\rm pump}$ and P_0 are converted output power, pump power and signal power, respectively. All powers were measured at the output of the PLC. The variation in normalized conversion efficiency mean that the transfer of the data onto the pulse vary from channel to channel.

We experimentally demonstrated 160-Gb/s (20 Gb/s $\times$ 8) multiplexing (Fig. 2). In order to simplify the setup, eight 20-Gb/s NRZ format optical modulation signals ($\lambda_{\rm pump} = 1544$ nm) were generated using a CW optical source, a lithium niobate intensity modulator operating at 20 Gb/s, an optical amplifier and a 1×8 coupler. Each optical path length differences between adjacent channels was set to be longer than two timeslots in order to prevent adjacent channels being the same data. A 20-GHz optical clock ($\lambda_0 = 1552$ nm) was generated from a spectrally sliced supercontinuum (SC) source that consisted of an actively mode-locked Er-doped fiber laser, an optical amplifier and SC fiber (SCF) [11]. The optical modulation signal and optical clock were injected into the PLC-OTDM-MUX. The average input powers of the optical modulation signal and optical clock were 19 dBm/ch and 23 dBm, respectively. As discussed previously, the optical clock was split into eight optical paths in PLC-L, such that the clock power per channel is 14 dBm. In this condition, the output 160-Gb/s OTDM signal power was -15 dBm. Fig. 3 shows the optical spectrum of PLC-OTDM-MUX output. The output of the PLC-OTDM-MUX was introduced to a BPF to extract the OTDM signal ($\lambda_{\rm conv} = 1536$ nm). A theoretical analysis of transmission performance showed that output

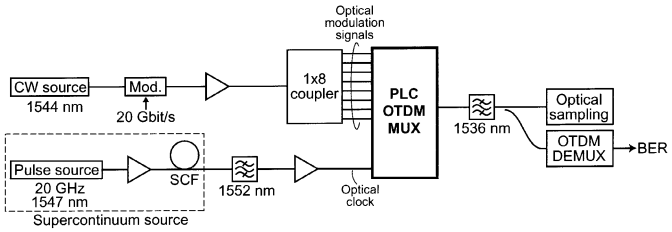


Fig. 2. Experimental setup for 160-Gb/s multiplexing.

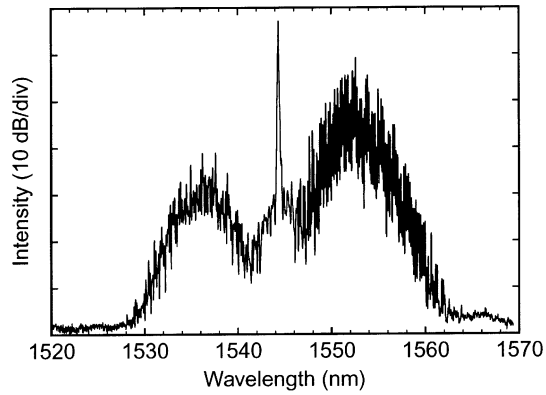


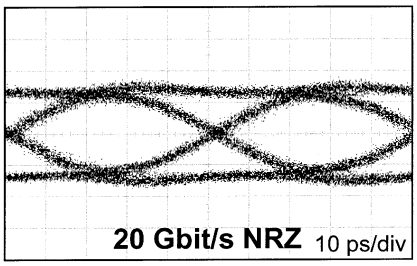
Fig. 3. Optical output spectrum of PLC-OTDM-MUX. 1544 nm: 20-Gb/s NRZ optical modulation signal, 1552 nm: 20-GHz optical clock, 1536 nm: 160-Gb/s OTDM signal.

optical power of -15 dBm will be sufficient for 160-Gb/s single-span transmission. Higher output optical power enables us to achieve 160-Gb/s multiple-span transmission.

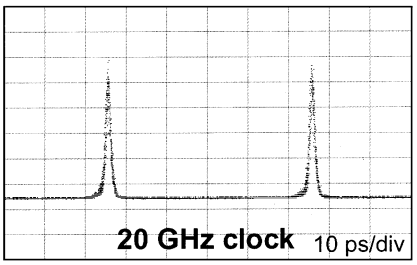
The waveforms of the optical signals were measured by a conventional sampling oscilloscope [Fig. 4(a)] and a 0.9-ps resolution optical sampling system [12] [Fig. 4(b) and (c)]. Fig. 4(a)–(c) show the waveforms of the optical modulation signal, the optical clock and the 160-Gb/s OTDM signal, respectively. As seen in Fig. 4(c), the eye diagram of the 160-Gb/s OTDM signal was observed. The pulsewidth of the OTDM signal was 2.0 ps. The time-bandwidth product $\Delta t \Delta \nu$ was 0.41, therefore, the output OTDM signal pulse is a nearly transform limited pulse. Stable multiplexing was achieved as a result of the all-optical modulation and the integration of optical components on the PLC platform.

The 160-Gb/s OTDM signal was demultiplexed to 10-Gb/s for bit-error-rate (BER) measurement using FWM [13]. Fig. 5 shows the BER performance of the demultiplexed 10-Gb/s signals. There was no error floor and the power penalties were less than 2.2 dB. This power penalties may be due to conversion efficiency variation of the PPLN and difference of crosstalk influences after demultiplexing. These results show that the multiplexer can generate a low noise OTDM signal. In this experiment, each channel was imprinted with the same data. Even in practical systems, which utilize independent data channels, it will be no problem if pulsewidth is sufficiently narrow (pulsewidth $<$ 2.0 ps).

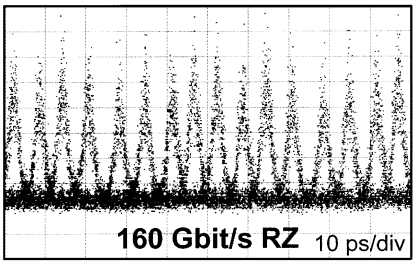
The output optical power from the PLC-OTDM-MUX can be increased by using a more efficient waveguide. The PPLN device used in this experiment was made using the technique described in [9], however its performance was limited by nonuniformities in fabrication. An optimized device would result in a



(a)



(b)



(c)

Fig. 4. Measured waveforms. (a) 20-Gb/s NRZ optical modulation signal, (b) 20 GHz optical clock, (c) 160-Gb/s OTDM signal. The stable waveform of OTDM signal was observed. The waveforms (b) and (c) were measured by a 0.9 ps resolution optical sampling system.

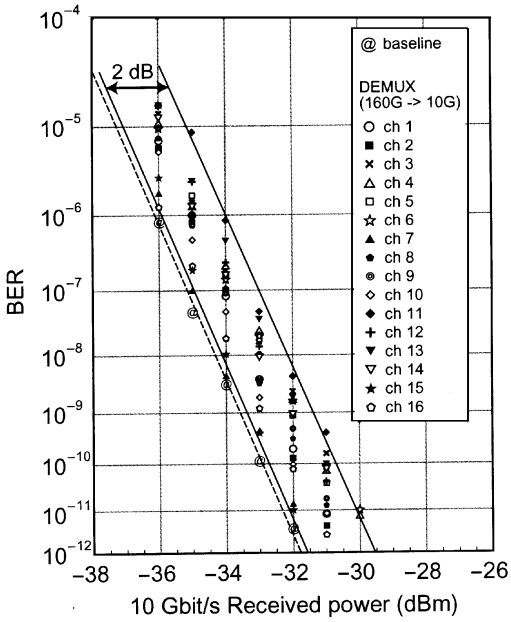


Fig. 5. BER performance. BER was measured after demultiplexing to 16 × 10 Gb/s.

5-dB improvement in normalized conversion efficiency η, such that the output power would be increased by 10 dB. For example, an optimized waveguide fabricated using the technique described in [9] has recently been used to demonstrate wavelength conversion in a cascaded $\chi^{(2)}$ configuration with +2 dB external efficiency with only 175-mW pump power [14].

IV. Conclusion

An OTDM was constructed by integrating PLCs and PPLN waveguides. With this device, eight 20-Gb/s optical signals were successfully multiplexed into a 160-Gb/s OTDM signal. This device offers the advantages of compactness, high stability, and low noise.

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