Signal Processing Using All-optical Wavelength Conversion –Application using Hybrid-integrated XPM Device and SIPAS

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Abstract

The explosive demand for data traffic requires high-speed all-optical signal processing by wavelength conversion using a device such as a planar lightwave circuit (PLC) hybrid-integrated cross-phase modulation (XPM) device or monolithically integrated SIPAS. An XPM device operates with a low input power of –10 dBm and can be used to adjust the wavelength or monitor the polarization mode dispersion (PMD) of a WDM channel, while SIPAS provides high-speed operation. This paper reports bit-rate and format conversion between conventional high-speed (10 Gbit/s) NRZ signals and extremely high-speed (40 Gbit/s) RZ signals by multi-wavelength conversion. It also discusses PMD compensation, which is an important issue, especially for extremely high-speed signals.

1. Introduction

In the near future, the huge amount of data traffic will require a high bit rate of 10 Gbit/s, even in metropolitan networks, as shown in Fig. 1. The long-haul backbone network, which serves a number of metropolitan networks, will need an extremely high bit rate of more than 40 Gbit/s. Therefore, bit-rate conversion between 10- and 40-Gbit/s networks is indispensable, because most metropolitan users will not use the full 40-Gbit/s capacity. All-optical bit-rate conversion has the advantage of bit-rate independent operation and has the potential to overcome the speed limit of electrical devices. Prior to bit-rate conversion, a simple technique that adjusts the phase of the 10-Gbit/s channels is needed. Furthermore, the conversion should operate for any wavelength division multiplexing (WDM) channel wavelength.

For all-optical bit-rate conversion, extremely high-speed wavelength conversion using differential-phase modulation (DPM) is one of the most promising approaches [1], [2]. However, DPM devices usually need the return-to-zero (RZ) format, while 10-Gbit/s WDM systems use the non-return-to-zero (NRZ) format. This RZ format is also convenient for high-speed optical transmission, because the short-pulse RZ signal reduces the signal degradation from fiber nonlinearities, such as self-phase modulation [3], [4].

Bit-rate conversion is being developed at laboratories around the world. TDM-to-WDM conversion and WDM-to-TDM reconversion (TDM: time division multiplexing) have been demonstrated using a supercontinuum source [5]. TDM-to-WDM signal format translation has been achieved using bi-directional four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) [6] or monolithic Mach-Zehnder interferometer (MZI) module [7]. Mikkelsen *et al.* reported RZ-to-NRZ conversion using a monolithically integrated active Michelson interferometer [8]. However, a total experiment comprising bit-rate and format conversion/reconversion, as well as phase adjustment for any WDM channel, had not been done until the present work.

This paper reports a successful demonstration of full bit-rate conversion from 10-Gbit/s WDM channels of any wavelength to a 40-Gbit/s channel, including NRZ-to-RZ format conversion and reconversion. The key technique is wavelength conversion using a monolithic Sagnac Interferometer integrated with a Parallel-Amplifier Structure (SIPAS) [9]. The key

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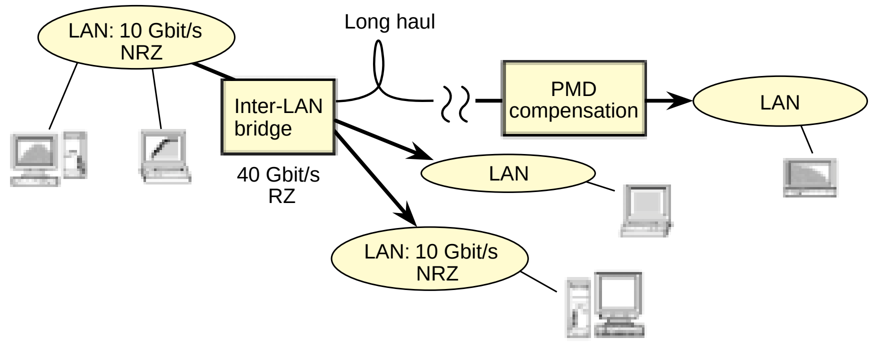

Fig. 1. Network configuration in the near future.

procedure, which is the phase adjustment of 10-Gbit/s signals, used slight wavelength conversion with hybrid-integrated cross-phase modulation (XPM) device [10].

Another important issue for extremely high-speed networks is the compensation of polarization mode dispersion (PMD). Monitoring the state of the differential group delay (DGD) is indispensable for PMD compensation, as shown in Fig. 2, and several approaches have been implemented using electronic circuits. A simple method for monitoring DGD is to measure the intensity of half the frequency of the input signal. This is an elegant method because it requires only a photodiode (PD), a narrow band-pass filter (BPF), and a power meter [11], [12]. However, it requires a high-speed PD, which limits network speed upgrades to 100 Gbit/s. The BPF should be strictly adjusted to the input frequency, which disturbs the bit-rate transparency of photonic networks.

For PMD compensation of extremely high-speed signals (> 80 Gbit/s), optical monitoring techniques are expected. Rosenfeldt et al. performed the world's first demonstration of PMD compensation at 80 Gbit/s, using a polarization-resolved evaluation of the degree of polarization (DOP) combined with a polarization scrambler at the fiber input [13]. Another technique for 160-Gbit/s compensation monitors the eye opening of the data signals using an optical sampling eye monitoring method [14]. This technique provides the most reliable information because the eye opening has a high correlation with the bit error rate (BER), which is the final target for improvements. However, both techniques may need expensive equipment for each WDM channel, which would make them difficult to apply to large WDM systems with numerous channels.

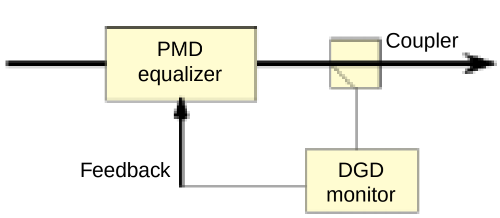

Fig. 2. Configuration of PMD compensator.

We have proposed a novel technique for monitoring the DGD state of an optical fiber using a hybrid integrated wavelength converter. Thanks to the XOR operation of the wavelength conversion, this technique is bit-rate-independent and format-independent. Hybrid integration is very attractive because a planar lightwave circuit (PLC) can easily implement a polarization beam splitter (PBS), one of the key components for PMD compensation. By monitoring the output power from the wavelength converter, we successfully compensated for the PMDs of 40- and 80-Gbit/s RZ, 40-Gbit/s NRZ, and 20-Gbit/s Manchester format signals. The measured power penalty was less than 0.8 dB.

2. Bit-rate conversion

2.1 Configuration for full bit-rate conversion

The configuration of the demonstration system is shown in Fig. 3. The key features are as follows.

I) NRZ/RZ and MUX

Four 10-Gbit/s NRZ WDM channels with a 100-GHz channel spacing (A) were launched into a polarization-independent electro absorption (EA) modulator [15] with 10-GHz sinusoidal modulation. The modulator simultaneously converted the four NRZ signals to RZ ones with a pulse width of 25 ps (B). A fiber loop was used to arrange the piled-up RZ pulses into a serial bit-stream (MUX), using with a single modulator and a single fiber, which is a simple and extensible technique for bit-stream formation. This technique can also be used in larger-scale WDM systems, e.g., ones with 8 or 16 channels.

II) Wavelength fitting and phase adjustment

In confirming NRZ/RZ and MUX operation, there are two important issues: the channel spacing, which must be nearly equal, and the phases of the four WDM channels, which must be adjusted. Using a multi-channel XPM module, we arranged the input WDM channels to have an equally spaced fixed wavelength. Then a small wavelength adjustment (e.g., 0.1 nm) provided a phase shift at the fiber loop, which assured the phase adjustment at the EA modulator. Thermal tuning of the CW source achieved this phase adjustment.

III) Bit-rate conversion using SIPAS

For 40-Gbit/s bit-rate conversion, four different wavelengths of the multiplexed bit-stream were converted to a single wavelength by using a SIPAS with a gating window of less than 25 ps (C in Fig. 4). DPM can compensate for the slow carrier recovery time of SOAs to achieve high-speed wavelength conversion. The SIPAS has low wavelength dependency and offers the possibility of filter-less operation.

IV) DEMUX and RZ/NRZ

An EA modulator was also used to demultiplex the converted 40-Gbit/s stream to the 10-Gbit/s RZ format (D in Fig. 4). Another DPM device with a gating window of 100 ps enlarged the pulse width, thus completing the 10-Gbit/s RZ-to-NRZ reconversion (E in Fig. 4).

2.2 Experimental results for full bit-rate conversion

The experimental setup is shown in Fig. 4. Four 10-Gbit/s WDM channels were converted to equal spacing using a multi-channel PLC-SOA hybrid integrated MZI module. The continuous wave (CW) and average signal powers of the XPMs were -2 to 2 dBm. A 10-MHz clock with a wavelength of 1310 nm was supplied, utilizing the unoccupied port of the XPM module. This clock is indispensable for synchronization of bit rate conversion. The four converted signals were coupled to an optical fiber with dispersion of 150 ps/nm. Therefore, a small wavelength adjustment of less than 0.5 nm provided a phase shift of 75 ps. Four phase-adjusted WDM channels with 100-GHz spacing from 1552 to 1555 nm were launched into an EA modulator with 10-GHz 4V sinusoidal modulation (A and B in Fig. 4). A second 2-km fiber loop with a total wavelength dispersion of –25 ps per 100 GHz was used to arrange the piled-up RZ pulses into a serial bit-stream with a pulse width of 25 ps. Part of the bit-stream was monitored and the wavelengths converted by the XPM modules were controlled to keep the most suitable values.

10- to 40-Gbit/s bit-rate conversion was done using DPM in a SIPAS. Four different wavelengths of the multiplexed bit-stream were converted to a single wavelength (1551 nm) by using the SIPAS with a gat-

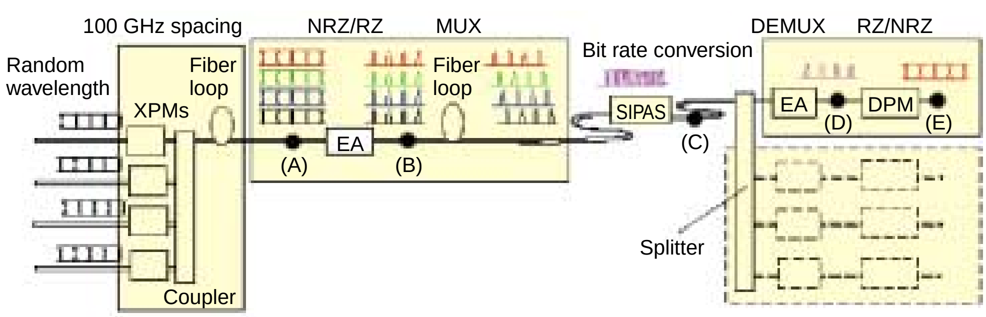

Fig. 3. Configuration of full bit-rate conversion.

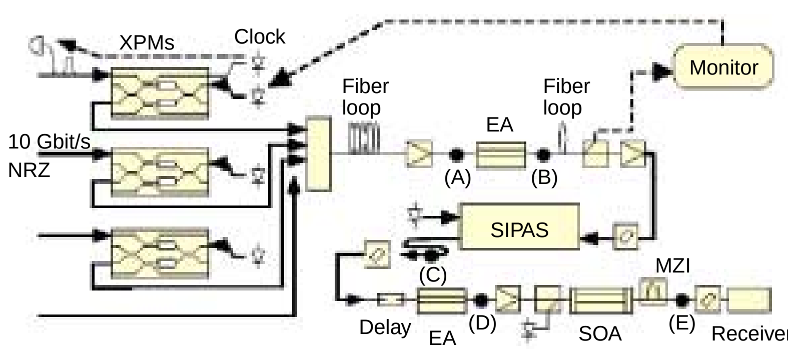

Fig. 4. Experimental setup of full bit-rate conversion.

ing window of less than 25 ps (C in Fig. 4). The CW and averaged signal powers were about 10 dBm. The current of the SOAs was about 200 mA.

A second EA modulator was used to demultiplex the 40-Gbit/s stream into 10-Gbit/s RZ format (D in Fig. 4). Another DPM device, consisting of a spot-size converter SOA (SS-SOA) and a PLC asymmetric MZI with a gating window of 100 ps, enlarged the pulse width, thus completing 10-Gbit/s RZ-to-NRZ conversion (E in Fig. 4). The input current of the SS-SOA was 80 mA. The CW and signal powers were about 0 dBm.

Figure 5 shows the four 10-Gbit/s bit stream signals before the SIPAS. By adjusting the wavelength of channel #3 by 0.1 nm (phase shift of 15 ps), we could avoid the cross point of the NRZ signal. Figure 6 shows the eye patterns measured at points A to E, shown in Fig.4. Clear eye openings were observed for NRZ-to-RZ conversion (Fig. 6(b)), 10-to-40-Gbit/s conversion (Fig. 6(c)), 40-to-10-Gbit/s reconversion (Fig. 6(d)), and RZ-to-NRZ reconversion (Fig. 6(e)). Figure 7 shows the BERs at points (A) to (E). The receiver sensitivity at a BER of 10^{-9} was less than -32 dBm. Only a small power penalty of less than 0.8 dB was observed. These results indicate that the above techniques will be useful for future bit-rate conversion.

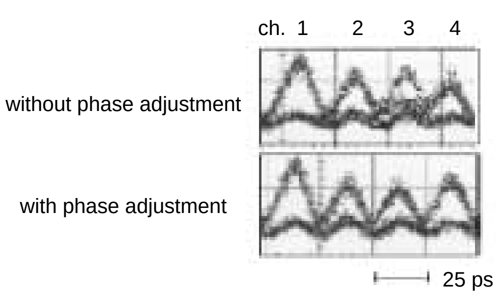

Fig. 5. Eye patterns before the SIPAS.

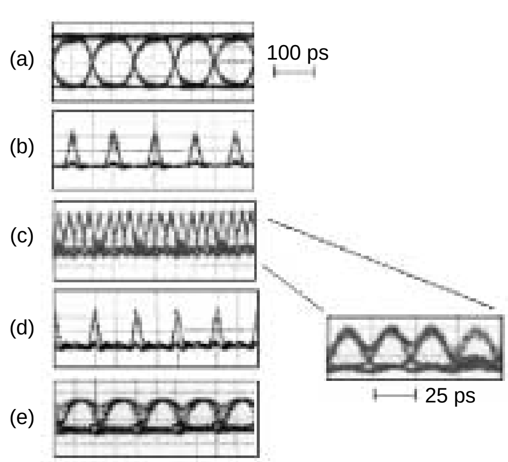

Fig. 6. Eye patterns of full bit-rate conversion.

3. PMD compensation

3.1 DGD monitoring technique using a hybrid integrated wavelength converter

Figure 8 shows a schematic view of the hybrid integrated XPM device. We use PLC hybrid integration, which is attractive for constructing optical modules with fiber array pigtails.

The DGD monitoring technique is as follows. The input optical powers of the polarization states (TE and TM) are each fed to both arms of the XPM device. The device is normally set to the cross state. This minimizes the output power of the converted light at the bar port, which is the monitor port of the DGD. If a large DGD exists, the phase difference between the two arms switches the converted light from the cross port to the monitor bar port, whose output power increases as shown in Fig. 9. A minimum output power means the DGD value is also at the comfortable minimum state, which should be kept by controlling the PMD equalizer. As a result, the XPM device operates as an XOR circuit. The monitor port shows "0" when the input powers of the two arms are equal, while it shows "1" when they are unequal, as shown in Fig. 10. This circuit has the

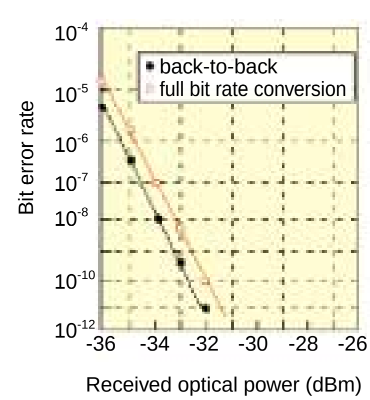

Fig. 7. BER of full bit-rate conversion.

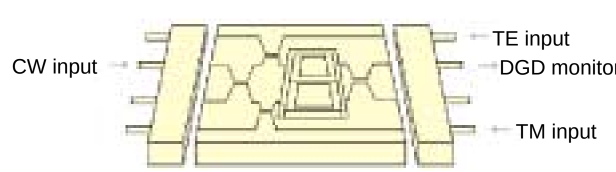

Fig. 8. DGD monitor using hybrid integrated XPM device.

potential to work at >100 Gbit/s, because the push-pull switching mechanism of DPM cancels the slow relaxation of the induced refractive index change [16].

3.2 Experimental setup and results

Figure 11 shows the experimental setup for PMD compensation. We used four types of optical signals: 40-Gbit/s RZ and NRZ signals, a 20-Gbit/s Manchester signal, and an 80-Gbit/s RZ signal.

To emulate the waveform distortion caused by PMD, we prepared a polarization-maintaining fiber (PMF) whose DGD between the fast and slow axes was about 30 ps. The power ratio between the two principal polarization states was changed from 0 to 10 dB by adjusting the polarization controller (PC) before the PMF.

To equalize the PMD, a second PC and a variable DGD emulator were used. Part of the signal was divided for monitoring, and its polarization states were divided by a bulk PBS module. The optical powers of the divided two polarization states were equalized to within 1 dB using the SOAs and each was fed to both arms of the hybrid integrated wavelength converter. The optical lengths between the PBS and the wavelength converter arms were equalized using optical delay lines. Of course, this optical length adjustment can be achieved easily if the integrated PLC-PBS is used. The wavelength converter has input power monitor ports with power meters, which make it possible to adjust the optical power of both arms.

A DFB laser with a wavelength of 1552 nm was used as the optical source of the XPM device. With SS-SOA current biases of 80 and 82.5 mA, the XPM device was normally set to the cross state. It operates as an XOR circuit. The output power from the XOR circuit (bar port) was minimized by controlling the PMD equalizer. The optical signal, after PMD compensation, was optically demultiplexed to 10-Gbit/s RZ format using an EA modulator, and the BER was evaluated.

Figure 12 shows the eye patterns for the 40-Gbit/s RZ, 40-Gbit/s NRZ, and 20-Gbit/s Manchester signals. Though large waveform distortions were observed before PMD compensation, a clear eye pattern was observed afterwards. Figure 13 shows the BER for RZ and NRZ formats. The power penalty was less than 0.8 dB. These results confirm that format-independent PMD compensation was achieved

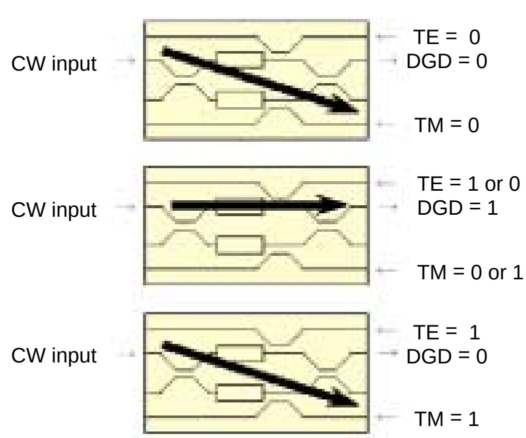

Fig. 9. Principle of DGD monitor using hybrid integrated XPM device.

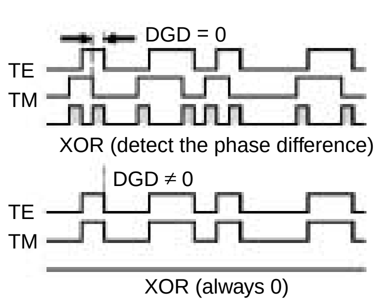

Fig. 10. Operation of a DGD monitor as an XOR circuit.

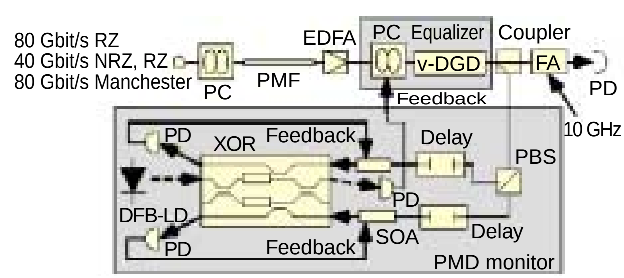

Fig. 11. Expermental setup of PMD compensator.

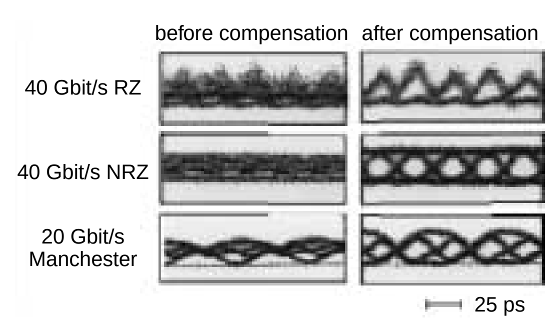

Fig. 12. Eye patterns for 40-Gbit/s RZ, 40-Gbit/s NRZ, and 20-Gbit/s Manchester format signals.

by the hybrid integrated wavelength converter.

Figure 14 shows the eye patterns for 80 Gbit/s, with DGDs of 12.5 and 25.0 ps. Again, clear eye patterns were observed after PMD compensation. The compensated optical signal was optically demultiplexed to 10 Gbit/s by the SIPAS, and the BER was evaluated. The minimum received optical power at BER of 10^{-9} was -21 dBm, and the power penalties were less than 0.9 dB. These results confirm the extremely high bit-rate operation of the all-optical XOR circuit.

4. Conclusion

The extremely high-speed network expected in the near future will require bit-rate conversion and polarization mode dispersion (PMD) compensation. This paper described novel techniques using all-optical signal processing. Full bit-rate conversion was successfully demonstrated using a monolithically integrated SIPAS. Bit-rate-independent and format-independent PMD compensation has been achieved using a hybrid integrated cross phase modulation (XPM) device.

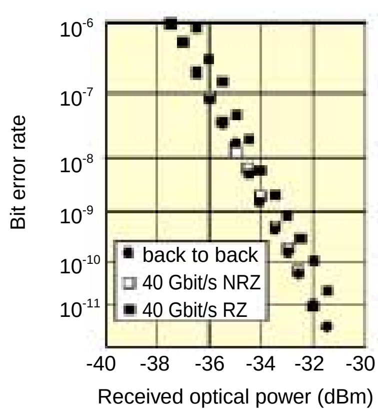

Fig. 13. BER for 40-Gbit/s RZ and 40-Gbit/s NRZ signals.

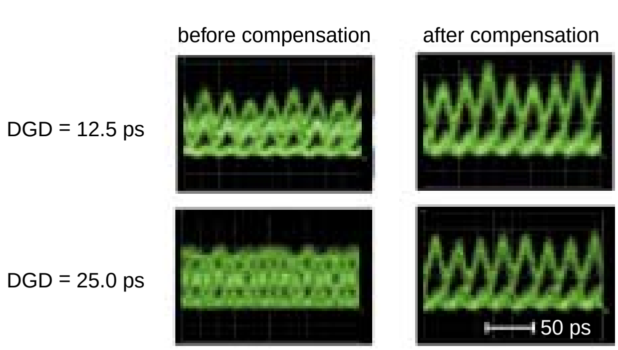

Fig. 14. Eye patterns for 80-Gbit/s RZ signals.

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