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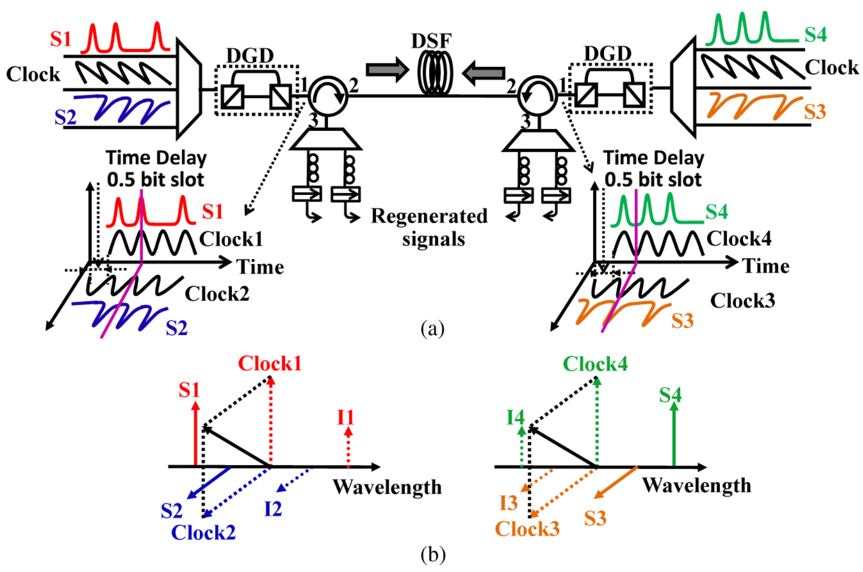

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Simultaneous 3R Regeneration of 4 x 40-Gbit/s WDM Signals in a Single Fiber

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Abstract: We experimentally demonstrate simultaneous 3R regeneration of 4 $\times$ 40-Gbit/s WDM channels, which is based on the four-wave mixing (FWM) in a single dispersion-shifted fiber. The multichannel 3R regeneration performance is validated by bit-error rate (BER) measurements. Receiver powers at a BER of 10^{-9} are improved by 5.2 dB, 4.8 dB, 3.3 dB, and 3.9 dB for the four WDM channels, respectively. Mitigation of the interchannel nonlinearities is achieved mainly through an interchannel 0.5-bit slot time delay, which is introduced by differential group delay. Bidirectional propagation and polarization multiplexing are also applied to relieve the interchannel FWM.

Index Terms: Multiwavelength all-optical 3R regeneration, four-wave mixing (FWM), all-optical signal processing, optical communication.

1. Introduction

All-optical regeneration is one of the highly desirable functionalities for future optical communication systems, where the optical signal-to-noise ratio (OSNR) requirements become very strict [1]. It is believed that they can operate more power efficiently than optical–electrical–optical (OEO) regenerators at network nodes. Single-channel all-optical regeneration has been demonstrated using different devices, such as highly nonlinear fiber (HNLF), semiconductor optical amplifier (SOA), periodically poled lithium niobate (PPLN), and silicon nanowire [2]–[8], among which the highest data rate of single-channel regenerator has been achieved to be 640 Gbit/s [6]. However, it would be very beneficial if such a high-speed optical regenerator could process multichannel signals at the same time. As most transmission today is based on wavelength-division multiplex (WDM) systems, it would be also power efficient to regenerate WDM signals using a single device, although it has been so far considered quite difficult. In addition, multichannel processing using a single device can be only done in an all-optical way instead of OEO method.

Most of the demonstrated multichannel regeneration schemes are based on fiber nonlinearities. However, interchannel interferences such as cross-phase modulation (XPM), cross-gain modulation (XGM), and four-wave mixing (FWM) usually limit their performance. Self-phase modulation (SPM)-based schemes (Mamyshev regenerator) have been proposed for multichannel 2R regeneration [9]–[12]. In these cases, some kinds of multiplexing (e.g., polarization and direction) are applied to relieve interchannel XPM and FWM [9]–[12]. In paper [10], in order to process 4 $\times$ 10-Gb/s WDM channels simultaneously, data signals with very short pulse duration (corresponding to wide bandwidth in the frequency domain) are required to reduce the interchannel interference. It would

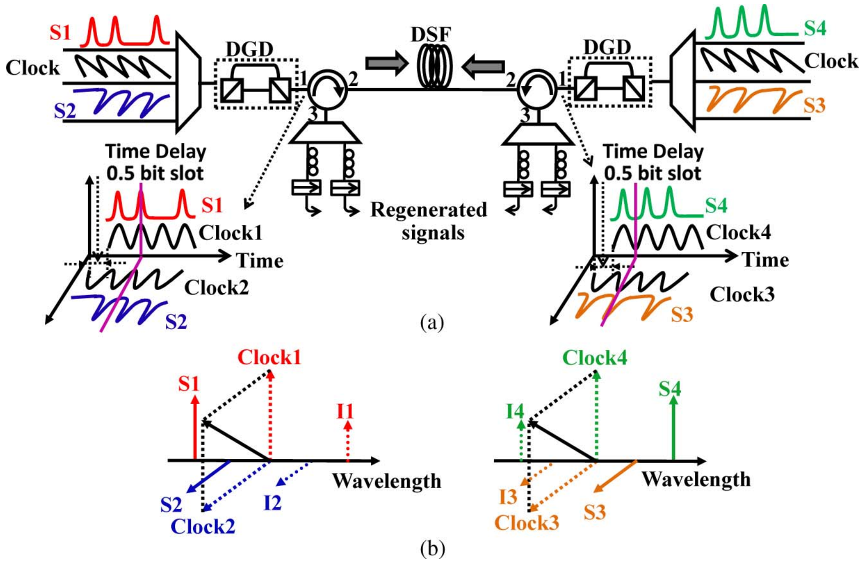

Fig. 1. (a) Principle of regenerator operation for 4 × 40-Gbit/s WDM signals, which is based on FWM in a single fiber. (b) Wavelength position of the four WDM signals and the clock.

be more desirable if this scheme could process data signals with practical pulse duration (e.g., 33% or 50% duty cycle). In additional, only a few of the demonstrated multichannel regeneration schemes [13]–[15] have shown 3R regeneration, in which multichannel retiming unit is included.

In this paper, we demonstrate simultaneous all-optical 3R regeneration for 4 × 40-Gbit/s return-to-zero on–off keying (RZ-OOK) WDM channels, which is based on the FWM in a dispersion-shifted fiber (DSF). A 0.5-bit slot time delay between the two copropagating signals introduced by differential group delay (DGD) can mitigate the interchannel interference. The duty cycle of the degraded data pulse is 50%. Bidirectional propagation in the fiber and polarization multiplexing are also used to relieve the FWMs among the four channels. The regeneration performances are confirmed by bit-error rate (BER) measurements.

2. Principle and Experimental Setup

Fig. 1(a) shows a schematic of the regenerator. By using bidirectional propagating of four channels at different wavelengths, simultaneous regenerating of four WDM channels can be achieved. To suppress the interchannel FWM between the two signals propagating in the same direction, the two data signals are polarization orthogonally multiplexed. However, the interchannel FWM cannot be completely suppressed due to the limited polarization extinction ratio (PER) of the device. To further reduce interchannel FWM and mitigate the interchannel XPM and XGM, a DGD in the regenerator is used to introduce a 0.5-bit slot time delay between the two channels with orthogonal polarizations in the same direction. When the data signal and clock of one channel are at the pulse peak, those of the other channel will be at the pulse bottom, shown in Fig. 1(a). In this way, the FWM, XPM, and XGM between orthogonally polarized channel pairs will be suppressed sufficiently. S1, S2, and the clock are fed into the DSF in the forward direction, and S3, S4, and the clock in backward direction. The resulting output signals are then separated by filters and polarizer.

Fig. 1(b) shows the wavelength positions of four WDM data signals for the regenerator setup. The wavelengths of four data signals are at S1, S2, S3, and S4, respectively. The clock signal is generated from the clock recovery unit, and the wavelength is at the middle of the data signals. The regenerator includes a polarization controlling stage in order to make the data signals and clock linearly polarized, S1 and S2 orthogonal to each other, and the same for S3 and S4. The clock polarization is adjusted to 45° with respect to all signals polarizations. The clock signal acts as pump and generates reshaped and retimed data signals replica on the idler wavelengths based on

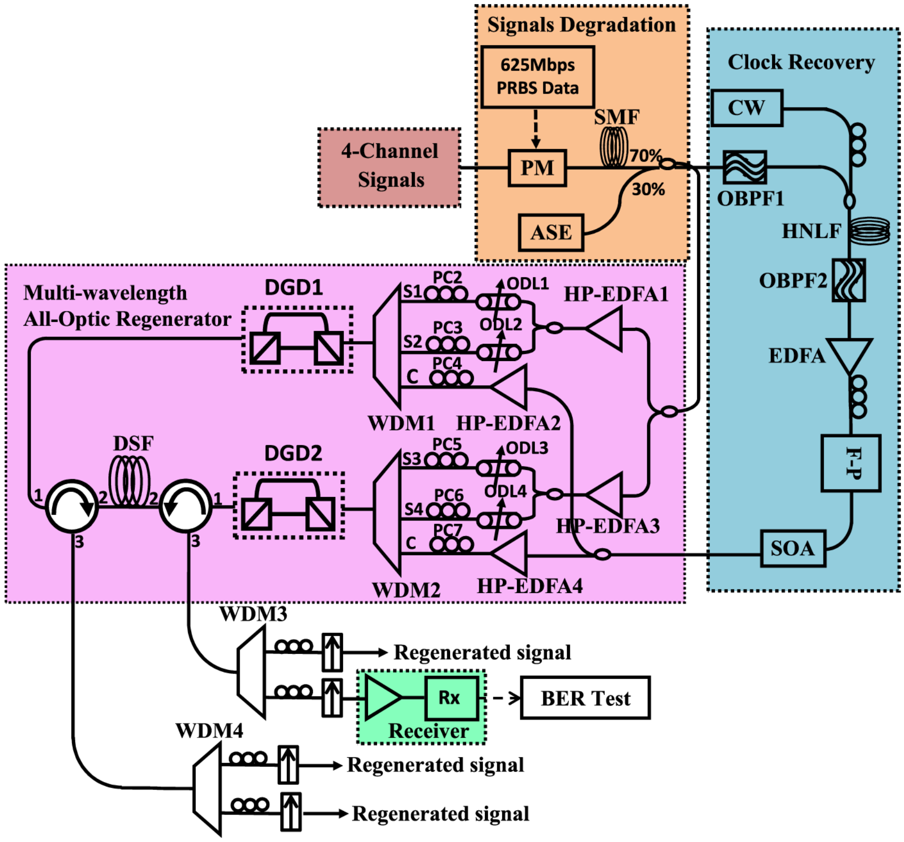

Fig. 2. Experimental setup of the 3R regeneration for 4 $\times$ 40-Gbit/s WDM signals.

the parametric saturation in the fiber. The wavelengths of S1 and S4 are symmetric relative to the clock and the same for the S2 and S3. Note that regenerated S1 and S2 (I1 and I2) are at the same wavelengths with S4 and S3 in this scheme (the same for I4 and I3 with S1 and S2). In this way, the four output wavelengths of the regenerator did not occupy more bandwidth compared with the four input wavelengths, which are in compliance with the international telecommunication union (ITU) standard.

The experimental setup of the 3R regeneration of 4 $\times$ 40-Gbit/s WDM signals is shown in Fig. 2. It mainly includes 4 $\times$ 40-Gbit/s WDM transmitter, signals degradation, clock recovery unit, multi-wavelength all-optical regenerator, and a 43-Gbit/s preamplified receiver with a BER test.

The 4 $\times$ 40-Gbit/s WDM signals are generated by simultaneously amplitude modulating four continuous-wave (CW) lights (the wavelengths of which are 1547.72 nm, 1550.92 nm, 1557.36 nm, and 1560.61 nm, respectively) with a 40-GHz sinusoidal clock, followed by an amplitude modulation with a 40-Gbit/s pseudorandom bit sequences (2^7-1 PRBS). The generated four WDM signals are launched into the degradation unit. In the degradation unit, the four signals are phase modulated with an asynchronous 625-Mbit/s PRBS (2^7-1) signal. A 2-km single-mode fiber (SMF) with a dispersion of 34 ps/nm converts the asynchronous phase modulation into the random timing jitter. At the same time, the data signals are also distorted by the dispersion. The amplitude noise is introduced by adding a broadband amplified spontaneous emission (ASE) noise about -3 dBm (total four data signals power is 3 dBm) generated from an erbium-doped fiber amplifier (EDFA) [16].

The clock recovery unit is based on wavelength conversion and a high-finesse Fabry–Pérot (F–P) filter. The degraded S1 is selected by an optical bandpass filter (OBPF1). S1, together with a CW signal at 1553.82 nm, is launched into a HNLF for XPM-based wavelength conversion. A 0.5-nm OBPF2 centered at 1554.1 nm is used to extract the wavelength converted signal. The converted signal copied the whole information of S1 and the wavelength of the converted signal exactly meets

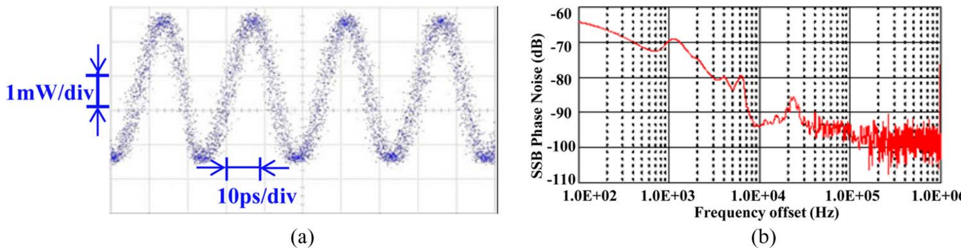

Fig. 3. (a) Waveform of the 40-GHz recovered clock (b) SSB phase noise of the 40-GHz extracted clock.

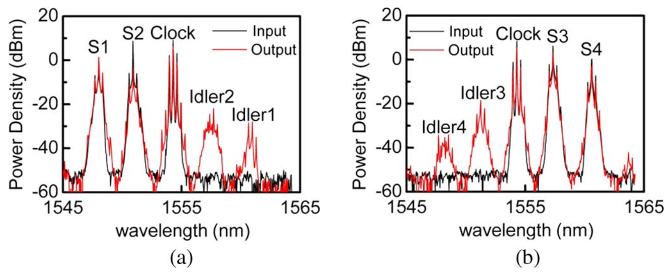

Fig. 4. Spectrum in and out of the DSF (a) forward and (b) backward.

one of the transmission peaks of F–P filter in order to extract the clock information from the converted signal. The wavelength converted signal is injected into the F–P filter with a free-spectral range (FSR) of 40 GHz and a finesse of 1000. Finally, the extracted clock pulses, with an average power of 0 dBm, are launched into a SOA to reduce the low-frequency amplitude noise based on self-gain-modulation effect [17]. The bias current of the SOA is set to 200 mA.

In the multiwavelength all-optical regenerator, S1 and S2 are amplified by a high-power EDFA (HP-EDFA1). The recovered 40-GHz clock is amplified by the HP-EDFA2. The output power of HP-EDFA1 and HP-EDFA2 are 24.1 dBm and 23 dBm, respectively. The two signals and the clock are combined together by the WDM1 and then launched into the DGD1. The polarization controllers (PC2 and PC3) are used to align the polarization of the incoming signals (S1 and S2) to the axis of the DGD1.

The clock polarization is 45° with respect to the axis of the DGD1. Two optical delay lines (ODL1 and ODL2) are used to align the two signals (S1 and S2) to the clock when they are launched into the DGD1. A 0.5 bit slot time delay is introduced by DGD1 between the two signals. It is same for the S3, S4, and the clock with the DGD2. The output power of HP-EDFA3 and HP-EDFA4 are 25 dBm and 23 dBm, respectively. Two circulators placed on both sides of a 3.2-km DSF (zero-dispersion wavelength at 1553 nm, dispersion slope $S = 0.077$ ps/nm^2/km, nonlinear coefficient $\gamma = 4.8$ W^{-1}km^{-1}) are used to separate the signals counter-propagating in the fiber. The idlers of the FWMs are filtered by the WDM3 and WDM4. The PER of the DGD is 21 dB; thus, there are still some crosstalk between the copropagating two data signals. The polarization controllers and polarizer are required at the output of WDM3 and WDM4 to remultiplex the regenerated signals.

3. Results

In the clock recovery unit, the waveform of the recovered 40-GHz clock is shown in Fig. 3(a). Fig. 3(b) shows the single-sideband (SSB) phase noise of the recovered clock. The SSB phase noise is -92.67 dBc/Hz at 10 kHz and the calculated root-mean-square (RMS) timing jitter is 180 fs according to the equation provided in paper [18] (in the 100 Hz $\sim$ 1 MHz frequency range).

The spectra at the input and output of the DSF for the two directions are shown in Fig. 4. The spectra of all data signals after FWM are broadened a little due to self-phase modulation, but they are not overlapped with each other. The eye diagrams of the four data signals before and after the

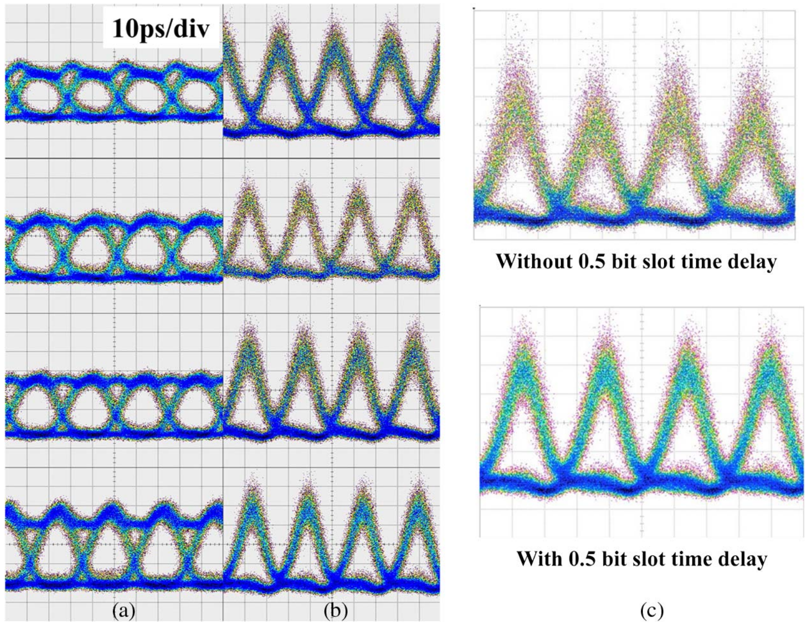

Fig. 5. 40-Gbit/s eye diagrams of (a) Degraded and (b) Regenerated data signals for Ch1, Ch2, Ch3, and Ch4 from top to bottom (c) Regenerated eye diagram comparison without/with 0.5 bit slot time delay for channel 4.

TABLE 1

Improvement of the ER and the RMS timing jitter

Channel Deg./Reg.	Ch1 Deg./Reg.	Ch2 Deg./Reg.	Ch3 Deg./Reg.	Ch4 Deg./Reg.
ER (dB)	9.9/12.2	9.4/13.6	10.2/15.7	8.3/13.0
Jitter (ps)	2.7/1.5	2.1/1.4	2.2/1.5	2.6/1.2

3R regeneration are shown in Fig. 5(a) and (b). We can see the eye diagrams of the 4 $\times$ 40-Gbit/s RZ-OOK signals are improved after the 3R regeneration. Fig. 5(c) shows experimental regenerated eye diagram comparison for channel 4 on performance of the multichannel regenerator with and without the 0.5-bit slot time delay. The regenerated eye diagram without 0.5-bit slot time delay is obviously much noisier than that with 0.5-bit slot time delay. It can be concluded that the 0.5-bit delay is of crucial importance and playing a key role here. The extinction ratio (ER) has been improved by 2.3 dB (Ch1) to 5.5 dB (Ch3). The improvements of the ER and the RMS timing jitter are shown in Table 1. It should be noted that the RMS timing jitter of the degraded and the regenerated data signals are measured by the digital communication analyzer (DCA; Agilent 86100A). Timing jitter of the regenerated data signals seems worse than the extracted clock signal due to the limited resolution of the oscilloscope, but the timing jitters of all the degraded data signals have been improved.

BER measurements are performed for all the channels as a function of received power at the 43-Gbit/s receiver, shown in Fig. 6. The degradation of the data signals causes about 8.2 dB, 7.8 dB, 7.1 dB, and 6.9 dB (for Ch1, Ch2, Ch3, and Ch4, respectively) power penalty at the BER of 10^{-9} compared with the back-to-back (B2B) cases. We performed two measurements for the 4 $\times$ 40-Gb/s 3R regeneration. These are regenerations with other three channels off (single-channel regeneration) and with other three channels on. After regeneration with other three channels off, the receiver powers at the BER of 10^{-9} are improved by 6.1 dB, 6.7 dB, 4.5 dB, and 4.4 dB (for Ch1, Ch2, Ch3, and Ch4), respectively. However, the receiver powers at a BER of 10^{-9} are improved by

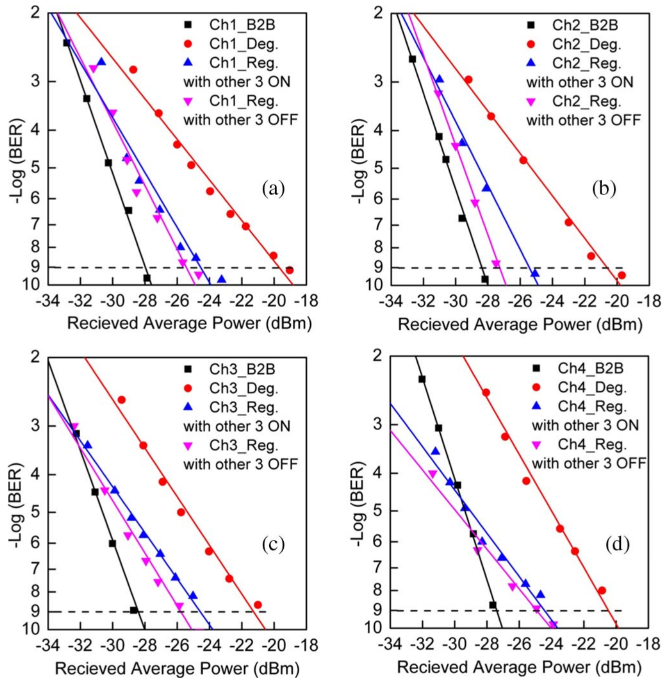

Fig. 6. BER measurements for the 4 $\times$ 40-Gbit/s signals back to back, degraded signals and regenerated signals. (a) Ch1 (b) Ch2 (c) Ch3 (d) Ch4.

5.2 dB, 4.8 dB, 3.3 dB, and 3.9 dB for the four channels with the other three channels on. The difference is mainly due to the limited PER of the DGD at the input and polarization coupling between copropagating data signals with orthogonal polarization in the DSF. The performance of the regeneration with all channels on could be improved by using a polarization-maintaining DSF (PM-DSF). The slopes of the BER curves are different, which is a result of different receiver responses at different wavelengths.

4. Conclusion

We have demonstrated simultaneous 3R regeneration of 4 $\times$ 40-Gbit/s WDM signals based on parametric saturation in a DSF. In our scheme, an interchannel 0.5-bit slot time delay is introduced by a DGD to mitigate the interchannel interference. The four-wavelength 3R regeneration is realized by bidirectional operation in a fiber and orthogonal polarization for copropagating signals. After 3R regeneration, the RMS time jitter and the ER of the four channels have been improved. The four-wavelength 3R regeneration performances are confirmed by BER measurements. The 5.2-dB, 4.8-dB, 3.3-dB, and 3.9-dB received power improvements at the BER of 10^{-9} are obtained for the four channels, respectively.

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