4-wavelength 2R regeneration based on self-phase modulation and inter-channel walk-off control in bidirectional fiber configuration

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ABSTRACT

We propose a novel multi-wavelength regeneration scheme in which timing walk-off on different WDM channels is controlled to avoid the overlapping of the channels in time domain such that effective mitigation of the nonlinear inter-channel impairments can be obtained, and the number of supported channels in the regeneration is increased by applying a bidirectional fiber configuration. In our scheme, optical 2R regeneration is successfully demonstrated for four 10-Gb/s RZ-OOK WDM channels spaced by 300 GHz. Both the scalability and the cascadability of our proposed regenerator were also evaluated in numerical simulations.

Keywords: 2R regeneration, self-phase modulation, nonlinear crosstalks, timing walk-off

1. INTRODUCTION

The multi-wavelength application of the optical 2R regeneration based on self-phase modulation (SPM) followed by offset filtering (also known as the Mamyshev technique[1]) is always a challenge due to the severe nonlinear inter-channel crosstalks, i.e., cross-phase modulation (XPM) and four-wave mixing (FWM). To date, only a few schemes have been proposed to mitigate those nonlinear interactions among different WDM channels such that the multi-wavelength operation of the Mamyshev regenerator can be realized. Those approaches can be mainly divided into two categories. The first type relies on a suitable design of the fiber dispersion map which can induce fast walk-off time between different WDM channels, by using large channel spacing (e.g. 600 GHz). This fast walk-off time induced on the WDM channels can average out the phase shifts due to the XPM caused by the other channels, thus weakening the nonlinear inter-channel crosstalks in the regeneration[2,3,4]. The second type makes use of the polarization multiplexing in a polarization maintaining bidirectional HNLF configuration with the polarization control[5]. The polarization multiplexing separates the WDM channels in polarization and hence can reduce their nonlinear crosstalks.

In this paper, we propose to use the timing walk-off control on different WDM channels to avoid their overlapping in time domain such that the nonlinear inter-channel impairments can be effectively mitigated. The number of supported channels in the regeneration is increased by applying a bidirectional fiber configuration. In our experiment, we demonstrated optical 2R regeneration for four 10-Gb/s WDM channels spaced by 300 GHz. In addition, our numerical simulation results show the scalability and the effectiveness of the proposed regenerator to support up to ten 10-Gb/s WDM channels.

2. SYSTEM ARCHITECTURE OF THE REGENERATOR

Fig. 1 shows the system architecture of our proposed multi-wavelength 2R regenerator based on SPM and inter-channel walk-off control. The input signals to the regenerator are multiple degraded WDM signals. In order to mitigate the nonlinear inter-channel crosstalks, i.e., XPM and FWM, we introduce the timing walk-off control on different WDM channels. This control mechanism is employed to guarantee that the pulses on different wavelength channels do not have overlapping in time domain when they propagate through and induce SPM in the highly nonlinear fiber. As a result, the nonlinear crosstalks generated by XPM and FWM can be mitigated. The WDM signals, after proper inter-channel walk-off control and amplification by EDFA, are interleaved into two groups and launched into the 2-km highly nonlinear fiber from the two ends for SPM-induced spectral broadening. Here the use of the bidirectional HNLF configuration can

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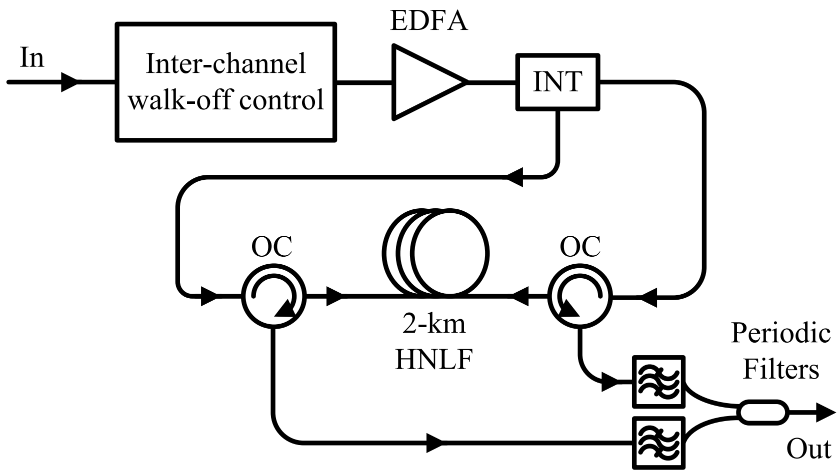

Figure 1. Proposed system architecture of the multi-wavelength 2R regenerator based on SPM and inter-channel walk-off control. EDFA: erbium-doped fiber amplifier; HNLF: highly nonlinear fiber; INT: interleaver; OC: optical circulator.

increase the number of supported channels in the regeneration. At last, offset filtering is applied to the spectrally broadened signals from both sides of the fiber. It is noted that sufficient channel spacing between different WDM channels should be assigned to prevent the possible spectral overlapping (linear crosstalk) due to the SPM-induced spectral broadening of the WDM signals. Actually, the use of bidirectional fiber configuration also helps improve the spectral efficiency but Rayleigh backscattering effect is thus caused and needs to be investigated. In terms of the scalability of our proposed 2R regenerator, utilizing polarization multiplexing of the signals is one straight-forward approach to increase the number of supported channels in the proposed scheme, on condition that the polarization-maintaining HNLF and polarization controls are used. In addition, the increase of supported channel number can also be realized by time-interleaving more WDM channels within one signal's bit period using the inter-channel walk-off control. This method requires narrow signal pulses to prevent their timing overlapping and maintain good mitigation of the nonlinear inter-channel interactions among the WDM channels. Our numerical simulation results show that our proposed regenerator can be scaled up for supporting the 10x10-Gb/s WDM upgrade scenario using this inter-channel walk-off control. Actually the scalability of supported channel number of the regenerator in real implementations is mainly limited by the EDFA bandwidth and gain.

3. EXPERIMENTAL SETUP

To investigate and verify the regenerative performance of our proposed multi-wavelength regeneration scheme, we have experimentally demonstrated the all-optical 2R regeneration for four wavelength channels based on the setup shown in Fig. 2.

Since narrow signal pulses with high peak power are required in the scheme to generate sufficient SPM-induced spectral broadening for signal regeneration, the four RZ-OOK WDM signals at 10 Gb/s in our experiment were generated by super-continuum followed by spectrum slicing, as shown in Fig. 2(a). A mode-locked fiber laser (MLFL) at 1536 nm, with repetition rate and full-width at half-maximum (FWHM) of 10 GHz and 3.3 ps, followed by a high-power erbium-doped fiber amplifier (EDFA) was used to generate the super-continuum effect in a piece of 1-km dispersion-flattened highly nonlinear fiber (DF-HNLF), of which the zero-dispersion wavelength, the dispersion slope at 1550 nm and the nonlinear coefficient are 1550 nm, 0.01 $ps/nm^2/km$ and 11.2 $W^{-1} \cdot km^{-1}$, respectively. The average input power launched into the DF-HNLF for the super-continuum effect is 15 dBm. A following optical band-pass filter with a 3-dB bandwidth of 12-nm was used to suppress the side modes in the subsequent spectral slicing process through using a 16-port-to-16-port arrayed-waveguide grating (AWG) with 100-GHz channel spacing and 0.35-nm bandwidth for individual channel. The four useful WDM signals sliced out are at the wavelength from 1533.67 nm to 1540.78 nm and spaced by

300 GHz. Channel powers were equalized to minimize the possible performance variation of the four WDM signals in the later regeneration process. After the data modulation by an intensity modulator and power amplification by an EDFA, the four channels were launched into a spool of 80-km single mode fiber (SMF) followed by two dispersion-compensating modules, of which the dispersions are -680 ps/nm and -666 ps/nm at 1545 nm respectively, for the introduction of propagation impairments in the fiber transmission. Then the degraded WDM signals were input to the regenerator shown in Fig. 2(b). The inter-channel walk-off control in this experiment was realized by using the optical tunable delay lines. It is noted that this walk-off control can also be realized by using a single piece of SMF with suitably designed length in the actual implementation for bit-synchronous WDM signals with equal channel spacing, however, the additional pulse broadening induced by the SMF should be taken into account. Since we employed the bidirectional fiber configuration, two of the four WDM signals spaced by 600 GHz were operated in each propagation direction of the HNLF and the timing walk-off between the two channels in the same propagation direction was controlled to be the optimal 50 ps for the 10-Gb/s signals.

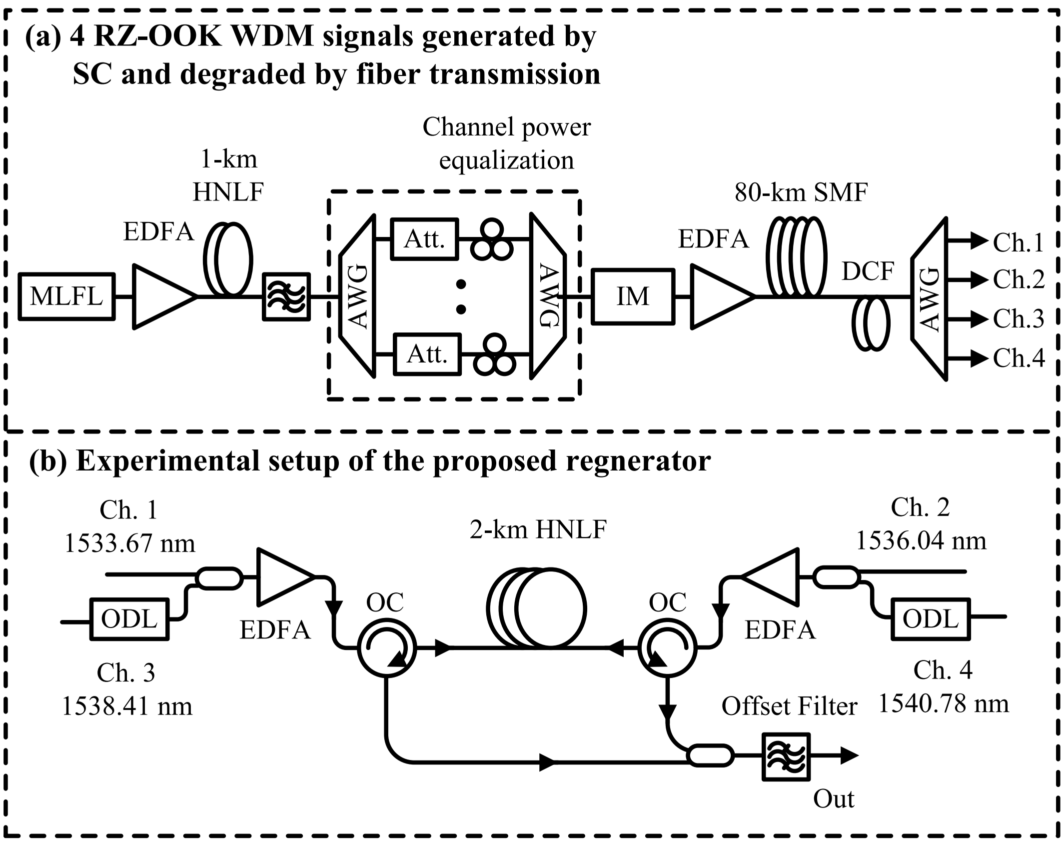

Figure 2. Experimental setup. MLFL: mode-locked fiber laser; IM: intensity modulator; Att.: attenuator; ODL: optical delay line. AWG: arrayed waveguide grating.

After the signals were amplified to have the average power of around 19.8 dBm at each fiber input, they are launched into a piece of 2-km HNLF, of which the zero dispersion wavelength, the dispersion slope and the nonlinear coefficient are 1550 nm, 0.019 ps/nm^2/km and 10.5 $W^{-1}\cdot km^{-1}$ respectively, from the two sides for the SPM-induced spectral broadening. Finally, a 0.3-nm bandwidth optical band-pass filter was used for offset filtering on the signals with 1.06-nm offset. It is worth noted that the scheme can be further upgraded to support 8 channels if polarization multiplexing is applied. Since wavelengths of the regenerated signal are shifted, even number of regenerators can be used in the transmission link if the wavelength-preserving inline regeneration is needed.

4. RESULTS AND DISCUSSIONS

Fig. 3(a) shows the eye diagrams of the four WDM channels before and after the regeneration, respectively. Those amplitude fluctuations on the signals' space levels are suppressed by the offset filtering as their power are not high enough to generate sufficient spectral broadening and hence are rejected by the filter, while the fluctuations on the mark levels is reduced since the pulses with larger power will experience larger loss and a self-regulating effect on signals' mark levels is thus obtained. We can see in Fig. 3(a) that clear eye openings are obtained for all the channels after regeneration as the nonlinear inter-channel crosstalks are significantly mitigated, thanks to the proper inter-channel timing walk-off introduced inside the regenerator. By comparison, the signal's eye can be totally close after regeneration, as shown in Fig. 3(b), without the proper inter-channel walk-off due to severe nonlinear interactions among channels. Effective extinction ratio improvements on the regenerated signals with proper walk-off control can be obtained due to the successful reduction of those amplitude noises on both the mark and the space levels. BER measurement was also carried out to confirm the regenerative performance of our proposed regenerator. The results are shown in Fig. 3(c). More than 4-dB improvements of the receiver sensitivity at BER of 10^{-9} were obtained for the regenerated channels. And we did not observe significant variation of the regeneration performance among different channels. In addition, no remarkable Rayleigh backscattering induced power penalty was noticed in the bidirectional fiber configuration used for the regeneration.

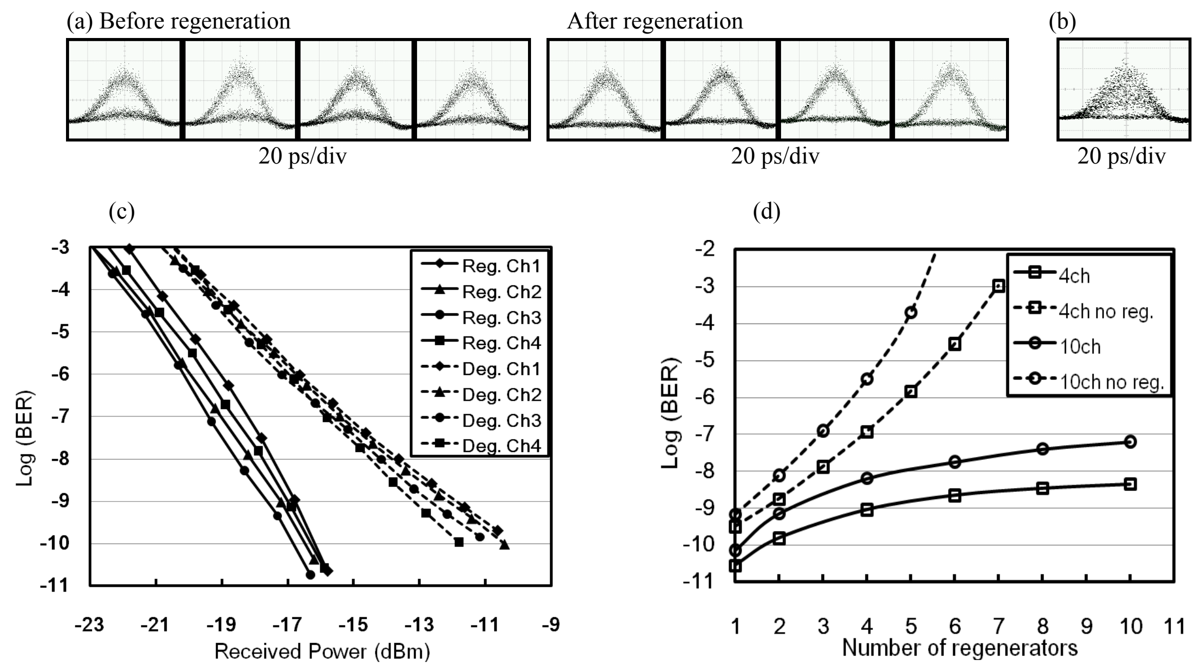

Figure 3. (a) Eye diagrams of the 4 channels before and after the regeneration, (b) Eye diagram of one regenerated WDM channel without proper inter-channel timing walk-off, (c) BER measurements of 4 channels before and after the regeneration, (d) BER evolution versus the number of inline regenerators for 4- and 10-channel operations in numerical simulation.

In addition, the salability and inline multi-stage regeneration of the regenerator were also investigated by numerical simulations. In our simulation, the regenerator can be scaled up to support ten 10-Gb/s WDM channels (five for each direction) with 1.6-nm channel spacing[6], and the optimal inter-channel timing walk-off for the 10-channel operation is 20 ps for every two channels spaced by 3.2 nm in each propagation direction. Fig. 3(d) shows the BER evolution of one of the WDM channels with the increased number of regenerators (one regeneartor for every span of 80-km SMF with full dispersion compensation). We can see that the use of regenerators gives a significant increase in the transmission distance with certain acceptable signal quality.

It should also be mentioned that proper timing walk-offs on the WDM channels are critical to the regeneration performance of our proposed scheme. The performance tolerance of our proposed regenerator to the improper timing walk-offs of channels is also evaluated in our experiment. Fig. 4 gives the receive sensitivity of channel 1 (at 1533.67 nm) at BER of 10^{-9} versus different timing walk-off values of channel 3 (at 1538.41 nm) in the same propagation direction in regeneration. As what we may expect, timing walk-off of around 50 ps gives the best regeneration quality of the signals due to the successful mitigation of the nonlinear inter-channel crosstalks because of the sufficient separation of the pulses on different channels in time domain. However, when the timing walk-off deviates from the optimal value, the timing overlapping of the pulses on different wavelength channels will gradually increase, leading to gradually degraded regeneration performance. In Fig. 4, we notice the eye closesure and about 3-dB power penalty of the signal when the timing walk-off is 30 ps away from the optimal value, due to the increase of nonlinear inter-channel crosstalks. The curve actually depends on the signal's pulsewidth. Narrower signal's pulsewidth will give a better tolerance to the error of timing walk-off at the cost of broader spectral width needed for an individual channel.

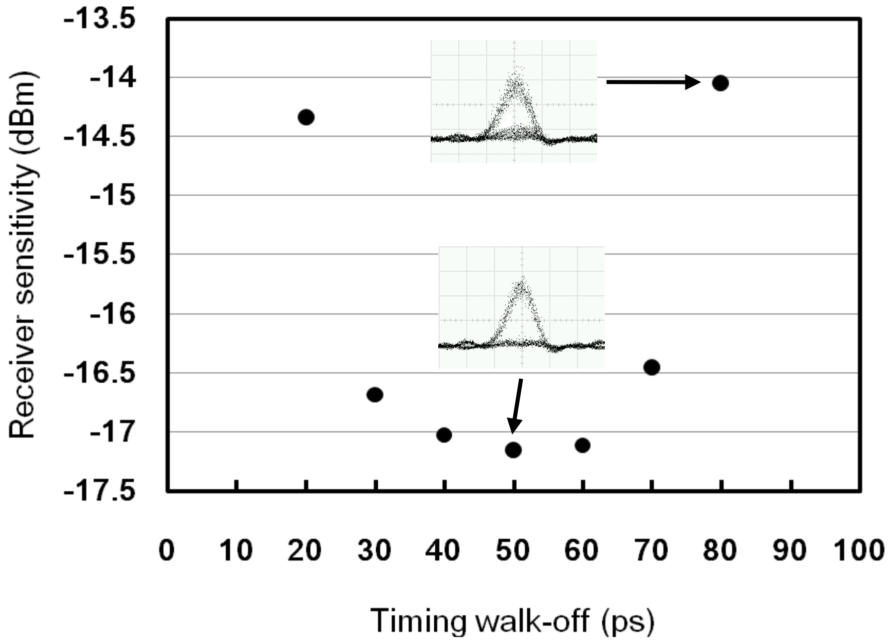

Figure 4. Receiver sensitivity of channel 1 (1533.67 nm) at BER of 10^{-9} versus different timing walk-off values of channel 3 (1538.41 nm) in the same propagation direction in regeneration.

The frequency offset of the filter used for offset filtering in the SPM-based regeneration is also critical to the regenerator performance. It is because when the frequency offset of the filter is too small (the filter center is close to the signal carrier), those amplitude fluctuations on space levels of the signal may have enough power to generate sufficient SPM-induced spectral broadening and pass through the filter. This leads to an insufficient rejection of the amplitude noises on signal's space levels. Fig. 5(a) shows the eye evolution of one regenerated channel as we increase the filter offset from 0 nm with a 0.25-nm step. We can see that better and better suppression of the "zero" level fluctuations can be obtained. However, it should be mentioned that the filter offset should not be too large as the signal power will suffer after large-offset filtering. In addition, some "one" pulses with lower power levels may be rejected by the filter with large offset and thus errors are caused on the signal. Fig. 5(b) gives the receiver sensitivity of one WDM channel at BER of 10^{-9} versus different filter offsets in our experiment. The degradation of receiver sensitivity when the filter offset is larger than the optimal value (1 nm) is mainly due to the increased amount of ASE noise from the EDFA used before BER measurement for pre-amplification when the signal power is small after offset-filtering and the aforementioned rejection of weak "one" pulses. The optimal filter offset depends on the signals' peak power after EDFA as the amplified signals with different power levels can induce different strengths of SPM in the HNLF and hence have different spectral broadening. In particular, larger filter offset should be chosen for signals with larger spectral broadening, while simultaneously maintaining certain acceptable signal power in the regeneration because larger filter offset can provide sufficient noise suppression on signals' space levels. Fig. 5(c) shows the optimal filter offset versus the signal power launched into the HNLF in our numerical simulations. In the simulations, we used the 10-Gb/s RZ-OOK signal with

FWHM of 13ps at 1545.8 nm. The HNLF is 2 km in length and has the zero-dispersion wavelength (ZDW) of 1550 nm, the dispersion slope of 0.019 ps/nm^2/km and the nonlinear coefficient of 10.5 W$^{-1}\cdot$km^{-1} respectively. At low signal power, the optimal filter offset remains roughly constant as no apparent regeneration property can be obtained. Besides, it should be noted that the output signal's pulsewidth can be kept the same as the input signal's pulsewidth if an offset filter with the same spectral bandwidth as the input signal's spectrum is used.

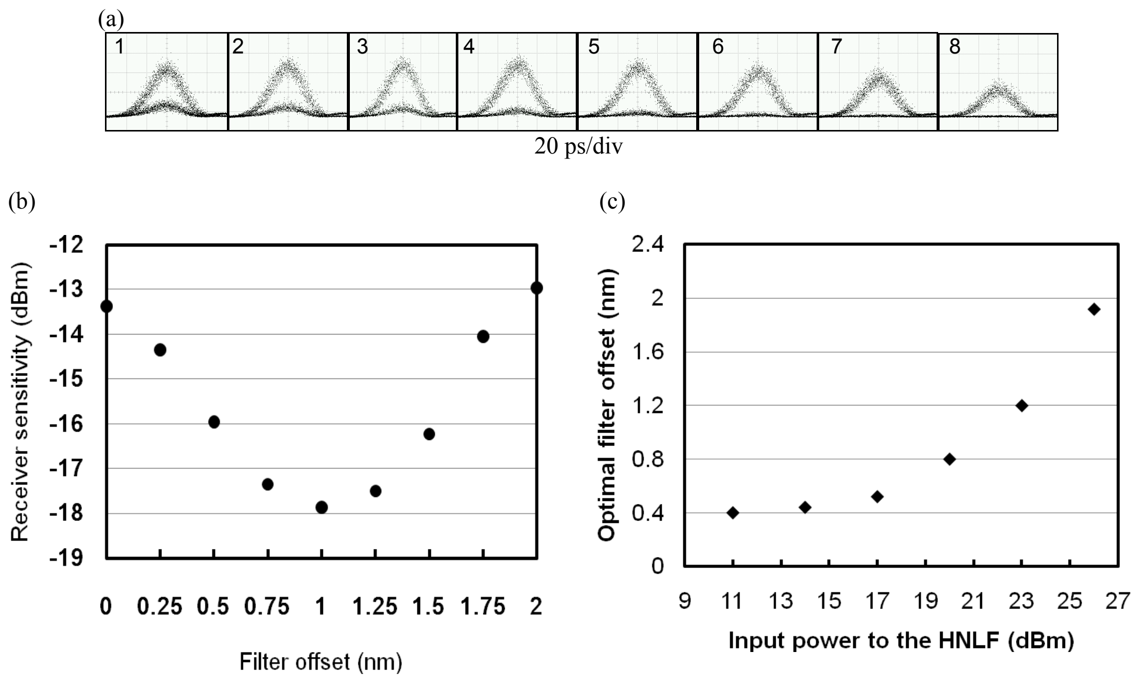

Figure 5. (a) 1-8, Eye diagrams of one regenerated signal as the filter offset is increased with a 0.25-nm step. (b) Receiver sensitivity of one WDM channel at BER of 10^{-9} versus different filter offsets in the experiment. (c) Optimal filter offset versus signal power launched into the HNLF in numerical simulations.

5. CONCLUSIONS

We have experimentally demonstrated optical 2R regeneration for four 10-Gb/s RZ-OOK WDM channels with 300-GHz channel spacing utilizing our proposed multi-wavelength regeneration scheme based on self-phase modulation and inter-channel walk-off control in a bidirectional fiber configuration. In our experiment, the nonlinear inter-channel crosstalks are effectively mitigated because of the proper timing walk-off introduced on the WDM channels. BER measurement shows more than 4-dB improvement of receiver sensitivity at BER of 10^{-9} for the regenerated signals. In addition, the effects of improper timing walk-off and filter offset on the performance of the regenerator are also investigated. The results show that both the proper inter-channel timing walk-off and filter offset are critical to the quality of the regenerated signals. Numerical simulation results further show the scalability and the effectiveness of the proposed regenerator to support up to ten 10-Gb/s WDM channels.

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