

Cascadability properties of MZI-SOA-based all-optical 3R regenerators for RZ-DPSK signals

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Abstract: We experimentally demonstrate 50 cascaded all-optical 3R regenerators over a 1,000km transmission distance for 10-Gb/s return-to-zero differential phase-shift keying (RZ-DPSK) signals. The regenerator consists of integrated Mach-Zehnder interferometer (MZI) semiconductor optical amplifier (SOA) based wavelength converters. Regenerative properties and tolerance to pattern dependent effects have been studied in terms of Q-factor measurement, and error free operation with input OSNR of 20dB/0.1nm has also been demonstrated.

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OCIS codes: (230.7405) Wavelength conversion devices; (250.5980) Semiconductor optical amplifiers.

References and links

1. A. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, C. Doerr, L. Stulz, A. Agrawal, S. Banerjee, D. Grosz, S. Hunsche, A. Kung, A. Marhelyuk, D. Maywar, M. Movassaghi, X. Liu, C. Xu, X. Wei, and D. M. Gill, "2.5 Tb/s (64 x 42.7Gb/s) transmission over 40 x 100 km NZDSF using RZ-DPSK format and all-raman-amplified spans," in *Optical Fiber Communication Conference and Exhibit*, Technical Digest (Optical Society of America, 2002), paper FC2-1.
2. K. Croussore, C. Kim, and G. Li, "All-optical regeneration of differential phase-shift keying signals based on phase-sensitive amplification," *Opt. Lett.* **29**(20), 2357–2359 (2004).
3. Z. Li, Y. Dong, J. Mo, Y. Wang, and C. Lu, "Cascaded all-optical wavelength conversion for RZ-DPSK signal based on four-wave mixing in semiconductor optical amplifier," *IEEE Photon. Technol. Lett.* **16**(7), 1685–1687 (2004).
4. I. Kang, C. Dorrer, L. Zhang, M. Rasras, L. Buhl, A. Bhardwaj, S. Cabot, M. Dinu, X. Liu, M. Cappuzzo, L. Gomez, A. Wong-Foy, Y. F. Chen, S. Patel, D. T. Neilson, J. Jaques, and C. R. Giles, "Regenerative all-optical wavelength conversion of 40Gb/s DPSK signals using a SOA MZI," in *Proceedings of 31st European Conference and Exhibition on Optical Communication (ECOC)* (Institute of Electrical and Electronics Engineers, New York, 2005), **8**, 29–30, paper Th. 4.3.3.
5. P. Vorreau, A. Marculescu, J. Wang, G. Bottger, B. Sartorius, C. Bornholdt, J. Slovak, M. Schlak, C. Schmidt, S. Tsadka, W. Freude, and J. Leuthold, "Cascadability and regenerative properties of SOA all-optical DPSK wavelength converters," *IEEE Photon. Technol. Lett.* **18**(18), 1970–1972 (2006).
6. I. Kang, C. Dorrer, L. Zhang, M. Dinu, M. Rasras, L. L. Buhl (Larry), S. Cabot, A. Bhardwaj, X. Liu, M. A. Cappuzzo, L. Gomez, A. Wong-Foy, Y. F. Chen, N. K. Dutta, S. S. Patel, D. T. Neilson, C. R. Giles, A. Piccirilli, and J. Jaques, "Characterization of the dynamical processes in all-optical signal processing using semiconductor optical amplifiers," *IEEE J. Sel. Top. Quantum Electron.* **14**(3), 758–769 (2008).
7. G. Gavioli, B. C. Thomsen, V. Mikhailov, and P. Bayvel, "Cascadability properties of optical 3R regenerators based on SOAs," *J. Lightwave Technol.* **25**(9), 2766–2775 (2007).
8. X. Yi, R. Yu, J. Kurumida, and S. J. B. Yoo, "A theoretical and experimental study on modulation-format-independent wavelength conversion," *J. Lightwave Technol.* **28**(4), 587–595 (2010).
9. K. N. Nguyen, T. Kise, J. M. Garcia, H. N. Poulsen, and D. J. Blumenthal, "All-optical 2R regeneration of BPSK and QPSK Data using a 90° Optical Hybrid and Integrated SOA-MZI Wavelength Converter Pairs," in *Optical Fiber Communication Conference and Exhibit*, Technical Digest (Optical Society of America, 2011), paper OMT3.

1. Introduction

All-optical regenerators and wavelength converters for phase sensitive communication formats have the potential to increase the allowable transmission lengths with reduced cost and power dissipation over optoelectronic/electronic regenerators [1]. Differential Phase Shift Keying (DPSK) is a phase-modulation format with improved sensitivity and robustness towards nonlinear impairments. Wavelength conversion of PSK signals can be categorized as phase-coherent type or phase-incoherent types. In phase-coherent methods, phase-sensitive optical nonlinearities such as fiber-nonlinearity [2] and four-wave mixing (FWM) in semiconductor optical amplifier (SOA) [3] are used to preserve the phase information during the conversion process. However, these approaches only offer a restricted wavelength conversion range and require high input power since their conversion efficiencies are still low. The phase-incoherent type, used in this work, exploits the more efficient cross-phase modulation (XPM) effect in a Mach Zehnder-interferometer (MZI) –SOA structure. Such devices have been demonstrated in integrated form with their regenerative properties reported [4–6].

In addition to the regenerative properties, cascadability is one of the most important characteristics for regenerators since in a real system, regenerators must operate in cascade [7]. Cascaded operation is particularly important when transmission distances are limited due to nonlinearities for high bit rate coherent systems. Cascaded operation of DPSK wavelength converters is reported in [3] by using FWM approach, but only 4 cascades were obtained with error free operation.

Experimental cascaded operation of MZI-SOA based regenerators has not been shown to the best of our knowledge. In this paper, we report demonstration of a novel approach where PSK signals are first converted to ASK signals for controlling the phase difference between the interferometer arms to obtain signals that are phase-encoded. We successfully demonstrate 50-lap cascades of all-optical 3R regenerators using MZI-SOA with corresponding 1,000-km transmission for 10-Gb/s RZ-DPSK signals and demonstrate its regenerative properties.

2. Experimental setup for DPSK 3R regenerators

The experimental setup for the all-optical DPSK regenerator is shown in Fig. 1. An RZ-DPSK signal is generated using a pair of LiNbO₃ Mach-Zehnder modulators (MZM) connected in tandem. A 2⁷-1 pseudo-random bit sequence (PRBS) is used to encode the phase information onto 1550nm optical light from a Brillouin fiber laser with a linewidth of 300Hz. The signals are then converted to an amplitude shift keying (ASK) signal and its complement using a fiber-based one-bit delay interferometer (DI). The ASK signals are then used as bit-aligned push/pull optical gating signals to an MZI-SOA-based wavelength converter. An input pulse transfers the RZ pattern onto a probe signal ($\lambda_2 = 1560\text{nm}$) by inducing a π nonlinear phase shift in its respective interferometer SOA arm. The two SOAs are controlled very similarly to the push-pull operation of DPSK modulators. Due to the π phase difference between the upper and lower arms of the MZI-SOA, the optical phases of the output pulses owing to the ASK gating signal and its complement are different by π [4–6]. Thus, the phase information is transferred to a DPSK signal with a new wavelength ($\lambda_2 = 1560\text{nm}$). The 1550nm gating signals are filtered out with a 1.0nm wide optical bandpass filter, while the 1560nm DPSK signals are converted to two ASK signals by another one-bit DI, and are used as gating signals for the second wavelength converter. At the second stage, the phase information is transferred to an optical clock signal with the original wavelength ($\lambda_1 = 1550\text{nm}$) to retune the input signal. The optical clock is generated using a 300MHz bandwidth filter-based electrical clock recovery (CR) circuit. The recovered electrical clock drives an MZM (pulse carver) which generates a 10GHz optical pulse train with 40ps pulse width. The 10GHz pulse train is synchronized to the incoming wavelength converted signal from the first stage. The 1560nm

gating signals are filtered out with an optical bandpass filter, and thus, regenerated DPSK signals with the original wavelength (λ_1) are obtained.

Measured eye diagrams of transmitter and regenerated signal are also shown in Fig. 1. The typical extinction ratio of the regenerated signal is over 15dB, a similar value to that of the transmitted signal. Maintaining an extinction ratio comparable to the input signal enables the regenerators to operate in cascade.

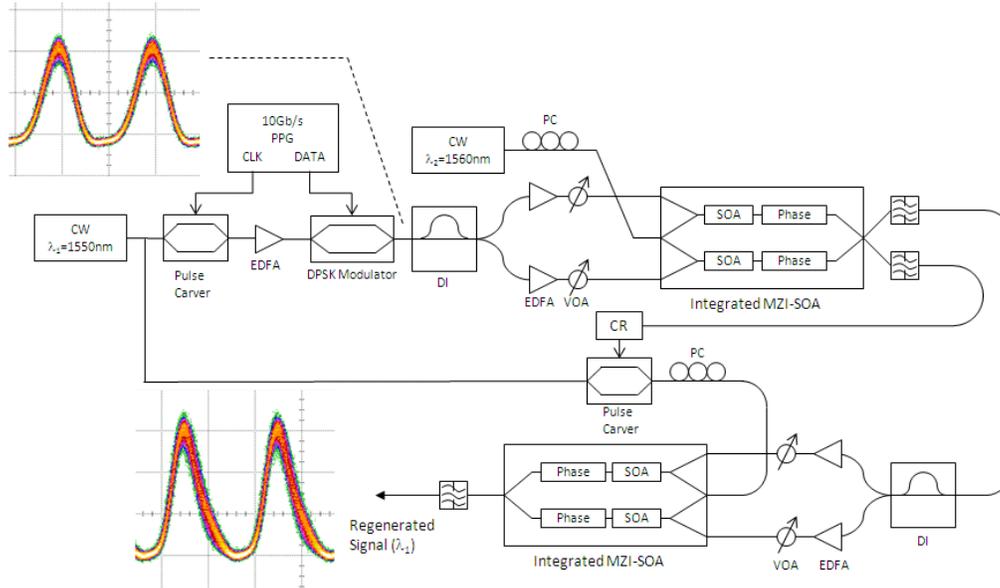


Fig. 1. All-optical DPSK regenerator setup.

3. Cascadability properties

To investigate the regenerative and cascadability properties of the regenerator, we used the recirculating-loop setup shown in Fig. 2. The transmission loop span consist of a 1nm wide optical bandpass filter, a non-zero dispersion shifted fiber (NZDSF) (large effective area fiber; LEAF) link where dispersion is fully compensated by dispersion compensating fiber (DCF). The recirculating loop spans a length of 20km. The launched average optical power into the fiber was set to -10dBm by a variable optical attenuator (VOA) to ensure that the transmission was in the linear regime. An EDFA is inserted into the loop to compensate for the loop losses. The total loop loss is 22dB (including the insertion loss of VOA). The transmitter ($\lambda_1 = 1550\text{nm}$) generates a 10Gb/s RZ-DPSK signal with 40ps full-width at half-maximum pulses, encoded with 2^7-1 PRBS. Recirculating loop operation is performed by controlling two acousto-optic modulators (AOM). The Tx-AOM lets signals in via a 3dB coupler and fills the loop. After the loop is filled, the Loop-AOM is turned on and the signals keep recirculating in the loop. Every lap around the loop, the signal is split by 3dB coupler and detected by a receiver. In the receiver, the signal is demodulated by a single-ended one-bit DI and split to photodetector (PD) and electrical CR circuit to be analyzed by a bit error rate tester (BERT). A gating signal is provided to the BERT in order to measure a specific lap.

The all-optical DPSK regenerator alters the data encoding due to the demodulation of the DPSK signal using a DI. Thus, an appropriate pre-coding or post-coding scheme as discussed in [5,6] is necessary for the actual data sequence. In this measurement, however, the implementation of the coding change is not necessary for signals encoded with PRBS owing to the special property of PRBS: a DPSK PRBS data sequence demodulated by using a one-bit DI is the time-shifted version of the original PRBS. Recently, a coherent demodulation

method using a 90° optical hybrid has been suggested and demonstrated [8,9], and no pre- or post-coding is required by exploiting such schemes.

Figure 3 shows measured eye diagrams at the receiver for the back-to-back and the regenerated signals with cascaded laps of 1, 10, 20 and 50. Clear eye openings are maintained up to 50 cascaded laps. Figure 4 shows experimental Q-factor evolution for the regenerated signals in cascade. The Q-factor is evaluated by Gaussian approximation, using measured BER with changing the decision thresholds, which represents the noise distribution of the received signal. Although the noise distribution after the regeneration does not obey the Gaussian statistics, the Q-factor can still be used as a qualitative measure of the signal degradation [7]. The received power is set to -30dBm in all the Q-factor measurement in this work. To investigate the tolerance of the regenerators to the pattern dependent effects, we also plot the data with different PRBS pattern length of 2^9-1 and $2^{11}-1$. Error free transmission and Q-factor of more than 15.9 can be maintained up to a total of 50 regenerator laps, corresponding to a 1,000km transmission. In the first few laps, longer PRBS encoded signals show a slight degradation in Q-factor. This degradation is attributed to the pattern dependent characteristics of the regenerators. Since the MZI-SOA wavelength converter is not operated in differential mode, the MZI-SOA response is limited by the slow gain recovery time of the SOAs.

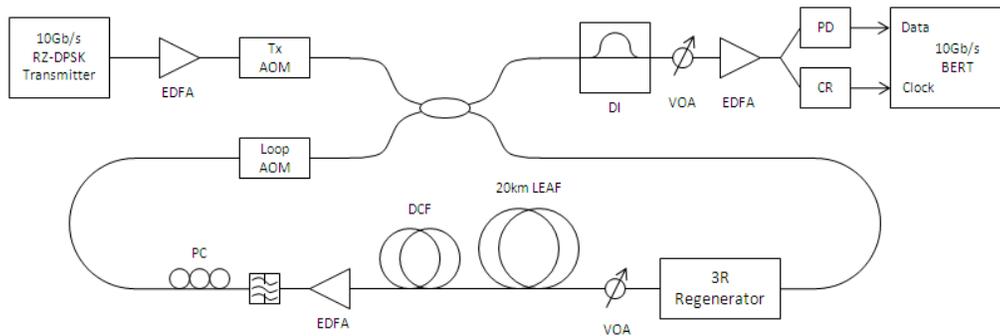


Fig. 2. Recirculating loop setup for the measurement of cascaded regenerators.

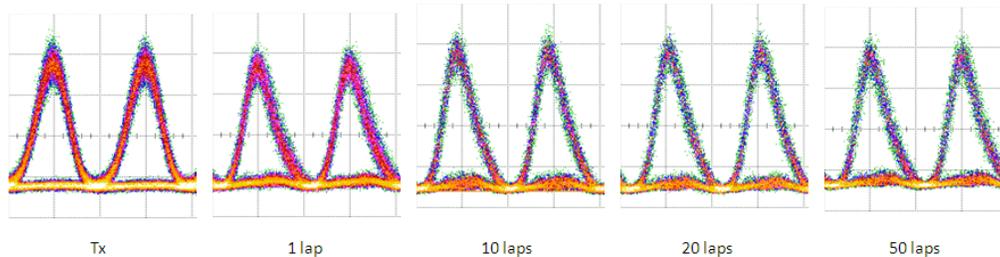


Fig. 3. Eye diagrams at the receiver with single-ended DI, for Tx and specific cascaded laps; 1, 10, 20, 50 laps.

To further investigate the regenerative properties and the pattern dependent effects of the regenerators, we measured the Q-factor of the regenerated signals by changing the optical signal to noise ratio (OSNR) of the transmitter. The transmitter OSNR was degraded by coupling the output from an amplified spontaneous emission (ASE) light source to the DPSK modulator input. Figure 5 shows Q-gain as a function of the input OSNR with varying PRBS pattern lengths. Here, Q-gain is defined as the Q-factor improvement by the regenerators compared to the transmitter Q-factor. In the case that the input OSNR is higher than 30dB/0.1nm, the transmitter Q-factor is high, consequently the Q-gain stays at low value and is slightly less than 0 dB for the PRBS $2^{11}-1$ due to the pattern dependence of the regenerator.

The reshaping properties of the regenerators are demonstrated by noting that the Q-gain increases as the transmitter OSNR decreases. The Q-factor of the regenerated signals is plotted in Fig. 5. A degradation of transmitter Q-factor, especially with higher levels of ASE, is observed for longer PRBS patterns. This is due to the bandwidth limitations of the DPSK modulator and its driving electronics, in addition to modulator arm imbalance. The relatively low regenerated Q-factor for longer patterns can also be explained by similar patterning effects in the MZI-SOA wavelength converters. However, Q-factor of over 15.8 and error free operation can be maintained for all PRBS pattern lengths even when the input OSNR is degraded down to 20dB/0.1nm. The performance of the regenerator for further degraded input signals is a prospect for the future work.

Finally, Fig. 6 shows the BER curves measured for up to 30 regenerator laps. The reference back-to-back (B2B) measurement was performed by detecting the transmitter signal via the 3dB coupler. 3R measurements show power penalties less than 1dB with respect to B2B, for up to 30 laps. The 1R measurements (only EDFA amplification) were also taken by removing the cascaded regenerators from inside the loop, and the measured BER curves are plotted in Fig. 6. The 1R measurements exhibited a 1dB and 4dB power penalty for 10 and 20 laps, respectively. Improvements demonstrated in 3R measurements compared to 1R, clearly show the benefits of the cascaded regenerators.

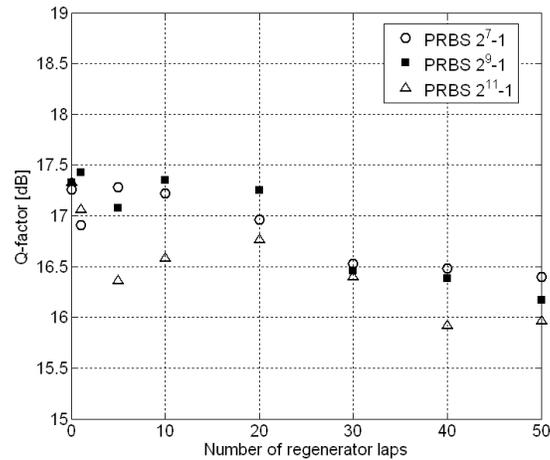


Fig. 4. Experimental Q-factor evolution with different PRBS encoding.

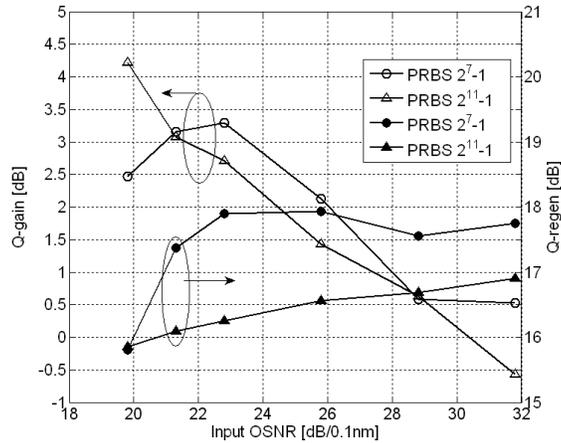


Fig. 5. Experimental Q-gain and Q-factor after regeneration as a function of input OSNR with different PRBS encoding.

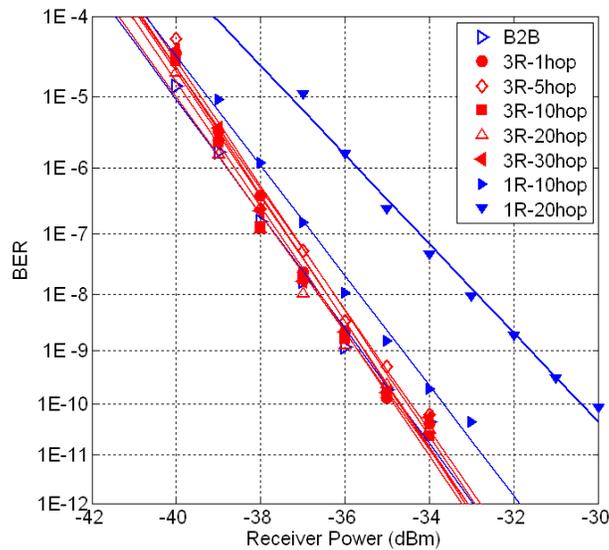


Fig. 6. BER curves of cascaded signals.

4. Conclusion

We experimentally demonstrate cascaded operation of all-optical 3R regenerators for 10Gb/s RZ-DPSK signals. A transmission length of 1,000km was achieved using a recirculating loop setup with 20km of regenerator spacing (50 laps). The regenerative properties and the tolerance to the pattern dependent effects have also been studied, and the obtained results showed that the regenerators are capable of operating error free and maintaining Q-factor of over 15.8 using signals with OSNR values as low as 20dB/0.1nm. The demonstrated cascaded regenerators are scalable to higher bit rates by operating the MZI-SOAs in differential mode [5].

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