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Abstract: A simplified optoelectronic 3R regenerator without electrical signal processing is demonstrated by utilizing the nonlinear electro-optical transfer function of an electroabsorption modulator. 3R regeneration of impaired 10-Gb/s RZ signals is demonstrated, verifying the proposed concept.

OCIS codes: (060.2330) Fiber optics communications, (060.2340) Fiber optics components

References and links

1. O. Leclerc, B. Lavigne, E. Balmefrezol, P. Brindel, L. Pierre, D. Rouvillain, and F. Seguineau, "Optical Regeneration at 40 Gb/s and Beyond," J. Lightwave Technol. **21**, 2779-2790 (2003).
2. T. Otani, T. Miyazaki, and S. Yamamoto, "40-Gb/s Optical 3R Regenerator Using Electroabsorption Modulator for Optical Networks," J. Lightwave Technol. **20**, 195-200 (2002).
3. S. Watanabe, "Technologies of 160 Gbit/s Optical 3R-Regeneration," in *Proc. European Conference on Optical Communication 2004*, Stockholm, Sweden, September 5-9, 2004, paper Tu4.1.2.
4. W. Kuebart, B. Lavigne, M. Witte, G. Veith, and O. Leclerc, "40 Gb/s transmission over 80000 km dispersion shifted fibre using compact opto-electronic-3R regeneration," in *Proc. European Conference on Optical Communication 2003*, Rimini, Italy, September 21-25, 2003, paper Mo4.3.1.
5. G. Gavioli and P. Bayvel, "Amplitude jitter suppression using patterning-tolerant, all-optical 3R regenerator," Electron. Lett. **40**, 688-690 (2004).
6. Y. Kisaka, A. Hirano, M. Yoneyama, and N. Shimizu, "Simple 2R repeater based on EA modulator directly driven by uni-traveling-carrier photodiode," Electron. Lett. **35**, 1016-1017 (1999).
7. S. Z. Zhang, Y.-J. Chiu, P. Abraham, and J. E. Bowers, "25-GHz Polarization-Insensitive Electroabsorption Modulators with Traveling-Wave Electrodes," IEEE Photon. Technol. Lett. **11**, 191-193 (1999).
8. M. N. Sysak, J. S. Barton, L. A. Johansson, J. W. Raring, E. J. Skogen, M. L. Masanovic, D. J. Blumenthal, and L. A. Coldren, "Single-Chip Wavelength Conversion Using a Photocurrent-Driven EAM Integrated With a Widely Tunable Sampled-Grating DBR Laser," IEEE Photon. Technol. Lett. **16**, 2093-2095 (2004).

1. Introduction

Re-shaping, re-timing, and re-amplification (3R regeneration) of optical signals is considered an essential capability for extending the reach of long-haul transmission and also for restoring the impairments imposed by a complex optical network. Several all-optical approaches have been proposed [1-3] and up to 160 Gb/s operation was reported [3]. On the other hand, the speed of optoelectronic 3R regeneration has been increased to 40 Gb/s using electronic flip-flop circuits [4]. In most all-optical 3R regenerators, the input and output optical waves are mixed in a non-linear medium at high power levels. Despite of its high-speed potential, there can be several issues for the all-optical approaches: 1) the non-linear medium may be sensitive to the polarization and wavelength of the input signal; 2) high power optical amplifiers may be required and tunable optical filters are needed to suppress amplified spontaneous emission (ASE) noise; 3) regeneration at the same wavelength would require cascading two stages of regenerator with an intermediate wavelength, which complicates the design [2]. Recent developments of all-optical 3R regenerators have made progress to relax some of these limitations, especially those based on semiconductor optical amplifiers [5]. In terms of these issues, optoelectronic 3R regenerators may have advantages over their all-optical counterparts: 1) due to the use of a receiver, the polarization and wavelength dependence can be minimized; 2) high-power optical amplifiers and tunable optical filters are not required since electrical amplifiers are used instead; 3) regeneration at the same wavelength without cascade is inherently viable because the input and output signals are not mixed optically. These advantages make optoelectronic 3R regeneration very competitive when the bit-rate can be handled by electronics. Nevertheless, cost and power consumption are among the concerns. It is then of great interest to simplify the configuration of optoelectronic regenerators.

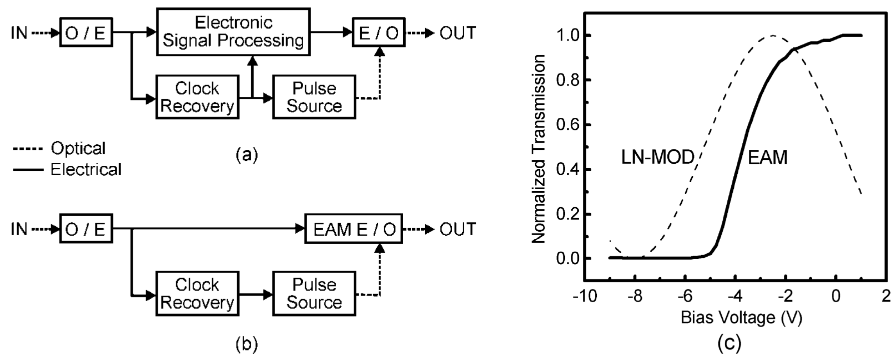

Fig. 1. (a) Conventional optoelectronic 3R regenerator; (b) simplified optoelectronic 3R regenerator; (c) E/O transfer functions in linear scale

The nonlinear electro/optical (E/O) transfer function of an electroabsorption modulator (EAM) has been demonstrated to suppress amplitude noise in a 2R regenerator [6]. In this work, we extend this concept further to realize a simplified optoelectronic 3R regenerator where the electronic signal processing unit in conventional regenerator (Fig. 1(a)) can be eliminated, resulting in a simpler configuration (Fig. 1(b)). In the simplified approach, the detected electrical signal directly drives the EAM to gate a regenerated (re-timed and well-shaped) pulse train. The amplitude noise in the input signal is suppressed through the nonlinear gating process. Fig. 1(c) shows the step-like E/O transfer function of the EAM [7], which is ideal for compressing the noise on the mark and the space levels [1]. In contrast, the sinusoidal transfer function of a $LiNbO_3$ modulator (LN-MOD) does not have flat transmission regions and does not result in strong noise suppression. We demonstrate this concept with 10-Gb/s return-to-zero (RZ) data format and evaluate the 3R regeneration performance with respect to timing tolerance, ASE accumulation, and dispersion tolerance.

2. Experiments and results

The experimental setup of the proposed 3R regenerator is shown in Fig. 2(a). The EAM used in this work has traveling-wave electrodes (TW) and two microwave ports [7]. It requires 2.6 V to change the normalized transmission from 0.1 to 0.9 (transition voltage). This means that the amplitude of the electrical driving signal must be larger than 2.6 V in order to utilize the two flats of the transfer function for effective noise suppression.

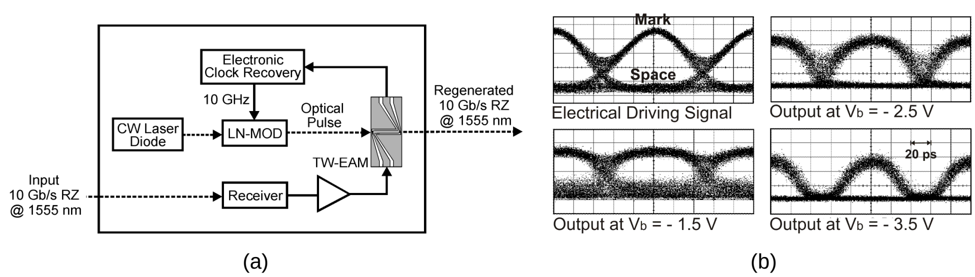

Fig. 2. (a) Experimental setup; (b) the electrical driving signal and the corresponding gating windows at different bias voltages

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The input optical signal is a 40-ps, 10-Gb/s RZ with 2^31-1 pseudo-random binary sequence (PRBS) at 1555 nm. The input power level is fixed at –12 dBm for all experiments. The input signal is first detected by a 10-Gb/s receiver and then boosted by a 10-Gb/s non-inverting broadband amplifier to 9 V peak-to-peak in order to drive the TW-EAM from the lower microwave port. The combined electrical gain is 56 dB. Due to a lower impedance (25-Ohm) of the TW-EAM, the amplitude of the electrical driving signal is reduced to 6.8 V inside the device but is still 2.6 times the transition voltage. The finite bandwidth of the receiver and the amplifier can broaden the pulsewidth of the electrical signal, allowing improved timing tolerance without a pulse shaper as required by all-optical approaches [3]. The electrical driving signal then goes out of the upper microwave port of the TW-EAM and is utilized by a commercial electronic clock recovery unit to recover a synchronized 10-GHz electrical clock. The nominal timing jitter is 245 fs. A LN-MOD is driven by the recovered electrical clock to regenerate a 10-GHz, 40-ps optical pulse train at the same wavelength, which is then gated by the TW-EAM to complete the 3R regeneration. Fig. 2(b) shows the optical outputs when a continuous-wave (CW) is fed into the TW-EAM (instead of the pulse train), which probes the shape of the gating window. At –1.5 V of bias voltage (V_b), the mark is sufficiently clamped and the output eye has a wide flat top, indicating a strong noise suppression capability on the mark and a wide timing jitter tolerance. However, the noise on the space is increased when compared to that of the electrical driving signal. The reverse bias voltage has to be increased to suppress the noise on the space, at the expense of reducing the width of the flat top on the mark. Ideally, the larger the driving voltage (or the smaller the transition voltage), the more flat transmission region can be utilized and, hence, better noise suppression capability.

The proposed 3R regenerator is first evaluated with a high-quality input signal. The bias voltage is set at –2.0 V and remains the same for all experiments. As shown in Fig. 3(a), the regenerated eye is very clean and has a slightly reduced pulsewidth (35 ps) due to the shape of the gating window. Bit-error-rate (BER) measurements showed no power penalty, indicating that the regenerator itself does not impose signal degradation. Polarization dependence is not observed since the receiver has a polarization dependent loss of only 0.06 dB. The timing tolerance is evaluated by shifting the phase of the electrical 10-GHz clock to the LN-MOD, which changes the relative timing of the pulse train and the gating window generated by the TW-EAM. Fig. 3(c) shows that within 1-dB of power penalty, up to 36 ps of timing shift is allowed. Combining this with the polarization insensitivity, good tolerance to polarization mode dispersion (PMD) can be expected.

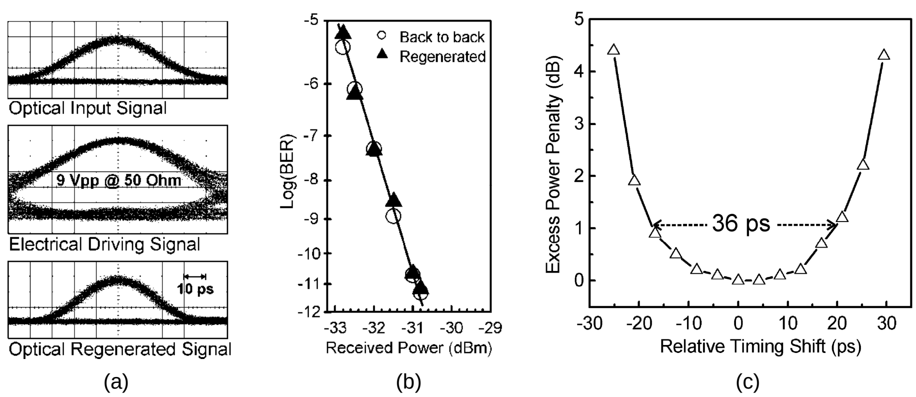

Fig. 3. Results with a high-quality input signal (a) eye diagrams; (b) BER; (c) timing tolerance

Next, the regeneration of an ASE degraded signal is evaluated. The optical signal to noise ratio (OSNR) of the input signal is degraded by adding ASE noise from an Erbium-doped fiber amplifier (EDFA). The OSNR is degraded to 20 dB (with 0.1 nm resolution) and a 2.4 nm optical band-pass filter is used to suppress out-of-band noise. Fig. 4(a) shows that the added ASE leads to observable beating noise on the mark and Fig. 4(b) indicates that 1.2 dB

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of power penalty is imposed. After regeneration, the noise is significantly reduced and a negative power penalty of 0.8 dB is obtained. The OSNR of the regenerated signal is improved to 56 dB, which is given by the laser source in the regenerator. The high OSNR improvement benefited from the fact that the input and output waves are not mixed optically in the optoelectronic regenerator.

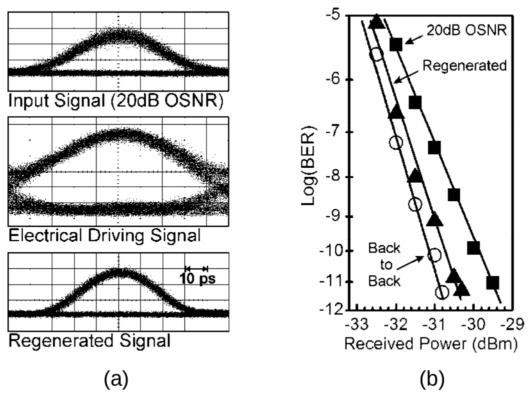

Fig. 4. Results with a 20-dB OSNR input signal (a) eye diagrams; (b) BER

The input OSNR is further degraded to 16 dB with a 2.8-dB power penalty, as shown in Fig. 5. An error floor is observed below 10^{-10} BER. The amplitude of the electrical driving signal is reduced by 20% due to the increased optical noise. Nevertheless, the regenerated signal has a negative power penalty of 1.6 dB at 10^{-9} and the eye is clean. The OSNR is also 56 dB. However, an error floor still exists after regeneration. This may be caused by the fact that the E/O transformation does not remove all the noise close to the center of the eye, which leads to an error floor. Also, the reduced driving voltage also limits the regeneration performance. These results may suggest that regeneration should be implemented before the OSNR drops below a certain level.

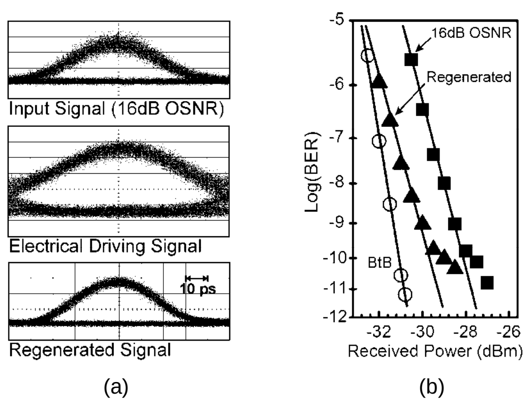

Fig. 5. Results with a 16-dB OSNR input signal (a) eye diagrams; (b) BER

Finally, the tolerance to dispersion is evaluated by propagating the input signal through 25-km of SMF-28 fiber without any dispersion compensation. As shown in Fig. 6(a), the eye is broadened and distorted, which also leads to a 20% smaller driving signal amplitude. The regenerated signal is well shaped without significant power penalty. A slight change in BER slope is observed, which may be caused by the mixed effect of decreased electrical amplitude and increased intersymbol interference. However, even though no negative power penalty is

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obtained in this case, the dispersion experienced by the input signal is reset after regeneration and the signal is re-timed and re-shaped.

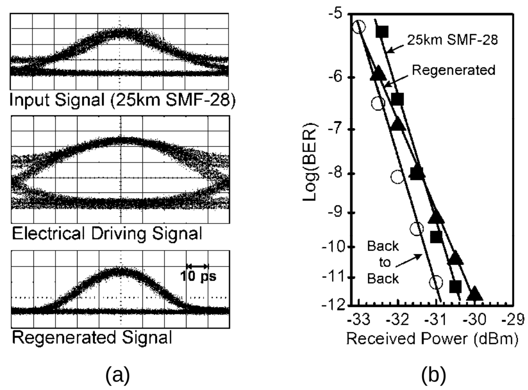

Fig. 6. Results with a dispersed input signal (a) eye diagrams; (b) BER

The ASE noise suppression capability can be further improved by inverting the polarity of the electrical driving signal [6]. This is due to the facts that the ASE beating noise is stronger on the mark and the EAM has a much flatter transmission region at high reverse bias, as shown in Fig. 1(c). The bias point can be adjusted towards higher reverse bias to suppress more ASE noise on the mark while keeping the space transparent. The concern of degraded signal to noise ratio caused by the electrical amplifier [6] can be counteracted by a strong nonlinear E/O transformation and a large driving voltage. In this particular realization, up to 56 dB of electrical gain was employed but very effective regeneration can still be obtained. The use of a photodiode to drive the EAM directly is the most compact realization of this concept [6] but the regeneration performance would strongly relay on the actual voltage swing produced by the photodiode and the transition voltage of the EAM. The proposed approach can also function as a 3R regenerative wavelength converter if the internal CW wavelength can be tuned within the operating wavelength range of the EAM. Given the recent developments in integration technology [8], high level integration of this concept for a low cost and compact optoelectronic 3R regenerator is promising.

3. Conclusion

A simplified optoelectronic 3R regenerator is proposed and demonstrated at 10-Gb/s. The decision function is realized by the nonlinear E/O transformation of the TW-EAM, which eliminates sophisticated electronic signal processing. The performance including timing and dispersion tolerance as well as ASE accumulation was evaluated, indicating effective regeneration using this simplified optoelectronic approach.

Acknowledgments

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