First Field Demonstrations of 1000-hop Cascaded All-Optical 3R Regeneration in 10 Gb/s NRZ Transmission

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Abstract: This paper demonstrates all-optical 3R regeneration in 10-Gb/s NRZ field trials with various regeneration spacings up to 462 km. The 3R regenerator has achieved 1000-hop cascaded error-free transmission (total 66,000-km) without hop-to-hop power penalties.

OCIS codes: (060.4510) Optical communications; (230.1150) All-optical devices

1. Introduction

Optical regeneration has drawn increasing attention for future all-optical networking. All-optical "3R" regeneration is particularly attractive, because it can improve signal quality in both the amplitude and time domains, even when incoming signals are severely degraded. While numerous publications have reported on many types of 3R regenerators, many of them employ a return-to-zero (RZ) format [1], [2], and only a few papers discuss 3R regeneration with non-return-to-zero (NRZ) signals [3], [4]. This paper demonstrates inline 3R regeneration in 10-Gb/s NRZ field trials with up to 1000 cascaded regeneration stages. The cascadability of the 3R regenerator is investigated with three different regeneration spacings of 66, 264, and 462 km, corresponding to optical signal to noise ratios (OSNR) of 33, 25, and 22 dB (0.1nm bandwidth) at the 3R regenerator input.

2. Experimental Setup and Results

Fig. 1 shows the experimental setup. The two acoustic optical modulator (AOM) switches enable recirculation loop transmission to evaluate the cascadability of an inline 3R regenerator. As a transmission line, up to 7 sets of field fibers in a loop-back configuration between Burlingame and Palo Alto were used. The field fibers are standard single mode fibers (SMF) with a roundtrip length of 66 km. A two-stage erbium-doped fiber amplifier (EDFA) with a dispersion compensating fiber (DCF) in its middle stage follows each 66-km field fiber. The 3R regenerator was located after a predetermined number (N) of the fiber spans (N=1, 4, or 7; corresponding to a regeneration spacing of 66, 264, or 462 km). After the 1st, 4th, and 7th span, residual dispersion values were within ±30 ps/nm, and OSNR degraded to 33, 25, and 22 dB, respectively, from the initial value of 45 dB.

The 3R regenerator consists of a clock recovery part and a regeneration part. In the clock recovery part, the SOA-MZI1 in the non-inverting differential operation mode generates a RZ pulse at each data bit transition in the NRZ signal, providing a NRZ to pseudo RZ (PRZ) conversion. This process amplifies the weak 10-GHz clock frequency component in the NRZ signal. The following Fabry-Perot filter, with a free spectral range of 10 GHz and a finesse of 100, filters out the clock frequency component and generates an optical clock signal [5]. The recovered clock signal showed strong pattern-dependent amplitude variations, which is typical of passive optical clock recovery techniques. The clock frequency component in the NRZ signal is very weak especially when long word lengths are used. Here, the experiment adopted a short pseudo random bit sequence (PRBS) of 2^7-1 to focus our attentions to the regeneration spacing dependence of the 3R regenerator cascadability. The subsequent saturated semiconductor optical amplifier (SOA) and fiber Bragg grating filter (FBG1) suppress the amplitude variations [6]. The recovered optical clock signal is converted into an electrical signal that synchronously modulates the data stream for retiming. In the regeneration part, the SOA-MZI2 provides 2R regeneration, and especially suppresses the mark level noise of the incoming distorted signal. The synchronous modulator LN2 driven by the optically-recovered clock offers a retiming function, as well as a NRZ to RZ conversion. The SOA-MZI3 followed by the FBG3 converts the RZ format back to a NRZ format. Both of the SOA-MZI wavelength converters operate in the inverting mode to preserve the signal wavelength and polarity.

Fig. 2 shows eye diagrams after the various recirculation loop transmission experiments with the three different regeneration spacings and input OSNR levels. The eye diagrams with inline 3R regeneration show clear eye openings, while the corresponding eye diagrams for the same or a smaller lap number without 3R regeneration suffer from amplitude and timing jitter noise accumulations. With 3R regeneration, almost identical eye diagrams are obtained from Lap1 to each final lap in every regeneration spacing case.

Figures 3(a), (b), and (c) show bit error rate (BER) curves. Without 3R regeneration (1R only), the power penalty steadily increases with the lap number. With 3R regeneration, however, the power penalty is much lower than that in the 1R cases. When regeneration spacing is 66 km and input OSNR is 33 dB (Fig. 3(a)), the BER results with only 1R show a 1.3-dB power penalty from Lap1 to Lap5. On the other hand, the BER curves with 3R overlap with each other without an error floor, and hop-to-hop power penalties are almost negligible up to Lap1000, which corresponds to a transmission distance of 66,000 km. When regeneration spacing is 264 km (Fig. 3(b)), the 1R-Lap1 curve shows a power penalty 1.5-dB higher than that in Fig. 3(a) due to the reduced OSNR of 25 dB. After 3R, however, the power penalty is improved by 1.2 dB, which is comparable to that in the 33-dB OSNR case in Fig. 3(a). The BER curves are almost identical up to Lap10 before they start to show bending. Transmission up to Lap100 (26,400 km in distance) has been achieved with a BER error floor at around $1x10^{-8}$. For the 462-km regeneration spacing (Fig. 3(c)), the 3R results are much better than those of 1R, but an error floor at $1x10^{-8}$ develops after Lap3 (1,386 km in distance) due to too severe signal degradations (22-dB OSNR) before the optical regeneration.

3. Summary

We conducted 10-Gb/s NRZ field trials of cascaded 3R regeneration with three different regeneration spacings. The inline 3R regenerator drastically improves signal quality, cascadability, and transmission distance, compared to those without 3R regeneration. 66-km spaced 3R regeneration with a 33-dB input OSNR has achieved 1000-hop cascaded error-free transmission (66,000 km in distance) without a power penalty. 264-km spaced 3R regeneration with a 25-dB input OSNR has exhibited 100-hop cascaded transmission (26,400 km in distance) with a BER error floor at ~$1x10^{-8}$.

4. References

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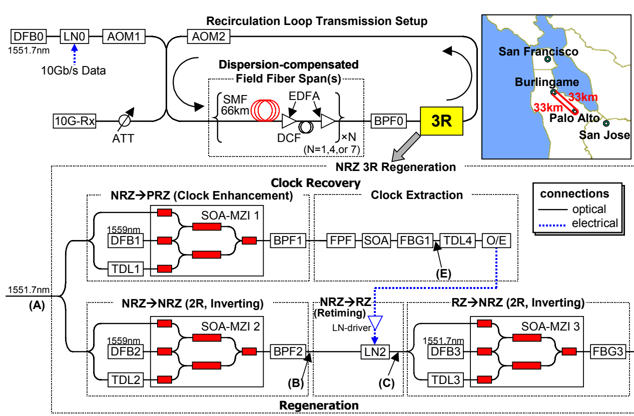

Fig. 1. Experimental setup.

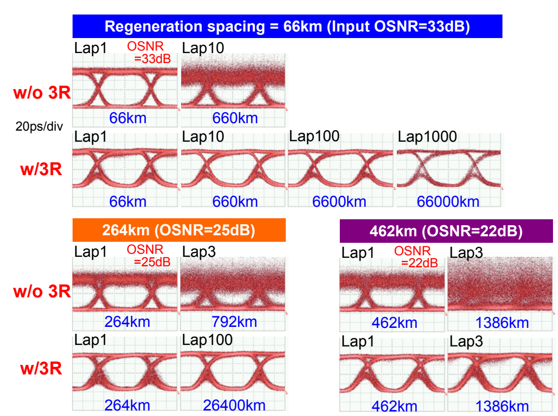

Fig. 2. Eye diagrams.

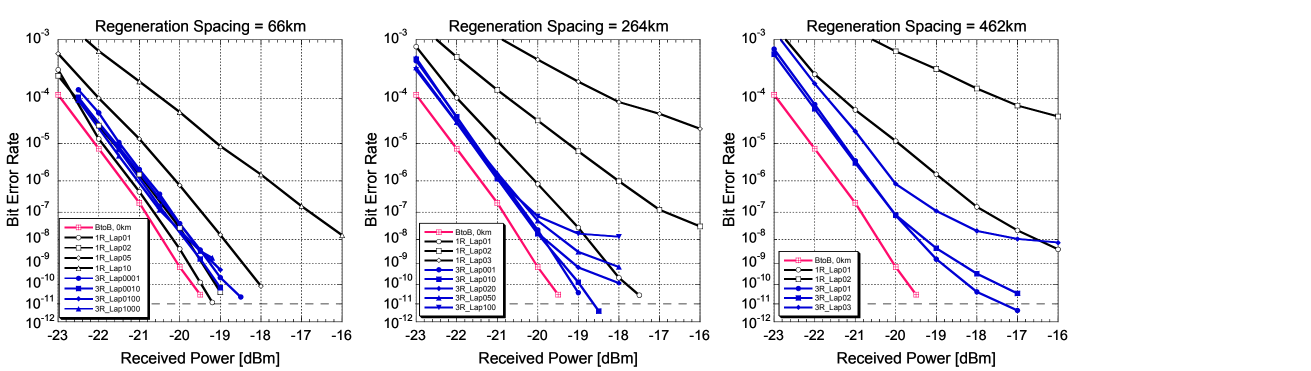

Fig. 3. BER curves after recirculation loop transmission for regeneration spacings of (a) 66 km, (b) 264 km, and (c) 462 km.