Demonstration of Optical 3R Regenerator for 10 Gb/s NRZ signal in Reconfigurable Recirculating Loop Transmission

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Abstract: This paper demonstrates optical 3R regeneration for a 10 Gb/s nonreturn-to-zero (NRZ) data format. Semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI) wavelength converters, synchronous modulator, and Fabry-Perot filter (FPF) are used for 3R regenearation including all-optical clock recovery. Recirculating loop transmission experiments compare transmission performances with different 3R regenation spacings. Transmission with the 3R regenerator shows significant performance improvement over that without 3R regeneration in terms of eye diagram, Q-factor, and transmission distance. Q-factors around 20 dB are obtained up to a transmission distance of 5000 km when the 3R regeneration spacing is 100 or 500 km.

Keywords: All-optical clock recovery, Fabry-Perot filter, nonreturn-to-zero format, optical regeneration, semiconductor optical amplifier based Mach-Zehnder interferometer

1. Introduction

All-optical signal regeneration is a key technology for future all-optical networking. Particularly “3R” regeneration, which performs the full functions of reamplification, reshaping, and retiming, is attractive, because it can improve signal quality in both the amplitude and time domains. Although numerous publications have reported on many types of optical 3R regenerators, many of them employ a return-to-zero (RZ) data format [1]- [4]. Compared to the RZ format, the NRZ format features a narrower spectral width suitable for dense wavelength division multiplexing (WDM) and a higher tolerance to wavelength dispersion. Thus the NRZ format is widely used in the current dense WDM and other systems. On the other hand, optical clock recovery from a NRZ signal is relatively challenging, because a NRZ signal has very weak clock components in its optical spectrum due to the finite rise time of the electrical-to-optical conversion process. While a number of previous publications reported on optical clock recovery from a NRZ signal [5]-[7], they did not incorporate it into a 3R regenerator. A few papers [8], [9] discuss optical 3R regeneration for the NRZ format, where electrical clock recovery methods were employed.

This paper demonstrates optical 3R regeneration for the NRZ data format as well as all-optical clock recovery from the NRZ signal. The proposed 3R regenerator utilizes SOA-MZI wavelength converters in both the clock recovery and the 3R regeneration processes. Semiconductor-based devices are promising because of their potential for compact integration and low power consumption. The cascaded 3R regenerator Transmission with an extended distance is demonstrated utilizing a reconfigurable recirculating loop transmission setup that facilitates transmission with variable 3R regeneration spacings.

2. Experimental Setup

2.1 Reconfigurable Recirculating Transmission Setup

Figure 1 shows the setup for recirculating loop transmission to evaluate transmission performance with cascaded 3R regenerators. The transmitter generates 10 Gb/s NRZ signal. The 100-km dispersion-compensated transmission line consists of two sets of 50-km LEAF fibers followed by a two-stage erbium-doped fiber amplifier (EDFA) and a dispersion compensating fiber (DCF). To reduce optical signal-to-noise ratio (OSNR) degradation while maintaining the linear optical transmission regime, the input power levels to the LEAF and DCF fibers are set moderately high at 5 dBm and –3 dBm, respectively. The measured OSNR and the estimated residual dispersion at the 3R regenerator input are 37.7dB (0.1 nm bandwidth) and 22 ps/nm, respectively. Three acoustic optical modulator (AOM) switches are used to control looping operation with a reconfigurable function [10]. The AOM1 fills data streams to the loop. After the transmission, the signal is split into two and either amplified by the EDFA or regenerated by the 3R regenerator. The AOM2 and AOM3 operate complimentarily and select either 1R or 3R for each lap of the data stream. Data stream after each lap arrives at the receiver but the gating trigger function enables one to observe only the data stream after a designated number of recirculating loops.

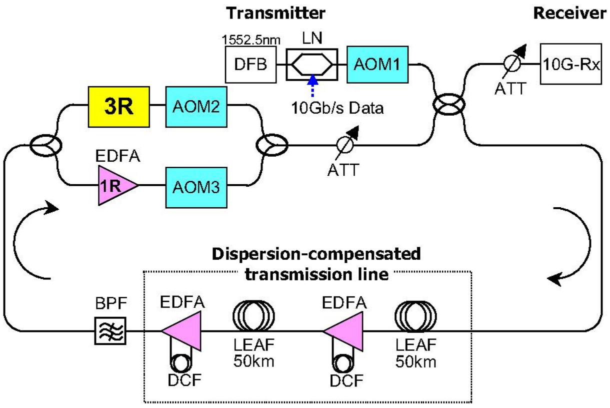

Figure 1 : (a) Reconfigurable recirculating loop transmission setup to enable cascasded 3R regeneration with a variable 3R regeneration spacing.

2.2 3R Regenerator Setup

Figure 2 shows the setup of the 3R regenerator and eye diagrams measured at monitor locations (a)~(g) in the setup. The 3R regenerator consists of a clock recovery part and a signal regeneration part. In the clock recovery part, the SOA-MZI1, operating in the non-inverting differential operation mode, converts the incoming NRZ signal into pseudo RZ (PRZ) format. This conversion process generates a RZ pulse at every rising and falling edge in the NRZ signal and amplifies the weak 10-GHz clock components. The subsequent FPF, whose free spectral range and finesse are respectively 10 GHz and 100, recovers an optical clock signal by extracting 10-GHz clock components from the PRZ signal [6], [11], [12]. The limiting amplification effect of the subsequent gain-saturated SOA reduces pattern-dependent amplitude variations observed at the output of the FPF. The narrow spectral filtering effect in the fiber Bragg grating filter (FBG1) forces the recovered optical clock signal to a smooth sinusoidal waveform and further reduces pattern-dependent variations involving higher frequency components. The optical-to-electrical converter (O/E) converts the recovered optical clock signal into an electrical signal that synchronously modulates the data stream for retiming.

In the signal regeneration part, the two wavelength converters (SOA-MZI2&3) operating in the inverting mode provide 2R regeneration while preserving the signal wavelength and polarity. Although both of the SOA-MZIs have differential signal inputs, they basically operate in the single-arm condition, and the delayed signal inputs are supplementarily used to improve eye openings. Since the SOA-MZI wavelength converters operating in the inverting mode possess a better noise clamping property on the mark level of their input signal, both of the mark and space levels are reshaped effectively through the pair of inverting-mode SOA-MZIs. The synchronous modulator LN2 driven by the recovered optical clock signal provides a retiming function, as well as NRZ-to-RZ conversion. The SOA-MZI3, followed by the FBG3 with a 3-dB bandwidth of 0.22-nm, converts the RZ format back to the NRZ format. The eye diagram Figure2-(g) at the 3R regenerator output shows a clear eye opening and a high extinction ratio of around 10 dB.

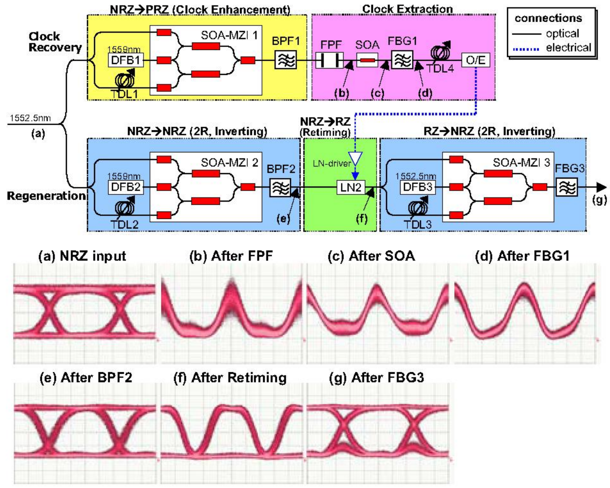

Figure 2 : Setup of the 3R regenerator for NRZ signal and eye diagrams at the monitor locations (a)~(g).

3. Experimental Results

Figure 3 shows eye diagrams after recirculating loop transmissions with different conditions. The notation of (*m* x 1R + *n* x 3R) indicates a recirculating loop transmission experiment with *m*-times 1R followed by *n*-times 3R. Without 3R regeneration (1R only), the eye diagrams in the first row exhibit noise accumulation in both the amplitude and time domains, as well as waveform distortion due to the imperfect dispersion compensation. When 3R regeneration is performed at every lap, identical eye diagrams are obtained with clear eye openings. When 3R regeneration is performed after several laps of the recirculating loop with 1R, the eye diagrams in the third row show degradation as *m* increases. With *m=4* (3R is performed once after 500km transmission with only 1R), the eye diagrams is almost identical as in the “5x3R” case. In the case of *m=9*, the eye is still clearly open but gets slightly blur. When *m=14*, the eye opening is obviously reduced, because the incoming signal (as seen in “15x1R” of the first row) is too degraded to be sufficiently restored.

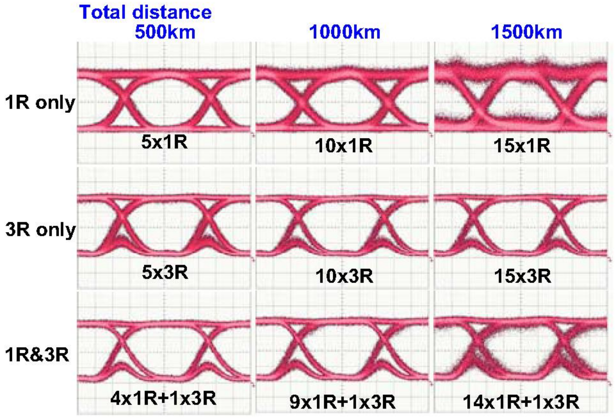

Figure 3 : Eye diagrams after recirculating loop transmission in the three cases of 1R only, 3R only, and combination of 1R and 3R.

Since the 3R regenerator shows a certain degree of signal improvement when the transmission distance before 3R regeneration is equal to or smaller than 1000 km, transmissions with increased lap numbers are performed in three different 3R regeneration spacing cases of 100, 500, and 1000 km (Figure 4).

When the 3R regeneration spacing is relatively short at 100 km, the eye diagrams are almost identical up to Lap 100, which corresponds to a transmission distance of 10,000 km. The eye diagrams with the 500-km 3R spacing exhibit the very similar waveforms up to 5000 km but the mark level looks slightly blur at 5000 km. When the 3R regeneration spacing is 1000 km, the eye diagrams show gradual increase in the amplitude noise on the mark level and the timing jitter noise, as the transmission distance increases.

Figure 5 depicts the Q-factor as a function of transmission distance. The upper horizontal axis shows the corresponding lap number. The Q-factors for the 1R only case are also plotted for reference. The Q-factors are measured from bit error rate (BER) vs. threshold voltage curves, with a constant optical input power of –15 dBm into the receiver. In the case of 1R only, the Q-factor monotonously decreases from the initial value of around 20. On the other hand, when the 3R regeneration spacing is 100 and 500 km, the Q-factors remain almost constant around 20 dB to Lap 100 (10,000 km) and Lap 50 (5,000 km), respectively. When the 3R regeneration spacing is

1000 km, the Q-factor starts to drop above a 2000-km transmission distance. These Q-factor results are in agreement with the eye diagram results.

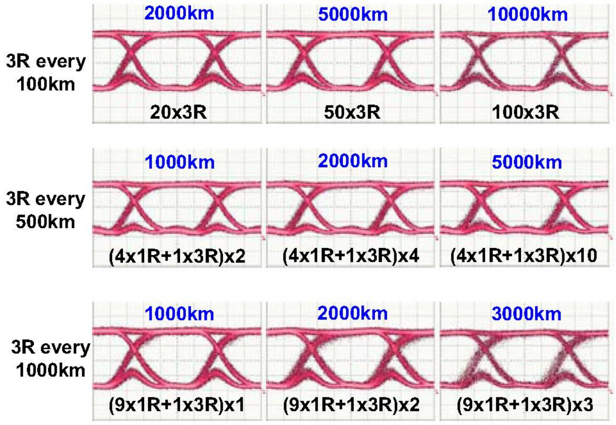

Figure 4 : Eye diagrams after recirculating loop transmissions with 3R regeneration spacings of 100, 500, and 1000 km.

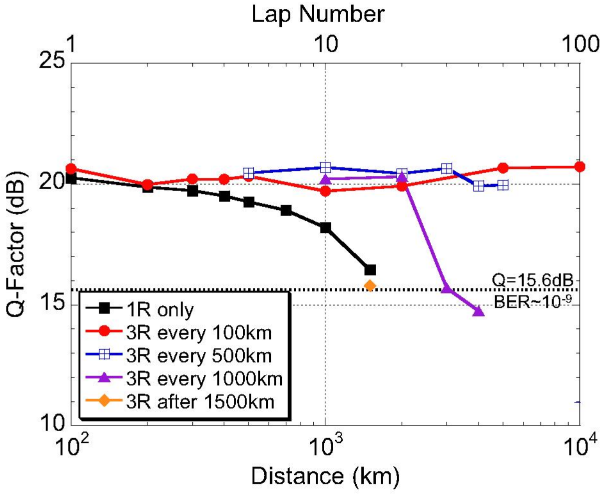

Figure 5 : Q-factor vs. transmission distance and lap number with various 3R regeneration spacings and without 3R regeneration.

4. Conclusion

We have demonstrated a 3R regenerator for a 10 Gb/s NRZ signal. Cascaded 3R regeneration is performed utilizing a reconfigurable recirculating loop transmission. A SOA-MZI based NRZ-to-PRZ converter combined with a FPF performs clock recovery from the NRZ signal. A pair of SOA-MZI wavelength converters and a synchronous modulator provide the 3R regeneration function. Eye diagrams and Q-factors are measured and compared after various cases of recirculating loop transmissions with different 3R regeneration spacings. The 3R regenerator improves signal quality and extends transmission distance, compared to those without 3R regeneration. Although the short 3R regeneration spacing of 100 km is advantageous to sustain identical eye diagrams after large lap numbers, the comparable Q-factors are obtained even when the 3R regeneration spacing is extended to 500 km, which is beneficial from an economical point of view.

5. Aknowledgment

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6. References

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7. Glossary

SOA-MZI: Semiconductor optical amplifier based Mach-Zehnder interferometer

DFB:	Distributed Feedback (laser diode)
ATT:	Attenuator
LN:	$LiNbO_3$ modulator
FPF:	Fabry-Perot filter
SOA:	Semiconductor Optical Amplifier
BPF:	Band-pass Filter
TDL:	Tunable Delay Line
FBG:	Fiber Bragg Grating filter