# Jitter Reduction in a 40 Gb/s All-Optical Packet-Mode 3R Regenerator Using Integrated MZI-SOA Switches

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**Abstract** *We describe phase jitter reduction from 4 to 1 ps for different optical packet lengths in an all-optical 40Gb/s 3R-regenerator, based on integrated MZI-SOAs. Error-free BER operation with 2.5 dB power penalty improvement is demonstrated.*

## Introduction

3R regenerators (Re-amplification, Re-timing, Re-shaping) are indispensable modules for optical communications. In particular, they are employed to counteract transmission impairments at intermediate nodes or end user terminals and restore the original signal quality. In view of future optical networks, all-optical 3R regenerators are introduced as a promising option for deployment in order to increase the capacity and flexibility of the network by handling short IP-like data packets at 40Gb/s (or higher data rates) and at the same time reduce the hardware cost since no optoelectronic conversions will be required. In practice, the deployment of all-optical regenerators will come closer to reality, if they are also capable of regenerating highly degraded signals while using integrated, small foot-print devices. The former requirement will boost regeneration-free transmission distance, while the latter will ease regenerator-on-chip integration.

Optical 3R regeneration at 40 Gb/s has been reported by employing electro-absorption modulators and highly non-linear fibre [1], or a semiconductor optical amplifier (SOA) with a Mach-Zehnder Interferometer (MZI) [2]. Yet in these cases, a high-frequency electrical circuit has been employed for the clock acquisition in which case an optoelectronic conversion becomes inevitable. An optically-clocked 40 Gb/s 3R regenerator has been proposed in [3] where regeneration was accomplished through a self-pulsating laser and a MZI switch.

In this paper we demonstrate for the first time a true all-optical 40Gb/s packet-mode 3R regenerator that reduces rms phase jitter from 4 to 1 ps and is entirely composed of hybrid integrated MZI-SOAs in terms of active elements. The proposed design involves a wavelength converter (WC), a clock recovery (CR) and a decision element in cascade. The data and clock remain in the optical domain thus no optoelectronic converters are required.

## Experiment

The experimental setup consists of the 40 Gb/s optical packet generator, a hybrid integrated MZI-SOA operated as a wavelength converter, the 3R regenerator circuit employing a fibre Fabry-Perot filter (FFP) and two hybrid integrated MZIs, and the 40:10 demultiplexing circuit as shown in figure 1. The original pulse train was produced by a semiconductor mode-locked laser (MLL) operating at a repetition rate of 10.025 GHz and at a wavelength of 1556 nm. An electrical circuit was employed to introduce sinusoidal phase variation of the generated 4ps optical pulses through a variable electrical phase shifter driven by a 10MHz function generator [4]. The jittered signal was used for mode-locking the semiconductor laser and also to drive the demultiplexing circuit for 10 Gb/s channel demultiplexing. Optical data ($2^7$-1 PRBS) was generated by a $LiNbO_3$ electro-optic modulator driven by a 10.025 Gb/s pattern generator. A fibre- based bit-interleaver was used to multiply the data rate to 40.1 Gb/s, and different length data packets

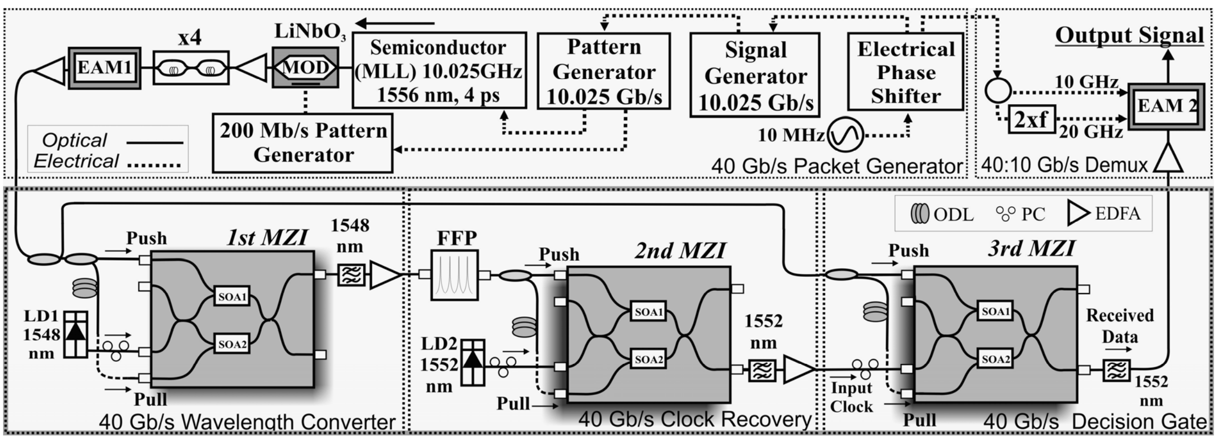


*Figure1: Experimental set-up*

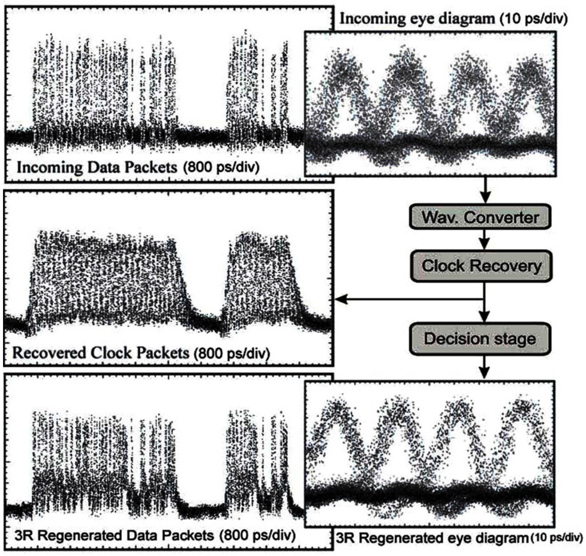


*Figure 2: Oscilloscope traces and eye diagrams*

were generated by modulating the 40.1Gb/s data stream with an electro-absorption modulator (EAM1). The signal was then split and fed to the WC and to the decision gate. The WC adds stability to the circuit by applying local parameters to the incoming packets such polarization, phase and potentially wavelength [5]. The signal was wavelength converted to 1548 nm through the MZI-SOA (1st MZI) operating with a push-pull control scheme for high speed operation. The wavelength converted signal was then amplified and injected into the clock recovery circuit.

The CR employed a low-Q FFP filter with free spectral range (FSR) equal to the line rate (40.1 GHz) and finesse of 39 and a MZI-SOA (2nd MZI) saturated by a CW signal at 1552 nm (LD 2). The FFP filter transformed the data packets into clock packets with intense amplitude modulation, whereas the MZI equalized the pulses after of the FFP filter [6]. A push-pull configuration was adopted to reduce the switching window of the MZI-SOA. Through a simple AND operation at the 3$^{rd}$ MZI, the incoming data (used as the two differential controls) was imprinted on the low jitter clock pulses used as the input signal. Demultiplexing of the 10 Gb/s channels was achieved by driving EAM2 with the electrically jittered 10.025 GHz sinusoidal signal combined with a 20.05 GHz component obtained through a RF frequency doubler and a 20 GHz microwave filter.

Table 1: Power/energy requirements of 3R

| MZI | INPUT | CONTROL (PUSH-PULL) |
|---|---|---|
| *1$^{st}$ MZI (WC)* | 6.5 dBm (CW) | 200 fJ - 100 fJ (pulse energy) |
| *2$^{nd}$ MZI (CR)* | 6.0 dBm (CW) | 300 fJ - 250 fJ (pulse energy) |
| *3$^{rd}$ MZI (AND)* | 100 fJ (pulse energy) | 90 fJ - 20 fJ (pulse energy) |

## Results

The 3R regenerator was tested with short data packets of different durations. The oscilloscope traces and eye diagrams obtained are summarized in figure 2. The recovered clock packets persist for a duration

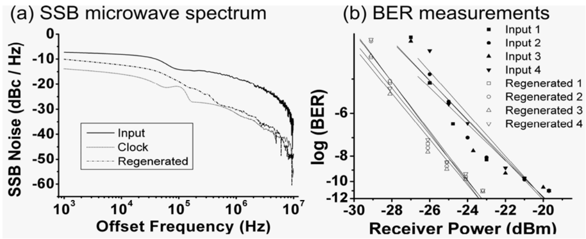


*Figure 3: Phase jitter and BER measurements*

equal to the corresponding incoming data packet length (3.6 ns and 1.6 ns for the left and the right hand side packet respectively) in addition to 100 ps of rise-time (lock-in time) and 350 ps of fall time. The regenerated data packets are obtained after the 3rd MZI. The energy requirements of each MZI are summarized in Table 1 verifying femto-Joule range operation.

Significant phase jitter reduction was confirmed by integrating the single side band (SSB) noise spectra from offset frequency of 1kHz to 10MHz on the second microwave harmonic of the demultiplexed 10.025Gb/s channels (figure 3(a)). The root-mean-square (rms) values were 4 ps for the input, 900 fs for the recovered clock and 1 ps for the regenerated signal. Phase reduction originates from the FFP filter transfer function, which is centred to the carrier, suppressing the data harmonics. Amplitude noise reduction is achieved by operating the 2nd MZI in the saturation regime, smoothing out pulse amplitude fluctuations. Bit-Error-Ratio (BER) measurements were carried out on the 10 Gb/s channels as shown in figure 3(b). Error-free operation with negative power penalty of more than 2.5 dB is demonstrated.

## Conclusions

We have presented a 40 Gb/s true all-optical 3R regenerator for different length packets based on integrated MZI-SOA switches. The phase jitter has been reduced from 4 ps to 1 ps while a power penalty improvement of 2.5 dB was obtained for the regenerated signal. Three identical small-footprint integrated MZIs were employed, constituting the first step towards the integration of the entire 3R regenerator as aimed by the IST-MUFINS project [7].

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## References


1 M. Daikoku et al, IEEE J. Lightwave. Technol., 24, (2006), 1142.
2 B. Lavigne et al., in OFC 2003, 3, PD15 - P1-3.
3 J. Slovak et al., in ECOC 2004, We.2.5.7, 388.
4. A. Poustie et al, in ECOC 2005, We.2.4.6, p.413.
5 O. Leclerc et al., IEEE J. Lightwave. Techol., 21, (2003), 2779
6 D. Tsiokos et al., in ECOC 2005, We4.P.022, 545
7 http://mufins.cti.gr.