Cascaded Operation of a 2R Burst-Mode Regenerator for Optical Burst Switching Network Transmission

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***Abstract*—We demonstrate the cascaded operation of an all-optical 2R burst-mode regenerator consisting of a single Mach–Zehnder interferometer, using a loop configuration that introduces a 6-dB power variation on each recirculation of the data. The device is shown to regenerate error-free 10-Gb/s data streams for up to six successive loop recirculations.**

***Index Terms*—Burst-mode regenerator (BMR), dynamic range, integrated Mach–Zehnder interferometer (MZI), optical burst switching (OBS), optical packet switching, optical signal processing.**

I. Introduction

OPTICAL burst switching (OBS) has been introduced as a concept to provide collective treatment of packet flows, to relax the need for individual packet processing in IP routers, and to offer increased network efficiency and traffic transparency [1]. However, in such an OBS network environment, edge or intermediate nodes have to deal with data bursts exhibiting large variations in their power level since they arrive at the node after having traveled through diverse optical paths of the network [2], [3]. To equalize the power level of these data bursts and to ensure error-free regeneration, burst-mode regenerators (BMRs) have been proposed. 3R BMRs capable of performing power level equalization as well as regeneration including retiming of the bursty data, have been demonstrated for 10 and 40 Gb/s [4], [5]. 3R burst-mode regeneration in every node of an OBS network will naturally reduce degradations of the bursty traffic [5] through the network hops. However, the exclusive use of 3R BMRs will also result in increased cost and complexity due to the retiming function of each regenerator. 2R BMRs have also been shown [6], [7] and they are far simpler to implement than 3R equivalents. A 2R BMR circuit comprising of two semiconductor optical amplifiers (SOAs) and an integrated wavelength converter has been demonstrated to equalize a 40-Gb/s optical packet stream with packet-to-packet power variations of 8 dB [6]. More recently, an even simpler 2R BMR was reported, consisting of a single hybrid integrated SOA Mach–Zehnder interferometer (MZI) with unequal splitting ratio couplers [7]. The device was shown to operate error-free with 40-Gb/s variable length, asynchronous optical packets with up to 9-dB packet-to-packet power variation.

A straightforward way to reduce the OBS network complexity and cost is to use a number of consecutive 2R BMRs for burst power equalization, before full 3R burst-mode regeneration is required. Such a concept will only be useful if 2R BMRs can be shown to be capable of successively regenerating bursts error-free. So far, cascaded 2R regeneration studies have been performed for nonbursty data formats only [8], [9], reporting 2R cascaded regeneration for 10-Gb/s return-to-zero (RZ) data format and 10-Gb/s nonreturn-to-zero data using an SOA-assisted saturable absorber module [8] and an SOA-MZI wavelength converter, respectively [9].

A first attempt to examine the number of successive error-free regenerations that can be performed with the single MZI, 2R BMR of [7] in a loop experiment has been reported in [11], showing four cascades. In this letter, we present new results obtained for 10-Gb/s $2^{15}-1$ pseudorandom binary sequence (PRBS) data streams with RZ format of 8-ps pulsewidth, reporting that error-free regeneration was possible even after six recirculations. Moreover, included timing jitter measurements prove the validity of the proposed network transmission concept while allowing for a discussion on its limitations.

II. Concept and Experiment

The loop configuration was designed in order to simulate the aggregation of the bursty data traffic in an OBS switch. This was achieved by incorporating a modulator into the loop so that part of the recirculating data experienced, each time, severe attenuation before entering the 2R BMR. In order to attenuate different parts of the recirculating data in every transit, the modulator period T_{MOD} and the loop period T_{LOOP} were arranged following the expressions:

$$T_{\mathrm{LOOP}} \neq m \cdot T_{\mathrm{MOD}}, \quad \text{where } m \text{ integer} \qquad (1)$$
$$k \cdot T_{\mathrm{MOD}} = n \cdot T_{\mathrm{LOOP}}, \quad \text{where } k,\ n \text{ integers.} \qquad (2)$$

As such, parts of the recirculating data were attenuated and regenerated more times than others after several loop transits. To illustrate this operation, Fig. 1(a) depicts a schematic of the data within a loop load for its second transit. The data stream entering the loop has been divided into a gray zone that represents the part of the data that has already been attenuated and regenerated once and a second part that contains the nonattenuated data. As this data stream enters the modulator for the second time, parts of both data areas are attenuated. Power equalization at the 2R BMR creates a third data area, shown in the figure as a dashed

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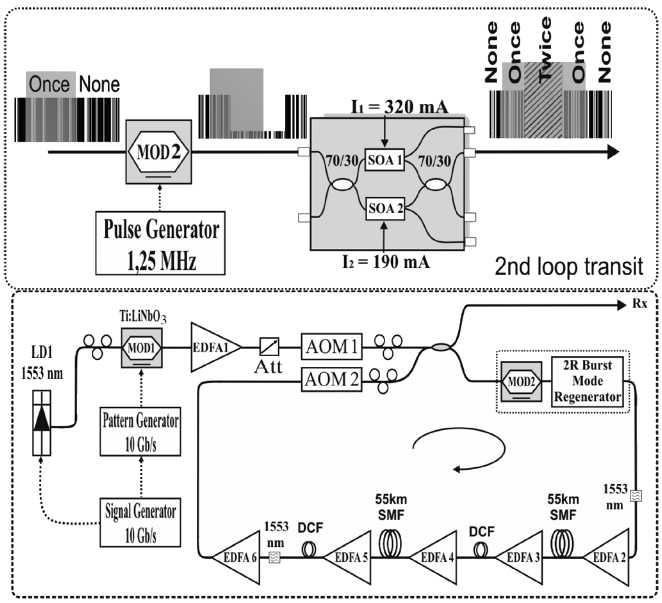

Fig. 1. (a) Graphic representation of the recirculating signal for the second loop transit. (b) Loop experimental setup.

zone, which represents the data parts that have been attenuated and regenerated twice. This sequence of loss and regeneration continues for the following loop transits affecting different parts of the data, so that finally different parts of the data stream undergo attenuation and regeneration more times than others.

Fig. 1(b) shows the experimental setup of the recirculating loop. A distributed-feedback laser diode was gain-switched at 10 GHz to produce 8-ps pulses at 1553 nm. The generated pulse train was modulated in a Ti : $LiNbO_3$ modulator (MOD 1) driven by a 10-Gb/s pattern generator providing a $2^{15}-1$ PRBS data pattern. This signal was amplified in an erbium-doped fiber amplifier (EDFA) before entering the recirculating loop via the loop switch. The loop switch consisted of an acoustooptic modulator (AOM 1) to control the filling time of the loop and an additional AOM (AOM 2) to control the number of round-trips that the signal travels before detection. The recirculating loop consists of two spans of 55-km single-mode fibers (SMFs). Each span was followed by dispersion-compensating fiber (DCF) (-1360 and -340 ps/nm, respectively) to compensate chromatic dispersion and an EDFA to compensate the power loss. The input powers in the two SMF spans are 8 and 7.8 dBm, respectively, and the input power in the DCFs are 2.2 and 0.4 dBm, respectively. An optical filter of 1-nm bandwidth was used at the output of the second DCF fiber.

MOD 2 was a second Ti : $LiNbO_3$ modulator and provided the repetitive loop loss, driven by a low rate signal of 800-ns period to form a two-level data stream with 6-dB power difference after each transit. The power varying data signal was fed into the 2R BMR, circuit that consists of a single, hybrid integrated MZI. This MZI had couplers of unequal splitting ratios (70/30) and was configured to self-switch the incoming data traffic. Self-switching was achieved by exploiting the unequal splitting ratio of the couplers and by using different current values (320 and 190 mA) for the two SOAs in the interferometer arms [9]. With this arrangement, the saturation properties of the two SOAs, along with the interferometric transfer function of the unequal splitting ratio coupler MZI, provided power equalization in the data stream. The average power of the data stream at the input of the 2R-BMR was 0 dBm and a 1-nm bandwidth optical filter was used at its output.

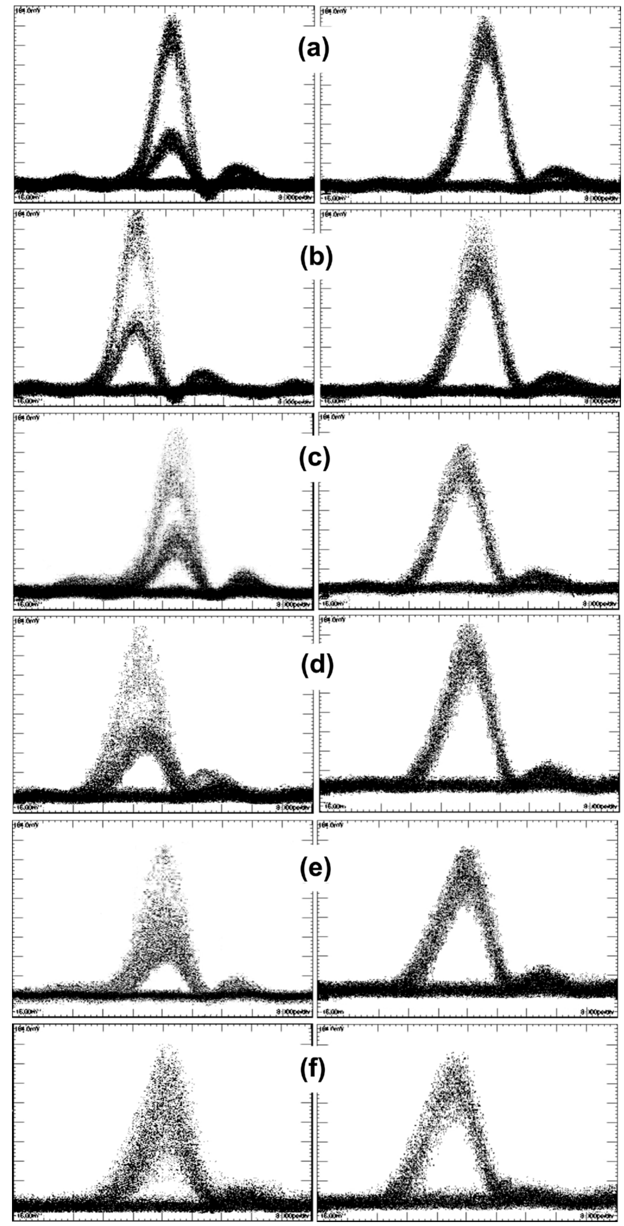

Fig. 2. Input and output signal eye diagrams for (a) first, (b) second, (c) third, (d) fourth, (e) fifth, and (f) sixth loop transit. The time scale is 8 ps/div.

III. Results and Discussion

Fig. 2 illustrates the evolution of the 2R burst-mode regeneration process through eye diagrams for successive transits of the signal through the loop. Left-side eye diagrams depict the signal immediately after MOD 2 inside the loop and represent the input signal of the 2R-BMR for every pass. Right-side eye diagrams show the regenerated signal at the output of the loop.

Fig. 3 shows the bit-error-rate (BER) curves for the output signal after each loop. The base-line is taken to be the BER curve obtained with MOD 2 set at transparency, so that the input signal

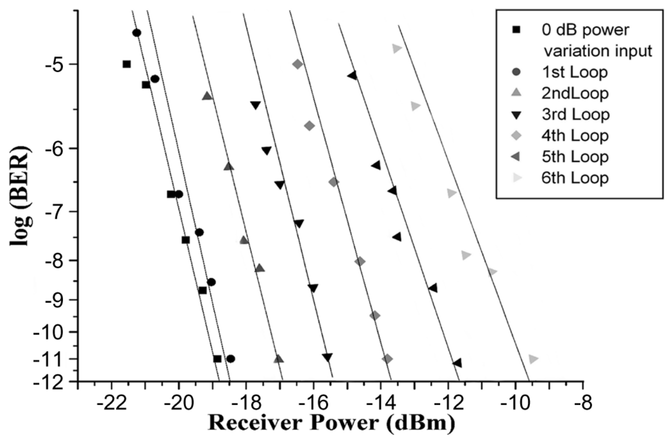

Fig. 3. BER measurements after each loop transit.

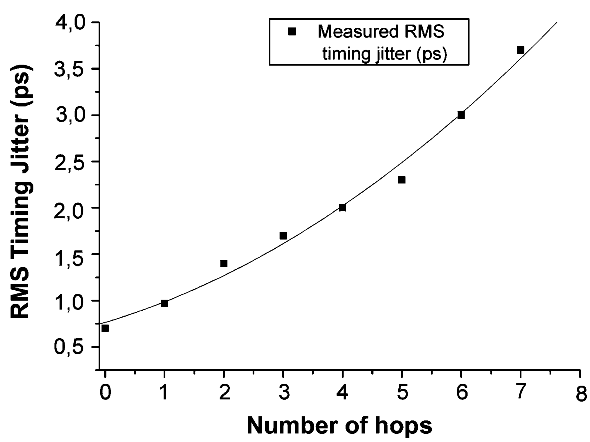

Fig. 4. Measured rms timing jitter for seven consecutive loops.

suffers no power variations. With MOD 2 driven to produce the two 6-dB differing power levels in the data stream shown in the left column of Fig. 2(a), an error floor of 10^{-5} was obtained in the BER measurements at the maximum power allowed to the receiver. This error floor curve is not depicted in Fig. 3. Introduction of the BMR-MZI in the loop resulted in the near complete power equalization in the data stream at its output after the first transit and the clearly open eye of the right side of Fig. 2(a). The power penalty for this signal compared to the BER of the base-line was only 0.4 dB. In the second transit, equalization is repeated after the 6-dB modulator loss, but this time less well and an excess power penalty of 1.4 dB was obtained with respect to the first transit. In the following transits, the equalization process continues but is increasingly less ideal as different parts of the data stream undergo attenuation and regeneration more times than others. This results in a larger power variation in the modulated signal and an increasing spread of the "1s" after equalization and gradual worsening in the eye opening at the output. As Fig. 3 shows, error-free regeneration was obtained for up to the sixth transit with increasing power penalty. The seventh transit exhibited an error floor at 10^{-8}.

One reason that the power penalty increases for the transits following the first is that the 2R BMR in the loop has parameters statically optimized for the first transit. As the signal properties change on successive transits, the initial parameter setting of the 2R BMR is no longer optimum and this adds further to the nonideal equalization. Therefore, the six error-free cascades achieved in this experiment present the lower bound of cascades that can be expected to be achieved in a real sequence of 2R BMRs where operating parameters of BMRs can be individually optimized. The power penalty increase between successive loops is also due to the timing jitter accumulation induced by the absence of the retiming functionality. Fig. 4 shows the root-mean-square (rms) timing jitter accumulation during seven successive loops, measured with a 50-GHz bandwidth oscilloscope. The figure suggests that if this device is followed by a 3R BMR that is capable of suppressing signal rms timing jitter by 2 ps or more [5], complete jitter compensation should be possible even after five successive cascades. Application of clock recovery modules that can provide more intense jitter reduction [11] suggests that jitter suppression may be possible with a 3R BMR, even after six consecutive MZI-2R BMRs.

IV. Conclusion

We have presented the cascaded operation of a simple all-optical 2R burst-mode regenerator that consists of a single integrated SOA-MZI with couplers of unequal splitting ratio. The device performance was investigated using a loop configuration arranged to produce data sequences that resemble a data burst assembled by unequal power level data packets. Error-free burst-mode regeneration of these power varying data streams has been obtained for six cascades.

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