40 Gb/s 2R Burst Mode Receiver with a single integrated SOA-MZI switch

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Abstract: We demonstrate a novel scheme for 2R burst mode reception capable of operating error-free with 40 Gb/s variable length, asynchronous optical data packets that exhibit up to 9 dB packet-to-packet power variation. It consists of a single, hybrid integrated, SOA-based Mach-Zehnder Interferometer (SOA-MZI) with unequal splitting ratio couplers, configured to operate as a self-switch. We analyze theoretically the power equalization properties of unequal splitting ratio SOA-MZI switches and show good agreement between theory and experiment.

OCIS codes: (060.4510) Optical communications; (230.1150) All-optical devices; (250.5980) Semiconductor Optical Amplifiers.

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1. Introduction

Multi-access networks such as Optical Burst/Packet Switching and Passive Optical Networks (PONs) have been introduced as efficient and flexible solutions for broadband applications,

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since they provide improved bandwidth utilization and offer a higher degree of data transparency [1]. In these architectures data packets are transmitted asynchronously from different network locations and travel through different optical paths, so that they exhibit large variations in optical power on reaching the receiver end. Burst Mode receivers undertake to handle asynchronous and unequal power level data packet streams and to ensure error free reception and as such they are key elements for the realization of burst and packet switched networks [2].

Specifically, the role of 2R Burst Mode Receivers is first to perform power equalization between asynchronous data packets that arrive at the node having different power levels, and then to provide 2R-regeneration of the input signal by means of suppressing signal degradations induced by accumulation of noise. So far, power equalization but without 2R regeneration has been reported utilizing optical limiting amplifier configurations [3,4]. Power equalization and 2R regeneration of continuous 10 Gb/s data streams have been demonstrated with a SOA-based delayed interferometer [5] and a Michelson interferometer [6]. 2R burst mode reception has been reported with a circuit that includes a 2-element module consisting of two gain-clamped SOAs for optical power limiting and a wavelength converter configuration for 2R regeneration, demonstrating error-free reception of optical bursts at 40 Gb/s with packet per packet power fluctuation of 8 dB [7].

In this article we demonstrate a simple 40 Gb/s all optical 2R Burst Mode Receiver built with a single, hybrid integrated, SOA, Mach-Zehnder Interferometer (HMZI) which has unequal splitting ratio couplers. This unbalanced SOA-MZI exploits the non-linear transfer function of the interferometer to suppress the ‘0’ noise level and the gain dynamics of the SOAs to achieve packet power equalization. We analyze theoretically the power equalization properties of this scheme by deriving a frequency domain theoretical transfer function. We also demonstrate experimentally that it can receive asynchronous and variable length data packets with up to 9 dB power fluctuation error free, and show good agreement with the theoretical analysis. "Major attributes of the circuit are that it relies on standard, hybrid fabrication technology used in commercial MZI devices and that it is simple. This is important for a WDM burst mode receiver (BMR) where a single MZI device is required for each wavelength channel. Fortunately, from a device perspective, multi-element MZI arrays are becoming available [8].

2. Principle of operation and theoretical analysis

Figure 1 depicts a SOA-based MZI switch configured as a 2R Burst Mode Receiver. It consists of an input and an output coupler with splitting ratio, *a*, and of two optical branches, each one employing a SOA as the nonlinear active element. The burst-mode data packets are inserted as the input signal into the MZI and split into two spatial components of unequal powers *a*P and (1-*a*)P. The signal component with a power level of *a*P is injected into SOA1 and the second component is launched into SOA2. For successful burst-mode reception, the two SOAs have to operate at different current conditions I_1 and I_2, respectively, with each driving current determined by the corresponding SOA input signal power. For higher input power a higher current value is required, indicating that SOA1 is driven by $I_1>I_2$, since *a*P>(1-*a*)P (*a* denotes the higher splitting ratio). In this way, each amplifier is forced to operate in its saturated regime for the high level packets and in its small-signal gain regime for the low level

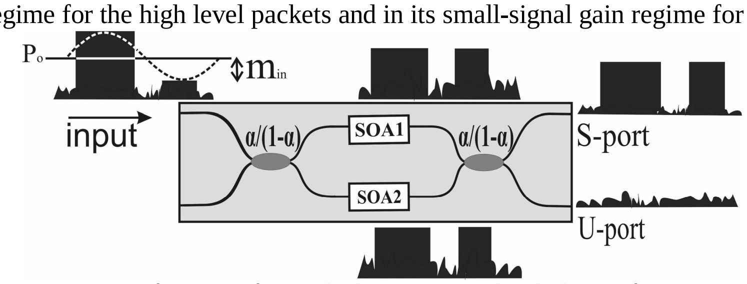

Fig. 1. Configuration of unequal splitting ratio Mach-Zehnder Interferometer

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packets. To this end, high gain is perceived by the low power level packets, whereas low gain is experienced by the higher power level packets, resulting to a nearly power equalized packet stream at the output of each SOA. In addition, the different driving conditions of the two SOAs in combination with the unbalanced nature of MZI provide a differential phase shift between the two spatial components, since the packet stream traveling through SOA1 experiences a higher gain value and as a result a greater phase shift than the corresponding signal traveling through SOA2, according to the relationship $\varphi = -(\alpha_n/2)\ln G$ (α_n is the linewidth enhancement factor) [9]. By appropriately adjusting the two driving current values, an approximately π differential phase shift between the two power equalized packet streams at the two branches can be obtained, whereas the noise accompanying the signal will be suppressed [6] as a result of the interferometric transfer function of the device. In this respect, self-switching operation is achieved and the interference of the two spatial components at the output coupler of the MZI yields a nearly-noise released power equalized packet stream at the Switched port (S-port) of the MZI.

For the theoretical analysis of the self-switching operation and the packet power equalization properties of the proposed 2R burst-mode receiver, we consider the unbalanced MZI shown in Fig.1 with the two SOAs assumed to be two identical devices. The transfer function of the S-port is then provided by Eq. (1)

$$P_S(t) = \{a^2 G_1(t) + (1-a)^2 G_2(t) - 2(1-a)a\sqrt{G_1(t)G_2(t)}\cos\left(-\frac{\alpha_n}{2}\cdot \ell n\frac{G_2(t)}{G_1(t)}\right)\}P_{in} \quad (1)$$

where P_{in} is the input signal optical power, α_n denotes the SOA linewidth enhancement factor and $G_1(t)$ and $G_2(t)$ are the upper and lower branch SOA gains, respectively [9].

In the case of amplitude modulated input pulse signal, the energy of the k-th individual pulse inserted into the MZI can be expressed as

$$U_{in}^{k}(t) = P_0\left(1 + m_{in}\cdot\cos\left(\Omega\cdot k\cdot T\right)\right)\cdot\int_{-\infty}^{t} a(t')dt' \qquad (2)$$

In (2), $a(t)$ represents the pulse waveform, P_0 is the average peak power value across the whole input signal sequence, m_{in} is the modulation depth index, Ω is the modulation frequency and T is the pulse period. The physical representation of these parameters is illustrated in Fig.1.

The modulation depth index $m_{o/p}$ at the S-output port of the MZI is obtained by calculating the pulse peak power for every self-switched pulse. When the whole input pulse energy has been inserted into the respective SOA, the time-dependent integral contained in (2) can be replaced with a constant value A. The peak power of the k-th switched pulse is obtained by replacing the integral with A, using (2) into the gain and phase relationships provided in [10] and inserting the resulted expressions in (1). The switched pulse peak power is then expanded into a Taylor series around the zero value of m_{in} and is expressed as a sum of a dc power component and an oscillating, modulating power component at Ω. The amplitude modulation depth index at the output of the gate $m_{o/p}$ is defined as the ratio of the modulating power at Ω to the dc optical power. The resulting expression is a function of m_{in}, a, α_n, of the average gain values $G_1\big|_{m_{in}=0}$ and $G_2\big|_{m_{in}=0}$ and of the first derivatives of $G_1(m_{in})$ and $G_2(m_{in})$ at $m_{in}=0$. For optimized self-switching performance, the average peak powers aP_0 and $(1-a)P_0$ have to correspond to an induced differential phase shift of π. This requirement leads to $G_1\big|_{m_{in}=0} = G_2\big|_{m_{in}=0}\cdot\exp\left(2\pi/\alpha_n\right)$. By using this condition in the fractional expression of the amplitude modulation depth index $m_{o/p}$, following relationship is derived:

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$$\frac{m_{o/p}}{m_{in}} = 1 + \frac{U_{in}}{U_{sat}} \cdot \frac{\left\{ \left(1 - G_1\big|_{m=0}\right) \left[a^3 + a^2(1-a)\exp\left(\frac{\pi}{\alpha_n}\right) \right] + \left[1 - G_1\big|_{m=0} \cdot \exp\left(\frac{2\pi}{\alpha_n}\right) \right] \cdot \left[(1-a)^3 \exp\left(\frac{2\pi}{\alpha_n}\right) + a(1-a)^2 \exp\left(\frac{\pi}{\alpha_n}\right) \right] \right\}}{a^2 + (1-a)^2 \exp\left(\frac{2\pi}{\alpha_n}\right) + 2a(1-a)\exp\left(\frac{\pi}{\alpha_n}\right)} \quad (3)$$

Eq. (3) is the basic theoretical result derived within this article and provides the frequency domain transfer function characteristics of the proposed configuration. It shows that the relationship between $m_{o/p}$ and m_{in} is linear, depending on a, on α_n, on the initial G_{1o} gain value and on the average input pulse energy $U_{in}=P_oA$. The validity of Eq.(3) extends for the parameter space for which π differential phase shift is obtained between the two interferometer branches, which for our set of parameter values corresponds to U_{in}/U_{sat} ranging from 0 to 0.6.

Let us now define the amplitude modulation between two packets as the decimal logarithm of the power ratio between the higher level to the lower level packet. This implies that the amplitude modulation between the input and between the output packets depicted in Fig. 1 can be expressed as $10 \cdot \ell og\left[(1+m_{in})/(1-m_{in})\right]$ and $10 \cdot \ell og\left[(1+m_{o/p})/(1-m_{o/p})\right]$, respectively. By replacing $m_{o/p}$ with its expression in (3), the calculation of the output amplitude modulation for any given input amplitude modulation becomes possible.

Figure 2 shows the output amplitude modulation versus U_{in}/U_{sat} for different coupling ratios and input amplitude modulation of 3, 6, 10 and 13 dB. Fig. 2(a) corresponds to the case of 50/50 splitting ratio, showing that although amplitude modulation reduction is achieved, the output amplitude modulation remains strong. Fig. 2(b) shows results for 70/30 coupling ratio and is almost a flat line parallel to the U_{in}/U_{sat} axis, revealing that the output amplitude modulation is reduced to less than 2 dB for a wide range of average U_{in}/U_{sat} values, even when the input amplitude modulation exceeds 10 dB. Amplitude modulation reduction of the unbalanced MZI is even more pronounced for 90/10 splitting ratio, as shown in Fig. 2(c), where the output amplitude modulation is always less than 1 dB. For all the theoretically obtained graphs of Fig. 2, the α_n-parameter and the initial gain value G_{1o} were chosen to have the typical values of 6 and 1000 respectively.

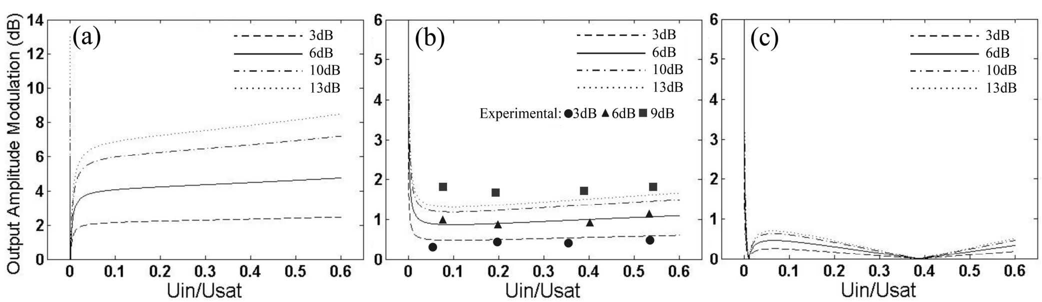

Fig. 2. Theoretically obtained graphs for m_{out} vs U_{in}/U_{sat} for coupling ratios: (a)50/50 (b) 70/30 (c) 90/10

3. Experimental Setup

Figure 3 shows the experimental setup used to evaluate the 2R burst-mode reception capabilities of the proposed scheme. It consists of the 40 Gb/s optical packet generator, a hybrid integrated MZI (HMZI) with unequal splitting ratio couplers that comprises the 2R burst mode receiver, and an Electro-Absorption Modulator (EAM) used as a 40 to 10 Gb/s demultiplexer. The input packet generator was designed to produce a stream of variable length, asynchronous data packets exhibiting arbitrary and controllable power levels to simulate bursty traffic. A 1553 nm DFB laser was gain switched at 10.025 Gb/s to produce 3 ps pulses after both linear and non-linear compression. A Ti:$LiNbO_3$ electro-optic modulator

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and a fiber bit-interleaver were used to form a 2^7-1 PRBS data pattern at 40.1 Gb/s. A second Ti:$LiNbO_3$ electro-optic modulator driven by a 3.3 Gb/s pattern generator was used to produce a sequence of two different data packets of unequal length. This packet stream was then launched into a third Ti:$LiNbO_3$ modulator driven with a low rate signal so as to partially modulate only one of the two consecutive packets and to allow the second packet through unaffected. As a result a sequence of two data packets with unequal power levels was obtained at the modulator output. This signal was then introduced into a split-and-delay multiplexer in order to form asynchronous data packets. The asynchronous multiplexer consisted of a 3 dB coupler with fiber lengths of 250 nsec differential delay at its outputs and a second 3 dB coupler to recombine the relatively delayed signals. A variable optical delay line (ODL) and an optical attenuator were employed in the two branches so as to be able to control the phase alignment and the power level of the interleaved packet streams. The resulting signal was then inserted as the input signal into the 2R burst-mode receiver, which consisted of a hybrid integrated SOA-MZI with 70/30 input and output coupling ratios. The SOAs provided small signal gain of 23 dB at 200 mA and 30 dB at 300 mA and their U_{sat} parameter was 700 fJ.

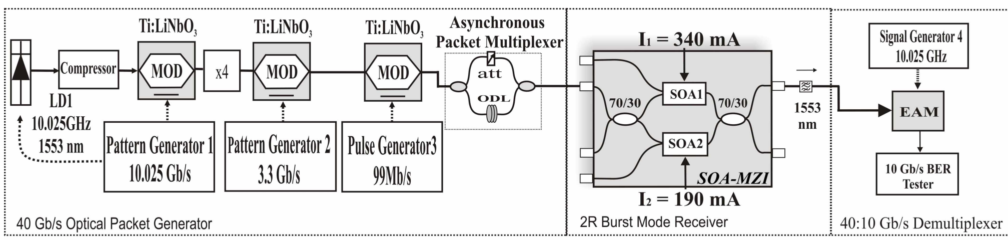

Fig. 3. Experimental setup

4. Results and discussion

In order to evaluate the performance of this 2R BMR concept, streams of packets with different power level characteristics were constructed and launched into the unequal coupling ratio HMZI. The packet streams consisted of consecutive packets with unequal lengths of 48 and 75 bits that arrived asynchronously to the 2R BMR setup. The two SOAs of the 2R BMR were driven with different current values of 340 mA and 190 mA. Figure 4 presents the results with the top rows showing the input signal pulse traces and eye diagrams and the bottom rows showing their corresponding outputs.

Figure 4(a) shows the input signal consisting of a sequence of packets whose mark value is consecutively altered from packet to packet between 2 power levels of 9 dB difference. In the input eye diagram, the low power level packet cannot be identified as it is masked by the response of the 40 GHz photodiode. At the output of the 2R BMR the initial 9 dB power difference was reduced to 2 dB and an open eye was obtained. The inner packet amplitude modulation is due to the linear patterning effect [11] introduced by the slow SOA gain recovery time that was greater than the bit period in both SOAs, having a value of 60 ps and

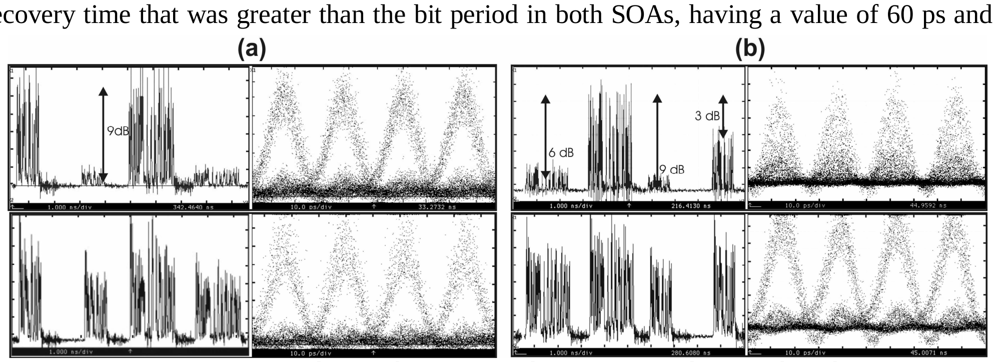

Fig. 4. Input (top row) and output (bottom row) pulse traces (timescale:1ns) and eye diagrams (timescale:10ps) for input packets with (a) 2 power levels and (b) 4 power levels

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80ps respectively for the given SOA driving currents. In order to determine the dynamic range of average input power levels within which this 2R BMR scheme can operate, the mark value at the output was recorded for a broad range of average input signal pulse energies and for packet sequences whose mark value at the input varied from packet-to-packet by 3, 6 and 9 dB. Results from these measurements are shown in Fig. 2 (b) together with the theoretically obtained curves for output power difference versus pulse energy for a 70/30 coupling ratio MZI switch and show good agreement between theory and experiment. The figure indicates that for input pulse energies between 110 fJ to 390 fJ corresponding to values of U_{in}/U_{sat} between 0.15 to 0.6, the power difference is reduced from 3, 6 and 9 dB at the input, to 0.5 dB, 1dB and 2 dB respectively at the output. These results essentially imply that besides being capable to suppress a large power variation at its input, this BMR scheme can maintain this performance over a broad range of mean input powers. .

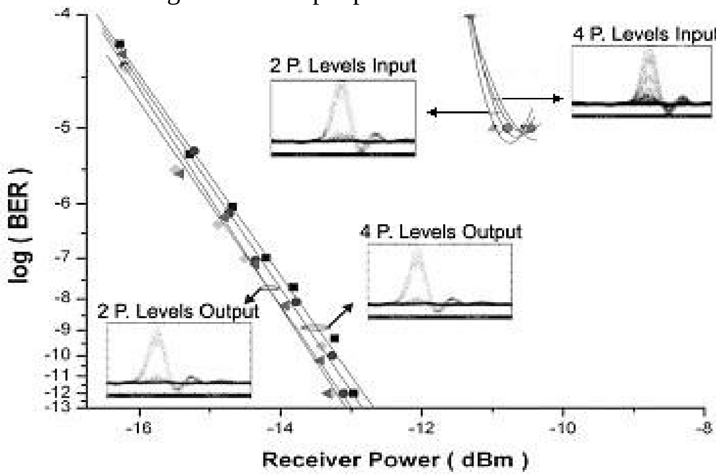

Fig. 5. BER curves for two demuxed channels for : 2P. level input, 4P.level input, 2P level output, 4P. level output

The power equalization properties of the BMR were also investigated with a 4 power level sequence of packets with differences of 3, 6 and 9 dB between them. Figure 4(b) shows this input signal pulse trace and the corresponding eye diagram which is fully closed. Once again at the output of the circuit the packets were power equalized within 2 dB and a clear, open eye was obtained with current driving values of the SOAs fixed to the same values as before. This indicates that the unequal coupling ratio HMZI can simultaneously equalize packet sequences of multiple levels as may be expected with true bursty traffic.

For the BER measurement procedure synchronous data packets were used, generated by properly adjusting the ODL included in the asynchronous packet multiplexer. BER measurements were carried out for both types of input packet sequence configurations with two and four packet power levels. An EAM was used for demultiplexing the 40 Gb/s packets into 10 Gb/s data streams. Figure 5 shows the BER measurements for two of the four demultiplexed 10 Gb/s channels. Input signal BER curves indicate an error floor at 10^{-5}, even for the maximum input power allowed on the receiver. The corresponding curves at the output of the 2R BMR show that the error floor was eliminated and that power equalization within 2 dB provided error free operation. This was achieved without using any guardbands for reducing the amplitude modulation imposed on the packet signal by the SOA gain excursions, indicating that no limitations in terms of the number of consecutive ‘zeroes’ or the number of preamble bits in the data packets are required. It should be mentioned that the BER measurements for the 4–level signal exhibit a marginal power penalty with respect to the corresponding 2-level signal curves, although in Fig. 4 the eye opening of 2-level output signal appears slightly degraded compared to the 4-level output signal. This is due to the extra OSNR degradation of the 4-level input signal induced by the additional modulator and EDFA used for the 4-level signal generation. Finally, BER measurements were carried out also for

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the case of high quality power equalized data packets used as the input signal, revealing that in this case the proposed device induces a power penalty of only 0.6 dB.

5. Conclusion

We have presented a novel scheme for 2R burst mode reception, capable at operating error-free with 40 Gb/s variable length, asynchronous optical packets exhibiting 9 dB packet-to packet power fluctuation. The setup is simple and requires only one SOA-MZI with unequal splitting ratio couplers, configured as a self-switch. The theoretical analysis has confirmed the power equalization properties of this burst mode receiver and has shown good agreement with the experimental results.

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