Bit-Error-Rate Assessment of 170-Gb/s Regeneration Using a Saturable Absorber and a Nonlinear-Fiber-Based Power Limiter

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***Abstract*—A 170-Gb/s all-optical 2R regenerator made up of a fast saturable absorber and a highly nonlinear-fiber-based power limiter is reported for the first time. Bit-error-rate assessment of one of the four 42.5-Gb/s optical time-division-multiplexed tributaries shows a receiver sensitivity improvement.**

***Index Terms*—Nonlinear optics, optical fiber communication, optical signal processing, semiconductor devices.**

I. Introduction

ALL-OPTICAL regeneration is a key element to increase tolerances to various impairments of very high bit-rate optical time-division-multiplexed (OTDM) systems. To reshape the signal, a regenerator must have a nonlinear output power versus input power response. Semiconductor-based saturable absorbers (SAs) are particularly attractive because of their small size, passive behavior, and large bandwidth. They have demonstrated their strong potential for high bit-rate optical regeneration at 10, 40, and 170 Gb/s [1]–[4].

The possibility to create nonradiative carrier recombination centers in the multiquantum-well (QW) structure through high energy ion implantation technique [5] can lead to a carrier recombination time compatible with very high bit-rate signal processing. Recent experiments using a microcavity SA have shown extinction ratio enhancement of a 170-GHz clock frequency laser source [4], [6]. However, the reported microcavity SA mainly enhances the extinction ratio of the signal without any improvement on high power levels [7]. Consequently, complementary function acting on high-power levels is required to achieve a complete 2R regeneration (reamplifying and reshaping). The power limiter based on a nonlinear fiber and centered filtering appears to be the best complementary function at 170 Gb/s [8].

In this letter, we assess, for the first time to our knowledge, at a bit-rate of 170 Gb/s, a regenerator composed of an SA and a highly nonlinear-fiber-based power limiter.

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II. Regenerator Architecture and Transmission Function

A. SA Structure

The SA is an asymmetric Fabry–Pérot cavity structure fabricated at LPN-CNRS, France. The active layer is composed of seven InGaAs–InP QWs irradiated by 12-MeV Ni^{6+} ions with a dose of 10^{12} cm^{-2}. This heavy ion irradiation creates defects in the structure acting as carrier recombination centers reducing the carrier lifetime in the cavity. With this irradiation dose, the $1/e$ absorption recovery time is estimated to 1.5 ps.

The SA reflectivity increases with the incident power, so that low power levels are significantly attenuated while high power levels are much less attenuated. This results in a signal extinction ratio enhancement, called the contrast. Moreover, the active layer is contained in a cavity so as to both decrease the switching power threshold and increase the contrast. The back mirror is made by deposition of a silver layer whereas a Bragg reflector $(TiO_2 - SiO_2)$ is used as the front mirror.

The contrast of this structure was measured in [4] and [6] with an autocorrelator and a low frequency pump probe experiment.

In order to characterize the SA, a pump probe experiment was performed at 170 Gb/s. The pump is a 170-Gb/s signal at 1558 nm, 1.5-ps full-width at half-maximum (FWHM), with a pseudorandom bit sequence (PRBS) of $2^7 - 1$ bits. The pump is coupled to a continuous-wave probe signal centered at the resonance of the SA at 2 dBm. Both signals are injected into the SA. The probe is then modulated by the pump through cross-absorption modulation in the SA. At the output, a filter rejects the pump signal, and the modulated probe is analyzed with an optical sampling oscilloscope (OSO) with 1-ps resolution. The contrast of the SA, corresponding to extinction ratio of the probe, is depicted in Fig. 1. An extinction ratio enhancement of 8 dB was obtained for an input average power of 15.1 dBm. The probe FWHM was found to be 1.5 ps at the output of the component.

SA alone does not provide regeneration especially because there is no full absorption saturation with telecommunication signals [7]. For complete regeneration, a power limiter completes the SA function as presented in the next section.

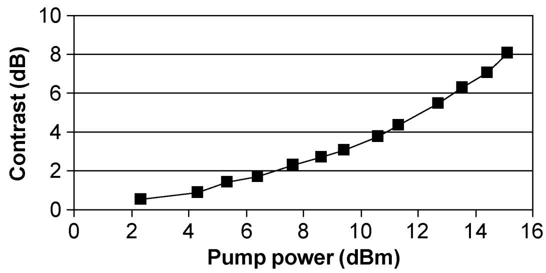

Fig. 1. SA contrast versus pump power at 170 Gb/s.

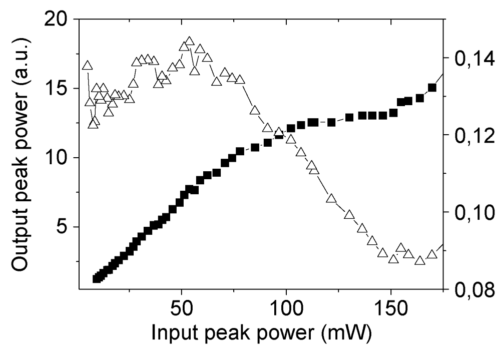

Fig. 2. Output peak power and transmission function $P_{\rm out}/P_{\rm in}$ of the power limiter at 170 Gb/s as a function of the input peak power.

B. Dynamic of the Power Limiter

As the SA does not reduce the intensity noise on the high power levels, a dynamic power limiter is required to obtain a full 2R regenerator. Different solutions were investigated so far with an SA. At 10 Gb/s, the dynamic response of a semiconductor optical amplifier (SOA) was used to limit the intensity fluctuations [3]. At 40 Gb/s, two solutions were investigated. The first one is based on soliton effects in a fiber [1], [2] and the second one is based on a new QW-SA [9]. At 170 Gb/s, the fiber-based solution appears more appropriate. The principle of operation was described in [8] and [10]. An amplified signal entering a highly nonlinear fiber (HNLF) with anomalous dispersion undergoes self-phase modulation. This leads to a spectral broadening related to the peak power. This signal is then filtered through a centered optical filter that limits the spectral broadening. As the spectral broadening also depends on the characteristics of the optical fiber, an appropriate set of parameters of the fiber allows us to obtain a power limiting function. The parameters of the HNLF used in this experiment are the following: fiber loss $\alpha = 0,6$ dB/km, chromatic dispersion $D = 0,7$ ps/nm/km, fiber length $L = 920$ m, nonlinear coefficient $\gamma = 11\ \mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$. The filter is a second-order supergaussian filter with a 3-nm bandwidth at 3 dB. Fig. 2 shows the output peak power (measured at the OSO) as well as the transmission response as a function of input peak power (deduced from average power). As expected, the output peak power curve exhibits a plateau for an input power ranging from 110 to 145 mW.

Usually, the dynamic of a power limiter tends to reduce intensity fluctuations on high power levels but it also leads to an extinction ratio degradation. Indeed, the power transmission coefficient, defined as the ratio between the output and input powers, decreases when the input power increases, as shown in Fig. 2. This means that $T^1/T^0 < 1$ where $T^1 = P^1_{\rm out}/P^1_{\rm in}$, and $T^0 = P^0_{\rm out}/P^0_{\rm in}$ with $P^1_{\rm in}$ and $P^0_{\rm in}$ the input powers for the high and low levels, respectively, and $P^1_{\rm out}$ and $P^0_{\rm out}$ the output powers for the high and low levels, respectively. According to this definition, $P^0_{\rm in}$ falls in the low power level region while $P^1_{\rm in}$ falls in the high power level region in Fig. 2. $P^1_{\rm out}/P^1_{\rm in}$ (respectively, $P^0_{\rm out}/P^0_{\rm in}$) corresponds to the ratio $P_{\rm out}/P_{\rm in}$ in the high power (respectively, low power) level region in Fig. 2. Therefore, it is straightforward to demonstrate that the extinction ratio $\tau{\rm ex}_{\rm out}$ at the output is lower than the extinction ratio $\tau{\rm ex}_{\rm in}$ at the input

$$\tau{\rm ex}_{\rm out} = \frac{P^1_{\rm out}}{P^0_{\rm out}} = \frac{T^1 \cdot P^1_{\rm in}}{T^0 \cdot P^0_{\rm in}} = \frac{T^1}{T^0}\tau{\rm ex}_{\rm in} < \tau{\rm ex}_{\rm in}.$$

This limiting function alone would thus not provide regeneration of the signal, especially if it is cascaded into a transmission link. However, thanks to the complementaries of SA and power limiter functions, a full 2R regenerator is obtained when both are cascaded, as shown in [1] and [2].

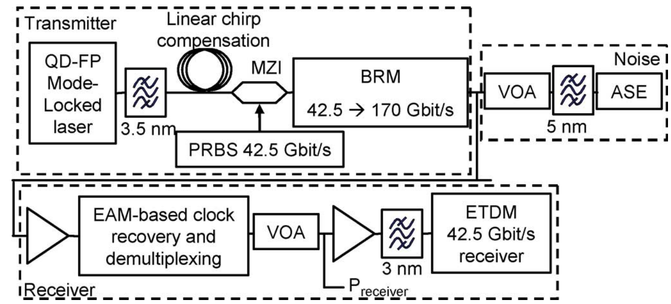

Fig. 3. Back-to-back experimental setup.

III. Experimental Setup

A. Back-to-Back Experiment Setup

The experimental setup of the back-to-back configuration (when the transmitter is placed in front of the receiver) is shown in Fig. 3. A quantum-dash Fabry–Pérot (QD-FP) mode-locked laser and a 3.5-nm bandpass filter are used at the transmitter to generate a short-pulse optical clock at 42.5 GHz at 1550 nm [11]. Main part of the chirp of the laser is compensated for by a standard single-mode fiber. The optical clock is modulated through a Mach–Zehnder interferometer (MZI) modulator at 42.5 Gb/s with a $2^7 - 1$ PRBS. A bit-rate multiplier (BRM) multiplexes four delayed versions of the signal to provide a 170-Gb/s data stream. The temporal FWHM of the pulses is 1.5 ps.

To assess the regenerator ability to reduce the intensity noise, the optical signal-to-noise ratio (OSNR) is degraded at the transmitter output. The noise, added to the signal, is generated by an amplified spontaneous emission (ASE) source. A 5-nm optical filter limits the noise spectrum around the working wavelength and an attenuator allows to adjust the OSNR at the transmitter.

On the receiver side, an electrooptical phase-locked loop, based on electroabsorption modulation (EAM), is used both as the 42.5-GHz clock recovery and time-domain demultiplexer from 170 Gb/s to four trains at 42.5 Gb/s [11]. Because of this double function of the loop, this setup does not enable the analysis of the four 42.5-Gb/s tributaries as there is a single position of the delay line that leads to clock locking, and it

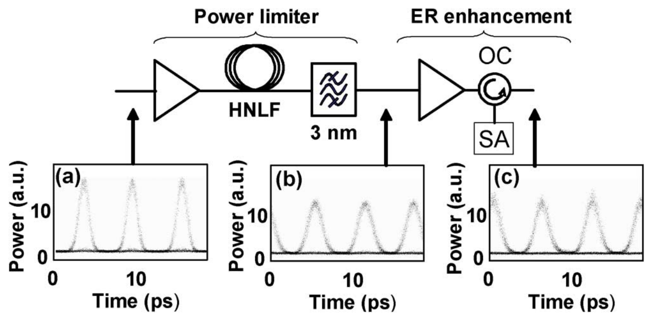

Fig. 4. Regenerator setup.

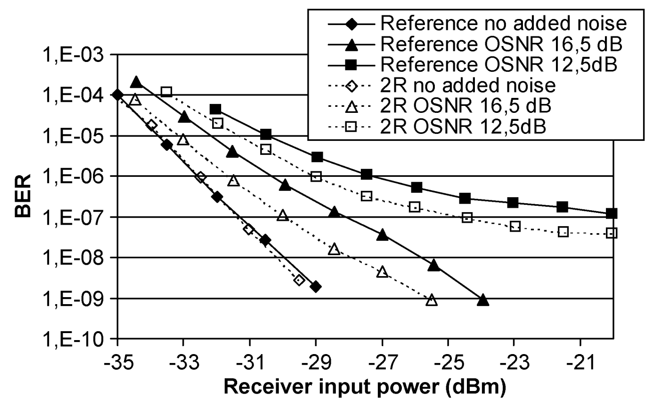

Fig. 5. Receiver sensitivity with and without the regenerator.

cannot be changed to select a tributary. Later on, the study is performed on a single tributary. The signal is then optically preamplified and received on a standard 42.5-Gb/s electrical time-division-demultiplexing (ETDM) receiver.

B. Regenerator Setup

The experimental setup of the regenerator is depicted in Fig. 4. The power limiter is placed in the first position. The signal is amplified before entering the HNLF to achieve an input power of 15.7 dBm. After being filtered by a 3-nm supergaussian filter, the signal enters the second stage enhancing its extinction ratio. The signal is amplified before being reflected on the SA through an optical circulator (OC) with an input power of 8 dBm (extinction ratio improvement of 2.5 dB), corresponding to an optimum in this experiment. The corresponding eye diagrams measured with an OSO are included in the figure. The eye diagram after the power limiter is slightly broadened due to the optical filtering function. After the SA, pulses are slightly compressed and high power levels are a bit degraded. This is expected since the SA attenuates the pulse edges. It is to notice that the regenerator parameters were optimized to have the power limiter in front of the SA; however, similar performances are foreseen if their positions were swapped and the regenerator parameters properly optimized.

IV. Results

In order to assess the regenerator ability to reduce the intensity noise, we present, in Fig. 5, the receiver sensitivity when it is limited by optical noise with (empty symbols, dotted lines) and without the regenerator (full symbols, continuous lines). The bit-error rate (BER) between 10^{-4} and 10^{-9} (limit for experimental stability reasons) was measured as a function of the receiver input power, for different OSNR values, measured in a 5-nm bandwidth in front of the regenerator. Without added ASE noise (diamonds) (OSNR of 22.3 dB), we observe that both curves are superposed, meaning that the regenerator does not introduce any penalty. In the case of an OSNR of 16.5 dB (triangles), an improvement of 2 dB on the receiver sensitivity was obtained for a BER of 10^{-8}. An improvement of 4.5 dB for a BER of 10^{-7} was measured for an OSNR of 12.5 dB (square). This receiver sensitivity improvement shows the regenerator ability to reduce excess optical noise at 170 Gb/s.

V. Conclusion

We have reported on the first BER assessment at 170 Gb/s of a 2R regenerator combining an SA in a microcavity and a power limiter using a HNLF. Up to 8-dB extinction ratio improvement has been measured in a 170-Gb/s pump probe experiment. Receiver sensitivity measurements in a back-to-back configuration have shown a sensitivity improvement of 2 dB for a BER of 10^{-8} with an OSNR of 16.5 dB at the input of the regenerator.

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