IEEE JOURNAL OF
PHOTONICS TECHNOLOGY LETTERS
A PUBLICATION OF THE IEEE LASERS AND ELECTRO-OPTICS SOCIETY

MMM 2005 VULUME 17 NUMBER 1 IPTLEL

PAPER

Reprinted from
IEEE Photonics Technology Letters, vol. 17, no. 1, pp. 244-246

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SOA-Based Optical 2R Regenerator

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***Abstract*—Optical performance monitoring is demonstrated using the nonlinear response of a semiconductor optical amplifier. The monitoring device is derived from a recently proposed all-optical wavelength converter for 10- and 40-Gb/s return-to-zero (RZ) modulated signals. We show experimental results for both optical signal-to-noise ratio monitoring and dispersion monitoring on 40-Gb/s RZ signals and Q factor correlation on a 10-Gb/s RZ signal. The performance monitor signal correlates with the Q factor and can provide an unambiguous signal quality measure with potential application to quality of service and fault management.**

***Index Terms*—Nonlinear optics, optical communication, optical components, optical fiber communication, optical pulse measurements, semiconductor optical amplifiers (SOAs).**

I. Introduction

OPTICAL performance monitoring is vital in high-bit-rate transparent networks in order to provide essential functions such as quality of service, fault management, dynamic provisioning, and restoration [1]. In order to become viable for network applications, all-optical regeneration and wavelength conversion require simple and cost-effective techniques that can provide performance monitoring in the optical domain. Of particular importance are methods that correlate with bit-error-rate performance for optical signal-to-noise ratio (OSNR) and dispersion impairments.

Most previous work in optical performance monitoring is not readily combined with all-optical regeneration techniques. Examples include optical sampling [2], polarization extinction ratio measurements [3], and subcarrier multiplexing [4]. Recently, Westbrook *et al.* demonstrated a dispersion monitor as part of a highly nonlinear fiber-based 2R regenerator [5]. Here we present a technique that uses a novel semiconductor optical amplifier (SOA)-based 2R regenerator [6], [7] as a platform to monitor both noise and dispersion on return-to-zero (RZ) signals. The technique enables simultaneous 2R regeneration, wavelength conversion, and optical performance monitoring.

In this technique, the data signal is combined with a continuous-wave (CW) field at the desired conversion wavelength and coupled into the SOA, as shown in Fig. 1. The CW field is influenced by the data signal through both cross-gain and cross-phase modulation in the SOA. A 2R regenerated and wavelength converted signal is recovered by filtering the red-shifted portion of the CW field. This method is similar to 2R regeneration based upon self-phase modulation in highly nonlinear fiber. As in the fiber approach [5], a simple monitoring signal can be derived from the 2R regeneration process. However, because the SOA-based regenerator incorporates cross-gain modulation, the monitor shown here is also sensitive to intensity noise. Hence, the signal can be used for OSNR monitoring as well as dispersion monitoring. Although this technique cannot provide independent measurements of each impairment, it can provide monitoring coverage for both, similar to the role of Q factor, which is advantageous for many applications, such as locating faults and performance monitoring [1].

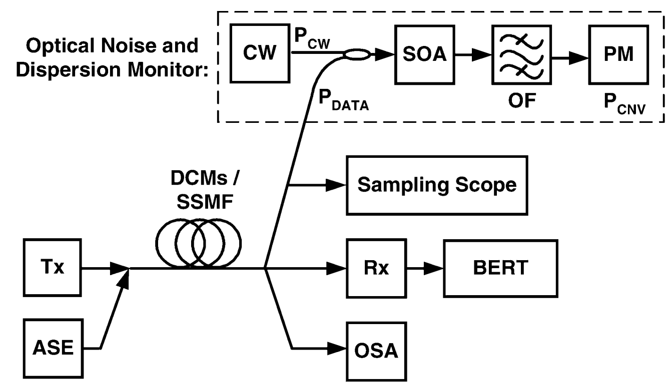

Fig. 1. Experimental setup to vary noise and accumulated dispersion on data signal P_{DATA}. The wavelength converted monitoring signal P_{CNV} is generated by mixing P_{DATA} with CW signal P_{CW} in the SOA and selected by the optical filter (OF). ASE: Amplified spontaneous emission source. CW: CW laser. Tx: Optical data source. PM: Power meter. Rx: receiver. BERT: Bit-error-rate tester.

We note that at 10 Gb/s we obtain both regeneration and wavelength conversion. At 40 Gb/s, the regeneration is limited by the speed of the SOA and to date we have only observed wavelength conversion, although we expect that this device limitation can be overcome [7]. We also examine monitoring signals taken from separate filters centered at different positions in the converted spectrum and their relative sensitivities for stand-alone monitoring applications.

II. Results

The experimental setup is depicted in Fig. 1. An erbium-doped fiber amplifier is used as an amplified spontaneous emission source and added to the data signal to vary the OSNR. The signal is then passed through dispersion-compensating modules and standard single-mode fiber to accumulate chromatic dispersion.

Manuscript received June 22, 2004; revised August 19, 2004. The work of P. Vorreau was supported by the German National Academic Foundation.

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Digital Object Identifier 10.1109/LPT.2004.838622

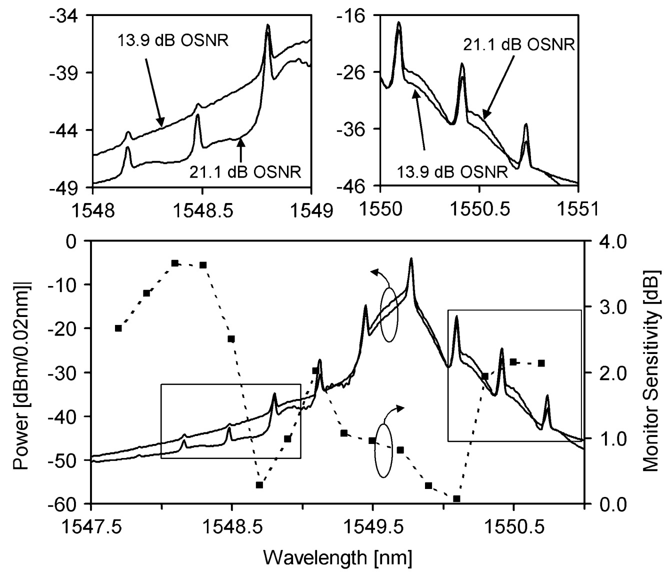

Fig. 2. SOA output spectrum at the converted signal wavelength and monitor sensitivity to OSNR changes. The two top figures are magnified views of the spectral regions that have the highest sensitivity shown boxed; 40-Gb/s RZ data signal was used.

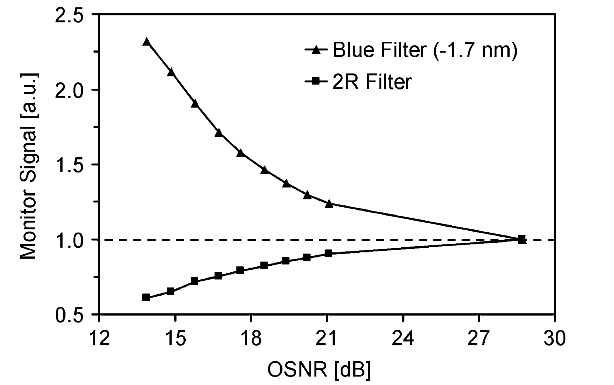

Fig. 3. Monitor signal OSNR dependence for two filter positions, normalized to the maximum OSNR value (40-Gb/s data signal).

The data signal input to the SOA is also sent to an optical receiver and bit-error-rate tester. OSNR values of the data signal were obtained from the optical spectrum analyzer. Experiments were conducted using both 40- and 10-Gb/s RZ pseudorandom binary sequence signals with a 33% duty cycle. The bit pattern length was varied between 2^7–1 and 2^{31}–1 for both bit rates. No pattern dependence was found in the results. During all measurements, the total data power P_{DATA} was held constant within a 0.2-nm bandwidth for 10 Gb/s and a 0.9-nm bandwidth for 40 Gb/s.

Two different SOA devices were used for the different data rates. The one for 40 Gb/s had a saturation output power of -7 dBm while the one for 10 Gb/s had a saturation output power of 2 dBm, both operated with 200 mA. The CW field (1550 nm) and the data signal (1559 nm) were individually amplified, attenuated, and filtered to maintain constant SOA input powers of 3.8 and 2.3 dBm, respectively.

Fig. 2 shows the SOA output at the converted signal wavelength for both 21.1- and 13.9-dB OSNR (0.1 nm) with a data rate of 40 Gb/s. Increasing optical noise will increase the spread of pulse amplitudes about the average mark level. Increased pulse amplitudes lead to larger frequency shifts and, therefore, increased spectral spreading, as observed on the blue side (magnified, left). Gain saturation effects result in a reduction in the optical power spectral density on the red side, which is most sensitive to the peak amplitude (note that the magnified view on the red side has the opposite dependence on OSNR compared to the blue side). The cross-gain modulation reduces the gain at the converted wavelength for higher peak power in the data signal. Therefore, high data pulse amplitudes due to noise give a larger red shift (cross-phase modulation), but the amplitude of the CW light is suppressed (cross-gain modulation). This effect can create a reduction of the average spectral density in the red-shifted portion of the converted light spectrum as the OSNR on the data decreases. Noise will also spread the spectrum over a wider wavelength range and increase the broad-band background, which for constant input power can contribute to the observation in Fig. 2. Self-saturation is also expected to play a role and a complete account of the detailed SOA behavior is beyond the scope of this work.

Dispersion or other pulse broadening effects will reduce the red-shift simply due to the reduced peak amplitude of the marks, as observed in other systems with cross-phase modulation [5]. However, in this system, both low noise and higher peak power (i.e., good RZ signal quality) result in more power in the red-shifted spectrum. The resulting monitoring signal is straightforward: The total power in the wavelength-converted signal is proportional to the signal quality. Thus, the monitoring signal can be taken as the ratio of the converted signal power (P_{CNV}) to the input data signal power $(P_{\mathrm{DATA}}) : P_{\mathrm{CNV}}/P_{\mathrm{DATA}}$ or simply P_{CNV} if the input power is held constant, as was done here.

In order to investigate the optimum filtering conditions, the optical filtering of the converted spectrum (see Fig. 2) was implemented by recording the full spectra in a 0.02-nm bandwidth and applying filter functions to these spectra in software. A filter function obtained from measurements of a 100/200-GHz interleaver was used for this analysis.

The monitoring filter sensitivity as a function of wavelength was examined by applying the filter every 0.2 nm in the spectra for 13.9- and 21.1-dB OSNR (0.1 nm). For every center wavelength setting, the filter output in the clean case was subtracted from the noisy case. This relative power difference is defined as the filter sensitivity in decibels in Fig. 2.

Fig. 3 shows the monitoring signal normalized to the maximum OSNR reading, as the OSNR is varied. Curves are shown with the filter aligned for 2R regeneration and optimized for sensitivity on the blue (-1.86 nm) or red ($+0.44$ nm) side. As indicated by Fig. 3, the signal increases for filtering on the blue side and decreases for filtering on the red side. The blue side shows a stronger dependence on OSNR and the sensitivity increases as the signal quality degrades.

The monitoring signal is found to vary linearly with Q factor in the range 4.5–9 (linear Q), as shown in Fig. 4. These results were obtained while varying the OSNR of a 10-Gb/s data signal. In general, results at 10 Gb/s were qualitatively similar to those shown in Figs. 2, 3, and 4 for 40 Gb/s. The Q factor values were derived from synchronous histograms on the optical sampling

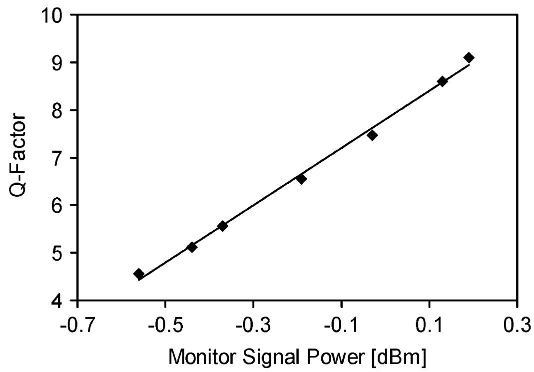

Fig. 4. Measured Q factor as a function of the monitor signal for the blue filter position when changing the OSNR (10-Gb/s data signal). The optical filter was in the blue position. A linear trend line is added for better visibility.

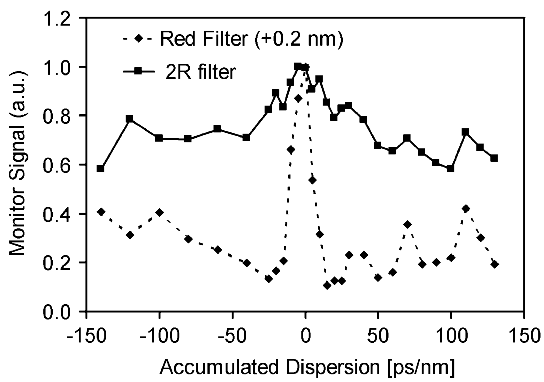

Fig. 5. Monitor signal for 40-Gb/s data as a function of accumulated dispersion.

scope, triggered on the data pattern to avoid inaccuracies due to pattern dependence [8].

The setup shown in Fig. 1 was also used for dispersion monitoring experiments. The monitoring signal as a function of accumulated dispersion is shown in Fig. 5. The data signal power into the SOA was held constant and the converted signal power is normalized to the zero dispersion point. In this case, the reduction in the average level of the marks translates directly into a reduction in the red-shift. The 2R filter provides a dispersion-monitoring signal with coarse sensitivity, whereas using the red filter location, a highly sensitive signal is obtained. Secondary peaks at high dispersion values are due to intersymbol interference, as seen in other monitoring techniques [5]. Note that for red filtering both noise and dispersion decrease the monitoring signal, which provides an unambiguous indication of signal quality. The dependence of the blue shift on OSNR may also provide the opportunity to distinguish between noise and distortion.

III. Conclusion

A new technique for optical performance monitoring has been introduced that is based upon the 2R regeneration signal from an SOA. Although the sensitivity of the signal to OSNR is weak (as seen in Figs. 2, 3, and 4), it is of interest because it correlates directly with signal quality for both noise and distortion and, therefore, may be appropriate for optical performance monitoring applications. The new technique potentially enables SOA-based regeneration with integrated performance monitoring, which is essential for many practical applications of these devices in transparent networks. In addition to being used with the 2R regenerator, this technique can be used as a stand-alone monitor or integrated with other SOA based processing components.

Acknowledgment

The authors would like to thank R. Giles for his support and encouragement.

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