Investigation of Simultaneous 2R Regeneration of Two 40-Gb/s Channels in a Single Optical Fiber

L. Provost, F. Parmigiani, P. Petropoulos, and D. J. Richardson

***Abstract*—We experimentally investigate the simultaneous all-optical signal processing of two 40-Gb/s wavelength-division-multiplexing optical streams spaced by ~5 nm using self-phase modulation and offset filtering in a single highly nonlinear fiber to achieve a 2R optical regeneration. Using a bidirectional configuration, we demonstrate efficient mitigation of the interchannel crosstalk. We experimentally observe no degradation of the regenerator performance arising from the presence of the second channel as compared to the single-channel case.**

***Index Terms*—All-optical regeneration, nonlinear (NL) optical devices, optical Kerr effect, self-phase modulation.**

I. Introduction

OPTICAL signal processing has attracted much attention over recent years, motivated by the possibility to alleviate the electronics bottleneck associated with high-speed optical communication systems. Among the various processing functions, optical regeneration is regarded as particularly attractive in high-bit-rate (>40 Gb/s) systems, as it is key to enabling ultralong-haul transmission without the requirement for optical–electronic–optical (OEO) repeaters. In essence, optical regeneration refers to the restoration of the quality of the signal by providing reamplification, power equalization, and noise suppression (2R), and/or retiming operations (3R). Although numerous implementations of optical regenerators have been reported for single-channel systems, their ability to allow processing of more than one channel is limited by the interchannel crosstalk inevitably introduced by the very nonlinear (NL) effects used in the NL optical gates of the regenerators. This limitation greatly reduces the economic sustainability of such all-optical devices as compared to OEO systems.

Owing to their ultrafast response time (<1 ps), NL gates based on the optical Kerr effect in highly nonlinear fibers (HNLFs) are undoubtedly attractive. To date, only a few works have studied the extension of such NL gates to a multichannel environment for 2R applications, by either employing specific chromatic dispersion management [1], [2] or dispersion decreasing fiber [3] to mitigate interchannel crosstalk. In this letter, we demonstrate a simple scheme for the extension of a fiber-based optical 2R regenerator that allows the processing of two 40-Gb/s channels within the same HNLF.

Manuscript received August 20, 2007; revised September 26, 2007. This work was supported by the STREP/European Project TRIUMPH IST-027638.

The authors are with the Optoelectronics Research Centre, University of Southampton, SO17 1BJ, U.K. (e-mail: lap@orc.soton.ac.uk).

Digital Object Identifier 10.1109/LPT.2007.913662

Proposed by Mamyshev in [4], the optical regenerator under consideration relies on the dependence of the spectral broadening induced by self-phase modulation on the pulse intensity. Subsequent filtering acts as the decision element by discriminating pulses of high/low input power levels. The extension of this regenerator to a multichannel environment is limited by interchannel crosstalk arising both from cross-phase modulation (XPM) and four-wave mixing (FWM). The crosstalk manifests itself by the introduction of asymmetries of varying strength to the broadened spectrum due to partial interactions between copropagating pulses of adjacent channels. This crosstalk can be minimized by ensuring 1) that the copropagating pulses walk completely through each other, in which case XPM adds a constant phase shift across the full duration of the pulse, and 2) that the interaction distance between pulses of adjacent channels is minimized, which ensures that the phase-matching condition for FWM is cancelled. Both these conditions are satisfied in the bidirectional implementation considered here, which allows two channels to propagate in the same HNLF but in opposite directions. By doing so, an ultimate maximization of the walk-off time between channels is achieved (~10 ns/m for silica-based fibers), and FWM does not take place. We reported initial results using this technique to regenerate two channels operating at 10 Gb/s in [5]. In the following, we present the implementation of the proposed scheme for the regeneration of two 40-Gb/s channels and demonstrate that the inclusion of a second channel does not introduce any additional penalty to the system performance.

II. Experimental Setup

The experimental setup is depicted in Fig. 1. Two chirp-compensated gain-switched distributed feedback laser diode sources operating at 1550.0 nm (Channel 1) and 1554.6 nm (Channel 2) are used to generate 6.1- and 6.2-ps Gaussian pulses, respectively, at a repetition rate of 10 GHz. The two channels are coupled together and then temporally multiplexed up to 40 Gb/s. The data streams are then modulated using an electroabsorption modulator driven by a 2^{31}-1-long pseudorandom bit sequence before being split with narrow optical filters (0.7-nm bandwidth) to allow the signals to be fed to the two HNLF ports. The filtering slightly widens the pulses to 6.7 ps for Channel 1 and 7.1 ps for Channel 2. Each optical channel is then amplified to meet the input power requirements and fed to the HNLF. Two optical circulators are used to separate incoming from outgoing signals at the two fiber input–output ports. The 1-km-long HNLF exhibits a chromatic dispersion of −1.7 ps/nm/km, an NL coefficient of 18 /W/km at 1550 nm, and an attenuation of 2.1 dB/km. At each of the outputs of the two fiber ports tunable

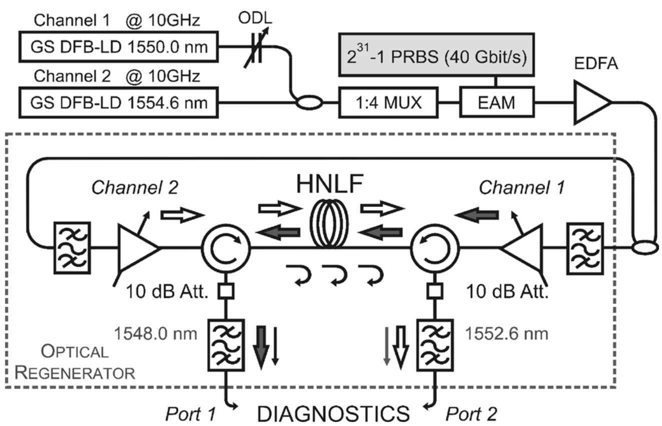

Fig. 1. Experimental setup (ODL: Optical delay line; MUX: multiplexer), with channel paths (in transmission and Rayleigh-backscattering illustration for Channel 2).

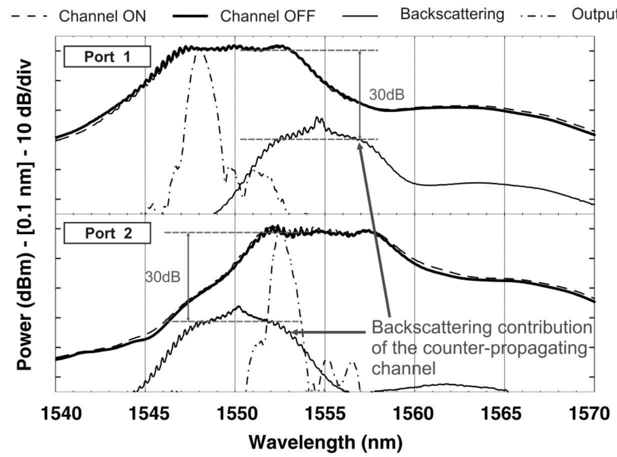

Fig. 3. Transmitted and backscattered spectra at the output fiber Ports 1 and 2 in the presence (ON) and the absence (OFF) of the interfering channel. Output spectra after the output filter (dotted–dashed line).

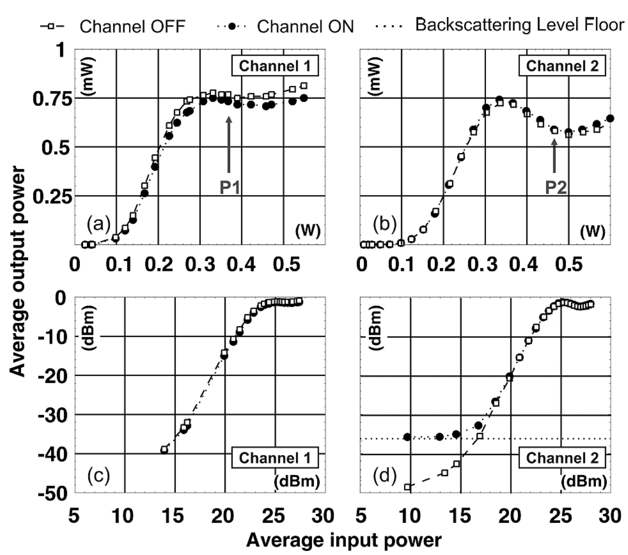

Fig. 2. Power TFs (in linear and log scales) of Channels 1 and 2 in the presence (channel ON) and in the absence (channel OFF) of the counterpropagating signal.

filters with a 0.57-nm bandwidth are used to provide the offset filtering. Each output channel is offset by the same relative value of −2 nm as compared to the incoming carrier wavelengths, in order to preserve the initial channel separation.

III. Results

The transfer functions (TFs) of the regenerator were measured for the two channels, when a second channel operating at a nominal input power (denoted as P_1 and P_2 for Channels 1 and 2, respectively) was either absent (OFF) or present (ON). Fig. 2 shows the various TFs plotted both in linear and logarithmic scales. Channel 1 exhibits a large plateau whereas a nonmonotonic behavior is observed for Channel 2. This different behavior can be fully explained by consideration of the detailed scaling rules that link the pulsewidth and HNLF chromatic dispersion at each of the two wavelengths to the regenerator performance characteristics [6].

In the OFF case and operating at $P_1 \sim 370$ mW, the output pulse extinction ratio (which represents the peak power ratio between one and zero pulses) was found to be ∼33 dB for Channel 1 for an input extinction ratio of 10 dB. The corresponding number for Channel 2 and for $P_2 \sim 470$ mW was ∼34.8 dB. In the same figures, we plot the TFs measured in the presence of both channels (ON case). The agreement in the TFs between the two cases indicates that the regenerator operating capacity is not affected by the presence of a counterpropagating channel. This observation still holds when observing the TF of Channel 1 on a logarithmic scale. However, at low input powers, Channel 2 experiences a constant output power level (at −36.2 dBm) when Channel 1 is present [Fig. 2(d)]. The main consequence of this power floor is to reduce the previous output extinction ratio by 3.6 dB (to a value of 31.2 dB).

The origin of this constant power floor is attributed to an additional spectral contribution generated by the Rayleigh-backscattering of the counterpropagating channel along the HNLF [7] as illustrated in Fig. 3, in which the spectra measured at the two outputs of the HNLF in the absence or presence of the two channels are reported.

Depending on the position of the offset filter, the amount of overlap between the forward-propagating and the backscattered signal varies at the wavelength of the output filter, leading to a varying degree of penalty at the regenerator output. It is worth noting that the strength of the contribution of the backscattered signal has a strong dependence on the operating parameter settings (fiber properties, length, and input power) and the wavelength separation of the incoming channels. There is, however, a weaker dependence on the initial channel spacing, because of the fairly flat top shape exhibited by backscattering spectrum that limits the crosstalk level. For example, by reducing the channel separation to 2.3 nm, an increase of ∼7 dB (to a value of ∼29 dBm) is expected for the floor level on the TF of Channel 2 (worst case).

Furthermore, as shown in Fig. 3, since the backscattering level is found to be ∼30 dB below the transmitted signal, we observed an excellent matching of the transmitted broadened spectra in the presence/absence of the interfering channel. This

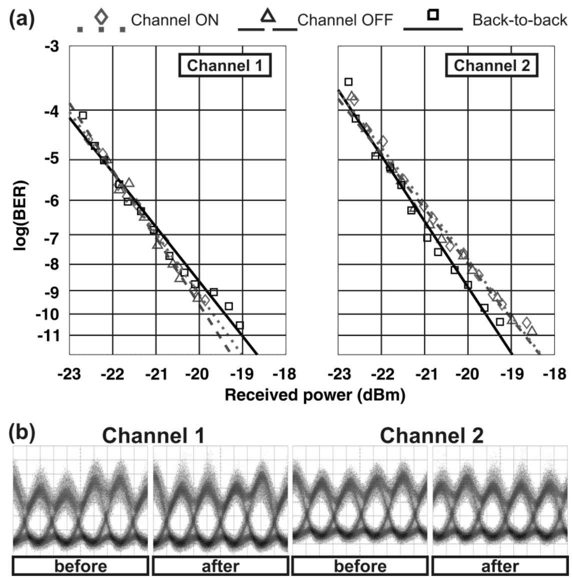

Fig. 4. (a) BER measurement in the presence (channel ON) and in the absence (channel OFF) of the interfering channel and back-to-back measurement. (b) Eye diagrams at the regenerator input and output (detection bandwidth = 20 GHz).

observation corroborates the mitigation of the NL crosstalk offered by the proposed scheme. In addition, no experimental evidence of stimulated Brillouin scattering was observed in this experiment.

In order to assess the impact of the Rayleigh-backscattering on the system performance, we performed bit-error-rate (BER) measurements for both channels in the presence/absence of the interfering channel [see Fig. 4(a)]. As compared to the back-to-back measurement and in the absence of the second interfering channel, the optical regenerator introduces −0.4- and +0.5-dB power penalties for Channels 1 and 2, respectively, for error-free operation (BER $= 10^{-9}$). When the two channels are simultaneously present, no significant additional power penalty (<0.1 dB) is introduced as compared to the single channel case. The corresponding eye diagrams of the two channels before and after the regenerator are shown in Fig. 4(b). Finally, Fig. 5 represents the corresponding autocorrelation traces and we are able to demonstrate a slight and qualitative reduction in the pulse pedestals for both channels after the regenerator. The corresponding output pulse durations are 6.3 and 7.0 ps for Channels 1 and 2, respectively.

IV. Conclusion

We have demonstrated the possibility to extend the Mamyshev regenerator to a dual-channel case by adopting a bidirectional scheme in a single HNLF. Through an experiment involving two channels operating at 40 Gb/s, we have demonstrated that any XPM- and FWM-induced interference is effectively mitigated in this scheme. Furthermore, we identified Rayleigh backscattering as the major source of interchannel crosstalk. BER measurements, however, have shown that this interference does not introduce any additional power penalty as compared to the single-channel case.

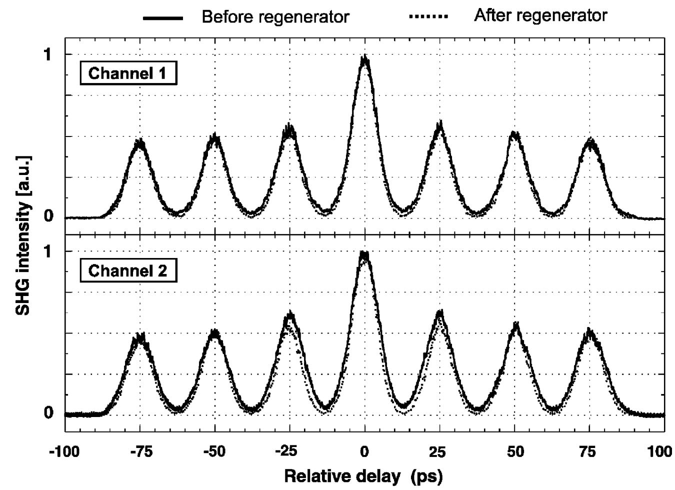

Fig. 5. Autocorrelation traces of the two channels at the input and the output of the regenerator.

Acknowledgment

The authors would like to acknowledge the Furukawa Electric Company (Japan) and K. Mukasa for the loan of the HNLF used in the experiment and Anritsu U.K. for the loan of the 40-Gb/s BER tester.

References

[1] T. Ohara, H. Takara, S. Kawanishi, T. Yamada, and M. M. Fejer, "160-Gb/s all-optical limiter based on spectrally filtered optical solitons," *IEEE Photon. Technol. Lett.*, vol. 16, no. 10, pp. 2311–2313, Oct. 2004.
[2] T. L. Lakoba and M. Vasilyev, "A new robust regime for a dispersion-managed multichannel 2R regenerator," *Opt. Express*, vol. 15, pp. 10061–10074, 2007.
[3] D. V. Kuksenkov, S. Li, M. Sauer, and D. A. Nolan, "Nonlinear fibre devices operating on multiple WDM channels," in *Eur. Conf. Opt. Commun. (ECOC'05)*, Glasgow, U.K., 2005, Paper Mo.3.5.1.
[4] P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," in *Proc. ECOC'98*, 1998, pp. 475–476.
[5] L. Provost, F. Parmigiani, C. Finot, P. Petropoulos, and D. J. Richardson, "Self-phase modulation-based 2R optical regenerator for the simultaneous processing of two WDM channels," in *CLEO/Europe-IQEC*, Munich, Germany, 2007, Paper CI2-1-TUE.
[6] L. Provost, C. Finot, K. Mukasa, P. Petropoulos, and D. J. Richardson, "Design scaling rules for 2R-optical self-phase modulation-based regenerators," *Opt. Express*, vol. 15, pp. 5100–5112, 2007.
[7] M. Matsumoto, "Efficient all-optical 2R regeneration using self-phase modulation in bidirectional fiber configuration," *Opt. Express*, vol. 14, pp. 11018–11023, 2006.