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All-optical regeneration of multi-wavelength signals

Pallavi G. Patki and Michael Vasilyev
Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019
Vasilyev@uta.edu

Taras I. Lakoba
Department of Mathematics and Statistics, University of Vermont, Burlington, VT 05405

Abstract: We discuss our experimental results on 8×10 Gb/s all-optical 2R regeneration, enabled by the innovative dispersion management scheme in Mamyshev regenerator based on off-center filtering of self-phase-modulation-broadened signal spectrum.

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One of the keys to enabling future all-optical networks is all-optical regeneration, which eliminates the accumulation of the signal impairments without sacrificing the transparency. Over the last two decades, many 2R (re-amplification, re-shaping) and 3R (re-amplification, re-shaping, re-timing) regeneration methods have been proposed and demonstrated. However, they are still not considered practical alternatives to the state-of-the-art electronic-domain regenerators. One of the underlying reasons is that, despite all the research efforts, all-optical regenerators remain inherently single-channel devices (just like their electronic counterparts) and, as such, cannot offer the advantage of optical processing parallelism that has propelled optical fibers and amplifiers to widespread use. Indeed, the simultaneous regeneration of multiple wavelength-division-multiplexing (WDM) channels represents a formidable challenge, because the operation of an all-optical regenerator fundamentally relies on optical nonlinearity leading to debilitating four-wave-mixing (FWM) and cross-phase-modulation (XPM) interactions among the channels. For example, in [1], strong XPM forced the use of polarization interleaving and limited the total number of the regenerated channels to four. Two more four-channel regeneration experiments employed a combination of polarization multiplexing and bi-directional propagation [2] and very low duty cycle pulses combined with low spectral efficiency (600 GHz spacing with 10 Gb/s) [3] to avoid inter-channel interactions. These approaches cannot be used for a large number of WDM channels. A limited success has been achieved in simultaneous re-timing of multiple channels using a single modulator [4], but it assumes synchronous clocks for all WDM channels, which is not realistic in a network context.

In recent work [5], we proposed a 2R regenerator scheme capable of handling many WDM channels simultaneously. It is based on the simple and robust Mamyshev's regenerator [6], in which the conventional highly nonlinear fiber (HNLF) is replaced by a novel dispersion-managed nonlinear medium. This medium's dispersion properties are tailored to multi-channel operation in such a way that different WDM channels propagate with very different group velocities whereas various frequency components of the same channel travel at the same velocity. High phase- and group-velocity mismatch between the channels (inter-channel dispersion) dramatically suppresses FWM and XPM. At the same time, dispersion within each channel's band is kept small to preserve the pulse integrity and ensure large spectral broadening of the signal by self-phase-modulation (SPM). We proposed to build this novel medium from short pieces of highly-dispersive HNLF, separated by periodic group-delay devices (PGDDs) with periodic saw-tooth-like group-delay spectrum, so that the group-delay spectrum of each HNLF-PGDD unit section is staircase-like [5]. Although our dispersion-managed scheme has been inspired in part by PGDD-assisted dispersion-managed soliton (DMS) work [7, 8], 2R regenerator operates in a very different (strongly nonlinear) regime, where SPM dominates over residual dispersion, and DMS results are not applicable.

We recently presented the experimental results proving that for single channel, our dispersion-management scheme does not adversely affect the regeneration [9]. For this task we built a recirculating loop, where, instead of cascading multiple identical HNLF-PGDD sections, we used only one such section and passed signal through it multiple times, thereby minimizing the required resources.

The real PGDD, in addition to phase response, also exhibits amplitude response limiting the useful bandwidth of each channel to ~40% of the channel spacing. The performance degradation due to this bandpass filtering prompted us to look for a regime of regenerator operation different from [5]. In [10], we discovered such a regime that required anomalous average dispersion of the regenerator, in which the performance was significantly better and more robust with respect to variation of parameters than in the normal-average-dispersion regime of [5]. This regime was used in our first multi-channel 2R regeneration experiments [11], which proved that for multiple channels, the inter-channel nonlinearities are strongly suppressed by our dispersion-management scheme and are not seriously degrading the regenerator's performance.

In this paper, we describe our experiments on simultaneous 2R regeneration of 8×10 Gb/s channels with 200-GHz spacing (Fig. 1). Most of the setup is similar to that in [9, 11], except that in the loop we use 1.25 km of dispersion-compensating fiber (DCF) with nonlinear constant $\gamma \sim 5\ (\mathrm{W{\cdot}km})^{-1}$ and dispersion $D = -120$ ps/nm/km as a nonlinear medium and a PGDD as the enabler of our dispersion map with staircase-like group-delay spectrum, with ~+20 ps/nm net residual dispersion per loop, as proposed in [10]. The average power per channel of 10-Gb/s 50% RZ signals is 60 mW in the DCF. We generate the signals in eight 200-GHz-spaced channels by interleaving two co-polarized sets of 400-GHz-spaced WDM channels which are modulated by two independent pattern generators (PGs) driven by slightly different clock frequencies. In addition, a 0.5-km DCF ensures 2-bit delay between the adjacent channels within each set, decorrelating the patterns originating from the same PG. This ensures that we study a realistic worst-case scenario of co-polarized uncorrelated WDM channels, with random delays between the pulses of the neighboring channels. To quantify the performance improvement by the regenerator, we degrade the signal by 25% amplitude jitter via adding a small amount of light from a crosstalk laser tuned to the signal's wavelength. After 6 circulations in the loop, the regenerated signals are selected, one at a time, by two 0.2-nm-wide tunable filters (OBPFs) with net FWHM≈20 Ghz and ~0.15-nm offset from the original signal's wavelength (in a practical device, this could be done by a periodic bandpass filter). The eye-opening improvements for all 8 channels after their simultaneous 2R regeneration, measured by comparing curves of the bit-error rate vs. power entering the receiver's optical pre-amplifier, are shown as inset in lower-left corner of Fig. 1. The top inset shows the eye diagrams for channel #4 (1550.80 nm). All 8 channels demonstrate eye-opening improvement better than 1.6 dB.

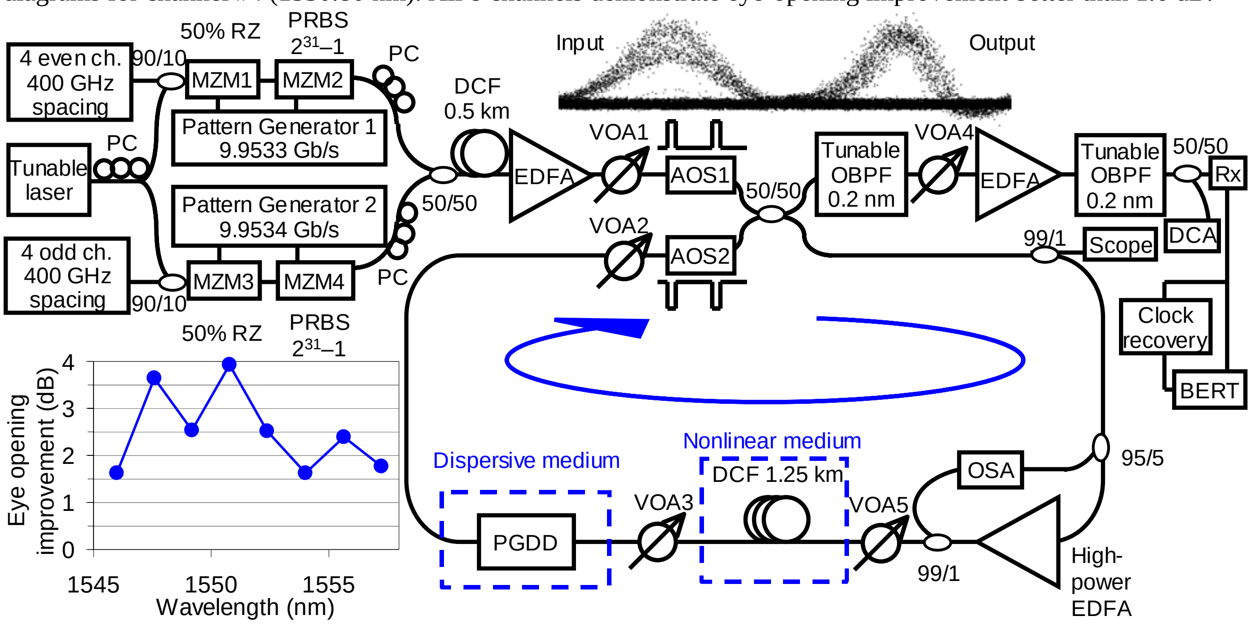

Fig. 1. Experimental setup. Inserts: (top) eye diagrams of channel 4 (1550.80 nm) before and after regeneration, (lower left) eye-opening improvements for all 8 channels.

In summary, we have experimentally demonstrated simultaneous 2R regeneration of 8×10-Gb/s WDM channels in a dispersion-managed configuration of Mamyshev's regenerator. We believe this approach has a potential for a dramatic reduction in the cost of all-optical networks. We would like to thank V. L. DaSilva and S. Bickham of Corning Inc. for providing the dispersion-compensating fiber, as well as P. Young of Photodigm Inc. for lending us the second BER tester. This work was supported in part by NSF grants DMS-0507429 and DMS-0507540.

References

[1] T. Ohara, H. Takara, A. Hirano, K. Mori, and S. Kawanishi, IEEE Photon. Technol. Lett. **15**, 763 (2003).
[2] L. Provost et al, IEEE Photon. Technol. Lett. **20**, 1676 (2008).
[3] C. Kouloumentas et al, IEEE Photon. Technol. Lett. **20**, 1169 (2008).
[4] O. Leclerc et al, Electron. Lett. **36**, 1574 (2000).
[5] M. Vasilyev and T. I. Lakoba, OFC 2005, paper OME62; Opt. Lett. **30**, 1458 (2005).
[6] P. V. Mamyshev, ECOC 1998, Vol. 1, pp. 475--476.
[7] X. Wei, X. Liu, C. Xie, and L. F. Mollenauer, Opt. Lett. **28**, 983 (2003).
[8] L. F. Mollenauer, A. Grant, X. Liu, X. Wei, C. Xie, and I. Kang, Opt. Lett. **28**, 2043 (2003).
[9] P. G. Patki, V. Stelmakh, M. Annamalai, T. I. Lakoba, and M. Vasilyev, CLEO 2007, paper CMZ3; FiO 2007, paper FThS3.
[10] T. I. Lakoba and M. Vasilyev, Opt. Express **15**, 10061 (2007).
[11] M. Vasilyev, P. Patki, and T. I. Lakoba, OFC 2008, paper OWK3.