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All-Optical Wavelength Conversion and Multichannel 2R Regeneration Based on Highly Nonlinear Dispersion-Imbalanced Loop Mirror

Nan Chi, Lin Xu, Kim S. Berg, Torger Tøkle, and Palle Jeppesen

Abstract—All-optical wavelength conversion has been achieved to generate a multichannel return-to-zero optical source for wavelength-division-multiplexed (WDM) systems by using a nonlinear optical loop mirror consisting of a common dispersion-shifted fiber. After WDM transmission over 40-km SMF, the WDM signals are successfully regenerated by a novel regenerator including reshaping and reamplification based on a dispersion-imbalanced loop mirror consisting of an SMF and a highly nonlinear dispersion-shifted fiber.

Index Terms—Dispersion-imbalanced loop mirror, nonlinear optical loop mirror, 2R regeneration, wavelength conversion.

I. INTRODUCTION

ALL-OPTICAL regeneration restoring degraded transmission signals and avoiding conversion between the optical and electronic domains is of increasing interest in future all-optical telecommunication networks because it can improve flexibility, reliability, and scalability of networks. Various techniques have been proposed and demonstrated to realize both 2R (reamplification, reshaping) and 3R (including retiming) regenerators. The regenerative medium can be either passive optical fiber [1] or active components such as distributed feedback (DFB) lasers, electro-absorption modulators, and semiconductor optical amplifiers (SOAs) [2]–[5]. The scheme based on an electro-absorption modulator with cross-absorption modulation effect has been tested up to 40 Gb/s [3]. 3R regenerative devices with Mach-Zehnder configuration exploiting the cross-phase modulation (XPM) effect in SOAs have performed at 40 Gb/s [4], and the ultrafast nonlinear interferometer configuration containing an SOA has allowed 3R regeneration at faster speeds up to 84 Gb/s [5]. For the fiber-based regenerators, the operating speed is determined by ultrafast fiber nonlinearity, which provides response times down to a few femtoseconds. Though some of these techniques could perform with a tunable wavelength, so far research has focused on single-carrier operation, and multiwavelength regeneration has not been demonstrated. However, multiwavelength regenerators are a necessity in all-optical wavelength-division-multiplexed (WDM) systems.

In this letter, we report a multiwavelength 2R regenerator for the first time; it is based on a dispersion-imbalanced loop

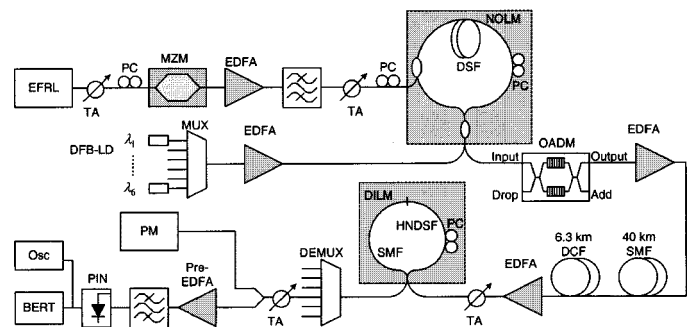


Fig. 1. Experimental setup. EFRL: erbium fiber ring laser. PC: polarization controller. MZM: Mach-Zehnder modulator. MUX: WDM multiplexer. DEMUX: WDM demultiplexer. TA: tunable attenuator. PM: power meter. Osc: oscilloscope.

mirror (DILM). The multiwavelength return-to-zero (RZ) signal source of 6×10 Gb/s with average pulsewidth of 7 ps is based on wavelength conversion by use of a nonlinear optical loop mirror (NOLM). After transmission over 40-km conventional fiber, the six-channel WDM signal is successfully regenerated by the DILM simultaneously. The receiver sensitivity is improved by 3–4 dBm after the regeneration. The increase in signal pulsewidth induced by the transmission is also compensated by the 2R regenerator.

II. EXPERIMENT

The experimental setup is shown in Fig. 1. The six-channel RZ pulses are realized by using wavelength conversion in an NOLM, which is similar to [6]. The NOLM consists of 3-km dispersion-shifted fiber (DSF) that has zero dispersion at 1554.7 nm and a dispersion slope of 0.08 ps/nm/km. The control signal is generated by a 10-GHz 1559-nm erbium fiber ring laser (EFRL) with a full-width at half-maximum (FWHM) pulsewidth of 4.1 ps. The pulsewidth bandwidth product is around 0.42, which means the signal source gives a Fourier-transform-limited pulse that is chirp free. After the LiNbO_3 modulator, the pulse is modulated by a pseudorandom bit sequence of $2^{31} - 1$. In order to get sufficient XPM effect in the NOLM, the control signal is amplified to an average power of 18 dBm. A 2-nm bandwidth bandpass filter is used after the erbium-doped fiber amplifier (EDFA) to suppress the amplified spontaneous emission (ASE) noise and to broaden the pulsewidth to 6.9 ps, because the walkoff effect will be smaller for broader pulses. Then the control signal is coupled

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The authors are with the Research Center for Communications, Optics, and Materials, Technical University of Denmark, Lyngby DK-2800, Denmark (e-mail: nc@com.dtu.dk).

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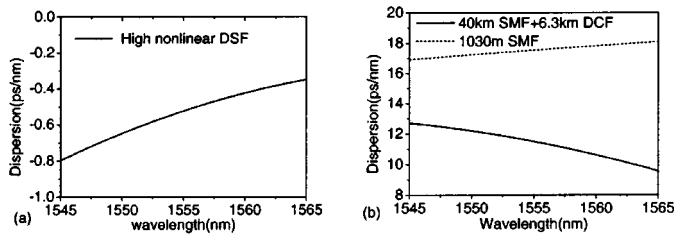


Fig. 2. Dispersion of (a) the highly nonlinear DSF and (b) of the transmission span and the 1030-m SMF.

into the loop by a 50/50 coupler. A tuneable attenuator is used to obtain the optimum control power. The probe continuous-wave (CW) light signals are generated by six DFB lasers and are combined in a WDM multiplexer with a frequency spacing of 200 GHz. The wavelengths of the lasers are 1549.3, 1550.9, 1552.5, 1554.1, 1555.7, and 1557.3 nm, respectively, in compliance with ITU-standardized wavelength proposal. A 1559-nm optical add-drop multiplexer (OADM) acts as a notch filter at the output of the NOLM to suppress the control pulses before the WDM signals are amplified and transmitted.

In [6], wavelength conversion of eight-channel CW light signals that include the wavelengths of 1559.0 and 1560.6 nm besides the wavelengths mentioned above was reported. The reason why we only use six channels here is that the control wavelength must be the same as the fixed add-drop wavelength of the OADM, which is equal to channel 7 in [6]. The polarization controller within the fiber loop is indispensable to simultaneously achieve good output power and extinction ratio of the six channels. Another polarization controller inserted before the control signal is coupled into the loop provides more flexibility to accomplish good conversion performance.

After transmission over the fiber span including 40-km conventional SMF and 6331 m DCF, the transmitted signals are then reamplified and put into the DILM for reshaping. The DILM, constructed from a 50/50 coupler and 1030 m of SMF and 1-km highly nonlinear DSF, acts as a nonlinear filter that transmits only the part of the pulse having appropriate peak power and pulse duration [7], [8]. The total input power and output power of the DILM are 20 and 17.6 dBm, respectively. The WDM signals after wavelength conversion and 40-km transmission have different power levels due to the walkoff in the NOLM that acts as a wavelength converter; as a consequence, the output power per channel of the DILM has a different power level. The power fluctuation between the six wavelengths is within 2.6 dB.

Due to the narrow pulsewidth, a consideration of the peak power and typical nonlinear coefficients indicates that a very low dispersion fiber is needed to generate sufficient nonlinearity for switching. The dispersion measurement on the highly nonlinear DSF shows very small ($-0.5 \sim -0.8$ ps/nm/km) anomalous dispersion at the operating wavelengths of the six channels [see Fig. 2(a)]. The SMF length in the DILM must be carefully designed so that the total dispersion accumulated over the 40-km fiber as well as over the SMF in the DILM will become approximately flat in the operating wavelength range. Fig. 2(b) shows the dispersion curve of the 40-km SMF plus the 6.3-km DCF, and of the 1030-m SMF in the DILM. The differences between

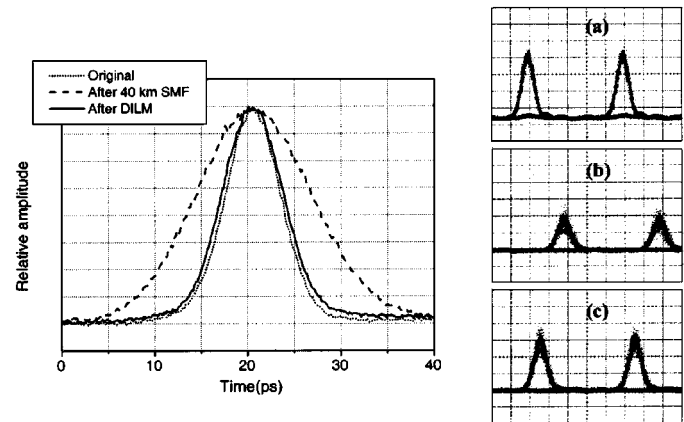


Fig. 3. Measured pulsewidths by an autocorrelator and eye diagrams of (a) control signal, (b) of channel 5 after 40-km transmission, and (c) of channel 5 after regeneration.

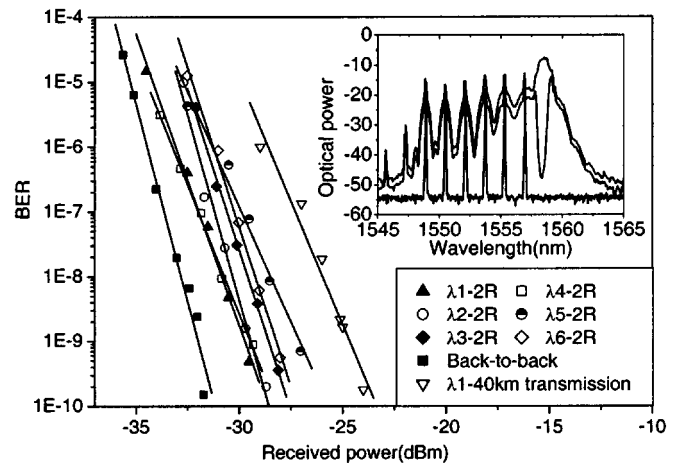


Fig. 4. BER measurements of back-to-back, channel 1 after 40-km transmission and six channels after 2R regeneration. The inset shows optical spectra of original CW probe light signals, of output after NOLM, and of output after OADM.

the accumulated dispersions of the six wavelengths are within 0.8 ps/nm, which guarantee the multiwavelength operation of the DILM.

Since channel 5 has the largest walkoff, it is expected to suffer the largest penalty after 40-km transmission following wavelength conversion, and this was confirmed by the experimental results. The penalty of channel 5 after wavelength conversion and 40-km transmission is larger than 6 dBm. The measured pulsewidths, along with eye diagrams of control pulses, of channel 5 after transmission and of channel 5 after regeneration are shown in Fig. 3. The inset eye diagrams are measured by a 30-GHz photodiode. A very clear and open eye diagram after combined wavelength conversion, transmission, and regeneration can be seen. After 40-km transmission, the pulsewidth is broadened to 14.2 ps, but becomes compressed to 7.5 ps by the DILM. The bit-error-rate (BER) performances of the regeneration of the six channels, back-to-back, and channel 1 after transmission, are measured and shown in Fig. 4. The receiver sensitivity is increased by 3–4 dB by the 2R regenerator.

III. CONCLUSION

We have demonstrated 6×10 Gb/s wavelength conversion based on NOLM. Multiwavelength 2R regeneration based on a DILM consisting of 1030-m SMF and 1-km highly nonlinear DSF shows enhancement of receiver sensitivity and compression of the pulsewidth for the six channels.

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