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Reduction of Gordon–Mollenauer Phase Noise by Midlink Spectral Inversion

S. L. Jansen, *Student Member, IEEE*, D. van den Borne, *Student Member, IEEE*, C. Climent Monsalve, S. Spälter,
P. M. Krummrich, G. D. Khoe, *Fellow, IEEE*, and H. de Waardt

***Abstract*—We show that spectral inversion can be employed for regeneration to reduce the effect of phase noise (Gordon–Mollenauer phase noise) in a nonreturn-to-zero differential phase-shift-keying based transmission system. Several locations of the spectral inverter in an eight-span transmission link have been investigated. We show that the best results are obtained when the spectral inverter is placed in the middle of the link. Compared to the transmission system without spectral inverter, an improvement of over four decades in bit-error-rate performance is achieved.**

***Index Terms*—Fiber nonlinearity, fiber-optics communications, midlink spectral inversion (SI), optical phase conjugation, optical transmission.**

I. INTRODUCTION

ONE OF the most promising phase-encoded modulation formats is differential phase-shift-keying (DPSK) [1], [2]. Its main advantages over ON–OFF keying (OOK) are that DPSK has, in combination with balanced detection, a 3-dB higher sensitivity and is more robust to nonlinear impairments and narrow-band filtering. However, unlike in OOK-based transmission, nonlinear phase noise, usually referred to as Gordon–Mollenauer noise, can substantially impair the performance of phase encoded signals in long-haul transmission systems [3], [4].

In order to extend transmission distance in these long-haul transmission systems, optical reamplification and reshaping (2R) regeneration can be employed. Several optical 2R regeneration techniques have been proposed for phase encoded signals [5], [6], however, only few successful experiments have so far been reported [7], [8]. Spectral inversion (SI), or optical phase conjugation, is one of these proposed optical 2R regeneration techniques. SI is a technique where the spectrum of the data signal is inverted in the transmission link (typically in the middle). Nonlinearities experienced in the first part of the link are then reverted, so that impairments are reduced after transmission. It has experimentally been shown that a spectral inverter can compensate for intrachannel nonlinearities and thereby extend the transmission length at 40-Gb/s DPSK [8]. In this experiment, however, all intrachannel nonlinearities are considered all together and the influence of nonlinear phase noise is not shown explicitly.

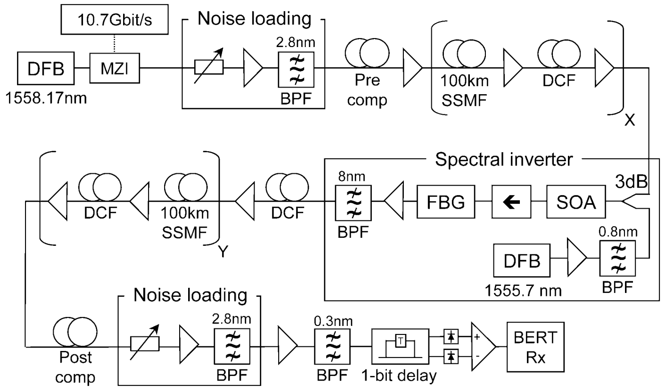

Fig. 1. Experimental setup.

The experiments presented in this letter show that the effect of Gordon–Mollenauer noise can be reduced by four decades of bit-error rate (BER) employing midlink SI. In order to emphasize the effect of this phase noise, a high-fiber input power is used and the optical signal-to-noise ratio (OSNR) before transmission is intentionally reduced. We find that the best suppression of the phase noise is obtained when the SI is placed in the middle of the transmission link. At low transmitted OSNR, where the effect of the phase noise is strongest, over four decades of performance improvement is observed through the use of SI.

II. EXPERIMENTAL SETUP

Fig. 1 depicts the experimental setup. A continuous-wave (CW) signal was generated at 1558.2 nm by a distributed feedback laser. This CW light was modulated by a Mach–Zehnder interferometer (MZI) modulator with a bitrate of 10.7 Gb/s in a push–pull configuration (pseudorandom bit sequence length of $2^{31} - 1$). The modulation format of the data signal was nonreturn-to-zero DPSK. Before transmission, a noise generation scheme consisting of an attenuator, amplifier, and a bandpass filter was inserted, enabling setting the OSNR of the data signal at system input.

The signal was precompensated by a dispersion compensating fiber (DCF) with -510 ps/nm. The 800-km transmission link consisted of X spans before the spectral inverter and

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S. L. Jansen, D. van den Borne, G. D. Khoe, and H. de Waardt are with the COBRA Institute, Eindhoven University of Technology, Eindhoven 5612, The Netherlands (e-mail: s.l.jansen@tue.nl; d.v.d.borne@tue.nl; g.d.khoe@tue.nl; h.d.waardt@tue.nl).

C. C. Monsalve is with the Polytechnic University of Madrid, Madrid 28040, Spain (e-mail: peugey@yahoo.com).

S. Spälter and P. M. Krummrich are with Siemens AG, COM, Fixed Networks, Munich D-81359, Germany (e-mail: stefan.spaelter@siemens.com; peter.krummrich@siemens.com).

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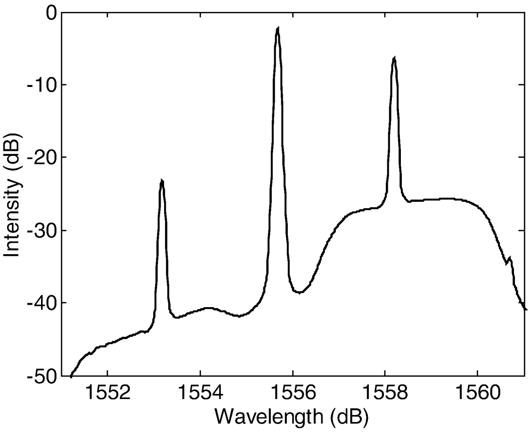

Fig. 2. Optical spectrum at the output of the optical phase conjugator (spectral resolution of 0.1 nm).

$Y = 8 - X$ spans after. Each standard single-mode fiber (SSMF) span with a length of 100 km was followed by a DCF module to compensate for the chromatic dispersion. The average under compensation per span was 55 ps/nm. The loss of the SSMF spans varied between 21 and 24 dB and the loss of the DCF modules varied between 10 and 13 dB. In order to enhance the effect of Gordon–Mollenauer noise, high input powers were used; the input powers into the SSMF and DCF were 11.5 and 1.5 dBm, respectively.

SI of the data signal was realized by four-wave mixing (FWM) in a semiconductor optical amplifier (SOA). In order to enable WDM conversion, a periodically poled lithium niobate can be employed [9], [10]. Inside the SOA with a length of 2 mm, the pump signal at 1555.7 nm and the data signal at 1558.2 nm generated an FWM product at 1553.3 nm. The FWM product has the inverted signal spectrum from the incoming data signal. Through this process, the sign of the cumulative chromatic dispersion is inverted as well; hence, a DCF module was used after the spectral inverter in order to obtain the same cumulative dispersion as the original signal. This is valid for all measured configurations (including the asymmetric configurations). The saturation power of the SOA was 8 dBm. In the experiment, the injection current of the SOA was set to 730 mA and the input optical powers into the SOA were 11 and -1 dBm for the control and the data signals, respectively. After conversion the pump was removed by a fiber Bragg grating (FBG). An isolator prevented light reflected by the FBG from propagating back into the SOA. Finally, an 8-nm bandpass filter (BPF) filtered the converted data signal. After transmission, the dispersion was optimized to achieve the minimum BER and the OSNR of the signal was set to 12 dB using an attenuator, an amplifier, and a 2.8-nm BPF. Before the receiver, a 0.3-nm BPF removed the out-of-band amplified spontaneous emission. The DPSK detector consisted of an asymmetric MZI with a 1-bit delay, a balanced receiver, and a 10.7-Gb/s BER tester.

III. RESULTS

Fig. 2 depicts the optical spectrum after the SOA. In this plot, the incoming data signal can be seen on the right side at 1558.2 nm. In the center, the CW pump is present at 1555.7 nm and on the left side, the FWM product is generated at 1553.3 nm. The OSNR at the input and output is 20.3 and 19.6 dB, respectively. The conversion efficiency, defined as the difference in optical power levels between the input and the converted output data signal, is -16.4 dB in this setting. This conversion efficiency could be improved by placing the pump and control in the wavelength configuration as defined in [11]. In this experiment, however, such an alignment was not possible due to constraints from the gain spectrum of the SOA.

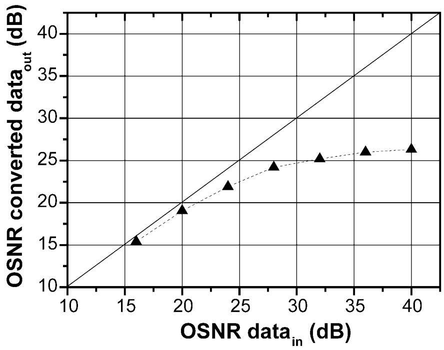

Fig. 3. OSNR of the output converted data signal as a function of the input data (at a spectral resolution of 0.1 nm).

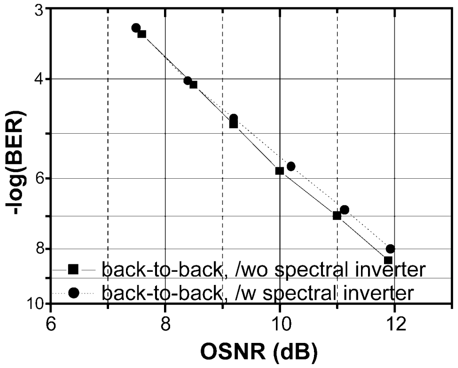

Fig. 4. Back-to-back BER performance with and without FWM-based optical regeneration.

The OSNR of the converted data signal as a function of the input data signal is plotted in Fig. 3. The straight line in the plot represents $\mathrm{OSNR_{in}} = \mathrm{OSNR_{out}}$. From this plot it can be seen that the output OSNR almost equals the input OSNR, for low input OSNR (16 dB). However, for high input OSNR, the noise floor of the SOA reduces the output OSNR to the maximum value of 26-dB output OSNR. The OSNR of the converted FWM peak is limited by the amplified spontaneous emission of the SOA itself.

Fig. 4 depicts the back-to-back BER performance of the DPSK transmitter with and without spectral inverter. Without spectral inverter, a BER of $1 * 10^{-9}$ was measured at an OSNR of 12.1 dB. The measured OSNR sensitivity penalty due to the spectral inverter is less than 0.2 dB, hence, it can be concluded that the contribution of the FWM conversion processes and the SOA to nonlinear impairments is small and can be neglected.

The BER performance for the transmission system without SI and the system with the symmetrical $(X = Y = 4)$ SI configuration as a function of the transmitted OSNR are plotted in Fig. 5(a). At low transmitted OSNR (16 dB), the BER of the

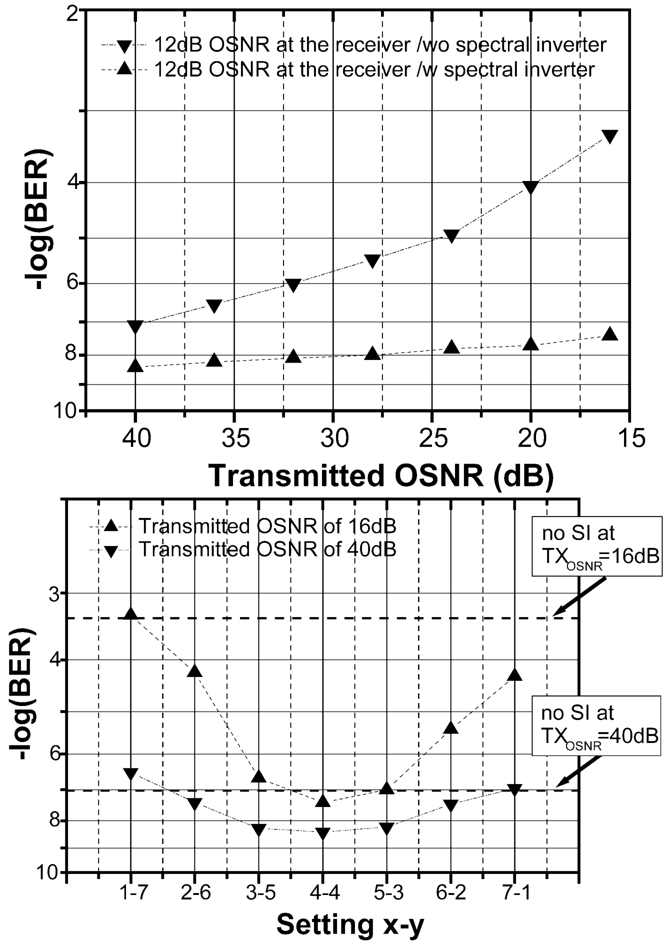

Fig. 5. (a) BER performance with and without SI (in the symmetrical configuration, $X = Y = 4$). (b) BER performance several SI locations (X = number of spans before SI; Y = number of spans after SI).

system without SI is impaired by Gordon–Mollenauer noise, whereas, the BER of the SI-based system shows almost no impact of the phase noise. Without the SI, the BER increased by almost four decades, where the BER of the link with SI increased only less then one decade. Over four decades of BER improvement is obtained for the SI-based configuration compared to the system without SI. At high transmitted OSNR (40 dB), the effect of the Gordon–Mollenauer noise is low. Due to some residual SPM-induced phase noise a small improvement in BER is observed for the SI-based transmission link, compared to the system without SI.

In order to test the dependence of the BER performance on the location of the SI within the link, the SI was placed in several locations and the BER performance was measured. The BER performance after the 800-km transmission link for the highest (40 dB) and the lowest (16 dB) transmitted OSNRs is plotted in Fig. 5(b). The two lines at a BER of $4 * 10^{-4}$ and a BER of $8 * 10^{-8}$ represent the performance of the system without SI at 16 and 40 dB transmitted OSNR, respectively.

The SI performs best for high and for low transmitted OSNR, when the device is placed in the middle of the link. The least effective location of the SI is after the first ($X = 1, Y = 7$) or before the last ($X = 7, Y = 1$) span of the transmission link. The performance at these places is comparable to the performance of the transmission link without SI. The spectral inverter does not regenerate the data signal in the sense that the distortions of the data signal are reduced right after the SI. It inverts the spectrum and, hence, the signal distortions are reverted along the rest of the transmission line. When the SI is placed too early in the link, no distortions occurred so far, hence, the regeneration effect is small. Additionally, due to the noise of the SOA, the OSNR is reduced in the SI, which causes more impairments due to phase noise in the transmission path after the SI. When the SI is placed at the end of the transmission link, the signal distortions cannot totally be reverted in the rest of the transmission line. This reduces the regeneration effect as well.

IV. CONCLUSION

We show that SI can be employed to reduce the effect of nonlinear phase noise (Gordon–Mollenauer noise) in a DPSK-based transmission system. The optimal position for the SI was found to be in the middle of the transmission link. For low transmitted OSNR, over four decades of improvement in BER was obtained.

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