DPSK Regeneration at 40 Gb/s and Beyond Using a Fiber-Sagnac Interferometer

Christos Kouloumentas, Marios Bougioukos, Alexandros Maziotis, and Hercules Avramopoulos

***Abstract*—We analyze the experimental demonstration of a phase-incoherent regeneration scheme for differential phase-shift keying signals at 40 Gb/s. The scheme is based on decoding of the input signal by a 1-bit delay interferometer and subsequent optical remodulation using a fiber-Sagnac interferometer. Power penalty improvement up to 3 dB is reported for phase, amplitude, and amplified spontaneous emission noise loaded signals. Simulation results are in agreement with the experimental findings, and reveal the capability of extending the method at ultrahigh data rates.**

***Index Terms*—Differential phase-shift keying (DPSK) regenerator, nonlinear optical loop mirror, nonlinear Sagnac interferometer.**

I. Introduction

DIFFERENTIAL phase-shift keying (DPSK) appears as the modulation format of choice for long-haul transmission systems due to its lower optical signal-to-noise ratio (OSNR) requirements and its higher tolerance to nonlinear effects compared to the on–off keying (OOK) format. As such, all-optical regeneration of DPSK signals is intensively researched in order to extend the transmission distance and increase the transparency in future DPSK-based optical networks.

DPSK regenerators should be capable of handling the phase in addition to the amplitude of input signals. Proposed subsystems are divided between concepts that deal separately with amplitude and phase noise in a two-step approach [1], and single-step concepts that either suppress the amplitude noise with minimal perturbation of the phase [2], [3] or restore both the amplitude and the phase of the signals. The latter class is divided in turn between methods based on phase-sensitive amplification [4] and less complex phase-incoherent methods that rely on DPSK-to-OOK conversion and subsequent optical phase remodulation [5]–[7].

Phase-incoherent regeneration has been demonstrated in the past with return-to-zero (RZ)-DPSK signals, using semiconductor optical amplifiers (SOAs) in interferometers [5]–[7]. The use of active elements allows for envisaging small-footprint circuits, but it is disadvantageous in terms of optical noise and data rate limitations [6], [7]. On the other hand, the use of highly nonlinear fibers (HNLFs) may have advantages due to their passive nature and their ultrafast nonlinear response. The fiber-based interferometric phase-incoherent regenerator and wavelength converter was numerically studied in [8], whereas in [9], we provided its experimental proof-of-principle at 40 Gb/s using a 1-bit delay interferometer (DI) and a nonlinear Sagnac gate.

In this communication, we extend the presentation of the experimental results and support their analysis with simulation studies that reveal the potential and the limitations of the method. Moreover, we numerically verify the capability of extending the method for optical time-division-multiplexed DPSK signals at ultrahigh data rates (160 Gb/s), predicting practically the same performance as in the 40-Gb/s case.

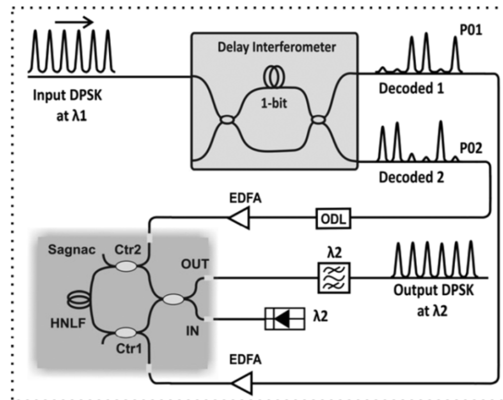

Fig. 1. Operating principle of the fiber-based DPSK regenerator and wavelength converter.

II. Operating Principle and Simulation Results

Fig. 1(a) describes the operating principle. The DPSK signal at wavelength λ_1 is decoded and converted by the DI into two complementary OOK streams that are amplified by erbium-doped fiber amplifiers (EDFAs) and act as controls in the Sagnac with their relative timing preserved. The latter is achieved by matching precisely the optical path lengths for the two OOK streams by means of fiber pieces of appropriate length and an optical delay line (ODL). The gate is fed with a continuous wave (CW) at λ_2. Consecutive pulses at the output (λ_2) have ideally a phase difference of 0 or π depending on the propagation direction of the dominant control pulses. For signals with phase noise only, the sum of peak powers $P_{01} + P_{02}$ is constant for every pair of pulses, and, thus, the phase noise is eliminated in the phase-shift keying (PSK) output stream [8]. Though part of the input phase will turn into amplitude noise, this is sufficiently suppressed by the transfer function of the gate. For amplitude noise, $P_{01} + P_{02}$ will vary creating phase noise at the output. The amplitude-noise reduction, however, can also in this case improve the overall signal quality.

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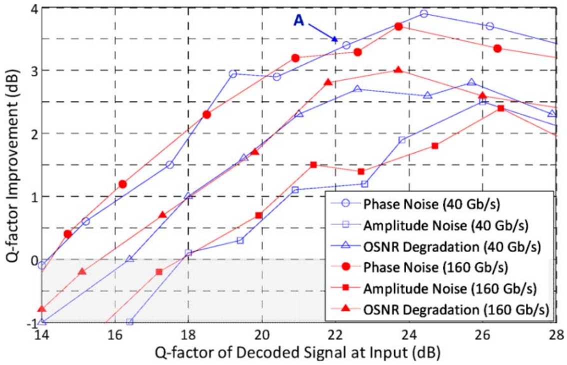


Fig. 2. Q-factor improvement of the decoded signals after the regenerator for different types of signal degradation at 40 and 160 Gb/s.

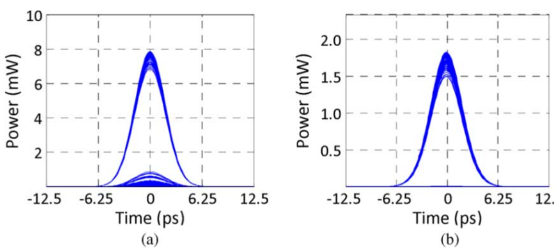


Fig. 3. Eye-diagrams of the 40-Gb/s decoded signal at the (a) input, and (b) output of the regenerator. The eye-diagrams correspond to point A in Fig. 2.

The DI cancels out the differential encoding of the input signal, and thus, the output of the regenerator becomes a simple PSK signal. Nevertheless, in a transmission system comprising a cascade of regenerators, the data can always be retrieved if the number of encoders equal to the number of DIs in the system including the final DI of the receiver [7].

To reveal the potential of the scheme, a simulation study was conducted based on the quality (Q)-factor of the decoded signals before and after the regenerator. Although this is not a completely faithful indicator of the PSK signals' quality since the noise distribution is modified by the DI, it can still be used as a qualitative measure. The setup was based on the diagram of Fig. 1, followed by a second DI to decode the output signal. We assumed a 40-Gb/s input DPSK stream at 1550 nm with 4-ps pulses, a CW at 1556 nm, and a 240-m-long HNLF with 11.5-$\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$ λ nonlinearity, 1.2-ps/nm/km dispersion, and 0.5-dB/km losses. Fig. 2 depicts the Q-factor $(20 \cdot \log Q)$ improvement after the regenerator for input DPSK signals with a variable degree of phase noise, amplitude noise, or OSNR degradation. In all cases, significant improvement is observed for input signal Q-factor values higher than $\sim$18 dB, whereas for values lower than 14 dB, the scheme fails to regenerate the input DPSK signal for all degradation types. Fig. 3(a) and (b) presents as an example the eye-diagrams of the input and output decoded signals for a certain degree of phase distortion (point A in Fig. 2). The improvement in this case is due to the suppression of the noise in the "0" level and is feasible despite the enhancement of the peak-power variation in the "1" level.

The study was extended to 160 Gb/s to investigate the potential for ultra-high-speed operation. The setup included again a 25-ps DI to decode and remodulate each one of the four 40-Gb/s tributaries separately. The DPSK pulses were assumed with half the pulsewidth (2 ps), and the input CW at 1562 nm in order to double the channel spacing and ensure the same level of linear crosstalk between the two signals. To retain in turn the same walk-off conditions in the HNLF between the controls and the input CW, the HNLF dispersion was assumed 0.6 ps/nm/km. Results in Fig. 2 reveal that practically the same performance as in the 40-Gb/s case can be expected for all types of distortion. The study also revealed that the induced timing-jitter at the output, and thus the overall performance, depend critically on the walk-off in the HNLF: regeneration for input decoded streams with Q-factor $\sim$13.5 dB was feasible for all types of distortion when an HNLF with reduced dispersion (0.3 ps/nm/km) was assumed.

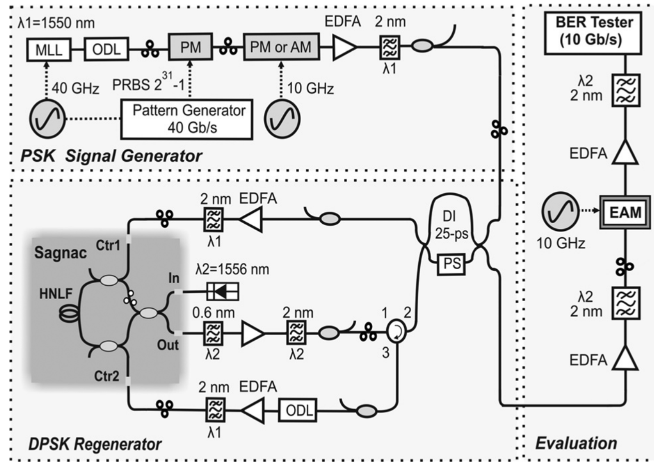
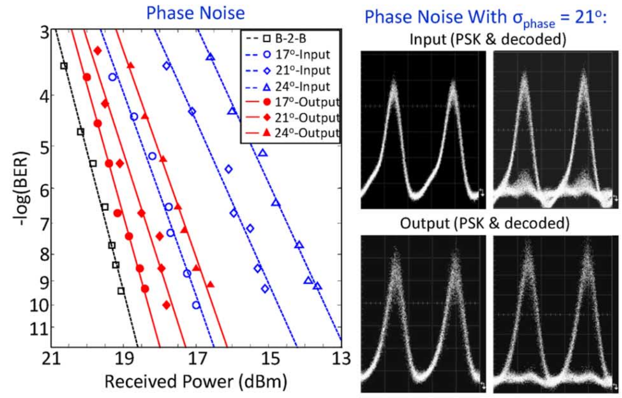


Fig. 4. Experimental setup at 40 Gb/s.

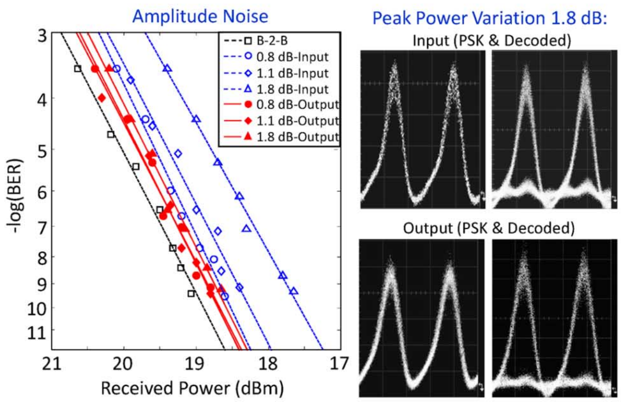
III. Experiment and Discussion

The 40-Gb/s experimental setup is depicted in Fig. 4. A train of $\sim$4-ps pulses at 1550 nm from a mode-locked laser (MLL) was phase modulated by the $2^{31}-1$ long pseudorandom bit sequence (PRBS). Either a phase (PM) or an amplitude modulator (AM) in cascade imposed the respective type of noise. They were driven by a 10-GHz sinusoidal signal with various peak-to-peak values resulting in different degrees of distortion. The HNLF parameters were as described in the 40-Gb/s simulations. Full switching of the 1556-nm input CW required $\sim$75-mW average power at the control ports. The PSK output was guided back into the same DI, and the OOK stream at one of its ports inserted the next stage for 40- to 10-Gb/s demultiplexing based on a electroabsorption modulator (EAM) and evaluation. In-phase and out-of-phase addition of bits was ensured for the input signal by the phase shifter (PS). For the output signal, the same was ensured by fine tuning the CW wavelength, and allowed for selecting either of the complementary streams. For amplified spontaneous emission (ASE) noise loaded signals, the distorting modulator was replaced by a variable attenuator.

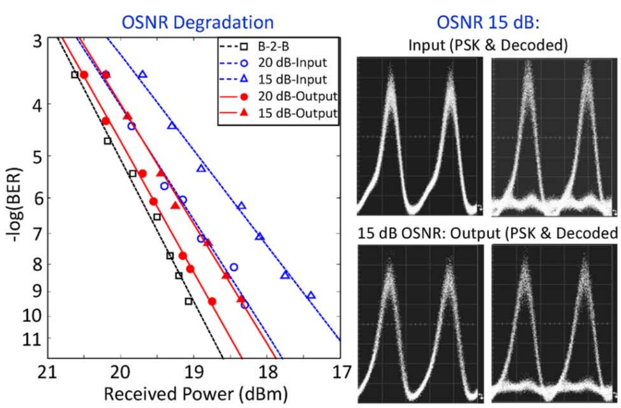
Evaluation was based on bit-error-rate (BER) measurements on the decoded streams before and after the regenerator. Each curve in Fig. 5 corresponds to the worst performing between the two complementary OOK streams and their 10-Gb/s tributaries, related to a 40-Gb/s PSK signal. The variation both between the two OOK streams and the tributaries was negligible due to the perfect symmetry of the gate and the absence of patterning effects, respectively. Fig. 5(a) shows BER curves for three cases of phase distortion of the input signal. The cases



(a)



(b)



(c)

Fig. 5. Experimental results for input signals with (a) phase-, (b) amplitude-, and (c) ASE noise. The left panel summarizes the BER measurements for various $\sigma_{\rm phase}$, peak power variation, and OSNR values at the input, respectively. The right panel depicts eye-diagrams of the PSK and the decoded signals at the input and output of the regenerator in selected cases.

are estimated to correspond to $\sim 17°$, $\sim 21°$. and $\sim 24°$ standard deviation of the phase difference between successive bits $(\sigma_{\rm phase})$. For highly distorted signals with power penalty in excess of 4 dB compared to the back-to-back (B-2-B) case, the regenerator could provide improvement of ~3 dB. Fig. 5(b) presents results for amplitude-noise loaded signals. Three cases are shown corresponding to 0.8-, 1.1-, and 1.8-dB peak power variation. In the most heavily distorted case, power penalty improvement of ~1 dB at the level of 10^{-9} BER was achieved. Results for OSNR degradation are given in Fig. 5(c), and reveal power penalty improvement of ~0.9 dB for 15-dB input OSNR. This is obtained despite the fact that linear ASE noise is a less favorable case due to the similar degrees of phase- and amplitude-distortion of the input signals [8]. On the contrary, higher performance is expected for Gordon–Mollenauer noise, as this resembles more to the favorable for the scheme phase-noise type of distortion. The performance homogeneity between the complementary OOK streams indicates that further power penalty improvement is feasible in all cases with a balanced receiver.

Eye-diagrams of input and output signals are shown in the right panel of Fig. 5, corresponding to $\sim\ 21°\sigma_{\rm phase}$ of the input signal [Fig. 5(a)], 1.8-dB peak power fluctuation of the input signal [Fig. 5(b)], and 15-dB input OSNR [Fig. 5(c)]. Phase noise results in low extinction ratio (ER) in the decoded signal. The regenerator suppresses the phase noise and allows for a decoded signal with higher ER but slightly enhanced peak power variation due to the partial conversion of the phase-into amplitude noise. Amplitude distortion on the other hand causes mainly peak-power variations on the decoded signal, and in this case regeneration is achieved mainly through their partial suppression. The case of OSNR degradation resembles more the case of amplitude distortion, and thus the regeneration is achieved again mainly due to the suppression of amplitude fluctuations. The conclusions described above are in very good agreement with the simulation results.

IV. Conclusion

We have experimentally demonstrated a DPSK regenerator based on decoding and optical phase remodulation using a fiber-Sagnac interferometer. Regeneration at 40 Gb/s has been achieved for phase-, amplitude-, and ASE-noise loaded DPSK signals. The applicability of the concept at higher data rates (160 Gb/s) has been indicated by simulation studies.

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