All-Optical Regeneration based on Phase Sensitive Amplification

Radan Slavík, Joseph Kakande, Francesca Parmigiani, Periklis Petropoulos, and David J. Richardson

Optoelectronics Research Centre, University of Southampton,
Southampton, SO17 1BJ, UK

***Abstract*- We review our recent results regarding regeneration of binary phase encoded signals using phase sensitive amplification in fibers.**

I. Introduction

Phase noise introduced during transmission both from optical amplifiers and the nonlinear interactions between channels represents a significant limiting factor to data transmission using (differential) phase-shift keyed modulation formats [1]. Consequently, there is great interest in developing all-optical regeneration schemes capable of eliminating phase (and ideally additionally amplitude) noise for phase-shift keyed signals. Phase regeneration of binary (or differential) phase shift keyed signals (PSK, DPSK) can be implemented directly by exploiting the phase-squeezing capability of phase sensitive amplifiers (PSAs) [2]. To perform also amplitude regeneration, the PSA can be operated in the saturation regime. To achieve PSA, however, a phase relationship between the PSA pump(s), the signal and any idlers present needs to be maintained. Recently, a scheme in which the carrier from a carrier-less PSK signal is recovered and then used to phase-lock the locally generated pumps with the incoming data prior to a degenerate PSA was published [3].

For regeneration of more complex formats, e.g. quadrature phase shift keyed signals (QPSK), modified PSA configurations were suggested and demonstrated recently [4]. Generally, they employ cascaded four wave mixing processes to achieve regeneration of more than the two phase levels allowed in a simple PSA.

Here, we present and discuss practical aspects of the PSK regenerator that has only the noisy carrier-less data at its input. Tests of the developed regenerator operating in the field as an in-line device are also shown.

II. Regenerator of PSK Signals

The most practical implementation of the PSK regenerator demonstrated so far [5] is shown in Fig. 1. First, the signal is combined with a CW local pump ('Pump 1', its frequency is 200 GHz apart from the data carrier frequency) using an add-multiplexer and then sent to a polarization maintaining highly nonlinear fiber (HNLF 1) to generate an idler wave that is inherently phase-locked to the data and Pump 1 waves. Note that due to the phase erasure process, the binary data modulation is not transferred to the idler [3]. Then, the three signals (Data, Pump 1, Idler) are separated in a 4-channel 200-GHz wavelength demultiplexer (DEMUX) placed behind a circulator. A mirror provides retro-reflection in the data path as well in the path for Pump 1 which also includes a piezo-electric fiber stretcher (PZT) and a variable attenuator. A semiconductor laser [6] which is injection locked to the idler, is used to generate Pump 2 in the idler path. Pump 2 is thus phase-locked to the idler (and thus also to the data and Pump 1). Note that since the injection locking is a much slower process than four wave mixing (having a (sub)-GHz bandwidth) any high frequency fluctuations (e.g., bit-to-bit phase variations) present on the original data signal are not transferred onto the output of the slave laser [3]. In the regenerator, the three optical waves involved in the regeneration process share a common path other than on the output side of the DEMUX. The data wave and the two pumps are then boosted in a high-power erbium doped fiber amplifier (EDFA) (total power of 29-32 dBm) before being launched into the PSA which consisted of 180-m of HNLF designed to have a high stimulated Brillouin scattering (SBS) threshold [7]. For optimum performance, the PSA is operated in deep gain saturation, with the data signal strongly depleting the pumps, resulting in a strong variation of pump power at the PSA output as a function of the relative phase between the pump and data beams. We use this feature to provide an error signal for the PZT fiber stretcher to compensate for the relative phase drifts between the interacting waves that occur due to environmental changes (primarily temperature) that causes relative phase variations of the signal when they do not propagate through the same fiber (as mentioned earlier, this is only behind the DEMUX). At the output, multiple copies of the regenerated data are present – including one at the original wavelength [8], Fig. 1.

III. Field Trial

To test the regenerator, we combined 38 channels on the 100 GHz DWDM ITU grid, each carrying 40 Gbit/s DPSK data. In order to facilitate placing the regenerator at the mid-point of our network, we chose to incorporate a wavelength shift in the regeneration process, Fig.1, allowing us to go twice through the network, Fig. 2 [8]. The network consisted of a Dark Fiber link (part of the UK JANET Aurora Network) that extends from Southampton to London and back again (400 km dispersion-compensated transmission distance, 6 in-line flat-gain EDFAs operated in automatic gain control

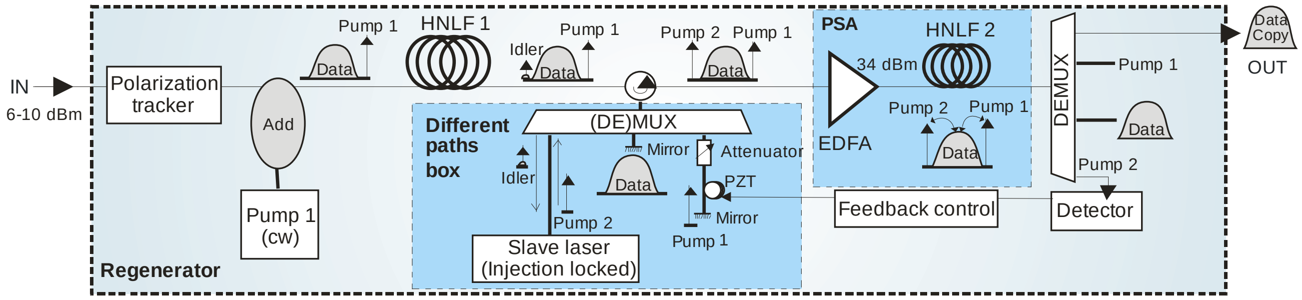

Figure 1. Regenerator set-up. In the field trial, the wavelength shifted data copy is used to allow for dual-pass of the entire network, effectively doubling the propagation distance and also allowing placing of the regenerator in the mid-point of the network.

mode). At its output, we dropped ITU Channel 27, performed wavelength conversion to the slot of Channel 23 (either with or without regeneration) and sent it through the link again with all other channels. To enable comparative study with/without regeneration conventional wavelength conversion could be carried out by switching off Pump 2, resulting in phase insensitive FWM-based λ-conversion.

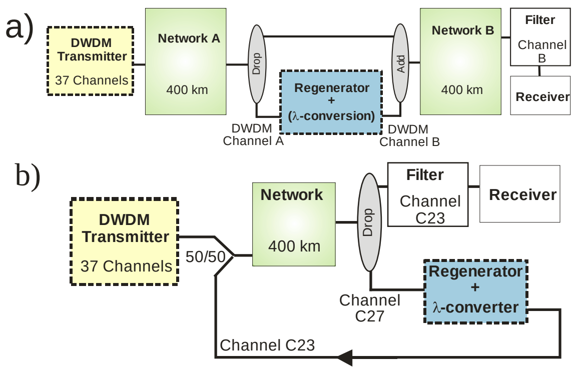

Figure 2. Model experiment with regenerator as an in-line device (a) and the implemented network that emulates the model network (b).

Results obtained after effective propagation through 800 km, Fig. 2b, are shown in Fig. 3.

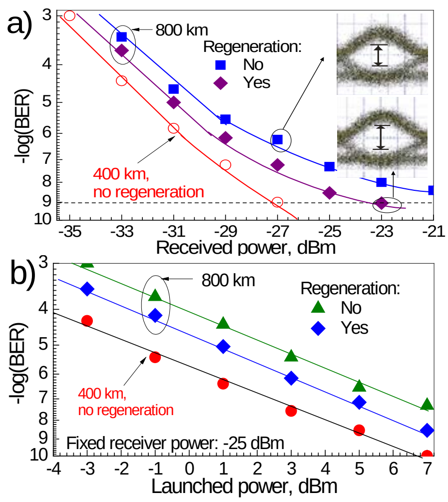

Figure 3. BER curves at the output (800 km) with and without mid-span regeneration: (a) for launched power of 5 dBm; (b) as a function of the launched power for fixed receiver power of -25 dBm. For reference, measurements of the signal at the mid-point (400 km) are also shown.

Use of a mid-point regenerator allows a reduction in the BER power penalty by a factor of two (e.g., at BER=10^{-6}, it reduces the penalty from 2 dB to 1 dB and at BER=10^{-9}, from 5 dB to 2 dB). The error floor of the regenerated data is one order of magnitude lower than without regeneration, meaning that the regenerator prevents about 90% of errors in this regime. A closer study of the eye diagrams, Fig. 3a, shows about a 20% larger eye opening for the regenerated signal. Varying the input power into the link, Fig. 3b, shows approximately 4 dB power penalty in the second round trip. This value is reduced to 2 dB when the regenerator is used.

IV. Conclusions

A phase and amplitude regenerator was tested in an installed transmission link and found to operate reliably. We tested the regenerator as an in-line device (in the middle of an 800-km link) and found it reduced the BER floor by one order of magnitude and reduced the power penalty by a factor of two.

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