Field-trial of an all-optical PSK regenerator in a 40 Gbit/s, 38 channel DWDM transmission experiment

Radan Slavík[1*], Joseph Kakande[1], Francesca Parmigiani[1], Lars Grüner-Nielsen[2], Richard Phelan[3], Josef Vojtěch[4], Periklis Petropoulos[1], and David J. Richardson[1]

1. Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
2. OFS, Priorparken 680, 2605 Brøndby, Denmark
3. Eblana Photonics, Dublin, Ireland
4. CESNET a.l.e, Zikova 4, Prague, Czech Republic
**r.slavik@soton.ac.uk*

Abstract: We report the first field-trial of a phase and amplitude regenerator highlighting the practicality of the technology. Sensitivity improvement and mitigation of transmission-induced noise with the regenerator placed in-line or at the receiver is demonstrated.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators, (190.4410) Nonlinear optics, parametric processes

1. Introduction

Phase and amplitude noise introduced during transmission both from optical amplifiers and the nonlinear interactions both within and between channels represents a significant limiting factor to data transmission using phase-shift keyed, PSK, modulation formats [1],[2]. Thus, the development of regeneration schemes capable of eliminating phase and amplitude noise for PSK signals is of great interest. Recently, we demonstrated a network-compatible regenerator for simple two-level PSK encoded signals [3] and also suggested how the technology might be scaled up to allow the regeneration of more spectrally-efficient modulation formats [4]. Following our first proof-of-principle demonstrations, we redesigned the two-level PSK regenerator to allow in-field tests and demonstrated its capability to operate in the presence of broadband phase noise [5] (the noise was emulated in these experiments by direct phase modulation of the signal).

However, in order to truly establish the viability and capability of the technology several key further tests are required. Firstly, it is essential to establish that the regenerator can process the forms of noise generated in a real network using typical network parameters (e.g., using a DWDM network operating within the C-band subject to realistic environmental perturbations e.g. polarization drifts/acoustic perturbations) rather than noise generated by artificial means in the laboratory. Moreover, in all experiments to date, only the performance of the regenerator when placed immediately in front of the receiver was characterized - highlighting the ability to correct for particular classes of error in differentially decoded systems [5]. The natural position of such regenerators however, is along the transmission line, where they can be used to reduce the build up of non-linear noise during signal propagation. Thus, the demonstration and testing of the regenerator as an in-line device is a matter of prime importance.

Here, we address both of these issues, demonstrating the key capabilities of the regenerator when operated as in-line device in a real network. For the purposes of this demonstration, we used 38 DWDM 40 Gbit/s channels on a 100 GHz grid covering most of the C-band (total capacity approaching 1.5 Tbit/s) and 400 km of installed fiber.

2. Set-up

A conceptual outline of our network and its practical implementation are shown in Fig.1a and Fig. 1b respectively. At the transmitter, we combined 37 CW lasers on a 100 GHz DWDM ITU grid and modulated them with 40 GHz, 2^{31}-1 PRBS DPSK data. To de-correlate adjacent channels, we split the odd/even channels in an interleaver, introduced 55 ns of relative delay, and then re-combined them, Fig. 1c. 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. This wavelength shift is not essential but illustrates another potentially useful functionality of the technology (wavelength conversion/multicasting) [6]. 37 channels (excluding ITU Channel 23) were sent down our Dark Fibre 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 with maximum input/output powers of -5/15 dBm, operated in automatic gain control mode, nominal gain 20 dB – Fig. 1d). The maximum average launched power into the link was 7 dBm. 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. Therefore a total of 38 channels occupied the frequency grid at any time. The regenerator used is described in [5] and has been designed to be largely insensitive to the thermal/acoustic pick-up. The device was mounted into a standard telecommunication rack along with other network components and test gear. (Note that our first generation device [3] was assembled on an vibration-isolated optical lab table). To compensate for polarization drift in the network, a polarization tracker was incorporated into the regenerator, which was configured to perform simultaneous regeneration and multicasting [6]. To enable comparative study with/without regeneration, conventional wavelength conversion could be carried out by switching off Pump 2 (Fig. 1f), resulting in phase insensitive FWM-based λ-conversion.

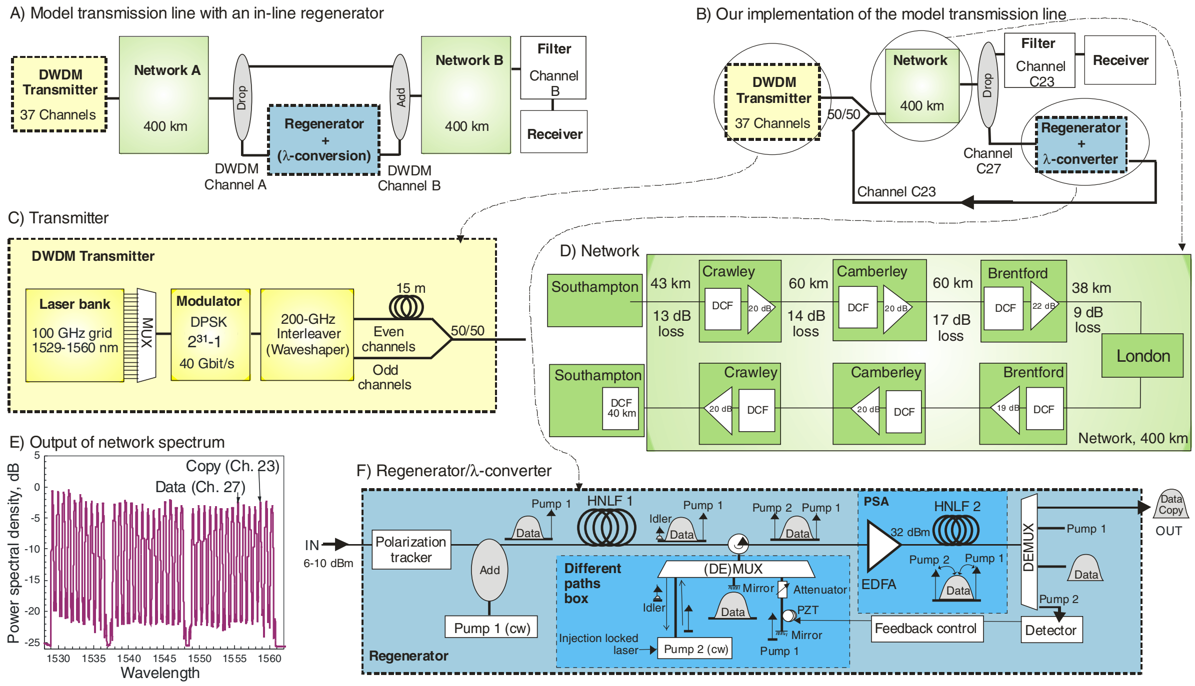

Figure 1: Experimental set-up.

The optimum power into HNLF 2 (Fig. 1f) was 32 dBm (about 3 dB higher than required for same-wavelength regeneration [5]). The receiver consisted of a 0.6-nm bandpass filter, attenuator (the received power was measured at its output), low-noise EDFA, a bandpass filter, a 1-bit delay interferometer (DLI), and a balanced photodetector.

3. Results

First, we characterized the transmitter/receiver and λ-conversion stages (without propagation through the network, Fig. 2a, triangles). Subsequently, we sent the signal through the network (400 km) and analyzed the λ-converted signal at the regenerator output, Fig. 2. The regenerator fully restored data fidelity giving a received power improvement of 1.5 dB at a BER=10^{-9}. Slight reshaping of the eye is also noted, Fig. 2a, which may be responsible for the slight improvement of the BER curve observed as compared to that measured without transmission. Fig. 2b shows the improvement provided by the regenerator as we varied the total power launched into the link (for a fixed power at the receiver). For identical performance, around 2 dB less total power can be sent through the link when the regenerator is used. As the BER improves monotonically with the launched power, we believe that the noise generated in the link is dominated by linear (ASE) rather than non-linear noise. This may be a consequence of using many channels (low power per-channel) and the relatively modest transmission distance.

Results obtained after two round-trips through the link (800 km, regenerator used “in-line”) are shown in Fig. 3. Use of a mid-point regenerator is capable of reducing the BER penalty by a factor of two (e.g., at BER=10^{-6}, it reduces the power penalty from 3 dB to 1.5 dB and at BER=10^{-8} from 5 dB to 2 dB). The error floor of the regenerated data is one order of magnitude down with regeneration relative to without, meaning that the regenerator prevents about 90% of errors in this regime. This is fully consistent with the earlier studies presented in [5]. 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, showed almost 4 dB power penalty in the second round trip. This value was reduced to 2 dB when the regenerator was used.

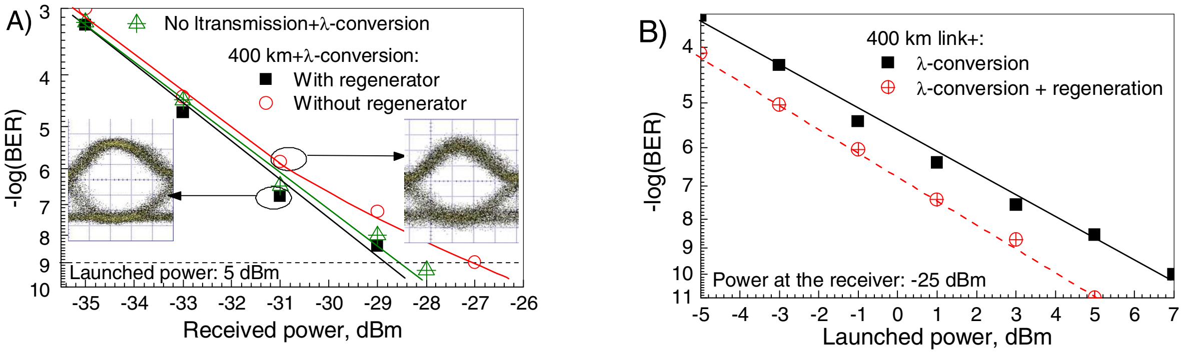

Figure 2: BER curves at the output of the 1st round-trip (400 km) measured at the data Channel 23. (A) Measured for the maximum power into the link (7 dBm). For reference, a measurement of the λ-converted signal without transmission is also shown (green triangles). (B) BER measurement for various powers launched into the link and a fixed receiver power of -25 dBm.

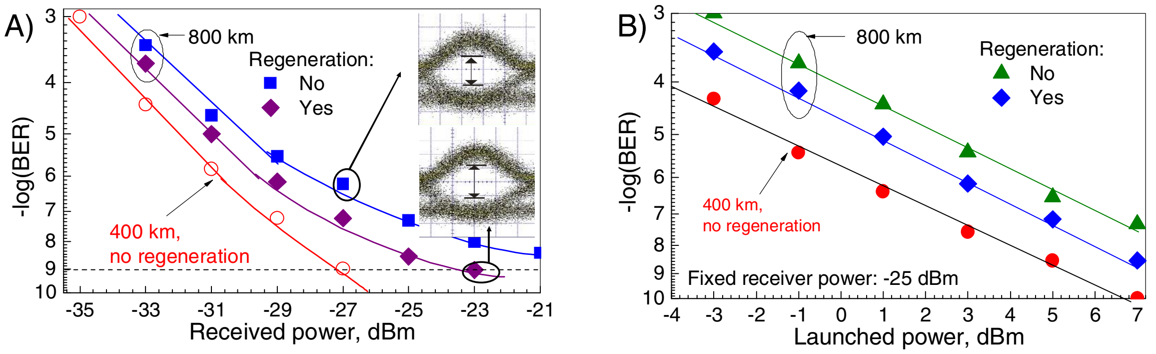

Figure 3: BER curves at the output of the 2nd round-trip (800 km) both with and without mid-span regeneration: (A) for a launched power of 5 dBm; (B) as a function of the launched power for a fixed receiver power of -25 dBm. For reference, measurements of the signal at the mid-point (after wavelength conversion) are also shown.

4. Conclusions

A phase and amplitude regenerator and wavelength converter based on phase sensitive amplification was tested in an installed transmission link and found to operate reliably over extended periods. We first tested the regenerator at the output of a 400-km long DWDM link. We found it successfully reduced the impact of transmission-generated noise to a similar level as found with artificially generated noise in previous laboratory experiments [5]. Following this characterization, we tested the regenerator as an in-line device for the first time (in the middle of an 800-km link). The regenerator reduced the BER floor by one order of magnitude and reduced the power penalty due to predominantly linear noise by a factor of two. Even greater improvements should be possible in the presence of nonlinear noise [5] although as of yet we have not been able to quantify this experimentally due to power limitations in the current network.

This research has received funding from the European Communities Seventh Framework Programme FP/2007-2013 under grant agreement 224547 (PHASORS) and 255368 (TOP CLASS). We acknowledge the support of JISC and JANET (UK) for the funding and provision of the JANET-Aurora dark-fiber facility.

6. References

[1] J.P. Gordon, and L.F. Mollenauer, "Phase noise in photonic communications systems using linear amplifiers," Opt. Lett. **15**(23), 1351–1353 (1990).
[2] A.H. Gnauck and P.J. Winzer, "Optical phase-shift-keyed transmission," J. Lightwave Technol. 23 (1), 115-130 (2005).
[3] R. Slavík et al, "All-optical phase and amplitude regenerator for next-generation telecommunications systems," Nature Photonics 4 , 690–695 (2010).
[4] J.Kakande, A.Bogris, R.Slavik, F.Pamigiani, D.Syvridis, P.Petropoulos, D.J.Richardson, "First demonstration of all-optical QPSK signal regeneration in a novel multi-format phase sensitive amplifier," paper PD 3.3, *ECOC 2010,* Turin 19-23, Sep 2010.
[5] R. Slavík, F. Parmigiani, J. Kakande, M. Westlund, M. Skold, L. Gruner-Nielsen, R. Phelan, P. Petropoulos, and D.J. Richardson, "Robust design of all-optical PSK regenerator based on phase sensitive amplification," OFC 2011, Los Angeles, 6-10 March, 2011.
[6] R.Slavik, J.Kakande, F.Parmigiani, L.Gruner-Nielsen, D.Jakobsen, S.Herstrom, P.Petropoulos, D.J.Richardson, "All-optical phase-regenerative multicasting of 40 Gbit/s DPSK signal in a degenerate phase sensitive amplifier," *ECOC 2010,* Mo1A2, Turin, 19-23 Sep 2010.