Multichannel Regeneration of Dual Quadrature Signals

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Abstract *We demonstrate the first multi-wavelength regeneration of quadrature phase shift keyed (QPSK) formatted signals, showing a simultaneous Q^2-factor improvement in excess of 3.8 dB for signals degraded by phase distortion*

Introduction

The capacity limits of WDM fiber transmission systems are now well understood[1], and several proposals to extend these limits have been proposed, including optical phase conjugation (50% capacity increase)[2], few mode fiber (M-fold capacity increase)[3] and all optical regeneration[4-6]. All optical regeneration offers the prospect of a significant increase in reach, or alternatively long haul transmission capacity using the existing fiber base. However, to be accepted as a potential solution, it is essential to be able to regenerate high modulation formats such as QPSK[5] or 8-star-QAM[6], and to process multiple wavelengths simultaneously[5]. In contrast to binary phase shift keyed (BPSK) regeneration high-order modulation format regeneration is significantly more complex to realize and whilst recent progress has been made, to the best of our knowledge there has been no report of simultaneous multi-channel QPSK regeneration.

In this paper we demonstrate for the first time, to our knowledge, simultaneous regeneration of two 10.9 Gbaud/s quadrature phase shift keyed (QPSK) signals, using phase sensitive amplification (PSA). For signals degraded by periodic phase modulation, we demonstrate simultaneous Q^2 factor improvements in excess of 3.8dB, for input Q^2-factors as low as 12.8dB and a maximum output Q^2-factor of 17dB.

Experimental Setup

The proposed scheme is depicted in Fig. 1-a). At the transmitter, two CW-lasers emitting at λ_1:1559.3nm and λ_2:1560.3nm were combined. Then, after being amplified to 12dBm they were fed through a Mach-Zehnder IQ modulator, which was driven by 10.9Gbit/s, 2^{15}-1 pattern length, normal and inverted PRBS patterns (54-bit relative delay) from a pulse generator, thus generating two 10.9Gbaud/s QPSK signals. The two modulated channels were amplified to 18dBm and de-correlated. Phase distortion was also added using a phase modulator driven by a 7GHz square wave from an independent source before launching them into the PSA.

The regenerator was based on Phase Sensitive Amplification (PSA)[7] and consisted of a carrier extraction/synchronization stage and a regeneration stage. The synchronization stage involved independent extraction of the carrier phase for both signals and translation to the required pump wavelengths, as well as, the generation of respective 3[rd]-order signal harmonics for implementing a 4-level phase quantization scheme[5].

The two QPSK signals, see Fig. 1-b) were combined with a strong CW pump signal at 1563.9nm and after amplification to 37dBm the three waves were launched into a highly nonlinear fiber (HNLF). The HNLF section of this experiment was a strained aluminous-silicate highly nonlinear fibre, whose increased stimulated brillouin scattering (SBS) threshold alleviated the need for active SBS suppression. It had a total length 350m, dispersion parameter in the range of -2 to 2ps/(nm·km), nonlinear coefficient γ: ~$7W^{-1}\cdot km^{-1}$ and total loss of 4dB. The optical spectrum at the output of the HNLF, taken at point D, is depicted in Fig. 1c). The common pump interacted through four wave mixing (FWM) with each one of the two QPSK modulated waveforms creating higher order harmonics of the conjugated signals and many other intermixing products. The 4[th] -order harmonics were stripped of the data modulation and were used to phase lock the local lasers of the PSA. Each of the two extracted carriers was independently self-locked to the combined phase of the data signals and the common pump, and had a well-defined relationship to the 3[rd] order harmonics, maintaining the required condition for the second stage of the regenerator.

After the carrier extraction stage the signal was split in two paths. In the lower path, the extracted carriers, at λ_{c1}:1545.74nm and λ_{c2}: 1548.9nm, were filtered and directed to the two local pump lasers, achieving their phase synchronization through optical injection locking. Each local pump emitted 8dBm of power. The two pumps and the full signal spectrum of the

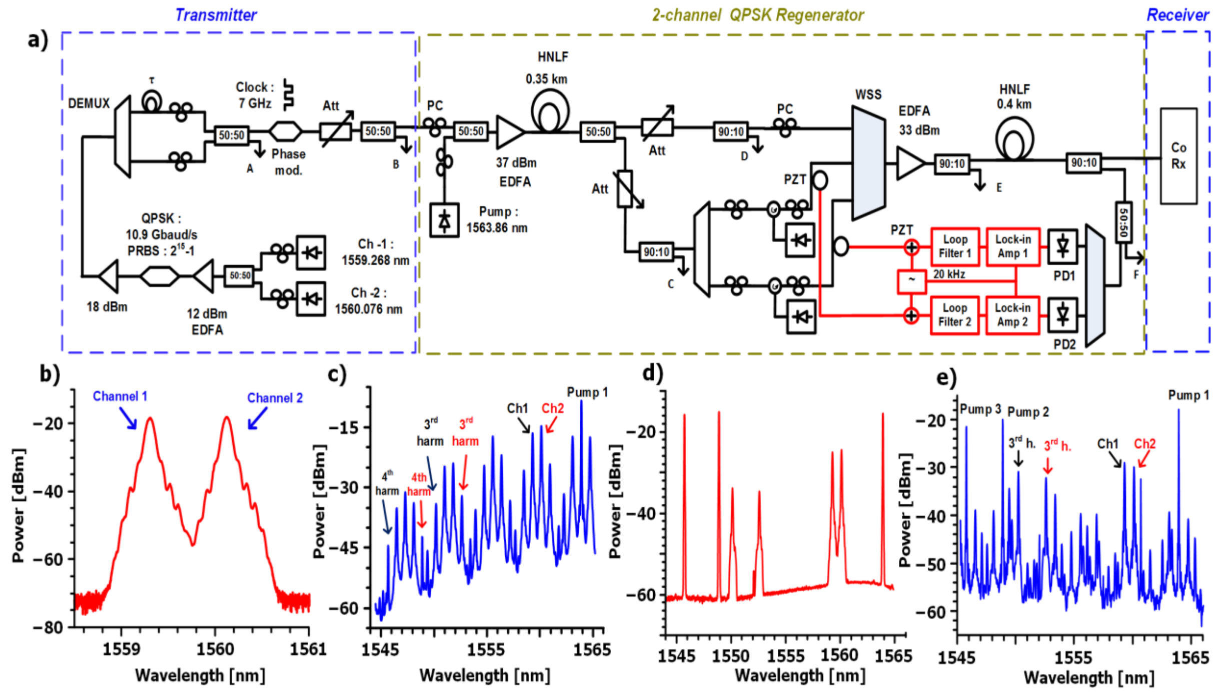

Fig. 1 a) Experimental setup of the proposed 2-channel QPSK regenerator. b) Optical spectrum of the two input signals. c) Optical spectrum at the output of the carrier extraction stage (point-D). d) Optical spectrum at the output of the second HP – EDFA (point- E). e) Optical spectrum at the output of the PSA regenerator (point-F).

upper path were directed to a wavelength selective switch (WSS), which suppressed all the unwanted spectral components and selected only the waves that were needed for the two channel regenerative scheme i.e. the common CW pump, the two propagating QPSK signals, the corresponding 3rd order harmonics and the two phase locked CW pumps (pump2, pump3). Fig. 1-d) depicts the filtered spectrum after being amplified to 33dBm, taken at point E. Subsequently, this was launched to a second HNLF section, with similar structure and properties to the first one, where the phase sensitive interaction took place. The final optical spectrum at the HNLF output was depicted in Fig. 1-e). Two piezoelectric fiber stretchers (PZTs), one for each pump path in a phase lock loop configuration provided compensation of the environmentally induced phase drifts[4].

Finally, at the receiver the two signals were de-multiplexed and coherently detected. Each channel was sampled and digitalized, using an 80GS/s real time oscilloscope with a 36GHz analogue bandwidth. Channel estimation was achieved off-line using typical digital signal processing (DSP) algorithms for clock recovery, polarization de-multiplexing, and phase estimation etc[7].

Results

At the carrier extraction stage the power ratio of the common pump to the signals was set higher than 6.0dB and the injected power to each injection locked laser was kept below -30 dBm to enable sufficient suppression of any residual phase modulation from the carrier extraction process (e.g. due to the imposed phase distortion at the PSA input). The regenerative properties of the scheme were strongly affected by the power ratio of the QPSK signals to their respective 3rd-order harmonics (idlers)[4,5]. Detailed performance evaluation has been carried out as a function of this parameter by measuring the Q^2-factor of the received signal at the output of the regenerator. Here, the Q^2-factor represents the electrical signal-to-noise (SNR) power ratio and it is related to the error vector magnitude according to $Q^2= 1/EVM^2$. In Fig. 3 we have plotted the Q^2-factor difference between the input and the output of the regenerator, i.e. $\Delta Q^2=10\cdot\log10(Q_{out}^2/\ Q_{in}^2)$, for two scenarios; i) when the input signal had not suffered any distortion, see Fig. 2a) and ii) when it had been heavily distorted in phase by the introduced 7GHz tone, see Fig. 2b. In the first case, the input Q^2-factor is 23dB. Optimum performance, with less than 3dB penalty, was observed for both channels when the signal-to-idler power ratio was 9dB, which is in accordance with the theoretical optimum for a single channel regenerator[5]. When the input constellations have been subjected to significant phase distortion, so that the input Q^2-factor is degraded to ~12.8dB, the regenerator enabled a significant Q^2-factor improvement of more than 3.8dB. The optimum operation occurred when

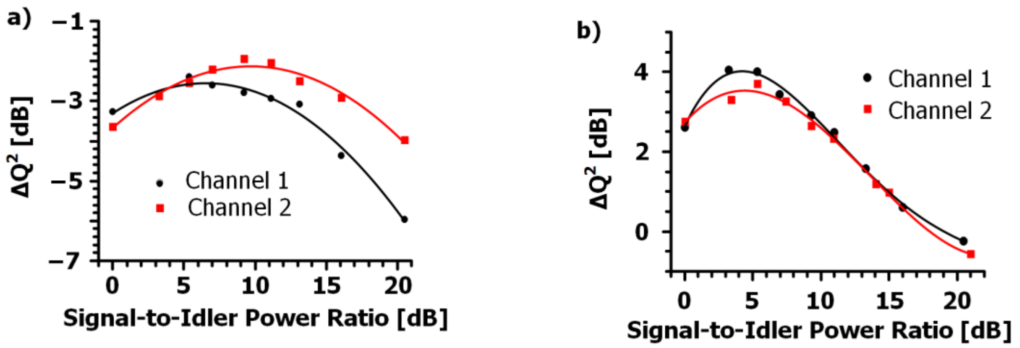

Fig. 2 a) Q^2-factor penalty at the output of the PSA for the two propagating channels as a function of the signal-to-idler power ratio at the absence of input phase distortion. The input Q^2-factor was ~23 dB for both channels. b) Corresponding Q^2-factor improvement due to the regenerative PSA operation, when the input channels were degraded by phase distortion. The input Q^2-factor for the two channels was ~13 dB.

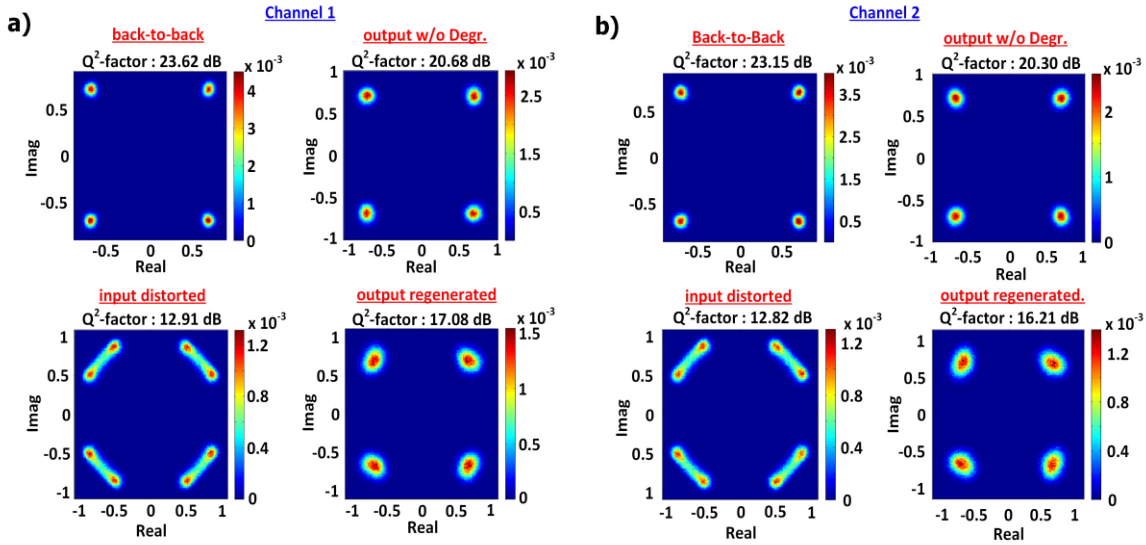

Fig. 3 a) Constellation diagrams of the received Channel-1 at the input (upper-left) and output (upper-right) of the PSA when no input phase distortion is present, as well as, when significant phase distortion has been introduced, see (lower-left) and (lower-right) diagrams, respectively b) Corresponding constellation diagrams for Channel- 2. In all cases, the signal-to-idler power ratio was set to 3dB. The color scale represents the density of points in the constellation diagram (i.e. number of samples per cell to the total number of received samples)

the signal-to-idler power ratio was within the range of 3 to 5 dB, less than the ~9 dB for an undistorted input.

Conclusions

We demonstrated, for the first time, the feasibility of multi-channel regeneration of state of the art dual quadrature modulation formats achieving more than 3.8dB improvement in the Q^2-factor performance. Extension of this work to higher wavelength counts, using nonlinear fiber with wider phase matching bandwidths or alternative multi-channel schemes will establish the commercial competitiveness of all-optical regeneration against pure optical amplification for future systems carrying QAM formatted data.

Acknowledgements

Tyndall National Institute is acknowledged for the loan of HNLF. The work has been supported by the Marie Currie-IEF project ARTISTE (IEF 330697), the EPSRC project UNLOC (EP/J017582/1), The Royal Society (WM120035-TEST), and the EU-ICT project FOX-C

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