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Dynamic Range Enhancement and Amplitude Regeneration in Single Pump Fibre Optic Parametric Amplifiers using DPSK Modulation

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Abstract

Input power dynamic range enhancement and amplitude regeneration of highly distorted signals are demonstrated experimentally for 40 Gbit/s RZ-DPSK in a single-pump fibre parametric amplifier with 22 dB small-signal gain.

Introduction

Nonlinear phase noise (NPN) is one of the most severe impairments in return-to-zero differential phase shift keying (RZ-DPSK) transmission. Limiting the intensity fluctuations of the signal has been shown to reduce the accumulation of NPN, hence the need for all optical intensity fluctuation reduction techniques that are furthermore transparent to the phase [1]. Gain saturation in a fibre optic parametric amplifier (FOPA) enables intensity equalisation of on-off keying (OOK) signals [2], and signal saturation induced by pump depletion due to the four-wave mixing (FWM) process has been investigated numerically for DPSK signals [1]. Preliminary experimental results based on amplitude histograms have also been reported in the non-amplifying regime and for low duty cycle pulses [3]. Recently, DPSK signal impairments in dual [4] and single pump [5] FOPA have been studied and the saturation of parametric gain has been exploited for OOK and DPSK amplitude regeneration in a Kerr switch relying on polarisation rotation [6]. However, to date, no confirmation of the regenerative behaviour of single-pump FOPA based on unambiguous BER measurements has been reported in the literature for DPSK modulation.

In this work, we experimentally show that the input power dynamic range of a single pump (amplifying) FOPA can be significantly enhanced for RZ-DPSK modulation as compared to RZ-OOK. Furthermore, we exploit this effect to demonstrate successful amplitude regeneration of a highly distorted 40 Gbit/s RZ-DPSK signal in a FOPA with over 20 dB gain.

Experimental set-up

The experimental set-up is depicted in Fig. 1. A 40 Gbit/s 33% RZ-OOK or RZ-DPSK signal is generated from a continuous wave (CW) laser using a Mach-Zehnder modulator (MZM) pulse carver driven by a 20 GHz sinusoidal signal followed by a data modulator driven with a 2^{31}-1 pseudo random binary (PRBS) sequence. The modulation format is selected by a proper choice of the bias and peak-to-peak voltage of the data signal applied to the second MZM.

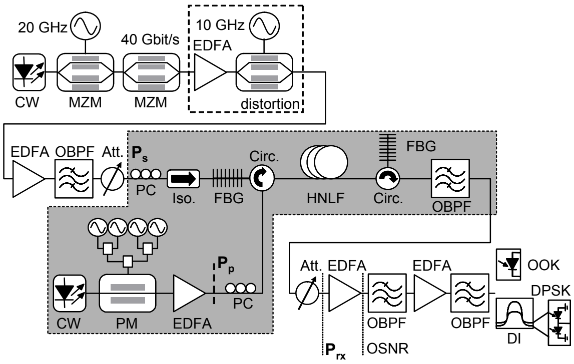

Figure 1: Experimental set-up.

The signal input power to the FOPA is then adjusted using an erbium doped fibre amplifier (EDFA) followed by an optical bandpass filter (OBPF) and a variable attenuator. The pump signal is derived from a CW laser amplified up to 30.5 dBm in an EDFA. In order to suppress stimulated Brillouin scattering, the pump is phase modulated using 4 sinusoidal tones at 123, 600, 1000 and 2350 MHz. Signal and pump are coupled into the 500 m highly nonlinear fibre (HNLF) using a fibre Bragg grating (FBG) and a circulator. The fibre has zero dispersion at 1560.5 nm, a dispersion slope equal to 0.015 ps/(nm^2·km), an attenuation of 0.74 dB/km and a nonlinear coefficient of 11.5 W^{-1}·km^{-1}. At the HNLF output, the signal wavelength is selected using another FBG followed by an OBPF and is input to a receiver consisting of an optical preamplifier and a 40 GHz photodiode (in the case of OOK) or a delay interferometer (DI) followed by a balanced detector (in the case of DPSK).

The FOPA was characterised for a pump wavelength of 1564.1 nm, as shown in Fig. 2. The on-off gain was measured at the HLNF output and peaks around 1549.5 nm and 1548.5 nm for 29.5 and 30.5 dBm pump power, respectively. Due to the availability of FBG at that wavelength, the signal was tuned to 1546 nm in the experiments. The FOPA exhibits clear saturation behaviour with small signal gains of 16 and 22 dB and input saturation powers of 13 and 9.5 dBm for 29.5 and 30.5 dBm pump power, respectively.

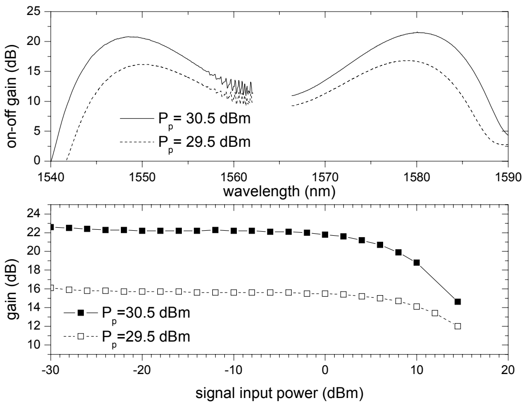

Figure 2: FOPA on-off gain spectrum (top) and gain as a function of signal input power (bottom).

Results and discussion

The optical signal-to-noise ratio (OSNR, measured in 0.1 nm bandwidth) penalty compared to back-to-back was measured at a bit-error-ratio of 10^{-9} as a function of signal input power to the FOPA (Fig. 3). The limitation of the performance of the amplifier by poor OSNR and nonlinearities at low and high input power, respectively, is clearly observed in the case of RZ-OOK. The higher penalty observed for 30.5 dBm pump power is due to enhanced self-phase modulation (SPM) at high path average power through the HNLF. However, the inherent resilience of RZ-DPSK to SPM, which is due to its periodic power envelope, results in lower penalty and larger high input power tolerance than for RZ-OOK. The onset of nonlinear degradation had actually not been reached with the maximum value of signal power that was available in our experiment (15 dBm).

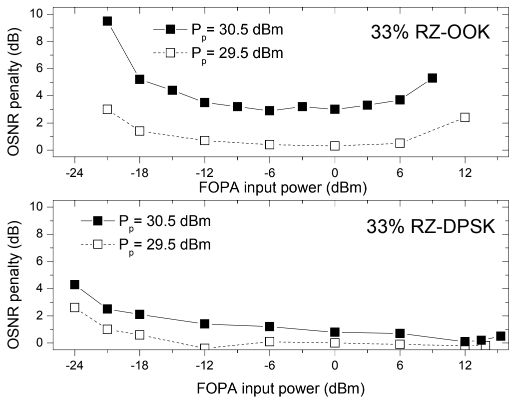

Figure 3: OSNR penalty as a function of FOPA input signal power for OOK and DPSK modulation.

This enhanced dynamic range is exploited to demonstrate amplitude regeneration of an RZ-DPSK signal. For this purpose, the signal is distorted by an extra MZM driven by a 10 GHz sinusoidal signal and input to the FOPA with 13.4 dBm average power in order to experience gain saturation. The distorted input signal is shown in Fig. 4-a). This distortion results in 3.5 dB penalty compared to a back-to-back undistorted RZ-DPSK signal and 4.1 dB penalty after propagation through the FOPA with the pump turned off. The optical waveform and the single-ended detected signal after demodulation (Fig. 4-c and b, respectively) clearly show severe intensity fluctuations. However, when the 30.5 dBm pump is turned on, those amplitude fluctuations are suppressed (Fig. 4-d, e). Accordingly, the penalty after the FOPA is reduced to 0.2 dB, clearly demonstrating its regenerative behaviour. For the same amount of intensity distortion and same pump power, even though Fig. 5 suggests that the intensity of an RZ-OOK signal can partly be equalised by FOPA saturation, the high SPM degradation prevents error-free detection of the signal.

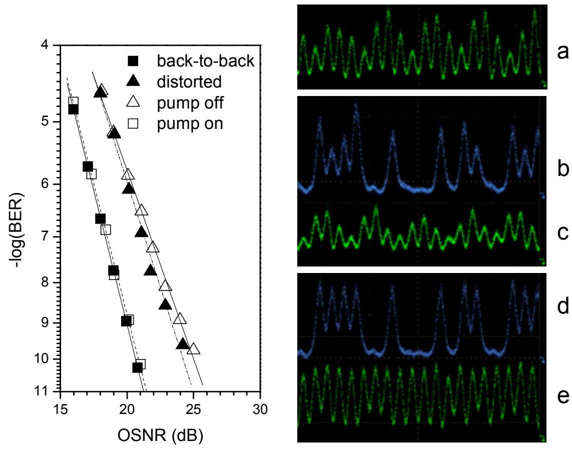

Figure 4: BER curves and patterns a): after distortion; b),c): at FOPA output with pump off; d),e): at FOPA output with pump on.

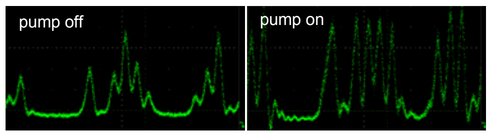

Figure 5: RZ-OOK waveforms at the FOPA output..

Conclusion

We have shown that single-pump FOPAs offer an increased input power dynamic range for RZ-DPSK modulation compared to RZ-OOK. This behaviour can be exploited to achieve intensity regeneration of RZ-DPSK signals in a FOPA with 22 dB gain, without being limited by SPM, as would be the case for RZ-OOK. The first unambiguous BER characterisation of a FOPA-based regenerator for amplitude equalisation of 40 Gbit/s RZ-DPSK signals was also presented.

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