Efficient Binary Phase Quantizer Based on Phase Sensitive Four Wave Mixing

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Abstract *We experimentally demonstrate an efficient binary phase quantizer operating at low pump powers. Phase-sensitive operation is obtained by polarization mixing the phase-locked signal/idler pair in a degenerate dual-pump vector parametric amplifier.*

Introduction

Phase insensitive and phase sensitive (PS) four-wave mixing (FWM) schemes, implemented mainly in highly nonlinear fibres (HNLFs), are often used as the basis for optical methods to process the newly emerged, spectrally efficient modulation format signals, which utilize both the phase and amplitude of the optical carrier. Single- and dual-pump configurations with the signal, idler and pump(s) being aligned either along the same polarization axis (scalar schemes) or on different polarization axes (vector schemes) and either non-degenerate or degenerate configurations (with the signal and idler being at either different or the same frequency, respectively) have been proposed[1-4]. For example, an ideal binary step-like phase response (desirable for the regeneration of binary phase shift keying, BPSK, signals) can be achieved through the coherent addition of the original signal and its first-order properly phase-locked FWM-generated complex-conjugate copy (idler) with comparable strength, usually only achieved at high pump powers[1]. This allows for large phase sensitive extinction ratio, PSER (defined as the difference between the maximum PS gain and the maximum PS de-amplification). It is desirable however, that large PSERs should be achieved at low pump powers. To this end, a careful balance between pump/signal powers, has allowed higher-order FWM components to be exploited in order to enhance the PS de-amplification and provide a large (asymmetric) PSER in a scalar configuration at nonlinear phase shifts (NPSs) as low as 0.8 rad[5]. We have recently demonstrated the principle of a technique that uses polarization mixing of a phase-locked signal-idler pair in a degenerate parametric amplifier with two orthogonally polarised pumps in order to achieve an asymmetric PSER of ~26 dB and thereby a binary step-like phase response at NPSs as low as 0.3 rad[6]. We referred to this scheme as polarization-assisted PSA. Herein, we evaluate the performance improvement achieved when this scheme is employed for the regeneration of a BPSK signal. Bit error ratio (BER) curves show an optical signal to noise ratio (OSNR) improvement of about 2 dB relative to input signals that are affected by different levels of broadband phase noise for a NPS of just 0.35 rad.

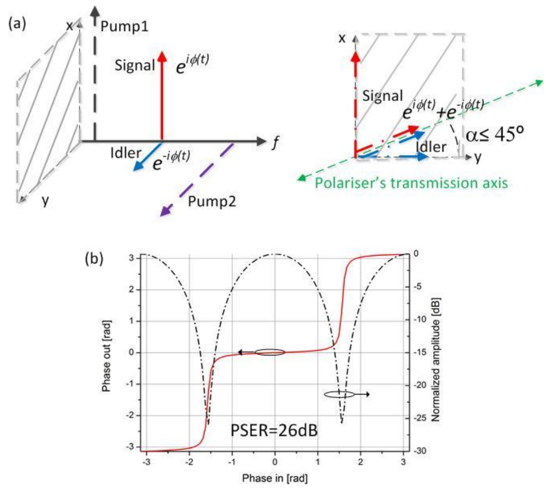

Fig. 1: Polarization-assisted PSA scheme operation principle (a) and a typical (simulated) amplitude and phase response versus input phase for a PSER of 26dB.

Operation Principle and Experimental Set-up

The operating principle of the polarization-assisted PSA scheme is sketched in Fig. 1 (a). Conventionally, in a degenerate dual-pump vector PSA, the signal is linearly polarized at 45° with respect to the two orthogonally polarized pumps, so that the generated complex conjugate copy (idler) interferes directly with the signal[7,8]. In our proposed scheme the signal is co-polarized with one of the pumps, so that the idler is generated in the orthogonal polarization axis and thus no PSA occurs on any of the two axes. However, by placing a polarizer at the output with its polarization angle properly chosen (depending on the strength of the generated idler), it is possible to exactly match the projection of the signal and idler beams along the polarizer's transmission axis even in the instance that the generated idler is significantly weaker than the signal, i.e. at low pump powers, achieving an excellent phase

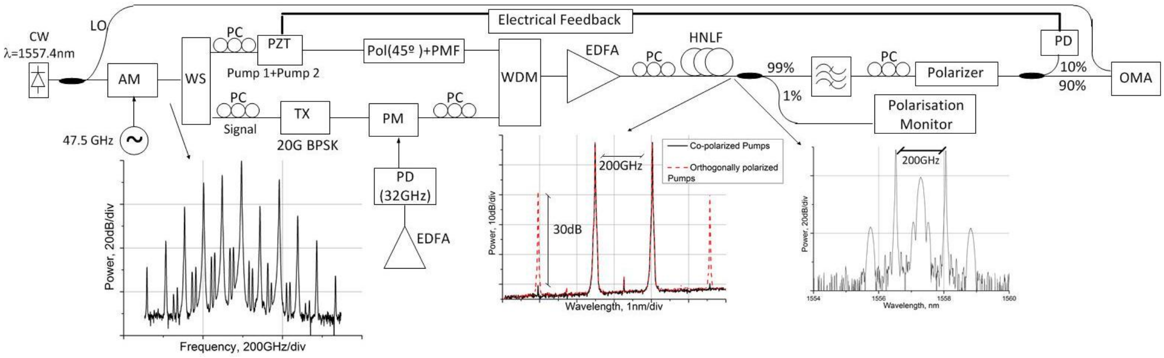

Fig. 2: Experimental set-up of the polarization-assisted PSA scheme. LO: local oscillator, TX: transmitter, PC: polarization controller, EDFA: erbium doped fibre amplifier, Inset figures: Initial optical comb spectrum, optical spectrum at the HNLF output (without the signal wave), when the two pumps are co-polarized (dashed red line) or cross-polarized (solid black line), and spectrum at the output of the HNLF when all the beams are on.

squeezing response. An example of a simulated amplitude and phase response versus input phase for a 26 dB PSER (a typical value in our experiment) is shown in Fig.1 (b) to highlight the almost ideal binary step-like phase response of the scheme. It is to be appreciated that in this regime, high PSERs only correspond to different degrees of de-amplification of the signal component (rather than its parametric amplification).

The corresponding experimental set-up is shown in Fig. 2. An overdriven amplitude modulator (AM) was used to modulate a 17 dBm, 1557.4 nm continuous wave (CW) laser to produce an optical frequency comb with ~50 GHz line spacing, see corresponding spectrum in the inset of Fig. 2. The comb was filtered and demultiplexed using a programmable filter (Finisar Waveshaper – WS) to separately select three lines of the comb to act as the phase-locked signal and pump waves. This implementation was chosen for convenience; for real-system applications, a pump-signal synchronization scheme would need to be employed instead, such as the one presented in [1]. The two pumps, spaced by ~200 GHz, were linearly polarized and aligned at 45º with respect to the primary polarisation axis of a carefully chosen short length of polarization maintaining fibre (PMF), thus ensuring that they were orthogonally polarized at the HNLF input[8]. An example of the optical spectrum at the output of the HNLF when the two pumps were co-polarized (red dashed line) or orthogonally polarized (black solid line), is shown in the inset of Fig. 2 for the same total power, when no signal was present. The FWM components generated solely by the pump interactions were reduced by 30 dB for the cross-polarized case as compared to the co-polarized one, highlighting the difference in bandwidth occupation between the corresponding scalar and vector schemes. The signal was modulated with a pseudo-random binary sequence to generate single-polarization 20 Gbaud BPSK. This was sent through a noise module to emulate the effects of phase noise. This comprised an ASE source, a broadband photo-detector (PD) and a 20 GHz RF amplifier and the resulting electrical white noise was used to drive a phase modulator through which the signal was passed. The signal was then combined with the pumps with the desired polarization and all the waves were amplified in an EDFA up to a total power of 20 dBm at the HNLF input. An example of the spectrum at the output of the HNLF is shown in the inset of Fig.2. A portion of the beams was used to monitor the relative polarization of the signal and the pumps. The signal together with the generated idler on the orthogonal polarization, were filtered out and fed into a carefully aligned polarizer to achieve PS operation. For this power setting, a PSER of 26.6 dB was measured (mainly limited by the polarization extinction of the polarization maintaining components used), while PSERs of about 2.5 dB and 5.6 dB, respectively were measured for the conventional vector PSA and scalar PSA operating at the same pump power levels (all schemes were based on dual-pump degenerate FWM). More detailed comparisons among the various PSA schemes were shown in [6]. The signal was then assessed using an optical modulation analyser (OMA). Slow thermo-acoustic relative phase drifts were suppressed by monitoring the signal power at the PSA output and controlling the PZT located in the path of the two pumps.

Experimental Results

Figure 3 shows the measured constellation diagrams for the BPSK signal at the input and output of the polarization assisted PSA for

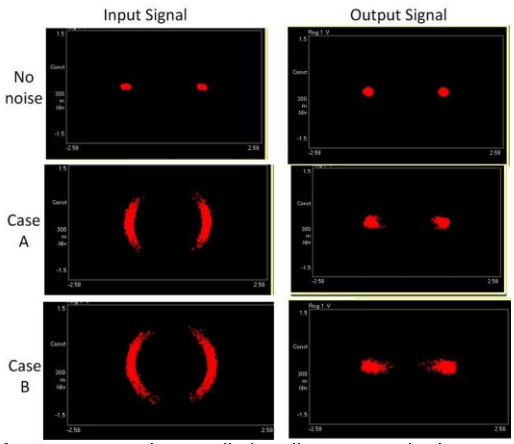

Fig. 3: Measured constellation diagrams at the input and output of the polarization assisted PSA for different amount of phase noise added.

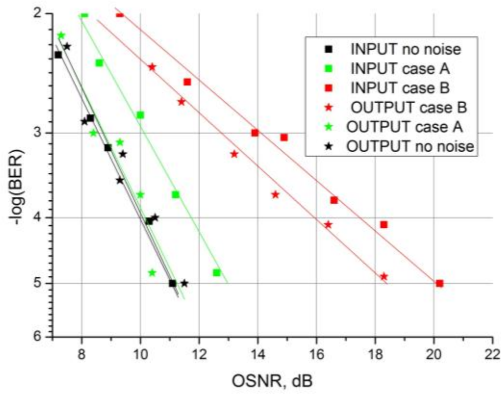

Fig. 4: Measured BER curves at the input and output of the polarization assisted PSA for different amount of phase noise added.

different amounts of emulated broadband phase noise. When no noise was induced, very similar performance was achieved with an error vector magnitude (EVM) of about 6% root mean square (rms) for both cases and phase errors of about 1º-2º rms. When phase noise was added to the input signal, phase errors of 14.4º rms (case A) and 21.3º rms (case B) were squeezed down to 3.7º rms at the PSA output, achieving an overall phase noise reduction of almost 4 and 6 times, respectively. Such impressive phase squeezing capabilities, obviously, came at the expense of phase to amplitude conversion via a cosine amplitude transfer function (Fig. 1 (b)) since the system operated far from saturation. An input magnitude error of 5-6% rms was degraded to 8% rms (Case A) and 12% rms (Case B) at the output. However, the EVMs were improved from 26% rms (Case A) and 37% rms (Case B) at the input to 10% rms and 13.5% rms, respectively at the output, showing significant overall performance improvement.

The corresponding BER curves are shown in Fig. 4 at the input (squares) and output (stars) of the polarization assisted PSA for the cases discussed above. When no noise was added to the signal, the PSA did not add any OSNR penalty as compared to the back-to-back operation (black symbols and lines). When phase noise corresponding to case A was added to the signal, an OSNR penalty of almost 2 dB was measured at a BER of 10^{-5} (green squares). However, after the PSA, a similar performance to the back-to-back was observed (green stars). When severe phase noise was added to the signal (case B, red squares), the PSA could still improve the system performance by about 2 dB as compared to its input (red stars).

Conclusions

We have demonstrated a polarisation-assisted PSA exhibiting a binary step-like phase response and allowing PSERs as high as 26.6 dB at nonlinear phase shifts as low as 0.35 rad. This scheme was used to achieve excellent phase squeezing for BPSK signals, showing ~2dB OSNR improvement compared to an input signal affected by broadband phase noise.

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References

[1] R. Slavik, et al., “All-optical phase and amplitude regenerator for next-generation telecommunications systems,” Nat. Phot., vol. 4, pp. 690–695, Oct. 2010.

[2] J. Kakande et al., “Multilevel quantization of optical phase in a novel coherent parametric mixer architecture”, Nat. Phot. 5, 748-752, (2011).

[3] Z. Tong, et al., “Towards ultrasensitive optical links enabled by low-noise phase-sensitive amplifiers”, Nat. Phot., vol. 5, pp. 430-436, 2011.

[4] T. Umeki, et al., “First demonstration of high-order QAM signal amplification in PPLN-based phase sensitive amplifier”, Opt. Exp., vol. 22 (3), pp. 2473-2482, 2014.

[5] M. Gao, T. Kurosu, T. Inoue and S. Namiki, “Efficient phase regeneration of DPSK signal by sideband-assisted dual-pump phase sensitive amplifier”, Electron. Lett., 39 (2), 140-141 (2013).

[6] F. Parmigiani, et al. “Novel Polarization-assisted Phase Sensitive Optical Signal Processor Requiring Low Nonlinear Phase Shifts”, STu2I.4 CLEO US 2014.

[7] C. J. McKinstrie and S. Radic, “Phase-sensitive amplification in a fiber”, Opt. Exp. 12, 4973-4979 (2004).

[8] A. L. Riesgo et al., “Demonstration of Degenerate Vector Phase-Sensitive Amplification”, We.3.A.3, ECOC 2013.