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A Novel Phase-Locking-Free Phase Sensitive Amplifier based Regenerator

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Abstract: We propose and demonstrate a novel PSK regenerator based on phase sensitive amplification without active phase-locking. The scheme is applied to regenerate a phase noise degraded 10-Gbit/s DPSK signal, improving receiver sensitivity by 3.5 dB.
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1. Introduction

Optical communication systems are migrating towards modulation formats that utilize both the phase and amplitude of the optical carrier, such as binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK) signals. In recent years, phase sensitive amplifiers (PSAs) have emerged as the most promising all-optical way to regenerate such signals, and regeneration has been demonstrated for BPSK [1,2] and QPSK [3,4]. When realizing such systems, the main challenge lies in keeping the pump(s) and the data signal carrier in phase at the PSA input. So far, this has mainly been achieved using active phase stabilization, such as electronic feedback loops or injection locked lasers.

We propose a novel scheme for PSA based regeneration without any electronic phase stabilization. The system is demonstrated in a DPSK regenerator with passive phase stabilization.

2. Concept

The main idea of the proposed scheme is to locally generate a suitable set of phase-locked carriers, and transfer the phase modulation of an incoming data signal to one of those carriers, without disturbing the phase relationship between the pumps and the data signal carrier. The method used is illustrated in Fig. 1: An optical comb consisting of three phase-locked carriers are used as pumps and signal in a PSA. The incoming PSK signal is passed through a delay interferometer (DI) and converted to an amplitude modulated signal. Cross-phase modulation (XPM) in a highly nonlinear fiber (HNLF) is employed to transfer the data modulation from the amplitude modulated signal to the phase of the central of the phase locked carriers. This is achieved by constructing a fiber loop where the two outer carriers, to be used as PSA pumps, propagate in one direction and the central carrier and the amplitude modulated signal travel in the opposite direction. The three locally generated carriers, one now containing the phase modulated data, are then sent to a second HNLF, where phase sensitive amplification regenerates the data modulated on the central carrier.

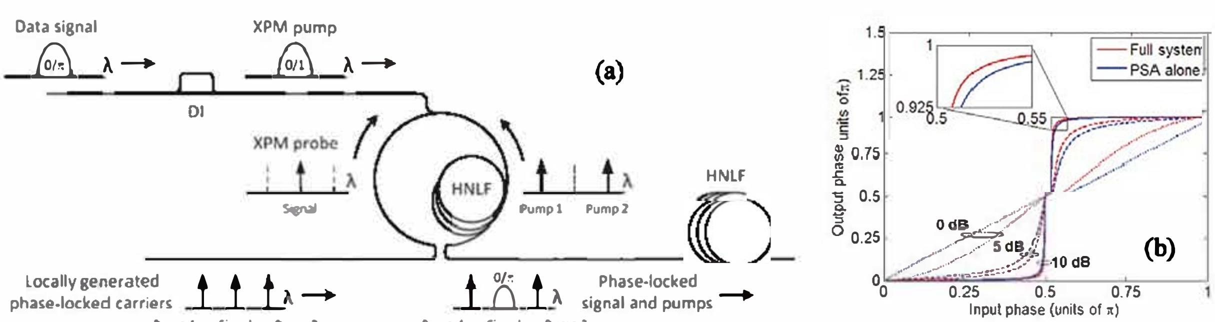

Fig. 1. (a) General scheme for passive phase stabilization. (b) Transfer function for the data modulation in the ideal system compared to that of an ideal PSA, for PSERs of 0 dB (dotted), 5 dB (dashed) and 10 dB (solid). ($g = 1$, 3.16 and 10 respectively.)

The data thus undergoes three processing steps. The DI converts phase modulation (φ) to modulation of output power (P) according to $P_{DI} = P_{in}\cos^2\frac{1}{2}(\varphi_1 - \varphi_2)$, XPM converts modulation of the signal power to phase modulation of the central carrier as: $\varphi_{XPM} = 2\gamma P_{DI}L$, and Finally the PSA regenerates the phase modulation of the central carrier by the transfer function $\tan\varphi_{PSA} = g^{-2}\tan\varphi_{XPM}$ [5,6]. φ_1 and φ_2 are the phases of two bits interfering in the DI, P_{in} is the input power of the incoming data signal, γ and L are the non-linearity coefficient and length of the HNLF used for XPM, and g is the gain of the PSA. Fig. 1 (b) shows the resulting transfer function for the data modulation in the ideal system compared to that of using only a PSA, for three different phase sensitive extinction ratios (PSERs) – defined as the ratio between the maximum and minimum phase sensitive gain. In the case of PSER = 0 dB ($g = 1$) the PSA is not regenerating, and the transfer function of the PSA alone (blue) is a straight line. However, the transfer function of the full system (red) shows signs of regeneration, due to the transfer function of the DI. For the two higher values of PSER the transfer function of the full system converges to an ideal staircase slightly faster than that of the PSA alone but is strongly dominated by the properties of the PSA for PSERs above ~10 dB.

3. Experimental setup

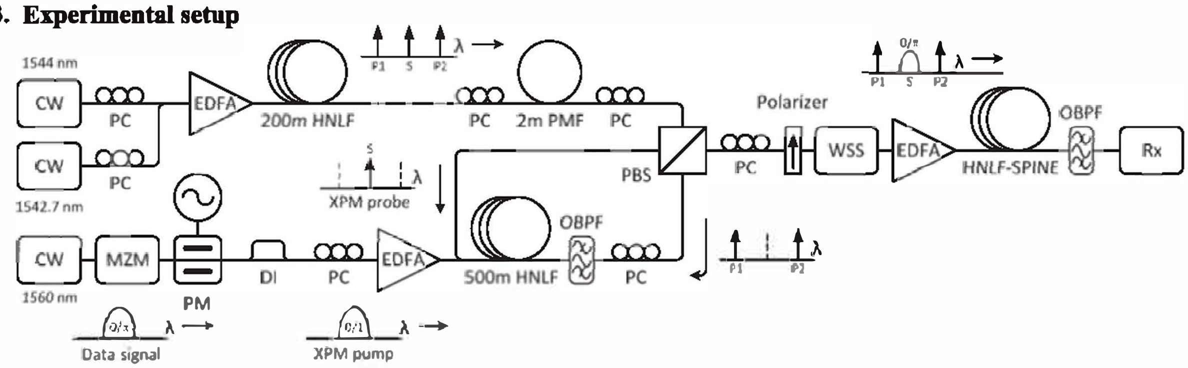

Fig. 2. The experimental setup for the phase-locking-free dual-pump degenerate PSA based regenerator.

The regenerator is demonstrated experimentally for a dual-pump degenerate PSA, as illustrated in Fig. 2, but is not limited to this specific type of PSA in general. Three phase-locked carriers are generated using four wave mixing (FWM), by injecting two continuous wave (CW) signals at 1544 nm (S) and 1542.7 nm (P1) from narrow linewidth (<100 kHz) external cavity lasers into a 200 m HNLF, to yield an idler at 1545.3 nm (P2). The phase of the generated idler obeys $\varphi_{Pump1} + \varphi_{Pump1} - 2\varphi_{Signal} = 0$ [5], which guarantees a stable phase relation. The three co-polarized carriers were aligned at 45° with respect to the primary polarization axis of a polarization maintaining fiber (PMF). The total birefringence of the PMF was matched to the spacing of the three carrier waves, resulting in a 90° rotation of the polarization of S relative to P1 and P2. Using a polarizing beam splitter (PBS) the carrier waves S and P1, P2 are sent in opposite directions inside a loop containing 500 m of HNLF.

An NRZ DPSK data signal is generated by modulating a CW at 1560 nm (linewidth <100 kHz) with a 10-Gbit/s pseudo-random bit sequence (PRBS) of length $2^{31} - 1$ using a standard Mach-Zender modulator (MZM). Phase noise was emulated by adding sinusoidal phase modulation to the DPSK signal using a phase modulator (PM) driven by a single RF tone generated from an unsynchronized RF source. To generate a pump for the XPM process, the phase modulated data signal is converted to an amplitude modulated signal in a 1 bit (100 ps) fiber DI and amplified using an erbium doped fiber amplifier (EDFA). The XPM pump is coupled into the loop in the same direction as S, and by carefully adjusting the XPM pump power, the phase of S is encoded with either 0 or π. The counter-propagating pumps encounter several thousand bits in the 500 m HNLF, and experience only a constant phase offset. After the HNLF, the XPM pump is removed using a 5 nm optical band pass filter (OBPF) centered at 1544 nm, and using a polarization controller (PC) the two pumps P1, P2 and the now DPSK modulated signal S are aligned to exit the loop by the remaining port of the PBS. At this point, S is still orthogonally polarized to P1 and P2, and a polarizer is used to project them onto the same plane of polarization, causing a 3-dB loss in power for all waves.

An optical processor (Finisar Waveshaper – WSS) is used to equalize the pumps, remove out of band noise and adjust the power and phase of S relative to the pumps P1 and P2, in order to optimize the PSA performance. The signal S and pumps P1, P2 are then launched into a 250 m HNLF with stable phase-matching for improved nonlinear efficiency (HNLF-SPINE). After phase-sensitive amplification in the HNLF-SPINE, P1 and P2 are removed using a tunable flat-top OBPF, and the output is sent to a pre-amplified DPSK receiver (Rx), using a 1 bit fiber DI followed by a balanced photodiode and an electrical low-pass filter with a bandwidth of 7.5 GHz, for bit-error-ratio (BER) testing.

4. Experimental results

At the output of the HNLF-SPINE, the signal and pump powers are measured using an optical spectrum analyzer as the phase of the data modulated signal S is swept relative to the phases of the pumps P1, P2 using the optical processor. Due to the inherent phase stability of this scheme, it is possible to characterize the phase-sensitive gain of the PSA under dynamic conditions, i.e. with a DPSK modulated data signal, as seen in Fig. 3(c). In order to increase the ONSR of the signal, the PSA is operated in mild saturation, as can be seen by the power fluctuation of the pumps. A total input power of 28.8 dBm and a pump to signal power ratio of 10 dB results in a PSER of 12 dB.

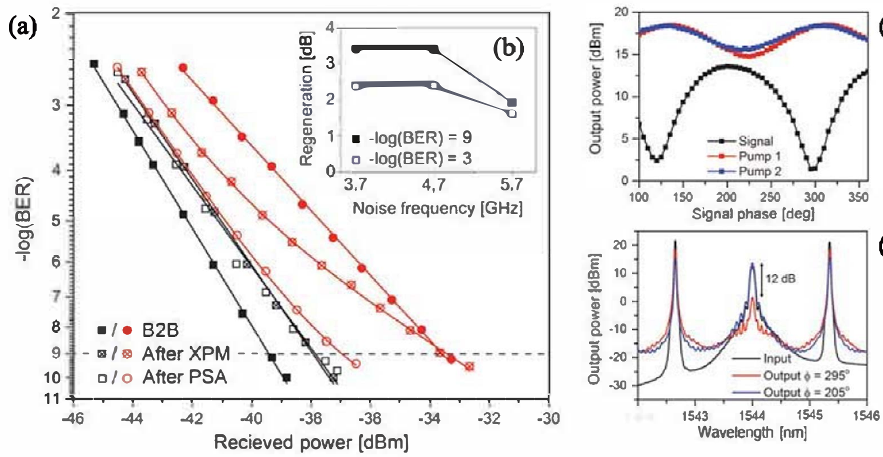

Fig. 3. (a) BER as a function of received power B2B (solid), after XPM (crossed) and after PSA (hollow), with (red) and without (black) 4.7 GHz phase noise. (b) Improvement in receiver sensitivity as a function of noise frequency at BER = 10^{-3} and BER = 10^{-9}. (c) Phase sensitive gain of the signal and pumps as a function of signal phase with 10 Gbit/s data modulation and no noise added. (d) Spectra at the input and output of the HNLF-SPINE for maximum and minimum output signal power (no noise added).

Comparison between the input spectrum and output spectra for maximum amplification (ϕ = 205°) and de-amplification (ϕ = 295°) are reported in Fig. 3(d), clearly showing the 12 dB difference between the signal power levels. Saturation can be reduced by reducing the signal power, at the cost of signal OSNR, and a static characterization of the PSA shows a PSER of 24.8 dB for a pump to (unmodulated) signal power ratio of 25.0 dB.

Phase noise is added as described above, and the modulation index and the frequency of the noise tone are varied to investigate the performance of the regenerator under different operating conditions. The BER of the signal is measured back-to-back (B2B), as well as before and after the PSA (labelled After XPM and After PSA, respectively), for no degradation as well as for noise tone frequencies of 3.7 GHz, 4.7 GHz and 5.7 GHz. For the reported measurements, the modulation index of the phase noise is fixed at 0.37. The resulting BER curves are shown in Fig. 3(a) for a noise frequency of 4.7 GHz. In the absence of added noise, the process of transferring the phase modulation of the data signal to the central of the three phase locked carriers (by DI and XPM) results in a power penalty of around 1.5 dB compared to the B2B reference, while the added penalty of the PSA is insignificant (<0.1 dB). When phase noise is added to the signal, the regeneration abilities of the DI is confirmed to be significant at low receiver power levels, but diminishing at a BER = 10^{-9}. After the PSA however, the output shows improved receiver sensitivity of 3.5 dB at BER = 10^{-9}, decreasing the power penalty to within 1 dB of the curve measured without added phase noise.

Similar trends are seen for noise tone frequencies of 3.7 GHz, 5.7 GHz, and the improvement in receiver sensitivity is shown as a function of noise tone frequency at BER = 10^{-3} and BER = 10^{-9} in Fig. 3(b). A reduced degree of regeneration can be seen for a noise tone frequency of 5.7 GHz; however, this is due to a lower B2B penalty caused by the electrical low-pass filter at the receiver, which partially compensates for the degradation caused by adding phase noise at this frequency.

5. Conclusion

We have proposed and demonstrated a novel PSK regenerator based on a phase sensitive amplifier not requiring active phase-locking. The performance has been investigated for a 10-Gbit/s DPSK signal under various phase-noise loading conditions, and an improvement in receiver sensitivity of 3.5 dB was observed at a bit-error-rate of 10^{-9}.

6. Acknowledgements

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