A NOVEL DEVICE TO ENHANCE THE OSNR BASED ON LOSSLESS POLARIZATION ATTRACTION

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We introduce a novel all-optical "noise cleaning" device, based on lossless polarization attraction, that provides an OSNR gain close to the theoretical 3dB limit. In addition, we demonstrate the robustness of polarization attraction against additive noise.

1. Introduction

Lossless polarization attraction (LPA) is a nonlinear phenomenon, based on the Kerr effect, that allows an all-optical control of the state of polarization (SOP) of a telecom signal, by the injection of a controlling continuous-wave (CW) pump laser [1]. Based on this phenomenon, a *nonlinear lossless polarizer* (NLP) can repolarize originally polarized signals whose degree of polarizatio (DOP) has degraded [2]. One of the most interesting applications of LPA has been recently proposed in [3], where the authors provide an all-optical nonlinear processing and regeneration of a 40Gb/s telecom signal. However, besides repolarization, few other applications of LPA have been proposed so far.

We propose here to employ a NLP to enhance the optical signal-to-noise ratio (OSNR) of a polarized optical signal. When a polarized signal is affected by unpolarized additive white Gaussian noise (AWGN), such as the amplified spontaneous emission (ASE) noise, one can get rid of the orthogonally polarized noise component, by filtering through an ideal polarizer aligned with the signal SOP. In general, the (time-varying) signal SOP is unknown, hence the alignment is difficult to accomplish. Thus, we aim at attracting the signal polarization towards the eigenstate of the ideal polarizer, by using a NLP. Our first task is to verify if LPA is still effective, in the presence of unpolarized AWGN. Then, we shall quantify the performance of the proposed noise cleaning device, through the traditional notion of noise figure F, equal to the ratio between input and output OSNR.

2. Polarization attracting noise cleaner setup

Fig. 1 shows the schematic diagram of the proposed all-optical device. The first section consists of a NLP (inner box), here designed in a counter-propagating configuration [1,3,4,5], although recent results have shown that a co-propagating configuration is more suitable to higher bit-rates and easier to optimize [2]. The NLP includes a dispersion-shifted fiber (DSF), with zero chromatic dispersion, at the input signal wavelength, attenuation α=0.2 dB/km, Kerr coefficient γ=1.99 $W^{-1}km^{-1}$, and a (fully-polarized) CW pump laser, with power P_p=2.4 W. The fiber is L=10 km long and is randomly birefringent, with a PMD coefficient D_{PMD}=0.05 ps/km$^{0.5}$, so that propagation is governed by the Manakov equation, hence polarization attraction can occur towards any pump SOP [2]. The input signal is represented by the (lowpass equivalent) Jones vector $E_{tx}(t)=A_{tx}(t)+W(t)$, where the noiseless input $A_{tx}(t)$, with power P_s, is a fully polarized telecom signal and W(t) is unpolarized AWGN, with power P_W (measured on a reference bandwidth B_0) so that, at the input, $OSNR_{in}=P_s / P_W$. Following the NLP, the "SPM Comp." block compensates for the self phase modulation (SPM) induced by the Kerr nonlinearity in the NLP, as further discussed in Sec.4.

The ideal polarizer, at the output of the device, must be aligned with the injected pump SOP (as remarked by a dashed line). Its task is to suppress the output polarization component not attracted by (hence orthogonal to) the pump SOP. When the NLP is perfectly effective, a noiseless polarized input signal $A_{tx}(t)$ would be attracted towards the pump SOP and pass through the polarizer without any loss. On the contrary, pure AWGN would not be attracted, since the SOP of unpolarized W(t) fluctuates on a too short time scale, compared with the

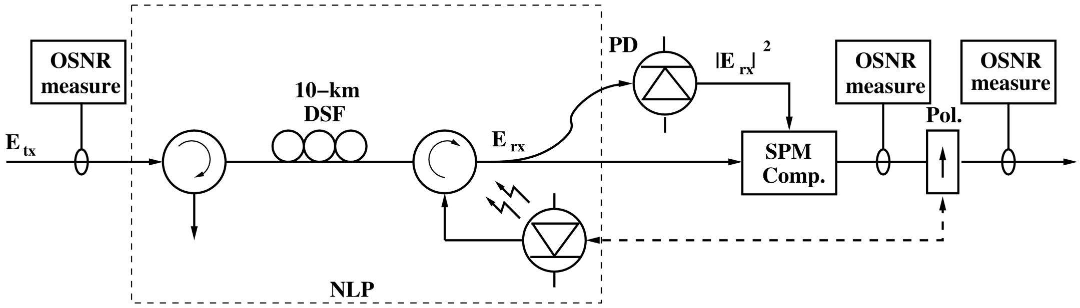


Fig. 1 Schematic setup of the all-optical noise cleaner, based on a nonlinear lossless polarizer (NLP, inner box). The ideal polarizer (Pol.) is aligned with the pump polarization.

transient time of LPA [1]. Hence, the output noise would remain unpolarized and only half of its power would pass through the polarizer. We are then tempted to conclude that the OSNR is increased by 3 dB, after the polarizer. This is however the application of linear reasoning to a nonlinear device, where the superposition of effects does not hold. Hence, we must first verify the effectiveness of polarization attraction in the presence of noise.

3. Polarization attraction of a noisy signal

Several studies have characterized the performance of NLPs as a function of system parameters [1,2,4,5], but few of them account for the presence of noise in the attracting pump [2] or in the attracted signal [3]. Unpolarized noise degrades the input signal DOP, hence can spoil the time-coherece of mutual pump and signal polarizations, which is a necessary prerequisite of LPA [1]. We quantify the performance of the NLP in Fig. 1 through the *degree of attraction* (DOA) [4], a normalized measure of LPA effectiveness. As shown in [4], DOA is the product between the output signal DOP and the mean SOP attraction (MSA), which is the projection of the time-averaged signal SOP onto the pump SOP [4]. For this test, we chose the input signal and pump polarizations as right-circular and linear-horizontal (so that DOA=0, at the NLP input), although results can be generalized to other SOPs [4].
Fig. 2 shows the DOA and its factors, as a function of the input OSNR. The noiseless input $A_{tx}(t)$ consists of a single intensity-modulated pulse, with duration T_S=1 μs and power P_s=600 mW. As numerically verified in [4], the single pulse is representative of an intensity-modulated bit packet, i.e., the same DOA is reached, for equal transmitted mean power. With the chosen signal and pump power, a significant degree of attraction (DOA≅0.8) is reached for the reference case of a noiseless input signal [4], reported in Fig. 2 with dashed lines. Here, $OSNR_{in}$ is measured on an optical bandwidth B_0=512 MHz, able to include the whole pulse spectrum (OSNR values are 13.88 dB lower, if measured on a bandwidth $\Delta\lambda$=0.1 nm, typical of Gigabit networks). Keeping the signal power fixed, we varied $OSNR_{in}$ between 5 and 30 dB, by varying the input AWGN power. Finally, for each $OSNR_{in}$, simulation results were averaged over 10 random noise realizations. Counter-propagation, within the NLP, is numerically solved through the SCAOS algorithm [5].
As seen in Fig. 2, the DOA of the noiseless case (dashed) is practically achieved for $OSNR_{in}$>15 dB. For lower values of $OSNR_{in}$, we recognize, by analyzing the DOA factors in Fig. 2(center, right), that the DOA decrease does not depend on the average signal attraction, which is not impaired by noise, since the MSA always coincides with the reference noiseless case. The lower DOA values are thus to be attributed to DOP degradation and, in particular, to the degradation of the input signal DOP, which is also reported in Fig. 2(center), for comparison. Its degradation (red curve) is an obvious consequence of the addition of unpolarized noise at the input, and is imprinted onto the output DOP (black line). Since no extra DOP degradation can be observed, we conclude that, at the OSNR values of our interest, the AWGN does not spoil the transient polarization attraction [1], hence noise does not significantly affect the effectiveness of LPA.

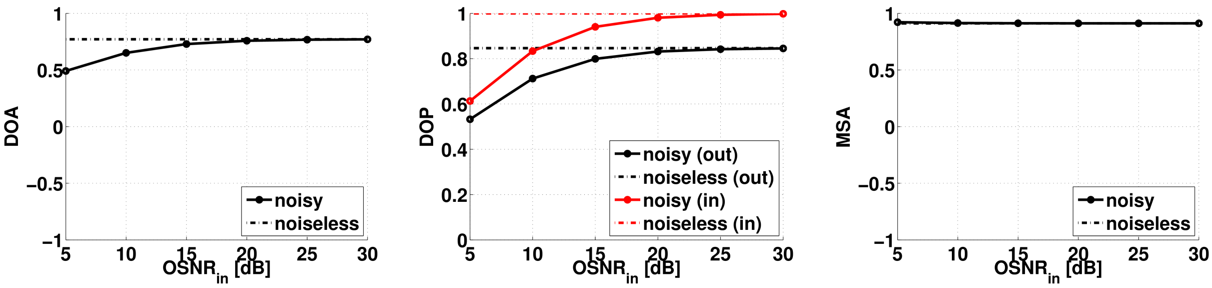


Fig. 2 LPA performance, for a noisy input pulse, quantified by the degree of attraction and its factors (dahsed: noiseless input). System parameters as in text.

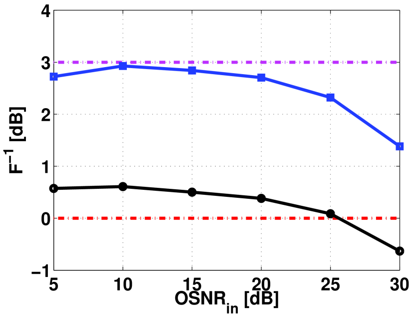
4. OSNR enhancement

We wish to evaluate the OSNR gain obtained by filtering away the signal component orthogonal to the pump SOP, through the ideal polarizer (Pol.) in Fig. 1. In order to measure the output OSNR, we must detect the useful signal $A_{rx}(t)$, from the received field $E_{rx}(t)=A_{rx}(t)+N(t)$, affected by the output noise $N(t)$. Since, as we verified, $N(t)$ is still with zero mean, the total average output power, $P_t=<||E_{rx}(t)||^2>=P_{rx}+P_N$, is equal to the sum of the average signal power, $P_{rx}=<||A_{rx}(t)||^2>$, and that of noise, $P_N=<||N(t)||^2>$. Hence, the output OSNR can be evaluated as $OSNR_{out}=P_{rx}/P_N=(P_t/P_{rx}-1)^{-1}$. While P_t can be easily measured, P_{rx} has to be evaluated after estimating $A_{rx}(t)$ from the noisy $E_{rx}(t)$. This is a delicate task, since, during nonlinear propagation in the NLP, the considerable signal and pump power (demanded by LPA) induces large (scalar) phase rotations on the optical field. In particular, being the pump CW, cross-phase modulation (XPM) only induces constant phase rotations, while SPM induces large phase swings, so that both (complex) components of $A_{rx}(t)$ typically average to zero, hence cannot be recovered by optical filtering. However, when signal propagates in the absence of chromatic dispersion, as in our case, it is possible to compensate SPM in the optical domain, e.g., through a phase modulator [6]. This task is accomplished, in Fig. 1, by the subsystem “SPM Comp.”, driven by the received field intensity. After removing SPM, we estimate $A_{rx}(t)$ by optical filtering and evaluate its mean power P_{rx}, hence $OSNR_{out}$.

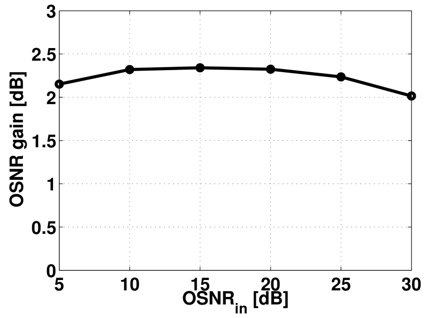
Fig. 3(a) shows the inverse of the noise figure, $F^{-1}=OSNR_{out}/OSNR_{in}$, as a function of $OSNR_{in}$. The (black) line with circles and that with squares (blue), report the values obtained by measuring $OSNR_{out}$, as described above, before or after applying the ideal polarizer, respectively, as evidenced in Fig. 1 by the blocks labelled “OSNR measure”. The dashed (magenta) line, at 3 dB, represents an upper limit to the performance of the device, while the dashed (red) line, at 0 dB, represents the theoretical reference value that we should measure before the polarizer. In fact, being LPA based on the Kerr effect, it does not entail any exchange of energy between signal and noise. Hence, the OSNR at the NLP output is the same as that at the input, and its corresponding noise figure is F=0 dB.

The reason for the mismatch between measured and theoretical (null) values of F^{-1}, in Fig. 3(a), lies in the optical filter used to extract $A_{rx}(t)$ from noise. In fact, as it typically occurs in telecommunications, the optical filter bandwidth B_N is the result of a trade-off between the goal of rejecting as much noise as possible and that of letting the noiseless signal pass undistorted: both objectives are only partially accomplished. In particular, at low $OSNR_{in}$, the filter captures a considerable amount of the (large) noise, within its passband, hence P_{rx} is overestimated, and so is $OSNR_{out}$. On the contrary, at high $OSNR_{in}$ values, noise is negligible, but the filter rejects part of the signal spectrum, so that P_{rx} is underestimated. Given the functional relationship between P_{rx} and $OSNR_{out}$ (singular value, for $P_{rx}\rightarrow P_t$), an even larger underestimation is produced for $OSNR_{out}$. We used a practical moving-average filter, with a (one-side) noise-equivalent bandwidth B_N=56.89 MHz, found by minimizing the (root mean square) deviation between the measured values (black-circles) and their null theoretical reference (red), in Fig. 3(a).

When measuring $OSNR_{out}$ after the polarizer, the same measurement artifacts occur, as described above, and produce similar mismatches on the corresponding curve (blue-



(a)



(b)

Fig. 3 (a) Inverse Noise Figure, F^{-1}, measured before (black-circles) and after (blue-squares) the polarizer in Fig. 1 (dashed lines: theoretical references); (b) OSNR gain thus obtained.

squares) in Fig. 3(a). Postulating that the mismatches for the two $OSNR_{out}$ measurements are the same, we can evaluate the OSNR gain, obtained by applying the ideal polarizer, from the difference (in log scale) between the two measured curves in Fig. 3(a). Such an OSNR gain is shown in Fig. 3(b) and varies between 2 and 2.5 dB, for all of the tested $OSNR_{in}$ values. Larger values, closer to the theoretical 3 dB limit, could be obtained by optimizing the NLP configuration. In fact, for our choice of parameters, only 88% of the total signal energy is attracted towards the pump SOP, in the case of a noiseless signal. The remaining fraction of signal energy (12%) is output orthogonal to the pump SOP and is then suppressed by the polarizer, along with the orthogonally polarized half of N(t). These figures are consistent with the results above ($10Log_{10}(0.88/0.5)= 2.5$ dB), further validating our measurement technique.

5. Conclusion

We demonstrate a novel, all-optical, *noise-cleaning* device that can ideally double the OSNR. The device applies to polarized, intensity modulated signals, that typically propagate in “legacy” links and still carry more than half of nowadays telecom traffic. The nonlinear lossless polarizer, lying at the heart of the device, can be designed in a co- or counter-propagating configuration, and its performance can be optimized [2], so that a corresponding increased performance is reached in the noise-cleaner. Being this work a proof-of-concept, we made simple and practical choices for the optical subsystems needed to detect the received signal and to estimate its OSNR. Despite these suboptimal choices, results show that the achieved OSNR gain is close to the theoretical 3 dB limit.

Bibliography

[1] V. V. Kozlov, J. Fatome, P. Morin, S. Pitois, G. Millot, and S. Wabnitz, “Nonlinear repolarization dynamics in optical fibers: transient polarization attraction”, *J. Opt. Soc. Am. B (JOSA-B)*, Vol. 28, N. 8, 2011, pp. 1782–1791.

[2] V. V. Kozlov, M. Barozzi, A. Vannucci, and S. Wabnitz, “Lossless polarization attraction of copropagating beams in telecom fibers”, *J. Opt. Soc. Am. B (JOSA-B)*, Vol. 30, N. 2, february 2013.

[3] P. Morin, J. Fatome, C. Finot, S. Pitois, R. Claveau, and G. Millot, “All-optical nonlinear processing of both polarization state and intensity profile for 40 Gbit / s regeneration applications”, *OSA Opt. Express*, Vol. 19, N. 18, 2011, pp. 17158–17166.

[4] M. Barozzi and A. Vannucci, “Performance analysis of lossless polarization attractors,” in Latin America Optics and Photonics Conference, OSA Technical Digest (online) (Optical Society of America, 2012), LM3C.4.

[5] M. Barozzi, A. Vannucci, and D. Sperti, “Lossless polarization attraction simulation with a novel and simple counterpropagation algorithm for optical signals”, *J. Europ. Opt. Soc. : Rap. Pub. (JEOS-RP)*, Vol. 7, 2012, pp. 12042.1-6.

[6] C. Xu, L. Mollenauer, and X. Liu, “Compensation of nonlinear self-phase modulation with phase modulators”, *IET Electron. Lett.*, Vol. 38, N. 24, 2002, pp. 1578-1579.