All-Optical Noise Cleaning Based on Co-Propagating Lossless Polarization Attraction

Matteo Barozzi and Armando Vannucci
Dipartimento di Ingegneria dell'Informazione
Università degli Studi di Parma,
viale delle Scienze 181/A, 43124 Parma, Italy.
matteo.barozzi82@gmail.com

***Abstract*—We exploit a recently proposed nonlinear lossless polarizer to suppress the noise component that is (bitwise) orthogonal to an optical signal. It is shown how the proposed technique yields an optical signal-to-noise ratio (OSNR) gain close to 3dB and how this gain can be theoretically predicted, for different input OSNR values, from the degree of polarization (DOP) of the repolarized output signal.**

***Keywords*—Kerr effect; cross-polarization modulation; polarization attraction; nonlinear lossless polarizer;**

I. Introduction

Lossless polarization attraction (LPA) is a nonlinear two-channel phenomenon, based on the Kerr effect, that occurs between a (possibly depolarized) signal and a fully polarized continuous wave (CW) pump. The state of polarization (SOP) of the signal is attracted towards that of the pump without any loss of energy [1-8]. In its first experimental demonstration [1], signal and pump, both with large power, counter-propagate in a short isotropic optical fiber. Since then, the same phenomenon has been observed and characterized in various conditions, including signal and pump with moderate power [2], in long birefringent telecom fibers [3], and in the co-propagating configuration [4].

The original counter-propagating configuration of LPA requires long (milliseconds) transient times [5] and is difficult to simulate numerically [6]. Instead, when pump and signal co-propagate, the transient times of LPA are shorter and depend on the relative propagation speed, i.e., on the pump-signal walk-off [4]. LPA is indeed the joint product of Kerr-induced nonlinear polarization rotation and a balanced amount of walk-off, whose impact, for given power levels, depends on the symbol period [7].

A recently proposed application of LPA is the enhancement of the optical signal-to-noise ratio (OSNR) of a fully polarized signal affected by unpolarized noise [8]. Its basic concept is to employ LPA to align the unknown signal SOP with the transparent SOP of a polarizing filter, whose task is to suppress the orthogonally polarized half of noise power. Based on LPA in the counter-propagating configuration [8], such a noise-cleaner is effective only for signals whose polarization coherence time is at least of the order of microseconds, hence for large, fully-polarized, bit-packets.

We wish here to apply the same principle of operation to signals whose polarization coherence time is of the order of the bit period (i.e., to "bitwise polarized" signals), hence excluding polarization multiplexing. Consistently, we shall refer to signals with a "legacy" binary amplitude modulation format, i.e., on-off keying (OOK). Moreover, we wish to exploit the efficiency of co-propagating LPA [4] to significantly reduce the required pump and signal power.

II. System setup and simulation parameters

Fig. 1 shows the system setup that we numerically simulated. The input signal is represented by the lowpass-equivalent Jones vector $\mathbf{E}_{tx}(t)=\mathbf{A}_{tx}(t)+\mathbf{W}(t)$, where $\mathbf{W}(t)$ is unpolarized additive white Gaussian noise (e.g., modeling amplified spontaneous emission). The noiseless signal $\mathbf{A}_{tx}(t)$ was intensity-modulated, at 10Gb/s, with a fixed mean power P_S, while noise power P_W was varied, so as to test different values of $OSNR_{in}=P_S/P_W$, measured at the input (Fig. 1). For the $OSNR_{in}$ values tested here (larger than 10 dB), the amount of nonlinear distortion is effectively dictated by signal power, and not by noise power. To simulate "bitwise polarized" signals, for every tested $OSNR_{in}$ value, we transmitted 2560 bits with a random polarization of the associated OOK pulse, uniformly distributed on the Poincaré sphere, so that the degree of polarization (DOP) of $\mathbf{A}_{tx}(t)$ is zero.

The dashed box labeled NLP delimits a "nonlinear lossless polarizer" in the co-propagating configuration [4]. This is made of a (fully polarized) CW pump laser, with power P_p, coupled with the signal and propagating in a nonlinear dispersion shifted fiber (DSF), with length L=20 km, scattering loss α=0.2 dB/km and Kerr coefficient γ=1.99 $W^{-1}km^{-1}$. The fiber polarization mode dispersion (PMD) coefficient, D_{PMD}=0.05 ps/km$^{0.5}$, is sufficiently small to guarantee that propagation is accurately modeled by the Manakov equation, so that LPA occurs towards any pump SOP [4]. The signal was placed at the fiber zero-dispersion wavelength λ_{zdw} while the pump wavelength $\lambda_p=\lambda_{zdw}+\Delta\lambda$ was selected so that chromatic dispersion induces a walk-off delay $T_D=D(\lambda_p)|\Delta\lambda|L$.

A possible solution to optimize the placement of the pump wavelength [7] is to choose a return-to-zero (RZ-OOK) modulation [3] with duty-cycle 33%, so that each bit is encoded on a pulse with duration T_S=33.3 ps. Setting the signal peak power at 200 mW (hence the mean power at P_S=33.3 mW) and the pump power at P_p=400 mW, an optimal $\Delta\lambda$=3.2 nm was found [7]. This value yields a walk-off T_D=64 ps, where $D(\lambda_p)$=1 ps/nm/km. Moreover, T_S+T_D is less than the bit-period (100 ps), which guarantees the absence of nonlinear pulse-to-pulse interactions mediated by the pump [4]. The

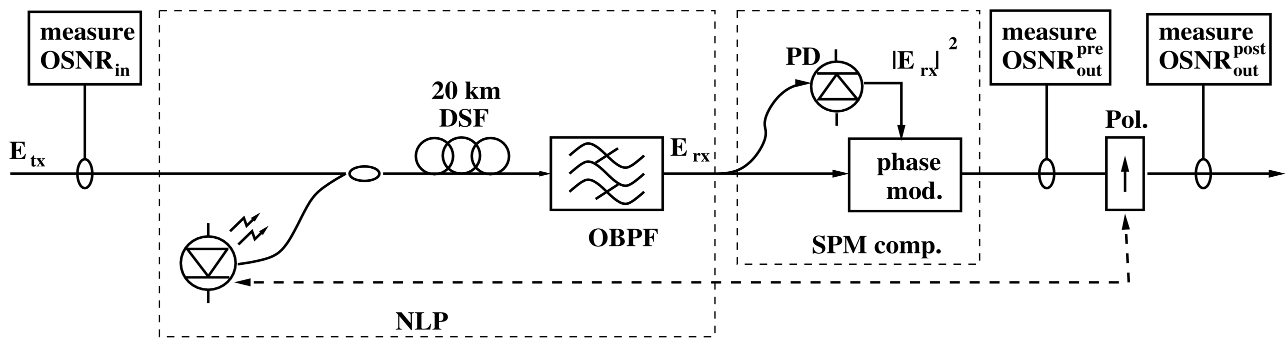

Fig. 1. Schematic setup of an all-optical noise cleaner. The nonlinear lossless polarizer (NLP) attracts the noisy signal towards the pump SOP; SPM compensation (SPM comp.) follows and, finally, an ideal polarizer (Pol.), aligned with the pump, removes the orthogonally polarized noise.

optical bandpass filter in Fig. 1 (OBPF) suppresses the pump and isolates the output signal $\mathbf{E}_{rx}(t)=\mathbf{A}_{rx}(t)+\mathbf{N}(t)$, where noise $\mathbf{N}(t)$ is no longer white.

As further discussed in the next section, colored noise makes the measurement of the output OSNR sensitive to the bandwidth of the signal spectrum, which is broadened, during nonlinear propagation, by all the known Kerr distortions. While cross-polarization modulation (XpolM) is the driving force of LPA, self- and cross-phase modulation (SPM, XPM) are irrelevant for LPA and it would be desirable to remove them. The purpose of the "SPM Comp." subsystem, in Fig. 1, is to equalize the distortions due to SPM. This task, that is normally unfeasible in the analog domain, can be accomplished here, since chromatic dispersion is absent, by a properly tuned phase modulator, driven by the photodetected (PD) intensity [9]. Lastly, we numerically verified that degenerate four-wave mixing (FWM) is negligible, for the parameter values used here.

The output OSNR was measured, as in Fig. 1, before ($OSNR_{out\text{-}pre}$) and after ($OSNR_{out\text{-}post}$) an ideal polarizing filter (Pol.). As remarked by the dashed line in Fig. 1, the transparent eigenstate of this polarizer must be aligned with the pump SOP, so that only the attracted portion of signal (and noise) passes through and contributes to the measurement of $OSNR_{out\text{-}post}$.

III. OSNR measurement and noise-cleaning

By varying $OSNR_{in}$, we evaluated the two output OSNR values. Consistently with the classic definition of noise figure F, we then calculated $F^{-1}=OSNR_{out}/OSNR_{in}$, both before and after the polarizer. The two values thus obtained for the inverse noise figure, $F^{-1}_{pre,post}$, are plotted in Fig. 2(a), with solid lines. All OSNR values were numerically evaluated according to ITU-T recommendations [10], i.e., the noisy signal was filtered, first on the signal bandwidth, to get the signal plus noise power, $P_T=P_R+P'_N$, then on an outer noise bandwidth, to estimate noise power P_N alone ($P_N = P'_N$ iff noise is white). Power values were referred to the standard bandwidth 0.1 nm, and so was the $OSNR=(P_T-P_N)/P_N$.

The horizontal (purple) dashed lines in Fig. 2(a), on the 0 dB baseline, shows the null value expected for F^{-1}_{pre}. In fact, the evaluation of $OSNR_{out\text{-}pre}$ should yield exactly the same value as $OSNR_{in}$, since the noisy input field $\mathbf{E}_{tx}(t)$ undergoes pure phase distortions, both in the fiber (SPM, XPM, XpolM) and in the phase modulator, up to the polarizer (Pol.). Thus, there is no exchange of energy between the frequency components of signal and noise, hence their power ratio (unaffected by scattering loss) is constant. However, as lower $OSNR_{in}$ values were tested by increasing the "noise load" P_W, the total transmitted power increases and so does the spectral broadening of the signal (despite SPM compensation). A consequent "leakage" of signal power onto the outer noise measurement bandwidth yields an overestimation of P_N, at the expense of an underestimated P_T, as we numerically verified, causing an increasing underestimation of both $OSNR_{out\text{-}pre}$ and $OSNR_{out\text{-}post}$. Indeed, this is an artifact related to the standard OSNR measurement technique and affects both solid curves in Fig. 2(a). Thus, it is the difference (in dB) between the solid curves in Fig. 2(a), i.e., $F_{post}^{-1}/F_{pre}^{-1}=OSNR_{out\text{-}post}/OSNR_{out\text{-}pre}$, plotted in Fig. 2(b), that yields the actual OSNR gain obtained by the device.

IV. Theoretical approximation of the OSNR gain

The dashed (red) curve, in Fig. 2(b), is an estimate for the OSNR gain, that can be obtained as follows. In the absence of noise, the effectiveness of LPA can be quantified by the average fraction ρ of attracted signal power [2], i.e., passing through the polarizer in Fig. 1. On the contrary, pure input noise is not attracted and remains unpolarized at the output, as verified, so that 50% of its power is suppressed by the polarizer, while the other half of noise power is co-polarized and passes through. Although linearity does not hold here, we can approximate the OSNR gain as the ratio of attracted signal power to co-polarized noise power: $\rho/0.5$. For instance, in the absence of noise ($OSNR_{in}=\infty$), simulation results yield $\rho=0.93$, i.e., 93% of the signal power is attracted towards the SOP of the pump (hence towards the transparent eigenstate of the polarizer), so that we can estimate the approximate OSNR gain as 0.93/0.5 (2.7 dB). Since additive noise decreases the effectiveness of LPA [8], this is the maximum OSNR gain that can be reached and is reported as an asymptotic value for F_{post}^{-1}, marked by the top (red) dashed line in Fig. 2(a). The fraction ρ has been shown to be in turn related to the output DOP of the signal [2,4] as $\rho=(1+DOP_{out})/2$, where DOP_{out} is obviously evaluated before the polarizer (one would trivially get DOP=1, after the polarizer). This is not surprising, since DOP_{out} quantifies the alignment between the average signal polarization and the pump SOP [4,7]. Still assuming halved noise power, at the polarizer output, the estimate for the OSNR

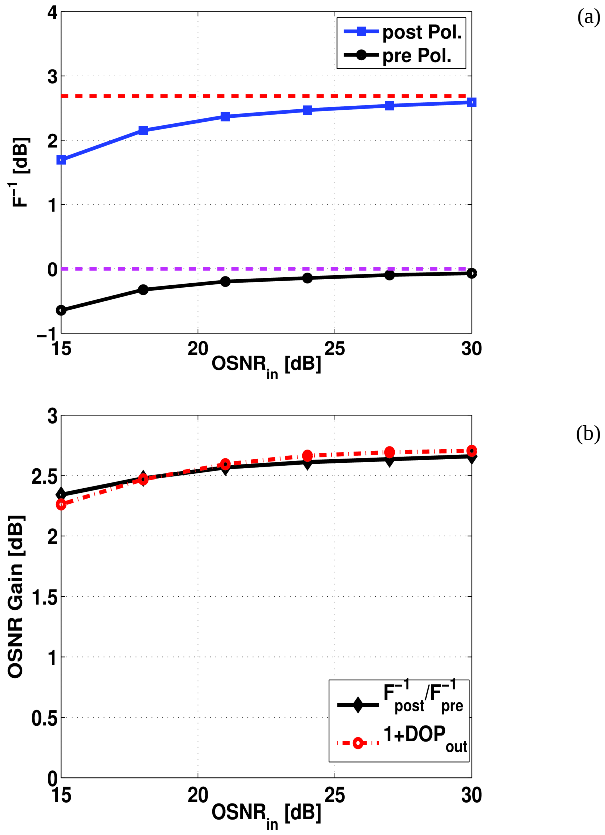

Fig. 2. (a) Inverse noise figure, measured before (*pre*) and after (*post*) the polarizer. (b) OSNR gain provided by LPA and its theoretical approximation.

gain is $\rho/0.5=(1+DOP_{out})$, reported in Fig. 2(b) as a function of $OSNR_{in}$. Clearly, both DOP_{out} and ρ decrease with $OSNR_{in}$, as the input noise increases [8]. The good match between the two curves confirms that the decrease of the OSNR gain, at low $OSNR_{in}$ values, has to be attributed to the degradation of DOP, brought about by noise.

V. Conclusions

We demonstrated that the phenomenon of lossless polarization attraction (LPA) can be applied to nearly double the OSNR of (partially polarized) signals affected by unpolarized noise. In the proposed setup, the benefits of LPA in the co-propagating configuration were exploited. First, its short transient times ensure an effective noise cleaning even for signals whose polarization varies across a bit-packet. In addition, an optimization of the pump wavelength, in the design of LPA, enhances its efficiency and allows a significant reduction of the required total power. Note that the total pump and signal power is equal to 434 mW, in the setup analyzed here, compared to the 3000 mW needed in counter-propagation to reach the same performance [8], or to the 900 mW in [3]. The device analyzed here employes a DSF with length 20 km; a shorter fiber can be used, if needed, provided that a highly nonlinear fiber is employed. The proposed all-optical noise cleaner yields an OSNR gain close to 3dB, for any input OSNR of practical interest. Results well match the theoretical approximation based on DOP measurement of the repolarized output signal.

Acknowledgment

We had many fruitful discussions on LPA with Victor V. Kozlov, who tragically died on 19 march 2013. May his memory live on.

References

[1] S. Pitois, J. Fatome, and G. Millot, “Polarization attraction using counter-propagating waves in optical fiber at telecommunication wavelengths,” Opt. Express, vol. 16, pp. 6646-6651, April 2008.

[2] M. Barozzi and A. Vannucci, “Performance analysis of lossless polarization attractors,” in *Proc. Latin America Optics and Photonics Conf. (LAOP 2012)*, Sao Sebastiao, Brazil, 2012, paper LM3C.4.

[3] J. Fatome, S. Pitois, P. Morin, and G. Millot, “ All optical control and stabilization of the polarization state of a 10 Gbit/s RZ telecommunication signal,” in *Proc. European Conf. On Optical Communication (ECOC'10)*, Torino, Italy, 2010, paper Th.9.C.4.

[4] V. V. Kozlov, M. Barozzi, A. Vannucci, and S. Wabnitz, “Lossless polarization attraction of copropagating beams in telecom fibers,” J. Opt. Soc. Am. B, vol. 30, pp. 530-540, March 2013.

[5] 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, vol 28, pp. 1782-1791, August 2011.

[6] M. Barozzi and A. Vannucci, and D. Sperti, “Lossless polarization attraction simulation with a novel and simple counterpropagation algorithm for optical signals,” J. Europ. Opt. Soc. Rap. Public., vol. 7, 12042, October 2012.

[7] M. Barozzi and A. Vannucci, “Optimal pump wavelength placement in lossless polarization attraction,” in *Proc. Fotonica 2013*, Milano, Italy, 2013, paper P.12.

[8] M. Barozzi and A. Vannucci, “A novel device to enhance the OSNR based on lossless polarization attraction,” in *Proc. Fotonica 2013*, Milano, Italy, 2013, paper C6.5.

[9] C. Xu, L. Mollenauer, and L. Xiang “Compensation of nonlinear self-phase modulation with phase modulator,” Electron. Lett., vol. 38, pp. 1578-1579, November 2002.

[10] Optical system design and engineering considerations, ITU-T Series G Supplement 39 (09/2012).