All-optical polarization control and noise cleaning based on a nonlinear lossless polarizer

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ABSTRACT

We propose an all-optical fiber-based device able to accomplish both polarization control and OSNR enhancement of an amplitude modulated optical signal, affected by unpolarized additive white Gaussian noise, at the same time. The proposed noise cleaning device is made of a nonlinear lossless polarizer (NLP), that performs polarization control, followed by an ideal polarizing filter, that removes the orthogonally polarized half of additive noise. The NLP transforms every input signal polarization into a unique, well defined output polarization (without any loss of signal energy) and its task is to impose a signal polarization aligned with the transparent eigenstate of the polarizing filter. In order to effectively control the polarization of the modulated signal, we show that two different NLP configurations (with counter- or co-propagating pump laser) are needed, as a function of the signal polarization coherence time. The NLP is designed so that polarization attraction is effective only on the "noiseless" (i.e., information-bearing) component of the signal and not on noise, that remains unpolarized at the NLP output. Hence, the proposed device is able to discriminate signal power (that is preserved) from in-band noise power (that is partly suppressed). Since signal repolarization is detrimental if applied to polarization-multiplexed formats, the noise cleaner application is limited here to "legacy" links, with 10 Gb/s OOK modulation, still representing the most common format in deployed networks. By employing the appropriate NLP configurations, we obtain an OSNR gain close to 3dB. Furthermore, we show how the achievable OSNR gain can be estimated theoretically.

Keywords: Nonlinear lossless polarizer; polarization attraction; optical noise cleaning; all-optical polarization control; optical communications subsystems.

1. INTRODUCTION

Controlling the state of polarization (SOP) of an optical signal is an open issue both in optical transmission systems and in optical signal processing, and has been a subject of intense research[1] (and references therein). Among the different techniques that have been proposed, to control polarization (e.g., by exploiting Raman gain, photorefractive materials, etc.), we shall concentrate here on lossless polarization attraction (LPA).[2,3] LPA is a nonlinear two-channel phenomenon, based on the Kerr effect, occurring between the signal whose SOP has to be controlled and a fully polarized continuous wave (CW) pump beam. Thanks to the interactions between signal and pump dictated by cross-polarization modulation (XpolM, i.e., the polarization-sensitive part of the Kerr effect), the signal SOP at the fiber output is attracted towards that of the controlling pump, regardless of the signal SOP at the fiber input, provided that the nonlinear fiber is randomly birefringent.[4] In its first experimental demonstration,[5] instead, 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 and its occurrence has been demonstrated also in the co-propagating configuration.[6]

Exploiting LPA, we can thus design an all-optical fiber-based device to control the SOP of an optical telecom signal, by using a counter- or a co-propagating pump laser. Such a device is called nonlinear lossless polarizer (NLP),[3,6] to underline that it does not entail any loss of signal energy, due to the Kerr interaction with the controlling pump. The original counter-propagating configuration of LPA requires long (microseconds) transient

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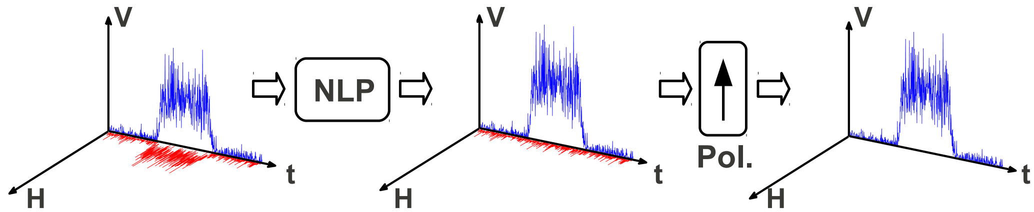

Figure 1. Principle of operation of a noise cleaner based on a nonlinear lossless polarizer.

times and large signal power (watts),[7] hence a counter-propagating NLP can repolarize only powerful signals with a slowly-varying SOP. 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 delay,[6] whose value can in turn be optimized, for given power levels, according to the symbol period.[8] As a consequence, a co-propagating NLP can repolarize signals with a fast-varying SOP, and can employ lower power levels.

Interesting applications of LPA have been proposed recently, including the all-optical nonlinear processing and regeneration of a 40 Gb/s modulated telecom signal,[9] the design of optical flip-flop memories,[10] and the enhancement of the optical signal-to-noise ratio (OSNR) of a telecom signal.[11,12] Referring in particular to the latter application, that we shall shortly refer to as noise cleaning, it has been shown that an all-optical *noise cleaner*, able to almost double the OSNR, can be implemented based on a NLP in one of the two configurations. Noise cleaning based on a counter-propagating NLP[11] has proven to be effective for telecom signals whose SOP does not change across many (thousands) consecutive bits, i.e., where the *polarization coherence time* is of the order of the whole bit-packet. In fact, in this scenario, it was demonstrated that the effectiveness of LPA is little impaired by unpolarized additive noise, at least for OSNR values of practical interest.[11] Using a NLP in the co-propagating configuration, the noise cleaning capabilities extend to telecom signals whose polarization coherence time is as short as the bit period,[12] although no direct proof was provided of the effectiveness of LPA in the presence of noise. In this work, we aim at presenting a comprehensive picture of a noise cleaner, based on NLP in both configurations. We shall compare the two solutions, with counter- and co-propagating pump, for signals with a fast or slowly varying SOP. Moreover, we shall analyze the effectiveness of co-propagating LPA with additive noise and extend to the counter-propagating configuration the method we proposed to theoretically estimate the gain achieved on the OSNR by the noise cleaner.[12] We shall quantify the performance of the proposed noise cleaner through the traditional notion of noise figure F and measure OSNR according to the method described by ITU-T[13] (we used a different method for counter-propagating noise cleaner[11]).

2. PRINCIPLE OF OPERATION

The idea behind the noise cleaning approach is that, 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 polarizing filter, aligned with the signal SOP. In the general case, the noiseless signal component is partially (de-)polarized. Hence, in order to obtain an OSNR enhancement, the noiseless signal should first be repolarized towards a unique SOP, coinciding with the transparent eigenstate of the polarizing filter, before passing through it. Otherwise, the polarization fluctuations of the signal would be transformed into intensity fluctuations, leading to a further degradation of the OSNR. We can thus employ a NLP, before the polarizing filter, whose task is to attract the signal SOP (unknown and time-varying, in general) towards the transparent eigenstate of the ideal polarizing filter.[11,12]

A two-stage device results, as schematically depicted in Fig. 1, where the first stage is a NLP, able to control the signal SOP, and the second stage is an ideal polarizing filter (Pol.), which aims at mitigating noise power. The three plots in Fig. 1 show how the optical power of the input signal, initially split between the horizontal (red) and vertical (blue) polarization components, is attracted by the NLP towards, e.g., the vertical (blue)

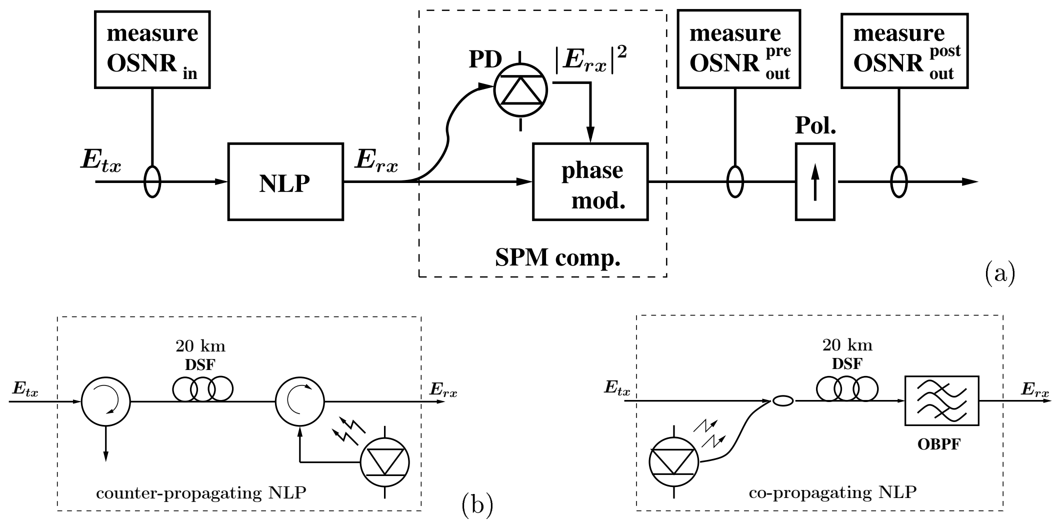

Figure 2. (a) Noise cleaner setup, with detail of NLP architecture in the counter-propagating (b) or co-propagating (c) configuration.

polarization. This is assumed to be the transparent SOP of the Pol., so that the vertically polarized optical power passes through the filter unchanged, while the orthogonally (horizontally) polarized optical power is filtered out. A similar picture holds for any attracting SOP, provided that the attracting SOP of NLP coincides with the transparent SOP of Pol. If the noiseless signal component is effectively attracted by the NLP, while the unpolarized noise component is not, the resulting OSNR is enhanced. Note that signal repolarization is detrimental, if applied to polarization multiplexed formats, hence we can apply the proposed noise cleaning strategy to optical signals with single polarization modulation formats. Consistently, in the following we shall concentrate on signals with a "legacy" binary amplitude modulation format, i.e., on-off keying (OOK).

It has been shown that NLPs realized in a counter-propagating configuration or in a co-propagating configuration are characterized by different *transient times*; in all cases, they provide an effective LPA only for input signals whose SOP is stable for a period larger than their transient times.[6,7] Despite possible depolarization effects — such as polarization mode dispersion (PMD) or XPolM, suffered by the signal along the transmission channel — the *coherence time* of the noiseless signal SOP is typically much larger than that of unpolarized noise. Hence, a NLP can be designed so as to effectively act only on the noiseless signal component and not on the noise. Assuming an ideal behavior of the NLP, the SOP of the noiseless input signal component would be attracted towards the transparent eigenstate of the Pol. and passes through it without any power loss, while unpolarized noise would not be attracted and remains unpolarized, so that half of its power would be suppressed by the Pol. filter. We are thus tempted to conclude that the noise cleaner can increase the OSNR by 3 dB, which is then the theoretical maximum OSNR gain achievable by the device in Fig. 1. This is however the application of a linear reasoning to a nonlinear device, where the superposition of effects does not hold, hence the noise cleaner performance has to be directly verified. In the following, we numerically evaluate the noise cleaner performance, as obtained in different scenarios.

3. SYSTEM SETUP AND SIMULATION PARAMETERS

Fig. 2(a) shows the proposed noise cleaner setup, that we numerically simulated. The first section is a NLP, where a fully-polarized CW pump laser, with power P_p, is coupled with the input signal, so as to attract the signal SOP towards the pump SOP. The NLP can be realized in the counter-propagating configuration, as detailed in Fig. 2(b),[3–5,11] where signal-pump coupling is accomplished by two optical circulators. Otherwise, one can employ a NLP in the co-propagating configuration, as in Fig. 2(c),[6,8,12] where signal and pump are first coupled, then the signal is isolated by the optical banpass filter (OBPF), after propagation. In both cases, the NLP includes a $L = 20$ km long dispersion-shifted fiber (DSF), with attenuation $\alpha = 0.2$ dB/km and Kerr coefficient $\gamma = 1.99\ \mathrm{W}^{-1}\mathrm{km}^{-1}$. The fiber is randomly birefringent, with a PMD coefficient $\mathrm{D_{PMD}} = 0.05\ \mathrm{ps/km}^{1/2}$ (a typical value for low PMD fibers), so that propagation is governed by the Manakov equation and LPA occurs towards any pump SOP.[4,7]

As recalled in Sec. 2, the two NLP configurations are characterized by different transient times, hence are suitable for input signals with different polarization coherence times. We numerically simulated the noise cleaner in Fig. 2 by injecting input signals with different polarization coherence time, power and duration. In all cases, the input signal was placed at the fiber zero dispersion wavelength (λ_{zdw}) and is represented by the (lowpass equivalent) Jones vector $E_{tx}(t) = A_{tx}(t) + W(t)$, where the noiseless input $A_{tx}(t)$ is an intensity-modulated telecom signal with a fixed mean power P_s, while $W(t)$ is unpolarized AWGN, modeling ASE noise, whose power P_w is varied so as to test different values of $\mathrm{OSNR_{in}} = P_s/P_w$. For the practical values of $\mathrm{OSNR_{in}}$ tested here (larger than 10 dB), the amount of nonlinear distortion is effectively dictated by signal power, and not by noise power. The signal output by the NLP is $E_{rx}(t) = A_{rx}(t) + N(t)$, where noise $N(t)$ is no longer white. As further discussed in Sec. 5, colored noise makes the measurement of the output OSNR sensitive to the bandwidth of the signal spectrum, which is broadened by Kerr distortions, during nonlinear propagation. While XpolM is the driving force of LPA, self- and cross-phase modulations (SPM, XPM) are irrelevant for LPA. Being the pump CW, XPM just yields a constant phase shift, while SPM produces a spectral broadening of the signal. The last Kerr distortion is degenerate four-wave mixing (FWM), which is negligible, for the parameter values used here, as we numerically verified. The purpose of the "SPM Comp." subsystem in Fig. 2(a) is to remove the SPM-induced spectral broadening, in order to ease OSNR measurement. The task of equalizing SPM distortions, that is normally unfeasible in the analog domain, can be accomplished here, since chromatic dispersion is absent at the signal wavelength λ_{zdw}, by a properly tuned phase modulator, driven by the photodetected (PD) signal intensity.[14]

The output OSNR was measured before ($\mathrm{OSNR_{out}^{pre}}$) and after ($\mathrm{OSNR_{out}^{post}}$) the Pol., as shown by the blocks in Fig. 2(a). As remarked in Sec. 2, the pump SOP and the transparent eigenstate of the Pol. must always be aligned to each other, so that only the attracted portion of the signal (and noise) passes through the filter and contributes to the measurement of $\mathrm{OSNR_{out}^{post}}$. In all simulations, we ensured that this condition is met by a proper alignment of the Pol. or by setting the pump SOP, as could be done in practice by using a polarization controller (not reported in Fig. 2).

4. POLARIZATION CONTROL OF A NOISY SIGNAL

Unpolarized noise degrades degree of polarization (DOP) of the input signal, hence can spoil the mutual time-coherece of pump and signal SOPs, which is, as stated, a necessary prerequisite for LPA. Although the performance of NLPs has been characterized as a function of system parameters,[2–4,7] few studies account for the presence of noise in the attracted signal.[9,11,12] Specifically, the effectiveness of a NLP for a noisy signal has never been explicitly verified in the co-propagating configuration, while it has been verified for a counter-propagating NLP.[11] Thus, we analyzed the performance of an NLP, in the presence of noise, in both counter- and co-propagating configurations, for input signals characterized by a polarization coherence time that is either "long", i.e., of the order of a bit-packet (*packetwise polarized signals*), or "short", i.e., of the order of a single bit (*bitwise polarized signals*). Thus, referring to a "legacy" bit-rate of 10 Gb/s, the coherence time ranges between 100 ps (a single bit period) and about 1 μs (a long Ethernet packet of 10^4 bits).

To quantify the performance of a NLP, in the case of completely polarized input signals, one can evaluate the degree of attraction (DOA),[3] which is a normalized measure ($\in [-1; 1]$) of how much the signal SOP is attracted onto the input pump SOP. The maximum theoretical value, DOA = 1, is strictly obtainable only in the case of an input signal whose (constant) SOP is already aligned with the attracting pump SOP. Otherwise, DOA = 1 represents an asymptotic value, for all partially polarized signals. When the input signal SOP varies, as in all practical cases, no matter how large the coherence time is, one must perform an ensamble averaging of the output DOA values over all possible input SOPs, i.e., calculate $\overline{\mathrm{DOA}}$.[3] It can be shown[6] that, at least in the case of fibers with moderate PMD, such an averaging yields the same result as the evaluation of the output DOP ($\overline{\mathrm{DOA}} = \mathrm{DOP}$). Since the nonlinear fiber described in Sec. 3 has the same $\mathrm{D_{PMD}}$ as that analyzed by Kozlov et al.,[6] we can quantify the performance of the NLP through the DOP of the output signal, for any polarization coherence time.

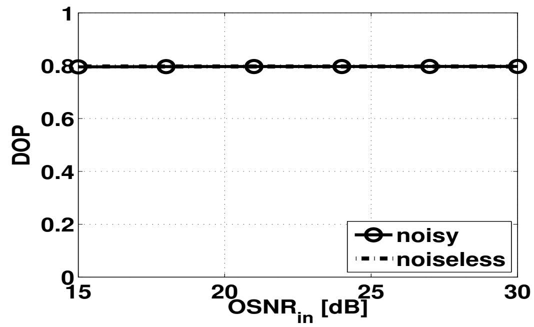

Figure 3. Performance of a counter-propagating NLP, obtained for packetwise polarized signals.

4.1 Packetwise polarized signals (slowly-varying SOP)

First, we evaluate the NLP effectiveness in controlling the SOP of an amplitude modulated optical signal characterized by a "slowly-varying" SOP, i.e., whose polarization is constant over a coherence time in the microseconds range. For these signals, a NLP designed in the counter-propagating configuration (Fig. 2(b)) has already been proven to be effective in controlling the signal SOP in a noiseless scenario.[4,7]

As we demonstrated,[3] the repolarization obtained by a counter-propagating NLP on an intensity-modulated fully polarized bit packet, with mean power P_s, is the same as that obtained on an input signal consisting of a single polarized pulse, with the same energy and power P_s. We set the pulse duration to $T_s = 1$ μs, so that it is representative of a packet of 10^4 OOK bits (@10 Gb/s).[3] We set the pump SOP as linear-horizontal (the same results would be obtained for any other pump SOPs, as verified[4]), and aligned with the Pol., while the input signal is varied for each transmitted packet, so that, statistically, it uniformly covers the Poincaré sphere.

In order to obtain an effective attraction of the noiseless signal, with a counter-propagating NLP, powerful signals are needed.[3–5] Exploiting a property of LPA, whose performance depends on the product between signal and pump power,[3] we employed strongly unbalanced power levels. In order to limit the SPM, we set the signal mean power to a level $P_s = 0.6$ W, much lower than the pump power $P_p = 2.4$ W.

Simulation results, reported in Fig. 3, show that a significant DOP $\cong 0.8$ is reached, at the output of the NLP, for a noiseless input signal, plotted as a reference, with a dot-dashed line. The solid line with symbols represents the DOP obtained for a noisy input signal, as a function of $\mathrm{OSNR_{in}}$, in a range of practical interest. Results clearly show that the control of the signal SOP performed by the NLP is not spoiled by the presence of additive noise, hence an effective performance of the noise cleaner can be expected, at least for the $\mathrm{OSNR_{in}}$ values tested here. For each DOP value in Fig. 3, simulation results were averaged over 100 random input packet SOPs and 10 random noise realizations. Counter-propagation of signal and pump was numerically solved using the SCAOS algorithm.[4]

The effectiveness of the counter-propagating NLP for packetwise polarized signals, that has just been shown, does not extend to shorter polarization coherence times. Results showed that the curve in Fig. 3 rapidly vanishes to zero, when the coherence time decreases. As an example, in the case of a coherence time as long as a 2500 bits (250 ns, @10 Gb/s), the DOP obtained in the noiseless case drops to 0.04.

4.2 Bitwise polarized signals (fast-varying SOP)

Given the severe performance degradation of a counter-propagating NLP in controlling a fast-varying signal SOP, i.e., an input signal whose polarization coherence time is shorter than the transient time of the NLP, we cannot expect any gain on the OSNR of such signals, from the noise cleaner with NLP as in Fig. 2(b). A solution to control a signal with a fast-varying SOP is to implement the NLP in the co-propagating geometry, as shown in Fig. 2(c).

In order to verify the potentials of a co-propagating NLP in severe conditions, we evaluated its performance for input signals whose polarization coherence time is of the order of one bit period (bitwise polarized signals). In numerical simulations, the transmitted noiseless signal $A_{tx}(t)$ consisted of a stream of 2560 bits with OOK

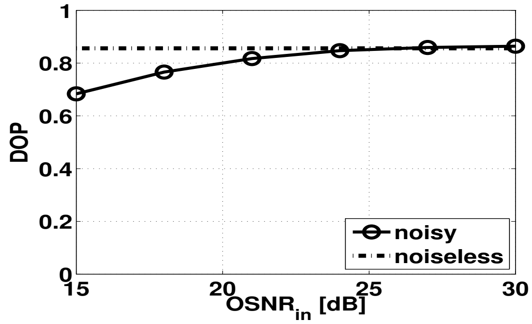

Figure 4. Performance of an optimized co-propagating NLP, obtained (also) for bitwise polarized signals.

modulation at 10 Gb/s, with a random SOP of each OOK pulse, uniformly distributed on the Poincaré sphere, so that DOP = 0, for $A_{tx}(t)$.

As we demonstrated,[8] the effectiveness of a co-propagating NLP is maximized when the walk-off delay between signal and pump is roughly twice the signal pulse duration. This is the reason for which we chose a specific return-to-zero (RZ-OOK) modulation format, with duty-cycle 33%, in the simulation results that follow. With this choice, each bit is encoded on a pulse with duration $T_s = 33.3$ ps, and a nearly optimal walk-off $T_D = 64$ ps can be reached by properly placing the pump wavelength, as in.[8,12] Furthermore, $T_s + T_D$ is less than the bit-period ($T_b = 100$ ps), which guarantees the absence of nonlinear pulse-to-pulse interactions mediated by the pump; this implies that each pulse interacts with the pump as if it were propagating alone into the fiber.

Fig. 4 shows the DOP of the output noisy signal $E_{rx}(t)$ as a function of $\mathrm{OSNR_{in}}$ (solid line with symbols). Results were obtained by setting the pump power at $P_p = 0.4$ W and the signal mean power at $P_s = 33.3$ mW (peak power equal to 200 mW). The overall transmitted power is almost an order of magnitude lower than the one transmitted in Sec. 4.1, which demonstrates the superior power efficiency of the co-propagating NLP configuration,[11,12] compared with the counter-propagating configuration. The DOP obtained for a noiseless input signal $A_{tx}(t)$ (dot-dashed line), equal to 0.86, is plotted along, as a reference. For lower $\mathrm{OSNR_{in}}$ values, the decrease of the output DOP demonstrates a degradation of the NLP effectiveness. As was already observed for a NLP with counter-propagation,[11] part of the decrease of DOP is a trivial consequence of the addition of unpolarized noise at the input. Nonetheless, results in Fig. 4 prove that a co-propagating NLP, with input signals characterized by a fast-varying SOP, is more sensitive to noise than a counter-propagating NLP. The maximum DOP degradation equals 0.16, and reduces to zero at larger $\mathrm{OSNR_{in}}$ values.

It should be remarked that the effectiveness of the co-propagating NLP, just shown for bitwise polarized signals, does not limit its suitability for signals with longer polarization coherence times, such as those examined in Sec. 4.1. For the same system parameters used in Fig. 4, we obtained the same DOP values, when increasing the coherence time of the transmitted signal.

5. NOISE CLEANING

After the NLP stage has performed a LPA of the signal towards the pump SOP, the Pol. stage yields an OSNR gain by filtering out the noisy signal component orthogonal to it. In order to estimate the OSNR gain, we resorted to the classical definition of noise figure, $\mathrm{F} = \mathrm{OSNR_{in}}/\mathrm{OSNR_{out}}$, and calculated F^{-1}, both before and after the Pol., i.e., $\mathrm{F}^{-1}_{\mathrm{pre,post}} = \mathrm{OSNR}^{\mathrm{pre,post}}_{\mathrm{out}}/\mathrm{OSNR_{in}}$. All OSNR values were numerically evaluated according to ITU-T recommendations,[13] on a standard reference bandwidth $B_0 = 0.1$ nm. In particular, the noisy signal was first filtered 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. The output OSNR was eventually evaluated as $\mathrm{OSNR} = (P_T - P_N)/P_N$. Note that the noise power measured on the two bandwidths is the same ($P_N = P'_N$) if and only if the output noise is white. Since the NLP is a nonlinear device, one must expect a colored noise at the output and, accordingly, some mismatches in the measurements.

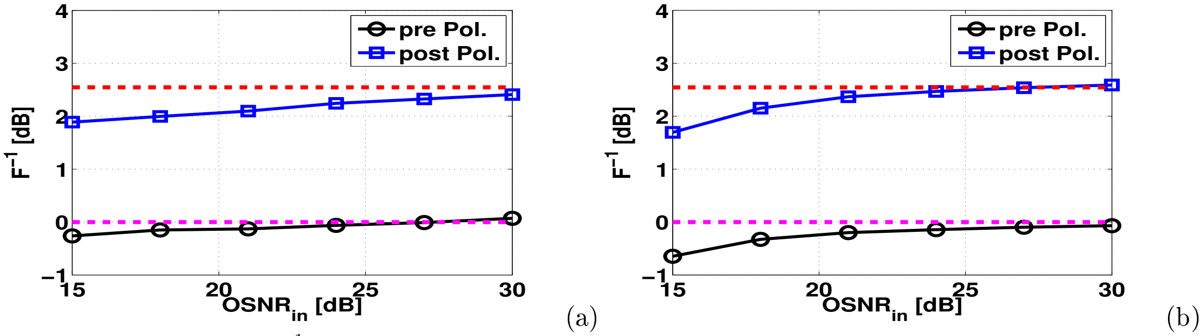

Figure 5. Inverse noise figure F^{-1}, evaluated before (pre) and after (post) the polarizing filter, that yields the OSNR Gain. Simulation results are obtained for a noise cleaner with a counter- (a) or a co-propagating (b) NLP configuration.

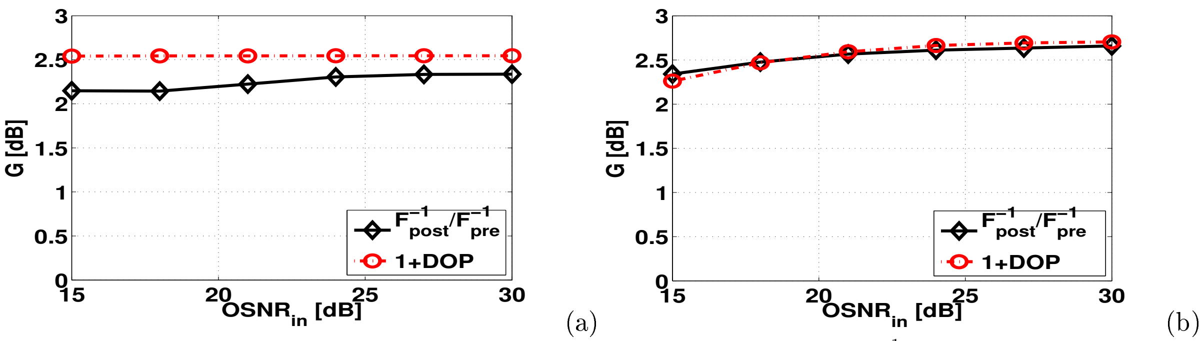

Figure 6. Effective OSNR gain, calculated as the increase in the inverse noise figure F^{-1}, due to a a noise cleaner with a counter- (a) or a co-propagating (b) NLP configuration. Dashed lines show the results of the theoretical approximation, as a function of input OSNR.

Fig. 5 shows F^{-1} as a function of OSNR_{in}, obtained for a noise cleaner with a counter- (a) or a co-propagating (b) NLP configuration. In the first case (Fig. 5(a)), the input signal is packetwise polarized, otherwise the counter-propagating noise cleaner is not effective (as was numerically verified in Sec. 4.1). In the second case (Fig. 5(b)), the input signal is bitwise-polarized, though the co-propagating noise cleaner is effective also for signals with slowly varying SOP (as was numerically verified in Sec. 4.2). In both Figs. 5(a) and (b), the solid lines with circles (black) and that with squares (blue), report the F^{-1} values obtained by measuring OSNR_{out} before or after the Pol., respectively, as evidenced in Fig. 2(a) by the blocks labeled "measure $\text{OSNR}_{\text{out}}^{\text{pre,post}}$". The dashed (red) lines represent an upper limit to the performance of the device, and are located at 2.5 dB and at 2.7 dB, in Figs. 5(a) and (b), respectively. As further discussed in Sec. 6, such a limit is due to the non ideal polarization control performed by the NLP on the signal, as evidenced by the DOP values in Figs. 3 and 4. Even in the noiseless case, a DOP < 1 reveals that a portion of the output signal power is still orthogonal to the pump, hence is suppressed by the Pol., along with half of the noise power. If the ideal condition DOP $= 1$ were met by the NLP, the upper limit for the noise cleaner performance would be 3 dB.

On the other hand, the lower dashed (magenta) lines in Figs. 5, located at 0 dB, represent the theoretical reference value that should be measured before the Pol.. In fact, the measurement of $\text{OSNR}_{\text{out}}^{\text{pre}}$ should yield exactly the same value as OSNR_{in}, since, as seen in Fig. 2, the noisy input field $E_{tx}(t)$ undergoes pure phase and polarization distortions, both in the fiber (SPM, XPM, XpolM) and in the phase modulator, up to the 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 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 OSNR_{out}.

Indeed, the artifact described above, that causes the mismatch between simulation results for F_{pre}^{-1} and its zero valued theoretical prediction in Fig. 5, is related to the standard OSNR measurement technique, hence affects both solid curves of each plot in Fig. 5. Thus, to get rid of such an artifact, we can estimate the actual OSNR gain G as the difference (in dB) between the solid curves in Fig. 5, i.e., $G = F_{post}^{-1}/F_{pre}^{-1}=OSNR_{out}^{post}/OSNR_{out}^{pre}$. Fig. 6 shows G, plotted with solid (black) lines, obtained by a noise cleaner realized with a counter- or a co-propagating NLP configuration (Figs. 6(a) and (b), respectively). In both cases, we obtained an OSNR gain between 2 dB and 3 dB, demonstrating that the proposed noise cleaner can effectively regenerate amplitude-modulated optical signals.

6. THEORETICAL APPROXIMATION

The dashed (red) curves in Fig. 6 represent an estimate of G, that can be evaluated from the measurement of the DOP of the signal output by the NLP, as follows.

In addition to the DOP, the effectiveness of a NLP, in the absence of noise, can be quantified by the average fraction ρ of signal power that has the same SOP as the pump.[3,5] Being the pump SOP aligned with the Pol., ρ is the fraction of signal energy that passes through Pol. in Fig. 2. As opposed to the noiseless signal, pure input noise is not attracted and remains unpolarized at the output, as numerically verified, so that 50% of its power is suppressed by the Pol.. Although linearity does not hold here, we can approximate G as the ratio of attracted signal to noise power: $\rho/0.5$. In the absence of noise ($OSNR_{in} = \infty$), simulation results showed that ρ equals 0.90 for the counter-propagating NLP acting on a packetwise-polarized signal (Sec. 4.1), while $\rho = 0.93$ for the co-propagating NLP acting on a bitwise-polarized signal (Sec. 4.2). Hence, 90% or 93% of the signal power was attracted towards the pump SOP, in the two scenarios. From these figures, we got the approximate G, equal to 0.90/0.5 (2.5 dB) and 0.93/0.5 (2.7 dB), respectively, marked by the upper dashed (red) lines in Figs. 5. Further theoretical analysis of LPA in the noiseless case,[3] have shown that the fraction ρ is in turn related to the DOP of the output signal $E_{tx}(t)$, by the simple relationship $\rho = (1 + \mathrm{DOP})/2$, where DOP is obviously evaluated before the Pol. (one would trivially get DOP = 1, after the polarizing filter). This relationship is not surprising, since DOP quantifies the alignment between the average signal SOP and the pump SOP.[6] Still assuming that the output unpolarized noise power is halved by the Pol., the approximation derived above for G becomes $\rho/0.5 = (1 + \mathrm{DOP})$, reported in Figs. 6 with dashed (red) lines. Note that the OSNR gain estimates in Fig. 6(a) and (b) as a function of $OSNR_{in}$ were evaluated straightforwardly, i.e., by summing 1 to the numerical values in Figs. 3 and 4 (and converting to the log scale).

As seen in Fig. 6, DOP decreases with $OSNR_{in}$, as the input noise increases. As stated in Sec. 4.2, the degradation of the output DOP is an expected behavior, physically related to the decrease of the input DOP due to the additive noise, despite the repolarization provided by the NLP. In Fig. 6, we can see a very good match between the theoretical approximation and the actual OSNR gain reached by the noise cleaner, at least in the co-propagating configuration. Larger discrepancies are observed in Fig. 6(a), for the counter-propagating configuration. The difference between G and its estimate is however in the order of 0.2 dB, compared to OSNR gain values always above 2 dB, in any of the tested configurations, further confirming the noise cleaning capabilities of the proposed device.

7. CONCLUSION

We proposed a novel all-optical noise cleaning device, conceived for modulated optical signal with single polarization carrier. The noise cleaner is based on the simple concept of suppressing the orthogonally polarized half of additive noise, through a polarizing filter, hence ideally reaching a 3 dB enhancement of the OSNR. The core of the device is a nonlinear lossless polarizer, that is able to dynamically control the time-varying SOP of partially polarized signals. Recent studies on lossless polarization attraction have shown that the NLP can be realized in two different configurations, with a counter- or a co-propagating pump laser. In this work, we tested, by numerical simulations, both configurations of the device, and applied them to the noise cleaning of signals with amplitude modulation at 10 Gb/s and with different speeds of variation of their polarization (i.e., different *polarization coherence time*).

Results show that signals with a polarization that is constant over thousands of bits (i.e., for *packetwise-polarized signals*) benefit by both configurations of the noise-cleaner, with an effective gain of the OSNR between 2 dB and 3 dB, at least for the tested input OSNR of practical interest. A similar gain was obtained as well for signal with a fast-varying polarization, on the scale of a bit period (i.e., for *bitwise-polarized signals*), by resorting to the co-propagating configuration of the noise cleaner. We thus showed that the more recently devised (and less studied) co-propagating LPA is more flexible and more power efficient, with a reduction of the overall average transmitted power from 3 W to less than 0.5 W. We showed that the achieved OSNR gain is strictly related to the performance of the NLP and can be theoretically estimated after measuring the DOP of signals at its output.

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