# Performance Analysis of Lossless Polarization Attractors

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**Abstract:** Following recent studies on Kerr-based polarization attractors, we characterize their performance by introducing the Degree Of Attraction. Results provide the guidelines for selecting pump power and fiber length, in the attractor's design.
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## 1. Introduction

Controlling the state of polarization (SOP) of an arbitrarily polarized optical signal is a fundamental task, both for optical signal processing applications and for optical communication systems. Recent results have shown that lossless polarization attraction can be realized by injecting a counter-propagating fully polarized continuous-wave (CW) pump in the nonlinear propagation fiber [1–3]. Based on the lossless and instantaneous Kerr interaction, the attractor can transform the SOP of any input signal into a unique output SOP, dictated by the pump. Nonetheless, complete attraction is only an asymptotical condition, and the study of transient polarization attraction [2,3], has highlighted that the attraction of the mean signal SOP occurs at the expense of a partial degradation of the degree of polarization (DOP). This can become a problem in a packet switched scenario, where the polarization of signals (bit-packets), with durations in the microsecond scale, has to be controlled.

The dynamics of nonlinear polarization interaction depend on the injected power levels and fiber length, which should be thus selected, when designing the attractor, to achieve the desired performance. To implement this process, we define a degree of (polarization) attraction (DOA), then quantify it by simulation, resorting to a recently introduced counter-propagation algorithm [3]. We investigate the dependence of DOA on power levels and fiber length, as well as its relation to the mean polarization attraction and DOP degradation.

## 2. Degree of polarization attraction (DOA)

Assume, in general, that a time-varying pump is injected at the output of a nonlinear fiber where polarization attraction takes place. Let the pump Stokes vector be **P**(t)=P(t)**p**(t), whose magnitude P(t) is the pump power while the unit magnitude vector (bold lower case) **p**(t) represents its SOP on the Poincaré sphere. Using a similar notation, **S**(t)=S(t)**s**(t), for the signal at the attractor's output, we define the degree of (polarization) attraction (DOA) as the maximum normalized cross-correlation between pump and signal Stokes vectors:
$DOA = \max_{\tau}\{\langle \boldsymbol{S}(t) \cdot \boldsymbol{P}(t+\tau)\rangle / \langle S(t)P(t+\tau)\rangle\}$, where < > denotes time-averaging and · is the scalar product. By definition, DOA∈[-1;1] and DOA=1 is reached if, for a given τ, the output signal SOP **s**(t)=**p**(t+τ) follows the injected pump SOP. Polarization attraction has been studied so far using a completely polarized CW pump[1–4], whose aim is to bring the input signal SOP onto the fixed pump SOP **p**. In this case, **P**(t)=P**p** is independent of time, and DOA simplifies to

$$DOA = \langle \boldsymbol{S}(t)\rangle \cdot \boldsymbol{p} / \langle S(t)\rangle = DOP \cdot MSA \qquad (1)$$

where, along with the standard definition of the degree of polarization (DOP= ||<**S**(t)>||/<S(t)>), we introduced the *mean SOP attraction*: $MSA = (\langle \boldsymbol{S}(t)\rangle / \|\langle \boldsymbol{S}(t)\rangle\|) \cdot \boldsymbol{p} = \boldsymbol{m} \cdot \boldsymbol{p} = \cos(\chi)$. The MSA has a precise geometrical meaning: since <**S**(t)> is the mean signal Stokes vector, χ is the angular distance between the attracting pump SOP **p** and the mean (power-averaged) signal SOP **m**, at the attractor's output.

Moreover, DOA can be physically measured by filtering the signal through an ideal polarizer, aligned with the pump SOP. It can be shown, from (1), that the ratio of signal energies detected after and before filtering is (1+DOA)/2.

## 3. Attractor's performance vs. power and fiber length

We perform numerical simulations and calculate DOA, DOP, and MSA, after letting pump and signal counter-propagate in a nonlinear NZ-DSF fiber [1] with Kerr coefficient $\gamma$=1.99 $W^{-1}km^{-1}$ and loss $\alpha$=0.2 dB/km. The fiber is randomly birefringent, although with negligible PMD, so that propagation is governed by the Manakov equation [2]. Hence, the Kerr effect is isotropic on the Poincaré sphere and polarization attraction occurs towards any fixed pump

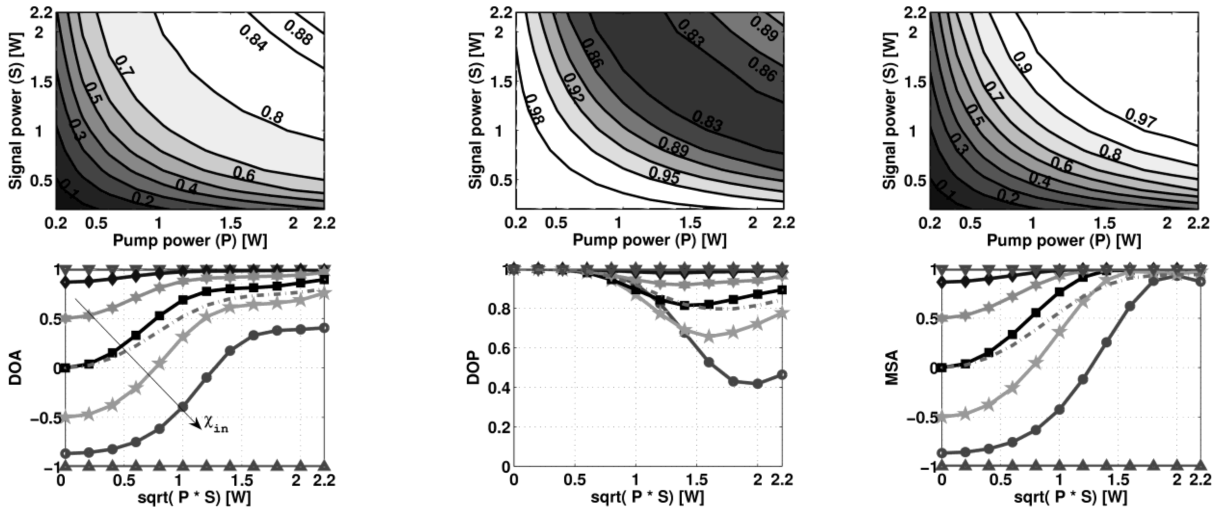


Fig. 1. (left to right) Degree of polarization attraction, DOA, and its factors DOP and MSA. (top) Contour levels vs. pump and signal powers (P and S), in the case $\chi_{in}$=90°. (bottom) DOA, DOP and MSA, as a function of $\sqrt{PS}$, for other input signal SOPs ($\chi_{in}$=0° to 180°, in 30° steps); dashed line: random input SOP.

SOP [2,3], here chosen linear horizontal, i.e., $\mathbf{p}=\mathbf{s}_1$ is the first Stokes axis. Counter propagation is solved by using the iterative SCAOS algorithm [3].

The counter-propagating pump is CW, with constant power P, while the input signal consists of a single intensity modulated pulse, with duration 1μs and power S, placed at the fiber zero-dispersion wavelength. We verified numerically that results do not change when introducing intensity modulation, at fixed mean power. The signal is thus representative of, e.g., a $10^4$ OOK-modulated bit packet (@10Gb/s). We assume a polarized input signal, $\mathbf{S}_{in}(t)=S_{in}(t)\mathbf{s}_{in}$, with $DOP_{in}=1$, that lies on the Poincaré sphere at an angular distance $\chi_{in}$ from the pump SOP, so that $\cos(\chi_{in})=\mathbf{s}_{in}\cdot\mathbf{p}$.

We first characterize the performance of a polarization attractor with fixed length L=10 km, as a function of pump and signal input power. Fig. 1(top) shows the contour levels of the DOA and of its factors (DOP and MSA), obtained by independently varying P and S between 0.2W and 2.2W. The linear horizontal and vertical components of the input signal are chosen with equal power, in Fig.1(top), so that $\chi_{in}$=90°, while results do not depend on their phase offset, that is randomly chosen. Starting from $\cos(\chi_{in})=0$, DOA increases monotonically with signals' power. Such a result is not trivial, since DOA in (1) is affected by an unavoidable DOP degradation, entailed in the dynamics of polarization attraction [2,3]. However, Fig.1(top center,right) shows that the DOP minimum, at intermediate power levels, is more-than-compensated by the increase of MSA, which measures the average signal attraction. A noteworthy result is that all contour plots perfectly overlap with equilateral hyperbolae, implying that DOA, DOP and MSA all depend on the pump-signal power product. This is true for any launched signal SOP $\mathbf{s}_{in}$, so that a plot versus $\sqrt{PS}$ (the geometric mean of pump and signal power) contains all the necessary information. The practical implication of this result is that even a weak signal can be effectively attracted, provided that the pump is powerful enough.

Fig.1(bottom) enlarges the picture by reporting the dependence of DOA, DOP and MSA on power ($\sqrt{PS}$), for other input signal SOPs: DOA curves, with different symbols, are obtained (top to bottom) for an increasing angular distance $\chi_{in}$ (0° to 180°, in 30° steps) from the pump SOP. In the left side of each curve, i.e., at low powers, propagation is in a quasi linear-regime, hence the input signal polarization is unchanged ($DOP \approx DOP_{in}=1$, $\chi\approx\chi_{in}$) and, from (1), DOA is close to $\cos(\chi_{in})$. The extreme $\chi_{in}$ values (symbols ∨, ∧) refer to a signal polarization equal/orthogonal to the pump, $\mathbf{s}_{in}=\pm\mathbf{p}$, where nonlinear polarization interaction is absent, hence DOA is constant. The dashed curves in Fig.1(bottom) are obtained by averaging over a random input signal SOP, uniformly distributed on the Poincaré sphere, hence represent the average performance of the lossless attractor. These curves yield the rule for setting the power levels, once the desired average DOA is fixed.

Next, we quantify, by numerical simulation, the degree of polarization attraction versus fiber length. In analogy with Fig.1, Fig.2(top) shows the contour plots of DOA, DOP and MSA, in the case $\mathbf{s}_{in}\perp\mathbf{p}$ ($\chi_{in}$=90°), as a function of equal pump and signal power (P=S) and *effective fiber length* $L_{eff}$, where the maximum $L_{eff}$=13km corresponds to a physical length L=20km [1]. Being polarization attraction driven by nonlinear polarization rotations induced by the pump along the nonlinear fiber, one can expect that its effect is proportional to the *nonlinear phase rotation*

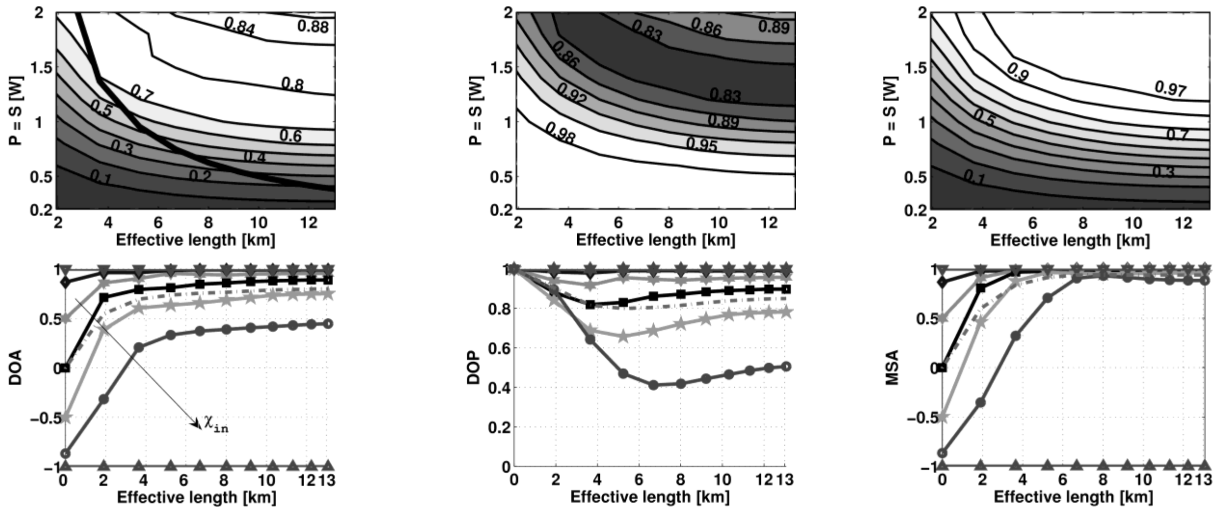


Fig. 2. (left to right) Degree of polarization attraction, DOA, and its factors DOP and MSA. (top) Contour levels vs. equal signal power P=S and effective length, in the case $\chi_{in}$=90°. (bottom) DOA, DOP and MSA, as a function of $L_{eff}$ (P=S=2W), for other input signal SOPs ($\chi_{in}$=0° to 180°, in 30° steps); dashed line: random input SOP.

$\varphi_{NL}=\gamma PL_{eff}$. An equilateral hyperbola, with constant $\varphi_{NL}$, is plotted onto the DOA contours in Fig.2, to show that this is not the case: the DOA increase with power is steeper than that with $L_{eff}$, hence a larger power is preferable to a longer fiber.

Fig.2(bottom) shows results obtained for different input signal SOPs, using an input power P=S=2W. DOA curves (top to bottom) are obtained for the same $\chi_{in}$ values as in Fig.1 (0° to 180°, in 30° steps), while dashed curves show the average value, obtained for a random input signal SOP. DOP and MSA plots, obtained for the same $\chi_{in}$ (same symbol), show once more how input signals with a SOP that is "far" from the pump (i.e., large $\chi_{in}$) suffer the impact of DOP degradation, on the achievable DOA. Even for large $\chi_{in}$ values, results show that most of the DOA increase is within the first 10kms of fiber (i.e., $L_{eff}\approx$8km), after which the attractor's performance does not improve significantly. The interest in using shorter fibers is due to PMD. In a randomly birefringent fiber [2,3], a large PMD coefficient can spoil polarization attraction, if the fiber is too long, due to the incoherent polarization evolution of pump and probe, located at different wavelengths [4]. Hence, the attractor's length can be limited to L=10km, as done in Fig.1.

## 4. Conclusions

We characterized, by numerical simulation, the performance of a lossless polarization attractor, when its free parameters (signal and pump power; nonlinear fiber length) are varied. The degree of attraction (DOA), introduced here, highlights the trade-off between the mean SOP attraction and an inevitable DOP degradation.

We find that the attraction of a polarized signal towards a counter-propagating CW pump increases with the pump-signal power product, which allows the designer to trade power between signal and pump. Results on the average attraction of a signal with random polarization yield the rule for setting the power levels. Although longer fibers increase the attractor's performance, length should be limited by the possible presence of PMD. Results show that lengths beyond 10km only yield a marginal improvement on the attractor's performance.

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