A SIMPLE COUNTER-PROPAGATION ALGORITHM FOR OPTICAL SIGNALS (SCAOS) TO SIMULATE POLARIZATION ATTRACTION

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We introduce a simple and fast SSFM-based algorithm, named SCAOS, for simulating the counter-propagation of optical signals. Applications to the vectorial counter-propagation of a polarized pump and probe demonstrate the phenomenon of lossless polarization attraction.

1. Introduction

In many photonics applications, especially in optical fiber based systems, the state of polarization (SOP) of light remains so far en elusive uncontrolled variable, that can dramatically affect systems performance and that one would like to control as finely as possible. Recent experiments and simulations [1-4] have demonstrated that a lossless polarization attractor can be realized, even using telecom fibers at moderate signal powers [2]. Based on the injection of a counter-propagating fully polarized continuous-wave (CW) *pump*, the attractor can transform the SOP of any input *probe* signal into a unique well-defined output SOP, dictated by the pump SOP. It is worth noting that, as opposed to other devices that employ polarization dependent loss/gain, as, e.g., those based on the Raman amplification, the physical mechanism behind the lossless polarization attractor is merely the Kerr effect [3]. Repolarizing an arbitrarily (un-)polarized optical signal by means of a lossless instantaneous nonlinear interaction is a fundamental effect of great interest for telecommunication applications and optical signal processing systems. Rather than discussing possible applications, we concentrate here on the numerical simulation techniques for this phenomenon, which entails counter-propagating signals as a fundamental prerequisite for the lossless attraction to happen [1].

Simulating polarization attraction requires the joint integration of the two vectorial nonlinear Schroedinger equations (VNLSE) of the pump and probe fields. Since the fields initial values are supplied at opposite fiber ends, the problem at hand is a *Boundary Value Problem* (BVP), that cannot be tackled with the split-step Fourier method (SSFM). Resorting to traditional finite difference integration requires large amounts of memory and long computation times: the authors of [1,2] perform numerical simulations in the case of a short fiber (2m) [1], leaving to experiments the case of long fibers (kms) [2].

In this work, we describe a novel iterative algorithm for the numerical simulation of counter-propagating optical signals, which is based on the SSFM, hence can be implemented in many traditional optical simulators that were originally devised for co-propagating channels. In addition, having the SSFM as the fast and efficient core of the algorithm's iterations makes it suitable for simulating counter-propagation even in (kilometers) long fibers [2], where finite difference integration is not practical. The proposed algorithm, named SCAOS (simple counter-propagation algorithm for optical signals), is then applied to simulate the nonlinear polarization interaction between a probe and a pump signals, that propagate in opposite directions, thus demonstrating the operation of a lossless Kerr-based polarization attractor.

2. The SCAOS algorithm

We wish to simulate the counter-propagation of a *probe* $E^{+}(z,t)$ and a *pump* signal $E^{-}(z,t)$, travelling within a fiber of length L, whose initial values $E^{+}(0,t)$ and $E^{-}(L,t)$ are given. Signal

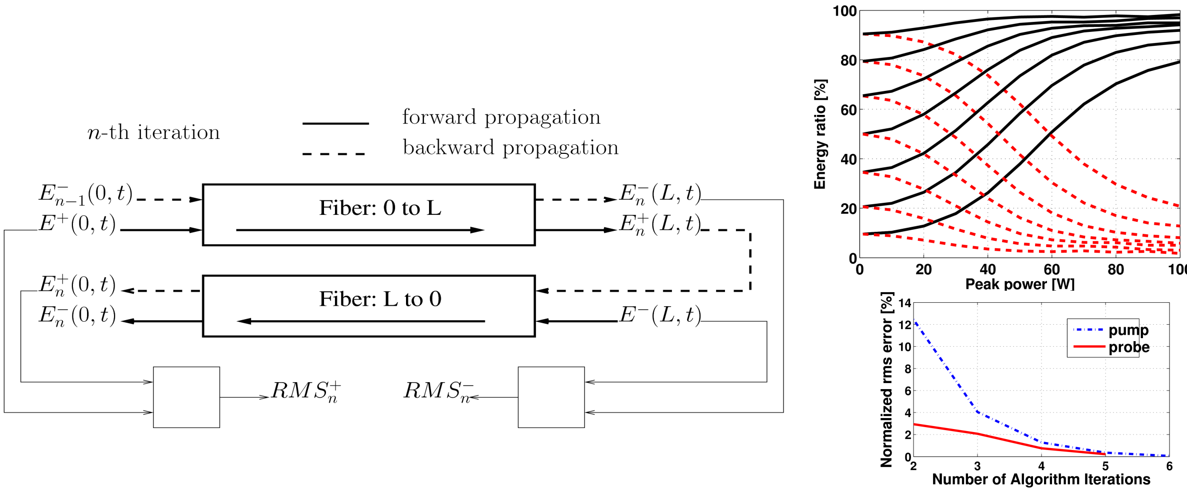

Fig.1 (left) Schematic description of the iterative SCAOS algorithm; (right top) fraction of probe energy attracted towards a right-circular pump SOP, in a short lossless attractor, as in [1]; (right bottom)residual normalized rms error during SCAOS iterations.

superscripts $^{\pm}$ identify the propagation direction, so that $E^+(t)$ propagates from z=0 to z=L, and vice-versa for $E^-(t)$. Hence, the final result is to calculate the outcoming probe $E^+(L,t)$ and pump $E^-(0,t)$. The basic idea behind the proposed algorithm is to let E^+ and E^- iteratively propagate from z=0 to z=L and vice-versa (i.e., in the "reverse fiber", as seen from z=L to z=0). In each propagation, one of the fields *forward-propagates*, starting from its given initial value, towards its output fiber end, while the other *backward-propagates*, i.e., travels according to an *inverse-Schroedinger equation*, starting from an estimated value. Backward-propagation is an option that can be easily implemented in the SSFM, which is originally devised for a fast and efficient (forward-)signal propagation. We did so, while implementing the whole SCAOS algorithm, within Optilux [5], the SSFM-based, open-source optical simulator developed at the University of Parma.

Fig.1(left) sketches the n-th algorithmic iteration. Before the first iteration, the initial pump estimate $E_0^-(0,t)$ is found by letting the pump initial condition $E^-(L,t)$ forward-propagate as a single field, from L to 0. After each half-iteration, the backward-propagating signal completes a round-trip towards its input fiber end, yielding a new n-th estimate for the input field ($E_n^-(L,t)$, at z=L, or $E_n^+(0,t)$, at z=0). A normalized root mean square (rms) error is calculated, between such an estimate and its true initial value. At the same time, the given initial (boundary) value is substituted to the estimate, so that the outcoming forward-propagating field ($E_n^+(L,t)$, at z=L, or $E_n^-(0,t)$, at z=0, which are the sought quantities) is refined, at the next iteration.

The rms errors $RMS_n^{\pm}$, evaluated for the pump and probe at n-th iteration, drive the stop criterion: the algorithm stops when both $RMS_n^{\pm}$ are below a certain threshold, meaning that the round-trip field estimates are sufficiently close to their true initial values. Fig.1(bottom-right), obtained for the polarization attraction setup of Sec.3, shows a typical behavior of the normalized rms errors, where the errors becomes negligible (below 0.1%) in a few iterations.

3. Application to lossless polarization attraction in a short highly nonlinear fiber

As a first application of the SCAOS algorithm, we simulate the system setup described in [1] and used for the first experimental demonstration of lossless polarization attraction. The counter-propagating pump and probe beams, both consisting of a completely polarized 10ns intensity-modulated light pulse, are transmitted on a highly nonlinear single mode fiber, with length L=2m. The large Kerr coefficient (γ=22W^{-1}Km^{-1}) and pulse intensities (up to 45W) used in the experiments allow a significant nonlinear interaction. In such a short fiber, propagation is governed by the VNLSE, where circular polarizations play a special role, hence a rigth circular polarization is chosen for the input pump SOP (S_3 in Stokes space).

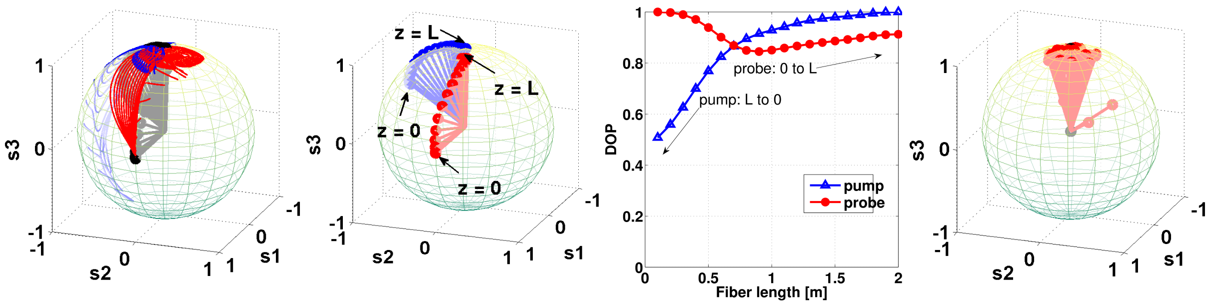

Fig.2 Lossless polarization attraction between pulses in a short fiber. Left to right (a-d): (a) SOP traces along z; (b) motion of the average attracted SOP; (c) resulting DOP, along z; (d) output average probe SOP (DOP=magnitude) for 50 random input SOPs.

After propagating 7 different input probe SOPs with increasing ellipticity and random azimuth, Fig.1(top-right) shows the fraction of output probe energy that is aligned with (solid line) or ortogonal to (dashed line) the input pump SOP, as a function of the equal pump and probe peak powers injected into the fiber. Results coincide exactly with those reported in [1] (obtained with finite difference integration), and show how, as power increases, each input probe SOP is attracted towards the right circular polarization imposed by the pump.
To gain further insight into the polarization attraction process, we report in Fig.2 details about the polarization states of the pump and probe along the fiber, in the case of an input probe with linear horizontal SOP and input powers 100W. The degree of polarization (DOP) of the launched pump and probe pulses is unitary. This is no longer true when the two signal beams start interacting: Fig.2(a) shows the *depolarization traces*, for the probe (red) and pump (blue), on the Poincaré sphere. Each trace represents the time evolution of the pulse's SOP, at a given position $z\in[0,L]$ along the fiber, and the inner black vectors represent its power-averaged SOP. From each trace, we report, in Fig.2(b-c), the average SOP and the DOP. The probe average SOP is attracted towards the pump SOP, with a relatively small depolarization, while the pump is much more depolarized and ends away from the input probe. Full results, as in Fig.2(a-c), are obtained with the SCAOS algorithm in 8*min* computation time, on an ordinary PC.
Different choices for the input probe SOP yield similar results: Fig.2(d) shows the resulting average output polarization, for 50 random input probe SOPs, along with the DOP of the output pulse, represented by the vectors' magnitude. The figure shows an effective polarization attraction towards the right-circular pump SOP, for all but those probe SOPs that are initially almost orthogonal to the pump. On the contrary, we verified that polarization attraction is not equally effective, in this setup, if the pump is not circularly polarized: a fact that has not been sufficiently pointed out in [1].

4 Application to lossless polarization attraction in a long telecom fiber

As demonstrated in [2], polarization attraction can happen even at moderate power levels, provided that the nonlinear polarization interaction occurs in a longer fiber. The second system setup to which we apply the SCAOS algorithm is similar to the one used for the experiments in [2]. An intensity modulated probe pulse, with duration 3μs and peak power 1.2W, undergoes lossless Kerr interaction with a counter-prapagating CW pump, with equal power, on an ordinary telecom fiber, with Kerr coefficient γ=1.99W^{-1}Km^{-1} and length L=10km. Thanks to the random birefringence of the fiber, propagation is governed by the Manakov equation [3-4], where the Kerr effect is isotropic, on the Poincaré sphere. Hence, we choose a linear horizontal pump SOP (similar results were obtained for any other tested pump SOP).
Simulation result are shown in Fig.3, in the same framework as those reported in Fig.2. Choosing a right-circular input probe SOP yields the *depolarization traces* reported in Fig.3(a) (10 traces, plotted every km of propagation). The probe average SOPs, plotted on a finer scale in Fig.3(b), show that attraction occurs towards the pump SOP, along a spiral

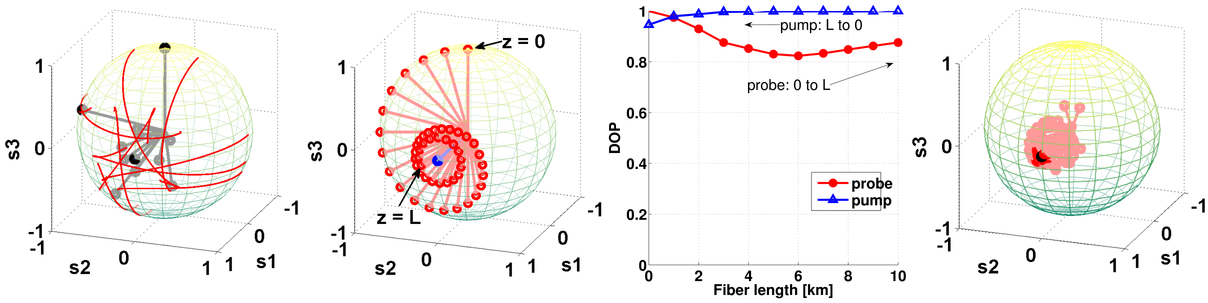

Fig.3 Lossless polarization attraction of a probe pulse towards a (linear horizontal) CW pump, in a long fiber. Left to right (a-d): (a) SOP traces along z; (b) motion of the average attracted SOP; (c) resulting DOP, along z; (d) output average probe SOP (DOP=magnitude) for 50 random input SOPs.

trajectory. The probe depolarization is visible in the DOP curve in Fig.3(c), while the pump depolarization is negligible here, being the pump much longer than the probe duration. Repeating the propagation for 50 random input probe SOPs yields similar results. Fig.3(d) shows the corresponding average output probe SOPs. Polarization attraction is testified by the 50 vectors surrounding the attracting pump SOP (S_1), where the output DOPs are reported as the vectors' magnitude.

5. Conclusions

We introduced a novel iterative algorithm, named SCAOS, to simulate the counter-propagation of optical signals, and implemented it in the *Optilux* simulator [5]. We applied SCAOS to simulate the nonlinear polarization interaction between a pump and a probe field, due to Kerr effect. Two system setups were analyzed, showing that polarization attraction takes place both in a short highly nonlinear fiber, where powerful signals are launched, and in a long telecom fiber, even with moderate signal powers. The algorithm, always converging in a few iterations (with fast computation times), allowed a detailed study of the signals' polarization evolution, thus pointing out the dynamics of lossless polarization attraction.

Acknowledgements

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