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[INVITED] Self-induced polarization tracking, tunneling effect and modal attraction in optical fiber☆

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ABSTRACT

In this paper, we report the observation and exploitation of the capability of light to self-organize its state-of-polarization, upon propagation in optical fibers, by means of a device called Omnipolarizer. The principle of operation of this system consists in a counter-propagating four-wave mixing interaction between an incident signal and its backward replica generated at the fiber output thanks to a reflective fiber loop. We have exploited this self-induced polarization tracking phenomenon for all-optical data processing and successfully demonstrated the spontaneous repolarization of a 40-Gbit/s On–Off keying optical signal without noticeable impairments. Moreover, the strong local coupling between the two counter-propagating waves has also revealed a fascinating aspect of the Omnipolarizer called polarization-based tunneling effect. This intrinsic property enables us to instantaneously let "jump" a polarization information onto the reflected signal, long before the expected time-of-flight induced by the round-trip along the fiber span. Finally, we discuss how the concept of self-organization could be generalized to multimode fibers, which paves the way to new important applications in the framework of spatial-mode-multiplexing.

1. Introduction

Among the three independent features that characterize a light beam propagating in a monomode optical fiber, namely, the frequency, energy and state-of-polarization (SOP), the SOP remains the most elusive variable which is still difficult to predict and control. Outstanding technological developments in the manufacturing process of standard monomode optical fibers have been realized in the past decade. Especially, the implementation of a fast spinning process during the drawing stage now enables fiber providers to deliver standard telecom fibers with spectacular weak levels of polarization-mode dispersion [1–4]. Nevertheless, the residual random birefringence associated with mechanical stress, bending, squeezing, vibrations or temperature variations make the SOP of a light beam totally unpredictable after a few dozens of meters of propagation [5–10]. However, from a general point of view, despite the recent tremendous technological developments in waveguide and fiber-based systems to mitigate polarization impairments, the basic principle of operation of the associated SOP control methods often rests upon a combative strategy rather than on a preventive strategy. For instance, in high-capacity coherent transmissions, polarization impairments such as polarization randomness, polarization-mode dispersion [11–15], polarization depending loss [16] or cross-polarization interactions [17,18] are efficiently managed at the receiver by means of digital signal processing [19–21]. As far as highly polarization dependent systems such as on-chip integrated optical circuits or fiber-based nonlinear processing devices, special designs and more or less complex polarization-diverse schemes (polarization diversity, bi-directional loop or polarization splitting/recombination) may ensure the mitigation of polarization-dependent performances [22–25].

In order to master or control the SOP of light in fiber-based systems, the most effective strategy consists in implementing an opto-electronic polarization tracker [26–30]. Such devices are generally based on linear polarization transformations followed by partial diagnostic combined with an active feedback loop control driven by complex algorithms. Thanks to this well-established technique, record polarization tracking speeds have been achieved, reaching several of Mrad/s for commercially available units [31–34].

On the other hand, in order to benefit from all-optical alternatives for the development of future transparent networks, nonlinear effects have emerged in the last decade as a possible way to all-optically master the polarization of light propagating in optical fibers. To this aim, several techniques have emerged in the

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literature in order to develop a nonlinear polarizer capable to repolarize an incident signal with 100% of efficiency, whilst preserving the quality of the temporal intensity profile. This phenomenon of polarization attraction in optical fibers or polarization pulling effect, has been the subject of numerous studies in the literature involving the Raman effect [35–43], the stimulated Brillouin backscattering [44–49], the parametric amplification [50–52] as well as a counter-propagating four-wave mixing process, also called nonlinear cross-polarization interaction [53–70]. For this last particular case, it has been shown that an arbitrarily polarized incident signal can be attracted toward a specific SOP, which is fixed by the polarization of the counter-propagating pump wave injected at the opposite end of the fiber [55]. This phenomenon of polarization attraction has been the subject of numerous studies, reporting the efficient repolarization of telecom signals at 10 and 40 Gbit/s, in combination with several types of optical functionalities by using the same span of fiber, e.g., intensity profile regeneration for On/Off keying (OOK) formats [61], noise cleaning [62], data packet processing [63], Raman amplification [64], spatial mode attraction [65]. Nevertheless, the common feature of all of these previous works is that the injection of an external reference pump wave is a prerequisite for the existence of the polarization attraction process.

At the opposite of this general rule, our recent experimental observations have demonstrated that a spontaneous polarization attraction process can also occur in the absence of any SOP reference beam in a device called Omnipolarizer [66]. In this novel solution, the signal beam interacts with its own counter-propagating replica generated at the fiber end thanks to a single reflecting component, e.g., Fiber Bragg-Mirror (FBG), coating or amplified reflective fiber loop setup [66–68]. In this particular case, the signal itself evolves in time towards a stationary state imposed by this self-induced nonlinear polarization attraction process. The aim of this paper is thus to provide a general overview of this phenomenon, as well as to highlight some new results and discuss future developments.

The paper is organized as follows: in the first two sections, we introduce the principle of operation and theoretical description of the Omnipolarizer. Then, we present in more details the experimental demonstration of self-induced polarization tracking of a 40-Gbit/s OOK signal reported in Ref. [66], enabling an error-free detection beyond a polarizer. In the second part of the manuscript we highlight a novel intriguing behavior of the Omnipolarizer, based on the strong local coupling between the two counter-propagating waves, which allows us to instantaneously induce a "jump" of polarization information onto the reflected signal, long before the expected time-of-flight into the fiber span, which may be described as a polarization-based tunneling effect. Finally, in the last sections we also discuss new perspectives for the generalization of the idea of self-organization to multimode fibers, and trace out our conclusions.

2. Principle of operation

The principle of operation of the Omnipolarizer is depicted in Fig. 1. The device basically consists in a few-km long standard optical fiber encapsulated in between an optical circulator at the input and a reflective element at the opposite end. In this configuration and in order to observe a self-induced repolarization process, an arbitrary polarized incident signal has to nonlinearly interact with its backward replica. For an efficient cross-polarization effect along the entire fiber length, the counter-propagating beams should propagate at least some few nonlinear lengths, where the nonlinear length reads as $L_{nl}=1/\gamma P$, with γ the nonlinear Kerr coefficient of the fiber and P the input power [71]. Therefore, in a typical configuration involving a 5-km long standard optical fiber with a Kerr coefficient $\gamma \approx 2\,\mathrm{W}^{-1}\,\mathrm{km}^{-1}$, a relatively high level of power close to 500 mW is necessary. *These are the typical fiber parameters allowing for an efficient repolarization. However we note that, for a precise and detailed analysis of the cross-polarization efficiency, the role of propagation losses should be carefully taken into account* [70] *as they reduce the average power along the fiber, which may considerably impact the cross-polarization nonlinear dynamics*.

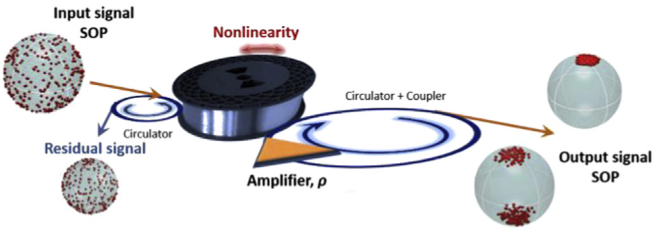

Fig. 1. Principle of operation of the Omnipolarizer.

Secondly, the Omnipolarizer can be characterized by its reflection coefficient ρ, which is defined as the ratio of power between backward and forward signals. Depending on the value of ρ, which has to be above 0.8 for an efficient interaction and can be even larger than 1 for specific purposes, two main operating regimes have been identified.

The first operating regime is the *bistable* regime, and is reached for a reflection coefficient below unity, typically $0.8 \le \rho \le 1$. Basically, it corresponds to a simple reflection at the fiber end, and thus can be also achieved by means of a mirror, a FBG, a special coating or an amplified reflective fiber loop with a moderate amplifier gain. In this regime, for any arbitrarily polarized input signal, two opposite poles of attraction for the output SOP can be identified on the Poincaré sphere (see Fig. 1). In practice, the sign of the input signal ellipticity defines which of the two SOPs is obtained in the output. Consequently, for an initially depolarized signal, i.e., quickly scrambled in time all over the Poincaré sphere, the output signal SOP distribution will be highly localized around both poles of the sphere at the fiber output (Fig. 1) [68].

In the second operating regime, the backward signal is amplified in such a way to achieve a reflective coefficient in the range of $1.2 \le \rho \le 2$. In this case, any arbitrarily polarized input signal is attracted towards a single output SOP, whose position over the Poincaré sphere can be controlled by means of the polarization rotation imposed by the feedback loop (practically by means of a classical polarization controller implemented into the reflective loop) [66–67]. Given that any input SOP vector over the Poincaré sphere is aligned to a unique SOP vector at the device output, we define this functionality as the *alignment* regime.

Finally, for larger reflection coefficients, i.e., $\rho \gg 1$, a chaotic dynamics can be reached, leading to an all-optical scrambling of the output polarization [72], which is briefly introduced in next section and discussed in more details elsewhere [73].

3. Theoretical description

In this section, we introduce the reader to the different regimes of the spatiotemporal dynamics of the Omnipolarizer. We indicate with $\mathbf{S}=[S_1,S_2,S_3]$ and $\mathbf{J}=[J_1,J_2,J_3]$ the Stokes vectors associated with the forward and backward beams, respectively, whereas $\mathbf{s}=\mathbf{S}/|\mathbf{S}|$ and $\mathbf{j}=\mathbf{J}/|\mathbf{J}|$ denote the corresponding unitary Stokes vectors which define the SOPs over the unit radius Poincaré sphere. The spatiotemporal dynamics of $\mathbf{S}$ and $\mathbf{J}$ in the fiber is ruled by the following coupled nonlinear partial differential equations [55]: