Observation of light-by-light polarization control and stabilization in optical fibre for telecommunication applications

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Abstract: In many photonics applications, especially in optical fibre based systems, the state of polarization of light remains so far an elusive uncontrolled variable, which can dramatically affect the performances of that systems and which one would like to control as finely as possible. Here, we experimentally demonstrate light-by-light polarization control via a nonlinear effect occurring in single mode optical fibre. We observe a polarization attraction and stabilization of a 10 Gbit/s optical telecommunication signal around 1550 nm. We also validate the potentiality of the device to annihilate very fast nanosecond polarization bursts. This result confirms yet another fascinating possibility to all-optical control the light properties in optical fibre.

OCIS codes: (060.4370) Nonlinear optics; fibers; (190.4370) Nonlinear optics, fibers; (230.4320) Nonlinear optical devices

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1. Introduction

Among the three independent features of a photon beam, e.g. number of photons, wavelength and state of polarization, the latter remains the most reluctant to control in many photonics applications, especially in optical fibre based systems [1,2]. In fact, while with the advent of the optical amplifier [3], the number of photons is nowadays easily controllable, as well as the current optical source devices are largely wavelength tunable [4,5], polarization of light remains so far the most elusive variable, which one would like to control as finely as possible. Indeed, despite the significant progress in the manufacturing process of optical fibres [6,7], the stochastic residual birefringence induces, after only a few kilometers of propagation, unpredictable polarization fluctuations [7–13]. Consequently, implementation of polarization sensitive devices such as silicon based high-contrast integrated optics [14,15] or photonic-crystal waveguides [16,17] are so far limited, thus delaying the development of future transparent networks. The attempts to control light polarization are currently based on two kinds of devices, i.e. the dissipative and the non dissipative elements. The first one is typically made of a polarizer, thus inducing a non-negligible amount of polarization depending losses. The output polarization is doubtlessly fixed and independent of the input but in that case, the input polarization fluctuations are transformed into intensity fluctuations at the device output, which is unacceptable in many practical applications. The second one is typically Lefebvre loops [18], wave-plates or electro-optic devices [19], which seem to be more attractive since it does not induce any polarization depending loss. This kind of devices allows transforming any input state of polarization into another state but the drawback is that resulting polarization fluctuations are the same as the input. In order to combat these impairments, current approaches allowing an active polarization control are based on optoelectronic elements coupled to feedback algorithms [19,20]. These systems are thus limited by the electronic response time and are not fast enough to master strong polarization variations [13]. Moreover, they cannot be compatible with wavelength division multiplexing applications. Because of their quasi-instantaneous responses, nonlinear effects occurring in optical fibres have recently paid considerable attention as a possible way to all-optical control light polarization. So far, Raman effect [21], Stimulated Brillouin scattering [22–24], photorefractive two beam coupling [25] and four-wave mixing in isotropic optical fibre [26–30] have been proved to be

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attractive solutions to master the state of polarisation, but without any convincing experimental demonstration stimulating future emerging applications.

Here, we report the experimental demonstration of an all-optical polarization attraction process enabling control and stabilization of the state of polarization of an incident light beam. Based on nonlinear interaction occurring in a 20-km long single mode optical fibre between two counter-propagating waves, this novel device can be considered as an ideal polarizer in the sense that both output intensity and polarization are independent of the input polarization. We experimentally show that the polarization of a 10 Gbit/s telecommunication signal can be efficiently controlled and stabilized, independently of its initial fluctuations, even if a very short nanosecond polarization burst is applied.

2. Physical considerations

The physic involved in our system relies on the nonlinear interaction occurring between two counter-propagating waves propagating in an optical fibre. Indeed, we have demonstrated in previous works that two waves, a pump wave and a signal wave, injected with opposite directions in a perfectly isotropic fibre, tend to equalize their polarization ellipticities all along the fibre length whereas, in the same time, the angle between the principal axes of the pump and signal polarizations is attracted towards a value that only depends on the initial difference between the signal and pump ellipticities [26–28]. More precisely, the polarization stabilization mechanism described in this paper relies on a resonant four-wave mixing (FWM) process which involves the two circular polarization components of each wave (pump and signal waves). Thanks to this FWM, the counterpropagating pump wave induces a unidirectional exchange of energy between the two circular polarization components of the signal wave, leading to the so-called polarization attraction effect. We would like to point out that the backward configuration is an essential physical ingredient to observe the polarization attraction process. Indeed, it allows the signal polarization fluctuations to be continuously washed out from the system thanks to a transfer of polarization entropy between pump and signal waves [26–28]. At this point, it is important to notice that if the pump wave is injected with a circular polarization, the polarization attraction basin reduces to a single point, so that the signal polarization will be attracted towards a unique circular polarization state imposed by the pump wave [26–28]. This remarkable polarization attraction effect has been experimentally observed in previous studies where it was highlighted that fibre isotropy was a key element of the experiment success, in the sense that any perturbation of this isotropy inexorably lead to a dramatic decrease of the attraction efficiency [26]. For this reason, previous experiments have been restricted to short fibre lengths (a few meters only) with very intense nanosecond pump and signal waves (more than 50 W) [29,30], such parameters being incompatible with telecommunications applications.

In this paper, we consider a long low-PMD optical fibre, which can be modelled by a cascade of elementary isotropic segments separated by linear polarization rotators (the two rotation angles characterizing each rotator being fixed arbitrarily) [9–11]. Actually, analytical study of such a nonlinear system involving counter-propagating waves constitutes a very complex task, far beyond the scope of this paper. Nevertheless, intuitive pictures of the mechanisms involved in such a system can be obtained from the simple physical considerations discussed in the previous paragraph. Indeed, one can easily expect that, after propagation in an elementary isotropic fibre segment, the signal polarization tends to get the local ellipticity determined by the pump wave as shown by Figs. 1a and 1b. If we now consider that the pump polarization ellipticity S_2^{pump} is arbitrarily changed between two adjacent segments (Fig. 1c), one can anticipate that, after propagation in a large number of elementary attractors, all the signal polarizations will be localized in the same hemisphere of the Poincaré sphere, so ellipticity difference between the pump and signal waves will be the same for all polarization states (Fig. 1d). Such a configuration allows the signal polarization to be attracted towards a unique attraction point, only fixed by the initial pump polarization and by the fibre properties. The main advantage of such a scheme is that, by increasing the

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nonlinear interaction length, one can significantly decrease the pump and signal powers required to observe the attraction.

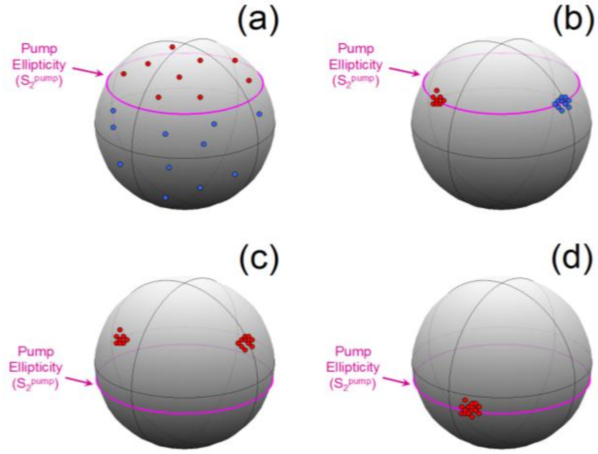

Fig. 1. (a) State of polarization at the input of a first isotropic section of fibre (b) Output of the first section (c) Input of the following section with change of the pump polarization (d) output of the section.

3. Experimental setup

Figure 2 illustrates the experimental setup. The polarization attractor consists of a 20-km long Non-Zero Dispersion-Shifted Fiber (NZDSF, D = 1.8 ps/km.nm at 1550 nm) characterized by a low polarization mode dispersion (PMD) of 0.03 $ps/km^{1/2}$. As mentioned in previous section, this weak value of PMD allows us to model the fiber as a concatenation of several ideal attractors such as described in ref [26,27]. The key advantage of such a configuration is that, compared to preliminary results obtained in nanosecond regime [29,30], increasing the nonlinear interaction length by three orders of magnitude enables to significantly decrease the average powers required to observe the attraction process. Moreover, because of the residual PMD of the fiber and its associated polarization random walk along the fiber length, the attraction phenomenon is no longer restricted to circular polarizations. The fiber is then coupled to two optical circulators so as to inject and monitor the two counter-propagating waves. The initial signal is made of an optical 2^{31}-1 return–to-zero pseudo random bit sequence (PRBS) cadenced at 10 Gbit/s with 30-ps pulses and a wavelength of 1548 nm (Photline Technologies Modbox). A polarization scrambler was also inserted in order to introduce random polarization fluctuations. Finally, before injection into the optical fiber, an Erbium doped fiber amplifier (EDFA) was used to reach the suitable average power of 300 mW. The counter-propagating pump beam, defined to control and stabilize the output polarization state of the signal, consists of a linearly polarized incoherent wave with a spectral bandwidth of 30-GHz centered around 1545 nm and an average power of 600 mW. At the system output, the signal polarization state was analyzed on the Poincaré sphere by means of a commercially available polarization analyzer. Finally, a 30-GHz bandwidth oscilloscope associated with a bit error rate (BER) analyzer allowed to monitor in real-time the intensity profile of the out coming pulses and signal quality.

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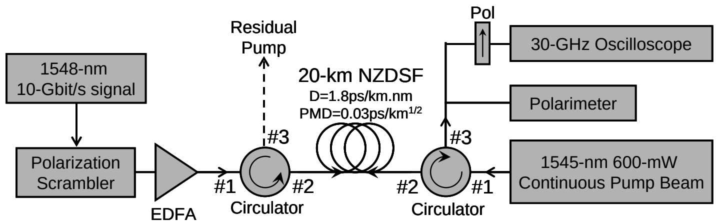

Fig. 2. Experimental setup. Pol Polarizer.

4. Experimental results

Figure 3a shows on the Poincaré sphere, the polarization state of the 10-Gbit/s signal at the input of the system. Because of the polarization scrambling process, the points are uniformly distributed onto the sphere. When the counter-propagating pump wave is injected into the optical fiber with a 600-mW average power, we clearly observe that most of the points are now localized into a small area, indicating an attraction and stabilization of the polarization state of the signal wave (Fig. 3b). At the same time, we can observe in Fig. 3c that the polarization fluctuations of the signal are vanished from the system by being transferred to the pump wave, which is now roughly scrambled at the output of the fibre. Such fluctuation exchanges ensure conservation of the global polarization entropy of the system.

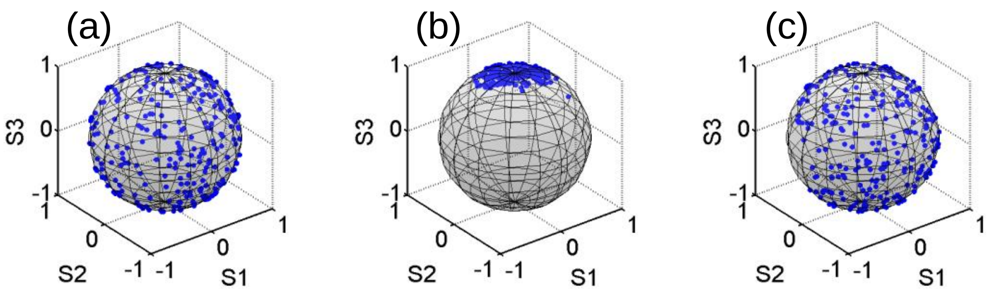

Fig. 3. Experimental observation of the polarization stabilization effect on the Poincaré sphere: (a) polarization of the signal wave at the system input (b) Signal polarization after nonlinear interaction with the counter-propagating pump wave. The pump and signal powers were 600 mW and 300 mW, respectively (c) Output polarization of the pump wave.

The efficiency of the polarization attraction process is more striking when monitored in the temporal domain. To this aim, we have inserted a polarization depending device, i.e. a polarizer at the output of the system (Pol in Fig. 2). We have then recorded the 10-Gbit/s output signal eye diagrams by means of a 30-GHz bandwidth oscilloscope. Figure 4 represents the eye-diagrams of the initially polarization scrambled signal monitored after the polarizer without (Fig. 4a) and in presence (Fig. 4b) of the counter-propagating pump beam. In the pump-free configuration (Fig. 4a), the polarization fluctuations are transformed into intensity fluctuations through the polarizer, leading to a complete dramatic closure of the eye-diagram. By injecting the counter-propagating pump wave (Fig. 4b), a clear polarization stabilization is obtained. As can be seen, all the out coming pulses have now almost identical polarizations, so that the opening of eye-diagram is now efficiently recovered.

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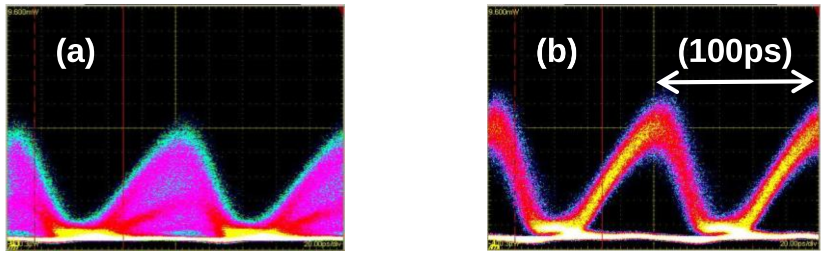

Fig. 4. Eye-diagrams of the 10-Gbit/s signal at the system output and monitored behind a polarizer (a) without and (b) in presence of the counter-propagating pump beam.

We have also measured the corresponding bit-error-rate (BER) of the 10-Gbit/s signal as a function of the average power incoming on the receiver (Fig. 5a). The reference is illustrated by the back-to-back configuration (i.e. at the fiber input) in blue crosses. At the output of the system, when the polarization of the signal is scrambled, corresponding to the eye-diagram of Fig. 4a, the BER is limited to 10^{-5} (green triangle). When the counter-propagating pump wave is injected (red circles), the quality of the transmission is greatly improved and low BER penalties were obtained on the receiver.

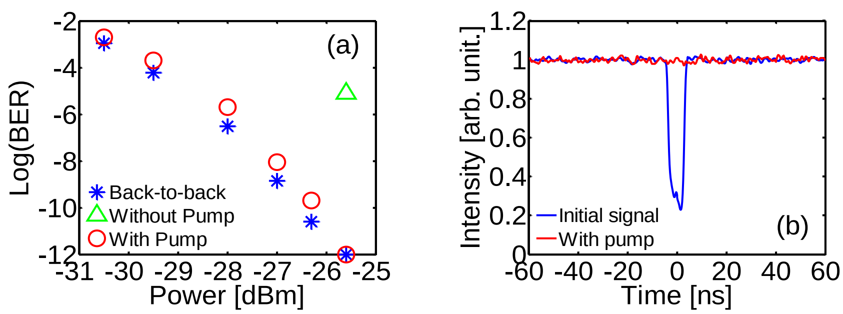

Fig. 5. (a) Evolution of the bit error rate as a function of average power in back-to-back configuration (blue crosses); at the output of the system, with polarization scrambling and after a polarizer with (red circles) and without (green triangle) the counter-propagating pump beam (b) Intensity profile of the 6-ns polarization burst observed after a polarizer by means of a low bandwidth oscilloscope, without (blue line) and with (red line) counter-propagating pump wave.

Finally, we have monitored the ability of our system to annihilate a polarization burst, i.e. a strong and fast variation of the polarization signal state [13]. Such a dramatic event is fortunately rare but could be observed in a telecommunication line and is difficult to avoid with present systems based on active electronic feedback [19]. To this aim, a polarization burst, having a temporal width of 6 ns, was introduced into the initial 10-Gbit/s signal by means of a 15-GHz bandwidth optoelectronic polarization modulator. Figure 5b shows the intensity profile of the polarization burst, observed with a low bandwidth oscilloscope at the output of the system and detected after a polarizer. In absence of counter-propagating pump beam, Fig. 5b in blue line, we observe a strong variation of the intensity, which could be disastrous for any sensitive polarization component. When the pump beam is injected, red line, the polarization burst was efficiently reduced by the attraction process, leading to an error-free transmission (BER = 10^{-12}). Before conclusion, we would like to indicate the principal physical factors that limit the attraction process efficiency. The first one is clearly the Polarization Mode Dispersion (PMD) of the fiber, which should be as low as possible. Indeed, the four-wave mixing process responsible for the polarization attraction effect is, in theory, exactly phase-matched only in a perfectly isotropic fiber. In practice, we have checked that the efficiency of the polarization stabilization starts to decrease significantly only for PMD values greater than 0.05 ps/km$^{1/2}$. Another issue which have to be managed in our system is the spontaneous Brillouin scattering. As well known, once the Brillouin threshold is

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reached, this effect manifests itself by the generation of backward-propagating Stokes waves. Nevertheless, this effect can be significantly reduced by using a pump wave having a large spectral bandwidth combined with a 100-MHz phase modulation for the signal wave. Finally, it should be noted that the temporal and spectral profiles of the signal wave can be slightly affected by various nonlinear effects, such as self-phase modulation, which are susceptible to occur during the propagation in the optical fiber.

5. Conclusions

In conclusion, we have reported the experimental observation of an all-optical polarization attraction process allowing control and stabilization of the state of polarization of a 10-Gbit/s optical signal at 1550 nm. This phenomenon is based on a four-wave mixing process and was observed thanks to the injection of a counter-propagating pump wave, involving average powers below 1 W. We have also demonstrated that our optical device could strongly reduce intense and fast polarization variations as short as 6 ns. Moreover, it is important to note that the attraction process is only sensitive to signal and pump average powers so that the device could be compatible with higher bit rates and other modulation formats, such as phase modulation formats.

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