Universal polarization domain walls in optical fibers as topological bit-entities for data transmission

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Abstract: We demonstrate the existence of a universal class of polarization domain-walls in conventional optical fibers. We exploit these topological polarization knots as bit-entities for data transmission beyond the Kerr limits of normally dispersive fibers.
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1. Introduction

A domain wall (DW) is a type of topological defect that connects two spatial stable states of a physical system. Despite the fact that DWs are widely studied in ferromagnetic materials [1], in which they bind regions of spins or magnetic dipoles aligned in different directions, it is important to note that their equivalent in optics have been poorly exploited so far. Originally, optical DWs refer to vectorial structures that have been predicted theoretically by M. Haelterman in the defocusing regime of an isotropic single-mode fiber more than 20 years ago [2]. They are fundamentally related to the Berkhoer and Zakharov modulational instability phenomenon [3]. The domain wall corresponds to a localized structure of the kink type that connects two regions of space with different polarizations: In the transition region, the electromagnetic field switches between two stable states with orthogonal circular polarizations. In this framework, the fast polarization knots leads to two anticorrelated coupled twin-waves for which the strong binding force imposed by cross-phase interaction can compensate for linear and nonlinear impairments induced by chromatic dispersion and self-phase modulation, respectively. The polarization distribution is then locked along the propagation within well-defined and robust temporal regions interconnected by polarization domain walls (PDWs) [2]. In 1999, Kockaert *et al.* have experimentally investigated the vectorial modulational instability process in a small piece of one meter isotropic fiber and reported an indirect observation of anticorrelated polarization dynamics [4]. Here we report the first direct observation of PDWs in classical optical fibers commonly used in optical communications. In this way, we show that, at variance with traditional PDWs [2-4], conventional fibres exhibit previously unrevealed distinguished properties, which support the existence of PDWs in any arbitrary polarization basis. For this reason, the novel class of polarization structures reported here has been qualified as universal PDW. We provide an experimental demonstration of the existence of these fundamental structures and exploit their unique topological properties for optical data transmission beyond the nonlinear Kerr-induced limitations of classical normally dispersive fibers.

2. Experimental results

In order to generate a periodic train of PDWs, we have implemented the experimental setup of Fig. 1. A 1555-nm continuous-wave was first intensity modulated by 30-ps square-shape pulses at a repetition rate of 14 GHz. This pulse train is then split in 2 out-of-phase, delayed and polarization multiplexed fields so as to obtain a pure orthogonal polarization flip-flopping at 28-GHz. After amplification, these PDWs are injected into a 10-km long normally dispersive standard fiber (TWHD from ofs D = –14.5 ps/nm/km at 1555 nm).

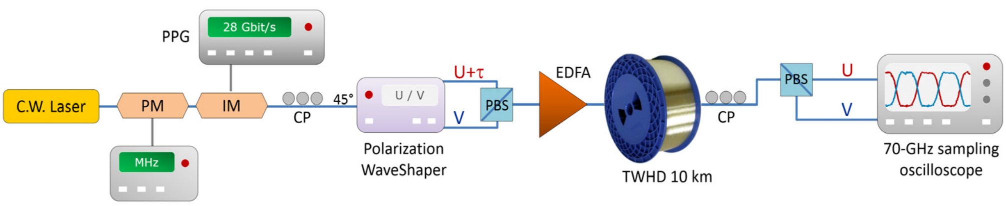

Fig. 1. Experimental setup.

Figure 2a illustrates the signal monitored at the output of the 10-km long fiber as a function of the injected power when only one polarization component of the domains is injected. Due to the combined effects of chromatic dispersion and self-phase modulation, the output signal is rapidly deteriorated into a complex periodic pattern, which subsequently leads to the development of shock-wave (wave breaking) singularities inherent to the defocusing regime considered here. In contrast, as shown in Fig. 2b, when both orthogonally polarized twin-waves are injected into the fiber (independently of the input polarization basis), the cross-phase modulation locks the two signals one with each other in a symbiotic fashion. In fact, as a chain of particles trapped in a periodic potential, here the energy contained in each domain is confined due to the perfect balance between chromatic dispersion, self-phase modulation and cross-phase modulation occurring at the domain interfaces.

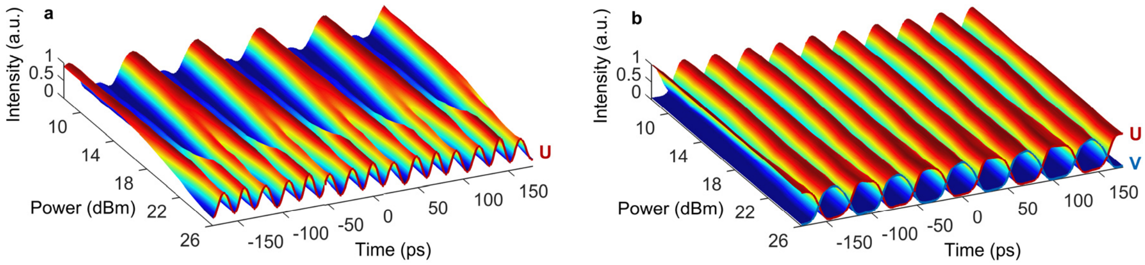

Fig. 2 Intensity profile of the output signal as a function of power (a) A single polarization component propagates (b) Both twin-waves propagate.

In order to confirm that the system propagates genuine kink solitons, we have assessed the capability of PDWs to transmit optical data. To this aim, we propagate a 10-Gbit/s binary sequence corresponding to the ASCII code of the ERC project acronym PETAL. The encoded PDWs propagate in a first 25-km long reel of TWHD fiber before amplification and propagation in a second span of 25 km. Figure 3a illustrates the PETAL sequence monitored after 50 km of propagation as a function of the transmitted power when only one of the two twin-waves is injected. In this case, we clearly observe a significant signal degradation leading to a complete loss of the data. In contrast, when both twin-waves propagate simultaneously (Figure 3b), we can clearly observe that the energy remains efficiently locked within each well-defined temporal regions. These observations confirm the capacity of PDWs to be addressed individually as well as the solitary nature of such kink structures.

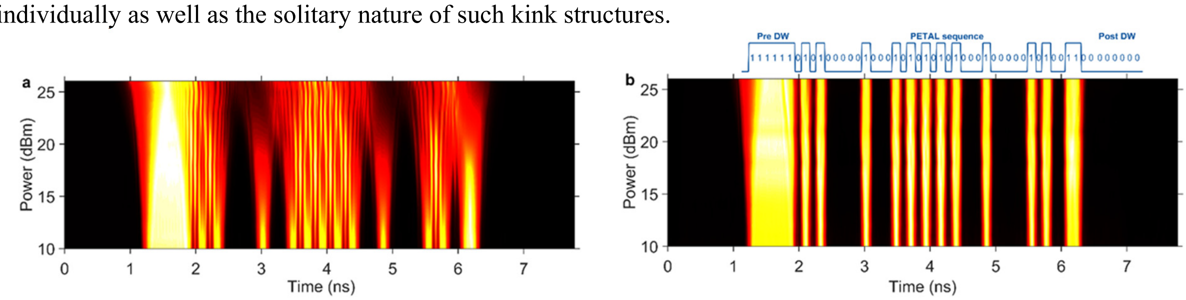

Fig. 2 Intensity profile of the 10-Gbit/s PETAL sequence after 50 km of propagation as a function of injected power (a) A single polarization component propagates (b) Both twin-waves propagate.

4. Conclusion

In conclusion, we report the first experimental demonstration of polarization domain walls propagation in conventional telecom optical fibres. We have exploited their symbiotic and topological properties to establish a 10-Gbit/s data transmission beyond the Kerr-induced limitations usually imposed in classical optical fibres. We stress that the present observation of PDWs in standard optical fibers goes against the commonly accepted opinion that the Manakov equations accurately model light propagation in random birefringent telecom fibers, since this model is inherently unable to support PDWs. We ascribe the present observations to the fast spinning process imposed on modern manufactured fibres, which leads to an effective cancelling of random birefringence. This spinning effect then turns randomly birefringent fibres into a new type of fibres whose properties are at the frontier between the traditional Manakov fibres and isotropic-like fibres, which allows for universal PDWs propagation in any arbitrary polarization basis. Finally, recent results will also be presented which reveal the spontaneous emergence of synchronized PDWs from a system of incoherent random waves, leading to a remarkable phenomenon of polarization segregation, in analogy with order–disorder phase transitions in ferromagnetic materials.

5. References

[1] A. M. Kosevich, "Dynamical and topological solitons in ferromagnets and antiferromagnets". In Solitons (Elsevier, 1986)

[2] M. Haelterman and A. P. Sheppard, "Polarization domain walls in diffractive or dispersive Kerr media," Opt. Lett. **19**, 96-98 (1994).

[3] A. L. Berkhoer and V. E. Zakharov, "Self excitation of waves with different polarizations in nonlinear media," JETP **31**, 486-490 (1970).

[4] P. Kockaert, M. Haelterman, S. Pitois and G. Millot, "Isotropic polarization modulational instability and domain walls in spun fibers," Appl. Phys. Lett. **75**, 2873-2875 (1999).