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Distributed polarimetric measurements for optical fiber sensing

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ABSTRACT

Distributed polarimetric measurements based on Rayleigh scattering in single mode optical fibers are effective tools for the characterization of the polarization properties of fibers. Since these properties are easily influenced by external perturbations, distributed polarimetric measurements turn out to be an interesting approach to distributed fiber optic sensors. This paper reviews the field putting emphasis on its underlying principles and unique applications, such as magnetic field mapping and twist measurement.

1. Introduction

The ability of measuring a physical field with continuity along a path is a unique feature of fiber optic sensors (FOSs). These distributed sensors (DFOSs) are based on the scattering processes—namely Brillouin, Raman and Rayleigh scattering, that take place in the fiber when it is probed with a properly prepared optical signal [1–4]. In most of the applications, these sensors are based on the observation of either amplitude, frequency or phase of the backscattered light. Nonetheless, there is a class of DFOSs that are based on the observation of backscattered light polarization. In principle, this approach can be applied to all the three kinds of scattering; yet, in practice, polarization has been so far considered only in Rayleigh based DFOSs.

Polarization-based DFOSs exploit the fact that polarization in single-mode fibers can be easily influenced and modified by the external environment. Actually, any small perturbation breaking the cylindrical symmetry of the ideal fiber may induce detuning and coupling between the two (ideally degenerate) fundamental modes, resulting in a polarization variation of both the forward propagating light and the corresponding backscattered one. This effect can be exploited to implement a distributed sensor and, indeed, polarization-based DFOS has been the first distributed sensor ever proposed. Actually, the original idea dates back to 1980, when Rogers proposed the polarization optical time domain reflectometer (P-OTDR) to distributedly measure polarization variation along the fiber for sensing purpose [5,6]. It is worthwhile remarking that Rogers did not simply proposed a DFOS, but put forth the idea of distributed sensing itself. In fact, while the OTDR had been suggested by Barnosky and Jensen already in 1976 [7,8], the first proposal of an OTDR as a distributed sensor was made by Hartog et al. only in 1983 [9]. Similarly, Raman-based DFOSs have been publicly proposed not earlier than 1984 by Rogers himself [10] and in 1985 by Dakin et al. [11] (Dakin filed also a patent in 1983 [12]), while Brillouin-based DFOSs were first suggested in 1989 [13,14].

Differently from DFOSs based on the analysis of amplitude, frequency or phase of the backscattered light, which have found successful commercial application, and despite they are the forerunners of distributed sensors, polarization-based DFOSs are not yet a mature technology and are still subject of research activity. Actually, Rogers' original idea was indeed sound and ushered in a general interest about distributed sensors; however, it soon turned out that exploiting the full potential of light polarization is not easy. There are two main problems hindering the development of polarization-based DFOSs.

The first one is the fact that polarization variation is not due only to the external physical field under monitoring, but it is also greatly affected by fiber intrinsic asymmetries, induced during production and cabling. Typically, the latter effect dominates the former, and as a result a polarization-based DFOS must have a rather high spatial resolution even when the targeted spatial resolution on the physical field is not so high. This constraint clearly arises technical difficulties. The second problem is that the measured quantity, i.e. the polarization of the backscattered light, is not directly related to the local properties of the fiber, but it is affected by the whole roundtrip propagation. Consequently, local properties can be retrieved only after an inverse scattering problem has

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been solved, and this has requested the development of an accurate theoretical model and proper data analysis algorithms.

As a consequence, after Rogers proposed the P-OTDR as a tool to implement a DFOS, only few practical examples were made, barely proving the concept [15–17]. Differently, most of the attention turned to the use of P-OTDR (or more in general of polarization sensitive reflectometry) to the statistical characterization of polarization properties of telecommunication fibers, in the framework of the research activity about polarization mode dispersion, which in the 1990s and early years of 2000 was considered one of the ultimate obstacles to the increase of transmission capacity [18–29]. Actually, the statistical nature of those investigations allowed to relax constraints on spatial resolution, enabling the use of less performing experimental setups and simplified theoretical models.

The increasing general interest about FOSs, however, revived attention also on polarization-based DFOSs [30–52], which indeed offer unique features. Actually, beside being able to sense quantities like temperature and strain, that can be sensed also by other non polarization-sensitive techniques [2–4], polarization-based DFOSs have the unique ability of distributedly sensing also twist and magnetic field, two applications that are unparalleled by other approaches.

This paper reviews principles and recent developments of Rayleigh-based distributed polarization sensors. The practical implementation of polarization DFOSs is discussed in Section 2, whereas Section 3 summarize the main aspects of the theoretical model describing polarization-based DFOSs. While most of the mathematical details are not reported for simplicity, the Section highlights the main principles that characterize distributed polarization measurements. Finally, Section 4 describes the main applications, with emphasis in particular on magnetic field and twist sensing.

2. Experimental setup

Distributed polarimetric fiber optic sensors are based on the measurement of the state of polarization (SOP) of the backscattered light, which varies as a function of the scattering position in response to external perturbations, as described in details in the following section. In general, this kind of measurements can be performed with a polarization-sensitive version of a standard reflectometer. To this aim, both optical time domain reflectometers (OTDR) and optical frequency domain reflectometers (OFDR) can and have been used. The two solutions differ substantially in term of measurement range, spatial resolution, accuracy and measurement time.

Polarization sensitive OTDR (P-OTDR) can achieve measurement range in the order of several kilometers, but its spatial resolution, which is set by the length of the probe optical pulse, is typically larger than half a meter [24]. Moreover, the measurement time can be in the order of minutes. An alternative is represented by photon-counting OTDR [51]. This reflectometer has spatial resolution in the order of centimeters, but the measurement time is even longer. Conversely, OFDR-based solutions (P-OFDR) achieve much higher spatial resolution, in the order of few millimeters, but the measurement range is limited to few tens of meters [53–55]. Longer ranges can be achieved compromising on spatial resolution. P-OFDR may take advantage of high-speed wavelength-scan lasers, so that typically it is faster that P-OTDR, and measurements can be taken in few tens of seconds. Furthermore, owing to the high sensitivity of their coherent receiver, P-OFDRs are usually more accurate than P-OTDR in measuring the SOP, and may achieve relative uncertainty below 1% (defined as the mean uncertainty on the components of the 3-dimensional unit Stokes vector).

Independently of which kind of reflectometer is used, two main approaches to the measurement of the backscattered SOP may be envisaged, depending on whether the measurement should retrieve partial or complete information; correspondingly, setup and data analysis procedure are less or more complex. In the simplest case (Fig. 1(a)), a polarizer is interposed between the reflectometer and the sensing fiber. In this way, both the probe light and the backscattered one are polarized, and variations of the backscattered SOP are converted in power fluctuations. As described in Section 3, the speed of these fluctuations is related to local birefringence strength; nevertheless, other properties such as birefringence orientation cannot be recovered by this scheme.

The second approach (Fig. 1(b)) aims at measuring the complete SOP of backscattered light. This can be achieved by separating the forward path from the backward one, and inserting a polarization analyzer in the latter. A common solution consists in cascading a rotating quarter wave-plate and a fixed polarizer [56]. Repeating the measurement of the backscattered power for at least four known orientations of the quarter wave-plate allows to calculate the SOP for each scattering point. Other configurations can be envisaged. Of course, if the reflectometer is custom build, the polarization analyzer can be inserted just before the receiver, avoiding the use of the double circulators. Furthermore, OFDRs typically have polarization-sensitive receivers that provides amplitude and phase of the two polarization components [57]. These data are enough to calculate the SOP, relieving from the need of and external polarization analyzer. Finally, solutions based on multi-port polarization analyzers coupled with multiple receivers have been proposed too [58].

The measurement of the complete backscattered SOP brings a richer, yet still not complete, information about the fiber. Actually, the complete polarization characterization of the fiber requires the measurement of its representative matrix, which can be achieved by measuring the backscattered SOP for at least two different input SOPs. For this reason the schematic shown in Fig. 1(b) has a polarization controller in the forward path. As described in Section 3, by properly analyzing the raw data provided by this measurement procedure enable a complete characterization of fiber polarization properties. Clearly, this comes at the cost of an increase in measurement time.

3. Propagation of polarization in optical fibers

In order to understand limits and potentials of polarization DFOSs, it is worthwhile analyzing with some detail the underlying theoretical principles.

If we neglect polarization dependent loss, which are negligible in optical fibers, the state of polarization (SOP) of light can be represented in the 3-dimensional real space of unit Stokes vectors [56]. Accordingly, the SOP of forward propagating light can be expressed as $\hat{s}(z) = \boldsymbol{F}(z)\hat{s}_0$, where z is the longitudinal coordinate along the fiber, $\hat{s}_0$ and $\hat{s}(z)$ are the 3D unit Stokes vectors representing SOP at the fiber input and at z, respectively, and $\boldsymbol{F}(z)$ is the Mueller matrix (3×3 and real) representing forward propagation along the fiber. We recall that Mueller matrices are orthogonal and represent rotations in the Stokes space [59]. Consequently, the variation of $\boldsymbol{F}$ with z can be written as

$$\frac{d\boldsymbol{F}}{dz} = \bar{\beta}(z) \times \boldsymbol{F}(z), \quad \boldsymbol{F}(0) = \boldsymbol{I}, \tag{1}$$

where $\boldsymbol{I}$ is the identity matrix, and $\bar{\beta}(z) = (\beta_1, \beta_2, \beta_3)^T$ is the birefringence vector, a mathematical quantity that summarizes the local effects of all the perturbations that act on the fiber at z.[1] Equivalently we can also write

[1] Simple algebraic considerations allow to consider $(\bar{a}\times)$ as a linear operator, whose expression is a 3×3 skew-symmetric matrix [59].