Sensitivity of Polarization Maintaining Fibres to Temperature and Strain for Sensing Applications

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The sensitivity of a polarization maintaining fibre (PMF) to external effects has been investigated. Using a polarimeter, the evolution of the state of polarization (SOP) on the Poincaré sphere was observed for the light transmitted into a PMF as a function of temperature and longitudinal strain. In theses conditions, the SOP describes a circle on the Poincaré sphere. Temperature and strain have proven to communicate a linear behaviour to the rotation angle described by the SOP on the Poincaré sphere. The authors also discuss the feasibility of a distributed sensor exploiting this phenomenon.

Work position

On today's industry market, sensors are no more important but mandatory. Their applications are sparse: manufacturing monitoring, people and goods security, smart structures, etc. Within all these possible applications, the demand for distributed sensors is continuously increasing.

This paper proposes to analyze the sensitivity of Polarization Maintaining Fibres (PMF) to temperature and strain for sensing applications. The analysis has been performed using a polarimeter. Results are presented and are supported by simulations. An interesting issue exploiting the PMF sensitivity is discussed and concerns the distributed measurement of the temperature or strain via a reflectometry technique.

Polarization in PMF – Theoretical background

In electrodynamics, *polarization* is the property of electromagnetic waves, such as light, that describes the direction of their transverse electric field. More generally, the state of polarization (SOP) is the pattern drawn in the transverse plane by the extremity of the electric field vector as a function of time at a fixed position in space. That pattern represents an ellipse that can degenerate into a circle (circular polarization) or a straight line (linear polarization).

The *birefringence* in optical fibres is defined as the difference in refractive index between a particular pair of orthogonal polarization modes (called the eigenmodes) and results from the presence of asymmetries in the fibre section.

The Polarization Maintaining Fibre (PMF) intentionally creates consistent linear birefringence pattern along its length, prohibiting coupling between the two orthogonal polarization directions.

Two parameters are needed for the representation of linear polarization in optical fibres: δ, the phase retardance between the two orthogonal linear states, and q, the azimuth of the fastest linear polarization mode with respect to *Ox*.

The *beat length* is a length of fibre through which the polarization SOP is recovered whatever the input SOP (i.e. the polarized light undergoes a complete revolution of polarization). PMF exhibit a beat length of about 3 mm.

Polarization effects can be described by a mathematical formalism based on a matrix representation. In the Stokes formalism, a state of polarization is represented by a four-dimensional vector S, called the Stokes vector.

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad \text{where} \quad \begin{aligned} S_0 &= \textit{Total amount of power} \\ S_1 &= P_0 - P_{\frac{\pi}{2}} \\ S_2 &= P_{\frac{\pi}{4}} - P_{\frac{-\pi}{4}} \\ S_3 &= P_{CR} - P_{CL} \end{aligned}$$

where P_θ denotes the power of the light passed through a linear polarizer set at an angle θ with the x axis. P_{CR} and P_{CL} represent the optical powers of the light after passing though a right- or left-handed circular polarizer, respectively.

It is generally more common to work with the normalized Stokes parameters, where $s_i = S_i / S_0$ (for i=1 ..3). Consequently, the normalized Stokes parameters vary from -1 to +1. They can be assigned to the Cartesian coordinates *xyz*. Then, any given state of polarization, i.e. any given triplet (s_1, s_2, s_3), corresponds to a unique point on or within a sphere: the Poincaré sphere. That sphere is a powerful and elegant graphical tool for describing states of polarization transformation induced by optical systems. It is represented on figure 1. The two poles of the sphere represent left and right-hand circularly polarized light. Points on the equator indicate linear polarizations. All other points on the sphere represent elliptical polarization states

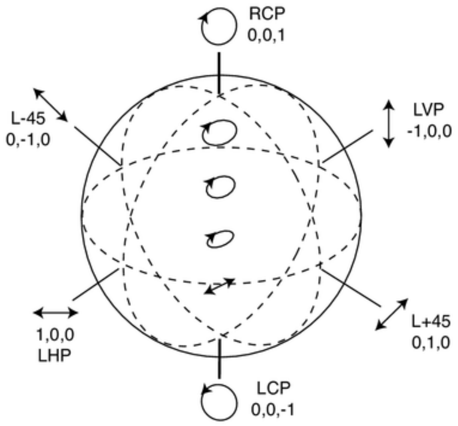

***Figure 1**: Poincaré Sphere. Any given polarization state corresponds to a unique point on the sphere. The two poles of the sphere represent left- and right-hand circularly polarized light (LCP and RCP respectively). Points on the equator indicate linear polarizations (L)*

Experimental results

The experimental setup is presented in figure 2. During operation, the laser source injects a light signal into the PMF via a linear polarizer in order to fix the state of polarization of the light launched into a 2 meters long bow tie fibre. The outgoing signal is then analyzed with the polarimeter. A *polarimeter* is an instrument indicating on the Poincaré sphere the state of polarization of a given light signal.

Depending on the physical effect under study, the PMF is either placed into a temperature controlled oven, or subject to controlled longitudinal strain.

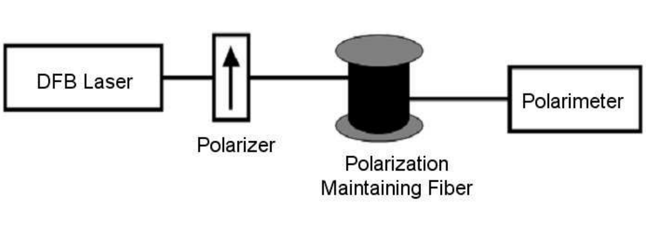

***Figure 2**: The polarimeter permits one to visualize on the Poincaré sphere the evolution of the light signal going out of the PMF.*

The figures 3a and 3b represent two snapshots of the same Poincaré sphere illustrating the SOP evolution of the light outgoing the PMF when the latter is placed into the temperature controlled oven between 0°C and 60°C. At 0°C, the SOP occupies a fixed position on the sphere. When temperature increases till 60°C, the SOP describes a certain number of circles. The rotation angle behaves linearly with temperature and its evolution is represented on figure 5. The behaviour of the PMF has proven to be very sensitive to temperature: 2.73 rad/°C.

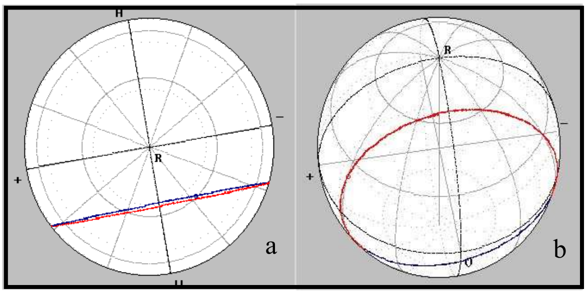

Figure 3 (a, b)*: Two snapshots of the evolution of the SOP of the light outgoing the PMF subject to a temperature variation between 0°C and 60°C.*

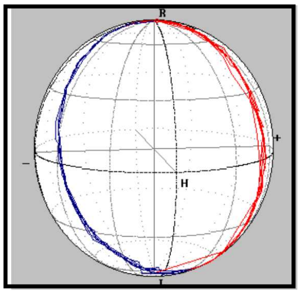

Figure 4*: Evolution of the SOP of the light outgoing the PMF subject to longitudinal strain*

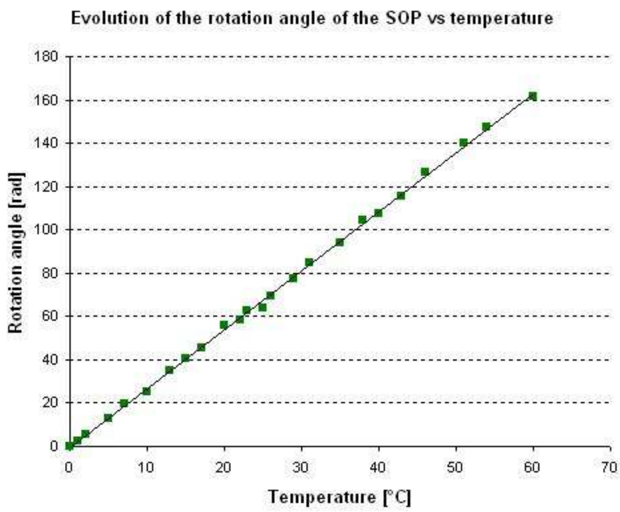

Figure 5: *Evolution of the rotation angle of the SOP on the Poincaré sphere when the PMF is subject to temperature*

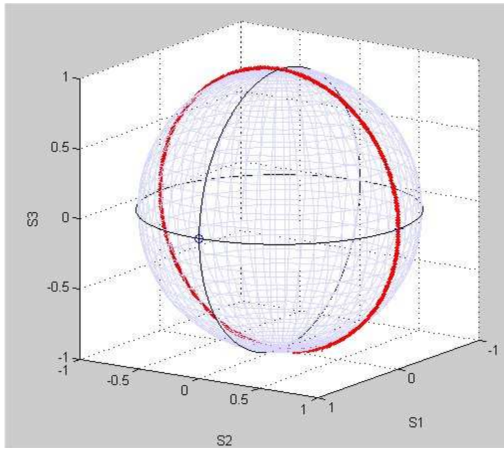

Figure 6: *Simulation of the evolution of the rotation angle of the SOP on the Poincaré sphere*

Similarly, figure 4 represents the evolution of the SOP of the light signal outgoing the PMF when the latter is subject to a controlled longitudinal strain. Here, again, the SOP clearly describes a circle. But the setup doesn't permit to quantify the strain.

In the Stokes formalism, the transmission matrix of an optical system is represented by a 4x4 matrix of real numbers, the Mueller matrix. It relates the input and output Stokes vectors of the optical device. For a given PMF of length L and whose polarization parameters are δ and q, the corresponding Mueller matrix can be written as [1]:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2\frac{\delta L}{2} + \sin^2\frac{\delta L}{2}\cos 4q & \sin^2\frac{\delta L}{2}\sin 4q & -2\sin\frac{\delta L}{2}\cos\frac{\delta L}{2}\sin 2q \\ 0 & \sin^2\frac{\delta L}{2}\sin 4q & \cos^2\frac{\delta L}{2} - \sin^2\frac{\delta L}{2}\cos 4q & 2\sin\frac{\delta L}{2}\cos\frac{\delta L}{2}\cos 2q \\ 0 & 2\sin\frac{\delta L}{2}\cos\frac{\delta L}{2}\sin 2q & -2\sin\frac{\delta L}{2}\cos\frac{\delta L}{2}\cos 2q & \cos^2\frac{\delta L}{2} - \sin^2\frac{\delta L}{2} \end{pmatrix}$$

In the case of a PMF whose eigenmodes are properly placed with respect to the coordinates system (q=0), the matrix reduces to:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta L & \sin\delta L \\ 0 & 0 & -\sin\delta L & \cos\delta L \end{pmatrix}$$

With properly chosen input Stokes vector - representing light linearly polarized at $\pi/4$ with respect to Ox ($s_1=s_3=0$, $s_2=1$), the corresponding output Stokes vector reduces to ($s_1=0$, $s_2= \cos\delta L$, $s_3= -\sin\delta L$), without loss of generality.
Therefore, the linear variation of the rotation angle of the circle described by the SOP on the Poincaré sphere directly corresponds to a linear variation of the δ parameter. In other words, in PMF, the birefringence is directly proportional to temperature.
Simulations have also been undertaken. The PMF was modelled as a 5 meters long fibre, with a 3 mm beat length and with various q angles. Various input angles were considered. Results were presented on a Poincaré sphere, as the example illustrated on figure 6 where the polarizer at the fibre's input is oriented at $\pi/4$ with respect to the fast axis of the modelled PMF. The linear behaviour of the rotation angle of the SOP was observed when δ was subject to a linear increase.

Conclusion - Discussion

This paper presents the experimental and simulation study of the sensitivity of PMF to external physical effects like temperature and longitudinal strain.
In our experiments, the birefringence in PMF has exhibited a linear behaviour with respect to temperature with a high sensitivity (2.73 rad/°C). A direct measurement of a temperature change is therefore possible through analysis of the SOP. Longitudinal strain measurements did also led the SOP to describe circles, but the current setup doesn't allow us to quantify the applied strain and therefore to draw conclusions.
Distributed sensors usually deal with reflectometry techniques. In the past, we have developed a Polarization OTDR (Optical Time Domain Reflectometer) allowing the distributed measurement of the birefringence along an optical fibre [2]. As small resolution lengths are needed for the PMF study (as the beat length is about 3 mm), OFDR (Optical Frequency Domain Reflectometry) technique should be used instead of OTDR, as it permits to decrease the resolution length to the sub-centimetre scale. A distributed temperature or strain measurement is then possible along a PMF.

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References

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