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

C. Crunelle, M. Wuilpart, P. Mégret
cathy.crunelle@fpms.ac.be

POLYTECH.MONS

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.

Polarization basics

In electrodynamics, polarization is the property of electromagnetic waves, such as light, that describes the direction of their transverse electric field.
→ 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. It 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)

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
- q, the azimuth of the fastest linear polarization mode with respect to Ox.

Polarization representation

Polarization effects can be described by a matrix representation.

Stokes formalism: a SOP is represented by a 4-dimensional Stokes vector S.

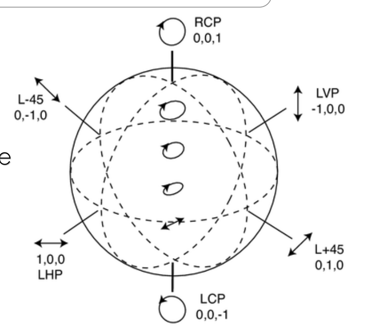
$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \text{ where } \begin{cases} S_0 = \text{Total amount of power} \\ S_1 = P_0 - P_{\frac{\pi}{2}} \\ S_2 = P_{\frac{\pi}{4}} - P_{\frac{-\pi}{4}} \\ S_3 = P_{CR} - P_{CL} \end{cases}$$

P_θ = light power passed through a linear polarizer set at θ with respect to Ox
P_{CR} (P_{CL}) : light powers after passing though a right- (left-) handed circular polarizer

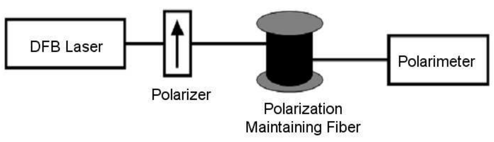
We usually deal with normalized Stokes parameters $s_i=S_i/S_0$ (i=1..3)

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 the transformation induced in the states of polarization by optical systems.

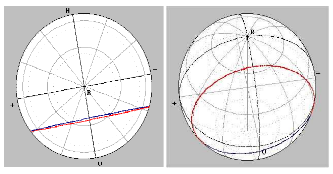
A polarimeter can be used to visualize any SOP on the Poincaré sphere.



Experimental results - Simulations



During operation, the laser source injects a light signal into the PMF (2 meters long bow tie fibre) via a linear polarizer in order to fix the state of polarization of the launched light. The outgoing signal is then analyzed with the polarimeter.

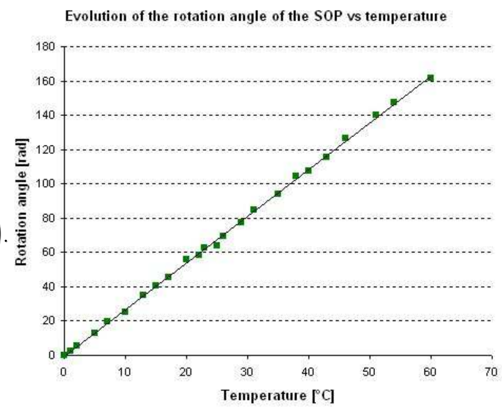


SOP variation when the PMF is subject to temperature: 2 snapshots of the polarimeter screen

For the temperature dependence study, the PMF is placed into a temperature controlled oven

At 0°C, the state of polarization (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.

The behaviour of the PMF has proven to be very sensitive to temperature: 2.73 rad/°C. That corresponds to a 0.2 mm variation in beat length for a 100°C variation (from 3mm to 2,8mm).



Longitudinal strain measurements did also led the SOP to describe circles, but the current setup doesn't allow us to quantify the applied strain.

In the Stokes formalism, the transmission matrix of an optical system is represented by a 4x4 matrix of real numbers, the Mueller matrix M. It relates the input and output Stokes vectors, S_{in} and S_{out}, of the optical device: $S_{in} = M \cdot S_{out}$

For a PMF of length L and whose polarization parameters are δ and q, the corresponding Mueller matrix M can be written as:

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

For a PMF whose eigenmodes are properly placed with respect to the coordinates system (q=0), M reduces to:

reduces to →

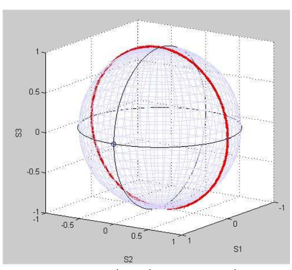
$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta L & \sin\delta L \\ 0 & 0 & -\sin\delta L & \cos\delta L \end{pmatrix}$$

It implies →

At $s_{in} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ corresponds $s_{out} = \begin{pmatrix} 0 \\ \cos\delta L \\ -\sin\delta L \end{pmatrix}$

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.



SOP variation when the PMF is subject to temperature: simulation

Simulations have also been undertaken. The PMF was modelled as a 5 meters long fibre, with a 3 mm beat length. Different q angles and different input angles were considered. Results were presented on a Poincaré sphere, where the polarizer at the fibre's input is oriented at π/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.

Conclusions - Discussion

This paper presents the experimental and simulation study of the sensitivity of PMF to external physical effects like temperature and longitudinal strain.

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 state of polarisation.

With such a high sensitivity, it is thus interesting to further study its applications to distributed sensing issues. As small resolution lengths are required for the PMF study (the beat length is about 3 mm), OFDR (Optical Frequency Domain Reflectometry) technique has to be considered in order to locally study the PMF behaviour with respect to temperature (and strain).