A Non-Intrusive Characterization of Long Fiber Link Birefringence

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Abstract

We show that the optical fiber birefringence can be characterized using two easily measured parameters, the differential group delay and the Faraday rotation angle induced by a weak magnetic field.

Introduction

Optical fibers have intrinsic birefringence, a phenomenon wherein two orthogonal states of polarization, called eigenstates, differ in their group and phase velocities. The birefringence changes in strength and direction along the fiber length. The strength of the birefringence is usually characterized by the *beat length* L_B, whereas the spatial rate of change of the birefringence by the *correlation length* L_F. Although the values of L_B and L_F are very important in describing the polarization properties of a fiber, no simple procedure exists to date that can non-intrusively (i.e., without cutting the fiber) measure the beat lengths and the birefringence correlation length in long telecom fibers.

In this paper we present a novel method that permits the estimation of the average L_B and L_F. First, we show analytically that these parameters are related to two measurable quantities, namely the root mean square (rms) fiber differential group delay (DGD) $\tau_{\rm rms}$, and the polarization rotation angle induced by a weak magnetic field $\theta_{F,\rm rms}$. Then, we propose a way of inverting this analytical dependence based on the use of parametric maps in a plane containing the two measurable quantities $\tau_{\rm rms}$ and $\theta_{F,\rm rms}$.

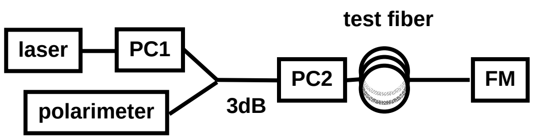

Figure 1: Experimental setup for the measurement of the Faraday rotation angle. PC: polarization controller. FM: Faraday mirror.

While measurements of $\tau_{\rm rms}$ can be accomplished by means of standard techniques, the most convenient way to measure Faraday rotation is a round trip configuration [1,2] using a Faraday mirror at one fiber end. Fiber needs to be placed in a weak axial field of few tens of μT. A typical setup, for the details of which we refer the reader to ref. 1, is shown in Fig.1.

Theory

The mean square DGD of a fiber and the mean square polarization rotation induced by a weak magnetic field of intensity B aligned to the fiber axis can be evaluated by solving the following set of linear ordinary differential equations, obtained using the fixed-modulus model for fiber birefringence [3-5]:

$$\frac{\rm d}{{\rm d}z}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} -1/L_F & 2A'(z) & 0 \\ -2A'(z) & -1/L_F & -2\pi/L_B \\ 0 & 2\pi/L_B & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}, \quad (1)$$

where $A(z)$ is the profile spin function and $A'(z)$ is its z-derivative. By setting $u_1 = 2\pi/\omega L_B$ and $u_2 = u_3 = 0$, with ω being the optical angular frequency, it is possible to compute the mean square DGD as

$$\tau^2_{\rm rms} = \frac{4\pi}{\omega L_B}\int_0^L x_1(z){\rm d}z, \quad (2)$$

where L is the fiber length. By setting instead $u_3 = 1$ and $u_1 = u_2 = 0$, it is possible to compute the mean square Faraday rotation angle as

$$\theta^2_{F,\rm rms} = 8\beta_F^2\int_0^L x_3(z){\rm d}z, \quad (3)$$

where $\beta_F = 2VB/\mu_0$ is the birefringence induced by the magnetic field, with $V = 0.75\text{x}10^{-6}$ rad/A being the Verdet constant of the fiber. For given fiber length, spin profile function and magnetic field, the rms-DGD and the rms-Faraday rotation angle can be regarded as two functions of L_B and L_F: $\tau_{\rm rms} = \tau_{\rm rms}(L_F, L_B)$, $\theta_{F,\rm rms} = \theta_{F,\rm rms}(L_F, L_B)$, . Such non-trivial functional dependence can in principle be inverted, hence it is possible to extract L_F and L_B out of a joint measurement of rms-DGD and rms-Faraday rotation angle. We describe below the procedure for the estimation of L_F, being that of L_B equivalent.

For an expedite estimation of the correlation length we propose to use maps in the plane $(\tau_{\rm rms}, \theta_{F,\rm rms})$ parameterized to the beat length, i.e. families of curves drawn for fixed values of L_F and for varying L_B. When using such a representation, the result of the measurement represents a point in the plane $(\tau_{\rm rms}, \theta_{F,\rm rms})$ and the curve intercepting that point gives the desired value of the correlation length.

While the maps shown here refer to the fixed modulus model for the birefringence, they can easily be redrawn for other birefringence models [5] using Monte-Carlo simulations.

Results and discussion

The vast majority of recent and modern fibers can be grouped into the two families of constantly spun and periodically spun fibers. Although applicable to any fiber spin profile, we apply our technique to a couple of fibers representative of those two families. In the numerical examples we used a fiber length of 25 km and a magnetic field of 50 μT.

Case of constantly spun fibers

Unidirectional constant spin is described by the spin function $A(z) = 2\pi z / Z$, where Z is the spin pitch. Figure 2 shows a map in the plane $(\tau_{\text{rms}}, \theta_{F,\text{rms}})$ for the spin pitch Z = 2 m. Each solid curve corresponds to a different value of L_F and is drawn for the beat length L_B varying from 1 m to 20 m (lower values of L_B correspond to higher values of the rms-DGD).

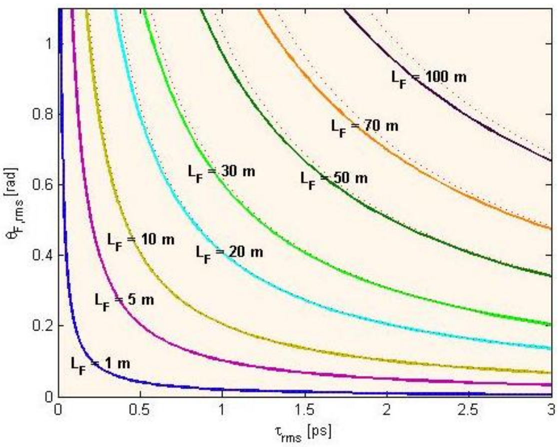

Figure 2: Maps in the measurement plane for a 25 km long constantly spun fiber with spin pitch equal to 2 m. Each curve shows the values of the rms-DGD and the rms-Faraday rotation angle achievable for the reported value of the birefringence correlation length L_F and for the beat length L_B varying from 1 m to 20 m.

In the case of constant spin it is possible to give an analytical expression to the curves in the map, valid in the asymptotic regime (see ref. 3 for details):

$$\theta_{F,rms}\tau_{rms} \approx \frac{4\beta_F L}{\omega}\left[1+\left(\frac{4\pi L_F}{Z}\right)^2\right]^{1/2} \qquad (4)$$

Equation (4) describes the map as a family of hyperboles with coefficients that depend on the correlation length L_F. Equation (4) is also plotted in Fig. 1 by dotted lines for each value of L_F. The plot shows the excellent capability of the analytical approximation Eq. (4) to describe the map in a wide region of values of rms-DGD and rms-Faraday rotation angle. In that region Eq. (4) can easily be inverted in favour of L_F, hence providing the wanted estimate with satisfactory accuracy.

Case of periodically spun fibers

Periodic spin is described by a spin function such that $A(z+Z) = A(z)$, with Z being the spin pitch. We apply our technique to the special case $A(z) = A_0 \sin(2\pi z / Z) + A_0 \cos(4\pi z / Z)$. Figure 3 shows the corresponding map in the plane $(\tau_{\text{rms}}, \theta_{F,\text{rms}})$ for the spin pitch Z = 10 m and for the spin amplitude A_0 = 4.8 rad.

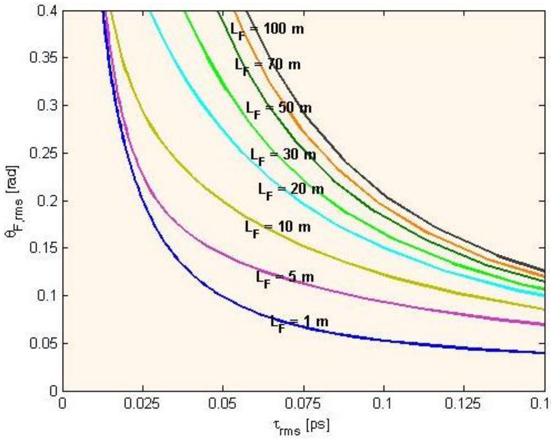

Figure 3: Same curves as in Fig. 2 for a 25 km long periodically spun fiber with spin function $A(z) = A_0 \sin(2\pi z / Z) + A_0 \cos(4\pi z / Z)$. The spin pitch was Z = 10 m and the spin amplitude A_0 = 4.8 rad.

The similarity between the maps in Fig. 2 and Fig. 3 shows that the proposed technique is almost independent of the specific spin profile.

Conclusions

We proposed a novel method for estimating the average beat length and correlation length of the birefringence of a fiber of given spin profile. The technique is non-intrusive and requires the measurement of two parameters only, the mean DGD and the mean Faraday rotation angle induced by a weak magnetic axial field.

References

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