A Reflectometric Technique for an Almost Complete Characterization of Birefringence in Single-Mode Optical Fibers

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Abstract *A reflectometric technique able to characterize almost completely fiber birefringence is experimentally validated. Linear and circular birefringence can be measured, although the latter appears as a rotation of the former.*

Polarization sensitive optical time domain reflectometry (P-OTDR) has been proposed about 25 years ago as a tool to measure the birefringence in single-mode optical fibers (see [1] and references therein). Since then, many papers have been devoted to the analysis of the gathered data. In fact, the P-OTDR basically provides only the evolution of the state of polarization (SOP) of the backscattered field; therefore, retrieving information about the birefringence is a matter of data modelling and analysis.

Actually, the Mueller matrix $\boldsymbol{F}(z)$ representing forward propagation in a fiber obeys the equation $d\boldsymbol{F}/dz = \bar{\beta}(z) \times \boldsymbol{F}(z)$, where the birefringence vector $\bar{\beta} = (\beta_1,\, \beta_2,\, \beta_3)^T$ is the quantity one would like to measure. It is worthwhile expressing $\bar{\beta}(z)$ as $\bar{\beta}_L(z) + \bar{\beta}_3(z)$, where $\bar{\beta}_L = \beta_L(\cos 2\theta,\, \sin 2\theta,\, 0)^T$ is the linear component and $\bar{\beta}_3 = (0,\, 0,\, \beta_3)^T$ is the circular one. Similarly, the round-trip Mueller matrix $\boldsymbol{B}(z)$ representing propagation up to a point z, backscattering and backward propagation to the fiber input reads $\boldsymbol{B}(z) = \boldsymbol{M}\boldsymbol{F}^T(z)\boldsymbol{M}\boldsymbol{F}(z)$, where $\boldsymbol{M} = \mathrm{diag}(1,\, 1,\, -1)$ [1].

A P-OTDR can basically measure $\boldsymbol{B}(z)$; the issue is then to retrieve information about $\bar{\beta}(z)$ from this quantity. However, whether $\boldsymbol{B}(z)$ contains the complete information about $\bar{\beta}(z)$ or not has not been completely clarified yet. In this paper the intrinsic limits of any P-OTDR measurement will be assessed and a technique to extract as much information as possible from $\boldsymbol{B}(z)$ will be described.

The first thing that has to be noted is that the backscattered SOP, $\hat{s}_B(z) = \boldsymbol{B}(z)\hat{s}_0$, is invariant under any rotation around the longitudinal axis of the fiber. In particular, let $\mathcal{R} = \{\hat{x}',\, \hat{y}',\, \hat{z}\}$ be a moving reference frame obtained by rotating the laboratory frame around the fiber axis $\hat{z}$, by an angle $\Theta(z) = -\int_0^z \beta_3(t)dt/2$. In the Stokes space this transformation is described by the matrix $\boldsymbol{R}_3[2\Theta(z)]$; therefore, with respect to $\mathcal{R}$, the Mueller matrix representing the forward propagation reads $\boldsymbol{F}_R(z) = \boldsymbol{R}_3(z)\boldsymbol{F}(z)$. Similarly, the round-trip is described by $\boldsymbol{B}_R(z) = \boldsymbol{M}\boldsymbol{F}_R^T(z)\boldsymbol{M}\boldsymbol{F}_R(z)$; nonetheless, note that $\boldsymbol{R}_3$ and $\boldsymbol{M}$ commute, thus $\boldsymbol{B}_R(z) = \boldsymbol{B}(z)$.

To gain more physical insight on this result, note that with respect to $\mathcal{R}$ the birefringence vector reads $\bar{\beta}_R(z) = \boldsymbol{R}_3[2\Theta(z)]\bar{\beta}_L(z)$. This means that the SOP $\hat{s}_B(z)$ backscattered by a fiber with generic birefringence $\bar{\beta}(z)$ can be thought as being backscattered by a fiber with birefringence equal to $\bar{\beta}_R(z)$. In other words, a reflectometric measurement is intrinsically unable to distinguish between circular birefringence and rotation of the linear birefringence. This is a fundamental limit that cannot be avoided, unless some other measurement diversity (such as optical frequency, for example) is exploited.

Once the limits of reflectometric techniques have been assessed, the point is how to extract all the available information. Before facing this problem, it is worthwhile including in the analysis also the polarization effects of the patch-cords unavoidably present in any P-OTDR set-up. Let $\boldsymbol{F}_{1,2}$ represent the optical path from the P-OTDR laser source to the fiber input and let $\boldsymbol{F}_{2,3}$ represent the path from the fiber input to the P-OTDR receiver. Then, the measured round-trip matrix reads $\boldsymbol{B}_M(z) = \boldsymbol{F}_{2,3}\boldsymbol{B}(z)\boldsymbol{F}_{1,2}$ and is governed by the equation $d\boldsymbol{B}_M/dz = \bar{\beta}_B(z) \times \boldsymbol{B}_M(z)$, where the round-trip birefringence vector $\bar{\beta}_B(z)$ can be effectively calculated from the measured matrix $\boldsymbol{B}_M(z)$ [1]. According to the argumentation given above, there is no lost of generality in assuming that $\boldsymbol{B}(z)$ represents a fiber with birefringence $\bar{\beta}_R(z)$; therefore, $\bar{\beta}_B(z) = 2\boldsymbol{F}_{2,3}\boldsymbol{M}\boldsymbol{F}_R^T(z)\bar{\beta}_R(z)$.

Consider now the matrix $\boldsymbol{Q}(z) = \boldsymbol{F}_{2,3}\boldsymbol{M}\boldsymbol{F}_R^T(z)$. Recalling that $d\boldsymbol{F}_R/dz = \bar{\beta}_R \times \boldsymbol{F}_R$, the following result can be proved:

$$\frac{d\boldsymbol{Q}}{dz} = (\boldsymbol{F}_{2,3}\boldsymbol{M}\boldsymbol{F}_R^T\bar{\beta}_R) \times \boldsymbol{Q} = \frac{1}{2}\bar{\beta}_B \times \boldsymbol{Q}\,. \qquad (1)$$

Note also that $\bar{\beta}_R(z) = \boldsymbol{Q}^T(z)\bar{\beta}_B(z)/2$; so it seems that $\bar{\beta}_R(z)$ might be calculated upon integrating (1). Nonetheless, in order to get exactly $\boldsymbol{Q}(z)$, (1) should be integrated with initial condition $\boldsymbol{Q}(z_0)$, z_0 begin the point where the integration is started. However, $\boldsymbol{Q}(z_0)$ is unknown and cannot be easily measured.

To overcome this impasse, let $\boldsymbol{Q}_I(z)$ be the solution of (1) with initial condition $\boldsymbol{Q}_I(z_0) = \boldsymbol{I}$, so that $\boldsymbol{Q}(z) = \boldsymbol{Q}_I(z)\boldsymbol{Q}(z_0)$. This allows to calculate the vector

$$\bar{v}(z) = \frac{1}{2}\boldsymbol{Q}_I^T(z)\bar{\beta}_B(z) = \boldsymbol{Q}(z_0)\bar{\beta}_R(z)\,. \qquad (2)$$

To get rid of the unknown rotation $\boldsymbol{Q}(z_0)$ note that $\bar{\beta}_R(z)$ is by definition linear; therefore, it lays on a

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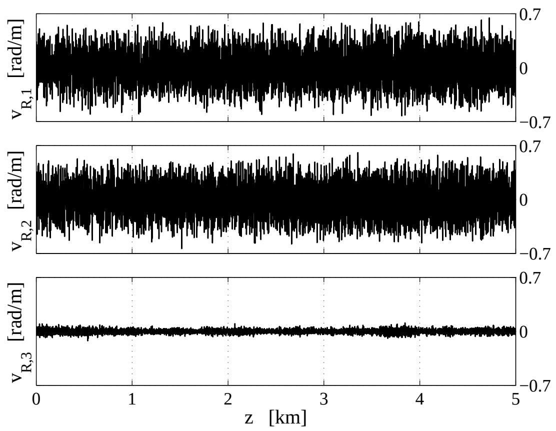

Figure 1. Components of $\bar{v}_R(z)$ as a function of z.

plane and so does $\bar{v}(z)$. Let $\hat{n}$ be a unit vector orthogonal to the plane where $\bar{v}(z)$ lays and let $\boldsymbol{T}$ be a rotation that maps $\hat{n}$ on $\hat{s}_3$. Then, the following final result is achieved:

$$\bar{v}_R(z) = \boldsymbol{T}\bar{v}(z) = \pm\boldsymbol{R}_3(\xi)\bar{\beta}_R(z)\,, \qquad (3)$$

where ξ is an unknown constant angle which is due (along with the sign uncertainty) to the non-uniqueness of the rotation $\boldsymbol{T}$.

To summarize, the proposed measurement technique goes through the following steps:

1) the round-trip birefringence vector $\bar{\beta}_B(z)$ is calculated from the measured evolution of $\boldsymbol{B}_M(z)$ [1];

2) the matrix $\boldsymbol{Q}_I(z)$ is calculated integrating (1) from an arbitrary point z_0, with initial condition $\boldsymbol{Q}_I(z_0) = \boldsymbol{I}$;

3) the vector $\bar{v}(z)$ is calculated from (2);

4) the unit vector $\hat{n}$ orthogonal to the plane of $\bar{v}(z)$ is determined (this can be done, for example, by minimizing $|\hat{n}\cdot\bar{v}|$);

5) one of the possible rotations mapping $\hat{n}$ on $\hat{s}_3$ is determined and, finally, $\bar{v}_R(z)$ is calculated from (3).

The vector $\bar{v}_R(z)$ is linearly polarized and its modulus is equal to the modulus of the linear component of the real birefringence vector $\bar{\beta}(z)$; furthermore, it is rotated by the angle $\phi(z) = \pm[\xi+\theta(z)+\Theta(z)]$, where ξ is unknown, $\theta(z)$ is the intrinsic rotation of the linear part of $\bar{\beta}(z)$ and $\Theta(z)$ is related to the circular birefringence, if present. The sign uncertainty prevents the determination of the absolute sense of rotation; yet, the sense variations are correctly tracked.

The proposed technique has been experimentally tested on some fibers (all wounded on shipping bobbin) which, according to previous measurements [2], were suspected of being twisted at constant rate due to bobbin rewinding. The twist causes a rotation of the linear birefringence by the angle $\tau(z) = 2\pi\tau_0 z$ (τ_0 being the twist rate) and induces a circular birefringence equal to $g\tau'_z(z)$, with $g \simeq 0.14$ [3]. This should appear in $\bar{v}_R(z)$ as a rotation by an angle $(2-g)\tau(z)$. The aim of the experiment is to determine if $\bar{v}_R(z)$ actually has such a deterministic rotation or not. Measurements have been performed with the P-OTDR described in [1].

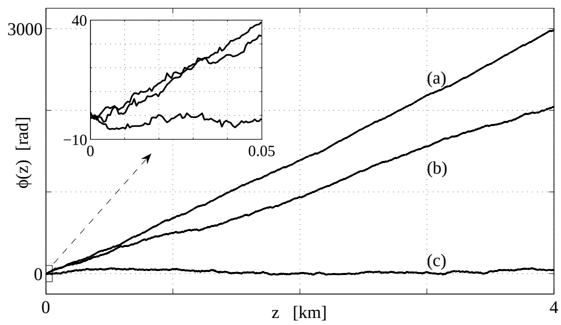

Figure 2. $\phi(z)$ for three different fibers: (a) twisted G.652, (b) twisted G.655 and (c) untwisted G.655.

As a first example, fig. 1 shows the three components of $\bar{v}_R(z)$ as a function of z, measured on a 5 km long section of G.652 fiber. The third component of $\bar{v}_R$ is not exactly equal to zero because of the measurement noise. Yet, it is about one order of magnitude lower that the other two components, confirming the reliability of the theoretical model given above.

Fig. 2 shows the angles $\phi(z)$ by which the linear part of $\bar{v}_R(z)$ is rotated; each curve corresponds to a different fiber. In particular, curve (a) corresponds to a G.652 fiber; clearly, $\phi(z)$ grows linearly with z at a rate of about 0.75 rad/m, corresponding to a twist rate of $\tau_0 \simeq 0.064$ rad/m. This values agrees with the rate of 0.069 rad/m estimated with the technique presented in [2]. The random intrinsic rotation $\theta(z)$ of the birefringence are visible on a smaller scale in the inset of fig. 2. Curve (b) presents similar results obtained on a different fiber (G.655); in this case $\tau_0 \simeq 0.043$ rad/m. Finally, curve (c) refers to a G.655 fiber which does not show sign of twist: indeed, in this case $\phi(z)$ does not have any linear growth.

In conclusion, a novel reflectometric technique has been presented that can correctly track modulus and orientation of the linear birefringence vector. If the fiber has also circular birefringence, this appears as a further contribution to the birefringence rotation. The technique may be potentially extended to perform a point-wise characterization of the spin profile in spun fibers, provided that the P-OTDR has sufficient spatial resolution.

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