Local Birefringence Measurements in Single-Mode Fibers with Coherent Optical Frequency-Domain Reflectometry

B. Huttner, J. Reecht, N. Gisin, R. Passy, and J. P. von der Weid

***Abstract*—Measurements of intrinsic and induced birefringence of optical fibers are performed at 1550 nm using the optical frequency-domain reflectometry technique. The experiment confirms the theoretical analysis, which predicts the appearance of oscillations on the detected Rayleigh backscattering intensity, with periods equal to the polarization beat length L_b and to $L_b/2$. Polarization mode-coupling length values are obtained from local birefringence and polarization mode dispersion measurements.**

***Index Terms*—Optical fiber measurements, optical fiber polarization, optical interferometry, reflectometry.**

I. Introduction

POLARIZATION mode dispersion (PMD) is a statistical quantity describing the effects of the distributed birefringence in the distortion of a light signal along an optical fiber. In the theoretical modeling of this phenomenon, the fiber can be described as a concatenation of pieces of homogeneous fibers with a mean modal birefringence B [1]. Their mean length is known as the coupling length h. For fibers that are long compared to h, the PMD of the fiber is equal to $B\sqrt{hl}$, where l is the length of the fiber. Therefore, knowledge of this parameter h is very important in the transmission properties of single mode fibers.

Optical frequency-domain reflectometry (OFDR) is well known as a tool for optical fibers and devices characterization [2]. In this technique, the frequency of the laser source is linearly swept as a function of time, and the reflected field under investigation interferes coherently with a fixed reflection, known as the local oscillator (LO) field. Due to the linear frequency sweep of the source, for each reflection in the fiber there is a corresponding beat frequency, so that the intensity of the reflected field from each point can be obtained as the Fourier transform of the interference signal. Since the state of polarization (SOP) of the reflected field with respect to the LO affects the intensity of the interference signal, OFDR is naturally a polarization sensitive reflectometer. In this sense, the OFDR is a useful complement to the polarization OTDR (POTDR) [3], [4], and enables one to measure short-scale effects, albeit at a much shorter distance than the POTDR [5]. In this letter, we use the OFDR technique to analyze polarization effects in the Rayleigh backscattering signal in order to get information on the local birefringence along the fiber.

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II. Experimental Procedure

The description of our OFDR has been given in previous works [2]. Bending birefringence was induced by wrapping a low birefringence fiber around spools of various diameters. Care had been taken to avoid excess tension in the spooling process, which would add uncontrolled stress birefringence to the desired bending birefringence. The far-end reflection of the measured fibers was eliminated in order to reduce the noise floor due to the phase noise of the laser.

A standard single-mode fiber (SMF), with a rather high value of the PMD, was used to demonstrate the polarization mode coupling length determination. The PMD was measured by the interferometric method [1], to give 1.9 ps/$\sqrt{\text{km}}$.

III. Theoretical Model

The fiber under test is represented by a concatenation of homogeneous trunks i, with birefringence axis $\vec{b}_i$. We assume that the fiber is homogeneous, so that the phase birefringence $\beta \equiv \Delta n/c$, where Δn is the difference in refractive index between the two polarization eigenmodes, is independent of the trunk. Note that, with this definition, β is measured for example in picoseconds per meter. The effect of the birefringence on polarized light can be represented on the Poincaré sphere by a rotation of the polarization vector $\vec{p}_{\mathbf{in}}$ around the birefringence axis, with angle $\alpha = \beta\omega z$, where z is the distance covered in the fiber. The local birefringence can be characterized by the period of the rotation, called the beat length, which can be written as

$$L_b = \lambda/c\beta. \tag{1}$$

When β is independent of the wavelength, which is a good approximation for real fibers, the two concepts of phase and group (or modal) birefringence are identical: $B \equiv \partial(\beta\omega)/\partial\omega = \beta$. This approximation was experimentally tested in [6], and the difference was found to be less than 10%. Therefore, in the remaining, we shall identify β and B.

The Rayleigh backscattering is equivalent to a reflection from a mirror, and is represented on the Poincaré sphere by a symmetry $\hat{S}_{xOy}$ with respect to the equator. Therefore, if we denote the total rotation induced in the fiber till point z by $\hat{R}_{\mathrm{tot}}(z)$, the SOP of the backscattered light is given by [7]

$$\begin{aligned}\vec{p}_{\mathrm{out}} =&\hat{R}_{\mathrm{tot}}^{-1}(z) \circ \hat{S}_{xOy} \circ \hat{R}_{\mathrm{tot}}(z)\vec{p}_{\mathrm{in}} \\ =&\vec{p}_{\mathrm{in}} - 2(\hat{R}_{\mathrm{tot}}^{-1}(z)\vec{e}_z \cdot \vec{p}_{\mathrm{in}})\hat{R}_{\mathrm{tot}}^{-1}(z)\vec{e}_z \end{aligned} \tag{2}$$

where we used $\hat{S}_{xOy}\vec{p} = \vec{p} - 2(\vec{e}_z \cdot \vec{p})\,\vec{e}_z$. The interference between backscattered light and the LO is thus modulated by a polarization-dependent factor given by

$$\begin{aligned}A_{\mathrm{pol}} \equiv&\frac{1+\vec{p}_{\mathrm{out}} \cdot \vec{p}_{LO}}{2} = \frac{1+\vec{p}_{\mathrm{in}} \cdot \vec{p}_{\mathrm{LO}}}{2} \\ &- (\hat{R}_{\mathrm{tot}}(z)\vec{p}_{\mathrm{in}} \cdot \vec{e}_z)(\hat{R}_{\mathrm{tot}}(z)\vec{p}_{\mathrm{LO}} \cdot \vec{e}_z). \end{aligned} \tag{3}$$

This expression is identical to the one given in [8][1] for the case of a single trunk. It is however written in a simpler geometrical form. The total rotation $\hat{R}_{\mathrm{tot}}(z)$ is a product of the rotations induced in each trunk i. As the local birefringence is constant along the fiber, the periodicity of $\hat{R}_{\mathrm{tot}}(z)$ is also constant, and equal to L_b. In fact, if we decompose the two vectors $\vec{p}_{\mathrm{in}}$ and $\vec{p}_{\mathrm{LO}}$ into their components parallel and orthogonal to the axis of the last trunk, we easily see that, in general, both L_b and $L_b/2$ enter into the expression of A_{pol} [4], [8], [9]. The relative intensity depends on the direction of the polarization vectors $\vec{p}_{\mathrm{in}}$ and $\vec{p}_{\mathrm{LO}}$ with respect to the rotation axis. Therefore, it varies along the fiber. Intuitively, the value $L_b/2$ could be expected from the fact that the light makes a round-trip, to the backscatterer and back. The term in L_b may appear for example when one of the polarization vectors, $\vec{p}_{\mathrm{in}}$ or $\vec{p}_{\mathrm{LO}}$, is parallel to the rotation axis. In general, the expression for A_{pol} in (3) is rather cumbersome. It simplifies for the case of a single trunk. Then, for a circular birefringence ($\hat{R}_{\mathrm{tot}}(z)$ is a rotation around $\vec{e}_z$), A_{pol} becomes independent of z. On the other hand, for a purely linear birefringence, the periodicity of A_{pol} is $L_b/2$ [4], [9].

It is important to note that, even for purely linearly birefringent trunks, the total rotation for several trunks may be around any axis, including the circular ones. Therefore, circular birefringence may be induced by twist as in [4] and [9], but it may also arise due to mode couplings between linearly birefringent trunks.

IV. Results and Discussion

In order to verify the capability of the OFDR technique for local birefringence measurements we used bend-induced birefringence as a controlled way to generate known values of linear birefringence. The calculation of the bend-induced birefringence in single mode silica fibers has been performed by Ulrich *et al.* [11], and can be written as

$$\beta \approx \frac{0.133}{c}\left(\frac{d}{D}\right)^2 \tag{4}$$

where d and D are, respectively, the fiber and the spool diameters. In this experiment, we use a fiber with a low

[1] Note that in [8, eq. (2)], a term: $\cos(\omega Bz)(\vec{p} \cdot \vec{e}_z)$ is missing in the squared expression.

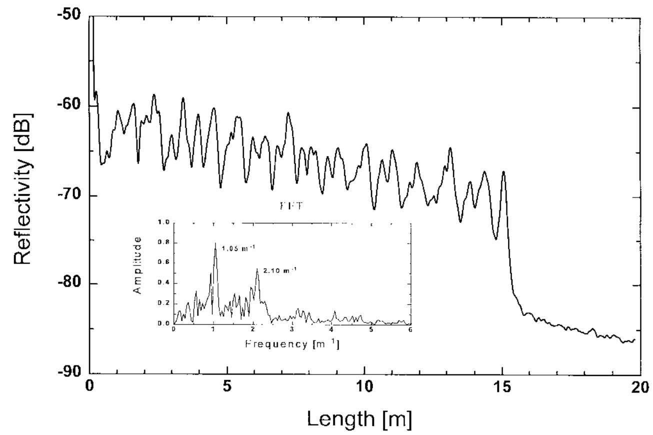

Fig. 1. Rayleigh backscattering for a fiber wrapped around a spool with a diameter of 4 cm. The oscillations due to the bend-induced birefringence are clearly visible. Two main peaks are clearly visible in the Fourier transform of the signal, shown in the inset. The bend induced beat length in this case is 0.95 m.

birefringence. Indeed, the Rayleigh backscattering level of this fiber after the fading noise filtering was flat even on our longest OFDR range of 80 m. We thus estimate the beat length corresponding to its intrinsic birefringence to be above 20 m. By wrapping this fiber around spools of various diameters, we generated bend-induced birefringence, with a corresponding beat lengths varying between 70 cm and 4 m. Therefore, while the intrinsic birefringence is certainly much lower than the induced one, it is still not entirely negligible. The amplitude of the overall birefringence is thus mainly due to the bending, but the direction of the birefringence tensor axes is given by the sum. Therefore, the fiber still may be considered as a succession of homogeneous trunks, each trunk having a different birefringence axis $\vec{b}_i$, but the same local birefringence, given by the bending.

Fig. 1 shows the example of a 4-cm diameter spool with a 15-m-long fiber. We can see the oscillations induced by the birefringence. The Fourier transform of this Rayleigh backscattering signal is shown in the insert, and two main peaks are clearly recognized, corresponding to the two periodicities L_b and $L_b/2$ as predicted by the theory. The bend-induced beat length is then 0.95 m.

Various samples of the same fiber, spooled with diameters varying from 3.1 cm up to 8 cm were measured. For each sample, we made Fourier transforms of the signal, as in Fig. 1 for example, and the two major peaks in the Fourier transforms were taken into account. The results are shown in Fig. 2, where we plot the measured periodicities as a function of the square of the spool diameter. The squares represent the shorter periodicity, which should correspond to $L_b/2$, and the circles to the longer one, corresponding to L_b. The plot shows two lines with rates linked by a factor of two, which confirms the theory developed here. As suggested in [4] and [9], the apparition of the double frequency simplifies the identification of the beat lengths. The theoretical value of the slope can be calculated by using (1) and (4) to be $L_b \approx 0.07\,D^2$, where L_b is in m and D in centimeters, to facilitate the comparison with Fig. 2. The agreement with the experimental values is

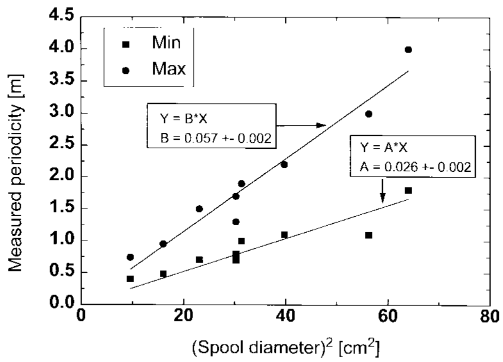

Fig. 2. Measured periodicities as a function of the square of the spool diameter. The two values, $\min$ and $\max$, for each point correspond to the two major Fourier components. They are distributed along two straight lines, with a factor of two in the slopes, as described in the theory. This shows that the birefringence is mainly due to the bending of the fiber, with characteristic dependence on the square of the diameter.

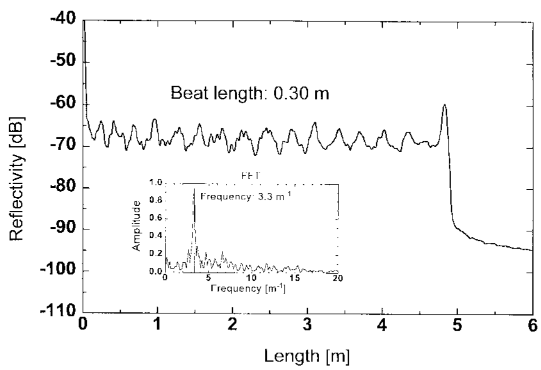

Fig. 3. POFDR measurement of a single mode fiber. The oscillations in the Rayleigh backscattering are due to the intrinsic birefringence of the fiber. The main peak in the Fourier transform corresponds to a periodicity of 3.3 m^{-1}, whereas the double frequency is barely visible at 6.6 m^{-1}. The polarization beat length is $L_b = 30$ cm, while the second peak corresponds to $L_b/2$.

quite good, confirming the capability of the OFDR technique in local birefringence measurements.

In order to determine the polarization mode coupling length we used an optical fiber with a rather high PMD. This PMD was measured by the interferometric method [1] to be 1.9 ps/$\sqrt{\text{km}}$. A 5-m-long piece of this fiber was kept loose on the optical table, to avoid any bending effect. The result of the OFDR scan is presented in Fig. 3, where the oscillations induced by the local birefringence can be clearly seen. A Fourier transform of this curve is shown in the inset, and gives the frequency of these oscillations, about 3.3 m^{-1}. A very small second peak, at 6.6 m^{-1}, is an indication that the main peak corresponds to the beat length L_b, while the second peak corresponds to $L_b/2$. The fact that both peaks appear in the Fig. 3 helps identifying the correct beat length to be $L_b =$ 30 cm. This would correspond to a PMD of 17 ps for a 1-km-long optical fiber with no mode coupling, a value much higher than the experimentally measured. This confirms that this fiber has some mode coupling. The equation linking the PMD, the intrinsic birefringence and the coupling length is derived in [1], [10]. For the case of a coupling length h which is small with respect to the fiber length l, and using the approximation that the group birefringence is equal to the phase birefringence ($B = \beta$), we get

$$\text{PMD} = \frac{\lambda}{cL_b}\sqrt{lh}. \tag{5}$$

From (5), we derive the value of the coupling length: $h \approx 12$ m. We emphasize that a measurement of the PMD alone cannot give the value of this parameter. For example, a low value of the PMD may be due either to a low intrinsic birefringence, or to a small coupling length. Our measurement thus enables a more complete characterization of the optical fiber.

V. Conclusion

We have used the OFDR to analyze polarization effects in optical fibers. Measurement of the bend-induced birefringence led us to the expected dependence in the square of the spool diameter and the observation of two periodicities, corresponding to the beat length L_b and to $L_b/2$. Measurement of the intrinsic birefringence, together with a measurement of the global PMD of the fiber enabled us to estimate the coupling length of the fiber. This letter shows an example of the use of the OFDR as a complement to the POTDR, which gives information on polarization effects in optical fibers on a much larger scale (resolution of several meters, range of several kilometers). The OFDR is well adapted to measurements with range below one hundred meters, and a few centimeters resolution.

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