Analysis and measurement of birefringence in single-mode fibers using the backscattering method

Byoung Yoon Kim and Sang Sam Choi

Korea Institute of Science and Technology, P.O. Box 131, Dong Dae Moon, Seoul, Korea

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The local parameters of linear, circular, and elliptical birefringence of backscattered light along a single-mode fiber are analyzed, and the twist-bending-induced elliptical birefringence in an extremely low birefringent single-mode fiber is measured using the backscattering method. The experimental results are in good agreement with the theoretical calculations. For a 130-μm-diameter fiber, twisted by 133°/m and wound around a drum of 15-cm radius, the induced elliptical birefringence is $\frac{Q_1}{\lambda} = 180°/\lambda$ at $\lambda = 904$ nm.

There has been considerable interest in the polarization property of single-mode optical fibers because it significantly affects the operations of various interferometric devices that utilize single-mode fibers. The state of polarization (SOP) of light propagating along a single-mode fiber can be influenced by perturbations, such as bending and twisting. Therefore knowledge of the local distribution of the SOP, or the evolution of polarization, is required to locate and identify the causes of the irregularities of the SOP along the fiber. For this purpose, the backscattering method was applied to measure the linear birefringence in a single-mode fiber, and a promising result was reported. However, a single-mode fiber can exhibit not only linear birefringence but also circular and elliptical birefringence, depending on the types of perturbations. Therefore analysis of the SOP of the backscattered signal is necessary. In this Letter we analyze the evolution of the SOP of the backscattered light, and the twist-bending-induced elliptical birefringence in an extremely low birefringent single-mode fiber is measured by the backscattering method for different input SOP's. The experimental results are compared with the calculations.

Calculations

Ulrich and Simon developed a perturbation theory for analyzing the evolution of the SOP along a fiber with various kinds of perturbations. According to that theory, the evolution of the SOP under the influence of linear, circular, and elliptical birefringence can be represented in a simple geometrical way on a unit Poincaré sphere (Fig. 1). Any SOP corresponds to a point on the unit sphere, and the evolution of the SOP $C(l)$ along the fiber length $l$ is represented as a rotation of the input SOP $C(0)$ about the birefringence vector $\Omega = \alpha + \beta$ with rotating power $|\Omega|$. Here $\alpha$ and $\beta$ denote the circular and linear birefringence, respectively, and these can be regarded as special cases of elliptical birefringence.

In this way, the SOP can be characterized by two parameters, the longitude $2\phi$ and the latitude $2\psi$, which describe the azimuth and ellipticity, respectively, of the SOP. Moreover, when the azimuth of $\beta$ is fixed on the Poincaré sphere, as in the case of a coiled fiber with no intrinsic linear birefringence, we can choose the direction of $\beta$ as the $x$ direction of the unit sphere for simplicity.

Denote the longitude and latitude of the initial SOP $C(0)$ as $2\phi_0$ and $2\psi_0$, respectively, and define the angle $\theta$ as

$$\tan \theta = \pm|\alpha|/|\beta| \quad (-90° \leq \theta \leq 90°), \quad (1)$$

where the positive sign corresponds to the case in which $\alpha$ points to north (the left-rotatory optical activity). Then the evolution of the SOP along the fiber, i.e., $2\phi(l)$ and $2\psi(l)$, is related to the initial SOP, $2\phi_0$ and $2\psi_0$, in a matrix form as

$$C(l) = R_x(\theta)R_y(-\theta)R_y(-|\Omega|/\lambda)R_x(\theta) = \begin{pmatrix} \cos 2\psi_0 \cos 2\phi_0 \\ \cos 2\psi_0 \sin 2\phi_0 \\ \sin 2\psi_0 \end{pmatrix} \cdot \begin{pmatrix} \cos 2\psi_0 \cos 2\phi_0 \\ \cos 2\psi_0 \sin 2\phi_0 \\ \sin 2\psi_0 \end{pmatrix}, \quad (2)$$

where $R_x$ and $R_y$ are counterclockwise rotation operators about the $x$ and $y$ axes, respectively. That is,

$$R_x(\delta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \delta & \sin \delta \\ 0 & -\sin \delta & \cos \delta \end{pmatrix}, \quad R_y(\theta) = \begin{pmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{pmatrix}. \quad (3)$$

Linear and circular birefringence correspond to $\theta = 0°$ and $\pm90°$, respectively.

Before proceeding, we should find the operator for
The Poincaré sphere representation of the state of polarization and birefringence in a single-mode fiber.

Fig. 1. The Poincaré sphere representation of the state of polarization and birefringence in a single-mode fiber.

Fig. 2. The calculated evolution of polarization of backscattered light \( C_b(l) \) in an elliptically birefringent single-mode fiber. The input polarization is \( 2\phi_0 = 60^\circ, 2\varphi_0 = 0^\circ, \) and \( \theta = 45^\circ \). The parameters along the curve are \(|\Omega|/l\).

Experimental Results

The apparatus used to measure the birefringence is similar to an ordinary optical time-domain reflectometer (OTDR), except that a polarizing beam splitter is used instead of a beam divider. A train of pulses of 10-nsec half-width, which limits the resolution length to >4 m, with a 10-kHz repetition rate from a GaAs laser diode, is used as a light source, and the wavelength is 904 nm. The launched light is linearly polarized by a polarizing beam splitter. For the backscattered signal, the linear polarization component orthogonal to the launch polarization is detected by an avalanche photodiode. The single-mode fiber under test is a fiber of extremely low birefringence, with core and cladding compositions of GeO\(_2\)/SiO\(_2\) and B\(_2\)O\(_3\)/SiO\(_2\), respectively. The overall fiber diameter is 130 μm, the relative index difference is 1 \( \times \) 10\(^{-4}\), and the normalized backscattering in the single-mode fiber. During the backscattering process, the polarization of light is conserved, except that the propagating direction is reversed. This means changing \( 2\phi \) and \( 2\varphi \) of the SOP to \(-2\phi\) and \(-2\varphi\), respectively, on the unit sphere in Fig. 1. Therefore the operator \( B \) for the backscattering process becomes

\[
B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.
\] (4)

As a result, when the birefringence is independent of propagation direction, the SOP, \( C_b(l) \), of the light backscattered at \( l \) and guided back to the input end becomes

\[
C_b(l) = TBTC(0),
\] (5)

where \( T = R_y(\theta)R_x(-|\Omega|/l)R_y(-\theta) \). From this equation, the trajectory of the SOP on the Poincaré sphere can be obtained.

For linear birefringence (\( \Omega = \beta \)), Eq. (5) yields two complete circles about the \( x \) axis, i.e., \( \beta \) axis of Poincaré sphere when \(|\Omega|/l\) ranges from 0° to 360°, which indicates that the light traveled a distance \( 2l \) in the fiber. In the case of twist-induced circular birefringence (\( \Omega = \alpha \)), the SOP of the backscattered light is the same for all \( l \) and appears as a point on the unit sphere, i.e., \( C_b(l) = C_b(0) \) for all \( l \). The elliptical birefringence does not generate such simple trajectories. For example, when \( |\alpha| = |\beta| \), \( 2\phi_0 = 60^\circ \), and \( 2\varphi_0 = 0^\circ \), the calculated trajectory for twist-bending-induced elliptical birefringence is shown in Fig. 2. The parameters along the curve are \(|\Omega|/l\).

Fig. 3. Measured OTDR signals for twist–bending-induced elliptical birefringence for three different input states. The bending radius is 15 cm, and the twist rate is 133°/m.
frequency at 904 nm is 2.0. The intrinsic birefringence of this fiber is negligibly small (about 2°/m at 904 nm). This is determined by measuring the SOP of transmitted light as ~2 m of the fiber is shortened successively. To induce elliptical birefringence, 230 m of fiber was continuously twisted clockwise as it was wound around a drum of 15-cm radius. The twist angle is about 133°/m, and great care was taken to ensure that no tension was created. The OTDR signals for different input SOP's are shown in Fig. 3. These were averaged over 500 times to improve the signal-to-noise ratio. The periods of the signal variations in Figs. 3(a) and 3(c) are about 20 and 10 m, respectively. This corresponds to a birefringence ($|\Omega|$) of about 18°/m. The calculated signal patterns for those input SOP’s are shown in Fig. 4. The observed signal patterns appear to be similar to those calculated except, of course, for the expected OTDR exponential decay.

By using the results of Ref. 6 for bending-induced linear birefringence introduced by a 15-cm-bend radius, $|\beta| = 9°/m$. The circular birefringence $|\alpha|$ is about 16°/m, which agrees well with results previously reported.4,5 In conclusion, the evolution of the SOP of the backscattered light is analyzed in a simple geometrical way to measure the local distribution of polarization properties along a single-mode fiber. Measurement of twist-bending-induced elliptical birefringence in a single-mode fiber using an OTDR agree well with predictions. This technique seems to be a powerful tool for nondestructive measurement of the polarization property of single-mode fibers.

References