Precision measurement of modal birefringence of highly birefringent fibers by periodic lateral force

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Modal birefringence of highly birefringent fibers can be measured nondestructively by the elastooptic modulation method. Based on this modulation method, a new method for precisely measuring the wavelength dependence of modal birefringence in highly birefringent fibers is presented using an incoherent light source such as a fiber Raman laser.

I. Introduction

Applications of single-mode fibers to coherent optical fiber communication systems\textsuperscript{1} and fiber sensor systems\textsuperscript{2} require a definite state of polarization along the fiber length. Polarization-maintaining fibers such as elliptically clad\textsuperscript{3} and stress-applied\textsuperscript{4} single-mode fibers have a high internal birefringence that exceeds perturbing birefringence and produces linear polarization along the fiber.

One practical parameter for characterizing these birefringent fibers is modal birefringence, i.e., the effective refractive-index difference between the orthogonally polarized HE\textsubscript{11}\textsubscript{x} modes. To investigate the power spectrum of birefringent perturbations\textsuperscript{5} and the contribution of thermal-stress and geometrically induced birefringences to the modal birefringence,\textsuperscript{6} it is necessary to measure the wavelength dependence of modal birefringence.

Several methods for modal birefringence measurement have been reported thus far.\textsuperscript{6-8} However, contrary to the measurement of polarization mode dispersion, i.e., the group-delay time difference between the orthogonally polarized modes, it is difficult to measure precisely the wavelength dependence of modal birefringence. This is due to the effect of wavelength dispersion in the fiber material\textsuperscript{9} and the lower signal level.\textsuperscript{7}

In this paper, we present a simple method for precisely measuring the wavelength dependence of modal birefringence in highly birefringent fibers by the elastooptic modulation method.\textsuperscript{10}

II. Principle and Experimental Setup

Quasi-monochromatic light is assumed to be coupled into the HE\textsubscript{11}\textsubscript{x} mode (\(\alpha_P = 0^\circ\)) of the principal polarization modes, as shown in Fig. 1. It produces a field \(E_x\) with amplitude \(A\) at the fiber output, where

\[
E_x = A \exp(j\beta_x L),
\]

and \(\beta_x\) is the propagation constant of the HE\textsubscript{11}\textsubscript{x} mode, and \(L\) is the total fiber length. At location \(Z\), a periodic lateral force \(F\) is applied over a very short length of the fiber, so that it may be considered as a concentrated (pointlike) perturbation. To assume that there is always contact between the force-applying pressure jaws and the fiber, the periodic force \(F\) is superimposed on a large constant bias force \(F_0\) so that \(F + F_0 > 0\) at all times.

Experimental conditions can be chosen so that the periodic cross-polarization coupling coefficient \(K\), due to \(F\), is a small quantity, i.e., \(|K| \ll 1\), and the amplitude of \(E_y\) in Eq. (1) is negligibly affected by the coupling. The resulting field \(E_y\) in the cross-polarization state at the fiber output end can be determined from the relationship

\[
E_y = iKA \exp[j(\beta_y Z + \beta_y(L - Z))],
\]

where \(\beta_y\) is the propagation constant of the HE\textsubscript{11}\textsubscript{y} mode. The analyzer at some general azimuth \(\alpha_A\) passes the components \(E_x \cos(\alpha_A)\) and \(E_y \sin(\alpha_A)\), and the detector produces a signal proportional to the power \(P\), where

\[
P = |E_x \cos(\alpha_A) + E_y \sin(\alpha_A)|^2
= |A|^2[\cos^2(\alpha_A) + K \sin(2\alpha_A) \sin(\Delta \beta(L - Z))],
\]

and \(\Delta \beta\) is defined as \(\Delta \beta = \beta_x - \beta_y\). In this expression,
terms of the order of $K^2$ have been ignored because they are negligibly small.

The detector output signal is connected to a lock-in amplifier which extracts the ac signal amplitude $P_0(Z)$ from the signal $P$ in Eq. (3), where

$$P_0(Z) = P_1 K_0 \sin(2 \alpha_A) \sin(\Delta \beta (L - Z)).$$

Here $K_0$ is the amplitude of $K$, and the maximum possible dc power has been abbreviated as $P_1 = |A|^2$. When the signal $P_0(Z)$ is recorded as a function of the position $Z$, the beat length, $L_B = 2\pi/\Delta \beta$, shows up directly as the periodicity of the recorder trace. Accordingly, the modal birefringence $B$ can be obtained by the relationship, $B = \lambda / L_B$, where $\lambda$ is the operating wavelength.

From Eq. (4), the amplitude of this signal $P_0(Z)$ is maximum when the azimuth of the analyzer $\alpha_A$ is 45°. The experimental setup is shown in Fig. 2. The light source is a single-longitudinal-mode InGaAsP laser diode (LD) operating at the 1.30-μm wavelength. A power of $-100 \mu W$ was coupled into a PANDA fiber through a quarterwave plate and a rotatable polarizer. The output light passed through the analyzer onto a Ge-photodiode connected to a current amplifier and a locking amplifier. The fiber was laid flat on a heavy metal base plate, and force $F + F'$ was applied to it by means of a small loudspeaker and a blade spring system. Its radius of curvature $r_c$ at the point of contact with the fiber was 0.5 mm. The loudspeaker was sinusoidally driven with a 0.4-V peak amplitude signal at a frequency of 470 Hz in a broadband resonance region.

III. Experimental Results

A. Mode Coupling by Periodic Lateral Force

Beat length measurements were performed using an $\sim$3 m long, 150-μm diam bare PANDA fiber and the same PANDA fiber with a 900-μm diam nylon coating. Figure 3 shows the recorder output when the spring system was moved on the test fiber at a speed of 100 μm/sec by a stepping motor. The time constant of the lockin amplifier was 400 msec. With a bare fiber, the maximum output signal of 1.8 mV was stable independently of the bias force $F'$ over a wide range as long as the total force $F + F'$ was positive.

From Fig. 3, the beat length of the fiber was determined to be 5.18 mm by averaging twelve periods. The relative error is $<0.3\%$. The modal birefringence at the 1.30-μm wavelength was found to be $2.51 \times 10^{-4}$ within a 0.3% error.

It can be seen from Eqs. (3) and (4) that the cross-polarization coupling amplitude $K_0$ is obtained by the relationship $K_0 = P_{ac}/2P_{dc}$, where $P_{dc}$ the dc power, is equal to $P_1/2$, and $P_{ac}$ is the maximum ac signal amplitude obtained by varying $Z$, i.e., $P_{ac} = P_1 K_0$. The results are plotted in Fig. 4 vs azimuth angle $\phi$ together with a theoretical curve (referred to in Sec. IV). To enable uniformly rotating the fiber cross section, the fiber was fixed on the rotatable stage at points 7 cm away on each side of the point under the lateral force, and the stages were sequentially rotated in one direction through the specified angles.
The cross-polarization coupling amplitude $K_0$ had maximum values $K_{\text{max}}$ of $1.4 \times 10^{-2}$ when $\phi$ equalled 45°, 135°, 225°, and 315°, which correspond to an angle of 45° with respect to the principal axes of the fiber. The maximum value of $K_0$ is 2 orders of magnitude larger than that obtained by the magnetooptic method.\(^7\) From Fig. 4, the 3-dB down angular width relative to the maximum value $K_{\text{max}}$ is $\sim 30^\circ$. This means that the adjustment of azimuth angle $\phi$ is not critical in obtaining a good SNR.

Since the elastooptic modulation method produces large mode coupling, the beat length of the nylon-coated fiber can be measured as shown in Fig. 5. The maximum coupling amplitude $K_{\text{max}}$ for the nylon-coated fiber was $6.4 \times 10^{-5}$, which is 2 orders of magnitude less than that for a bare fiber. The peak values of the signal fluctuated during movement of the spring system. However, from Fig. 5, the relative error of the beat length $L_B$ is 3%, and the obtained signals are sufficient to determine the beat length, i.e., modal birefringence, reliably.

The cross-polarization coupling amplitude $K_0$ is plotted vs azimuth angle $\phi$ as shown in Fig. 6. $K_0$ does not vary sinusoidally with $\phi$ and the four peaks of $K_0$ have different values so that $K_{\text{max}} = 6.42 \times 10^{-5}, 2.67 \times 10^{-5}, 4.85 \times 10^{-5}, 3.46 \times 10^{-5}$ as the azimuth progresses through a complete 360° cycle.

**B. Wavelength Dependence of Modal Birefringence**

To measure the wavelength dependence of modal birefringence, a light source with a wide tuning range or a broad-wavelength band is required. We employed, as a variable wavelength light source, a fiber Raman laser pumped by a Q-switched Nd\(^3+:\) YAG laser operating at the 1.064-μm wavelength. This source has the advantage that the variable wavelength range extends from 0.8 to 2.0 μm (Ref. 11), and that the usable light power is much higher than that of a white light source such as a halogen lamp. Figure 7 shows the experimental setup using a fiber Raman laser. The Q-switched pulses were a train of ~0.5-μsec pulse width, with 0.60 msec pulse separations. The peak power coupled into the Raman fiber was more than 200 W. This is sufficient to generate stimulated multiple-order Raman scattering completely across the 0.8-2.0-μm wavelength band with a 500-m fiber length.

A monochromator and bulk filter were used to sequentially select individual wavelengths. Total spectral width $\delta \lambda$ of the monochromator was set to be 400 Å to obtain high optical power. The corresponding coherence length $Z_c$ was $\lambda^2/\delta \lambda$, equal to 42 μm when $\lambda = 1.3 \mu m$. Contrary to the InGaAsP-LD, however, this short coherence length of the Raman laser degrades the interference signal described by Eq. (4) due to the polarization-mode dispersion of the fiber. For example, when the polarization mode dispersion $D$ of the test fiber is 2 psec/m, the fiber length $L$ must be $L < L_c = Z_c/cD = 7$ cm, where $c$ is the light velocity in a vacuum. This length is too short to set up the present beat length measurement system.

One method for solving this problem is to compensate the optical path difference between the two principal modes by splicing the same fibers with their principal axes crossed, as shown in Fig. 8. Due to the cross splicing, the main wave propagates, at first, in the fast HE\(_{11}^x\) mode and then in the slow HE\(_{11}^y\) mode, whereas, the coupled wave sequentially propagates in the HE\(_{11}^y\) and HE\(_{11}^x\) modes, respectively. In this configuration, the ac signal amplitude $P_0$ is represented by the expression

$$P_0(Y) = P_1K_0\sin(2\omega t)\sin(\Delta Y) e^{-\gamma Y}R(cDY),$$

where $R(\tau)$ is an autocorrelation function of the electric field\(^2\) of the incident broadband source, and $Y$ is a deviation from the point where the optical paths of the
main and coupled waves are equal. Therefore, by moving the spring system in the range \( |Y| < L_c/2 \), a signal level as high as that for a monochromatic light is obtained.

Two kinds of PANDA fiber, (a) and (b), were measured, where the cutoff wavelengths, \( \lambda_a \) and \( \lambda_b \), are 1.28 and 0.63 \( \mu m \), respectively, while the other parameters remain almost unchanged. Figure 9 shows the typical recorder output when a bare fiber (a) is employed, where the central wavelength of the light is 0.86 \( \mu m \). The periodicity observed in Fig. 9 shows the beat length, 1.60 mm, which shows a modal birefringence \( B \) of 5.34 \times 10^{-4} within a 0.3% error. The envelope of the signal corresponds to the autocorrelation function and determines the coherence length \( Z_c \) to be 20 \( \mu m \).

Figure 10 shows the wavelength dependence of the modal birefringence for the two fibers, (a) and (b). For fiber (a), fluctuations were observed in the measured values within the cutoff wavelength region, \( \lambda < \lambda_a \). This is due to the excitation of higher-order modes than the HE_{11} modes in the fiber.

IV. Discussion

As the elastic strains involved in the fiber are very small, it can be assumed that the externally produced stress and strain superimpose linearly on whatever stress/strain may be present internally in the fiber. Therefore, the stress/strain consideration made with respect to single-mode fibers, which are elastically iso-

The dependence of the coupling on the azimuth angle \( \phi \) is contained only in the factor \( \sin(2\phi) \) in Eq. (6). In this expression, \( n \) is the mean refractive index, quantities \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio of the material of the fiber in the core region, \( P_{11} \) and \( P_{12} \) are components of the stress-elastic tensor, and \( 2a \) is the outer diameter of the fiber. The numerical values of these parameters are \( n = 1.46, E = 7.68 \times 10^6 \) N/cm\(^2\), \( \nu = 0.186, P_{11} - P_{12} = 0.149 \), and \( \lambda = 1.30 \mu m \). The spring has a spring constant of 70 N/m, and the loudspeaker response to dc voltage is 0.1 mm/V. From this, the periodic force amplitude \( F_0 \) applied to the fiber is estimated to be \( 2.8 \times 10^{-3} \) N with a voltage amplitude of 0.4V.

Inserting the values given above, it is found that \( K_{\text{max}} = 5.1 \times 10^{-4} \) for \( \phi = 45^\circ \). The measured value of \( K_{\text{max}} \) (1.4 \times 10^{-2}) is higher by a factor of 27 than the calculated one. This discrepancy can be understood as a result of the increase of \( F_0 \) above its dc voltage due to system resonance. Because \( \sin(2\phi) \) dependence of \( K_0 \) is just fits the experimentally obtained values, linear superposition of internal and external stress/strain fields is very well established.

Cross-polarization coupling of the coated fiber can generally be expected to be smaller by the factor \( a/a' \), where \( 2a' \) is the outer coating diameter. Furthermore, the modification of the stress distribution in the composite structure in the coated fiber should be taken into account by using the elastic modulus \( E' \) of the homopolymer nylon. Using the values of \( 2a' = 900 \mu m \), and \( E' = 1.07 \times 10^5 \) N/cm\(^2\), the maximum coupling amplitude \( K_{\text{max}}^{\text{vl}} \) is estimated to be \( (a/a')^2 \times (E'/E) \times K_{\text{max}} = 3.25 \times 10^{-5} \), which is in good agreement with...
the observed peak value of $K_{\text{max}} = 3.46 \times 10^{-5}$ for the azimuth angle $\phi = 310^\circ$ in Fig. 6.

When the lateral force is applied for a long time, the polymer tends to yield slowly, thus changing the contact area between the pressure jaws and the coating. As a consequence, the stress difference in the fiber will also change somewhat. When the force is removed, the stress on the fiber will not decrease immediately and fully to the initial value (before applying the force). This is related to distortions observed in the coupling amplitude curve $K_0$ vs the azimuth angle $\phi$, as shown in Fig. 6.

As shown in Fig. 10, the modal birefringence $B$ decreases as the wavelength $\lambda$ becomes longer relative to the cutoff wavelength. The observed wavelength dependence of the modal birefringence agrees well with the experimental results reported.\(^8\)

For a PANDA fiber structure having a circular core and stress-applying parts on both sides of the core, the modal birefringence $B$ is only due to stress-induced birefringence. The stress-induced birefringence is given by the average of the material birefringence over the core and cladding with the electric field distribution squared as a weighting factor. From a finite element analysis,\(^{14}\) it is shown that the stress-difference, $\sigma_x - \sigma_y$, in the core is almost constant, whereas it decreases along the principal axes from the core center to the center position of the stress-applying part. When the operating wavelength becomes longer relative to the cutoff wavelength, the electric field of the HE\(_{11}\) modes spreads over not only the core but also the cladding. Then the modal birefringence $B$ decreases as the wavelength becomes longer.

**Conclusion**

We have presented a method for modal birefringence measurement in highly birefringent fibers by the elastooptic modulation method. With this modulation method, modal birefringence can be measured within a 0.3% error for a bare fiber and within 3% for a nylon-coated fiber. Furthermore, by splicing the same fibers with their principal axes crossed, the wavelength dependence of modal birefringence has also been measured within a 0.3% error using an incoherent light source such as a fiber Raman laser.

The authors would like to express their sincere thanks to H. Takata and N. Inagaki for continuous encouragement. They also thank K. Okamoto for helpful discussions and Y. Sasaki and T. Hosaka for supplying PANDA fibers. One of the authors, R. Ulrich, conducted this work while at NTT Ibaraki ECL as a visiting scientist.

**References**