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Temperature and Strain Sensitivities of High-Birefringence Elliptical Fibers

Feng Zhang
University of Waterloo

John W.Y. Lit
Wilfrid Laurier University, jlit@wlu.ca

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Temperature and strain sensitivity measurements of high-birefringent polarization-maintaining fibers

Feng Zhang and John W. Y. Lit

The strain and temperature sensitivities of three common commercial high-birefringent polarization-maintaining fibers (bow-tie, polarization-maintaining and absorption-reducing, and elliptical core fibers) have been measured by using a dynamic polarimetric method. The experimental setup and measuring process are described in detail. Where possible, the measuring data are compared with published data, and good agreement is obtained.

Introduction

Considerable research effort has recently been devoted to the design and development of high-birefringence (HB) polarization-maintaining (PM) fibers.[1] Birefringences in these fibers can be induced by built-in stress or by geometrical deformation of the fiber core.[2,3] The polarization state of the light can be well maintained when the state of an incident linearly polarized beam is coincident with one of the optical eigenaxes of the fiber. But when the polarization state injected into the fiber is at a 45° angle with one of the optical axes of the fiber, the difference in phase changes between the two eigenpolarization states is sensitive to environmental perturbations.[4] These two features make HB fibers indispensable in coherent optical transmission systems or in polarization-dependent sensors that are used in an unstable environment.

Because of various manufacturing techniques, different commercial HB PM fibers have rather diverse propagation properties when they are affected by external perturbations, such as temperature, strain, bending, and pressure. In order to improve the system properties in some applications, we need more study and comparison of these fibers.

The polarimetric method employing a polarizer and an analyzer is simple in principle.[5] It serves as the basis for polarimetric sensors or detection techniques. It is also suitable for a wide range of intrinsic birefringence values and can be extended to measure the sensitivities of fibers subjected to some external sources of mode coupling such as temperature and strain. In a polarimetric system, the basic polarizer and analyzer may be complemented by a Soleil compensator or quarter-wave plate to enhance the measurement range. However, measurement sensitivity is poor for retardation below 10° and the method suffers serious errors arising from imperfect optical components.[6] These inherent drawbacks arise simply because in general a static birefringence is being measured. Birefringence modulation vastly improves the measurement sensitivity.[7] The application of dynamic photoelastic birefringence modulation to measure low birefringence fibers and the temperature effect of bow-tie fibers has been reported.[6,8] Compared with the static polarimetry technique, the dynamic method is more sensitive, faster, and more accurate.

To understand the polarization properties of different kinds of PM fiber, experimental studies have been conducted. This paper describes the theory and experimental measurements of the temperature and strain sensitivities of three common types of commercially availabe HB PM fibers: bow-tie, polarization-maintaining and absorption-reducing (PANDA), and elliptical core fibers. The strain and temperature sensitivities of these three PM fibers have been measured by using a dynamic polarimetric method. The results are compared and discussed in detail.

When this research was performed F. Zhang was with Guelph— Graduate Work in Physics, Department of Physics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada. He is now with Opto-Electronics, Inc., 2538 Speers Road, Oakville, Ottawa, Ontario L6L 5K9 Canada. J. W. Y. Lit is with the Department of Physics and Computing, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada.
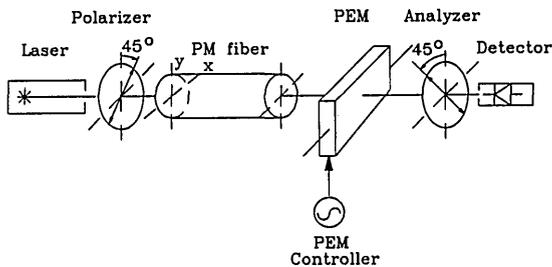
Fig. 1. Schematic diagram of dynamic polarimetry: PM fiber, polarization-maintaining fiber; PEM, photoelastic modulator.

Experimental Principle and Setup

Principle

Figure 1 shows two crossed polarizers oriented at ±45° with respect to the optical axis of a photoelastic modulator (PEM). A PM fiber is placed betwen the first polarizer and the PEM with its optical axes (fast and slow axes) aligned with the PEM optical axes that are in the x and y directions. The normalized electric field after the first polarizer is

$$\mathbf{E} = \frac{1}{\sqrt{2}}(i + j). \quad (1)$$

The birefringent phase retardation between the x and y polarization after a length of fiber L is given by

$$\delta\phi = \delta\beta L, \quad (2)$$

where $\delta\beta$ is the birefringence of the PM fiber. The phase shift produced by the PEM is

$$s = s_0 \cos(\omega t), \quad (3)$$

where $s_0 = \pi/2$ and $f = 50$ kHz. Therefore the electric field after phase modulation, modified by the fiber and PEM phase shifts, is

$$\mathbf{E}' = 1/\sqrt{2}\{i \exp[(\delta\phi + s)/2] + j \exp[-(\delta\phi + s)/2]\}. \quad (4)$$
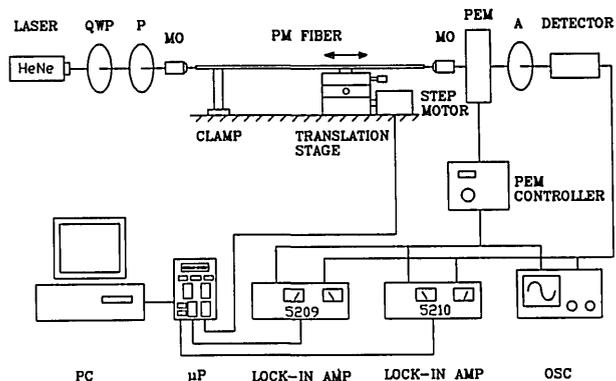

Fig. 2. Experimental setup for strain sensitivity measurement of PM fibers: QWP, quarter-wave plate; P, polarizer; A, analyzer; PEM, photoelastic modulator; MO, microscope objective (20×); OSC, oscilloscope.

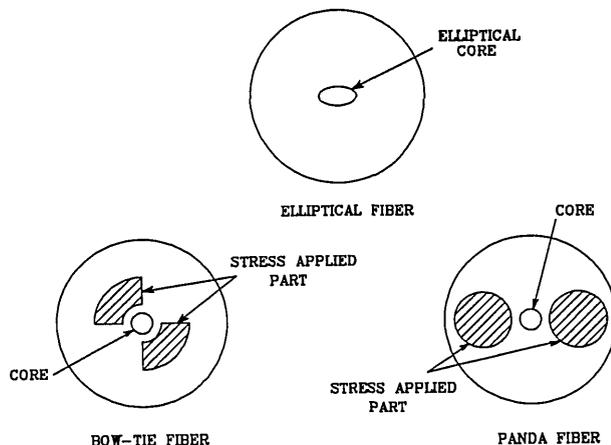Fig. 3. Structures of three tested PM fibers.

To get the output intensity I'' we must project $\mathbf{E}'$ onto the −45° transmitting axis of the analyzer, yielding

$$\mathbf{E}'' = 1/\sqrt{2}(i - j) \cdot \mathbf{E}' = \tfrac{1}{2}\{\exp[i(\delta\phi + s)/2]$$
$$- \exp[-i(\delta\phi + s)/2]\} = i \sin[\delta\phi + s]/2]. \quad (5)$$

The output intensity seen by the detector is

$$I'' = |\mathbf{E}''|^2 = \sin^2[\delta\phi + s)/2]$$
$$= \tfrac{1}{2}[1 - \cos(\delta\phi)\cos(s) + \sin(\delta\phi)\sin(s)]. \quad (6)$$

The cosine term here contains only even harmonics of the modulation frequency ω, while the sine term has the odd harmonics. After expanding the above equation in terms of $\cos(n\omega t)$, $n = 1, 2, 3, \ldots$, we obtain

$$I'' = \tfrac{1}{2}[1 - J_0(s_0)\cos(\delta\phi)] + J_1(s_0)\sin(\delta\phi)\cos \omega t$$
$$+ J_2(s_0)\cos(\delta\phi)\cos 2\omega t - \cdots. \quad (7)$$

If we can measure the amplitudes of the first and second harmonics,

$$I_1'' = J_1(s_0)\sin(\delta\phi), \qquad I_2'' = J_2(s_0)\cos(\delta\phi), \quad (8)$$

we can get the phase shift of PM fiber:

$$\tan(\delta\phi) = \frac{J_2(s_0)I_1''}{J_1(s_0)I_2''} = 0.4394 \frac{I_1''}{I_2''} \propto \frac{I_1''}{I_2''}. \quad (9)$$

Table 1. Parameters of Three Tested PM Fibers

Fibers	Wavelength (μm)	Beat Length (mm)	Attenuation (dB/km)	Core d (μm)	Cladding d (μm)
Bow tie[a]	0.633	1.0	12	4	125
PANDA[b]	0.633	2.0	12	4	125
Elliptical[c]	0.633	1.6	24	1 × 2	68

[a]York Technology.
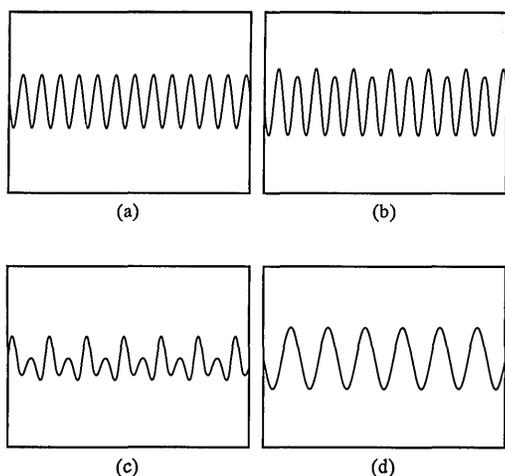[b]Alcoa Fujikura, Ltd.
[c]Andrew Corporation.

Fig. 4. Electrical output signals (observed on an oscilloscope) that change periodically between frequencies of $2f$ and $1f$ while the test fiber is pulled: (a) phase retardation $\delta\phi$ of fiber is 0 (frequency $2f$), (b) $0 < \delta\phi < \pi/4$, (c) $\pi/4 < \delta\phi < \pi/2$, (d) $\delta\phi = \pi/2$ (frequency $1f$). Here only a half-period is given.

The phase shift of PM fiber is independent of the laser intensity fluctuations because of the cancellation of the common intensity variation in the first and second harmonics.

Setup

Figure 2 shows the test setup that was used for strain measurements. Linearly polarized light that emerges with a fixed polarization plane from a 10-mW He–Ne laser with $\lambda = 0.633$ μm passes through a quarter-wave plate and a rotatable Glan–Thompson polarizing prism to produce linearly polarized light of constant intensity at a desired polarization angle. The laser beam was launched into a test PM fiber core with the help of a single-mode-fiber coupling system that has an adjustable mechanism and a 20× microscope objective lens. The output light from the test fiber was converged by a second single-mode-fiber coupling system. The light was modulated by a
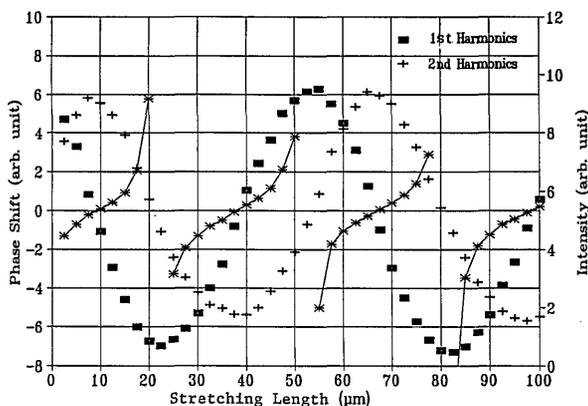
PEM and converted to an electronic signal by a wave analyzer.

The PEM uses the principle of photoelasticity to provide polarization modulation of a light beam. The instrument has two parts: a modulation head and a controller. The modulation head is a rectangular bar of fused silica bonded to a quartz transducer. The amplitude of the vibrations and therefore the magnitude of the birefringence phase shift was varied sinusoidally from 0 to $\pi/2$ electronically with the PEM controller by a 0–5 V, 50-kHz square-wave signal sent to the head. The PEM controller was also used to drive two EG&G lock-in amplifiers working in frequencies of $1f$ (50-kHz) and $2f$ (100-kHz) reference signals. An oscilloscope was used to display the signal. A microprocessor control led the lock-in amplifiers; it received and processed the $1f$ and $2f$ data from the amplifiers. The three tested PM fibers, shown in Fig. 3, are bow-tie fiber, PANDA fiber, and elliptical core fiber with the parameters listed in Table 1.

Fig. 6. Strain sensitivity measurement for PANDA fiber: *, phase shift that is due to fiber elongation; –, intensity of first harmonics; +, intensity of second harmonics.

Fig. 5. Strain sensitivity measurement for bow-tie fiber: *, phase shift that is due to fiber elongation; –, intensity of first harmonics; +, intensity of second harmonics.
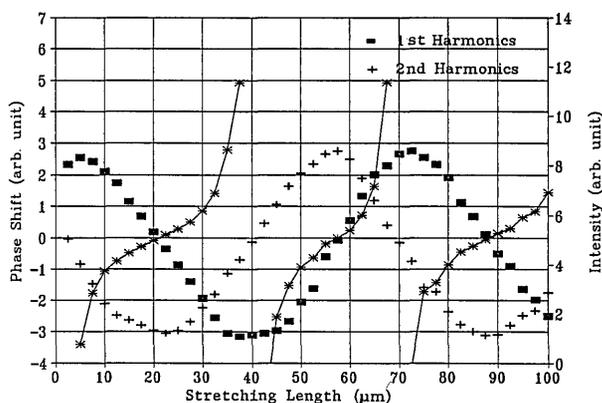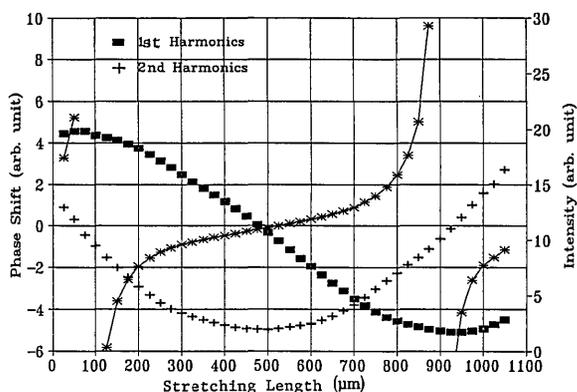

Fig. 7. Strain sensitivity measurement for elliptical fiber: *, phase shift that is due to fiber elongation; –, intensity of first harmonics; +, intensity of second harmonics.
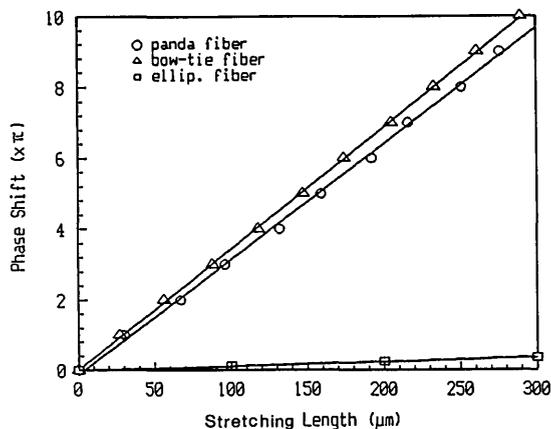
Fig. 8. Phase shift as a function of elongation for bow-tie, PANDA, and elliptical core fibers.
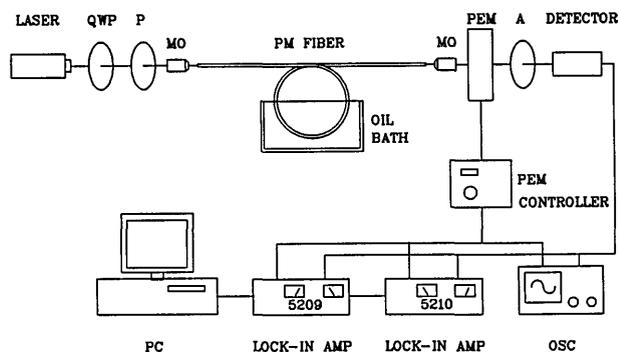

Fig. 9. Experimental setup for temperature sensitivity measurement of PM fibers. The abbreviations are the same as those defined in the caption to Fig. 2.

III. Strain Measurement

The fiber strain measurement system is shown in Fig. 2. A 67-cm-long PM fiber was attached to two height-adjustable rods by epoxy. One rod was positioned on an aluminum base plate and another on a translation stage, which was also positioned on the same base plate. The stage was movable in directions along and perpendicular to the test fiber, and it was driven by a stepping motor along the fiber. The strain in a testing PM fiber is produced by pulling the fiber (19 cm long) with a stepping motor that is controlled by a microprocessor. With the help of a dc motor has 1.8° step angles and a linear longitudinal movement of 500 μm/turn. Consequently, each step gives an axial displacement of 2.5 μm along the fiber.

Because the PM fibers are sensitive to temperature fluctuations, we used cotton and Styrofoam to insulate the whole test fiber after the system had been adjusted. When the measuring system is ready, we can automatically measure the phase retardation that is induced by strain. Basic programs have been written to control the microprocessor and the two lock-in amplifiers and to receive and process the 1f and 2f data from the amplifiers synchronically. The electrical output signal observed in the oscilloscope changes periodically between 2f and 1f because the phase retardation changes periodically from 0 to π while the test fiber is being pulled, as shown in Fig. 4. The signals with a 2f or 1f period correspond to total phases of $2n\pi$ or $(2n + 1)\pi$, $n = 0, 1, 2, \ldots$, of the

test fiber. The test results of bow-tie, PANDA, and elliptical core fibers are shown in Figs. 5, 6, and 7, respectively. The phase retardation curves in these figures, which were obtained from the ratio of 1f to 2f signals, give the relations between the phase change and the fiber elongation; they have periods of π. But the absolute values of phase in each branch can be given only after calibration.

The three fibers have been stretched until broken. The 1f and 2f signals as functions of strain for the bow-tie, PANDA, and elliptical core fibers are shown in Figs. 5, 6 and 7, respectively. The corresponding phase retardation curves in Fig. 8 show that the phase response to elongation of the fibers is linear and give the strain sensitivities of the test fibers: 107.74 rad/mm for bow-tie fiber, 102.54 rad/mm for PANDA fiber, and 3.77 rad/mm for elliptical fiber. Comparison of our results of the strain sensitivity measurements for the York HiBi fiber (bow tie) given in Table 1 with other researchers results listed in Table 2 shows that our results match well with the average of others. The strain sensitivity depends on the parameters of the test fibers, especially the beat length.

Glasses used in optical fiber applications behave as elastic bodies until they reach their breaking strength. The elastic strains were produced by elongations and

Table 2. Comparison of Strain Sensitivity (Δφ/ΔL) Measurements for York Bow-Tie Fiber

Strain Sensitivity (rad/mm)	Sources			
	Varnham *et al.*[a]	Leilabady *et al.*[b]	Hogg *et al.*[c]	This Work
Δφ/ΔL	120	65	82.03	107.74

[a]Ref. 9.
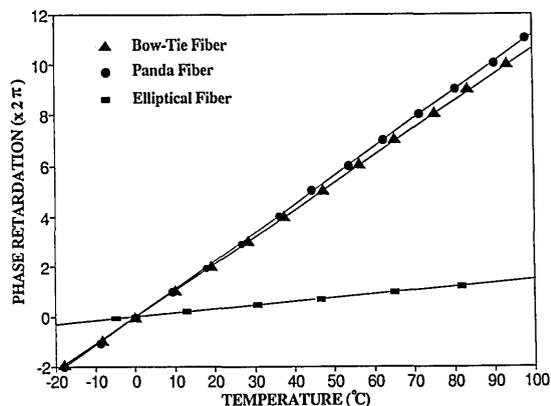[b]Ref. 10.
[c]Ref. 11.

Fig. 10. Phase shift as a function of temperature for bow-tie, PANDA, and elliptical core fibers.

rotations of the bonds between the atoms comprising the glass. Large elastic strains (>5%) can be obtained since the breaking strength of glass fibers can be large (5 GPa).[12] Strains of this magnitude require consideration of nonlinear elastic effects.[13,14] However, the breaking strength of a fiber depends on the quality of the fiber. Any inhomogeneity and flaws can significantly reduce the fiber strengths. Within the linear elastic effect range, the maximum strain of our three test fibers was <0.5%.

Temperature Measurement

The temperature sensitivity measurement system is shown in Fig. 9. 10 cm of a 1-m-long fiber was held strain free in a paraffin oil bath by a soft clamp. Temperature changes were produced with the help of a heating plate and dry ice. In order to cancel out the effects of the air draft and the room temperature variations, we used a common mode rejection method by cutting the whole fiber into two equal lengths and fusing them together with a 90° rotation. A differential temperature perturbation was avoided by insulating the nonheating part of the fiber with cotton and Styrofoam.

First, the paraffin oil was heated to 100°C; measurements were taken while the oil was cooling down to room temperature in order to obtain stable results. Dry ice continued to cool the oil to −10°C. The signal seen by the detector changes between the first harmonic and the second harmonic periodically as the temperature continues to increase (or decrease). The phase shifts as a function of temperature for the three fibers are shown in Fig. 10. It was found that the temperature sensitivity of the elliptical fiber, 1.1/m°C, was less than that of the bow-tie fiber, 7.35/m°C, and the PANDA fiber, 7.57/m°C. This shows that the birefringence induced by the shape deformation of fiber core has more temperature stability than that induced by built-in stress. Comparison of our results of the temperature sensitivity measurements for the York HiBi fiber (bow tie) with others listed in Table 3 show a good match with the average value of the other authors.

The phase change of HB PM fiber with temperature is caused mainly by the birefringence change with temperature, which is linear within our measuring range. However, this is not true if the tempera-

ture continues to increase. Birefringence of a bow-tie fiber changes with temperature from ~20°C to 1000°C has been reported.[8] The birefringence decreases to a minimum value with the temperature at ~450°C; it then increases to its original value at ~750°C. It is also reported that thermal hysteresis of the birefringence occurs when the fiber is quenched.

Conclusion

The strain and temperature sensitivities of three common types of commercially available high-birefringent PM fiber (bow tie, PANDA, and elliptical core) have been measured by a dynamic polarimetric method. The measurements are automatic and controlled by a microprocessor. The phase retardation of two eigenpolarizations in these fibers caused by strain and temperature variations has been measured and compared. The results show that, within the chosen measuring range, the phase retardation of these three fibers increases linearly with strain or temperature. The strain sensitivities of the bow-tie, PANDA, and elliptical core fibers are 107.74, 102.54, and 3.77 rad/mm, and the temperature sensitivities are 7.35, 7.57 and 1.1 rad/m°C, respectively. Comparison of our measurement results of strain and temperature sensitivities for York HiBi fiber (bow tie) with those of other researchers shows a good match with their averages.

Table 3. Comparison of Temperature Sensitivity ($\Delta\phi/L\Delta T$) Measurements for York Bow-Tie Fiber

Temperature Sensitivity (rad/m°C)	Sources					
	Jones and Jackson[a]	Leilabady et al.[b]	Waite et al.[c]	Kersey et al.[d]	Hogg et al.[e]	This Work
$\Delta\phi/L\Delta T$	10.00	4.99	4.99	2.62	4.35	7.35

[a]Ref. 15.
[b]Ref. 16.
[c]Ref. 17.
[d]Ref. 18.
[e]Ref. 11.

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