Accurate method for measuring the thermal coefficient of group birefringence of polarization-maintaining fibers

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We present a method to accurately measure the group birefringence variation with temperature in high-birefringence polarization-maintaining (PM) fibers using a distributed polarization analyzer. By analyzing polarization cross-talk peaks purposely induced at both ends of a PM fiber, the temperature coefficient of group birefringence can be accurately obtained. We confirm the theoretical prediction that the group birefringence of PANDA and TIGER PM fibers decrease linearly with temperature from −40 °C to 80 °C, and find that the temperature coefficients are $-5.93\times10^{-7}\,°\mathrm{C}^{-1}$ and $-5.29\times10^{-7}\,°\mathrm{C}^{-1}$ for two types of PANDA fibers, and $-5.36\times10^{-7}\,°\mathrm{C}^{-1}$ for a TIGER fiber.

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The stress-induced birefringence, such as that in PANDA and TIGER polarization-maintaining (PM) fibers, is expected to be temperature dependent because it is caused by anisotropic strain resulting from the differential thermal expansion of different regions in the fiber cladding, and to vary linearly with temperature in the vicinity of room temperature [1]. The thermal coefficient of the group birefringence is an important parameter for the application of PM fibers in different temperatures; however, few measurement results [1,2] are found in literature. The only plausible data were published by Flavin *et al.* [2], who measured the temperature dependence of the differential group delay of a PM fiber and obtained a linear temperature coefficient of $-1.733\,\mathrm{fs}/°\mathrm{C}\cdot\mathrm{m}$ (or $-5.2\times10^{-7}\,°\mathrm{C}^{-1}$) from 625 to 1075 nm.

The thermal coefficient of the group birefringence can be obtained by the accurate measurements of the group birefringence or beat length at different temperatures. Therefore, a good measurement setup must not only be able to measure the birefringence, but also allow the fiber under test to be placed in a temperature chamber without introducing significant measurement errors. The common methods for the beat length measurements of PM fibers include those of white-light spectral interferometry [1,3], wavelength scanning [4,5], and dispersive Fourier transform spectroscopy [2,6]. However, experimental setups for these methods are complicated and it is difficult to put the fiber under test into a temperature chamber without introducing large errors.

In this Letter, we report a new method of measuring the temperature variation of group birefringence of PM fibers using a distributed polarization cross-talk analyzer (General Photonics PXA-1000) and present the measurement results of three different PM fibers from three different manufacturers (PANDA-I, PANDA-II, and a TIGER PM fiber). The equipment can measure PM fibers with lengths up to 1.3 km and therefore allows a spool of PM fiber under test to be placed inside a temperature chamber with negligible error introduced. By linear-fitting data to the theoretical formula using the least squares method, we confirm that the group birefringence in PM fibers of stress-induced birefringence, such as PANDA and TIGER fibers, decreases linearly with temperature. We show analytically that the major measurement error is inversely proportional to the fiber length and the method has an accuracy of less than 1.5% when fiber length is longer than 40 m. We find with high confidence that the temperature coefficients of group birefringence are $-5.93\times10^{-7}\,°\mathrm{C}^{-1}$, $-5.29\times10^{-7}\,°\mathrm{C}^{-1}$, and $-5.36\times10^{-7}\,°\mathrm{C}^{-1}$ for PANDA-I, PANDA-II, and the TIGER fiber, respectively.

PANDA and TIGER PM fibers belong to stress-induced birefringent fibers and their birefringence Δn_b can be expressed by [1,7]

$$\Delta n_b = \gamma(T_0 - T), \tag{1}$$

where T is the temperature of the fiber under test, T_0 is the softening temperature of the silica glass with dopants in the stress-inducing region of the cladding, and γ is the thermal coefficient of birefringence of the PM fiber, the parameter to be measured in this paper.

The basic construction of a distributed polarization cross-talk analyzer [8] is shown in Fig. 1. A polarized super luminescent diode source (SLED in this Letter) with an extremely short coherence length (about 25 μm) is coupled into a PM fiber with its polarization aligned with the slow axis of the fiber. Assume at point B, a polarization cross talk is induced by an external disturbance and some light is coupled into the fast axis of the PM fiber, as shown in the insert of Fig. 1. Because light polarized along the fast axis travels faster than that along the slow axis, at the output of the fiber, the faster component will be ahead of the slow component by

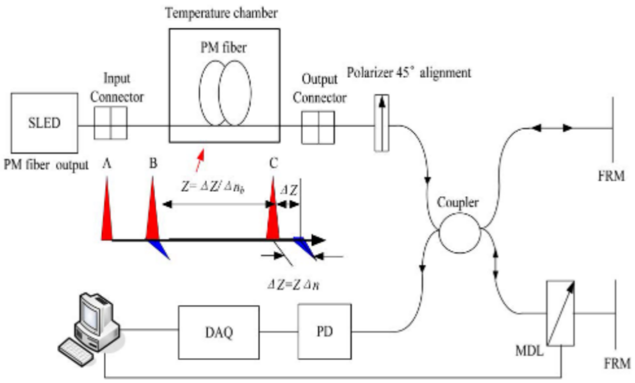

Fig. 1. (Color online) Simplified illustration of a distributed polarization cross-talk analyzer designed to obtain space-resolved polarization coupling along a length of PM fiber. The insert shows the delay relation between the original and the cross talk components. The PM fiber under test is placed inside a temperature chamber to expose it to different temperatures. Slight fiber axis misalignments at input and output connectors are induced to cause large polarization cross talks. MDL, FRM, PD, and DAQ are motorized delay line, Faraday rotation mirror, photodetector, and data acquisition card, respectively.

$$\Delta Z = Z \Delta n_b, \tag{2}$$

where Δn_b is the group birefringence of the PM fiber and Z is the length between the point where the cross talk occurs (B) and the output end (point C). The polarization components in the slow and fast axes are brought to interfere in the Michelson interferometer after going through a polarizer oriented 45° from the slow axis to produce interference peaks as a function of the relative delay. The coherence length of the light source (~25 μm with the SLED used) defines the spatial resolution of the polarization cross-talk measurement and is sufficiently high for the accurate measurement of cross talk locations.

Figure 2(a) shows typical polarization cross-talk curves of a PM fiber coil (PANDA-I) of 350.3 m at three different temperatures (40 °C, 0 °C, and −40 °C), as a function of relative delay. Because the distance Z between the two connectors (fiber length) can be measured by a ruler or an optical time-domain reflectometer (OTDR) and the relative delay ΔZ between the two high cross-talk points caused by input and output connectors on the far left and far right can be obtained precisely with the encoder of the motorized delay line, Δn_b can be obtained using Eq. (2). Clearly, the position of the peak corresponding to the output connector changes with temperature, as expected from Eq. (2). The fact that ΔZ decreases as the temperature increases indicates that Δn_b has a negative thermal coefficient. As mentioned previously, the thermal coefficient of the group birefringence γ can be obtained by linear-fitting Δn_b to Eq. (1) using the least squares method at different temperatures.

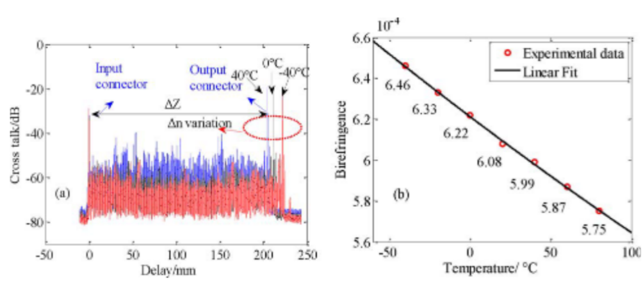

Fig. 2. (Color online) (a) Polarization cross-talk curves of a PM fiber as a function of the relative delay at 40°C, 0°C, and −40 °C. The peaks at the far left and right correspond to the cross talk induced at the input and output connectors, respectively, by slight axis misalignment. The rest of the peaks are induced by the stress of the fiber in various locations, which are not the concern of this paper. (b) Measured Δn_b at seven different temperatures.

We measure Δn_b of the PANDA-I coil at seven different temperature points (−40°C, −20°C, 0°C, 20°C, 40°C, 60°C, and 80 °C) using the polarization cross talk analysis method and the results are plotted in Fig. 2(b). As will be discussed later, we chose such a long fiber length (350.3 m) to minimize multiple measurement errors. Linear-fitting Δn_b to Eq. (1) obtains a thermal coefficient γ of -5.86×10^{-7} °C^{-1}. To obtain the repeatability of the measurement, we take three different measurements and the results are shown in Table 1.

To further verify the feasibility of this method, we measure Δn_b of other two PM fiber coils of the same length at the seven temperature points. One of them is also a PANDA PM fiber (PANDA-II), but is from a different manufacturer than PANDA-I. The other is a TIGER fiber. The measurement results are summarized in Table 1. The average thermal coefficients γ of the three types of PM fibers are -5.93×10^{-7} °C^{-1} (PANDA-I), -5.29×10^{-7} °C^{-1} (PANDA-II), and -5.36×10^{-7} °C^{-1} (TIGER).

Several error sources may contribute to the final measurement error of Δn_b, including the measurement errors δ_z of fiber length Z and $\delta_{\Delta z}$ of relative delay ΔZ in Eq. (2). Consequently, the total relative error $\delta_{\Delta z}/\Delta n_b$ can be obtained by the error transfer formula

$$\delta_{\Delta n_b}/\Delta n_b = \sqrt{(\delta_{\Delta Z}/\Delta Z)^2 + (\delta_Z/Z)^2} = \sqrt{(\delta_{\Delta Z}/\Delta n_b)^2 + (\delta_Z)^2}/Z. \tag{3}$$

It is important to notice that the relative error is largely inversely proportional to the total fiber length under test. In order to reduce the measurement error, the fiber length inside the temperature chamber should be sufficiently long. Table 2 lists all potential measurement errors contributing to the overall measurement accuracy. It is interesting to notice that the dominant error sources are the fiber pigtail length outside of the temperature chamber and the fiber length measurement tolerance. In general, if a fiber length can be accurately measured, a total fiber length larger than 40 m should be sufficient for accurate thermal coefficient γ measurement with an accuracy of less than 1.5%, assuming total fiber pigtail

Table 1. Measurement Results of the Thermal Coefficient γ of Three Different PM Fibers

Fiber Type	PANDA-I	PANDA-II	TIGER
1	-5.86×10^{-7}	-5.25×10^{-7}	-5.33×10^{-7}
2	-5.96×10^{-7}	-5.25×10^{-7}	-5.43×10^{-7}
3	-5.96×10^{-7}	-5.36×10^{-7}	-5.32×10^{-7}
Average γ	-5.93×10^{-7}	-5.29×10^{-7}	-5.36×10^{-7}

Table 2. Description and Estimation of Measurement Errors[a]

Error Source	Error Description	Error Magnitude	Relative Error ($\Delta n_b \sim 5\times10^{-4}$)
$\delta_{\Delta z}$	$\delta_{\Delta z1}$: delay accuracy of the motorized delay line	$\delta_{\Delta z1} = 1\mu$m	2×10^{-3}/Z
	$\delta_{\Delta z2}$: position error of the input connector's cross-talk peak, about 1/2 of the peak width W_0 (coherent length of the light source).	$\delta_{\Delta z2} = 12.5\,\mu$m	2.5×10^{-2}/Z
	$\delta_{\Delta z3}$: position error of the output connector's cross-talk peak broadened by birefringent dispersion [9], about 1/2 of the broadened peak width $W = [1 + 2\pi cZ(\Delta\lambda/\lambda)^2\Delta D]^{1/2}W_0$.	$\delta_{\Delta z3} = 1/2W = (156.25 + 2.78Z)^{1/2}$	$(6.25 + 0.11Z)^{1/2}\times10^{-2}/Z$
	$\delta_{\Delta z4}$: total length Z_{pigtail} of two fiber pigtails of the fiber spool outside of the temperature chamber that will introduce an error in ΔZ measurement at different temperatures: $\Delta Z = Zn_b(T) + Z_{\text{pigtail}}[\Delta n(T_R) - \Delta n_b(T)]$, where T_R is the room temperature	$\delta_{\Delta z1} = Z_{\text{pigtail}}[\Delta n_b(T_R) - \Delta n_b(T)]$	$0.1\times Z_{\text{pigtail}}/Z$, assuming $\Delta T = 100\,°$C
δ_z	δ_{z1}: error in fiber length measurement by a ruler or OTDR	$\delta_{z1} = 1\%Z$ by ruler $\delta_{z1} = 1.5$ m by OTDR	1% by ruler $1.5/Z$ by OTDR
	δ_{z2}: fiber length Z variation due to thermal expansion at different temperatures: however, a constant fiber length is assumed in Eq. (1)	$\delta_{z2} = 10^{-6}Z\times\Delta T$	10^{-4}, assuming $\Delta T = 100\,°$C

[a]Note that in Table 2, Z is measured in meters, ΔD [~0.018 ps/(km.nm)] is the coefficient of birefringence chromatic dispersion, and λ_0 and $\Delta\lambda$ are the center wavelength and the FWHM of the power spectrum of the light source (30 nm), respectively. In the error estimation of the position of a cross-talk peak, a readily achievable number of half of the peak width is used, although more accurate determination can be achieved with advanced data analysis [10].

length outside the temperature chamber is less than 4 m. In the measurements of Table 1, we choose a fiber length of 350 m to ensure measurement accuracy. Since there is no "golden standard" fiber available with an accurately known thermal coefficient of birefringence, the relative error's inverse proportionality to the fiber length is difficult to be verified experimentally. Nevertheless, the analytical results in Table 2 serve as a good guidance to performing the actual measurements.

In summary, we propose and demonstrate a novel method of using a distributed polarization cross-talk analyzer to measure the thermal coefficient of the group birefringence in high-birefringence polarization-maintaining fibers. The method is nondestructive, easy to implement, highly sensitive, and highly accurate. Finally, we quantitatively analyze potential error sources of the measurement method and find that the measurement error decreases linearly with the fiber length. The method has an overall accuracy of less than 1.5%.

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