Distributed Polarization X-talk Measurement for the production of Polarization-Maintaining Fiber Coils

Abstract: This note introduces the use of distributed polarization x-talk measurement for raw polarization maintaining fiber (PMF) quality inspection, PMF coil winding process monitoring, PMF coil adhesive curing and stress release monitoring, overall PMF coil quality inspection, and temperature induced stress determination. PMF birefringence temperature variation can also be precisely measured. The use of distributed polarization x-talk measurement at all of these stages of the process can greatly improve the performance of the finished PMF coils.

Keywords: fiber optical gyro; fiber coil winding; distributed polarization x-talk; on-line monitoring; polarization maintaining fiber (PMF); fiber winding defects, birefringence variation with temperature

1. Introduction

Fiber optic gyroscopes (FOGs) have many important applications in navigation systems and angular velocity sensors. The main component in an FOG is a fiber coil. The quality of the fiber and the coil winding directly affect the performance of the FOG.

Until recently, the evaluation of PM fiber for fiber coils consisted solely of measurements of insertion loss, extinction ratio, and other macroscopic performance characteristics. Distributed evaluation of the fiber was not possible. The use of multi-pole symmetric winding methods can improve transient characteristics of fiber coils [1]; however, such winding methods are difficult to implement because they require the correction of winding errors which can degrade the performance of the fiber coils. On-line winding monitoring methods include video monitoring [2], winding tension monitoring [3], and so on. Such methods are, at best, indirect indicators of the performance of the finished fiber coils; as they do not directly monitor performance during the winding process, they cannot always pinpoint the location of poorly wound sections. Traditional distributed analysis methods include the use of Brillouin Optical Time-Domain Reflectometry (B-OTDR) [4] to detect stress in the fiber coils [5, 6]. However, the spatial resolution and sensitivity of B-OTDR are low, as shown in Table 1, making it difficult to precisely pinpoint the location of stress points. In addition, thermal stress on fiber coils is difficult to test by traditional methods.

Distributed polarization crosstalk (x-talk) measurement has. been found to be a powerful tool for evaluation and in-process monitoring of PMF coils for FOGs [7, 8, 9], since x-talk in the coils is a primary determinant of gyroscope performance [10]. General Photonics' distributed polarization x-talk analyzer (PXA-1000) obtains space-resolved stress information by analyzing stress-induced polarization cross-coupling along a length of polarization maintaining (PM) fiber [11]. It is based on a white light interferometer design, but eliminates many of the limitations of traditional white light interferometers. This technology is capable of high accuracy and spatial resolution [7, 14] and large dynamic range[12,13], and is also insensitive to optical power fluctuations [15]. In addition, it is capable of measuring fiber lengths on a scale needed for FOG coils. The PXA-1000 can therefore be used to implement raw PMF quality inspection, fiber winding process monitoring, monitoring of adhesive curing and stress release in PMF coils, overall PMF coil quality inspection, and temperature induced stress determination. The polarization x-talk in the PMF coils can be detected and controlled by such process monitoring.

Table 1 Performance of BOTDR vs. PXA-1000

	BOTDR	*PXA-1000*
Crosstalk sensitivity (dB)	-60	-95
Dynamic range (dB)	Max. 15	75
Spatial resolution (m)	1 - 22	0.05
Fiber measurement range (km)	1 - 80	0 - 2.6

2. Principles of polarization x-talk measurement

2.1 Polarization x-talk

Modal birefringence greater than 10^{-4} has been realized in PMF [16]. In undisturbed PMF, there is minimal x-talk between the orthogonal polarization modes, and the magnitude of the polarization x-talk remains below –80dB everywhere along the fiber [17]. However, in the presence of an external stress which induces x-talk, the fiber in the vicinity of the stress point can be modeled as a concatenation of three PMF sections [18, 19, 20]. As shown in Figure 1, the undisturbed PMF sections have the same beat length L_{bo}, and their birefringence axes are aligned. The stress on the middle section causes a rotation of angle θ of its birefringence axes relative to those of the other two PMF sections, and its beat length is also changed to a new value L_b. A fraction of the propagating optical power will therefore be transferred from one polarization mode to the other mode during the light's traversal of this section of fiber. This transfer is defined as polarization x-talk.

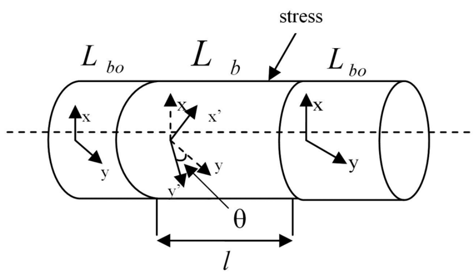


Figure 1 Model of the mechanism of polarization x-talk in PM fiber. The stress on the center section causes a relative rotation of the birefringence axes and hence the polarization x-talk.

Jones vector calculations can be used to determine the magnitude of x mode to y mode and y mode to x mode crosstalk [21].

$$h = h_{x\to y} = h_{y\to x} = \left|\sin\theta\cos\theta(1-\exp(-i2\pi l/L_b))\right|^2$$
$$= \sin^2(2\theta)\sin^2(\pi l/L_b) \qquad (1)$$

As shown in Eq. 1, x-talk magnitude is related to the length l, effective beat length L_b, and axis misalignment (relative to the unperturbed sections) θ of the perturbed section. During coil winding, factors such as excessive winding tension, adhesive-induced stress, or other winding defects can all result in crosstalk.

2.2 The PXA-1000

General Photonics' distributed polarization x-talk analyzer (PXA-1000) can pinpoint the locations of imperfections or areas of local stress on the fiber coil induced during the fiber winding process. Its 5 cm spatial resolution, −95 dB polarization x-talk sensitivity, and 2.6 km fiber measurement range make it uniquely suited to quality inspection and screening of PM fiber coils.

As shown in Figure 2, this distributed polarization x-talk analyzer is based on the structure of a "white light" interferometer. A broadband source (superluminescent diode, or SLD) couples a short-pulse wavetrain into one principal axis of a high birefringence PMF via a polarizer (point A in Figure 2a). At a polarization x-talk point caused by external stress, some light is coupled into a secondary low-power wavetrain in the orthogonal polarization (point B in Figure 2a). Because of the fiber birefringence, the wavetrains travel at different velocities. At the output of the fiber, their path difference is ΔnZ, where Δn is the birefringence index and Z is the fiber length between the x-talk point and the fiber end (point C in Figure 2a). A polarizer oriented at 45° to the principal axes, placed at the output of the fiber, projects both wavetrains onto the same state of polarization. The two wavetrains do not interfere if their path difference ΔZ is greater than the SLD's coherence length L_c, which is typically very short (about 10 μm). If the two wavetrains are sent into a scanned Michelson interferometer which can adjust the length of one optical path with a variable delay line (VDL), an interference signal occurs when the interferometer is balanced, but disappears when the path length imbalance is larger than the coherence length L_c. It reappears when the path length imbalance compensates for the path difference ΔZ between the two input wavetrains. Because, at this condition, interference occurs between the high-power primary wavetrain and the low-power secondary wavetrain, the interference signal intensity is equal to the power ratio between the two wavetrains. The x-talk point position can be calculated from $Z = \Delta Z / \Delta n$, and the x-talk intensity can be obtained from the interference signal strength [7].

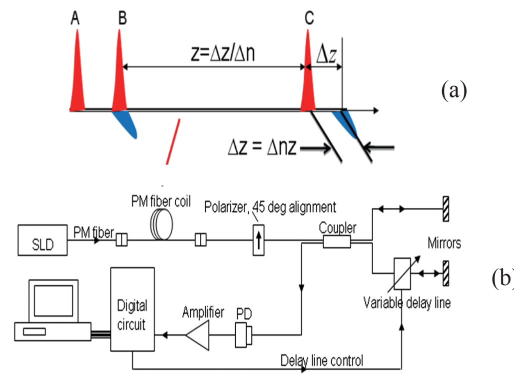


Figure 2 (a) Polarization crosstalk in a PM fiber. A single-polarization pulse is traveling in the fiber at point A. Crosstalk is induced by a stress at point B. The relative delay at output point C between the two pulses is ΔZ. The location Z of x-talk point B can be obtained from a measurement of relative delay ΔZ. (b) Structure of distributed polarization x-talk analyzer. A white light Michelson interferometer with a variable delay line is used to obtain the relative delay.

3 PMF coil evaluation via polarization x-talk testing

3.1 Polarization x-talk in a PM fiber coil

Stress on the PM fiber in a coil due to warping, pressure, tension, incorrect fiber position or other winding errors can cause high x-talk [16, 22, 23] at the stress location, which degrades the performance of the PMF [17, 24]. The magnitude and location of the x-talk caused by these winding errors can be measured with the system described above.

PMF coil polarization x-talk testing can be divided into several stages:

i. PM fiber QC: identify and eliminate intrinsic defects in the fiber used for fiber coils.

ii. On-line PMF winding monitoring: real-time detection of winding defects enables the winder to make corrections, control the winding tension, mark important winding positions, improve winding symmetry, reduce the coil defect rate, and generally improve coil quality.

iii. Adhesive curing and stress release monitoring.

iv. Overall PMF coil inspection.

v. Temperature induced stress measurement of the PMF coils provides understanding of the influence of the coil frame and adhesive on the performance of the coil.

vi. Measurement of the temperature variation of PMF birefringence by measuring polarization x-talk at different temperatures.

3.2 PM fiber QC

Figure 3 shows polarization x-talk measurement results for 1000 m of raw fiber. A high x-talk of -47 dB is observed at a location 381 m from the reference point. Detecting the position of defects in the fiber before winding allows the option of removing those sections of fiber.

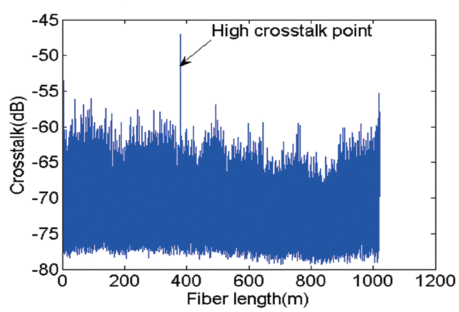


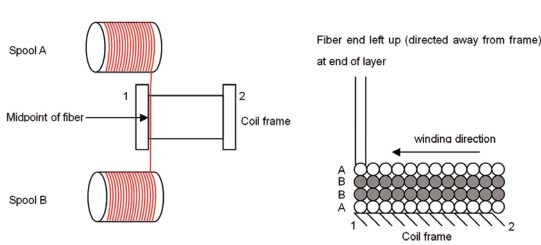
Figure 3 Polarization x-talk measurement of 1000 m of raw fiber. High x-talk (-47 dB) is observed at 381 m.

3.3 On-line PMF coil winding monitoring:

3.3.1 Real-time location of winding defects

Recently, fiber coils with the quadrupole symmetry winding method have come into common use for fiber gyro applications. In the quadrupole winding technique, the center of the fiber length to be wound is located, and the two halves of the fiber are wound onto holding spools (A and B). The coil winding begins at the midpoint of the fiber length, which is positioned at one side of the coil frame (side 1, in the picture below).

Figure 4 Quadrupole coil winding method. a) Coil winding

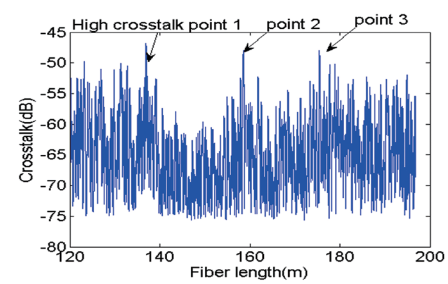


(a) (b)

begins from the midpoint of the fiber, and one layer of fiber is wound onto the coil from side 1 to side 2 of the coil frame, using the fiber from spool A. b) Cross section of one quadrupole, which consists of 4 layers of fiber in an ABBA structure.

One quadrupole is composed of 4 layers of fiber. The first layer is formed by winding fiber from spool A onto the frame from side 1 to side 2, leaving the fiber at the end of the layer up so that it doesn't become buried by subsequent layers. The next two layers are formed by winding fiber from spool B onto the frame from side 1 to side 2, then back from side 2 to side 1, leaving the end up so that it remains accessible. Finally, fiber from spool A is wound from side 2 to side 1, completing the 4th layer in the sequence. This 4-layer sequence is repeated as many times as necessary until the full length of fiber is wound onto the coil frame. The lengths of fiber in each quadrupole from spool A and spool B must be matched.

During winding, any defect in the coil structure, such as fiber crossovers that can cause layers not to lie flat, can cause crosstalk. One common source of crosstalk is the handling of the fiber ends that are left up when the fiber source is changed from spool A to spool B or vice versa, for example, the segment of fiber from spool A between the end of layer 1 and the beginning of layer 4, or the segment of fiber from spool B between the end of layer 3 and the beginning of layer 6. On-line monitoring of the PMF winding process allows the immediate identification and location of winding defects.



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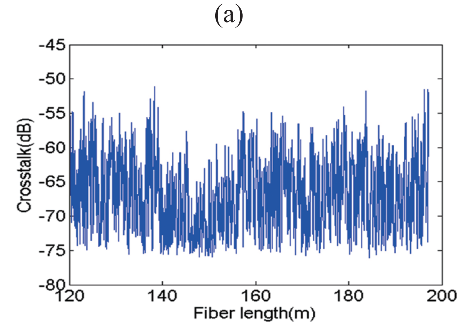


(b)

Figure 5 Polarization x-talk measurement results for layers 1-4 of a coil after initial winding (a) and after rewinding (b). Note that the high x-talk points observed during the initial winding are corrected by a more careful rewinding of the fiber.

Figure 5 shows the crosstalk measurements of layers 1-4 of a PM fiber coil after an initial winding attempt and then after a more careful rewinding. The measurement after the initial winding (Figure 5a) shows three high x-talk points at 136, 158 and 175m, with magnitudes -46, -47, and -48 dB, respectively, much higher than the average x-talk intensity in layers 1-4. When the four layers are rewound, the causes of the high crosstalk can be identified. In this case, the first high x-talk point occurs in the spool A fiber segment between layer 1 and layer 4, the second high x-talk point is due to a winding defect in the first layer, and the third high x-talk point occurs in the fiber segment between layer 3 and the next spool B layer. The on-line polarization x-talk testing identifies the errors in time for them to be remedied. When layers are rewound with better winding control, the most serious x-talk points can be eliminated. As shown in Figure 5(b), Table 2, and Table 3, polarization x-talk measurement results of layers 1-4 of the rewound coil show that the maximum x-talk is now -53 dB, the three previously observed high x-talk points have been eliminated, and the average x-talk of layers 1-4 is -66 dB, 2 dB lower than that of the coil after the initial winding.

Table 2 High x-talk points in layers 1-4 of the coil after initial winding.

	High x-talk point 1	*High x-talk point 2*	*High x-talk point 3*
position (m)	136.948	158.508	175.412
x-talk (dB)	-46.8799	-47.8237	-48.2796

Table 3 X-talk comparison of layers 1-4 after initial winding and after rewinding

	Initial winding	Rewinding
Average x-talk (dB)	-64.5541	-66.2945
Maximum x-talk (dB)	-46.8799	-53.3771
Position of maximum x-talk (m)	136.948	138.233

3.3.2 On-line control of winding tension

The distributed polarization x-talk analyzer can also be used to control the winding tension of a coil in real time by monitoring the magnitude of polarization x-talk in the fiber coil during winding. If the winding tension is very high, the polarization x-talk in the coil is correspondingly high. Comparing the x-talk intensity of the raw fiber and the fiber coils after winding indicates the amount of performance deterioration in the PMF due to winding, which can be used to determine the optimal range of winding tension.

As shown in Figure 6 and Table 4, the average x-talk intensity of fiber wound into two layers of a coil under high tension is -56 dB, 14 dB higher than that of the raw fiber, indicating significant deterioration of the fiber's polarization maintaining capability. The average x-talk intensity of the same fiber wound into two layers under a tension 4 times lower than that of the initial winding is -65 dB, 9 dB lower than the coil wound under high tension.

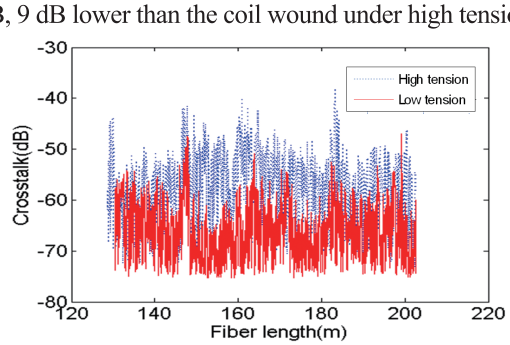


Figure 6 Polarization x-talk of layers 1-2 of a fiber coil wound at different tension levels. Solid line: low tension. Broken line: high tension

The coil winding tension must be maintained at a level high enough to maintain coil integrity, but low enough not to compromise the performance of the PMF.

Table 4 Polarization x-talk of fiber wound at different tension levels

	Average x-talk (dB)
High tension	-56.7677
Low tension	-65.6627
Raw fiber	-70.841

3.3.3 On-line testing for winding symmetry

The necessary winding symmetry can be achieved by using the counter on the winding machine or via polarization x-talk testing. As shown in Figure 7, the symmetry of the coiled fiber can be evaluated by marking the locations of selected points on the fiber by inducing temporary stress on the fiber at these points. When the first layer is finished, the position of the first layer end point (119.388m, in this example) can be obtained by polarization x-talk testing by temporarily stressing the fiber at that point. The fiber midpoint location in this case is 158.3m; therefore, the length of the fiber wound onto the frame from the A spool for the first quadrupole is 38.912m. Similarly, the length of the fiber wound onto the frame from the B spool for the first quadrupole is found to be 38.914m. The length difference is only 0.002m, indicating that the first quadrupole's symmetry is good. The PMF coils' symmetry can thus be assured by monitoring the position and length of every layer or quadrupole as it is formed using on-line testing of the polarization x-talk. Table 5 lists the positions and lengths of all quadrupoles in a 311 m fiber coil.

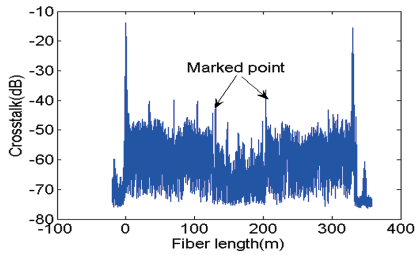


Figure 7 Identification of the locations of selected points on the fiber by inducing temporary stress on the fiber at these points.

Table 5 Positions and fiber lengths of quadrupoles in a 311 m fiber coil

	spool	*Position (m)*	*length (m)*
1st quadrupole	A	119.388	38.912
	B	197.214	38.914
2nd quadrupole	A	80.894	38.494
	B	235.572	38.358
3rd quadrupole	A	42.69	38.204
	B	273.688	38.106
4th quadrupole	A	3.1	39.59
	B	313.2	39.512
		A total length	155.2
		B total length	154.89

3.4 Monitoring PMF coil adhesive curing and stress release.

FOG performance, in terms of vibration-induced bias, is significantly influenced by the adhesive used. Both adhesive application and curing techniques can influence the polarization x-talk in the PMF coils. Polarization x-talk testing can therefore be used to analyze physical characteristics of different adhesives as well as techniques for adhesive curing and stress release, in order to optimize the adhesive process.

As shown in Figure 8 and Table 6, after adhesive curing and stress release, a coil's average polarization x-talk decreases relative to its level immediately after adhesive application (by about 6dB in this example). It is therefore important to monitor the process of adhesive curing and stress release. If adhesive curing and stress release of the PMF coils are poorly done, the PMF coils' polarization-maintaining performance can be seriously degraded.

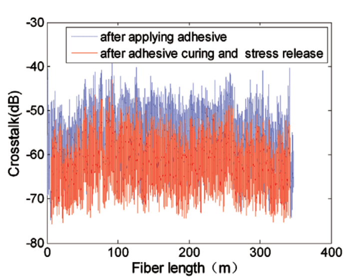


Figure 8 Polarization x-talk measurements of a PM coil after adhesive application and after adhesive curing and stress release. After adhesive curing and stress release (solid red line), the coil's average polarization x-talk decreases by 6dB relative to its level immediately after adhesive application (dashed blue line).

Table 6 Polarization x-talk of PMF coil after adhesive application and after adhesive curing and stress release

	After adhesive application	After adhesive curing and stress release
Average x-talk (dB)	-55.7442	-61.5071
Maximum x-talk (dB)	-37.6478	-43.0919
Position of maximum x-talk (m)	91.4709	91.8827

3.5 Overall PMF coil inspection

The overall polarization x-talk profile of a 311m PMF coil is shown in Figure 9 and Table 7. The average x-talk in this coil, which was optimized by on-line coil monitoring, raw PMF testing and other previously described techniques, is -68 dB, 2 dB higher than that of raw PMF (-70 dB); therefore, this coil's winding quality can be taken to be relatively good. However, high x-talk (-46dB) is still observed at 57m at a layer transition where the source spool is changed. In many cases, high x-talk points can be reduced or eliminated by improving the winding technique.

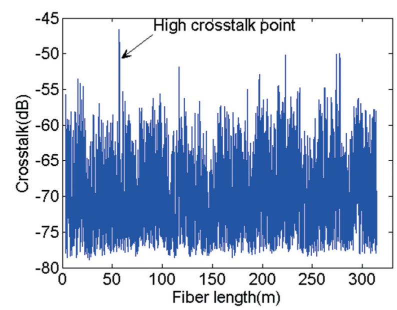


Figure 9 Polarization x-talk profile of a 311 m PMF coil. The overall polarization x-talk is relatively low for this coil; however, some high x-talk points can still be observed.

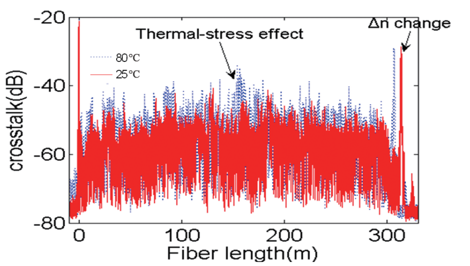
Table 7 Polarization x-talk in a 311 m coil

Average x-talk (dB)	-68.7424
Maximum x-talk (dB)	-46.6234
Position of maximum x-talk (m)	56.98

3.6 Measurement of temperature induced stress in PMF coils

The polarization-maintaining performance of a PM fiber coil deteriorates after heating, because the PMF, frame, and adhesive have different physical characteristics. A 315m PMF coil with a frame but no adhesive and a 1300m PMF coil with adhesive but no frame were heated from room temperature (25 °C) to 80 °C to observe changes in polarization x-talk caused by thermal-stress.

As shown in Figure 10 and Table 8, the average x-talk rises by 4 dB in the 315m coil and by 9 dB in the 1300m coil after heating. The average x-talk intensity of the 1300m coil increases by a greater amount because of the stress on the fiber caused by the temperature expansion coefficient of the adhesive. As shown in Figure 10 (a), the x-talk intensity of the 315m coil increases sharply at the midpoint of the fiber due to stress from the frame. The midpoint of the 1300m coil shows much lower thermal stress than that of the 315m coil because the 1300m coil has no frame. Evaluating changes in polarization x-talk of PMF coils caused by thermal stress effects at different temperatures can aid in the selection of adhesive and frame material for optimum performance of the completed FOG.



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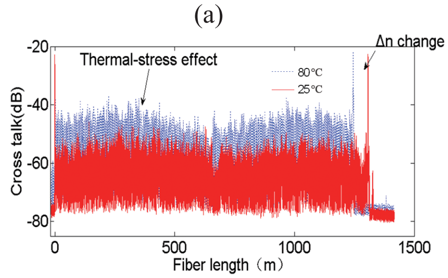

(b)

Figure 10 Changes in polarization x-talk of 315 m and 1300 m PMF coils due to thermal-stress effects. (a) 315 m coil (b) 1300 m coil.
Solid red lines: measured at 25°C; Dashed blue lines: measured at 80°C. Temperature induced birefringence changes can also be obtained from the location difference of the high x-talk points from the fiber connection points at the far right.

Table 8 Polarization x-talk of 315 m and 1300 m fiber coils at different temperatures

	315m 25°C	1300m 25°C	315m 80°C	1300m 80°C
Average x-talk (dB)	-57.258	-62.840	-53.898	-53.889
Maximum x-talk (dB)	-40.626	-45.843	-34.215	-36.925
Position of maximum x-talk (m)	130.620	142	153.880	224.165

3.7 Measurement of temperature variation of PM fiber birefringence

As shown in Figure 10, the temperature induced birefringence change can also be obtained from the change in location *Z* of the high x-talk points corresponding to the fiber connection points at the far right of the measurement plot. Δn for the PM fiber can be calculated at different temperatures using the simple formula

$$\Delta n_1 Z_1 = \Delta n_2 Z_2 \qquad (2)$$

Table 9 lists a 330m PMF coil's birefringence Δn at different temperatures.

The birefringence temperature variation coefficient 5.3E-7 can be obtained from the slope of the fitted line of the Δn vs. temperature plot, as shown in Figure 11. Test results for PMF coils produced by different manufacturers are listed in Table 10. The average birefringence temperature variation coefficient is 5.6e-7 (°C^{-1}).

Table 9 *Δn* of a 330m PMF coil at different temperatures

Temperature (°C)	-40	-20	0	20	40	60	80
Δn(E-4)	4.75	4.83	4.93	5.04	5.14	5.27	5.40

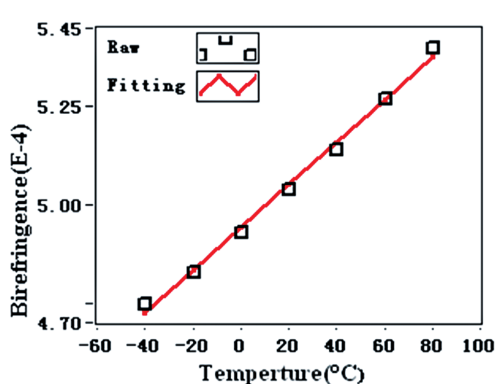

Figure 11 Linear fit to a plot of Δn vs. temperature for a PM fiber coil. The birefringence temperature variation coefficient 5.3E-7 can be obtained from the slope of the fitted line.

Table 10 Birefringence temperature variation of PMF coils from different manufacturers

	Coil 1	Coil 2	Coil 3	Coil 4	*Coil 5	*Coil 6	Average
birefringence variation with temperature (°C^{-1})	5.5e-7	5.6e-7	6.0e-7	5.8e-7	5.3e-7	5.4e-7	5.6e-7

* Denotes a different manufacturer

Summary

Distributed polarization x-talk measurement has been demonstrated to be an effective method for improving the quality of PMF coils at various stages in the coil production process, including raw PMF quality inspection, in-process coil winding monitoring, overall PMF coil inspection, and temperature induced stress testing. Test results can be used to identify coil imperfections as they occur, reduce the defect rate, monitor adhesive curing and stress release, and improve general coil quality. Distributed polarization x-talk measurement also enables precise measurement of PM fiber birefringence variation with temperature.

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Fig. 9. Enhancement of contrast ratio with rotation of analyzer at two different points. 90 T. XU et al.

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