Distributed polarization analysis with binary polarization rotators for the accurate measurement of distance-resolved birefringence along a single-mode fiber

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Abstract: We describe a first distributed polarization analysis (DPA) system using binary polarization rotators in an optical frequency domain reflectometer (OFDR) capable of measuring the variations of polarization states along a single-mode fiber (SMF). We demonstrate using such a DPA system to accurately measure the distance-resolved birefringence with 12 fiber loops of different radii with different birefringence values along a length of SMF and obtain a bending-induced birefringence coefficient (BBC) of $6.601 \times 10^{-10} \text{m}^2$, agreeing well with the theoretically estimated value of $5.334 \times 10^{-10} \text{m}^2$. To further verify the measurement accuracy, we obtain the birefringence values of the 12 fiber loops of different radii one at a time using a non-distributed polarization analysis system with an accuracy traceable to a birefringence standard made with a quartz crystal, and obtain a BBC value of $6.490 \times 10^{-10} \text{m}^2$, agreeing well with our distributed measurement with a relative error of only 1.68%. In addition, we measure the residual birefringence of the SMF with both distributed and non-distributed polarization analysis systems and obtain similar results with a relative error of only 0.59%. Our experiments not only validate the performances of our DPA system, but also the first to use DPA to experimentally obtain the accurate birefringence values along the SMF and verify the theory of bending-induced birefringence. Our work further proves that such an OFDR-based DPA system is a practical tool for optical component characterization, nondestructive optical material inspection, and distributed fiber optic transversal stress sensing.

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1. Introduction

Accurate polarization analysis is important both for scientific research for understanding the optical properties of different matters [1–4] and for applications in fiber optic communication and sensing systems [5–9]. Most polarization analysis systems can only measure the accumulative polarization effects of a matter on an optical beam, such as the changes in the state of polarization (SOP) and the degree of polarization (DOP) after it passes through the whole length of the matter, and therefore can only help to obtain the average polarization properties of the matter, such as those characterized by parameters of birefringence, diattenuation, or photo-elasticity. Because such parameters are vectors or even tensors with varying orientations along the optical path, the “average” cannot be used to infer the local values of the parameters. For example, in a single mode fiber (SMF), the birefringence (often referred to as differential group delay, DGD) and the diattenuation (often referred to as polarization dependent loss, PDL) often vary rapidly along the fiber both in their orientations...
and magnitudes. The fiber may have strong local birefringence or diattenuation, however, at some moment in time, the average birefringence or diattenuation may be close to zero.

As another example, in a silicon crystal ingot, the local residual stress may be generated during the crystal growing process, which will cause local birefringence via photo-elastic effect [10–12]. Such local stress degrades the quality of the silicon crystal ingot such that when the silicon ingot is diced into thin wafers, cracks may develop when high local stress is encountered [11,12]. Therefore, it is important to develop a nondestructive method or an instrument to perform distributed polarization analysis (DPA) for obtaining such local or distance-resolved polarization properties, such as local stress induced birefringence. When the location of such a local stress is determined, one may either discard the wafer containing the stress region for quality concerns, or cut a thick wafer to avoid crack for less demanding applications, such as solar cells.

Another practical area for DPA is the optical component characterization, such as photonics integrated circuits (PICs). Defects in such an optical component include cracks, discontinuities, internal stresses, and waveguide birefringence. Therefore, it is critical not only to obtain the information relating to the distribution of internal reflections, but also the distribution of birefringence with a spatial resolution much less than 1 mm for fully characterizing and understanding the performance of such a component. Present optical frequency domain reflectometer (OFDR) and optical coherence domain reflectometer based techniques can only obtain the space-resolved reflection information [13–16] and therefore are not capable of characterizing stress and birefringence inside PICs.

Distributed transversal stress fiber optic sensing is also important for certain applications [9,17–20], although it has been much less studied compared with distributed strain and temperature sensing [21,22]. Techniques which can be used for distributed transversal stress sensing include distributed polarization crosstalk analysis with white light interferometer [7,8,20], polarization optical time domain reflectometer [23–27] and polarization OFDR [9,28,29], using either polarization maintaining fibers (PMFs) or SMFs as sensing medium. Compared to the SMF-based distributed fiber sensing, using the PMF as fiber sensing medium is more expensive and sometimes even impractical for long range measurement applications. Generally, transversal stress can induce a local birefringence via the photo-elastic effect in a SMF [30–32], and therefore distributed birefringence measurement can be used to obtain the space-resolved stress along the fiber for multiple sensing applications [9,28]. As reported in [30] and [31], when a fiber is bent, a certain birefringence will be induced by the lateral internal stress with a well defined value proportional to the inverse square of the bending radius. Therefore, bending-induced birefringence can also be used to characterize the performance and accuracy of a distributed birefringence measurement system which has the potential for being used for distributed transversal stress sensing. The measurements of bending-induced birefringence reported in [30–33] are non-distributed. Palmieri et al. [28] performed distributed birefringence measurement in two spun fibers and a ribbon made of unspun fibers with different bending radii using a polarization-sensitive OFDR (PS-OFDR) with a spatial resolution of 3 cm, which is insufficient to accurately verify the theoretical relationship between birefringence and bending radius. In addition, the measurement range of Palmieri’s PS-OFDR was 30 m, limiting it as a practical distributed sensing system for applications requiring long range.

In previous publications [34–36], we reported a novel polarization analysis system relying on a polarization state generator (PSG) and a polarization state analyzer (PSA) made with binary magneto-optic (MO) crystals to achieve high accuracy. Such a non-distributed polarization analysis (NDPA) system has been proved to achieve exceptionally high accuracy measurements of SOP, DOP, linear and circular birefringence, PDL and polarization extinction ratio. In this work we describe a novel DPA system incorporating the same type PSG and PSA made with binary MO polarization rotators [34,35] in an OFDR system. We call such a DPA system as polarization analyzing OFDR (PA-OFDR). For each input SOP
generated by the PSG, the SOP of the reflected light wave at any point in an optical path, such as in an optical fiber or waveguide, can be precisely measured using PSA in the OFDR. By generating 4 distinctive input SOPs with the PSG and analyzing the corresponding SOPs of reflected light at each point along the optical path for each input SOP with the PSA, the Mueller matrix of the optical medium at each point in the optical path can be obtained. Consequently, the birefringence vector of the optical medium at each point along the optical path can be derived. Because of the high speed (~20 μs) and high repeatability advantages of the binary PSG and PSA, the PA-OFDR is also of high speed and high accuracy in obtaining both the SOP distribution and the birefringence vector distribution along the optical path. In comparison, a PS-OFDR using analog polarization analysis shows low measuring speed and precision [37,38] compared with our binary polarization analysis, or only has partial polarization analysis capability [39], while a polarization analysis system made with PSG and PSA [36,40] can only obtain the final SOP and total accumulative (non-distributed) birefringence of the whole optical path. Here our PA-OFDR has a birefringence measurement resolution of <2 × 10⁻⁷, a birefringence spatial resolution (BSR) of 0.25 mm, a reflection spatial resolution (RSR) of 10 μm, a measurement range of 100 m limited by the coherence length of the tunable laser (TL) source used in the system, and a backscattering sensitivity of -130 dB.

It is difficult to prove the correctness of spatial SOP distribution measurement inside an optical fiber or an optical waveguide because the SOP is not well defined and changes with time. In order to verify the measurement accuracy of DPA with our PA-OFDR, we choose to measure the birefringence distribution inside an optical fiber because it can be well defined and stable over time. We first make 12 fiber loops with different radii in a length of SMF under test (SMF-UT) to induce different well defined local birefringence values [30] and then use our PA-OFDR to measure the birefringence distribution along the fiber. By fitting the experimental data to the theoretical equation, a bending-induced birefringence coefficient (BBC) of 6.601 × 10⁻¹⁰ m² for the SMF-UT is obtained, agreeing well with the theoretically estimated value of 5.334 × 10⁻¹⁰ m². To further demonstrate the measurement accuracy, we use a commercial NDPA system (PSGA-100, General Photonics Cor.) with its accuracy validated with a quartz crystal of precisely known birefringence [34–36,40] to measure the birefringence of 12 individually loops, one at a time, made using the SMF from the same batch as the fiber under test (FUT). Again by curve-fitting the experimental data to the theoretical equation, a BBC of 6.490 × 10⁻¹⁰ m² is obtained, with a relative error of only 1.68% from the distributed measurement result above. Additionally, the residual birefringence (RB) values of the SMF-UT obtained from the distributed measurement using the PA-OFDR and the accumulative measurement using the NDPA system are 2.545 × 10⁻⁷ and 2.560 × 10⁻⁷, respectively, agreeing well with each other, with a relative error of only 0.59%. Note that to the best of author’s knowledge, this is the first time that a DPA method is used to experimentally verify the theoretical expression for bending-induced birefringence and to accurately determine the BBC. As an added confidence, the accuracies of the experimental data are cross-checked with both distributed and non-distributed methods. We anticipate that the proposed DPA technique and the corresponding PA-OFDR system will find useful applications in optical component characterization, nondestructive optical material inspection, as well as in distributed transversal stress sensing with high spatial resolution and accuracy.

2. Principle and theory

2.1 Principle of distributed polarization analysis (DPA) and measurement system

Figure 1 shows the basic schematic of our DPA system called PA-OFDR. Light from a TL with a long coherence length is coupled into a PMF. Around 5% is coupled out by a first coupler C1 to a k-clock consisting of a first circulator (CIR1) and a Michelson interferometer.
made with SMF in which two Faraday rotation mirrors (FRMs) are used to eliminate polarization fluctuations. The outputs from the interferometer are detected and amplified by a first balanced photodetector (BPD1) to get the incremental frequency of the TL. The light in the PMF continues to propagate and around 10% is coupled out by a second coupler C2 as a local oscillator beam. The remaining light first goes through a PSG and is then directed into the SMF-UT via a second circulator (CIR2). The back scattered and reflected light from the SMF-UT is directed to port 3 of CIR2 and then goes through a PSA before entering a PMF to be mixed at a third coupler C3 with the local oscillator beam from C2. The interference signals from two outputs of C3 are detected and amplified by a second balanced detector (BPD2), and its output is finally sent to the analog to digital converter (ADC) in the digital circuit board to be converted to digital signal with 16 bit resolution. The zero crossings of the interference signal from the k-clock interferometer detected by BPD1 are converted to trigger pulses in the digital circuit to trigger the ADC so that the signal from BPD2 is digitized with equal frequency spacing. The working principle of the k-clock and the data processing algorithm can be found in detail in [41]. Fast Fourier transform (FFT) of the digitized signal then reveals the location information of backscattered and reflected light originated at different locations in the SMF-UT. Note that both PSG and PSA are made with binary MO crystals [34–36], as shown in the inset of Fig. 1. The PSG is capable of generating 4 distinctive SOPs while the PSA is capable of analyzing any SOP with 4 distinctive logic states or MO settings [36].

Figure 2 shows the data acquisition and processing flow chart for measuring the SOP matrix as a function of \( z \). For each frequency scan of the TL, the PSG generates one of four SOPs and the PSA measures the SOP with four sequential MO settings, and a total of 16 frequency scans and PSG/PSA settings are required to get the full Stokes (or SOP) matrix \( M(z) \) of the signal returned from each point along the SMF-UT. When a polarized light is propagating in the SMF-UT, the evolution of the light’s SOP can be described using the well-known equation of motion of the Stokes vector \( \vec{S}(z) \) [42,43] as

\[
\frac{d\vec{S}(z)}{dz} = \mathbf{W}(z) \times \vec{S}(z),
\]

(1)
where $z$ is the distance of light propagated within the fiber, $\overline{W}_{r}(z)$ is the local round-trip birefringence vector. In practice, one may use the following steps to calculate the birefringence $[36,44–46]$. For a small fiber segment with a length of $\Delta z$, the SOP matrix $M_{r}(z+\Delta z)$ at $z+\Delta z$ relates to the SOP matrix at $z$ by $M_{r}(z+\Delta z) = M_{r}(z)M_{r}(z)$, where $M_{r}(z)$ is the Mueller matrix of the fiber segment $\Delta z$ and can be obtained as

$$M_{r}(z) = M_{r}(z+\Delta z)M_{r}^{-1}(z),$$

(2)

where the PDL of the fiber is assumed to be negligible. It can be shown that the retardation angle $\theta(z)$ can be expressed as $[44–46]$

$$\theta(z) = \cos^{-1}\left(\frac{Tr[M_{r}(z)]-1}{2}\right) = \frac{2\pi\Delta n(z)\Delta z}{\lambda},$$

(3)

where $Tr[M_{r}(z)]$ stands for the trace of matrix $M_{r}(z)$ and the factor of 2 accounts for the round trip passage of light in the fiber segment. Finally, the local birefringence $\Delta n(z)$ can be calculated from the $\theta(z)$ as

$$\Delta n(z) = \frac{\theta(z)\lambda}{4\pi\Delta z},$$

(4)

where $\lambda$ is the wavelength. In data processing, $\lambda$ is chosen as the center wavelength of TL’s wavelength scan.

Fig. 2. Data acquisition and processing flow chart for obtaining the state of polarization (SOP) matrix as a function of $z$. Note that $M_{r}(z)$ can be reduced to a $3 \times 3$ matrix if polarization dependent loss (PDL) in the fiber can be neglected $[43]$. Also note that the SOP vectors along $z$ are derived from $r_{g}(f)$ and therefore already contain the information of SOP variations caused by frequency variations.
2.2 Theory of bending-induced birefringence in SMF

Bending-induced birefringence $\Delta n$, which is mainly caused by lateral internal stress in a bent SMF, can be represented by the well-known expression as [30]:

$$\Delta n = \frac{n^3}{4} \left( P_{12} - P_{11} \right) \left( 1 + \sigma \right) \left( \frac{r}{R} \right)^2,$$

where $n$ is the refractive index of the core, $P_{11}$ and $P_{12}$ denote the strain-optical coefficients, $r$ is the cladding radius, $R$ is the bending-radius and $\sigma$ is the Poisson's ratio. As shown in Eq. (5), the local birefringence of the SMF is inversely proportional to the square of the bending radius, and we can define a BBC $k$ as

$$k = \frac{n^3 r^2}{4} \left( P_{12} - P_{11} \right) \left( 1 + \sigma \right).$$

Hence, Eq. (5) can be rewritten as:

$$\Delta n = k \left( \frac{1}{R} \right)^2.$$

Since $P_{12} - P_{11} = 0.15$, $\sigma = 0.17$ for fused silica [30] and $n = 1.46$, $r = 62.5 \, \mu m$ for SMF, according to Eq. (6), the theoretical value of BBC $k$ for common SMF can be estimated to be $5.334 \times 10^{-10} \, m^2$. Note that such an estimate was calculated by assuming the optical fiber made with fused silica with a uniform cross section and did not consider the contributions from a more complicated fiber cross section with core, cladding and buffer coating.

3. Measurement setup and results

![Fig. 3. (a) Experimental setup of bending-induced birefringence measurement. (b) Illustration of a setup of 12 fiber loops with different bending radii in SMF-UT, with each loop having a single turn. Inset showing the photo of the 12 fiber loops.](image)

In order to demonstrate the distributed bending-induced birefringence measurement feasibility of our PA-OFDR, and to verify the correctness of the theory as described above, we designed a simple experimental system as shown in Fig. 3(a). A Yenista TL (TUNICS
T100S-HP) with a linewidth of ~100 kHz and a wavelength tunable range from 1520 nm to 1600 nm was used as the frequency-swept laser source for the PA-OFDR and output the polarized light to the PA-OFDR through a PMF jumper. The clock signal was communicated between the TL and the PA-OFDR via a general-purpose interface bus (GPIB). Twelve fiber loops with different radii were made along the SMF-UT with a total length of ~4.5 m to produce the bending-induced birefringence variations as a function of bending radius. As shown in Fig. 3(b), the bending radius gradually decreases from ~3.75 cm to ~1.00 cm with a 0.25 cm interval for the 12 fiber loops along the SMF-UT. The fiber loops were produced by respectively looping 12 different sections of the SMF-UT around 12 glass rods with different radii, and then removing the rods to relax the fiber after the loops fixed on a paperboard using adhesive tapes as shown in the inset, in order to avoid introducing undesired strain or stress to the fiber loops. Specifically, we rotated the rod instead of wrapping the fiber around the rod for minimizing the fiber twist. The radii of the 12 glass rods were measured using a vernier caliper. The experimental data was obtained and processed by a LabVIEW based data acquisition system.

The distributed birefringence variation along the SMF-UT section (from 7.0 m to 12.0 m) with the 12 fiber loops was measured using the PA-OFDR as shown in Fig. 4(a). It can be seen that loops with smaller radii induce higher local birefringence and loops with larger radii have wider peak and low peak value, consistent with our expectations. In data processing, the measured SOP data along the SMF-UT was divided into numerous segments, each having a length of $\Delta z$ and then the birefringence value of each fiber segment was calculated. This fiber segment length $\Delta z$ is defined as BSR. We used 6 different BSRs (0.25 mm, 0.5 mm, 1 mm, 5 mm, 20 mm and 100 mm) to calculate the distributed birefringence along the SMF-UT and plotted the results using different line shapes with different colors. In general, BSR is much larger than RSR because a minimum distance is required to accumulate sufficient SOP changes above the noise level of the measurement system for the accurate birefringence calculation using Eq. (2). The smaller the local birefringence, the larger the minimum distance or BSR is required for a sufficient SOP change, however, the BSR should not be larger than the feature length of the local birefringence to be measured. Here, the feature length corresponds to the length of the fiber having a birefringence induced by the fiber bending/loop. On the other hand, the larger the local birefringence, the smaller BSR should be selected. As can be seen from the curves, an inappropriate selection of BSR produces different measurement errors for the fiber loops with different radii, corresponding to different local birefringence with different feature length. For instance, the 100 mm BSR produces the smallest error for measuring the birefringence induced by the fiber loop No. 1 with 3.75 cm radius while produces the largest error for measuring the birefringence induced.

![Fig. 4. (a) Birefringence curves of the SMF-UT section with 12 fiber loops of different radii measured by PA-OFDR in different birefringence spatial resolutions (BSRs). (b) Zoom-in curves located around loop No. 10 in (a).](image-url)
by the fiber loop No. 12 with ~1.00 cm radius because the BSR is already larger than the perimeter of loop No. 12. Figure 4(b) shows the zoom-in measurement curves of loop No. 10 in Fig. 4(a), and one can see that all BSR selections, except for BSR of 100 mm and 20 mm, are adequate for accurate birefringence measurements for this loop. Fortunately, the BSR of 0.25 mm is adequate for the accurate measurement of birefringence produced by all of the fiber loops. In order to avoid the measuring uncertainties, we performed 20 repeated measurements and each curve in Fig. 4 represents 20 times average. Note that the birefringence distribution inside a perfect circular fiber loop is expected to be uniform in theory. The Gaussian-like birefringence distribution in each fiber loop was possibly caused by the following reasons: i) low-pass digital filtering during data processing, ii) averaging of multiple data traces, including multiple frequency scans in each measurement and 20 full-measurements, and iii) imperfections of the fiber loops, such as non-circularity, curvature non-uniformity at both ends of each loop when fiber transitioning from a straight section to a curved section, birefringence induced by adhesive tapes for fixing each loop, fiber bend between two adjacent loops, and fiber twist. In Fig. 4(a), from the black solid line, a small bump between the peak (11) and (12) can be observed, which is induced by the fiber bending between the loop No. 11 and loop No. 12 as shown in the inset of Fig. 3.

\[ \Delta n = 6.601 \times 10^{-10} \left( \frac{1}{R} \right)^2 + 2.365 \times 10^{-7}. \]  

As can be seen in Eq. (8), experimentally obtained value of \( \Delta n \) is 6.601 \( \times 10^{-10} \) m\(^2\), in good agreement with the theoretical value of 5.334 \( \times 10^{-10} \) m\(^2\). Note that, as shown in Fig. 5(a), a RB is apparently present in the measurement data as the bending radius goes to infinity, which was not included in Eq. (7). We believe that this RB is the contribution of the inherent geometric asymmetry and internal stress in the SMF-UT, and
a constant term should be added in Eq. (7) to represent it. Consequently, curve fitting yields a RB of $2.365 \times 10^{-7}$ in Eq. (8). As a comparison, Fig. 5(b) shows the birefringence distribution along a SMF-UT section (from 6.0 m to 7.0 m) without any birefringence inducing loop, measured by our PA-OFDR using a BSR of 0.25 mm. The average of $2.545 \times 10^{-7}$ is highly consistent with the value from the curve fitting, indicating that the PA-OFDR is capable of performing distributed RB measurement with high accuracy. In addition, from the measured RB results in Fig. 5(b), we conclude that the birefringence measurement resolution of the PA-OFDR is better than $2 \times 10^{-7}$. The RB measurement capability and accuracy of the PA-OFDR will be further discussed in the next section.

It is worth noting that the birefringence of a fiber to be measured by our DPA system cannot be too high to cause the accumulated retardation over the minimum BSR length larger than $\pi$, which will cause phase wrapping errors. Another limitation is that a large number of laser wavelength scans are required, which causes the broadening of the birefringence measurement resolution and losing some detailed spatial features. However, these limitations can be resolved by improving the data acquisition and processing algorithms, and using lasers with much faster wavelength scanning rates.

4. Validations with a non-distributed polarization analysis (NDPA) system

4.1 Residual birefringence (RB) validation

To verify the presence of RB in SMFs and the measurement accuracy of the PA-OFDR, we used a high precision NDPA system, also made with binary MO crystal based PSG and PSA, as described in detail in [34–36,40], to measure the RB of a fiber under test (FUT) with a length of ~4.5 m from the same fiber batch as in the previous experiment in Section 3, using the experimental setup shown in Fig. 6. We call such a NDPA system PSGA (polarization state generating and analyzing). It is important to note that the birefringence measurement accuracy of the PSGA has been validated with a quartz crystal of precisely known birefringence [36] and therefore is traceable to the quartz birefringence standard [47]. The FUT was connected with the output port of the PSG and the input port of the PSA with two low-stress connectors, and was loosely deployed on an optical table with a minimum bending radius of ~0.5 m along the whole fiber length, as shown in Fig. 6. Such a large bending radius only contributes a bending-induced birefringence on the order of $10^{-9}$ from Eq. (7), which is two orders of magnitude lower than the expected RB value and therefore can be neglected.

![Fig. 6. Measurement setup of FUT’s residual birefringence (RB) based on PSGA system.](image)
In measurements, the PSG generates 6 distinctive input SOPs one at a time and the PSA analyzes the output SOPs from the FUT for each input SOP with 6 distinctive MO logic settings to obtain the Mueller matrix of the FUT as a function of wavelength [32]. The accumulative DGD $\tau(\omega)$ of the FUT then can be obtained from the Mueller matrix analysis as described in [36,40,48]. Note that here we use 6 distinctive logic states for polarization generation and analysis, as compared with 4 distinctive logic states in the DPA system described in the last section, for higher measurement accuracy [36]. Please note that, compared with the transmission measurement of the NDPA system, the backscattering measurement of the DPA system has a much smaller signal to noise ratio, so the potential gain in accuracy resulting from adding 2 more SOP states in DPA may be over shadowed by the higher noise in the system. In addition, adding two more SOP states in both PSG and PSA means increasing the total laser frequency scans from 16 to 36, which will significantly increase the data acquisition and processing time, and therefore increase the measurement uncertainties caused by temperature drift. In fact, for fibers with negligible PDL, we reduced the SOP to 3 states to reduce measurement time. Finally, the RB $\Delta n_{rb}$ of the FUT can be obtained as:

$$\Delta n_{rb} = \frac{\tau(\omega)c}{L},$$

(9)

where $L$ is the length of the FUT and $\omega$ is the angular frequency. Six groups of repeated measurements were carried out and the results are listed in Table 1. In each group of the measurements, ten repeated experiments were performed and the average DGD $\tau(\omega)$ was calculated. Note that we slightly re-arranged the FUT layout on the optical table before each group of the measurements started. As shown in Table 1, the average of six measured RB values is calculated to be $2.560 \times 10^{-7}$, which is very close to the average RB of $2.545 \times 10^{-7}$ measured by the PA-OFDR, with a relative error of only 0.59%, validating both the measurement accuracy of the PA-OFDR and the correctness of the fitted Eq. (8). Note that unlike the DPA method described in Section 3, NDPA method described here can only obtain the accumulative RB of the FUT along the whole fiber length $L$. The small deviations of the BBC between the theoretical and experimental values and the RB between values obtained with DPA and NDPA may be attributed to the following factors: i) the slight inaccuracies of the parameters used in the theoretical calculation as compared to those of a real fiber, ii) the inaccuracies of the bending radius measurements of the 12 fiber loops, iii) the errors associated with the non-circularity of the fiber loops because the fiber loops may not be perfectly circular, and iv) the errors associated with the fiber twist.

Table 1. Repeated measurements of FUT’s RB with NDPA system

<table>
<thead>
<tr>
<th>Groups</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>RB</td>
<td>$2.546 \times 10^{-7}$</td>
<td>$2.549 \times 10^{-7}$</td>
<td>$2.577 \times 10^{-7}$</td>
<td>$2.586 \times 10^{-7}$</td>
<td>$2.556 \times 10^{-7}$</td>
<td>$2.544 \times 10^{-7}$</td>
</tr>
<tr>
<td>Average</td>
<td>$2.560 \times 10^{-7}$</td>
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4.2 Bending-induced birefringence validation

Because the birefringence measurement accuracy of the NDPA system (PSGA) is traceable to the birefringence standard of a quartz crystal [36], it will be convincing to use the PSGA to validate the accuracy of the bending-induced birefringence values measured with our DPA system (PA-OFDR). Since the PSGA is of a non-distributed birefringence measurement system, for each bending induced birefringence measurement, only a single fiber loop can be made in the FUT. In the experiment, we selected a FUT of the same length and from the same fiber batch as in the experiment in Section 3. As shown in Fig. 7(a), for each measurement, we made a single fiber loop on the FUT and measured its birefringence with the PSGA. Total
12 sets of measurements were performed, each having a different loop radius gradually decreasing from ~3.75 cm to ~1.00 cm with a 0.25 cm interval. Each set measurement was repeated 10 times and the average of the 10 measurements was taken as final birefringence value of the corresponding fiber loop. The fiber loops were produced using the same glass rods as described in Section 3. The FUT with the fiber loop was affixed with adhesive tapes on the optical table for measurement stability. The adhesive tape is of soft material to minimize the pressure-induced birefringence. Theoretically, the bending-induced birefringence $\Delta n_{\text{loop}}$ resulting from looping a loop with a perimeter of $l_{\text{loop}}$ can be calculated from the DGD $\tau_{\text{loop}}(\omega)$ of the fiber loop as [36]

$$\Delta n_{\text{loop}} = \frac{\tau_{\text{loop}}(\omega)c}{l_{\text{loop}}}.$$  \hfill (10)

To eliminate the contribution of the RB in the FUT, a reference measurement of the FUT’s Mueller matrix $M_{\text{ref}}$ without a loop was first taken before each Mueller matrix $M_{\text{total}}$ measurement of the FUT with the loop was performed. The Mueller matrix of the FUT of the loop without the RB contribution can be obtained with

$$M_{\text{loop}} = M_{\text{total}} \cdot M_{\text{ref}}^{-1}.$$  \hfill (11)

Finally, the DGD $\tau_{\text{loop}}(\omega)$ can be calculated from the Mueller matrix $M_{\text{loop}}$ of the fiber loop detailed in [36,48,49]. Note that, for avoiding the error introduced by the tapes, we also used the same tapes on the FUT for the Mueller matrix $M_{\text{ref}}$ measurement.

Using the methodology described above, the bending-induced birefringence $\Delta n_{\text{PSGA}}$ for all of the 12 fiber loops were measured and plotted in Fig. 7(b) using the red squares. Note that the birefringence value for each bending radius is the average of 10 repeated measurements. We curve fitted the PSGA measurement data in Fig. 7(b) to Eq. (7), and obtained Eq. (12) with an Adj. R-Square of 0.99743 as

$$\Delta n_{\text{PSGA}} = 6.490 \times 10^{-10} \left( \frac{1}{R} \right)^2.$$  \hfill (12)
Note that the BBC obtained here is $6.490 \times 10^{-10}$ m$^2$, highly consistent with the value of $6.601 \times 10^{-10}$ m$^2$ obtained using our PA-OFDR, with a relative error of only 1.68%. For visual comparison, the birefringence data measured by the PA-OFDR in Fig. 5 was also plotted in Fig. 7 (b) with blue circles, but note that the RB has been subtracted from every data point. It is evident that the data points obtained with the two different methods agree well with each other, with a maximum birefringence measurement relative error of 8.71%. The slight deviation may be attributed to the measurement uncertainties of the perimeters of the 12 fiber loops and the errors resulting from the RB induced by the adhesive tapes for affixing the FUT on the optical table.

It is important to notice that the measurements above with a PSGA not only validated the performance of our distance-resolved birefringence measurement with our PA-OFDR, in Section 3, but also cross checked the accuracy of what we believed to be the first BBC measurement of a SMF.

5. Conclusions

We reported what we believe to be the first DPA system, called PA-OFDR, incorporating highly accurate PSG and PSA made with binary MO polarization rotators in an OFDR. Such a system is capable of accurately determining the local SOP of the reflected light, and therefore the distance-resolved birefringence distribution along a SMF. We demonstrated its capability by measuring bending-induced birefringence of precisely made fiber loops because their birefringence values are well defined and proportional to the inverse square of the loop radii. With our DPA system, for the first time, the proportional constant, BBC, was accurately determined by making 12 fiber loops of different radii and measuring their corresponding birefringence values to be $6.601 \times 10^{-10}$ m$^2$, agreeing well with the theoretically estimated value of $5.334 \times 10^{-10}$ m$^2$. To further validate the measurement accuracy of our DPA system, we used a highly accurate NDPA system called PSGA, whose measurement accuracy is traceable to quartz birefringence standard, to individually measure the birefringence values of the 12 loops and obtained a BBC of $6.490 \times 10^{-10}$ m$^2$, with a relative error of only 1.68% from the DPA measurement result of $6.601 \times 10^{-10}$ m$^2$. Additionally, the RB values of the fiber measured with both the DPA and NDPA systems were $2.545 \times 10^{-7}$ and $2.560 \times 10^{-7}$, respectively, agreeing well with each other, with a relative error of only 0.59%. It is worth to note that to the best of author’s knowledge, this is the first time that a DPA method is used to experimentally verify the theoretical expression for bending-induced birefringence and to accurately determine the BBC. As an added confidence, the accuracies of the experimental data were cross-checked with both the distributed and non-distributed methods, with a maximum birefringence measurement relative error of 8.71%. The results reported in this paper show that the proposed DPA technique and the corresponding PA-OFDR system may find useful applications in optical component characterization, nondestructive optical material inspection, as well as in distributed transversal stress sensing with high spatial resolution and accuracy.

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References


