Truly distributed birefringence measurement of polarization-maintaining fibers based on transient Brillouin grating

Yongkang Dong,[1,2] Liang Chen,[1] and Xiaoyi Bao[1,*]

[1]*Fiber Optics Group, Department of Physics, University of Ottawa, Ottawa, Canada K1N 6N5*

[2] *aldendong@gmail.com*

**Corresponding author: xbao@uottawa.ca*

Received October 22, 2009; revised December 4, 2009; accepted December 7, 2009; posted December 16, 2009 (Doc. ID 118973); published January 13, 2010

We report on what we believe to be the first truly distributed birefringence measurement of polarization-maintaining fibers (PMFs) based on transient Brillouin grating (TBG). A TBG is created by two short pump pulses in the slow axis of the PMF, and then the birefringence-related TBG spectrum is mapped by scanning a probe pulse launched in the fast axis, where the local birefringence can be calculated using the birefringence induced frequency shift. Two types of widely used PMFs, bow-tie and panda, with a length of 8 m were measured at a spatial resolution of 20 cm, and the results show that the birefringence features a periodic variation, and their variation ranges are $\sim 2.4\times 10^{-6}$ and 1.3×10^{-6} along the test fibers, respectively.

OCIS codes: 060.2420, 290.5900.

Polarization-maintaining fibers (PMFs) have attracted considerable interest in the telecommunication and optical sensing community. The phase modal birefringence of the PMF is an important parameter for its applications. During the fabrication of the PMF, owing to the nonuniformity of the materials and environmental condition change in fiber drawing process, it is inevitable to introduce birefringence variation along the fiber. Many methods have been proposed to measure the birefringence of the PMF [1–4]. However, to the best of our knowledge, up to now the reported methods can give only the average birefringence of the test fiber and cannot characterize the birefringence variation along the fiber. In this Letter, we propose what we believe to be the first truly distributed birefringence measurement of the PMF based on a transient Brillouin grating (TBG).

Recently, a Brillouin-grating-based light storage was proposed in a single-mode fiber [5]. This Brillouin grating is similar to a conventional fiber Bragg grating in that they are both local refractive-index-modulated gratings. Besides, the Brillouin grating has two additional unique features: one is that it is a moving grating, which introduces a Brillouin frequency shift (BFS) to the reflected light with respect to the probe light, and the other is that it completely disappears after a few tens of nanoseconds, which is determined by the phonon lifetime so that we also call it the TBG. In our birefringence measurement scheme, two short counterpropagating pump 1 and pump 2 pulses, where the frequency of pump 1 is larger than that of pump 2 by a BFS ω_B, are launched into one axis of the PMF to excite a TBG through stimulated Brillouin scattering. Following the pump 2 pulse, a long probe pulse is launched into the other axis, and energy from the probe pulse could be partly reflected at the expense of the TBG. A maximum reflected probe signal could be obtained when the frequency difference $\Delta\omega$ between pump 2 and the probe satisfies the phase-matching condition [6–8]. According to the conservation of momentum during the scattering process, the four waves involved are related by

$$\frac{\omega_B}{V} = \frac{n_f(\omega)\omega}{c} + \frac{n_f(\omega+\omega_B)(\omega+\omega_B)}{c} = \frac{n_s(\omega-\Delta\omega)(\omega-\Delta\omega)}{c} + \frac{n_s(\omega+\omega_B-\Delta\omega)(\omega+\omega_B-\Delta\omega)}{c}. \quad (1)$$

Here V is the velocity of the Brillouin grating; ω, $\omega+\omega_B$, $\omega-\Delta\omega$, and $\omega+\omega_B-\Delta\omega$ are the frequencies of probe, reflection, pump 2, and pump 1 waves, respectively; and n_f and n_s are the phase refractive indices of fast and slow axes, respectively. Using Taylor expansion to the refractive index of the slow axis and omitting the second- and higher-order terms, Eq. (1) can be written as

$$\frac{n_f(\omega)\omega}{c} + \frac{n_f(\omega+\omega_B)(\omega+\omega_B)}{c} = \frac{n_s(\omega)\omega}{c} + (-\Delta\omega)\frac{\mathrm{d}(n_s(\omega)\omega)}{c\,\mathrm{d}\omega} + \frac{n_s(\omega+\omega_B)(\omega+\omega_B)}{c} + (-\Delta\omega)\frac{\mathrm{d}(n_s(\omega+\omega_B)(\omega+\omega_B))}{c\,\mathrm{d}\omega}. \quad (2)$$

Define $n_s^g(\omega)=\mathrm{d}(n_s(\omega)\omega)/\mathrm{d}\omega$, i.e., the group refractive index of the slow axis. We then have

$$\Delta\omega(n_s^g(\omega)+n_s^g(\omega+\omega_B)) = (n_s(\omega)-n_f(\omega))\omega + (n_s(\omega+\omega_B) - n_f(\omega+\omega_B))(\omega+\omega_B). \quad (3)$$

Neglecting the group dispersion, i.e., $n_s^g=n_s^g(\omega)=n_s^g(\omega+\omega_B)$, and because of $\omega_B \ll \omega$, using $\omega \doteq \omega+\omega_B$

0146-9592/10/020193-3/$15.00

and $\Delta n(\omega)=n_s(\omega)-n_f(\omega)\doteq n_s(\omega+\omega_B)-n_f(\omega+\omega_B)$, finally we have

$$\Delta\omega=\frac{\Delta n(\omega)\omega}{n_s^g}. \tag{4}$$

Here $\Delta n(\omega)$ is the phase modal birefringence.

There are two schemes to perform the birefringence measurement: one is that the TBG is excited in the fast axis and probed in the slow axis, and the other is that the TBG is excited in the slow axis and probed in the fast axis. For both cases, the frequency differences between pump 2 and the probe are the same, which is proportional to the local birefringence. To precisely measure the birefringence frequency shift and thus accurately calculate the birefringence, we choose the second scheme. In this scheme, the frequency difference between pump 1 and the probe is smaller than the birefringence-induced frequency shift by a BFS, and can be measured by a high-speed photodetector and an electrical spectrum analyzer. So the actual birefringence-induced frequency shift equals the measured frequency difference between pump 1 and the probe plus a BFS.

The experimental setup of the distributed birefringence measurement of the PMF based on the TBG is shown in Fig. 1. Two narrow linewidth (3 kHz) fiber lasers operating at 1550 nm are used to provide pumps 1 and 2, and their frequency difference is locked by a phase-locking loop in a frequency counter. A tunable laser with a wavelength resolution of 0.1 pm is used as the probe wave. The frequency difference between pump 1 and the probe is monitored and recorded by a high-speed detector with a bandwidth of 45 GHz and a 44 GHz electrical spectrum analyzer (E4446A, Agilent). An electro-optic modulator (EOM), EOM1, is used to generate a 2 ns square-shaped pulse. Two high-extinction-ratio EOM2 and EOM3 are used to generate a square-shaped 2 ns pump 2 pulse and a 8 ns probe pulse with the extinction ratio higher than 45 dB, which are then combined with a 3 dB coupler. The powers of pump 1, pump 2, and probe pulses in the PMF are about 200 mW, 30 W, and 30 W, respectively. Two pump pulses are launched into the slow axis, and the delay between them is well controlled to create a TBG at a specific location.

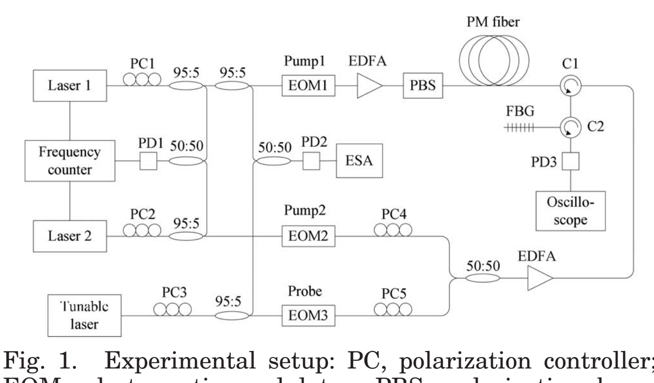

Fig. 1. Experimental setup: PC, polarization controller; EOM, electro-optic modulator; PBS, polarization beam splitter; C, circulator; PD, photo-detector; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FBG, fiber Bragg grating.

The probe pulse is launched into the fast axis with a time delay of 2 ns with respect to the pump 2 pulse, where the delay is chosen to separate the transmitted pump 1 pulse and the reflected signal in the time domain. A tunable fiber Bragg grating with a bandwidth of 0.2 nm is used to filter out the transmitted pump 1 pulse.

An 8 m bow-tie fiber (HB1500T) and an 8 m panda fiber (PM-1550-HP) are used as fibers under test. The bow-tie fiber has a mode field diameter of 10.5 μm, and its nominal beat-length is smaller than 2 mm at 633 nm, whose BFS is 10.815 GHz at room temperature and whose Brillouin spectrum width is 61 MHz. The panda fiber has a mode field diameter of 10.5 μm, and its nominal beat-length is smaller than 5 mm at 1550 nm, with a BFS of 10.871 GHz at room temperature and a Brillouin spectrum width of 60 MHz. Both fibers were in loose state to avoid strain-induced birefringence.

The measured TBG spectrum is the convolution of the probe pulse spectrum and the intrinsic TBG spectrum, and thus a longer probe pulse can give a narrower spectrum and a better frequency and birefringence accuracy [8]. In addition, the effective length of the TBG, i.e., the spatial resolution, is ~20 cm for 2 ns pump pulses.

Fixing the frequency difference of pumps 1 and 2 at 10.815 GHz for the strongest TBG in the bow-tie fiber, its response is measured by scanning the tunable laser. The measured typical TBG spectra of the bow-tie fiber are shown in Fig. 2, where most part of the fiber exhibits a two-peak spectrum, as shown in Fig. 2(a), except at 0.5–0.7 m with a three-peak spectrum, as shown in Fig. 2(b). The fitting spectrum width is ~140 MHz, which comes from the convolution of the intrinsic TBG and 8 ns pulse spectra. The multipeak spectrum means that there are multiple waveguide modes existing in the individual axis of the PMF, and thus the birefringence should be replaced with multimode propagation refractive indices for this fiber, since it characterizes the refractive index difference between different polarization modes; each peak corresponds to a phase refractive index difference between two axes of the PMF.

Because peaks a and b exist along the entire fiber, as shown in Fig. 2, we choose these two peaks to characterize the birefringence of the bow-tie fiber with the average group refractive index of silica core of 1.4683. The calculated birefringence is plotted in Fig. 3. It can be seen that the birefringence has a characteristic periodic variation with a period of

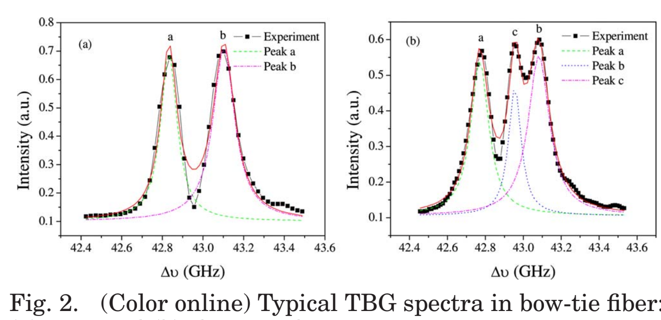

Fig. 2. (Color online) Typical TBG spectra in bow-tie fiber: (a) two- and (b) three-peak spectra.

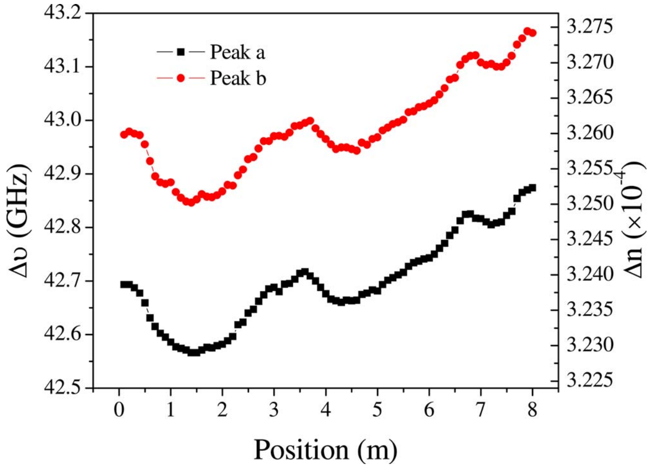

Fig. 3. (Color online) Measured distributed birefringence of 8 m bow-tie fiber using peaks a and b.

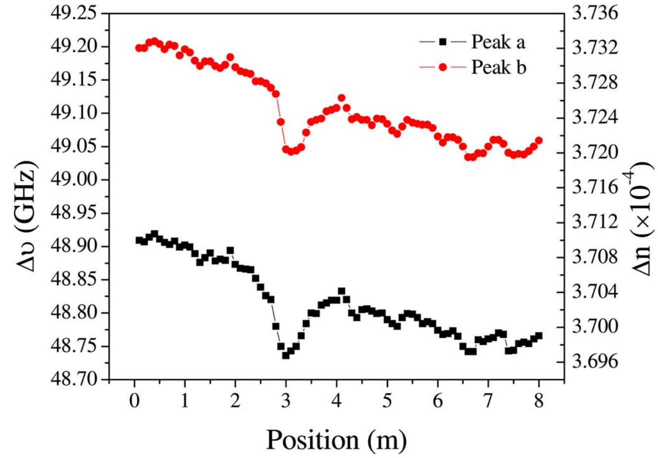

Fig. 5. (Color online) Measured distributed birefringence of 8 m panda fiber using peaks a and b.

$\sim$3.5 m and exhibits an increasing tendency along the fiber, which indicates that there could be another large period. Different periods could correspond to different disturbance factors during the fiber drawing process. The two peaks exhibit the same variation tendency with the frequency difference between them kept as a constant. The average frequency difference between the two peaks is 286 MHz, which corresponds to a refractive index difference of 2.16×10^{-6} between two fine waveguide modes. For individual peak, the birefringence variation range is $\sim 2.4 \times 10^{-6}$ along the 8 m fiber.

The measured typical TBG spectra of the panda fiber are shown in Fig. 4 and, as the same with that in the bow-tie fiber, most part of the fiber exhibits a two-peak spectrum, as shown in Fig. 4(a), except minor sections with a three-peak spectrum, as shown in Fig. 4(b). Peaks a and b are used to characterize the birefringence of the panda fiber, and the calculated birefringence is plotted in Fig. 5. The two peaks also have the same variation tendency with the frequency difference between them kept as a constant. There is no obvious periodic characteristic within the measured length except a dip at the location of $\sim$3 m. The average frequency difference between the two peaks is 294 MHz, which corresponds to a refractive index difference of 2.22×10^{-6}. For individual peak, the birefringence variation range is $\sim 1.3 \times 10^{-6}$ along the 8 m fiber.

The temperature variation was very small during the measurement process and could be neglected. We redid the same experiment several times at different time periods and got the same results, which also prove that the temperature variation does not play a role in the reported results.

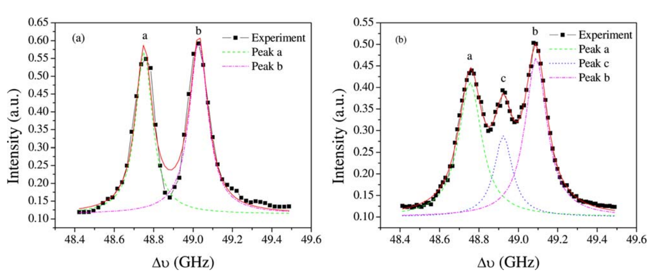

Fig. 4. (Color online) Typical TBG spectra in panda fiber: (a) two- and (b) three-peak spectra.

In summary, we have proposed and demonstrated a truly distributed birefringence measurement of the PMF based on the TBG, where two short pump pulses are used to create a local TBG and a long probe pulse is used to map the TBG spectrum associated with the local birefringence. The birefringence of bow-tie and panda fibers with a length of 8 m was measured with a spatial resolution of 20 cm. The results show that there are multiple waveguide modes in the individual axis of the PMF with a very small refractive index difference so that this fine mode structure cannot be observed previously with the usual method. The birefringence exhibits a characteristic periodic variation along the test fiber. Different disturbance factors during the fiber drawing introduce different periods, and thus a longer fiber should be used to fully characterize the birefringence variation.

The authors acknowledge ISIS Canada and Natural Sciences and Engineering Research Council (NSERC) Discovery Grants for their financial support of this research.

References

1. B. E. Olsson, M. Karlsson, and P. A. Andrekson, IEEE Photon. Technol. Lett. **10**, 997 (1998).
2. C. S. Kim, Y. G. Han, R. M. Sova, U. C. Paek, Y. Chung, and J. U. Kang, IEEE Photon. Technol. Lett. **15**, 269 (2003).
3. D. A. Flavin, R. McBride, and J. D. C. Jones, Opt. Lett. **27**, 1010 (2002).
4. P. Hlubina and D. Ciprian, Opt. Express **15**, 17019 (2007).
5. Z. Zhu, D. J. Gauthier, and R. W. Boyd, Science **318**, 1748 (2007).
6. V. P. Kalosha, W. Li, F. Wang, L. Chen, and X. Bao, Opt. Lett. **33**, 2848 (2008).
7. K. Y. Song, W. Zou, Z. He, and K. Hotate, Opt. Lett. **34**, 1381 (2009).
8. Y. Dong, X. Bao, and L. Chen, Opt. Lett. **34**, 2590 (2009).