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Birefringence in anisotropic optical fibres studied by polarised light Brillouin reflectometry*

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Abstract. **Modal birefringence (the difference between the effective refractive indices of orthogonal polarisation modes) is one of the key parameters of anisotropic single-mode fibres, characterising their ability to preserve a linearly polarised state of input light. This parameter is commonly measured using short pieces of fibre, but such procedures are destructive and allow the birefringence to be determined only at the ends of long fibres. In this study, polarised light Brillouin reflectometry is used to assess birefringence uniformity throughout the length of an anisotropic fibre.**

Keywords: *birefringence, polarisation-maintaining fibres, anisotropic fibres, Brillouin reflectometry.*

1. Introduction

In evaluating the suitability of long lengths of anisotropic optical fibre for use in fibre-optic sensors of physical quantities, it is important to have information about the uniformity of the polarisation properties of the fibre throughout its length. Burdin et al. [1, 2] reported a polarised light reflectometry-based method allowing one to locate polarisation cross-talk regions and estimate the cross-talk level. Another key parameter of single-mode anisotropic fibres, determining their polarisation stability, is their modal birefringence, $B = |n_x - n_y|$, where n_x and n_y are the effective refractive indices of the fibre core for orthogonal polarisation modes. The birefringence of fibres is commonly measured by spectral techniques [3 – 5] or by methods in which light is modulated before being launched into fibre. Among the modulation methods, the local pressure method is widely used [6]. In most cases, short (~1 m) pieces of fibre are used or the average birefringence of a long length of fibre is measured. Because of random variations in fibre parameters, which are always produced in the course of fibre drawing, the birefringence value may vary along the fibre.

The birefringence of bulk crystalline samples has already been studied by Brillouin reflectometry [7]. Brillouin scattering is light scattering as a result of interaction with acoustic phonons. The frequency shift of the backscattered light [8] is

$$f = 2nV/\lambda, \tag{1}$$

where n is the effective refractive index of the medium; V is the speed of sound; and λ is the wavelength of the light in vacuum. Lee and Hwangbo [7] evaluated the difference between the ordinary and extraordinary refractive indices from the difference in Brillouin frequency shift between the ordinary and extraordinary rays in a crystalline sample. Similar measurements can be made for anisotropic optical fibres. One can then assess the birefringence distribution along the fibre. Sequentially exciting first one polarisation mode and then the other, one can obtain two Brillouin reflectograms. The difference between the reflectograms (between the Brillouin frequency shifts) in each fibre section is proportional to the modal birefringence B:

$$f_x - f_y = \frac{2(n_x - n_y)V}{\lambda} = \frac{2BV}{\lambda}. \tag{2}$$

The main purpose of this work was to study the feasibility of using Brillouin reflectometry for nondestructive birefringence evaluation along Panda-type anisotropic fibres. In this type of fibre, birefringence originates from the anisotropy in the internal stress field produced by inserting stress elements in the form of borosilicate glass rods with a thermal expansion coefficient exceeding that of silica glass.

2. Experimental

The birefringence along an anisotropic optical fibre was studied experimentally using a setup schematised in Fig. 1.

Brillouin reflectograms were obtained with an Omnisens DiTeSt STA-R202 Brillouin optical time domain analyser (BOTDA), based on stimulated Brillouin scattering (SBS) [8]. Its parameters are as follows: operating wavelength, 1550 nm; maximum number of averaging steps, 10^4; minimum spatial resolution, 1 m. For typical B values of Panda-type anisotropic fibres (~5×10^{-4}) and the speed of sound in bulk silica glass ($V \approx 5\times10^3$ m s^{-1}), we obtain from (2) $f_x - f_y \approx 3$ MHz. Given this, the frequency scan step (frequency resolution) of the BOTDA was taken to be 0.1 MHz. To extend the dynamic range and, accordingly, reduce the noise component of the signal, the probe pulse duration was 100 ns and the number of

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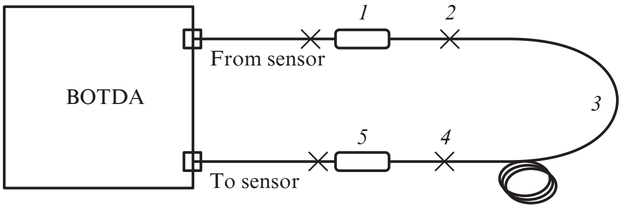

Figure 1. Experimental setup: (*1*, *5*) fibre-pigtailed optical polarisers; (*3*) sample; (*2*, *4*) fusion splices between polarisation-maintaining fibres with orientation along their optical axes.

signal averaging steps was 10^4. Note that the method for obtaining distributed birefringence was intended for long (~1 km) lengths of anisotropic fibres. Because of this, in adjusting parameters we aimed at determining as accurately as possible the difference between Brillouin reflectograms of two polarisation modes. In that case, high spatial resolution was not necessary.

To obtain a Brillouin reflectogram of each polarisation mode of the fibre, optical polarisers with fibre pigtails were fusion-spliced to both ends of the fibre so that their polarisation axes were parallel to the optical axis of one of the polarisation modes. The parameters of the polarisers were as follows: operating wavelength range, 1550 ± 50 nm; minimum polarisation extinction, 30 dB; maximum loss, 0.5 dB. The splices were made using a Fujikura PM-100 fusion splicer, as described previously [9].

To correlate the difference between the Brillouin shifts of polarisation modes to birefringence, it is necessary to perform a series of measurements on Panda-type fibres differing in birefringence. Another possibility is to study fibre whose birefringence varies along its length. In our experiments, we used a specially fabricated fibre with the following parameters: length, 450 m; attenuation, 1 dB km^{-1}; cutoff wavelength, 1054 nm; mode field diameter, 6.9 μm; cladding diameter, 80 ± 2 μm; linear birefringence profile along the fibre length.

After the measurements with the BOTDA, the data were checked. The anisotropic fibre was cut into segments ~50 m in length, and 1-m sections in each segment were investigated by a spectral interferometric technique [4] schematically illustrated in Fig. 2. This technique determines the beat length L_b of polarisation modes, which is then used to calculate the birefringence: $B = \lambda / L_b$.

With the experimental setup in question, B was determined with an absolute accuracy of 10^{-6} refractive index units, which allows one to use it for checking the proposed method.

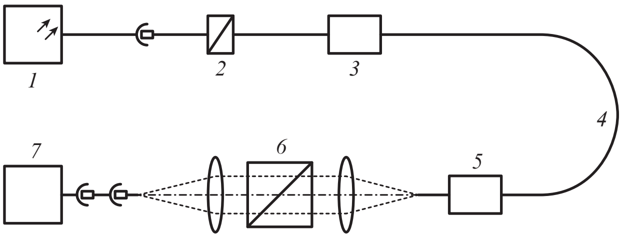

Figure 2. Experimental setup for spectral birefringence measurements: (*1*) broadband light source; (*2*) fibre polariser; (*3*) alignment stage orienting the polariser output for identical excitation of both polarisation modes in anisotropic fibres; (*4*) sample; (*5*) alignment stage; (*6*) Glan–Thompson polarising prism; (*7*) Yokogawa AQ6319 optical spectrum analyser.

3. Discussion

Figure 3 shows Brillouin reflectograms for both polarisation modes in the Panda anisotropic fibre studied. The reflectograms represent the Brillouin frequency shift as a function of z-coordinate, measured along the fibre axis. The difference in Brillouin frequency shift between the polarisation modes, about 3.5 MHz, is due to the distinction between the effective refractive indices of the polarisation modes. Figure 3 clearly demonstrates the possibility of visually monitoring the birefringence along an anisotropic fibre, at least at $B \sim 5\times10^{-4}$. At $f_B \sim 10.58$ GHz and a typical refractive index of the core of Panda-type fibres (~1.47), the speed of sound estimated using relation (1) is $V = 5580$ m s^{-1}.

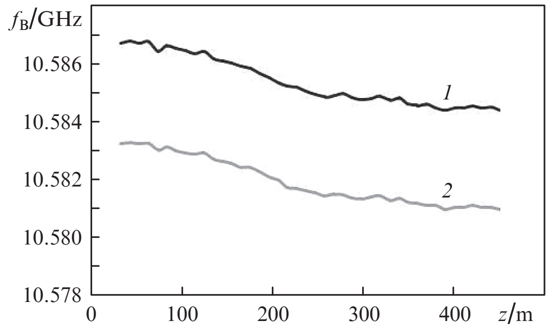

Figure 3. Brillouin frequency shift as a function of z-coordinate for the (*1*) slow and (*2*) fast polarisation modes.

Figure 4 shows the difference between the Brillouin reflectograms of the polarisation modes. The Brillouin frequency shift difference decreases along the fibre by about 0.1 MHz (from 3.5 to 3.4 MHz). As follows from (1), the frequency 0.1 MHz corresponds to about 10^{-6} refractive index units. Since the frequency scan step was 0.1 MHz, there is high noise in Fig. 4. It is worth noting that the variation in the relative Brillouin frequency shift difference along the fibre is within 5%. Using the speed of sound calculated above, we can evaluate the modal birefringence. At frequency shifts of 3.5 and 3.4 MHz, we obtain $B = 4.86\times10^{-4}$ and 4.72×10^{-4}, respectively.

Figure 5 presents the birefringence profile along the fibre as determined by a spectral technique. It is seen that the birefringence decreases along the fibre from 6.4×10^{-4} to 6.1×10^{-4}.

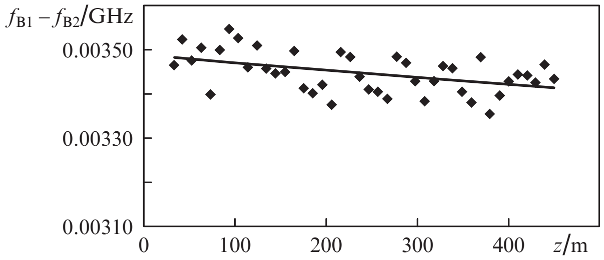

Figure 4. Difference between the Brillouin reflectograms of the polarisation modes in the anisotropic fibre.

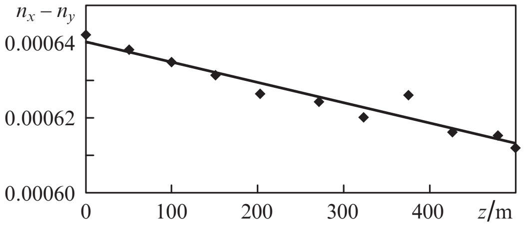

Figure 5. Modal birefringence profile along the fibre as determined by a spectral technique.

The relative birefringence change is also about 5%, which agrees with that evaluated from Brillouin reflectograms. At the same time, the absolute difference $n_x - n_y$ is about 30% greater. This can be accounted for by the SBS mechanism underlying the operation of the BOTDA. In the SBS process, electrostriction induces density changes in the medium, which in turn lead to refractive index modulation [10]. The resultant refractive index changes, small compared to the initial value of 1.47, are comparable to the birefringence value. Thus, the underestimated value of B obtained by SBS measurements can be accounted for by the fact the two modes with mutually orthogonal polarisations differ in photoinduced refractive index changes.

Thus, using only Brillouin reflectograms obtained by SBS measurements, one can assess relative changes in B, but its absolute value cannot be determined. Therefore, to find the absolute birefringence value throughout the fibre length, one should determine the birefringence at the ends of a long length of the fibre by another technique and then correct the results obtained with the BOTDA.

4. Conclusions

The present results demonstrate that polarised light Brillouin reflectometry enables nondestructive assessment of the birefringence profile in long lengths of anisotropic fibres. At a frequency scan step of 0.1 MHz, the accuracy in the frequency shift difference between the polarisation modes is 10^{-6} refractive index units and coincides with that in our spectral measurements. It is reasonable to conclude at this stage of our research that the proposed polarised light Brillouin reflectometry method is suitable for high-speed analysis of distributed polarisation properties along the length of anisotropic fibres after the drawing process. To further improve the method, it should be tested with a large number of samples in order to assess its accuracy in practice. Further work is planned to compare the proposed technique to other approaches for birefringence measurements along the length of anisotropic fibres.

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