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Measurement of pressure sensitivity of modal birefringence of birefringent optical fibers using a Sagnac interferometer

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The paper presents a method of measuring the sensitivity of modal birefringence to pressure in birefringent optical fibers, based on a Sagnac interferometer with a birefringent fiber. In this method, the pressure sensitivity of modal birefringence of the optical fiber is determined on the basis of the measurement of the pressure sensitivity of the Sagnac interferometer including the fiber being measured, and the measurement of the group modal birefringence of that fiber, which is also performed by using the Sagnac interferometer. Utilizing the above method, measurements were performed of the pressure sensitivity of modal birefringence of birefringent optical fibers: a photonic crystal fiber and a bow-tie fiber, in the wavelength range 1460–1600 nm. Presented are the results of these measurements and their comparison with the results obtained by using different methods for the same types of fibers.

Keywords: birefringent fiber, birefringence, pressure sensitivity.

1. Introduction

The primary parameter of optical fibers of high birefringence determining their suitability for sensorics is the sensitivity of their modal birefringence to an external excitation. The sensitivity of phase modal birefringence $\partial \Delta n / \partial x$ and the sensitivity of group modal birefringence $\partial \Delta n_G / \partial x$ to an external excitation x are distinguished. These parameters are determined on the basis of the measurement of the polarimetric sensitivity of the fiber defined as $K_x = (1/L)\, \partial \Delta \varphi / \partial x$, where L is the length of the fiber, upon which the excitation x is acting, $\Delta \varphi$ is the phase difference between the polarization modes, caused by the excitation. This measurement (of the polarimetric sensitivity) is most often performed by using for this purpose a fiber optic polarimetric interferometer enabling the measurement of $\Delta\varphi$. The measure $\Delta\varphi$ of in this measurement is the number of fringes of the interference image [1–5]. Less frequently used to this end is a polarimeter, where the phase shift is determined by observing the Poincaré sphere [6, 7].

Both for practical reasons and for the purpose of gaining knowledge, the magnitude and sign of $\partial\Delta n/\partial x$ and $\partial\Delta n_G/\partial x$ are determined. Consequently, the magnitude and sign of the polarimetric sensitivity K_x are determined. To find the sign of K_x, special procedures have been developed [3–5, 8].

The paper presents an indirect method of measuring the pressure sensitivity of modal birefringence of birefringent optical fibers based on a Sagnac interferometer with the birefrinent optical fiber to be measured installed in its loop. The analytical relations used in this measurement method are given. Also given is the method of determining the sign of the group modal birefringence, the knowledge of which is required to determine the sign of the phase modal birefringence. The Sagnac interferometer with a birefringent fiber only enables the measurement of the magnitude of the group modal birefringence of that fiber.

The results of measurements are presented of the pressure sensitivity of phase modal birefringence and group modal birefringence of two types of highly birefringent fibers: a photonic crystal fiber manufactured by Blaze Photonics Ltd., with the designation PM-1550-01, and a bow-tie type fiber manufactured by FiberCore, designated HB1500T, which were carried out using the proposed method. The measurements were performed in the wavelength range 1460–1600 nm. On the basis of the measurements, the main advantages of the proposed measurement method are summarized.

2. Measurement method

The basis for the method of measuring the pressure sensitivity of modal birefringence of birefringent fibers is provided by the shift of the interference spectrum of the Sagnac interferometer with a birefringent fiber under the effect of pressure on that fiber. The diagram of the arrangement for measuring the pressure sensitivity of modal birefringence of birefringent fibers is presented in Fig. 1.

It comprises the fiber optic Sagnac interferometer with the birefringent fiber, a system for applying pressure and equipment cooperating with the interferometer: a wideband light source – a SLED and an optical spectrum analyzer (OSA).

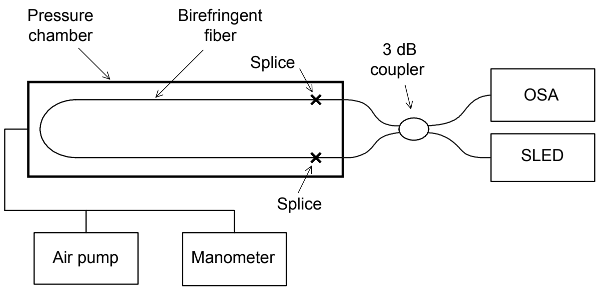

Fig. 1. Scheme of the measuring arrangement.

The 3 dB coupler of the interferometer splits the beam from the source into two beams of equal amplitude, which propagate in its loop in opposite directions. The beams, after traveling through the loop, including the birefringent fiber, recombine in the coupler creating an interference image. The spectrum of this image is periodic, with the period depending on the length of the birefringent fiber segment and the birefringence value of the fiber. The action of pressure on the birefringent fiber of the interferometer causes its spectrum to shift. The pressure sensitivity of modal birefringence of the birefringent fiber can be determined using the known relation describing the phase difference δ between the modes of a birefringent fiber of length L, assuming that the phase modal birefringence Δn of that fiber is dependent on the pressure p and the wavelength λ

$$\delta = \frac{2\pi L}{\lambda}\Delta n(\lambda, p) \tag{1}$$

The change of the phase difference caused by the changes of these quantities can be calculated as the total differential of Eq. (1) and written as the relation:

$$\Delta\delta = -\frac{2\pi L \Delta n_G}{\lambda^2}\Delta\lambda + \frac{2\pi L}{\lambda}\frac{\partial \Delta n}{\partial p}\Delta p + \frac{2\pi L}{\lambda}\frac{\Delta L}{L} \tag{2}$$

where $\Delta n_G = [\Delta n - \lambda(\mathrm{d}\Delta n/\mathrm{d}\lambda)]$ is the group modal birefringence.

For maxima the phase difference $\delta = 2\pi$, so that $\Delta\delta = 0$, then from Eq. (2), assuming that the pressure does not cause any longitudinal strain of the birefringent fiber ($\Delta L = 0$), one obtains:

$$\frac{\partial \Delta n}{\partial p} = \frac{\Delta n_G}{\lambda}\frac{\Delta\lambda}{\Delta p} = \frac{\Delta n_G}{\lambda}K_{Ip} \tag{3}$$

where $K_{Ip} = \Delta\lambda/\Delta p$ is the pressure sensitivity of the Sagnac interferometer. On the basis of Eq. (3) it is possible to calculate $\partial\Delta n/\partial p$ by measuring the pressure sensitivity K_{Ip} of the Sagnac interferometer and the group modal birefringence Δn_G of the birefringent fiber for a given wavelength. Using the Sagnac interferometer, the group modal birefringence can be determined on the basis of measuring the spectrum period Λ of the Sagnac interferometer with the fiber to be measured, according to the formula:

$$|\Delta n_G| = \frac{\lambda^2}{\Lambda L} \tag{4}$$

where L is the length of the fiber segment in the loop of the interferometer.

The pressure sensitivity of the phase modal birefringence as a function of the polarimetric pressure sensitivity is given by the expression [4]

$$\frac{\partial \Delta n}{\partial p} = \frac{K_p \lambda}{2\pi} \tag{5}$$

Taking into account Eqs. (3)–(5), the polarimetric pressure sensitivity K_p can be related to the pressure sensitivity of the Sagnac interferometer by the following formula:

$$K_p = \frac{2\pi}{\Lambda L} K_{Ip} \tag{6}$$

where Λ is the spectrum period of the Sagnac interferometer with a birefringent fiber of length $L = 1$ m.

The pressure sensitivity of the group modal birefringence $\partial \Delta n_G / \partial p$ is determined from the relation:

$$\frac{\partial \Delta n_G}{\partial p} = \frac{\partial \Delta n}{\partial p} - \lambda \frac{\partial^2 \Delta n}{\partial \lambda \partial p} \tag{7}$$

To make use of Eq. (7) to calculate $\partial \Delta n_G / \partial p$, $\partial \Delta n / \partial p$ is approximated by a polynomial.

The sign of the pressure sensitivity of the phase modal birefringence is determined based on the sign of the pressure sensitivity of the Sagnac interferometer and the sign of the group modal birefringence of the fiber to be measured according to Eq. (3). The sign K_{Ip} of is determined directly from the measurement thereof as the sign of the ratio of the wavelength increase caused by the pressure increase, in other words K_{Ip} is determined by the direction of the interference spectrum shift caused by the pressure increase. If the spectrum shifts in the direction of higher wavelengths (to the right on the optical spectrum analyzer screen) with the pressure increasing, then the sign of K_{Ip} is positive; if the spectrum shifts in the direction of lower wavelengths (to the left on the OSA) with the pressure increasing, the sign of K_{Ip} is negative. With the Sagnac interferometer the magnitude of the group modal birefringence can be measured in accordance with Eq. (4). The sign of the group modal birefringence can be determined by a simple experiment. A segment of a birefringent fiber, whose group birefringence sign is known, should to be fusion spliced to the tested fiber installed in the Sagnac loop according to the birefringence axes. If the sign of the group modal birefringence of the added fiber is positive ($\Delta n_{G_x} > \Delta n_{G_y}$) and if the period of the spectrum with the added fiber segment is smaller than without it, then the birefringence of the tested fiber has a positive sign, and if the period of the spectrum is greater, then Δn_G of the tested fiber has a negative sign. The sign of the pressure sensitivity of the group modal birefringence is determined on the basis of the sign of the pressure sensitivity of the phase modal birefringence and the sign of its derivative with respect to the wavelength according to Eq. (7).

3. Results of measurements

The above-described measurement method was applied to determine the pressure sensitivity of modal birefringence of the birefringent photonic crystal fiber PM-1550-01 and the conventional bow-tie type birefringent fiber HB1500T. The measurements were carried out in the wavelength range 1460–1600 nm. To illuminate the interferometer in this wavelength range, two SLEDs were utilized: one with a central wavelength of 1522 nm and a 3 dB bandwidth of 50 nm and the second with a central wavelength of 1563 nm and a 3 dB bandwidth of 40 nm. Both diodes have non-polarized output beams. During the construction of the interferometer loop the investigated segments of both birefringent fibers, the PM-PCF and the bow-tie, were connected to the SMF-28 fiber by fusion splicing. A standard electric arc splicer was used for this purpose. The measurement of the transmitted beam of the sensor was performed using an optical spectrum analyzer.

First, the group modal birefringence of the tested birefringent fibers was determined on the basis of Eq. (4) by directly measuring the period of the recorded interference spectrum and the wavelength, as shown in Fig. 2. Taking into account the recommendations given in [9], concerning the selection of the period with regard to the measurement uncertainty of the period and the wavelength, segments of the PM-PCF and bow-tie birefringent fibers with lengths of 350 mm and 832 mm, respectively, were used. The measurement results are shown in Figs. 3 and 4.

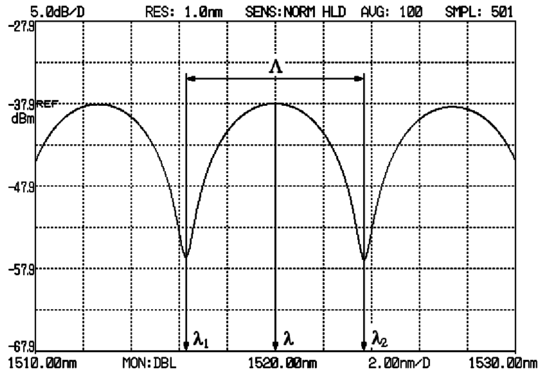

Fig. 2. Recorded segment of the interference spectrum of the Sagnac interferometer with a birefringent fiber.

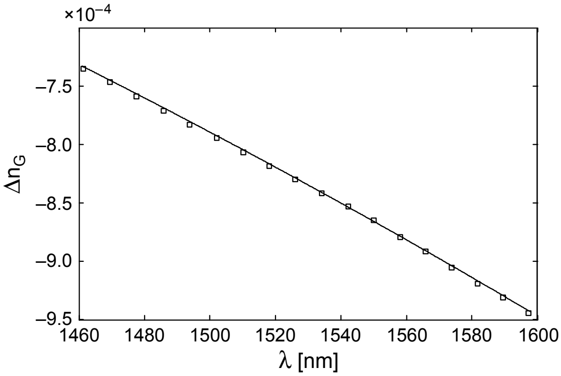

Fig. 3. Group modal birefringence of the birefringent photonic crystal fiber as a function of wavelength.

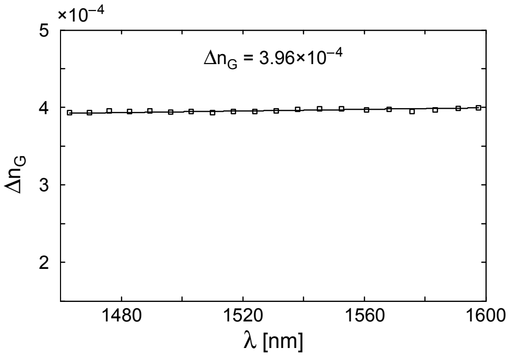

Fig. 4. Group modal birefringence of the bow-tie birefringent fiber as a function of wavelength.

The relation between the magnitude of the group modal birefringence of the PCF and the wavelength determined from the measurements was approximated with the power function $|\Delta n_G| = 9.049\times10^{-13}\lambda^{2.815}$, where λ is expressed in nanometers. The group modal birefringence has a negative sign. Its wavelength dependence $\Delta n_G = f(\lambda)$ is shown in Fig. 3. The sign of the PCF's group modal birefringence was determined according to the procedure described in Section 2, using for this purpose a segment of the bow-tie fiber.

Over the investigated range of wavelengths this dependence is consistent with the $\Delta n_G = f(\lambda)$ dependence for the same type of PM-PCF, determined for a broad range of wavelengths (500–1600 nm) and reported in [10]. The magnitude of the group modal birefringence of the fiber for $\lambda = 1550$ nm is $\Delta n_G = 8.56\times10^{-4}$ which is consistent with the results of [11, 12]. The group modal birefringence of the bow-tie fiber does not depend on the wavelength and its value is $\Delta n_G = 3.96\times10^{-4}$ and is consistent with the result given in [1].

Subsequently, the measurements of the pressure sensitivity of the Sagnac interferometer with segments of the tested birefringent fibers were performed. The lengths of the segments were 300 mm for the photonic crystal fiber and 500 mm for the bow-tie fiber. The measurements were carried out in the arrangement, whose diagram is shown in Fig. 1. The segments of the tested fibers were placed inside a pneumatic hose, to which compressed air was fed from a reversible air (pneumatic) pump of the type PPH-25. In the case of testing the photonic crystal fiber, one end of the pneumatic hose was connected to the output valve of the pump and the other end was fitted with a sealing grommet, through which the segments of the SMF-28 fiber, fusion spliced to the ends of the PM-PCF, were passed. The routed outside ends of the SMF-28 fiber were sealed in the grommet with epoxy adhesive. In the case of testing the bow-tie fiber, in the output valve of the pump a four-way (cross) pipe fitting was installed, in which the segments of pneumatic hoses were attached to the opposite ends. This enabled the tested fiber to be placed inside the pneumatic hoses without bending it. Routing the fiber outside and sealing the ends of the pneumatic hoses were carried out the same way as in the case of the PM-PCF fiber. In Fig. 5 the interference spectrum of the Sagnac interferometer

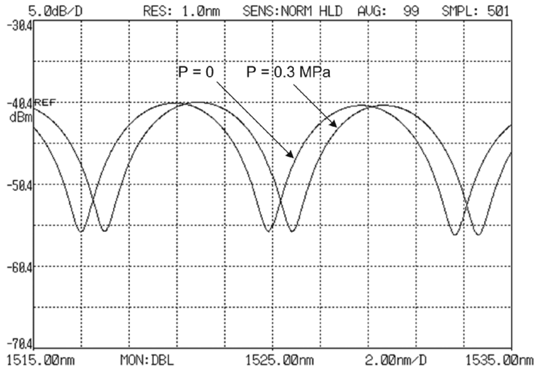

Fig. 5. Interference spectrum of the Sagnac interferometer with the PCF for two values of pressure acting on the fiber.

with the PCF is shown for two values of pressure acting on the fiber. The results of the measurements are shown in Figs 6 and 7. The curves were approximated with power functions: $K_{Ip} = 1.867\times10^{6}\lambda^{-1.807}$ for the PM-PCF and $K_{Ip} = 0.03386\lambda^{0.5986}$ for the bow-tie fiber, in which the wavelength is expressed in nanometers.

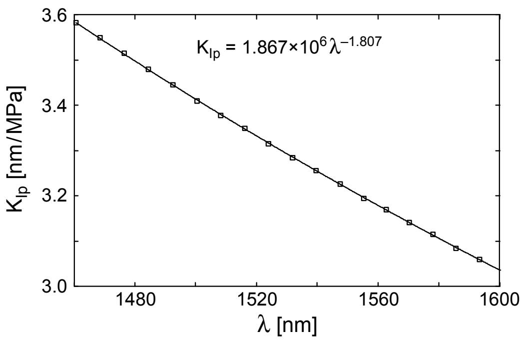

Fig. 6. Pressure sensitivity of the Sagnac interferometer with the photonic crystal fiber as a function of wavelength.

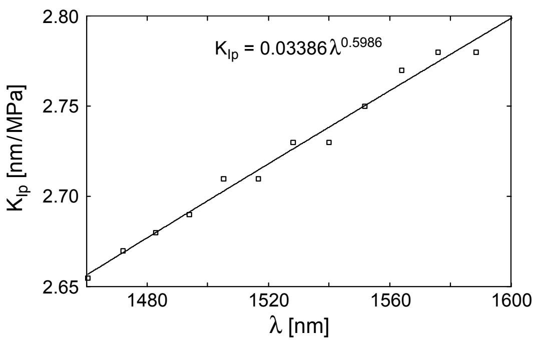

Fig. 7. Pressure sensitivity of the Sagnac interferometer with the bow-tie fiber as a function of wavelength.

From Fig. 6 it is seen that the pressure sensitivity of the Sagnac interferometer with the birefringent photonic crystal fiber exhibits only a slight dependence on the wavelength, wherein with increasing wavelength, the sensitivity decreases. This decreasing of the sensitivity in the measured wavelength range is equal to 15% of the maximum value. The pressure sensitivity of the Sagnac interferometer with the bow-tie birefringent fiber slightly increases with increasing wavelength (Fig. 7). This increase does not exceed 6% of the minimum sensitivity in the measured wavelength range.

Using the measurement results of the modal birefringence of the tested fibers and the measurement results of the pressure sensitivity of the Sagnac interferometer with segments of those fibers, on the basis of Eq. (3) the pressure sensitivity of the phase modal birefringence was calculated. The calculated relation $\partial\Delta n/\partial p$ was approximated and then, using Eq. (7), $\partial\Delta n_G/\partial p$ was calculated. The results of those calculations are shown in Figs. 8–10.

The calculated pressure sensitivity of the phase modal birefringence of the photonic crystal fiber in the wavelength range 1460–1600 nm has a constant value $\partial\Delta n/\partial p = -1.79\times10^{-6}$ MPa^{-1}. Thus, the value of the pressure sensitivity of the group modal

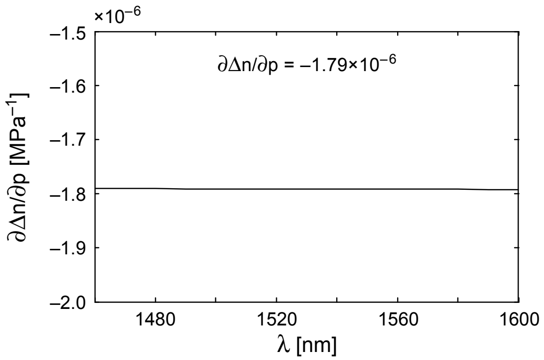

Fig. 8. Pressure sensitivity of the phase modal birefringence of the photonic crystal fiber as a function of wavelength.

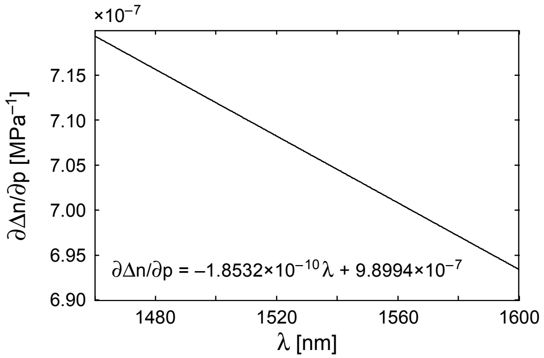

Fig. 9. Pressure sensitivity of the phase modal birefringence of the bow-tie fiber as a function of wavelength.

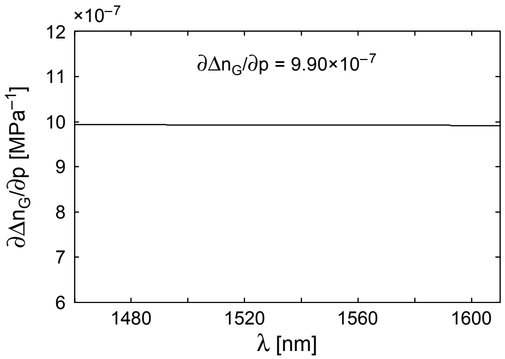

Fig. 10. Pressure sensitivity of the group modal birefringence of the bow-tie fiber as a function of wavelength.

birefringence of the fiber, based on Eq. (5), is the same $\partial \Delta n_G/\partial p = -1.79\times10^{-6}$ MPa^{-1}. With regards to the nature of the changes in the pressure sensitivity, those results are consistent with measurement results obtained in [3], which were performed for the same type of fiber. The values of the pressure sensitivity of the modal birefringence agree relatively well with the values of the sensitivity obtained in [3].

Also the absolute value of the polarimetric pressure sensitivity and its changes as a function of wavelength, determined on the basis of Eq. (6), are consistent with those obtained in [3] for the same type of fiber. The calculated pressure sensitivity of the phase modal birefringence of the bow-tie fiber in the range 1460–1600 nm decreases linearly from 7.19 to 6.93 MPa^{-1}. Using the slope of the approximated relation $\partial \Delta n/\partial p = f(\lambda)$, the value of the pressure sensitivity of the group modal birefringence was calculated on the basis of Eq. (5). It is equal to $\partial \Delta n_G/\partial p = 9.90\times10^{-7}$ MPa^{-1}. Those results correspond well with the results obtained in [1] for the same type of fiber.

4. Conclusions

The results of the performed measurements of the pressure sensitivity of the modal birefringence of birefringent photonic crystal fibers and bow-tie fibers, and the consistency of those results with the results obtained by other authors and included in [1, 3], for the same types of fibers, confirm that the method of measuring the sensitivity of the modal birefringence based on the Sagnac interferometer is correct. The method is characterized by simplicity of the measuring arrangement, its entirely fiber optic structure, the ease of performing the measurement itself and a relatively low measurement uncertainty. For these reasons it can be applied to both scientific research and technical measurements.

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