Optics Communications 375 (2016) 43–48

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Spectral-domain measurement of the strain sensitivity of phase modal birefringence of polarization-maintaining optical fibers

Cezary Kaczmarek

Institute of Electronics and Information Technology, Lublin University of Technology, Nadbystrzycka 38 A, 20-618 Lublin, Poland

ARTICLE INFO

Article history:
Received 10 January 2016
Received in revised form
29 April 2016
Accepted 1 May 2016
Available online 10 May 2016

Keywords:
Polarization maintaining fibers
Birefringence
Sensitivity to strain

ABSTRACT

The paper presents a new and simple method of measuring the strain sensitivity of phase modal birefringence ($d\Delta n/d\varepsilon$) of polarization maintaining fibers (PMFs). The method is based on measuring the spectral strain sensitivity of a strain sensor in the configuration of a Sagnac interferometer with a PMF. The measured spectral strain sensitivity of the sensor is used to determine the strain sensitivity of phase modal birefringence and the polarimetric strain sensitivity of the PMF. In addition, a new procedure for determining the sign of the strain sensitivity of phase and group modal birefringence of a PMF. Using this method, measurements of the strain sensitivity of modal birefringence of PMFs were performed: a PM-PCF and a Bow-Tie fiber, in the wavelength range 1460–1600 nm. A comparison of the results of these measurements with results obtained using other methods for the same types of fibers is presented.

1. Introduction

Polarization maintaining fibers (PMFs), also called highly birefringent fibers, are often used as active strain elements in fiber optic sensors of mechanical quantities. The sensitivity of modal birefringence of these fibers to strain is the main parameter, which determines the possibility of using them in these sensors. There is, therefore, a need for improving the existing and developing new methods of measuring this parameter for PMFs. The sensitivity of the phase modal birefringence to strain $d\Delta n/d\varepsilon$, and the sensitivity of the group modal birefringence to strain $d\Delta n_G/d\varepsilon$ are distinguished.

The strain sensitivity of phase modal birefringence $d\Delta n/d\varepsilon$ of a PMF is usually determined on the basis of a measurement of the polarimetric strain sensitivity of this fiber K_ε. The sensitivity K_ε represents the change of the phase shift between the polarization modes induced by a unit change of strain of a unit length segment of the fiber. This measurement is most often performed in the time domain using for this purpose a fiber optic polarimetric interferometer. The measure of the change of the phase shift between the polarization modes in this measurement is the number of fringes of the interference image [1–5]. Less often, a polarimeter is used for this purpose and the phase shift is determined by observing the Poincaré sphere [6–8]. The sensitivity K_ε of a PMF can also be determined on the basis of the wavelength spectrum of a polarimetric interferometer with the tested PMF [9]. Both for practical and scientific reasons the magnitude and the sign of $d\Delta n/d\varepsilon$ are determined. Thus, the magnitude and the sign of the polarimetric sensitivity K_ε are also determined.

For determining the sign of K_ε special procedures have been developed [3,5–7,9]. The sensitivity $d\Delta n_G/d\varepsilon$ is calculated on the basis of its defining equation using an approximation of the measured sensitivity $d\Delta n/d\varepsilon$ of the fiber [1,3].

The inconveniences of measuring $d\Delta n/d\varepsilon$ using a polarization interferometer are associated with the employment of bulk optical elements in its structure and the need of adjusting the setup for guiding the light into and out of the tested fiber segment. The use of a polarimeter for measuring $d\Delta n/d\varepsilon$ is limited due to the high cost of this instrument.

This paper presents a new and simple method of measuring the sensitivity $d\Delta n/d\varepsilon$ of PMFs. The method is based on the measurement of the spectral strain sensitivity $K_{s\varepsilon}$ of a strain sensor in the configuration of a Sagnac interferometer with a PMF [10–13]. The measured $K_{s\varepsilon}$ of the sensor is used to determine the strain sensitivity $d\Delta n/d\varepsilon$ and the polarimetric strain sensitivity K_ε of the PMF. Additionally, a new procedure of determining the sign of $d\Delta n/d\varepsilon$ and a new procedure of determining the sign of $d\Delta n_G/d\varepsilon$ of a PMF are given.

Results of measurements of the strain sensitivity of phase and group modal birefringence for two types of PMFs are presented: a PM-PCF manufactured by Blaze Photonics Ltd with the trade designation PM-1550–01 and a conventional Bow-Tie PMF manufactured by FiberCore with the designation HB1500T. The measurements were performed using the proposed method in the wavelength range 1460–1600 nm. The obtained results were compared to results obtained using other methods for the same types of fibers.

E-mail address: c.kaczmarek@pollub.pl

http://dx.doi.org/10.1016/j.optcom.2016.05.001

2. Measurement method

A diagram of the setup for measuring the strain sensitivity $d\Delta n/d\varepsilon$ of PMFs is presented in Fig. 1. The setup includes a Sagnac interferometer with a PMF acting as a Sagnac interferometer strain sensor (SISS), a system for applying strain to the tested fiber and equipment cooperating with the sensor: a wideband light source – a SLED and an optical spectrum analyzer (OSA).The 3 dB coupler of the interferometer splits the beam from the source into two beams of equal intensity, which propagate in its loop in opposite directions. The beams, after traveling around the loop, including the PMF, interfere in the coupler creating an interference image. The wavelength spectrum of this image is periodic, with the period depending on the length of the PMF segment and the birefringence value of the PMF. A strain of the PMF of the interferometer induces a shift of its spectrum. The spectrum shift, that is the shift ξ of a selected point of the spectrum, is defined by the wavelength λ corresponding to it. The point selected is usually one of the minima of the spectrum. This is the basis of the method of measuring the sensitivity $d\Delta n/d\varepsilon$. The measurement of ξ makes it possible to determine the spectral sensitivity $K_{s\varepsilon}$ of the SISS, required to determine the sensitivity $d\Delta n/d\varepsilon$ and the polarimetric sensitivity K_ε.

The phase difference $\Delta\phi = \phi_x - \phi_y$ between the x and y polarization modes, which propagate in a PMF, is given as

$$\Delta\phi = 2\pi\cdot\Delta n\cdot L/\lambda, \tag{1}$$

where Δn, L, λ are: the phase modal birefringence, the length of the PMF, and the wavelength, respectively.

Neglecting the insertion loss of the Sagnac loop, the transmission of the Sagnac interferometer in relation to the phase difference can be written as

$$T = [1 - \cos(\Delta\phi)]/2\cdot \tag{2}$$

Transmission T as a function of wavelength is related to the group modal birefringence Δn_G of the PMF, which is demonstrated by expression (3), obtained after differentiating (1) and making simple transformations

$$d\Delta\phi/d\lambda = -2\pi\cdot L\cdot\Delta n_G/\lambda^2 \tag{3}$$

$T(\lambda)$ is a periodic function of wavelength. The period of the transmission spectrum, that is, the spacing between consecutive

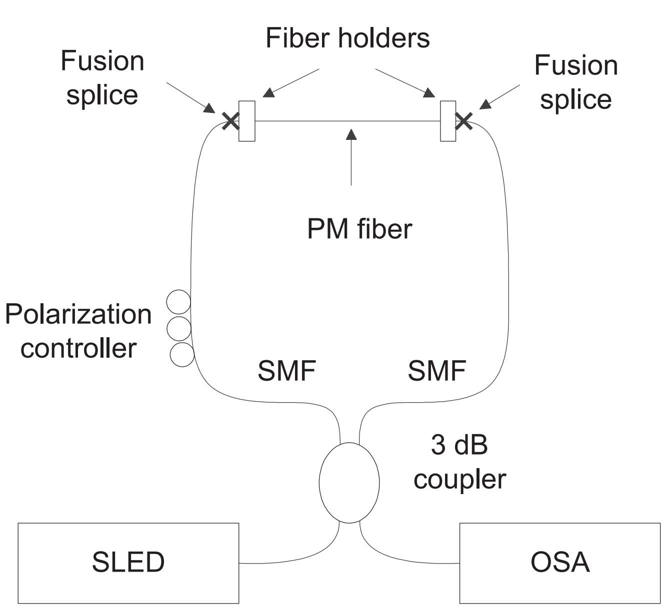

Fig. 1. Schematic of the experimental setup.

transmission dips Λ, is determined by the relationship

$$\Lambda = \lambda^2/(L\cdot\Delta n_G) \tag{4}$$

The polarimetric strain sensitivity K_ε is defined by the following expression

$$K_\epsilon = \frac{1}{L}\frac{d(\Delta\phi)}{d\epsilon} \tag{5}$$

where $d(\Delta\phi)$ is the change of the phase difference between the polarization modes induced by the strain of the fiber $d\varepsilon$, and L is the length of the strained fiber.

If in the equation defining K_ε one takes into account the relationship between the change of the phase difference and the change of the shift of the spectrum, that is $d(\Delta\phi) = 2\pi\cdot d\xi/\Lambda$, one obtains

$$K_\varepsilon = \frac{2\pi}{\Lambda}K_{s\varepsilon}, \tag{6}$$

where Λ is the period of the SISS with the PMF of a unit length, and $K_{s\varepsilon}$ is the spectral strain sensitivity of the SISS with the tested fiber, determined by the relationship

$$K_{s\varepsilon} = \frac{1}{L}\frac{d\xi}{d\varepsilon}. \tag{7}$$

The spectral strain sensitivity $K_{s\varepsilon}$ represents the shift of the spectrum of the SISS induced by a unit change of strain of a fiber with a unit length. Relationship (6) makes it possible to determine the absolute value of the sensitivity K_ε based on the measured: sensitivity $K_{s\varepsilon}$ and the period of the spectrum Λ of the SISS. The sign of K_ε is not the same as the sign of $K_{s\varepsilon}$. The sign of K_ε is the same as the sign of the strain sensitivity of phase modal birefringence $d\Delta n/d\varepsilon$. The sensitivity K_ε can also be expressed as

$$K_\epsilon = \frac{2\pi}{\lambda}\left(\frac{d\Delta n}{d\epsilon} + \Delta n\right). \tag{8}$$

Taking into account Eq. (6) in Eq. (8), one obtains the following relationship

$$\frac{d\Delta n}{d\epsilon} = \frac{\lambda}{\Lambda}K_{s\epsilon} - \Delta n. \tag{9}$$

Relationship (9) makes it possible to determine the absolute value of the sensitivity $d\Delta n/d\varepsilon$. It will be possible to determine the sign of $d\Delta n/d\varepsilon$ after transforming Eq. (9) using Eq. (4) into the form

$$\frac{d\Delta n}{d\epsilon} = \frac{\Delta n_G}{\lambda}\frac{d\xi}{d\epsilon} - \Delta n. \tag{10}$$

The sign of the first term of Eq. (9) is determined on the basis of the sign of this term in Eq. (10), that is, on the basis of the sign of the spectral strain sensitivity $k_{s\varepsilon} = d\xi/d\varepsilon$ of the strain sensor and the sign of the group modal birefringence of the tested fiber.

The sign of $k_{s\varepsilon}$ is determined directly from measurements, based on the direction of the spectrum shift induced by the strain increase. If the spectrum shift towards higher wavelengths with increasing tensile strain, the sign of $k_{s\varepsilon}$ is positive, if the spectrum shift towards lower wavelengths with increasing strain, the sign of $k_{s\varepsilon}$ is negative. Using the Sagnac interferometer one can measure the absolute value of the group modal birefringence according to Eq. (4). The procedure for identifying the sign of the group modal birefringence was given in [14].

The strain sensitivity of group modal birefringence $d\Delta n_G/d\varepsilon$ is determined from the relationship

$$\frac{d\Delta n_G}{d\epsilon} = \frac{d\Delta n}{d\epsilon} - \lambda\frac{d^2\Delta n}{d\lambda\ d\epsilon}. \tag{11}$$