Optical Fiber Technology 33 (2017) 45–50

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Fiber optic temperature sensing with enhanced sensitivity based on spectral interferometry

J. Militky, M. Kadulova, D. Ciprian, P. Hlubina *

Department of Physics, Technical University Ostrava, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic

ARTICLE INFO

Article history:
Received 25 January 2016
Accepted 6 November 2016
Available online 11 November 2016

Keywords:
Spectral interferometry
Channeled spectrum
Birefringent fiber
Birefringent crystal
Temperature sensing
Wavelength interrogation

ABSTRACT

Temperature sensing with enhanced sensitivity based on the spectral interference of polarization modes in a highly birefringent (HB) fiber is proposed and demonstrated. A temperature sensor employs a tandem configuration of a birefringent quartz crystal and HB fiber placed between an analyzer and a polarizer. In the setup a modified channeled spectrum is generated, which shifts with the temperature change of the sensing part of the HB fiber. We analyze the measurement method theoretically and show that the sensitivity of the temperature sensing based on the wavelength interrogation is enhanced in comparison to a standard method with a fiber interferometer. We also demonstrate the enhancement of the temperature sensitivity for three HB fibers under test. Experimental results show that the temperature sensing can reach a sensitivity of −0.30 nm/K, which is enhanced in comparison to −0.10 nm/K reached for a standard measurement.

1. Introduction

Optical fibers are very attractive in fiber sensing applications due to their advantages such as small size, low weight, and electromagnetic immunity. Sensing of a large variety of physical parameters with high sensitivity, wide dynamic range and high resolution [1] is also possible owing to advanced optical fiber technology enabling the development of fiber long period and Bragg gratings [2,3], in-fiber Fabry–Perot [4,5] or Mach–Zehnder [6] interferometers, D-shaped fibers [7], photonic crystal fibers [8,9], and birefringent fibers [10]. These structures have been used to build up fiber optic sensors of physical parameters such as strain [4], temperature [4–7], pressure [9], etc.

Standard highly birefringent (HB) fibers with elliptical-core or stress-applying elements have been successfully used as active elements of fiber optic sensors for measuring numerous physical parameters such as strain, temperature and pressure [10–13]. Some of the sensor configurations are working in the spatial domain and utilize white-light interferometric methods [11–13]. The other configurations are working in the spectral domain and in some arrangements, the phase change to be measured is inscribed in the spectral interference fringes detected by a spectrometer [14–16]. To enhance the sensitivity of the fiber optic sensors, HB holey fibers with much higher flexibility in shaping both modal birefringence and sensitivity have emerged as potential structures of sensor configurations [17–21]. Other ways of enhancing the sensitivity are based on new approaches to measurement methods [22].

In this paper, temperature sensing with enhanced sensitivity based on the spectral interference of polarization modes in HB fiber is proposed and demonstrated. First, an experimental setup comprising a white-light source, a polarizer, HB fiber, an analyzer and a spectrometer is considered. Second, the first experimental setup is extended with a birefringent quartz crystal, which is in tandem with the HB fiber. In the setup a modified channeled spectrum is generated, which shifts with the temperature change of the sensing part of the HB fiber. We analyze the measurement method theoretically and show that the sensitivity of the temperature measurement based on the wavelength interrogation is enhanced in comparison to a standard method with a fiber interferometer. We also demonstrate the enhancement of the temperature sensitivity for three HB fibers under test. Experimental results show that for the first setup the temperature measurement can reach a sensitivity of −0.10 nm/K. For the second setup the sensitivity of the temperature measurement is enhanced and reaches −0.30 nm/K.

2. Theoretical background

2.1. Standard configuration

Let us consider an experimental setup with HB fiber of length L placed between a polarizer and an analyzer adjusted at 45° with respect to the fiber eigenaxes as shown in Fig. 1. In this setup,

---

* Corresponding author.
E-mail address: petr.hlubina@vsb.cz (P. Hlubina).

http://dx.doi.org/10.1016/j.yofte.2016.11.011
1068-5200/

a linearly polarized optical field, propagating along the axis of the HB fiber, in which only the fundamental mode in both x and y polarizations is excited, is disturbed by the external physical quantity – temperature. The spectral intensity at the output of the HB fiber is given as [15]

$$I(L;\lambda) = I_0(\lambda)\{1 + V(L;\lambda)\cos[(2\pi/\lambda)B(\lambda)L]\}, \tag{1}$$

where $I_0(\lambda)$ is the reference spectral intensity, $B(\lambda)$ is the phase modal birefringence and $V(L;\lambda)$ is the visibility term, which is dependent on the group modal birefringence $G(\lambda)$ via the relation

$$V(L;\lambda) = \exp\{-(\pi^2/2)[G(\lambda)L\Delta\lambda_R/\lambda^2]^2\}, \tag{2}$$

where $\Delta\lambda_R$ is the width of the spectrometer response function.

The interference of the polarization modes at the output of the experimental setup shows up as a channeled spectrum with the period

$$\Lambda(\lambda) = \frac{\lambda^2}{|G(\lambda)L|}, \tag{3}$$

representing also the free spectral range (FSR), which is larger for a shorter fiber.

Using the experimental setup shown in Fig. 1, with the length L_T of the HB fiber subjected to temperature changes, we can measure the polarimetric temperature sensitivity of the fiber. It is defined by the following relation

$$K_T(\lambda) = \frac{1}{L_T}\frac{\mathrm{d}[\phi_x(\lambda) - \phi_y(\lambda)]}{\mathrm{d}T}, \tag{4}$$

and represents an increase in the phase shift between the two polarization modes of the investigated HB fiber induced by the unit change of the temperature acting on the unit fiber length [20].

Because the interference of polarization modes of the investigated HB fiber shows up as a channeled spectrum, a shift of the wavelength position of a given interference maximum or minimum with temperature can be utilized for temperature sensing. In other words, the wavelength interrogation can be used. The corresponding temperature sensitivity $S_T(\lambda)$, representing the wavelength shift of the interference maximum induced by the unit change of the temperature, is given by [19,23]

$$S_T(\lambda) = \frac{\mathrm{d}\lambda_{max}}{\mathrm{d}T} = \frac{\lambda^2}{2\pi}\frac{K_T(\lambda)L_T}{G(\lambda)L}. \tag{5}$$

2.2. Tandem configuration

To enhance the sensitivity of the temperature measurement, the HB fiber in tandem with a birefringent crystal of the group birefringence $G_c(\lambda)$ and the thickness d can be used as shown in Fig. 2.

The spectral intensity at the output of the tandem configuration, when a polarizer and an analyzer are adjusted at 45° with respect to the polarization axes of the HB fiber with $G(\lambda) > 0$ and $G_c(\lambda) > 0$, is given by [15]

$$I(z;\lambda) = I_0(\lambda)\{1 + V(z;\lambda)\cos\{(2\pi/\lambda)[B(\lambda)z - B_c(\lambda)d]\}\}, \tag{6}$$

where $B_c(\lambda)$ is the phase birefringence of the crystal. The period of the spectral modulation in this case is given by

$$\Lambda_c(\lambda) = \frac{\lambda^2}{|G(\lambda)L - G_c(\lambda)d|}, \tag{7}$$

where $G_c(\lambda)$ is the group birefringence of the crystal.

It results from Eq. (7) that the equalization wavelength λ_0 is resolvable in the recorded spectrum when the overall group birefringence in a tandem configuration of a birefringent crystal and HB fiber is zero [26] and the relation

$$G(\lambda_0)L = G_c(\lambda_0)d \tag{8}$$

is fulfilled.

Once again the wavelength interrogation can be used and the corresponding temperature sensitivity $S_T^c(\lambda)$ is given by

$$S_T^c(\lambda) = \frac{\lambda^2}{2\pi}\frac{K_T(\lambda)L_T}{[G(\lambda)L - G_c(\lambda)d]}. \tag{9}$$

The sensitivity of the temperature sensing in the tandem configuration is enhanced compared to that with a standard configuration and the corresponding enhancement factor EF, which is

$$\mathrm{EF} = \frac{|G(\lambda)L|}{|G(\lambda)L - G_c(\lambda)d|}, \tag{10}$$

is increasing by decreasing the denominator of Eq. (10), or in other words, by shifting a spectral region of the measurement toward the equalization wavelength.

3. Experimental setups

The first experimental setup used primarily in measuring the polarimetric sensitivity of HB fiber to temperature is shown in Fig. 1. It consists of a broadband source – a halogen lamp (HL-2000, Ocean Optics), light of which is launched into a fiber terminated by a lens. From the lens a collimated beam propagates through a Glan–Taylor calcite polarizer (Thorlabs) the transmission azimuth of which is adjusted at 45° with respect to the polarization axes of the HB fiber. The light beam is focused by a microscope objective into the HB fiber. A section of the HB fiber of length $L_T = 76.2$ mm is attached to a resistive foil heater (HT10K, Thorlabs) and its temperature is varied via a temperature controller (TC200, Thorlabs). At the output of the HB fiber, microscope

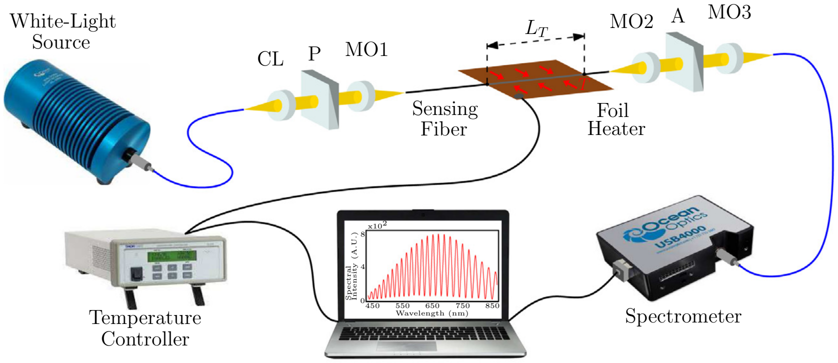

Fig. 1. Experimental setup with a sensing fiber; collimating lens (CL), polarizer (P), analyzer (A) and microscope objectives (MO1–MO3).