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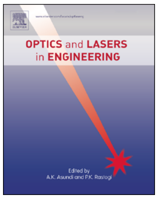

Temperature sensing using the spectral interference of polarization modes in a highly birefringent fiber

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ABSTRACT

The spectral interference of polarization modes in a highly birefringent (HB) fiber to measure temperature is analyzed theoretically and experimentally. A tandem configuration of a birefringent delay line and a sensing HB fiber is considered and the spectral interferograms are modelled for the known birefringence dispersion of the HB fiber under test. As the delay line, a birefringent quartz crystal of a suitable thickness is employed to resolve a channeled spectrum. The channeled spectra are recorded for different temperatures and the polarimetric sensitivity to temperature, determined in the spectral range from 500 to 850 nm, is decreasing with wavelength. It is demonstrated that the temperature sensing is possible using the wavelength interrogation, i.e., the position of a given interference maximum is temperature dependent. The temperature sensitivity of the HB fiber under test is −0.25 nm/K and the resolution is better than 0.5 K.

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1. Introduction

Optical fibers are of great importance in sensing different physical parameters with high sensitivity, wide dynamic range and high resolution [1]. Moreover, fiber optic sensors possess advantages such as small size, low weight and electromagnetic immunity. Among the fiber optic sensors, temperature sensors with different structures and principles of operation have been extensively investigated [2–11]. As an example, the sensors were realized by using a special microstructure in a single-mode fiber such as Bragg gratings [2,3], long period gratings [4], an in-fiber Fabry–Perot [5] or Mach–Zehnder [6] interferometer, a tapered fiber [7], and a D-shaped fiber [8]. Included are also sensors enabling high-temperature measurements [9] and simultaneous measurements of temperature and strain [10], and sensors based on the in-line reflection principle of operation [11]. The microstructures are post-fabricated and require complicated processes employing techniques such as UV-laser writing, laser machining, fusion tapering, and chemical etching. Consequently, many fiber optic sensors have been proposed which are based on specialty optical fibers such as polarization-maintaining fibers, photonic crystal fibers, and multi-core fibers, and the special structure in the fiber is formed during the fabrication and no extra post processing for fabricating a fiber sensing head is needed.

A large number of in-line fiber optic sensor configurations utilize interference between polarization modes [12–16]. 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 [12–16]. Some of the sensor configurations are working in the spatial domain and utilize white-light interferometric methods [12–14]. The interferometric systems are available even when the group optical path difference between polarization modes is larger than the source coherence length. In this case a tandem configuration of two interferometers, a sensing fiber interferometer and a birefringent calcite plate to compensate the group delay between the polarization modes introduced by the sensing fiber, can be utilized [12,14]. The other configurations are working in the spectral domain and use two birefringent optical fibers [16] or are based on the shift of the transmission spectrum dip [17]. In some configurations, the phase change to be measured is inscribed in the spectral interference fringes detected by a spectrometer [18–20]. Some of these configurations have been primarily used for measuring the dispersion of birefringence in polarization-maintaining fibers by processing a stationary-phase point spectrum [21] or channeled spectrum [22]. In addition, the principle of channeled spectrum is utilized for optical switching [23,24].

Standard HB fibers exhibit temperature-sensitive birefringence so that when they are used for sensing other parameters than temperature, such as strain, the temperature cross-sensitivity affects the measurement accuracy significantly. To overcome this limitation, HB holey fibers with much higher flexibility in shaping

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modal birefringence and significantly less temperature dependence than standard HB fibers have emerged as active elements of fiber optic sensors [25–28].

In this paper, theoretical and experimental analysis of a spectral-domain technique utilizing the interference of polarization modes of an elliptical-core HB fiber to measure temperature is presented. The analysis is motivated by the fact that spectral analysers with a sufficiently high resolution, such as compact spectrometers, are easily accessible. Moreover, a tandem configuration is proposed to resolve spectral interference fringes for a long HB fiber. The method, utilizing a compact spectrometer in a visible spectral range, is based on the wavelength interrogation, i.e., the position of a given interference maximum as a function of temperature is measured. A tandem configuration of a birefringent delay line and a sensing HB fiber is considered and first, the spectral interferograms are modelled for the known spectral dependence of both the phase and group modal birefringence of the HB fiber under test. As the delay line, a birefringent quartz crystal of a suitable thickness is employed to resolve a channeled spectrum in a range as wide as possible. Second, the polarimetric sensitivity to temperature is measured and it is higher at shorter wavelengths so the HB fiber under test is suitable for temperature sensing at a wavelength of about 520 nm. Finally, it is revealed that when a part of the sensing HB fiber, which is placed in a chamber, is exposed to temperature changes, a shift of the wavelength position of a given interference maximum is present. The temperature sensitivity reaches −0.25 nm/K and the resolution is better than 0.5 K.

2. Theoretical background

Consider a sensing HB fiber of length z in an experimental setup shown in Fig. 1. 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 alone with a polarizer and an analyzer adjusted at 45° with respect to the fiber eigenaxes is given as [19]

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

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

The interference of the polarization modes at the output of the experimental setup shows up as the spectral modulation (channeled spectrum) with the period inversely proportional to the group modal birefringence $G(\lambda)$, which means that for the longer sensing HB fiber the period of the spectral modulation is smaller [20].

If the resolving power of a spectrometer is insufficient to resolve the channeled spectrum, 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. 1. The spectral intensity at the output of the tandem configuration with a polarizer and an analyzer adjusted at 45° with respect to the polarization axes of the HB fiber is for $G(\lambda) > 0$ and $G_c(\lambda) > 0$ given by [19]

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

where $B_c(\lambda)$ is the phase birefringence of the crystal. The period of the spectral modulation depends on the difference $G(\lambda)z - G_c(\lambda)d$, which means that the equalization wavelength is resolvable in the recorded spectrum when the overall group birefringence in the tandem configuration of the birefringent crystal and the HB fiber is zero [20].

2.1. Theoretical spectral interferograms

Consider an elliptical-core PM fiber whose phase and group modal birefringence dispersions are known from previous measurements [22]. The group modal birefringence as a function of the wavelength (see Fig. 2) was measured by a method of spectral tandem interferometry [21] with the precision better than 0.1%. The phase modal birefringence as a function of the wavelength (see Fig. 3) was deduced from the wavelength dependence of the group modal birefringence [22,29] when value $B = 8.55 \times 10^{-5}$

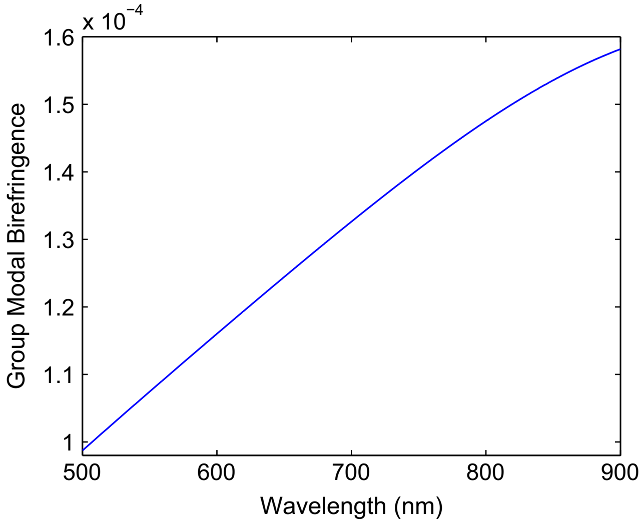

Fig. 2. Measured spectral dependence of the group modal birefringence in the HB fiber under test.

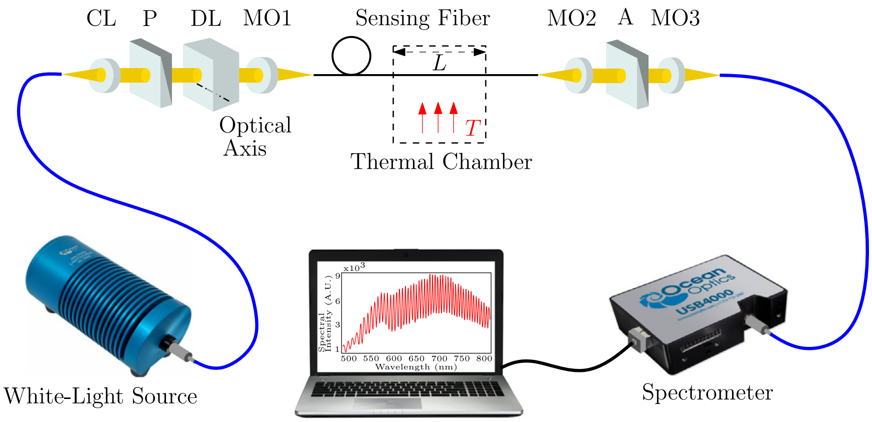

Fig. 1. Experimental setup with a sensing fiber to record channeled spectra; collimating lens (CL), polarizer (P), delay line (DL), analyzer (A) and microscope objectives (MO1–MO3).

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