Highly birefringent photonic bandgap Bragg fiber loop mirror for simultaneous measurement of strain and temperature

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A highly birefringent photonic bandgap Bragg fiber loop mirror configuration for simultaneous measurement of strain and temperature is proposed. The group birefringence and the sharp loss peaks are observable in the spectral response. Because the sensing head presents different sensitivities for strain and temperature measurands, these physical parameters can be discriminated by using the matrix method. It should be noted that this Bragg fiber presents high sensitivity to temperature, of ~5.75 nm/°C, due to the group birefringence variation. The rms deviations obtained are ±19.32 $\mu\varepsilon$ and ±0.5 °C, for strain and temperature measurements, respectively.

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High-birefringent fiber loop mirrors (Hi-Bi FLM) can be used in optical sensing, namely in gyroscope applications [1] and strain [2], temperature [3], liquid level [4], and displacement [5] measurements. The Hi-Bi FLM consists of a simple directional optic coupler where the two output ports are spliced with a section of Hi-Bi fiber in between. Light from the optical source is divided through the coupler, and the two split light beams travel through the fiber in opposite directions. The difference of optical path is guaranteed due to the Hi-Bi section fiber. At the output port the two light beams interfere and the visibility of the fringe can be optimized by the polarization controller.

Bragg fibers were first proposed by P. Yeh *et al.* [6] in 1978, and consist of a solid circular photonic bandgap microstructure (i.e., an alternation of low and high refractive index layers), surrounding a low refractive index core. Recently, it has been demonstrated that this kind of fiber is suitable for high-power fiber lasers [7], supercontinuum generation [8], and optical sensing [9]. In particular, for optical sensing, a strain and temperature discrimination using a modal interferometer based on two different geometry (circular and octagonal) Bragg fibers has been demonstrated [10]. Polarization-preserving photonic bandgap Bragg fibers have also been demonstrated by the inclusion of boron-doped rods inside the core [11].

In this work, we use a Hi-Bi photonic bandgap Bragg fiber inside a fiber loop, in order to obtain a Sagnac interferometer sensor. Because of the characteristics presented by this configuration, it is possible to obtain a combination of the group birefringence and the sharp loss peak in the spectral response, allowing the characterization of the two measurands in strain and temperature.

Figure 1 presents the experimental setup of the Hi-Bi Bragg fiber loop mirror (BFLM) sensor. It is composed of a supercontinuum optical source with a spectral bandwidth of 600–1700 nm, a Hi-Bi BFLM, a polarization controller, and an optical spectrum analyzer (OSA; Ando AQ-6315B with a resolution of 0.05 nm).

The Hi-Bi Bragg fiber used in this experiment, described elsewhere [11], had an external diameter of 120 μm, and a length of ~1.27 m. Figure 1 also shows the cross section of the fiber, which presents three concentric high-index rings, and two small *B*-doped regions inside the core. The inclusions yield a group birefringence approximately equal to 1.58×10^{-5} [11].

Figure 2 shows the spectral response of the interferometer, in a range of 350 nm, between 1200 and 1550 nm. The spectrum pattern fringes result from the Hi-Bi FLM group birefringence. One can also observe the presence of two additional sharp loss peaks, at ~1303 nm and ~1443 nm. These peaks are due to intrinsic transmission properties of this Hi-Bi Bragg fiber, as shown in [11]. This well-known phenomenon appears when the refractive index of the core is close to that of silica, inducing slight coupling between core and first ring modes. The power coupled into the first ring is lost as the splice with the standard single mode fiber operates as a transverse spatial filter. Finally, the decrease of light intensity as the wavelength increases is due to the optical loss, which is characteristic of this Bragg fiber [11]. The study of the peak wavelength dependence of the Hi-Bi BFLM (group birefringence) and of the sharp loss peaks with strain and temperature was done at wavelengths λ_{FLM} (1386 nm) and λ_{SLP} (1443 nm), respectively.

A simple theoretical model was used to describe the spectrum behavior of the Hi-Bi BFLM, without considering the sharp loss peaks. The optical losses were well described by a second order polynomial. On the other hand,

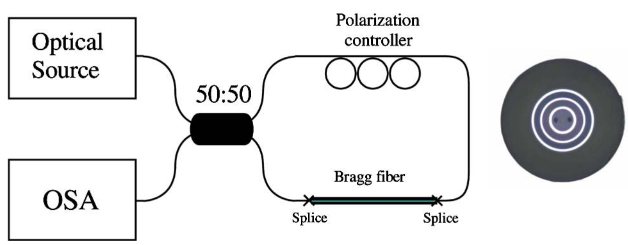

Fig. 1. (Color online) Experimental setup (left) and cross section (right) of the Hi-Bi Bragg fiber.

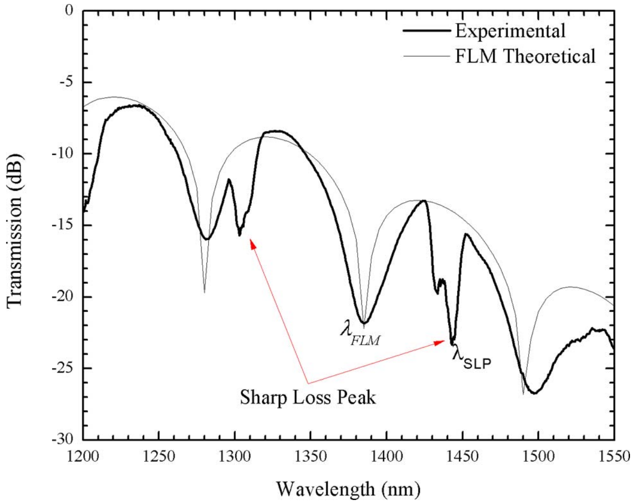

Fig. 2. (Color online) Measured and computed spectral response of the Hi-Bi Bragg FLM.

the behavior of the fringes is sinusoidal, according to Eq. (1)

$$T = \left[\cos\left(\frac{\varphi}{2}\right)\sin(\theta)\right] \tag{1}$$

where $\varphi = 2\pi LG/\lambda$, L is the length of the Hi-Bi fiber, G the group birefringence, and λ the operation wavelength. The first factor in Eq. (1) refers to the phase difference variation of the interferometer, while the second factor is associated with the visibility, which has its maximum value when $\theta = \pi/2$.

It is interesting to separately study the behavior of the transmission spectrum with strain and temperature variations. For strain characterization, the sensing head, the Hi-Bi Bragg fiber segment, was attached to a translation stage with a resolution of $1\,\mu$m. All strain measurements were done at room temperature (~23 °C). For temperature characterization, the sensing head was placed in a tubular oven, which permitted an error associated to temperature reading smaller than 0.1 °C.

In Fig. 3, the wavelength ($\Delta\lambda$) dependence with the variation of strain ($\Delta\varepsilon$) is shown. The strain sensitivity is $47.18\,\mathrm{pm}/\mu\varepsilon$ and $8.34\,\mathrm{pm}/\mu\varepsilon$ for the Hi-Bi BFLM peak wavelength (λ_{FLM}) and sharp loss peak wavelength (λ_{SLP}), respectively. In both cases, the sensitivity is positive (redshift), which means that the path length increases as the strain increases. The fiber sensitivity is higher when considering the change in λ_{FLM}. On the other hand, the behavior against temperature variations is quite different, as can be seen in Fig. 4. One could only increase temperature ~7 °C above room temperature due to the selected spectral response range of 350 nm. The high birefringence of this Bragg fiber is produced by geometrical effect of the core created by the two B-doped inclusions. When the fiber is subjected to temperature variation, there is a decrease in the thermo-optic effect. Consequently, the group birefringence decreases, and there is a wavelength shift towards smaller wavelengths (blueshift). As far as the sharp loss peak is concerned, the wavelength increased with the applied temperature, as expected. The sensitivity is $-5.75\times10^3\,\mathrm{pm}/°\mathrm{C}$ when considering the change of the group birefringence and $111.84\,\mathrm{pm}/°\mathrm{C}$ for the sharp loss peak wavelength variation. The observed difference in the sensitivity coefficients allows the possibility of using this sensing head for simultaneous measurements of strain and temperature. In order to determine strain and temperature from the measured Bragg wavelength shifts, the following matrix can be written

$$\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix} = \frac{1}{D}\begin{bmatrix}\kappa_{\varepsilon\mathrm{FLM}} & -\kappa_{\varepsilon\mathrm{SLP}}\\ -\kappa_{\mathrm{TFLM}} & \kappa_{\mathrm{TSLP}}\end{bmatrix}\begin{bmatrix}\Delta\lambda_{\mathrm{SLP}}\\ \Delta\lambda_{\mathrm{FLM}}\end{bmatrix}, \tag{2}$$

where $D = \kappa_{\varepsilon\mathrm{FLM}}\kappa_{\mathrm{TSLP}} - \kappa_{\varepsilon\mathrm{SLP}}\kappa_{\mathrm{TFLM}}$ is the matrix determinant. In order to have a sensing head with proper discrimination performance, this determinant value should not be too small [12]. Inserting the sensitivity coefficients calculated previously yields

$$\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix} = \frac{1}{53.23\times10^3}\begin{bmatrix}47.18 & -8.34\\ 5.75\times10^3 & 111.84\end{bmatrix}\begin{bmatrix}\Delta\lambda_{\mathrm{SLP}}\\ \Delta\lambda_{\mathrm{FLM}}\end{bmatrix}. \tag{3}$$

The output response of the sensing head is illustrated in Fig. 5. The figure is obtained by fixing one measurand

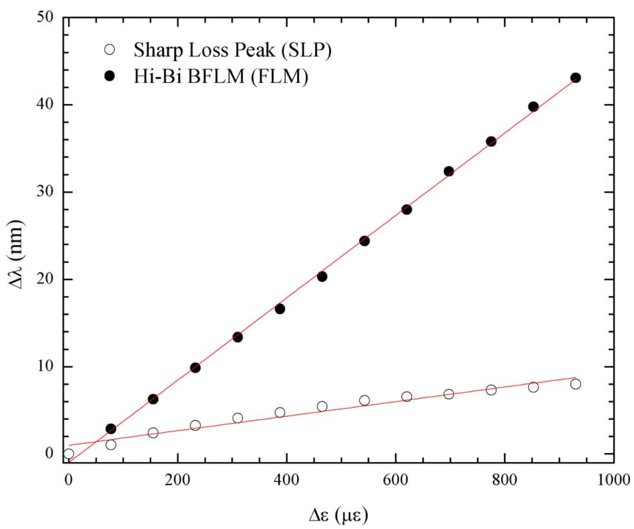

Fig. 3. (Color online) Response to strain when the Hi-Bi Bragg fiber is subjected to deformation.

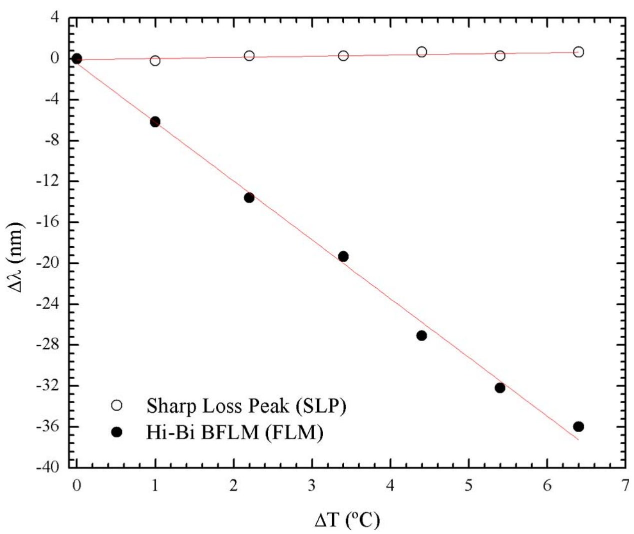

Fig. 4. (Color online) Response to temperature when the Hi-Bi Bragg fiber is subjected to temperature variation.

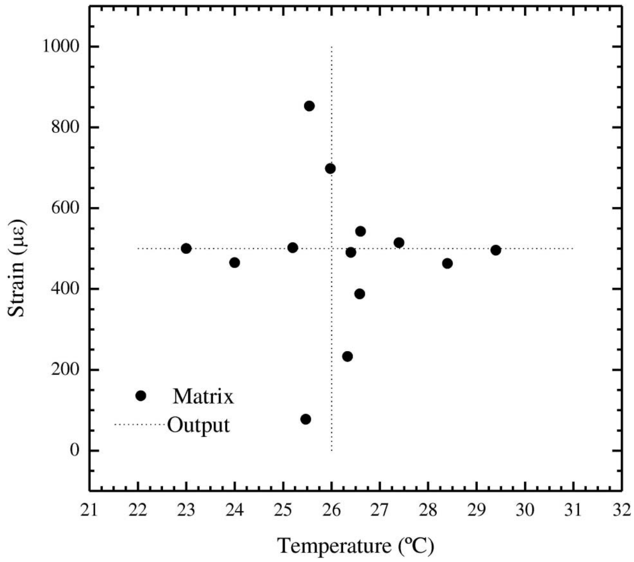

Fig. 5. Sensor output as determined by Eq. (3) for variation in strain at constant temperature and for variation in temperature at constant strain.

and varying the other one, in both cases. The dotted lines indicate the applied values, and the dots represent the variations of the measurands, calculated through the matrix in Eq. (3). Ideally, an agreement between these values should be expected. The rms deviations for strain and temperature measurements were $\pm 19.32\,\mu\varepsilon$ and $\pm 0.50\,°\mathrm{C}$, respectively. Therefore, and in principle, more favorable rms deviation values can be obtained if a more sensitive interrogation technique is utilized [13].

In summary, a highly birefringent photonic bandgap Bragg fiber loop mirror for simultaneous measurement of strain and temperature was demonstrated. In virtue of the Bragg fiber geometry, two sharp loss peaks and the interferometer signature were observed in the spectral response. The sensing head presented different sensitivities for strain and temperature measurements. In fact, the sensitivity of peak wavelength of the Hi-Bi BFLM compared to the wavelength change of the chosen sharp loss peak is about 6 times higher for strain and 45 times higher for the temperature. The rms deviation of these measurements, obtained through the matrix method, was about $19.32\,\mu\varepsilon$ and $0.50\,°\mathrm{C}$, for strain and temperature, respectively. Finally, in the case where this sensor is used only for temperature measurement, the wavelength variation of only one peak needs to be monitored. For high temperature sensitivity, the Hi-Bi BFLM peak is the one that shows higher sensitivity. A resolution of $0.002\,°\mathrm{C}$ can be achieved using an OSA with a measurement resolution of 10 pm.

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