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Simultaneous strain and temperature measurement using a highly birefringence fiber loop mirror and a long-period grating written in a photonic crystal fiber

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ABSTRACT

We present a new design for simultaneous strain and temperature measurement using a high-birefringence fiber loop mirror (HiBi-FLM) concatenated with a temperature-insensitive long-period grating (LPG) written in a photonic crystal fiber (PCF). The FLM acts as a sensor head, while the LPG in PCF serves as a filter to convert wavelength variation to optical power change. By measuring the wavelength variation and the power difference of two near peaks in the spectral response of this configuration, simultaneous strain and temperature measurement is obtained.

1. Introduction

Fiber loop mirrors (FLMs) have been demonstrated for a number of applications such as wavelength filters and sensors [1–3]. In a FLM, two interfering waves counter-propagate through the same fiber, and are exposed to the same environment. This makes it less sensitive to environmental disturbance. A FLM made of highly birefringent fiber (HiBi-FLM) has several advantages, including input polarization independence and high extinction ratio, in addition to the good environmental stability and low cost, which are the main characteristics of the FLM [1].

HiBi-FLMs have been employed for temperature and strain measurement. For example, a temperature sensor based on a HiBi-FLM has showed a sensitivity of 0.94 nm/°C, which is ~94 times greater than that of a fiber Bragg grating [3]. However, when a HiBi-FLM is used to measure strain or other parameters, its cross-sensitivity to temperature may degrade sensor performance. The temperature effect must be discriminated or eliminated when they are used for strain sensing. One suggestion is to measure simultaneously strain and temperature by using HiBi-FLMs with an additional sensing part [4,5]. In [4], simultaneous measurement of strain and temperature was realized by utilizing the different temperature and strain characteristics of a HiBi fiber and a long-period grating (LPG). Concatenation of two types of HiBi fibers in a FLM was also used to discriminate temperature and strain [5]. Recently, work based on two cascaded HiBi-FLMs was demonstrated for simultaneous measurement of strain and temperature [6]. For the two cascaded FLMs approach, only the FLM containing the section of fiber with elliptical inner cladding fiber acts as the sensor head. The discrimination of strain and temperature was achieved by simultaneously monitoring the wavelength and the optical power variation of one peak in the transmitted spectrum of cascaded FLM system. However, it is relatively complex system.

In this paper, we present a simple but novel design for simultaneous strain and temperature discrimination by using a HiBi-FLM concatenated with a LPG written in a photonic crystal fiber (PCF). Similar to the sensing principle reported in [6], only the HiBi fiber within the FLM acts as a sensor head, while the LPG in PCF serves as a filter to provide wavelength dependent optical power transmission. Compared with the demonstration in [6], our configuration is much simpler and needs only a 3 dB coupler, a piece of HiBi sensing fiber and a LPG in PCF. The LPG in PCF is temperature-insensitive, thus the transfer function provided by the LPG keeps stable and is not effect by change of environmental temperature. PCFs are a new kind of fibers, which incorporate a number of air holes that run along the length of the fiber and are made of only one material (and air holes). Utilizing PCFs' low sensitivity to temperature, temperature-insensitive PCF-based devices can be implemented [2]. Recently, LPGs in PCFs were studied both

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theoretically and experimentally [7–10]. A LPG in the ESM-PCF with ∼0 temperature sensitivity was demonstrated, and applied as a temperature-insensitive strain sensor [10] and as a demodulator in a low cost FBG temperature sensor [11]. Here, the LPG in PCF acts as a temperature-insensitive optical wavelength filter. The LPG has a broad transmission dip and two spectral regions with opposite slopes around the resonant wavelength. Utilizing this property of the LPG, we choose two adjacent transmission peaks of the HiBi-FLM to be located, respectively within the two spectral regions with opposite slopes. When peaks of the FLM is blue-shifted, the magnitude of the peak located at the short wavelength side of the resonant wavelength which has a negative slope, will increases, while the magnitude of the peak located at a long wavelength side which has a positive slope, will decrease. Thus, when we monitor the ratio of two peak optical power, the sensitivity will be doubled. At the same time, all power fluctuations in the system will be eliminated effectively. Our experiments show that, by measuring simultaneously the wavelength shift of a peak and the optical power ratio between the two peaks, the proposed configuration can be used to discriminate strain and temperature.

2. Experimental setup

Fig. 1 shows the experimental setup. A broadband source launches the light into the HiBi-FLM via a 3 dB coupler. The transmitted light from the HiBi-FLM then enters the LPG written in PCF, and the output light spectrum is monitored using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm.

The PCF used in our experiments is an endless-single-mode PCF (ESM-PCF) purchased from Crystal Fiber A/S, and the cross-sectional scanning electron micrograph is also shown in Fig. 1. The mode field diameter is ∼6.4 μm, the spacing between the holes is ∼7.78 μm, and the diameter of the holes is ∼3.55 μm. The diameter of the entire holey region is ∼60 μm, and the outer cladding diameter of the PCF is 125 μm. The total length of the PCF is 5 cm, and both ends of the PCF are fusion spliced to single-mode fiber (Corning SMF-28) by using a regular splicing machine (Erisson FSU975). The loss of each splice is about 0.5 dB. A pulsed CO_2 laser is used to fabricate the LPG, and the details have been described previously [7]. The LPG inscribed has 40 periods and the period is about 467 μm. As shown in Fig. 2, the resonant wavelength of the LPG is 1552.45 nm and the dip is nearly 20 dB. The wavelength range in which a negative slope in the spectral transmission intensity occurs is 1520–1552.45 nm, i.e., about 32 nm. Meanwhile, the wavelength range with a positive slope is from 1552.45 to 1580 nm, i.e., about 28 nm. These entire two wavelength ranges could be utilized to convert wavelength change into power variation in our sensing system. However, it would be more convenient to have a linear region which can be used to convert the wavelength variation of the HiBi-FLM to intensity variation in the output of the LPG directly. As a result, the actual ranges used are smaller.

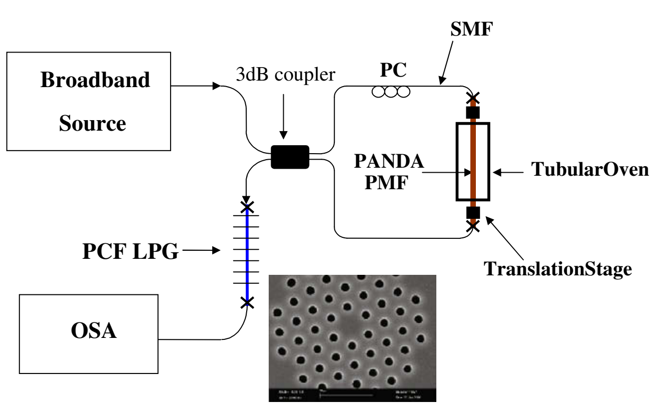

Fig. 1. Experimental setup of a FLM concatenated with a LPG in PCF. Red line, panda fiber; blue line, PCF; black line, SMF. Inset, micrograph of the PCF. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

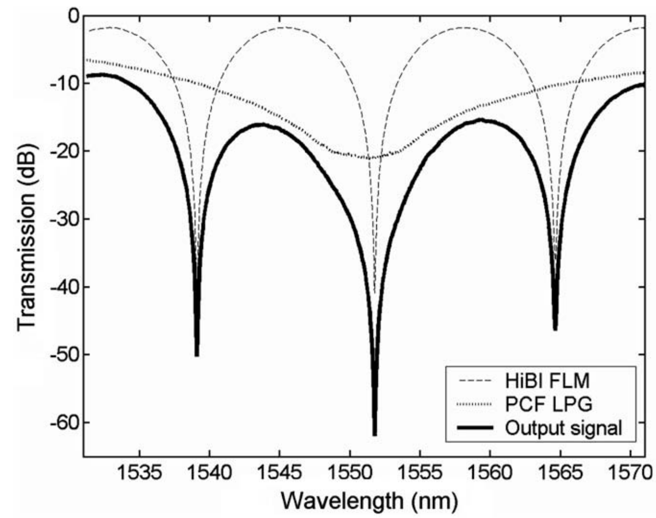

Fig. 2. Transmission spectra of the FLM and of the LPG in PCF and the output signal.

The HiBi-FLM is formed with a 3 dB coupler, a section of PANDA polarization maintaining fiber (PMF), and a polarization controller (PC). The PANDA PMF is provided by the TianJin CECT 46 Research Center of China has a core diameter ∼10 μm, a measured group birefringence of $\Delta n_g = 6.24 \times 10^{-4}$ at 1550 nm, and an attenuation of 1.0 dB/km. Both ends of the PANDA fiber are spliced to Corning SMF-28. The total insertion loss of the FLM is 2.4 dB. The length of the PANDA fiber in the FLM is about 30.5 cm (the total length for the FLM about 45 cm) and the wavelength spacing between the transmission peaks of the FLM is about 13 nm at 1545 nm. This value is determined considering that the wavelength spacing of the FLM is similar with the bandwidth of the LPG, thus by adjusting the state of the PC, we can make the two spectral peaks of the FLM be located in the middle of linear regions with opposite slopes of the LPG. Fig. 2 shows the transmission spectra of the FLM and the transmission signal after propagating through the FLM and the LPG.

In the experiment, the whole of PANDA fiber is used as a sensing element. Two ends of the PANDA fiber are attached to a fixed stage and a translation stage with a resolution of 1 μm, respectively, and placed in a tubular oven, which permits temperature resolution with as small as 0.1 °C. In some applications, a longer sensor head is not convenient. To solve this problem, we can use a part of the PANDA fiber as the sensor head or choose a HiBi fiber with a higher birefringence. The principles of sensing systems are same, but the sensitivities will decrease with the sensing length shorten.

The LPG in ESM-PCF is not subject to strain. The temperature characteristic of the LPG is tested by putting it in a temperature chamber. As shown in Fig. 3, the transmission spectrum remains stable when temperature was varied from 25 to 100 °C. The estimated sensitivity of the resonant wavelength to temperature is about 7 pm/°C. This confirmed that the stable wavelength to optical power conversion can be realized by using the temperature-insensitive LPG.

3. Experiment and results

In general, the strain and temperature information can be recovered simultaneously by a standard matrix inversion method.

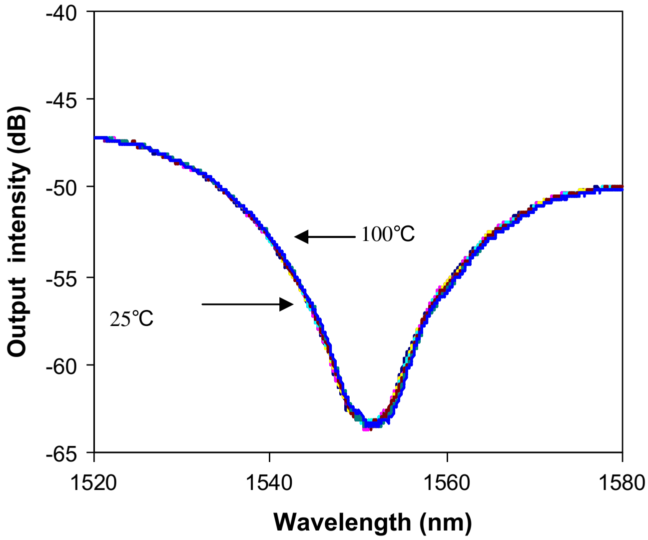

Fig. 3. The transmission spectra of the LPG in the PCF at different temperature (from 25 to 100 °C)

If two optical parameters X and Y are perturbed simultaneously by both temperature and strain, then

$$X = A\Delta T + B\Delta\varepsilon \quad (1)$$

$$Y = C\Delta T + D\Delta\varepsilon \quad (2)$$

where A, B, C and D are regarded as constant values and can be determined by measuring the temperature and strain responses separately for X and Y. The temperature and strain variations can thus be evaluated by a standard matrix inversion method [12].

Here, we utilize two parameters to resolve temperature and strain, which are the wavelength variation $P1/P2$ of the peak around 1545 nm, and the ratio signal of optical powers $P1/P2$ (unit in mW) between the peaks around 1545 and 1558 nm, respectively. $P1$ and $P2$ are gotten at the same condition since the light from the broadband passes through the same path and puts into the OSA. Thus, $P1/P2$ will reduce all of fluctuations of the sensor system because $[P1(1+a)]/[P2(1+a)]$ still equals to $P1/P2$, "a" expresses a ratio of small fluctuations. Here, $\Delta P = -\log(P1/P2)$ is used for convenient. In principle, the variation of dip wavelength around 1539 nm and the optical power ratio of the two dips around 1539 and 1565 nm can also be utilized to simultaneously measure temperature and strain. However, the optical powers at the dips are not stable because the dips have a relatively low power, and are affected easily by noises. Hence, we here utilize the peak wavelength variation and the ratio signal of optical power between two peaks. To ensure the peak wavelength accurately, we firstly mark the wavelength of three dips 1539, 1552, and 1565 nm, respectively. Then get two mean values as wavelengths of two peaks, which one is obtained from dips 1539 and 1552 nm, and another is from of dips 1552 and 1565 nm.

In experiments, the broad resonant transmission of the LPG provides us two spectral regions with opposite slopes in the wavelength range 60 nm. Utilizing this property of LPG, we choose the peaks around 1545 nm and 1558 nm of the FLM, which are at the two spectral regions of LPG, respectively, as shown in Fig. 2. When peaks of the FLM is blue-shifted, the optical power of the peak at 1545 nm increases, while the optical power of the peak at 1558 nm decreases. Utilizing the processing $P1/P2$, it effectively gives a signal that not only eliminates all power fluctuations in the system, but also doubles the sensitivity of the sensor system to the parameter variation.

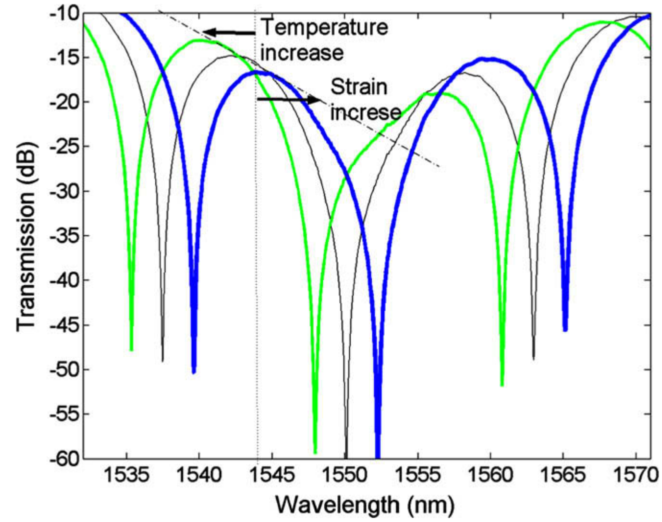

Fig. 4. Output spectra of the system, when strain or temperature is applied to the sensing head.

Fig. 4 shows the spectral response of the sensor system when strain or temperature variation is applied. It can be seen that the peak wavelength increases when strain is increased, because the optical path length increases with stretching axially. While the power differential ΔP decreases with the applied strain. On the other hand, when temperature is increased, the peak wavelength decreases and ΔP increases. The wavelength behavior can be explained by thermally induces refractive-index change and thermal expansion of the HiBi fiber. Utilizing different sensitivities of $\Delta\lambda$, ΔP to $\Delta\varepsilon$ and ΔT, we can recover $\Delta\varepsilon$ and ΔT applied on the sensor.

Fig. 5 shows the strain response for constant temperature. A linear fitting to the experimental data gives a wavelength sensitivity to strain 36 pm/με. The power ratio also varies linearly with the applied strain. The sensitivity of the ratio signal to strain is −0.089 dB/με. In Fig. 6, the temperature response is shown for a constant strain. A high wavelength temperature sensitivity of −0.76 nm/°C has been achieved. The sensitivity of the ratio signal to temperature is high as 1.583 dB/°C.

From Eqs. (1) and (2), the experimental results allow us to write two equations for $\Delta\lambda$ and ΔP as:

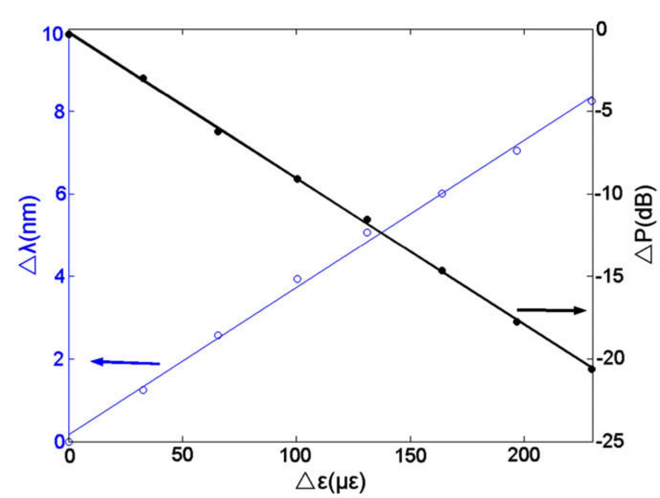

Fig. 5. Strain response of the system using a HiBi-FLM concatenated with a LPG in PCF.

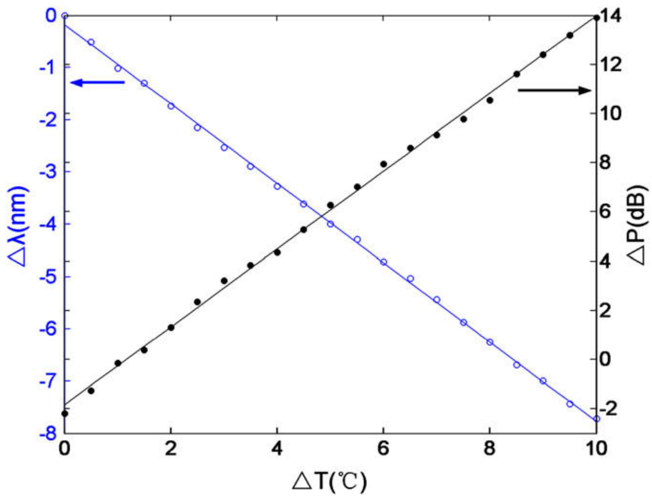

Fig. 6. Temperature response of the system using a HiBi-FLM concatenated with a LPG in PCF.

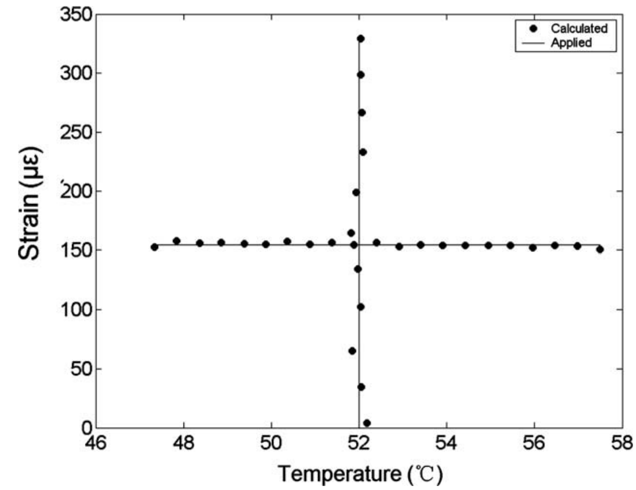

Fig. 7. The output signal of the system with applied strain and temperature.

$$\Delta\lambda = -0.76\Delta T + 0.036\Delta\varepsilon \quad (3)$$
$$\Delta P = 1.583\Delta T - 0.089\Delta\varepsilon \quad (4)$$

Thus, we can get two equations for ΔT and $\Delta\varepsilon$, resulting in

$$\Delta T = -8.27\Delta\lambda - 3.34\Delta P \quad (5)$$
$$\Delta\varepsilon = -147.94\Delta\lambda - 70.98\Delta P \quad (6)$$

with $\Delta\lambda$, ΔP, ΔT, and $\Delta\varepsilon$ are, respectively, in nanometers (nm), in decibels (dB), in degrees centigrade (°C) and in microstrain (με). Resolutions of the sensing system are limited by the resolution of OSA. In experiment, we used the OSA with a spectral resolution 0.02 nm. When the resonant wavelength of the FLM caused by the applied stain or temperature shifts 1 nm, the change of the power ratio of two peaks is ~2.4 dB, gotten from Figs. 5 and 6. Thus in our experimental condition, we achieve a strain resolution of ~6.2 με and temperature resolution of 0.31 °C.

The capability of system for simultaneously strain and temperature measurement has also been evaluated and shown in Fig. 7. First, we experimentally measured a serial data of strains applied on the sensing fiber in a range of 0–330 με at a fixed temperature of 52 °C. The second serial data are measured when the temperature applied on the sensing fiber varies from 47.3 to 57.5 °C and the strain applied is fixed at 155 με. The calculated strain and temperature are marked as black circles in Fig. 7. From those two serials data, we can get the maximum errors between the measured values using our sensor and the applied values are ±8.9 με and ±0.32 °C for strain and temperature respectively, which is accordant to the resolutions. The errors are smaller than the results ±21 με and ±1.1 °C in Ref. [6].

4. Conclusion

In conclusion, we have proposed and experimentally demonstrated a novel design for simultaneous measurement of strain and temperature. The sensor setup with a FLM concatenated with a temperature-insensitive LPG in PCF. Only PANDA fiber in the FLM acts as a sensor head for monitoring the strain and temperature change, while the LPG in PCF serves as a stable wavelength to optical power converter. By choosing a suitable length of the PANDA fiber, we realize two adjacent peaks of the FLM to be located respectively within two transmission spectral regions with opposite slopes of the LPG. When we monitor the optical power difference between two peaks, the sensitivity of the sensing system is doubled, and the optical power fluctuation of the light source is eliminated effectively. Experimental results show that the sensing system can discriminate strain and temperature with a high resolution of ±8.9 με and ±0.32 °C. The sensor is simple and easy to manufacture.

Acknowledgments

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