Optics Communications 284 (2011) 2145–2148

Contents lists available at ScienceDirect

Optics Communications

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

Simultaneous measurement of strain and temperature with a long-period fiber grating inscribed Sagnac interferometer

Juan Kang [a,b,*], Xinyong Dong [a], Chunliu Zhao [a], Wenwen Qian [a], Mengchao Li [b]

[a] Institute of Optoelectronic Technology, China Jiliang University, Hangzhou Zhejiang 310018, China
[b] School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

ARTICLE INFO

Article history:
Received 31 October 2010
Received in revised form 31 December 2010
Accepted 4 January 2011
Available online 15 January 2011

Keywords:
Sagnac interferometer
Strain and temperature measurements
Polarization maintains fiber
Long-period fiber grating

ABSTRACT

A Sagnac interferometer with a long-period fiber grating (LPG) inscribed in the polarization-maintaining fiber (PMF) is proposed and experimentally demonstrated for simultaneous measurement of strain and temperature. Due to the different responses of the LPG and the Sagnac interferometer to strain and temperature, simultaneous measurement can be achieved by monitoring the wavelength shifts and the intensity changes of a resonance dip of the sensor setup. The experimental results show that the achieved sensitivities to strain and temperature are 6.4×10^{-3} dB/με and 0.65 nm/°C, respectively.

1. Introduction

Sagnac interferometers based on polarization-maintaining fibers (PMFs) or highly birefringent (Hi-Bi) fiber have been reported in temperature, strain, liquid level and displacement measurement [1–4]. The previous studies showed that temperature sensors based on Sagnac interferometer have a higher sensitivity than that of a long-period fiber grating (LPG) by about two orders [4,6]. The strain sensors based on Sagnac interferometers or LPGs and FBGs have also been proposed and characterized [5]. These sensors possess lots of advantages including easy manufacturing, simple design, and high sensitivity. However, these previously reported Sagnac interferometer sensors cannot measure multiple parameters simultaneously with high sensitivity and low cost. By inserting a LPG into the fiber loop of a PMF-based Sagnac interferometer, simultaneous measurement of temperature and strain has been reported [2,3]. But the sensor head, constructed by combining two fiber sections, a conventional single-mode fiber including the LPG and the PMF [2,3], shows disadvantages of large size, high cost, and discommodious operation.

In this work, a fiber-optic strain and temperature sensor is proposed, which is composed of a Sagnac interferometer with LPG inscribed in polarization-maintaining fiber (PM-LPG). The sensor was experimentally demonstrated to measure strain and temperature simultaneously. LPG inscribed in PMF was fabricated by CO_2 laser, and two resonance wavelengths were observed duo to the birefringence in the PMF. Then one of the resonance dips in transmission spectra was monitored. We found that its intensity changed with applied strain and its wavelength varied with temperature change. A matrix equation is used for demodulation of simultaneous strain and temperature measurements.

2. Principle

The experiment setup of the proposed Sagnac interferometer is shown in Fig. 1. It consists of a broadband light source, a 3 dB fiber coupler with conventional SMF and a piece of PMF, on which a LPG was inscribed by a CO_2 laser using the point-to-point method with a period $\wedge = 480$ um and length $L_{LPG} = 24$ mm. The 3 dB coupler equally splits the input optical light power into two counter-propagating waves. A polarization control (PC) is used to adjust the polarization states of the two waves. The two counter-propagating waves were then recombined at the 3 dB fiber coupler to interference with each other. The output spectrum was recorded with an optical spectrum analyzer (OAS) with a resolution of 0.01 nm. The periodicity transmission output spectrum of Sagnac interferometer was modulated by transmission spectrum of LPG, as is shown in Fig. 2.

The solid line in Fig. 2 represents the transmission spectrum of the fiber Sagnac interferometer, and was modulated by the dash line from the transmission spectrum of PM-LPG. The fiber Sagnac interferometer acts like a multi-centre bandpass filter. The PM-LPG appears two resonance wavelengths Dip-A (1548.125 nm) and Dip-C (1579.625 nm), which represents two polarization state of PMF. The length of the PMF with the modal birefringence of 5×10^{-4} at 1550 nm was about $L_{PMF} = 1.4$ m. The following equation is used to estimate the wavelength spacing between two neighboring minima (or maxima) in the transmission spectrum, $\Delta\lambda = \lambda^2/BL$, where B is the modal

* Corresponding author. Institute of Optoelectronic Technology, China Jiliang University, Hangzhou Zhejiang 310018, China.
E-mail address: kjuan@hotmail.com (J. Kang).

0030-4018/$ – see front matter
doi:10.1016/j.optcom.2011.01.002

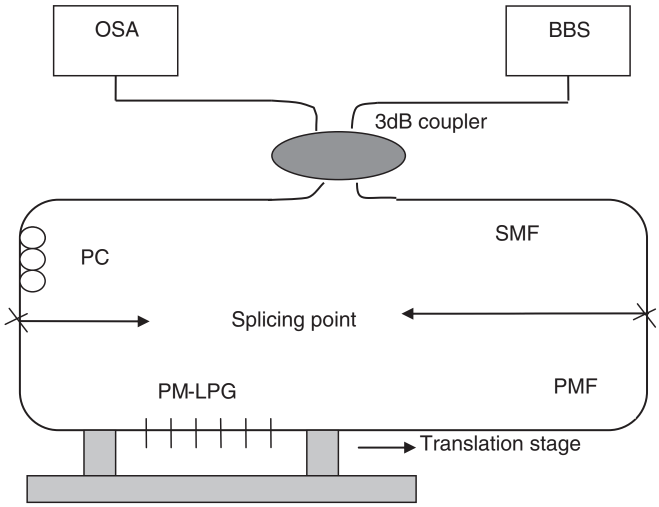

Fig. 1. Schematic of the proposed Sagnac interferometer sensor.

birefringence, L is the length of the PMF, and λ is the operating wavelength. The calculated value is 3.432 nm, which is quite close to the experimental result, 3.4 nm. The two resonance dips of the Sagnac interferometer of Dip-A2 (1548.025) and Dip-B (1560.35 nm) were chosen for simultaneous measurement of strain and temperature by measuring the intensity changes and the wavelength shifts, respectively.

When strain was applied to the PM-LPG under certain temperature, the transmission spectrum of the PM-LPG is shifted and resulted in the intensity changing at Dip-A2. It was also found that intensity at Dip-A2 changed with the applied strain Δε and the temperature Δn, which can be expressed as

$$\Delta P = K_{11}\Delta\varepsilon + K_{12}\Delta T \qquad (1)$$

where K_{11} is intensity sensitivity of strain with the unit of dB/με, and K_{12} is intensity sensitivity of temperature with the unit of dB/°C.

When temperature was changed around the PM-LPG under certain applied strain, transmission spectrum of both the Sagnac interferometer and PM-LPG were shifted. It had been reported that temperature sensor based on Sagnac interferometer may have a high sensitivity about one and two orders magnitude higher than that of a long-period fiber grating and fiber Bragg grating sensors [6–9]. So the wavelength of Dip-B was selected for temperature measurement. The wavelength shifts at Dip-B with the variation of temperature Δn and the applied strain Δε can be given by

$$\Delta\lambda = K_{21}\Delta\varepsilon + K_{22}\Delta T \qquad (2)$$

where K_{21} is wavelength sensitivity of strain with the unit of nm/με, K_{12} is wavelength sensitivity of temperature with the unit of nm/°C.

Because periodicity transmission spectrum of Sagnac interferometer was modulated by PM-LPG and the PMF ($L_{PMF}=1.4$ m) was longer than PM-LPG ($L_{LPG}=24$ mm), the applied strain ($\varepsilon=\Delta L/(L_{PMF}\times L_{LPG})\approx 0$) has no contribution to the wavelength shift at Dip-B, which means K_{21} equaling zero. According to Eqs. (1) and (2), matrix Equation of measured strain and temperature can be expressed as:

$$\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix} = \begin{bmatrix}K_{11} & K_{12}\\ K_{21} & K_{22}\end{bmatrix}^{-1}\cdot\begin{bmatrix}\Delta P\\ \Delta\lambda\end{bmatrix} = \begin{bmatrix}K_{11} & K_{12}\\ 0 & K_{22}\end{bmatrix}^{-1}\cdot\begin{bmatrix}\Delta P\\ \Delta\lambda\end{bmatrix} \qquad (3)$$

In experiments, the measured strain and temperature of Sagnac interferometer can be calculated by Eq. (3) through monitoring the intensity variation of Dip-A2 and the wavelength shift of Dip-B, respectively.

3. Experimental results

In experiments, we fixed one end of the PM-LPG and stretched the other end by using a translation stage. Fig. 3 shows several transmission spectra of the Sagnac interferometer around the transmission minimum at Dip-A2 (1548.025) under different applied strains. The intensity at Dip-A2 varied 26.08 dB to the smaller value direction when the strain was increased from 10 g to 50 g. The applied strain was transferred to unit strain from 1.1 mε to 5.5 mε with following equation, $F=E\cdot A\cdot\varepsilon$, where $E\approx 7.27\times 10^{10}\mathrm{N/m^2}$ means Young modulus [10], A is cross area of fiber. The experimental data are shown in Fig. 4. The linear fitting to the experimental data gives intensity-strain sensitivity at Dip-A2 of 0.58 dB/g ($K_{11}=6.4\times 10^{-3}$dB/με) and a high R^2 value of 0.995, which means that the linearity of the intensity to strain response is good. The experimental

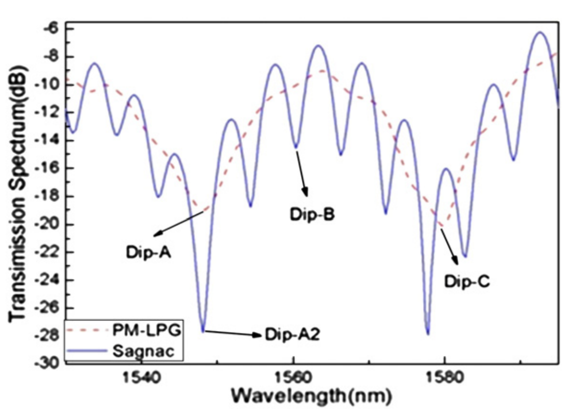

Fig. 2. Transmission spectra of the PM-LPG (dash line) and the Sagnac interferometer sensor (solid line).

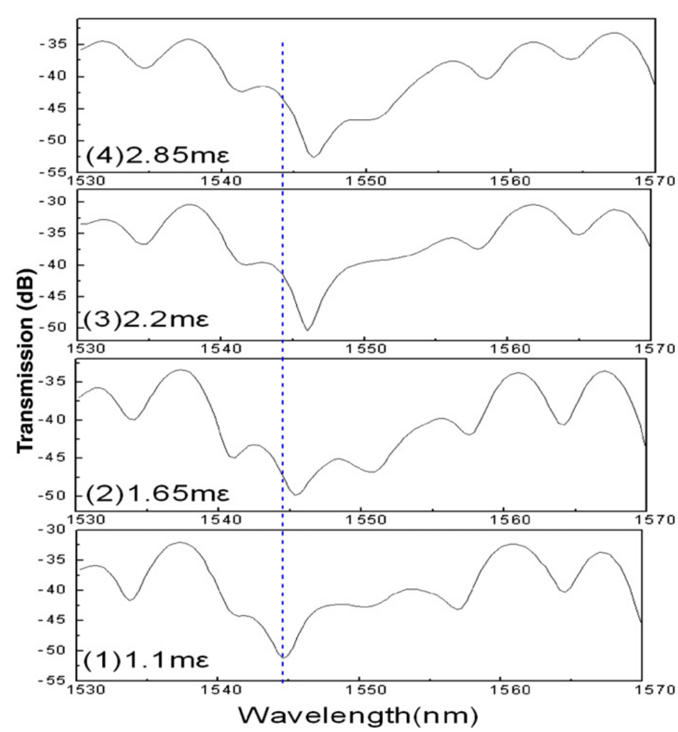

Fig. 3. Measured transmission spectra under different applied strain.

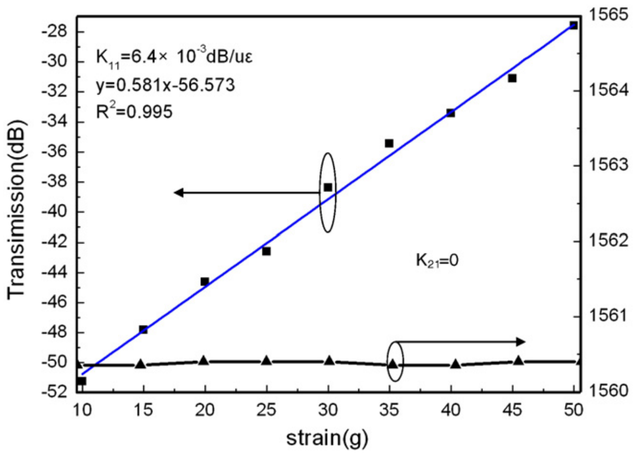

Fig. 4. Intensity of Dip-A2 under different applied strain.

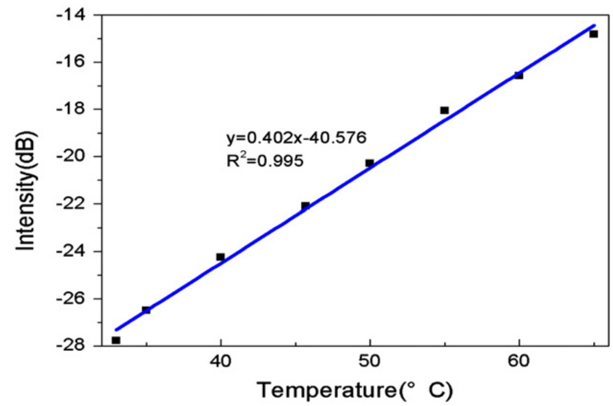

Fig. 6. Intensity of Dip-A2 under different temperature.

data also show a wavelength-strain sensitivity at Dip-B of $K_{21}=0$, which agrees well with the theoretical prediction.

The temperature test was performed in a temperature-controlled container. The transmission minimum at Dip-B (1560.35) was shifted to the shorter wavelengths by 24.3 nm when the temperature was increased from 33 °C to 70 °C. The measured results are shown in Fig. 5, where the solid dots are the measured values and the real line represents the fitting values. The temperature sensitivity of Dip-B is $K_{22}=-0.65$ nm/°C and a R^2 value of 0.998, which is much higher (about 11 times) than the previously reported value of 0.058 nm/°C in a single mode fiber LPG temperature sensor [6]. The temperature sensitivity is in good agreement with the previously reported value in Ref. [3], where the Sagnac interferometer was only composed of PMF. The intensity sensitivity of wavelength at Dip-A2 was calculated at the same time with K_{12} of 0.402 dB/°C and R^2 of 0.995, as shown in Fig. 6. The measured results have good repeatability.

Substituting the sensitivity coefficients into Eq. (3), the matrix equation of PM-LPG inscribed Sagnac interferometer for simultaneous strain and temperature can be rewritten as

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} 6.4\times10^{-3} & 0.402 \\ 0 & -0.654 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta P \\ \Delta\lambda \end{bmatrix} \tag{4}$$

With this equation, both strain and temperature can be calculated from the measurement results of the intensity at Dip-A2 and wavelength shift at Dip-B, even when the both parameters are changed simultaneously. Actually, all the dips have the same wavelength shifts. Thus, for wavelength shift measurements, we can choose other dips if the extinction coefficient of Dip-B is not enough high. Further experiments were performed to verify Eq. (4) by changing the applied strain and temperature simultaneously. The calculation results from the experimental data showed good agreement with the values of applied strain and temperature. For optical power fluctuations not induced by the measurands, e.g. light source power change, the light source power changes in this report were quite small, only 1% within 2 h. And a more accurate measurement can be obtained by monitoring the light power change. A small portion of power can be split from the light source as the reference to correct the dip intensity changes.

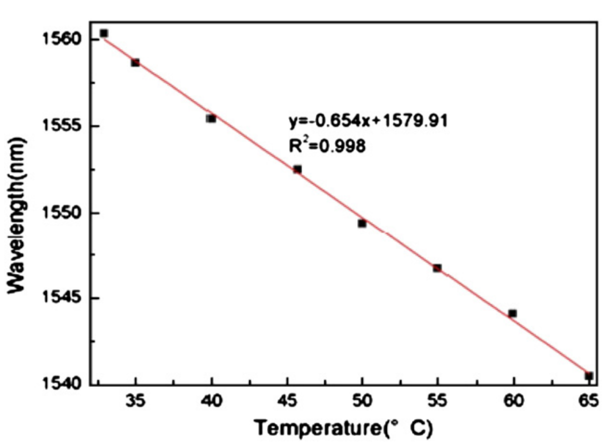

Fig. 5. Wavelength shift of Dip-B under different temperature.

4. Conclusion

A sensing head based on a PM-LPG inscribed Sagnac interferometer was reported for simultaneous measurements of strain and temperature. The PM-LPG was fabricated by CO_2 laser with point-to-point method. The measurement matrix equation was derived and the sensor setup with a strain-sensitivity of 6.4×10^{-3} dB/με and a temperature-sensitivity of 0.65 nm/°C were demonstrated. This configuration setup allows different kinds of multi-parameter measurements through tailoring the LPG characteristics. The sensitivity of intensity-strain can also be improved through tailoring the transmission spectrum of PMF-LPG. Compared with the conventional PMF based Sagnac interferometer sensors and FBG or LPG sensors, this sensor is capable of multi-parameter measurements. And it is also simple, easy to manufacture, potentially low cost.

Acknowledgments

This work was supported by a grant from the Major State Basic Research Development Program of China (973 Program) (Project no. 2010CB327804), Public Grant of Zhejiang Province China (2010C33056) and Technology Department of Zhejiang Province China (2009C11049).

References

[1] Xinyong Dong, H.Y. Tam, Applied Physics Letters 90 (2007) 151113.
[2] O. Frazão, S.O. Silva, J.M. Baptista, J.L. Santos, G. Statkiewicz-Barabach, W. Urbanczyk, J. Wojcik, Applied Optics 47 (27) (2008) 4841.
[3] O. Frazão, L.M. Marques, S. Santos, J.M. Baptista, J.L. Santos, IEEE Photonics Technology Letters 18 (22) (2006) 2407.
[4] Y. Liu, B. Liu, X. Feng, W. Zhang, G. Zhou, S. Yuan, G. Kai, X. Dong, Applied Optics 44 (12) (2005) 2382.
[5] C. Caucheteur, F. Lhomme, K. Chah, M. Blondel, P. Megret, Optics and Lasers in Engineering 44 (2006) 411.

[6] Hu. Xing-liu, Liang Da-kai, Lu. Guan, Zeng Jie, Spectroscopy and Spectral Analysis 30 (3) (2010) 851.
[7] V. Bhatia, D. Campbell, R.O. Glaus, Optics Letters 22 (9) (1997) 648.
[8] G. Rego, P.V.S. Marques, H.M. Salgado, J.L. Santos, Electronics Letters 41 (2) (2005) 60.
[9] B. Guan, H. Tam, X. Tao, X. Dong, IEEE Photonics Technology Letters 12 (6) (2000) 675.
[10] Bai-Ou Guan, Hwa-Yaw Tam, Shun-Yee Liu, IEEE Photonics Technology Letters 16 (1) (2004) 224.