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Jie Huang
Missouri University of Science and Technology, jieh@mst.edu

Xinwei Lan

Amardeep Kaur
Missouri University of Science and Technology, kaura@mst.edu

Haining Wang

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/ele_comeng_facwork/3257

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Reflection-based phase-shifted long period fiber grating for simultaneous measurement of temperature and refractive index

Jie Huang
Xinwei Lan
Amardeep Kaur
Hanzheng Wang
Lei Yuan
Hai Xiao
Missouri University of Science and Technology
Department of Electrical and Computer Engineering
Rolla, Missouri 65409
E-mail: xiaoha@mst.edu

Abstract. We report a reflection-based phase-shifted long period fiber grating (PS-LPFG) and demonstrate its capability for simultaneous measurement of temperature and external reflective index (RI). The sensor device comprises a grating directly written by CO_2 laser and silver-coated end face. A π-shifted LPFG is presented with two attenuation bands through its reflection spectrum. These two bands have different sensitivity towards temperature and external RI that can be used for simultaneous measurement of the two variables. The experimental results show that this probe-type PS-LPFG performs well in terms of linearity and sensitivity. [DOI: 10.1117/1.OE.52.1.014404]

Subject terms: phase-shifted long period fiber grating; simultaneous measurement; temperature; refractive index.

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1 Introduction

Precise and *in situ* monitoring of liquid refractive index (RI) is of great importance in many chemical and biological applications[1]; however, the temperature cross-sensitivity usually leads to an unreliable result. To reduce or compensate the temperature fluctuation influences, it is essential that the temperature and external RI be detected simultaneously, especially in real-time systems. Fiber-integrated optics have enabled better sensing technology for temperature and RI because of the compact size, high sensitivity, multiplexing capability, and *in situ* monitoring capability. In recent years, various fiber-optic structures have been proposed and demonstrated for simultaneous measurement of temperature and external RI, such as sampled fiber Bragg grating (FBG),[2] slanted multimode FBG[3] and dual long period fiber grating (LPFG),[4] etc.

LPFG is a good candidate for temperature and RI monitoring because of its high sensitivity; but it might be difficult to use because of its transmission structure. Traditional LPFG works in the transmission mode, making it very sensitive to bending. Bending could induce a large and sometimes unpredictable change in the optical path difference that could make it difficult to interpret the sensor signal. The most prominent issue of the transmission structure is crosstalk, due to axial strain while measuring RI or temperature, because a certain amount of initial strain needs to be applied to make sure that the grating is properly placed. Hence, a probe-type configuration is needed to eliminate the crosstalk. The reflection-based optical fiber probe can be easily immersed into the test liquid and is more robust. Not much work has been focused on using the reflection-based fiber sensor to monitor two parameters simultaneously so far.

For simultaneous measurement of temperature and external RI, a phase-shifted long period fiber grating (PS-LPFG) has been used. The PS-LPFG, first proposed by Ke,[5] typically is fabricated by changing the amplitude of index modulation or the length between the two adjacent grating sections to induce a phase shift. Several attenuation bands are generated in the transmission spectrum, and this pattern has been used for gain flattening fiber filters.[6] Considering that different attenuation bands have different sensitivities towards the temperature and RI, it could potentially be used for multiparameter monitoring.

In this letter, the CO_2 laser (SYNRAD, Firestar v20) was used to inscribe the reflection-based PS-LPFG on a standard single mode fiber (SMF) (Corning SMF-28) using point-by-point irradiation technique. Compared with the UV inscription technique, the CO_2 laser point-by-point irradiation technique is more flexible and cost-effective since no photosensitive fibers and phase masks are required.[7,8] The reflection-based PS-LPFGs have been successfully used for simultaneous measurement of temperature and RI in the work presented here. The new device can work as a multiparameter sensor with the unique advantages of robustness, operating in the reflection mode and insensitivity to bending.

2 Experiments and Discussions

As shown in Fig. 1, the sensing part comprises a grating section with grating period of 312 μm (LP08 mode) and a mirror on the fiber end face at a quarter-period separation distance from the grating end. The quarter grating period will behave as a half grating period because of the effective path taken by the travelling light; going through the grating, reflecting back from the mirror and going through the grating again. Two gratings (on the same fiber with the same period) with a half period separation will induce a π-shifted LPFG.[5] The output power of CO_2 laser for fabricating the LPFG was 7.5 W. The grating was 62 points long and the 63rd point was marked using a higher power laser pulse (10 W) to make it visible. The end of the fiber was cleaved at the visible mark using a homemade cleaving system with an online

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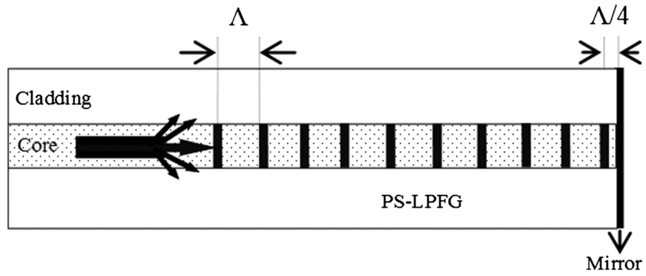

Fig. 1 Schematic of the proposed sensor (light split into cladding modes in LPFG section).

monitoring device and then polished while monitoring the reflection spectrum. The end-face was polished until two resonant dips appeared and had almost equal attenuation strength. The end face was coated with silver using a sputtering machine (Denton Vacuum, DESK V). Before coating, the sensing region was inserted into a tube to ensure the mirror formation on the end face of the fiber and to protect sides of the fiber from being polished. Thus, a reflection-based π-shifted LPFG was fabricated. The total length of the sensing region was about 18.5 mm.

According to the analysis of PS-LPFG using F-Matrix,[5] the destructive mode coupling is converted to the constructive mode coupling, and one grating resonance will be split into two or more resonances based on the number of phase shift sections and the length of grating part. In this experiment, a π-shifted LPFG was inscribed by a half period separation part between two identical gratings. When the phase shift is equal to an integral multiple of π (in this case, a half period represents one π shift), the spectral response becomes symmetrical.

During the experiment, the light emitting from a broadband source (Agilent 83437A, in the wavelength range of 1300–1700 nm) propagates through a 2×1 (3 dB) coupler and the sensor part. The reflection spectrum is monitored by an Optical Spectrum Analyzer (OSA AQ 6319) with a resolution of 50 pm. Figure 2 shows the spectrum of the reflection-based PS-LPFG. The center wavelengths of the two resonant dips are 1475.50 nm and 1519.55 nm, respectively. The grating strength of each dip is about 20.60 dB and 20.43 dB, respectively. The full wave at half maximum (FWHM) of each dip are 5.9 and 6.1 nm, respectively. These two dips are not identical because the polishing process cannot ideally control the polished length. In other words, the phase shift is not a precisely controlled π in the experiment, and that will induce an asymmetrical spectral response. We know the equation for the phase shift value is $\Delta\phi = 2\pi L_s/\Lambda$, where $\Delta\phi$ is the desired phase shifted value in radian, L_s is the separation length between the two adjacent gratings, Λ is the grating period. In this case, the value of L_s will be doubled as compared with the transmission structure because of the back and forth of the light path. Thus, a 10 μm length error will lead to a 0.128π phase shift error.

In case the environmental temperature rises, both the effective RIs of the cladding mode and core mode increase. However, the RI of the core mode will change more than the cladding mode because the thermo-coefficient of the Ge-doped silica core is larger than that of the cladding. The thermal-induced fringe shift of the reflection-based PSLPFG can be approximated as

$$\frac{\Delta\lambda}{\lambda} = \left[\left(\frac{1}{\Delta n_{\mathrm{eff},i}}\right)\left(\frac{\partial \Delta n_{\mathrm{eff},i}}{\partial T}\right) + \mathrm{CTE}\right]\Delta T, \tag{1}$$

where $\Delta n_{\mathrm{eff},i}$ is the sum of changes of effective RI of the core and the ith-order cladding mode. The coefficient of thermal expansion (CTE) is about $0.55 \times 10^{-6}/°\mathrm{C}$. Consequently, the wavelength of the attenuation peak will induce a red shift as the environmental temperature increasing. The temperature sensitivity of the reflection-based PS-LPFG depends on the cladding mode order, as well as different resonant wavelengths, because the effective RI of the cladding mode is also related to the wavelength. Hence, we could assume that these two resonant dips have different a sensitivity with respect to the ambient temperature.

For the temperature measurement, the sensor probe was placed into an oven (Yamato, DX300) and the reflection spectrum was measured as the oven temperature increased from 30°C to 100°C in steps of 10°C. Asbestos and a quartz tube were applied to decrease the air flow effect and keep the environmental temperature stable. Figure 3 shows the temperature response of the reflection-based PS-LPFG. The red

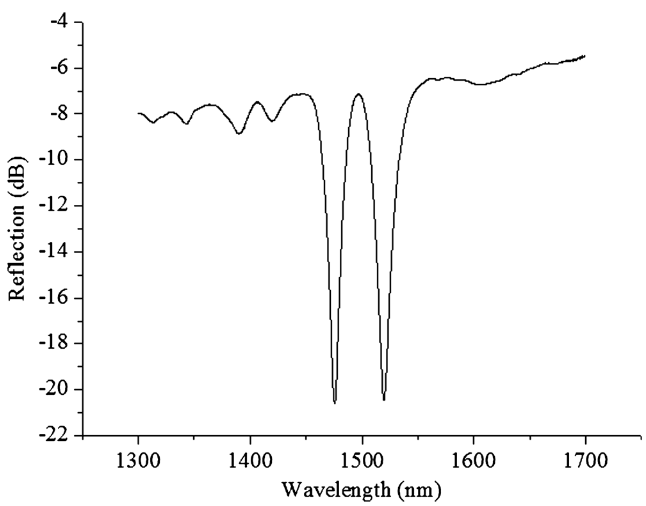

Fig. 2 Spectrum of a reflection-based PSLPFG.

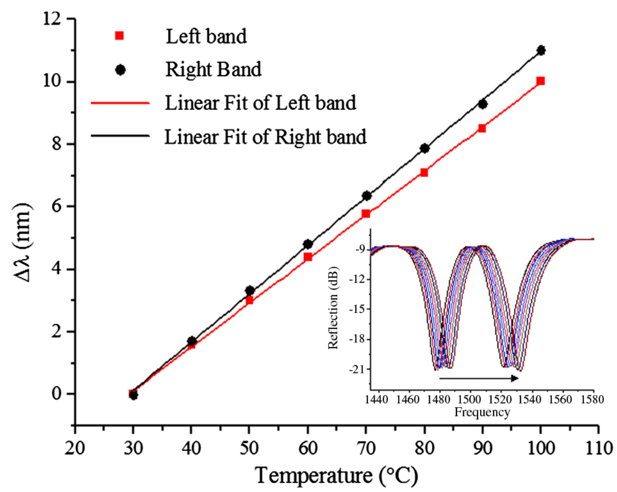

Fig. 3 Temperature responses of the reflection-based PS-LPFG.

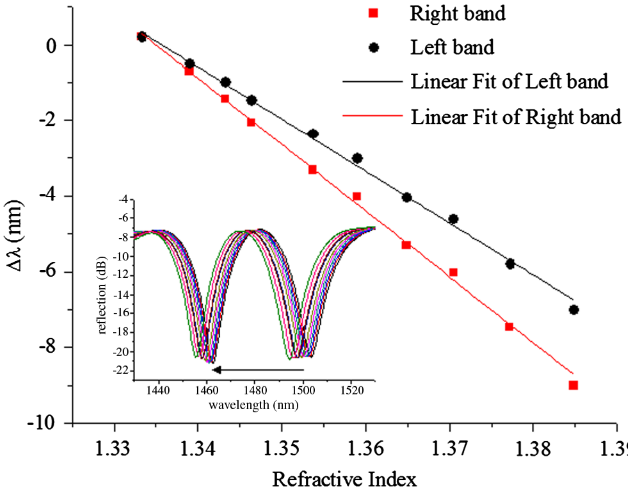

Fig. 4 RI responses of the reflection-based PS-LPFG

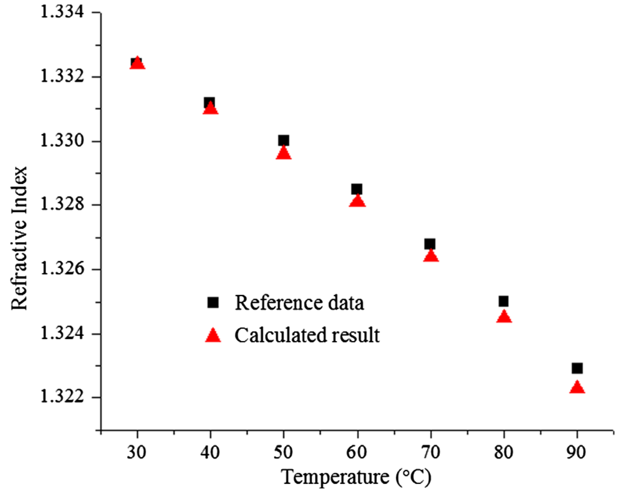

Fig. 5 Comparison between calculated data and reference data.

line and black line represent the linear fit of the normalized wavelength shift in the left and right attenuation dips, respectively. The experimental result shows that the temperature response is nearly linear in terms of wavelength shift in both attenuation bands. The right band with a slope of 0.155 nm/°C is obviously more sensitive than the left band (0.141 nm/°C).

For external RI measurement, the sensor probe was directly immerged into the sucrose solution. Ten cups of the sucrose solution with different concentrations were prepared [0.0, 4.090, 7.039, 9.142, 13.877, 17.197, 20.760, 24.084, 27.878, and 32.101 (unit: percentage)]. The corresponding RIs are 1.3333, 1.3390, 1.3433, 1.3464, 1.3537, 1.3590, 1.3649, 1.3705, 1.3772, and 1.3848, respectively.[9] A careful clean and dry process (using deionized water) was done after each measurement to remove the crosstalk of different solutions. The measured and normalized external RI response of PS-LPFG was shown in Fig. 4. The red line and black line stand for the normalized linear fit of the right and left attenuation bands, respectively. The two lines are relatively linear in that RI range. The right band has a slope of −174.8 nm/RIU, which is relatively higher than that of the left band (−137.1 nm/RIU).

For the different sensitivities of the two attenuation bands to temperature and RI, we could define a characteristic matrix $M_{T,\mathrm{RI}}$ to represent the sensing performance of the PS-LPFG,

$$\begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} = M_{T,\mathrm{RI}} \begin{bmatrix} \Delta T \\ \Delta n \end{bmatrix} = \begin{bmatrix} 0.155 & -174.8 \\ 0.141 & -137.1 \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta n \end{bmatrix}. \quad (2)$$

The characteristic matrix could be used for simultaneous measurement of temperature and external RI from the wavelength shifts of the two resonant dips. In this case, the temperature should be limited within 1.0°C if the measurement range of RI is about 0.02. To demonstrate the capability and measurement accuracy of this method, we measured the change in RIs of the deionized water as a function of ambient temperature, as shown in Fig. 5. The red dots represent calculated results through the characteristic matrix of the sensor; the black dots are reference data for comparison.[10] As shown in Fig. 5, the calculated results agreed well with the reference data in terms of trend of changing in RI as temperature increased. As a result, the proposed sensor can be used for simultaneous measurement of temperature and RI after proper calibration.

3 Conclusion

In summary, we proposed and demonstrated an in-fiber single probe using a PS-LPFG for simultaneous measurement of temperature and external RI. This type of sensor is easily immerged into liquid and is more compact and robust to operate; plus, the axial strain or bending crosstalk is eliminated automatically. The proposed device is simple to fabricate, potentially low-cost, mechanically robust and miniaturized in size, which makes it very attractive for a refractive-index sensing probe with temperature compensation. The possibility to yield more dips in the spectrum offers opportunities for simultaneous multiparameter detection.

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Jie Huang is currently a PhD candidate at Missouri University of Science and Technology. He received his BS and MS in opto-electronics engineering and electrical engineering from Tianjin University and Missouri University of Science and Technology in 2009 and 2012, respectively. His research has focused mainly on the combination of microwave and optics and the development of fiber optic/coaxial cable based sensors. He was awarded a one-year graduate fellowship by IEEE Instrumentation & Measurement Society in 2012. Jie is student members of OSA, IEEE, SPIE, and a member of IEEE-Instrumentation and Measurement Society (IMS) and ISA.

Xinwei Lan is a PhD student in Hai Xiao's group in the Electrical Engineering Department at Missouri University of Science and Technology. His research is focused on developing optical fiber-based devices and instrumentation for chemical, biological and harsh environmental sensing applications. He is a member of OSA, SPIE, and IEEE.

Amardeep Kaur received her MS in electrical engineering from Missouri University of Science and Technology at Rolla in 2009, where he is currently working towards a PhD in electrical engineering. She is a research assistant with the Photonics Technology Lab (PTL) headed by Dr. Hai Xiao. Her research interests include femto-second laser fabrication, harsh environment sensing, optical fiber-assisted structural health monitoring, and optical fiber-based sensing in general.

Hanzheng Wang is a PhD candidate in Electrical & Computer Engineering Department at Missouri University of Science & Technology, where he received his MS in electrical engineering in 2009. Since 2010 he has worked as a graduate research assistant with the S&T Photonics Technology Lab. His research projects include fiber optics and optical microresonator-based chemical, temperature sensors. He is a member of SPIE, OSA and ISA.

Lei Yuan is a joint PhD candidate in School of Mechanical Engineering from Beijing Institute of Technology. He has worked on micro-structure fabrication by using femto-second laser and micro resonator optical sensors with Missouri University of Science & Technology PTL group since 2011.

Hai Xiao has been a professor of electrical engineering at Missouri University of Science & Technology since 2006. He received his PhD in electrical engineering from Virginia Polytechnic Institute and State University in Blacksburg, Virginia, in 2000. Prior to that, he was an assistant professor of electrical engineering at New Mexico Institute of Mining and Technology, worked at the Optoelectronic Center of Lucent Technologies/Agere Systems in Breinigsville, Pennsylvania, and was a senior research associate at the Center for Photonics Technology of the Bradley Department of Electrical and Computer Engineering at Virginia Tech. His research interests include functional integration of nanomaterials with photonic devices to develop microphotonic sensors for applications in defense, energy, environmental, and biomedical areas; fiber optic sensors for applications in harsh environments; characterization and modeling of optical properties of nanomaterials and nanostructures; and medical imaging.