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Regular Articles

A cascade structure made by two types of gratings for simultaneous measurement of temperature and strain

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ABSTRACT

In this paper, a new cascade structure is presented to measure temperature and strain simultaneously. It is made of a CO_2-laser-notched long-period fiber grating (CO_2-LFPG) and a modular LFPG. Experiments prove that the temperature sensitivity of the modular LPFG is about 5 times lower than that of the CO_2-LFPG. Before and after connecting the modular LPFG and the CO_2-LPFG together, the experimental results indicate that the temperature and the strain sensitivities of them almost have no change and are retained. The temperature and the strain sensitivities of modular LPFG (resonance wavelength at 1258 nm) are −15.4 pm/°C and −1.2 pm/με, respectively. And the temperature and the strain sensitivities of CO_2-LPFG (resonance wavelength at 1356 nm) are 58.3 pm/°C and −0.5 pm/με, respectively. Through the experiments, the feasibility of using the proposed sensor to measure strain and temperature simultaneously has been verified. Therefore, it is strongly believed that the proposed sensor can be used to achieve simultaneous measurement of strain and temperature.

1. Introduction

Long-period fiber grating has attracted much attention in the field of optical research in recent years because of its many unique advantages. It was first developed by Vengsakar et al. in 1996 [1]. With its deep research, LPFGs are widely used to measure the sensitivities of temperature, strain, bend, refractive index, etc. [2–5]. LPFGs can be manufactured in many ways such as low-frequency CO_2 laser radiation [6], femtosecond laser radiation [7], periodically tapering [8], periodically splicing [9], and electric arc discharge method [10]. The sensors made by different ways have favorable features in some sensing characteristics. For instance, the alternately splicing multiple single/multimode structure can measure curvature accurately on the all direction [9], and the pre-twisted LPFG can measure torsion and determine rotation direction [11]. However, a single LPFG is discommodious to measure two or even several parameters simultaneously sometimes. Therefore, concatenating two different structures of LPFGs is feasible to finish simultaneous measurement of two parameters. As a result, several optical fiber sensors have been proposed by connecting various types of structures. For example, a hybrid structure of a LPFG and a S fiber taper Mach-Zehnder interferometer was once used to complete the simultaneous measurement of temperature and refractive index [12]. And simultaneous measurements of temperature and strain can be accomplished by a hybrid structure of a tapered LPFG and a CO_2-LPFG [13].

In this paper, it is found that temperature sensing characteristic of the CO_2-LPFG is about 5 times higher than that of the modular LPFG. Based on this phenomenon, a hybrid structure is proposed by connecting these two types of LPFGs to measure temperature and strain simultaneously. By studying and analyzing the experimental data, it is proved that the proposed hybrid structure can achieve the simultaneous measurements of temperature and strain.

2. Experimental design and principle

This hybrid structure is made by connecting a CO_2-LPFG and a modular LPFG. The CO_2-LPFG is fabricated by CO_2-laser-notching, and it is fabricated by CO_2-laser-notching sculpture 50 grooves along the single-mode fiber. Fig. 1(a) shows the side view of CO_2-LPFG, and the total length of the CO_2-LPFG is 2.5 cm. As shown in Fig. 1(b), the modular LPFG is manufactured by splicing the single-mode fiber (SMF) and the no-core fiber (NCF) alternately and the grating with nine periods in total (one period with 200 μm NCF and 400 μm SMF). The side view of the modular LPFG is shown in Fig. 1(c), and the total period length of the modular LPFG is 5.4 mm. With being cut out smooth end faces by optical fiber cleaver beforehand, these two gratings are eventually connected by fusion splicer, and the distance between them is 7 mm.

The mode coupling of the conventional LPFG is the coupling

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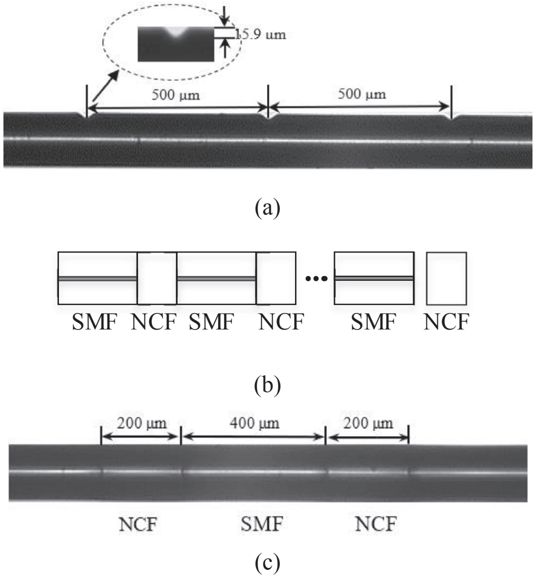

Fig. 1. (a) Side view of CO_2-LPFG; (b) Schematic diagram of modular LPFG; (c) Side view of modular LPFG.

between the core-based mode and the codirectional cladding mode, and the phase matching condition can be expressed as the following formula [14]:

$$\lambda_{res} = (n_{eff}^{co} - n_{eff}^{cl})\Lambda \tag{1}$$

where λ_{res} is resonant wavelength of the LPFG, Λ is the period of the grating, n_{eff}^{co} and n_{eff}^{cl} are the effective refractive index of fiber core mode and fiber cladding mode, respectively.

In order to study the temperature sensing characteristics, the above formula can be expressed as follows [15]:

$$\frac{d\lambda_{res}}{dT} = \left(\frac{dn_{eff}^{co}}{dT} - \frac{dn_{eff}^{cl}}{dT}\right)\Lambda + (n_{eff}^{co} - n_{eff}^{cl})\frac{d\Lambda}{dT} \tag{2}$$

As the temperature changes, the thermal expansion effect of the fiber is very insignificant, so it is feasible and undisputed to ignore $(n_{eff}^{co} - n_{eff}^{cl})\frac{d\Lambda}{dT}$. Consequently, the difference of temperature sensitivity is mainly determined by the thermo-optical coefficients of the fiber core and fiber cladding. In the whole cascade structure, the modular LPFG is made of single-mode fiber and no-core fiber. Because of particularity of no-core fiber without fiber core, according to the above formula (2), it is no doubt that the no-core fiber has a very low temperature sensitivity, and the modular LPFG made by it also has a very low temperature sensitivity.

3. Results and discussion

In order to experimentally verify that the cascade structure can measure temperature and strain simultaneously, the set-up is reported in Fig. 2. As shown in this figure, the structure is fixed between a fixed stage and a translation stage which is connected to a motion controller to apply tension to the grating. A Super-continuum Light Source (SLS) is connected with input port and put light into this fiber, and the light through the cascade structure reaches the output port and eventually enters an Optical Spectrum Analyzer (OSA). Meanwhile, a heating apparatus is placed to change the ambient temperature of the grating.

As shown in Fig. 3(a), it is the spectral graphic correlation of the modular LPFG and the CO_2-LPFG before and after the connection. Fig. 3(b) and (c) are shown to describe separately the temperature sensitivities and the strain sensitivities of the modular LPFG and the CO_2-LPFG (the resonance wavelength is selected for 1356 nm). In the process of the modular LPFG and the CO_2-LPFG measurement experiments, the strain changes once every 100 με (0–1200 με) and the temperature changes once every 20 °C (30–170 °C). The temperature sensitivities of the modular LPFG and the CO_2-LPFG are −10.4 pm/°C and 57.5 pm/°C, respectively, and the strain sensitivities are −1.0 pm/με and −0.6 pm/με, respectively.

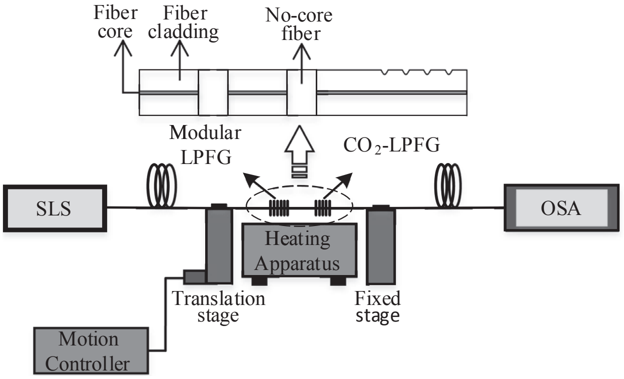

Fig. 2. Schematic diagram of experimental setup for temperature and strain simultaneous measurement.

Fig. 4(a) and (b) are shown to describe separately the temperature sensitivities and the strain sensitivities of Dip 1258 nm (Dip A) and Dip 1356 nm (Dip B) after two LPFGs cascaded. Keeping the structure straight (setting it to zero strain), the temperature sensitivities of Dip 1258 nm and Dip 1356 nm are −15.4 pm/°C and 58.3 pm/°C, respectively. And under room temperature condition, the strain sensitivities are −1.2 pm/με and −0.5 pm/με, respectively. It is found that the temperature and strain sensing characteristics of two resonance peaks only take place some minor changes. Based on this phenomenon, some experiments are run to complete the simultaneous measurement of temperature and strain by controlling the temperature at a steady level to measure the strain sensitivity, and repeating the strain measurements once every 20 °C as temperature increases.

According to the experiments described above, simultaneous measurement of temperature and strain can be achieved with two different resonant wavelengths of Dip 1258 nm and Dip 1356 nm. The shifts of two resonant wavelengths are set as $\Delta\lambda_A$ and $\Delta\lambda_B$. The variations of temperature and strain are respectively ΔT and $\Delta\varepsilon$. The temperature sensitivities and strain sensitivities of two dips are set to $K_{T\Delta\lambda_A}$, $K_{\varepsilon\Delta\lambda_A}$ and $K_{T\Delta\lambda_B}$, $K_{\varepsilon\Delta\lambda_B}$, respectively. When the temperature and strain of the cascade structure are changed at the same time, all parameters can be written in a matrix form as reported in [16]:

$$\begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = \frac{1}{D}\begin{pmatrix} K_{\varepsilon\Delta\lambda_B} & -K_{\varepsilon\Delta\lambda_A} \\ -K_{T\Delta\lambda_B} & K_{T\Delta\lambda_A} \end{pmatrix}\begin{pmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{pmatrix} \tag{3}$$

where $D = K_{\varepsilon\Delta\lambda_B}K_{T\Delta\lambda_A} - K_{\varepsilon\Delta\lambda_A}K_{T\Delta\lambda_B}$. According to the previous experimental results, $K_{\varepsilon\Delta\lambda_B} = -0.5$ pm/με, $K_{T\Delta\lambda_A} = -15.4$ pm/°C, $K_{\varepsilon\Delta\lambda_A} = -1.2$ pm/με, $K_{T\Delta\lambda_B} = 58.3$ pm/°C. D can be calculated as $77.2\ \mathrm{pm}^2\cdot°\mathrm{C}^{-1}\cdot\mu\varepsilon^{-1}$.

According to the above matrix (3), the measurement resolutions of the temperature and strain can be given by:

$$\begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = \frac{1}{77.2}\begin{pmatrix} -0.5 & 1.2 \\ -58.3 & -15.4 \end{pmatrix}\begin{pmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{pmatrix} \tag{4}$$

By analyzing the experimental results, the variations of temperature and strain can be calculated on the basis of matrix (4). So, the temperature and strain can be measured simultaneously in a small range near this condition. In the experiments, the OSA with wavelength resolution of 0.02 nm is exploited. Consequently, the temperature resolution can be estimated to be 0.18 °C and strain resolution can be estimated to be 19 με.

As shown in Fig. 5(a), it shows the different temperature sensitivities at different strain, and Fig. 5(b) shows the different strain