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Simultaneous wavelength and frequency encoded microstructure based quasi-distributed temperature sensor

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Abstract: A novel microstructure based temperature sensor system using hybrid wavelength-division-multiplexing /frequency-division-multiplexing (WDM/FDM) is proposed. The sensing unit is a specially designed microstructure sensor both frequency and wavelength encoded, as well as low insertion loss which makes it have the potential to be densely multiplexed along one fiber. Moreover, the microstructure can be simply fabricated by UV light irradiation on commercial single-mode fiber. Assisted with appropriate demodulation algorithm, the temperature distribution along the fiber can be calculated accurately. In theory, more than 1000 sensors can be multiplexed on one fiber. We experimentally demonstrated the feasibility of the scheme through building a sensor system with 9 microstructures multiplexing and with temperature resolution of 0.4°C.

1. Introduction

Optical fiber sensor (OFS) has attracted a lot of attentions over the past two decades. Various sensor techniques have been developed for the measurements of physical, chemical, and biological parameters [1,2]. The main advantages of OFS include immunity to electromagnetic interferences, chemically inert, biocompatible, high temperatures tolerance, as well as potential small size and light weight. Among the various types of fiber-optic sensors, fiber-optic Fabry-Pérot (FP) interferometric sensors are distinctive because of their high sensitivity, ease of fabrication, localization, and flexible multiplexing ability [3–7]. FP sensors can be classified as extrinsic Fabry-Pérot interferometric (EFPI) sensors and intrinsic Fabry-Pérot interferometric (IFPI) sensors. An EFPI sensor uses an air cavity between two cleaved fiber ends inserted into alignment ferrule and bonded by laser welding or epoxy adhesive [8,9]. However, weak interferometric signal, limitation on the cavity size due to coupling loss, and difficulty in multiplexing are the major intrinsic drawbacks of EFPI sensors. Furthermore, the mismatch in thermal expansion coefficients of fibers, alignment ferrules, and bonding materials will severely limit the sensor construction. Hence, the large coupling loss associated with EFPI sensors greatly reduces their multiplexing capability. In contrast, IFPI sensors, which are constructed inside the optical fiber itself, reduce the bonding difficulties experienced in EFPI sensor fabrication. They provide good merits such as miniature size, continuous geometry, robust structure, and versatile installation.

Various fabrication methods, such as dielectric thin films [10,11], and fiber Bragg gratings (FBGs) [12], were applied to construct the IFPI sensors. It has been demonstrated that FBG was a promising candidate for a wide range of sensing applications [13]. FBGs play an important role in OFS because of their intrinsic nature and advantages such as wavelength-encoded operation [14–16]. These in-line fiber reflectors can form the IFPI sensor system without the coupling and alignment efforts. FBG pairs with low reflectivity were used to form a FP interferometer and served as distributed sensors in coherent multiplexing scheme [17]. Although nearly identical FBGs can be used, which facilitate the massive production and reduce the system cost, the multiplexing scheme is quite complicated and the allowable number of sensors is still low, since the interference intensity decreases with the increase of the mismatch between the central reflection wavelengths of the two FBGs. More recently, chirped Bragg gratings with much wider spectral widths have been explored for the FP filters [18]. High finesses and wide spectral widths could be achieved with superimposed chirped Bragg gratings. However, this technique was expensive and complicated due to the fabrication of chirped FBGs.

In this paper, we proposed a microstructure temperature sensor which can be simultaneously wavelength and frequency encoded. With the hybrid frequency-division-multiplexing/wavelength-division-multiplexing (FDM/WDM) scheme, the sensor system has the potential of over 1000 multiplexing capacity along one single fiber. Quasi-distributed measurement of the temperature variation is demonstrated experimentally, with the temperature sensitivity of about 7.91ppm/°C.
2. Operation principle and manufacturing

2.1 Structure and Manufacturing of sensing units

The proposed sensor unit is a specifically designed UV-induced microstructure as shown in Fig. 1(a). It can be considered as Fabry-Pérot interferometer composed of two closely spaced uniform FBGs. While, different from conventional FBGs, the length of the two FBGs is ultra short, only hundreds of micrometers, and consequently very low reflectivity of about 0.03dB. The two FBGs are identical FBGs, and have the same optical properties. The distance between them which determine the free spectral range (FSR) of Fabry-Pérot interferometer is small and can be set freely. Therefore, the microstructures possess the superiority of wavelength encoding and frequency encoding, as well as low transmission loss.

The fabrication of the sensor is similar to the uniform FBG as shown in Fig. 1(b). A 266nm ND: YAG pulsed laser is used as the UV source. A cylinder lens is employed to focus the beam. Before the phase mask, there is a baffle plate closely to the phase mask, which has two identical very narrow slits just allow a few light beam to pass. The slit width determines the length (L) of the ultra-short FBG. The distance between the two slits d equals to the space interval of the two FBGs. As the motorized linear translation stage translates the UV light to over sweep the baffle plate, a microstructure can be fabricated quickly. Therefore, a microstructure with certain central wavelength and FSR could be obtained by choosing appropriate slits distance d and phase mask period 2Λ. During the fabrication, a broadband optical source is connected to the circulator port 1, while the circulator port 2 is connected to the fiber which is used to fabricate the microstructure. An optical spectrum analyzer (OSA) connected to the port 3 is used to monitor the reflect spectrum by the microstructure in order to control the reflectivity and the band width.

2.2 Sensing principle

According to the coupling mode theory, the reflectivity of an ultra-short FBG can be described as follows [19]:

\[ R_0 = \frac{\sin h^2(\sqrt{k^2 - \sigma^2}L)}{\cos h^2(\sqrt{k^2 - \sigma^2}L) - \frac{\sigma^2}{k^2}}, \]

where:
- \( R_0 \) is the reflectivity of the FBG.
- \( \sigma \) is the phase mask period.
- \( \Lambda \) is the free spectral range.
- \( k \) is the propagation constant.
- \( L \) is the length of the FBG.
where  and  are the effective refractive index and the “dc” index change spatially averaged over a grating period, which can be regarded as constants,  is the fringe visibility,  is the length of the FBG and  is the “design wavelength” related to grating period .

The microstructure can be regarded as a Fabry-Pérot interferometer formed by two ultra-short FBGs with space interval. Consuming the reflectivity of the ultra-short FBGs is very low such as 0.03dB, the Fabry-Pérot interferometer could be simplified as a two-beam interferometer. As a result, the reflect spectrum of the microstructure can be deduced to

\[
R_w = 2R_c[1 + \cos(4\pi n_{eff} L_w / \lambda)].
\]

where  is the cavity length of the Fabry-Pérot interferometer.

Assume  ,  ,  ,  ,  , and then we calculate the reflect spectra of the ultra-short FBG and the microstructure, as displayed in Figs. 2(a) and 2(b) respectively. It is obvious that the reflectivity of the ultra-short FBG is about 0.08%, while the reflectivity of the microstructure is about 0.3%, which means low insertion loss. And the envelope of the reflect spectrum of the microstructure is similar with the ultra-short FBG (-3dB band width smaller than 3nm).

At the peak positions of the reflect spectrum of the microstructure, the following equation can be established:

\[
2n_{eff} L_w = m\lambda.
\]

Where  is a signless integral. When the environment temperature changes, the cavity length of the microstructure will change due to the thermo-optic effect and thermal expansion effect.
It is obvious that the temperature change can be obtained by measuring the relative shift of any of the peaks.

2.3 Multiplexing principle

From Fig. 2(a) and Eq. (4), it can be seen that the reflect spectrum of each microstructure presents periodic cosine undulation along the reciprocal of the wavelength $\lambda$, while the period is determined by the cavity length of the microstructure. So when Fourier transform is applied to the reflect spectrum of multiple microstructure sensors with different cavity lengths connected in series, every sensor has its own peak in the Fourier transformation spectrum. So we can encode the sensor by the frequency. Based on this, we use FDM to multiplex sensors with different cavity lengths.

As shown in Fig. 2, the envelope of the reflect spectrum is similar with the ultra-short FBG, so the microstructures fabricated by different phase masks will occupy different positions in the reflect spectrum, which can be considered as the wavelength encoding characteristic. Hence, it is possible to multiplex many sensors with different grating periods by employing different phase mask.

By using the FDM/WDM technology, a large number of microstructure sensors can be multiplexed along one fiber. Due to the low insertion loss, the optical power budget can be neglected. Therefore, the multiplexing capacity is mainly determined by the number of wavelength channel and frequency channel decided by different cavity length in a certain wavelength channel.

Consuming the wavelength analysis equipment has a sweep bandwidth of about 80nm while the $-3$dB band width of the microstructure sensor is smaller than 3nm. However, the extra bandwidth budget for measurand variation should be considered in practical application. so there is a tradeoff between the measuring range and the multiplexing capacity. In the limiting case, assuming the measurement range is small enough to neglect the wavelength shift, and consequently the 25 wavelength channels could be achieved.

To calculate the frequency channel, the maximum cavity length and the minimum cavity length difference should be analyzed. On one hand, according to the Nyquist Sampling Theory, the minimum Free Spectrum Range (FSR) of Fabry-Pérot interferometer, determined by the maximum cavity length, could not be smaller than twice of the sampling interval of the wavelength interrogator. Meanwhile, the cavity length could not be longer than the phase mask to building up the FPI in practical application. In the experiment, we employed the Micron Optics si-720 with the sample interval of 5pm as the wavelength interrogator (corresponding to the cavity length of 8cm) and the phase mask with the length of only 1cm, so the cavity length should be less than 1cm under the two restrict factors. On the other hand, in order to the crosstalk among the sensors in the FFT spectrum, 200um is regarded as the minimum cavity length difference. In this way, exceed 40 sensors can be multiplexed in a WDM channel. Consequently, the number of the microstructure sensor multiplexed on one fiber could exceed 1000. In addition, if the FBG wavelength interrogator with better performance as well as the optimized frequency spectrum analyzing algorithm is employed, the multiplexing capacity could be further improved.

2.4 Data processing method

In order to achieve signal demodulation of the sensor, a FDM/WDM based algorithm is designed for distributed temperature measurement. As shown in Fig. 3, the program acquires the spectrum data from OSA or other spectrum analysis equipment firstly. And then the data is divided into different groups according to the envelope of the reflect spectrum, for the reason that the sensors fabricated with the same phase mask have the similar envelope. Processing every data group by the Fast Fourier Transform (FFT) algorithm, different peaks in the FFT spectrum are provided for the microstructures with different cavity length. According to the position of the frequency peak, the program can extract and recover the reflected optical spectrum of each microstructure by the digital finite impulse response (FIR) filter, which is approximate to the sine curve. By choosing one peak of the curve and
calculating its shift, the temperature change can be demodulated according to the Eq. (5). Meanwhile, the program can locate the sensor according to the wavelength and the cavity length which is unique encoded for every sensor. In this way, the temperature field distribution along the sensing fiber could be obtained.

3. Experimental results and discussion

In order to test the sensing system model developed in the previous section, an experimental setup, which 9 sensors are applied for, is configured as shown in Fig. 4. According to the pitch of the phase masks employed in the fabrication process, the sensors can be divided into three groups: 1054.86nm (Group 1), 1065.20nm (Group 2), and 1075.55nm (Group 3) which are marked with different colors of red, green and blue, respectively. All the ultra-short FBGs have the same grating length of 400um. Every group has three microstructure sensors with different cavity lengths, including 2mm (S_{1,1}, S_{2,1}, S_{3,1}), 4mm (S_{1,2}, S_{2,2}, S_{3,2}), and 6mm (S_{1,3}, S_{2,3}, S_{3,3}). Here, we define S_{m,n} as the code of the microstructure sensor, while m represents the serial number of wavelength, and n represents the serial number of frequency. The FBG sensing demodulator sm125-500, combining the high-power, low-noise swept laser source and analysis module, is used as the wavelength interrogator to monitor the reflection spectrum. The sm125-500 can sweep from 1510nm to 1590nm at the step of 5pm, the scan frequency of 2Hz with a wavelength accuracy 1pm, and wavelength stability of 1pm. The reflection spectrum data detected by sm125-500 is sent to computer for data processing. Two
Thermoelectric Coolers (TECs) based on the Peltier effect are employed to control the temperature change of the sensors as shown in Fig. 4.

During the experiment, limited by the number of the TECs, only three sensors were heated or cooled at the same time, two of which were heated by one TEC while one was cooled by the other TEC. The experiment was divided into two steps. First, we tested three sensors with different frequency encode while same wavelength encode: \( S_{3.1} \), \( S_{3.2} \), and \( S_{3.3} \). The sensors \( S_{3.1} \) \( (d = 2 \text{ mm}) \) and \( S_{3.2} \) \( (d = 4 \text{ mm}) \) were heated by one TEC from 5°C to 75°C with a step of 5°C, while the sensor \( S_{3.3} \) \( (d = 6 \text{ mm}) \) was cooled by the other TEC from 80°C to 5°C with a step 5°C at the same time. Second, we tested three sensors with different wavelength encode while same frequency encode: \( S_{1.3} \), \( S_{2.3} \), and \( S_{3.3} \). The sensors \( S_{1.3} \) \( (\lambda = 527.43 \text{ nm}) \) and \( S_{2.3} \) \( (\lambda = 532.6 \text{ nm}) \) were heated by one TEC from 5°C to 75°C with a step 5°C, while the sensor \( S_{3.3} \) \( (\lambda = 537.78 \text{ nm}) \) was cooled by the other TEC from 80°C to 5°C with a step of 5°C at the same time.

During the data processing, the reflection spectrum data extracted from the sm125-500 is divided into three groups according to the wavelength channel firstly. Then, using the Fast Fourier Transform (FFT) algorithm to analyze the frequency components of every data group in different wavelength channel, the peaks of which corresponds to different cavity lengths. Figures 5(a) to 5(d) show the reflection spectrum of the 9 sensors and the FFT spectrum of three groups at the room temperature, respectively. It is clearly that there are three peaks in the FFT spectrum of every group corresponding to 3 sensors with the same FBG wavelength while different cavity lengths.

According to the position of the frequency peak, the reflected optical spectrum of each microstructure can be extracted and recovered by the FIR digital filter. The recovered spectra of two typical sensors at different temperatures are shown in Figs. 6(a) and 6(b), respectively. The relative wavelength is the product of the serial numbers of the sample points and the wavelength interval. The adopted FIR digital filter is a band pass filter with linear phase. Although there is some information loss due to the filter algorithm, it doesn't deteriorate the measuring accuracy. It can be seen that the peaks shift with the temperature change. By choosing one peak of the curve and calculating its shift, the temperature variation can be demodulated.
Fig. 6. The recovered spectra of two typical sensors at different temperatures: (a) the sensor $S_{3-1}$ ($\Lambda = 537.78\text{nm}, d = 2\text{mm}$) (b) the sensor $S_{3-3}$ ($\Lambda = 532.6\text{nm}, d = 6\text{mm}$).

The temperature measuring results are shown Fig. 7. From Fig. 7, an approximately linear relation temperature change and the relative shift of the wavelength peak is demonstrated ($R^2>0.999$) with a sensitivity of about 7.91ppm/°C for all the sensors. Since the wavelength scanning resolution of sm125-700 is 5pm, the temperature resolution of the sensing system is about 0.4°C.

Fig. 7. (a) Experimental results of the sensors $d = 2\text{mm}, d = 4\text{mm}, d = 6\text{mm}$ while $\Lambda = 537.78\text{nm}$. (b) Experimental results of the sensors $\Lambda = 527.43\text{nm}, \Lambda = 532.6\text{nm}, \Lambda = 537.78\text{nm}$ while $d = 6\text{mm}$.
4. Conclusion

A simultaneous wavelength and frequency encoded microstructure based fiber temperature sensor system has been presented and demonstrated. Assisted with FDM/WDM technique, the multiplexing capacity of the scheme could be greatly improved. The theoretical analysis proves that the multiplexing capacity is possible increased to over 1000 with optimized design. Furthermore, 9 microstructures multiplexing with temperature resolution of 0.4°C was accomplished. Owing to the advantages of large multiplexing capacity, low insertion loss, manufacture simple and low cost, the proposed sensing scheme has a great potential for temperature monitoring of dams, tunnels and other distributed sensing applications.

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