Simultaneous measurement of refractive index, temperature and strain based on core diameter mismatch and polarization-maintaining FBG*

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(Received 17 November 2012)

A kind of fiber-optic sensor for simultaneous measurement of refractive index of surrounding medium, temperature and strain is described. Based on core diameter mismatch, a multimode-single mode-multimode (MSM) structure is presented. It is demonstrated that the three parameters can be measured respectively by the interference of the core mode and cladding modes excited in the single mode fiber (SMF). Then combined with a polarization-maintaining fiber Bragg grating (PMFBG) which has different sensing properties from MSM structure, three parameters are measured simultaneously. The experimental results show that PMFBG is insensitive to the refractive index and the refractive index sensitivity of the MSM structure is 96.04 nm·RIU^{-1}; the temperature sensitivities of the characteristic wavelength for MSM structure and the center wavelengths of fast and slow axes for PMFBG are 0.0911 nm·℃$^{-1}$, 0.00976 nm·℃$^{-1}$ and 0.0105 nm·℃$^{-1}$, respectively; the strain sensitivities of those are -0.013 nm·με^{-1}, 0.012 nm·με^{-1} and 0.012 nm·με^{-1}, respectively.

Document code: A **Article ID:** 1673-1905(2013)03-0238-3

DOI 10.1007/s11801-013-2403-1

Recently, fiber-optic sensors combined with interference of fiber gratings arouse great interest among the research scholars[1-3]. The refractive index measurement in liquids is an important issue for chemical, medical and biological applications[4]. However, most of the liquids to be measured are temperature-sensitive. Various types of fiber-optic sensors have been developed, such as hybrid structure of fiber Bragg grating (FBG), long period fiber grating (LPFG), cascaded LPFGs, tilted FBG, and fiber interferometers[5-9]. In fact, the strain acting on the sensors is often ignored, which has influence on the result of the measurement. Thus S. M. Lee[10] presented a structure which excited three different order modes in a core-etched fiber Bragg grating, and realized the measurement of three parameters simultaneously. However, the etched FBG is so fragile that it is inconvenient in the measurement, and the sensor can not be mass-producted.

In this paper, a multimode-single mode-multimode (MSM) structure based on fiber core diameter mismatch is achieved by inserting a section of single mode fiber (SMF) into two multimode fibers (MMFs), and then it is cascaded with a polarization-maintaining fiber Bragg grating (PMFBG)[11,12]. Because MSM structure and PMFBG have different response sensitivities to refractive index, temperature and strain, a sensitive matrix is used to realize the measurement of three parameters simultaneously. With simple structure, low cost and other advantages of optical fiber sensor, the sensor has an excellent application prospect in biochemistry field.

Fig.1 shows the experimental setup of the sensing system. In the experiment, suppose that there is no axial offset between SMF and MMF. When the light from a broadband sourse (BBS) is launched into the MSM structure through a section of input SMF, the fundamental mode and higher order guided modes are excited in MMF1. The core mode and cladding modes are excited in SMF1 when the modes in MMF1 are coupled into the

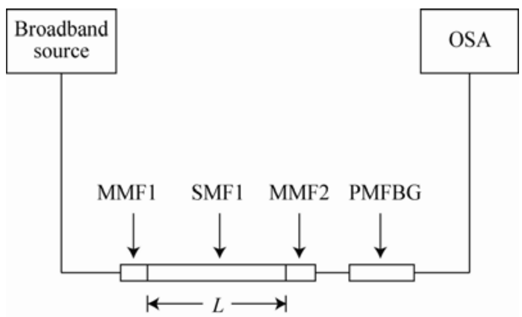

Fig.1 Schematic diagram of experimental setup

* This work has been supported by the Tianjin Natural Science Foundation (No.11JCYBJC00100 and 13JCQNJC01800).

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cladding of the SMF1. Due to the different effective refractive indices of the cladding modes and core mode, there is a phase difference generated at the SMF1-MMF2 splicing point. Thus, the light which satisfies the phase matching condition interferes in SMF1. The emitted light from SMF1 is recoupled into MMF2. After propagating through MMF2 and PMFBG, the spectrum of the light can be observed by the optical spectral analyzer (OSA).

When the modes excited in the MMF1 travel along MMF1, the redistribution of the electric field is aroused. The electric field distribution can be expressed as

$$E(r)=\sum_{m=1}^{N}\alpha_m F_m(r)\exp(\mathrm{i}\beta_m L_m), \quad (1)$$

where α_m and $F_m(r)$ are the field excitation coefficient and the normalized modal field distribution of the mth mode, respectively. β_m is the propagation constant of the mth mode, L_m is the length of MMF1, and N is the number of the modes excited in MMF1.

After the redistribution of the electric field, the core mode and cladding modes are excited in SMF1 when the light is coupled into the cladding of SMF1. The condition for a constructive interference between core mode and cladding modes can be given as

$$(\beta_{\mathrm{core}}-\beta_{\mathrm{cla}}^{m})L=2\pi N, \quad (2)$$

where β_{core} and β_{cla}^{m} are the propagation constants of core mode and the mth cladding mode, respectively. L is the length of SMF1.

The wavelength spacing between two adjacent maximum wavelengths (or minimum wavelengths) is shown as

$$\Delta\lambda=\frac{\lambda^2}{\Delta n_{\mathrm{eff}}L}, \quad (3)$$

where λ is the operation wavelength, Δn_{eff} is the effective refractive index difference between core mode and the mth cladding mode.

When the surroundings of the sensor change, Δn_{eff} and L change simultaneously, which leads to the change of interference between the cladding modes and the core guided mode. The peak-to-peak value corresponding to the interference spectrum is called as characteristic wavelength which changes with the external environment as well.

For PMFBG, the external refractive index has no impact on the inherent refractive index of PMFBG, so PMFBG is insensitive to the external refractive index. When the temperature and strain change simultaneously, because of thermal expansion effect, thermo-optic effect and elastic-optic effect, the two peaks of PMFBG on x axis and y axis, corresponding to the fast-axis mode and slow-axis mode, are shifted as:

$$\Delta\lambda_x(T,\varepsilon)=(\alpha_x+\xi_x)\Delta T+(1-P_{\mathrm{ex}})\Delta\varepsilon, \quad (4)$$

$$\Delta\lambda_y(T,\varepsilon)=(\alpha_y+\xi_y)\Delta T+(1-P_{\mathrm{ey}})\Delta\varepsilon, \quad (5)$$

where α, ξ, P_{e} are the thermal expansion coefficient, thermo-optic coefficient, the effective elastic-optic coefficient, respectively. ΔT and $\Delta\varepsilon$ are the variations of the temperature and strain, respectively.

In the experiment, the two sections of MMF (105/125; 6 mm) including MMF1 and MMF2, and a section of SMF1 (8/125; 25 mm) are produced by Yangtze Optical Fiber and Cable Company (YOFC). The center wavelengths of two peaks of PMFBG on x axis and y axis are 1546.32 nm and 1545.92 nm, respectively. The spectrum of the sensor is measured with Anritsu MS9710B OSA as shown in Fig.2. As the bandwidth of PMFBG is too narrow compared with the interference spectrum of MSM structure, Fig.2 is enlarged as shown in Fig.3. And the characteristic wavelength of interference can be chosen as 1551.82 nm.

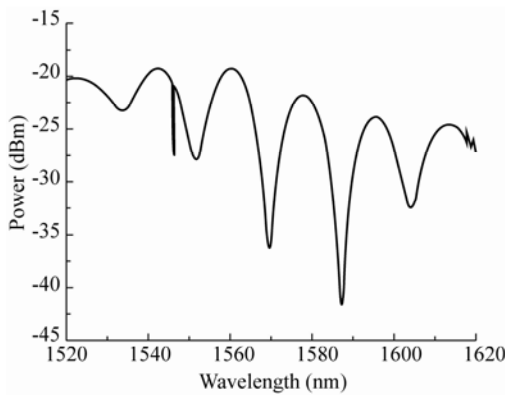

Fig.2 Spectrum of the output light after the sensor

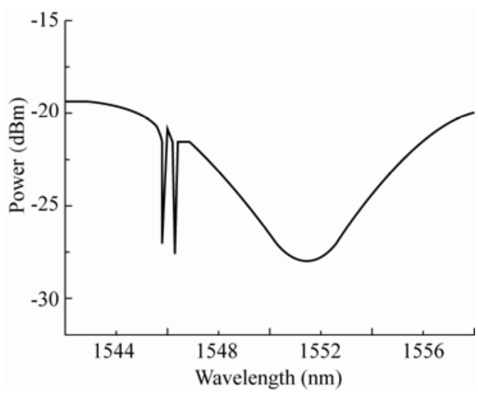

Fig.3 Enlarged spectrum of the light after sensor

Refractive index measurement is carried out by placing the sensing area (MSM structure and PMFBG) in liquids with known refractive index at room temperature. When the concentration of NaCl solution is from 0% to 25%, the refractive index changes from 1.3333 to 1.3798. By observing the shift of wavelengths, the refractive index response curves are obtained as shown in Fig.4. From Fig.4, PMFBG is insensitivive to the refractive index, while the characteristic wavelength of MSM has a sensitivity of 96.04 nm·RIU^{-1}.

In order to measure the effect of temperature, the sensing area is fixed to the thermostat (MH-5800). From

20 °C to 80 °C, the changes of wavelengths are recorded every 5 °C as shown in Fig.5. Fig.5 shows that the characteristic wavelength of MSM structure and two center wavelengths of PMFBG drift to the right as the temperature increasing. The temperature sensitivity of characteristic wavelength for MSM structure is 0.091 nm·°C^{-1}, and the temperature sensitivities of center wavelengths of x axis and y axis for PMFBG are 0.00976 nm·°C^{-1} and 0.0105 nm·°C^{-1}, respectively.

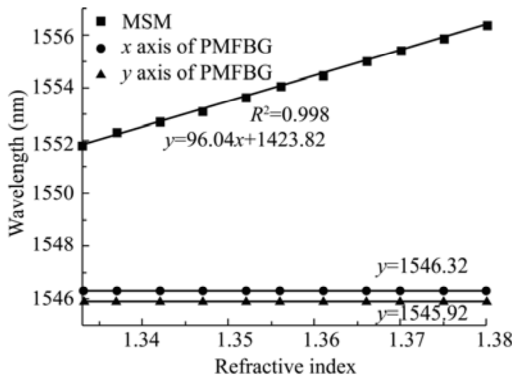

Fig.4 Characteristic curve of refractive index response

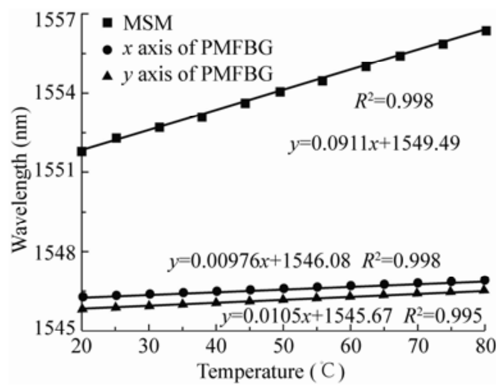

Fig.5 Characteristic curve of temperature response

At room temperature, in order to measure the effect of strain, the sensing area is fixed on the cantilever beam. In the range of 0−650 με, a set of data is recorded every 50 με, and the strain response curves are obtained as shown in Fig.6. Fig.6 shows that the strain sensitivity of characteristic wavelength for MSM is -0.013 nm·με^{-1}, and the strain sensitivities of center wavelengths of x axis and y axis for PMFBG are both 0.012 nm·με^{-1}.

Using the above experiments and linear fitting, a matrix can be obtained between the changes of the wavelengths and three parameters. The matrix can be expressed as

$$\begin{bmatrix} \Delta\lambda_{\mathrm{MSM}} \\ \Delta\lambda_x \\ \Delta\lambda_y \end{bmatrix} = \begin{bmatrix} K_{T_{\mathrm{MSM}}} & K_{\varepsilon_{\mathrm{MSM}}} & K_{n_{\mathrm{MSM}}} \\ K_{T_x} & K_{\varepsilon_x} & K_{n_x} \\ K_{T_y} & K_{\varepsilon_y} & K_{n_y} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta n \end{bmatrix} = \begin{bmatrix} 0.0911 & -0.0013 & 96.04 \\ 0.00976 & 0.0012 & 0 \\ 0.0105 & 0.0012 & 0 \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta n \end{bmatrix}. \tag{6}$$

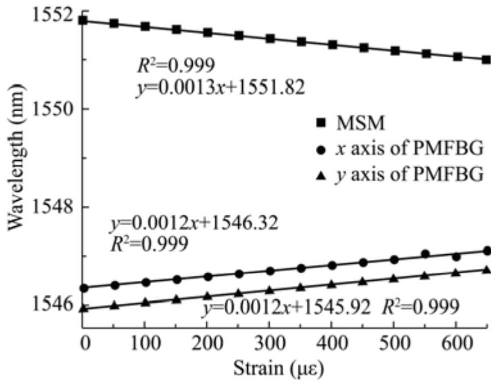

Fig.6 Characteristic curve of strain response

In this paper, a fiber-optic sensor for simultaneous measurement of refractive index, temperature and strain is demonstrated. An MSM structure and a PMFBG construct the sensing area of the sensor. Due to the different sensing properties between MSM structure and PMFBG, the three parameters are measured simultaneously by using a sensitive matrix. With the advantages of simple structure, low cost and convenient operation, this sensor can be mass-producted, and has an excellent development in biochemistry field in future.

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