Properties of sandwich-structure based Mach-Zehnder interferometer cascaded with FBG response to dual-parameter sensing*

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An all-fiber temperature and curvature sensor based on Mach-Zehnder interferometer (MZI) was proposed. The MZI was a sandwich structure which is composed of ring-core fiber (RCF), no-core fiber (NCF) and single-mode fiber (SMF). The temperature and curvature can be demodulated by the wavelength shift and the intensity variation of the dips respectively in the transmission spectrum. The measurement results show that the sensitivity of curvature is −7.88 dBm/m^{-1} in the range from 3.0 m^{-1} to 4.2 m^{-1} and the sensitivity of temperature is 53.5 pm/°C in the range from 60 °C to 200 °C. In addition, the cascaded FBG in the proposed structure, also sensitive to temperature, was used to monitor the fluctuation of temperature. The compact structure, the real-time temperature and the high curvature sensitivity make the sensor have the potential in the field of construction health monitoring and mining safety production.

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With the rapid development of construction health monitoring and machinery manufacturing, varieties of curvature sensors have been extensively studied. Fiber based curvature sensors have notorious advantages, such as light weight, easy fabrication, high sensitivity, as well as the electromagnetic interference-free.

Various curvature sensors based on fiber have been reported, which can be roughly classified into three categories: fiber grating[1], micro structured optical fibers[2] and in-fiber interferometers[3,4]. The fiber gratings for curvature sensing include fiber Bragg grating (FBG)[5,6] and long period fiber grating (LPFG)[7,8] and tilted fiber Bragg grating (TFBG)[9,10]. Due to their easy fabrication and reproduction, more and more curvature sensors based on fiber gratings have been reported. Micro structured optical fibers (or photonic crystal fiber) provide a new sets of particular optical properties like birefringence, dispersion and nonlinearities. Their unique capabilities make them attract wide attention in optical fiber curvature sensing[11,12]. The in-fiber interferometers for curvature sensors are achieved by special structure, such as tapers, lateral-offset splicing, peanut-shape, etc. As their flexible structures and high curvature sensitivity, the curvature sensors based on in-fiber interferometers possess great attractive[13,14]. In addition, the temperature cross-talk in the curvature measurement is a serious issue[15]. The change of temperature can influence the measurement of curvature sensing. Therefore, the simultaneous measurement of curvature and temperature is of great importance to avoiding the cross-talk.

In this paper, a design scheme of all-fiber temperature and curvature sensor based on Mach-Zehnder interferometer (MZI) was proposed. The MZI was a sandwich structure which is composed of ring-core fiber (RCF), no-core fiber (NCF) and single-mode fiber (SMF). The temperature and curvature can be demodulated by the wavelength shift and the intensity variation of the dips respectively in the transmission spectrum. The cascaded FBG in the proposed structure, also sensitive to temperature, was used to monitor the fluctuation of temperature. The compact structure, the real-time temperature and the high curvature sensitivity make the sensor with the potential in the field of construction health monitoring and mining safety production.

According to the fiber coupled mode theory, the light in the fiber core is incident into the cladding, and the corresponding core mode is excited. After the light passes through a certain distance, the coupling between the fiber core mode and the cladding mode will occur, forming interference. When light is transmitted in MZI sensor, the total light intensity generated after interference is shown as below[16]

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left[\frac{2\pi\left(n_{\mathrm{co}} - n_{\mathrm{cl},j}\right)}{\lambda}L\right], \quad (1)$$

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where I_1 is the light intensity of the core mode, I_2 is the light intensity of the cladding mode, λ is the incident wavelength, L represents the length of the sensor, n_{co} represents the core mode, $n_{cl,j}$ represents the effective refractive index of the jth-order cladding mode, and $\Delta\varphi$ represents the phase difference between the core mode and the jth-order cladding mode after a certain transmission distance, and satisfies

$$\Delta\phi=\frac{2\pi\left(n_{co}-n_{cl,j}\right)}{\lambda}L=\frac{2\pi\Delta n_{eff}}{\lambda}L, \quad (2)$$

where Δn_{eff} represents the effective refractive index difference between the core mode and the jth-order cladding mode. The phase difference satisfies $\Delta\varphi=(2m+1)\pi$. When m is an integer, the interference intensity is the minimum. At this time, the characteristic wavelength corresponding to the interference dip in the transmission spectrum is

$$\lambda_{dip}=\frac{2}{2m+1}\Delta n_{eff}L. \quad (3)$$

The broadband light source propagates in the FBG. According to the fiber coupled mode theory, the reflected narrowband light wave whose central wavelength matches the refractive index modulation phase of the fiber core is defined as below

$$\lambda_B=2n_{eff}\cdot\Lambda, \quad (4)$$

where λ_B is the central wavelength of the reflected light, n_{eff} is the effective refractive index and Λ is the grating period. It can be seen from Eq.(4) that the central wavelength shifts with the changes of n_{eff} and Λ.

A fiber interference structure based on MZI is designed and fabricated by using fiber fusion technology. Several segments of the required fiber are cut off, and the coating layer is removed. The residual coating layer is cleaned with alcohol. The core of NCF and the RCF is fused into the middle of the two SMFs by using the fiber fusion machine. The multiple sections are cut off by using the fiber cutter, and the MZI is fabricated. As the decreasing of RCF length, the free spectral range (*FSR*) will broaden and the extinction ratio (*ER*) will increase. In the meantime, the large transmission loss should be avoided by decreasing the RCF length. Based on all the analysis, the MZI was constituted by 5 mm NCF and 15 mm RCF. The structure of MZI is shown in Fig.1 as below.

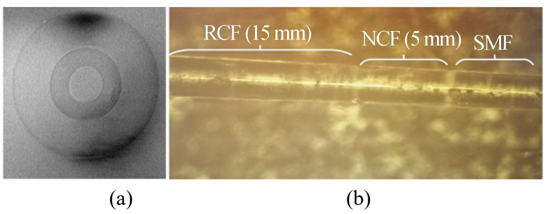


Fig.1 Structure of MZI sensor: (a) Cross section of RCF; (b) Real product of MZI

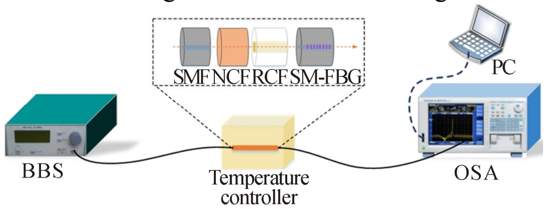
One end of the single mode fiber is connected with the bandwidth light source, and the other end is connected with the spectrometer. The spectrometer is used to observe the transmission spectrum of the fiber structure. The repeated operation process is used to observe the spectral change until the stable resonance dip transmission spectrum is seen, and the length of the sensing structure is selected. The structure of RCF and hollow-core fiber is special, which has high application value in temperature and bending sensing measurement.

The temperature sensing system consists of a broadband light source transmitter, a resistance furnace temperature controller, a self-made all-fiber dual-parameter sensor and a spectral analyzer.

The all-fiber dual-parameter sensor is placed in the glass tube of the resistance furnace temperature controller, and the middle position of the resistance furnace is close to the display temperature of the instrument panel. In order to ensure the accuracy of the measurement temperature, the optical fiber sensor should be placed in the middle position of the resistance furnace as far as possible.

In order to avoid the interference of other factors in the external environment in the process of measuring temperature, after putting the optical fiber sensing structure into the temperature controller of the resistance furnace, we need to make it in a natural straightening state as far as possible, and then use the adiabatic plug to block the two ends of the tube mouth of the resistance furnace, so that the temperature controller of the resistance furnace can be rapidly heated.

The work process of the temperature sensing system is as follows. Firstly, the broadband light source emits light wave signal, and then the light signal enters the sensing structure. The spectrum generated by the transmission of the optical fiber sensor after experiencing the change of the external temperature will also change accordingly. The change amount is resolved by the spectrometer and becomes the spectrum of the temperature change amount. Then through the computer data analysis, Origin diagram analysis of temperature wavelength drift can demodulate the change of external temperature, and then fit a curve according to the data, which can obtain the temperature sensitivity of the all-fiber dual-parameter sensor. The sensing structure is shown as Fig.2.



SMF: single-mode fiber; NCF: no-core fiber; RCF: ring-core fiber; SM-FBG: single mode fiber Bragg grating

Fig.2 Experimental setup for temperature sensing

The minimum temperature of the resistance furnace temperature controller set in temperature sensing experiment is 60 °C, and the maximum temperature is 200 °C. In the process of experiment, every heating up 20 °C, holding for 10 min, after the temperature value displayed by the instrument panel is stable, a data measurement is carried out and the wavelength change at this time is recorded. The spectral diagram is obtained by spectral analyzer, as shown in Fig.3.

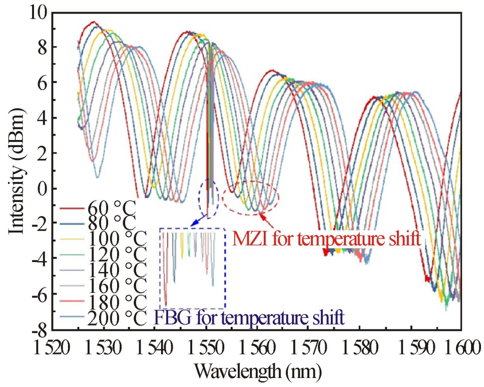
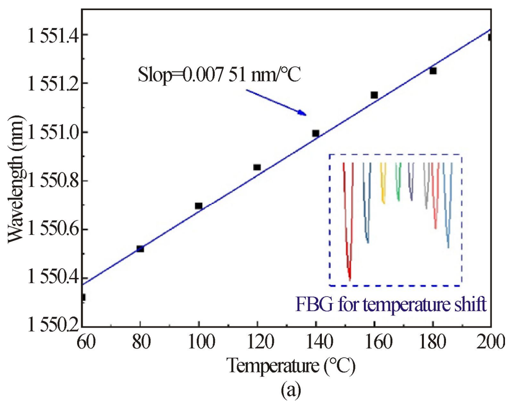


Fig.3 Spectral chart of temperature sensing experiment

It can be seen from the figure that the wavelength and intensity of FBG and MZI have changed in the process of heating from 60 °C to 200 °C. Taking the spectrum described in the figure as an example, under the influence of temperature, the central wavelength of FBG shifts from 1 550.322 4 nm to 1 551.388 2 nm, and the variation is very small and difficult to analyze. Under the influence of temperature, the wavelength of MZI shifts is obvious and the drift range is relatively large. Compared with the wavelength drift, the change of the intensity is very small. The intensity of FBG changes from −1.636 dBm to −0.966 dBm, and the value in the process of change increases first and then decreases. The intensity of MZI changes from −0.261 dBm to −0.993 dBm, and the value in the process of change decreases first and then increases. Both are nonlinear changes, and only changes about 0.8 dBm, which can be ignored. Therefore, we can use the drift of the central wavelength at different temperatures to calculate the temperature sensitivity.

By observing the spectrum of temperature sensing experiment, the sensitivity of FBG to temperature is 0.007 51 nm/°C, and the sensitivity of MZI structure to temperature is 0.052 29 nm/°C. The curves according to the wavelength drift are fitted as shown in Fig.4.



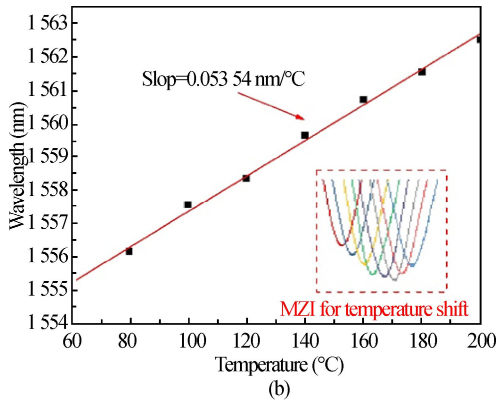


Fig.4 Characteristics of (a) FBG and (b) MZI temperature sensing

As shown in Fig.4, the wavelength shift of the FBG is much smaller than MZI interference (the sensitivity is about 0.007 51 nm/°C). However, the sensing stability of FBG is much better than MZI. So, the cascaded FBG in the proposed structure is used to improve the reliability of temperature sensing.

In the bending experiment of the fabricated all-fiber sensor, the interference spectral intensity formed with different bending curvatures will also change. The fiber sensor was fixed on a metal trip (the length was 9 cm), which benefits the consistence of bending direction. When the fiber structure bends, the interference cavity will undergo elastic deformation, which will change from a linear cavity to a curved cavity. Therefore, when the sensing structure bends, the intensity of the spectrum will change in a large range.

On the premise of stable external environment temperature, the self-made all-fiber dual-parameter sensing structure is connected to the fiber support alone. One end of the fiber is fixed, and the other end is pushed to move with a step of 5 μm. The fiber is bent according to a certain radian law, and the waveform changes of the spectrometer are observed and recorded. Then, the data are analyzed by computer. The curvature value is obtained by using the curvature formula, and the strength change under bending is analyzed. A curve is fitted according to the data, and the curvature sensitivity of the all-fiber dual-parameter sensor can be obtained. The bending experimental device is shown in Fig.5.

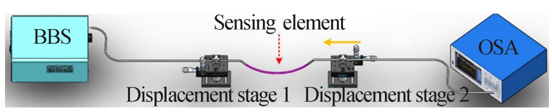


Fig.5 Experimental setup for curvature sensing

Several experimental tests were carried out on the curvature sensor, and one of the curvature changes was selected to analyze and calculate the curvature sensitivity. The spectrum extracted from the spectrometer is shown in Fig.6. From the observation of Fig.6(a), under the action of bending, the wavelength drift of FBG and MZI is not obvious, and the image fitted by the wavelength variation is not linear. The optical spectra are observed in the curvature range of 3.03—4.21 m^{-1}.

Furthermore, the optical spectra were identified by fast Fourier transform (FFT) shown in Fig.6(b). The amplitudes of various curvatures alter regularly under the curvature range of 3.03—4.21 m^{-1} at a specific frequency (0.079 nm^{-1}). That means the proposed sensor indeed excites many high-order modes to participate in interference. The spatial frequency can be expressed as below[17]

$$f = \frac{\Delta m_{\mathrm{eff}}}{\lambda^2} L, \tag{5}$$

where Δm_{eff} and L represent the differential model group index and the sensor length, respectively. It can be seen that the spatial frequency is proportional to Δm_{eff} and L.

As the increase of the curvature, the intensity of the interference dip 1 (around 1 538 nm) and dip 2 (1 544 nm) reveals an opposite trend, which can be seen clearly in Fig.6. The sensitivity of curvature is −7.88 dBm/m^{-1}, which can be observed in Fig.7.

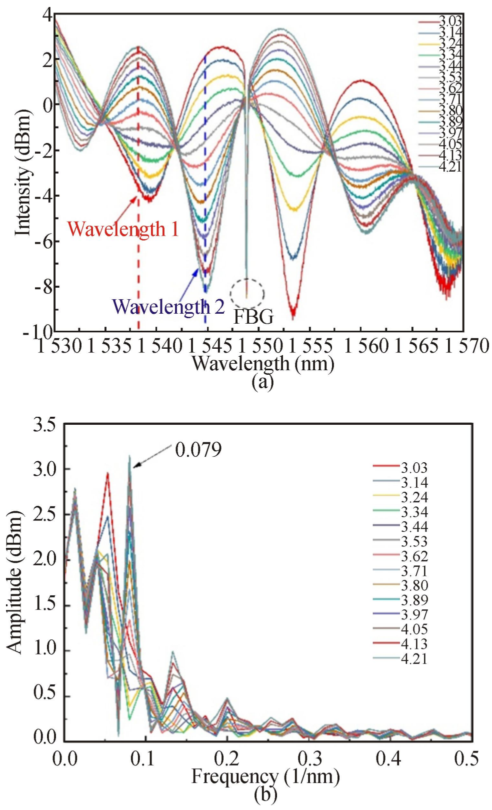


Fig.6 Spectra of curvature sensing: (a) Optical spectra; (b) Frequency spectra

In order to eliminate the cross sensitivity of temperature and bending, a special sensing structure is selected. With the specific structure of the sandwich structure, the dual-parameter sensing of temperature and curvature was achieved by monitoring the wavelength shift and intensity change of interference dips, respectively. Experimental results have shown that temperature is 53.5 pm/°C in the range from 60 °C to 200 °C and curvature is −7.88 dBm/m^{-1} in the range from 3.0 m^{-1} to

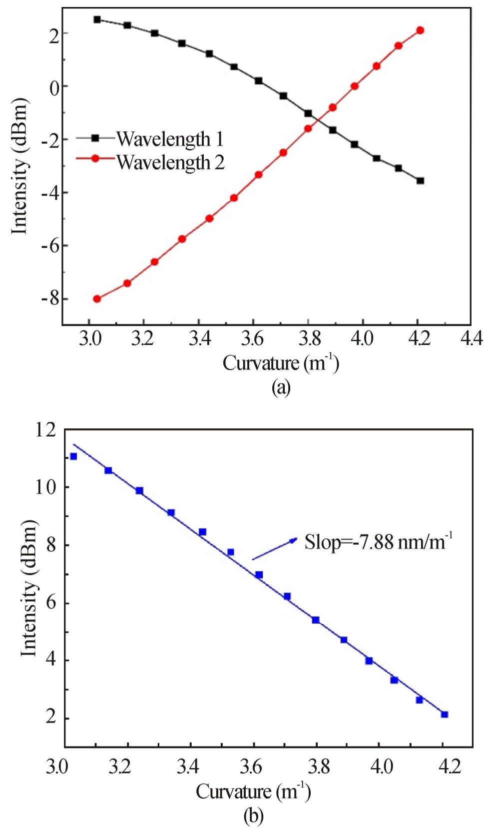


Fig.7 (a) Curvature sensing and (b) differential intensity for dip 1 and dip 2

4.2 m^{-1}. When measuring temperature, the main change is the drift of the wavelength, and when measuring curvature, the main change is intensity. Therefore, it can eliminate the cross sensitivity of temperature and curvature effectively. In addition, the cascaded FBG in the proposed structure, also sensitive to temperature, was used to improve the reliability of temperature sensing.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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