Research on Michelson interference refractive index sensing technique based on double-core microfiber*

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We propose a novel refractive index sensor based on Michelson interferometer by using double-core microfiber. Through the reflection of the end and taper of double-core fiber (DCF), the Michelson interference spectrum is formed. Owing to the structure characteristic of double-core microfiber, this interferometer can achieve the measurement of refractive index (RI) and temperature. The experimental results show that the refractive index sensitivity of the interferometer is 2 377.80 nm/RIU at the diameter of the taper waist of 8.76 μm. In the temperature ranges from 30 °C to 60 °C, the temperature sensitivity is 0.070 48 nm/°C. This sensor has the advantage of high refractive index sensitivity.

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Optical fiber sensors have lots of advantages, including strong anti-electromagnetic interference ability, low cost, simple configuration, high accuracy and others[1-3]. At present, many fiber refractive index sensors mainly include fiber grating refractive index sensors[4] and fiber interferometric refractive index sensors[5-10]. In 2017, Shen et al[11] produced a long-period fiber grating refractive index sensor, with a period of 25 μm ultraviolet (UV) inscribed and characterized. The sensor's refractive index sensitivity is 312.5 nm/RIU in the range from 1.315 to 1.395. In 2017, Cheng et al[12] produced a Fabry-Perot interferometric refractive index sensor. This sensor has an ultra-high sensitivity of 2 523.2 dB/RIU at refractive index (RI) of 1.435. In 2019, Min Shao et al[13] presented a liquid refractive index sensor based on 3-core fiber. A linear RI sensitivity of −151.56 dB/RIU is achieved in the sensing range of 1.333 5—1.372 0. In 2020, Fang Wang et al[14] proposed a sensor based on a folded-tapered multimode-no-core (FTMN) fiber. The sensor's refractive index sensitivity is 1 191.5 nm/RIU within a linear RI from 1.340 5 to 1.349 7. In 2020, Xinhu Fu et al[15] demonstrated a sensor composed of a Fabry-Perot (F-P) micro cavity based on graded-index few mode fibers. The maximum refractive index sensitivity is −16.03 dB/RIU with the refractive index change between 1.333 1—1.356 8. Among them the interferometer is simple and this type of sensors present some advantages compared to other conventional sensors, namely high resolution, easy fabrication, good electromagnetic interference immunity and so on. Therefore refractive index sensor based on Michelson interferometer is enjoyed by many researchers.

In this paper, a refractive index sensor based on Michelson interference using double-core microfiber is presented. The taper of double-core fiber (DCF) is sensitive to the change of refractive index. Through the process of tapered and coated, Michelson interference can be formed. In the simple structure, we can realize the measurement of refractive index and temperature. The Michelson interferometer based on double-core microfiber has the advantages of simple fabrication, good linearity and high refractive index sensitivity.

Fig.1 shows the structure of the proposed Michelson interferometer, which composes of single-mode fiber (SMF), multi-mode fiber (MMF) and DCF. Michelson interferometer is formed by tapered, which are fabricated on a section of DCF with the optical fiber fusion splicer. The MMF couples part of light energy into the two cores of DCF, and the light is reflected back through the right end face of DCF simultaneously, as shown in Fig.1(a). The end of the DCF is plated a silver film, which is used as a dielectric mirror. The DCF is plated and tapered to fabricate a microfiber sensor. The centric core of the DCF is the reference arm and the eccentric core is the sensing arm respectively. The core/cladding diameters of the SMF are 9/125 μm. The cross-section diagram of MMF with 105/125 μm is shown in Fig.1(a). In order to reduce the mode inter-mode interference, the length of

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multimode fiber is only 1 mm. The electron microscope of DCF is given in Fig.1(b). The refractive index of the three cores is 1.457 and the refractive index of the cladding is 1.444. The length of DCF is 6 cm. The length of the taper is 15.65 mm and the waist cone diameter of the taper is 8.76 μm.

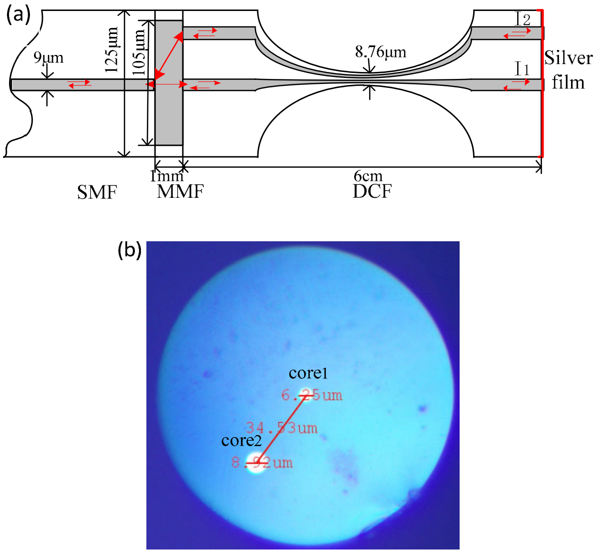


Fig.1 (a) Schematic diagram of Michelson interferometer with double-core microfiber; (b) Cross section of the DCF

According to the influence of micro/nano fiber diameter on the evanescent potential field, the ratio of evanescent potential field decreases with the increase of micro nano fiber diameter. When the diameter of the micro/nano fiber is 2 μm, the corresponding evanescent field proportion is 2.1%[16]. It can be seen that the light field has been concentrated in the core of the micro/nano fiber. In this Michelson interferometer, when a beam of laser is launched into the SMF, MMF and DCF, we can receive two beams of reflected laser (I_1 and I_2) at the incident port. Due to the influence of taper in DCF, the effective refractive index is different from the center core and the eccentric core. There is the optical path difference between core1 and core2, resulting in Michelson interference. The interference between the centric core and eccentric core of the proposed Michelson interferometer can be given as a function of the centric mode intensity I_1 and the eccentric cores mode intensity I_2:

$$I(\lambda)=I_1(\lambda)+I_2(\lambda)+2\sqrt{I_1(\lambda)I_2(\lambda)}\cos\varphi_{12}\,, \tag{1}$$

where λ is the wavelength of the input light, and $I_1(\lambda)$ and $I_2(\lambda)$ represent the light intensities of the centric core and the eccentric core, respectively. Consequently, φ_{12}, which is the phase difference of the two optical signals, can be expressed as

$$\varphi_{12}=\frac{4\pi\Delta n_{1-2\mathrm{eff}}L}{\lambda}\,, \tag{2}$$

where L is the length of Michelson interference arms. $\Delta n_{1\text{-}2\mathrm{eff}}=n_{1\mathrm{eff}}-n_{2\mathrm{eff}}$, $n_{1\mathrm{eff}}$ and $n_{2\mathrm{eff}}$ are the effective refractive indices of the centric core and the eccentric core, respectively. The resonant dip wavelength is given by

$$\lambda_m=\frac{4\Delta n_{1-2\mathrm{eff}}L}{2m+1},\quad m=0,1,2\ldots. \tag{3}$$

Assuming L is a constant, due to the influence of taper, the thermo-optic coefficient of the eccentric core is determined by the external medium. Therefore, the refractive index response of the Michelson interference can be described as

$$\frac{\mathrm{d}\lambda_m}{\mathrm{d}n}=\frac{\lambda_m}{n_{1\mathrm{eff}}-n_{2\mathrm{eff}}}\left(\frac{\mathrm{d}n_{1\mathrm{eff}}}{\mathrm{d}n}-\frac{\mathrm{d}n_{2\mathrm{eff}}}{\mathrm{d}n}\right). \tag{4}$$

After the double-core fiber is tapered, the taper region has strong evanescent field characteristics. As the refractive index of the surrounding changes, the interference spectrum will drift. According to the amount of the spectrum shift, the change of the refractive index can be obtained for sensing region. The refractive index sensitivity S_{RI} of the structure[17] can be expressed as

$$S_{\mathrm{RI}}=\frac{\mathrm{d}\lambda}{\mathrm{d}n_{\mathrm{SRI}}}=\frac{\lambda\dfrac{\partial\Delta n_{1-2\mathrm{eff}}}{\partial n_{\mathrm{SRI}}}}{\Delta n_{1-2\mathrm{eff}}-\lambda\dfrac{\partial\Delta n_{1-2\mathrm{eff}}}{\partial\lambda}}=\frac{\lambda}{G}\frac{\partial\Delta n_{1-2\mathrm{eff}}}{\partial n_{\mathrm{SRI}}}\,, \tag{5}$$

where n_{SRI} is the ambient refractive index, and G is the group effective refractive index difference. The DCF's transmission modes are calculated by FEM, and then the effective refractive index values corresponding to different modes are obtained. When the external refractive index is 1.334 0 and 1.362 0, the simulation results of the effective refractive index and propagation constant of the DCF can be obtained. Finally, the relationship between the refractive index sensitivity and the diameter of double-core microfiber is calculated when the ambient refractive index is 1.334 0 and 1.362 0. The calculation result is shown in Fig.2.

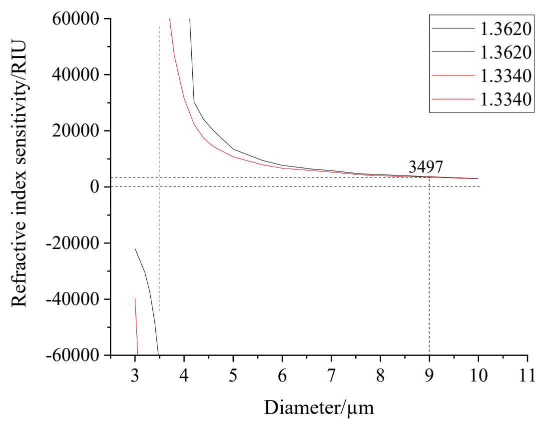


Fig.2 Relationship between the refractive index sensitivity and the diameter of double-core microfiber when the ambient refractive index is 1.334 0 and 1.362 0

From Fig.2, S_{RI} is on both sides of the dispersion turning point. When the fiber diameter is smaller than the dispersion turning point, S_{RI}<0, the region is very small. When the fiber diameter is larger than the turning point, S_{RI}>0, the region is large. When the fiber diameter is equal to the dispersion turning point, the refractive index sensitivity is extremely high, approaching $\pm\infty$. Ultra-high refractive index sensitivity of 10^4 nm/RIU is easily obtained on both sides of the turning point. For example, when the ambient refractive index is 1.362 0, the dispersion turning point is 3.8 μm. S_{RI} are 30 504 nm/RIU and 30 250 nm/RIU at the diameters of 3.2 μm and 4.2 μm, respectively. Therefore, the high refractive index sensitivity of microfiber can be used to obtain the micro change of the surrounding refractive index.

The schematic diagram of the refractive index sensing experimental setup is shown in Fig.3. It consists of a broadband light source (BBS, SC-5), a circulator, the sensing structure and an optical spectral analyzer (OSA, Yokogawa AQ6370C). Silver film is deposited on the flat end surface of DCF by thermal evaporation using multi-functional high vacuum coating machine. A broadband light source (BBS) of 450 nm to 2 400 nm wavelength range is used as the light source. Light is launched from BBS into the sensing structure via a circulator, and the reflected light through the circulator is measured and analyzed by the OSA. The maximum resolution of the OSA is 0.02 nm. The taper is fixed on the glass slide to ensure that the sensing structure is in a straight state, furthermore the sensing structure are immersed in solution.

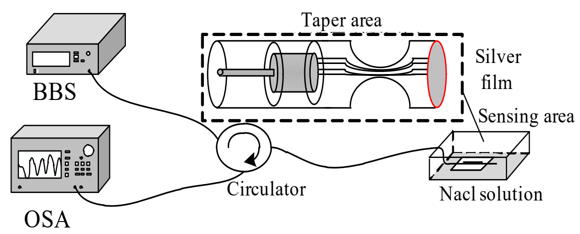


Fig.3 Schematic diagram of refractive index sensing experimental setup

The light emitted by the light source is transmitted to the end of DCF through the circulator and reflected back, and finally output to the spectrometer through the circulator. The taper region of DCF is the sensing unit. The taper region is fixed on the glass slide to ensure that the sensing unit is in a straight state. When the sensing unit is immersed in NaCl solution and the interference spectrum is shown in Fig.4. Because the light is transmitted through SMF-MMF-DCF and the light is reflected back, furthermore, the fiber is fused and tapered, therefore, the light loss is relatively large. However, the interference phenomenon mainly focuses on the interference depth and the wavelength drift.

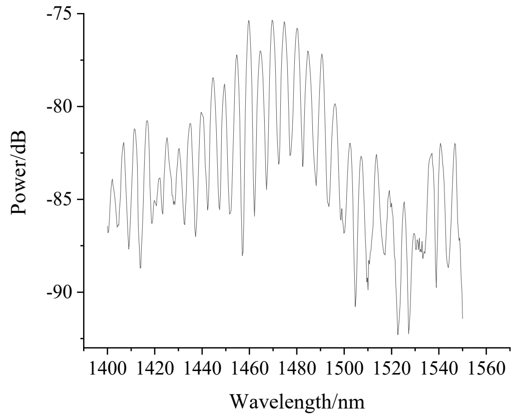
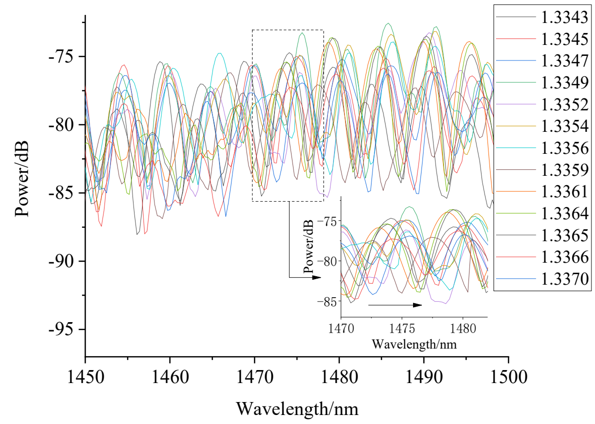
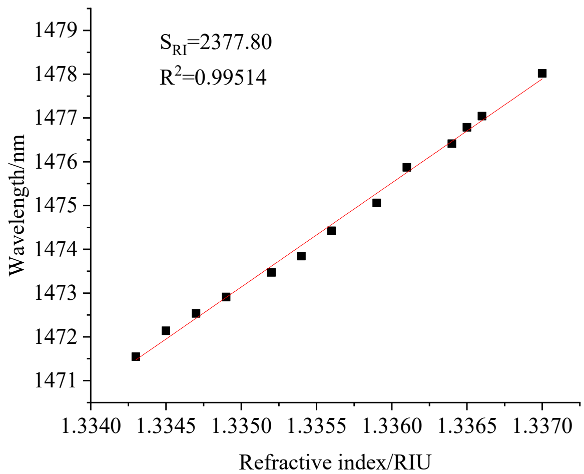


Fig.4 Reflection spectrum of the hybrid fiber interference sensor

When the refractive index of NaCl solution is from 1.334 3 to 1.337 0, the interference spectrum from 1 450 nm to 1 500 nm is obtained as shown in Fig.5(a). The refractive index sensitivity of the sensor can be obtained, as shown in Fig.5(b).



(a)



(b)

Fig.5 (a) Relation between light intensity and the wavelength of Michelson interference; (b) Relation between the wavelength and refractive index of Michelson interference

According to Fig.5(a), with the increase of the refractive index of the solution, the interference spectrum shifts to the long wavelength. This is because that as the refractive index increases the optical path difference between the centric core and the eccentric core changes. The curves of interference spectrum of different refractive index solution are chaotic, which may be caused by the unavoidable experimental noise or the processing of experimental operation. Fig.5(b) indicates that the sensor is very sensitive to the change of refractive index of the environment. When the taper waist is 15.65 mm, the refractive index sensitivity of Michelson interferometer is 2 377.80 nm/RIU. The refractive index sensitivity obtained is highly linear.

The sensing unit is placed horizontally in the temperature control box, as shown in Fig.6. Temperature control accuracy of the control box is 0.1 °C. Temperature in the control box ranges from 30 °C to 60 °C, with the interval of 3 °C.

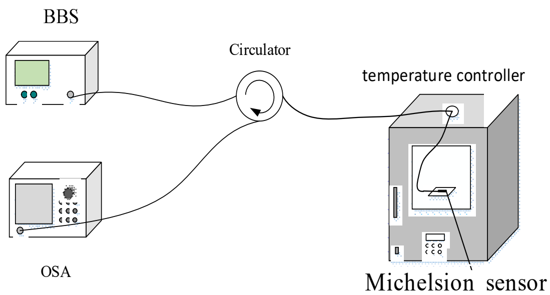
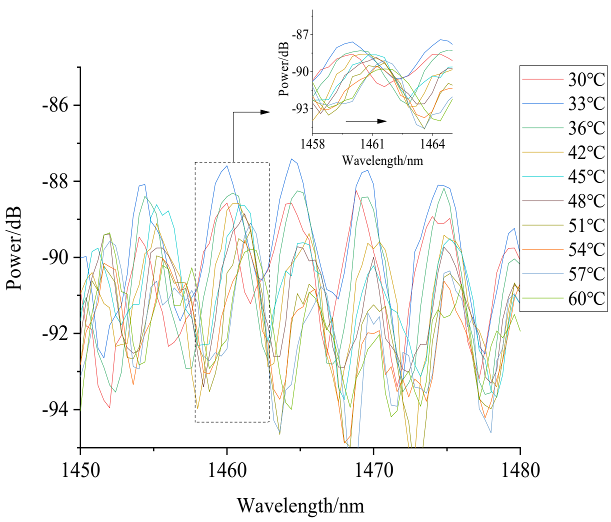
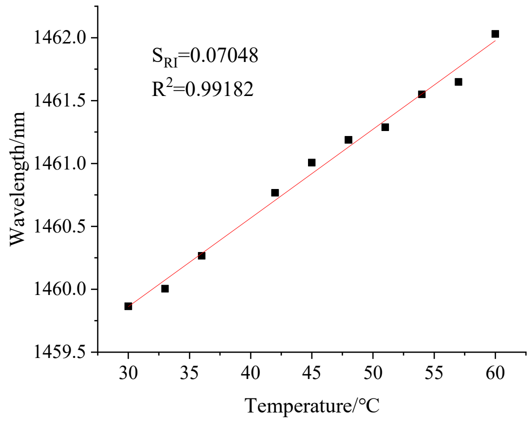


Fig.6 Schematic diagram of temperature sensing experiment system

When the temperature is from 30 °C to 60 °C, the interference spectrum from 1 450 nm to 1 480 nm is obtained as shown in Fig.7(a). The wave trough near the wavelength of 1 460 nm is selected as the observation point and the change of the spectrum with the temperature is obtained. The temperature sensitivity of the sensor is as shown in Fig.7(b).



(a)



(b)

Fig.7 (a) Relation between light intensity and the wavelength of Michelson interference; (b) Relation between wavelength shift and temperature of Michelson interference

Fig.7(a) indicates that the interference spectrum shifts to the long wavelength with the increase of the temperature. According to Fig.7(b), when the temperature changes from 30 °C to 60 °C, the temperature sensitivity of the sensor is 0.070 48 nm/°C, with good linearity.

Comparing this type of sensor with other types of refractive index sensors, as shown in Tab.1, this type sensor based on the double-core microfiber has the higher refractive index sensitivity.

Tab.1 Sensitivity comparison

Sensor structure	RI sensitivity	Temperature sensitivity (nm/°C)	References
MZI based on 3-core	2 665.06 nm/RIU	−0.108 4	[18]
MI based on DCF	2 377.80 nm/RIU	0.070 48	Our work
FTMN	1 191.5 nm/RIU	DipA: 0.064 8 DipB: 0.059 8	[14]
MI based on 3-core	−151.56 dB/RIU	0.048	[13]
F-P	−16.03 dB/RIU	0.010 52	[15]

Because of the strong linear relationship between the refractive index and the temperature of the Michelson interferometer, the cross sensitivity of the refractive index and temperature can be solved by combining the Michelson with fiber Bragg grating (FBG). The FBG was inscribed in single-mode fiber by excimer laser irradiation through a phase mask. According to the two parameter matrix operation method, the matrix can be constructed:

$$\begin{bmatrix} \Delta\lambda_{\mathrm{F}} \\ \Delta\lambda_{\mathrm{M}} \end{bmatrix} = \begin{bmatrix} K_{n\mathrm{F}} & K_{T\mathrm{F}} \\ K_{n\mathrm{M}} & K_{T\mathrm{F}} \end{bmatrix} \begin{bmatrix} \Delta n \\ \Delta T \end{bmatrix}, \tag{6}$$

where $\Delta\lambda_{\mathrm{F}}$ is the wavelength drift of FBG, $\Delta\lambda_{\mathrm{M}}$ is the wavelength drift of Michelson, $K_{n\mathrm{F}}$ is the refractive index sensitivity of FBG, $K_{T\mathrm{F}}$ is the temperature sensitivity of FBG, $K_{n\mathrm{M}}$ is the refractive index sensitivity of Michelson, $K_{T\mathrm{M}}$ is the temperature sensitivity of Michelson, Δn is the change of refractive index, and ΔT is the variation of temperature.

First, the refractive index and temperature characteristics of FBG and Michelson are measured by spectrometer. Then they are combined to measure the wavelength drift of FBG and the wavelength drift of Michelson. The simultaneous measurement of dual parameters can be realized by Eq.(6).

In conclusion, we propose and demonstrate a novel sensor of refractive index sensing, which is based on the Michelson interferometer using double-core microfiber. The refractive index sensitivity of sensor we obtained is about 2 377.80 nm/RIU in the range of 1.334 3—1.337 0 and the temperature sensitivity is 0.070 48 nm/°C in the range from 30 °C to 60 °C. Theoretical analysis shows that the sensor can solve the cross sensitivity problem of refractive index and temperature by combining FBG. According to the above characteristics, the sensor can achieve high refractive index sensitivity within a certain range. Therefore, there is a huge application space for safety monitoring in biochemistry, pharmaceutical chemistry and other fields. Due to the small size of multi-core microfiber, special attention should be paid to the packaging and protection of the sensor.

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