All-Fiber Inline Michelson Interferometer for Simultaneous Measurement of Refractive Index and Temperature

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Abstract
An all-fiber inline Michelson interferometer is presented for simultaneous measurement of refractive index and temperature, which interferometer fabricated by fusion splicing two single-mode fibers to form up-taper with the appropriate parameters. The temperature sensitivity is 63.36 pm/ºC in the range of 20 ºC and 60 ºC, and the RI sensitivity is -13.01 nm/RIU in the range of 1.333 and 1.388 at the wavelength of 1582.6 nm. At the same time, the sensitivity of this structure to temperature and RI are 62.73 pm/ºC and -11 nm/RIU at the wavelength of 1571.1 nm, respectively. This structure can be used to concurrently measure temperature and RI owing to the different sensitivities of them to the two wavelengths. In addition, the device has the advantages of simple structure, easy fabrication, large structural strength and low-cost.

Keywords
Temperature; Refractive Index; Michelson Interferometer; Up-Taper; Optical Fiber Sensor; All-Fiber Sensor

Introduction
In recent years, optical fiber Michelson interferometers (MIs) have been intensively studied in measurement of various parameters, such as refractive index (RI) [1-2], temperature [3], stress [4], Vibration-displacement [5], humidity [6, 7] etc. The sensor of temperature and RI has important application in many biological and chemical environments. Compared with traditional electrical sensors, optical fiber sensors have many advantages, such as high sensitivity, small size, easy fabrication, low-cost and immunity to electromagnetic interference. So far, myriad of techniques based on MIs have been proposed to measure RI and temperature. Some use special fibers to form the composite interference structure. Yingyu Yu et al. proposed a MI consisting of a single abrupt taper, and the cleaved surface is used as the reflection mirror [8]. Fufei Pang et al. proposed a RI sensor constructed by splicing a length of double-cladding (DC) fiber into standard single-mode fiber (SMF) [9]. Above two articles can only measure one quantity (temperature or RI), and the process of manufacturing this sensor is complicated. Xu Yan et al. proposed a MI composed of a SMF core-offset fusion spliced with a thin-core fiber (TCF) [10]. Jing Zhang et al. proposed a configuration of MI with a section of Hi-Bi fiber serving as one of the interference arm [11]. Le Xu et al. proposed a high-temperature sensor demonstrated by a fiber-taper machine and electric-arc discharge [12]. Those structures can realize simultaneous measurement, but their sensitivity is not high or the process of manufacturing this sensor is complicated.

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In this paper, an all-fiber inline MI for simultaneous measurement of RI and temperature is fabricated, which interferometer fabricated by fusion splicing two SMFs to form up-taper with the appropriate parameters, after that we splice the sensor with a hollow tube. The experiment results show that it can realize a RI sensitivity of -13.01 nm/RIU and a large temperature sensitivity of 63.36 pm/°C at the wavelength of 1582.6 nm. In the same temperature and RI range, the temperature sensitivity of 62.73 pm/°C and RI sensitivity of -11 nm/RIU are obtained at the wavelength of 1571.1 nm. Due to the different sensitivities of temperature and RI to the two wavelengths, this structure can be used to concurrently measurement.

2. Device Fabrication and Operating Principle

The schematic diagram of proposed sensor structure is sketched in Figure 1(a). And the microscope image of up-taper is shown in Figure 1(b). First, we removed the coating on the end of the SMF. Then, the end face of SMF is flat by using fiber cleaver (Fujikura, CT-32). Setting the fusion parameters of commercial fusion splicer (Fujikura, 80S) as follows: the duration time of discharge is 3000 ms; the discharge intensity is set as standard; the overlap distance is 150 μm, which is important to the formation of up-taper. With the appropriate parameters, two SMFs are welded to form up-taper. In order to avoid the impact of the external environment on the reflected light of the fiber end face, we spliced a section of hollow tube with internal diameter of 50 μm and the external diameter of 150 μm to the SMF, and the other side of the hollow tube is made into an irregular shape by increasing the discharge parameters. In experiment, the length of the MI is 2.7 cm. The waist diameter of up-taper is 171μm and the taper length is 310 μm.

When input light comes to the up-taper, the higher order cladding mode can be excited. The light transmitted through the fiber core will form the fundamental mode. After a distance of transmission, the fundamental mode and higher order cladding mode reach the end of the fiber. Due to the Fresnel reflection principle, they will be reflected back at reflecting end face. As shown in Figure 1(a). When the fundamental mode and higher order cladding mode reflected reach the up-taper, the higher order cladding mode will be coupled into the fiber core. They will form interference resulted from the phase difference between the fundamental mode and higher order cladding mode.

The RI difference exists on both sides of the fiber end face, so the reflectivity of the interface can be expressed by Fresnel formula

\[ R = \left( \frac{n_1 - n_0}{n_1 + n_0} \right)^2 \]  

Where \( n_1 \) is the RI of the fiber, \( n_0 \) is the RI of the air. The interference of MI is composed of many two-mode interference with different intensity, for simplicity, the reflection spectrum of MI is expressed as two dominant mode interference

\[ I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\varphi) \]  

Where \( I_1 \) and \( I_2 \) are the light intensity in the two interference modes, respectively. \( \varphi = 2\pi \Delta n_{\text{eff}} l \) is the phase difference of the two interference modes, \( \Delta n_{\text{eff}} \) is the effective RI difference of the fundamental mode and the higher order mode, \( l \) is the MI length. When the phase difference satisfies \( \varphi = (2m+1)\pi \), \( m \) is the order of the interference, the dip wavelength can be written as

\[ \lambda_m = \frac{2\Delta n_{\text{eff}} l}{2m+1} \]  

Both of the external temperature and RI changing will cause the interference fringes movement, thus we obtain the sensitivities of measured parameters by tracking the wavelength shift of interference fringes. So the temperature sensitivity of the MIs can be expressed by

\[ \frac{\Delta \lambda_m}{\Delta T} = \left( \frac{\Delta n_{\text{eff}}}{n \Delta T} + \frac{\Delta l}{l \Delta T} \right) \lambda_m \]
where \( \frac{\Delta n_{\text{eff}}}{\Delta T} \) is the thermo-optic coefficient of fiber material. \( \frac{\Delta l}{\Delta T} \) is the thermal expansion coefficient of fiber material. As shown in Equation (4), it is evident that the changes in temperature affect the RI and the length of the MIs, and leading to the shift of interference wavelength. More accurately, the differential thermo-optic coefficient and the differential thermal expansion coefficients determine the sensitivity of the sensor.

When the RI of the external environment changes, the effective RI of the cladding mode will change. But the effective RI of the fundamental mode is constant. So the change of the dip wavelength in the interference fringes can be expressed as:

\[
\delta \lambda_m = \frac{\Delta n_{\text{eff}}}{\Delta n_{\text{eff}}} \lambda_m
\]

(5)

where \( \Delta n_{\text{eff}} \) is the change of \( n_{\text{eff}} \). \( \lambda_m \) is the wavelength of the \( m^{th} \) order interference dip. \( \delta \lambda_m \) is the change of \( \lambda_m \). As shown in Equation (5), it is evident that the changes of \( \Delta n_{\text{eff}} \) will lead to the shift of interference wavelength.

3. Experimental Results and Discussion

The schematic diagram of the temperature sensing experimental setup is shown in Figure 2. The broadband source is used as the light source and the optical spectrum analyzer (OSA, anritsu cma5000) is used to monitor the reflection spectra of Michelson interferometer.

Figure 2: Schematic Diagram of the Temperature Sensing Experimental Setup

We put the sensor in the water tank and increase the temperature from 20 °C to 60 °C. The reflection spectra at different temperature are shown in Figure 3. The extinction ratio of the wavelength we select is around -9 dB. Figure 4(b) is the reflection spectra at the wavelength of 1582.6 nm. It can be seen that a red shift of the reflection spectra happens with the increase of the temperature. Experimental results show that the temperature sensitivity is 63.36 pm/°C with a value of \( R^2 = 0.9991 \) at the wavelength of 1582.6 nm, as shown in Figure 4(a). At the wavelength of 1571.1 nm, the temperature sensitivity is 62.73 pm/°C with a value of \( R^2 = 0.9998 \), as shown in Figure 5(a).

We change the RI of liquid from 1.333 to 1.384 by glycerin and calibrate it with an Abbe RI instrument. Then we put the sensor into the solution with different RI. Recording the reflection spectrum with a spectrometer at room temperature as shown in Figure 6. After measuring the RI, the sensor needs to be carefully cleaned with alcohol. The extinction ratio of the spectra is around -9 dB. Figure 4(b) is the reflection spectra with different RI liquids at the wavelength of 1582.6 nm. It can be seen that a blue shift of the reflection spectra happens with the increase of the RI. As shown in Figure 7(a), the sensitivity of this proposed interferometer to RI is -13.01 nm/RIU with a value of \( R^2 = 0.9843 \) at the wavelength of 1582.6 nm. In Figure 8(a), the RI sensitivity is -11 nm/RIU with a value of \( R^2 = 0.9752 \) at the wavelength of 1571.1 nm.

Figure 3: Reflection Spectra of the Structure with Different Temperature

Figure 4(a): Wavelength Shifts as a Function of the Surrounding Temperature; (b) Reflection Spectra with Different Temperature at 1582.6nm
The experimental results show reflection spectrum has red shift for temperature whereas reflection spectrum of RI has blue shift. Due to different response of temperature and RI to the two wavelengths, it can realize to simultaneously measure RI and temperature. The resolution matrix for concurrent measurement can be expressed as

$$\begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix} = \begin{bmatrix} k_{1,n} & k_{1,T} \\ k_{2,n} & k_{2,T} \end{bmatrix} \begin{bmatrix} \Delta n \\ \Delta t \end{bmatrix}$$

where \(\Delta \lambda_1\) and \(\Delta \lambda_2\) represent the wavelength shifts of dip wavelength \(\lambda_1\) and dip wavelength \(\lambda_2\), respectively; \(k_{1,n}\) and \(k_{2,n}\) are respectively the RI sensitivity of two wavelengths we are interest in, and \(k_{1,T}\) and \(k_{2,T}\) are respectively the temperature sensitivity of \(\lambda_1\) and \(\lambda_2\); \(\Delta n\) and \(\Delta t\) are respectively variations of RI and temperature; \(k\) is the sensitivity matrix.

Using the standard matrix inversion method, we can get the variations of RI and temperature

$$\begin{bmatrix} \Delta n \\ \Delta T \end{bmatrix} = \frac{1}{det(k)} \begin{bmatrix} k_{2,T} & -k_{1,T} \\ -k_{2,n} & k_{1,n} \end{bmatrix}^{-1} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix}$$

Using the experimental data, we can rewrite the resolution matrix as

$$\begin{bmatrix} \Delta n \\ \Delta T \end{bmatrix} = \begin{bmatrix} -11 & 0.06278 \\ -13.01 & 0.06336 \end{bmatrix}^{-1} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix}$$

It can rewrite by

$$\begin{bmatrix} \Delta n \\ \Delta T \end{bmatrix} = \begin{bmatrix} 0.5288 & -0.5240 \\ 108.5906 & -91.8137 \end{bmatrix}^{-1} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix}$$
4. Conclusion
In conclusion, an all-fiber inline MI for simultaneous measurement of RI and temperature is proposed and fabricated. The fabrication process of the device is very simple and only involves splicing two SMF to form up-taper. We splice a section of hollow tube to the SMF and make the other side of it into an irregular shape to avoid the influence of the external environment on the reflected light. We obtain the sensitivity of temperature and RI at the wavelength of 1571.1 nm and 1582.6 nm by experiment. Experimental results show that the reflection spectrum has red shift with the increase of temperature and blue shift with the increase of RI. Owing to different response of temperature and RI to the two wavelengths, it can realize to simultaneously measurement. In addition, the device has the advantages of simple structure, easy fabrication, large structural strength and low-cost.

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