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A robust high refractive index sensitivity fiber Mach–Zehnder interferometer fabricated by femtosecond laser machining and chemical etching

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ABSTRACT

A fiberized refractive index (RI) Mach–Zehnder interferometer (MZI) based on a micro V-shaped slot in fiber core is fabricated in a standard single mode optical fiber by femtosecond laser machining and chemical etching. The interference fringe of the MZI would shift with the variation of the ambient RI. The experimental results show that the RI sensitivity for the sensor is about -10^4 nm/RIU (refractive index unit) within the RI range between 1.332 and 1.352. Its robust structure and high sensitivity will have attractive potential application in chemical, biological and environmental monitoring.

1. Introduction

Refractive index (RI) measurement gives important information in medical, chemical, industrial and environmental application. In most modern applications, there is a demand for miniaturization, real time and in situ sensing. Fiber-based technology provides feasible, simple, low cost, and highly sensitive alternatives. Product of this interest, several RI sensors based on mature fiber technology have been recently proposed. According to their operation principle, they can be mainly divided into two kinds, sensors detecting light intensity or transmission spectrum. The former include D shape polished fiber [1,2], micro hole fiber [3], and the later include fiber Bragg grating (FBG) structure [4], long period fiber grating (LPFG) structure [5], optical ring resonator [6], Fabry–Perot interferometer (FPI) [7], and Mach–Zehnder interferometer (MZI) [8–15].

Among the various RI sensors, the RI sensitivity of fiber interferometer is much higher. Although the sensor based on single-mode micro-fiber Sagnac loop interferometer exhibits quite high sensitivity to the ambient RI, which is found to be 12,500 nm/RIU (refractive index unit) [16], the sensor size is several millimeter, which cannot be used in miniaturized detection. All-optical fiber sensors based on FPI and MZI have been successfully fabricated in various structures by femtosecond laser pulses. The size of effective detecting unit is several tens to several hundreds of micrometers. The RI sensitivity of fiber FPI cavity fabricated by femtosecond laser micromachining and fusion splicing is ~994 nm/RIU [17]. And the MZI sensor with D-shape fiber core exhibits ultrahigh RI sensitivities of 3754.79 ± 44.24 nm/RIU with refractive index ranging from 1.0001143 to 1.0002187, and $12{,}162.01 \pm 173.92$ nm/RIU with refractive index ranging from 1.3330 to 1.33801 [18]. This paper investigated a micro V-shaped removal structure is introduced in SMF by femtosecond laser irradiation and hydrofluoric acid (HF) chemical etching. An in-line fiber MZI is formed with the mono microstructure. Since the removal structure is smaller than tenth fiber volume, the sample has nearly the same robust performance as the fiber without any damage. The transmission spectra can be controlled by HF etching process, and when the RI value of water-based sodium chloride (NaCl) water solution is in the 1.332–1.352 range, the output spectrum dip shifts with the sensitivity up to $-12{,}031.75 \pm 108.19$ nm/RIU, and the linearity is greater than 0.997.

2. Sensor fabrication and operation principle

In a conventional single-mode optical fiber (Corning SMF-28e), whose core diameter and cladding diameter are 8.2 μm and 125 μm, respectively. The RI of the core is higher than that of the

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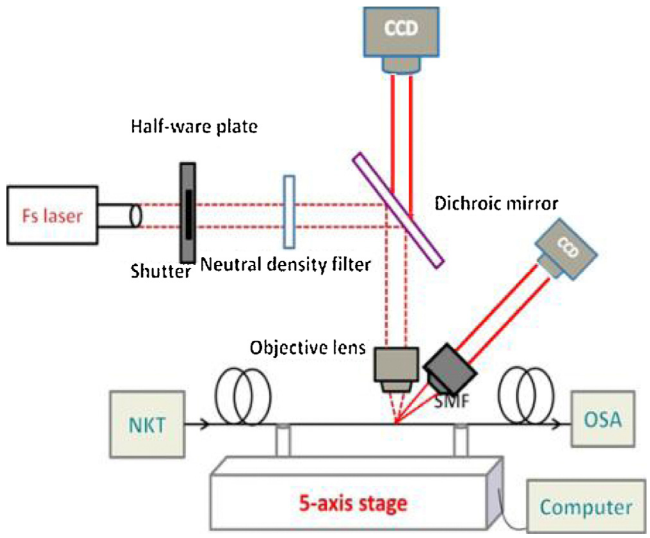

Fig. 1. Schematic diagram of the femtosecond laser fabrication and measurement system.

cladding; therefore, the light is confined to the host fiber mainly. In order to split the light in fiber core into two paths, a micro V-shaped slot in fiber core is fabricated along the fiber by femtosecond laser machining and chemical etching. The femtosecond laser (Spectra-Physics, Inc.) with central wavelength of 800 nm, pulse width of 120 fs and repetition rate of 1 kHz is utilized for the sensor micromachining. The laser pulse energy is attenuated through a neutral density attenuator to less than 10 μJ before the 10× objective lens (NA = 0.25). A wide band source (NKT Inc.) with 500–2400 nm optical spectra range and an optical spectrum meter (Agilent Technologies Inc.) (86142B) with 10 pm wavelength accuracy are employed to monitor the transmission spectra by wavelength sweeping.

The fiber samples are amounted in V-grooves on a five axis nano-translation stage (Newport, Inc). Visual confirmation of focusing is provided by means of two CCD cameras imaging through the microscope objective lens. The size of the machined regions as well as the impact on optical transmission caused by damage within the guiding fiber core strongly depends on the pulse energy and the scanning speed. The value of femtosecond laser scanning speed is 20 μm/s. Femtosecond laser machining is performed in layers from the core toward the surface of the fiber, the scanning width in each layer is 2 μm and the step size is 7 μm. The pulse energies in the first two scanning cycles near fiber core and the later seven scanning cycles in cladding are 4 μJ and 10 μJ, respectively. After femtosecond laser processing, the transmission of the sample is not attenuated evidently. Then the samples are immersed in 5% HF solution for several tens minutes, and a micro slot is formed in SMF. The RI sensitivity of samples is measured in a solution pool by increasing the concentrations of NaCl in water solution. A schematic diagram of fabrication and of the measurement set up is shown in Fig. 1.

The micro slot cross section is shown in Fig. 2. The top of the micro structure has two wings in cladding, which is caused by the higher pulse energy (10 μJ) femtosecond laser ablation cladding. Since the surface of fiber is ablated firstly, the remaining rough structure would cause the scattering of femtosecond laser to two sides, thus created two wings. However, the two wings have slight influence on the transmission of the spectrum, which can be ignored, and the forming structure is considered as a narrow V-shaped slot.

The fabricated structure forms a MZI whose core mode light transmission in two main paths, the remaining fiber core and the

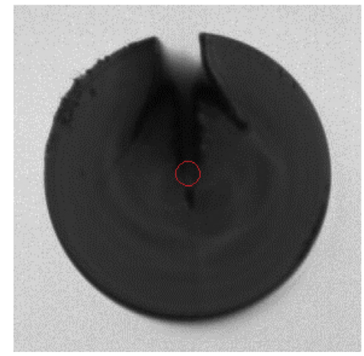

Fig. 2. Cross section of micro slot in SMF fabricated by femtosecond laser and HF etching.

micro V-shaped slot. The interference intensity can be expressed by [11]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{2\pi\Delta n_{eff} L}{\lambda} + \phi_0\right) \quad (1)$$

where I_1 and I_2 are the intensities along the two light paths; Δn_{eff} is the difference between effective refractive index of the remaining fiber core and the micro V-shaped slot; L is the slot length; λ is the wavelength; and ϕ_0 is the initial interference phase. The fringe visibility is optimized to maximum when $I_1 = I_2$.

According to Eq. (1), the m^{th} transmission spectrum interference fringes trough λ_m meets the following equation:

$$\frac{2\pi\Delta n_{eff} L}{\lambda_m} + \phi_0 = (2m+1)\pi \quad (2)$$

Thus,

$$\lambda_m = \frac{2\pi L}{(2m+1)\pi - \phi_0}\Delta n_{eff} \quad (3)$$

$$\Delta\lambda_m = \frac{2\pi L}{(2m+1)\pi - \phi_0}\Delta(\Delta n_{eff}) = S_{RI}\Delta n_{ext} \quad (4)$$

S_{RI} is the sensor RI sensitivity, Δn_{ext} is the RI change of external environment.

The phase difference of two adjacent interference signals is 2π. That is

$$\left(\frac{2\pi\Delta n_{eff} L}{\lambda_{m+1}} + \phi_0\right) - \left(\frac{2\pi\Delta n_{eff} L}{\lambda_m} + \phi_0\right) = 2\pi \quad (5)$$

$$\frac{1}{\lambda_{m+1}} - \frac{1}{\lambda_m} = \frac{1}{\Delta n_{eff} L} \quad (6)$$

where λ_m and λ_{m+1} are the wavelengths corresponding to the two adjacent interference signals. Note that m is the m^{th} interference order. It indicates that the free spectral range ($FSR = \lambda_{m-1} - \lambda_m$) decreases as the ablation length or the effective RI difference of the interference two arms increases, which is adverse for the detection range.

3. Mechanical characteristics and mode numerical simulation

Sensors will inevitably expose to shock environment during manufacture, transportation and use. Practical application of the sensor should have not only high sensitivity, also has a high reliability. A model of 150 μm optical fiber and that with 50 μm V-shaped slot are build respectively. The left cross section is fixed, and a 6 mN surface tension along negative Y direction is applied on the right cross section. SiO_2 has elasticity modulus of 55 GPa and Poisson's ratio of 0.25.