Ultrafast Laser Fabrication of Novel Fiber Mach-Zehnder Interferometer Sensors and Its Cost-Effective Alternative Manufacturing Methods

(Invited Paper)

Wang Sumei[1] Jiang Lan[1*] Li Benye[1] Zhao Longjiang[1] Yang Jinpeng[1]
Wang Mengmeng[1] Xiao Hai[2] Lu Yongfeng[3] Hai-Lung Tsai[4]

[1] *School of Mechanical Engineering, Beijing Institute of Technology, Beijing* 100081, *China*
[2] *Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO* 65409, *USA*
[3] *Department of Electrical Engineering, University of Nebraska-Lincoln, Lincoln, NE* 68588-0511, *USA*
[4] *Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO* 65409, *USA*

* *Corresponding author: jianglan@bit.edu.cn*

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Abstract The recent progresses of fiber sensor fabrication in our group are reviewed. Novel inline fiber Mach-Zehnder interferometer (MZI) sensors with various structures are proposed and manufactured by femtosecond laser fabrication and fusion splicing for high-quality sensing of refractivity-sensitive parameters such as temperature, concentration, humidity, pressure, stress and strain: a) for an MZI sensor with a trench on a single-mode fiber, the refractive index (RI) sensitivity of acetone vapor is about 10^4 nm/RIU (refractive index unit) and the temperature sensitivity is 51.5 pm/℃ from 200 to 875 ℃; b) For an MZI consisting of two micro-air-cavities, the sensitivity is 501.5 nm/RIU and the detection limit is 1.994×10^{-6} RIU at the refractive index of 1.4; c) to reduce the fabrication cost, a new fusion-splicing based method is proposed to fabricate MZI sensors; the sensitivity is 664.57 nm/RIU with a detection limit of 1.5×10^{-6} RIU and its cost is tens of times cheaper than those of commercialized long period fiber Gratings; Also, 5×10^{-5} acetone vapors are successfully detected by the MZI sensors coated with zeolite thin films.

Key words sensors; novel fiber Mach-Zehnder interferometer; femtosecond laser micromachining; fusion splicing
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1 Introduction

Optical fiber sensors with various schemes such as fiber gratings, interferometers and other interesting configurations have been developed greatly in recent years. Fiber sensors based on interferometers are among those with the highest sensitivity in various fiber structures. The fringe visibilities of interference signals are typically higher for transmission-type interferometers [such as Mach-Zehnder Interferometer (MZI)] than reflection-type interferometers (such as Fabry-Perot interferometer). Since a larger fringe visibility of higher quality sensor suggests a better resolving effect for sensing applications, sensors based on transmission-type interferometers are of great potentials for chemical and biological sensing area. Femtosecond (fs)-lasers open wide-range and exciting new possibilities in micro/nano-scale fabrication[1~4], which presents unique advantages in three dimensional (3D) structuring of transparent materials[5], especially for fiber devices[6] such as ultrasensitive ultracompact optical sensors[7,8]. In additional to fs-lasers fabrication[9,10], arc fusion splicing[11] has also been used to make fiber sensors including Fabry-Perot sensors, micro-air-cavities of fiber sensors and long-period fiber grating (LPFG) sensors[12]. Recently, it is discovered that zeolite thin film coating can significantly improve sensitivity of LPFG sensors[13,14]. On the other hand, most-recently developed fiber-based MZI sensors seem very promising due to the high fringe visibility, high refractive index (RI) sensitivity, and long temperature sensing range[15,16].

Here, we review the recent progresses of fiber sensor fabrication in our group. Various fiber MZI structures are designed and fabricated by the fs-laser. Also, a new method is proposed to fabricate fiber MZI sensors to reduce the cost, in which two splice points are modified by using a fusion splice and then concatenated together. The inline MZI sensors are coated with zeolite films. Upon selective adsorption and desorption of the target analyte molecules, the zeolite thin film changes its refractive index. High sensitivity can be achieved for the refractive index changes in the close vicinity of the fiber. The fiber sensors are applied for refractive index and temperature test. The sensitivity of 664.57 nm/RIU (refractive index unit) and detection limit of 1.5×10^{-6} RIU are obtained using thinned cladding MZI sensors with high production repeatability and very low cost. Significant wavelength shift is observed for 5×10^{-5} acetone vapor in nitrogen (N_2) by the new MZI sensors with zeolite thin film coating. With very low fabrication cost and high production repeatability, the new MZI fiber sensors demonstrate exciting potentials in high-quality sensing of refractivity-sensitive parameters such as temperature, concentration, humidity, pressure, stress and strain.

2 Experimental setup

The scheme of an fs-laser fiber system for sensor fabrication is shown in Fig. 1. The central wavelength, pulse width and repetition rate of the fs-laser (Spectra-Physics, Inc.) are 800 nm, 35 fs and 1 kHz, respectively. The laser pulse energy is attenuated through a half-wave plate and a polarizer to less than 50 μJ. Then, several neutral density filters are applied to reduce the pulse energy to less than 600 nJ before the objective lens. The attenuated fs-laser beam is focused into the fiber sample by an objective lens with numerical apertures (NA) of 0.45. The diameters of the single-mode fiber core and cladding are 8.2 and 125 μm respectively. For fabrication of 3D microstructures, fiber samples are translated by a six-axis motion stage (PI). A detection system (Agilent 8163B, USA) consisting of a tuneable laser and an optical power meter is employed to monitor the transmission spectra by wavelength sweeping. Nitrogen gas is used to blow off the debris during the fs-laser fabrication process, which assists to obtain a high quality MZI.

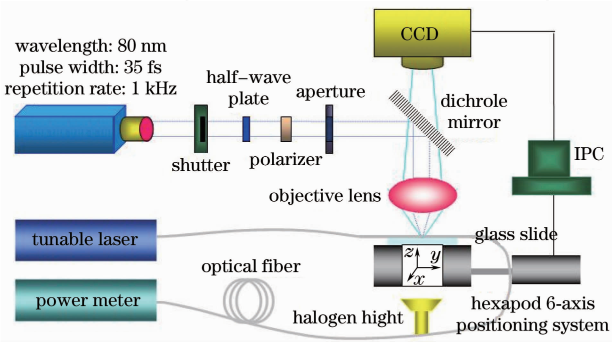

Fig.1 Schematic diagram of the fabrication system experimental setup

3 Results and discussions

3.1 Trench structure MZI fiber sensors fabricated by an fs-laser

Trench structure MZI fiber sensors are fabricated. As shown in Fig. 2, the fiber core is partially removed and the input testing laser beam (I_{in}) is then split into two portions: one (I_1) through the remained core and the other (I_2) through the cavity in the ablated trench, i.e., the MZI interferometer consists of two light arms: 1) a microcavity arm by the removed part of the fiber core (cavity) and 2) the remained fiber core arm.

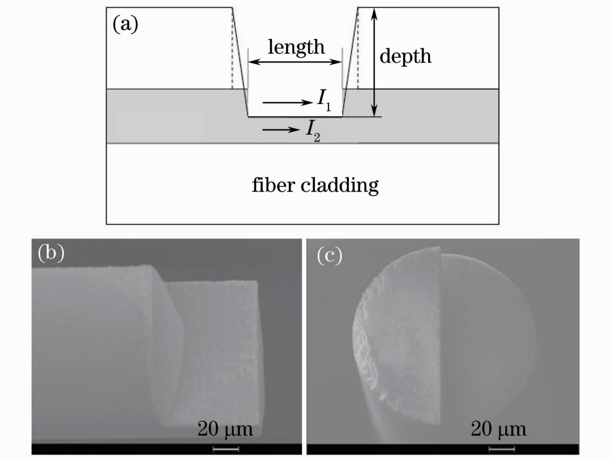

Fig.2 Trench structure MZI fabricated by fs-laser pulses (a) structural illustration, (b) side view (a half part), (c) cross section

An MZI with the trench length of about 75 μm is obtained and the transmission spectra in atmosphere varying with 1st ~ 8th scanning cycles are shown in Fig. 3. In each scanning cycle, the fs-laser scans in x-y plane and then the motion stage moves in z direction at the same depth controlled by a hexapod 6-axis positioning system, which ensures the desired ablation depth. In the 1st scanning cycle, the ablation depth is about 60 μm in z direction, for which, the transmission spectrum shows an attenuation peak with a relative low value. Figure 3 shows the transmission spectra evolutions varying from the 1st scanning cycle to the 8th scanning cycle. The fringe visibiltiy increases from the 1st scanning cycle to the maximum at the 5th scanning cycle and then decreases from the 6th to the 8th scanning cycle. According to the theory for MZI[16], the fringe visibility depends on the intensity of I_1 and I_2, and reaches the maximum value while $I_1 = I_2$. With the laser irradiation scanning, the ablated surface becomes more and more bright. No distinct change is observed in the 8th scanning cycle. Tens of MZI sensors with different ablated lengths are fabricated, which demonstrates a high repeatability. The fs-laser processing stops when a desired transmission spectrum is detected. During the whole fabrication process, the transmission spectrum is timely monitored for each scanning cycle.

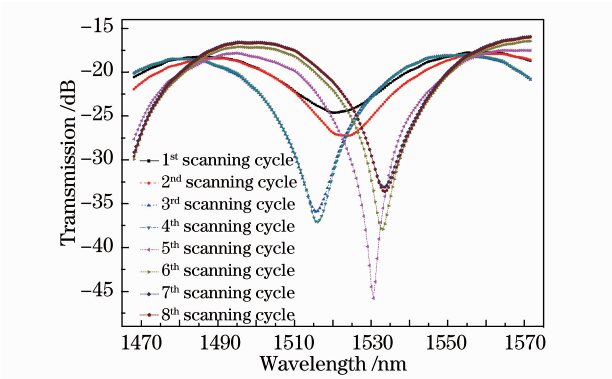

Fig. 3 Transmission spectra vary with scanning cycles[16]

Figure 4 shows the gas sensing tests in air and acetone vapor by using the MZI sensor. The MZI sensors are of very high efficiency and repeatability with the fringe visibility of 25 dB. The wavelength shift of about 6.5 nm demonstrates the promising potentials in chemical and biological detections.

Figure 5 shows temperature measurements by using the proposed fiber sensor. The interference dip wavelength shows a red shift with the temperature increase. The temperature sensitivity estimated by least square linear fitting is 51.5 pm/℃ from 200 to 875 ℃ that is significantly higher than the upper temperature limit, about 300℃, of commercial LPFG sensors.

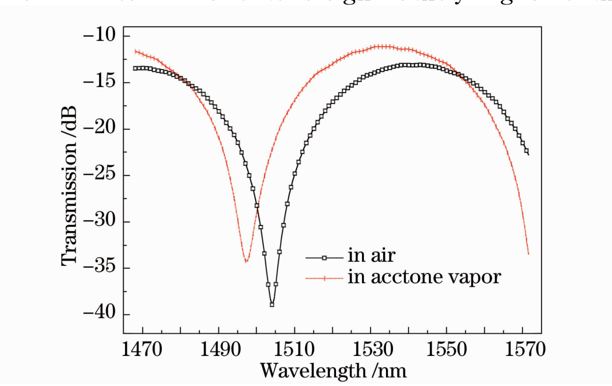

Fig. 4 Sensing tests in air and acetone vapor

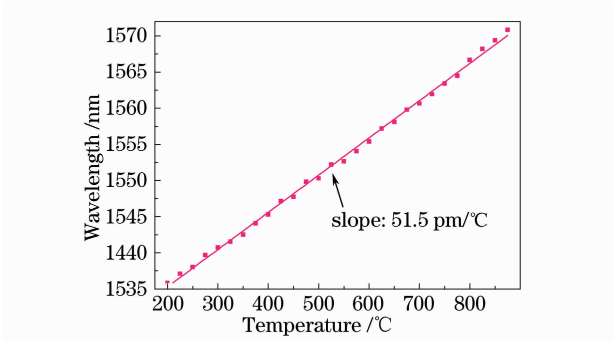

Fig. 5 Temperature sensing property of the MZI sensor

3.2 Air cavity-based MZI fiber sensors fabricated by an fs-laser

As shown in Fig. 6(a), another MZI structure consisting of two air micro-cavities is fabricated in a single-mode optical fiber by the fs-laser. A micro-hole on the fiber-end is first ablated as shown in Fig. 6(b). The diameter and depth of the hole are about 8 and 12 μm, respectively. Then, a micro-air-cavity is formed by splicing the micro-hole fiber end with a normal cleaved fiber end using a fusion splicer. After spliced together by arc fusion, the cylindrical hole becomes a ellipsoid cavity as shown in Fig. 6(c). A same micro-air-cavity with the length of 15 mm after the first one along the fiber core axis is also made as shown in Fig. 6(a). Hence, a fiber interferometer is then formed.

For the MZI of this type, the fringe visibility is 17 dB and the full width at half maximum (FWHM) is 0.06 nm in air. The interference dip wavelength as a function of external RI in sucrose solutions of different concentrations is shown in Fig. 7. The RI sensitivity of 501.5 nm/RIU is obtained at the refractive index of 1.4, which is several times higher

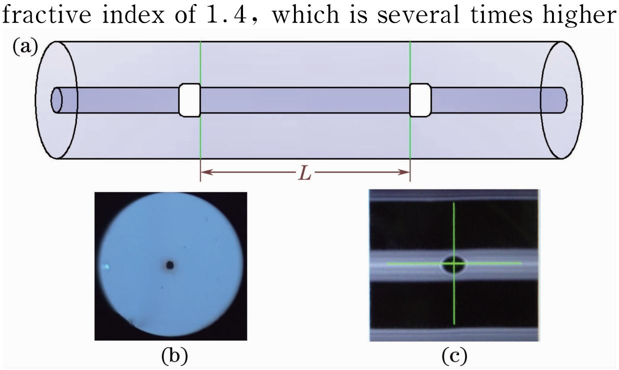

Fig. 6 (a) Schematic diagram of the MZI composed of two micro-air-cavities, (b) fiber end with a hole, (c) formed micro air cavity than that of LPFG or taper-based devices. The detection limit is 1.994×10^{-6} RIU for a detecting system with a resolution of 1 pm. In addition, the MZI sensor of this type is more robust than the aforementioned MZI fiber sensor of a trench structure.

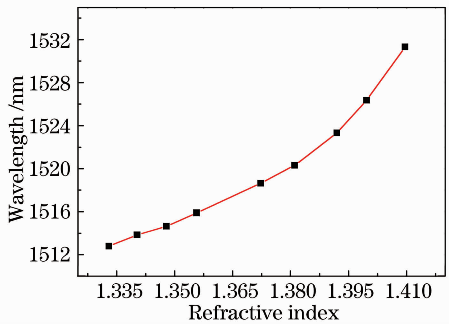

Fig. 7 Interference dip wavelength of the MZI sensor as a function of external RI in sucrose solutions of different concentrations

3.3 Taper-based MZI fiber sensors fabricated by fusion splicing

The fs-laser fabrication of MZI sensors is of high quality, yet, with high cost. To reduce the cost, a new fabrication method is proposed for fiber MZI sensors, in which, the MZI is formed by concatenating two modified splice points made by using a fusion splicer. The two normal cleaved ends become ellipsoidal during the first discharge. Then, the two ellipsoidal heads are moved to be contacted in the center of the splicer electrodes. The two ellipsoidal heads are fused together by the second discharge. The other splice junction point is formed by the same process separated by a distance of L. The transmission spectrum of an MZI with length of 36 mm is shown in Fig. 8. The fringe visibility is 25 dB.

The proposed fabrication method is applicable for not only photonic crystal fibers but also ordinary

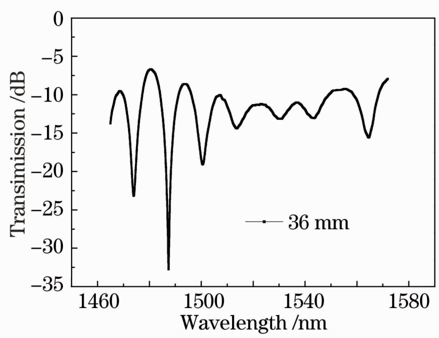

Fig. 8 Transmission spectrum of an MZI fabricated by fusion splicing

optical fibers, whose cost is tens of times cheaper than those of commercialized LPFGs. The fabricated MZI has advantages such as simpleness, cost-effective, high-quality and high-robustness. It can be used to measure temperature, concentration, stress, strain and so on. With a gas sensitive film coating, it can also be used as a gas sensor.

Figure 9 shows the shift of the maximum attenuation wavelength (around 1492.8 nm) with respect to the external RI changes. The sensitivity is 24.05 nm/RIU. In order to improve the RI sensitivity of the MZI sensor, wet chemical etching is applied to remove part of the cladding using hydrofluoric (HF) acid solution at a concentration of 20%. The etched part is in the center of the two junction points with the length of 15 mm and the residual fiber diameter of 30 μm. Figure 10 shows the shift of the maximum attenuation wavelength (around 1507 nm) with respect to the external RI change. At a resolution of 1 pm of the detecting system, the detection limit is 1.5×10^{-6} RIU.

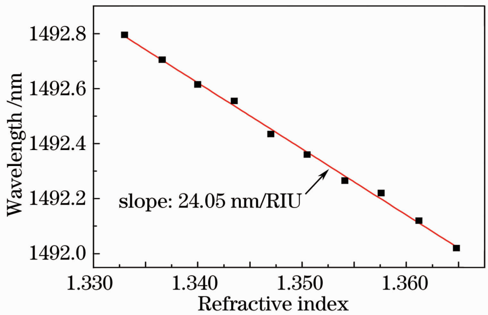

Fig. 9 Shift of the maximum attenuation with the external RI change

With zeolite thin film coating, gas sensitivity of 5×10^{-5} is achieved by the MZI sensors. Zeolites are crystalline aluminosilicate materials possessing a unique combination of chemical and optical prop-

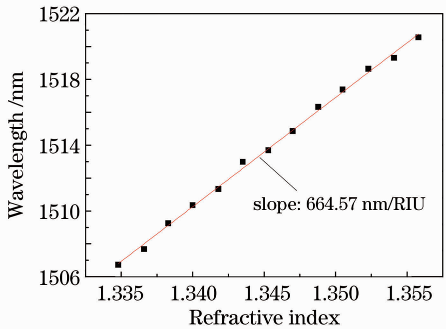

Fig. 10 Shift of the maximum attenuation wavelength versus the external RI change for the thinned cladding zeolite-film coating MZI with a diameter of 30 μm

erties that is ideal for various optical chemical sensors. The uniform molecular scale pore size and enormous surface-to-mass ratio make zeolites ideal sorbents for selective molecular adsorption. Thin MFI-zeolite film is formed on the fiber surface. The transmission spectra of the gas sensor response to various concentrations of acetone vapor in N_2 environment are shown in Fig. 11. As the acetone vapor concentration increases, a blue shift is observed in the transmission spectra.

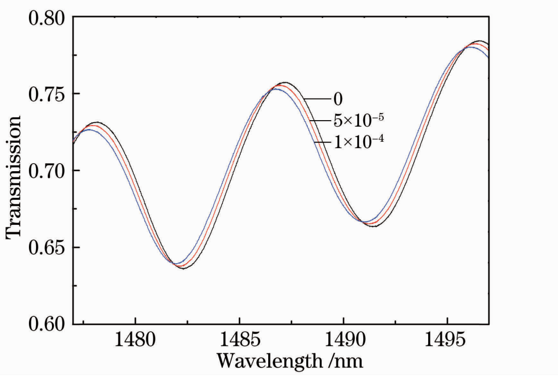

Fig. 11 Transmission spectra of the MZI gas sensor response to various concentrations of acetone vapor in N_2

4 Conclusions

The recent progresses on fabrication of high performance fiber sensor in our group are reviewed. Trench-structure MZI and air cavity-based MZI structure are designed and fabricated by the fs-laser, which is of high quality, yet, high cost. Also, to reduce the fabrication cost, a new method is proposed to fabricate fiber MZI sensors by concatenating two modified splice points made by using a fusion splicer. The inline MZI sensors are coated with zeolite films. The MZI fiber structures are applied to sense temperature and refractive index changes. Using the MZI sensors with a trench structure in fibers, the RI sensitivity is 10^4 nm/RIU for acetone vapor and the temperature sensitivity is 51.5 pm/℃ from 200 to 875 ℃ that is significantly higher than the upper temperature limit, about 300 ℃, of the commercial LPFG sensors. The theoretical measurement limit of the new MZI sensor can be above 1100 ℃. The RI sensitivity is 501.5 nm/RIU with the micro-air-cavity based structure and the detection limit is 1.994×10^{-6} RIU at the RI of 1.4. For the simple MZI sensor fabricated by fusion splicing, the RI sensitivity is greatly improved after a part of the cladding is removed by hydrofluoric (HF) acid solution. The sensitivity of 664.57 nm/RIU and detection limit of 1.5×10^{-6} RIU are obtained for the thinned cladding MZI fiber sensor. The MZI sensors are applied for direct measurement of acetone vapor of 5×10^{-5} in N_2 after being coated with zeolite thin film. The MZI sensors are of very high fabrication and sensing repeatability with many advantages including structure simpleness, reliability, compactness, robustness, high sensitivity, high flexibility, high production repeatability, and simple low-cost fabrication process. Development of high performance fiber inline sensors based on transmission-type interferometers, especially fiber sensors that can detect two or more physical parameters simultaneously is an important and prospective direction in optical sensing area.

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2011年“纪念《光学学报》创刊30周年特刊”
征　稿　启　事

创刊于1981年的《光学学报》是中国光学学会主办的第一本期刊。30年来，在历任主编王大珩院士、王之江院士、王润文研究员、徐至展院士和现任主编曹健林研究员的领导下，《光学学报》取得了一系列的成绩。2010年影响因子达到2.0，在国内物理类科技期刊中排名第一，连续7年荣获“百种中国杰出学术期刊”，被世界重要检索系统EI，CA，AJ和INSPEC等收录。《光学学报》始终致力于为我国光学科技人员与国内外同行进行学术交流、开展学术讨论以跟踪学科前沿和发展我国光学事业服务。《光学学报》刊登的论文集中反映了中国光学科技的新概念、新成果和新进展，其内容主要包括光纤光学与光通信、激光光学、信息光学、光学测量、光谱学、薄膜光学、量子光学、非线性光学、光学器件和材料等。为了纪念《光学学报》创刊30周年，编辑部计划在2011年9月正刊上出版“纪念《光学学报》创刊30周年特刊”，现特向国内外广大专家征集研究快报、研究论文和综述，以期集中反映我国近年来在光学及其相关领域取得的重大成就。

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