Optics & Laser Technology 44 (2012) 640–645

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

High sensitivity Mach–Zehnder interferometer sensors based on concatenated ultra-abrupt tapers on thinned fibers

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ARTICLE INFO

Article history:
Received 21 July 2011
Received in revised form
8 September 2011
Accepted 13 September 2011
Available online 29 September 2011

Keywords:
Mach–Zehnder interferometer
Refractive index sensor
Fiber taper

ABSTRACT

This study proposes a simple, cost-effective method to fabricate fiber-based Mach–Zehnder interferometer (MZI) sensors by concatenating two ultra-abrupt fiber tapers together using a fusion splicer. By concatenating, the taper diameter and length ratio is 1:1 that is much greater than that (1:10) by stretching. The refractive index sensitivity is comparable to the MZI sensors based on long-period fiber grating pairs or stretched fiber taper pairs. The MZI fiber claddings are etched to improve the sensitivity of refractive index measurements. The sensitivity is 664.57 nm/RIU (refractive index unit) for the refractive index ranging from 1.3348 to 1.3558, which is 2–6 times greater than those measured by long period fiber gratings (LPFGs) after sensitivity enhancement.

1. Introduction

Optical sensors have attracted tremendous research interests in recent years [1–5]. Among many promising photonic devices, fiber-based Mach–Zehnder interferometer (MZI) stand out for their proven success in monitoring of quantities changes such as temperature, strain, solution concentration, etc [6–8]. To form an MZI in a single fiber, a relative phase difference of two beams originated from the same laser light is needed, which can be achieved by allowing the two beams traveling in different paths. A number of fabrication techniques have been proposed to make a fiber MZI, including the fiber tapering [6,7], microstructure collapsing on a photonic crystal fiber [8], core mismatch [9,10], imbedded micro air-cavity in fiber [11–13], pair of LPFGs [14], and laser heating induced microbend [15].

High-order cladding modes are excited in the fiber MZI, which are guided by the cladding-ambient interface and directly exposed to the environment. The refractive index change of the environment can significantly change the effective propagation constant of the cladding modes. Thus, the fiber MZI can be used as refractive index sensor by testing the phase shift of the interference fringe. On other hand, a thinned cladding LPFG can increase the evanescent field in the external medium and lead to sensitivity enhancement as a RI sensor [16].

Among various types of MZIs, the fiber taper-based structure has the advantages of simpleness and high repeatability [6,7]. To obtain effective coupling between core and cladding modes, large taper angle is needed [17]. The fiber tapers are usually made by stretching a fiber under high heat or electrical arc condition, which limits the shortest length of the device. The tapered region has a typical length of $\sim$600 μm [7]. However, when the taper-based MZI is used as a refractive index sensor, the sensitivity is low. Recently, to improve the RI sensitivity, Wu et al. proposed a sandwiched taper MZI that is fabricated by stretching the fiber [18]. But the sensitivity is also relatively low.

A photonic crystal fiber (PCF) is used to make an MZI by micro air-holes collapsing using a fusion splicer [8]. The collapsed air-holes can excite high-order cladding modes in the section of PCF between the two splices, which induces a relative phase difference for the two beams transmitted in the fiber core and cladding. Hence, interference fringes are formed. In this work, we propose an MZI consisting of two ultra-abrupt fiber tapers fabricated by a fusion splicer using traditional single mode fiber. By concatenating, the taper length and diameter ratio is 1:1 that is much greater than that (1:10) by stretching reported in the previous works [7]. When it is used as a RI sensor, the sensitivity is comparable to LPFG pair MZI sensors without sensitivity enhancement [14] and the taper-based MZI sensors fabricated by the stretching method [6,7]. However, the fabrication process is simple with high robustness. In order to improve the RI sensitivity of the proposed MZI sensor, wet chemical etching is applied to remove part of the cladding in the center of the two ultra-abrupt fiber tapers. A sensitivity of 664.57 nm/RIU is obtained for a thinned cladding MZI. At a resolution of 1 pm of the detecting system, the detection limit is 1.5×10^{-6} RIU.

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0030-3992/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlastec.2011.09.013

2. Device principle and fabrication

Fig. 1(a) shows the schematic diagram of the proposed device consisting of two ultra-abrupt fiber tapers and a section of thinned cladding. The first ultra-abrupt fiber taper couples part of the light from the core mode into the cladding modes, and part of the light in cladding modes is coupled back into the core at the second ultra-abrupt fiber taper. Interference is then formed when the light from the cladding meets with the light guided in the core. The interference signal reaches minimum when the phase difference between cladding and core modes satisfy the following condition [9]:

$$2\pi(n_{core}^{eff}-n_{cl,m}^{eff})\frac{L}{\lambda_v}=(2k+1)\pi \quad (1)$$

where L is the interferometer length; k is an integer; λ_v is the maximum attenuation wavelength of the k^{th} order; n_{core}^{eff} and $n_{cl,m}^{eff}$ are the effective refractive indices of the core mode and the m^{th} order cladding mode, respectively. The effective refractive index of the cladding mode changes with the variations of external refractive index, and it results in a shift of the maximum attenuation wavelength. The sensitivity can be expressed as [9]

$$S=\frac{d\lambda_v}{dn_{ext}}=-\frac{2L}{2k+1}\frac{\partial n_{cl,m}^{eff}}{\partial n_{ext}}\Bigg/\left[1-\frac{2L}{2k+1}\left(\frac{\partial n_{core}^{eff}}{\partial\lambda}-\frac{\partial n_{cl,m}^{eff}}{\partial\lambda}\right)\right] \quad (2)$$

where$n_{ext}$is the external refractive index. According to Eq. (2), the sensitivity can be increased by increasing the interferometer length L. However, it is impractical to increase the length of the interferometer indefinitely for a compact sensor. Instead, in this letter, the sensitivity of the MZI sensor is greatly increased by etching the fiber cladding between the two splice points. As the fiber diameter decreases, the optical power related to the evanescent wave of cladding modes significantly grows in the external medium. Thus, the enhancement of sensitivity is expected when the fiber diameter of the interaction area between the sensor and the medium is reduced. Similar result is reported in thinned cladding LPFG sensors [16].

The fiber inline Mach–Zehnder interferometer is fabricated by a conventional fusion splicer. Two cleaved fiber ends are put into the V-grooves made on the electrodes fixture of the splicer, the ends are aligned automatically by the splicer. The ellipsoidal heads are individually formed at the first discharge, but they are formed under the same arc condition (arc duration and current). The shapes of the formed ellipsoidal heads are similar. Fig. 1(b) shows the microscopic image of the ellipsoidal head, under 50X objective. Then, the two ellipsoidal heads are moved to be contacted in the center of the splicer electrodes. The two ellipsoidal heads will be fused together by another discharge. The other splice junction point is formed through the same process separated by a distance of L. Fig. 1(c) shows the microscope image of the ultra-abrupt fiber taper after the two ellipsoidal heads are fused together. The fiber core and cladding are melted together at the ellipsoidal region. Due to the fusion and deformation of the fiber core and cladding, the light will spread into the cladding at the first splice point and meet with the light transmitted in the core at the second splice point. To get high contrast interference fringe, a 3 dB taper is preferred. Proper discharge arc duration and current of the electrodes are selected to minimize the losses and achieve robust splices. Table 1 shows the obtained transmission loss and diameter-length ratio using various fabrication parameters. In this study, the arc duration is 1200 ms and the current is 50% of the default value. The length of the ultra-abrupt fiber taper is only ~100 μm, while a stretched fiber taper has a typical taper length of ~600 μm [6,7].

In order to examine the mechanical properties of the MZIs, an axial tension force F is applied to the MZIs and is increased gradually until the fiber is ruptured. About 50-mm polymer coating of the fiber is removed in the experiments. Firstly, an MZI fabricated by the new method is tested and the fiber is ruptured when the axial tension force reaches 5.9 N, where the tapers have a length of 100 μm and diameter of 98 μm. However, for an MZI with two tapers (length of 600 μm and diameter of 62 μm) fabricated by stretching, the MZI is ruptured with an axial

Table 1
Transmission loss and diameter-length ratio under various discharge fabrication parameters (arc duration and current percent of the default value).

Arc duration (ms)	*Current percent of the default value*		
	60%	50%	40%
1600	1:1.12 1.8 dB	1:1.41 2.5 dB	1:1.52 2.7 dB
1200	1:1.2 2.5 dB	0.98:1 3 dB	1:1.32 4.5 dB
800	1:1.22 6 dB	1:1 7.5 dB	0.76:1 8.2 dB

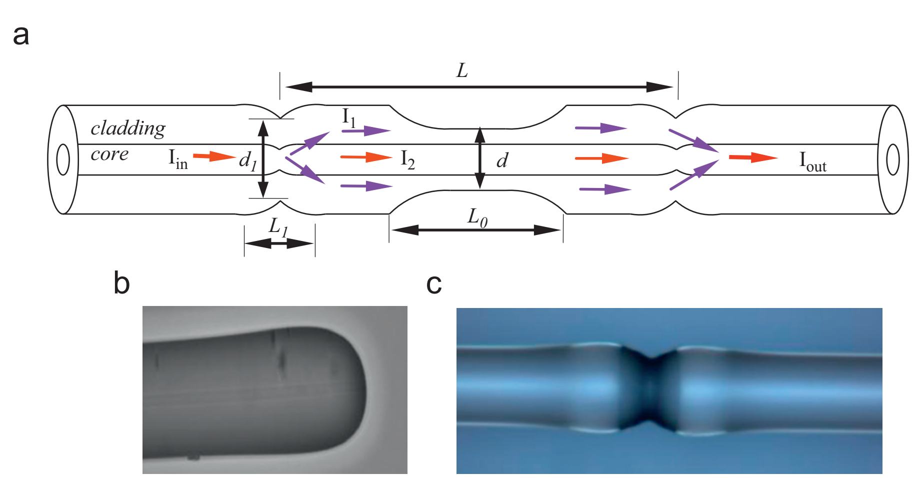

Fig. 1. Proposed MZI sensor consisting of two ultra-abrupt fiber tapers: (a) schematic diagram; (b) microscopic image of the ellipsoidal head formed by one time discharge; (c) microscopic image of the ultra-abrupt fiber taper by splicing together the two ellipsoidal heads, where the length of the tapered region L_1 is ~100 μm and the diameter d_1 is 100 μm. (dimensions are not to scale).