Dumbbell shaped inline Mach–Zehnder interferometer for glucose detection

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ABSTRACT

A simple inline Mach Zehnder Interferometer (MZI) with a dumbbell-shaped structure is developed for measuring glucose concentration in distilled water. The MZI is fabricated using an arcing function of a fusion splicer. The sensor consists of two bulges separated by a tapered waist. The MZI generates a good reflected interference spectrum where the dip wavelength is red-shifted with the increase of glucose concentration. This is due to the increase of the surrounding refractive index, which reduces the phase difference between the core and cladding modes. As the glucose concentration increases from 0% to 12%, the dip wavelength increases from 1554.419 to 1554.939 nm in a quadratic manner with the coefficient of determination of 0.9818. It is also found that the sensor has a sensitivity of 0.04 nm/% with a linearity of 96.7%. The limit of detection is 4.5%. This preliminary result shows that the proposed probe can be used as a sensor to detect glucose concentration in distilled water.

1. Introduction

Fiber based sensors have been developed and used for measuring humidity, refractive index (RI), temperature, strain and others [1–3]. Compared to conventional sensors based on mechanical and electrical properties, optical fiber sensors offer many advantages such as compactness, high sensitivity, immunity to electromagnetic interference and volatile surrounding and resistance to corrosion. One of the most popular probes made of optical fiber is Mach–Zehnder Interferometer (MZI) which is widely used for various sensing purposes [4–7]. For instance, inline fiber MZI sensors have been utilized for monitoring changes in refractive index, strain and temperature [1–3]. Wang et al. proposed in-line MZI by femtosecond laser for refractive index measurement [5]. Although the technique can form a micro in-line MZI in micron size but it needs expensive equipment for the cavity fabrication. In the last ten years, many MZI sensor designs have been proposed including those using tapered fibers such as cladded multimode tapered fiber [8], biconical tapered fiber [9] and – three cascaded single mode fiber tapers [10]. This is attributed to the characteristics of tapered fibers which allow a higher portion of evanescent field to travel inside the cladding and thus it is more sensitive to the physical changes of its surrounding. Others method based on the MZI are long-period gratings (LPGs) [11,12], two different single-mode fibers (SMFs) [13,14] and some other special configurations [15–17].

In an MZI used for sensing refractive index (RI), a fraction of the fundamental core mode power leaks out as cladding mode which is sensitive to the RI of the surrounding medium [18]. Based on this operating principle, the MZI sensor can be employed to detect the refractive index of any liquid. Meanwhile, in some of the structures such as LPGs, core-offset and other insertions, the difference in

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path lengths between the core and cladding modes usually changes with the ambient temperature and strain [19]. This change makes the spectra red shift or blue shift thereby realizing a sensitive temperature or strain sensor.

In this paper, a simple inline MZI with a dumbbell-shaped structure is proposed. The MZI is then used to detect various glucose concentration in distilled water. The proposed MZI structure consists of two bulges connected by a tapered waist.

2. Fabrication and characterization of inline MZI

The inline MZI is fabricated using a standard silica single-mode fiber (SMF), fiber stripper, cleaver and fusion splicer machine. The SMF has core and cladding diameters of 8.3 μm and 125 μm, respectively. The first step in fabricating the MZI structure is to strip and cleave an SMF into two sections, each with a flat and smooth end-surface, as illustrated in Fig. 1(a). Then the end facets of the two sections are matched and fused using the manual "arc" function of the splicer machine. First, the fusion splicer softens the ends of the two fibers with heat. Then it exerts pressure from both sides to bring the two sections together to merge in the middle and fuse them back into a single fiber. When the "arc" function is used repeatedly, more silica material is lumped in the middle thus forming the first bulge at the joint as shown in Fig. 1(b). Once the first bulge is formed, the linked fiber is then cleaved again at 1 mm away from the center of the first bulge as depicted in Fig. 1(c). The two cleaved fiber sections are fused again using the "arc" function to form the second bulge. The completed dumbbell structure is shown in Fig. 2 where the diameters of the first and second bulges are approximately around 198 μm and 196 μm respectively. The splicer setting used in fabricating the bulges is given in Table 1.

For a broadband spectrum input, an interference pattern in the output can be obtained when an optical path difference (OPD) exist between the cladding mode and core mode. Since the two bulges act as a beam splitter and combiner, changes in their diameters (or thickness) lead to the change in output transmission spectrum where the extinction ratios of the interference fringe can be controlled. To verify these characteristics, we produce several dumbbells shaped MZIs with different diameters and detect their transmission spectra. Fig. 3 shows the bulges of three different MZIs with diameters of 177 μm, 183 μm and 195 μm and Fig. 4 shows their respective transmission spectra. As shown in the figure, an interference comb spectrum is obtained for all MZIs with a free spectral range of around 3.6 nm. It is observed that the extinction ratio of the interference spectrum increases from 0.18 dB to 0.22 dB as the bulge diameter increases from 177 μm to 195 μm.

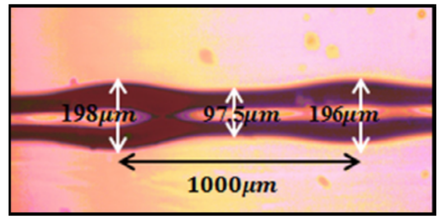

Fig. 2. The proposed dumbbell shaped MZI.

Table 1
Splicer setting used in fabricating the bulges.

Parameters	Units	Values
Fusion time	s	1.65
Prefusion	s	0.05
Arc gap	μm	20
Overlap	μm	80

3. Experimental setup for the glucose sensor

Fig. 5 shows the experimental setup used to measure changes in refractive index by using the proposed MZI sensor with a bulge diameter of 195 μm. The input signal from an amplified spontaneous emission (ASE) laser source is launched into a sensor probe via a 3 dB coupler. The reflected signal from the sensor is then routed into an optical spectrum analyzer (OSA) through the same coupler. When the input single mode light beam reaches the first bulge of the sensor probe, it is divided into two parts where the first part continues to propagate in the core. The second part travels in the cladding of the SMF. Due to the OPD between cladding mode and core mode, an interference pattern is generated as shown in Fig. 6. In our experiment, the dumbbell shaped MZI probe is immersed into glucose solution of different concentrations ranging from 0% to 12%. The solution was prepared by mixing glucose and distilled water with different proportions of 0%, 2%, 4%, 8%, 10% and 12%, which corresponds to mixtures with refractive indices of 1.333, 1.336, 1.339, 1.3425, 1.3461, 1.3494 and 1.353, respectively. The solution refractive index is measured using a refractometer. Due to the compact structure of the sensor, a single drop of the liquid solution is enough to surround the whole dumbbell shape. The MZI was cleansed with deionized water and compressed air after each measurement.

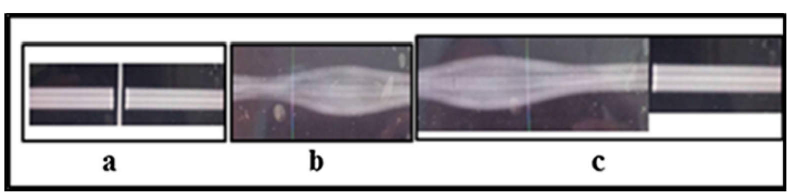

Fig. 1. Illustration of the fabrication procedure of the proposed inline MZI.

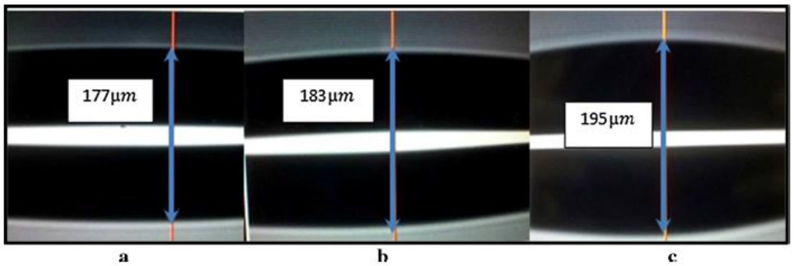

Fig. 3. Bulges of MZI with diameter of (a) 177 μm, (b) 183 μm and (c) 195 μm.

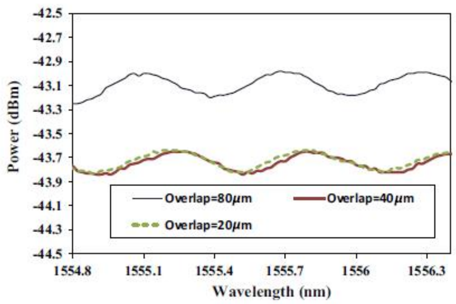

Fig. 4. The transmission spectra of the MZI for three different bulge diameters.

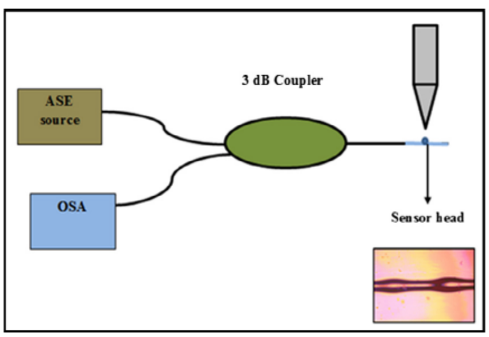

Fig. 5. The experimental setup of the proposed glucose sensor.

Fig. 6 shows the reflected interference spectrum with the different glucose concentration as the surrounding material. The reflected spectrum is also measured with distilled water (0% concentration) for comparison purpose. It could be seen that the interference spectrum is red-shifted in the increase of glucose concentration. This is attributed to the increase of the refractive index of the surrounding medium, which reduces the phase difference between the core and cladding modes. It is also observed that the output spectrum from the MZI probe produces an unsmooth curve due to the non-uniqueness of the cladding modes. While the inline MZI is placed in glucose solution, the difference of refractive index between the cladding and

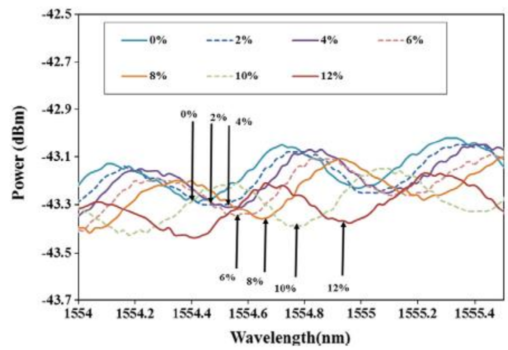

Fig. 6. shows the reflected interference spectrum with the different glucose concentration as the surrounding material.

glucose solution is big enough to support several cladding modes in the dumbbell structure. All the non-uniqueness cladding modes interfere with the core mode while oscillating inside the dumbbell structure.

The change in the transmission dip wavelength with the increase in glucose concentration is depicted in Fig. 7. At first the result is fitted with a linear trend where the coefficient of determination is 0.9355. The coefficient presents the goodness of fit such that a high value enables a good prediction of unknown by the model. It is found that the sensor has a sensitivity of 0.04 nm/% with a linearity of 96.7% and the limit of detection of 4.5%. The value of the limit of detection is obtained by dividing the standard

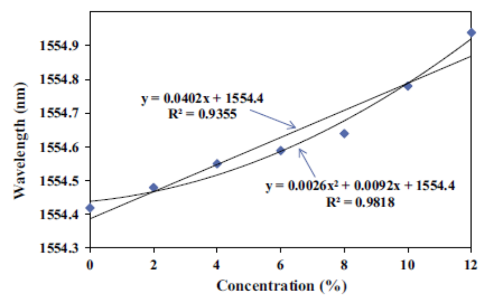

Fig. 7. The measured dip wavelength of the interference spectrum against the glucose concentration in distilled water.

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