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# Mach-Zehnder interferometer refractive index sensing probe based on dual microfiber coupler

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ABSTRACT

The dual microfiber coupler Mach-Zehnder interferometer (MZI) was proposed. Its optical and sensing characteristics have been theoretically analyzed by changing the geometrical structure parameters such as the diameter for both thick and thin microfibers, the microfiber spacing and the length of interference region. The dual microfiber coupler MZI was fabricated and experimentally demonstrated for sensing refractive index with a sensitivity of 408 nm/RIU in the range of 1.3381−1.3522. This MZI has a flexible structure and is promising to be integrated with planar waveguides to develop the novel photonic devices.

## 1. Introduction

Microfiber has the smooth surface, uniform diameter, ultra-low optical transmission loss and strong confinement ability for optical field [1]. The good mechanical and optical properties enable its great potential application value in exploring the photonic devices, optical sensing, nonlinear optics and quantum optics, etc. [2–4]. To obtain the excellent sensing performance, a variety of different microfiber sensing probes have been proposed and verified with different measurement ranges and sensitivities, including Mach-Zehnder interferometer (MZI) sensors [5], gratings [6], resonant ring, etc. [7]. Being a common interference method to explore the fiber sensors, MZI is usually realized by the coupling between the high and low order modes of two microfibers in the same diameter [8]. Different MZIs have been constructed from single-tapered fibers (reflective type) [9] or micron double-tapered fibers (transmission type) [10], core-offset fusion structure [11], coating layer function surface [12] and laser processing microstructure [13].

So far, a variety of microfiber MZI structures have been proposed. In 2012, Rong et al. proposed an MZI using a fine-core-fiber single-mode-fiber fine-core-fiber (TCF-SMF-TCF) structure with mismatched cores [14]. Sun et al. suggested a SMF-TCF-SMF structure fiber sensor to determine the temperature with a sensitivity of 72.89 pm/℃ during 20–70 ℃ [15]. The above-mentioned MZIs have the stable structures, but where the signal and reference light beams are played by the high-order and low-order optical modes respectively, which are seriously affected by the external environment, resulting in the unstable interference spectrum. In 2013, Chen et al. designed a biconvex tapered SMF sensor [16]. When the refractive index changes between 1.40–1.44, the sensitivity can reach -268.5 nm/RIU. By replaced the refractive index solution with different concentration of specific biological substances, the sensitivity

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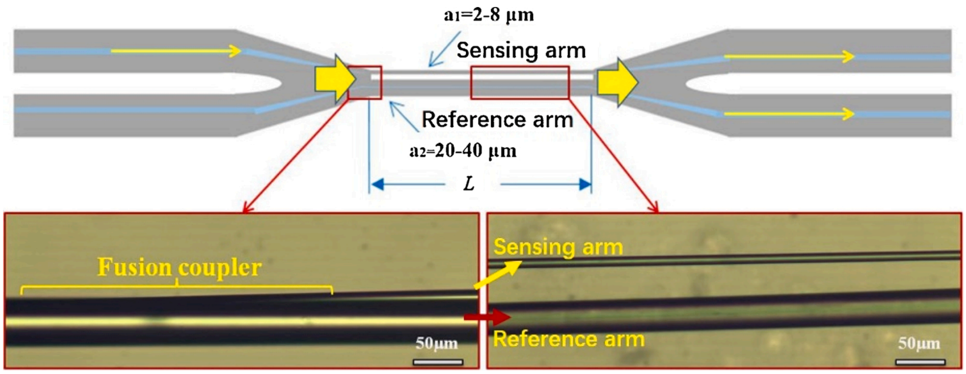


**Fig. 1.** Schematic diagram of dual microfiber coupler MZI and its microscope picture of different regions.

for detecting goat immune protein reached 27.37 nm/(ng/mm$^2$). This work provides a reference for the application of microfiber based MZIs in biochemical sensing. In 2014, Yu et al. reported an MZI structure using microfibers as the sensing arm [17], and placed it on a flexible poly(trimethylene terephthalate) microfiber glass substrate coated with magnesium difluoride. The sensitivity of measuring refractive index is extremely high. However, the production of the sensing probe is technically difficult. In 2015, Zhao et al. proposed a photonic crystal fiber (PCF) interferometer structure with a fused-tapered joint [18]. Compared with the previous ordinary PCF-MZI, the sensitivity has increased from 108.2 nm/RIU to 252 nm/RIU. However, the introduction of PCFs has greatly increased the manufacturing cost. In 2016, Melo et al. used the hafnium oxide coating layer to produce an MZI with a sensitivity of up to 1307 nm/RIU [19]. Sun et al. designed an ultra-sensitive microcavity MZI fabricated by femtosecond laser direct writing and high-frequency etching [20]. The sensitivity can reach 104 nm/RIU, but the fabrication process is complicated. The etching process is not easy to accurately control and have poor repeatability.

All of the aforementioned microfiber MZIs cannot or can only change the length of the reference arm and the sensing arm in a small range. Recently, a 9 µm single-tapered microfiber was proposed, but its optical path difference was changed by bending microfiber [21]. In order to overcome this problem, the microfiber coupler based miniature MZI is designed using a smaller diameter microfiber with an evanescent field effect and another larger diameter microfiber as the sensing arm and the reference arm, respectively.

## 2. Dual microfiber coupler MZI

The structure of miniature MZI is shown in Fig. 1. The blue and gray parts refer to the core and cladding, respectively. Two SMFs were heated and stretched separately to obtain microfibers with different diameters as the reference arm and sensing arms of MZI. The fiber coupler manufacturing technology was adopted to construct two fusion tapers and respectively used as the light splitting and combining nodes of MZI. In this structure, the diameter of the finer microfiber with the evanescent field effect is $a_1$, which was used as the sensing arm, having the thinner diameter of ~ 2 µm; the diameter of the thicker microfiber is $a_2$, which is used as the reference arm, having the thicker diameter of >20 µm. Microfibers have the uniform diameter, the distance $d$, and the length of sensing area $L$ (~3 cm), as shown in the insert picture on the right. The optical signal was separated and guided into the two optical microfibers for transmission after passing through the coupling zone with the fusion tapers (as indicated in the insert picture on the left). The optical signal in the microfiber will be transmitted along the outside of the fiber in the form of an evanescent field. The change of the external refractive index results in the optical path difference between the two arms. Finally, the light waves from the two arms were re-coupled in the second coupling zone to form Mach-Zehnder interference.

The microfibers were prepared using a hydrogen-oxygen flame scanning and stretching method through a multifunctional fiber fusion taper machine system (IPCS-5000-ST). The optical SMF was fixed by vacuum fiber clips, heated at a high temperature under a flame to become the melt state. At the same time, a certain speed is controlled to stretch its both ends to form a cone area at the heating point. The microfiber length was adjusted by changing the scanning speed of the flame torch. The evanescent field was expanded outward to sense the environment change. The flame temperature, flame size, stretch speed, and scanning range exerted the affect on the reliability and stability of the microfiber coupler.

## 3. Theoretical analysis

The microfiber MZI sensor model was built in FDTD solutions software, and the perfect absorption boundary was used. The light source was located at the end of the core of thick microfiber. The wavelength of light source is 1500 nm–1600 nm. The monitor was fixed after the coupling point. The smallest diameter of microfiber was chose as 2 µm due to the equipment limit. When the thin microfiber diameter $a_1$ is 2 µm, the thick fiber diameter $a_2$ is 10 µm, the distance is 20 µm, and the interference region length is 100 µm, the resonance spectrum was observed in the monitor at coupling point, as shown in Fig. 2(a). When $a_1$ changed from 2 µm, 5 µm–6 µm, the corresponding sensor sensitivity were verified to be 948 nm/RIU, 760 nm/RIU and 840 nm/RIU, respectively, as compared in Table 1. The refractive index sensing characteristic curve of the thin microfiber at 2 µm was indicated in Fig. 2(b).

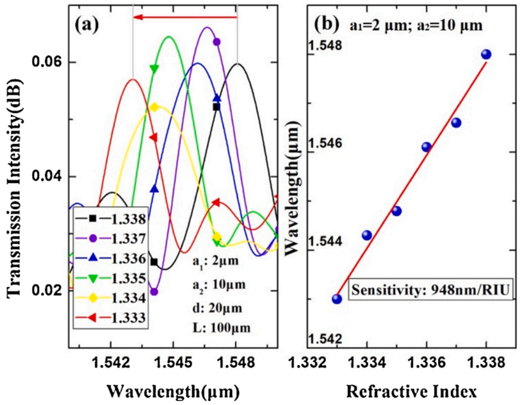


**Fig. 2.** (a) Spectral peak of microfiber MZI refractive index probe (with $a_1$: 2 μm; $a_2$: 10 μm) varies with refractive index in 1.338-1.333; (b) sensing characteristic fitting curve.

**Table 1**
Sensing performance comparison for MZI probes with different parameters.

| Model types | Structural parameters (μm) | | | | Sensitivity (nm/RIU) |
|---|---|---|---|---|---|
| | Sensing length *L* | Distance *d* | $a_1$ | $a_2$ | |
| | | | 2 | 10 | 948 |
| | | 20 | 5 | | 760 |
| Simulation | 100 | | 6 | | 840 |
| | | 10 | 2 | 15 | 974 |
| | | 15 | | 20 | 868 |
| Experiment | ~3 0000 | ~ 30 | 8 | 35 | 408 |

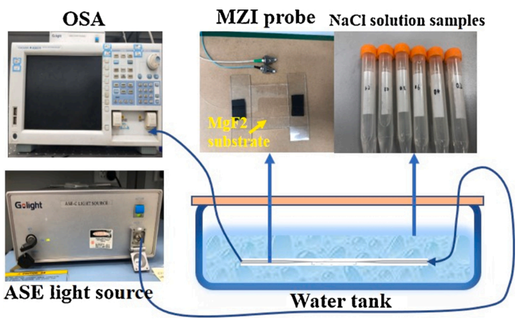


**Fig. 3.** Experimental schematic of MZI refractive index probe for determining NaCl solution with different concentration.

The thinner microfiber has a stronger evanescent field, but it is difficult to promise a best sensing performance or maximum sensitivity. When the microfiber diameter $a_1$ was fixed as 6 μm, the spacing *d* was 20 μm, the interference area length *L* was 100 μm, and the diameter of $a_2$ was 10 μm, 15 μm, 20 μm, the simulation demonstrated the corresponding sensitivity of 840 nm/RIU, 974 nm/RIU and 868 nm/RIU, respectively. The spacing *d* and the length of the interferometer area will also affect the sensing characteristics, resulting in the corresponding refractive index sensitivity in the range of 800−1000 nm/RIU.

## 4. Experimental verification

NaCl solutions with different concentrations provided different refractive index environments to test the sensing performance of the microfiber based miniature MZI. The NaCl solubility is 35.9 g at room temperature, corresponding to the maximum concentration of 26.5 %. However, the NaCl crystals in the high-concentration are easy to precipitate and contaminate the surface of optical fiber. To ensure the accuracy and efficiency of experiment, low-concentration NaCl solution was used in this work.

The experimental diagram was illustrated in Fig. 3. The water bath method was adopted to calibrate the refractive index sensing characteristics. The MZI structure contains a thin microfiber with a diameter of 8 μm and a thick microfiber with a diameter of 35 μm. The whole structure was fixed on an $MgF_2$ substrate with a refractive index of 1.38, which was introduced to replace the ordinary glass slide to effectively reduce the light leakage.

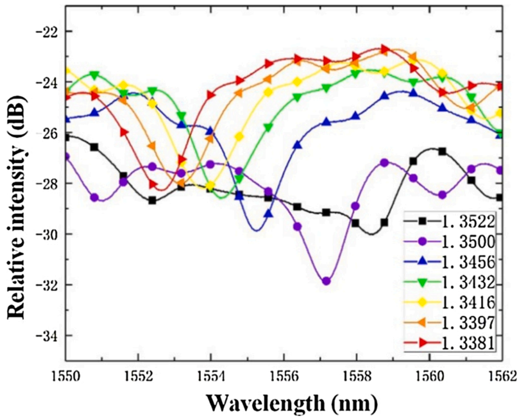


**Fig. 4.** Dip blue-shifts with decrease of NaCl solution concentration (Corresponding to refractive index during 1.3522-1.3381) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

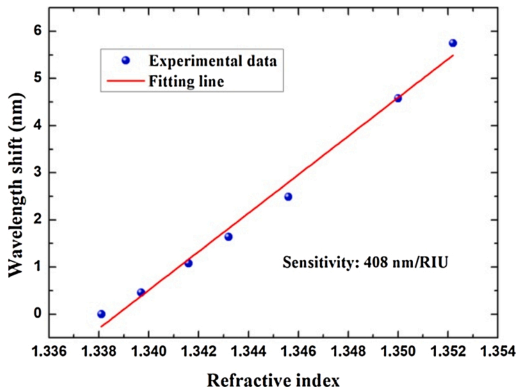


**Fig. 5.** Refractive index sensing curve.

The entire structure was put into a water tank, in which 12 % NaCl solution was filled with a refractive index of 1.3522. The position of the specific resonance peak on spectrum is observed and recorded with a spectrum analyzer (YOKOGAWA-AQ6370, resolution 0.02 nm). When a fixed amount of pure water was dropped in the solution, the refractive index was measured in real time using an Abbe refractometer (WAY-2S). The interference spectrum as a function of external refractive index was recorded, as shown in Fig. 4.

When the refractive index of NaCl solution decreases from 1.3522 to 1.3381, the resonance dip continuously blue-shifts by 5.75 nm with the corresponding wavelength values of 1558.34 nm, 1558.80 nm, 1559.42 nm, 1559.98 nm, 1560.83 nm, 1562.92 nm, 1564.09 nm. The corresponding refractive index sensing characteristic curve is shown in Fig. 5.

The sensing performance of the MZI refractive index probes with different structural parameters for simulation and experimental samples have been compared in Table 1.

The experimental results indicate that a refractive index sensitivity of 408 nm/RIU. This result is lower than that of simulation model, attributing to the structural parameter difference between the experiment and simulation. In particular, the length $L$ of the signal arm is difficult to be further reduced. Because the width of the oxyhy-drogen flame is 5−8 mm, the distance between the two coupling regions must be far enough to ensure the welding quality, resulting in the MZI length of ∼3 cm, which is much longer than the theoretical model. But the bigger structure is difficult to verify in simulation, subject to the too fine grid and the requirement for large memory. In the experimental process, the MZI length is expected to be further reduced by optimizing the fabrication technology of coupling region. Furthermore, the interference spectrum of the MZI interferometer with a too long microfiber is unstable during the measurement, corresponding to the unregular change of the wavelength drift for its crest and trough. Because one section of the long microfiber will be attached on the reference microfiber and caused the optical coupling loss, exerting the impact on the interference spectrum. However, the interference change only depends on the refractive index change of the environment around the microfiber.

## 5. Conclusions

The microfiber MZI sensor has been proposed. The influence of the main structural parameters on the sensor performance was studied, including the thin fiber diameter $a_1$, the thick fiber diameter $a_2$, the distance between the two fibers $d$, and the length of the interference region $L$, which help to optimize the sensing performance. In general, a better interference effect and sensing characteristics can be obtained for the smaller $a_1$ and $a_2$. Increasing $d$ contributes a higher sensitivity, but the worse quality for the interference spectrum, which can be improved by using a longer fiber. Using different concentrations of NaCl solutions to provide different refractive index environments, the sensitivity of the dual-fiber-coupled MZI was experimentally verified to be 408 nm/RIU in the measurement range of $1.3381-1.3522$. This microfiber coupler based MZI has flexible structure and good stability, and can be used to develop biochemical sensing probes with high-performance. However, limited by the current experimental conditions, the microfiber after heating and stretching becomes brittle, being easy to damage during the preparation process; the influence of ambient temperature on the sensing performance also needs further study.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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