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A fiber inline interferometric refractive index (RI) sensor consisting of a microchannel and a fiber taper is proposed in this letter. The microchannel is fabricated by combining femtosecond laser micromachining and arc fusion splicing. No subsequent chemical etching process is needed. Three sensors with microchannel widths of 4, 8, and 10 µm are prepared. The sensitivity in the RI range from 1.33 to 1.35 is up to ∼361.29 nm/RIU at the microchannel width of 8 µm. The sensitivity is ∼20 times greater than that of the paired taper-based MZI sensors and long period fiber grating pair MZI sensors.

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fiber with appropriate arc conditions. The centerline of the microchannel is aligned to coincide with the fiber end. Microchannels with three different widths of 4, 8, and 10 µm are fabricated in the fiber end. All the channels have a depth of 10 µm. One of the microchannels with a width of 10 µm is shown in Fig. 1(c).

An abrupt tapered fiber is fabricated through fusion-splicing, 10 mm away from the microchannel. Details on the fabrication of the fiber taper can be found elsewhere[23]. The microscope image of the fiber taper with a length and a diameter of ∼100 µm is shown in Fig. 1(b). The three interferometers with widths of 4, 8, and 10 µm are denoted as MZI-1, MZI-2, and MZI-3, respectively.

To measure the transmission spectra, one end of the interferometer is connected to a tunable laser (Agilent 81980A) with a wavelength range from 1 465 to 1 575 nm, whereas the other end is connected to an optical power meter (Agilent 8163B). The transmission spectra of the three interferometers with different microchannel widths of 4, 8, and 10 µm are illustrated in Fig. 2. The transmission losses of the fibers with only one microchannel are 4.5, 9, and 12 dB when the microchannel widths are 4, 8, and 10 µm, respectively (Fig. 2). When a fiber taper is added by fusion splicing, interference fringes are observed on the spectra. The extinction ratios are approximately 8, 10, and 6 dB for MZI-1, MZI-2, and MZI-3, respectively. When the microchannel width is larger than the diameter of the fiber core, more light will be reflected and scattered by the cross section when passing through the microchannel, producing obvious loss and noise. Therefore, the sensor with a microchannel width of 10 µm has larger noise and loss than the others.

The fiber taper is used to couple part of the fundamental core mode to higher cladding modes. At the same time, some energy left in the core continues to propagate forward in the fiber core. Parts of the cladding modes are coupled back to the core when meeting the microchannel, which is apart from the taper with a distance of 10 mm. The phase difference between the cladding mode \( L P_{\text{cl}} \) and core mode \( L P_{\text{m}} \) traveling the same distance \( L \) can be expressed as \( \varphi = 2\pi \Delta n_{\text{eff}} L / \lambda \), where \( \Delta n_{\text{eff}} \) is the difference of the effective refractive indices between the core and cladding modes, and \( \lambda \) is the operating wavelength. The interference signal reaches its minimum when \( 2\pi \Delta n_{\text{eff}} L / \lambda = (2k+1)\pi \), where \( k \) is an integer. The effective refractive index of the cladding mode changes with the variations in the external refractive index, resulting in a shift in the maximum attenuation wavelength. The sensitivity can be expressed as[24]

\[
\frac{\Delta \lambda}{\Delta n_{\text{ext}}} = \frac{2L}{2k+1} \frac{\partial n_{\text{eff,cl,m}}}{\partial n_{\text{ext}}} \left[ 1 - \frac{2L}{2k+1} \left( \frac{\partial n_{\text{eff,core}}}{\partial \lambda} - \frac{\partial n_{\text{eff,cl,m}}}{\partial \lambda} \right) \right],
\]

where \( n_{\text{ext}} \) is the external refractive index; \( k \) is an integer, \( \lambda_{\text{m}} \) is the maximum attenuation wavelength of the \( k \)th order, and \( n_{\text{eff,core}} \) and \( n_{\text{eff,cl,m}} \) are the effective RIs of the core and the \( m \)th order cladding modes, respectively. The RI of the channel directly affects the light transmission behavior in the core-cladding interface[13]. The change in the channel fluids can directly influence the interference spectra of the interferometers, which leads to change in the maximum attenuation wavelength. As shown in Fig. 2, the extinction ratios become larger when the MZIs are immersed into water. Especially for MZI-2, the extinction ratio is 25 dB, mainly because an optimal interference condition is obtained in the water caused by the reduction in the RI difference.

The RIs of the proposed fiber sensors are measured in a clean room with almost constant temperature to eliminate the effects caused by temperature fluctuations. During the measurements, all sensors are straightened and fixed on a fiber holder to avoid bending-induced signal change. Salt solutions with different concentrations (0.0%, 0.99%, 1.96%, 2.91%, 3.85%, 4.76%, 5.66%, and 6.54% (mass percent)) are used in the experiments. The corresponding RIs are 1.3330, 1.3348, 1.3366, 1.3383, 1.3400, 1.3418, 1.3435, and 1.3453, respectively[25]. The sensor is cleaned by distilled water and dried air between each measurement.

The maximum attenuation peak wavelengths in 1.3330 are chosen as the starting recorded wavelength, which are marked by a, b, and c in Fig. 2. These wavelengths denote the maximum attenuation wavelengths of 1539.96, 1520.26, and 1486.01 nm, respectively. The wavelength

![Fig. 1](image1.png)

**Fig. 1.** Proposed MZI sensor consisting of a fiber taper and a microchannel. (a) Schematic diagram and (b) microscope images of the fiber taper with diameter and length of ∼100 µm; (c) microchannel with a width of ∼10 µm.

![Fig. 2](image2.png)

**Fig. 2.** Transmission spectra of the MZIs in air and in the liquid with RI = 1.333. (a) A single taper and single microchannel with different widths in air: (b) 4, (c) 8, and (d) 10 µm, respectively.
shifts of the three maximum attenuation peaks with respect to the change in external RI are shown in Fig. 3. All attenuation peaks shift to longer wavelengths with the increasing RI, with corresponding sensitivities of 268.46, 361.29, and 228.98 nm/RIU. The RI sensitivity of MZI-2 is higher than the others because the difference in the effective index between the core mode filled with liquid to be measured and the cladding mode is largest when the microchannel width is closest to the diameter of the fiber core (8.2 µm). In the same RI range, the sensitivity is ~20 times greater than those of the LPFG pair MZI sensors and the tapered-fiber pair MZI sensors. Although the sensitivity is lower than that reported in Refs. [17,18], the fabrication time is much shorter, and the structure is more robust.

We also compare the sensitivities between two attenuation peaks. For MZI-2, two attenuation peaks, marked by b0 and b in Fig. 2, are chosen as the recorded wavelengths. The results show that the sensitivity of the attenuation peak b0 is 236.59 nm/RIU (Fig. 4). The change in the measured transmission spectra with the RI is also displayed in Fig. 4, which demonstrates that the RI sensitivity varies with the maximum attenuation peaks. These changes are primarily due to the fact that different cladding modes have different mode field areas, and the sensitivities are different for various cladding modes. Li et al. [26] recently reported that higher-order cladding modes have larger mode field areas and are more easily affected by the surrounding RI. Thus, higher-order cladding modes exhibit lower mode indices and higher sensitivities. The different sensitivity results shown in our study are in accordance with the peak shift discrepancy reported in Ref. [26].

In conclusion, we propose a novel RI sensor based on a fs laser-fabricated microchannel combined with a fusion-spliced fiber taper. The microchannel is obtained by combining direct fs laser pulse ablation and the arc fusion-splicing technique, without subsequent chemical etching process. Three types of interferometers are fabricated with different microchannel widths of 4, 8, and 10 µm. The results demonstrate that the RI sensitivity depends on the microchannel width and the selection of the attenuation peaks. The obtained maximum sensitivity in the RI range from 1.33 to 1.35 is 361.29 nm/RIU when the microchannel width is 8 µm. The sensitivity is ~20 times greater than that of the paired taper-based LPFG pair MZI sensors. Moreover, the proposed MZI has high potential for developing microfluidic fiber devices for chemical and biological sensing applications.

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