Opto-Electronic Advances

Supplementary information

December 2024, Vol. 7, No. 12

DOI: 10.29026/oea.2024.240105 CSTR: 32247.14.oea.2024.240105

High-resolution tumor marker detection based on microwave photonics demodulated dual wavelength fiber laser sensor

Jie Hu[1], Weihao Lin[1], Liyang Shao[1]*, Chenlong Xue[1], Fang Zhao[1], Dongrui Xiao[2]*, Yang Ran[3], Yue Meng[4], Panpan He[5], Zhiguang Yu[5], Jinna Chen[1] and Perry Ping Shum[1]

[1]Department of Electronic and Electrical Engineering, Southern University of Science and Technology, Shenzhen, 518055, China; [2]School of Electrical Information Engineering, Hunan Institute of Technology, Hengyang, 421002, China; [3]Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou, 510632, China; [4]Department of Clinical Laboratory, Guangdong Provincial People's Hospital, Guangdong Academy of Medical Sciences, Guangzhou, 511436, China; [5]Medcaptain Medical Technology Co., Ltd., Shenzhen, 518055, China.

*Correspondence: LY Shao, E-mail: shaoly@sustech.edu.cn; DR Xiao, E-mail: 11849550@mail.sustech.edu.cn

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Section 3: The influence of different taper diameters on the response sensitivity of the effective RI of micro-fiber with the change of external RI is researched.
Section 4: By longitudinal comparison, the influence of different bending diameters on the response sensitivity of the effective RI varies with the external RI can be obtained.

Supplementary information for this paper is available at https://doi.org/10.29026/oea.2024.240105

Section 1: Comparison of simulation results between the straight optical fiber sensor and the bending structure (with same tapered diameter of 15 μm).

It can be seen from the electromagnetic field distribution diagram that with the same taper diameter, bending design to form a lasso structure enhances the intensity of evanescent field on the surface of the taper region, and expands the light-matter interaction region, which helps to enhance the sensitivity. In our previous work, there was a similar simulation comparison, and the comparison of detailed experimental results also proves this point[S1].

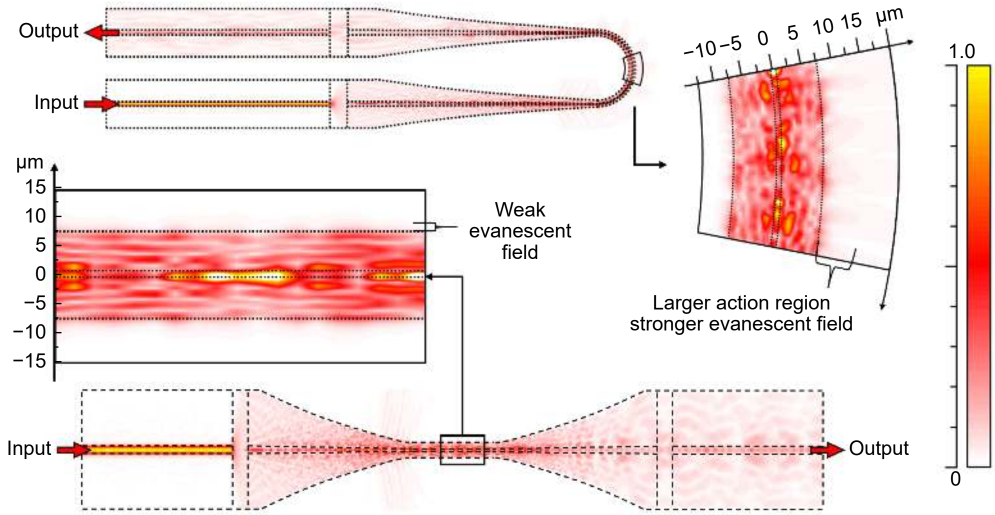

Fig. S1 | The simulation results of the light field energy distribution of the tapered optical fiber sensor (tapered diameter of 15 μm) when the structure was bent (lasso shaped) and straight.

When the ambient refractive index (RI) increases from 1.333 to 1.336, the effective RI of the micro-fiber (tapered diameter of 15 μm, bending diameter of 3 mm) are calculated, which shows a growing trend.

The distribution of electromagnetic fields on the fiber cross section are also shown. Due to the bending of the optical fiber, the stretching and extrusion of the fiber material makes the RI of the fiber at the cross section no longer uniform. The equivalent conversion of bending induced RI changes of optical fiber material can be seen in reference[S2].

Due to the bending of the optical fiber, the RI on the cross section is not uniform, resulting in the decentered electromagnetic field distribution at the cross section. At the same time, it also makes the outer surface of the micro-fiber have a strong evanescent field (green circled region in Fig. S2(b)), which can be seen in the intensity distribution of electric field mode at the radial direction (y-axis) of micro-fiber.

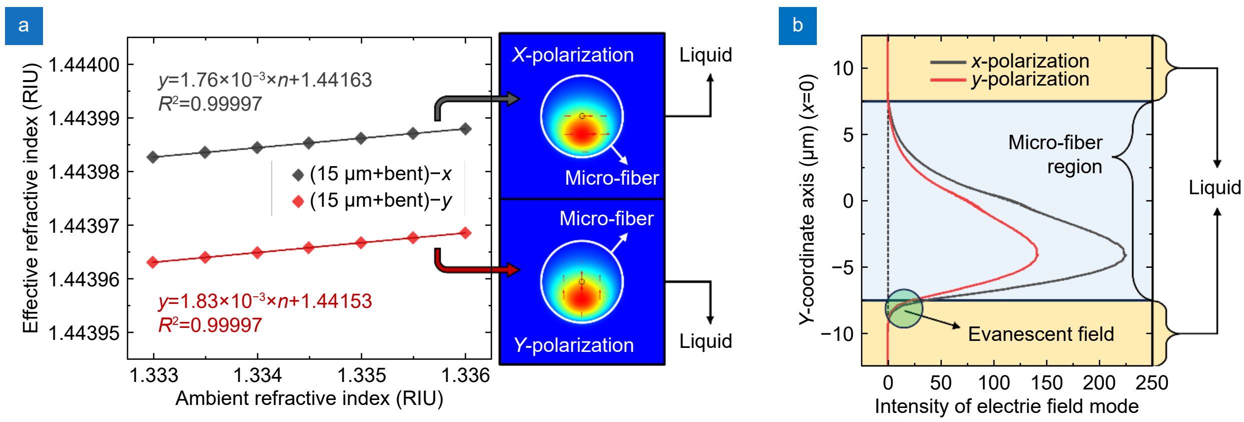

Fig. S2 | (**a**) Simulated effective RI of the micro-fiber (tapered diameter of 15 μm, bending diameter of 3 mm) when the ambient RI increase from 1.333 to 1.336. The electric field distribution diagram inside the micro-fiber is also shown here. (**b**) The intensity distribution of electric field mode at the radial direction (y-axis) of micro-fiber with diameter of 15 μm (light blue marked region) in liquid with RI of 1.333 (light yellow marked region).

Section 2: Simulation results of effective RI of micro-fiber with different taper diameter and different bending diameter when the ambient RI increases from 1.333 to 1.336.

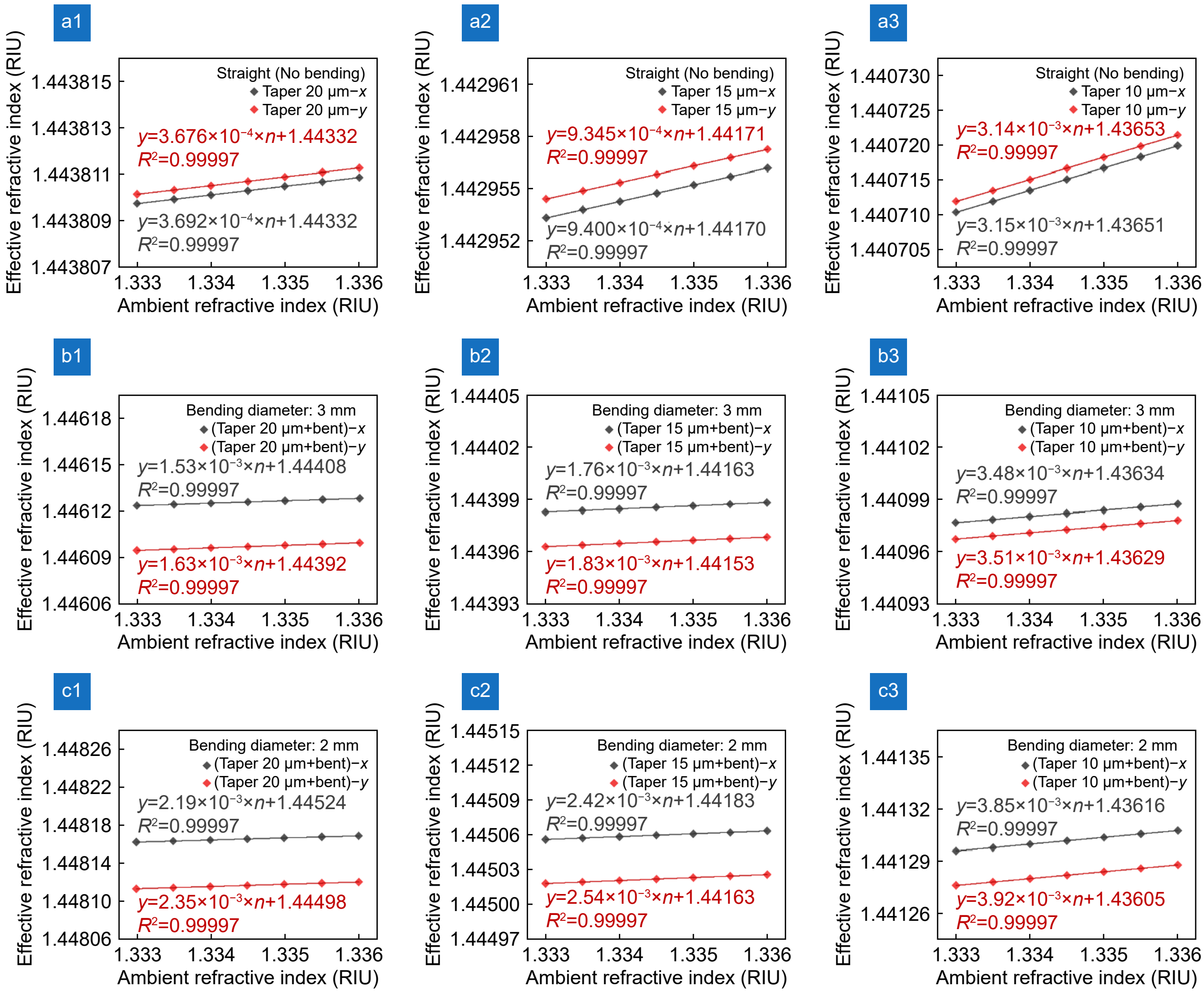

Fig. S3 | The effective RI of micro-fiber as the function of ambient RI from 1.333 to 1.336. (**a**) The straight micro-fiber sensor with taper diameter of 20 μm (a1), 15 μm (a2), and 10 μm (a3). (**b**) Lasso-shaped micro-fiber sensor with bending diameter of 3 mm and with taper diameter of 20 μm (b1), 15 μm (b2), and 10 μm (b3). (**c**) Lasso-shaped micro-fiber sensor with bending diameter of 2 mm and with taper diameter of 20 μm (c1), 15 μm (c2), and 10 μm (c3).

Section 3: The influence of different taper diameters on the response sensitivity of the effective RI of micro-fiber with the change of external RI is researched.

By horizontal comparison, Fig. (a1–a3) present the effective RI of straight micro-fiber with taper diameter of 20 μm, 15 μm, and 10 μm as the function of ambient RI. When the ambient RI increase from 1.333 to 1.336, the effective RI of micro-fiber all increases. Besides, the smaller the taper diameter, the increase sensitivity is higher. When taper diameter increases from 20 μm to 10 μm, the response sensitivity of effective RI increases tenfold.

For lasso-shaped (bending diameter of 3 mm) micro-fiber sensor with taper diameter of 20 μm (b1), 15 μm (b2), and 10 μm (b3), when the ambient RI increase from 1.333 to 1.336, the effective RI of micro-fiber also increases. When taper diameter increases from 20 μm to 10 μm, the response sensitivity of effective RI increases to around 220%.

For lasso-shaped (bending diameter of 2 mm) micro-fiber sensor with taper diameter of 20 μm (c1), 15 μm (c2), and 10 μm (c3), when the ambient RI increase from 1.333 to 1.336, the effective RI of micro-fiber also increases. When taper diameter increases from 20 μm to 10 μm, the response sensitivity of effective RI increases to around 170%.

Section 4: By longitudinal comparison, the influence of different bending diameters on the response sensitivity of the effective RI varies with the external RI can be obtained.

When the sensor with a tapering diameter of 20 μm is bent from the straight state (a1) to the bending diameter of 3 mm (b1) and 2 mm (c1), the response sensitivity of the effective RI changes with the external RI is increased by 4 times and 6 times, respectively.

When the sensor with a tapering diameter of 15 μm is bent from the straight state (a2) to the bending diameter of 3 mm (b2) and 2 mm (c2), the response sensitivity of the effective RI changes with the external RI is increased to around 180% and around 260%, respectively.

When the sensor with a tapering diameter of 10 μm is bent from the straight state (a3) to the bending diameter of 3 mm (b3) and 2 mm (c3), the response sensitivity of the effective RI changes with the external RI is increased to around 110% and around 120%, respectively.

All in all, the smaller taper diameter, as well as the smaller bending diameter, help to improve the response sensitivity of the effective RI of the micro-fiber to the external RI variation. However, with the same degree of bending, when the diameter of the micro-fiber decreases, the extrusion of the fiber material becomes weaker, resulting in weaker changes in the RI distribution on the fiber cross section, so that the increasement of the response sensitivity due to the bending is weakened.

Experimental measured interference spectra of lasso-shaped fiber sensors (bending diameter of around 2 mm) with taper diameter of 18.7 μm, 14.4 μm and 11.7 μm when the ambient RI increase from 1.3339 to 1.3369 are shown here, and their corresponding response sensitivity are calculated, respectively. When the ambient RI increases, interference spectra of lasso-shaped fiber sensors with different taper diameters are all shift to the direction of longer wavelength (red shift). The fiber sensor with smaller diameter has a larger spectral response sensitivity. The sensitivities of lasso-shaped micro-fiber sensor with taper diameters of 18.7 μm, 14.4 μm and 11.7 μm are 826.62 nm/RIU, 1037.21 nm/RIU and 1432.29 nm/RIU.

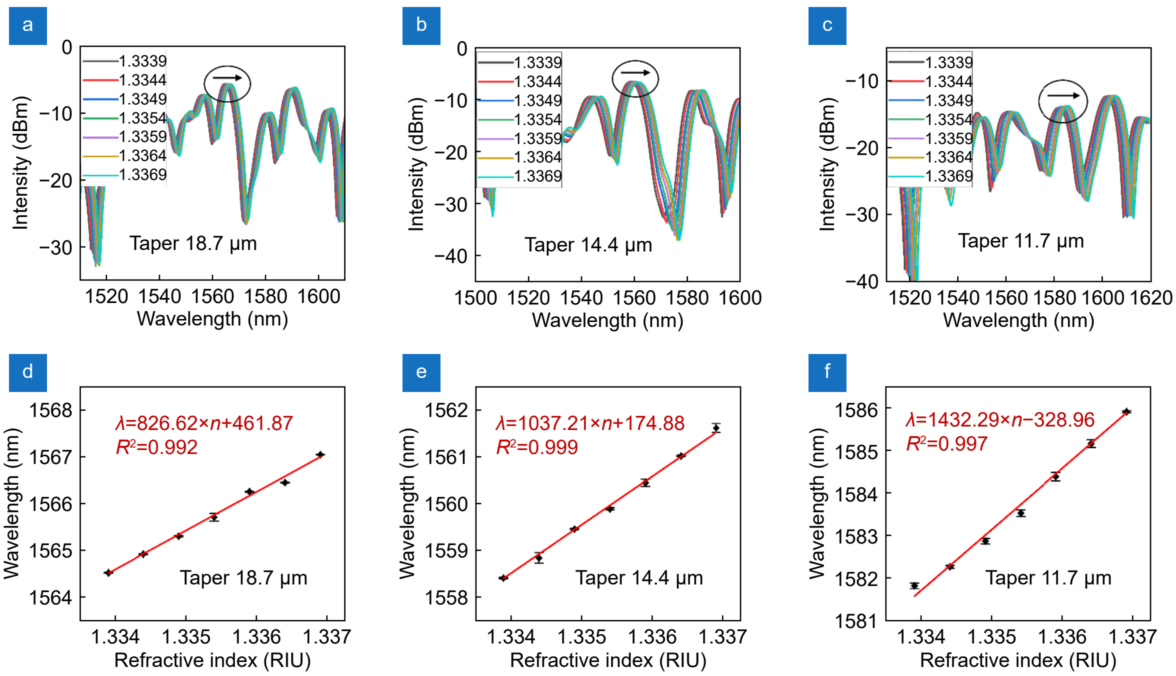

Fig. S4 | The interference spectra of lasso-shaped fiber sensor (bending diameter of around 2 mm) with taper diameter of (**a**) 18.7 μm, (**b**) 14.4 μm and (**c**) 11.7 μm when the ambient RI increase from 1.3339 to 1.3369. The corresponding response sensitivity of fiber sensor with taper diameter of (**d**) 18.7 μm, (**e**) 14.4 μm and (**f**) 11.7 μm.

References

S1. Hu J, He PP, Zhao F et al. Magnetic microspheres enhanced peanut structure cascaded lasso shaped fiber laser biosensor for cancer marker-CEACAM5 detection in serum. *Talanta* **271**, 125625 (2024).

S2. Yang BY, Niu YX, Yang BW et al. High sensitivity balloon-like refractometric sensor based on singlemode-tapered multimode-singlemode fiber. *Sens Actuators A Phys* **281**, 42–47 (2018).