Mie Scattering-Enhanced Fiber-Optic Refractometer

Guigen Liu, Yihui Wu, Kaiwei Li, Peng Hao, Ping Zhang, and Ming Xuan

***Abstract*—A kind of biconically-tapered optical fiber (BTOF) modified by silica nanospheres is proposed to implement detection of refractive index (RI), especially low RI, with strong nonlinearity and enhanced sensitivity; this idea arose from an interesting experiment with a BTOF whose surface was very rough. The mechanisms of the nonlinear characters are investigated and explained by the coupling effects of Mie scattering and multimode propagation, and this phenomenon is repeated in several experiments with different fibers. Measured sensitivity magnification of more than 100 from a 2.8-μm-thick and 14-mm-long BTOF after modification by 400-nm silica nanospheres is shown in this letter.**

***Index Terms*—Mie scattering, multimode propagation, refractometer, tapered optical fiber.**

I. INTRODUCTION

FIBER-OPTIC evanescent wave sensors (FOEWSs), especially those based on micro/nano wires, are very promising in label-free immunoassay with high sensitivity, in which the alterations in refractive index (RI) due to protein binding are detected [1]-[4]. But there are still some challenges that have been blocking the commercialization of FOEWSs in the authors' opinion. In fact, they only show high sensitivity when the surrounding RI is very close to that of the fiber [5]-[7], therefore, they are infeasible in measuring RI much lower than that of the fiber (normally around 1.46 for glass fibers), e.g. some biomolecules have RI as low as 1.36 [8]. Many groups have tried to improve the sensitivity by decorating optical fibers with nanoparticles [9]-[13] which either introduce localized surface plasma resonance absorption or increase the effective cladding RI, however, their sensitivity remains low when measuring low RI. During one of our attempts, an experiment with a BTOF, which was accidentally etched to be rough, showed high sensitivity over a wide RI range of 1.33–1.465 (Fig. 1 (a)). The rough BTOF has a strong nonlinear response and is rather sensitive to low RI, indicating the potential to address the issue. However, rough fibers cannot be reproduced well, efforts are therefore devoted to artificially construct similar fibers modified by silica nanospheres which introduce scattering losses from the evanescent field (Fig. 1(b)). Silica nanospheres are chosen since they are identical to fibers in material. In this Letter we are the first, to our best knowledge, to demonstrate a transmission-loss-based refractometer with wide detection range and enhanced sensitivity based on the coupling effects of scattering losses and multimode propagation.

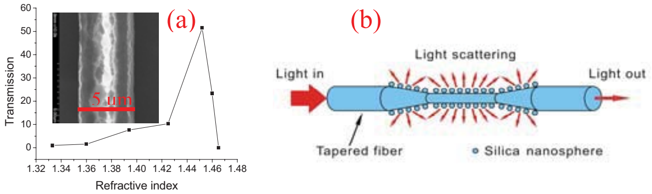

Fig. 1. (a) Transmission versus RI for a rough BTOF. Inset: scanning electron microscope (SEM) image. (b) Schematic of a BTOF modified by silica nanospheres.

II. EXPERIMENTS

Here, smooth BTOFs were made from commercial single-mode fibers (SMF-28, Corning) through chemical etching [14], and silica nanospheres were synthesized using the Stöber method [15]. The nanospheres were covalently immobilized on smooth fibers following the protocols in [16]. In order to quantify the influence of nanospheres, we first tested the response of a smooth unmodified fiber to RI, after which the same smooth fiber was modified by silica nanospheres and then measured. The experiments were carried out with a simple transmission measuring setup.

Measured results of a 2.8 μm thick and 14 mm long BTOF were recorded in Fig. 2. For the unmodified BTOF (black curve in Fig. 2 (a)), the transmitted optical power changes marginally (less than 10%) in the RI range of 1.33–1.39, however, gradual power drop begins to appear when RI exceeds 1.39 and becomes more pronounced when surrounding RI is closer to that of fiber. For the BTOF modified by 400-nm nanospheres (black curve in Fig. 2 (b)), transmission increases from 1 to 22.70 when surrounding RI increases from 1.33 to 1.41; on the contrary, transmission decreases dramatically from 23.12 to 0.12 when surrounding RI increases from 1.43 to 1.46. Thus, the modified BTOF has a detection range of 1.33-1.46 which is much broader than 1.39-1.46 of the unmodified one. Both unmodified and modified BTOF respond nearly linearly when surrounding RI is close to that of fiber core, thus a linear fitting is performed in RI range of 1.44-1.46 and the slope of fitting line is defined as sensitivity. The sensitivity of the modified BTOF is more than 100 (100.89) times as

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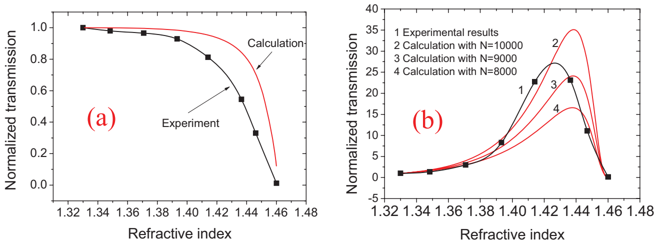

Fig. 2. Measured and calculated transmission as a function of surrounding RI for (a) unmodified and (b) modified BTOF. Both measured and calculated transmission are normalized so that RI is 1.33 for the convenience of comparison.

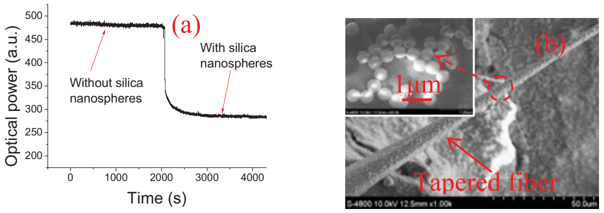

Fig. 3. (a) Output power versus time during the modification process of the BTOF. (b) SEM images of the modified BTOF.

high as that of the unmodified one, reaching a resolution of 1.8×10^{-5} RIU (refractive index unit) if resolution is defined as 3 times the ratio of noise to sensitivity. The resolution can be further improved by reducing the comparatively large noise of our spectrometer. Fig. 3 (a) verifies the scattering looses during the immobilization process monitored at 633 nm. The modified fiber was flushed by deionized water in the end and no output power variation occurred, indicating the permanent attachment of nanospheres to the fiber. The adherence of silica nanospheres to the fiber surface is also shown by a SEM image (Fig. 3 (b)).

III. THEORETICAL EXPLANATION

Theoretical simulations have been done to explain the experimental results. In our case, silica nanospheres are assumed to scatter light without absorption and mutual interferences. The scattering losses from a single isolated spherical particle are well established by the Mie theory [17], in which scattering efficiency is defined as the fraction of power scattered by a single particle. Let T, P_{in} and P_{out} denote the transmission of unmodified BTOF, input power and output power, respectively, thus

$$P_{out} = P_{in} T, \tag{1}$$

for the unmodified fiber, and

$$P_{out} = P_{in} T \exp(-\eta Q_{sca} N), \tag{2}$$

where η, Q_{sca}, and N denote power fraction in the evanescent field, scattering efficiency, and the number of nanospheres, respectively, for the modified fiber. Based on the assumption that all the scattered power is lost which is equivalent to absorption loss, Eq. (2) is rational according to the model of a fiber-optic absorbing sensor [14]. Equation (2) is further proven by Fig. 3 (a), i.e., larger number N of nanospheres introduces more losses.

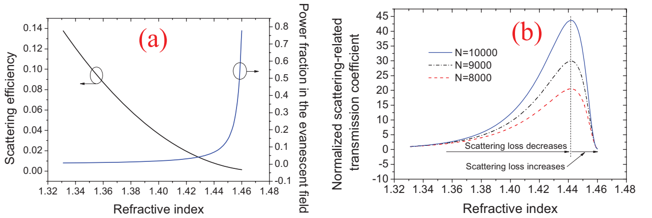

Fig. 4. Calculated (a) scattering efficiency and power fraction in the evanescent field and (b) scattering-related transmission coefficient (SRTC) as a function of surrounding RI. SRTC is normalized so that RI is 1.33 for the convenience of comparison.

The transmission T of the unmodified BTOF, which is described by multimode propagation [7], [18]-[19], is plotted in Fig. 2 (a) (red curve). The difference between the experiments and calculations is attributed to approximations in the simulation of multimode propagation [18], [19].

Compared with Eq. (1), Eq. (2) has an extra component of $\exp(-\eta Q_{sca} N)$, which is the contribution of scattering losses and is here termed scattering-related transmission coefficient (SRTC). SRTC depends on both η and Q_{sca} for certain N. According to the SEM images, the N value is only roughly estimated owing to the ununiformity of nanosphere distribution. Three N values of 8000, 9000 and 10000 are involved in the calculations which are enough to reveal the influence of N value and explain the experimental results.

Scattering efficiency Q_{sca} and power fraction η versus surrounding RI is plotted in Fig. 4 (a). In the calculations, silica nanospheres have RI of 1.475 [20]. Clearly, scattering efficiency Q_{sca} decreases as surrounding RI increases, on the contrary, power fraction η in the evanescent field increases as surrounding RI increases, especially η increases dramatically when RI is close to 1.46. Therefore, RI dependence of SRTC (Fig. 4 (b)) has two opposite trends: (1) In low RI range of 1.33-1.44, SRTC increases as RI increases, which is because of less scattering losses due to smaller scattering efficiency; (2) In high RI range of 1.44-1.46, SRTC decreases immensely as RI increases, which is because of more scattering losses due to dramatically growing evanescent field.

The properties of SRTC give rise to the transmission behavior of the modified fiber (Eq. 2), which is shown in Fig. 2 (b) (curves 2-4). In low RI range of 1.33-1.44, the transmission increases dramatically due to less scattering losses as RI increases. In high RI range of 1.44-1.46, the transmission decreases dramatically due to both more scattering losses and weaker mode propagation as RI increases. It also shows that the larger the N, the bigger the sensitivity improvement. Calculated results when N is 9000 (curve 3) are identical to experimental results (curve 1), and the differences are attributed to the estimated N value, assumption of no absorption by silica nanospheres, and approximations in the simulation of multimode propagation [19], [20], etc.

The theoretical explanation is proved by several experiments with repeatable phenomena. As shown in Table I, transmitted power increases/decreases as RI increases from 1.33 to 1.41 for three modified/unmodified BTOFs, while it decreases as RI increases from 1.43 to 1.46 for both modified and

TABLE I

MEASURED POWER CHANGES FOR THREE DIFFERENT MODIFIED AND UNMODIFIED (IN PARENTHESES) BTOFS OPERATING AT TWO WAVELENGTHS OF 458 AND 633 nm. D AND L DENOTE WAIST DIAMETER AND LENGTH OF THE BTOF, RESPECTIVELY

		Fiber 1 (D = 4.8 μm, L = 4 14 mm)		Fiber 2 (D = 2.8 μm, L = 14 mm)		Fiber 3 (D = 2.8 μm, L = 7 mm)	
RI change		1.33 to 1.41	1.43 to 1.46	1.33 to 1.41	1.43 to 1.46	1.33 to 1.41	1.43 to 1.46
Transmitted power change (a.u.)	458 nm	313 to 376 (667 to 584)	270 to 38 (425 to 110)	29 to 173 (141 to 108)	144 to 0 (60 to 0)	34 to 67 (505 to 425)	56 to 2 (235 to 44)
	633 nm	566 to 873 (1517 to 1419)	824 to 203 (1294 to 588)	24 to 545 (425 to 302)	555 to 3 (99 to 2)	71 to 157 (1054 to 867)	143 to 7 (618 to 121)

unmodified fibers. The experiments shown in Fig. 2 are those of fiber 2 in Table I at 633 nm. Note that the transmitted power is significantly reduced and thus the signal-to-noise ratio is lower for the modified fibers.

It should be noted that there exists a turning (peak) point around 1.43 (Fig. 2 (b)). Although the modified fiber has enhanced sensitivities in low and high RI ranges, the sensitivity is greatly reduced near the turning point which depends on the fiber diameter, operating wavelength, size and RI of nanospheres. However, discussion of the turning point is beyond the scope of this Letter.

IV. CONCLUSION

Detection range broadening and sensitivity enhancement for a fiber-optic refractometer using silica nanospheres have been experimentally obtained and theoretically analyzed. The transmission behavior of a modified BTOF is a coupling effect of scattering losses and multimode propagation. The measured sensitivity magnification is more than 100 for a 2.8 μm thick and 14 mm long BTOF after modified by 400 nm silica nanospheres. This performance can be further improved by the optimization of parameters such as diameter and RI of the nanosphere and length and diameter of the BTOF.

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