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Pilot demonstration of refractive index sensing using polymer optical fiber crushed with slotted screwdriver

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Abstract: We demonstrate power-based refractive index (RI) sensing using a polymer optical fiber (POF) crushed with a slotted screwdriver. This structure can be easily fabricated by simply pressing the end of a slotted screwdriver against part of the POF. Neither external heat sources, chemicals, nor ultrasonic transducers, which have been conventionally used, are necessary. The transmitted power has a linear RI dependence in the RI range from ~1.32 to ~1.43 (coefficient: 173 dB/RIU (RI unit)). The temperature dependence of the transmitted power is experimentally shown to be negligible, which indicates the potential of this structure as a temperature-independent RI sensor.

Keywords: optical fiber sensors, refractive index sensing, polymer optical fibers

Classification: Optical systems

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1 Introduction

Optical fiber sensing techniques have been intensively explored because of their capability to measure a variety of physical parameters, such as strain [1, 2], temperature [1, 2], pressure [3], acoustic impedance [4, 5], humidity [6], reflectivity [7, 8], nuclear radiation [9], etc. Fiber-optic refractive index (RI) sensing has also been receiving increasing attention in chemical, biomedical, and pharmaceutical research areas, and a number of techniques have been reported for several decades [10, 11, 12, 13]. One of the most cost-efficient RI sensing techniques with high sensitivity is based on evanescent waves generated at the tapered region of glass optical fibers [12, 13]. Glass optical fiber tapers are, however, so fragile that we need to take special care in fabricating and handling them. One solution for this problem is the use of polymer optical fiber (POF) tapers [14, 15, 16, 17, 18, 19, 20], which are much more flexible than glass fibers.

To date, many methods of tapering POFs have been reported. Two well-known methods are based on a heat-and-pull technique with an external heat source [14, 15, 16, 17] and a chemical etching technique [18], but the use of external heat sources and chemicals is neither safe nor convenient. To overcome this issue, a POF tapering technique of converting the propagating light energy into heat without the use of an external heat source has been developed [19]. However, high-power light injection is required, which sometimes causes burning at the POF ends [21] and/or a so-called fuse phenomenon [22, 23]. An RI sensor using V-shaped POFs has also been developed [20], but with relatively low measurement accuracy because of the structural instability. Furthermore, RI sensing using an ultrasonically crushed POF has recently been reported [24], but it requires an ultrasonic transducer, which is inconvenient in some applications.

In this study, we demonstrate RI sensing using a POF crushed with a slotted screwdriver. The end of a slotted screwdriver is simply pressed against part of the

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POF with a constant load. This structure can be easily fabricated without the use of external heat sources, chemicals, or ultrasonic transducers. First, the transmitted power is found to show a linear RI dependence in the RI range from ~1.32 to ~1.43 [coefficient: 173 dB/RIU (RI unit)]. The transmitted power is then found to exhibit almost no temperature dependence at around room temperature, which indicates the feasibility of temperature-independent RI sensing.

2 Experimental setup

The POF used here was a perfluorinated graded-index (PFGI-) POF [25, 26] with a core diameter of 50 µm, a cladding diameter of 70 µm, an overcladding diameter of 490 µm, and a propagation loss of ~0.25 dB/m at 1550 nm. The RIs of the core center, cladding layer, and overcladding layer at 1550 nm were 1.356, 1.348, and 1.590, respectively. The core and cladding layer comprised polyperfluorobutenylvinyl ether with different dopant concentrations, and their boundary was invisible. In contrast, the overcladding layer was made up of polycarbonate (mechanically much stronger than the core and cladding), of which the boundary with the cladding layer was observable with a microscope. The water absorption of PFGI-POFs is reported to be much lower than that of standard poly(methyl methacrylate)-based POFs [14, 16]; this is preferable for liquid RI sensing [27].

Fig. 1 depicts the POF processing procedure. The end of a slotted screwdriver (tip thickness: 0.3 mm; tip angle: 17°) was pressed with a 20-N load for 60 s against the midpoint of the 30-cm-long POF on an anvil composed of stainless steel. The crushed region of the POF was directly (i.e., not bent as in Refs. 20 and 24) used as a sensing head.

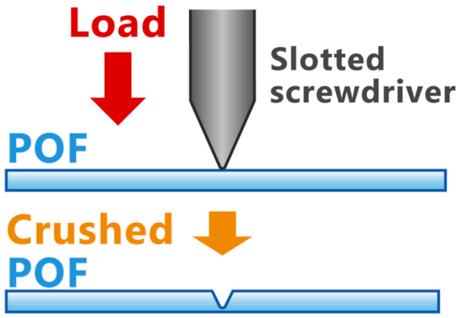

Fig. 1. Processing procedure of the crushed polymer optical fiber (POF).

Fig. 2 is an experimental setup for RI sensing using the crushed POF, which was straightly aligned. The output light from a laser at 1550 nm (power: 10 dBm; bandwidth: ~1 MHz) was passed through a 1-m-long silica single-mode fiber (SMF) and injected into the POF. The transmitted light was subsequently directed to an optical spectrum analyzer (OSA) via a 3-m-long silica multimode fiber (MMF; core diameter: 50 µm) to mitigate the optical coupling loss at the POF output end. The power of its spectral peak was measured with 10 times averaging. Both POF ends were connected to the silica fibers by butt-coupling using “ferrule connector/subscriber connector (FC/SC)” adaptors [26].

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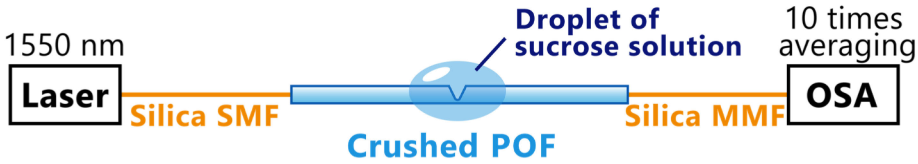
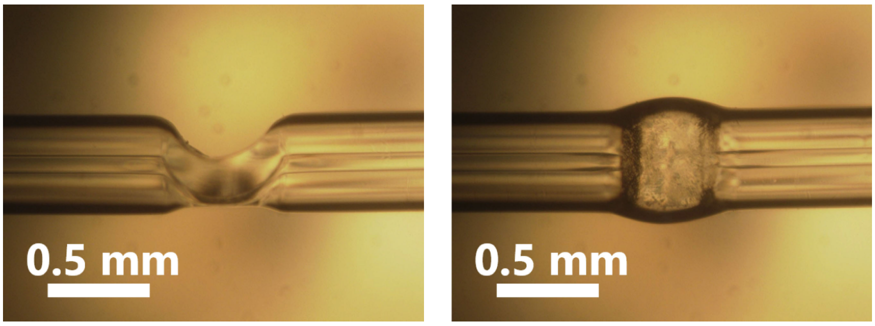


Fig. 2. Experimental setup for the refractive index sensing using the crushed polymer optical fiber (POF). MMF: multimode fiber, OSA: optical spectrum analyzer, and SMF: single-mode fiber.

3 Experimental results

First, we investigated the RI dependence of the transmitted power when the crushed region was surrounded by a sucrose solution (~0.1 ml) at 25°C. By controlling the concentration in the range from 0% to 60%, its RI was varied from 1.318 to 1.426 (with the RI dependence on optical wavelength taken into consideration) [28]. The temperature dependence of the transmitted power was then measured in the range from 10°C to 35°C when the ambient RI of the crushed region was 1.366 (concentration: 30%).

Figs. 3(a) and (b) show the side-view and top-view micrographs of the crushed POF, respectively. The ~600-µm-long region was crushed with a maximal depth of ~210 µm. The crushed region had a height of ~260 µm, which was approximately half of the initial outer diameter (490 µm) of the uncrushed region. The width of the crushed region was ~610 µm, which was ~1.2 times larger than the initial outer diameter. The boundary between cladding and overcladding layers is clearly observed in Fig. 3(a); at the crushed region, the core and cladding layer (not exposed to the atmosphere) are pressed and curved in the same way as the overcladding layer. The optical propagation loss at the crushed region was approximately 26 dB at 1550 nm.



(a) (b)

Fig. 3. Micrographs of the crushed polymer optical fiber: (a) side view and (b) top view.

Fig. 4(a) shows the measured RI dependence of the transmitted power at 25°C. The vertical axis was normalized so that the power at RI = 1.318 (sucrose concentration = 0%) became 0 dB. With increasing RI, the transmitted power increased (the loss decreased) with a dependence coefficient of 173 dB/RIU (To verify the reproducibility of this sensor, we tested three more samples, all of which showed similar behaviors with dependence coefficients ranging from 153 to 175 dB/RIU).

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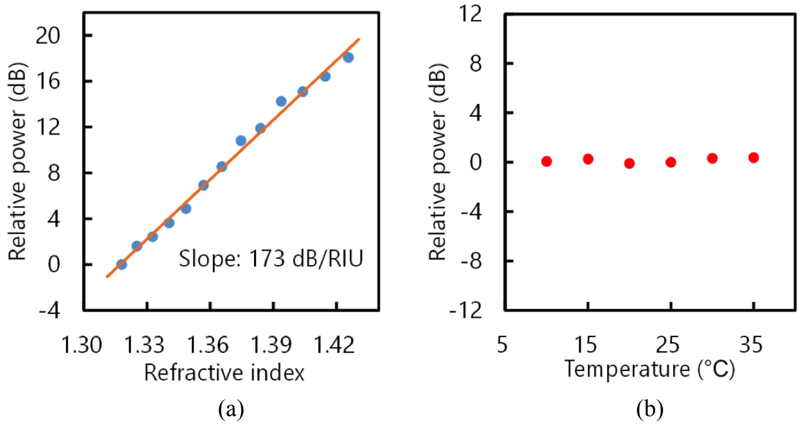

Fig. 4. (a) Measured relative transmitted power dependence on the refractive index (RI). (b) Relative transmitted power dependence on temperature when the refractive index was 1.366.

Simple comparison of the absolute value with those in previous reports measured under different conditions and POF structures cannot avoid being unfair. However, the positive coefficient of the transmitted power against RI was in agreement with some of the previous POF-based results [20, 29], and can be explained as follows. Namely, as the RI of the liquid approaches that of the overcladding layer (~1.59), the light leaking at the crushed region re-enters the POF [29]. Note that this positive dependence is opposite to those of an ultrasonically crushed POF [24] and a D-shaped POF [30], which have much longer crushed/D-shaped regions (6 mm and 10 mm, respectively). When the RI was 1.366 (sucrose concentration: 30%; nearly located at the midpoint of the linear region), the measurement error, defined as the standard deviation of the power fluctuations (the power was measured every 1 minute for 1 hour) was +/−0.26 dB. Note that the transmitted power was not influenced when part of the uncrushed regions of the POF was touched by the sucrose solutions.

Finally, we measured the temperature dependence of the transmitted power in the temperature range from 10°C to 35°C, as shown in Fig. 4(b). The RI was set to 1.366. The vertical axis was normalized so that the power measured at 25°C became 0 dB; the range of the vertical axis (from −12 to +12 dB) was set to almost the same as that of Fig. 4(a) for easy comparison. In order to evaluate the genuine characteristics of the sensor, the influence of the RI dependence of the sucrose solution on temperature was compensated in advance [31]. The transmitted power was almost constant irrespective of temperature with a fluctuation amplitude of +/−0.24 dB, which is comparable to the measurement error of this sensor. This result indicates that temperature-independent RI sensing is potentially feasible by use of this method.

4 Conclusion

We demonstrated RI sensing using a POF crushed with a slotted screwdriver. This structure can be easily fabricated with no need to employ external heat sources, chemicals, or ultrasonic transducers. The only requirement is to simply press the end of a slotted screwdriver against part of the POF. The transmitted power

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was experimentally shown to have a linear RI dependence with a coefficient of 173 dB/RIU in the RI range from ~1.32 to ~1.43. When the RI was 1.366, the temperature dependence of the transmitted power was found to be negligible at around room temperature, which leads to the possibility of temperature-independent RI sensing. Thus, we believe that this simple RI sensing technique using a POF crushed with a slotted screwdriver will be of great convenience in achieving temperature-independent fiber-optic RI sensing for chemical, biomedical, pharmaceutical, and process-control applications in the future.

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