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BRIEF NOTE

Refractive index sensing using V-shaped polymer optical fibers

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Although polymer optical fiber (POF) tapers with high flexibility have been used to measure the refractive indices (RIs) of liquids, their fabrication have caused some inconvenience including the need to use external heat sources or chemicals. Here, as an alternative, we develop a simple, secure, and low-cost method of measuring RIs of liquids using V-shaped bent POFs. When the bending angle is 120° (experimentally optimized), with increasing RI, the transmitted power increases almost linearly with a dependence coefficient of approximately 210 dB/RI unit.

Fiber-optic refractive index (RI) sensing has been attracting a great deal of attention in biological and chemical research fields, and various techniques have been developed.[1–4] Among them, RI sensing using evanescent waves generated at the tapered region of glass optical fibers[3,4] is one of the most cost-efficient and sensitive techniques. Glass optical fiber tapers are, however, fragile and require careful fabrication and handling. One strategy of tackling this problem is to exploit polymer optical fiber (POF) tapers,[5–10] which provide extremely high flexibility.

Conventionally, POF tapers are fabricated by a heat-and-pull technique with an external heat source[5–8] or a chemical etching technique.[9] However, employing external heat sources (flame,[5] a compact furnace,[6,7] a solder gun,[8] etc) and chemicals is neither convenient nor sufficiently secure. Although a POF tapering technique of converting propagating light energy into heat without the use of an external heat source has also been developed,[10] an artificial optical loss of 23 dB needs to be initially induced, resulting in its high total optical loss (48 dB). The requirement of high-power light injection also poses a serious issue, because it may cause burning at the POF ends[11] or a so-called fuse effect.[12]

In this work, we demonstrate RI sensing using a V-shaped bent POF. To fabricate the sensing part, it is necessary to locally cut the overcladding layer of a POF sample and then bend that region. With no need to employ heat sources or chemicals, this technique is extremely simple, secure, and low in cost. We investigate the optimal bending angle at which the transmitted power increases almost linearly with a dependence coefficient of ~210 dB/RI unit (RIU).

The POFs employed in the experiment were perfluorinated graded-index (PFGI-) POFs[13,14] with a core diameter of 62.5 µm, a cladding diameter of 70 µm, an overcladding diameter of 750 µm, and a propagation loss of ~250 dB/km at 1550 nm. The RIs of the core center, cladding, and overcladding were 1.356, 1.348, and 1.590, respectively. The core and cladding layers were composed of the same material (i.e., polyperfluorobutenylvinyl ether; with different dopant concentrations), and their boundaries were not visible; the overcladding layer was composed of polycarbonate. Compared with standard poly(methyl methacrylate)-based POFs,[5,7] one important advantage of PFGI-POFs in RI sensing of liquids is that their water absorption is extremely low.[15]

The POF processing procedure is depicted in Fig. 1(a). The midpoint of the overcladding layer of a ~25-cm-long POF was cut (notched) for ~300 µm using a fiber cutter and was bent into a V-shaped manner. Here, the bending angle was defined to be 0° when the POF was straight (not bent). An example micrograph of the V-shaped POF is shown in Fig. 1(b). The core/cladding layer was bared to air.

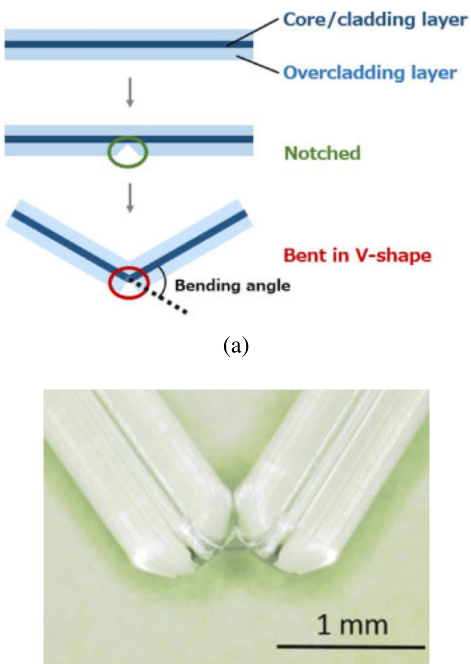

Fig. 1. (Color online) V-shaped POF: (a) processing procedure, and (b) example micrograph (bending angle = 120°).

Fig. 2. (Color online) Schematic of the experimental setup for refractive index sensing. EDFA, erbium-doped fiber amplifier; LD, laser diode; OSA, optical spectrum analyzer.

The experimental setup for RI sensing using the V-shaped POF is schematically shown in Fig. 2. The output light from a laser diode (LD) at 1550 nm was amplified to 10 dBm (fixed power) with an erbium-doped fiber amplifier (EDFA) and injected into the POF. The transmitted light was amplified by 35 dB (fixed gain), and its spectral peak power was measured using an optical spectrum analyzer (OSA) with 100-times averaging. Both ends of the POF were connected to silica

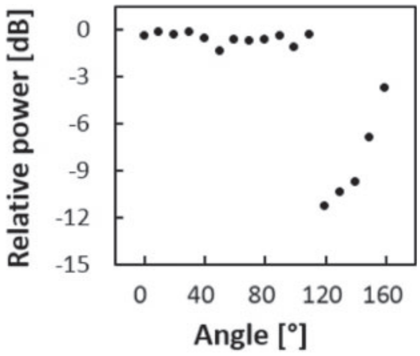

Fig. 3. Dependence of relative power reduction on bending angle.

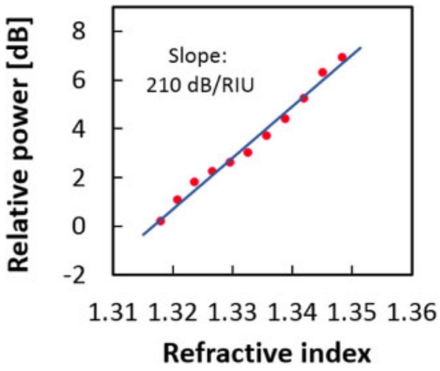

Fig. 4. (Color online) Relative transmitted power plotted as a function of the refractive index of liquid at the bending angle of 120°. Measured data are shown as red circles, and the blue line is a linear fit.

single-mode fibers (SMFs) by butt-coupling via FC/SC adaptors.[14]

First, we measured the reduction in the transmitted power as a function of the bending angle when the V-shaped region was immersed into water at 25 °C (with an RI of 1.318 at 1550 nm). On the basis of this result, the bending angle used for RI sensing was determined. Then, we investigated the RI dependence of the transmitted power when the V-shaped region was immersed into sucrose solution at 25 °C, the RI of which was varied from 1.318 to 1.348 by controlling the concentration in the range from 0 to 20%.[16]

Figure 3 shows the bending angle dependence (every 10°) of the reduction in the transmitted power when the V-shaped region was immersed into water. The vertical axis is the value relative to the transmitted power when the V-shaped region was placed in air. At angles lower than 110°, the power reduction was less than 2 dB, i.e., the transmitted power was almost insusceptible to the ambient material properties. At the angle of 120°, the power reduction abruptly increased to approximately 11 dB. In the range from 120 to 160°, the power reduction gradually became small with increasing angle, probably because of the multimodal effect (a non-monotonic dependence of optical loss on bending radius is reported in SMFs).[17] Thus, the bending angle used for RI sensing, at which the highest sensitivity is expected, was determined to be 120°. The bending loss at this angle measured in air, i.e., the difference in transmitted light power before and after POF processing, was approximately 7 dB, which was ~18 dB lower than that[10] of the aforementioned POF tapering method without external heating (excluding the initial artificial loss).

Subsequently, the RI dependence of the transmitted power was investigated at the bending angle of 120° (Fig. 4). The vertical axis is the value relative to the transmitted power when the V-shaped region was immersed into water. With increasing RI, the transmitted power increased monotonically, and the dependence was almost linear in this RI range (though on a log scale) with a coefficient of approximately 210 dB/RIU. This positive RI dependence of the transmitted power is the same as that in one of the POF-taper-based sensors,[9] and can be explained by the theory of evanescent wave absorption of cladded multimode fiber tapers.[18]

In conclusion, a simple, secure, and low-cost method for measuring RIs of liquids by using V-shaped POFs was demonstrated. When the bending angle was 120°, the transmitted power increased almost linearly with increasing RI of liquids, and the dependence coefficient was ~210 dB/RIU. We anticipate that this method will be a promising alternative to POF-taper-based RI sensing.

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1) H. J. Patrick, A. D. Kersey, and F. Bucholtz, J. Lightwave Technol. **16**, 1606 (1998).
2) T. Takeo and H. Hattori, Jpn. J. Appl. Phys. **21**, 1509 (1982).
3) Z. Tian, S. S. H. Yam, J. Barnes, W. Bock, P. Greig, J. M. Fraser, H. Loock, and R. D. Oleschuk, IEEE Photonics Technol. Lett. **20**, 626 (2008).
4) A. Leung, K. Rijal, P. M. Shankar, and R. Mutharasan, Biosens. Bioelectron. **21**, 2202 (2006).
5) D.-J. Feng, G.-X. Liu, X.-L. Liu, M.-S. Jiang, and Q.-M. Sui, Appl. Opt. **53**, 2007 (2014).
6) N. Hayashi, H. Fukuda, Y. Mizuno, and K. Nakamura, J. Appl. Phys. **115**, 173108 (2014).
7) Y. Jeong, S. Bae, and K. Oh, Curr. Appl. Phys. **9**, e273 (2009).
8) A. A. Jasim, N. Hayashi, S. W. Harun, H. Ahmad, R. Penny, Y. Mizuno, and K. Nakamura, Sens. Actuators A **219**, 94 (2014).
9) Y. M. Wong, P. J. Scully, H. J. Kadim, V. Alexiou, and R. J. Bartlett, J. Opt. A **5**, S51 (2003).
10) H. Ujihara, N. Hayashi, K. Minakawa, M. Tabaru, Y. Mizuno, and K. Nakamura, Appl. Phys. Express **8**, 072501 (2015).
11) Y. Mizuno, N. Hayashi, and K. Nakamura, Opt. Lett. **38**, 1467 (2013).
12) Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. Todoroki, Appl. Phys. Lett. **104**, 043302 (2014).
13) Y. Koike and M. Asai, NPG Asia Mater. **1**, 22 (2009).
14) Y. Mizuno and K. Nakamura, Appl. Phys. Lett. **97**, 021103 (2010).
15) S. Ando, T. Matsuura, and S. Sasaki, Chemtech **24**, 20 (1994).
16) D. R. Lide, *Handbook of Chemistry and Physics* (CRC Press, Boca Raton, FL, 2004).
17) A. Harris and P. F. Castle, J. Lightwave Technol. **4**, 34 (1986).
18) S. Guo and S. Albin, Opt. Express **11**, 215 (2003).