Japanese Journal of Applied Physics **51** (2012) 080202 **RAPID COMMUNICATION**
http://dx.doi.org/10.1143/JJAP.51.080202

High-Speed Measurement of Refractive Index Using Dielectric Multilayer Films Deposited on Optical Fiber End

Kyung-Su Kim, Yosuke Mizuno, and Kentaro Nakamura

Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama 226-8503, Japan

Received May 8, 2012; accepted June 3, 2012; published online July 12, 2012

We have recently developed a refractive index (RI) sensor using a band-pass filter composed of dielectric multilayer films deposited on an optical fiber end. The RI is detected as a shift in the wavelength characteristics, and can be read with an optical spectrum analyzer used in this sensor. In this study, we employ a high-speed demodulator, which converts the optical wavelength information into electrical voltage through the slope of the spectral characteristics. A response time of as short as several tens of microseconds is achieved. We also compare the RI sensitivity of the proposed sensor with that of a simple Fresnel-based RI sensor.

Refractive index (RI) sensors have been used in a wide range of applications including biochemistry, chemical/environmental analysis, and ultrasonic-wave detection.[1–15] Many types of RI sensor using optical fibers have been developed so far because of their following advantages: compact size, cost efficiency, flexibility in design, remote-sensing capability, multiplexibility, and immunity to electromagnetic interference. Not only intensity-domain techniques that exploit the RI dependence of the Fresnel power but also a variety of frequency-domain techniques have been developed. Typical examples include RI sensors based on (1) fiber Bragg gratings (FBGs),[1–4] (2) long-period gratings (LPGs),[5–8] and (3) interferometers.[9–12] Although these techniques have their own advantages, none of them is applicable to the RI measurement of solids.

To extend their application range, we have developed a novel RI sensor using a band-pass filter (BPF) comprising dielectric multilayer thin films (DMFs) deposited on an optical fiber end.[16] This structure, called a BPF on a fiber end (BOF),[17] eliminates incident light with a particular wavelength, which is dependent on the RI of the materials attached. The BOF-based RI sensor has many advantages such as high spatial resolution, cost efficiency, simplicity, robustness, and applicability not only to gases and liquids but also to solids. Its measurement speed was, however, low owing to the use of an optical spectrum analyzer (OSA) with a second-order sweep time, which needs to be enhanced for such applications as real-time RI monitoring[13] and ultrasonic-wave detection.[14,15]

In this study, we demonstrate high-speed RI measurement with the BOF-based sensor by using a fast demodulator, which converts the optical wavelength information into electrical voltage using the linear slopes of the reflection spectra. A several tens of microseconds response time is experimentally achieved, which corresponds to the dynamic behavior of the sample liquid. The RI sensitivity of the BOF sensor is also compared with that of a simple RI sensor based on Fresnel reflection to clarify its benefits.

For high-speed RI measurement, the optical wavelength information needs to be converted into electrical voltage. This conversion is made up of two steps: from wavelength information to optical power, and from optical power information to voltage. To achieve the first step, a linear slope region of the reflection spectra needs to be selected,[17–20] to which the wavelength of a light source is set. The second step can be easily achieved by using a photodetector (PD), which operates much faster than the OSA.

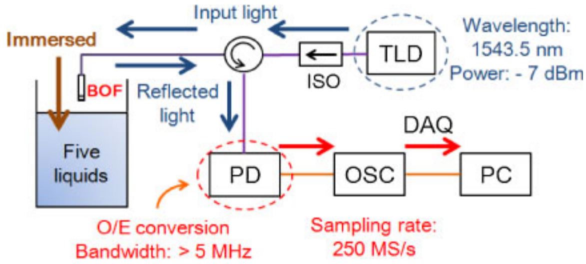

Fig. 1. (Color online) Schematic experimental setup for high-speed RI measurement. DAQ, data acquisition; ISO, isolator; OSC, oscilloscope; PC, personal computer; PD, photodetector; TLD, tunable laser diode.

The experimental setup for the RI measurements based on high-speed demodulation without comprising an OSA is schematically shown in Fig. 1. The structure of the BOF was the same as that previously reported.[16] Judging from the reflection spectra of this BOF,[16] the wavelength of the tunable laser diode (TLD) was set to 1543.5 nm. Its output light with a power of -7 dBm was injected into the BOF via an optical circulator. The reflected light from the BOF was converted to an electrical signal using a PD with a bandwidth of over 5 MHz, and was monitored employing an oscilloscope (OSC) with a sampling rate of 250 MS/s. As materials to be measured, we employed air and five types of liquid: water ($n \sim 1.33$), ethanol ($n \sim 1.36$), index-matching oil (I) ($n \sim 1.44$), matching oil (II) ($n \sim 1.60$), and matching oil (III) ($n \sim 1.74$). The BOF was immersed into the liquids by hand.

Figure 2 shows the measured temporal change of the output voltage for the five types of liquid, which were attached to the BOF in air. The voltage decreased according to the RIs of the different liquids. The time constant of the PD was estimated to be less than 0.2 µs, since the cutoff frequency was over 5 MHz. However, a several tens of microseconds response time was observed for the voltage change, which was much longer than the time constant of the PD. This delay may be attributed to the time for the sample liquids to cover the sensing area of the BOF, which is determined by their density, viscosity, and surface tension. From Fig. 2, the RI dependence of the output voltage can be plotted as shown in Fig. 3. The slope of its linear approximation was -27.95 mV/RIU (refractive index unit). The slight discrepancy of the experimental data from the approximated line is probably caused by the fact that, as RI changes, the optical power also slightly changes.[16]

Next, we compared the experimental sensitivity of the BOF-based RI sensor with the theoretical sensitivity of a

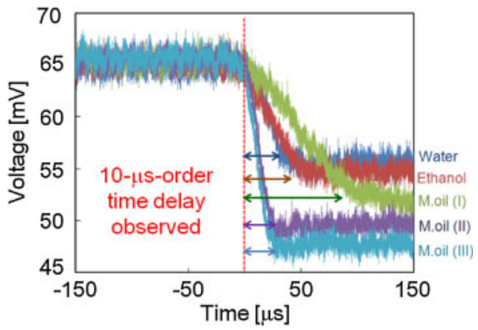

Fig. 2. (Color online) Temporal change of the output voltage.

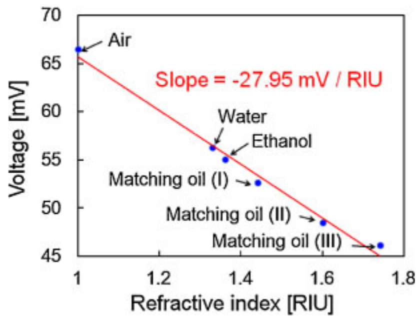

Fig. 3. (Color online) RI dependence of the output voltage.

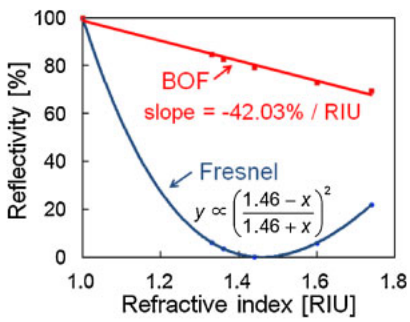

Fig. 4. (Color online) Comparison of RI dependences of reflectivity between BOF and F-RI sensors.

simple Fresnel-reflection-based RI (F-RI) sensor composed of a silica single-mode fiber (SMF) end. A comparison of the RI dependences of the reflectivity between the two methods is shown in Fig. 4, where we normalized the vertical axis, i.e., the reflectivity, so that it becomes 100% when the sensing fiber ends are open in the air. The RI sensitivity can be evaluated using the absolute values of their slopes, which are given in Fig. 5. While the sensitivity of the F-RI sensor drastically changes according to RI, that of the BOF sensor is constant regardless of RI, which leads to ease of handling. Within the RI range of approximately 1.46, the sensitivity of the BOF sensor is higher than that of the F-RI sensor. It has been shown that this range can be further extended by optimizing the BOF structure.[21]

In conclusion, high-speed RI measurement was successfully demonstrated with the BOF-based RI sensor by fast demodulation, where the optical wavelength shift was converted into electrical voltage change using the slopes of the

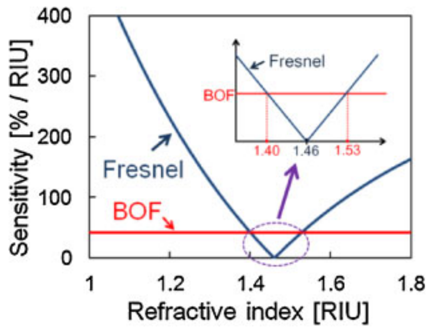

Fig. 5. (Color online) Comparison of RI dependences of sensitivity between BOF and F-RI sensors.

reflection spectra. The response time of the sensor is subject to the dynamic behavior of the sample liquids, and was as short as several tens of microseconds. The RI sensitivity of the BOF sensor was also compared with that of a simple F-RI sensor, and the BOF sensor was, with ease of handling, found to be more suitable for the measurement of RI of approximately 1.46. The next task to be performed is to identify the optimal BOF structure for maximizing the RI sensitivity. We believe that this information will be of great significance in applying the BOF sensor to real-time RI monitoring as well as to ultrasonic-wave detection in the future.

Acknowledgements The authors are indebted to Dr. Onoda and Mr. Nakano, Watanabe Co., Ltd., for providing the BOF samples. One of the authors (YM) is grateful to the Research Fellowships for Young Scientists from the Japan Society for the Promotion of Science (JSPS) and to research grants from the Foundation of Ando Laboratry and the Murata Science Foundation.

1) W. Liang, Y. Huang, Y. Xu, R. K. Lee, and A. Yariv: Appl. Phys. Lett. **86** (2005) 151122.
2) A. Iadicicco, A. Cusano, A. Cutolo, R. Bernini, and M. Giordano: IEEE Photonics Technol. Lett. **16** (2004) 1149.
3) X. Shu, B. A. L. Gwandu, Y. Liu, L. Zhang, and I. Bennion: Opt. Lett. **26** (2001) 774.
4) X. Sang, C. Yu, T. Mayteevarunyoo, K. Wang, Q. Zhang, and P. L. Chu: Sens. Actuators B **120** (2007) 754.
5) V. Bhatia and A. M. Vengsarkar: Opt. Lett. **21** (1996) 692.
6) H. Tsuda and K. Urabe: Sensors **9** (2009) 4559.
7) J. H. Chong, P. Shum, H. Haryono, A. Yohana, M. K. Rao, C. Lu, and Y. Zhu: Opt. Commun. **229** (2004) 65.
8) H. J. Patrick, A. D. Kersey, and F. Bucholtz: J. Lightwave Technol. **16** (1998) 1606.
9) Z. Tian, S. S.-H. Yam, and H.-P. Loock: Opt. Lett. **33** (2008) 1105.
10) T. Wei, Y. Han, Y. Li, H.-L. Tsai, and H. Xiao: Opt. Express **16** (2008) 5764.
11) Y. Wang, M. Yang, D. N. Wang, S. Liu, and P. Lu: J. Opt. Soc. Am. B **27** (2010) 370.
12) Z. L. Ran, Y. J. Rao, W. J. Liu, X. Liao, and K. S. Chiang: Opt. Express **16** (2008) 2252.
13) J. L. Elster, M. E. Jones, M. K. Evans, S. M. Lenahan, C. A. Boyce, W. Velander, and R. VanTassel: Proc. SPIE **3911** (2000) 105.
14) J. Staudenraus and W. Eisenmenger: Ultrasonics **31** (1993) 267.
15) B. Shen, Y. Wada, D. Koyama, R. Isago, Y. Mizuno, and K. Nakamura: Proc. SPIE **7753** (2011) 77539W.
16) K. S. Kim, Y. Mizuno, M. Nakano, S. Onoda, and K. Nakamura: IEEE Photonics Technol. Lett. **23** (2011) 1472.
17) S. Onoda, N. Tsukamoto, M. Ogino, K. Yamashita, O. Yumoto, K. Inoue, and Y. Komatsu: IEEE Photonics Technol. Lett. **20** (2008) 688.
18) Y. J. Rao: Meas. Sci. Technol. **8** (1997) 355.
19) D. C. Betz, G. Thursby, B. Culshaw, and W. J. Staszewski: Smart Mater. Struct. **12** (2003) 122.
20) J. R. Lee and H. Tsuda: Meas. Sci. Technol. **17** (2006) 2920.
21) K. S. Kim, Y. Mizuno, M. Nakano, S. Onoda, and K. Nakamura: IEICE Tech. Rep. **111** (2011) 43.