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High-Sensitivity Multimode Interference Refractive Index Sensor using Small-Core Single-Mode Fiber for Biosensing

Tomohiro Aiga, Shuji Taue and Hideki Fukano

Okayama Univ.
3-1-1, Tsushima naka, Kita-ku, Okayama-shi,
Okayama 700-8530, Japan
Phone: +81-86-251-8138 E-mail: en19401@s.okayama-u.ac.jp

Abstract

An optical fiber refractive index (RI) sensor using multimode interference (MMI) composed of unclad multimode fiber sandwiched by small-core single-mode fibers has been proposed and demonstrated. A very high sensitivity of less than 6×10^{-6} at an RI of over 1.35 has been realized.

1. Introduction

Recent progress in optical fiber communication systems has resulted in high-quality optical fibers as well as high-performance laser sources and detectors with low cost. In addition, because silica fiber has high immunity to electromagnetic interference and strong tolerance to corrosive chemical substances, silica-based optical fiber sensors using low-cost active optical devices are very attractive for determining the physical and biochemical properties of substances. In recent years, there has been much interest in determining the physical parameters of cells such as size, shape, and refractive index (RI) of living cells as demanded in biological studies. The effective RI measured in a buffer solution is a key indicator to reflect cell states. Therefore, a very-high-sensitivity RI measurement in buffer solution is essential for biosensing with optical fiber.

In this paper, very-high-sensitivity RI sensor using multimode interference (MMI) has been proposed. The MMI characteristics are enhanced by using small-core single-mode fibers for input and output fibers, resulting in a very high sensitivity of 6×10^{-6} at an RI of 1.35 in conventional buffer solution. To our knowledge, this is the highest sensitivity so far reported for an MMI refractive index fiber sensor.

2. Operation principle

It has been observed that optical interference in a multimode waveguide produces periodic optical focusing points; this phenomenon is known as MMI [1]. In optical fiber devices, the MMI concept can also be realized by using a step-index multimode fiber (MMF) sandwiched by two single-mode fibers (SMFs) consisting input and output fibers as shown in Fig. 1. Outputted light from an input SMF to an MMF diffracts and makes multimode lights. Totally reflecting multimode lights at the outer surface of the MMF transmit several times and then interfere at the end of MMF. The interference light coupled with the output SMF can be observed with an optical spectrum analyzer by the light intensity variation depending on its wavelength (λ). When transmitting light in an MMF with total reflection at its outer surface, evanescent light is formed, and its optical phase changes with the RI of the surrounding medium. In other words, this phase change shifts the interference condition; therefore, this shift reflects the change of RI.

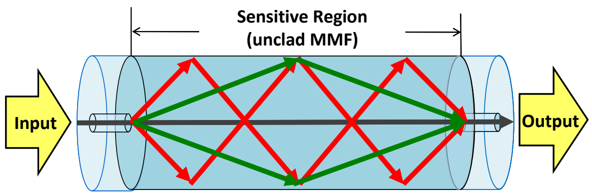
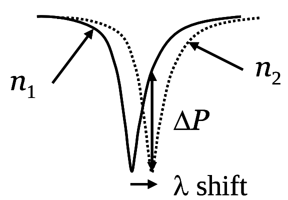


Fig. 1 Multimode interference (MMI) structure.

In the present study, an SMF with a smaller core than conventional 8.2-μm-core SMF was used to increase sensitivity. A small-core SMF leads to high sensitivity through two factors. First is the enhancement of diffraction at the input port due to light propagation from the small core. This produces higher light intensity of higher-mode lights. Second is the sharper angle dependence of coupling efficiency at the output port of a small-core SMF. These two factors produce a sharper MMI signal. When we measure different RI media with a RI difference (Δn) between them, the spectral change occurs as schematically shown in Fig. 2. Using the light intensity difference (ΔP) between the two spectra at a fixed λ, the sensitivity (S) can be estimated using the following equation for a given optical power resolution (δP) of the power meter. High sensitivity is obtained when ΔP increases. Therefore, the sharper the spectrum, the larger the ΔP, resulting in higher sensitivity of the RI sensor.



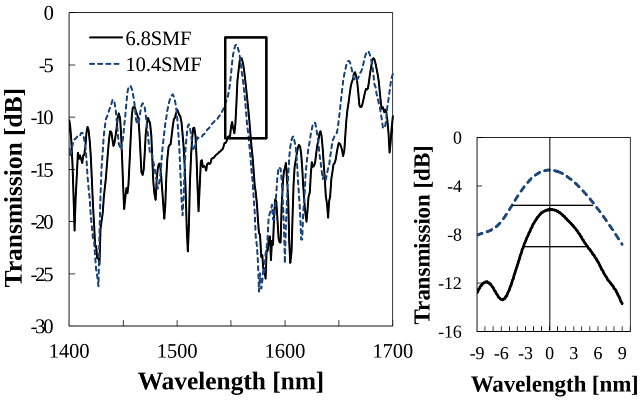
$$\Delta n = n_2 - n_1$$

$$S = \Delta n \frac{\delta P}{\Delta P} \quad (1)$$

Fig. 2 Transmission difference (ΔP) of an MMI sensor with a refractive index change.

3. Experimental

We tested two types of SMFs with mode diameters of 10.4 μm (10.4SMF: conventional SMF used for telecommunication) and 6.8 μm (6.8SMF) both at a λ of 1550 nm. The sensor part is an unclad MMF with a diameter of 125



(a) (b)

Fig. 3 (a) Transmission spectra at MMI sensors with normal core (10.4SMF) and small core (6.8SMF). (b) Peak spectra with normalized center at the peak wavelength.

μm. An amplified spontaneous emission (ASE) light with a wavelength of 1520–1620 nm was fed into the sensor fiber, and the transmitted light was observed using the optical spectrum analyzer. Figure 3 shows the measured MMI spectra at the sensor structure with an MMF of 58 mm, in which the input light with a λ of 1550 nm theoretically re-focused at the end of MMF. Although the peak wave-lengths differ slightly due to a small deviation in the fabri-cated MMF length, the full-width at half maximum (FWHM) of spectral peaks, as shown in Fig. 3 (b) with the horizontal axis normalized at the peak λ, were 10.4 and 7.7 nm for 10.4SMF and 6.8SMF, respectively. A sharper spectrum was obtained for the smaller-core SMF, showing an increase in the sharpness of the MMI signal.

We applied the proposed sensor with a MMF length of 80.75 mm for RI measurement of ethanol/water solutions while varying the volume ratio of ethanol from 0 to 99.5% in steps of 10%. This volume ratio causes the RI to vary from 1.333 to 1.363. Figure 4 shows the measured spectra with the interference dips used for evaluation of RI sensi-tivity. The interference wavelength red-shifted with in-creasing ethanol volume and peaked at about 80-90% as shown in Fig. 5. This tendency corresponds well with the reported RI values [2]. As described in Fig. 3, sensitivity can be evaluated in each range of 10% concentration using intensity variation. Figure 6 shows the RI dependence of estimated sensitivity when assuming a conventional optical power meter resolution of 0.01 dB. Since this type of sharper interference dip produces very high sensitivity within the narrow spectral range, this sensor has higher potential in microanalysis of living-cell measurements in buffer solution with a higher RI. For example, as phosphate buffered saline (PBS) solution has a normal RI of 1.350 [3], this sensor can detect the bio-material with an RI resolution as good as ~6×10^{-6}. Furthermore, if we can prepare a buffer solution with an RI of over 1.36, sensitivity becomes better than 3×10^{-6}, which is close to the sensitivity of sur-face plasmon resonance bio-sensors. This clearly indicates that this proposed simple MMI sensor is a very promising candidate for biosensing.

4. Summary

A very-high-sensitivity refractive index sensor using MMI structure composed of unclad MMF sandwiched by small-core SMFs has been proposed and demonstrated. The fabricated sensor shows a very high sensitivity of better than 6×10^{-6} in an RI range above 1.35.

Acknowledgements

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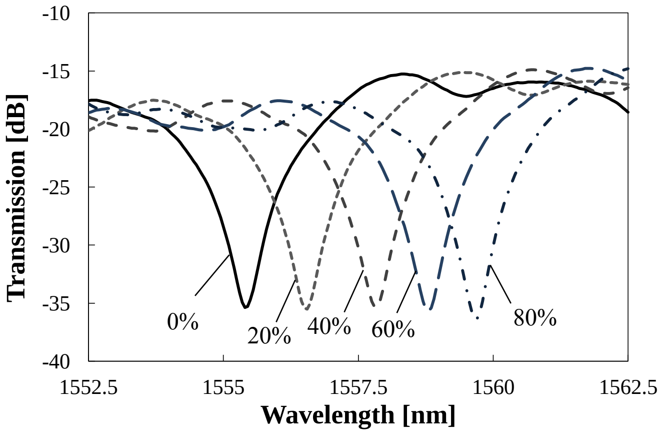

Fig. 4 Transmission spectra of the MMI sensor for dif-ferent ethanol/water solutions.

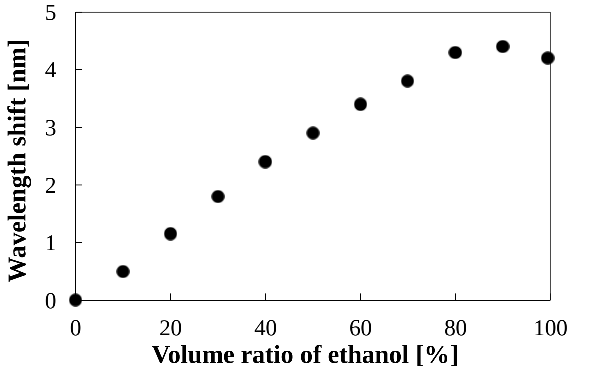

Fig. 5 Transmission wavelength shift of the MMI sensor for different ethanol/water solutions.

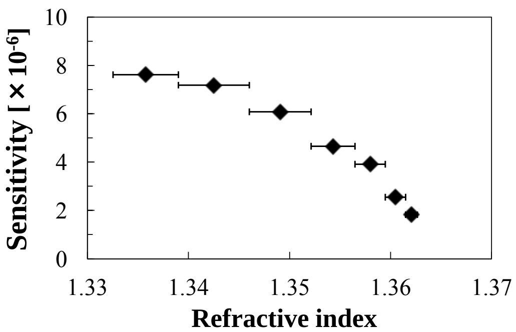

Fig. 6 Sensitivity dependence on refractive index.