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Fiber-optic Biosensor based on Multimode Interference using Small-core Single-mode Fiber

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Abstract

We demonstrated improved sensitivity in a fiber-optic biosensor based on multimode interference. To achieve higher sensitivity, smaller core single-mode fibers were used to generate higher order modes in a multimode fiber at the input port and a sharper angle dependence of the coupling efficiency at the output port. By using this sensor, a bio-sensing application was conducted with the biotin-streptavidin system.

1. Introduction

Many optical fiber sensors have been investigated for physical and biological measurements. Especially, silica-glass-made optical fibers have been studied in detail as they have good biocompatibility and chemical-resistance. The advancement of optical fiber communication technologies has resulted in improvements in the qualities and performances of optical devices, such as optical fibers, lasers, and detectors. As a result, high-sensitivity, in-line optical fiber interferometers are a major focus of research in fiber Bragg gratings (FBG) [1], long period fiber gratings (LPG) [2], etc. Additionally, optical fiber modal interferometers are also actively researched because of their high sensitivities and ease of fabrication. For example, a tapered single-mode fiber [3], core diameter mismatched fiber [4], and multimode interference (MMI) fiber [5] are fabricated by the heat pulling method or fusion splicing fibers with different core diameters. These fiber interferometers are applied as refractometers based on evanescent field interactions around the fiber. The refractive index (RI) variations of the evanescent field induce a Goos-Hänchen shift (optical phase shift), and the transmission spectrum is shifted accordingly.

In this study, we first experimentally confirm the improvement of the sensitivity of the MMI structure by using smaller core single-mode fiber (SMF). Subsequently, we demonstrate a fiber-optic biosensor based on MMI with smaller core SMF by using the biotin-streptavidin system.

2. Concept

Multimode interference with optical fiber

The MMI structure is a very simple and robust interferometer. As shown in Fig. 1, it is easily made by fusion splicing both ends of a multimode fiber (MMF) to single-mode fibers used as input and output (I/O) fibers. To measure the RI of a material around the fiber, an unclad multimode fiber acts as a sensing region. Light propagation modes in a multimode fiber interfere because of a modal dispersion and produce periodical optical focusing points corresponding to the wavelength. Therefore, the light coupled into the output SMF is analyzed as an interference spectrum. The wavelength of these spectral signals can be easily calculated and controlled by tuning the length of the MMF [5]. When the light propagating in the MMF is reflected at the fiber-material interface, the different values of RI in the evanescent field cause a transmission spectral shift.

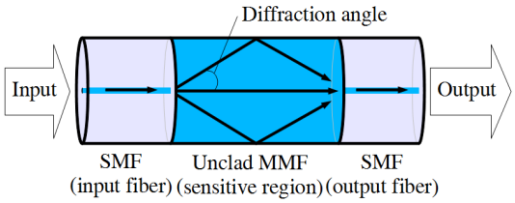

Fig. 1 The multimode interference (MMI) structure with an unclad multimode fiber (MMF) and single-mode fiber (SMF) on each end.

For measuring the light intensity difference between two spectra at a fixed wavelength with high sensitivity, it is important to take into account possible large amounts of spectral shift or rapid variations in the spectra. To obtain a transmission spectrum with higher resolution, greater modal dispersion is required in the MMF. This can be achieved by using either a longer MMF or smaller core SMF for the I/O fibers. The smaller core I/O fibers would produce a larger number of modes because of the larger diffraction at the input port of the SMF, and also produce a sharper angle dependence of the coupling efficiency at the output port of the SMF. Expecting an increase in stability and a size reduction of the sensing probe, we adopt smaller core SMF to achieve higher sensitivity. By using smaller core fibers, a very sensitive refractometer has been experimentally realized with a sensitivity of about 3×10^{-6} at an RI of 1.35, which is the nominal RI for a phosphate buffered saline (PBS) solution [6].

3. Experimental

Increased effect of diffraction with smaller core I/O fibers

Two types of MMI structures were fabricated with SMFs as the I/O fibers with mode-field diameters of 6.8 μm and 10.4 μm at a wavelength of 1550 nm. As shown in

Fig. 1, the I/O fibers for each type were fusion-spliced to a MMF with a core diameter of 125 μm. The other end of the input fiber was connected to an amplified spontaneous emission light source, and an optical spectrum analyzer was connected to the output fiber. To evaluate the sensing performance, a characteristic dip in the transmission spectra was observed.

Figure 2 shows transmission spectra measured in different ethanol/water solutions for an MMI structure with I/O fibers of the two different diameters mentioned above, and the length of each MMF was 34.8 mm. By using the same length of the MMF, similar spectral dips were observed for both types at a wavelength of approximately 1569 nm. However, a sharper and deeper spectral dip was obtained by using 6.8 μm I/O fibers. The spectral shift (Δλ) obtained by changing concentrations from 30 to 40%, which is equivalent to a RI change from 1.349 to 1.354 including the RI for a PSB solution, were measured as 0.65 nm and 0.80 nm for 6.8 μm and 10.4 μm I/O fibers, respectively. On the other hand, the maximum variation of light intensity (ΔI) at a fixed wavelength with the 6.8 μm and 10.4 μm I/O fibers were 4.565 dB and 2.691 dB, respectively. This result indicates that the sensitivity improves by a factor of 1.7 when using the smaller core SMF.

Bio-sensing application with biotin-streptavidin system

We demonstrated a fiber-optic biosensor with MMI structure that was fabricated with the I/O fibers of 6.8 μm and a sensing region consisting of an unclad MMF with a core diameter of 125 μm and length of 34.9 mm. The input fiber end was connected to a wavelength tunable laser source and the output to an optical power meter. The wavelength of the laser source was configured to scan from 1563.70 to 1565.70 nm with 0.05 nm steps to observe a characteristic spectral dip. In this experiment, it took 90 s to scan all the wavelengths. The surface of the MMF was modified with an amino-silane monolayer by using a 1% aqueous solution of (3-aminopropyl)-trimethoxysilane (APTMS) and then biotinylated with Biotin-$(AC_5)_2$ Sulfo-OSu (Dojindo). The modified MMF was installed inside an acrylic flow channel.

At first, the PBS solution was passed through the flow channel by using a peristaltic pump. The sensor was initially washed to provide a system baseline. The characteristic spectral dip was observed at the wavelength of 1564.75 nm. Subsequently, at 15 min, a prepared 1 ng/ml streptavidin (Nakarai Tesque) in PBS solution was passed to build up several complete biotin-streptavidin layers. Finally, at 43.5 min, PBS was passed to ensure that the streptavidin was firmly attached to the biotin on the sensor surface. As a result, the effective RI at the evanescent field was increased by the attached streptavidin. Figure 3 shows measurements of light intensity variations at a wavelength of 1565.05 nm. The light intensity at a longer wavelength side of the dip was decreased by the spectral red-shift due to the increased RI. In our previous study, the same concentration of the streptavidin had been detected by using the MMI structure fabricated with the I/O fibers of 10.4 μm and a longer

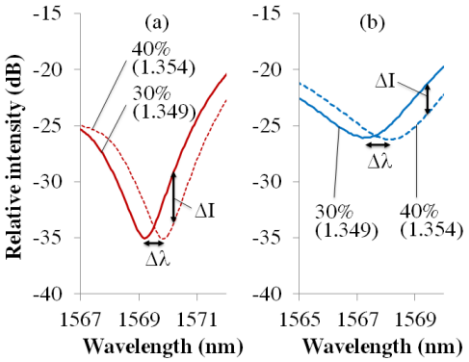

Fig. 2 Transmission spectra measured in different ethanol/water solutions for MMI structure with I/O fibers with (a) 6.8 μm and (b) 10.4 μm.

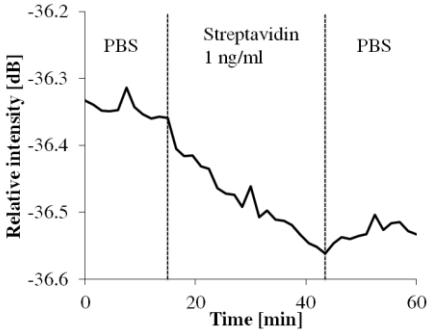

Fig. 3 Experimental result for bio-sensing demonstration. Time variation of a light intensity difference at a wavelength of 1565.05 nm was measured by flowing 1 ng/ml streptavidin.

MMF (58 mm) [7]. In comparison, we confirmed the enhancement of the change in light intensity by deposition of 1 ng/ml streptavidin. By using 6.8 μm I/O fibers, we also achieved a size reduction of the MMI biosensor with higher sensitivity.

4. Conclusions

The sensitivity of the RI sensor with MMI was improved by using smaller core SMFs. The sharper spectrum due to the greater modal dispersion leads to a size reduction of the sensing region and high sensitivity. As a demonstration of the biosensor, biotin-streptavidin interaction was observed with a concentration of 1 ng/ml. The reduction of the sensor size with higher sensitivity has possibilities to reduce the amount of testing solutions.

References

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