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Optical fiber sensor with multimode interference structure

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1. Introduction

With the decrease in the cost of high-quality optical fibers, rapid advancements have been made in the research and development of optical fiber sensors [1-4]. Optical fiber sensors are expected to find application in fields where the traditional electric and chemical reaction sensors cannot be applied. In an optical fiber sensor, the sensing function is performed using the evanescent waves on the surface of the fiber. In addition, an optical fiber sensor with a multimode interference (MMI) structure has been reported [1-5]. The configuration of the MMI structure is very simple and enables the detection of the change in the refractive index of the surrounding medium [3-4].

In this study, we examine the variation of interference wavelength with changes in the sensing part length. The results measured by an MMI-structured optical fiber sensor are compared with those calculated from the MMI theory [6]. Next, we investigate the spectrum characteristics of the interference signal for the input and output (I/O) fibers with different types of fibers and different core diameters. Finally, we demonstrate the use of an optical fiber sensor with a MMI structure for refractive index measurement.

2. Multimode interference structure

It has been observed that optical interference in a multimode waveguide produces periodical optical focusing points; this phenomenon is known as MMI [7]. A MMI structure can be configured with several types of axially spliced optical fibers [1-5].

As shown in Fig. 1, we used an unclad fiber as the large-core fiber for the sensing part so that the propagated light undergoes total reflection at the boundary with the surrounding medium. The relationship between interference wavelength λ_0 and sensing part length L is as follows [6]:

$$L = \frac{d^2 m}{\lambda_0} n \qquad (1)$$

where d is the core diameter of the sensing part; m, a natural number; and n, the refractive index of the large-core sensing fiber. When the refractive index of the surrounding medium changes, the effective core diameter also changes because of the change in the penetration of evanescent waves into the surrounding medium, resulting in the interference wavelength shifts.

3. Experimental setup

An unclad pure silica multimode fiber with a core diameter of 125 μm (MMF125) was used as the sensing part. I/O fibers were fusion-spliced with the sensing fiber, as shown in Fig. 1. The measurement system comprised a white light source (TQ8111, Advantest), and an optical spectrum analyzer (MS9710C, Anritsu) was used for optical observation. The spectral change caused by the MMI structure was observed in the 700–1700 nm wavelength range.

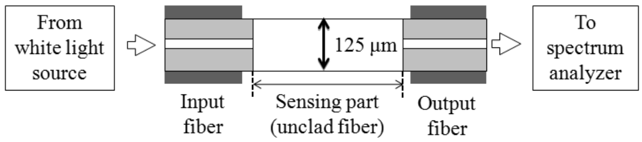


Fig. 1 MMI structure with unclad fiber and experimental system

4. Experimental results and discussion

4.1 Output spectrum with MMI structure

To confirm the wavelength selectivity caused by MMI, we measured and compared the transmission spectra of the fiber with and without the MMI structure. The I/O fibers comprised a graded-index multimode fiber with a core diameter of 50 μm (GIMMF50), and a 104-mm-long MMF125 was used as the sensing part. Figure 2 shows an example of the measured spectra. It is observed that the output power decreases slightly for all wavelengths with the addition of a MMI structure. Periodical interference signals are confirmed as labeled in Fig. 2 (A, B, C, and D).

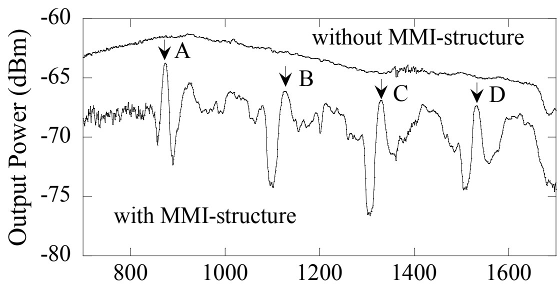


Fig. 2 Output spectra

4.2 Dependence of interference wavelength on sensing part length

We measured the spectrum of MMI-structured optical fibers for 17 different values of L, ranging from 24 mm to 104 mm, in order to investigate the relationship between interference wavelength and L. The I/O fibers comprised a

GIMMF50. The results are shown in Fig. 3, wherein the A, B, C, and D labels correspond to the ones in Fig. 2. The theoretical values agree well with the measured values for all values of m (solid line).

The larger m and longer L are thought to correspond higher sensitivity because both parameters increase the number of times of total-reflection. From Fig. 3, we can set the desired interference wavelength by adjusting m and L.

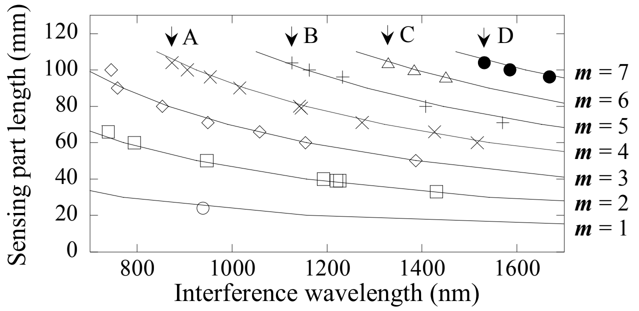
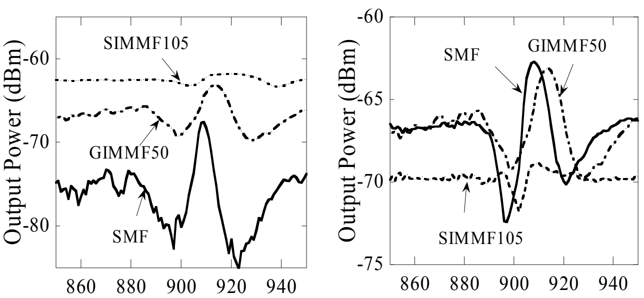


Fig. 3 Interference wavelength versus sensing part length

4.3 Spectrum change with I/O fibers

To study the spectrum change with change in the type of I/O fibers used, we compared three types of I/O fibers: step-index multimode fiber with a core diameter of 105 μm (SIMMF105), GIMMF50, and single-mode fiber (SMF). The L was fixed at 100 mm. The spectrum characteristics for the three types of (a) input fibers and (b) output fibers are shown in Fig. 4.

Small-core fibers (SMF) exhibit remarkable wavelength selectivity when used as the input or output fiber. The interference signal almost disappears when a larger-core fiber (SIMMF105) is used as the input or output fiber.



(a) (b)

Fig. 4 Spectrum characteristics change with
(a) Input fiber: Three types, Output fiber: GIMMF50
(b) Input fiber: GIMMF50, Output fiber: Three types

From these relationships, we conclude that a high-sensitivity optical fiber sensor can be made by using an MMI structure with small-core I/O fibers, a long sensing part, and a large m.

5. Demonstration of refractive index measurement

As a demonstration of the MMI-structured optical fiber sensor, we measured the interference wavelength dependence on the refractive index of the materials surrounding an MMI structure comprising SMF I/O fibers and a 53-mm-long MMF125 sensing part. An interference wavelength with an m of 3 was used as the signal. We measured the spectrum of ethanol/water solutions while varying the volume ratio of ethanol from 0 to 99.5% in steps of 10%. The variation in the interference wavelength with changes in the volume ratio is plotted in Fig. 5 for the 1st (×) and 2nd (○) tests. For comparison, the reported refractive index [8] is also shown, as a solid line.

The interference wavelength red shifted with increasing ethanol volume and peaked at about 80%, which corresponds well with the reported values. The values obtained from the 1st and 2nd tests were almost the same, showing good reproducibility.

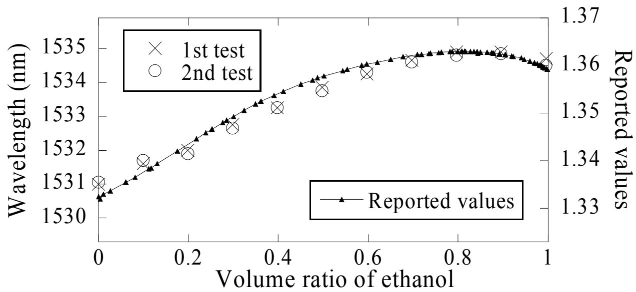


Fig. 5 Volume ratio of ethanol in water versus interference wavelength

6. Conclusion

We studied how to increase the sensitivity of an MMI-structured optical fiber sensor. We confirmed the interference wavelength shift in response to changes in the sensing part length. The experimental and theoretical wavelength values agree well for all values of m. Hence, it was clarified that the wavelength of an interferometer can be set by adjusting the sensing part length. Moreover, it was important to use small-core I/O fibers because they afforded a distinct interference signal. We also demonstrated the use of a MMI-structured optical fiber sensor for the refractive index measurement of a water/ ethanol solution. The results indicate the possibility of developing a refractive-index sensor more sensitive than those currently available.

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