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High-sensitivity optical fiber refractive index sensor using multimode interference structure

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Abstract: This letter presents the experimental investigation to increase the sensitivity of an optical fiber refractive index sensor with a multimode interference (MMI) structure. It is confirmed that the interference wavelength can be set in the long-wavelength region by adjusting the sensing-part length. Moreover, it is shown that the fineness of the cores in the input and output fibers is essential to obtain a sharp interference signal. We demonstrate the high sensitivity of an MMI-structured optical fiber sensor by applying it to refractive index measurements of ethanol/water solutions. This refractive index sensor reveals a resolution as fine as 1.8×10^{-5}, which is the highest value so far reported in this type and has one order higher sensitivity than a commercially available Abbe refractometer ($\sim 10^{-4}$).

Keywords: MMI, multimode interference, optical fiber sensor, refractive index sensor

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Optical fibers have been applied to sensing various physical and biochemical properties. For measurement of the refractive index of surrounding material, many promising results have been reported with a polished fiber [1], a tapered fiber [2], a surface plasmon resonance technique using gold [3], and a long-period fiber grating [4]. However, these sensors need a relatively fine structure whose fabrication process is strictly controlled. On the other hand, a three-segmented fiber structure that produces multimode interference (MMI) has been proposed [5, 6] as a new type of refractometer. The configuration of the MMI structure is very simple and enables the detection of a change in the refractive index of the surrounding medium.

In this letter, the variation in interference wavelength with changes in sensing-part length is experimentally investigated. The results measured using an MMI-structured optical fiber are compared with those calculated from the MMI theory [7]. Next, the spectral-domain interference signal for input and output (I/O) fibers with different types and core diameters to obtain sharp interference characteristics for high-resolution measurements of refractive index is investigated. From the experimental data, we choose the configuration of a refractive index measurement device operable at a wavelength of around 1.5 μm as used in optical fiber communications. The fabricated device shows a high sensitivity of 1.8×10^{-5}, which is better than the value of 4.37×10^{-4} reported in [5] or the value of $\sim 10^{-4}$ for conventional Abbe refractometers.

2 Multimode interference structure

It has been observed that optical interference in a multimode waveguide produces periodic optical focusing points, and this phenomenon is known as

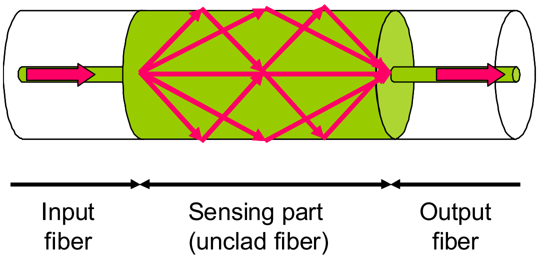

Fig. 1. Studied optical fiber with multimode interference (MMI) structure.

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MMI [7]. An MMI structure can be configured with several types of three-segmented axially spliced optical fibers. As shown in Fig. 1, we used an unclad fiber of pure silica with a diameter of 125 μm as the large-core fiber for the sensing part so that the propagated light underwent total internal reflection at the boundary with the surrounding medium. Input and output (I/O) fibers were fusion-spliced with the sensing fiber. The relationship between interference wavelength λ_0 and sensing-part length L is as follows [7]:

$$\lambda_0 = \frac{d^2 m}{L} n \tag{1}$$

where d is the core diameter of the sensing part, m is an order number, and n is the refractive index of the large-core sensing fiber. When the refractive

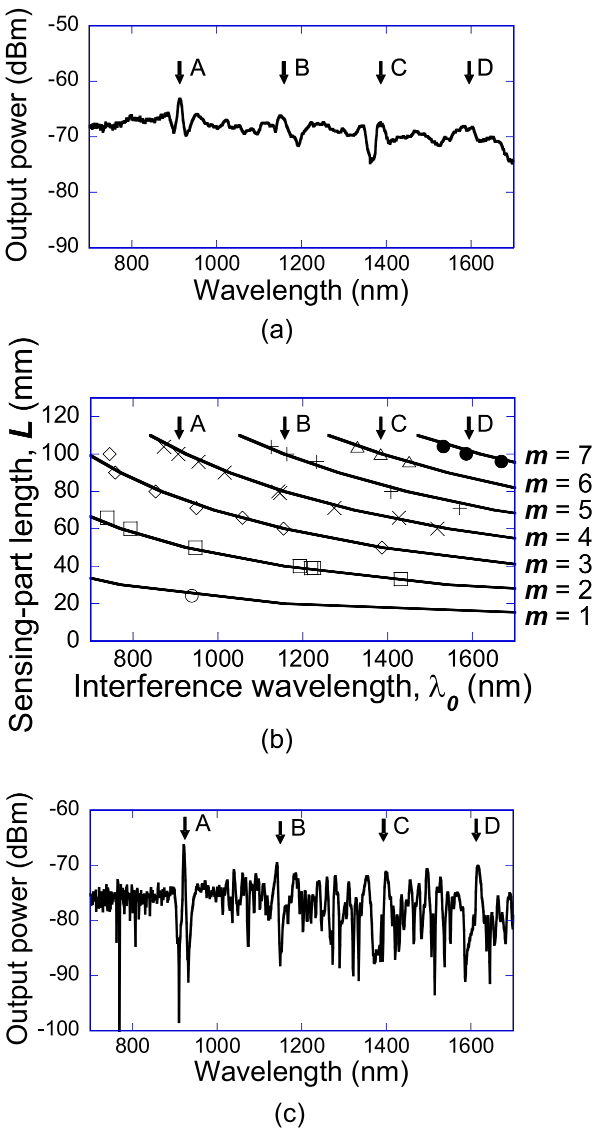

Fig. 2. (a) Output spectra of a device with 100-mm sensing-part length. Input and output fibers are graded index multimode fibers. (b) Interference wavelength versus sensing part length. m is an order number. (c) Input and output fibers are single mode fibers.

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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. As a result, the shift in the interference wavelength reflects the change in the surrounding medium.

To study the change in the MMI spectrum with the change in the type of I/O fibers used, we measured the transmission spectra of a fiber with a 100-mm-long unclad fiber as the sensing part with different I/O fibers. We compared three types of I/O fiber: step-index multimode fiber with a core diameter of 105 μm, graded-index multimode fiber with a core diameter of 50 μm (GIMMF50), and single-mode fiber (SMF). A white light was incident on the input fiber and the output light was observed by optical spectrum analyzer. Figure 2 (a) shows an example of the measured spectra with GIMMF50 for both I/O fibers. The periodic interference signals confirmed are labelled as A, B, C, and D in Fig. 2 (a).

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. 2 (b), where the labels A, B, C, and D correspond to those in Fig. 2 (a). The theoretical points (solid lines) agree well with the measured points for all values of m. A larger m or longer L leads to higher sensitivity because the number of total internal reflections increases with either parameter. Based on Fig. 2 (b), we can set the desired interference wavelength by adjusting m and L.

MMI signals tend to be sharp at I/O fibers with narrow core. As shown in Fig. 2 (c), the spectrum exhibits remarkably sharp characteristics at interference wavelengths when SMF is used as the input and output fiber. Note that the periodic interference wavelengths (A, B, C, and D) are almost the same as those labelled in Fig. 2 (a), because the MMI wavelengths are given by Eq. (1) irrespective of the I/O fibers. This is thought to be due to intense diffraction from the small-core input fiber and restricted interference at the small-core output fiber. Therefore, we conclude that a high-sensitivity optical fiber sensor can be made using an MMI structure with smaller I/O fiber cores, a longer sensing part, and a larger m.

3 Refractive index sensor

We set the fiber sensing-part length at 53 mm to obtain an interference wavelength of around 1.5 μm and we selected a sharp notch to reveal a high sensitivity. I/O fibers were SMF and input light was incident from an amplified-spontaneous-emission light source, which can emit higher power than a white light source. We measured the spectrum of ethanol/water solutions while varying the volume ratio of ethanol from 0 to 80%, which corresponds to a refractive index change from 1.333 to 1.363. Figure 3 shows the output spectrum for different volume ratios. When we set the wavelength to 1535 nm, the variation in output power between the ratios of 0 and 0.8 was as large as 17.1 dBm. It is known that the typical precision of a commercial optical

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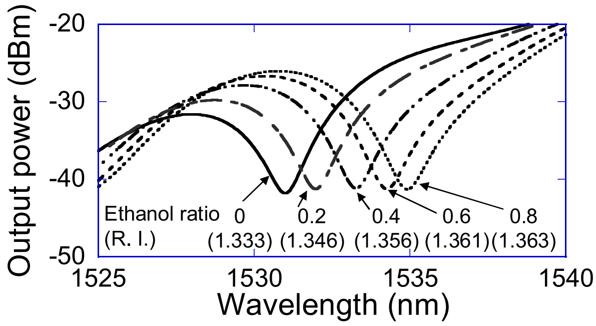

Fig. 3. Output spectra of a device with 53-mm sensing-part length for different ethanol/water volume ratios. The numbers in parentheses are the corresponding refractive index.

power meter is about 0.01 dB. Therefore, the resolution obtained is 1.8×10^{-5}, which is much finer than the resolution of a commercially available Abbe refractometer ($\sim 10^{-4}$).

4 Conclusion

Fusion-spliced MMI fibers each composed of an unclad fiber (sensing part) sandwiched between input/output fibers are fabricated and how the interference wavelength shifted in response to changes in the sensing-part length is investigated. The experimental and theoretical interference wavelengths agreed well with each other for various sensing-part lengths. Hence, it was confirmed that the wavelength of an interferometer can be set by adjusting the sensing-part length. Moreover, it was found important to use small-core I/O fibers to obtain a sharp interference signal. The MMI-structured optical fiber sensor for measuring the refractive index of an ethanol/water solution yielded a resolution as fine as 1.8×10^{-5}.

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