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High-Sensitivity, Short-Length Optical Fiber Refractive-Index Sensor using a Multimode Interference Structure with an End-Face Mirror

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Abstract

A high-sensitivity reflection-type refractive index (RI) sensor has been fabricated by forming a gold mirror at the end of a sensor fiber. The fabricated sensor shows a sensitivity as fine as 1.7 × 10^{-5} with only half the sensor length compared with that of a conventional two-port multimode interference RI sensor.

1. Introduction

Because silica-based optical fibers used in optical telecommunications have several features, such as high immunity to electromagnetic interference, low optical loss, strong tolerance to corrosive chemical substances, and low cost, their application as sensors, without the need for an electrical signal, is very attractive. In an optical fiber sensor, the sensing function is performed using an evanescent wave on the surface of the fiber. The evanescent wave is formed with total internal reflection of the propagating light in the fiber and is affected by the surrounding medium.

An optical fiber multimode interference (MMI) structure is very simple and enables the sensitive detection of the change in the refractive index of the surrounding medium when using an unclad fiber as a sensor [1-4]. However, a conventional sensor with an MMI structure needs two ports for light input and output. This configuration limits the situations in which it can be applied, as it requires a large amount of space for installation.

To solve these problems, a reflection type refractive index optical fiber sensor using MMI was successfully fabricated by forming a gold mirror at the end-face of the sensor fiber. This sensor has only one port for light input and output. The sensor shows a very high sensitivity of 1.7 × 10^{-5}, which is better than that of conventional MMI sensors.

2. Multimode Interference Structure

Figure 1 shows a conventional MMI structure configured with a multimode fiber (MMF) jointed to singlemode fibers (SMFs) at both ends, which work as input and output optical ports. When light guided through the input-SMF is incident on the large-core MMF, it is diffracted and then distributed in several modes. In Fig. 1, because the surrounding medium of the unclad MMF is air, which functions as the cladding, total-internal-reflected rays propagate in the MMF and thus interfere with each other, resulting in the formation of periodic optical focusing points. This is known as MMI, and the fused SMF at the end of the MMF outputs the light produced by interference, as shown in Fig. 2. For this MMI, the following relation holds:

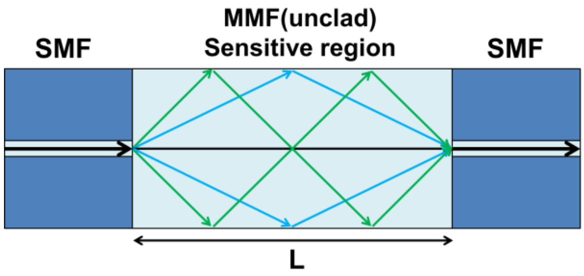

Fig. 1 Multimode interference (MMI) structure.

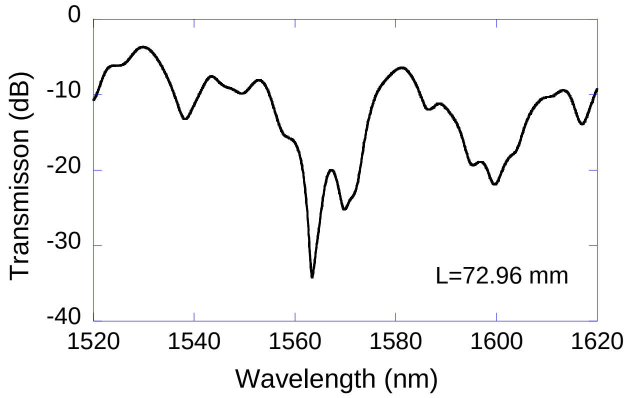

Fig. 2 Transmission spectrum of the MMI sensor.

$$\lambda_0 = \frac{n_{core} D^2}{L} m, \qquad (1)$$

where λ_0 is the interference wavelength, n_{core} is the refrac tive index of the MMF, D is the core diameter of the MMF, L is the length of the MMF, and m is the interference order number. The important characteristic of MMI is that λ_0 can be easily designed to be in the wavelength region used in the corresponding optical fiber communication system.

An evanescent wave is formed in a region in which total internal reflection occurs. The intensity of the evanescent wave decays exponentially with the distance from the interface, and the penetration depth (z) of the evanescent wave changes with the refractive index of the surrounding medium. This means that the effective core diameter becomes as large as $D + 2z$, resulting in shifts in the interference wavelength. Therefore, RI can be sensed via MMI optical signa measurement.

To overcome the two-port structure, we fabricated a reflection-type MMI structure, as shown in Fig. 3. The end of the MMF sensing region was covered with sputtered gold. When using this reflection structure, the doubled length of the sensing part is equal to L in eq. (1) owing to light reflection.

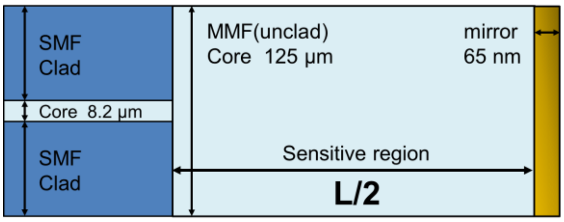

Fig. 3 Reflection-type MMI structure.

3. Experimental

An unclad pure silica multimode fiber with a core diameter of 125 μm was used as the sensing part. A sensing part length of 36.3 mm was designed to obtain a sharp interference signal around a wavelength of 1550 nm. An SMF acting as I/O ports was fusion-spliced with the sensing fiber, as shown in Fig. 3. A gold thickness of 65 nm and an average reflection efficiency of ~98% were estimated from the discrete evaluation using a flat-glass-plate sputtered with gold. The measurement system comprised an amplified spontaneous emission (ASE) light source with wavelengths ranging from 1520 to 1620 nm, a circulator, and an optical spectrum analyzer, which was used for optical observation in the wavelength domain.

4. Results and discussion

We measured the spectra of ethanol/water solutions while varying the volume ratio of ethanol from 0 to 99.5% in steps of 10%. Figure 4 shows the measured spectra as a solid line and dotted line for water and ethanol, respectively. The interference signal dip was red-shifted by 3.95 nm from water to ethanol, and the variation in output power between them at the wavelength of 1580.3 nm was as large as 15.76 dB. Because the RI difference between water and ethanol is 0.0266, the sensitivity estimated using the wavelength resolution of the optical spectrum analyzer (0.05 nm) is 3.4×10^{-4}, and using the optical power resolution of the optical power meter (0.01 dB), the sensitivity is 1.7×10^{-5} at this refractive index range. These sensitivities are almost comparable or slightly better than those of conventional two-port MMI RI sensors [3, 4]. This high sensitivity clearly indicates that the MMI phenomenon is maintained in almost the same condition as with a normal MMI structure, even with light reflection from a sputtered gold mirror.

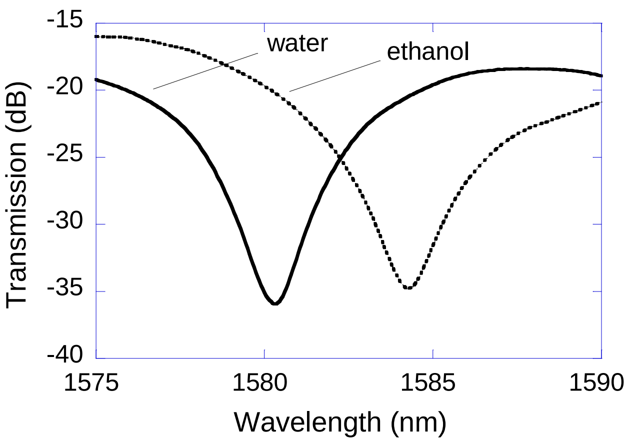

Fig. 4 Transmission spectra of the reflection-type MMI sensor in ethanol and water.

The wavelength of the interference dip varied with changes in the volume ratio, as plotted in Fig. 5. The interference wavelength red-shifted with increasing ethanol volume and peaked at about 80%, which corresponds well with the reported values [5], as depicted by the dashed line. These results demonstrate that the reflective-type MMI RI sensor reported in this paper has high potential because it can maintain a high reflection efficiency with an end-face mirror.

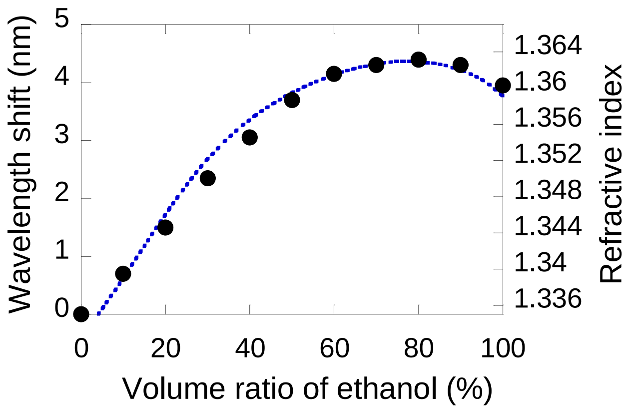

Fig. 5 Transmission wavelength shift of the MMI sensor at different ethanol/water solutions.

4. Summary

A reflective-type MMI refractive index sensor was fabricated by forming a gold mirror at the end of a sensor fiber. The fabricated sensor with only half of the sensor length of a conventional two-port MMI sensor showed a sensitivity as fine as 1.7×10^{-5} without degrading the MMI phenomenon using a mirror.

Acknowledgements

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