

Multimode-interference-structure optical-fiber temperature sensor with high sensitivity

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Abstract: We have developed a very simple high-sensitivity fiber temperature sensor using multimode interference. The fabricated multimode interference structure comprises a large-core multimode fiber (MMF) sandwiched between single-mode fibers. Silicone rubber is coated onto the MMF as a cladding material. This silicone rubber coating exhibits a large refractive-index change with temperature that produces a very fine temperature resolution as low as $1 \times 10^{-2}^{\circ}\text{C}$.

Keywords: temperature sensor, 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

Silica-based optical fiber sensors have been used to determine the physical and biochemical properties of substances because they have attractive features such as high immunity to electromagnetic interference, low optical

loss, strong tolerance to corrosive chemical substances, and low cost. There are many reports on optical-fiber temperature sensors using fiber Bragg gratings (FBGs). Owing to the high-temperature endurance of silica fibers, they function over a wide temperature range. However, because the wavelength (λ) shift with temperature is low owing to the low thermal expansion coefficient of the silica fiber, a resolution in λ of 0.001 nm is required to resolve a temperature difference of $\sim 0.1^\circ\text{C}$, which corresponds to a sensitivity of $\sim 0.01 \text{ nm}/^\circ\text{C}$ [1].

Hence, we developed a high-sensitivity optical-fiber temperature sensor using multimode interference (MMI) [2]. MMI is generated by a simple structure consisting of a multimode fiber (MMF) sandwiched between single-mode fibers (SMF) at both ends. The MMI optical signal is highly sensitive to the refractive-index (RI) change of the medium surrounding the MMF; hence, it has been used in some RI sensor applications [3, 4, 5, 6]. The influence of the coreless MMF diameter on the external RI variation of a liquid has been examined, and ultra-high sensitivity of the device to the variation in temperature in a high-RI liquid has been attained [7].

In this letter, the relationship between the wavelength shift of the MMI signal and the temperature in an MMI structure, where the MMF was coated with temperature-sensitive solid materials, is investigated. The obtained wavelength sensitivity for the sensor coated with silicone rubber is roughly 10 times higher than that of an FBG sensor, and the estimated temperature resolution ranging from 30 to 80°C is as fine as $1 \times 10^{-2}^\circ\text{C}$.

2 Operation principles

Figure 1 (a) shows the SMF ($\Phi 8.2\text{-}\mu\text{m}$ core in $\Phi 125\text{-}\mu\text{m}$ cladding)–MMF ($\Phi 125\text{-}\mu\text{m}$ core only)–SMF ($\Phi 8.2\text{-}\mu\text{m}$ core in $\Phi 125\text{-}\mu\text{m}$ cladding) structure (SMS) fabricated by fiber fusion. When light guided through the input

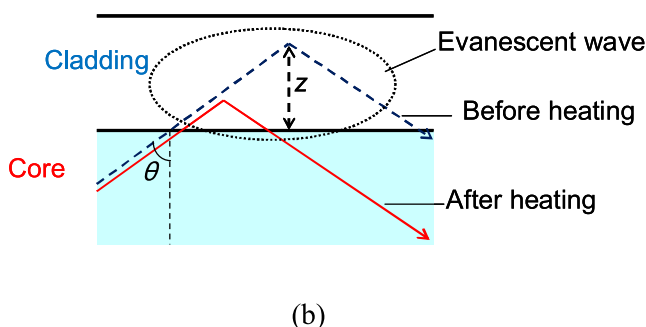
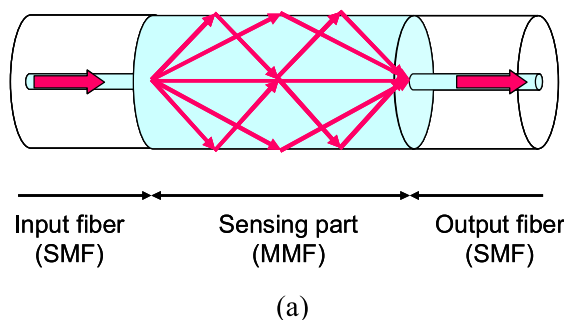


Fig. 1. (a) Schematic fiber structure. (b) Schematic image of an evanescent wave.

SMF is incident onto the large-core MMF, it is diffracted and then distributed in several modes. In Fig. 1 (a), the totally internally reflected rays propagate in the MMF and thus interfere with each other because the surrounding medium of the MMF is air, which functions as the cladding. This is known as MMI, and the fused SMF at the end of MMF outputs the light produced by interference. For this MMI, the following relation holds:

$$\lambda_0 = \frac{n_1 D^2}{L} m, \quad (1)$$

where λ_0 is the interference wavelength, n_1 is the RI 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 [8]. The intended MMI signal at any λ can be utilized by specifying the MMF length.

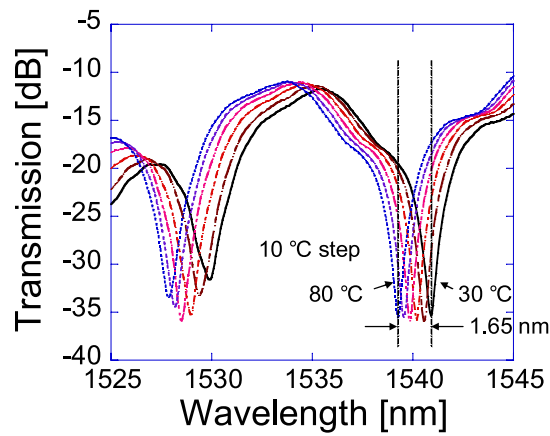
An evanescent wave is formed in the region in which total internal reflection occurs. The intensity of the evanescent wave decays exponentially with the distance from the interface, and the penetration depth of the evanescent wave (z , where field intensity becomes $1/e$) is given as follows:

$$z = \frac{\lambda_0/n_1}{2\pi\sqrt{\sin^2\theta - (n_2/n_1)^2}}, \quad (2)$$

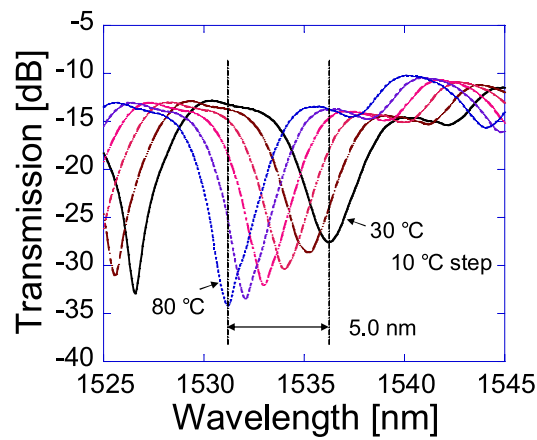
where θ is the incident angle from the core to the cladding, and n_2 is the RI of the cladding. This means that the effective core diameter becomes as large as $D + 2z$. Therefore, if we use a cladding material with highly temperature-sensitive RI, the temperature can be sensed via MMI optical-signal measurements. A schematic for z is shown in Fig. 1 (b). Because an effective change in D affects λ_0 owing to D^2 in Eq. (1), a high sensitivity is obtained.

3 Experimental

In this study, two types of materials (fluoroacrylate and silicone rubber) were compared as the cladding material for the MMF. Light from an amplified-spontaneous-emission (ASE) source was fed into the input SMF, and MMI light transmitted to the output SMF was measured with an optical spectrum analyzer. The sensor was placed on a hot plate, and the temperature was varied from 30–80°C. Figure 2 shows the measured transmission spectra of the 120-mm-long MMI sensor with (a) fluoroacrylate and (b) silicone rubber. The spectrum dip shifts towards shorter wavelengths with an increase in the temperature. The shift for silicone rubber is as large as 5.0 nm, compared to 1.65 nm for fluoroacrylate. The shift to shorter wavelengths implies that the RI of the cladding material decreases with an increase in temperature. A larger shift for the silicone rubber implies a larger RI change, which is attributed to its thermal expansion coefficient that is about five times larger than that of fluoroacrylate. Figure 3 shows the dip wavelength dependence on temperature at the MMI sensor with silicone rubber, which exhibits good linearity ranging from 30 to 80°C. A 5.0-nm shift with a temperature increase of 50°C indicates that the sensitivity is 0.1 nm/°C, which is about



(a)



(b)

Fig. 2. Measured transmission spectra of the 120-mm-long MMI sensor with (a) fluoroacrylate and (b) silicone rubber.

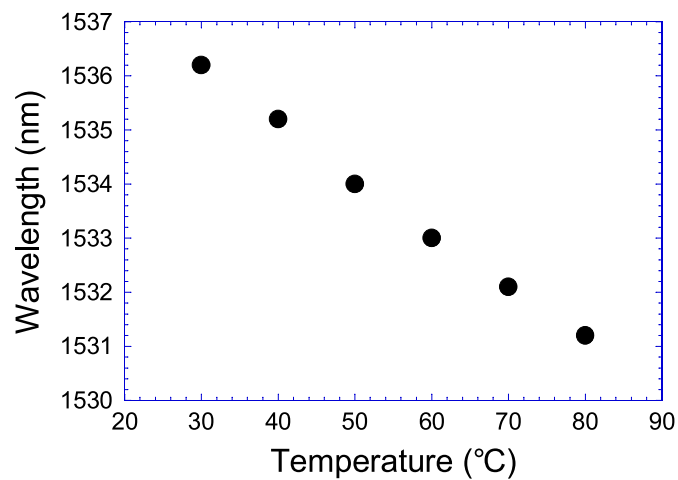


Fig. 3. Dip wavelength dependence on temperature.

10 times greater than that of an FBG temperature sensor.

Because this MMI sensor can easily be designed along with the interference wavelength used in the optical-fiber communication system, a

high-resolution wavelength-tunable semiconductor laser can be utilized. If we use a conventional wavelength-tunable laser with a wavelength resolution of 0.001 nm, the estimated temperature resolution is as fine as $1 \times 10^{-2}^{\circ}\text{C}$.

4 Conclusion

We have demonstrated a very simple, high-sensitivity optical fiber temperature sensor using MMI. For the silicone rubber coated onto the MMF as a cladding material, a large RI change with temperature produced a sensitivity as high as $0.1 \text{ nm}/^{\circ}\text{C}$ based on the wavelength shift. A temperature resolution of $1 \times 10^{-2}^{\circ}\text{C}$ was evaluated when assuming a conventional tunable semiconductor laser source with a wavelength resolution of 0.001 nm.

Acknowledgments

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