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Sensitivity Enhancement in Refractive Index Measurement based on Optical Fiber Multimode Interference with Gold Nanoparticles

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Abstract

We investigated the combination of fiber-based multimode interference (MMI) with gold nanoparticles (NPs). The extinction of light due to the presence of NPs was confirmed in the telecom wavelength range (1300-1600 nm). We examined the variation of transmission with wavelength by changing the surrounding medium. The sensitivity of the MMI with NPs was measured to be approximately 218.28 nm/RIU (refractive index unit) for a refractive index range from 1.3325 to 1.3591.

1. Introduction

Evanescent waves on the surface of an optical fiber can be used for sensing the absorption [1], refractive index (RI) [2,3], and temperature [4,5] of the surrounding material. One attractive structure for sensitive measurement is the multimode interference (MMI) structure [3-5] that employs the optical interference between modes in an unclad multimode fiber (MMF). The evanescent wave around the bare MMF can interact with the surrounding medium that acts as a cladding layer. A variation in the RI of this cladding induces a Goos–Hänchen shift (optical phase shift) in the total internal reflection region. As a result, a change in the transmission spectrum is observed.

It is well known that the localized surface plasmon resonance (LSPR) of noble-metal NPs changes its resonant condition when the RI around the nanoparticle varies. The resonance wavelength is not restricted to the visible region, and it may also appear in the near infrared range, including the telecom band.

In this study, we synthesized gold NPs and deposited them around the full circumference of the MMF, which acts as the sensor of the MMI structure. By changing the synthesis conditions, the amount of extinction in the telecom wavelength range was controlled owing to the size and aggregation of NPs adhered to the MMF. The sensitivity of the MMI was confirmed by observing transmission spectra while changing the RI of surrounding medium.

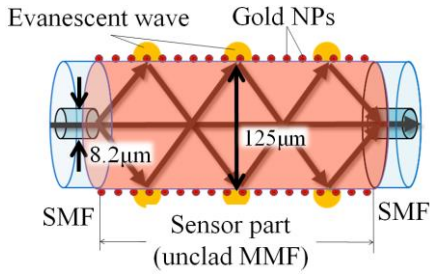

Fig. 1 Multimode interference (MMI) structure with gold nanoparticles (NPs).

2. Experimental methods

Multimode interference structure

We used an unclad fiber of pure silica with a diameter of 125 μm as an MMF portion sandwiched between single mode fibers (SMFs). The SMFs act as input and output fibers and had a small core diameter of 8.2 μm. To evaluate optical interference in the telecom wavelengths, one end of the input fiber was connected to a light source, and an optical spectrum analyzer was connected to the output fiber. The output spectrum from the MMI structure is affected by the medium surrounding the MMF.

Gold NPs synthesis and adhesion on optical fiber

Gold NPs were synthesized through the reduction of hydrogen tetrachloroaurate (III) tetrahydrate ($HAuCl_4 \cdot 4H_2O$) using trisodium citrate ($C_6H_5O_7Na_3$). To control the size and the dispersibility of NPs, we synthesized three types of gold NP solutions by adding the trisodium citrate in concentrations of (a) 0.4%, (b) 0.07%, and (c) 0.03% (w/v) to 0.01% (w/v) hydrogen tetrachloroaturate (III) tetrahydrate solutions. The trisodium citrate was used for the reduction and as a protective group of NPs. The average diameters of synthesized NPs were 15, 37, and 53 nm for conditions (a), (b), and (c), respectively. The NPs were adhered to the MMF by using a 1% (v/v) aqueous solution of 3-aminopropyltriethoxysilane (APTES) as a silane coupling agent. Figure 2 shows extinction spectra of three types of gold NPs adhered with the same procedure to a hetero-core fiber structure. [6] The evanescent waves generated outside the fiber reflect only the extinction spectrum without interference. For condition (a), only the char-

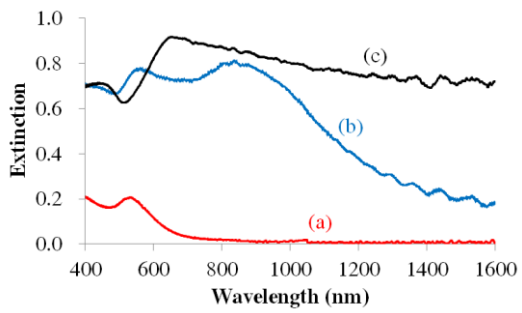

Fig. 2 Absorption spectra of gold NPs adhered on the MMF. The gold NPs were synthesized by using (a) 0.4%, (b) 0.07%, and (c) 0.03% (w/v) trisodium citrate solutions.

acteristic extinction occurred around a wavelength of 550 nm. On the other hand, extinction with a broadened band at longer wavelengths, including telecommunication wavelengths, occurred with the conditions (b) and (c).

3. Results and Discussion

The transmission spectrum shift due to the varying RI of the surrounding medium was observed by using an amplified spontaneous emission light source with a wavelength range of 1520-1620 nm. Figure 3 shows measured transmission spectra of the MMI with and without NPs for condition (c), when the material around the sensor region was either water or ethanol. The gold NPs adhered to the MMF led to a decrease in transmission intensity, and the dip signal became broader and more gradual because of the light scattered by the NPs. The wavelength shift caused by the varying RI around the sensor was clearly increased by the presence of the gold NPs. The sizes of the shift for the MMI with and without NPs for condition (c) were 8.0 nm and 3.75 nm, respectively. Figure 4 shows the amount of the wavelength shift for the varying RI during the transition from water to ethanol measured using the MMI structure with three different types of NPs as well as without NPs. The wavelength shifts for all of the MMI structures have the same trend that has a peak at 80 to 90% of the ethanol/water ratio. The results for the MMI at condition (a) and without NPs are similar, but the MMI for conditions (b) and (c) show a larger shift. As shown in Fig. 2, the size of the wavelength shift for each type of NPs adhered to the sensor region seemed to correspond to the extinction amount in the wavelength range of 1400-1600 nm. As previously described, the optical phase shift in the total internal reflection region causes the interference signal to shift. The enhancement of this shift indicates that the increase of the optical phase shift was definitely related to the size and the adhesion state of the NPs at the interfacial surface.

In order to determine the relationship between the size of the wavelength shift and RI, we referred to the reported value of the RI for the volume ratio of ethanol in water. [7] The obtained sensitivities of the MMI with NPs for conditions (a), (b), (c), and without NPs were approximately 98.23, 130.97, 218.28, and 102.32 nm/RIU, respectively,

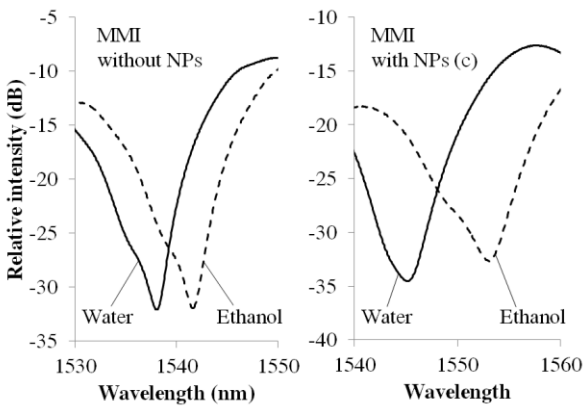

Fig. 3. Transmission spectra at the telecom wavelength range in water and ethanol surrounding the MMI (left) and the MMI with NPs synthesized under condition (c) (right).

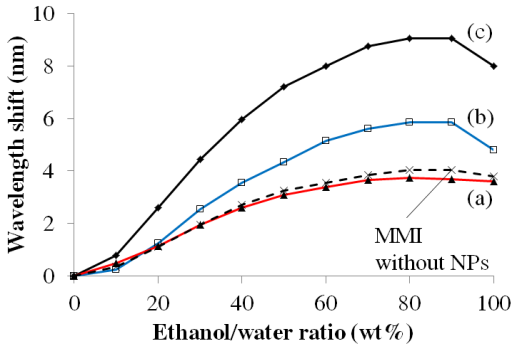

Fig. 4. Ethanol/water ratio versus dip signal wavelength shift obtained using the MMI structure with the three types of NPs and without NPs.

with an RI range from 1.31535 (water) to 1.35199 (ethanol). The sensitivity of MMI RI sensor was roughly twice as high when using gold NPs with condition (c) compared to the case without NPs.

4. Conclusions

We experimentally investigated the combination of the MMI and gold NPs. The amount of extinction in the telecom band was controlled by changing the concentration of the trisodium citrate that was used as a reduction agent and disperser. By using MMI with NPs, the transmission was decreased and the spectra became more gradual, but the spectral shift increased with the varying RI of the surrounding medium. The shift amount of the MMI with NPs at condition (c) was almost twice as large as that for the MMI only. From the results, it is thought that the increase in the size of the shift is related to the extinction amount in the telecom wavelength range. The resultant sensitivity of the MMI with NPs was about 218.28 nm/RIU for a refractive index range from 1.31535 to 1.35199 at the telecom wavelength range. The sensitivity of the RI sensor using the MMI structure could be easily improved by accurately controlling the adhesion of the gold NPs. Furthermore, this sensor system has potential for bio-sensing applications because both gold NPs and silica optical fibers have good biocompatibility.

Acknowledgements

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