Fabrication of Tilted Fiber Bragg Grating as a Sensor of Refractive Index of Liquids

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Abstract

We have developed a fabrication technique of tilted fiber Bragg gratings (TFBG) for refractive index sensor of liquids. We demonstrated that a simple technique using a combination of 266-nm laser and a phase mask with a period of 1.065 μm was quite effective for the fabrication of the TFBG. Using fabricated TFBGs which had the tilted angles of 3.3˚, 6.7˚, 7.3˚, 8.0˚, and 9.9˚, we tried to measure the refractive index of liquids which have different indices. Water, ethanol and glycerine solutions (12%, 24%, 35%, 46%, 66%, and 84%) were used as samples. For the measurement, a 10-mm long TFBGs were covered with a sample liquid droplet. The transmission spectra in the cladding mode and core mode were observed by an optical spectrum analyzer. We have directed our attention to the fact that wavelength of cladding mode shifts to be longer with the increase of refractive index of sample liquids. Utilizing this wavelength shift, we proposed a new measurement method. As a result, we could successfully measured the refractive index of liquids within a range from 1.00 to 1.41 with a maximum resolution of 3.0×10^{-3}. In addition, we have found that a contact length of only 2.4 mm is necessary to obtain 90% of signal intensity of 10-mm long TFBG.

Keywords: Tilted fiber Bragg grating, Refractive index, Phase mask, Cladding mode

1. INTRODUCTION

The fiber sensors are widely used in physical sensing such as temperature, strain, vibration, pressure, liquid level and so on[1)]. The increasing of fiber sensor development for these purposes has many advantages, *ie*, electro-megnetic immunity, small size, stability, harmless, and high sensitivity[2)]. Photosensitivity of fiber core was reported by Hill *et al.* in 1978[3)]. Since then, this invention has been a significant background for the many kinds of fiber sensor developments. Especially, the fiber Bragg gratings (FBGs) which consist of a periodic modulation of the refractive index in the core of a single mode optical fiber have become widely used for distortion sensors[4)].

Recently, in addition to the FBG sensors, tilted fiber Bragg grating (TFBG) have become to attract considerable attention for sensing application. Because in TFBG, not only the properties of the core but also informations in the cladding affect the reflection spectrum. Therefore in TFBG, non-mechanical phenomena which are informations through the surface of the cladding can be detected, while normal FBG can observe only mechanical phenomena in the core such as change in length since the cladding prevents the optical information to the core from the outside. Although one might think that the temperature is able to be detected using the normal FBG at a glance, this is also measured by mechanical volume change due to the thermal expansion. Fabrication of TFBG has been conventionally performed using the Lloyd mirror interferometer by 244-nm Ar^+ ion laser and the spectra have been observed in previous work[5)]. In addition, it has been reported that refractive index of liquid is able to detect in principle by using the envelope of the cladding mode of TFBG. However, adjustment of the Lloyd mirror causes a instability of the period of the grating and furthermore, use of Ar^+ ion laser results in a large difficulty when this technique is considered to apply on a commercial basis.

In this research, we have developed a simplified fabrication technique of TFBG using a combination of 266-nm laser and conventional phase mask which is able to use without a complicate optical adjustment. Besides, we also tried to characterize the fabricated TFBG as a sensor for refractive index of liquids. As a result, we found a new method to estimate the index of liquid with a wider measurement range compared to the conventional method that has been reported in previous work[5)].

2. BASIC PROPERTIES OF TFBG

The FBGs are made using laser beam interference technique. Fundamental structure of FBG and TFBG are shown in Figure 1. A single core mode is produced in the FBG transmission spectrum. Basically, the wavelength shift in the core mode is used to detect mechanical change in the fiber, therefore wavelength of core mode is utilized to measure only physical parameters[6)].

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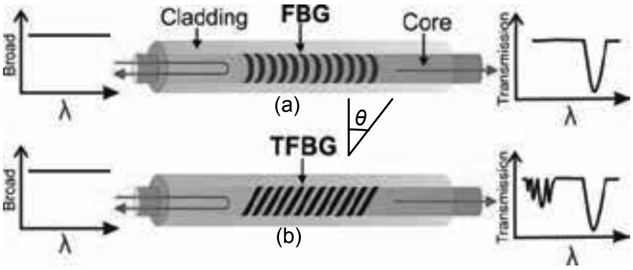

Fig. 1. Structure of (a) FBG, and (b) TFBG

The wavelength of core mode in the FBG (λ_B) can be calculated by the following equation,

$$\lambda_B = 2n_{eff.\ core}\,\Lambda_{pm}, \tag{1}$$

where $n_{eff.\ core}$ is effective refractive index of the core, and Λ_{pm} is the grating period.

FBGs are intrinsically insensitive to the environment, because the core modes are well-screened from incident of the light from outside due to the presence of the cladding[7]. On the other hand, in the case of the TFBG which has a tilt angle θ, not only the core mode but also a number of cladding modes are observed in the reflection spectrum. The reflection wavelengths of the cladding modes ($\lambda_{cladding}$) are calculated using the following equation,

$$\lambda_{cladding} = \frac{(n_{eff.\ core} + n_{eff.\ cladding})\Lambda_{pm}}{\cos\theta}, \tag{2}$$

where $n_{eff.\ cladding}$ is the effective refractive index of the cladding which is corresponding to each reflecting order in the cladding mode. The wavelength and amplitude of the cladding mode are affected by optical properties of the surrounding material. The detailed spectral behavior in the core and the cladding modes have been reported in previous work[8].

3. EXPERIMENTAL

3.1 Fabrication of TFBG

The experimental setup for fabrication of TFBG is shown in Figure 2. We used a 4ω Nd:YAG laser and a wavelength converter to produce pulsed 266-nm UV laser beam. The beam was reflected by five mirrors and linearly focused on a sample fiber by three cylindrical lenses. The laser pulses with an energy of 50 mJ/pulse were produced by this laser. The beam was introduced to an optical fiber core through a phase mask made of silica glass. In this technique, periodically modulated UV beam was produced by interference of diffracted two laser beams due to the phase mask. The minimum distance between the phase mask and the fiber sample was approximately 1 mm. Tension of the fiber was kept at 5.9×10^{-4} N during fabrication process with the UV beam irradiation

A H_2 loaded SBG-15 (*Newport corp.*) photosensitive optical fiber was used for the sample fiber. This fiber is a single mode and germanium-boron-codoped fiber. We used sample fibers of 250 mm long. The polymer jacket at the center part of the fiber was removed by 50 mm long for UV beam irradiation. The polymer jacket at both ends of the fiber were also removed by 20 mm long in order to connect an optical spectrum analyzer (OSA) and an ASE light source. The fiber Bragg grating was made in the center part of fiber using phase mask technique. A phase mask with a grating period of 1.065 μm was used. This phase mask creates a grating in the fiber core with a period Λ_{tfbg} along the longitudinal direction which follows the equation 3.

$$\Lambda_{tfbg} = \frac{\Lambda_{pm}}{2\cos\theta_{ext}}, \tag{3}$$

where Λ_{pm} and θ_{ext} are grating period of the phase mask and the external tilt angle between the grating and the sample fiber, respectively. A phase mask of 10 mm long was used in this experiment.

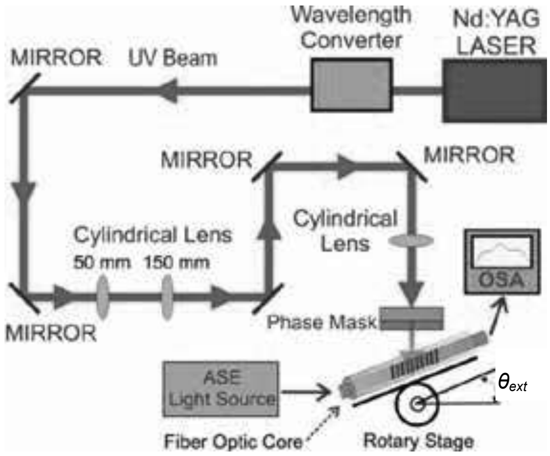

Fig. 2. Experimental setup

The fiber was fixed on a rotary stage to adjust the θ_{ext} easily. The θ_{ext} were chosen at 5˚, 10˚, 11˚, 12˚ and 15˚, which were corresponding to the incident angle of modulated beam to the fiber surface. Since refraction of the UV beam occurs between air and fiber material by during fabrication, the tilt angles in the fiber core become 3.3˚, 6.7˚, 7.3˚, 8.0˚ and 9.9˚, respectively. The probe light with a wavelength range from 1520 to 1610 nm was used for the transmission spectral measurement. Two mechanical splicers were used for connecting the fiber to the light source and the OSA. The typical irradiation period of the UV beam to obtain an enough intensity for measurement was 20 minutes. We checked the spectral change during TFBG fabrication.

3.2 Refractive index measurement

We put a droplet of sample liquid which covered whole the TFBG with a length of 10 mm for refractive index measurement. Experimental setup to measure the refractive index of liquid is shown in Figure 3. Two holders were used to keep the TFBG stable on the glass plate without applying tension. The liquids used were include water, ethanol, and glycerine solutions. The reason for choosing the glycerine solution is that the refractive index of the solution can be easily adjusted in wide index range by simple mixing of the glycerine and water[9]. The concentration of glycerine solution used in the experiment was from 12% to 84%. The detailed information for index of samples was summarized in Table 1.

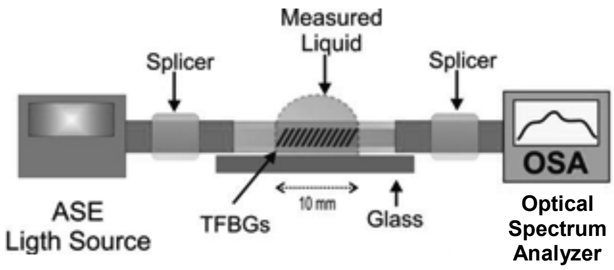

Fig. 3. Refractive index measurement procedure

Table 1. Refractive index of sample

Sample	Ref.Index
Air	1.0003
Water	1.3255
Ethanol	1.3539
Glycerine 12%	1.3417
Glycerine 24%	1.3579
Glycerine 35%	1.3727
Glycerine 46%	1.3876
Glycerine 66%	1.4146
Glycerine 84%	1.4389

We observed the core and the cladding modes in the transmission spectra and investigated the relationship between the spectral change and to the change in refractive index.

4. RESULTS

4.1 Characteristic of fabricated TFBG

Transmittance spectra of 0˚-TFBG (namely normal FBG) after 2 minutes irradiation is shown in Figure 4. Only the core mode LP_{11} was observed in this spectrum. The intensity of the core mode LP_{11} was 9.5 dB at 1544 nm.

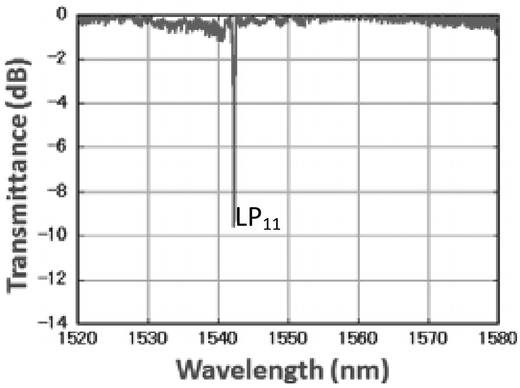

Fig. 4. Transmission spectra 0˚-TFBG

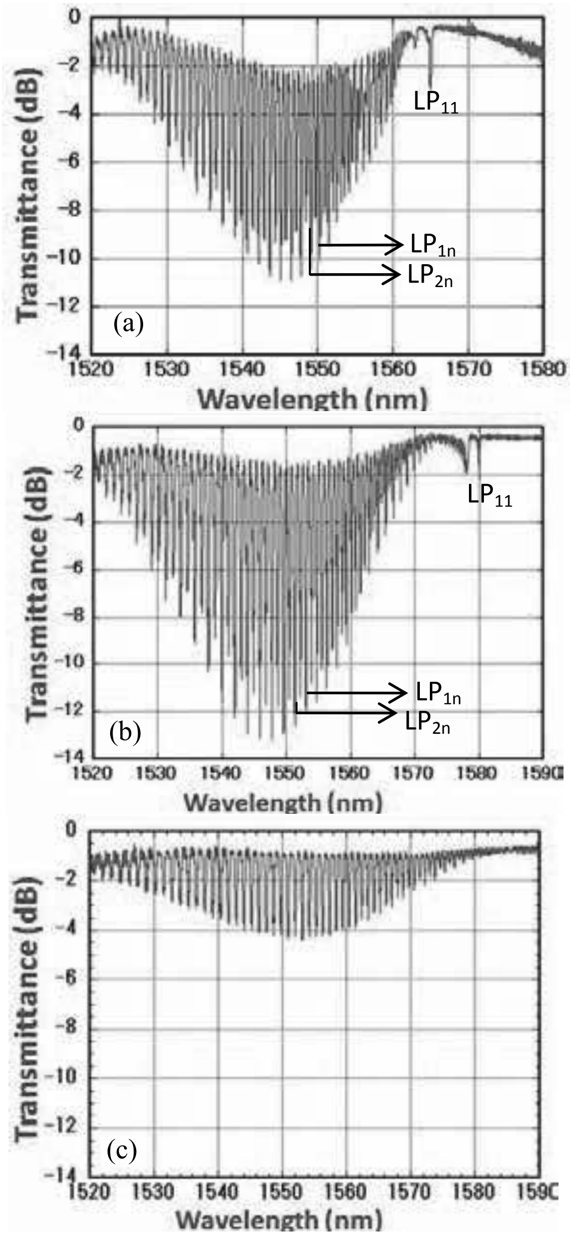

Fig. 5. Transmission spectra of fabricated TFBGs with tilted angles of (a) 6.7˚, (b) 8˚ and (c) 9.9˚

Figure 5(a) shows the transmission spectra of the 6.7˚-TFBG after 20 minutes irradiation time. We investigated not only core mode LP_{11}, but also the cladding modes in a spectral range approximately from 1520 to 1563 nm. The core mode shifted to the longer wavelength and reached 1565 nm, and its intensity decreased to 2.5 dB. The maximum intensity of 9 dB in the cladding mode was observed at a wavelength of 1546 nm. In the cladding mode, superposition of two coupling modes (LP_{1n} and LP_{2n}) were observed.

Figure 5(b) shows the transmission spectra of the 8˚-TFBG after 20 minutes irradiation. In the case of 8˚-TFBG, the longer wavelength and smaller intensity of the core mode compared to 6.7˚-TFBG were observed. The peak wavelength and the intensity were 1580 nm and 2 dB, respectively. The cladding mode were observed in a range from 1520 to1578 nm. The maximum intensity of the cladding mode was 11.5 dB at 1548 nm. We observed two coupling modes in the cladding mode as well.

Figure 5(c) shows the transmission spectra of the 9.9˚-TFBG after 20 minutes irradiation. In this case, the core mode was disappeared. The cladding modes were observed in a range from 1520 to 1580 nm. Although the apparent superposition of the two coupling modes were not observed, we could confirm that both of them were present because the wavelength difference between two adjacent peaks was almost same as the those in the case of 8˚-TFBG.

4.2 Characteristic of liquid measurement

Using the 8˚-TFBG which exhibited the strongest coupling in cladding mode, the experiments for measuring the refractive index of liquids were performed. The result are shown in Figure 6.

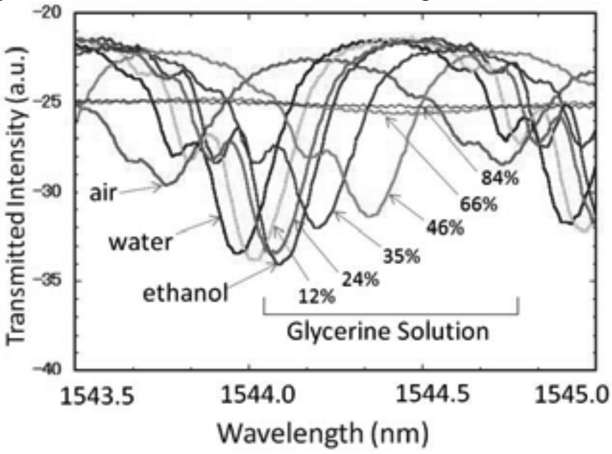

Fig. 6. Refractive index measurement of liquids in 8˚-TFBG

In Figure 6, spectral change of a selected one peak in the cladding modes is indicated. We selected a peak at 1543.76 nm which was the nearly strongest peak in the air. As shown in the figure, the peak wavelength shifted to longer as the refractive index of liquid became larger.As a result, the wavelength shift from 1543.76 to 1544.40 nm corresponding to the index from 1.00 to 1.41. In addition to the wavelength change, the smooth change in the peak intensity was also observed. Laffont *et al.*[5] have used this change in intensity to estimate the index of liquid and demonstrated that the refractive index of liquids from 1.35 to 1.44 was able to estimated by calculating areas of the envelope of cladding modes. In this work, we concentrated to investigate the change in wavelength intending the more accurate measurement.

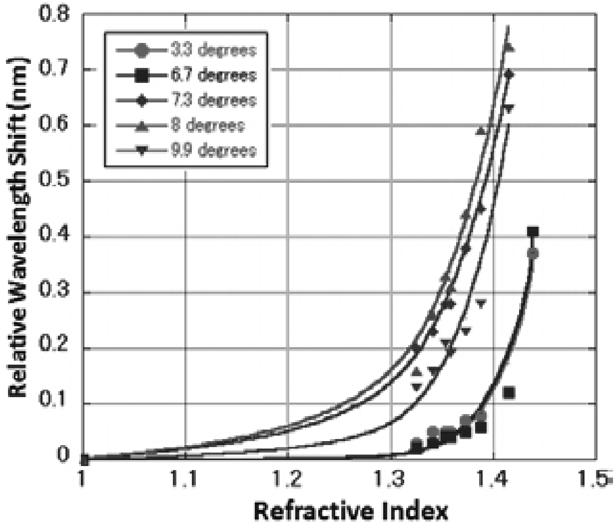

Fig. 7. Relative wavelength shift of TFBG with different tilt angle

Similar experiments have been done for the other TFBGs with different tilt angles. Figure 7 shows the relative wavelength shift to the refractive index of the liquids and air for TFBGs which have various tilted angles. The maximum correlation was achieved at 8˚-TFBG. From the tilt angle of 3.3˚ to 8˚, the correlation between the index and obtained data became stronger as the tilt angle became larger. However, in the case of 9.9-TFBG, the correlation became slightly weaker than 8˚-TFBG.

We estimated the resolution of index change Δn in this method the following equation,

$$\Delta n = \frac{dn_l}{d\Delta\lambda} , \qquad (4)$$

where n_l is the index of liquids and $\Delta\lambda$ is the relative wavelength shift. Figure 8 shows the result. The resolution indicated in Figure 8 was obtained as the index change corresponding to the spectral change of 20 pm since the wavelength resoulution of the OSA used in this experiment was 20 pm. As shown in the figure, 8°-TFBG indicated the maximum sensitivity within a wide refracrive index range. The values were approximately from $9.2x10^{-2}$ to $3.0x10^{-3}$ depending on the index.

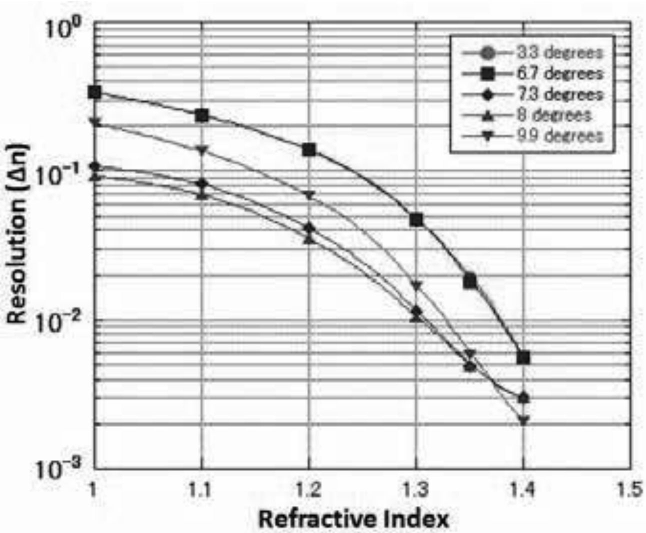

Fig. 8. Resolution of refractive index

The results of the experiment for estimating the spatial resolution of detection are shown in Figure 9. In the figure, the ordinate stands for the normalized peak intensity of the selected cladding mode, and the abscissa stands for the length of liquid droplet which is partially covered the 8°-TFBG. It was found that only 2.4 mm is necessary to contact with the sample liquid in order to get 90% of signal change at 10-mm droplet. This fact implys that the contact length of 2.4 mm is enough to get an information from the liquid which is almost same as the data mentioned above.

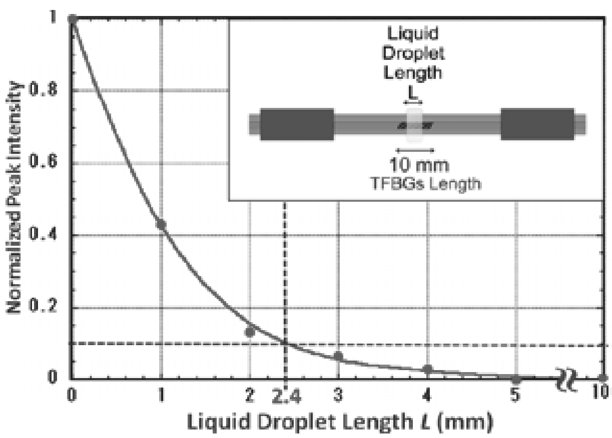

Fig. 9. Spatial resolution of detection in 8°-TFBG

5. DISCUSSION

Based on our experiment, we can say that successfull fabrication of TFBG is performed by combining of 266-nm laser and the phase mask. This technique is more simple compared to the previous method[5] by combination of 244-nm laser and the Lloyd mirror interferometer. The maximum peak intensity in cladding mode and sensitivity were achieved in the case 8°-TFBG. The reason of the weaker intensity of 9.9-TFBG than 8°-TFBG is considered to be some degradations of interference due to increase of distance between the phase mask and the fiber sample position during the fabrication.

Figure 10 shows the peak wavelength of 8°-TFBG as a function of refractive index of liquids. The square dots show the measured peak wavelength with 8-TFBG. The circle dots in the figure indicate the data treated with the method presented by Laffont *et al.*[5]. By comparing these two curves, we can say that our estimation method has the wider measurement range. In principle it is considered to be very difficult to estimate the index less than 1.33 by their mothod.

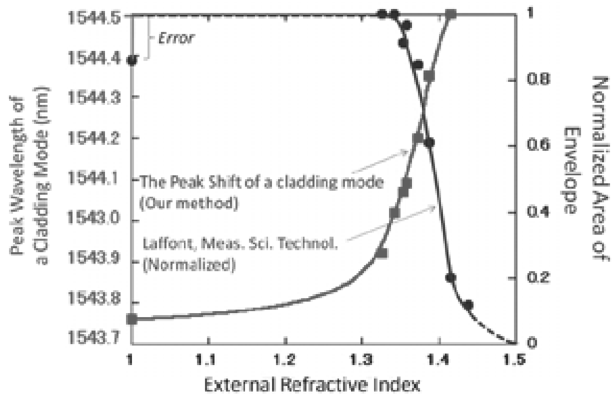

Fig. 10. Peak wavelength compared by Laffont's method in 8°-TFBG

Finally, we could demonstrated that only small part was necessary to contact with liquids. This fact suggests the possibility for development of very small sensors which may be applied in medical and biological applications.

6. CONCLUSIONS

Several TFBGs have been fabricated and its transmittance spectra during fabrication has been investigated. We have also measured the refractive index of liquid using a response of wavelength shift in a cladding mode against the index change of liquid droplet. Based on our experiment, we conclude that:

1) TFBG can be fabricated with a simple technique using combination of 266-nm laser and the phase mask.
2) The fabricated 8°-TFBG can be used to measure refractive index of liquid from 1.00 to 1.41.

3) The resolution of detecting the index change is $9.2x10^{-2}$ to $3.0x10^{-3}$ for 8°-TFBG depending on the index.
4) It has been found that only 2.4 mm is enough to contact to the liquid for measurements refractive index of liquid.

The TFBG is considered to be very promissing for the sensors of bio-chemical phenomena in medical and biological fields.

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