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Thermal Characteristics of Temperature Sensor Using Fiber Bragg Grating for Optical Sensor Network Communication

Jae-Wook Kim[1]* and Yong-Hwan Son[2]

[1] *Department of Electronic Engineering, Namseoul University, 91 Daehak-ro, Seonghwan-eup, Seobuk-gu, Cheonan-si, Chungnam, 330-707, Korea*
[2] *Department of Electrical and Electronic Engineering, Yonsei University, 134 Shinchon-Dong Seodaemun-Gu, Seoul, 120-749, Korea*

[1]*jwkim@nsu.ac.kr*, [2]*sonyh38@yonsei.ac.kr*

Abstract

In this paper, we present thermal characteristics of temperature sensor using fiber Bragg grating(FBG), including peak reflectivity, FWHM bandwidth and various normalized refractive index change along temperature variation. The temperature stability of FBG temperature sensor can be changed by varying the refractive index change and grating length. The proposed FBG temperature sensor can measure up to about 600℃ and heating time from 1000 hours. We can easily expect that various numerical results can be utilized as important ones when a sensor for measuring a temperature is implemented using a FBG technique.

Keywords: *FBG; temperature sensor; reflectivity; bandwidth*

1. Introduction

FBG have been successfully implemented in a variety of optical signal processing devices, such as wavelength selective components, pulse compressors and fiber sensors [1-5]. It is simply fiber device that reflects a particular wavelength by Bragg condition. The wavelength shift can be achieved through thermal method [6]. The FBG temperature sensor reflects one particular wavelength and transmits all others, and the reflected wavelength can vary with the sensor's temperature, thus, FBG temperature sensors have been widely used in applications in monitoring temperature [7]. It is important to check and analyze the variations of both characteristics and stability when a FBG is utilized as an optical sensor measuring the temperature.

In this paper, various characteristics of an optical sensor using a FBG, which is made from Ge and Ge & B co-doped silica fiber, are presented and discussed: The shift of a Bragg center wavelength of an optical sensor, its full-width half-maximum(FWHM) bandwidth, its reflectivity, and the variation of reflective index. How much is the stability of temperature changed is shown and analyzed.

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2. Fiber Bragg Grating Sensor

The strongest interaction or mode coupling occurs at the Bragg wavelength λ_B given by [8]

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Where Λ is the grating period and n_{eff} is the effective refractive index of the fiber. The effective refractive index, as well as the periodic spacing between the grating planes, will be affected by changes in temperature. Using eq. (1) the shift in the Bragg grating center wavelength due to temperature changes, ΔT_{FBG} is given by [8-10]

$$\Delta\lambda_B = 2(\Delta\Lambda)n_{eff} + 2\Lambda(\Delta n_{eff}) = \lambda_B(\frac{\partial n_{eff}}{\partial T}\frac{1}{n_{eff}} + \frac{\partial\Lambda}{\partial T}\frac{1}{\Lambda})\Delta T_{FBG} \tag{2}$$

Where $\alpha_\Lambda = (1/\Lambda)(\partial\Lambda/\partial T)$ is the thermo-optic coefficient that is approximately equal to 8.6×10^{-6} for the Ge doped silica fiber, and $\alpha_n = (1/n_{eff})(\partial n_{eff}/\partial T)$ is the thermo-expansion coefficient that is approximately equal to 0.55×10^{-6} for the silica fiber [8]. Hence, the shift in the Bragg grating center wavelength simplifies to eq. (2)

$$\Delta\lambda_B = \lambda_B(\alpha_n + \alpha_\Lambda)\Delta T_{FBG} \tag{3}$$

The use of (3), temperature sensitivity of FBG, ST_{FBG} is defined by

$$ST_{FBG} \equiv \frac{\Delta\lambda_B}{\Delta T_{FBG}} = \lambda_B(\alpha_n + \alpha_\Lambda) \tag{4}$$

Thus, shift of Bragg grating center wavelength along temperature variation, $\lambda_{B(shift)}$ is given by

$$\Delta\lambda_{B(shift)} = \lambda_B + ST_{FBG}\Delta T_{FBG} \tag{5}$$

The index grating couples the forward and propagating waves through Bragg diffraction. In the coupled-wave analysis, the intra-cavity field is written as [11]

$$E(z) = A(z)\exp(iqz) + B(z)\exp(-iqz) \tag{6}$$

Where $A(z)$ and $B(z)$ are the amplitudes of the forward and backward propagating waves, q is propagation constant, z is propagation direction. The use of (1) in the wave equation provides the coupled-wave equations [11]:

$$\frac{dA(z)}{dZ} = i\delta A(z) + i\kappa B(z) \tag{7a}$$

$$\frac{dB(z)}{dZ} = -i\delta B(z) - i\kappa^* A(z) \tag{7b}$$

Where δ is a measure of the detuning of the laser mode from the Bragg wavelength and κ is coupling coefficient. Since (7a) and (7b) can then be solved analytically, the propagation through a subsection is carried out by using the prescription [11-13].

$$\begin{bmatrix} A_{out} \\ B_{out} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} A_{in} \\ B_{in} \end{bmatrix} \tag{8}$$

where A and B represent the amplitudes of forward and backward propagating waves and S is a 2×2 matrix with complex coefficients as a function of temperature given by [10, 14].

$$\begin{aligned} S_{11}(\lambda,T)_{\Delta T_{FBG}} &= [1 - r(\lambda,T)^2_{\Delta T_{FBG}}]^{-1}[\exp\{jq(\lambda,T)_{\Delta T_{FBG}} L\} \\ &\quad - r(\lambda,T)^2_{\Delta T_{FBG}} \exp\{-jq(\lambda,T)_{\Delta T_{FBG}} L\}] \\ S_{22}(\lambda,T)_{\Delta T_{FBG}} &= [1 - r(\lambda,T)^2_{\Delta T_{FBG}}]^{-1}[\exp\{-jq(\lambda,T)_{\Delta T_{FBG}} L\} \\ &\quad - r(\lambda,T)^2_{\Delta T_{FBG}} \exp\{jq(\lambda,T)_{\Delta T_{FBG}} L\}] \\ S_{21}(\lambda,T)_{\Delta T_{FBG}} &= -S_{12}(\lambda,T)_{\Delta T_{FBG}} \end{aligned} \tag{9}$$

where L is grating length, $q(\lambda,T)_{\Delta T_{FBG}} = \pm[\delta(\lambda,T)^2_{\Delta T_{FBG}} - \kappa(\lambda,T)^2_{\Delta T_{FBG}}]^{1/2}$ is propagation constant as a function of temperature,

$r(\lambda,T)_{\Delta T_{FBG}} = [q(\lambda,T)_{\Delta T_{FBG}} - \delta(\lambda,T)_{\Delta T_{FBG}}]/\kappa(\lambda,T)_{\Delta T_{FBG}}$ is effective reflection coefficient of the grating as a function of temperature, $\kappa(\lambda,T)_{\Delta T_{FBG}} = \pi\Delta n/\lambda_B$ is coupling coefficient as a function of temperature and $\delta(\lambda,T)_{\Delta T_{FBG}} = 2\pi(1/\lambda - 1/\lambda_B)$ is the detuning as a function of temperature. The transmission and reflection spectra as a function of temperature are then obtained by imposing the boundary condition $B_{out}(L) = 0$ and are given by [15, 16],

$$\begin{aligned} T(\lambda,T)_{\Delta T_{FBG}} &= \left|\frac{A_{out}}{A_{in}}\right|^2 = \left|S_{11}(\lambda,T)_{\Delta T_{FBG}} - \frac{S_{12}(\lambda,T)_{\Delta T_{FBG}} S_{21}(\lambda,T)_{\Delta T_{FBG}}}{S_{22}(\lambda,T)_{\Delta T_{FBG}}}\right|^2 \\ &= \left|\frac{1}{S_{11}(\lambda,T)_{\Delta T_{FBG}}}\right|^2 \end{aligned} \tag{10a}$$

$$R(\lambda,T)_{\Delta T_{FBG}} = \left|\frac{B_{in}}{A_{in}}\right|^2 = \left|\frac{S_{21}(\lambda,T)_{\Delta T_{FBG}}}{S_{22}(\lambda,T)_{\Delta T_{FBG}}}\right|^2 \tag{10b}$$

In the FBG sensor, the reflectivity of the Bragg center wavelength is calculated by coupling coefficient and grating length of the refractive index change with the following formula [8].

$$R = \tanh^2(\kappa \bullet L) \tag{11}$$

The reflectivity of a FBG sensor can be changed because of the variation of a coupling coefficient due to the change of a refractive index. How much a refractive index change as a function of temperature, Δn_T will be changed according to the temperature is shown in the following equation [17].

$$\Delta n_T = \Delta n_0 \frac{1}{(1 + A \bullet t^{\alpha})} \tag{12}$$

Where $\Delta n_0 (2\times10^{-4})$ is initial refractive index of FBG at the starting temperature prior to temperature authorization, and t is the amount of time the temperature is changed from 0℃ to 1000℃. Also, from the silica optical fiber where the Ge becomes doping, $A = 1.86\times10^{-3}\exp(7.64\times10^{-3T})$ and $\alpha = T/5250$, and in case of Ge & B co-doped becomes doping, $A = 0.192\times10^{-3}\exp(13.1\times10^{-3T})$ and $\alpha = T/2941$ according to 'Erdogan power law parameter'[18]. Therefore, the normalized reflectivity of FBG temperature sensor is expressed in compliance with (11) and (12) using the following formula.

$$R_N(L,T) = \tanh^2\left[\frac{\pi\Delta n_T(T)L}{\lambda_B}\right] \tag{13}$$

The FWHM bandwidth of FBG temperature sensor can be reduced depending on the variation of a refractive index. The pattern of its reduction is presented by the following equation [18].

$$\Delta\lambda(L,T) = \frac{\lambda_B^2\left[\pi^2 + \left(\frac{\pi\Delta n_T(T)}{\lambda_B}L\right)^2\right]^{1/2}}{\pi \cdot n_{eff} L} \tag{14}$$

Both the reflectivity and the bandwidth of an optical spectrum become small because the grating period and refractive index are changed due to the variation of temperature. Therefore, it is important how much an optical sensor can be stable depending on the changes of an operating temperature.

3. Numerical Analysis and Results

When a temperature around a FBG sensor in Ge and Ge & B co-doped silica fiber was changed, the relation between it and Bragg center wavelength, the optical spectrum of a FBG sensor, reflectivity, bandwidth, and the change of refractive index were calculated numerically. At this time, the grating length of FBG sensor was 10[mm], and the initial refractive index, Δn_0 was 2×10^{-4}.

Figure 1 shows the numerical analysis of Bragg center wavelength of FBG sensor using the equations of (5) and (6). When the Bragg center wavelength was 1554.502[nm] at 30℃, the FBG sensor at 100℃ temperature moved to 1555.497[nm] by 0.995[nm], it moved to 1556.920[nm] at 200℃, to 1558.342[nm] at 300℃, to 1559.764[nm] at 400℃, to 1561.187[nm] at 500℃, to 1562.609[nm] at 600℃, to 1564.031[nm] at 700℃, and to 1565.454[nm] at 800℃. We can understand that Bragg center wavelength was shifted by 0.014182[nm] per 1℃ compared to the initial one because of thermo-optic coefficient and thermo-expansion coefficient.

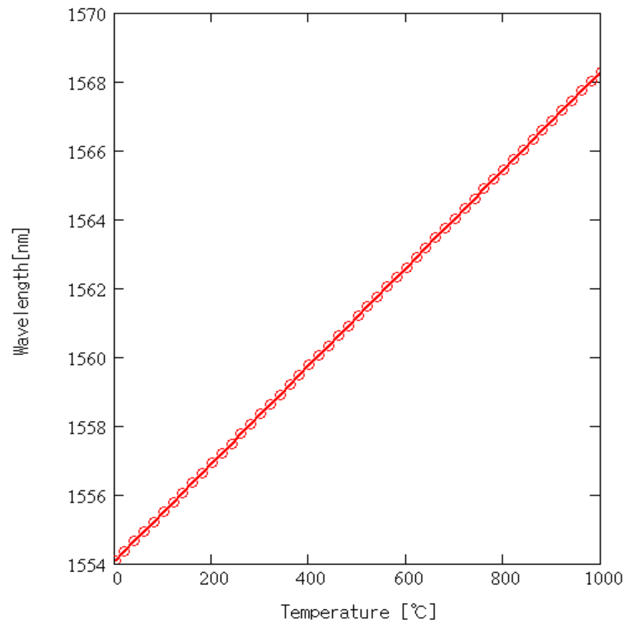
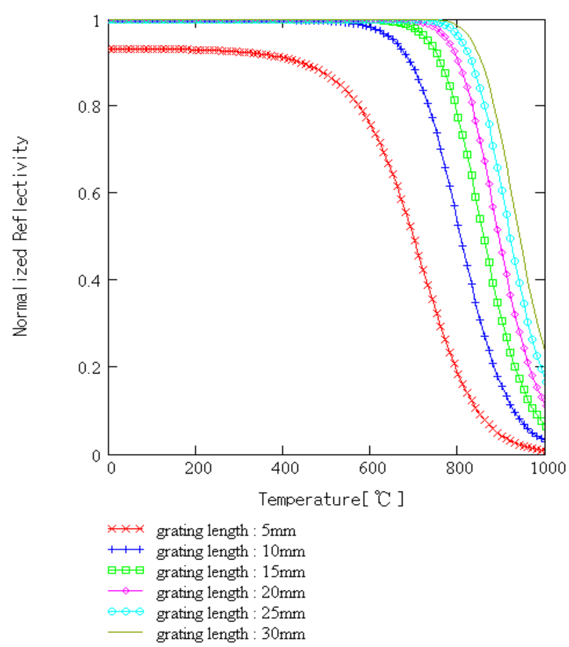
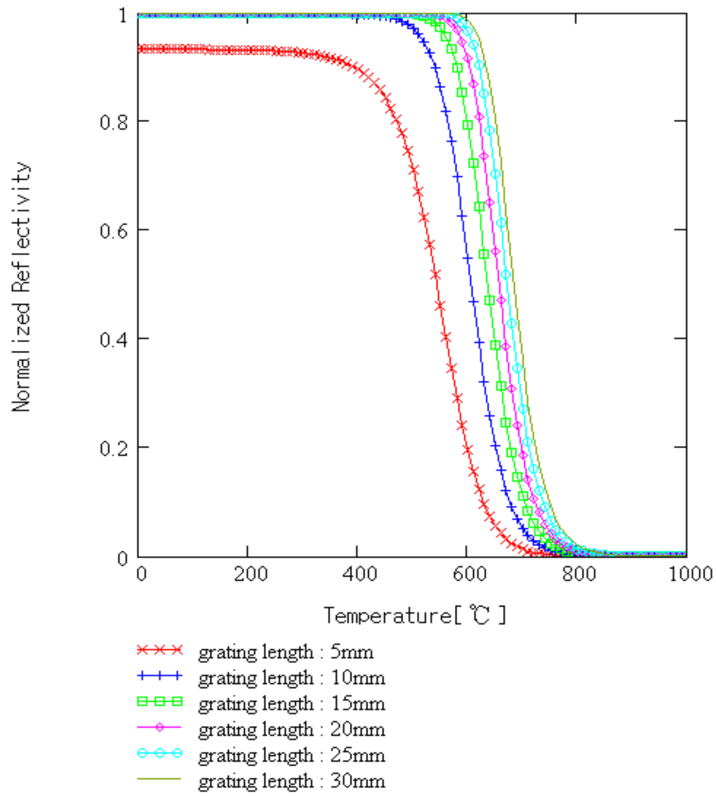


Figure 1. Bragg Center Wavelength Shift of the FBG Temperature Sensor along Temperature Variation

As shown in Figure 1, it is possible to measure the amount of the variation of a temperature by that of a Bragg center wavelength because it is changed linearly according to temperature.



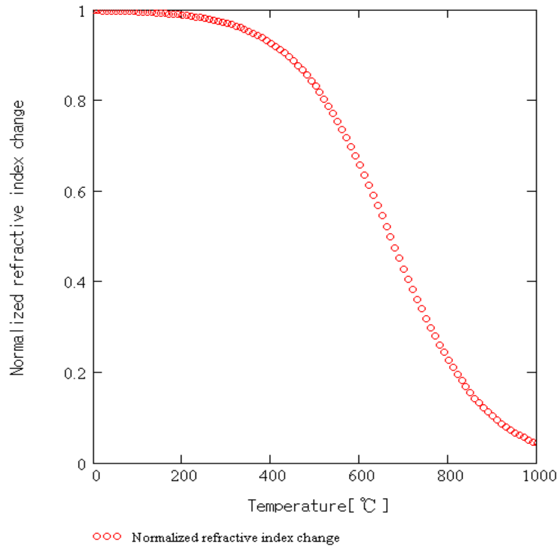
(a)



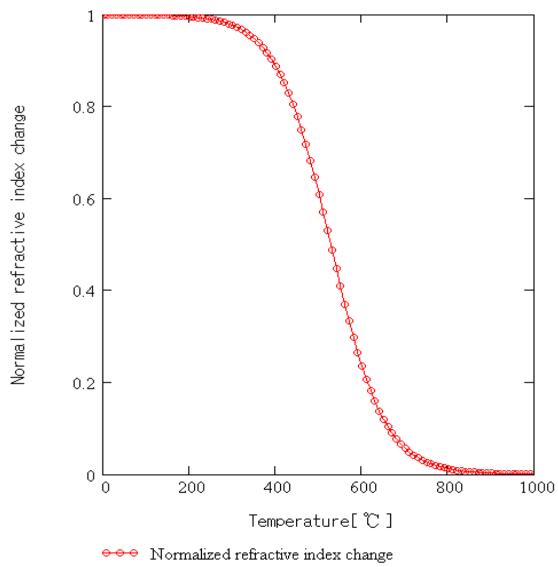
(b)

Figure 2. Normalized Reflectivity of the FBG Temperature Sensor along Temperature Variation: (a) Ge, (b) Ge & B

Figure 2 shows the variations of reflectivity against both grating length and temperature when the initial refractive index of a FBG sensor was $\Delta n_0(2\times10^{-4})$. We can observe that the reflectivity of FBG temperature sensor becomes stable up to 600℃ and it becomes unstable rapidly around 700℃ and 800℃. Also, it is possible to measure the temperature of its circumstances in even wider region because the reflectivity becomes large according to the grating length of a FBG sensor. The amount of the reduction of Ge & B co-doped silica fiber becomes larger than Ge doped silica fiber in the high temperature region. Especially, it is impossible to measure a temperature because the optical spectrum of a FBG sensor, which is made from Ge & B co-doped silica fiber, shows the reflectivity near zero in case of over 700℃.



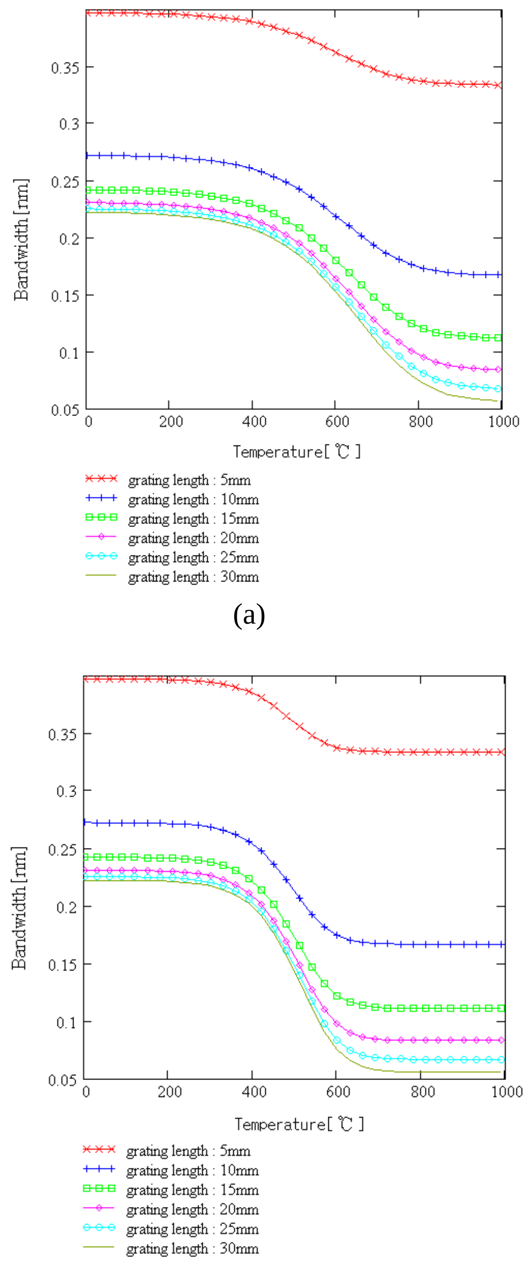
(a)



(b)

Figure 3. Normalized Refractive Index Change of the FBG Temperature Sensor along Temperature Variation: (a) Ge, (b) Ge & B

Figure 3 shows the normalized refractive index change when temperature is changed according to the equation of (12). As shown in Figure 3, it is rarely varied within 600℃, and is rapidly reduced over this temperature in case of the initial refractive index of $\Delta n_0(2\times10^{-4})$. We can easily expect that this phenomenon will make the reflectivity of FBG temperature sensor low. Also, we can observe that refractive index was rapidly reduced in case of Ge & B co-doped silica fiber compared to Ge doped silica fiber.



(a)

(b)

Figure 4. Bandwidth of the FBG Temperature Sensor along Temperature Variation: (a) Ge, (b) Ge & B

By using equation (14), the Bragg center wavelength bandwidths of a FBG temperature sensor are presented in the Figure 4. The variation of each bandwidth was small up to 600℃ while it was reduced rapidly over this temperature. We can see that errors can be generated during the measurement of temperature because the linewidth becomes narrow in case of the grating length of 30 mm. As shown in Figure 2, optical sensor based on a FBG with a grating length below 30 mm should be implemented considering the above mentioned points. Also, the reduction of bandwidth of Ge & B co-doped silica fiber is more increased compared to Ge doped silica fiber in the high temperature range.

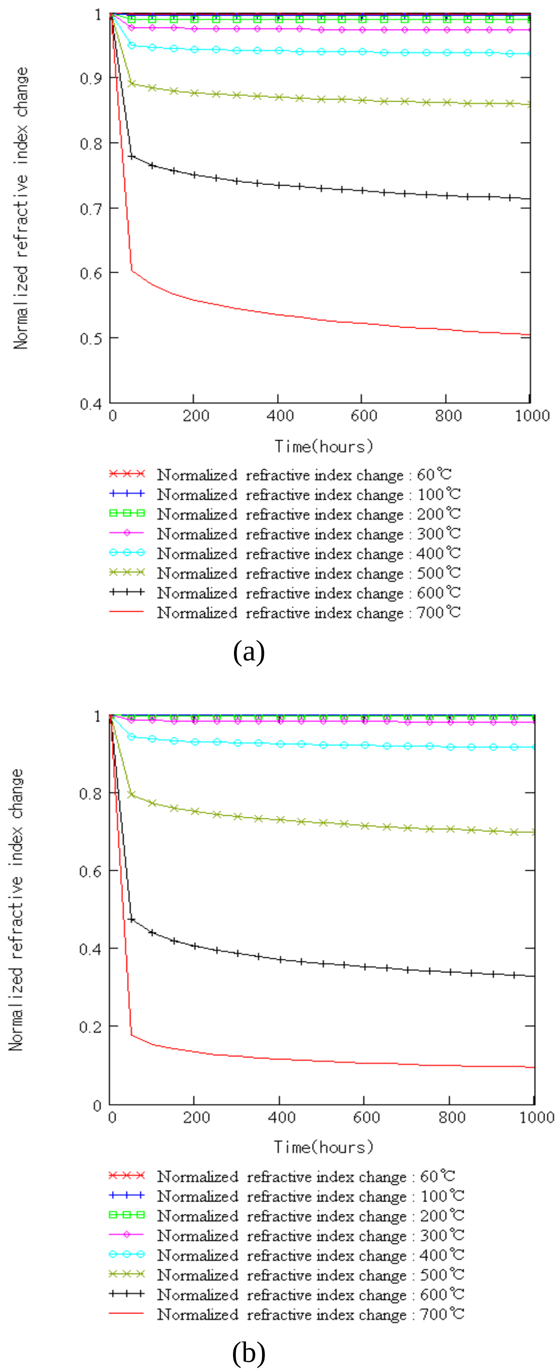
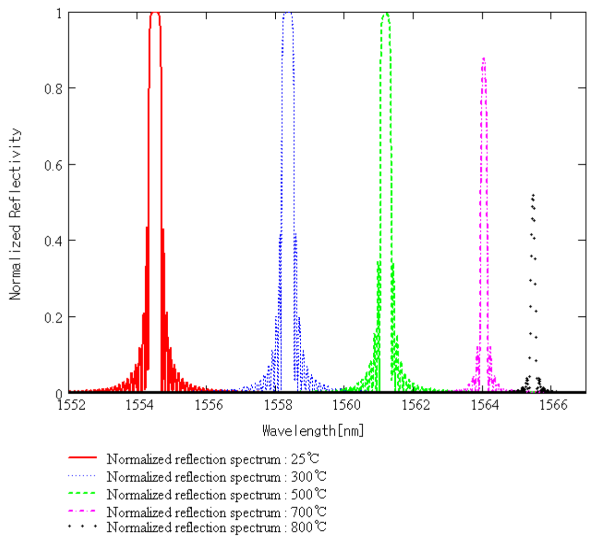
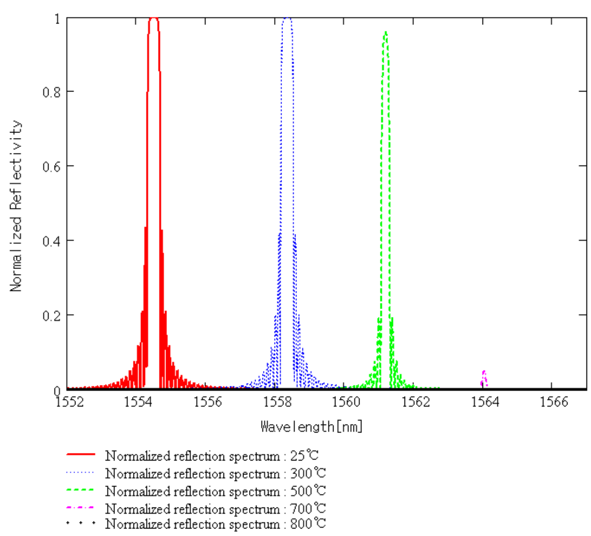


Figure 5. Normalized Refractive Index Change of the FBG Temperature Sensor along Exposure Time: (a) Ge, (b) Ge & B

Figure 5 shows the variations of a refractive index changes against the exposure time of a FBG temperature sensor in order to measure its variation at a certain temperature. The change of a refractive index can be negligible even when the exposure time was over 1000 hours within the temperature of 600℃. However, it was reduced rapidly in spite of the very short time over 700℃. This result tells us that there can be severe errors when the temperature was measured at this temperature. Also, we could observe that the refractive index of Ge & B co-doped silica fiber was reduced larger than Ge doped silica fiber in terms of the heating time and temperature.



(a)



(b)

Figure 6. Reflection Spectra of the FBG Sensor along Temperature Variation: (a) Ge, (b) Ge & B

Figure 6 shows each optical spectrum of a FBG temperature sensor when a Bragg center wavelength was shifted depending on the changes of a temperature at a grating length of 10 mm. They were calculated numerically using various numerical results and the equation of

(10). As shown in Figure 6, it is possible to measure each temperature within 600℃ because a Bragg center wavelength was changed linearly. However, many measurement errors can be generated over 700℃ because the reflectivity and bandwidth of a center wavelength are all reduced. Also, we can observe that the same errors can occur over 500℃ in Ge & B co-doped silica fiber due to the same reason as that of the above mentioned.

4. Conclusions

In this paper, the characteristics of a FBG temperature sensor were investigated by presenting various numerical results. It is possible to measure a temperature within a certain temperature region because a Bragg center wavelength is varied linearly according to its operating temperature. However, the reflectivity of a Bragg center wavelength was reduced over a limited high temperature.

As we can see the presented results at this paper, the change of a refractive index was very small up to 600℃ while it was reduced rapidly over this temperature. The bandwidth of a FBG temperature sensor was not changed within 600℃, and it was reduced rapidly over 600℃. Therefore, it is difficult to obtain the wanted bandwidth over this temperature. The normalized refractive index is rarely changed up to 600℃ at the exposure time of 1000 hours. Over 600℃, its change becomes large in spite of the very short exposure time because the change of refractive index is large.

Accordingly, it is possible to obtain the stability of a FBG sensor within 600℃. Also, we can observe that the same errors can occur over 500℃ in germanium & boron co-doped silica fiber due to the same reason as that of the above mentioned. However, it is difficult to measure the accurate temperature over this temperature. We can easily expect that various numerical results can be utilized as important ones when a sensor for measuring a temperature is implemented using a FBG technique.

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Authors

Jae-Wook Kim

Jae-Wook Kim received the B.S., M.S., and Ph. D. degrees in electronic engineering from Hoseo University, Asan, Korea in 1993, 1998 and 2003 respectively. He is currently working as a professor in electronic engineering, Namseoul University. His current research interests are magnetic material, magnetic device and optical device.

Yong-Hwan Son

Yong-Hwan Son received the B.S., M.S., and Ph. D. degrees in electronic engineering from Hoseo University, Asan, Korea in 1999, 2001 and 2008 respectively. He is currently working as a research professor in electrical and electronic engineering, Yonsei University. His current research interests are optical device, optical sensor and optical system for communications.

