Thermal Characteristics of Fiber Bragg Grating temperature sensor in Ge doped and Ge & Boron co-doped fiber

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Abstract: In this paper, we report thermal characteristics of a FBG temperature sensor in germanium(Ge) doped and Ge & Boron(B) co-doped fiber, including peak reflectivity, FWHM line-width, and various refractive index change as well as thermal stability of a FBG temperature sensor. The reflectivity of a FBG temperature sensor with refractive index change is affected by its thermal stability. Ge doped FBG temperature sensor has thermally stability better than Ge & B co-doped FBG temperature sensor. Also, both FBG temperature sensor has thermally stability up to about 500℃ and 1000 hours. The proposed FBG temperature sensor can be applicable as a high temperature measurement sensor.

1. Introduction

Fiber Bragg grating(FBG) have been successfully implemented in a variety of optical signal processing devices, such as wavelength selective components, pulse compressors and fiber sensors[1]. It is simply fiber device that reflects a particular wavelength by Bragg condition. The wavelength shift can be achieved through thermal method[2].

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[3].

In this paper, we report thermal characteristics of a FBG temperature sensor in germanium(Ge) doped and Ge & Boron(B) co-doped fiber, including peak reflectivity, FWHM line-width, and various refractive index change as well as thermal stability of a FBG temperature sensor.

2. Principle of FBG Temperature Sensor

The strongest interaction or mode coupling occurs at the Bragg wavelength λ_B given by[4]

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

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[4-6]

$$\begin{aligned}\Delta\lambda_B &= 2(\Delta\Lambda)n_{eff} + 2\Lambda(\Delta n_{eff}) \\ &= \lambda_B\left(\frac{\partial n_{eff}}{\partial T}\frac{1}{n_{eff}} + \frac{\partial \Lambda}{\partial T}\frac{1}{\Lambda}\right)\Delta T_{FBG}\end{aligned} \tag{2}$$

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[4]. 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

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

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. [3]

$$R = \tanh^2(\kappa \cdot L) \tag{6}$$

Where L is grating length of FGB temperature sensor, $\kappa = \pi\Delta n/\lambda_B$ is coupling coefficient. If temperature causes refractive index of the FBG to change, coupling coefficient also changes, and it affects the reflectivity of the FBG sensor. The refractive index change, Δn_T affected by the temperature is calculated with the following formula[7].

$$\Delta n_T = \Delta n_0 \frac{1}{(1 + A \cdot t^{\alpha})} \tag{7}$$

Where $\Delta n_0 (= 2 \times 10^{-4})$ is initial refractive index difference of FBG prior to temperature authorization, and t is duration of time the temperature is exerted. 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 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'[8]. Therefore, the normalized reflectivity of FBG sensor is expressed in compliance with (6) and (7) using the following formula.

$$R_N(L,T) = \tanh^2\left[\frac{\pi\Delta n_T(T)L}{\lambda_B}\right] \tag{8}$$

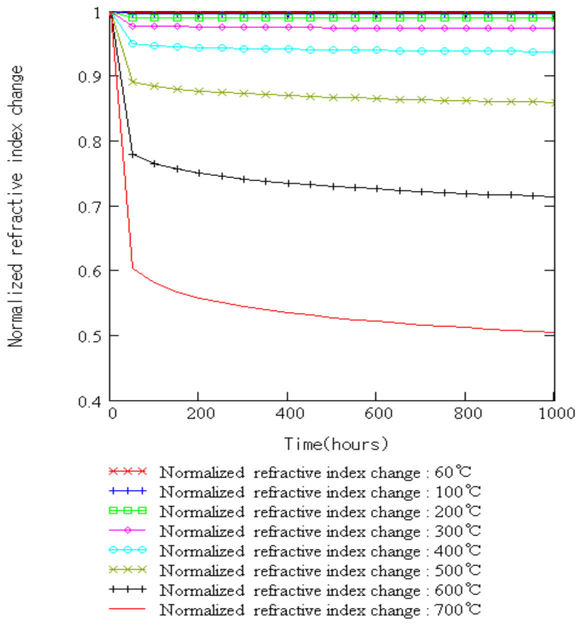
When FWHM bandwidth of FBG sensors changes in temperature, the refractive index changes consequently, and it too reduces accordingly. The variations in temperature of FWHM bandwidth is calculated with the following formula [8].

$$\Delta\lambda(L,T) = \frac{\lambda_B^2\left[\pi^2 + \left(\frac{\pi\Delta n_T(T)}{\lambda_B}L\right)^2\right]^{1/2}}{\pi\cdot n_{eff}L} \tag{9}$$

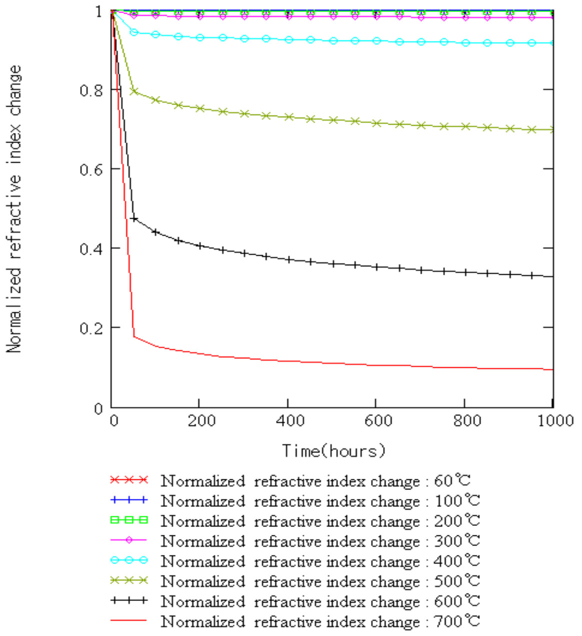
3. Numerical Analysis and Results

Figure 1 shows the normalized refractive index of FBG sensor along temperature and exposure time variation.

The change in refractive index is negligible even when temperature is exerted up to 1000 hours at 600℃, but at 700℃ or above, the refractive index significantly decreases and the affect on FBG's reflectivity is pronounced which results in an error when measuring temperature. Also, duration of heat exertion and temperature causes FBG sensor of Ge & B co-doped silica fiber to decrease in refractive index more than Ge doped silica fiber.



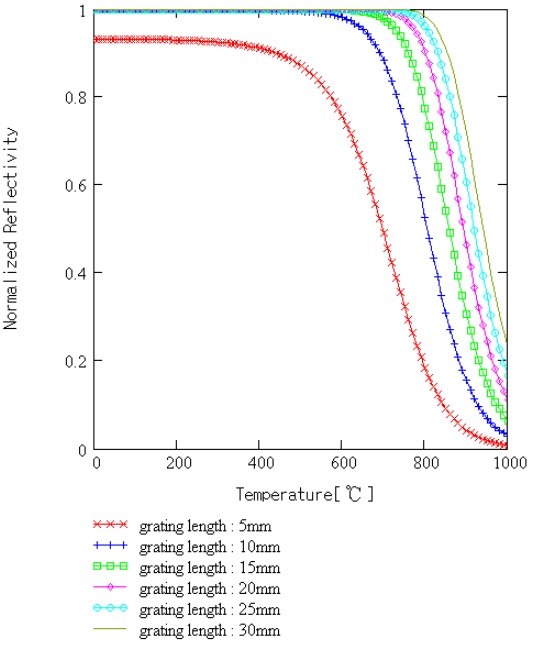
(a)Ge doped



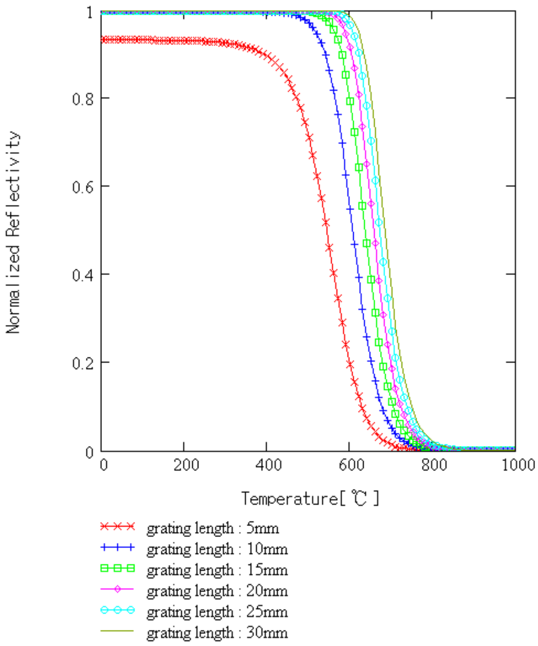
(b)Ge & B co-doped

Fig. 1 Normalized refractive index change of the FBG temperature sensor along heating time

The figure 2 illustrates that when FBG sensor refractive index is $\Delta n_0(=2\times10^{-4})$, expression (8) can be used to find the reflectivity in grating length when heat is exerted to the FBG sensor. The reflectivity of center Bragg wavelength shows stability up to 600℃, but it gradually decreases to 700℃ and at 800℃, it is discernible that reflectivity of center wavelength rapidly decreases which can lead to poor, unacceptable performance of FBG sensor.



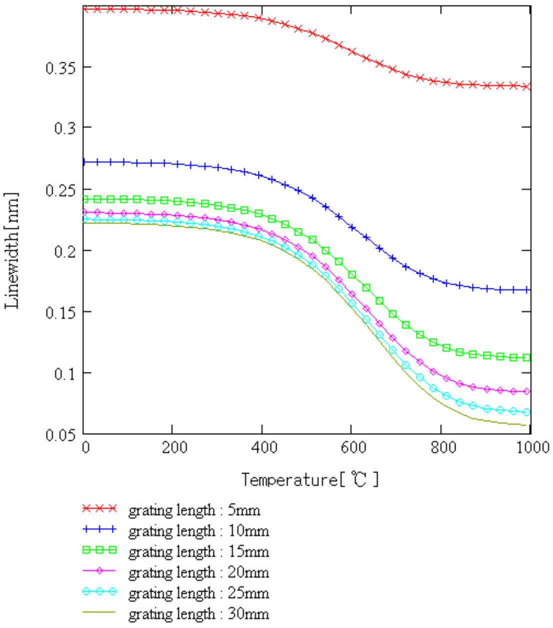
(a)Ge doped



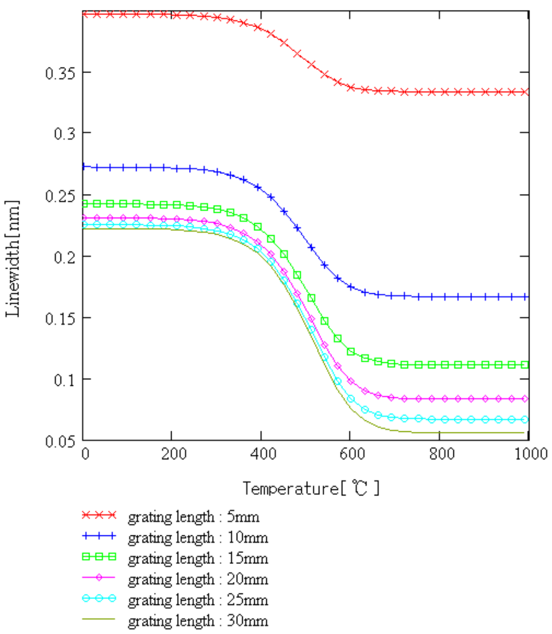
(b)Ge & B co-doped

Fig. 2 Normalized reflectivity of the FBG temperature sensor along temperature variation

By using expression (9), the change in spectrum's linewidth when temperature is exerted to the FBG sensor is shown in figure 3. When temperature up to 600℃ is exerted to the FBG sensor, the change in linewidth of spectrum is negligible. However, the spectrum's linewidth significantly decrease above 600℃, and it is understood that FBG sensor of Ge & B co-doped silica fiber has greater decrease in linewidth than germanium doped silica fiber at high temperature range.



(a)Ge doped



(b)Ge & B co-doped

Fig. 3 Linewidth of the FBG temperature sensor along temperature variation

4. Conclusions

In this paper, we report thermal characteristics of a FBG temperature sensor in germanium(Ge) doped and Ge & Boron(B) co-doped fiber, including peak reflectivity, FWHM line-width, and various refractive index change as well as thermal stability of a FBG temperature sensor.

The reflectivity of a FBG temperature sensor with refractive index change is affected by its thermal stability. When ever the temperature of a FBG changes, the Bragg wavelength shift toward a long wavelength with any increase of temperature due to the thermal expansion effects on refractive index modulation and grating period. This method is appropriate for the temperatures ranging from 0˚C to 1000˚C.

Normalized reflective index of Ge & B co-doped FBG temperature sensor has a large change according to temperature, compare with, Ge doped FBG temperature sensor has a small change. Consequently, Ge doped FBG temperature sensor has thermally stability better than Ge & B co-doped FBG temperature sensor. Also, both FBG temperature sensor has thermally stability up to about 500℃ and 1000 hours. The proposed FBG temperature sensor can be applicable as a high temperature measurement sensor.

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