High-sensitive Fiber Bragg Grating Sensor for Different Temperature Application

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Abstract The main physical quantities in fiber Bragg grating are temperature and strain. The temperature sensors for different materials have been analyzed in this work. The sensing can be possible on the range of Bragg wavelength shifts occurred by the temperature change in the medium. Thus, the temperature is measurement based on the wavelength shifting of the fiber Bragg grating. The mathematical descriptions and simulation of various parameters of FBG temperature sensor are also included in the work.

Keywords Fiber Bragg grating (FBG) · Reflectivity · Temperature sensor
Thermo-optic coefficient · Thermal expansion coefficient

1 Introduction

Fiber Bragg gratings are periodic changes of the refractive index occurred in the core of an optical fiber and formed by UV laser light under particular condition. Many functions like reflection and filtering can be performed by this device in a highly efficient manner. The most important revolution of fiber Bragg gratings is in the field of telecommunications. FBG is also used in the optical fiber sensor field. This is the simple device of a periodic modulation of the refractive index in the core

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The original version of this chapter was revised: Incorrect co-author name has been corrected. The erratum to this chapter is available at https://doi.org/10.1007/978-981-10-7395-3_77

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V. Janyani et al. (eds.), *Optical and Wireless Technologies,* Lecture Notes
in Electrical Engineering 472, https://doi.org/10.1007/978-981-10-7395-3_8

of the fiber. FBG strain sensors are dependent on the property of material, and it is a complicated phenomenon as both the temperature and strain regulate the reflected wavelength of the sensor. To measure adequate temperature, we must compensate the strain effects on the FBG and vice versa. The Bragg grating is also used in coupling light from one propagating mode to another mode [1–4].

The central wavelength of the reflected component satisfies the Bragg relation.

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

where λ_B is reflected wavelength of Bragg grating, n_{eff} is refractive index in the core of the fiber, Λ is period of the grating. We are considering a light wave propagation in the z-direction.

$$n(z) = n_{eff} + \Delta n \cos(2\pi z/\Lambda) \tag{2}$$

where Δn is the amplitude of the refractive index perturbation.

By using coupled mode theory, the description of reflectivity properties of a grating [5].

$$r = \frac{\sinh^2\left(\sqrt{(k^2 - \hat{\sigma}^2)}\ L\right)}{\cosh^2\sqrt{(k^2 - \hat{\sigma}^2 L^2)} - (\hat{\sigma}^2/k^2)} \tag{3}$$

where L is grating length, k is ac coupling coefficient, $\hat{\sigma}$ is general dc self-coupling coefficient, and r is reflectivity.

The FBGs have unique feature which makes its suitable to wavelength division multiplexing techniques. Thus, it can be used for multiple parameter of sensing with different Bragg wavelengths along a single fiber.

2 Spectral Reflectivity Dependence on Grating Length

We have analyzed that spectral reflectivity depends on different grating length L, 1, 2, 3, and 6 mm. At 3 mm, the reflectivity reaches maximum value. When the grating length is increased to L = 6 mm, it is as similar as of 3 mm plot with slight changes shown in Fig. 1 As the grating length is increased, bandwidth decreases.

Figure 2 shows linear behavior between the change in grating length and that of the shift in center wavelength. As noted from the graph, with the variation in the grating length, the center wavelength correspondingly shifts. When the length is increased wavelength increases.

Figure 3 also shows linearity, whenever the variation in refractive index is observed, the center wavelength also gets changed. The Bragg wavelength used for calculation of different external parameter like strain, temperature, pressure, etc. [2, 3].

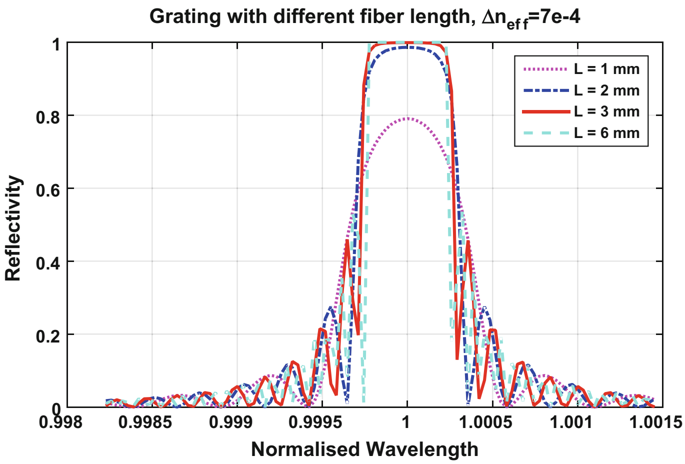

Fig. 1 Reflection spectra of gratings with different lengths

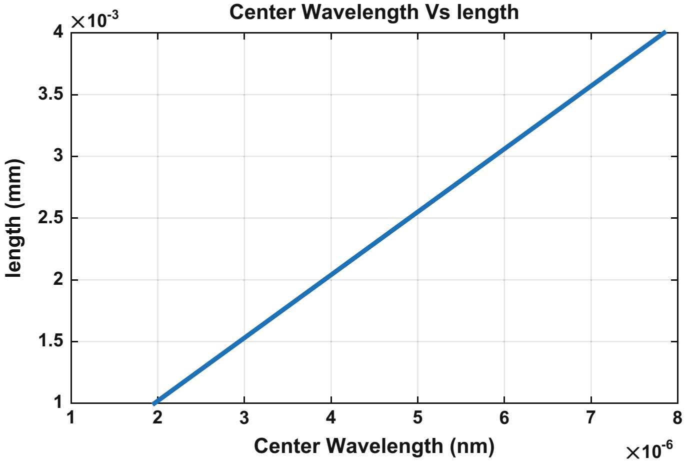

Fig. 2 Effect of grating length on center wavelength

3 Principle of Optical Fiber Bragg Grating Temperature Sensors

FBG sensors are used due to its real-time processing, high sensitivity and stability properties [6]. Due to these properties, optical sensors are widely used as compared to electrical sensors. One of the important applications appropriate for fiber sensors is in the area of temperature analysis. For temperature sensing, the Bragg

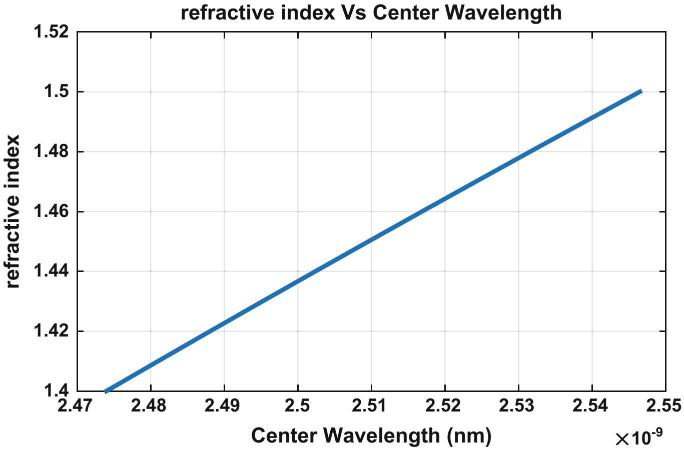

Fig. 3 Effect of refractive index on center wavelength

wavelength is a function of the temperature of material. The temperature is directly related to changes in the refractive index of the fiber along with thermal expansion coefficient of the material.

At this Bragg wavelength, there will be a peak in the reflection spectra. Due to temperature change or strain effect, there will be a shift in the Bragg wavelength. This can be written mathematically as follows:

$$\Delta\lambda_B = 2\left(n_{eff}\frac{\Lambda}{L} + \Lambda\frac{n_{eff}}{L}\right)\Delta L + 2\left(n_{eff}\frac{\Lambda}{T} + \Lambda\frac{n_{eff}}{T}\right)\Delta T \tag{4}$$

In the above equation, the first term is due to induced strain and the second term is due to temperature change.

Due to temperature only, the second term will be taken into consideration [6].

$$\Delta\lambda_B = 2\left(n_{eff}\frac{\Lambda}{T} + \Lambda\frac{n_{eff}}{T}\right)\Delta T \tag{5}$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{2n_{eff}\frac{\Lambda}{T}\Delta T}{\lambda_B} + \frac{2\Lambda\frac{n_{eff}}{T}\Delta T}{\lambda_B}$$

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(\frac{1}{\Lambda}\frac{\Lambda}{T} + \frac{1}{n_{eff}}\frac{n_{eff}}{T}\right)\Delta T \tag{6}$$

where n_{eff} is the effective refractive index of the fiber core and Λ is the grating period. Whenever FBG is in contact with a substrate, then change in grating period is observed due to change in temperature. The variation in grating period not only occurs due to thermal expansion of the fiber but it also takes place due to strain induced by thermal expansion of the substrate.

4 The Refractive Index of the Fiber Core Changes Due to Thermo-Optic Effect

The above equation represents the temperature sensitivity of the FBG. The first term is the thermal expansion coefficient, and the second term is thermal-optic coefficient. Due to change in temperature, ΔT, the shift in Bragg wavelength, is given as [6].

$$\frac{\Delta\lambda_B}{\lambda_B} = [\alpha + \xi]\Delta T \tag{7}$$

$$\Delta\lambda_B = \lambda_B[\alpha + \xi]\Delta T \tag{8}$$

where $\xi = \left(\frac{1}{n_{eff}}\right)\left(\frac{\Delta n_{eff}}{\Delta T}\right)$ is the thermal-optic coefficient of the fiber, and $\alpha = \frac{1}{\Lambda}\frac{\Lambda}{T}$ is the thermal expansion coefficient of the substrate. For temperature sensor, it is obvious that physical interface and thermal expansion of substrate would be greater than the fiber optic length [2, 3]. The Table 1 shows the thermos-optic and thermal expansion coefficient of silica, glass and PMMA with fixed temperature range.

Here, two different material silica and Glass with their different thermal expansion coefficient and different thermo-optic coefficient are used. As shown from Fig. 4 with the change in temperature there is change in wavelength in this graph silica material shows more variation than glass material with same temperature variation.

Here, Polymethyl methacrylate (PMMA) material is used. In Fig. 5, as the temperature increases the wavelength decreases linearly. The linear relation can be used for sensing the temperature. The temperature range depends on the material used for sensing. For PMMA, from Figs. 4 and 5, we observe that silica should be preferred as it shows greater wavelength variation.

Table 1 Optical properties of the materials

Serial no	Material	Thermo-optic coefficient (ξ)	Thermal expansion coefficient (α)	Temperature (T) (°C)
1	Silica [9, 10]	$2 \times 10^{-8}K^{-1}$	$0.55 \times 10^{-60}C^{-1}$	25 – 100
2	Glass [7–9]	$-6.4 \times 10^{-6}K^{-1}$	$8.5 \times 10^{-60}C^{-1}$	25 – 100
3	PMMA [8]	$-1.1 \times 10^{-4}K^{-1}$	$73 \times 10^{-6}K^{-1}$	25 – 100

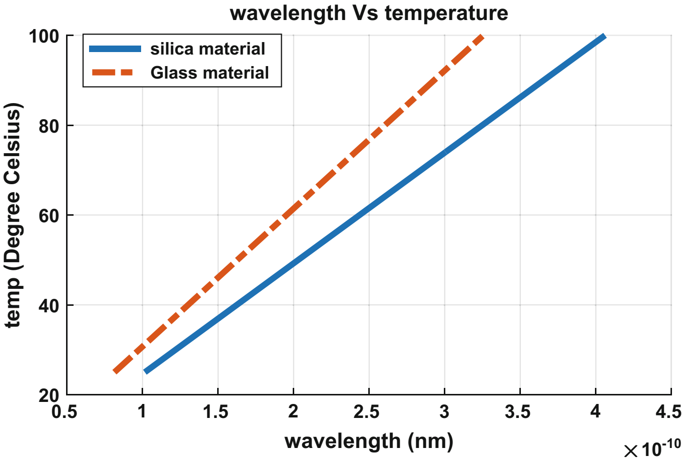

Fig. 4 Change in wavelength with change in temperature for silica and glass material

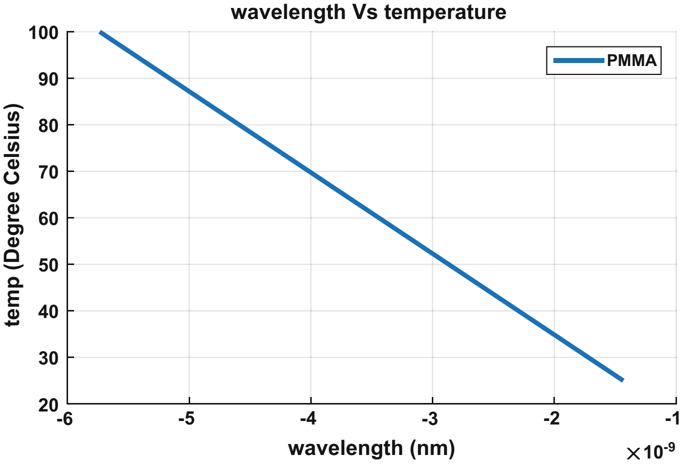

Fig. 5 Change in wavelength with change in temperature for PMMA material

5 Conclusion

The modeling and simulation with MATLAB for optical fiber Bragg grating were realized. The reflectivity and bandwidth are varied with change in grating length. The bandwidth of fiber Bragg grating was inversely proportion to the grating length. The center wavelength is analyzed with change in grating length and refractive index. When the refractive index and length are increased, the center wavelength also increases. The temperature variation of three different materials is analyzed with their different thermal-optic coefficient and thermal expansion coefficient with simulation graph to illustrate their effect. Thus, it can be used for high-sensitive temperature sensor application. WDM gives each FBG sensor to its separate wavelength range within the light spectrum. FBG result shows measurements sensor is inconsistent with light intensity losses/attenuations due to bending or transmission.

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