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Characterization of Fiber Bragg Grating for applications in Nuclear Research Reactors

Abd El-Naser A.Mohamed[a], Ahmed Nabih Zaki Rashed[a], Mohamed Z. Elsiefy[a], M. M. Zaky[b], Ahmed I.Elsaket[c,*]

[a] Dept. of Electronics and Electrical Communications Engineering, Faculty of Engineering, Minufiya University, Egypt.
[b] Dept. of Engineering, Nuclear Research Center, Atomic Energy Authority, Egypt.
[c]Dept. of Nuclear Safety and Radiological Emergencies, NCRRT, Egypt.

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A B S T R A C T

The work presented in this paper characterize the fiber Bragg grating (FBG) for temperature measurement for the safe operation in material testing reactors (MTR). Fibre Bragg Grating is the key technology used to covers many applications in nuclear reactors in order to sense different physical parameters such as temperature, strain, etc. This paper investigates the modelling of Bragg grating based on MATLAB, through solved coupled mod equations in order to achieve maximum reflectivity. In addition, modelling of fiber Bragg grating as a temperature sensor for nuclear applications using opti-grating software is presented. Furthermore, Apodization techniques for signal processing also used to provide accurate measurements which required in nuclear applications.

1. Introduction

The nuclear industries have been increased rapidly due to the demand for electricity generation with nuclear energy which has a large scale relative to other energy resources [1]. On the other hand there is a wide range of atom for peace applications through the utilization of research reactors such as medicine, industry, agriculture, research development…etc. Egypt second research reactor (ETRR-2) is one of those high neutron flux reactor, belongs to category 2 and it has many advantages as a research reactor. The measurements for the safety system are done by three redundant sensors.

There are problems causes due to the presence of ionizing radiation in the application of electronic or photonic equipment in this field [2].

Instrumentation and continuous monitoring to safety parameters during reactor operation are a major issue for safe operation [3]. Researches has turned to FBG as one attractive type of a sensing system in nuclear reactors applications which offer several advantage over the traditional electronic sensors [4] such as immunity to electro-magnetic interference where no electrical current presented at the sensing point, suitable for high temperature operation, small size, intrinsically safe which does not cause explosion when used in nuclear reactors [5-6], ease of multiplexing that allows a single fiber cable with many of gratings to measure a large range of parameters in nuclear reactors applications using wavelength division multiplexing technique [7] and proved highly greater sensitivity [8-9].

In this paper, the reflectivity was analyzed with different fiber grating length which acts as one of the critical parameter for effective and high performance of FBG to use as a temperature sensor in nuclear research reactor. The paper is divided for

* Corresponding author. Tel.:+0-102-776-1712
E-mail address: ahmadteb177@gmail.com.

following sections: Section 2 indicates the radiation effects on FBG, section 3 indicates modelling of FBG to achieve maximum reflectivity, section 4 illustrates FBG temperature sensors, section 5 presents Apodized fiber Bragg grating signal processing and section 6 represent conclusion.

2. Thermal Radiations Effects on FBG

Radiation-induced losses in the transmitting fiber because of several phenomena, emission, radiation-induced attenuation and compaction, also causes an error in the Bragg wavelength evaluation. The effect of radiation and temperature on FBGs can expressed as [10]

$$\lambda_B(d,T) = 2n(d,T)\Lambda(d,T) \tag{1}$$

Where d refers to total radiation dose, T is the value of current temperature. Apply Taylor series expansion to equation, and high order terms for temperature dependent ignore, but terms up to second order to wavelength shifted induced by radiation are observed, which given as [10]

$$\lambda_B(d,T) = 2n(d_0,T_0)\Lambda(d_0,T_0) + 2\left[\Lambda\frac{\partial n}{\partial d} + n\frac{\partial \Lambda}{\partial d}\right]_{d=d_0,T=T_0}\Delta d + 2\left[\Lambda\frac{\partial^2 n}{\partial d^2} + n\frac{\partial^2 \Lambda}{\partial d^2}\right](\Delta d)^2 + 2\left[\Lambda\frac{\partial n}{\partial T} + n\frac{\partial \Lambda}{\partial T}\right]_{d=d_0,T=T_0}\Delta T \tag{2}$$

Where $\lambda_B(d_0,T_0) = 2n(d_0,T_0)\Lambda(d_0,T_0)$, so equation can be transferred into [10]

$$\lambda_B(d,T) = 2\left[\Lambda\frac{\partial n}{\partial d} + n\frac{\partial \Lambda}{\partial d}\right]_{d=d_0,T=T_0}\Delta d + 2\left[\Lambda\frac{\partial^2 n}{\partial d^2} + n\frac{\partial^2 \Lambda}{\partial d^2}\right](\Delta d)^2 + 2\left[\Lambda\frac{\partial n}{\partial T} + n\frac{\partial \Lambda}{\partial T}\right]_{d=d_0,T=T_0}\Delta T \tag{3}$$

The first two terms are Bragg wavelength shift induced by irradiation dose, and the third term refers to temperature variation induced wavelength shift. The refractive index of any optical material can be described by the Sellmeier formula. Where refractive index for optical material given as a function of temperature, operating wavelength and radiation dose as the following formulas [11],

$$n^2(T,\lambda,d) = A(T,d) + \frac{B(T,d)\lambda^2}{\left(\lambda^2 - C(T,d)\right)} + \frac{D(T,d)\lambda^2}{\left(\lambda^2 - E\right)} \tag{4}$$

Where the constants A, B, C, D, E are listed in Ref.[11]. From previous gamma and neutron irradiations results can be summarized as [4,5]-[8,9]:

- The chemical synthesis of the fiber optic used for inscription the FBGs is a major parameter that affects the radiation sensitivity of FBGs.
- The lowest sensitivity to irradiation dose achieved by standard highly germanium doped photosensitive fiber optic, without any fabrication processing. Temperature sensitivity for FBG does not influenced by gamma irradiation dose up to 1.5 MGy.
- For high neutron flux [2], the FWHM of the gratings stay almost unaltered until to total gamma dose of approximately 160 MGy and totally fluencies 8×10^{18} neutron/cm^2.

The problems of the attenuation induced by radiation can be solved by splicing the FBG sensor, also used radiation resistant plexus to keep an acceptable SNR [3]. The main advantage of FBG is the sensing information encoded in narrowband wavelength, which makes the sensor insensitive to broadband-radiation [5]. So FBG temperature sensor could be used as a temperature sensor in the nuclear reactor.

3. Models of FBG

To model the FBG, the coupled mode theory (CMT) is used which considered as one of the best tools in understanding the optical properties of gratings [11]. The CMT is a mathematical tool to describe the wave propagation and interactions with materials in optical waveguide. The CMT sees the fiber grating structure as perturbation to an optical waveguide. For a single mode FBG, the coupled mode equations are given by [12]:

$$\frac{dA(z)}{dz} = jB(z)K\exp\left[j(\beta_1 - \beta_2)z\right] \tag{5}$$

$$\frac{dB(z)}{dz} = jA(z)K^*\exp\left[-j(\beta_1 - \beta_2)z\right] \tag{6}$$

Where A(z) and B(z) are the complex amplitudes of forward propagating and backward-propagating modes respectively. The transfer matrix method is applied to solve the coupled mode theory equations and to obtain the spectral response of fiber grating. The grating length (L) is divided for uniform sections; where each section represented by a 2x2 matrix, so a global matrix for grating is provided by multiplying all these matrices.

The section length (Δ) can given by $\Delta = L / N$ where N number of sections. Solving the coupled mode equations by applying the appropriate boundary conditions we find the transfer matrix of form Ti that describe the amplitude of the forward-propagation mode and the backward-propagation mode before and after the ith uniform sections[13]:

$$\begin{bmatrix} A_i \\ B_i \end{bmatrix} = T_i \begin{bmatrix} A_{i-1} \\ B_{i-1} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} A_{i-1} \\ B_{i-1} \end{bmatrix}$$

Where A_i and B_i are the amplitudes of the forward propagation mode and backward-propagation mode after the ith uniform sections and A_{i-1} and B_{i-1} are the amplitudes of the forward-propagation mode and backward-propagation mode before the ith uniform sections. The elements of the transfer matrix for one section are given by [14]:

$$T_{11} = T^*{}_{22} = \cosh(\gamma l_i) - i\frac{\Delta\beta}{\gamma}\sinh(\gamma l_i) \qquad (7)$$

$$T_{12} = T^*{}_{21} = -\frac{k}{\gamma}\sinh(\gamma l_i) \qquad (8)$$

Where l_i is the length of the i^{th} uniform section, the k is a coupling coefficient and for uniform FBG can given by $k = \frac{\pi\Delta n_{eff}}{\lambda}$, Δn_{eff} is a change in refractive index, β refer to propagation constant of fiber core: $\beta = \frac{2\pi n_o}{\lambda}$, $\Delta\beta$ is a wave vector detuning: $\Delta\beta = \beta - \frac{\pi}{\Lambda}$,and $\gamma = \sqrt{k^2 - \Delta\beta^2}$ is the imaginary part for which $\Delta\beta > k$.

The reflection coefficient given by: $R = \frac{T_{21}}{T_{11}}$ so the reflectivity of FBG as a function of both different grating length and wavelength [15]. With uniform index modulation and period can given by

$$R(L,\lambda) = \frac{k^2 \sinh^2(\gamma L)}{\Delta\beta^2 \sinh^2(\gamma L) + k^2 \cosh^2(\gamma L)} \qquad (9)$$

L is a total length of grating.

At the Bragg grating center wavelength λ_B, the $\Delta\beta = 0$ so the reflectivity becomes

$$R(L,\lambda) = \tanh^2(\gamma L) \qquad (10)$$

For a uniform FBG the spectral response is affected as the length of the grating is changed by external perturbation such as strain, temperature and pressure. Reflectivity was obtained and analyzed at different values of grating length, it must increase in order to achieve highly accurate reading. Figures (1-5) shows the reflectivity of the uniform FBG increased as the grating length increased but reflectivity of side lobes must take in account. Also, as shown in the figure the bandwidth of a FBG reduced as increasing in grating length.

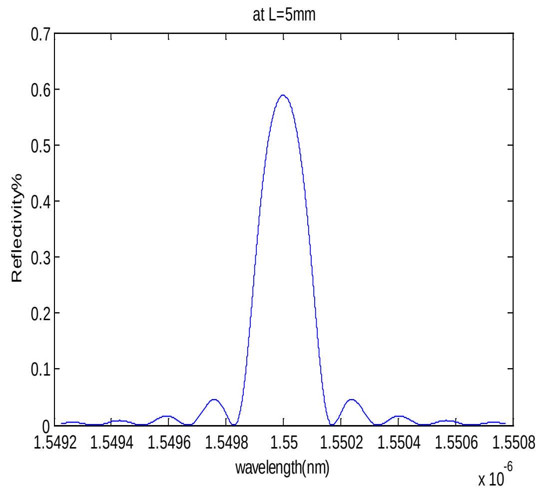

Fig. 1. The measured reflection profile at L=5mm

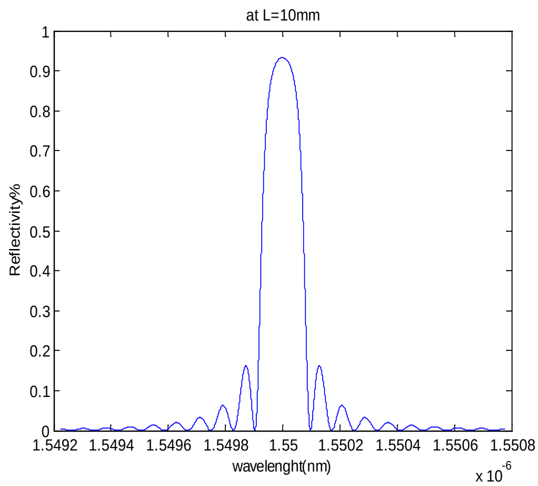

Fig. 2. The measured reflection profile at L=10mm

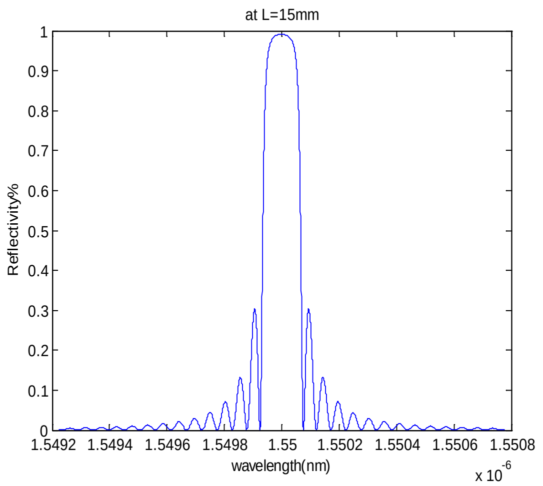

Fig. 3. The measured reflection profile at L=15mm

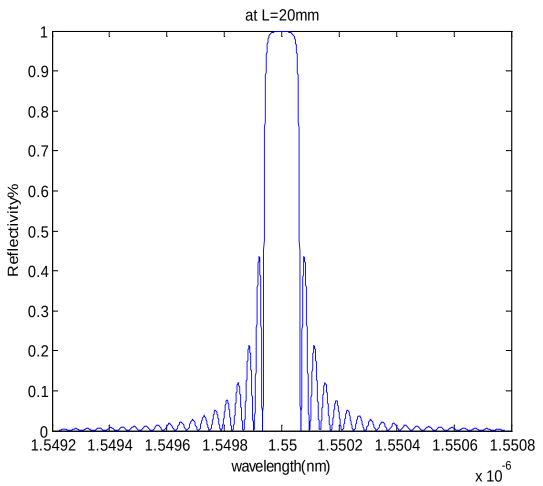

Fig. 4. The measured reflection profile at L=20mm

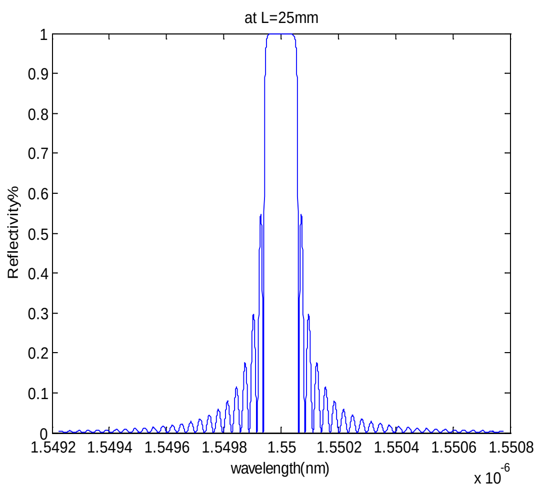

Fig. 5. The measured reflection profile at L=25mm

4. Fiber Bragg Grating Temperature Sensors

The traditional technology, the thermocouples, causes a drift of the measurement due to irradiation that needs a calibration and a response time of one second. In order to cancel the drift, to reduction the response time and to increase the precision, two alternatives can be considered: improving the same technology or developing a new one [1]. Also, using the optical fiber technology improves safety because of the temperature sensor diversification.

Fiber Bragg grating based sensor device used for measuring multi parameters such as temperature, strain, pressure and flow has been studied over the past several years [13]. The main principle for FBG sensor is that the centre of the reflected wavelength form FBG will change according to a change in temperature and strain due to stress or pressure [7-8].

Sapphire optical fiber provides a highly resistant against radiation and has a melting point up to 2000 ^{0}C [16], so this fiber ideal for using in ETRR-2 as temperature sensor for these reasons:

- Provide excellent temperature profile also at low temperatures given radiation resistant [17]. Sapphire FBG is used as a temperature sensors up to 1600 ^{0}C [18].
- FBG written in sapphire are therefore ideally suited for the ETRR-2 because the sensing information is wavelength encoded and can therefore bear high levels of radiation and attenuation.
- A very desirable attribute for sapphire FBGs easily multiplexing several gratings into one optical fiber and ease to de-multiplex the spectral information to obtain the temperature at each grating [18].

The FBG reflects a specific wavelength and transmits all others of the light, where the reflected wavelength (λ_B) depend on refractive index (n) of the material and grating period (Λ), and given by [7]

$$\lambda_B = 2n_{eff}\Lambda \qquad (11)$$

Temperature and strain induced Bragg wavelength shifted shown as [19]

$$\Delta\lambda_B = \lambda_B\left[\Delta T\left(\alpha + \frac{1}{n}\frac{dn}{dT}\right) + \varepsilon\left(1 - \frac{n^2}{2}\left[p_{12} - \nu\left(p_{12} + p_{11}\right)\right]\right)\right] \qquad (12)$$

$$\Delta\lambda_B = \lambda_B\left[\Delta T\left(\alpha + \frac{1}{n_{eff}}\frac{dn}{dT}\right)\right] \qquad (13)$$

$$K_T = \lambda_B\left(\alpha + \frac{1}{n_{eff}}\frac{dn}{dT}\right) \qquad (14)$$

Where (ΔT) temperature change, (α) temperature optic coefficient, (ε) applied strain,(ν) poisons ratio and (p_{11} and p_{12}) are the strain optic coefficients and K_T is the coefficient for temperature sensitivity. Shift in Bragg wavelength $\lambda_{B|T}$ induced by temperature changes ΔT is described by [20]

$$\Delta\lambda_{B|T} = \lambda_B(\alpha + \xi)\Delta T \qquad (15)$$

$$\alpha = \frac{1}{\Lambda}\left(\frac{\partial\Lambda}{\partial T}\right), \qquad (16)$$

$$\xi = \frac{1}{n_{eff}}\left(\frac{\partial n_{eff}}{\partial T}\right) \qquad (17)$$

Where, ΔT is the change in temperature, Λ is the grating period, α refer to thermal expansion coefficient for the fiber, and ξ is the thermo-optic coefficient which is dependent on the type and concentration of the dopants [21]. As shown in Figures (6, 7) at inlet temperature to the reactor core37.1^{0}C the Bragg wavelengths were 1.55018 µm for FBG written in silica optical fiber and 1.55038µm for a Sapphire Bragg grating respectively.

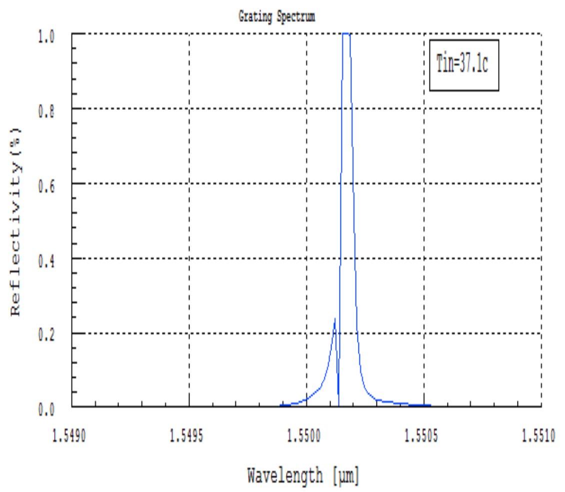

Fig.6 Shift of the Bragg wavelength for FBG written in silica optical fiber at T_{in}=37.1 ^{0}C

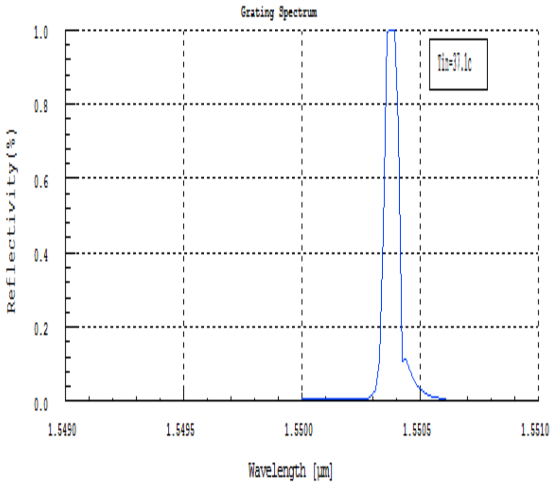

Fig.7 Shift of the Bragg wavelength for a Sapphire Bragg grating at T_{in}=37.1 ^{0}C

At different temperature for a researcher reactor as shown in Figure8, the temperature sensitivity given by slop of curve that obtained from Bragg wavelength shift over temperature. It is found that temperature sensitivity of sapphire FBG nearly0.11pm/^{0}C, where its value is three times higher than silica FBG due to high refractive index of the sapphire. So that sapphire FBG is used as a temperature sensor in nuclear reactor applications.

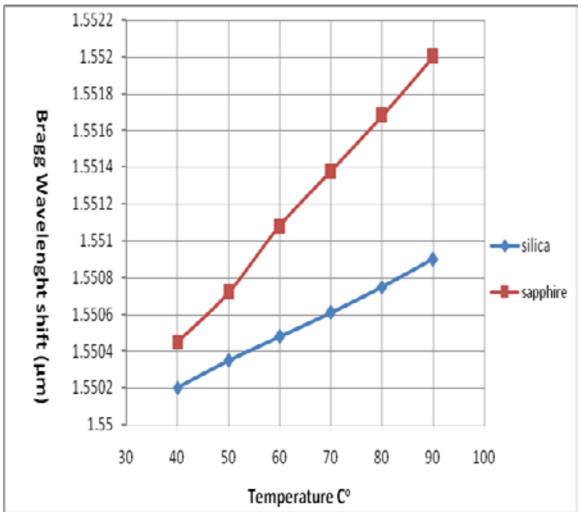

Fig. 8. Shift of the Bragg wavelength at different temperature

5. Apodized Fiber Bragg Grating signal processing

The power reflectivity of a grating with a uniform index modulation along the fiber length has harmonics on the sides of the main lobe that are unwanted and may be suppressed by the execution called Apodization [22, 23]. Apodization is a process of tapering the strength of the grating at either end .Suppression of the side lobes is important in order to eliminate crosstalk between information channels [24]. Power is also wasted because of these side lobes. Simulation results show that the strength of side lobes is completely minimized in reflectivity spectrum. The Fourier transform of a Gaussian is also a Gaussian. As shown in figure (9) the Gaussian function extends to infinity, it must either be truncated at the ends of the window, or itself windowed with another zero-ended window so Gaussian profile with high side lobe suppression is used for temperature sensing applications. From Figures (10, 11) the shift in Bragg wavelength as a result of temperature changes for the inlet and outlet temperature for both FBG written in silica optical fiber and Sapphire Bragg grating respectively, all of side lobes have been completely eliminated which provide an accurate temperature measurements that must be achieved in nuclear applications.

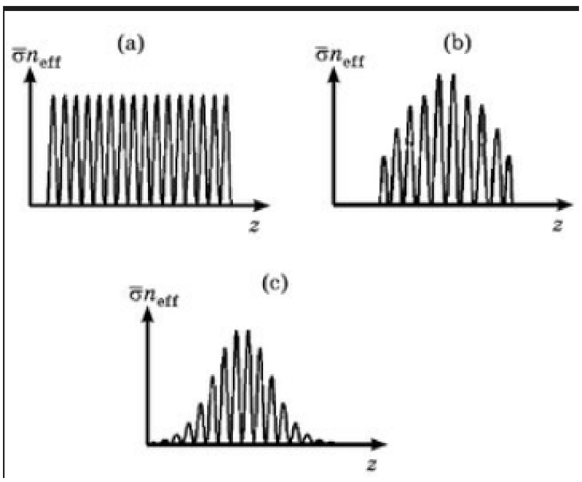

Fig.9 Refractive index modulation peak of different Apodization profile a) uniform (non apodized) index change b) tangent hyperbolic Apodization index change c) Gaussian apodized index change

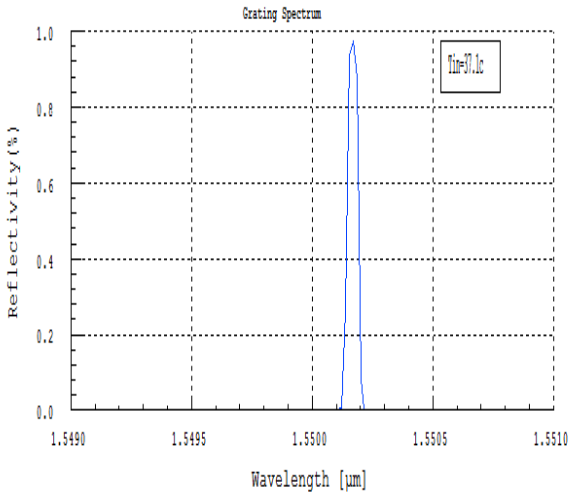

Fig.10 Apodized reflectance spectrum for FBG written in silica optical fiber at T_{in}=37.1 ^{0}C

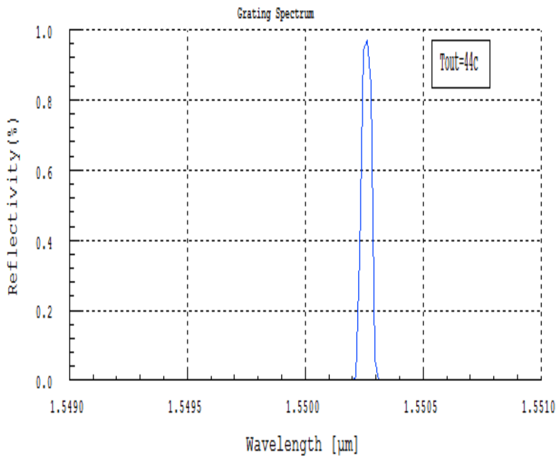

Fig.11 Apodized reflectance spectrum for FBG written in silica optical fiber at T_{out}=44 ^{0}C

6. Conclusion

In a summary, we have investigated the characterization of FBG and its signal processing for nuclear research reactor application. It is found that FBG is one attractive type for using in nuclear reactors applications. Overview of FBG sensor theory is presented and its simulation under high temperature variation. It is observed that the reflectivity of FBG increases with the increase of grating length. As well as it is indicated that a temperature increase produces a linear increase in the reflected Bragg wavelength (λ_B) of the FBG without affecting the shape of the reflection spectrum. From comparison results, it is found that temperature sensitivity of sapphire FBG nearly0.11pm/^{0}C, where its value is three times higher than silica FBG due to high refractive index of the sapphire. Also, by using Gaussian Apodization type; side lobes in reflectivity spectrum are totally suppressed.

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