Uniform Fiber Bragg Grating modeling and simulation used matrix transfer method

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Abstract

This paper presents the modeling and simulation of an optical fiber Bragg grating for maximum reflectivity, minimum side lobe. Gating length represents as one of the critical parameters in contributing to a high performance fiber Bragg grating. The reflection spectra and side lobes strength were analyzed with different lengths .The side lobes have been suppressed using raised cosine apodization while maintaining the peak reflectivity. Such simulations are based on solving coupled mode equations by transfer matrix method.

Keywords: Fiber Bragg grating, Reflection, Apodization, simulation Transfer Matrix Method.

1. Introduction

Optical fiber gratings are important components in fiber communication and fiber sensing fields. For normal fiber gratings, by properly choosing the period, length, index modulation amplitude, chirp and apodization function, one can flexibly design and optimize grating reflection or transmission spectra to satisfy many applications [1]. Although optical fibers have been used for many decades, the last 10 to 20 years have shown a lot of further development. The introduction of FBGs, photonic crystal fibers and new plastic optical fibers, to name only the most important new fields, has dramatically widened the range of possible applications.

The FBGs are used extensively in telecommunication industry for dense wavelength division multiplexing, dispersion compensation [2,3], laser stabilization, and Erbium amplifier gain flattening, simultaneous compensation of fiber dispersion , dispersion slope and optical CDMA [4,5]. By exploiting the characteristics exhibited by these gratings, numerous areas have been marked in which their usage has brought drastic advancements and continues to do the same. The FBG works on the principle that when ultraviolet light (UV) illuminates a certain kind of optical fiber, the refractive index of the fiber is changed permanently, this effect is called photosensitivity. Alternatively, the refractive index will last for several years if it is followed by proper annealing [6].

The optical fiber with germanium doped core remains the most important material for grating purposes. The first in-fiber Bragg grating was demonstrated by Ken Hill in 1978 [7].

Initially, the gratings were fabricated using a visible laser propagating along the fiber core. In 1989, Gerald Meltz and colleagues demonstrated the much more flexible Transverse Holographic Technique [6] where the laser illumination came from the side of the fiber. This technique uses the interference pattern of ultraviolet laser light to create the periodic structure of FBGs. Since this discovery, the development in the field of Bragg gratings has experienced a tremendous growth. FBGs offer ample advantages but the most important is the flexibility in spectral characteristics. Many researchers have been work done in this field also [1, 8].
There are a number of parameters on which the spectra of FBG has shown dependency such as change in refractive index, bending of fiber , grating period, mode excitation conditions, temperature and fiber Bragg grating length [9,10,11,12].

In this paper, the effect on the Reflection spectra of FBG is analyzed at the varied grating length. The paper is divided into following sections. Section 2 covers the theory and modeling (coupled mode theory and transfer matrix method) of FBGs as well as the working principle of FBGs. Section 3 deals with the results and discussion about the modeling and simulation work done on FBGs at typical specifications using MATLAB. Lastly, section 4 draws the conclusion of the work done.

2. Theory

The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the modes of waveguide. In optical fibers the core-cladding boundary conditions lead to coupling between the electric and magnetic field components.

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Each mode has its specific propagation constants. If the periodic perturbation is introduced alongside the fiber the mode will exchange its power. This phenomenon is known as mode coupling. Fiber gratings can be broadly classified into two types: Bragg gratings (also called reflection and short-period gratings), in which coupling occurs between modes traveling in opposite directions; and transmission gratings (also called longperiod gratings), in which the coupling is between modes traveling in the same direction.

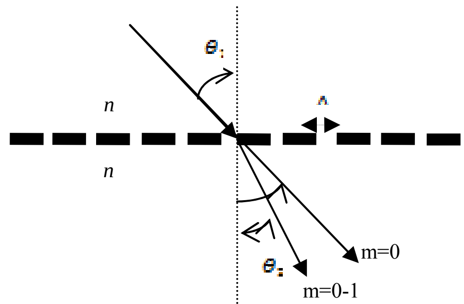

Fig. 1 the diffraction of light wave by a grating

A fiber grating is simply an optical diffraction grating, and thus its effect upon a light wave incident on the grating at an angle can be described by the familiar grating equation:

$$n\sin(\theta_2) = n\sin(\theta_1) + m\frac{\lambda}{\Lambda}. \qquad (1)$$

Where $\theta_2$the angle of the diffracted wave and the integer m is determines the diffraction order (Fig. 1). [11].

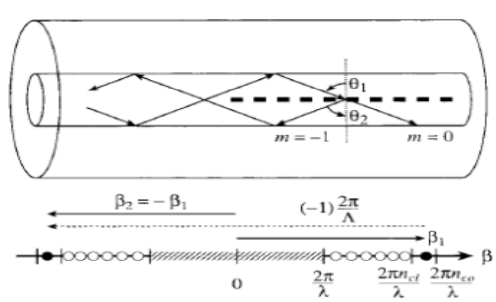

Fig. 2 Core mode Bragg reflection by a fiber Bragg grating

Fig. 2 illustrates reflection by a Bragg grating of a mode with a bounce angle of θ_1 into the same mode traveling in the opposite direction with a bounce angle of θ_2 =-θ_1. β is the z component of wave propagation constant k is the main parameter in describing fiber modes, is simply:

$$\beta = \frac{2\pi}{\lambda} n_{eff} \text{, where } \quad n_{eff} = n_{co}\sin\theta \qquad (2)$$

The mode remains guided as long as β satisfies the condition $n_2k < \beta < n_1k$

Where n_1 and n_2 are core and cladding refractive index and:

$$k = \frac{2\pi}{\lambda} \qquad (3)$$

2.1 Coupled mode theory

Coupled Mode Theory is a method to analyze the light propagation in perturbed or weakly coupled waveguides.
The basic idea of the *Coupled Mode Theory method* is that the modes of the unperturbed or uncoupled structures are defined and solved first. Then, a linear combination of these modes is used as a trial solution to Maxwell's equations for complicated perturbed or coupled structures. After that, the derived coupled mode equations can be solved analytically or by numerical methods.
The coupled-mode equations describe their complex amplitudes, *A(z)* and *B(z):*

$$\frac{dA(z)}{dz} = jB(z)K\, exp[j(\beta_1 - \beta_2)z]$$
$$\frac{dB(z)}{dz} = jA(z)K^*\, exp[-j(\beta_1 - \beta_2)z] \qquad (4)$$

In our simulation, the coupled mode equations are based on non-orthogonal coupled mode theory [13, 14]. Both the waveguide nature coupling and grating coupling are considered. In order to formulate the coupled mode equations, waveguide modal constants, fields, and coupling coefficients are calculated based on waveguide and grating profiles.
In our work the well-known transfer matrix method is applied to solve the couple mode equations and to obtain the spectral response of the fiber grating. In this approach, the grating is divided into uniform sections; each section is represented by a 2*x*2 matrix. By multiplying these matrices, a global matrix that describes the whole grating is obtained.

2.2 Transfer matrix

Divide the grating into a sufficient number N of sections so that each section can be approximately treated as uniform. Let the section length be $\Delta = \mathrm{L/N}$ .By applying the appropriate boundary conditions and solving the coupled-mode equations similar to the procedure in Section (2.1), we find the following transfer matrix relation between the fields at z and at z + Δ.

$$\begin{bmatrix} u(z+\Delta) \\ v(z+\Delta) \end{bmatrix} = \begin{bmatrix} \cosh(\gamma\Delta) - i\frac{\Delta\beta}{\gamma}\sinh(\gamma\Delta) & -\frac{\kappa}{\gamma}\sinh(\gamma\Delta) \\ i\frac{\kappa}{\gamma}\sinh(\gamma\Delta) & \cosh(\gamma\Delta) + i\frac{\Delta\beta}{\gamma}\sinh(\gamma\Delta) \end{bmatrix} \begin{bmatrix} u(z) \\ v(z) \end{bmatrix} \quad (5)$$

We can connect the fields at the two ends of the grating through

$$\begin{bmatrix} u(L) \\ v(L) \end{bmatrix} = T \begin{bmatrix} u(0) \\ v(0) \end{bmatrix} \quad (6)$$

Where

$$T = T_N * T_{N-1} * \dots . T_i \dots . T_1 \quad (7)$$

The matrix T_j is the transfer matrix written in (5) with κ the coupling coefficient of the jth section. As a result, T is a 2 × 2 matrix with elements

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \quad (8)$$

The matrix T_i for one section is defined by

$$T_i = \begin{bmatrix} \cosh(\gamma l_i) - i\frac{\Delta\beta}{\gamma}\sinh(\gamma l_i) & -\frac{\kappa}{\gamma}\sinh(\gamma l_i) \\ i\frac{\kappa}{\gamma}\sinh(\gamma l_i) & \cosh(\gamma l_i) + i\frac{\Delta\beta}{\gamma}\sinh(\gamma l_i) \end{bmatrix} \quad (9)$$

The reflection coefficient is calculated by the relation:

$$R = \frac{T_{21}}{T_{11}} \quad (10)$$

The characteristics response from Bragg Grating can be analyzed fully described by

1. The center wavelength of Grating λ_B
2. Peak reflectivity R_{max} of grating which occur at λ_B
3. Physical length of Grating L.

For a grating with uniform index modulation and period the reflectivity is given by

$$R(L,\lambda) = \frac{\kappa^2 sinh^2(\gamma L)}{\Delta\beta^2 sinh^2(\gamma L) + \kappa^2 cosh^2(\gamma L)} \quad (11)$$

R: Grating reflectivity as a function of both grating length and wavelength.
L: total length of grating.
The coupling coefficient κ (z) is defined by the following equation

$$\kappa(z) = \frac{\pi}{\lambda} . \Delta n . g(z) . v \quad (12)$$

If the FBG is uniform, then Δn_{eff} is constant, g (z) =1,v the fringe visibility and is usually estimated at 1.

$$\kappa = \frac{\pi \Delta n_{eff}}{\lambda}.$$

$\Delta\beta$: wave vector detuning, given by $\Delta\beta = \beta - \frac{\pi}{\Lambda}$
β: Fiber core propagation constant, given by $\beta = \frac{2\pi n_0}{\lambda}$

$$\gamma = \sqrt{\kappa^2 - \Delta\beta^2}.$$

For light at the Bragg grating center wavelength,λ_B, there is no wave vector detuning and so $\Delta\beta = 0$. The reflectivity function then becomes

$$\mathrm{R}(\mathrm{L},\lambda) = tanh^2(\gamma L) \quad (13)$$

3. RESULTS AND DISCUSSION

The parameters used for Simulation are core index = 1.47, cladding index = 1.457, λ =1550 nm, change in refractive index, $\Delta n_{eff} = 1e^{-4}$, grating period, Λ= 5.3e-7. The grating length has been varied from L =05 mm to 40mm.

For different values of grating length (table 1), Reflection spectra was obtained and analyzed. From the spectra, it was confirmed that the spectral properties of uniform gratings comes out to be similar to *sinc* function. The reflection spectra for different grating length 5 mm, 07 mm, 10 mm, 15 mm and 25 mm is shown below in (fig. 3,4,5,6,7).At L=05mm, 07mm, 10mm, and 15 mm successively the maximum reflectivity is 59.86%**,** 79.04%**,** 93.28%**,** 99.09% and 99.98%.At L=25 mm, the reflectivity reaches 99.98% but increase in the reflectivity of sides lobes .After that, if the length is incremented further, it is observed that maximum reflectivity maintains the same value of 99.99%.

Table 1: Reflectivity for different grating lengths

Grating Length (mm)	Reflectivity obtained (%)
05	59.86
07	79.04
10	93.28
15	99.09
16	99.39
18	99.73
20	99.90
22	99.95
25	**99.98**
28	99.99
30	99.99
35	99.99
40	99.99

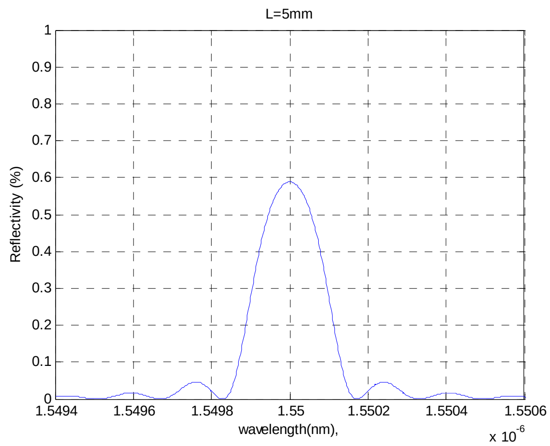

Fig. 3 Reflection spectrum at L = 05mm

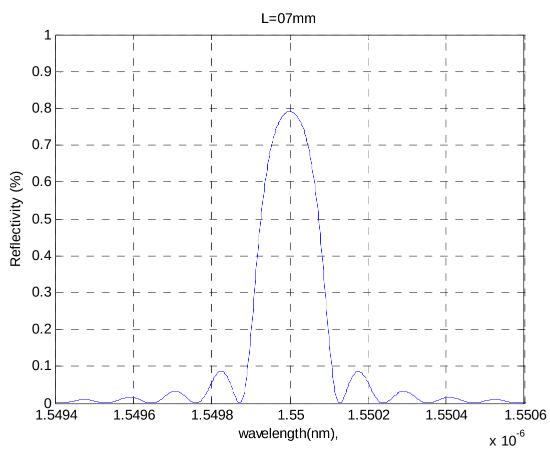

Fig. 4 Reflection spectrum at L = 07mm

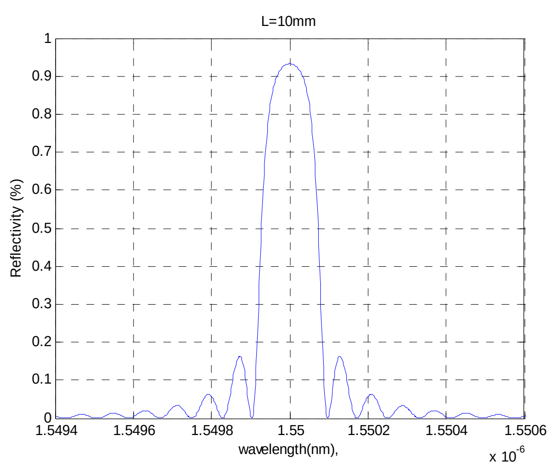

Fig. 5 Reflection spectrum at L = 10mm

The reflectivity reaches 99.99% but it is accompanied with a significant increase in the reflectivity of side lobes.

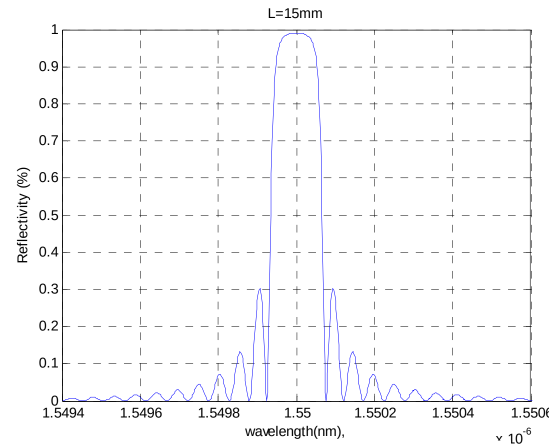

Fig. 6 Reflection spectrum at L = 15mm

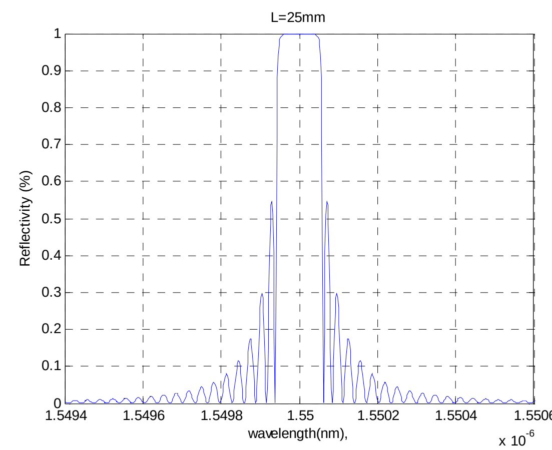

Fig. 7 Reflection spectrum at L = 25mm

As shown in Fig. 8 from the above results, upon consideration of the reflectivity of the uniform FBG, it was confirmed that the simulated uniform FBG showed better performance as the grating length increased and achieved 99.98 % reflection at the grating length of 25 mm.

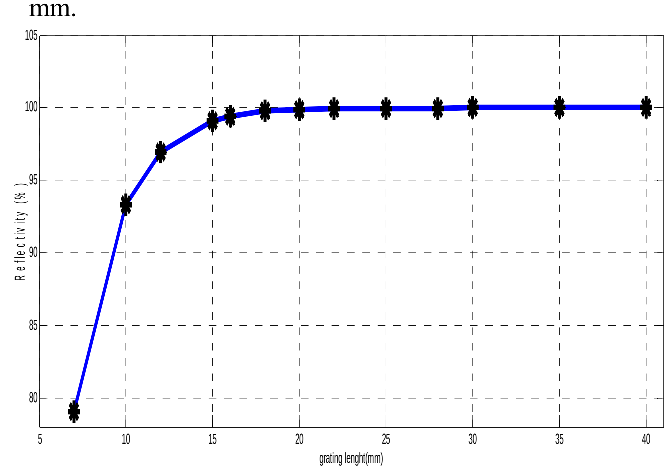

Fig. 8 relation between uniform FBG reflectivity and grating length

A uniform FBG is accompanied by a series of side-lobes adjacent to the Bragg wavelength. A very effective method for eliminating the side-lobes of an FBG is apodization.

Apodization is achieved by a contoured inscription of the grating in order to reduce the refractive index change towards the ends of the grating.

The transfer matrix method can be adjusted to accommodate for the apodization of an FBG by replacing $g(z)$ in equation (12) with for example, the following raised cosine apodization.

$$g(z) = \Delta n_{eff}.\frac{1}{2}.\left\{1+\cos\left(\frac{z\pi}{L}\right)\right\}. \tag{14}$$

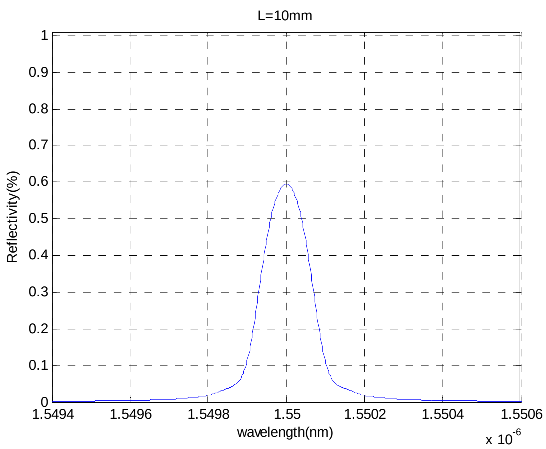

Fig. 9 Apodized reflectance spectrum at L = 10mm

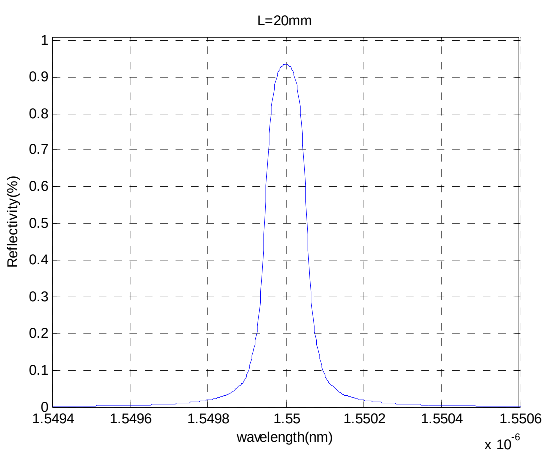

Fig. 10 Apodized reflectance spectrum at L = 20mm

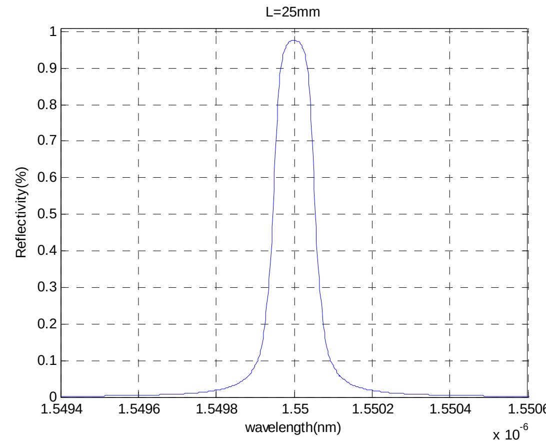

Fig. 11 Apodized reflectance spectrum at L = 25mm

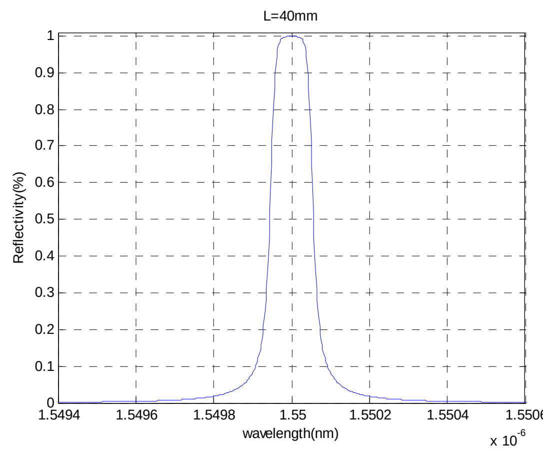

Fig. 12 Apodized reflectance spectrum at L = 40mm

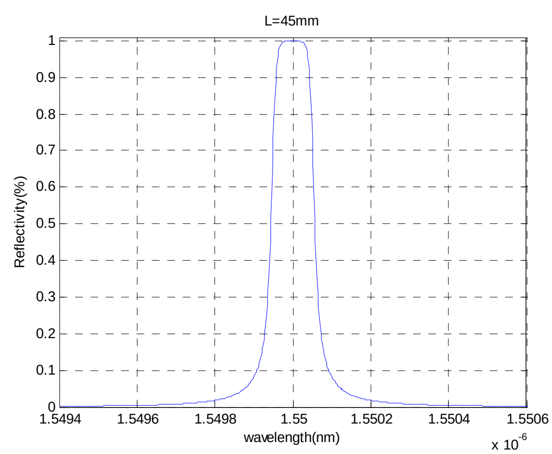

Fig. 13 Apodized reflectance spectrum at L = 45mm

Other apodization functions that are used in the communications industry include pure cosine, Gaussian, sinc and Kaiser profils [11, 15].

Fig. 9, 10,11,12,13 illustrates the reflectance spectrum response of an apodized FBG for different grating length. At L=10mm,20mm,25mm,40mm and 45mm the maximum reflectivity is is 59.47%**,** 93.55%**,** 97.62%**,** 99.88% and 99.99%.Note that all of side lobes have been completely eliminated But reflected power can be increased by increasing the length of apodized FBG.

Table 2: Reflectivity of Apodized FBG for different grating lengths

Grating Length (mm)	Reflectivity obtained (%)
10	59.47
15	82.94
20	93.55
25	97.62
28	98.70
30	99.14
35	99.69
40	99.88
42	99.92
45	**99.99**
50	99.99
55	99.99
60	99.99

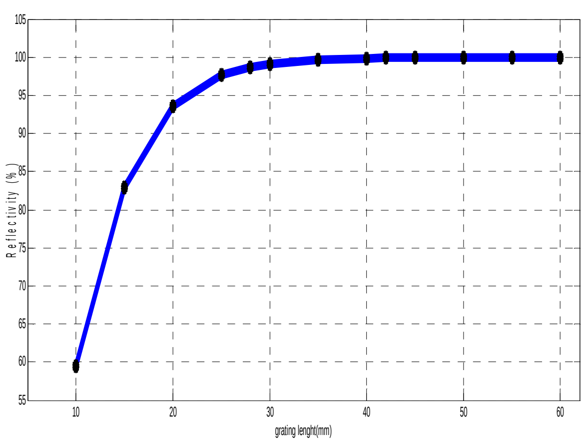

Fig. 14 relation between Apodized F BG reflectivity and grating length

The reflectivity showed an exponential increase over the elevation of grating lengths, as shown in Fig. 14. From the above results, upon consideration of the reflectivity elevation of apodized FBG, it was confirmed that the simulated apodized FBG showed better performance as the grating length increased and achieved 99.99 % reflection at the grating length of 45 mm.

Based on the results obtained for uniform FBG, the variation in the reflectivity, the side lobe suppression and apodized FBG, optical fiber Bragg grating for maximum reflectivity, minimum side lobe is tabulated below:

	Length FBG	reflectivity	Sides lobe
Unifom FBG	10 mm	99,99%	Between 10% and 50%
Apodized FBG	45 mm	99;99%	0%

4. Conclusion

In this work, we have described the signal characteristics of FBG with various grating lengths using simulation method. We conducted quantitative analyses on the reflectivity with the increases of grating length. The conclusions obtained from this study are as follows.
1. The reflectivity of fiber grating increases with the increase in grating length.
2. The reflectivity increased with the elevation of grating length in which it achieves 99,99% in reflection at grating length 10 mm and maintained this value for longer length.
3.We got full Suppression of side lobes in reflectivity curve for Raised cosine Apodization at the cost of reduced reflected power. But reflected power can be increased by increasing the length of apodized FBG.The reflectivity increased with the elevation of grating length in which it achieves 99,99% in reflection at grating length 45 mm and maintained this value for longer length.

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