Fiber Bragg Grating Modeling, Characterization and Optimization with different index profiles

SUNITA UGALE
Electronics Engineering Department
S. V. National Institute of Technology, Ichchhanath, Surat, Gujarat, India
Email: spu.eltx@gmail.com

Dr. V. MISHRA
Senior Member IEEE
Electronics Engineering Department
S. V. National Institute of Technology, Ichchhanath, Surat, Gujarat, India
Email: vive@eced.svnit.ac.in

Abstract:
This paper presents the modeling and characterization of an optical fiber grating for maximum reflectivity, minimum side lobe power wastage. Grating length and refractive index profile are the critical parameters in contributing to performance of fiber Bragg grating. The reflection spectra and side lobes strength were analyzed with different lengths and different refractive index profiles. Apodization techniques are used to get optimized reflection spectra. The simulations are based on solving coupled mode equations by transfer matrix method that describes the interaction of guided modes.

Keywords: *Fiber Bragg Grating, Coupled mode theory, simulation, reflectivity, Apodization.*

1. Introduction

Fiber Bragg gratings are spectral filters based on the principle of Bragg reflection. They typically reflect light over a narrow wavelength range and transmit all other wavelengths. When light propagates by periodically alternating regions of higher and lower refractive index, it is partially reflected at each interface between those regions. If the pitch of the grating is properly designed, then all partial reflections add up in phase and can grow to nearly 100%, for a specific wavelength even if the individual reflections are very small. The condition for high reflection is known as Bragg condition. For all other wavelengths the out of phase reflections end up cancelling each other, resulting in high transmission [1, 2].

FBG Sensors are based on the fact that Bragg wavelength changes with change in pitch of the grating and the change in refractive index. Thus, any physical parameter which cause change in above mentioned parameters can be sensed using FBG, by measuring the shift in Bragg wavelength. FBG is the key component for dispersion compensation and WDM. [4, 5, 7].

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 [3, 6]. In optical fibers the core-cladding boundary conditions lead to coupling between the electric and magnetic field components.

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 long-period gratings), in which the coupling is between modes traveling in the same direction.

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:

$$n\sin\theta_2 = n\sin\theta_1 + m\,(\lambda/\Lambda)$$

Where θ_2 is the angle of the diffracted wave and the integer m determines the diffraction order (see Fig. 1). [8].

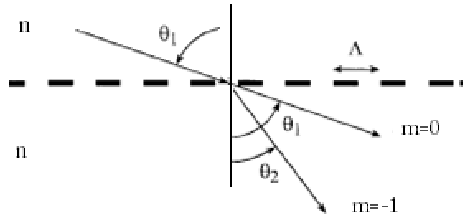

Fig. 1. The diffraction of light wave by a grating

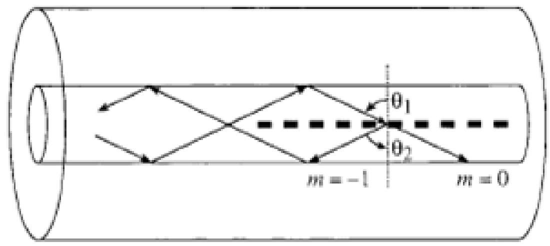

Fig. 2. Core mode Bragg reflection by a fiber Bragg grating.

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

$$\beta=(2\pi/\lambda)n_{eff}$$

Where, $n_{eff} = n_{co}\sin\theta$

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 $k=2\pi/\lambda$

The boundary between truly guided modes and leaky modes is defined by the cutoff condition $\beta=n_2k$. As soon as β becomes smaller than n_2k, power leaks out of the core into the cladding region [10, 11].

3. Modeling

Refer Figure 3, the fiber contains a Bragg grating, of length L and uniform pitch length Λ. The electric fields of the propagating waves can then be expressed as

$$E_a(z, t)= A(z)\, e^{i(\omega t-\beta z)} \quad (1)$$

$$E_b(z, t)= B(z)\, e^{i(\omega t+\beta z)} \quad (2)$$

For the backward and forward propagating waves, respectively

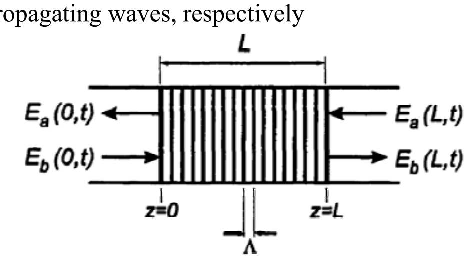

Fig. 3. Propagating waves in Bragg grating

The coupled-mode equations describe their complex amplitudes, *A(z)* and *B(z)*

$$\frac{dA(Z)}{dz} = i\kappa B(z)e^{-2i(\Delta\beta)z}$$

$$0 \le z \le L$$

$$\frac{dB(Z)}{dz} = -i\kappa^* A(z)e^{+2i(\Delta\beta)z} \quad (3)$$

If we assume that both forward and backward waves enter the grating, then assume the boundary conditions *B(0) = Bo* and *A(L) = AL.* Substituting these boundary conditions into equation 3, we can solve for the closed-form solutions and thus the z-dependence of the two waves.

$$a(z)=A(z)e^{-i\beta z}$$

$$b(z)=B(z)e^{i\beta z} \quad (4)$$

The reflected wave, *a(0)*, and the transmitted wave, b(L) can be expressed by means of the scattering matrix

$$\begin{bmatrix} a(0) \\ b(L) \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a(L) \\ b(0) \end{bmatrix} \quad (5)$$

Substituting *a(L)*and b(0) from equation 4 into equation 5 we get

$$S_{11} = S_{22} = \frac{iSe^{-i\beta 0L}}{-\Delta\beta sinh(SL) + iScosh(SL)}$$

$$S_{12} = \frac{\kappa}{\kappa *} S_{21} e^{2i\beta 0L} = \frac{\kappa sinh(SL)}{-\Delta\beta sinh(SL) + iScosh(SL)} \quad (6)$$

Based on equations 5 and 6, the scattering matrix, we can obtain the transfer-matrix, or

T-matrix equation

$$\begin{bmatrix} a(0) \\ b(0) \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} a(L) \\ b(L) \end{bmatrix} \quad (7)$$

Where

$$T_{11} = T^{*}{}_{22} = \frac{\Delta\beta sinh(SL) + iScosh(SL)}{iS} e^{-i\beta 0L}$$

$$T_{12} = T^{*}{}_{21} = \frac{\kappa sinh(SL)}{iS} e^{-i\beta 0L} \quad (8)$$

This matrix approach is effective at treating a single grating as a series of separate gratings each having reduced overall lengths and different pitch lengths, and describing each with its own T-matrix. Combining all the matrices yields the properties of the initial non-uniform grating. The resultant system of matrices is treated as an individual matrix

$$[T_L] = [T_1][T_2] \dots [T_M] \quad (9)$$

Light passing through successive optical elements can be calculated by series of matrices, as such

$$\begin{bmatrix} a(0) \\ b(0) \end{bmatrix} = [T_M][T_{M-1}] \dots\dots [T_1] \begin{bmatrix} a(L) \\ b(L) \end{bmatrix} \quad (10)$$

The characteristics response from Bragg Grating can be 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
4. Refractive index of core of optical fiber n_{co}
5. Amplitude of induced core index perturbation Δn

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

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

Where

R: Grating reflectivity as a function of both grating length and wavelength

L: total length of grating

κ: coupling constant, given by $\kappa=\pi\Delta n/\lambda$

$\Delta\beta$: wave vector detuning, given by $\Delta\beta=\beta-(\pi/\Lambda)$

β: fiber core propagation constant, given by $\beta=2\pi n_0/\lambda$

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

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

$$R(L,\lambda)=\tanh^2(SL)$$

4. Results and analysis

The parameters chosen for simulation [1, 9]:

Profile type: Step index, single mode

Grating type: Volume index
Modulation depth: 0.0012
Cladding index: 1.45
Waveguide width and height: 5.25µm
Period: 0.5 µm,
Free space wavelength: 1.55 µm

The reflectivity of Uniform FBG changes with different grating lengths as shown in table 1 The reflectivity increases with increase in grating length as well as index difference. Almost after a length of 2.5mm, 100% reflectivity is achieved. Strength of side lobes in reflectivity curve of Uniform FBG increases with increase of grating length and index difference as indicated in table 2.

The power wasted in side lobes can be minimized by applying different index profiles, called as Apodization.

Doping concentration variation limits the index variation to maximum value Δn_o. Index inside core after FBG has been printed can be expressed by

$$n(z) = n_{co} + \Delta n_{0.} A(z).n_d(z) \qquad (11)$$

where n_{co}- core refractive index,
$n_d(z)$-index variation function
Δn_0- maximum index variation
A(z)-Apodization function

For uniform FBG with no apodization index variation function $n_d(z)$ is given as

$$n_d(z) = sin\frac{2\pi z}{\Lambda}$$

Where Λ: constant grating period, A=1

Table 1. Dependence of reflectivity on grating length and index difference

FBG	Δn_0:0.01 Λ=0.5319	Δn_0:0.008 Λ=0.5325	Δn_0: 0.005 Λ=0.5334	Δn_0: 0.003 Λ=0.5339
L mm	R	R	R	R
0.5	62.52%	60.24%	53.76%	42.58%
1	94.65%	93.76%	90.80%	83.59%
1.5	99.4%	99.11%	98.51%	96.43%
2	100%	100%	99.7%	99.1%
2.5	100%	100%	100%	100%
5	100%	100%	100%	100%
10	100%	100%	100%	100%
20	100%	100%	100%	100%

R: Reflectivity, Δn_0: index difference, L: Length

Table 2. Dependence of side lobe strength on grating length and index difference

FBG	Δn: 0.01	Δn_0: 0.008	Δn_0: 0.005	Δn_0: 0.003
L mm	Side lobe strength	Side lobe strength	Side lobe strength	Side lobe strength
0.5	5.14	0.048	0.039	0.027
1	17.8	0.168	0.1420	0.102
1.5	32.74	0.312	0.2708	0.205
2	46.34	0.447	0.398	0.314
2.5	61.2	0.558	0.508	0.416
5	86.3	0.823	0.804	0.740
10	100	1	1	0.909
20	100	1	1	1

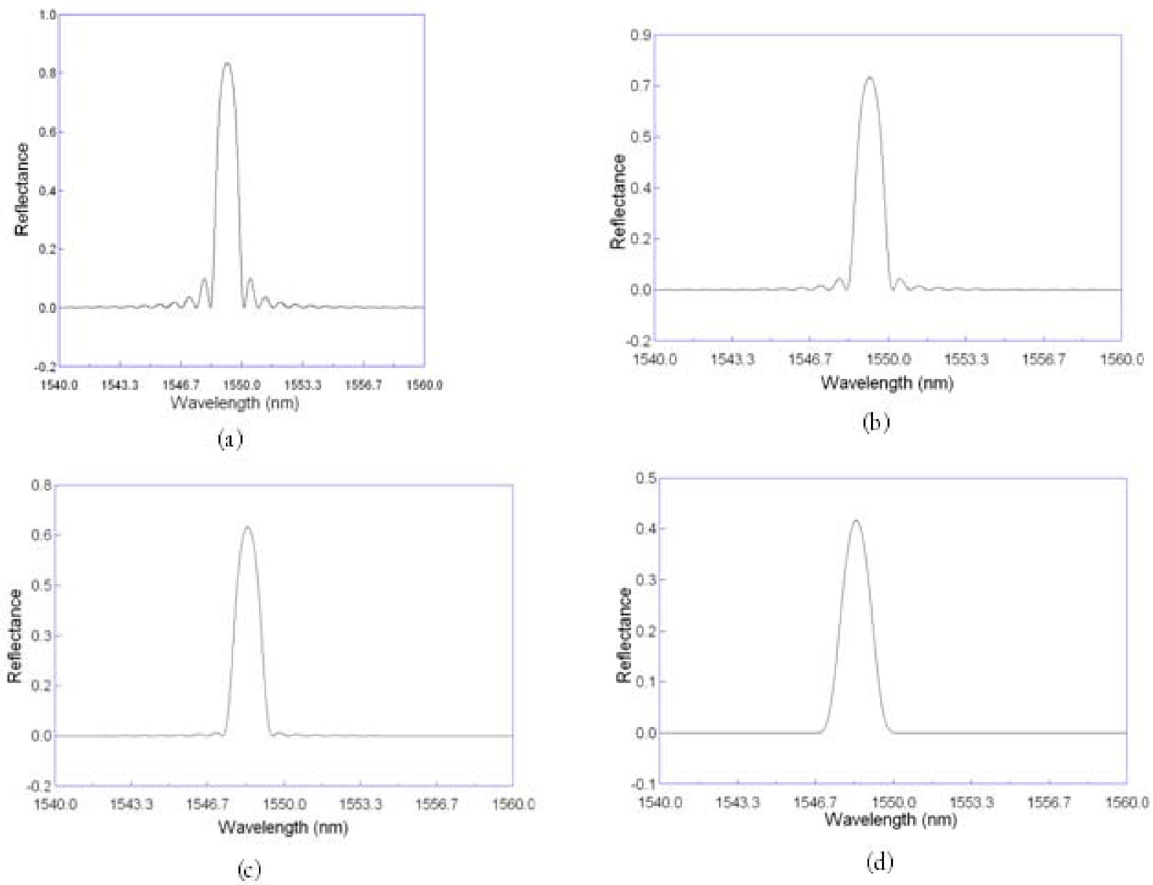

Fig. 4. Reflectance curve for uniform FBG with (a) no apodization, (b) sync apodization, (c) Gaussian Apodization, (d) Raised Cosine Apodization

Apodization function A(z) in equation (11) can be changed to reduce the side lobes as shown in figure (4, 5, 6 & 7).

For sinc Apodization $A(z) = sinc\left(\frac{z-L/2}{\Lambda_T}\right)$

Where Λ_T=sync function parameter

For Gaussian Apodization

$$A(z) = exp\left(-4\left(\frac{z-L/2}{L}\right)^2\right)$$

For Raised cosine Apodization

$$A(z) = \alpha\left(1 + cos\left[\frac{\pi(z-L/2)}{L}\right]\right)$$

Where α is raised-cosine parameter

5. Conclusion

We have studied the different characteristics of FBG with various grating lengths. The quantitative analysis on maximum reflectivity and side lobe strength reduction is done and following conclusions are obtained. The reflectivity increases with increase in grating length as well as index difference. Almost after a length of 2.5mm, 100% reflectivity is achieved. Strength of side lobes in reflectivity curve of Uniform FBG increases with increase of grating length and index difference which can be reduced by applying apodization.

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 FBG.

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