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Optimization of Uniform Fiber Bragg Grating Reflection Spectra for Maximum Reflectivity and Narrow Bandwidth

Nagwan I. Tawfik[1], Walid S. Eldeeb[2], M. B. El_Mashade[3], A. E. Abdelnaiem[2]
[1] Department of Electrical engineering and computer, Higher Technological Institute, 10th of Ramadan city, Egypt.
[2] Department of Electronics and Communications, Faculty of engineering, Zagazig University, Egypt.
[3] Department of Electrical Engineering, Faculty of engineering, Al Azhar University, Egypt.

ABSTRACT
Fiber Bragg grating has made a big revolution in telecommunication systems. The existence of fiber Bragg grating is needed when an optical fiber amplifier and filter are used. They can be used as band reject filter or band pass filter for optical devices. The design parameters of the fiber Bragg grating affect the output characteristics of it. The purpose of this paper is to simulate and analyze the spectral characteristics of the uniform fiber Bragg grating (FBG) for achieving maximum reflectivity and narrow bandwidth. This can be achieved by studying the effect of the structural parameters of the uniform fiber Bragg grating such as; grating length and refractive index modulation on the reflectivity and spectral bandwidth of the FBG. The simulations are based on the numerical solution of the coupled- mode equations. The effect of changing the refractive index shape is also considered in this analysis. The simulation results show that the reflectivity of FBG will increase when the grating length and the refractive index modulation increase. Besides, the spectral bandwidth will decrease by the increase of grating length. It will also increase when the refractive index modulation increase. This study deduces that the change of the refractive index shape doesn't have any effect on the spectral response of the uniform FBG.

Keywords- *Couple mode theory, Coupling coefficient, Fiber Bragg grating, Photosensitivity, Reflectivity, Refractive index modulation, Spectral bandwidth.*

I. INTRODUCTION

Fiber Bragg grating is a periodic perturbation of the refractive index along the core of the optical fiber. It has an important role in optical communication system especially when designing optical amplifiers and filters. The modulation of the refractive index can be achieved by exposing the core of the fiber to ultra-violet radiation. This produces change in the refractive index of the core. Photosensitivity is an important characteristic in optical fiber. It was discovered at the Canadian Communication Center in 1978 by Ken Hill et al [1]. It allows the fabrication of FBG in the fiber core. Photosensitivity means the ability to change the refractive index of the core when it is irradiated by a UV light [1]. There are more factors affecting the photosensitivity of the optical fiber such as; irradiation source, fiber core composition and the past history of fiber before the irradiation. The photosensitivity of fiber can be enhanced by hydrogen loading. The first fiber grating was called (self-induced grating). It works only at the writing wavelength which is the ultraviolet wavelength. The refractive index of the core is changed permanently. Germanium doped silica fibers are used in the fabrication of FBG because it is photosensitive which means that the refractive index of the core is changed by the exposure of light. The amount of change depends on the intensity and duration of the exposure. It also depends on the photosensitivity of fiber so that for high reflectivity the level of doping with germanium must be high. There are several techniques for the fabrication of FBG such as; phase mask technique, Holographic technique and point by point technique [2]. Easy fabrication is obtained by phase mask technique. FBG has many applications in optical communication systems such as; dispersion compensation, wavelength converters, fiber grating lasers and amplifiers, laser stabilization, wavelength division multiplexing, selective mirrors and optical Code Division Multiple Access(CDMA) [3]. FBGs have many advantages such as; low losses, done into the fiber, stability, reduced maintenance, flexibility in spectral characteristics, simple structure and low insertion loss [4]. The most attractive subject in studying fiber Bragg grating is the spectral characteristics of FBG. There are several design parameters which affect the spectral response of FBG such as: grating length, refractive index modulation and grating period [5, 6]. By choosing proper values for these parameters one can achieve maximum reflectivity and narrow bandwidth for better performance of the FBG. This paper aims to design the FBG for better performance and maximum reflectivity. Also it studies the effect of grating length and refractive index modulation on the reflectivity and spectral bandwidth of uniform FBG.

The paper is organized as follows: section I provides an introduction to the fiber Bragg grating including fabrication techniques and its applications. In section II the paper presents a study of the basic structure of fiber Bragg grating and couple mode theory which is used for the analysis of uniform FBG. The discussion and the simulation results are presented in section III with illustrated graphs for each case.

II. UNIFORM FIBER BRAGG GRATING

A. FIBER BRAGG GRATING STRUCTURE

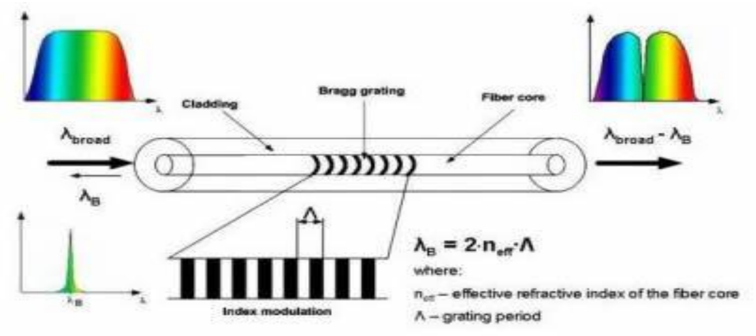

Fig 1. Basic structure of fiber Bragg grating

The basic structure of the uniform fiber Bragg grating is illustrated in Fig 1. [7]. as shown in Fig 1, the refractive index of the core is modulated by a period of Λ. When light is transmitted through the fiber which contains a segment of FBG, part of the light will be reflected. The reflected light has a wavelength equals to the Bragg wavelength so that it is reflected back to the input while others are transmitted. The term uniform means that the grating period, Λ, and the refractive index modulation, δn, are constant over the length of the grating. A grating is a device that periodically modifies the phase or the intensity of a wave reflected on, or transmitted through it [5]. The equation relating the grating spatial periodicity and the Bragg resonance wavelength is given by:$\lambda B = 2n_{eff}\,\Lambda$ where $n_{eff}$is the effective mode index and Λ is the grating period [6]. Fig. 2 shows the different types of Bragg gratings which are (a) transmission (long-period) grating (Fig. 2-A) and reflection (short-period) grating (Fig. 2-B). In reflection grating; coupling occurs between modes travelling in opposite direction, while in transmission grating; coupling occurs between modes travelling in the same direction [8].

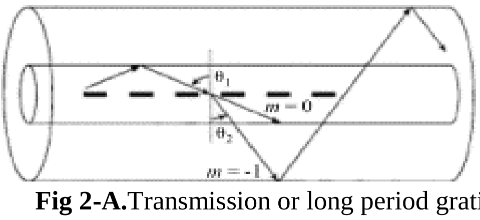

Fig 2-A. Transmission or long period grating

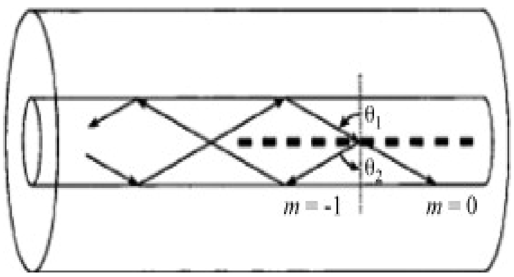

Fig 2-B. Reflection or short period grating

B. THEORY AND PRINCIPLE OF OPERATION

Studying the spectral characteristics of the uniform fiber Bragg grating is accomplished by the solution of coupled-mode equations. Coupled-mode theory is an important tool for understanding the design of fiber Bragg grating [7]. FBG can be considered as a weak waveguide structure so that the couple-mode theory can be used for the analysis of light propagation in weak waveguide structure such as FBG. The couple-mode equations that describe light propagation in FBG can be obtained using couple-mode theory. The couple mode theory was initially introduced in the early 1950's for microwave devices and later applied to optical devices in the early1970's [5]. It is the most straightforward technique as it accurately models the optical properties of the most fiber gratings [9]. Assume that the transverse component of the electric field can be written as a superposition of the ideal modes labeled j (i.e. the modes in an ideal waveguide with no grating perturbation), such that:

$$\vec{E}_t(x,y,z,t) = \sum_j [A_j(z)\exp\left(j\beta_j z\right) + C_j(z)\exp(-j\beta_j z)].\vec{e}_{jt}(x,y)\exp(-i\omega t). \quad (1.1)$$

Where $A_j(z)$ and $C_j(z)$ are slowly varying amplitude of the jth mode travelling in the +z and –z directions, respectively. The transverse mode fields $\vec{e}_{jt}(x,y)$ might describe the bound core or radiation LP modes, or they might describe cladding modes.

$$\beta_j = \frac{2\pi}{\lambda} n_{eff} \quad (1.2)$$

Where β_j is the mode propagation constant. While the modes are orthogonal in an ideal waveguide and hence, don't exchange energy, the presence of a dielectric perturbation cause the modes to be coupled such that the amplitudes A_j and C_j of the jth mode evolve along the z axis according to:

$$\frac{dA_j}{dz} = i\sum_k A_k(K_{kj} + K_{kj}^{*})\exp\left[\left(i\left(\beta_k - \beta_j\right)z\right] + i\sum_k C_k\left(K_{kj} - K_{kj}^{*}\right)\exp\left[-i\left(\beta_k + \beta_j\right)z\right] \quad (2.1)$$

$$\frac{dC_j}{dz} = -i\sum_k A_k(K_{kj} - K_{kj}^{*})\exp\left[\left(i\left(\beta_k + \beta_j\right)z\right] - i\sum_k C_k\left(K_{kj} + K_{kj}^{*}\right)\exp\left[-i\left(\beta_k - \beta_j\right)z\right] \quad (2.2)$$

Where$K_{kj}(z)$is the transverse coupling coefficient between modes j and k and is given by:

$$K_{kj}(z) = \frac{\pi}{4}\iint_{-\infty}^{\infty} dxdy\,\Delta\varepsilon(x,y,z)\vec{e}_{kt}(x,y).\vec{e}_{jt}^{*}(x,y) \quad (3)$$

where$\Delta\varepsilon$is the perturbation to the permittivity, approximately $\Delta\varepsilon \cong 2n\delta n$when $\delta n \ll n$. The longitudinal coefficient $K_{kj}^{*}(z)$ is analogous to $K_{kj}(z)$ but generally $K_{kj}^{*}(z) \ll K_{kj}(z)$ for the fiber modes, so this coefficient is usually neglected. The two new coefficients are:

$$\sigma_{kj}(z) = \frac{\omega n_{co}}{2}\delta n_{dc}(z)\iint_{core} dxdy\,\vec{e}_{kt}(x,y).\vec{e}_{jt}^{*}(x,y) \quad (4)$$

$$k_{kj}(z) = \frac{\omega n_{co}}{4}\delta n_{ac}(z)\iint_{core} dxdy\,\vec{e}_{kt}(x,y).\vec{e}_{jt}^{*}(x,y) \quad (5)$$

Where σ is the Direct-Current (DC) (period-averaged) coupling coefficient and k is the Alternating-Current (AC) coupling coefficient.δn_{dc} is the "dc" index change over the grating length and δn_{ac} represents the distribution of the index change due to apodization.

The general coupling coefficient is given by:

$$K_{kj}(z) = \sigma_{kj}(z) + 2k_{kj}(z)\cos\left[\frac{2\pi}{\Lambda}z + \emptyset(z)\right] \quad (6)$$

Where Λ is the grating period and $\emptyset(z)$ describes grating chirp.

Equations (2) to (6) are the coupled-mode equations that describe fiber grating spectra.

For a single-mode Bragg grating the simplified coupled-mode equations can be expressed as:

$$\frac{du}{dz} = j\hat{\sigma}\,u(z) + jkv(z) \quad (7.1)$$

$$\frac{dv}{dz} = -j\hat{\sigma}\,v(z) - jku(z) \quad (7.2)$$

Where the amplitudes u and v are given by:

$$u(z) = A(z)\exp\left(i\delta z - {}^{\emptyset}/_{2}\right) \quad (7.3)$$

$$v(z) = C(z)\exp\left(-i\delta z + {}^{\emptyset}/_{2}\right) \quad (7.4)$$

The coefficient $\hat{\sigma}$ is the general "DC" coupling coefficient and is given by:

$$\hat{\sigma} = \delta + \sigma - \frac{1}{2}\frac{d\emptyset}{dz} \quad (8)$$

Where σ is the "DC" coupling coefficient. For a single mode fiber it is given by:

$$\sigma = \frac{2\pi}{\lambda}\,g[\delta n_{dc}(z) + C\delta n_{ac}(z)] \quad (9)$$

The constant C is a parameter that accounts for additional UV- induced change of the average index along the fiber. g is the overlap integral of the guided mode in the photosensitivity region.

The "AC" coupling coefficient is given by:

$$k = \frac{\pi}{\lambda} g\delta n_{ac}(z) \quad (10)$$

C. SOLVING COUPLE MODE EQUATIONS FOR UNIFORM FIBER BRAGG GRATING

For uniform fiber Bragg grating the coupled mode equations will be simplified to first-order ordinary differential equations with constant coefficients. To find the reflectivity of uniform fiber Bragg grating by applying boundary conditions:

$$u\left(-L/_2\right) = 1 \text{ and } v\left(L/_2\right) = 0. \quad (11)$$

So the analytical solution for the coupled mode equations for amplitude and power reflection coefficients will be:

$$\rho = \frac{-k\sinh\left(\sqrt{k^2-\hat{\sigma}^2}\,L\right)}{\hat{\sigma}\sinh\left(\sqrt{k^2-\hat{\sigma}^2}\,L\right)+i\sqrt{k^2-\hat{\sigma}^2}\cosh\left(\sqrt{k^2-\hat{\sigma}^2}\,L\right)} \quad (12)$$

$$r = \frac{\sinh^2\left(\sqrt{k^2-\hat{\sigma}^2}\,L\right)}{\cosh^2\left(\sqrt{k^2-\hat{\sigma}^2}\,L\right)-\frac{\hat{\sigma}^2}{k^2}} \quad (13)$$

For uniform fiber Bragg grating with sinusoidal refractive index variation $k = \frac{\pi\delta n\eta(V)}{\lambda}$ where $\eta(V)$ is a function of fiber V parameter and is, approximately given by:

$$\eta(V) = 1 - 1/_{V^2}. \quad (14)$$

The detuning δ is given by:

$$\delta = 2\pi n_{eff}\left(\frac{1}{\lambda} - \frac{1}{\lambda_B}\right). \quad (15)$$

For maximum reflectivity:

$$R_{peak} = \tanh^2(kL). \quad (16)$$

Reflective bandwidth $\Delta\lambda_{FB}$ of uniform FBG is defined as wavelength bandwidth between the first zero reflective wavelength of both sides of peak reflection wavelength. It can be calculated by:

$$\Delta\lambda_{FB} \cong \frac{{\lambda_B}^2}{n_{eff}\pi L}\sqrt{[(kL)^2 + \pi^2]}. \quad (17)$$

Where L is the grating length, n_{eff} is the effective mode index and λ_B is the Bragg wavelength.

III. RESULTS AND DISCUSSIONS

The parameters used for the simulations are; diameter of the core ($D_{core} = 1.8\mu m$), core index ($n_{co} = 1.47$), cladding index($n_{cl} = 1.457$) and Bragg wavelength($\lambda_B = 1559nm$).When choosing sinusoidal refractive index profile as shown in Fig 3., the dependence of reflectivity and spectral bandwidth on the grating length is investigated as shown in Fig 4.

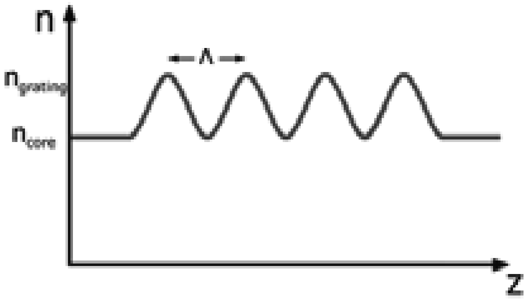

Fig 3. Sinusoidal refractive index profile

In the analysis we choose $\delta n = 4 * 10^{-4}$. It is obvious from the results of this figure that the spectral characteristics of the uniform fiber Bragg grating takes the form of sinc function. As the grating length is increased, reflectivity is increased but the spectral bandwidth is decreased. Also the side lobes are increased with the increase of the grating length. With the increase of the grating length we found that the reflectivity reaches its maximum value then it saturates. The reflectivity reaches unity at grating length equals 4mm. by the increase of the grating length the reflectivity remains unity. It was observed also that the maximum wavelength equals Bragg wavelength (λ_B) and the increase of the grating length doesn't have any effect on the maximum wavelength as it remains the same with the increase of the grating length.

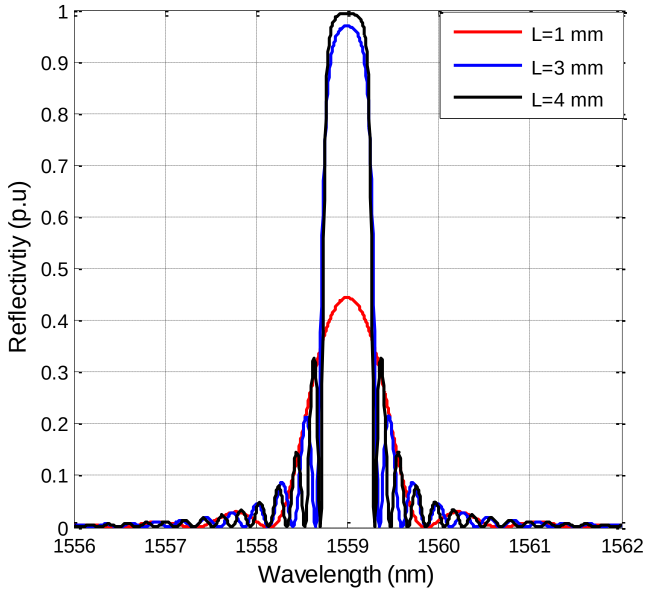

Fig 4. Reflectivity spectrum for different grating length with sinusoidal refractive index profile

Next we study the effect of refractive index modulation (δn) on the reflectivity and the spectral bandwidth as shown in Fig 5.

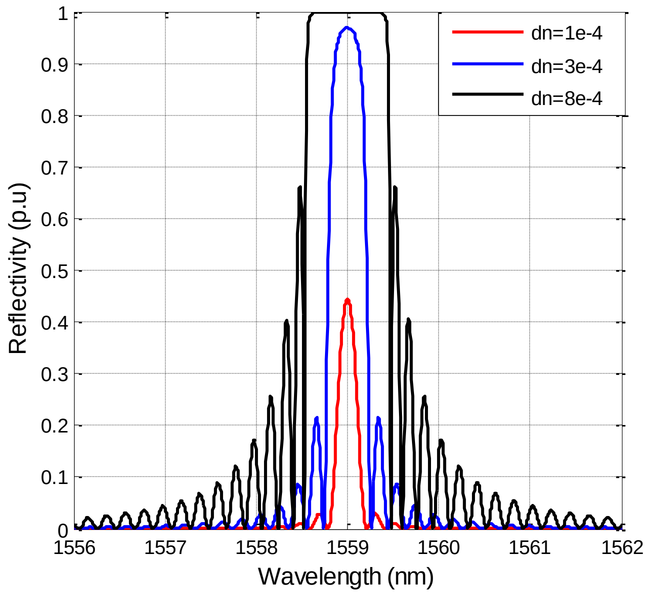

Fig 5. Reflectivity spectrum for different refractive index modulation values with sinusoidal refractive index profile

We choose L=4mm in the analysis. It can be observed that as the refractive index modulation is increased, both the reflectivity and the spectral bandwidth are increased and the side lobes are increased as well. It was obvious from the figure that the reflectivity would be increased until it reached its maximum value then it saturates at a specific value of the refractive index modulation. It reaches unity at $\delta n = 4 * 10^{-4}$ then it saturates. Also the change of refractive index modulation doesn't affect the maximum wavelength which will equal Bragg wavelength for any value of refractive index modulation.
Let us now turn our attention to the effect of square refractive index profile as shown in Fig 6.

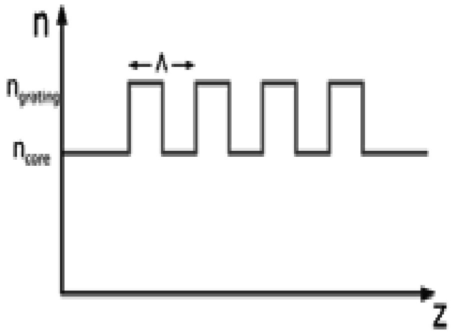

Fig 6. Square refractive index profile

When studying the effect of grating length and refractive index modulation on the reflectivity and spectral bandwidth with the new refractive index shape the following results have been obtained:

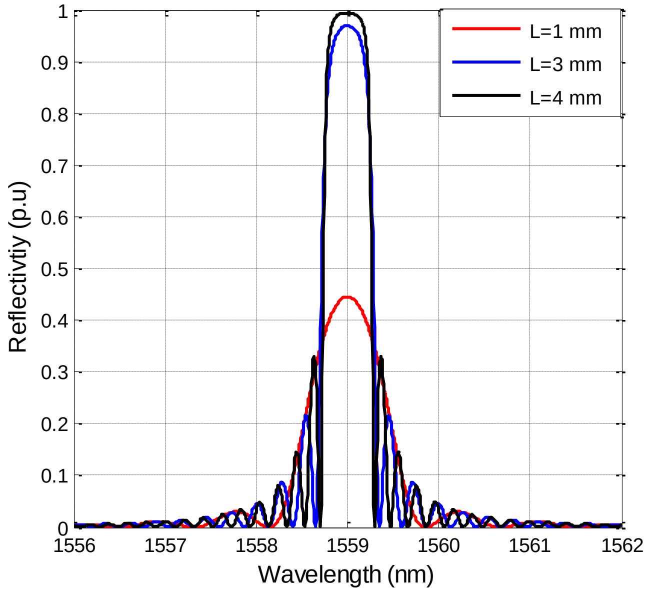

Fig 7. Reflectivity spectrum for different grating length with square refractive index profile

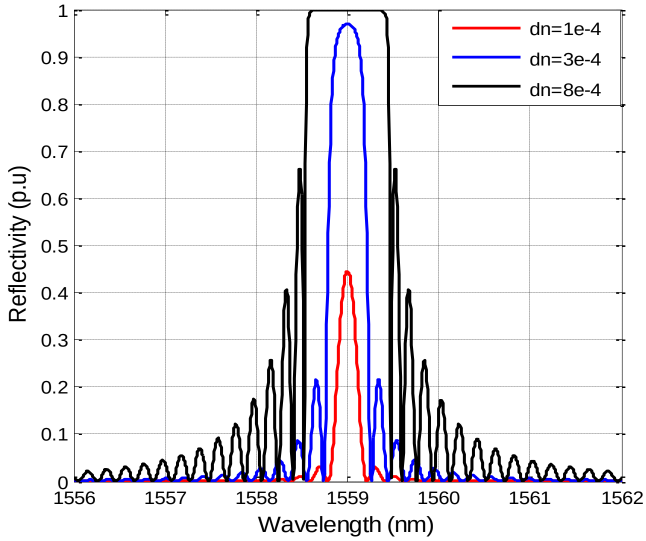

Fig 8. Reflectivity spectrum for different refractive index modulation with square refractive index profile

Figures 7 and 8 show that the shape of the refractive index profile doesn't affect the spectral characteristics of the uniform FBG. So changing the refractive index profile doesn't have any effect on the spectral characteristics of the uniform fiber Bragg grating.
In Fig 9. A relation between maximum reflectivity and grating length has been investigated.

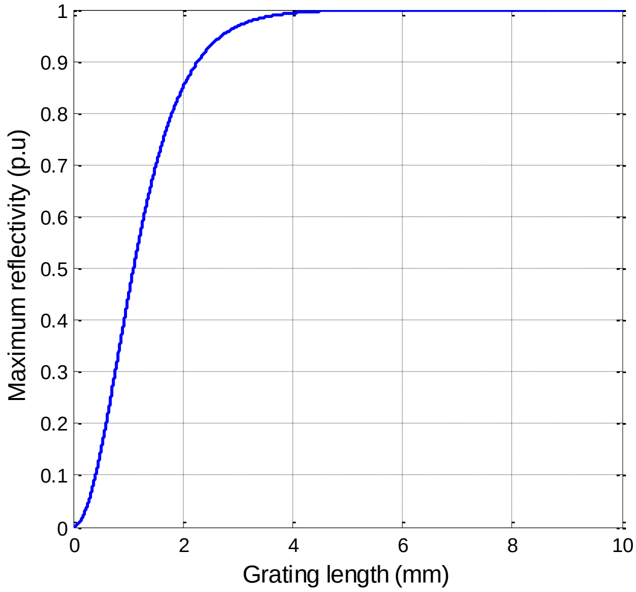

Fig 9. Relation between maximum reflectivity and grating length

It was observed that, as the grating length is increased, maximum reflectivity is obtained until it reaches its maximum value then it saturates. It will reach unity at L=4mm.
The relation between the maximum reflectivity & the refractive index modulation is shown in Fig 10.

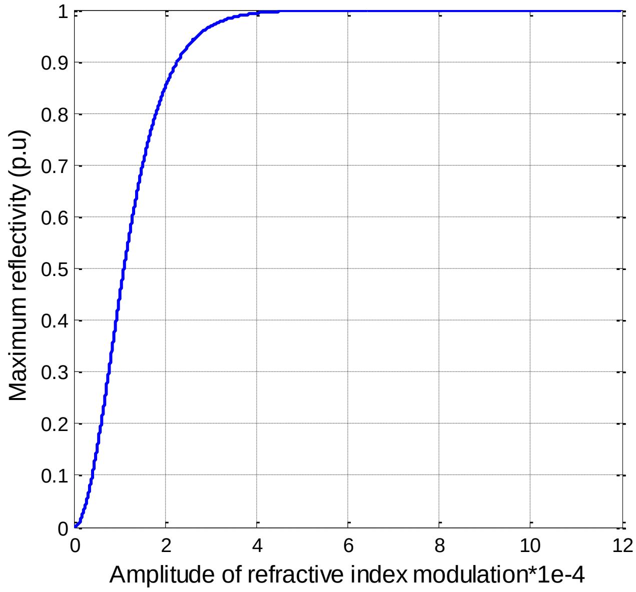

Fig 10. Relation between maximum reflectivity and refractive index modulation

It was clear that, as the refractive index modulation is increased, the maximum reflectivity is obtained and then it saturates. It will reach unity at $\delta n = 4 * 10^{-4}$. The relation between the spectral bandwidth and the grating length is shown in Fig 11.

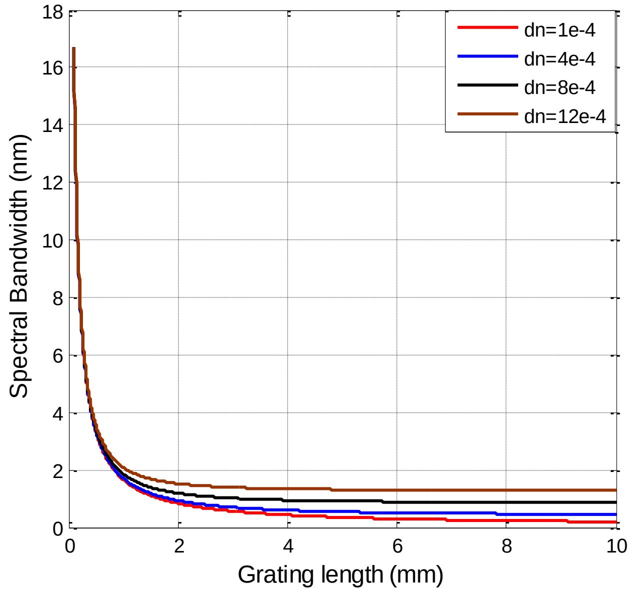

Fig 11. Relation between spectral bandwidth and grating length for different values of dn.

It was investigated that, for grating length shorter than approximately 1mm a small variation in length produces a big variation in the bandwidth. For grating length larger than approximately 5mm it was investigated that the bandwidth isn't affected by the change of grating length, while it is increased by the increase of refractive index modulation.

In Fig 12. A relation between spectral bandwidth and amplitude of refractive index modulation was investigated. It was clear that as the amplitude of refractive index modulation is increased, spectral bandwidth is increased.

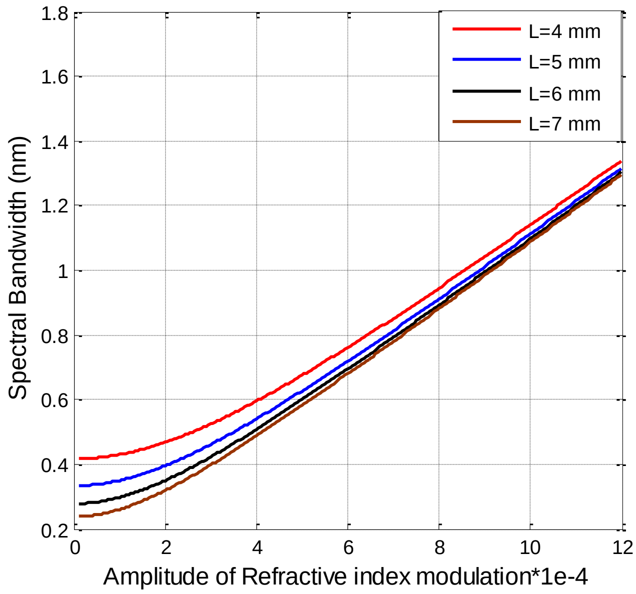

Fig 12. Relation between spectral bandwidth and refractive index modulation for different grating lengths

For better performance of the uniform FBG, proper values for L and δn must be chosen to satisfy maximum reflectivity and narrow bandwidth. If L and δn are chosen as L=5mm and $n = 4 * 10^{-4}$, the maximum reflectivity and narrow bandwidth can be obtained but the problem of side lobes can be solved by using a podization which means modulation of the amplitude δn along the grating length.

IV. CONCLUSIONS

From all the previous work it was concluded that the structural parameters of the uniform fiber Bragg grating have a significant effect on the reflectivity spectrum and the bandwidth. It was clearthat the spectral characteristics of the uniform fiber Bragg grating takes the shape of sinc function. It was investigated that as the grating length is increased, reflectivity is increased but the spectral bandwidth is decreased. With the increase of refractive index modulation both reflectivity and spectral bandwidth are increased. The shape of the refractive index profile doesn't effect on the spectral characteristics of the uniform fiber Bragg grating. For better performance of the uniform fiber Bragg grating proper values for grating length and refractive index modulation must be chosen to achieve maximum reflectivity and narrow bandwidth.

REFERENCES

[1] K. O. Hill and G. Meltz, "Fiber Bragg Grating technology: fundamentals and over-view",J Lightwave Technol, vol. 15, pages 1263–1276, 1997.

[2] Kashyap. R, "*Fiber Bragg Gratings*", San Diego: Academic Press, 1999.

[3] Abdallah Ikhlef, Rachida Hedara, Mohamed Chikh-bled. "Uniform Fiber Bragg Grating modeling and simulation used matrix transfer method". IJCSI International Journal of Computer Science Issues, Vol. 9. Pages. 368-374, 2012.

[4] Santosh Pawar, Shubhada Kumbhaj, Pratima. Sen & Pranay Kumar Sen. "Fiber Bragg Grating Filter for Optical Communication: Applications and Overview". International Journal of Advanced Electrical and Electronics Engineering, (IJAEEE), Vol.2. Pages. 51-58, 2013.

[5] Deba Kumar Mahanta. "Design of Uniform Fiber Bragg grating using Transfer matrix method". International Journal of Computational Engineering Research (IJCER). Vol. 03. Pages 8-13, 2013.

[6] Dinesh Arora, Dr.Jai Prakash, Hardeep Singh & Dr.Amit Wason. "Reflectivity and Braggs Wavelength in FBG". International Journal of Engineering (IJE), Vol. 5. Pages 341-349, 2011.

[7] Jyotsna Rani Mahapatra, Manisha Chattopadhyay. "Spectral Characteristics of uniform fiber Bragg grating using couple mode theory". International Journal of Electrical, Electronics and Data Communication, Vol.1. Pages 40-44, 2013.

[8] Turan Erdogan. T. "Fiber grating spectra". Journal of Lightwave Technology, vol.15. Pages 1277-1294, 1997.

[9] Ho Sze Phing, Jalil Ali, Rosly Abdul Rahman and Bashir Ahmed Tahir. "Fiber Bragg grating modeling, simulation and characteristics with different grating lengths". Journal of Fundamental Sciences vol.3. Pages 167-175, 2007.