Fiber Bragg Grating Filter for Optical Communication: Applications and Overview

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Abstract – **Recently, optical fiber Bragg grating have attracted a great deal of attention because of their importance in designing new devices to meet a need range of optical communication systems. An intense investigation of the possibility of using this optical device for all optical ultrafast applications is achieved by allowing their dielectric characteristics to be varied in such a way that a periodic perturbation of their refractive index along the length of the optical fiber will be formed. The coupled mode method, on the other hand, has been proven to be one of the most powerful analytical techniques that are usefully applied to a wide range of optical devices. In this paper, a coupled mode equations has been solved for fiber Bragg grating to analyze the grating structures that exhibit attractive optical properties that make them suitable for optical communication system as a wavelength filter. The paper also describes a simplified theoretical model to analyze the linear reflection characteristics of uniform fiber Bragg grating at low excitation intensity. The linear coupled mode theory has been adopted to calculate the reflectivity of the grating in the linear regime. We derived the solutions for both forward and backward propagating field amplitudes considering the propagation of a CW laser beam through the grating.**

Keywords – Optical Fiber Communication, Bragg Grating, Optical Filter, Optical Signal Processing.

I. INTRODUCTION

The ever-increasing need for communication capacity has brought the field of optics into focus for the past decades. Fiber optics is the only technique known today to have the power to meet the strong demands for flexibility and high bandwidth posed by the rapidly growing communication networks. The optical systems were primarily used in point-to-point long distance links [1, 2]. In the future, fiber optic networks will be routed directly into neighborhoods, households, and even to the back of each computer [3, 4]. In the more distant future, it is possible that even the signals bouncing between the different components inside the computer will be transmitted and received optically [5]. Today, optical network and signal processing requires converting the optical information into electrical signals, processing in the electronic domain, and converting back to the optical domain before retransmission. Such an operation requires detection, retiming, reshaping, and regeneration at each switching and routing point. This necessitates complex and expensive electronic and electro-optical hardware at each routing and switching node. In addition, the ability to perform signal processing operations entirely within the optical domain would eliminate the requirement of optical-electrical-optical conversions, while providing the agility and speed inherent to optical elements. As optical fiber gradually replaces copper cables, it will become necessary for many of the electronic network components to be replaced by equivalent optical components: such as splitters, filters, routers, switches etc.

In order to have all such optical components to be compact, manufacturable, low-cost, and integratable, it is highly desirable that they be fabricated in an optical fiber. The inline optical fiber based component demonstrated the tremendous potential applications over the optical components fabricated on a semiconductor planar surface using lithographic techniques. Fiber Bragg grating offers one possible solution for constructing inline optical devices to fulfill above requirements. Advantages of fiber Bragg grating over competing semiconductor material based optical components include all-fiber geometry, low insertion loss, low absorption loss, low scattering loss, high return loss, and potentially low cost. Moreover, the most distinguishing feature of fiber Bragg grating is the flexibility they offer for achieving desired spectral characteristics. Numerous physical parameters can be varied including: induced index change, length, apodization, period chirp, fringe tilt and desired wavelength.

After the observation of photosensitivity in Ge doped silica fiber by Hill et al. in 1978 [6] and side exposed holographic technique to make FBG with controllable period by Meltz in 1989 [7], FBGs has been used as a critical component for many applications in optical fiber communication and sensor system such as, optical filters, pulse compressor, and dispersion compensator [8-11] etc. Recently, intensive research and development activities are carried out on a variety of FBGs which includes uniform, chirped, tilted, apodized FBGs to study their band pass and band rejection responses [12].FBG based optical filters have been widely investigated in photosensitive fibers [13], semiconductor waveguides [14] and polymer waveguides [15]. Kashyap *et al*. [16] have developed ultra-steep edge high rejection (>74 dB) filter using FBG. The most significant of such FBG based filter is the linewidth of its reflection spectrum, which is relatively narrow. As a consequence of this property, the selectivity of FBG is high. This feature is an attractive aspect of FBGs that can be used in an optical fiber as notch filters. On the other hand, the reflection wavelength of FBG is determined by the grating period and the effective refractive index. Because of this, FBG can be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector. The modern technological techniques can make the reflectivity of FBG close to unity over the reflection band [17–21]. Moreover, the large dispersive behaviors of the Bragg grating structures make them good devices for linear dispersion comparators, optical add/ drop multiplexers (OADM) in wavelength division multiplexing (WDM) systems and optical multiplexers–demultiplexers with an optical circulator. Propagation of solitons is another application of FBGs. Nonlinear pulse propagation and compression have been also reported in short period FBGs. Due to the existence of a stop band in the transmission spectrum of FBGs, known as a photonic bandgap (PBG), the nonlinear pulse propagation has many applications (such as an optical switch) in them [22–24].

In the present work, we have studied analytically the filter characteristics of fiber Bragg grating using coupled mode theory. We have solved linear coupled mode equations and obtained the expression for reflectivity of fiber Bragg grating for a CW laser beam. The present paper also covers the fundamental optical properties of fiber Bragg grating and its applications in optical communication system for high speed modern photonic technology. The work in this paper summarizes as follows: In section II we describe the physical model of an optical fiber Bragg grating and obtained the conditions for dispersion relation. This section covers the complete analytical model to characterize the optical wave propagation in fiber Bragg grating. In Section III, a description of photonic bandgap is presented. In which most of the incident frequencies are transmitted and reflected from the grating. The filter response of fiber Bragg grating is investigated in Section IV. We also describe the applications of such spectral response in an optical communication system. The estimation of bandwidth of fiber Bragg grating described in Sections V. We provide a theoretical expression to calculate the bandwidth of grating by changing the various physical parameter of Bragg grating. Finally, Section VI gives a brief description of the phase response of grating to gives the information about the phase changes at Bragg resonance wavelength in the Bragg grating.

II. PHYSICAL MODEL FOR ANALYSIS OF BRGG GRATING

Fiber Bragg grating is defined as a periodic perturbation of the refractive index along the fiber length. This perturbation is formed by exposing the core of the fiber to an intense optical interference pattern. Several methods have been adapted to study and analyze the reflection and transmission characteristics of FBG. However, in present analytical study we take coupled mode theory into consideration. According to this theory, it is assumed that at any point along the grating within the single-mode fiber there is a forward propagating mode and a backward propagating mode. Coupled-mode theory is described in a number of texts; detailed analysis can be found in [25-29]. The notation in this section follows most closely that of G. P Agrawal [30]. Throughout this thesis, we assume that the fiber is lossless and single mode in the wavelength range of interest. Moreover, we assume that the fiber is weakly guiding, i.e. the difference between the refractive indices in the core and the cladding is very small. Then the electric and magnetic fields are approximately transverse to the fiber axis, and we can ignore all polarization effects due to the fiber structure and consider solely the scalar wave equation.

According to the coupled mode theory, the total field at any value of z can be written as a superposition of the two interacting modes and the coupling process results in a z-dependent amplitude of the two coupled modes. It is assumed that any point along the grating within the single-mode fiber has a forward propagating mode and a backward propagating mode. Thus the total field within the core of the fiber is given by

$$\vec{E}(z,\omega) = F(x,y)\left(\vec{A}_f(z,\omega)\exp(i\beta_B z) + \vec{A}_b\exp(-i\beta_B z)\right) \tag{1}$$

Where $\vec{A}_f$ and $\vec{A}_b$ represents the amplitudes of the forward and backward propagating modes, respectively, $\beta_B = \pi/\Lambda$ is the Bragg wave number for the first order grating. It is related to the Bragg wavelength through the Bragg condition $\lambda_B = 2n_{eff}\Lambda$ which can be used to define the Bragg frequency $\omega_B = \pi c / n_{eff}\Lambda$ and $F(x,y)$ is the transverse modal field distribution. The total field given by Equation (1) has to satisfy the wave equation given by

$$\nabla^2\vec{E} + n^2(\omega,z)\omega^2/c^2\vec{E} = 0, \tag{2}$$

In the above formula, $n(\omega,z)$ denotes the refractive index variation along the FBG and is given by

$$n(\omega,z) = n_{eff}(\omega) + n_2\left|\vec{E}\right|^2 + n_g(z). \tag{3}$$

Here, n_{eff} is the average refractive index of the grating, n_2 is the Kerr coefficient and $n_g(z)$ is the periodic index variation and $\vec{E}$ is the electric field propagating inside the grating. Substituting Equation (1) and Equation (2) into Equation (3) and considering a slowly-varying envelope approximation, we can obtain the following coupled mode equations in time [30]:

$$\frac{\partial A_f}{\partial z} = i\delta A_f + i\kappa A_b \tag{4}$$

and
$$-\frac{\partial A_b}{\partial z} = i\delta A_b + i\kappa A_f \tag{5}$$

In the above equations, we focus only on the linear case in which the nonlinear effects are negligible. For such case we neglected the nonlinear parameter γ in the coupled mode equations. In equations (4) and (5), δ and κ are detuning parameter and linear coupling coefficient and nonlinear coefficient, respectively, and are defined as

$$\delta = 2\pi n\left(\frac{1}{\lambda} - \frac{1}{\lambda_B}\right) \text{ and } \kappa = \frac{\pi n_g}{\lambda_B} \tag{6}$$

To solve these equations, let us differentiate Equations (1.16) & (1.17) with respect to z

$$\frac{\partial^2 A_f}{\partial z^2} = i\delta\frac{\partial A_f}{\partial z} + i\kappa\frac{\partial A_b}{\partial z} \tag{7}$$

and
$$-\frac{\partial^2 A_b}{\partial z^2} = i\delta\frac{\partial A_b}{\partial z} + i\kappa\frac{\partial A_f}{\partial z} \tag{8}$$

Substituting $\frac{\partial A_b}{\partial z}$ and $\frac{\partial A_f}{\partial z}$ in Equation (7) & (8) from equation (4) and (5), we found the differential equations in the form

$$\frac{\partial^2 A_f}{\partial z^2} + \left(\delta^2 - \kappa^2\right)A_f = 0 \tag{9}$$

and
$$\frac{\partial^2 A_b}{\partial z^2} + \left(\delta^2 - \kappa^2\right)A_b = 0 \tag{10}$$

Let $\left(\delta^2 - k^2\right) = q^2$

$$\frac{\partial^2 A_f}{\partial z^2} + q^2 A_f = 0 \tag{11}$$

and
$$\frac{\partial^2 A_b}{\partial z^2} + q^2 A_b = 0 \tag{12}$$

A general solution of these linear equations takes the form

$$A_f(z) = A_1\exp(iqz) + A_2\exp(-iqz) \tag{13}$$

And
$$A_b(z) = B_1\exp(iqz) + B_2\exp(-iqz) \tag{14}$$

These equations show that z dependent parts of the forward and backward waves in the FBG are exponential with the propagation constant q. This parameter q representations the linear dispersion relation of fiber Bragg grating and defined as

$$q = \pm\sqrt{\delta^2 - k^2} \tag{15}$$

The constant A_1, A_2, B_1, B_2 in Equations (13) & (14) are interdependent and by using Equations (13) & (14) we find that these constants satisfy the following four relations:

$$(q-\delta)A_1 = \kappa B_1;\ (q+\delta)B_1 = -\kappa A_1 \tag{16}$$

$$(q-\delta)B_2 = \kappa A_2;\ (q+\delta)A_2 = -\kappa B_2 \tag{17}$$

One can eliminate A_2 and B_1 by using Equations (13) to (14) and write the general solution in terms of an effective reflection coefficient $r(q)$ as

$$A_f(z) = A_1\exp(iqz) + r(q)B_2\exp(-iqz) \tag{18}$$

$$A_b(z) = B_2\exp(-iqz) + r(q)A_1\exp(iqz) \tag{19}$$

where

$$r(q) = \frac{q-\delta}{\kappa} = -\frac{\kappa}{q+\delta} \tag{20}$$

is the effective reflection coefficient of the fiber Bragg grating. The q dependence of $r(q)$ and the dispersion relation (15) indicate that both the magnitude and phase of the backward reflection depend on the frequency ω.

III. CONCEPT OF PHOTONIC BANDGAP

The dispersion relation of Bragg gratings exhibits an important property known as the photonic bandgap as seen clearly in Fig. 1, where detuning parameter δ is plotted as a function of q for both a uniform medium (dashed line) and a periodic medium (solid line).

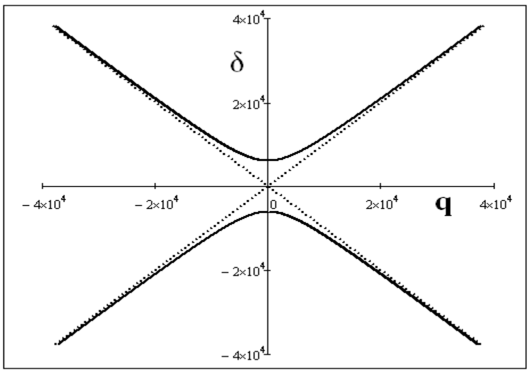

Fig. 1: Dispersion curves showing variation of δ with q and the existence of the photonic bandgap for a fiber grating.

For the uniform medium the slope is constant, and thus the dispersion is negligible. By introducing a grating, the dispersion relation is modified and if the frequency detuning δ of the incident light falls in the range $-\kappa < \delta < \kappa$, q becomes purely imaginary. Most of the incident field is reflected in that case since the grating does not support a propagating wave. The range $|\delta| \le \kappa$ is referred to as the photonic bandgap. For this range of detuning light cannot propagate through the grating and undergoes strong reflection. It is also called the stop band since light stops transmitting through the grating when its frequency falls within the photonic bandgap.

IV. FILTER RESPONSE OF BRAGG GRATING

The equation (18) and (19) gives the solution to the coupled mode equations in exponential form. The reflection and transmission coefficient of fiber Bragg grating can be calculated by using Eqs. (18) and (19) applying the appropriate boundary conditions as

$$A_b\,(z = 0) = 1 \text{ and } A_f\,(z = L) = 0 \tag{21}$$

where L is the length of the grating. Equation (21) implies that the incident wave has unit amplitude at z = 0 and the amplitude of the reflected wave at $z = L$ is zero because there is no reflected wave beyond $z = L$. The boundary conditions applying on the FBG structure is shown in Figure 2.

We defined the reflection coefficient of the FBG by the ratio of the amplitude of reflected wave at z = 0 to the amplitude of incident wave at z = 0 as

$$r_g = \frac{A_b(z=0)}{A_f(z=0)} = \frac{B_2 + r(q)A_1}{A_1 + r(q)B_2} \tag{22}$$

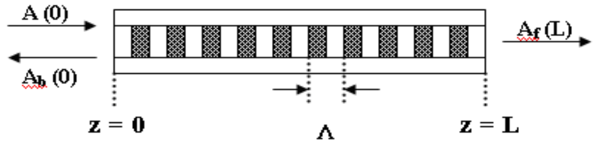

Fig. 2: Schematic of a FBG of length L illuminated by electromagnetic field of amplitude A(z).

If we use the boundary condition $A_b(L) = 0$ in Eq. (19),

$$B_2 = -r(q)A_1 \exp(2iqL) \tag{23}$$

Using Equation (20) and Equation (23) in Eq. (22), we obtained the reflection coefficient as

$$r_g = \frac{i\kappa \sin(qL)}{q\cos(qL) - i\delta \sin(qL)} \tag{24}$$

The corresponding expression for the reflectivity $R_g \left(= |r_g|^2\right)$ in the linear regime is found as

$$R_g = \frac{\kappa^2 \sin^2(qL)}{q^2\cos^2(qL) + \delta^2 \sin^2(qL)} \tag{25}$$

At resonance there is no detuning i.e $\delta = 0$, hence reflectivity is maximum. The expression for the reflectivity becomes:

$$R_{g\,\max} = |r_g(\delta = 0)|^2 = \tanh^2(\kappa L) \tag{26}$$

Varing some parameters such as grating length and magnitude of induced index change, it is possible to obtain narrow-band transmission as well as high reflectivity at the Bragg wavelength. Optimization of these parameters is fundamental when the objective is to use fibre Bragg gratings in band-pass filtering applications such as wavelength multiplexing/demultiplexing and add/drop optical filter.

Figure 3 shows the spectral response of the Bragg grating for the reflected wave condring five different Bragg gratings with increasing lengths (1) L = 0.5 mm, (2) L = 1.0 mm, (3) L = 2.0 mm, (4) L = 4.0 mm and (1) L = 8.0 mm. In all these cases we assumed effective index $n_{eff} \approx 1.451$, grating index $n_g \approx 0.5\times10^{-3}$ and Bragg wavelength $\lambda_B \approx 1550$ nm. From this figure, we can identify two different operating regimes. Firstly, when the product κL is small compared to 1, the reflectivity of the Bragg gratings is minimum. Since the grating begins and ends abruptly and extends for a length L, the spectral response has a characteristic "sinc" shape whose bandwidth is inversely proportional to the grating length L. We refer to gratings with $\kappa L < 1$ as weak Bragg gratings, because in general they only reflect a fraction of the incident light. The peak reflectivity in this regime depends upon the value of κ, but the overall spectral shape and bandwidth is determined only by the grating length. A weak Bragg grating does not make a suitable add/drop filter, because it only partially reflects the input signal. However, there are cases where the "sinc" shaped spectral response of a weak grating is desirable. In many binary communications systems, the encoded signal has precisely at the same "sinc"-shaped spectral response. Thus, the weak Bragg grating provides a convenient implementation of an all-optical matched filter, which should provide the optimal signal-to-noise ratio for detecting the signal in the presence of white background noise [31-33]. Secondly, for gratings where the product κL exceeds 1, the spectral response has a plateau-like shape, as shown in Fig. 3. In this regime, the grating has a very high reflectivity within a band of frequencies called the stopband.

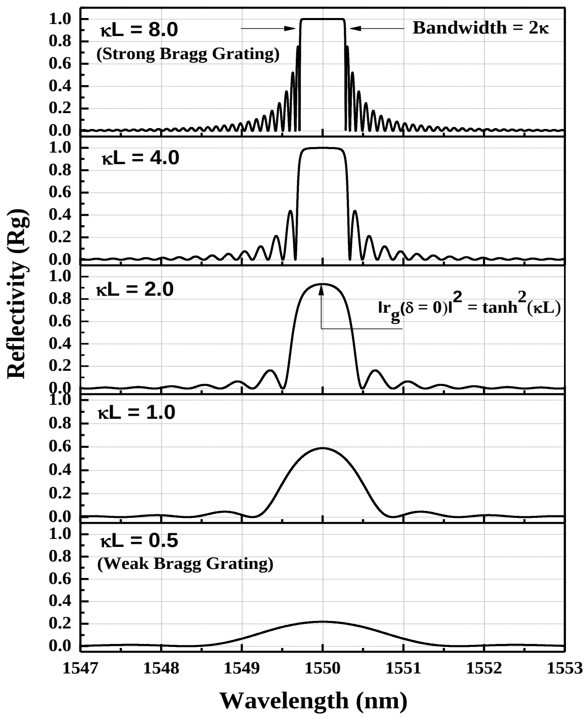

Fig. 3: Calculated reflection spectral response as a function of wavelength for five different fiber Bragg gratings, with increasing lengths.

Outside of the stopband, the spectral response shows a series of ripples or sidelobes. The sidelobes quickly decay as we move away from the Bragg condition until the structure is effectively transparent. If the grating is made longer without changing the value of κ, the bandwidth remains unchanged, but the peak reflectivity rises closer to 1, the spectrum becomes more square, and the sidelobes get closer together. An undesirable feature seen in Fig. 3 is the presence of multiple sidebands located on each side of the stop band. These sidebands originate from weak reflections occurring at the two grating ends where the refractive index changes suddenly compared to its value outside the grating region. Even though the change in refractive index is typically less than 1%, the reflections at the two grating ends form a Fabry–Perot cavity with its own wavelength-dependent transmission. An apodization technique is commonly used to remove the sidebands [31].

Fig. 4 shows the dependence of peak reflectivity $(R_{g\max})$ on the grating length and refractive index change. It is clear, that it is possible to reach the same peak reflectivity with shorter gratings using fiber with high n_g values. That is very useful to find effective length of grating.

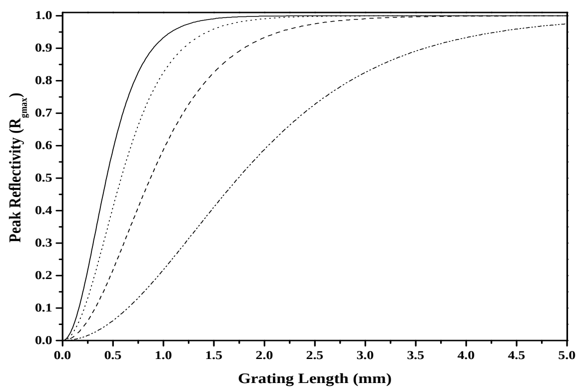

Fig. 4: Peak reflectivity $(R_{g\max})$ as a function of Bragg grating length (L), calculated for different values of grating index n_g (1) 0.25×10^{-3} (dashed dot curve), (2) 0.5×10^{-3} (dashed curve), (3) 0.75×10^{-3} (dotted curve) and (4) 1×10^{-3} (solid curve).

V. ESTIMATION OF BANDWIDTH OF BRAGG GRATING

Figure 3 shows the typical spectral response of an FBG. The peak reflectivity $(R_{g\max})$ at the Bragg wavelength λ_B is the most important parameter of interest in an FBG design. For a given $(R_{g\max})$, κL may be calculated from Equation (26). The quantity κL is required in order to obtain the bandwidth (BW) of an FBG's reflection spectrum (the difference in wavelengths between the first two reflection minima on either side of the main reflection peak). The reflection bandwidth, $\Delta\lambda$, for a uniform Bragg grating can be defined as [34]

$$\Delta\lambda = \frac{\lambda_B^2}{n_{eff}\,\pi L}\sqrt{\pi^2 + (\kappa L)^2} \tag{27}$$

Table 1: Calculated bandwidth of a fiber Bragg grating reflector at different values of κL .

S. No.	FBG Length (mm)	Grating index (n_g)	≈ κL	Max Reflectivity (%)	Band width (nm)
1	0.5	0.5×10^{-3}	0.5	22	3.35
2	1.0	0.5×10^{-3}	1.0	59	1.75
3	2.0	0.5×10^{-3}	2.0	93	0.98
4	4.0	0.5×10^{-3}	4.0	99	0.67
5	8.0	0.5×10^{-3}	8.0	100	0.57

It is important to note that for a given value of maximum reflectivity of fiber Bragg grating ($R_{g_{max}}$) and bandwidth$(\Delta\lambda)$, the value of κL from Equation (26) can be substituted in (27) to determine the desired length L of the FBG; thereafter, refractive index modulation n_g can be estimated from Equation (6). All the calculations are given in Table 1 where the value of n_{eff} and λ_B are assumed as 1.451 and 1550 nm, respectively. Table-1.1 reveals that, we can obtain a desired bandwidth of fiber Bragg grating by choosing proper values of grating length and grating index n_g .

VI. PHASE RESPONSE OF BRAGG GRATING

In previous sections we have calculated the amplitude and bandwidth of fiber Bragg grating from the coupled mode theory. From Equation (1.38), it is observed that the reflection coefficient of FBG is a complex value and it can be written in phasor form as [35]

$$r_g(\omega) = |r_g| \times \exp[i\phi_L(\omega)] \tag{28}$$

where $|r_g|$ and $\phi(\omega)$ are amplitude and phase of FBG, respectively. In order to complectely obtain a complete characterize the FBG, it is essential to know its amplitude and phase response. The amplitude and phase of the FBG can be calculated as .

$$|r_g|^2 = R_g = (X_L^2 + Y_L^2) \tag{29}$$

and

$$\phi_L = 2\tan^{-1}\left(\frac{Y_L}{\sqrt{X_L^2 + Y_L^2} + X_L}\right). \tag{30}$$

Here, X_L and Y_L are represent the real and imaginary part of the complex reflection coefficient and it is obtained using Equation (24) as

$$X_L = -\frac{\kappa\delta\sin^2(qL)}{q^2\cos^2(qL) + \delta^2\sin^2(qL)}\ , \tag{31}$$

$$Y_L = \frac{q\kappa\sin(qL)\cos(qL)}{q^2\cos^2(qL) + \delta^2\sin^2(qL)} \tag{32}$$

Finally, the phase of the reflected beal at length L in linear case can be written using Equation (30) as

$$\phi_L = 2\tan^{-1}\left(\frac{q\sin(2qL)}{2\sqrt{\sin^2(qL)}\sqrt{\delta^2 - \kappa^2\cos^2(qL)} - 2\delta\sin^2(qL)}\right) \tag{33}$$

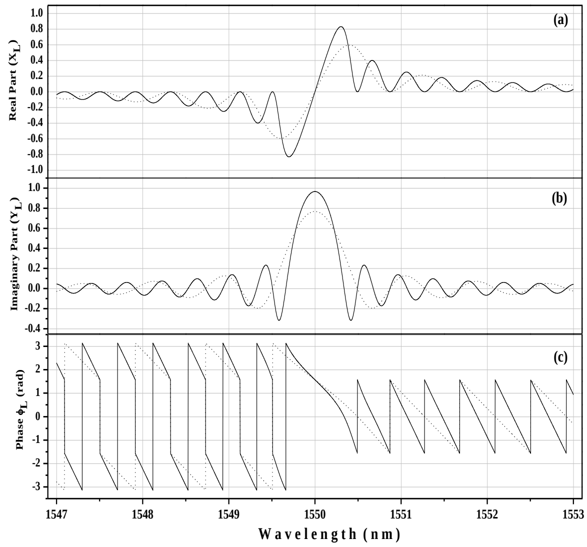

Fig. 5: Variation in (a) The real part (X_L) (b) the imaginary part (Y_L) and (c) the phase (ϕ_L) of reflection coefficient (r_g) plotted as a function of wavelength for two values of grating strength $\kappa L = 1$ (dotted curve) and $\kappa L = 2$ (solid curve).

Figure 5 shows the variation in (a) The real part (X_L) (b) the imaginary part (Y_L) and (c) the phase (ϕ_L) as a function of wavelength for two values of grating strength $\kappa L = 1$ (dotted curve) and $\kappa L = 2$ (solid curve). It is clear that in the region outside of the stop band, the phase of the light changes according to the unperturbed material refractive index wheareas inside the stop band, the phase decreases slowly with increasing strength of the grating.

VII. CONCLUSION

The objective of this work was to provide an overview and applications of fiber Bragg grating filter in the area of optical communication system and optical networks. Because a large amount of research activity has been carried out on this subject over the past dozen years, this paper summarized the basic optical spectral characteristics and functionalities of the device in lightwave technology. We evaluated the available solutions for this periodic device along with its physical model. We believe the present analytical study will be useful in future experimental work for the exploration of optical filter based fiber Bragg grating and for the development of various optical components for all-optical signal processing.

VIII. ACKNOWLEDGMENT

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