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DISPERSION AND SPECTRAL ANALYSIS OF LINEAR OPTICAL FIBER BRAGG GRATING

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ABSTRACT

The present research work reported the results of an analytical study of dispersion and spectral characteristics of uniform fiber Bragg grating under linear regime. We provides simplified mathematical model to analyze the dispersion and spectral properties of fiber Bragg gratings as a function of various physical parameters like grating length, detuning parameter, grating index, and operating light wavelength. The coupled mode equations have been solved analytically to obtain the expression of group delay, reflectivity and group velocity dispersion of the fiber Bragg gratings. Attention is paid to the study of grating induced group velocity dispersion with first, second and third order dispersion as well as the delay and spectral response of the grating. The study reveals that the grating induce dispersion compensated the fiber dispersion and such features of Bragg grating can be utilized as a dispersion management device with huge potentiality in the next generation of all-optical communication applications.

Keyword—Optical Fiber Communication, Bragg Grating, Optical Filter, Optical Signal Processing.

I. INTRODUCTION

In the present era fiber Bragg grating is used one of the most important optical fiber based component as a passive integrated device in optical signal processing applications. Recent developments in the field of lightwave communication system are optical fiber based components and devices because of its small size and ease of connectibility with the optical fiber links. 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. Most of the optical fiber based component which we are using in optical communication are erbium doped fiber amplifier (EDFA), fiber laser and fiber Bragg grating (FBG). Among them, FBG have used as a critical optical component for many applications in fiber optic communication and sensor systems [1-5]. There are several another applications of FBG such as optical fiber mode converters, grating based sensors, optical storage, optical computing, electro-optic devices, wavelength conversion devices etc. [6]. Fiber Bragg grating offers one possible solution for constructing inline optical devices to fulfill above requirements. Numerous physical parameters of FBG can be varied to achieving desired spectral properties including: induced index change, length, apodization, period chirp, fringe tilt and desired wavelength.

The basic physical process behind the FBG is a photosensitivity. The presence of GeO defects is crucial for photosensitivity to occur in optical fibers. Standard fibers have 3% Ge atoms in silica core, resulting in relatively small index changes. It has been studied by Hill et al. in 1978 [2]. The use of dopents such as phosphorus, boron and aluminum can enhance the photosensitivity to some extant. In early 1990s it was discovered that the amount of index change can be enhanced by two orders of magnitude by soaking the fiber in hydrogen gas at high pressure and room temperature [6, 7]. Another technique to enhance the photosensitivity is flame brushing. Some workers have reported that photosensitivity can be enhanced by doping of rare earth ions in fibers with holmium and thulium [8].

There is a growing interest in the study of dispersive and nonlinear properties of FBG due to their use in dispersion compensation, pulse shaping and photonic switching etc. For the analytical study of properties of FBG two different approaches have been commonly used. In one approach, Bloch formalism describing motion of electrons in semiconductors is applied to Bragg grating [9] and in another approach, forward and backward propagating wave are treated independently, and Bragg grating provides a coupling between them. This method is known as coupled mode theory and has been used with considerable success in several different contexts [10-13]. Some authors have reported the development process for constructing integrated Bragg gratings and phase related optical devices for a wide range of filtering functions for optical telecommunications [14, 15]. Intensive theoretical and experimental research work has been carried out by Kashayap [16, 17] at British Telecom on fabrication of various kinds of FBG like uniform nonuniform, chirped and apodized and their applications.

FBGs have been formed only in single mode optical fibers, and the spectral characteristics have been well known. In comparison to single mode fiber, multimode optical fiber has a merit of easy coupling with broadband optical sources such as light emitting diodes. With the idea Bragg grating in multimode optical fibers is possible, it would contribute to new applications in optical communications and optoelectronics, Wasner et al. [18] calculated the reflection spectrum of a bragg grating in multimode fiber and propsed application to bending sensors. Okude et al. [19] fabricated a Bragg grating in a short piece of multimode fiber with a core diameter 17.5 μm and spliced both ends with single mode fibers. Of late present some researchers have demonstrated formation of a Bragg grating in graded index multimode fibers and briefly reported their transmission spectrum [20-23]. 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.

Optical fiber Bragg gratings also have been shown to have practical application in compensation of dispersion broadening in long haul communication. While Lam et al. [24] first discussed the use of unchirped gratings for dispersion compensation, a subsequent landmark paper by Ouellette first describe the use of chirped reflection gratings to provide frequency dependent delay for recompression of dispersed pulses [25, 26]. Dispersion compensation using a uniform FBG in transmission is demonstrated both experimentally and numerically [27]. Litchinister et al. proposed a transmission based dispersion compensator employing an apodized, unchirped FBG and design a theoretical model for dispersion compensation based on the dispersive properties of the periodic structure [28]. Lee et al proposed a purely phase sampled Bragg grating for dispersion and dispersion slope compensation by introducing a chirp in the grating period and coupling coefficient [29]. Some of the author analyzed first time the cross phase modulation effect in fiber links with dispersion compensated by chirped FBG [30]. In this context some excellent review articles have been presented by Sumetsky et al. and Litchinitser et al. in 2005 and 2007 [31, 32].

The present work deals with the analytical study of dispersion and reflection properties of fiber Bragg grating using coupled mode theory under linear regime. We have solved linear coupled mode equations and obtained the expression for first second and third order dispersion as well as reflectivity of fiber Bragg grating. The work in this paper summarizes as follows: In section II we describe the physical model of group velocity of the optical fiber Bragg grating and also shows the dispersion relation conditions. In Section III, a first, second and third order dispersion properties of FBG are presented. In this particular we show how FBG is used as a dispersion compensator in optical communication system. The reflection and optical phase properties of fiber Bragg grating is investigated in Section IV. This section 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. We also describe the applications of such spectral response in an optical communication system. The delay response of fiber Bragg grating described in Sections V. We provide a theoretical expression to calculate the delay response of grating by changing the various physical parameter of Bragg grating.

II. GROUP VELOCITY OF THE FBG

Fiber Bragg grating is defined as a periodic perturbation of the refractive index along the fiber length. In the present analytical study we take coupled mode theory into consideration. 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

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

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

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

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

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

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]:

$$\frac{\partial A_f}{\partial z} = i\delta A_f + i\kappa A_b \quad (4)$$

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

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

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

To solve these equations, let us differentiate Equations (4) & (5) with respect to z

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

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

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

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

and

$$\frac{\partial^2 A_b}{\partial z^2} + (\delta^2 - \kappa^2)A_b = 0 \quad (10)$$

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

$$\frac{\partial^2 A_f}{\partial z^2} + q^2 A_f = 0 \quad (11)$$

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

A general solution of these linear equations takes the form

$$A_f(z) = A_1 \exp(iqz) + A_2 \exp(-iqz) \quad (13)$$

and $$A_b(z) = B_1 \exp(iqz) + B_2 \exp(-iqz) \quad (14)$$

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

$$q = \pm\sqrt{\delta^2 - k^2} \quad (15)$$

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).

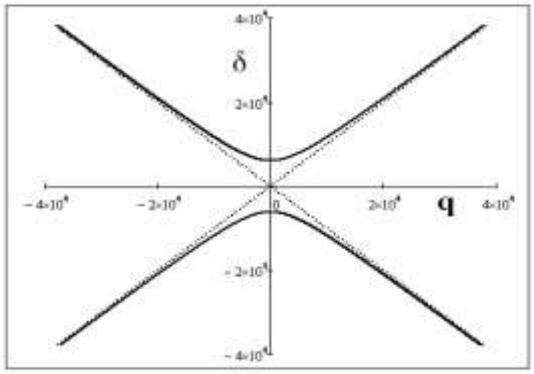

Figure 1: Dispersion curves showing variation of δ with q and the existence of the photonic bandgap for a fiber grating.

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 $|\delta|\leq\kappa$ 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. If the frequency detuning δ of the incident light falls outside the range $-\kappa<\delta<\kappa$ i. e. (outside the stop band but close to its edges) then light will be transmitted through the grating. The effective propagation constant of the forward and backward propagating waves can be written from Eqs. (1) and (13) is $\beta_e=\beta_B\pm q,$ where q is given by Eq. (15) and is a function of optical frequency through δ . This frequency dependence of β_e indicates that a grating will exhibit dispersive effects even if it was fabricated in a nondispersive medium. Expanding the parameter β_e in a Taylor series around the carrier frequency ω_0 of the wave, we get

$$\beta_e=\beta_0^g+(\omega-\omega_0)\beta_1^g+\frac{1}{2}(\omega-\omega_0)^2\beta_2^g+\frac{1}{6}(\omega-\omega_0)^3\beta_3^g+--- \quad (16)$$

where β_m^g is defined as

$$\beta_m^g=\frac{d^m q}{d\omega^m}\approx\left(\frac{1}{v_g}\right)^m\frac{d^m q}{d\delta^m}. \quad (17)$$

Is referred as mth order (with m =1, 2, 3....) dispersion parameter. Here, derivatives are evaluated at $\omega=\omega_0$. The superscript g correspond the grating. In the present work we have analyzed first, second and third order dispersion parameters. In Eq. (17), v_g is the group velocity of wave in the absence of the grating i.e ($\kappa=0$). Consider first the group velocity of the wave inside the grating as $V_G=1/\beta_1^g$ which can be calculated using Equation (17) as

$$V_G=\pm v_g\sqrt{1-\kappa^2/\delta^2}=c/n_0\sqrt{1-\kappa^2/\delta^2} \quad (18)$$

where the choice of ± signs depends on whether the wave is moving in the forward or the backward direction. Far from the band edges $(|\delta|>>\kappa)$, optical wave is unaffected by the grating and travels at the group velocity expected in the absence of the grating. However, as $|\delta|$ approaches κ , the group velocity decreases and becomes zero at the two edges of the stop band where $|\delta|=\kappa$.

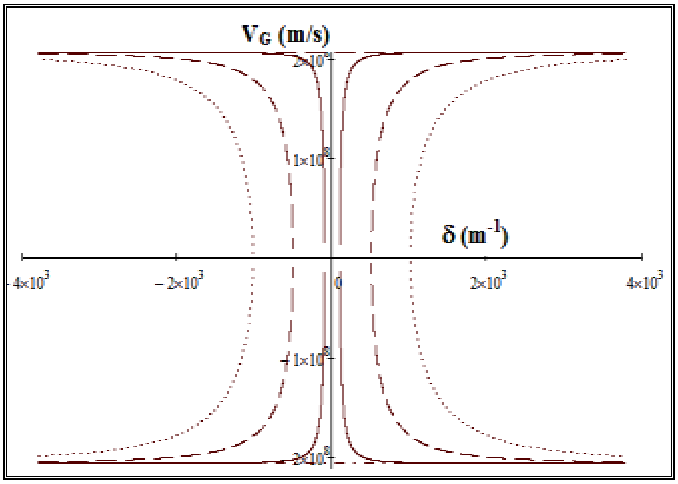

Figure 2: Curve showing variation of group velocity with in a fiber Bragg grating for three values of the coupling coefficient κ = 10 cm⁻¹ (dotted curve), κ = 5 cm⁻¹ (dashed curve) and κ = 1 cm-¹ (solid curve).

The group velocity curve of Equation (18) is illustrated in Fig. 2, for both an uniform medium (dashed line) and a periodic medium (solid line) for three values of the coupling coefficient $\kappa = 10$ cm^{-1} (dotted curve), $\kappa = 5$ cm^{-1} (dashed curve) and $\kappa = 1$ cm^{-1} (solid curve). Figure shows that close to the photonic bandgap, an optical wave experiences considerable slowing down inside a fiber Bragg grating.

III. DISPERSION PROPERTIES OF FBG

a) First Order Dispersion of the FBG

The first order dispersion parameter β_1^g represents dispersion of group velocity and this parameter is calculated using Equations (16) and (17) as

$$\beta_1^g == \left(\frac{1}{v_g}\right)\frac{dq}{d\delta} = \left(\frac{1}{v_g}\right)\frac{\delta}{q} \qquad (19)$$

The first order dispersion parameter is shown in Figure 3, where parameter β_1^g is plotted as a function of wavelength (λ) for three different values of the coupling coefficient $\kappa = 10$ cm^{-1} (dotted curve), $\kappa = 5$ cm^{-1} (dashed curve) and $\kappa = 1$ cm^{-1} (solid curve). In all such cases we have assumed effective index $n_0 \approx 1.451$, grating index $n_g \approx 0.0495\times10^{-3}$ and Bragg wavelength $\lambda_B \approx 1550$ nm. It is clear from the figure that under normal dispersion regime first order dispersion is higher for smaller coupling coefficient. While under anomalous dispersion regime behavior is opposite.

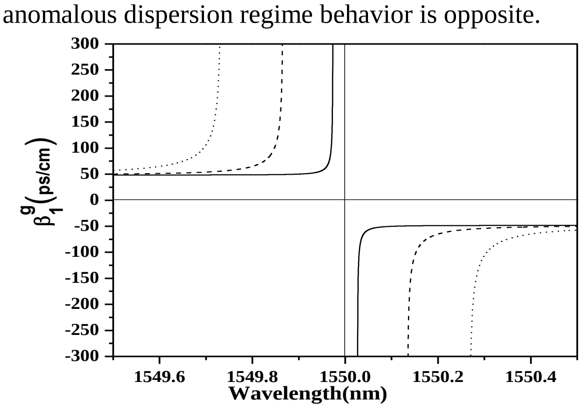

Figure 3: First order dispersion of FBG is plotted as a function of wavelength for three values of the coupling coefficient κ = 10 cm⁻¹ (dotted curve), κ = 5 cm⁻¹ (dashed curve) and κ = 1 cm⁻¹ (solid curve).

b) Second Order Dispersion of the FBG

The second order dispersion parameter β_2^g represents dispersion of group velocity and hence also called group velocity dispersion (GVD) parameter. This parameter is calculated as

$$\beta_2^g == \left(\frac{1}{v_g}\right)^2 \frac{d^2q}{d\delta^2} = \frac{\operatorname{sgn}(\delta)\frac{\kappa}{v_g^{\,2}}^2}{\left(\delta^2-\kappa^2\right)^{\frac{3}{2}}} \qquad (20)$$

The grating induced second order dispersion parameter β_2^g is shown in Figure 4, where GVD parameter β_2^g is sketched as a function of incident wavelength. The GVD exhibits two regimes, first for wavelength $\lambda < \lambda_R$ and $\beta_2^g > 0$, here the FBG is said to exhibit normal dispersion and second for wavelength $\lambda > \lambda_R$ and $\beta_2^g < 0$, where the FBG exhibit anomalous dispersion. In the normal dispersion regime, high-frequency components of an optical pulse travel slower than low-frequency (red-shifted) components of the same pulse. The opposite occurs in the anomalous dispersion regime where, low-frequency (red-shifted) components of an optical pulse travel slower than high-frequency (blue-shifted) components of the pulse.

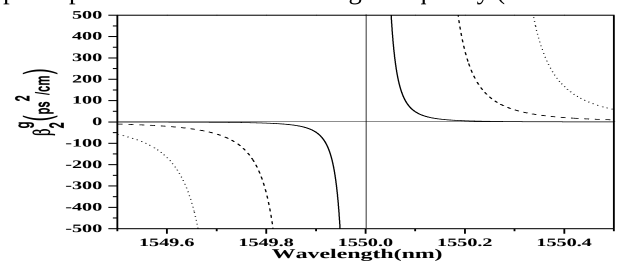

Figure 4: The second order dispersion parameter (GVD) of FBG is plotted as a function of incident wavelength for three different values of the coupling coefficient κ = 10 cm^{-1} (dotted curve), κ = 5 cm^{-1} (dashed curve) and κ = 1 cm^{-1} (solid curve).

The dispersion charaterstics of a fiber Bragg grating is relatively different than to the optical fiber. First, β_2^g changes sign on the two sides of the photonic band gap centered at the Bragg wavelength, whose position is easily varied and can be in any region of the optical band. This is in sharp contrast with GVD parameter β_2 for uniform optical fibers, which changes sign at the zero-dispersion wavelength that can be varied only in a range from 1300 nm to 1600 nm. Second, grating induced β_2^g is anomalous on the lower wavelength side of the band gap whereas β_2 for optical fibers becomes anomalous for incident wavelengths higher than the zero-dispersion wavelength. Third, the magnitude of β_2^g is higher than to GVD parameter β2 of optical fiber by a large factor. Also note that the grating induced GVD β_2^g becomes infinitely large at the two edges of the stop band.

c) Third Order Dispersion of the FBG

The third order dispersion parameter of fiber Bragg grating is given by β_3^g. The contribution of β_3^g is very small as compared to second order dispersion parameter β_2^g. But in the case of ultra-short optical pulse propagation in high speed optical communication, it is important to consider the parameter β_3 even when $\beta_2 \neq 0$. This parameter is obtained as

$$\beta_3^g = \frac{d^3q}{d\omega^{3.}} \approx \left(\frac{1}{v_g}\right)^3 \frac{d^3q}{d\delta^3} = \frac{3|\delta|\frac{\kappa}{v_g^{\,3}}^2}{\left(\delta^2-\kappa^2\right)^{\frac{5}{2}}} \qquad (21)$$

The third-order dispersion β_3^g induced by FBG is plotted as a function of incident wavelength in Figure 2.9.

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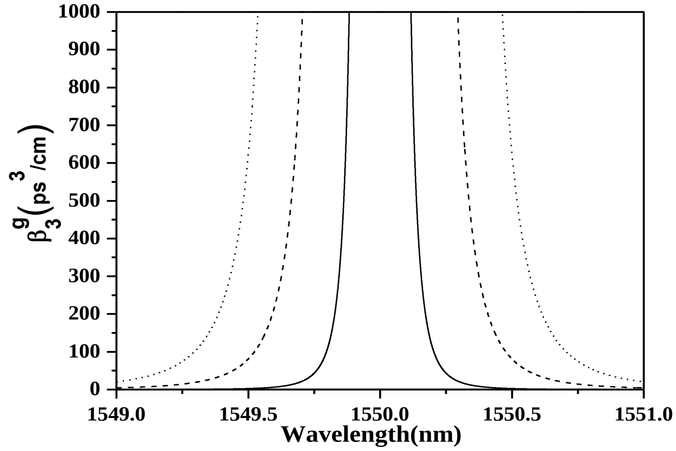

Figure 5: The third order dispersion parameter induced by FBG is plotted as a function of wavelength for three different values of the coupling coefficient κ = 10 cm⁻¹ (dotted curve), κ = 5 cm⁻¹ (dashed curve) and κ = 1 cm⁻¹ (solid curve).

From the Figure 2.9, it is observed that the third order dispersion parameter β_3^g remains positive on both sides of the stop band. The third-order dispersion of uniform optical fiber β_3 is always positive and distorts the optical pulse in optical fiber such that it becomes asymmetric with an oscillatory structure near one of its edges. Thus the second-order dispersion β_2 and third-order dispersion β_3 induced pulse broadening in optical fiber can be compensated by the grating induced GVD parameter β_2^g and third order dispersion.

IV. REFLECTION AND OPTICAL PHASE PROPERTIES OF FBG

a) Reflection Characteristics of FBG

In this section the spectral properties of FBG has been studied. 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:

$$(q-\delta)A_1 = \kappa B_1; \qquad (q+\delta)B_1 = -\kappa A_1 \qquad (22)$$

$$(q-\delta)B_2 = \kappa A_2; \qquad (q+\delta)A_2 = -\kappa B_2 \qquad (23)$$

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

$$A_f(z) = A_1 \exp(iqz) + r(q) B_2 \exp(-iqz) \qquad (24)$$

$$A_b(z) = B_2 \exp(-iqz) + r(q) A_1 \exp(iqz) \qquad (25)$$

where

$$r(q) = \frac{q-\delta}{\kappa} = -\frac{\kappa}{q+\delta} \qquad (26)$$

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.

The equation (24) and (25) 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. (24) and (25) applying the appropriate boundary conditions as

$$A_b(z=0) = 1 \text{ and } A_f(z=L) = 0 \qquad (27)$$

where L is the length of the grating. Equation (27) 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 6. 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

$$r_g = \frac{A_b(z=0)}{A_f(z=0)} = \frac{B_2 + r(q)A_1}{A_1 + r(q)B_2} \qquad (28)$$

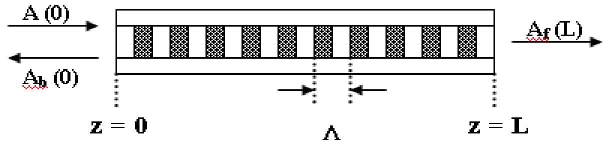

Figure 6: Schematic of a FBG of length L illuminated by electromagnetic field of amplitude A(z).

If we use the boundary condition $A_b(L) = 0$ in Eq. (25),

$$B_2 = -r(q)A_1 \exp(2iqL) \qquad (29)$$

Using Equation (26) and Equation (29) in Eq. (28), we obtained the reflection coefficient as

$$r_g = \frac{i\kappa \sin(qL)}{q\cos(qL) - i\delta \sin(qL)} \qquad (30)$$

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

$$R_g = \frac{\kappa^2 \sin^2(qL)}{q^2 \cos^2(qL) + \delta^2 \sin^2(qL)} \qquad (31)$$

Figure 7 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 and (3) L = 2.0 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. We refer to gratings with $\kappa L < 1$ as weak Bragg gratings, because in general they only reflect a fraction of the incident light. 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. For the gratings where the product κL exceeds 1, the spectral response has a plateau-like shape, as shown in Fig. 7. In this regime, the grating has a very high reflectivity within a band of frequencies called the stopband.

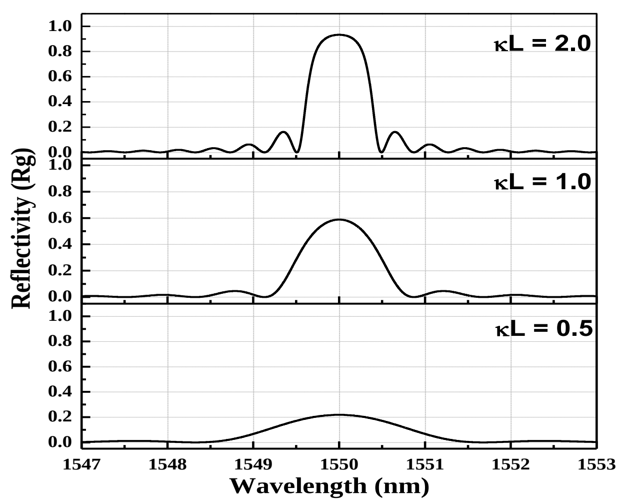

Figure 7: Calculated reflection spectral response as a function of wavelength for five different fiber Bragg gratings, with increasing lengths.

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. phase response of bragg grating

b) Optical Phase Characteristics of FBG

In previous subsections we have shown the reflection properties of fiber Bragg grating from the coupled mode theory. From Equation (30), it is observed that the reflection coefficient of FBG is a complex value and it can be written in phasor form as

$$r_g(\omega) = |r_g| \times \exp[i\phi_L(\omega)] \qquad (32)$$

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 .

$$|r_g|^2 = R_g = (X_L^2 + Y_L^2) \qquad (33)$$

$$\phi_L = 2\tan^{-1}\left(\frac{Y_L}{\sqrt{X_L^2 + Y_L^2} + X_L}\right). \qquad (34)$$

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

$$X_L = -\frac{\kappa\delta \sin^2(qL)}{q^2\cos^2(qL) + \delta^2\sin^2(qL)}, \qquad (35)$$

$$Y_L = \frac{q\kappa\sin(qL)\cos(qL)}{q^2\cos^2(qL) + \delta^2\sin^2(qL)} \qquad (36)$$

Finally, the phase of the reflected beal at length L in linear case can be written using Equation (34) as

$$\phi_L = 2\tan^{-1}\left(\frac{q\sin(2qL)}{2\sqrt{\sin^2(qL)}\sqrt{\delta^2 - \kappa^2\cos^2(qL)} - 2\delta\sin^2(qL)}\right) \qquad (37)$$

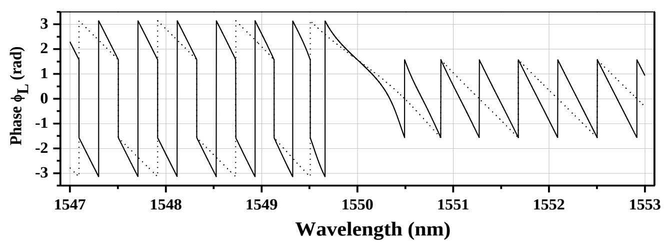

Figure 8: Variation in the phase (ϕ_L) of reflection coefficient (r_g) plotted as a function of wavelength for two values of grating strength $\kappa L = 1$ (dotted curve) and $\kappa L = 2$ (solid curve).

Figure 8 shows the variation in the optical 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.

V. Group Delay Response of FBG

Using this Equation the group delay experienced by the frequency component ω is calculated as

$$\tau_\rho = \frac{d\phi_L}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{d\phi_L}{d\lambda} \qquad (38)$$

Equation (38) shows the delay response of the grating. It is observed that we can easily vary the delay experienced by the frequency components by proper selection of the grating length and magnitude of induced index change. The rate of change of group delay with frequency determines the dispersion experienced by the frequency component. Thus the group velocity dispersion can be calculated as

$$D_\rho = \frac{d\tau_\rho}{d\lambda} = -\frac{\lambda}{\pi c}\frac{d\phi_L}{d\lambda} - \frac{\lambda^2}{2\pi c}\frac{d^2\phi_L}{d\lambda^2} \qquad (39)$$

This equation (39) shows the dependency of group velocity dispersion on the wavelength of incident wave inside the grating. The grating induced dispersion coefficient D_ρ determines the temporal broadening of the pulse, if $D_\rho < 0$ then grating shows the normal (positive) GVD and if $D_\rho > 0$ grating shows the anomalous (negative) GVD.

VI. Conclusion

The research work of this paper is to provide overview and applications of fiber Bragg grating device in the area of optical communication system as a dispersion compensator and optical filter. This paper summarized the basic dispersion, reflection and optical phase properties of fiber Bragg grating and its functionalities to be utilized in lightwave technology. We believe the present analytical study will be useful in future experimental work for the exploration of optical fiber Bragg grating based applications in all-optical signal processing.

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