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Optical Phase Alteration in Nonlinear Fiber Bragg Grating

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Abstract— The optical phase characteristics of fiber Bragg grating is studied under the influence of the Kerr nonlinearity. The expression of optical phase has been obtained analytically under nonlinear regime using coupled mode theory. The optical phase is studied by plotting the phase factor as a function of wavelength at various input intensities. The results show that the phase of the propagating beam is altered after specific excitation intensity. Such variation in the optical phase of beam can be utilizing the grating as a nonlinear device for optical phase modulator in all optical signal processing.

Keyword—Optical Phase, Transmittivity, Kerr Effect, Modulational Instabilities, Fiber Bragg Grating, Nonlinear Coupled Mode Equations.

I. INTRODUCTION

The development of the next generation all optical component based on fiber Bragg grating device has attracted a great deal of attention because of their importance in optical communication system. For complete knowledge of the spectral characteristics of the fiber Bragg grating, it is essential to know the amplitude and the phase response of the device. It is very easy to obtain the amplitude of the device from the coupled mode theory compared to the phase spectrum measurement. Several authors have proposed a method to calculate the phase, time delay and impulse response reconstruction from the complex reflection and transmission coefficient when FBG is operated under linear regime [1-3]. In linear regime it is found that the reflected and transmitted wave propagating in fiber Bragg grating maintains optical phase difference between zero or π radian.

Since the reflection and transmission characteristics of the grating depend on the effective refractive index of the fiber, hence, Kerr-like nonlinearity in the medium can alter the both amplitude and phase response of the grating. At high excitation intensity the reflection and transmission spectrum shift due to refractive index variation inside the grating. This property of the FBG is mainly used to make an optical tunable filter and optical switch in current photonic networks because of its high functionality and smallness [4]. Many interesting nonlinear phenomena such as optical bistability, multistability, optical switching, optical limiting, soliton propagation and pulse compression [5-9] have also been observed in FBG due to its intensity dependent refractive index change. But, the phase response of FBG at high excitation intensity is has not been given much attention.

In the present work, we focus our attention on analytical study of intensity dependent phase shift in an optical fiber Bragg gratings. Using the basic set of nonlinear coupled mode equations we have derived an expression for transmission coefficient of FBG and obtained real, imaginary and phase part of the transmitted wave. The result shows that the nonlinear phase increases stepwise with increasing input intensity and this phase modulation of the beam distorts the transmitted field to an extent such that the multiple switching states and optical pulsation occurs.

The present work deals with the analytical study of optical switching, optical transistor action and intensity dependent variation in peak reflectivity of fiber Bragg grating under nonlinear Kerr regime. Using nonlinear coupled mode equations, we have obtained the intensity dependent expression for reflectivity and peak reflectivity of fiber Bragg grating. The work in this paper summarizes as follows: In section II we describe the mathematical model to obtain the expression of nonlinear reflectivity and peak reflectivity. In Section III, The optical switching phenomena have been described by plotting the reflectivity as a function of input intensity. In Section IV the optical transistor characteristics of fiber Bragg grating has been examined. A intensity dependent peak reflectivity of FBG are presented in Section V. Using these expressions we have studied the peak reflectivity as a function of grating length at different input intensities.

II. THEORETICAL FORMULATION

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. The wave propagation in nonlinear FBG is governed by following NLCMEs [4]

$$i\frac{\partial A_f}{\partial z} + \delta A_f + \kappa A_b + \gamma(|A_f|^2 + 2|A_b|^2)A_f = 0,$$

(1)

$$-i\frac{\partial A_b}{\partial z} + \delta A_b + \kappa A_f + \gamma(|A_b|^2 + 2|A_f|^2)A_b = 0.$$

(2)

Here, δ, κ & γ are detuning parameter, coupling coefficient and nonlinear parameter, respectively and defined as.

$$\delta = 2\pi n\left(\frac{1}{\lambda} - \frac{1}{\lambda_B}\right),\ \kappa = \frac{\pi n_g}{\lambda_B} \text{ and } \gamma = \frac{2\pi n_2}{\lambda_B}.$$

In the following analysis we have solved the above NLCMEs analytically by neglecting higher order terms of backward propagating mode and solutions are obtained as [10]

$$A_f(z) = A_1 \exp(iS_1 z) + A_2 \exp(iS_2 z),$$

(3)

$$A_b(z) = B_1 \exp(iS_1 z) + B_2 \exp(iS_2 z).$$

(4)

With $S_1 = \frac{-\gamma I_0 + \sqrt{\gamma^2 I_0^{\ 2} + 4q_{nl}^2}}{2}$ & $S_2 = \frac{-\gamma I_0 - \sqrt{\gamma^2 I_0^{\ 2} + 4q_{nl}^2}}{2}$.

Here, $I_0 = |A_f|^2 + |A_b|^2$ is the input intensity at Bragg wavelength λ_B and q_{nl} is the nonlinear dispersion parameter in nonlinear Kerr regime and is defined as

$$q_{nl} = \pm\sqrt{q^2 + \delta\gamma\left(I_0 + 2|A_f|^2\right)},$$

(5)

where $q(=(\delta^2 - \kappa^2)^{1/2})$ is the linear dispersion parameter. It is clear from Equation (5) that the intensity of the input beam modifies the dispersion parameter and such modification affects the reflection and transmission characteristics of the grating. On substituting parameter q_{nl} in equations (3) and (4), the fields of forward and backward propagating modes take the forms

$$A_f(z) = A_1 \exp(iS_1 z) + t_{nl} B_2 \exp(iS_2 z)$$

(6)

$$A_b(z) = B_2 \exp(iS_2 z) + t_{nl} A_1 \exp(iS_1 z).$$

(7)

In the above equations, t_{nl} is the effective transmission coefficient under nonlinear regime and on mathematical simplification, one finds

$$t_{nl} = -\frac{\kappa}{S_1 + \delta + \gamma(I_0 + |A_f|^2)}.$$

(8)

Applying the proper boundary conditions, the nonlinear transmission coefficient (t_{ng}) for a grating of length L has been obtained by using equations (6) to (8) as

$$t_{ng} = \frac{A_f(z=L)}{A_f(z=0)} = \frac{(k'^2 - \kappa^2)\exp(iS_1 L)}{k'^2 - \kappa^2 \exp(ikL)}$$

(9) with $k' = \left(\frac{k}{2} + \tau\right)$,

$\tau = \delta + \gamma|A_f|^2$ and $k = \sqrt{\gamma^2 I_0^2 + 4q_{nl}^2}$.

Quite interestingly, the above formalism yields the expression for the transmittivity $T_{ng}\left(= |t_{ng}|^2\right)$ of the FBG acting like a nonlinear Fabry-Perot device as

(10) $$T_{ng} = \frac{1}{1 + \mathrm{F}\sin^2(\Phi/2)}$$

In the above expression, $F = 4k'^2\kappa^2/(k'^2 - \kappa^2)^2$ denotes the effective finesse, $\Phi = kL$ and L represents the length of the fiber Bragg grating. We also observe that the finesse of fiber Bragg grating cavity is intensity dependent and increases with increasing input intensity. From the complex transmission coefficient of Equation (9) one can calculate the phase of the fundamental beam as

$$\phi_{NL} = 2\tan^{-1}\left(\frac{Y_{NL}}{\sqrt{X_{NL}^2 + Y_{NL}^2} + X_{NL}}\right).$$

(11)

Here, terms X_{NL} and Y_{NL} represents real and imaginary parts of the complex nonlinear transmission coefficient which are obtained using Equation (12) as

$$X_{NL} = \frac{k'^4\cos(SL) + \kappa^4\cos(Sl - \Phi) - k'^2\kappa^2[\cos(SL - \Phi) + \cos(SL)]}{k'^4 + \kappa^4 - 2k'^2\kappa^2\cos(\Phi)}$$

(12)

$$Y_{NL} = \frac{k'^4\sin(SL) + \kappa^4\sin(Sl - \Phi) - k'^2\kappa^2[\sin(SL - \Phi) + \cos(SL)]}{k'^4 + \kappa^4 - 2k'^2\kappa^2\cos(\Phi)}$$

(13)

Also, L is the grating length, I_0 is the input intensity

III. Optical Phase Shift Analysis

In the previous section, we have obtained the expression for transmission coefficient and phase of the wave transmitted through the nonlinear fiber Bragg grating. On the basis of the theoretical formulations developed in the preceding sections (Equation 10 and 11), we have evaluated the previous derived formulism by plotting the transmittivity, transmitted intensity and phase with input intensity in Figure 1. Looking to the potentiality of the chalcogenide glass as FBG materials for nonlinear applications, we have made the numerical analysis with physical parameters of chalcogenide glass as effective index n_{eff} = 2.45, change in grating index $n_g = 3\times10^{-4}$, nonlinear Kerr coefficient $n_2 = 2.7\times10^{-17}$ m^2/W. The length of the grating L = 2 cm and Bragg wavelength λ_B = 1550 nm were chosen. In numerical analysis, we have illuminated a light at wavelengths λ = 1550.20 nm (dashed curve), λ=1550.40 nm (doted curve) and λ=1550.60 nm (solid curve) which are considered slightly higher then the Bragg wavelength but are lying inside the stop band of the Bragg grating. The variation in transmittivity, transmitted intensity and phase ϕ_{NL} as a function of input intensity is shown in Fig. 1(a), 1(b) and 1(c), respectively for various detuning wavelength .

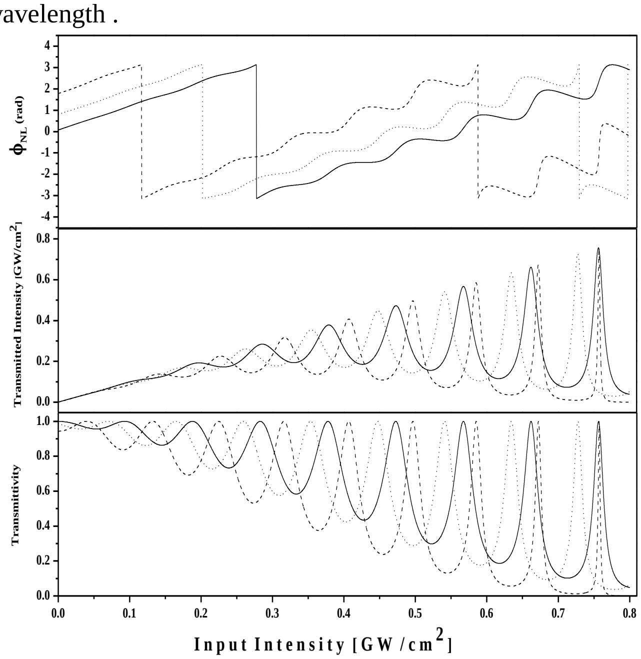

Figure 1: Variation in (a) the transmittivity (b) the transmitted intensity and (c) the nonlinear phase shift ϕ_{NL} as a function of input intensity for various detuning 1550.2 nm (dashed curve), 1550.4 nm (doted curve) and 1550.6 nm (solid curve).

A stepwise variation change is also obtained with increasing intensity shown in Fig. 1(c). It is found that if we operate the grating on the wavelengths upper to the Bragg wavelength, the strong oscillations in the transmittivity is observed as an exponentially growing function with increasing input intensity shown in Fig. 1(a). Due to the strong oscillations in the transmittivity, the transmitted field showing self pulsation in the input beam which is illustracted in Fig. 1(b) plotting the transmitted intensity with incident intensity. However, since the grating is already tuned at Bragg wavelength, the transmission is high at low intensity. If we increase the intensity of the input beam, the intensity induced redshift of the Bragg wavelength detunes the device further from Bragg resonance. As a consequence, bistability and multistability disappears and self pulsation occurs only at high excitation intensity. Such self pulsation can be considered in terms of many gap solitons formation inside the stopband of the grating. In 1998 Broderick et al. [14] has observed experimentally five gap soliton at a particular input intensity when the wavelength of the incident beam is tuned inside the photonic bandgap of fiber Bragg grating. They suggested that the bistable switching is associated with the formation of gap soliton inside the grating. In the present analysis, we observed a unique nonlinear feature is the stepwise variation in the phase with intensity. The large phase shift of the fundamental beam is possible due to the incorporating the Kerr nonlinearity in the medium $\phi_{NL} \propto n_2$. But, we conclude that the n_2 description is appropriate for the increasing the phase but it is not complete gives the details for the stepwise variation of the phase. The key variable for stepwise variation is the nonlinear phase change itself due to the sum and difference frequency generation inside the grating similar to the second harmonic generation process observed in nonlinear medium by Stegeman et al. in 1993 [15].

IV. Optical Phase Alteration Analysis

On the basis of the theoretical formulations developed above (Eqs. 11) for optical phase of FBG at high excitation intensity, we have plotted the optical phase as functions of wavelength at various input intensities of (a) 1 MW/cm^2 (b) 100 MW/cm^2 (c) 200 MW/cm^2 and (d) 400 MW/cm ^{2} in Figures 2.

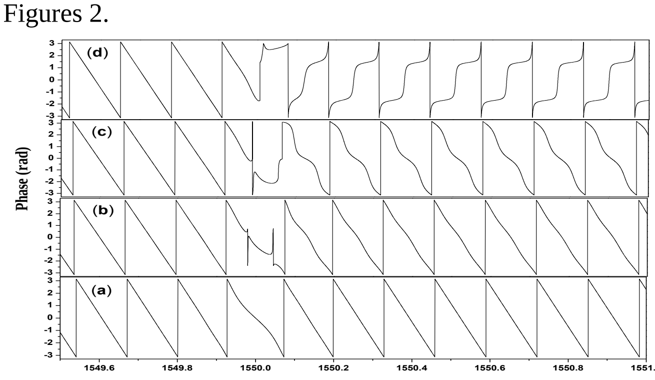

Figure 2: Optical phase as a function of wavelength at different input intensities of (a) 1 MW/cm^2 (b) 100 MW/cm^2 (c) 200 MW/cm^2 and (d) 400 MW/cm ^{2}.

The CW laser source in C-band (1535 –1565 nm) is assumed as the light source. All the results presented here are for chalcogenide FBG having effective refractive index n_{eff} = 2.45, change in grating index $n_g = 1\times10^{-4}$, nonlinear Kerr coefficient $n_2 = 2.7\times10^{-17}$ m^2/W. The length of the grating is taken as L = 7.5 mm and the wavelength is considered in the range 1549.5 nm to 1551 nm. We have considered the chalcogenide glass as FBG material due to high value of nonlinear Kerr coefficient n_2 in such glasses. The intensity dependent optical phase of FBG is plotted in Figure 2 using the above mentioned material parameters for $\kappa L \approx 1.5$. In these figures, the curves a, b, c and d represents the optical phase at incident intensities of 1 MW/cm^2, 100 MW/cm^2, 200 MW/cm^2 and 400 MW/cm^2, respectively It is clear from the Figure 2 that at higher input intensity, the phase of beam ϕ_{NL} is altered due to the contribution of intensity dependent refractive index change. One can also notice a few more important features from Figure 2 such as (i) At an input intensity of 1 MW/cm^2 (Figure 2(a)), the behaviour of FBG is linear and phase of the beam is vary due to the periodicity of the device at only Bragg wavelength and span of bandwidth of FBG. (ii) For input intensity lying between 100 and 200 MW/cm^2, the phase shows stepwise fashion for the wavelength which are lying above the Bragg wavelength λ_B (Figure 2(b) and 2(c)). (iv) At around 400 MW/cm^2 (Figure 2 (d)) the phase of beam in FBG is show intense stepwise for entire band (1550 nm -1551 nm). It is expected that at sufficiently high input intensity, large amount of nonlinearity is introduced in the medium which not only vary the phase but also revert the phase of the transmitted beam.

V. Conclusion

We have explored the optical phase characteristics of the fiber Bragg grating in the presence of Kerr nonlinearity in the medium. A complete nonlinear analysis of the device is provided using the nonlinear coupled mode theory. We inferred that the introduction of the Kerr nonlinearity in the system increases the optical phase shift in a stepwise fashion with increasing input intensity. These stepwise variation in phase of the grating will be very helpful in designing fiber Bragg grating based nonlinear optical devices such as optical phase modulator, multibit optical memory element and optical pulse generator. Also the at high input intensity the optical phase is altrerd. The results show that the phase of the propagating beam is altered with input intensity. We hope that such estimates may provide a valuable tool for determining the feasibility of future experimental work for the development of nonlinear optical components to be used in optical communication system.

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