Investigation on Reflection of Brillouin Dynamic Grating in Single Mode Optical Fibers

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Abstract— The theory of static fiber Bragg grating was used to investigate the phenomenon that the perturbation of the refractive index modulated during the process of SBS which named as Brillouin dynamic gratings in optical fibres. Then the reflection of Brillouin dynamic gratings are studied and simulated by the coupled-mode theory in single-mode optical fibers. It is shown that the reflectivity becomes larger and the FWHM becomes narrower with the length of Brillouin dynamic grating increasing. However, with the increasing of refractive index modulation, the reflectivity becomes larger and the FWHM becomes broad. Additionally, the maximum reflectance red-shifts with the increase of core index. Finally, the maximum reflectivity is 0.9329 when the length of Brillouin dynamic grating is 100 meters and the refractive index modulation is 1×10^{-8}.

1. INTRODUCTION

Optical fiber gratings is manufactured by the photosensitive characteristic of fiber, the refractive index of fiber core is modulated periodicity, where will occurred coherence reflection when the frequency have coincidence with phase-matching condition during incident light. With this special property and the advantage of optical fiber such as low losses, anti electromagnetism etc. It have developed into a mature technology with a wide range of applications in various areas, including physical sensing for temperature, strain, acoustic waves and pressure.

Stimulated Brillouin scattering (SBS) is a nonlinear process that can occur in optical fibers, which can be described classically as a nonlinear interaction between the pump and Stokes fields through an acoustic wave. The pump field generates an acoustic wave through the process of electrostriction. The acoustic wave in turn modulates the refractive index of the medium. This pump-induced index grating scatters the pump light through Bragg diffraction. Scattered light is downshifted in frequency because of the Doppler shift associated with a grating moving at the acoustic velocity v_a which is called Brillouin dynamic gratings (BDG).

In 2008, Song et al. [1] reported BDG in polarization-maintaining (PM) fibers. Dong et al. [2] analyzed BDG in PM fibers and pointed out that BDGs were weak gratings in 2010. The four-wave mixing model was given to demonstrate the characteristics of BDG by Zhou et al. [3] in 2011, moreover, they showed that the conventional grating model is too to describe BDG. L. Thevenaz et al. [4, 5] demonstrated a novel technique for BDG by modulating two pump waves and investigated its application. Meanwhile, the reflection spectrum of BDG was calculated by S. N. Jouybari et al. [6]. And in 2013, a model of BDG was presented by Primerov et al. [7]. The characteristics of BDG were discussed in dynamic-state conditions detailedly. In 2014, Dong et al. [8] proposed an ultrahigh-resolution optical spectrometry based on BDG. But so many theory research on BDG is based on four-wave mixing model.

In this letter, the theory of static fiber Bragg grating was used to investigate the phenomenon that the perturbation of the refractive index modulated during the process of SBS. Then the reflection of Brillouin dynamic gratings are studied and simulated by the coupled-mode theory in single-mode optical fibers. some interested results are obtained, and these results provide a theoretical basis for design and application of new optical devices.

2. THEORY MODEL

2.1. The Refractive Index of BDG in Single Mode Optical Fibers

The diagram of the BDG model is shown in Figure 1. Let us denote the optical waves vector $\vec{k}_i$, frequency ω_i, amplitude A_i, power P_i, $i = 1$ is pump1 optical wave, $i = 2$ is pump2 optical wave, $i = 3$ is probe wave, $i = 4$ is reflected wave respectively. And $\omega_1 = \omega_3$. Pump1 and pump2 are the same polarization state, probe wave and reflected wave are the same polarization state which is orthogonal to Pump1 and pump2. Acoustic wave1 is produced by the interaction of Pump1 and pump2, whose waves vector and frequency is $\vec{q}_1$, Ω_1 respectively. Acoustic wave2 is generated by

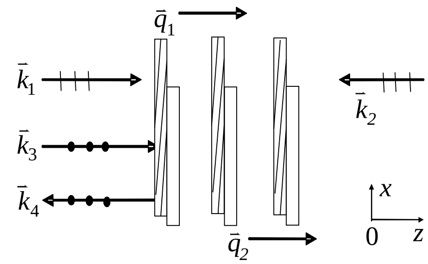

Figure 1: Diagram of the BDG model.

probe wave and reflected wave, $\vec{q}_2$, Ω_2 are its waves vector and frequency. Where $\vec{q}_1 = \vec{k}_1 - \vec{k}_2$, $\Omega_1 = \omega_1 - \omega_2$, $\vec{q}_2 = \vec{k}_3 - \vec{k}_4$, $\Omega_2 = \omega_3 - \omega_4$. Acoustic wave1 and Acoustic wave2 are propagating along the $+z$ direction. we describe the acoustic field in terms of the material density distribution. Acoustic wave1 and Acoustic wave2 can be expressed as

$$\tilde{\rho}_1(z,t) = \rho_0 + \left[\rho_1(z,t)e^{i(q_1 z - \Omega_1 t)} + c \cdot c\right] \tag{1}$$

$$\tilde{\rho}_2(z,t) = \rho_0 + \left[\rho_2(z,t)e^{i(q_2 z - \Omega_2 t)} + c \cdot c\right] \tag{2}$$

ρ_0 denotes the mean density of the medium. The material density obeys the equation [10]

$$\frac{\partial^2 \tilde{\rho}}{\partial t^2} - \Gamma' \nabla^2 \frac{\partial \tilde{\rho}}{\partial t} - v^2 \nabla^2 \tilde{\rho} = \nabla \cdot \vec{f} \tag{3}$$

where v is the velocity of the acoustic wave, Γ' is damping parameter and $\vec{f}$ is. We assume that $\Omega_1 = \Omega_2 = \Omega$. Then, under the conditions of steady-state, the variation of density that caused by acoustic wave are as follows

$$\rho_1(z,t) = \varepsilon_0 \gamma_e q_1^2 \frac{A_1 A_2^*}{\left(\Omega_B^2 - \Omega^2 - i\Omega\Gamma_B\right)} \tag{4}$$

$$\rho_2(z,t) = \varepsilon_0 \gamma_e q_2^2 \frac{A_3 A_4^*}{\left(\Omega_B^2 - \Omega^2 - i\Omega\Gamma_B\right)} \tag{5}$$

where ε_0, γ_e, Ω_B, Γ_B are the permittivity of free space, electrostictive constant, Brillouin frequency and Brillouin linewidth respectively. Since $\vec{q}_1$, $\vec{k}_1$, $\vec{k}_2$ and $\vec{q}_2$, $\vec{k}_3$, $\vec{k}_4$ can be regarded as two nonlinear process of SBS, considering about that the speed of acoustic wave without polarization is much smaller than the light, thus the variation of density that caused by acoustic wave is given by

$$\rho(z,t) = \varepsilon_0 \gamma_e q^2 \frac{A_1 A_2^* + A_3 A_4^*}{\left(\Omega_B^2 - \Omega^2 - i\Omega\Gamma_B\right)} \tag{6}$$

Due to the refractive index disturbance to the density is $\Delta n = \frac{\gamma_e}{2n_0\rho_0}\rho(z,t)$. Refer to the literatures [7, 11], the variation value of refractive index modulation in fibers should be expressed as

$$\Delta n = \frac{4\pi^2 \gamma_e^2 n_{eff}\left(\sqrt{P_1 P_2} + \sqrt{P_3 P_4}\right)}{n_0 \rho_0 \Omega_B \lambda_p^2 c_0 \Gamma_B A_{eff}} \tag{7}$$

where n_0 is the refractive index of the fiber core, n_{eff} is the effective mode index, λ_p is the wavelength of the pump1, c_0 is the speed of light in vacuum, A_{eff} is the acoustic-optic effective area.

2.2. The Improved Theory of Moving Gratings

We assume that the BDG can be treated as a weak uniform fiber Bragg grating with zero "dc" index and without grating chirp, the change of time can be neglected in steady-state conditions. Moreover, pump1, pump2 and probe wave are continuous wave with undepleted. Based on the theory of grating we can get the expression of probe wave and reflected wave

$$\frac{dA_3}{dz} = i\kappa A_4 e^{-i\Delta qz} \tag{8}$$

$$\frac{dA_4}{dz} = -i\kappa A_3 e^{i\Delta qz} \tag{9}$$

where $\kappa = \frac{2\pi}{\lambda}\Delta n$, $\Delta q = |\vec{q}_1 - \vec{q}_2|$. The reflectivity could be solved by Equations (8) and (9) along with the boundary conditions $A_3|_{z=0} = A_3(0)$ and $A_4|_{z=L} = A_4(L) = 0$.

$$R_{BDG} = \frac{\sinh^2(sL)}{\cosh^2(sL) - \left(\frac{\Delta q}{2\kappa}\right)^2} \tag{10}$$

With $s^2 = \kappa^2 - (\frac{\Delta q}{2})^2$, L is the length of the BDG, Under phase-ma,hing condition $\Delta q = 0$, the maximum reflectivity could be expressed as

$$R_{\max} = \tanh^2(\kappa L) \tag{11}$$

For the power of the reflected wave is caused by probe wave, the Equation (7) could rewrite as

$$\Delta n = \frac{4\pi^2\gamma_e^2 n_{eff}\left(\sqrt{P_1P_2} + \sqrt{\theta}P_3\right)}{n_0\rho_0 c_0\Omega_B\lambda_p^2\Gamma_B A_{eff}} \tag{12}$$

where $\theta = R_{\max}|_{P_3=0}$.

3. NUMERICAL SIMULATION AND RESULT DISCUSSION

3.1. The Reflectance of BDG with Low Pump Power

In the numerical simulations, we use the same parameters in reference [3], such as $\gamma_e = 0.902$, $c_0 = 3 \times 10^8$ m/s, $\rho_0 = 2210$ kg/m^3, $A_{eff} = 80$ µm^2, $\Omega_B/2\pi = 10875$ MHz, $\Gamma_B/2\pi = 30$ MHz, $\lambda_P = 1550$ nm, $L = 13$ m. Then the maximum reflectivity of the BDG varied with P_1, P_2 and P_3 is in Figure 2, Figure 3 and Figure 4, respectively. In Figure 2, $P_2 = 10$ mW, $P_3 = 100$ mW. $P_1 = 110$ mW, $P_3 = 63$ mW in Figure 3. And $P_1 = 110$ mW, $P_2 = 11$ mW in Figure 4.

Figure 2, Figure 3 and Figure 4 illustrate that a larger maximum reflectivity can be obtained by larger power which can be seen from Equation (11) and Equation (12). Because the value of refractive index modulation is caused by the test power, so the maximum reflectivity increases with the test power increasing. The trends of simulated results agrees very well with the results of Zhou et al. [3]. These results suggest that the BDG with Polarization-decoupled can be seen as the instructional outcome of two SBS processes in two orthogonal directions.

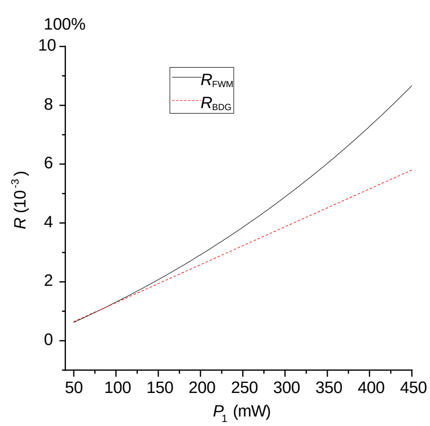

Figure 2: The reflectivity varies with P_1 for $P_2 = 10$ mW, $P_3 = 100$ mW.

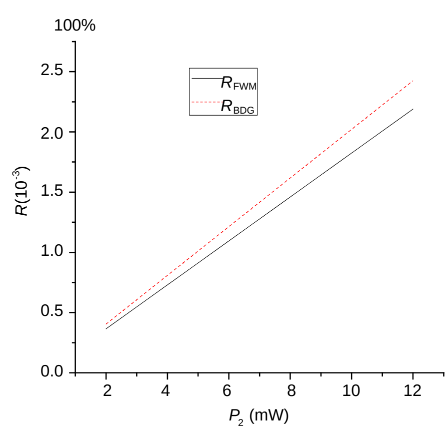

Figure 3: The reflectivity varies with P_2 for $P_1 = 110$ mW, $P_3 = 63$ mW.

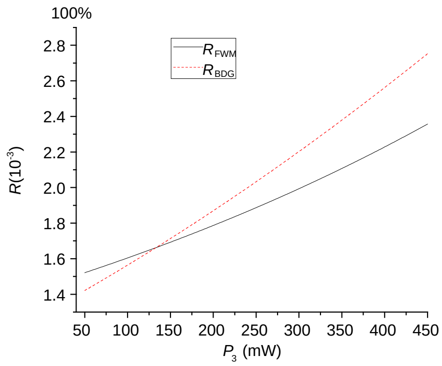

Figure 4: The reflectivity varies with P_2 for $P_1 = 110\,\mathrm{mW}$, $P_2 = 11\,\mathrm{mW}$.

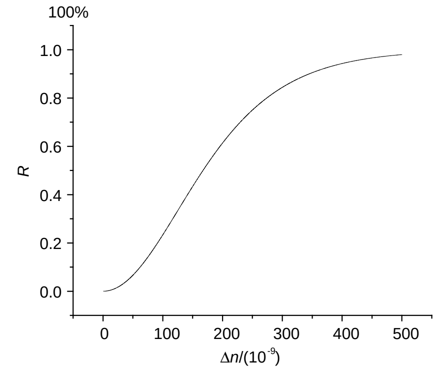

Figure 5: The relation between $R_{\max}$ and Δn.

3.2. The Maximum Reflectivity with Various Refractive Index Modulation

To demonstrate the relation between the maximum reflectivity and various refractive index modulation, $\Delta n \approx 0.23 \times 10^{-9}$ is obtained from Equation (12) when $P_1 = 110\,\mathrm{mW}$, $P_2 = 10\,\mathrm{mW}$, $P_3 = 306\,\mathrm{mW}$. Its keeps consistent with the prevenient related literatures [12, 13]. Figure 5 shows the curves of the maximum reflectivity and various refractive index modulation when Δn varies from 0.1×10^{-9} to 5×10^{-8}. It is indicated that the maximum reflectivity increases with the increase of refractive index modulation. The maximum reflectivity agrees well with the simulations by Dong et al. [14] at large pump power.

4. CONCLUSION

Based on the theory of gratings, the improved model of the BDG is given. The simulate results agrees well with the results of Four-wave Mixing method. Meanwhile the relationship between the maximum reflectivity and various refractive index modulation is studied. It has been realized that the larger refractive index modulation the higher maximum reflectivity. This paper may provide a theoretical basis for the design and application of new optical devices.

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