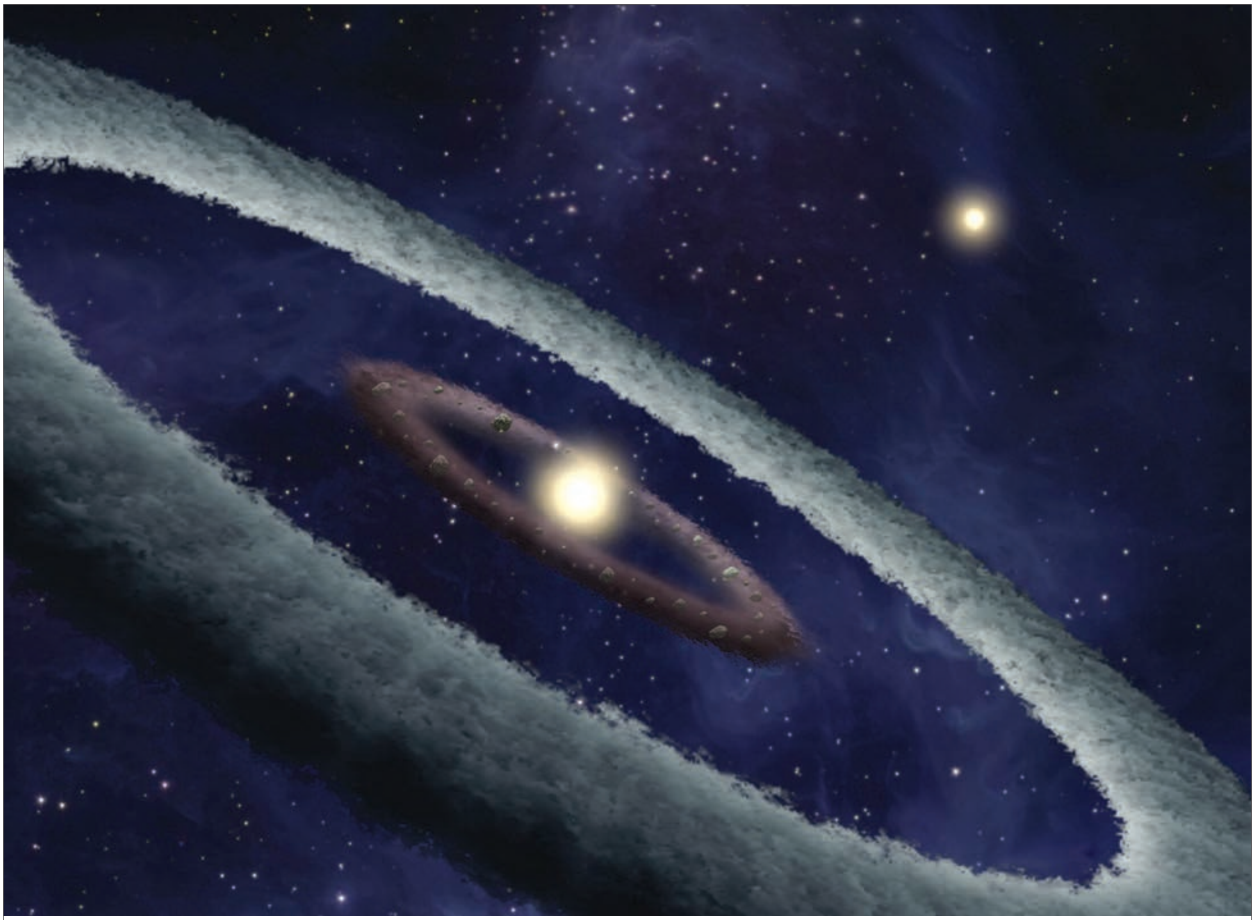

Research Journal of

Physics

ISSN 1819-3463

Academic
Journals Inc.

www.academicjournals.com

Research Journal of Physics 7 (1): 9-16, 2013
ISSN 1819-3463 / DOI: 10.3923/rjp.2013.9.16
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Reflectivity of the Linear and Nonlinear Gamma Irradiated Apodized Chirped Bragg Grating under Ocean

[1,2]Taymour A. Hamdalla
[1]Department of Physics, Faculty of Science, Tabuk University, Tabuk, Saudi Arabia
[2]Department of Physics, Faculty of Science, Alexandria University, Alexandria, Egypt

ABSTRACT

The reflectivity of the fiber Bragg grating under different external effectors is discussed. The effect of Co^{60} gamma radiation on the effective refractive index of nine profile of apodized chirped Bragg grating has been studied, comparisons between the reflectivity of the gamma irradiated and non irradiated fiber Bragg grating has been investigated. The electric field of these signals in the apodized chirped Bragg grating is first calculated from which, the new values of the refractive index are determined. The nonlinear effects appear on the reflectivity of traveling signals. The grating is also affected by the undersea level temperature and pressure. The irradiated Sinc profile is the profile having the greatest reflectivity ($R \approx 0.99$ in the nonlinear case).

Key words: Reflectivity, apodized profiles, bragg grating, ocean depth

INTRODUCTION

Apodized chirped Bragg grating have become one of the preferred derives in many application. Such as the temperature sensing, Wavelength Division Multiplexing (WDM) and dispersion compensation. A Fiber Bragg Grating (FBG) is a wavelength selective fiber optic component. Its operation relies on the periodic modulation of the refractive index inside the core refractive index (Dtolen, 1991).

Optical system present in a radiation field suffers from uncharacteristic behavior that is related to the radiation. The background environment plays a role in the variation of the systems normal parameters. For example, undersea cables are exposed to an accumulation dose in the range of 2.5 and 25 rad during the work life (Medhat *et al.*, 2002). FBG is proving to be one of the most important recent developments in the field of the optical fiber technology. FBGs basically constitute generalized distributed reflectors whose reflection spectra and dispersion characteristics are wavelength-dependent and can be accurately adjusted by proper design. It is important in some applications to lower and if possible eliminate the reflectivity of these side lobes, or to apodized the reflection spectrum of the grating (Hinton, 1998). For example, in the Dense Wavelength Division Multiplexing (DWDM), it is important to have a very high rejection of the nonresonant light in order to eliminate cross talk between information channels, and therefore, apodization becomes necessary.

Any change in the fiber properties, such as strain, temperature, or pressure which varies the modal index or grating pitch, will change the Bragg wavelength (Mahran *et al.*, 2009). Therefore, this change is studied in the following, including undersea fiber cables that use Wavelength Divisions Multiplexing (WDM) techniques. Both linear and nonlinear fibers are taken into consideration.

MATHEMATICAL MODEL

The refractive index of the fiber n_o can be calculated from (Medhat *et al.*, 2002):

$$n^2 = A(T,\gamma) + \frac{B(T,\gamma)\lambda^2}{\lambda^2 - C(T,\gamma)} + \frac{D(T,\gamma)}{\lambda^2 - E} \tag{1}$$

where, T is the temperature in K, γ is the total dose in MGy, E is constant =100 μm:

$$A(T,\gamma) = A(\gamma)F_A(T), B(T,\gamma) = B(\gamma)F_B(T), C(T,\gamma) = C(\gamma)F_C(T) \text{ and } D(T,\gamma) = D(\gamma)F(T) \tag{2}$$

Also:

$$\begin{aligned} A(\gamma) &= 1.329631 + 2.7\times10^{-4}\exp\left(\frac{\gamma}{0.319319}\right) \\ B(\gamma) &= 0.82863 + 7.7\times10^{-4}\exp\left(\frac{\gamma}{0.440013}\right) \\ C(\gamma) &= 0.01105 + 4.7\times10^{-6}\exp\left(\frac{\gamma}{0.391139}\right) \\ D(\gamma) &= 0.98481 + 11\times10^{-3}\exp\left(\frac{\gamma}{0.964626}\right) \end{aligned} \tag{3}$$

where, A, B, D are dimensionless while C and E are in μm^2:

$$\begin{aligned} F_A(T) &= \frac{1.3389822 - 3.7\times10^{-4}(T-T_o)}{1.338922} \\ F_B(T) &= \frac{0.819526 - 3.3843\times10^{-4}(T-T_o)}{0.819526} \\ F_C(T) &= \frac{0.011127 - 3.1\times10^{-6}(T-T_o)}{0.011127} \\ F_D(T) &= \frac{1.0155995 - 2.8\times10^{-3}(T-T_o)}{1.055995} \end{aligned} \tag{4}$$

where, $0.1\leq\gamma$, $MGy\leq1$, T_0 = 298 K.

The refractive index along the grating length varies periodically in the form (Andreas and Kalli, 1999):

$$n(z) = n_o + n_1(z).\cos\left[\frac{2\pi}{\Lambda}z + \phi(z)\right] + n_2E^2(z) \tag{5}$$

where, E(z) is the electric field, n_o is the average refractive index change of the fiber core, $n_1(z)$ is the amplitude of periodic index change, n_2 is the nonlinear Kerr coefficient, Λ is the Bragg period and Φ(z) describes the phase shift.

The electric field inside the grating can be written as:

$$E(z,t) = [A_f(z,t)\exp(ikz) + A_b(z,t)\exp(-ikz)]\exp(i\omega_0 t) \tag{6}$$

where, A_f and A_b are the envelope functions of the forward and backward traveling waves, both of which are assumed to be slowly varying in space and time, ω_o is the carrier frequency at which the pulse spectrum is initially centered and k is the propagation constant.

Using the coupled mode theory of Lam and Garside that describes the reflection properties of the FBG, the reflectivity of a grating with constant modulation amplitude is given by Aitchison *et al.* (1990):

$$R(l,\lambda) = \frac{\Omega^2 \sin h^2(sl)}{\Delta k \sin h^2(sl) + s^2 \cos h^2(sl)} \tag{7}$$

where, $R(l,\lambda)$ is the reflectivity that is a function of the grating length, l and wavelength, λ. $\Delta k = k\text{-}\pi/\lambda$ is the detuning wave vector and $s^2 = \Omega^2\text{-}\Delta k^2$.

The coupling coefficient, Ω, for sinusoidal variation of index perturbation along the fiber axis is given by:

$$\Omega = \frac{\pi \Delta n}{\lambda} M_p \tag{8}$$

where, M_p is the fraction of the fiber mode power contained by the fiber core. On the basis that the grating is uniformly written through the core, M_p can be calculated:

$$M_p = 1 - V^{-2} = 1 - \left[(\frac{2\pi}{\lambda}) a (n_o^2 - n_{cl}^2)^{1/2} \right]^{-2} \tag{9}$$

where, V is the normalized frequency of the fiber, a is the core radius, n_{co}, n_{cl}, respectively, the core and cladding indices. At the Bragg center wavelength, there is no detuning wave vector and $\Delta k = 0$. Therefore, the expression for the reflectivity becomes:

$$R(l,\lambda) = \tan h^2(\Omega l) \tag{10}$$

The main apodization profiles considered in the present investigation are (Eggleton *et al.*, 1996), Sine profile, Sinc profile, Positive-tan h profile, Blackman profile, Gauss profile, Hamming profile, Cauchy profile, Bartlett profile and Raised sine profile.

RESULTS AND DISCUSSION

The apodization of the fiber gratings using a phase shift mask with variable diffraction efficiency. A cosine apodization technique obtained by repetitive, symmetric longitudinal stretching of the fiber around the center of the grating, while the grating was written, has been recently reported by Hill and Meltz (1997).

Figure 1 shows the core refractive index as a function of dose at a specified wavelength and temperature, and it is clear from the figure that the core refractive index with increase exponentially with the dose increase. Which affect all the parameters related it.

The existence of any fiber cable under ocean depth acts to change the behavior of this cable, because of the temperature decrease and the pressure increase. One of our aims in this thesis is to

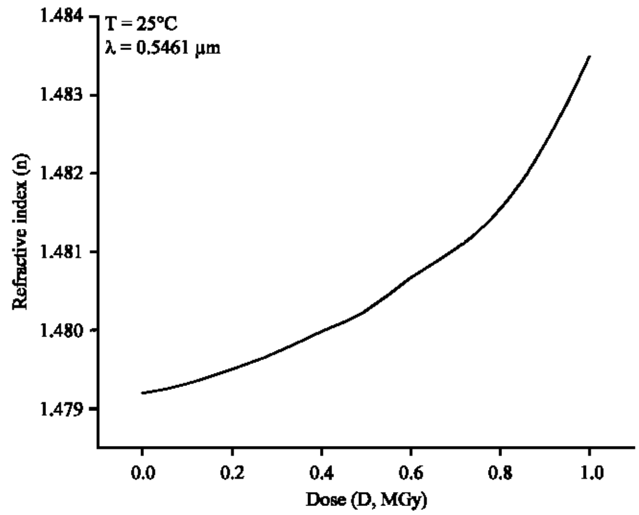

Fig. 1: Core refractive index variation with the gamma dose

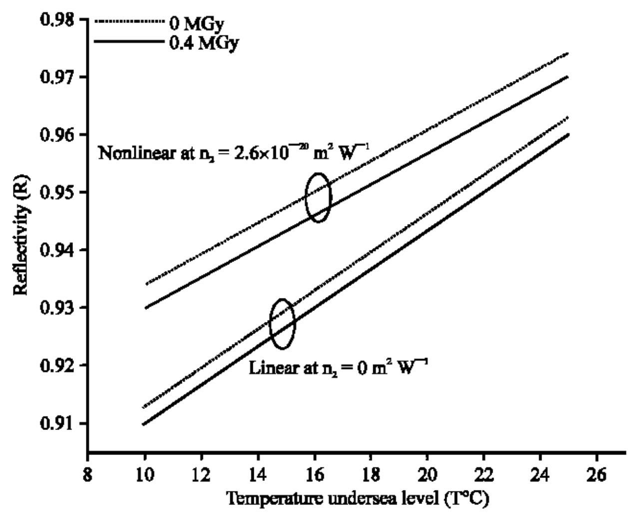

Fig. 2: Effect of the temperature on the reflectivity with temperature undersea level in the linear and nonlinear cases of the apodized chirped grating (sine profile) at wavelength 0.5461 μm

study the reflectivity of the apodized Chirped Bragg grating under ocean depth. Under the ocean depth there is a lot of sources that could emits gamma radiation with low activity. The undersea effect will be added to the radiation effect which leads to the total change.

The nonlinear reflection of optical pulses in a chirped FBG is also studied by Lenz (1998). The reflectivities of the Bragg wavelength has been discussed by Mahran *et al.* (2009). The effect of radiation by gamma source is discussed by Gusarv *et al.* (2002).

Temperature effect on the gamma irradiated FBG: Figure 2 shows the variation of the reflectivity with the temperature under sea level for a reflected wavelength (λ = 0.5461 μm) of the signal traveling in the chirped FBG in the linear and nonlinear cases for the sine profile. The variations of the reflectivity have been calculated under the effect of the temperature range (10-25°C). Figure 2 also shows the comparison between the irradiated and no irradiated for sine

Table 1: The maximum values of reflectivity (R_{max}) for the different profiles in the linear and nonlinear cases at different temperatures, under 0.4 MGy of the gamma radiation

	Linear case $n_2 = 0\ m^2\ W^{-1}$		Nonlinear case $n_2 = 2.6\times10^{-20}\ m^2\ W^{-1}$	
Profile	R_{max} at 25°C	R_{max} at 10°C	R_{max} at 25°C	R_{max} at 10°C
Blackman	0.93	0.92	0.98	0.96
Cauchy	0.92	0.90	0.96	0.94
Sinc	0.94	0.92	0.98	0.96
Sine	0.92	0.91	0.99	0.96
tan h	0.88	0.87	0.91	0.89
Gauss	0.91	0.90	0.95	0.94
Hamming	0.90	0.89	0.91	0.88
Bartlett	0.90	0.89	0.92	0.90
Raised Sine	0.91	0.90	0.96	0.94

profile with the high power signals and low power signals. The chosen dose is about 0.4 MGy which is creating a change in the refractive index for about 0.02 leads to an increase in the reflectivity about 0.03. This radiation is energy that caused perturbation of molecules that lead to increase in the refractive index.

As shown in Table 1, the sine profile has the highest value of the reflectivity. It considered the best profile for the selection of the wavelengths in all the chirped apodized grating profiles (≈0.99) at 25°C. The Blackman and sine profiles at reflectivities of (0.98), they considered the second order of the wavelengths selection. While raised sine, Gauss and Cauchy have reflectivities (0.95) in the nonlinear case. The tan h, Bartlett and Hamming profile have the lowest performance in the wavelengths selection (in the linear and nonlinear cases). All the profiles show a change in reflectivity (≈0.2) when the temperature changes from 25-10°C. This is the range of the change in temperature under the ocean depth. It is recommended to operate the FBG in the nonlinear case when the temperature decreases under the ocean depth.

Pressure effect on the gamma irradiated FBG: Figure 3 shows the variation of the reflectivity with the undersea level pressure for the signal traveling reflected from apodized chirped FBG (sine profile) in the linear and nonlinear cases. The variations of the reflectivity have been calculated under the effect of pressure range 0-10 MPa. The Fig. 3 also shows the comparison between the radiated and irradiated cases. The increase in the reflectivity appear due to the nonlinearity and the radiation because the two term in addition to the under water pressure has a great effect on the refractive index, that cause a great change in the reflectivity which appear as a useful effect on the properties of the grating which we need to let it reach reflectivity of 1.

As shown in Table 2, the highest value of the reflectivity is the Sinc profile where its value in the nonlinear case reaches the maximum reflectivity (≈1). So, it is considered the best profile for the selection of the wavelengths in all of the apodized profile.

While Blackman is considered the second rank of the wavelengths selection because the values of reflectivity in the nonlinear case is equal to 0.985 at 10 MPa. The tan h, Bartlett and Hamming profiles operate with low performance in the wavelengths selection (in the linear case and nonlinear) having the smallest values in the reflectivity (≈0.9).

Ocean depth effect on the gamma radiated FBG: The existence of any fiber cable under ocean depth acts to change the behavior of this cable, because of the temperature decrease and the

Table 2: The maximum values of reflectivity (R_{max}) for the different profiles in the linear and nonlinear cases at different pressures for the radiated apodized chirped FBG

	Linear case $n_2 = 0$ m^2 W^{-1}		Nonlinear case $n_2 = 2.6\times10^{-20}$ m^2 W^{-1}	
Profile	R_{max} at 0 MPa	R_{max} at 10 MPa	R_{max} at 0 MPa	R_{max} at 10 MPa
Blackman	0.94	0.96	0.965	0.985
Cauchy	0.93	0.95	0.960	0.980
Sinc	0.95	0.97	0.990	1.000
Sine	0.93	0.95	0.965	0.980
tan h	0.90	0.92	0.930	0.940
Gauss	0.92	0.93	0.950	0.960
Hamming	0.90	0.89	0.900	0.910
Bartlett	0.90	0.91	0.925	0.935
Raised sine	0.89	0.92	0.955	0.955

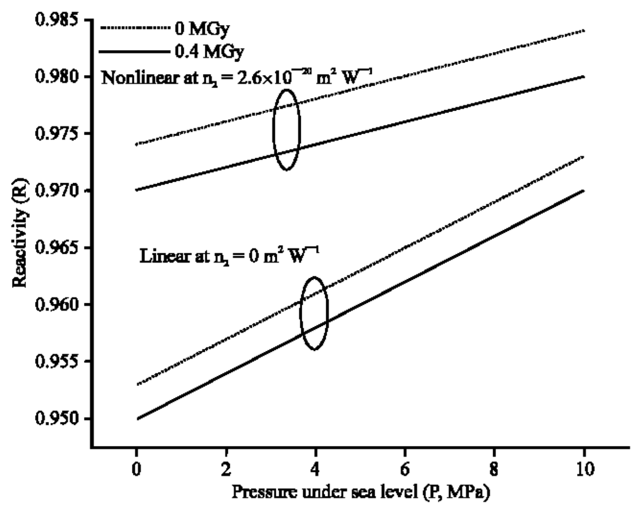

Fig. 3: Effect of the pressure on the reflectivity with wavelength in the linear and nonlinear cases of the apodized chirped grating (sine profile)

pressure increase. One of our aims in this thesis is to study the reflectivity of the apodized chirped bragg grating under ocean depth. The ocean depth will change from 0 and 1 km. The temperature variation, in this range will be from 27 till 8°C. Also, the pressure is changed from 0-10 MPa.

Figure 4 shows the variation of the reflectivity with the wavelength of the signal traveling in the chirped FBG in the linear and nonlinear cases for the sine profile for non radiated apodized FBG. The variations of the reflectivity have been calculated under the effect of the ocean depth range 0-1 km. Figure 4 shows the same behavior but taking into account the gamma radiation affects on the apodized FBG (sine profile) for a dose 0.4 MGy. The increase that occurs in the values of the reflectivity due to the Gamma radiation on the apodized FBG is explained by the perturbation of molecules that lead to increase in the refractive index.

Table 3 shows a comparison between the maximum reflectivity at the sea level and at 1 km ocean depth for the linear and nonlinear cases. The profile of the highest reflectivity is Blackman with 0.98 at 1 km depth in the nonlinear case. While Cauchy and sine are the second rank with 0.97 reflectivities at 1 km depth. Also, it is clear that the reflectivity of 7 profiles increases with the

Table 3: The maximum values of reflectivity (R_{max}) for the different profiles in the linear and nonlinear cases at 0 and 1 km

	Linear case $n_2 = 0\ m^2\ W^{-1}$		Nonlinear case $n_2 = 2.6\times10^{-20}\ m^2\ W^{-1}$	
Profile	R_{max} at 0 km	R_{max} at 1 km	R_{max} at 0 km	R_{max} at 1 km
Blackman	0.93	0.95	0.97	0.98
Cauchy	0.91	0.92	0.95	0.97
Sinc	0.95	0.95	1.00	1.00
Sine	0.92	0.93	0.96	0.97
tan h	0.88	0.90	0.92	0.94
Gauss	0.90	0.91	0.94	0.95
Hamming	0.86	0.87	0.89	0.90
Bartlett	0.90	0.91	0.92	0.93
Raised sine	0.91	0.92	0.95	0.96

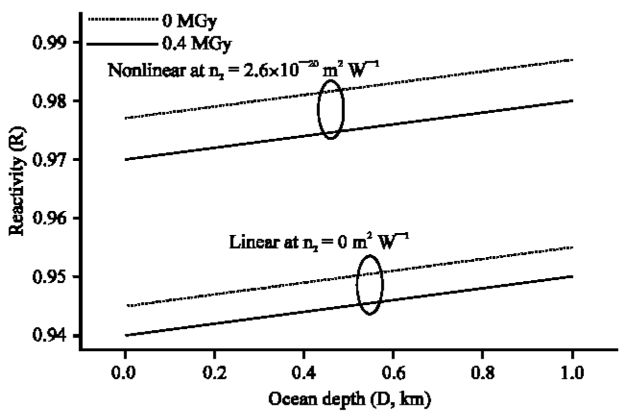

Fig. 4: Effect of the ocean depth on the reflectivity with ocean depth in the linear and nonlinear cases of the apodized chirped grating (sine profile) for a wavelength of 0.5461 μm

ocean depth. This is because the pressure of 1 km depth (10 MPa) will show an increase in the reflectivity greater than the decreases in the reflectivity that result from the drop in the temperature at 1 km (8°C).

While in the Sinc profile the change in pressure and in the temperature gives the same change in the reflectivity. So, the net change in the reflectivity will be zero.

CONCLUSION

The grating reflectivity of chirped FBG will change due to the change in the type of the apodized chirped Bragg grating. The reflectivity of the apodized chirped FBG will show a great increase due to the gamma irradiation exposure. A comparison between the different types leads to choose the best profile in the selection performance. Sinc profile is the profile having the greatest reflectivity (R≈0.99 in the nonlinear case) while the lowest one is in Hamming profile (R≈0.85 in the nonlinear case) under the ocean depth effect. Also, the results show that the nonlinearity and the gamma radiation act as a parameters that will help in the reflectivity increase by the increasing in the refractive index of the chirped FBG.

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