Design of Multistage Fiber Bragg Grating (FBG) with Variable Filter Parameters

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***Abstract*—Dispersion is the main problem that limits long-distance and high-speed optical fiber transmission. Bit error rate, the signal-to-noise ratio, and system performance all suffer from dispersion. Many dispersion adjustment strategies have been created to combat this. One of the effective methods for compensating for dispersion is the usage of Fiber Bragg Grating (FBG). In the suggested model, cascaded Uniform Fiber Bragg Grating (UFBGs) with various lengths, a constant grating period, and a constant gap between FBGs are used. This system is modeled, analyzed, and compared for the best performance and different applications. The control parameters affecting the system are the coupling coefficients, total number of cascaded UFBGs, grating periods, effective refractive index, and the total number of grating periods. The control parameters for this system are studied to compensate for the effect of dispersion. A bandwidth of 1.2 THZ is obtained when the number of cascaded UFBGs is equal to 5, 1.87 THZ is obtained when the number of cascaded UFBGs is equal to 10, 2.62 THZ is obtained when the number of cascaded FBGs is equal to 20, and 6.24 THZ is obtained when the number of cascaded FBGs is equal to 50. MATLAB is used to simulate the mathematical equations for the suggested system.**

***Keywords*—cascaded FBGs, control parameters, dispersion compensation, Fiber Bragg Grating (FBG)**

I. Introduction

An optical Fiber's Bragg Grating (FBG) is a small section that contains planes with various refractive indices inside of it. In the case of a uniform FGB, these planes are scattered evenly, whereas Chirped Fiber Bragg (CFBG) gratings have asymmetrical distributions [1, 2]. In the case of uniform FGB, the planes pass all other wavelengths and only reflect a single wavelength with a specific bandwidth known as the Bragg wavelength [3]. In the case of CFBG, more wavelengths are reflected from various distant planes that are spaced apart unevenly along the core [4, 5]. The demand of optical fiber technology in telecommunications is rapidly increasing due to its large bandwidth, high data rate and low-cost reliable optical communication links. Dense Wavelength-Division-Multiplexed (DWDM) system is currently adopting to increase the data carrying ability and an efficient utilization of optical fiber networks [6, 7]. The FBG's usage as a filter is well recognized. The Bragg wavelength λ_β is determined by Eq. (1), in [8].

$$\lambda_\beta = 2\, n_{eff}\, \Lambda \tag{1}$$

where n_{eff} is the fiber core's actual refractive index at the free space center wavelength (n_{eff}=$\sqrt{n_2 \times n_3}$) as n2, and n3 are the two materials of the grating's refractive indices, and Λ is the distance between two adjacent grating planes is formed by the fiber's grating period [9].

When a variety of wavelengths are emitted from the light source in such optical communication systems, these wavelengths propagate along the optical fiber with varying velocities and arrive at the receiver at different times, leading to dispersion [10–12]. Bit rates, the signal-to-noise ratio, and system performance all suffer from dispersion [13, 14]. To overcome this, many dispersion compensation techniques have been developed. The use of Fiber Bragg Grating (FBG) is one of the efficient tools used in dispersion compensation [15, 16]. In the case of uniform FGB, the planes reflect a single wavelength with a certain bandwidth $\Delta\lambda$ called Bragg wavelength and pass all other wavelengths. In the case of CFBG, more wavelengths are reflected from different unequal distant planes, along the core, which gives it the ability to compensate dispersion.

Erdogen's coupled mode theory is used to estimate the reflectivity attained in FBG at each grating inside the fiber. At each I'th grating, the reflectivity $Ri(\lambda)$ is provided in accordance with Eq. (2) [17].

$$Ri(\lambda) = \frac{\sin h^2\,(L_g\sqrt{k^2-\sigma_i^2})}{\cos h^2\,(L_g\sqrt{k^2-\sigma_i^2}) - \frac{\sigma_i^2}{k^2}} \tag{2}$$

where σ_i is the dc self-coupling coefficient that yields the dependency of wavelength for every grating and is provided in Eq. (3), k is the ac-coupling coefficient between the two modes, Lg is the length of the grating, and λ is the wavelength.

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$$\sigma_i = \delta + \sigma - \frac{1}{2}\frac{d\phi}{dz} \quad (3)$$

where σ is the dc (period averaged) coupling coefficient, $\frac{d\phi}{dz}$ is the change in grating chirp, and δ is determined by Eq. (4) [17].

$$\delta = 2\pi n_{eff}\left(\frac{1}{\lambda} - \frac{1}{\lambda_D}\right) \quad (4)$$

where the transmitted wavelength is λ and the design wavelength for very weak gratings is λ_D. When coupled mode theory is used with the reflectivity equation, Eq. (5) is produced.

$$\sigma_I(\lambda) = \frac{\pi}{\lambda}\delta n_{eff} + 2\pi\, n_{eff}\,\left(\frac{1}{\lambda} - \frac{1}{\lambda_{B,i}}\right) \quad (5)$$

where δn_{eff} is the magnitude of the refractive index modulation, $\lambda_{B,\ i}$ is the Bragg wavelength, and λ is the wavelength.

The remainder of this paper is organized as follows. Literature review is discussed in Section II. The proposed system is discussed in Section III. Simulation results are displayed and discussed in Section IV. Section V is devoted to the main conclusions.

II. Literature Review

Surveying this subject's literature review shows that, despite the benefits of these technologies, dispersion is the major factor that affects the optical signal. In Ref. [18], different types of dispersion compensation techniques are used to minimize dispersion where the effects of using Dispersion Compensation Fiber (DCF) and Chirped Fiber Bragg Grating (CFBG) individually on the system performance are investigated. In Ref. [19], the dispersion compensation scheme is studied using four cascaded CFBGs to compensate for the dispersion accumulated over 100 km of a conventional fiber, where a tan apodization profile was used in CFBG. In Ref. [20], a DCF is used with linear chirped apodized FBG. The effect of input power, distance, and input bit rate is investigated. The system performance is analyzed in terms of eye-diagram, Bit Error Rate (BER) and Q-factor. The work of Ref. [10] proposes a unit consisting of four uniform cascaded FBGs connected to the transmitter to get a narrower full-width half maximum bandwidth of the transmitted optical signal to reduce the propagation delay of the output signal in the optical fiber. In Ref. [11], the use of CFBG has been discussed to compensate Dispersion in a Wavelength-Division Multiplexing (WDM) system. The simulation also optimized the power levels and CFBG length on the Q-factor and BER. In this model, it is proposed to use cascaded uniform Fiber Bragg Grating (UFBGs) with various lengths, a constant grating period, and a constant gap between FBGs. The control parameters for this system are studied to compensate for the effect of dispersion. As the internal characteristics of FBG have been studied and this is what distinguishes this study from other studies.

III. System Description

A. Two Cascaded UFBGs

Case study employing two cascaded uniform FBGs with two materials and equal spacing, as illustrated in Fig.1. Where the second stage's input signal is the output signal of the first stage. The control parameters of the two-uniform cascaded FBGs are illustrated in table I. The proposed model mathematical equations are simulated with Matlab. Where ∧ is the grating period. *n*1, *n*2 is the refraction index of one of the grating's materials, the refractive index of the other material of the grating respectively, ne is the core's effective refractive index, dne is the magnitude of refractive index modulation, Lg is the fiber grating's length, N is the number of grating periods and K is the two modes coupling coefficients.

TABLE I. Control Variables of Two FBGS in Cascade

Parameter	Value
∧	490 nm, 493.6 nm
*n*1, *n*2	1.4496,1.7
ne	1.57
N	1000
dne	1×10^{-4}
FBG length	0.49 mm, 0.493 mm
K	1×10^{-5}

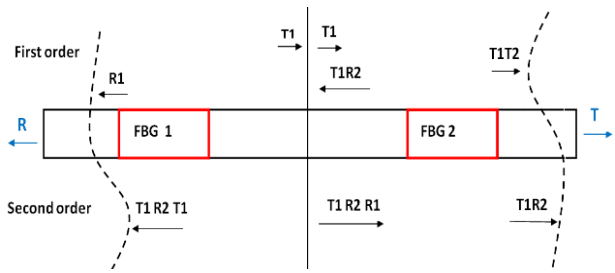
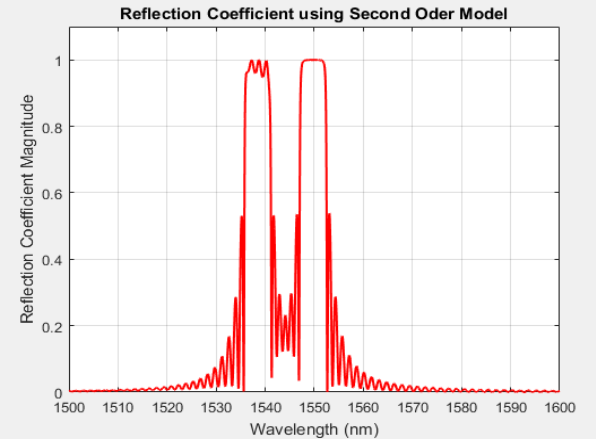


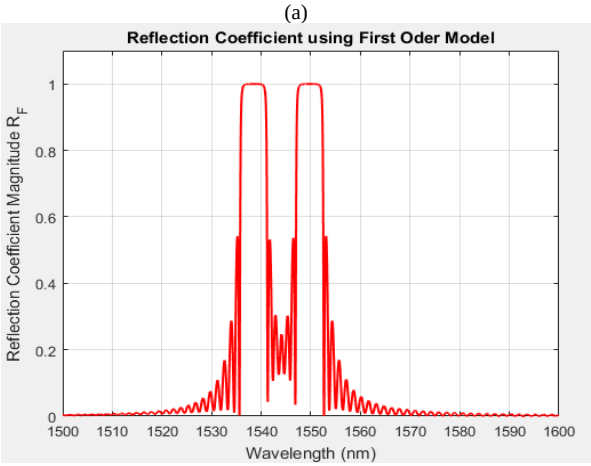
Fig. 1. Two cascaded uniform FBGs.

where T_f and R_f are the first order transmission and reflection respectively. T_s and R_s are the second order transmission and reflection respectively. T1 and T2 are the transmissions from FBG1, and FBG2 respectively. R1 and R2 are the reflections of FBG1, and FBG2 respectively. From first order cascaded UFBGS model T_f = T1×T2, and R_f =R1+ (T1×R2). From second order T_s= (T1×T2) + (T1 ×R1×R2), and R_s =R1+ (T1^2 × R2). Reflection from the first and second order is shown in Fig. 2. The error between the first and second order is depicted in Fig. 3.

Since the error between the second and first order is so minimal, the third order can be disregarded based on the prior figure.



(a)



(b)

Fig. 2. Reflection coefficient using (a) first-order model, (b) second-order model.

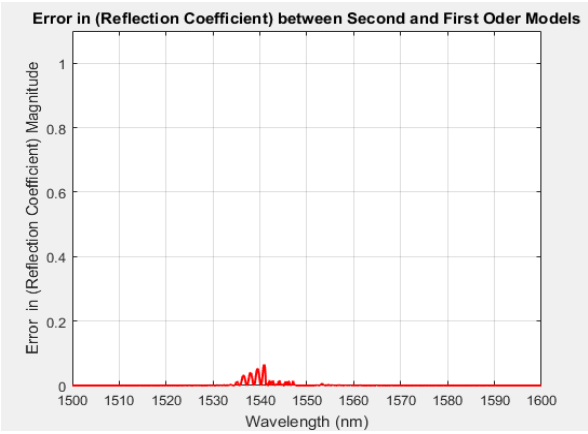


Fig. 3. Error in reflection coefficient between second and first-order model.

B. M Cascaded FBG with Variable Lengths

The proposed system and the structure of M cascaded UFBGs are shown in Figs. 4 and 5 respectively. It is composed of M cascaded FBGs regions with different lengths. Each FBG region has a uniform period. The separation between FBGs is also uniform. The proposed system aims to compensate for the effect of dispersion and his mathematical equations are simulated with MATLAB.

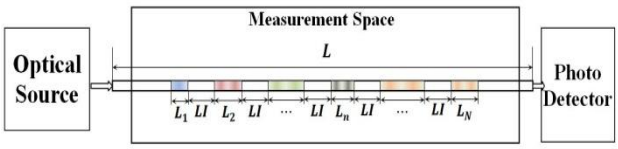


Fig. 4. The proposed system.

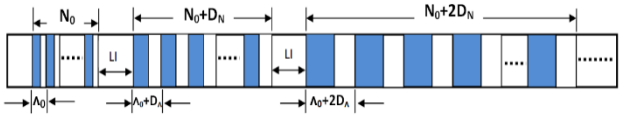


Fig. 5. Structure of M cascaded UFBG.

Where N0 is the total number of the grating period for the first FBG, DN is the increment in the total number of the grating period, Λ_0 is the grating period for the first FBG, $D\Lambda$ is the increment in the grating period, LI is the interface between two UFBGs and M is the total number of UFBGs.

IV. Results and Discussions

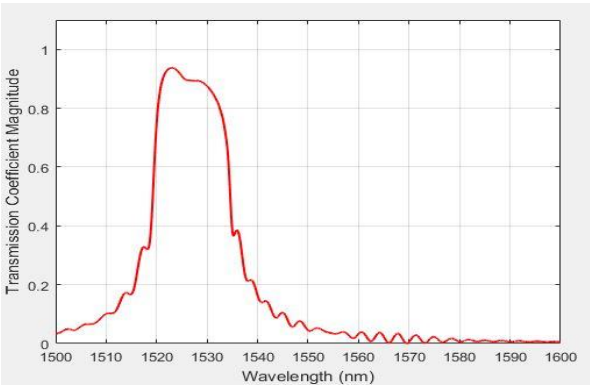
The performance of the system is impacted by several parameters; including Λ_0, N0, M, and K (control parameters for optimization). The values of control parameters used in this are listed in Table II.

TABLE II. Control Parameters of M Cascaded Ufbgs

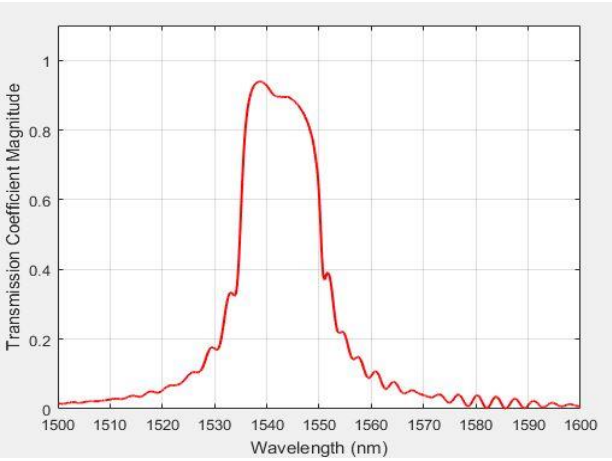
Parameter	Value
Λ_0	490 nm
$n1$, $n2$	1.4496,1.7
ne	1.57
D_N	10
dne	1×10^{-4}
$D\Lambda$	0.3
K	1×10^{-5}
N_o	400
M	10
FBG length	0.49 mm

A. Performance Impact of Changing Λ

The position of λB is altered by using alternative values for Λ_0, such as Λ_0=490 nm and Λ_0=485 nm, as illustrated in Fig. 6.



(a)

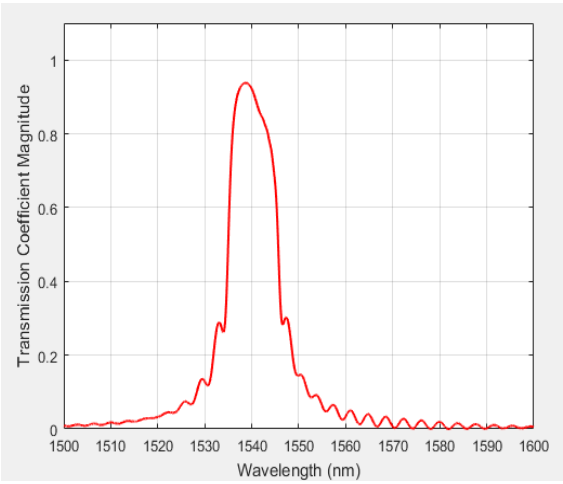


(b)

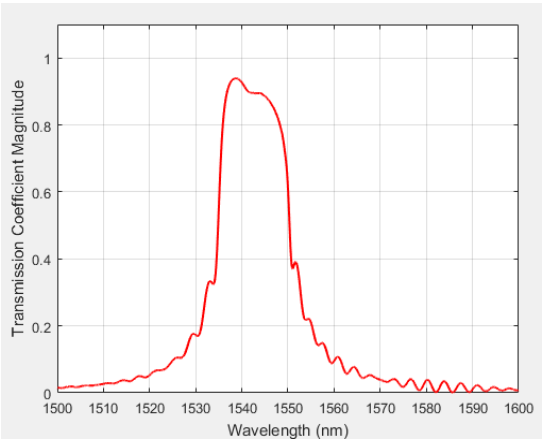
Fig. 6. Reflection coefficient magnitude using (a) ʌ=490 nm, (b) ʌ=485 nm.

B. Effect of Changing M on the Performance

Employing various M values, such as M=5, M=20, and M=50; the following are several values of bandwidth that are obtained. 1.2 THZ is the band width at M=5, 1.87 THZ at M=10, 2.62 THZ at M=20, and 6.24 THZ at M=50. Figure 7 illustrates how the bandwidth grew as the number of cascaded UFBGs increased.



(a)



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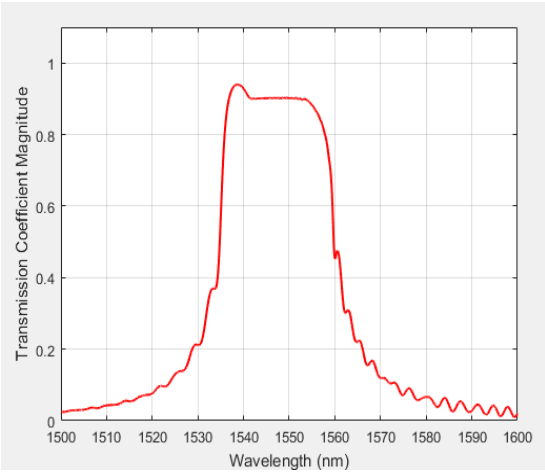
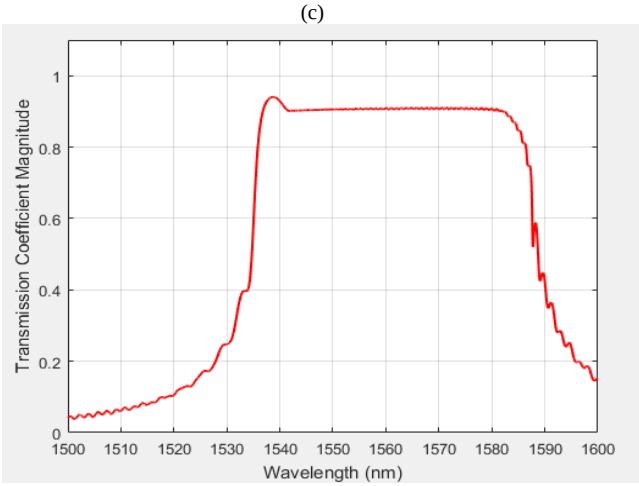


(c)



(d)

Fig. 7. Reflection coefficient magnitude using (a) M =5, (b) M=10, (c) M=20, (d) M=50.

Fig. 8 demonstrates that when the number of FBGs increased, the bandwidth also did. But there is a trade-off between increased bandwidth and roll-off factor that can be considered based on application as demonstrated in Fig. 9.

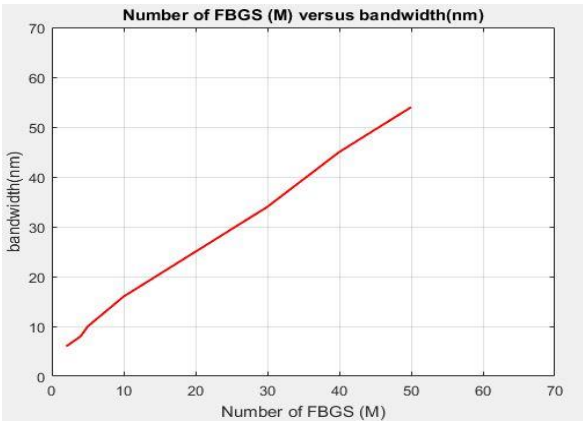


Fig. 8. Relation between bandwidth and number of cascaded UFBGs.

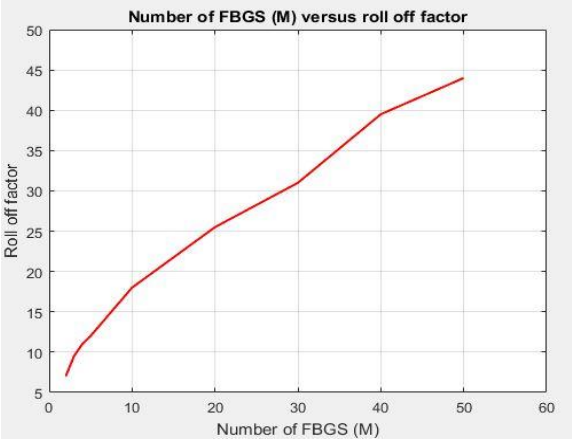


Fig. 9. Relation between roll-off and number of FBGs.

C. Impact of K Change on the Performance

The use of coupling coefficients of various values, such as k = 1×10^{-5}, 1×10^{-4}, and 5×10^{-4}; as illustrated in Fig.10, flatness rises as the coupling coefficient increases. Flatness is the bandwidth that retains its maximum value, approximately 98 percent of its maximum value.

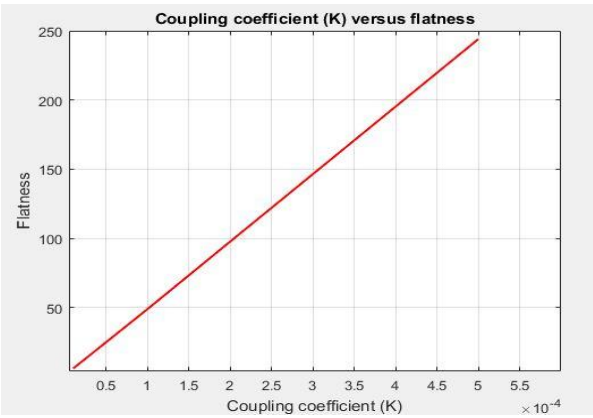


Fig. 10. Relation between flatness and number of cascaded UFBGs.

Roll-off factor increases as the coupling coefficient increases as shown in Fig. 11. The band between the central frequency and the point at which the signal's strength drops to 0.1 of its greatest value is known as the roll-off. The tradeoff between increasing flatness and roll-off factor can be considered according to applications.

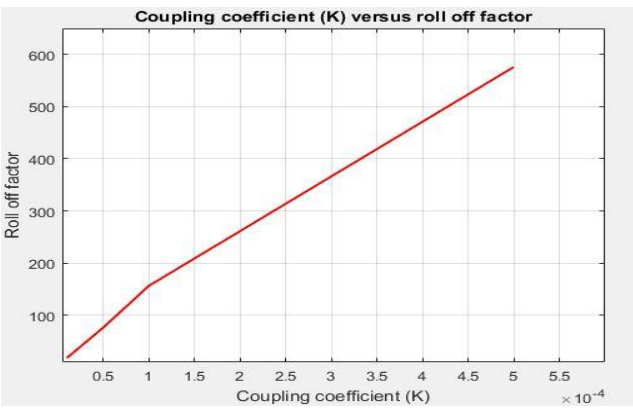


Fig. 11. Relation between bandwidth and coupling coefficient.

D. Impact of N Change on the Performance

Using different values of N such as N=20, 100, 200, 300, 400, 500, 600, 700, 800, and 1000. Fig. 12 illustrates how the signal's strength is affected by the total number of grating periods.

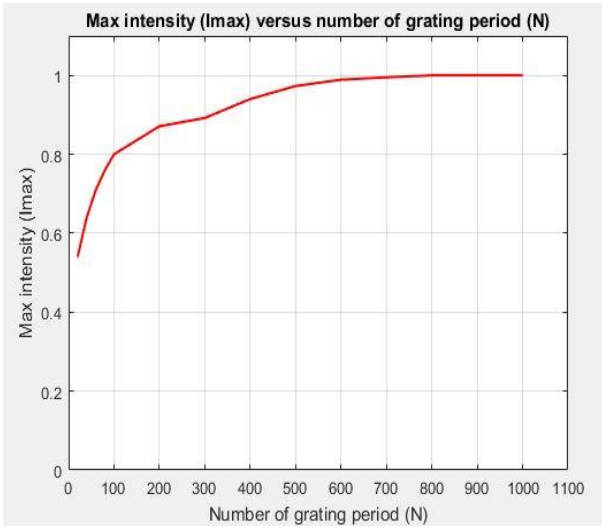


Fig. 12. Relation between max intensity and number of FBGs.

From the previous figure, it is shown that from N=800 the intensity is 1, and N below 20 isn't required as it has low intensity.

V. Conclusions

It is necessary to transform the FBG into a chirped structure for use in dispersion compensation. From the design of the M cascaded UFBGs optical transmission system, the control parameters affecting the system are the grating period, effective refractive index, total number of FBGs, coupling coefficient, and the total number of grating periods. It can be inferred from the results that the grating period and effective refractive index have an impact on where the Bragg wavelength is located. Signal strength is affected by the total number of the grating period. The total numbers of FBGs affect the bandwidth of the signal but there is a tradeoff between increasing bandwidth and the roll-off factor. The coupling coefficient affects signal bandwidth but there is a tradeoff between increasing flatness and the roll-off factor. These trade-offs can be considered according to applications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

H.A.M.A., K.F.A.H. and A.S.M. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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