Dispersion Compensation Using Chirped Apodized Fiber Bragg Gratings in Transmission with Low Eye Closure Penalty

Ahmed Abd El Aziz (**ah_zizo_6901@yahoo.com**) and Moustafa H. Aly[*] (**mosaly@aast.edu**)

Arab Academy for Science & Technology & Maritime Transport, Alexandria, Egypt
* Member of the Optical Society of America (OSA).

Abstract Dispersion compensation using linearly chirped apodized fiber Bragg grating (AFBG) in transmission has been proposed. Trapezoidal grating profile is assumed. The effective medium method is used to model the grating operation. Compared to uniform AFBG, improved bandwidth and less eye closure penalty are obtained at shorter gratings.

Keywords: Apodized Fiber Bragg Grating, chirped gratings, dispersion, dispersion slope, dispersion compensation, bandwidth, eye closure penalty.

1. INTRODUCTION

Fiber Bragg gratings (FBGs) became one of the most important components for the design of optical communication systems. Since they are very attractive components for being passive, linear and compact, they are the key components for wavelength division multiplexing (WDM) applications and dispersion compensation in both reflection and transmission [1-3]. The use of unchirped ramped gratings in transmission has been investigated by K. Hinton [4].

For FBGs to operate in high performance optoelectronic applications, proper apodization is needed. Apodization helps in removing the resonant cavity effects of uniform Bragg gratings. Moreover, the transition between reflection and transmission is very abrupt [4].

The use of apodized fiber Bragg gratings (AFBGs) in transmission is preferred sometimes over using them in reflection for several reasons: i) When operating in reflection, it requires the use of a circulator which produces losses into the system and increases the complexity and cost of the dispersion compensator, ii) the signal optical field must interact strongly with the grating, which means that any imperfection in fabrication will lead to a degradation of system performance because it will affect its property as a compensator. Oppositely, when operating in transmission the device can be spliced into the transmission link directly. Also, the interaction between the signal optical field and the grating is much weaker [4].

In this paper, we will show that by chirping the AFBG, used as a dispersion compensator in transmission, some of the limitations that appeared in unchirped AFBGs are improved.

2. AFBG IN TRANSMISSION

In order to model the operation of an AFBG in transmission, the "**effective medium method**" is used [5]. The refractive index, at any distance z, of the AFBG along its length L is

$$n(z) = n_o \left[1 + \sigma(z) + 2h(z)\cos\left(\frac{2\pi}{\Lambda} z + 2\phi(z)\right) \right], (1)$$

where n_o is the background refractive index, Λ is the nominal Bragg grating pitch, σ is the variations in the average refractive index, h is the modulation amplitude (>0) and ϕ is the grating phase.

Using (1) in Maxwell's equations and applying perturbation techniques, the grating can be represented as an "**effective medium**" with a refractive index n_{eff}, an effective dielectric permittivity ζ, an effective magnetic permeability μ, and an effective local impedance Z. The local detuning $\delta(z,\Delta)$ is defined as [4]

$$\delta(z,\Delta) = \Delta + \frac{\pi}{\Lambda}\sigma(z) - \frac{d}{dz}\phi(z), \qquad (2)$$

where $\Delta(k) = kn_o - (\pi/\Lambda)$ with $k(=2\pi/\lambda)$ the free space wave number of the incident light.
Defining $\kappa(z) = h(z)\pi/\Lambda$ results in

$$\varepsilon(z,\Delta) = \delta(z,\Delta) + \kappa(z), \qquad (3\text{-}a)$$

and

$$\mu(z,\Delta) = \delta(z,\Delta) - \kappa(z). \qquad (3\text{-}b)$$

Therefore

$$n_{eff}(z,\Delta) = \sqrt{\varepsilon\mu} = \sqrt{\delta^2(z,\Delta) - \kappa^2(z)} \quad (4\text{-}a)$$

$$Z^2(z,\Delta) = \frac{\mu}{\varepsilon} = \frac{\delta(z,\Delta) - \kappa(z)}{\delta(z,\Delta) + \kappa(z)}. \qquad (4\text{-}b)$$

The dispersion d(k) and the dispersion slope d'(k) of the grating is given, respectively, by

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c} \frac{d^2}{d\Delta^2} \arg\{t(\Delta)\} \text{ps/nm}, \qquad (5\text{-}a)$$

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{n_o}{c} \frac{d^3}{d\Delta^3} \arg\{t(\Delta)\} \text{ps/nm}^2, \quad (5\text{-}b)$$

where t(Δ) is the transmission coefficient [4]

$$t(\Delta) = 4Z(0,\Delta)\left|\frac{Z(L,\Delta)}{Z(0,\Delta)}\right|^{1/2} \cdot \{1/[e^{i\varphi}(Z(0,\Delta)+1)$$
$$(Z(L,\Delta)+1) - e^{-i\varphi}(Z(0,\Delta)-1)(Z(L,\Delta)-1)]\}.(6)$$

and φ(z) is its phase given by [4]

$$\varphi(z) = \int_0^L n_{eff}(z,\Delta)dz. \qquad (7)$$

Well away from the reflection band edges, the argument of the transmission coefficient arg{t} can be simplified to

$$\arg\{t(\Delta)\} = \text{sgn}(\Delta)\varphi(\Delta), \qquad (8)$$

at its lowest order, because n_{eff} is real and sgn(Δ) = +1 for Δ>0 and -1 for Δ<0. This result is precise for apodized gratings (i.e. h (0) =h (L) =0 and is continuous for all z).
The effect of apodization on the grating leads to express the dispersion and the dispersion slope of the compensator, respectively, as

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c} \int_0^L \frac{\kappa^2(z)dz}{\left[\delta^2(z,\Delta) - \kappa^2(z)\right]^{3/2}}, \qquad (9)$$

and

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{3n_o}{c} \int_0^L \frac{\kappa^2(z)\delta(z,\Delta)dz}{\left[\delta^2(z,\Delta) - \kappa^2(z)\right]^{5/2}}. \quad (10)$$

3. CHIRPED AFBG DISPERSION COMPENSATOR

One of the most interesting Bragg grating structures with immediate applications in telecommunications is the chirped Bragg grating. This grating has a monotonically varying period [6].

For the rest of the paper, a chirped grating is considered, with constant variations in the average refractive index for the length of the grating (σ(z) =0) and both the grating phase, φ(z), and the nominal Bragg grating pitch, Λ, change linearly with the grating length as

$$\varphi(z) = \varphi_o + az, \qquad (11)$$

$$\Lambda = \Lambda_o + \Lambda_1 z, \qquad (12)$$

where φ_o is the starting phase, a is the linear change in the grating phase, Λ_o is the starting period, and Λ_1 is the linear change along the grating length. Hence, the local detuning can be written as

$$\delta(z,\Delta) = \frac{2\pi}{\lambda}n_o - \frac{\pi}{\Lambda_o + \Lambda_1 z} - a, \text{ (nm}^{-1}), \qquad (13)$$

Therefore

$$\kappa(z) = h(z)\frac{\pi}{\Lambda_o + \Lambda_1 z} \cdot (1/\text{m}). \qquad (14)$$

A range of profiles h (z) studied for uniform gratings and results have shown that the trapezoidal profile provides a dispersion compensation over the widest bandwidth [4].

As stated above, we must take into consideration the changes of κ(z) and the local detuning δ(z,Δ) on the dispersion and dispersion slope of the compensator by substituting (13) and (14) in (9) and (10).

As seen from (9) and (10), if d(k) is nonzero, then so is d'(k). Therefore, we must also consider the impact of the compensator between the

dispersion and the dispersion slope of the grating is very important.

The performance of the compensator can be measured using its bandwidth. The bandwidth of a dispersion compensator is given by [4]

$$\Delta\lambda = \frac{d(k)}{d'(k)}. \qquad (15)$$

This equation gives the maximum bandwidth of a signal which can be compensated without the AFBG dispersion slope affecting the signal [4]. That is, the wider the bandwidth, the better the compensated system performance.

Another measure for the performance of the compensator is its eye closure penalty. That is, the less the penalty, the better the compensated system performance [7] and [8]. The eye closure penalty for chirp free signals is given by

$$P(dB) = 10\log\left(\frac{1}{1-\gamma.l^2}\right), \qquad (16)$$

where γ is directly proportional to the level of intersymbol interference and l is the transmission link length. γ is given by [7] and [8]

$$\gamma = \left(\frac{\pi}{4}\right)^2 \frac{\lambda^4 D^2 B^4}{c^2}, \qquad (17)$$

where D is the fiber dispersion and B is the bit rate [7]. For a dispersion compensator, the dispersion d of the compensator is set to negate the impact of fiber dispersion. That is,

$$d(k) = -D.l. \qquad (18)$$

Using (18) together with (9) and (17) in (16), one can get

$$P(dB) = 10.\log\left(\frac{1}{1-\left(\frac{\pi}{4}\right)^2 \frac{\lambda^4 B^4}{c^2} d^2(k)}\right). \qquad (19)$$

This equation gives the eye closure penalty for a chirped AFBG compensator to cancel the impact of fiber dispersion.

4. NUMERICAL RESULTS AND DISCUSSION

In this section, the chirping effect on the grating performance (as a dispersion compensator) is numerically introduced.

As stated in the previous section, results are based on the assumption that the grating is linearly chirped. The following table illustrates the grating specifications used in this paper.

Name	Symbol	Value
Background refractive index	n_o	1.5
Starting Grating period	Λ_o	516.6 nm
Linear change along the grating	Λ_1	100 nm/m
Linear change in grating phase	a	0.00012 nm^{-1}
Grating length	L	50 cm
Variations in the average refractive index	$\sigma(z)$	0

Table.1 FBG specifications.

As shown in (9) and (10) respectively, the dispersion and dispersion slope of the compensator depend on both the local detuning $\delta(z,\Delta)$ and the grating profile h(z).

Figures 1 and 2 show the impact of the grating length on the relationship between the local detuning $\delta(z,\Delta)$ and wavelength. It is clear that the detuning value increases along the grating and is not appreciably affected by the wavelength change.
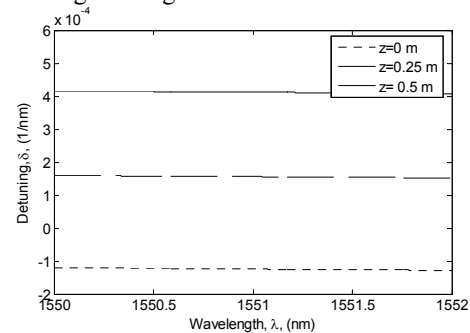

Fig. 1 Impact of grating length on the relationship between local detuning and wavelength.

At the beginning of the grating, the detuning at the beginning of the grating (at z=0) depends on

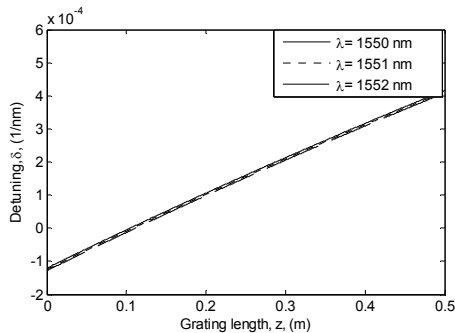the value of the linear change in the phase, a, of the grating as shown in (13).

Fig 2 Impact of wavelength on the relationship between local detuning and grating length.

The trapezoidal profile has h(0) = h(L)= 0 with h(z) all continuous and attaining a maximum of 1000 m^{-1} in a 50 cm grating. The key parameters that determine the limitations of the profile as a dispersion compensator, are the strength of the grating {max of $\kappa(z)$}, the grating length, and degree of apodization. The degree of apodization can be represented as the fraction Frc of the length of the grating used to increase $\kappa(z)$ from zero to its maximum value.

Figure 3 displays the trapezoidal profile used before and after chirping the grating with. It is obvious that $\kappa(z)$ shown in (14) decreases along the grating just after it reaches its maximum when chirped gratings are used.
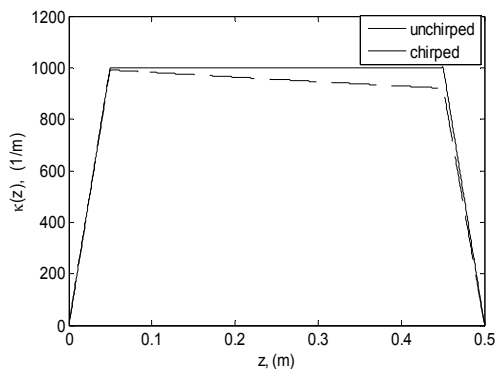

Fig.3 Trapezoidal profile before and after chirping the grating at Frc=0.1.

Figure 4 shows the dispersion properties of the grating. It is clear that fiber dispersion can be compensated along the spectrum using chirped gratings. We can control the wavelengths at which fiber dispersion is compensated by changing the value of Λ_1, (13).
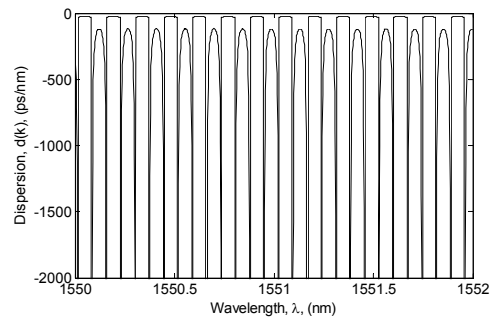

Fig. 4 Dispersion compensator properties.

Equation (10) is plotted in Fig. 5 showing the dispersion slope of the compensator at different wavelengths.
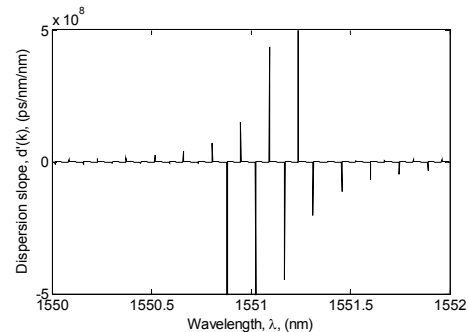

Fig. 5 Compensator dispersion slope properties.

The relation between the dispersion and the dispersion slope of the grating is illustrated in Fig. 6. One can notice that to compensate a larger amount of fiber dispersion, second order dispersion terms may distort the signal. Although the higher order dispersion terms for the fiber can be negligible, Fig. 6 shows that this may not be the case for the higher order AFBG terms.
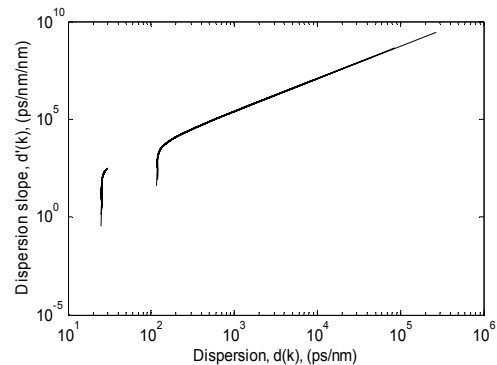

Fig. 6 Dispersion versus dispersion slope.

As mentioned before, the bandwidth given by (15) is an important measure for the grating performance; the greater the bandwidth the better

is the grating. As shown in Fig. 7, certain grating lengths give a very wide bandwidth. From Fig. 7, it is clear that the bandwidth is maximum in the range z=0.301 m to 0.2825 m. These values also give a nearly zero eye closure penalty (at 10 Gbps) as seen in Fig. 8. This means that shorter gratings than that of unchirped (uniform) gratings with wider bandwidth and less eye closure penalty can be obtained using chirped AFBG in transmission.
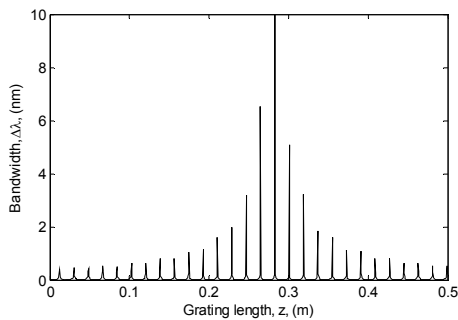

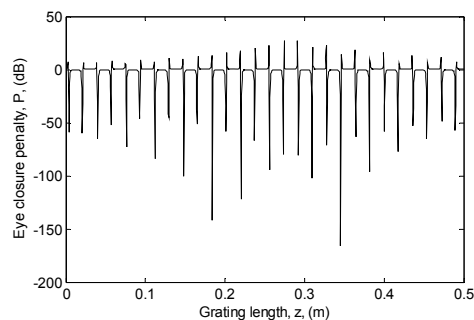Fig.7 Dispersion compensator bandwidth against grating length.

Fig. 8 Eye closure penalty along the grating.

5. CONCLUSION

Dispersion compensation using linearly chirped AFBG in transmission has been investigated through a trapezoidal grating profile with apodization degree of 0.1.

Compared to uniform AFBG, improved bandwidth and less eye closure penalty (about zero dB) is obtained at shorter gratings (chirped grating length $\approx$ 28 cm and corresponding length of unchirped grating $\approx$ 50 cm [4]). This means solves some of the technical problems accompanied by long gratings.

6. References

1] N.M. Litchinitser, B.J. Eggleton, and D.B. Patterson, "Fiber Bragg Gratings for Dispersion Compensation in Transmission: Theoretical Model and Design Criteria for Nearly Ideal Pulse Recompression," J. Lightwave Technol., vol. 15, no. 8, p.1303, 1997.

2] Moustafa H. Aly and Heba A. Fayed, "Compensating Bragg Wavelength Drift due to Temperature and Pressure by Applying an Artificial Strain," Proceeding of the 3rd Saudi Technical Conference, vol. IV, pp. 105-110, Reyadh, Saudi Arabia, Dec. 11-14, 2004.

3] N.M. Litchinitser, B.J. Eggleton, and D.B. Patterson, "Dispersion of Cascaded Fiber Gratings in WDM Lightwave Systems," J. Lightwave Technol., vol.16, no. 8, p.1523, 1998.

4] Hinton, Kerry, "Dispersion Compensation Using Apodized Bragg Fiber Gratings in Transmission," J. Lightwave Technol., vol.16, no. 12, pp. 2336-2346, 1998.

5] Polladian, L. (1993), Graphical and WKM Analysis on Nonuniform Bragg Gratings, Phys. Rev. E, Vol. 48 (No.6), p.4758.

6] Othonos, Andreas and Kalli, Kyriacos, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Artech House Inc., 1999.

7] N. Antoniades, I. Roudas, G. Ellinas, and J. Amin, "Transport Metropolitan Optical Networking: Evolving Trends in the Architecture Design and Computer Modeling," IEEE/OSA J. Lightwave Technol., vol. 22, no. 11, pp. 2653-2670, 2004.

8] N. Antoniades, A. Boskovic, I. Tomkos, N. Madamopoulos, M. Lee, I. Roudas, D. Pastel, M. Sharma, and M. Yadlowsky, "Performance Engineering and Topological Design of Metro WDM Optical Networks," IEEE J. Select. Areas Commun. (Special Issue on WDM Based Optical Networks), vol. 20, pp. 149–165, 2002.