AFBG for Dispersion Compensation in Transmission: Effect of Parameters of the Two Beam Interference Fringe Technique

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ABSTRACT

In this paper, the dispersion compensation in transmission is modeled and investigated using apodized fiber Bragg grating (AFBG). The two-beam interferometer is used in AFBG manufacture. The effect of different interferometer parameters is studied for large bandwidth transmission at a zero eye closure penalty with linearly chirped gratings. The parameters under investigation for only one arm of the interferometer are d (arm length), the angle θ (beam angle) and λ (the writing wavelength). Eight different apodization profiles are studied including their effects on the performance of the compensator.

Keywords: Apodized chirped fiber Bragg gratings, dispersion and dispersion slope, interferometer.

1. INTRODUCTION

Apodized chirped fiber Bragg gratings have become one of the preferred approaches to dispersion compensation in optical systems. Alternative approaches for using fiber Bragg grating (FBGs) for dispersion compensation have also been researched including the use of unchirped ramped gratings operated in reflection and in transmission [1]. The use of apodized fiber Bragg gratings (AFBGs) in transmission for dispersion compensation has several advantages over using them in reflection. Operating the grating in reflection requires the use of a circulator which introduces losses into the system. The circulator also increases the complexity and cost of the dispersion compensation unit. In contrast, if an AFBG is used in transmission, the device can be spliced directly into the transmission link. This will avoid the losses due to bulk optical devices such as the circulator [2]. Chirped gratings may be fabricated using all the techniques for inscribing conventional Bragg gratings. The first report of chirped grating fabrications was by A. Othonos et al [3], who used a conventional two beam UV interferometer to produce a uniform period fringe pattern in a tapered photosensitive fiber. In this method, the chirp is achieved by the approximately linear variation of the fiber effective index along the tapered section.

This paper discusses the use of AFBGs, operated in transmission, as dispersion compensators using a far more flexible and controllable approach to chirped grating fabrication relying on two beam interference which is based on the use of dissimilar curvatures in the interfering wave fronts. This is accomplished by placing two lenses in the two arms of an interferometer. Different apodization profiles and design parameters are investigated showing their effects on the performance of the compensator. The best performance is characterized by a short grating that provides, simultaneously, a maximum bandwidth and a minimum eye closure penalty.

I. THEORY

The chirping effect on the grating performance as a dispersion compensator for different profiles is analyzed by Kerry Hinton [1]. In order to model the operation of an AFBG in transmission, the "**effective medium method**" is used. The refractive index, at any distance, z, of the AFBG along its length, L, is

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$$n(z)=n_o[1+ \sigma(z)+2h(z)\cos(2\pi z/\Lambda + 2\,\varphi(z)], \tag{1}$$

where, n is the background refractive index, L is the nominal Bragg grating pitch, σ is the variation in the average refractive index, $h(z)$ is the grating apodization profile, h is the modulation amplitude (> 0) and φ is the grating phase.

Using Eq. (1) in Maxwell's equations and applying perturbation techniques, the grating can be represented as an "**effective medium**" with an effective refractive index, n_{eff}, an effective dielectric permittivity, ε, an effective magnetic permeability, μ, and an effective local impedance, z.
A local detuning of a grating, d (z, D), is defined as [1]

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

where

$$\Delta(k) = kn_o - \frac{\pi}{\Lambda} \tag{3}$$

with $k=2\pi/\lambda$ the free space wave number of the incident light.
Both medium permittivity and permeability as function of z are obtained, respectively, as

$$\varepsilon(z,\Delta) = \delta(z,\Delta) + \kappa(z) \tag{4}$$

and

$$\mu(z,\Delta) = \delta(z,\Delta) - \kappa(z) \tag{5}$$

where

$$\kappa(z) = h(z)\frac{\pi}{\Lambda} \tag{6}$$

Therefore, the effective refractive index, n(z, D), is

$$n_{eff}(z,\Delta) = \sqrt{\varepsilon\mu} = \sqrt{\delta^2(z,\Delta) - \kappa^2(z)} \tag{7}$$

and the effective local impedance, Z(z, D), is

$$Z^2(z,\Delta) = \frac{\mu}{\varepsilon} = \frac{\delta(z,\Delta) - \kappa(z)}{\delta(z,\Delta) + \kappa(z)}. \tag{8}$$

The dispersion, d(k), and the dispersion slope, d'(k), of the grating are, respectively, given by [1]

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c}\frac{d^2}{d\Delta^2}\arg\{t(\Delta)\} \quad \text{ps/nm} \tag{9}$$

and

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{n_o}{c}\frac{d^3}{d\Delta^3}\arg\{t(\Delta)\} \quad \text{ps/nm}^2 \tag{10}$$

where the transmission coefficient has an amplitude, t(D), given by

$$t(\Delta) = 4Z(0,\Delta)\left|\frac{Z(L,\Delta)}{Z(0,\Delta)}\right|^{1/2} . e^{-i\varphi}\left(Z(0,\Delta)-1\right)\left(Z(L,\Delta)-1\right)]\} \quad (11)$$

and a phase, φ*(z)*, given by

$$\varphi(z) = \int_0^L n_{eff}(z,\Delta)dz. \quad (12)$$

When using AFBGs, the grating profile, *h(z)*, grows and decays continuously from and to zero. So, *k(0)=k(L)=0*. Hence

$$Z(0,\Delta)=Z(L,\Delta)=1. \quad (13)$$

Therefore, the transmission coefficient can be written in the form

$$t(\Delta) = e^{-i\varphi} \quad (14)$$

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

$$\arg\{t(\Delta)\} = \mathrm{sgn}(\Delta)\varphi(\Delta), \quad (15)$$

at its lowest order, because n_{eff}, is real, where

sgn(D) = +1, for D > 0, (16-a)
sgn(D) = -1, for D < 0, (16-b)

This result is precise for AFBGs (i.e. *h(0)=h(L)=0*) and is continuous for all values of z. The effect of the apodization in the grating leads to express the dispersion and the dispersion slope of the compensator, respectively, as [1]

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c}\int_0^L \frac{\kappa^2(z)dz}{\left[\delta^2(z,\Delta)-\kappa^2(z)\right]^{3/2}} \quad (17)$$

and

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{3n_o}{c}\int_0^L \frac{\kappa^2(z)\delta(z,\Delta)dz}{\left[\delta^2(z,\Delta)-\kappa^2(z)\right]^{5/2}}. \quad (18)$$

One of the most interesting FBG structures with immediate applications in telecommunications is the chirped fiber Bragg grating (CFBG). This grating has a monotonically varying period [1]. A CFBG is considered with constant variations in the average refractive index for the length of the grating (s(z) = 0). The grating phase φ*(z)* is assumed to change linearly with the grating length as

$$\varphi(z) = \varphi_o + az \quad (19)$$

where φ_o is the starting phase, a is the linear change in the grating phase, i.e.

$$\frac{d}{dz}\varphi(z) = a \quad (20)$$

The grating pitch, Λ(z), is [3]

$$\frac{d_1 cos\theta + z}{\sqrt{d^2 + 2d\, z\, cos\theta + z^2}} + \frac{D cos\theta_2 - z}{\sqrt{D^2 + 2D\, z\, cos\theta_2 + z^2}} \quad (21)$$

Figure 1 shows the general arrangement, with a lens in each arm of the UV interferometer: the interfering beams 1 and 2 pass through lenses of focal lengths f_1 and f_2, respectively. The coordinate z is the distance along the grating from the origin defined by the point where the two beam axes intersect on the fiber axis. θ and φ are the angles which the respective beams make with the optical fiber, and d and D are the distances from the lens focal points to the point z = 0.

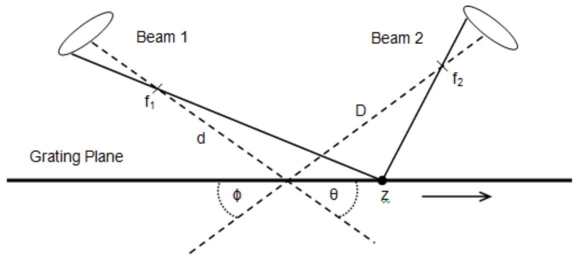

Fig.1 Arrangement for the formation of a chirped grating by the interference between dissimilar wave fronts using cylindrical lenses in each arm of the interferometer.

The Bragg wavelength of the grating is clearly a function of the position z, given by [3]

$$\lambda_B = 2\, n_{eff}\, \Lambda(z) \tag{22}$$

In this paper, a single cylindrical lens is used in just one arm of the interferometer resulting in a large bandwidth, linearly chirped gratings, where D → ∞, which corresponds to having no lens in the second arm of the interferometer. It clearly indicates an almost linear variation of the reflected wavelength with distance along the grating. The bandwidth of the chirped grating may be selected by the appropriate combination of lens focal length and position [3]. Hence, the grating period, Λ, in Eqs. (2) and (6) is to be replaced by Λ(z). The effect of changing the apodization profiles with the quadratic dispersion parameter for off resonance grating is investigated using eight different profiles: Positive Tanh, Cauchy, Sin, Gauss, Hamming, Raised Cosine, Raised Sine and Blackman. These profiles are, respectively, displayed in Fig. 1.

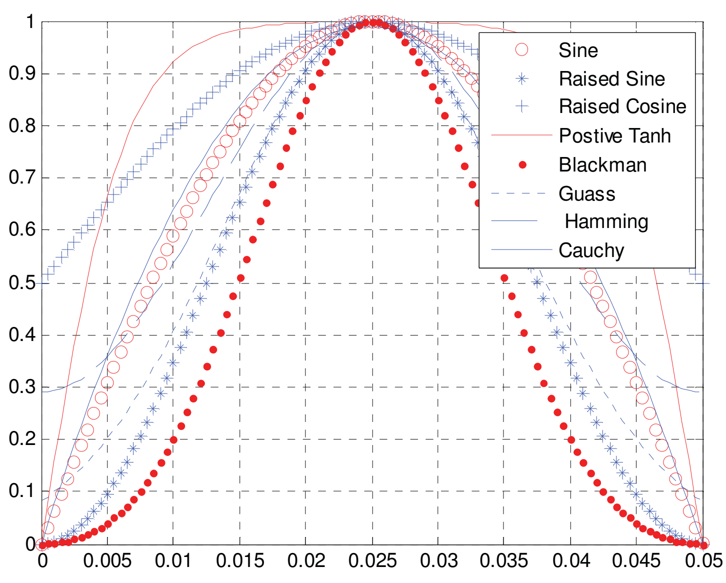

Fig. 1 Apodization profiles versus Bragg grating length.

The apodization functions correspond to well known window functions employed in filter design to suppress side lobes in the rejected band [4]. The values of the parameters which provide an efficient way to control the characteristics of the functions are chosen such that all the profiles have similar characteristics. This is composed with a flat region at the grating center and a constant slope decaying characteristics towards the grating edges. The displayed results show that the positive tanh profile is the most successful profile. It has h(0) = h(L) = 0, with h(z) all continuous. It also satisfies the previous terms for selection of apodization profile with a flat region at the grating center which is the highest among the different used profiles and a constant slope decaying characteristics towards the grating edges.

The compensator performance can be measured using its maximum bandwidth, Δλ, defined as [1]

$$\Delta\lambda = \frac{d(k)}{d'(k)} \tag{23}$$

Another measure for the performance of the compensator is its eye closure penalty, given, in terms of the transmission link length *l*, by [1]

$$P(dB) = 10\log\left(\frac{1}{1-\gamma\ell^2}\right) \tag{24}$$

where γ is directly proportional to the level of intersymbol interference and is given, as a function of the fiber dispersion, D, and the bit rate, B, by [1]

$$\gamma = \left(\frac{\pi}{4}\right)^2 \frac{\lambda^4 D^2 B^4}{c^2} \tag{25}$$

The dispersion, d, of the dispersion compensator is set to negate the impact of fiber dispersion. That is

$$d(k) = -\,D\,l. \tag{26}$$

Using Eq. (26) together with Eqs. (17) and (25) in Eq. (24), one can get

$$P(dB) = 10.\log\left(\frac{1}{1-\left(\frac{\pi}{4}\right)^2 \frac{\lambda^4 B^4}{c^2} d^2(k)}\right). \tag{27}$$

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

II. RESULTS AND DISCUSSION

A computer simulation is performed for the described model for the different apodization profiles versus grating length. For large bandwidth compensation, using a 10 Gbps bit rate, a linearly chirped grating is designed using a single cylindrical lens in just one interferometer arm. This situation is modeled by Eq. (21) with D → ∞, using a grating designed for a centre wavelength at 1550 nm. The chirp rate and grating length and hence the bandwidth may be selected by the appropriate combination of lens focal length and position. The key parameters that determine the limitations of the profile as a dispersion compensator are: the strength of the grating {maximum value of *k(z)*}, the grating length, L and the degree of apodization, Frc, which is the fraction of the grating length used to increase k(z) from zero to its maximum value.

The effect of the beam 1 on the different grating profiles is investigated. The beam distance, d, the beam angle, θ, and the writing wavelength λ are changed within different ranges. As explained earlier, our interest is to find the short gratings that provide the widest bandwidth as well as zero eye closure penalty. As a sample of results, the Positive-Tanh profile is chosen. Figures 2 to 7 show the effect of the parameter d (arm length) on the bandwidth and eye closure penalty. The obtained results are summarized in Table 1 representing the grating length corresponding to maximum bandwidth at zero eye closure penalties.

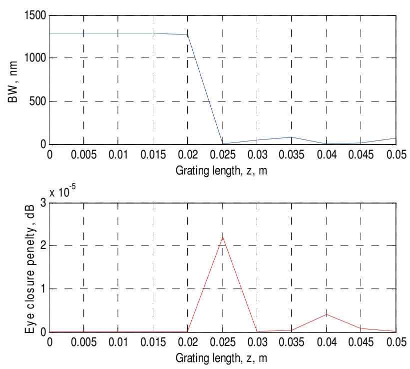

Fig.2 d = 10 mm

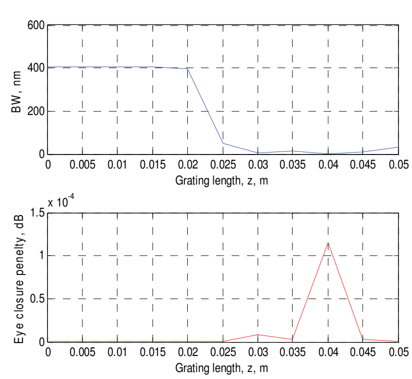

Fig.3 d = 50 mm

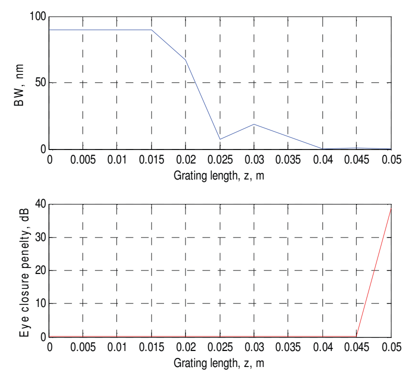

Fig.4 d = 100 mm

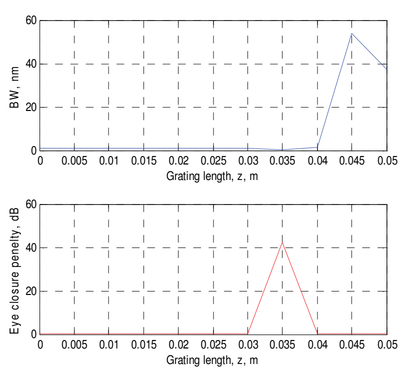

Fig.5 d = 200 mm

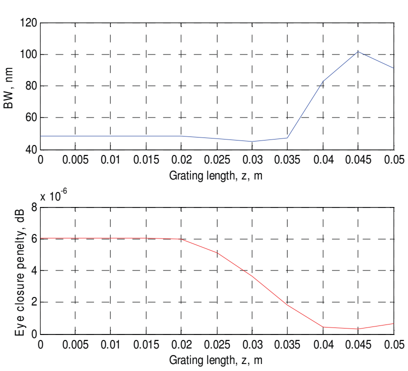

Fig.6 d = 300 mm

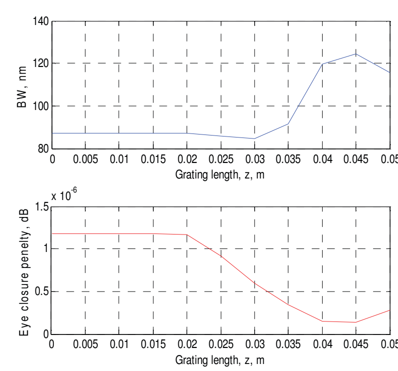

Fig.7 d = 400 mm

Table 1 Effect of the arm length, d.

d (mm)	10	50	100	200	300	400
Length (m)	0.005	0.005	0.005	0.045	-	-
Max. BW(nm)	1300	410	80	56	-	-

From Table1, one can notice that, the shortest (best) length of the arm of the interferometer which gives the highest bandwidth with zero eye-closure penalty is 10 mm, and if it exceeds 200 mm, it has non-zero eye closure penalty.

The effect of the beam angle, θ, is displayed in Figs. 8 to 13 and is summarized in Table 2.

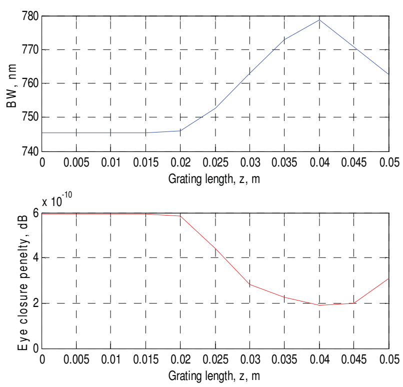

Fig.8 θ = π

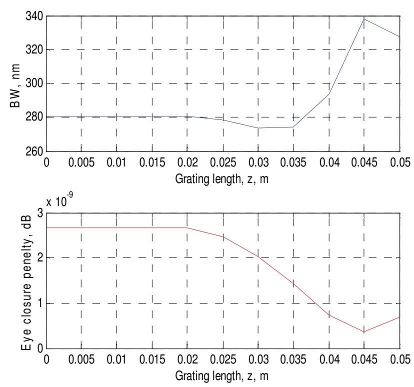

Fig.9 θ = π/2

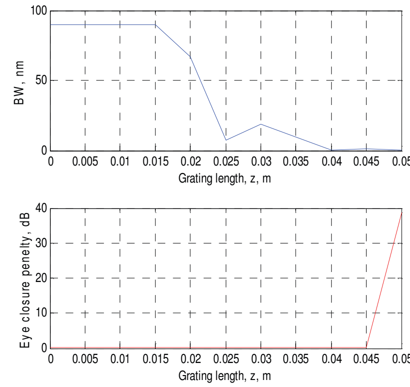

Fig.10 θ = π/3

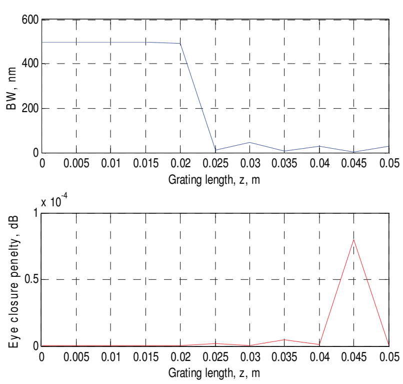

Fig.11 θ = π/4

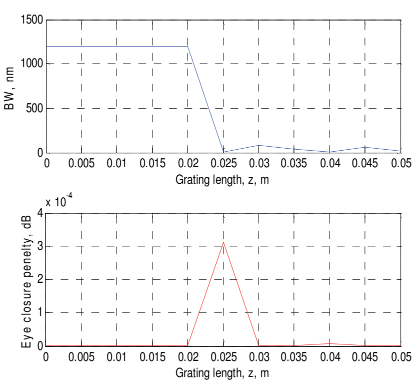

Fig.12 θ = π/9

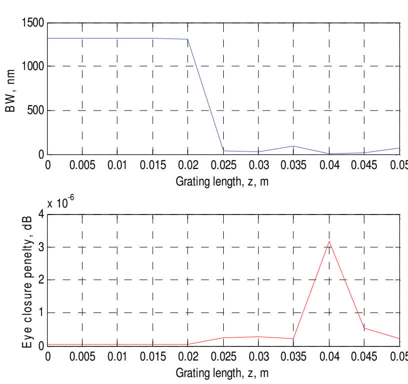

Fig.13 θ = π/12

Table 2 Effect of the beam angle, θ.

θ (degree)	π	π/2	π/3	π/4	π/9	π/12
Length (m)	-	-	0.005	0.005	0.005	-
Max. BW(nm)	-	-	80	500	1200	-

From Table 2, it is clear that, the beam angle π/9, gives the shortest grating length with maximum bandwidth.

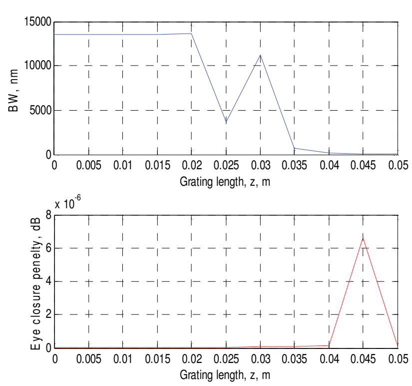

Fig.14 λ = 350 nm.

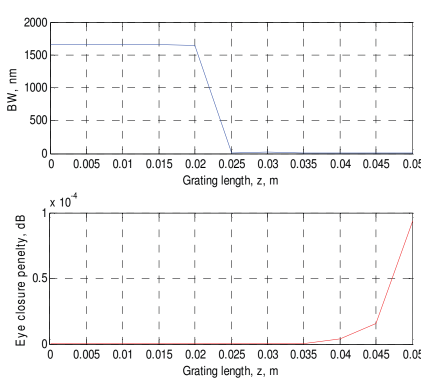

Fig.15 λ = 450 nm.

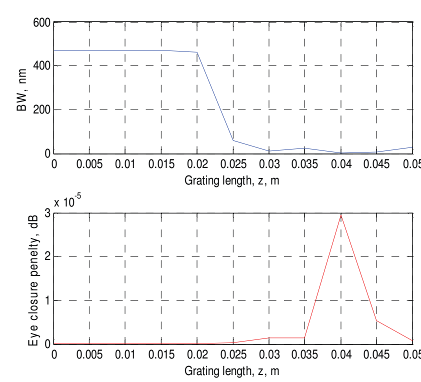

Fig.16 λ = 550 nm.

Figures 14 to 19 show the effect of the writing wavelength, λ, and Table 3 summarizes the results.

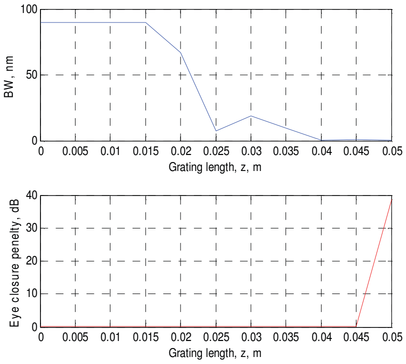

Fig.17 λ = 650 nm.

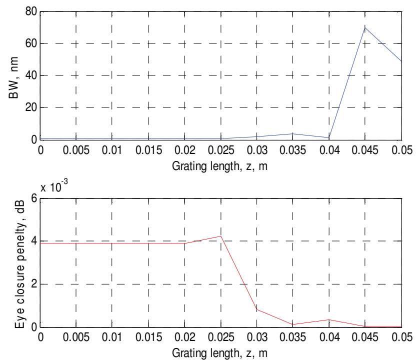

Fig.18 λ = 750 nm.

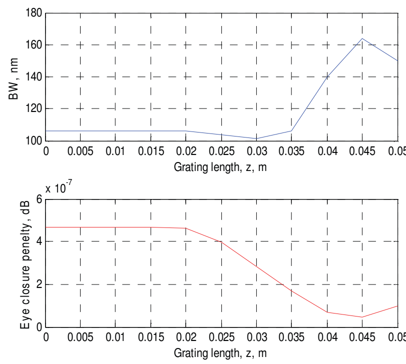

Fig.19 λ = 850 nm.

Table 3 Effect of the writing wavelength, λ.

λ (nm)	350	450	550	650	750	850
Length (m)	0.02	0.005	0.005	0.005	0.045	-
Max. BW(nm)	14000	1700	480	80	70	-

From Table 3, it is evident that, the lower writing wavelength, 350 nm, gives the highest bandwidth, which doesn't exist in any other profile, while having non-zero eye closure penalty at 850 nm.

The procedure is repeated for the remaining (seven) apodization profiles. Tables 4, 5 and 6 represent the grating length and the highest bandwidth, corresponding to zero eye closure penalties, including the effects of d, θ and λ for the different profiles.

Table 4 Effect of d (with fixed θ and λ).

d(m) / profiles	Sin		Raised Sin		Blackman		Positive Tanh		Hamming		Raised Cosine		Cauchy		Gaussian	
	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)
0.01	0.035	24	0.03	16	0.005	58	0.005	1300	0.005	21	-	-	0.005	310	0.005	35
0.02	0.025	10	0.045	13	0.03	26	0.005	410	0.01	11	0.015	18	0.01	180	0.005	160
0.1	0.03	22	0.02	22	0.015	13	0.005	80	0.035	17	0.025	78	0.015	74	0.005	180
0.2	0.04	110	0.04	125	0.03	64	0.045	56	0.04	115	0.025	147	0.005	135	0.005	194
0.3	-	-	-	-	-	-	-	-	-	-	-	-	0.005	175	0.005	195
0.4	-	-	0.04	158	-	-	-	-	-	-	-	-	0.005	200	0.005	195

Table 5 Effect of θ (with fixed d and λ).

θ° / profiles	Sin		Raised Sin		Blackman		Positive Tanh		Hamming		Raised Cosine		Cauchy		Gaussian	
	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)
π	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
π/2	-	-	-	-	-	-	-	-	-	-	-	-	0.005	240	0.005	510
π/3	0.03	22	0.02	22	0.015	13	0.005	80	0.035	17	0.025	78	0.015	74	0.005	180
π/4	0.02	17	0.02	15	0.025	8	0.005	500	-	-	0.01	9	0.005	90	0.005	50
π/9	0.045	13.5	-	-	0.005	135	0.005	1200	0.005	4	0.05	450	0.01	120	0.005	80
π/12	0.04	16	0.01	73	0.005	90	-	-	0.005	5.2	0.05	530	0.005	220	0.005	120

Table 6 Effect of λ (with fixed d and θ).

λ(nm) / profiles	Sin		Raised Sin		Blackman		Positive Tanh		Hamming		Raised Cosine		Cauchy		Gaussian	
	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)	L(m)	BW(nm)
350	0.005	100	0.05	44	0.005	20	0.005	14000	0.01	60	0.045	1080	0.005	150	0.005	85
450	0.005	18.5	0.05	13	-	-	0.005	1700	0.045	14	0.005	17	0.005	24	0.025	25
550	0.04	12.5	0.025	16	0.04	8	0.005	480	0.025	12.5	-	-	0.005	100	0.005	33
650	0.03	22	0.02	22	0.015	13	0.005	80	0.035	17	0.025	78	0.015	74	0.005	180
750	0.04	138	0.04	140	0.03	80	0.045	70	0.04	145	0.025	180	0.005	900	0.005	250
850	-	-	-	-	-	-	-	-	-	-	-	-	0.005	200	0.005	300

III. CONCLUSION

The dispersion compensation properties of ABFG's, operating in transmission through different profiles, have been analyzed using MATLAB. By using low range of writing wavelength (350 ~ 850 nm), the results show that the Positive Tanh profile gives an overall superior performance, as it provides the maximum bandwidth with shortest grating length corresponding to zero eye closure penalty. The highlighted results in the above tables are that one can choose easily which arm length, beam angle or writing wavelength would be used with any profile for best dispersion compensation.

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