

Dispersion Compensation Using Tunable Chirped Apodized Far Off Resonance Fiber Bragg Gratings in Transmission

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Abstract: Comparison between the results of strain and temperature dependent center Bragg wavelength shift have been accomplished using different apodization profiles to produce linearly chirped apodized far off resonance fiber Bragg gratings for the design of an optimum Dispersion compensator. The chirping is made using the ultraviolet (UV) phase mask method.

Key words: Apodized chirped fiber Bragg grating, off resonance grating, dispersion and dispersion slope, interferometer, photosensitive fiber, strain, center Bragg wavelength shift.

INTRODUCTION

Data transmission in optical fibers is generally limited by power loss and pulse distortion. The availability of erbium doped amplifiers (EDFAs) for systems operating in the third optical window, around 1.55 μ m, has removed the loss limitation. An alternative to the dispersion compensating fibers is the chirped fiber gratings which are of particular interest since they are compact, low loss, and polarization insensitive and do not induce nonlinear effects. As dispersion is roughly proportional to the grating length, relatively long grating is needed. Chirp can be induced after the inscription of a constant pitch grating by creating a temperature gradient along the grating using piezoelectric stacks, or by bonding the Bragg grating on an active mechanical support structure^[1].

Such configurations can use the FBG itself as both cavity feedback and tuning element, where they work as either the sensor, whose strain-induced deformations shift the Bragg center wavelength, or the tuning element with deformations induced by a stretching device as first proposed by Ball and Morey and used in spectroscopy by Wetjen *et al.*^[2]. Due to limited deformation capacity of the mechanical device or to mechanical characteristics of the fiber optic, the tuning range with the goal of dynamically sweeping the Bragg wavelength is restricted to a few nanometers and to a low tuning frequency. A standard FBG can be stretched to about 1% or less of its length, since the UV exposure during the FBG imprinting is the main cause that deteriorates its mechanical resistance. For such a standard FBG with a typical strain sensitivity of 1.2

pm strain, tunability over a 12 nm wide interval at best would be obtained^[2].

For the improvement of the dispersion compensation characteristics of the chirped FBG, apodization is applied for which the group delay becomes linear and the modulation associated with the presence of side lobes is eliminated. The use of apodized FBGs (AFBGs) in transmission for dispersion compensation has several advantages over using them in reflection. To operate the grating in reflection requires in order realizing wavelength division multiplexing (WDM), various wavelength sensitive devices are required to perform the multiplexing and demultiplexing of signals at different wavelengths, so that the whole system can be practical. A conventional optical FBG has desirable spectral characteristics for multiplexing and demultiplexing. 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 if the grating is operated in transmission. The interaction between the signal optical field and the grating is much weaker. Hence, imperfections in the grating do not become impressed upon the signal field for dispersion compensation.

AFBGs are now considered commercially viable technology for dispersion compensation. In the following, we will focus on the grating dispersion slope. This is for two reasons; first, this dispersion slope cannot be removed, irrespective of the fabrication technology. Second, due to the divergence of dispersion approaching the reflection band edge, compensating optical links with high dispersion results in the

dispersion slope dominating the group delay ripples. Hence, in this configuration, grating dispersion slope imposes the fundamental limit to system performance^[3].

A previous work on the far off resonance gratings has been investigated by J. E. Sipe *et al.*^[4]. They gave an approximate analytic expression for the wave number of light, proving that operation at low wavelengths compared to the Bragg resonance wavelength of the grating results in lower values of the quadratic dispersion produced by the grating. They also showed that the applications of this method include dispersion compensation and fiber lasers in which the quadratic dispersion is crucial in determining the properties of emitted pulses^[4].

This paper discusses the eye closure penalty (ECP), resulting from application of the FBG as a dispersion compensator. Positive ECP equates to a degradation of system performance, the larger the ECP, the greater the degradation. It is assumed that the dispersion compensator exactly compensates fiber dispersion of the optical link over the signal bandwidth. For WDM systems, and a FBG operating in reflection, each channel may have its own FBG compensator, or one very long grating may simultaneously compensate all channels. When operated in transmission, each channel must have its own grating. Hence, in this case, a multichannel system may have a set of FBGs for each channel to compensate for dispersion in that channel over the length of the link^[5]. In this paper, the use of linearly chirped apodized far off resonance fiber Bragg gratings AFBGs, operated in transmission, as dispersion compensators using a far more flexible and controllable, tunable approach to chirped grating fabrication. Different apodization profiles and design parameters are studied showing their effects on the performance of the compensator for the design of an optimum dispersion compensator.

2. Theory: We start with the expressions for the local wave number, $k(z)$, obtained by J. E. Sipe *et al.*^[4]

$$k(z) = \bar{k} \left[1 + a_1(z) - \frac{1}{2} a_2(z) + \sum_{m=2}^{\infty} a_m(z) \frac{\bar{k}^2}{(m^2 K^2 - \bar{k}^2)} + \dots \right] \quad (1)$$

However, the wave number of the resulting plane wave solution is not \bar{k} , associated with the reference refractive index \bar{n} , but is changed due to the off resonant grating. This shift is given by (1). We will drop reference to all higher order resonances. Also, ignoring the DC contribution to the grating's refractive

index profile, we then find that the wave number shift for a grating with unit strength is given by

$$k(z) \equiv \frac{\bar{k}^{-2}}{(K^2 - \bar{k}^2)} \quad (2)$$

where $K = 2p/L$ and $\bar{k} = \omega \bar{n} / c$.

The following is the mathematical model of the AFBG in transmission including the study of the chirping effect on the grating performance as a dispersion compensator for different profiles. In order to model the operation of an AFBG in transmission, the "effective medium method" is used^[6]. The refractive index, at any distance, z , of the AFBG along its length, L , is

$$n(z) = n_0 \left[1 + \sigma(z) + 2h(z) \cos \left(\frac{2\pi}{\Lambda} z + 2\phi(z) \right) \right] \quad (3)$$

where, n_0 is the background refractive index, L is the nominal Bragg grating pitch, s is the variations in the average refractive index, h is the modulation amplitude (>0) and f is the grating phase.

The Bragg grating resonance, which is the center wavelength of back reflected light from a Bragg grating, depends on the effective index of refraction of the core and the periodicity of the grating. The effective index of refraction, as well as the periodic spacing between the grating planes, are affected by changes in strain and temperature. These changes cause a shift in the Bragg grating center wavelength given by^[7]

$$\Delta \lambda_B = 2 \left(\Lambda \frac{\partial n_{eff}}{\partial l} + n_{eff} \frac{\partial \Lambda}{\partial l} \right) \Delta l + 2 \left(\Lambda \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda}{\partial T} \right) \Delta T \quad (4)$$

The first term represents the strain effect on an optical fiber. This corresponds to a change in the grating spacing and the strain optic induced change in the refractive index. The shift in the center wavelength due to a strain, ϵ_z , is expressed as^[7]

$$\Delta \lambda_{BS} = \lambda_B (1 - P_e) \epsilon_z \quad (5)$$

where P_e is an effective strain optic constant defined as

$$P_e = \frac{n_{eff}^2}{2} [P_{12} - \nu(P_{11} + P_{12})] \quad (6)$$

p_{11} and p_{12} are components of the strain optic tensor, and ν is the Poisson's ratio. For a typical germanosilicate optical fiber, $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.16$, and $n_{eff} = 1.482^{[7]}$. These values yield a 1.2 pm shift as a result of applying $1\mu\epsilon$ to the Bragg grating satisfying the off resonance condition grating^[4].

The second term in (4) represents the temperature effect, where a shift in the Bragg wavelength, $\Delta\lambda_{BT}$, due to a temperature change, ΔT , may be written as

$$\Delta\lambda_{BT} = \lambda_B(\alpha_A + \alpha_n)\Delta T \quad (7)$$

where $\alpha_L=(1/L)(\partial L/\partial T)$ is the thermal expansion coefficient for the fiber (@ $0.55 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for silica). The quantity $\alpha_n=(1/n_{eff})(\partial n_{eff}/\partial T)$ represents the thermo optic coefficient, which is approximately equal to $8.6 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$ for the germania doped silica core fiber. Clearly, the expected sensitivity for a 1550 nm Bragg grating is approximately 13.7 pm/ $^\circ\text{C}$, satisfying the off resonance condition grating^[4].

Using (3) 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, $\delta(z,D)$, is defined as^[6]

$$\delta(z, \Delta) = \Delta(k) + \frac{\pi}{\Lambda} \sigma(z) - \frac{d}{dz} \phi(z) \quad (8)$$

where

$$\Delta(k) = kn_o - \frac{\pi}{\Lambda} \quad (9)$$

Both ϵ and μ as functions of z are obtained as

$$\epsilon(z, \Delta) = \delta(z, \Delta) + \kappa(z) \quad (10)$$

and

$$\mu(z, \Delta) = \delta(z, \Delta) - \kappa(z) \quad (11)$$

with

$$\kappa(z) = h(z) \frac{\pi}{\Lambda} \quad (12)$$

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

$$n_{eff}(z, \Delta) = \sqrt{\epsilon\mu} = \sqrt{\delta^2(z, \Delta) - \kappa^2(z)} \quad (13)$$

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

$$Z^2(z, \Delta) = \frac{\mu}{\epsilon} = \frac{\delta(z, \Delta) - \kappa(z)}{\delta(z, \Delta) + \kappa(z)} \quad (14)$$

The grating dispersion, $d(k)$, and the dispersion slope, $d'(k)$, are, respectively, given by^[6]

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c} \frac{d^2}{d\Delta^2} \arg\{t(\Delta)\} \text{ ps/nm.} \quad (15)$$

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{n_o}{c} \frac{d^3}{d\Delta^3} \arg\{t(\Delta)\} \text{ ps/nm}^2. \quad (16)$$

where the transmission coefficient has an amplitude, $t(D)$, given by^[1]

$$t(\Delta) = 4Z(0, \Delta) \left| \frac{Z(L, \Delta)}{Z(0, \Delta)} \right|^{1/2} \cdot \{1/[e^{i\varphi}(Z(0, \Delta) + 1) (Z(L, \Delta) + 1) - e^{-i\varphi}(Z(0, \Delta) - 1)(Z(L, \Delta) - 1)]\} \quad (17)$$

and a phase, $j(z)$, given by^[1]

$$\varphi(z) = \int_0^L n_{eff}(z, \Delta) dz \quad (18)$$

When AFBGs are used, the grating profile, $h(z)$, grows and decays continuously from and to zero value; therefore $\kappa(0) = \kappa(L) = 0$. Hence,

$$Z(0, \Delta) = Z(L, \Delta) = 1 \quad (19)$$

Therefore, the transmission coefficient can be rewritten in the form

$$t(\Delta) = e^{-i\varphi} \quad (20)$$

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

$$\arg\{t(\Delta)\} = \text{sgn}(\Delta)\varphi(\Delta) \quad (21)$$

at its lowest order because n_{eff} is real, where $\text{sgn}(D) = +1$ for $D > 0$ and $= -1$ for $D < 0$.

This result is precise for AFBGs (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^[6]

$$d(k) = -\frac{2\pi n_o^2}{\lambda^2 c} \int_0^L \frac{\kappa^2(z) dz}{[\delta^2(z, \Delta) - \kappa^2(z)]^{3/2}} \tag{22}$$

and

$$d'(k) = \left(\frac{2\pi n_o}{\lambda^2}\right)^2 \frac{3n_o}{c} \int_0^L \frac{\kappa^2(z) \delta(z, \Delta) dz}{[\delta^2(z, \Delta) - \kappa^2(z)]^{5/2}} \tag{23}$$

One of the most interesting Bragg grating structures with immediate applications in telecommunications is the chirped fiber Bragg grating (CFBG)^[6]. In a CFBG, $s(z) = 0$ and both the grating phase, $f(z)$, and the grating pitch, $L(z)$, are assumed to change linearly with z , the distance along the fiber, as

$$\phi(z) = \phi_0 + \alpha z \tag{24}$$

where ϕ_0 is the starting phase, α is the linear change in the grating phase. The change of phase along the grating, df/dz , will result in "a".

The CFBG period, $L(z)$, (using the UV phase mask chirping technique) can be linearly expressed with z as^[7]

$$\Lambda(z) = \frac{\Lambda_{pm}}{2} \left[1 - z \left(\frac{\alpha}{f-r} \right) \left(1 - \frac{\lambda_w^2}{\Lambda_{pm}^2} \right)^{-1/2} \right] \tag{25}$$

where Λ_{pm} is the phase period, λ_w is the writing beam wavelength, α is the tilting angle with respect to the mask, f focal length of the lens and r is the distance between the lens and the mask.

The Bragg wavelength of the grating as a function of the chirped grating period is given by^[5,7]

$$\lambda_B = 2n_{eff} \Lambda(z) \tag{26}$$

Hence

$$\delta(z, \Delta) = \left\{ \frac{\bar{k}^2}{(K^2 - \bar{k}^2)} n_o - \frac{\pi}{\Lambda(z)} - \alpha \right\} \text{ nm}^{-1} \tag{27}$$

and

The effect of the apodization profiles with the quadratic dispersion parameter for off resonance grating is investigated using eight different profiles: positive tanh, Cauchy, sine, Gauss, Hamming, sinc, raised sine and Blackman. These are respectively displayed in Fig.

1. The apodization functions correspond to well known window functions employed in filter design to suppress side lobes in the rejected band^[2]. The values of the parameter values 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 compensator performance can be measured using its bandwidth. The bandwidth of a dispersion compensator, DL , is given by^[6]

$$\Delta\lambda = \frac{d(k)}{d'(k)} \tag{28}$$

This equation gives the maximum bandwidth of a signal which can be compensated without the off resonance AFBG dispersion slope affecting the signal^[6].

Another measure for the performance of the compensator is its eye closure penalty. The eye closure penalty for chirp free signals is given by^[6]

$$P(dB) = 10 \log \left(\frac{1}{1 - \gamma \ell^2} \right) \tag{29}$$

where γ is directly proportional to the level of intersymbol interference and ℓ is the transmission link length. g is given by^[6]

$$\gamma = \left(\frac{\pi}{4} \right)^2 \frac{\lambda^4 D^2 B^4}{c^2} \tag{30}$$

where D is the fiber dispersion and B is the bit rate^[6]. For a dispersion compensator, the dispersion, d , of the compensator is set to negate the impact of fiber dispersion. That is,

$$d(k) = -D\ell \tag{31}$$

Now, (31) together with (22) and (30) can be used in (29) to get the eye closure penalty.

In this paper, the linearly chirped apodized far off resonance fiber Bragg gratings is considered. The chirping is assumed first to be using the phase mask technique. Strain and temperature effects are then studied. The compensator bandwidth at zero dB eye closure penalty is then calculated with and without these effects for different apodization profiles.

RESULTS AND DISCUSSION

A computer simulation is performed for the strain and temperature dependent off resonance AFBG at the eight different apodization profiles. Using the UV phase mask chirping technique at each apodization profile, the compensator performance is studied to select the best one giving the maximum bandwidth at zero (or minimum) eye penalty. The obtained results are displayed in Figs. 2 through 8.

We start with the sine profile using the UV phase mask chirp technique. With no temperature or strain effects, a 4.4 nm maximum bandwidth at zero eye closure penalty is obtained at a grating length of 0.02 m. When the strain effect is taken into consideration, a compensator bandwidth of 4.6 nm at exact zero dB eye closure penalty is obtained at a grating length of 0.03 m, Figs. 2 and 3.

The same values of maximum bandwidth and grating length are obtained when the temperature effect is taken into consideration, Figs. 4 and 5.

Higher compensator bandwidths (at zero eye closure penalties) are obtained at different grating lengths are depicted for the tanh apodization profiles

when strain effect is considered and also when temperature effect is considered, Figs. 6-9.

The procedure is repeated for all other apodization profiles and the maximum compensator bandwidth is determined at zero eye closure penalties with and without taking the strain and temperature effects into consideration. The obtained results are summarized in Table I.

5. Conclusion: The characteristics of the strain and temperature dependent off resonance apodized linearly CFBGs written through UV phase mask technique have been studied systematically.

It is shown that the apodization profiles have a flat center region and apodized edges with continuously decreasing slopes. From the obtained results for the eight different apodization profiles, the **positive hyperbolic tangent** one has an overall superior performance. It provides highly linear time delay characteristics with minimum reduction in linear dispersion. It also has the maximum bandwidth (9.1 nm) and exactly zero dB eye closure penalty at a grating length of 0.045 m which is very reasonable practical value for a grating length.

Table I: Maximum bandwidth for different apodization profiles

Apodization profile	With No Strain and No Temperature Effect		With Strain Effect		With Temperature Effect	
	Bandwidth (nm)	Grating Length (m)	Bandwidth (nm)	Grating Length (m)	Bandwidth (nm)	Grating Length (m)
Sine	4.41	0.02	4.46	0.03	4.46	0.03
Raised sine	4.95	0.028	4.95	0.025	4.95	0.025
Sinc	4.00	0.03	4.00	0.03	4.00	0.03
Positive tanh	9.10	0.04	9.10	0.045	9.10	0.045
Blackman	2.7	0.04	2.69	0.032	2.69	0.032
Gauss	4.45	0.035	4.45	0.03	4.465	0.035
Hamming	3.85	0.025	3.95	0.035	3.85	0.045
Cauchy	7.1	0.025	7.10	0.025	7.20	0.02

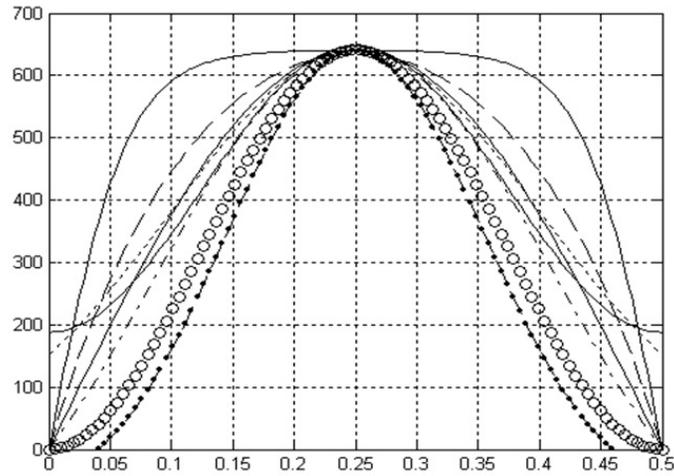


Fig. 1: Apodization profiles versus Bragg grating length.

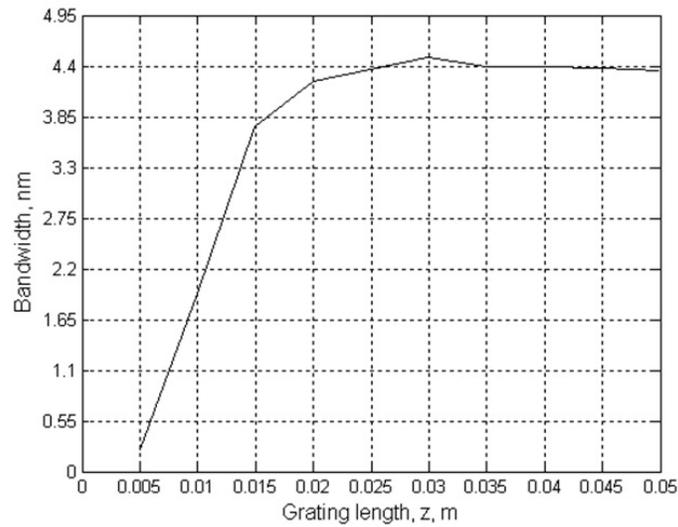


Fig. 2: Dispersion compensator bandwidth against grating length of the sine profile (Strain effect).

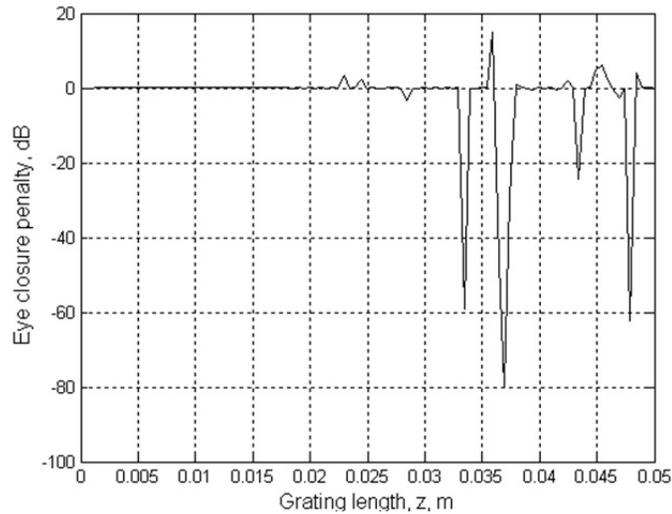


Fig. 3: Eye closure penalty along the grating of the sine profile (Strain effect).

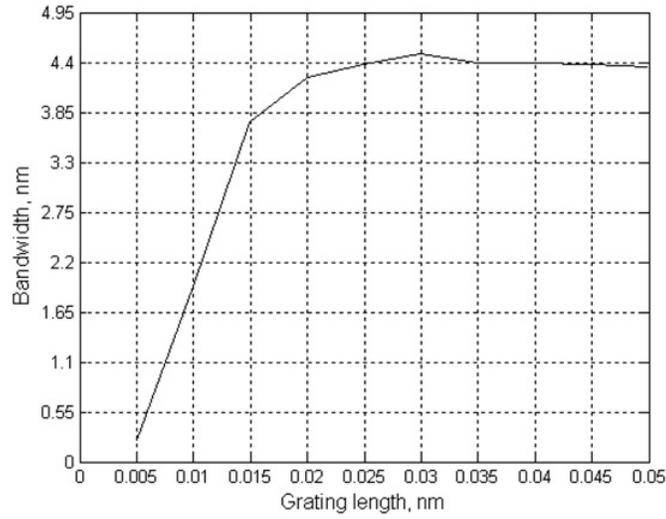


Fig. 4: Dispersion compensator bandwidth against grating length of the sine profile (Temperature effect).

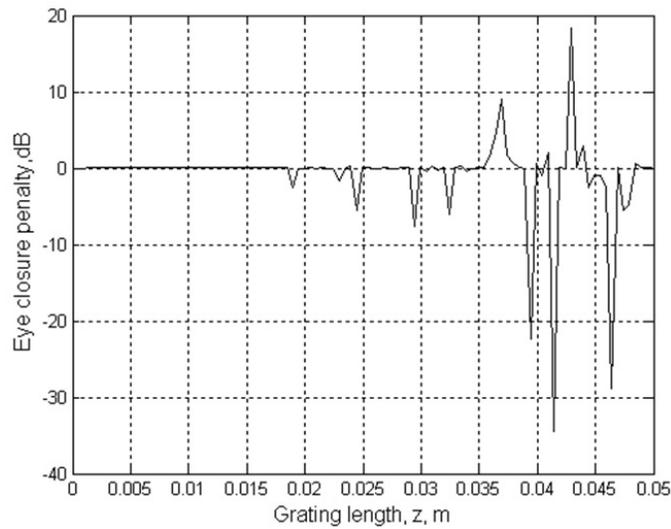


Fig. 5: Eye closure penalty along the grating of the sine profile (Temperature effect).

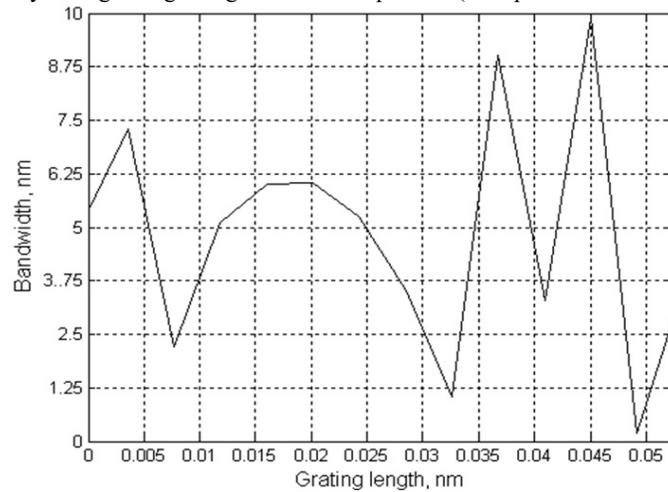


Fig. 6: Dispersion compensator bandwidth against grating length of the tanh profile (Strain effect).

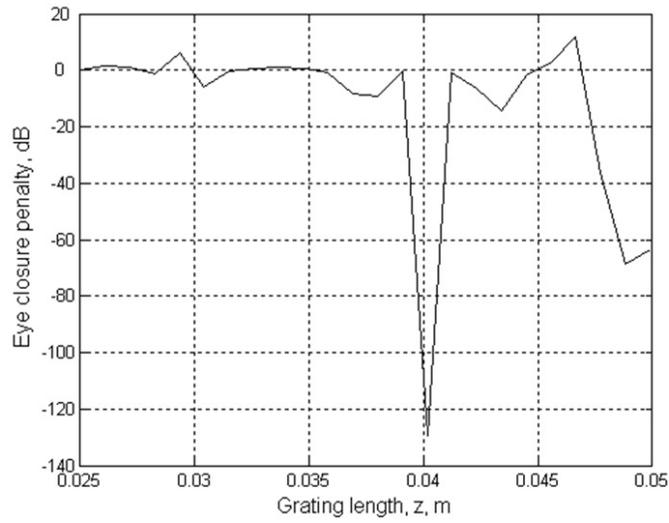


Fig. 7: Eye closure penalty along the grating of the tanh profile (Strain effect).

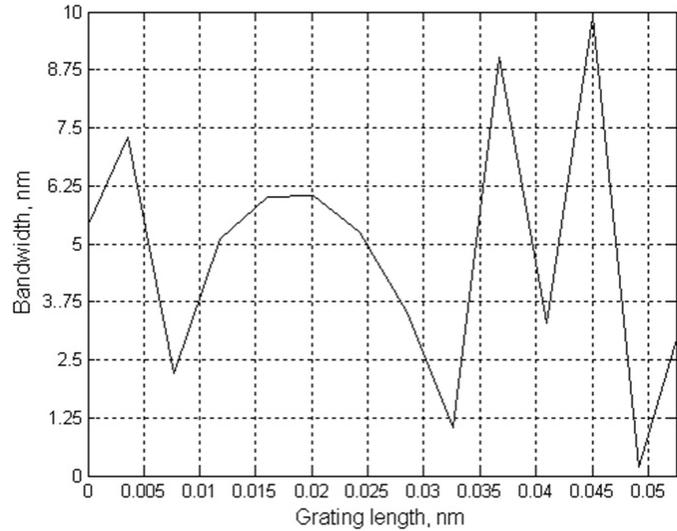


Fig. 8: Dispersion compensator bandwidth against grating length of the tanh profile (Temperature effect).

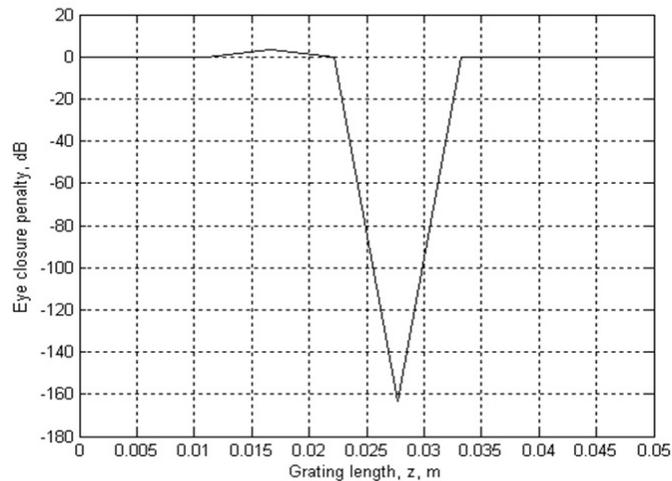


Fig. 9: Eye closure penalty along the grating of the tanh profile (Temperature effect).

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