OPTIMIZATION OF HYPERBOLIC TANGENT APODIZED CHIRPED FIBER BRAGG GRATINGS (CFBG) FOR DISPERSION COMPENSATION IN OPTICAL FIBER COMMUNICATION

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Abstract:

Chirped fiber Bragg grating is a promising approach for dispersion compensation in optical fiber communication systems, since it's passive optical component, fiber compatible and has low insertion losses and low costs. Unapodized CFBG is fail to achieve the expected performance due to high ripples in time delay response. Many apodization profiles are suggested to optimize grating performance. Among them, hyperbolic tangent (tanh) apodization profile result in overall superior performance. In this work, the reflection spectrum of CFBG is solved by numerical solution of Reccati differential equation. Results show that, the characteristics of the tanh apodized CFBG can varied systematically according to an angular tanh apodization profile parameter called truncation parameter (a_{tr}). By using this parameter the characteristics of the grating is assist in term of limitations of full-wave half maximum reflection bandwidth and minimizing average time-delay ripples for different truncation parameter values. Results show that for a given chirped parameter value CFBG approach optimal performance at truncation parameter of 4. In optical communication bandwidth of 0.5nm CFBG can compensate linear dispersion of 100 km of standard optical fiber length, the required grating length is 10 cm. According to these results, the truncation parameter must be chosen carefully in performance optimization of the hyperbolic tanh apodized chirped fiber Bragg grating.

Keywords: Apodization, chirped fiber Bragg grating, dispersion compensating grating, group-delay ripple.

تحسين اداء محزز الحيود المقسم باستخدام صيغة تعديل الظل تمام لمعالجة التقزح في اتصالات الالياف الضوئية

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الخلاصة

يعتبر محزز الحيود المقسم اسلوب واعد للاستخدام في تعديل ظاهرة التقزح في انظمة اتصالات الالياف الضوئية, وذلك لانه متلائم مع الالياف الضوئية و ذو توهين قليل للقدرة الضوئية مع كلفته المنخفضة. فشل محزز الحيود المقسم الغير معدل في تحقيق الاداء المرجو منه, وذلك بسبب وجود موثرات غير خطية في الطيف الزاوي. وعلى هذا الاساس تم اقتراح عدد من دوال التعديل. من بين هذه الدوال التي اعطت اداء منقطع النظير هي صيغة الظل تمام. تم في هذا العمل حساب الطيف الترددي لمحزز الحيود القسم وذلك باستخدام احدى الطرق العددية لحل معادلة ركاتي التفاضلية. النتائج اشارت الى انه يمكن تغيير خصائص صيغة تعديل الظل تمام بتغير متغير يسمى عامل الانقاص. حيث تم دراسة تاثير هذا العامل على خصائص محزز الحيود القسم من حيث تاثيره التذبذب الموجود في الطيف الزاوي كذلك تاثيره على النطاق الترددي لمحزز الحيود المقسم. اشارت النتائج الى انه عند قيمة معينة لعامل التقسيم يقترب محزز الحيود المقسم الى افضل اداء له عند قيمة لعامل الانقاص مقدرها 4. لنظام اتصالات ضوئي بطيف ترددي مقداره 0.5nm , يستطيع محزز الحيود المقسم من تعديل التقزح المتراكم في الليف الضوئي لمسافة 100 km . بحيث ان طول محزز الحيود المطلوب هو 10 cm . بالاعتماد على النتائج السابقة, تظهر بوضوح الحاجة الى حساب عامل الانقاص بشكل دقيق وذلك لتحسين اداء محزز القسم ذو صيغة تعديل الظل تمام.

Nomenclature

$n(z)$	:	Refractive index
n_o	:	Bragg grating refractive index
Λ	:	Grating period
L	:	Grating length
$\theta(z)$	:	Chirping function
$f(z)$	:	Apodization function
C	:	Chirping parameter
v_1	:	Foreword propagation wave
v_2	:	Backward propagation wave
$q(z)$	:	Complex coupling coefficient
δ	:	Phase shift per unit length
λ_b	:	Bragg wavelength
a_{tr}	:	Truncation parameter
a_{eff}	:	Apodization parameter
$\Delta\tau$	:	Time delay ripples

Introduction

Fiber Bragg grating has emerged as important components in a Varity of light wave applications. Their unique filtering properties and versatility as in-fiber devices are illustrated by their use in wavelength stabilized laser, fiber lasers, remotely pumped amplifiers, Raman amplifier, phase conjugators, converter, passive optical networks, wavelength division multiplexers/demultiplexers, add/drop multiplexer , gain equalizer and dispersion compensators. This last one can be achieved with a special Fiber Bragg Grating type called chirped gratings. In chirped Fiber Bragg Grating (CFBG) the period variation of the refraction index is not constant. Gratings with linear variation are the ones with application for dispersion compensation [Govid, 2005] , [Govid, 2001].

Light propagating within the FBG with a wavelength twice the grating period is reflected. Used as a dispersion compensator, the grating period could be reduced linearly down the length of grating (i.e. chirped mode). Therefore, the shorter wave-length is reflected at a point farther into the device than the longer wavelength. As , intramodal dispersion reflects the fact that the shorter (blue) wavelength of the optical pulse travel faster than the longer (red) wavelength, this wavelength-dependent time delay can be used to produce negative dispersion being perfect to compensate dispersion in optical telecommunications systems. Using fiber Bragg gratings for dispersion compensation is a promising approach, because they are passive optical components, fiber compatible, have low insertion losses and low costs.

Periodic or aperiodic fiber gratings with constant refractive index modulation depth (i.e., unapodized), however, show reflection spectra with large side lobes, and large amplitude ripples especially in CFBG as well as highly nonlinear dispersion characteristics which make them unsuitable for high-performance applications. These characteristics are attributed to residual multiple reflections at the grating ends and can be significantly suppressed by a suitable variation (apodization) of the modulation depth along its length [D. Paster, 1996], [M. N. Zervas, 1996],[R. I. Laming].

The apodization requirements of aperiodic gratings (i.e. CFBG) are expected to be quite different to the ones of the periodic counterparts. It is already known that the reflection spectrum of an apodized, periodic standard grating follows closely the Fourier transform of the applied apodization profile. As a result, smooth and tight apodization profiles result in enhanced side-lobe suppression and superior grating performance. Various apodization profiles have been considered theoretically and experimentally in order to smoothen the reflection spectrum and linearize the dispersion characteristics of aperiodic (chirped) gratings [M. N. Zervas, 1996],[R. I. Laming]. It has been realized that tight apodization profiles, in general, result in smooth features at the expense, however, of grating reflectivity, bandwidth, and dispersion. Excessively tight apodization profiles, on the other hand, might unnecessarily truncate gratings (reduce their effective length) and, in some applications, could impose severe limitations in the writing process.

In this paper, hyperbolic tangent apodization profile is studied and analyzed systematically. We study the effect of the angular truncation parameter of the tanh apodization profile on the CFBG performance. The study is directed in term of bandwidth limitation and linearized time delay characteristics, which make CFBG suitable for using in dispersion compensation applications. In section II, of this paper Fiber Bragg Grating model is presented, where Reccati differential equation is solved using 4th order Rung-Kutta algorithm. Section III, explain and define the effect the truncation parameter of the tanh apodization profile on the CFBG characteristics. The main results of the present paper are discuss and compared in section IV. Finally, section V gives the conclusion of the work.

Chirped FBG model

Wave propagation in optical fibers is analyzed by solving Maxwell's equations with appropriate boundary conditions. Many techniques are suggest for simulating fiber Bragg gratings [L. Poladian, 1993],[J. E. Sipe, 1994],[Johannes, 2000]. All the techniques have varying degrees of complexity. However, the simplest method is the straightforward numerical integration of the coupled-mode equations. In this contest, fiber Bragg Grating scattering of waves in a waveguide occurs when the refractive index is varying in the longitudinal direction .It can assume that the refractive index is varying as a quasi-sinusoidal function:

$$n(z) = n_0 + f(z)\cos(\frac{2\pi}{\Lambda}z + \theta(z)) \quad (1)$$

Where, n_0 is the fiber Bragg grating reference index, $f(z)$ is the apodization function and $\theta(z) = (2\pi/\Lambda)Cz^2$ is the chirping function where, C (in m^{-1}) is the chirp parameter and Λ is the grating period. The functions $f(z)$ and $\theta(z)$ are slowly varying compared to Λ. If the fiber is in single mode operation, it supports only the fundamental mode, which has two components propagating in opposite directions. In the corrugated region, the forward propagating wave v_1 and the backward propagating wave v_2 are related by the coupled mode equations:

$$\frac{dv_1(z;\delta)}{dz} = -i\delta v_1 + q(z)v_2$$
$$\frac{dv_2(z;\delta)}{dz} = +i\delta v_2 + q^*(z)v_1 \qquad (2)$$

In (2), v_1 and v_2 are the complex amplitude envelopes of the waves, obtained by removal of the spatial dependence $exp(\pm i\pi z/\Lambda)$. $q(z)$ is defined as the complex coupling coefficient

$$q(z) = \frac{-i\pi}{2n_0\Lambda} f(z)\exp(-i\theta(z)) \qquad (3)$$

and δ is the phase shift per unit length compared to the Bragg wavelength $\lambda_b = 2n_0\Lambda$.

$$\delta = \beta - \beta_b = \frac{2\pi n_0}{\lambda} - \frac{\pi}{\Lambda} - \frac{1}{2}\frac{d(\theta(z))}{dz} \qquad (4)$$

We further define the local reflection coefficient as :

$$\rho(z;\delta) = \frac{v_2(z;\delta)}{v_1(z;\delta)} \qquad (5)$$

By calculating, $d\rho/dz$ and substituting dv_1/dz and dv_2/dz from the coupled mode equation (2), we get the well-known Riccati equation

$$\frac{d\rho}{dz} = 2i\delta\rho - q(z)\rho^2 + q^*(z) \qquad (6)$$

This differential equation can be numerically solved for the reflection coefficient $r(\delta) = \rho(0,\delta)$ at the beginning of the grating of length L by using the 4th order Runge–Kutta and the boundary condition $\rho(L,\delta) = 0$.

Apodization of CFBGs

Fiber gratings are not infinite in length, so they have a beginning and an end. Thus, they begin abruptly and end abruptly. The Fourier transform of such a "rectangular" function immediately yields the well known *sinc* function, with its associated side-lobe structure apparent in the reflection spectrum. The transform of a Gaussian function, for example, is also a Gaussian, with no side lobes. A grating with a similar refractive modulation amplitude profile diminishes the side lobes substantially. The suppression of the side lobes in the reflection spectrum by gradually increasing the coupling coefficient with penetration into, as well as gradually decreasing on exiting from the grating, is called apodization.

Many apodization profiles has been suggested to optimize CFBG characteristics, such as raised sine, sine, sinc, tanh and Blackman profiles. Karin [Karin, 1998], studied the effect of these profiles on the chirped fiber grating characterstics, and established the optimum relation between the degree of the apodazation and the resulting interrelated grating characteristic. Their results show that the hyperbolic-tangent apodazation profile results in overall superior performance, as it provide dispersion compensators with highly lineareized time delay characteristic with minimum reduction in linear dispersion, compared with the unapodized case.

The hyperbolic tangent profiles can implement using the following equation.

$$f(z)=\begin{cases} tanh(a_{tr}z/L & 0\le z\le L/2 \\ tanh(a_{tr}(L-z)/L & L/2\le z\le L \end{cases} \tag{7}$$

Where, the parameter a_{tr} is best to be called as truncation parameter, since it control the truncation of the apodization function and, L is the CFBG length. **Figure (1)** shows tanh apodazation profile plot against grating length, for different truncation parameter ($a_{tr}=1$ *to* $a_{tr}=20$). From previous figure, it evidence that the truncation parameter play important role in optimizing in chirped grating characteristics i.e their effect on smoothing reflection response and linearized time delay characteristics with minimum reduction in linear dispersion. We define another parameter which is useful in our discussion is the apodization parameter a_{eff} [P. S. Cross] :

$$a_{eff}=\frac{area \text{ of apodized FBG}}{area \text{ of unapodized FBG}}=\frac{\int_0^L f(z)dz}{\int_0^L dz} \tag{8}$$

The smaller the apodization parameter, the tighter the apodization profile. Small apodization parameters correspond to small grating effective lengths. For unapodized gratings, $a_{eff}=1$. In next section, we investigate the effect of the truncation parameter a_{tr} on the tanh apodized chirped fiber Bragg grating characteristics, i.e. minimization unwanted time delay ripples $\Delta\tau$ in phase response as well as it's effects on the full-wave half maximum (FWHM) reflection bandwidth. **Figure (2)** shows the simulation steps that we are used in this work in the computation of the reflection spectrum of the hyperbolic tanh apodized linearly chirped fiber Bragg grating.

Results

In this work direct numerical integration method is used to solve non-linear Reccati differential equation using 4^{th} order Runge-Kutta method for reflection spectrum of CFBG. The CFBG parameter used in our simulation are as follow; Fiber Bragg Grating length $L=10cm$, Chirped parameter $C=1e\text{-}2/m$, Optical center wavelength $\lambda_B=1550nm$, Fiber grating refractive index $n_0=1.5$. When the number of samples of coupling coefficient is small, it is necessary to include an interpolation routine to increase the number of samples in order to reduce the error in the Runge–Kutta algorithm. Such an algorithm is implemented in Matlab_7.4, yielding an efficient reflection spectrum calculation algorithm. The computation of a reflection spectrum takes about 20 minute for a “Chirped” grating on a Dual-Core 1.8GHz and 512 Mbyte ram. We first consider unapodized CFBG properties, i.e. magnitude and time-delay response. In this contest two condition are required for fiber Bragg grating to be used as a perfect dispersion compensation device; first, the magnitude spectrum must be flat and second, the time delay characteristic must have negative linear dispersion slop adequate to compensate of fiber dispersion along define fiber length. **Figure (3a)** and **Figure (3b)** shows the magnitude and time delay characteristic of unapodized CFBG. It clearly that, the amplitude spectrum displays perfect flat response, while time-delay {**Figure (3b)**} behavior of unapodized CFBG displays high unwanted ripples. Hence these ripples make CFBG not suitable for optical communication applications, especially of using it as a dispersion compensator.

Figure (4a) shows the reflection spectrum of CFBG with hyperbolic tanh apodized profile for different truncation parameter $\{a_{tr}=1, 5, 10, 15 \text{ and } 20\}$, the unapodized case is also shown for comparison. The value of $a_{tr}=1$ is not suitable for optical communication since, it cause high magnitude truncation and attenuation in reflection spectrum (compare with **Figure (1)**) .i.e minimizing the apodization parameter, and it shown here for comparison. It evidence that as truncation parameter increase, the CFBG 3dB bandwidth increase (broaden) this result of increasing apodization parameter a_{eff} of the apodization function. The effect of the apodazation truncation parameter on the time delay linearization is shown, in **Figure (4b)** for $a_{tr}=20$.

From previous figures it clearly that the parameter a_{tr} play an important role in linearize time delay characteristics of the tanh apodized CFBG. Hence, we try to study the effect of the varying truncation parameter on the removing unwanted ripples in time delay response as well as it’s limitation of the FWHM reflection bandwidth. **Figure (5)** shows the full-wave half maximum reflection bandwidth plotted against truncation parameter for different chirped parameter values. It noted that, sever reduction in FWHM reflection bandwidth occure at truncation parameter values of $a_{tr}=\{1,2,3\}$ especially for high chirped values i.e. $C=1.5e\text{-}2/m$. For example at $C=1.5e\text{-}2/m$, the percentage reduction in FWHM reflection bandwidth is *55%, 42% and 31%* for truncation parameter of $a_{tr}=1$, *2 and 3* respectively. For $a_{tr}>4$ the apodization profiles have less pronounce effects on the reduction of FWHM reflection bandwidth. **Figure (6)**, show the average time delay ripples $\Delta\tau$ plotted against truncation parameter for three different chirp parameter values. The average time delay ripple $\Delta\tau$ is given by the mean value of the absolute difference of the actual time delays from the best fitted straight line. It Cleary that, the average time delay ripples is exponentially related to chirped parameter value .i.e. the level of $\Delta\tau$ become more sever for large chirped parameter values. Hence, for each curve of **Figure (6)**, their, exist A point for truncation parameter value, at which the average time delay ripples is minimized ($a_{tr}=4$). Again for $a_{tr}>4$ the time delay increase nearly linearly with a_{tr}, and become more sever for large a_{tr} values. According to these results, the truncation parameter must be set to value of 4 in performance optimization of the hyperbolic tangent apodized chirped fiber Bragg grating. For example, for any value of chirped parameter, CFBG approach optimal performance at truncation parameter of 4. This results from that, the increasing in truncation parameter beyond $a_{tr}=4$, the full wave half maximum become broader and incorporate more ripples in reflection spectrum and hence, increasing the level of the average time delay ripples. In addition of using chirped FBG as dispersion compensation, it can be used as in line optical filter, that remove out of band amplified spontaneous emission (ASE) noise and other transmission non-linearties. These two characteristics are studied and summarized in **Figure (7)**. The optical fiber compensating length in km and the FWHM reflection bandwidth are calculated against chirping parameter for tanh ($a_{tr}=4$) apodized CFBG. It evidence that as chirping parameter increase, fiber compensating length decrease exponentially (since the grating dispersion parameter is exponentially related to chirp parameter) while FWHM reflection bandwidth increases linearly. Hence, it can optimize CFBG characteristics by choosing appropriate chirp parameter value. For single channel dispersion compensation and optical communication bandwidth of 0.5nm, using **Figure (7)**, chirp parameter must be set at $C=0.002/m$ that resulting compensating fiber length of 100 km over standard fiber with dispersion parameter of $\{D=17ps/(nm.km)\}$, the required grating length is *10cm*.

Conclusion

The reflection spectrum and time delay characteristics of apodized linearly chirped Fiber Bragg grating have been studied and analyzed. The reflection spectrum of chirped grating is calculated by direct numerical integration of Rccati differential equation yielding an efficient reflection spectrum calculation algorithm. It shown that the truncation parameter (a) of the hyperbolic tanh apodization profile can play an important rule in optimizing CFBG characteristics .i.e. minimum reduction in FWHM reflection bandwith and linearized time delay characteristics. A systematic study show that for any chirped parameter value, tanh apodized CFBG results in optimal performance at truncation parameter of 4. For single channel dispersion compensation and optical communication bandwidth of 0.5nm, 10cm grating length can compensating dispersion accumulated along fiber length of 100 km over standard fiber {D=17ps/(nm.km)}. It can concluded from these results, that for a given chirped parameter value, there exist a truncation parameter value at which CFBG approaches optimal performance.

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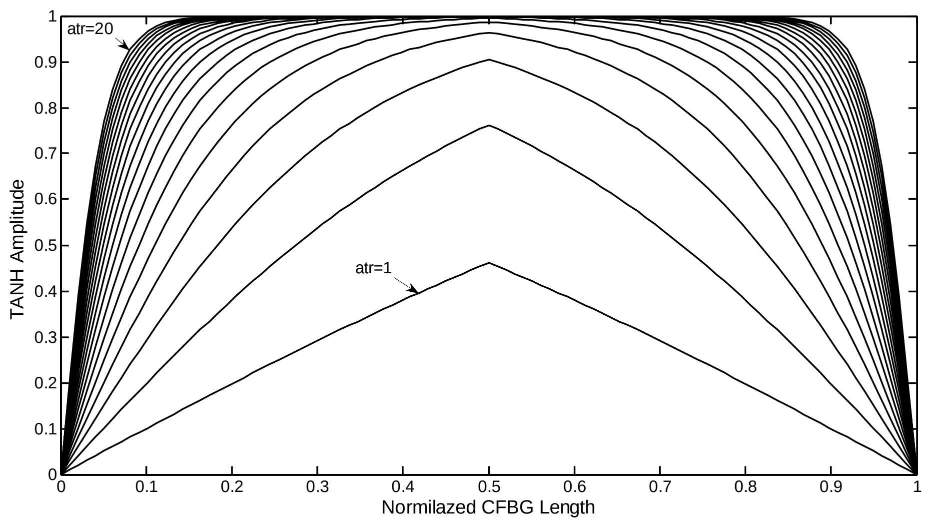

Figure (1): Hyperbolic tangent apodization profile for different truncation parameter values

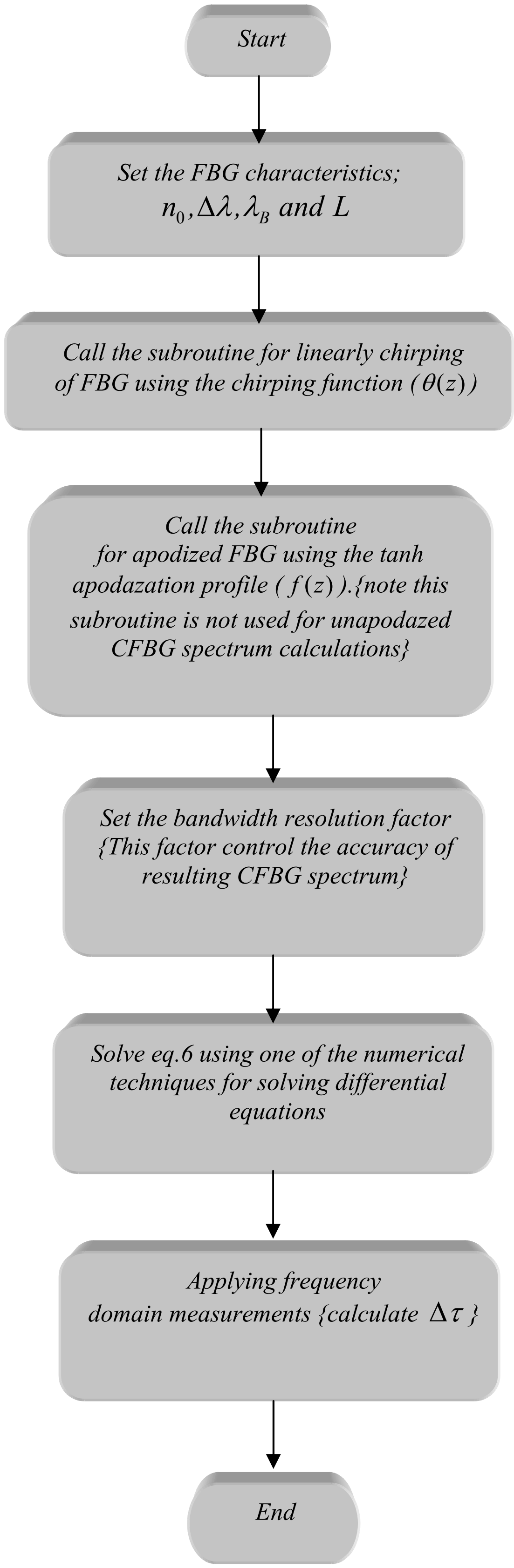

Figure (2): Flowchart for spectrum calculation of CFBG.

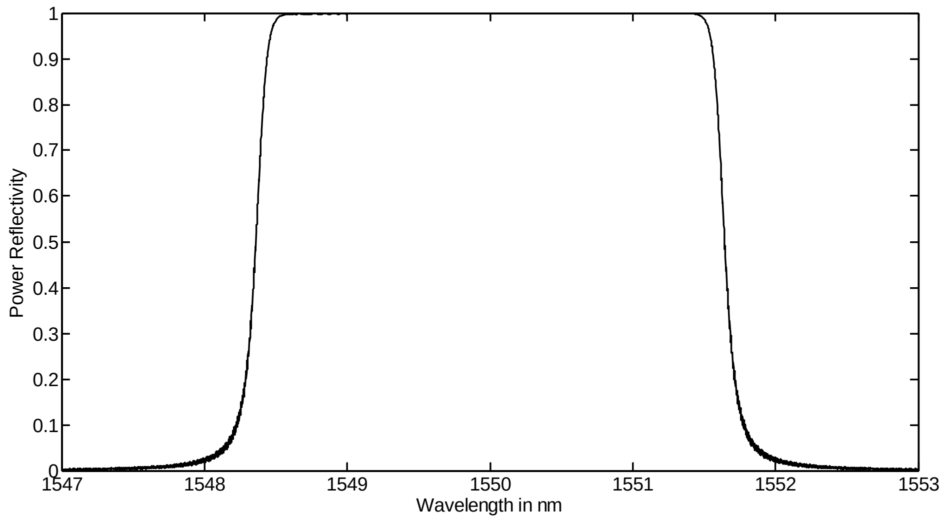

Figure (3a): Power reflectivity versus wavelength of unapodized linearly chirped FBG

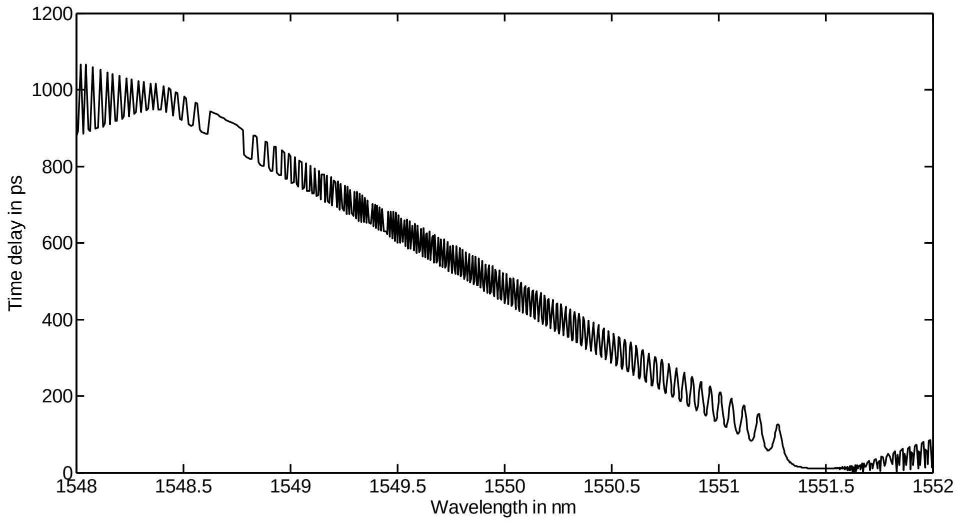

Figure (3b): Time delay response versus wavelength of unapodized linearly CFBG

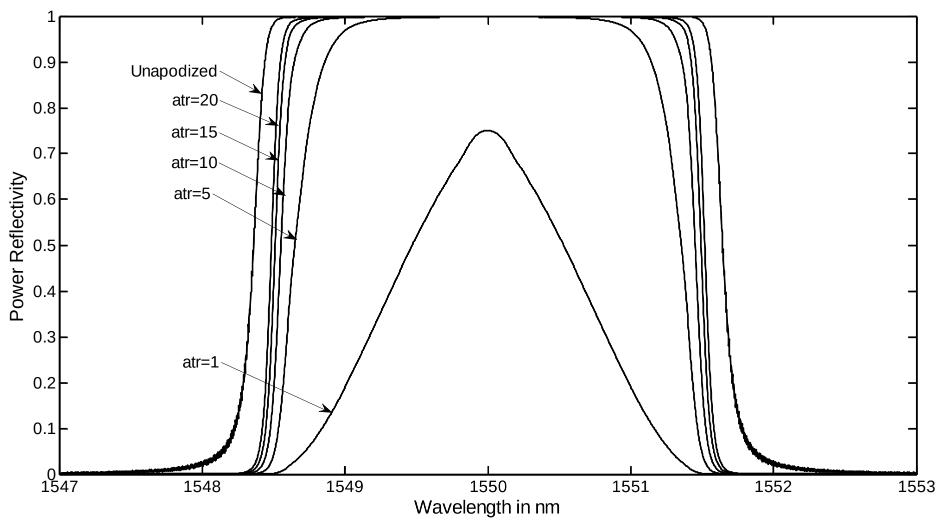

Figure (4a): Power reflectivity against wavelength for different truncation parameter values

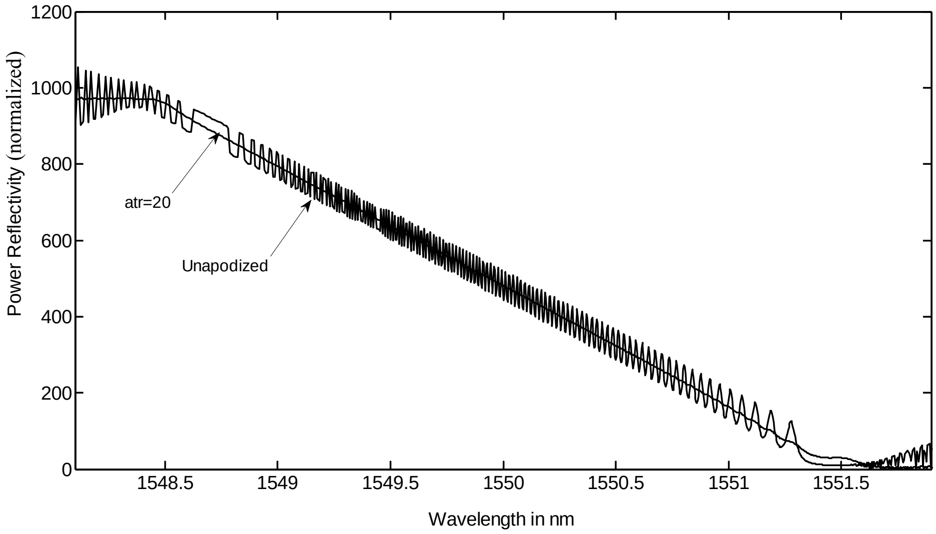

Figure (4b): Time delay response against wavelength for tanh (atr=20) apodized and unapodized CFBG

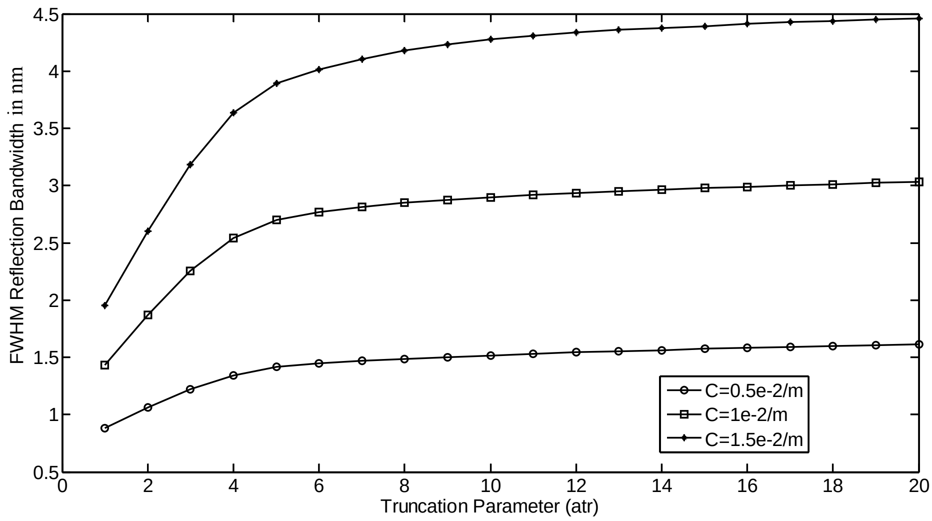

Figure (5): FWHM reflection bandwidth in nm against truncation parameter for different chirped parameter values

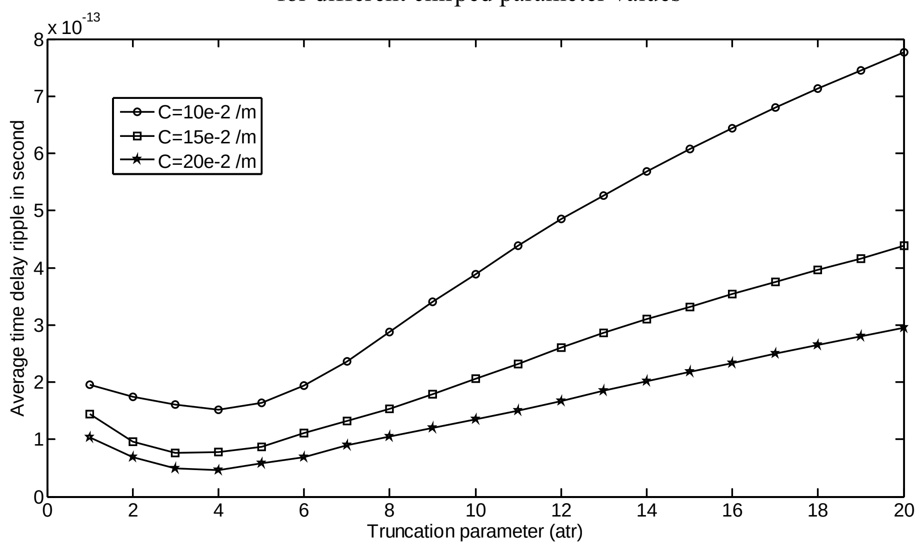

Figure (6): Average time delay ripples against truncation parameter for different chirped parameter values

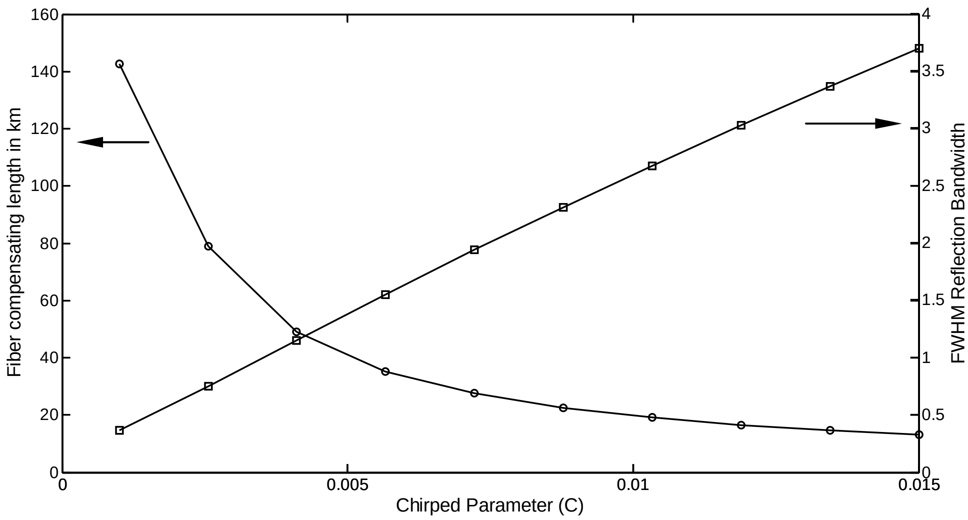

Figure (7): Fiber compensating length in km and FWHM reflection bandwidth in nm against chirp parameter for tanh (a_{tr}=4) apodized CFBG