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Investigations on Variation of FBG Parameters for Tanh Apodization Profile

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Abstract—*Chirped fiber bragg grating is a promising approach for dispersion compensation. Many apodization profiles are suggested to optimize grating performance. In this paper, we have presented the optimization of hyperbolic tangent profile for fiber bragg grating (FBG) as dispersion compensator in optical communication systems. Also we have investigated the effect of variation of FBG parameters for this optimized profile.*

1. INTRODUCTION

The Optical fiber is one of the most important media in communication system[1]. Due to its several advantages and negligible transmission loss it is used in high speed data transmission[2-3]

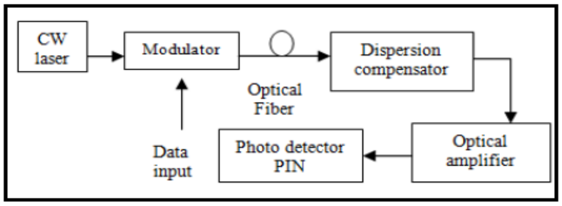


Fig. 1: Optical communications block diagram

The main performance limiting factor in Optical Fiber Communication is the Dispersion[4]. In fiber optical high bit rate (such as 10Gb/s or 40Gb/s) long haul systems, dispersion compensation is the most important thing to be considered for design. Dispersion limits the bandwidth or information carrying capacity of a fiber[5]. Without dispersion compensation each symbol would be broadened and it would overlap with neighboring ones creating the distortion of the detected signal. [6].

There are many methods for dispersion compensation such as DCF, DSF, DFF, Chirped FBG, EDFA, Apodized FBG, Decision point adjustment etc. Comparisons have already been done to find that FBG is better than DCF [7]. DCF is also limited in optical input power to avoid nonlinear impairments, has a relatively high insertion loss and is bulky. Studies have also shown that pre compensation and post compensation methods have been realized based on FBG and DCF and it has been found that post compensation FBG performs better[8-9] FBGs have negligible nonlinearity, low insertion loss and small size, all fiber configuration, highly selective filtering and flexibility. 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. Two most important advances in FBG design are apodization and chirp. In chirped Fiber Bragg Grating (CFBG) the periodic variation of the refractive index is not constant which leads to different optical path length. 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 which is perfect to compensate dispersion in optical telecommunications system.

CFBG fiber gratings show reflection spectra with large side lobes as well as highly nonlinear dispersion characteristics which 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.[10] Unapodized CFBG fails to achieve the expected performance due to high ripples in time delay response. Various apodization profiles are suggested to optimize the grating performance and have been studied in literatures such as Gaussian, positive hyperbolic-tangent, quadratic-sine etc.[11] The dispersion is proportional to the length of the fiber. The length of optical fiber affects dispersion as increase in grating length leads to decrease in dispersion. When the length is increased the width becomes bulky and the magnitude reduces.[12] 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.[13] 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. The study is directed in term of bandwidth limitation and linearized time delay characteristics, which make CFBG suitable for use in dispersion compensation applications.

2. FIBER BRAGG GRATING

The principle of operation of FBG is Fresnel Reflection. It reflects a particular wavelength of light and transmits others. A fiber Bragg grating consists of a periodic modulation of the index of refraction along the core of an optical fiber. The fiber bragg grating is made so segments which reflects different wavelengths are in different positions along the length of fiber. Let the longer wavelengths arrived first and shorter wavelengths arrived last. The longer wavelengths are transmitted through to the last part of gratings and shorter wavelengths are reflected by the first part of grating. Due to this longer wavelength have to travel a longer distance, so they are delayed, allowing the shorter wavelength to catch up.[14] Layout of dispersion compensation module based on fiber bragg grating is shown below.

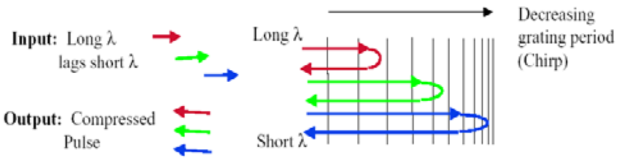


Fig. 2: Principle of operation of FBG

Fiber Bragg Grating plays a significant role in optical fiber communication as filter, stabilizer, gain flattening filter, dispersion compensator, optical router etc.[15] Furthermore, it is also used as sensor for sensing temperature, pressure and strain etc. The FBG is a special form of optical fiber where the refractive index of the core is variable. As a result, the wavelength response of the fiber changes and various application emerge. The FBG is written inside the core of a photosensitive optical fiber using Ultraviolet rays[16,17]. The periodicity of FBG can be of two kinds. e.g mechanical like variation of the core diameter and optical like variation of the refractive index of the core. Two identical counter propagating modes, forward and backward, get coupled in FBG and the energy is transferred from the forward travelling to the backward travelling wave. As a result, we get reflection of the modal energy which is strongly wavelength dependency. The most noticeable feature of FBG is the flexibility of desired spectral characteristics. Numerous physical parameters can be varied including induced index change, length, apodization, period chirp, fringe tilt, and whether the grating supports counter propagating or co-propagating coupling at a desired wavelength. The parameter enable FBG to ensure the desired applications stated above. Wave propagation in optical fibers is analyzed by solving Maxwell's equations with appropriate boundary conditions. Many techniques are suggested for simulating fiber Bragg gratings [18]. 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:

$$\mathrm{n(z) = n0 + f(z)\cos[}\left(\frac{2\pi}{\Lambda}\right)\mathrm{z + \theta(z)]}$$

where, $n0$ 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: [20]

$$\frac{\mathrm{dv1\ (z;\delta)}}{dz} = -\mathrm{i}\delta\mathrm{v1} + \mathrm{q(z)v2}$$

$$\frac{\mathrm{dv2(z;\delta)}}{dz} = +\mathrm{i}\delta\mathrm{v2} + \mathrm{q*(z)v1}$$

$v_1$and v_2 are the complex amplitude envelopes of the waves, obtained by removal of the spatial dependence *exp(±iπz /Λ).q(z)* is defined as the complex coupling coefficient $q(z) = \frac{-i\pi}{2n0\ \Lambda} f(z)\exp(-i\ \theta(z))$ and δ is the phase shift per unit length compared to the Bragg wavelength $\lambda_b = 2n_0\Lambda$

3. 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 have been suggested to optimize CFBG characteristics, such as raised sine, sine, sinc, tanh and Blackman profiles [19]. Study has been done on the effect of these profiles on the chirped fiber grating characterstics, and the optimum relation between the degree of the apodization and the resulting interrelated grating characteristic. Their results show that the hyperbolic-tangent apodization profile results in overall superior performance, as it provide dispersion compensators with highly linearized time delay characteristic with minimum reduction in linear dispersion, compared with the unapodized case.[20] The hyperbolic tangent profiles can be implemented using the following equation.

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

Where, the parameter atr is best to be called as truncation parameter, since it controls the truncation of the apodization function and, L is the CFBG length.[21] It is evident that the truncation parameter plays an important role in optimizing the 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 aeff [22]:

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

The smaller the apodization parameter, the tighter the apodization profile. Small apodization parameters correspond to small grating effective lengths. For unapodized gratings, *aeff*=1. We investigate the effect of the truncation parameter *atr* on the tanh apodized chirped fiber Bragg grating characteristics, i.e. minimization of unwanted time delay ripples Δτ in phase response as well as it's effects on the full-wave half maximum (FWHM) reflection bandwidth.

4. APODIZATION PROFILES

The main apodization profiles, considered in the present investigation, were the following:

1) raised sine profile:
$f(z) = sin^2(\frac{\pi z}{L})$ 0≤z≤L

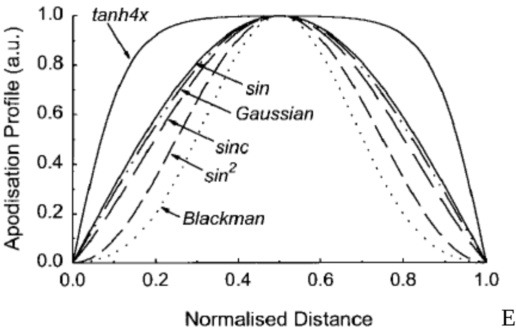
2) sine profile:
$f(z) = sin(\frac{\pi z}{L})$ 0≤z≤L

3) sinc profile:
$f(z) = \frac{\sin(x)}{x}$ x= $\frac{2\pi(z-L/2)}{L}$ 0≤z≤L

4) positive-tanh profile:
$f(z) = tanh(\frac{2az}{L})$ 0≤z≤L

5) Blackman
$f(z) = \frac{1+1.19\cos(x)+0.19\cos(2x)}{2.38}$ 0≤z≤L

For the unapodized linearly chirped grating, f(z) is equal to 1. For large-enough arguments, the function tanh(x) goes asymptotically to 1. The real parameter *a* determines the slope of the profile at z=0 and, therefore, the degree of apodization. All profiles are symmetric around the center of the grating and normalized so that f(L/2)=1. The various apodization profiles are plotted in Fig. 3 for visualization and comparison.



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For each profile f(z) we define an apodization parameter $\alpha_{eff=Leff/L.}$ The smaller the apodization parameter, the tighter the apodization profile. Small apodization parameters correspond to small grating effective lengths. For unapodized gratings, $\alpha_{eff=1}$ The apodization parameter values of the profiles considered in this analysis are listed in Table I.

Table 1: Apodization parameter

Apodisation profile f(z)	*Apodisation parameter* a_{eff}
Raised Sine	0.500
Sinc	0.589
Sine	0.636
Positive tanh (*a* = 4)	0.826

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