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Analysis of fiber Bragg grating with exponential–linear and parabolic taper profiles for dispersion slope compensation in optical fiber links

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ABSTRACT

In this paper, the effect of various taper profiles on dispersion slope compensation in optical fiber links is studied. Theoretical and numerical investigation of the linear and nonlinear group delays of tapered fiber Bragg grating's (T-FBG) under strain is made. Calculation is performed using Matlab code based on solving the coupled mode equation using transfer matrix method. Our study shows that the linear tapered FBG profile provide the best result than the linear-exponential profile which can compensate up to 500 km. As result, the spectral characteristics of tapered grating allow them to be used efficiently in high bit rates WDM and long-haul optical communication systems for chromatic dispersion of single-mode fiber.

1. Introduction

Interest in fiber Bragg gratings (FBGs) has grown increasingly in recent years due to their ease of fabrication and numerous applications in the field of optical fiber technology. In particular, they can be efficiently used for dispersion compensation in high-speed long-haul optical communication systems [1–3], short-pulse generation and restoration [4,5]. Besides, FBGs can be used for the implementation of high-quality fiber laser cavities of various geometries [6,7] and semiconductor diode stabilization [8]. Also, FBGs are spectral filters based on the principle of Bragg reflection [9]. FBG, first demonstrated by Hill et al. [10], is developed by inscribing periodic refractive index modulation into the core of optical fiber using intense ultraviolet (UV) source through interferometry, point-by-point or phase mask technique [11]. The variation of the refractive index gives rise to a photonic band gap inside their spectrum where linear waves cannot propagate [12].

In long-distance optical communication systems, fiber group velocity dispersion (about 17 ps/nm km for standard fibers) degrades system performance by limiting either the maximum bit rate or the distance length (less than 60 km for standard NRZ format at 10 Gbps) [13]. For 10-Gbps transmission system, the dispersion slope caused high order group delay is negligible [14]; but for high speed systems operating at 40 Gbps and beyond the dispersion slope has to be compensated. In recent years, there has been increasing interest in the study of linearly chirped fiber Bragg gratings with different apodization profiles in order to be used as compensator devices in high bit rate systems. Indeed, because fiber Bragg gratings are easy to make, inexpensive, low-insertion loss, compact, compatible with all fiber communication systems.

Of crucial importance is to study the dispersion characteristics of tapered FBGs under strain or stress. In ref [14], the authors have analyzed the dispersion characteristics of linearly tapered FBG. It was demonstrated, theoretically and experimentally, that linearly tapered FBGs display nonlinear group delay under strain, which means that the linearly tapered FBGs can be used in dispersion slope compensation.

In this work, using the same procedure of calculus as in ref. [14], we discuss, theoretically and numerically, the dispersion and dispersion slope cancellation characteristics of two types of tapered FBGs having exponential–linear and parabolic profiles. Our results are compared to those reported in ref [14].

2. Theory

This section will carry out the mathematical analysis of the linear coefficient of the group delay and the quadratic coefficient (dispersion slope) corresponding to the cases of exponential–linear and parabolic tapered FBGs. The study will therefore be split into the following two subsections.

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2.1. Exponential–linear tapered fiber Bragg grating

The radius along the linearly tapered fiber can be expressed as [15].

$$R(z) = R_0\left[e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right] \tag{1}$$

where R_0 is the original radius of the fiber and z_0 is the point along the z axis where the radius of the tapered fiber may come to zero. The cross-section area of the grating at position z is given by

$$A(z) = \pi R(z)^2 = \pi R_0^2\left[e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right]^2 \tag{2}$$

while tension F is applied to the fiber, the axial strain $\varepsilon(z)$ at the grating position z can be expressed as

$$\varepsilon(z) = \frac{F}{EA(z)} = \frac{F}{E\pi R_0^2\left(e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right)^2} = \varepsilon(0)/\left(e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right)^2 \tag{3}$$

where E is Young's modulus, and $\varepsilon(0) = F/E\pi R_0^2$ is the strain at position $z = 0$.

Therefore, the change of the period at original z point will be

$$\begin{aligned}\Delta\Lambda(z) &= \varepsilon(z)\Lambda_0 = \varepsilon(0)\Lambda_0/\left(e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right)^2\\ &= \Delta\Lambda(0)/\left(e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right)^2\end{aligned} \tag{4}$$

where Λ_0 is the original period at position $z=0$ without strain. Hence, the period under tension along the z axis changes to

$$\Lambda(z) = \Lambda_0 + \Delta\Lambda(z) = \Lambda_0 + \Delta\Lambda(0)/\left(e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}\right)^2 \tag{5}$$

When the taper slope is very small, that means $z \ll z_0$, the relationship between z and z' can be expressed as

$$z' = z + \frac{\Delta\Lambda(0)}{\Lambda_0}z = z\left(1 + \frac{\Delta\Lambda(0)}{\Lambda_0}\right) \tag{6}$$

To analyse of the group-delay characteristics, we can rewrite Eq. (6) in the form

$$e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1} = \left(\frac{\Delta\Lambda(0)}{\Lambda(z) - \Lambda_0}\right)^{1/2} \tag{7}$$

where $\Delta\Lambda(0) = \Lambda(0) - \Lambda_0$, When $z \ll z_0$, we expand $e^{-\frac{z}{z_0}} - \frac{z}{z_0}e^{-1}$ in Taylor series around $z = 0$, we obtain

$$e^{-\frac{z}{z_0}} = 1 - \frac{z}{z_0} + \frac{z^2}{2z_0^2} + \cdots \tag{8}$$

by neglecting the term of order two in Eq. (8), we can rewrite Eq. (7) in the form

$$z = \frac{z_0}{1+e^{-1}}\left\{1 - \left(\frac{\Lambda(z) - \Lambda_0}{\Delta\Lambda(0)}\right)^{-1/2}\right\} \tag{9}$$

Expanding $((\Delta\Lambda(0)/(\Lambda(z) - \Lambda_0))^{-1/2}$ in Taylor series at $z = 0$, we obtain

$$\begin{aligned}z = \frac{z_0}{1+e^{-1}}&\left(\frac{1}{2\Delta\Lambda(0)}(\Lambda\text{mol/L} - \Lambda(0))\right.\\ &\left.- \frac{3}{8\Delta\Lambda(0)^2}(\Lambda(z) - \Lambda(0))^2\right)\end{aligned} \tag{10}$$

Using (6) and (10), we obtain

$$\begin{aligned}z' = \frac{z_0}{1+e^{-1}}&\left(\frac{1}{2\Delta\Lambda(0)}(\Lambda(z) - \Lambda(z))\right.\\ &\left.- \frac{3}{8\Delta\Lambda(0)^2}(\Lambda(z) - \Lambda(0))^2\right)\left(1 + \frac{\Delta\Lambda(0)}{\Lambda_0}\right)\end{aligned} \tag{11}$$

Considering the refractive index changes with the applied strain because of the photo-elastic effect, the change of Bragg wavelength at original point is given by [16]

$$\begin{aligned}\Delta\lambda_B(z) &= \varepsilon(z)(1-\chi)\cdot\lambda_0 = \varepsilon(z)(1-\chi)(1-\chi)\cdot 2n_{eff}\Lambda_0\\ &= \Delta\Lambda(z)(1-\chi)2n_{eff}\end{aligned} \tag{12}$$

where χ is the photo-elastic effect and E is the Young's modulus, which describes the fiber lengthening effect ($\chi = 0.22$ for silica).

According to Eqs. (11) and (12), we can express z' as a function of the Bragg wavelength variation

$$\begin{aligned}z' = \frac{z_0}{1+e^{-1}}&\left(\frac{1}{2\Delta\Lambda(0)}\left(\frac{\Delta\lambda_B(z)}{(1-\chi)2n_{eff}}\right)\right.\\ &\left.- \frac{3}{8\Delta\Lambda(0)^2}\left(\frac{\Delta\lambda_B(z)}{(1-\chi)2n_{eff}}\right)^2\right)\left(1 + \frac{\Delta\Lambda(0)}{\Lambda_0}\right)\end{aligned} \tag{13}$$

The group delay experienced by a signal reflected from a particular position z' of the grating is given by $t = 2z'n_{eff}/c$, where c is the speed of light in vacuum. By substituting z' in this definition of t, we can obtain the function of group delay to wavelength as follows:

$$\begin{aligned}t = \frac{2n_{eff}z_0}{(1+e^{-1})c}\left(1 + \frac{\Delta\Lambda(0)}{\Lambda_0}\right)&\left(\frac{1}{2\Delta\Lambda(0)}\left(\frac{\Delta\lambda_B(z)}{(1-\chi)2n_{eff}}\right)\right.\\ &\left.- \frac{3}{8\Delta\Lambda(0)^2}\left(\frac{\Delta\lambda_B(z)}{(1-\chi)2n_{eff}}\right)^2\right)\end{aligned} \tag{14}$$

2.2. Parabolic tapered fiber Bragg grating

In the case of a parabolic profile, the radius along the linearly tapered fiber can be expressed as [15].

$$R(z) = R_0\left(1 - \frac{z}{z_0}\right)^{1/2} \tag{15}$$

The cross-section area of the grating at position z is given by

$$A(z) = \pi R(z)^2 = \pi R_0^2(1 - z/z_0) \tag{16}$$

The axial strain $\varepsilon(z)$ at the grating position z can be expressed as

$$\varepsilon(z) = \frac{F}{EA(z)} = \frac{F}{E\pi R_0^2(1 - z/z_0)} = \varepsilon(0)/(1 - z/z_0) \tag{17}$$

The change of the period at original z point will be

$$\Delta\Lambda(z) = \varepsilon(z)\Lambda_0 = \varepsilon(0)\Lambda_0/(1 - z/z_0) = \Delta\Lambda(0)/(1 - z/z_0) \tag{18}$$

The period under tension along the z axis changes to

$$\Lambda(z) = \Lambda_0 + \Delta\Lambda(z) = \Lambda_0 + \Delta\Lambda(0)/(1 - z/z_0) \tag{19}$$

Rewrite (19) as

$$z = z_0\left(1 - \frac{\Delta\Lambda(0)}{\Lambda(z) - \Lambda_0}\right) \tag{20}$$

$$z = z_0\left(\frac{\Lambda(z) - \Lambda(0)}{\Lambda(z) - \Lambda_0}\right) = z_0\left(\frac{\Lambda(z - \Lambda(0)}{\Lambda(z) + \Delta\Lambda(0) - \Lambda(0)}\right) \tag{21}$$