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Analysis of apodized phase-shifted long-period fiber gratings

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Abstract

We present a detailed theoretical analysis of the transmission spectra of apodized phase-shifted long-period fiber gratings (LPFGs). Simple analytical formulas are derived to provide insights into the characteristics of the gratings and facilitate their designs for specific applications. In particular, we focus on the achievement of zero or complete transmission at the resonance wavelength with zero- or π-phase-shifted gratings. The effects of index apodization and length apodization on the transmission spectra of the LPFGs are studied in detail. A number of numerical examples are given to illustrate the features of various kinds of LPFG designs.

Keywords: Coupled-mode theory; Long-period fiber gratings; Apodized gratings; Phase-shifted gratings; Optical filters; Wavelength-division multiplexers

1. Introduction

Long-period fiber grating (LPFG), which is produced by introduction of a periodic modulation of the refractive index in the core of a single-mode fiber, has generated tremendous interest in the fields of optical communications and optical sensing. An LPFG allows light coupling between the guided mode and the cladding modes, which results in a series of attenuation bands centered at discrete wavelengths in the transmission spectrum [1]. LPFGs have been developed into many useful components, including gain flattening filters for erbium-doped fiber amplifiers [2–8], dispersion compensators [9–11], widely tunable filters [12,13], and broadband add/drop multiplexers [14,15], as well as a wide range of optical sensors [16–18]. A distinct feature of LPFGs is their flexibility in achieving desired transmission characteristics by variation of the grating parameters (e.g., index modulation, grating period, grating length, chirping, phase shifts, etc.). For example, index apodization has been used for the elimination of side lobes in the transmission spectrum [19] and phase

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shifts have been introduced along an LPFG for the generation of narrow passing bands [20,21]. Flat-top band-pass filters [22] and band-rejection filters [23] have also been demonstrated with LPFGs consisting of multiple phase shifts.

In this paper, we present a detailed theoretical analysis of apodized phase-shifted LPFGs using the transfer matrix method. The general conditions for achieving zero or complete transmission at the resonance wavelength are derived. The effects of index apodization and length apodization on the transmission spectrum are discussed. Numerical examples are given for the design of band-pass, band-rejection, and comb filters. Our study provides a better understanding of the characteristics of LPFGs, which should facilitate the design of LPFG-based devices.

2. Method of analysis

We consider an LPFG consisting of M sections, as shown in Fig. 1, where φ is the phase shift between two adjacent sections. The grating pitch Λ is the same in all sections, but the amplitude of the index modulation and the length are allowed to vary from section to section. The resonance wavelength of the LPFG, λ_0, is determined by the phase-matching condition [1]

$$\lambda_0 = (N_{01} - N_{0m})\Lambda, \tag{1}$$

where N_{01} and N_{0m} are the effective indices of the LP_{01} and LP_{0m} $(m = 2, 3, 4, \ldots)$ modes, respectively. For a sinusoidal index modulation along the direction of wave propagation z, the coupled-mode equations for the ith section of the grating that describe the coupling of the amplitudes of the LP_{01} and LP_{0m} modes, $A(z)$ and $B(z)$, are given by [21]

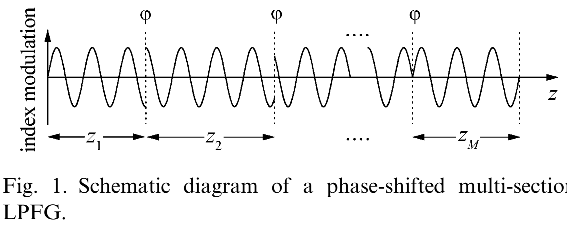

Fig. 1. Schematic diagram of a phase-shifted multi-section LPFG.

$$\frac{\mathrm{d}A}{\mathrm{d}z} = \kappa_i B\,\mathrm{e}^{\mathrm{j}2\delta z}\,\mathrm{e}^{-j\varphi_i}, \tag{2}$$

$$\frac{\mathrm{d}B}{\mathrm{d}z} = -\kappa_i A\,\mathrm{e}^{-\mathrm{j}2\delta z}\mathrm{e}^{\mathrm{j}\varphi_i}, \tag{3}$$

where

$$\delta = \frac{\pi}{\Lambda}\left(\frac{\lambda_0}{\lambda} - 1\right) \tag{4}$$

is the phase mismatch, which is a measure of the deviation of the operating wavelength λ from the resonance wavelength λ_0. κ_i is the coupling coefficient (a real positive number), which is proportional to the amplitude of the index modulation and the overlapping between the LP_{01} and LP_{0m} mode fields over the cross-sectional area of the fiber core (assuming index modulation in the fiber core only). φ_i is the initial phase of the ith section. The electric fields of the LP_{01} and LP_{0m} modes, $E_A(z)$ and $E_B(z)$, are related to their amplitudes by $E_A(z) = A(z)\mathrm{e}^{-\mathrm{j}\beta_{01}z}$, and $E_B(z) = B(z)\mathrm{e}^{-\mathrm{j}\beta_{0m}z}$, respectively, where β_{01} and β_{0m} are the corresponding propagation constants. Each section of the LPFG can be represented by a transfer matrix that relates the input and output electric fields of the modes [21]. Therefore, the output electric fields from the LPFG can be obtained by simply multiplying the transfer matrices of all sections [21]:

$$\begin{pmatrix} E_A(L) \\ E_B(L) \end{pmatrix} = F_M \cdots F_3 F_2 F_1 \begin{pmatrix} E_A(0) \\ E_B(0) \end{pmatrix}, \tag{5}$$

where

$$F_i = \begin{pmatrix} \mathrm{e}^{-\mathrm{j}(\beta_{01}-\delta)z_i} & 0 \\ 0 & \mathrm{e}^{-\mathrm{j}(\beta_{0m}+\delta)z_i} \end{pmatrix} \times \begin{pmatrix} \cos(Q_i z_i) - \mathrm{j}\frac{\delta}{Q_i}\sin(Q_i z_i) & \frac{\kappa_i}{Q_i}\mathrm{e}^{-\mathrm{j}\varphi_i}\sin(Q_i z_i) \\ -\frac{\kappa_i}{Q_i}\mathrm{e}^{j\varphi_i}\sin(Q_i z_i) & \cos(Q_i z_i) + j\frac{\delta}{Q_i}\sin(Q_i z_i) \end{pmatrix} \tag{6}$$

is the transfer matrix for the ith section, z_i is the corresponding section length, $Q_i = (\delta^2 + \kappa_i^2)^{1/2}$, $L = \sum_{j=1}^{i=m} z_i$ is the total length of the LPFG, and the initial phase is given by

$$\phi_i = \frac{2\pi}{\Lambda}\sum_{j=1}^{j=i-1} z_j + (i-1)\varphi. \tag{7}$$