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Filtering characteristics of film-coated long-period fiber gratings operating at the phase-matching turning point

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ABSTRACT

We present novel filtering characteristics of film-coated long-period fiber gratings (LPFGs) operating at phase-matching turning point (PMTP). The 3 dB bandwidth of a single broadband dip depends greatly on the film refractive index and thickness. A π-phase-shift in the grating center produces two band-rejection peaks between which the separation reaches 375 nm. This separation increases with the number M ($M > 1$) of π-phase-shifts that divide the LPFG uniformly. The central loss is constant at zero for odd M, whereas decreases with M for even M. Increasing film thickness and refractive index result in blue shifts of the dual peaks and enlarge the separations, which exhibits excellent tunabilities.

1. Introduction

A long-period fiber grating whose periodicity lies typically in the range of 100–1000 μm acts to couple the fundamental core mode to copropagating cladding modes, leaving a series of attenuation bands in the transmission spectrum. Owing to the advantages over the fiber Bragg gratings such as ease of fabrication, low insertion loss and low-level back reflection, LPFGs have experienced an increasing presence over the last years in communication [1,2] and sensing [3–5] applications. For conventional LPFGs, the couplings between core mode and lower-order cladding modes are usually interrogated where the bandwidths of attenuation peaks are ~10 nm. It has been revealed that when the grating period is relatively short, the phase-matching curves (PMCs) corresponding to the coupling from core mode to higher-order cladding modes manifest themselves as parabolas over the wavelength range of 900–2000 nm [6]. Each PMC has a turning point at which the slope of PMC turns from positive to negative; this point is termed phase-matching turning point. If the grating period is selected properly to let an LPFG operate at this turning point, the coupling produces a single loss peak whose 3 dB bandwidth ($\Delta\lambda_{3\,dB}$) exceeds 100 nm [7,8].

In recent years, great efforts have been dedicated to the research of long-period fiber gratings coated with high-refractive-index (HRI) films [9–11]. LPFG film sensors operating near the phase-matching turning point and little off resonance have been investigated theoretically and experimentally [12–14]. It was shown that tiny variation of film refractive index induced by the interaction between the functional film and measurand results merely in the change of intensity of the broad attenuation band, whereas the resonant wavelength is fixed. Hence, these film sensors are extremely suitable for intensity-interrogated photochemical and biosensors. So far, however, an investigation into the spectral characteristics of a film-coated LPFG working exactly at the phase-matching turning point is still absent, though the broadband width of common LPFGs operating at PMTP has been discussed [7,8]. Moreover, material dispersions are commonly not involved in the most of previous theoretical discuss of LPFG working at PMTP [7,8,12]. In fact, it is imperative to take into account the material dispersions in the theoretical analysis and numerical investigation of the spectrum properties of this kind of LPFG devices whose spectrum extends over an extremely wide range of wavelength. It is noticed that the presence of HRI films modifies the distribution of cladding-mode fields [9], which offers an efficient means to adjust the property of transmission spectrum. Therefore, a film-coated LPFG operating at PMTP promises tunable broadband characteristics of the transmission spectrum. Furthermore, when a π-phase-shift is introduced into this LPFG, dual-peak band-rejection filtering with large separation are not unexpected, since

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the phase-shifted long-period fiber gratings (PS-LPFG) based on the coupling between core mode and lower-order cladding modes have exhibited the similar filtering characteristics except for the small separation [15].

In this work, a thorough numerical investigation into the properties of PMTPs of a film-coated LPFG and the 3 dB bandwidth of loss peaks are presented, taking into account the impact of the material dispersions. Based on the coupled-mode theory, the transmission spectra are calculated by transfer matrix method (TMM) and the 3 dB bandwidths of broadband peaks are analyzed. Furthermore, the dual-peak band-rejection filtering characteristics of LPFGs with a single π-phase-shift and even multiple π-phase-shifts are investigated. Special attentions are paid to the influence of film parameter (refractive index and thickness) on the transmission spectra. Novel broadband and large-separation dual-peak filtering characteristics are expected to provide a theoretical guidance for fiber filter design

2. Theoretical analysis

2.1. Transfer matrix method

As is shown in Fig. 1(a), the structure of a film-coated LPFG can be considered as a four-layer model where the core and cladding are the first and second layer, respectively; the HRI film that is directly deposited on the cladding is the third layer and the surrounding medium is the fourth layer. The refractive index profile of this four-layer LPFG is illustrated in Fig. 1(b) where n_1, n_2, n_3 and n_4 represent the refractive indices of the core, cladding, film and surrounding, respectively. The radii of the core, cladding and film layer are denoted by a_1, a_2 and a_3, respectively, with the value $(a_3 - a_2)$ being the film thickness h_3. In the remainder of this paper, the fiber parameters n_3, n_4, a_1, a_2 and h_3 are 1.57, 1, 4.15 μm, 62.5 μm and 200 nm, respectively, unless otherwise stated.

The coupling mechanism between the core mode and an mth cladding mode in an LPFG can be described with a transfer matrix [16]:

$$F = \begin{bmatrix} \cos(sL) + i\dfrac{\delta}{s}\sin(sL) & i\dfrac{\kappa}{s}\sin(sL) \\ i\dfrac{\kappa}{s}\sin(sL) & \cos(sL) - i\dfrac{\delta}{s}\sin(sL) \end{bmatrix} \quad (1)$$

where κ is the cross-coupling constant between the core mode and the mth cladding mode; L is the grating period. δ is the small detuning parameter:

$$\delta = \frac{1}{2}\left(\beta_{co} - \beta_{cl}^{m} - \frac{2\pi}{\Lambda}\right) \quad (2)$$

where β_{co} and β_{cl}^{m} are the propagating constants of the core mode and mth cladding mode, respectively. The other parameter in Eq. (1) s is given as $s = \sqrt{\kappa^2 + \delta^2}$.

As is shown in Fig. 2, a PS-LPFG can be treated as an LPFG divided by the phase-shifts; thus the transfer matrix for a PS-LPFG can be given as:

$$F_{PS} = F_{M+1}F_{pM}\cdots F_{i+1}F_{pi}F_i\cdots F_{p1}F_1 \quad (3)$$

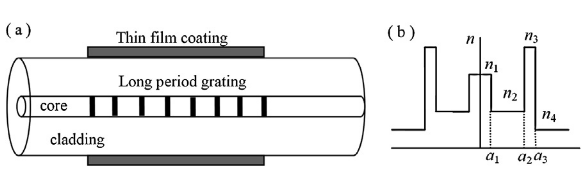

Fig. 1. Schematic of coated LPFG sensor: (a) structural diagram; (b) refractive index profile.

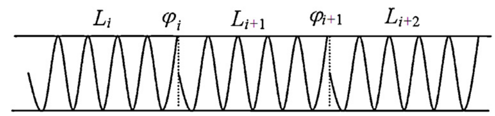

Fig. 2. Schematic of core refractive index modulation of a PS-LPFG.

where M is the total number of phase shifts; F_i is a matrix obtained by substituting the length of a grating segment L_i into Eq. (1), whereas F_{pi} is the transfer matrix associated with the ith phase shift φ_i:

$$F_{pi} = \begin{bmatrix} \exp\left(\dfrac{i\varphi_i}{2}\right) & 0 \\ 0 & \exp\left(-\dfrac{i\varphi_i}{2}\right) \end{bmatrix} \quad (4)$$

It is stressed that the broad-band resonant peaks of an LPFG working at PMTP, especially the large-separation dual-peaks in a PS-LPFG extend over an extremely wide wavelength range. Therefore, it is necessary to consider the material dispersion in theory analysis and numerical simulations. The dispersive characteristics of pure silica: SiO_2 and silica doped with dopants such as GeO_2 can be precisely evaluated by using the well-known Sellmeier equation [17]:

$$n^2 - 1 = \sum_{1}^{3}\frac{A_i\lambda^2}{\lambda^2 - B_i^2} \quad (5)$$

where λ is wavelength in the unit of μm, A_i and B_i are the Sellmeier coefficients. In the case of silica doped with GeO_2, these two coefficients are: $A_1 = 0.6961663$, $B_1 = 0.0684043$, $A_2 = 0.4079426$, $B_2 = 0.1162414$, $A_3 = 0.8974994$, $B_3 = 9.896161$ for pure silica (cladding), and $A_1 = 0.7003729$, $B_1 = 0.0684259$, $A_2 = 0.41973080$, $B_2 = 0.11767400$, $A_3 = 0.89583358$, $B_3 = 9.97010026$ for about 3.8 mole% GeO_2 doped (core) in photosensitive single mode fiber on estimation. Hence, the refractive indices of core and cladding n_1 and n_2 in Fig. 1 are calculated in the simulations in remainder of this paper.

2.2. Phase-matching turning point

The phase-matching condition for the coupling between the core mode and an mth cladding mode can be expressed as:

$$\lambda_{res,m} = [n_{eff}^{co}(\lambda_{res,m}) - n_{eff}^{cl,m}(\lambda_{res,m})]\Lambda \quad (6)$$

where $\lambda_{res,m}$ is the resonant wavelength at which the phase-matching condition is satisfied, n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective refractive indices (ERIs) of the core mode and mth cladding mode, respectively. Eq. (6) implies a certain relation between the grating period and resonant wavelength, since the ERIs are functions of wavelength. The phase-matching curves calculated according to Eq. (6) are illustrated in Fig. 3. Fig. 3(a) shows that for lower-order cladding modes ($m = 1$–10), the PMCs exhibit positive slopes throughout the wavelength range of 900–2000 nm; the resonant wavelength increases monotonously with grating period. Therefore, there is only one intersection between each PMC and a vertical line representing a specific period. This is the case related to the conventional LPFGs. For the higher-order cladding modes, however, the phase-matching condition maps out quadratic curves, as illustrated in Fig. 3(b). It is evident that each PMC contains a turning point at which the curve slope changes from positive to negative, i.e., $|d\lambda_{res}/d\Lambda| \to \infty$. Fig. 4 demonstrates the PMCs of $HE_{1,10}$ mode ($m = 19$) with and without consideration of material dispersion, where the two filled circles denote the respective turning points. By inspection from Fig. 4 it is clear that the consideration of material