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Spectral characteristics of a two-section multilayer long-period fiber grating sensor

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ABSTRACT

A novel long period fiber grating (LPFG) sensor structure is proposed in this paper. It is constituted by coating an over-layer partially on the fiber grating. Then the LPFG has a two-section multilayer transversely distributed refractive index structure. Using coupling mode theory and transfer matrix method, the influences of refractive index, thickness and length of the coating layer on the spectral characteristics of the new type LPFG were analyzed. The simulation results show that the resonant band is split due to the particularity of the LPFG structure, and the wavelength splitting is strongly dependent on the parameters of the coating layer. This LPFG designing may solve the cross sensitive problem and then realize synchronous measurement of temperature, strain and other physical quantities.

1. Introduction

Long-period fiber grating (LPFG) has been widely used in fiber telecommunication and optical sensing field since it was successfully inscribed into fiber by Vengsarkar in 1995 [1]. As optical sensor, LPFG can measure various parameters such as temperature, strain, and refractive index [2–6]. It possesses a number of attractive merits such as immunity to electromagnetic interference, low insertion loss, low cost, easy production, high sensitivity and so on. However, because of the large inherent sensitivity to temperature, strain and refractive index, conventional LPFG in general meet the problem of cross sensitive between different physical quantities. When one quantity is measured, variations from other quantities caused by environmental change will induce resonance wavelength shift and transmission peak loss, leading to the decrease of the sensitivity.

Many efforts have been endeavored to solve the cross-sensitivity of LPFGs, and many solutions have been proposed [6–14]. In 1996, Patrik constructed a combination of LPFG and Brag grating fiber with different response to stress and temperature, and realized simultaneous measurement of stress and temperature [7]. Inspired by this idea, combinations of two LPFGs, LPFG and polarization maintaining fiber and other sensor with different response to temperature, stress, bending and refractive index were designed and successfully realized two quantities simultaneous measurement [8–11]. However, all the proposals need two or more sensor combination, which increases the complexity and cost of the device. In 1997, Bhatia found that different resonance wavelength of LPFG has different sensitivity to stress and temperature [12]. By virtue of this merit, he achieved the two qualities simultaneous measurement on a single LPFG. Hereafter, Han inscribed a LPFG into polarization maintaining fiber and realized simultaneous measurement of stress and temperature using the resonance peak splitting phenomenon induce by birefringence effect [13]. Rego fabricated a specific LPFG on SMF-28 by arc discharge method [14]. This LPFG, which is divided into two zones with the same period but different fabrication parameters, possesses two neighboring resonance peak with different stress and temperature sensitivities. Though these methods achieved synchronous measurement of different physical quantities on one single LPFG, the system is still complex, high cost and applicable only for special situation. So it is necessary to further explore the solutions to cross sensitivity in LPFG before its practical application.

Based on the sensibility of LPFG to the medium beyond the cladding, a new type LPFG sensor composed of two-section with transversely distributed refractive index multilayer was proposed. The influences of refractive index, thickness and length of the coating layer on the spectral characteristics of the new type LPFG were analyzed using coupling mode theory and transfer matrix method. The simulation results show that the resonant band is

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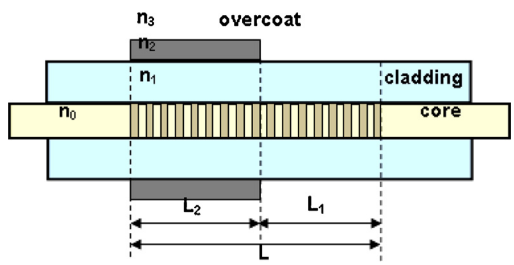

Fig. 1. Schematic diagram of the LPFG sensor composed of two-section multilayer transversely distributed refractive index.

split due to the particular structure of the LPFG, and the wavelength distance between the two split bands is highly dependent on the characteristics of the coating layer. By properly designing the coating layer, the novel LPFG may realize synchronous measurement of temperature, strain and other physical quantities.

2. LPFG structure design

The LPFG structure proposed in this paper was shown in Fig. 1. A conformal LPFG with the length of L is divided into two sections (L_1 and L_2). In section L_2, a coating layer with the refractive index of n_2 was deposited on the cladding layer, and then a four-layer structure is formed with a refractive index transversely distributed in a sequence of n_0, n_1, n_2 and n_3, where n_0, n_1 and n_3 denote the refractive index of core, cladding and outer environment respectively. Section L_1 is still composed of three layers with the refractive index of n_0, n_1 and n_3 in sequence. In this way, a conformal LPFG was transformed to a two-section with three-four layer structure.

3. Theoretical analysis

3.1. Transmission of the two-section LPFG

According to the coupled mode theory, the transmission matrix T_K of an m-order uniform LPFG with the length of L is expressed by [15]:

$$T_K^m = \begin{bmatrix} \cos(sL) + \dfrac{i\Delta\beta \sin(\mathrm{sL})}{2s} & \dfrac{iK}{s}\sin(sL) \\ \dfrac{iK^*}{s}\sin(sL) & \cos(sL) - \dfrac{i\Delta\beta\sin(sL)}{2s} \end{bmatrix}$$

where $s = \sqrt{K^2 + (\Delta\beta^2/4)}$, $\Delta\beta = \beta_0 - \beta_1 - (2\pi/\Lambda)$, $K = (\pi\delta n/\lambda)$, $\beta_0 = (2\pi/\lambda)n_{\mathrm{eff}}^{\mathrm{co}}$, $\beta_1 = (2\pi/\lambda)n_{\mathrm{eff}}^{\mathrm{cl}\text{-}m}$. $n_{\mathrm{eff}}^{\mathrm{co}}$ and $n_{\mathrm{eff}}^{\mathrm{cl}\text{-}m}$ are effective refractive index of fundamental mode of fiber core and m order cladding mode. Λ is the period of the grating and δn is the average effective refractive index modulation. K is the coupling coefficient.

The LPFG structure in Fig. 1 can be regarded as a sequential connection between a four-layer LPFG (L_2) and a three-layer LPFG (L_1). Based on coupling mode theory, the amplitude of the fundamental mode and the m order cladding mode in the same transmitting direction in the LPFG can be expressed as:

$$\begin{bmatrix} a_{\mathrm{co}}(L) \\ a_{\mathrm{cl}}(L) \end{bmatrix} = T_K(L_1,\, n_{1\mathrm{eff}}^{\mathrm{cl}\text{-}m}) \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} T_K(L_2,\, n_{2\mathrm{eff}}^{\mathrm{cl}\text{-}m}) \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{2}$$

where $\begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$ is the interface matrix between the two sections of the grating, $b_{11} = b_{22} = (n_{\mathrm{eff}}^{\mathrm{co}} - n_{\mathrm{eff}}^{\mathrm{cl}-m})/2n_{\mathrm{eff}}^{\mathrm{co}}$ and $b_{12} = b_{21} = (n_{\mathrm{eff}}^{\mathrm{co}} + n_{2\mathrm{eff}}^{\mathrm{cl}-m})/2n_{\mathrm{eff}}^{\mathrm{co}}$. Consequently, the transmission of the fundamental mode of the fiber core in the two-section LPFG can be concluded as:

$$T(\lambda) = \left|(t_{11}b_{11} + t_{12}b_{21})t_{13} + (t_{11}b_{12} + t_{12}b_{22})t_{23}\right|^2 \tag{3}$$

where $t_{11} = \cos(s_1L_1) + (i\Delta\beta_1 \sin(s_1L_1))/2s_1$, $t_{12} = (ik_1/s_1)\sin(s_1L_1)$, $t_{13} = \cos(s_2L_2) + (i\Delta\beta_2\sin(s_2L_2))/2s_2$, and $t_{23} = (ik_2/s_2)\sin(s_2L_2)$.

3.2. Dispersion equation of the core guided mode in the two-section LPFG

Though the LPFG proposed in this paper has three-four layer transversely refractive index distributed two-section structure, the effect of coating layer on the fiber core mode is small for a conformal single-mode weak fiber because of the big radius of the cladding. Therefore, when calculating the effective refractive index of the core fundamental mode in LPFG, the influence from coating layer can be neglected, and the conformal two-layer medium fiber model can be adopted. The dispersion equation of the fundamental core mode in weak single mode fiber is given by [16]:

$$V\sqrt{1-b}\frac{J_1(V\sqrt{1-b})}{J_0(V\sqrt{1-b})} = V\sqrt{b}\frac{K_1(V\sqrt{b})}{K_0(V\sqrt{b})} \tag{4}$$

where J_0 and J_1 are zero order and the first order Bessel functions. K_0 and K_1 are zero order and the first order Bessel functions. $V = (2\pi a_1\sqrt{n_0^2 - n_1^2}/\lambda)$ is the normalized frequency with a_1 as the radius of the fiber core, and $b = (n_{\mathrm{eff}}^{\mathrm{co}^2} - n_1^2)/(n_0^2 - n_1^2)$ is the normalized effective refractive index.

3.3. Characteristic equation of the cladding mode in the two-section LPFG

Accordingly, for the conformal weak single-mode fiber, the effect of coating layer on the guide mode is small because of the big radius of the cladding layer. When calculating the effective refractive index of the cladding, the characteristic equation of the three-layer mode can be equally adopted [17]:

$$\begin{aligned}
&[Ju_2(\Gamma_1 + K_4u_3\Gamma_2) - (\Gamma_3 + K_4u_3\Gamma_4)]\left[\left(\frac{Ju_2}{n_2^2}\right)\left(\frac{\Gamma_5}{n_4^2} + \frac{K_4u_3\Gamma_6}{n_3^2}\right)\right. \\
&\left. - \left(\frac{1}{n_1^2}\right)\left(\frac{\Gamma_7}{n_4^2} + \frac{K_4u_3\Gamma_8}{n_3^2}\right)\right] + \xi_{12}^2\xi_{34}^2\Gamma_2\Gamma_6 + \xi_{12}^2\xi_{23}^2\Gamma_9 p_{\nu 2}^2 \\
&+ \xi_{23}^2\xi_{34}^2\Gamma_{10}p_{\nu 3}^2 + \frac{2\xi_{23}\xi_{34}u_2\Gamma_{10}2^2}{a_2a_3n_2n_4u_3^2\pi^2} + \frac{\xi_{12}\xi_{23}\xi_{34}^2u_3 2^2 p_{\nu 3}^2}{a_1a_2n_1n_3u_2^2\pi^2} \\
&+ \frac{2\xi_{12}\xi_{34}2^4}{a_1a_2^2a_3n_1n_2n_3n_4u_2u_3\pi^4} = \xi_{12}^2\xi_{23}^2\xi_{34}^2p_{\nu 2}^2p_{\nu 3}^2 + \frac{2\xi_{23}\xi_{34}\xi_{12}^2u_2 2^2 p_{\nu 2}^2}{a_2a_3n_2n_4u_3^2\pi^2} \\
&+ \frac{2\xi_{12}\xi_{23}u_3\Gamma_9 2^2}{a_1a_2n_1n_3u_2^2\pi^2} + \xi_{12}^2(\Gamma_1 + K_4u_3\Gamma_2)\left(\frac{\Gamma_5}{n_4^2} + \frac{K_4u_3\Gamma_6}{n_3^2}\right) \\
&+ \xi_{23}^2\Gamma_9\Gamma_{10} + \xi_{34}^2\left(\frac{Ju_2\Gamma_6}{n_2^2} - \frac{\Gamma_8}{n_1^2}\right)(Ju_2\Gamma_2 - \Gamma_4)
\end{aligned} \tag{5}$$

where l is the order of the mode and the indexes in the equation can be express as following:

$$u_j^2 = k^2n_j^2 - \beta^2 = -w_j^2, \quad j = 1, 2, 3, 4; \quad k = \frac{2\pi}{\lambda},$$

$$J = J_l'(u_1a_1)/u_1J_l(u_1a_1), \quad K_4 = K_l'(w_3a_2)/w_3K_l(w_3a_2),$$