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The effects of the nanosized high refractive index overlay on tunable long period gratings with normal and reduced cladding diameters

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ABSTRACT

In this paper, we have theoretically demonstrated that the resonant wavelength of long period gratings (LPG) can be shift by a large magnitude by coating with only a thin overlay that has a refractive index higher than that of the glass cladding. The resonant wavelength shift results from the variation of the high refractive index (HRI) of the overlay. The effects of cladding modes re-organization on the sensitivity to the overlay HRI have been outlined. An additional parameter, the cladding diameter, is also considered for improving the sensitivity of LPG to HRIs in this work. The results suggest that the layered structure offers an efficient platform for achieving high-performance index-modulation fiber devices. Moreover, the reduction of the cladding diameter leads to a further improvement in sensitivity.

1. Introduction

In past years, in-fiber long period gratings (LPG) have been widely investigated in the field of optical sensing and communications [1]. They have the ability to couple energy from the core mode to different cladding modes with the same propagation direction. The central attenuation wavelength of the LPG is highly sensitive to the ambient refractive-index change [2,3] and, therefore, can be tuned by modulating the ambient refractive index by methods such as the thermo-optic effect [4], the electro-optic effect [5], or magneto-optical effects [6].

Up to date, most of the studies have concentrated on the analysis of the LPG response to the surrounding medium refractive index (SRI) smaller than that of silica [7,8]. Recently, Czapla et al. and we have reported the resonant wavelength shift of an LPG in response to an nm-thick high refractive index (HRI) LC overlay through temperature and electrical method [9–12]. Our experimental results showed that thermally induced shifts greater than 80 nm could be achieved in the attenuation bands of the transmission spectrum of an HRI LC-coated LPG within the temperature range from 58 °C to 60 °C [9–11]. In Ref. [12], Czapla et al. further showed that by reducing the thickness of the HRI LC medium of the LPG to the order of ∼1 μm, electrical control of the position of the attenuation bands in its transmission spectrum could be achieved as well. At a specific temperature range, an increase of the electrically induced shift of the attenuation band up to 11 nm was recorded [10]. It is worth mentioning that the tuning efficiency of an etched LPG using the electrical effect is less than 3 nm if the LPG is surrounded by a low refractive index LC material [13].

As a matter of fact, the presence of nm-scale HRI overlay induces strong changes in the cladding modes distribution [14], leading to a consequent enhancing of the tuning performance. In this work, a detailed study of LPG tunable range when they are coated with nm-thick overlay of refractive index higher than silica is presented. The LPG is analyzed in two steps. First, coupled mode theory is explained in Section 2 which is the basis for the calculation of LP modes in cylindrical multilayer waveguide. Second, the explanation of the effects of a thin overlay on LPG with normal and reduced cladding diameter is presented and coupled mode theory is applied for the calculation of the transmission spectra in LPG in Section 3. Finally, some conclusions are given in Section 4.

2. Theory background

The coupling between the core mode and the co-propagation cladding modes in a LPG acts as the spectral loss selection. The center wavelength λ_i of the ith attenuation band is given by the following phase-matching condition between the core and the cladding modes [15]

$$\lambda_i = \left(n_{co} - n_{cl}^{i}\right)\Lambda, \quad (1)$$

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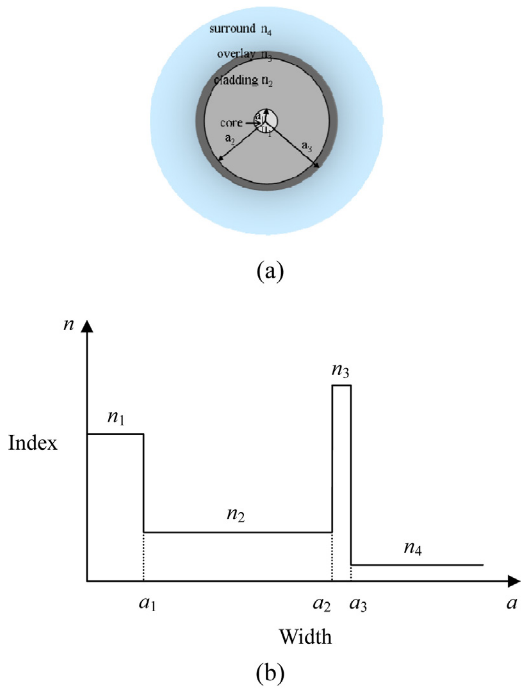

Fig. 1. Four-layer optical fiber modal.

where n_{co} and n_{cl}^{i} are the effective refractive indices of the core mode and the ith cladding mode, respectively. Λ is the grating period. The cladding modes excited in an LPG are usually numbered starting from the one with the highest effective index, so that higher order cladding modes have lower effective index. The effective index of the fundamental core mode is usually calculated by solving the scalar wave equation coming out from the weakly guidance approximation [15], so it is a linearly polarized mode (LP).

The structure of HRI coated LPG has four layers and the surrounding media is air as shown in Fig. 1. The calculation of the cladding mode effective index can be accomplished by following the transfer matrix method (TMM) proposed by Anemogiannis et al. [16].

The transverse electrical field component, with azimuthal order ν, propagating along the z axis, is given by [16]

$$R_\nu(r)=\begin{cases} A_0 Z_{\nu,1}\left(u_1\dfrac{r}{a_1}\right) & \text{for} \quad r\le a_1 \\ A_1 Z_{\nu,2}\left(u_2\dfrac{r}{a_2}\right)+A_2 T_{\nu,2}\left(u_2\dfrac{r}{a_2}\right) & \text{for} \quad a_1<r\le a_2 \\ A_3 Z_{\nu,3}\left(u_3\dfrac{r}{a_3}\right)+A_4 T_{\nu,3}\left(u_3\dfrac{r}{a_3}\right) & \text{for} \quad a_2<r\le a_3 \\ A_5 K_{\nu,4}\left(v\dfrac{r}{a_3}\right) & \text{for} \quad r>a_3 \end{cases}, \quad (2)$$

where

$$Z_{\nu,i}(x)=\begin{cases} J_\nu(x) & \text{if} \quad n_{\text{eff}}<n_i \\ I_\nu(x) & \text{if} \quad n_{\text{eff}}>n_i \end{cases},$$

$$T_{\nu,i}(x)=\begin{cases} Y_\nu(x) & \text{if} \quad n_{\text{eff}}<n_i \\ K_\nu(x) & \text{if} \quad n_{\text{eff}}>n_i \end{cases},$$

$$u_i=r_i k_0\sqrt{\left|n_i^2-n_{\text{eff}}^2\right|} \quad \text{for} \quad i=1,2,3,$$

$$v=r_3 k_0\sqrt{\left|n_{\text{eff}}^2-n_4^2\right|},$$

where r is the radius, J_ν and I_ν are the ordinary Bessel functions of first and second kind of order ν and Y_ν and K_ν are the modified Bessel functions of first and second kind of order ν, respectively. n_1, n_2 and n_3 are the core, cladding and overlay refractive indices, respectively, while n_4 is the surrounding refractive index and n_{eff} is the effective refractive index. a_1 and a_2 are the core and cladding radius and a_3-a_2 is the overlay thickness. In addition, A_1, A_2, A_3, A_4 and A_5 can be obtained, as function of A_0, by imposing the continuity of the fields at the interface between core and cladding, cladding and overlay and overlay and surrounding medium while A_0 is related to the optical power of the mode. Here, the effective refractive index of every cladding mode is achieved by numerical solution of the dispersion equation obtained by the continuity condition of the transverse fields.

According to the coupled mode theory [17], the interaction between optical modes is proportional to their coupling coefficient. Since the contribution of the longitudinal coupling coefficient can be negligible, we will refer to the transversal coupling coefficient as the general coupling coefficient. Based on the LP approximation, the coupling coefficient between each two modes in cylindrical coordinates can be expressed as [16,18]

$$K_{\nu j,\mu k}=\frac{\omega}{4P_0}\times\int_{\varphi=0}^{2\pi}\int_{r=0}^{\infty}\Delta\varepsilon(r,\varphi,z)\psi_{\nu j}(r,\varphi)\psi_{\mu k}(r,\varphi)r\mathrm{d}r\mathrm{d}\varphi, \quad (3)$$

where $\Psi(r,\varphi)$ is the transverse field for an LP mode, $\Delta\varepsilon(r,\varphi,z)$ is the permittivity variation, and P_0 is the power of each mode supposed to be the same. Since there is weak guidance between the core and the cladding of the fiber and there is no azimutal variation of the perturbed index profile, the permittivity can be expressed as

$$\Delta\varepsilon(r,z)\approx 2\varepsilon_0 n_0(r)\Delta n(r,z), \quad (4)$$

where ε_0 is the freespace permittivity, $n_0(r)$ is the refractive index profile of the structure without the perturbation, and $\Delta n(r,z)$ is the variation of the refractive index. This last function can be expressed as the product of three terms

$$\Delta n(r,z)=p(r)\sigma(r)S(z) \quad (5)$$

where $p(r)$ is the transverse refractive index perturbation, $\sigma(r)$ is the apodization factor, and $S(z)$ is the longitudinal refractive index perturbation factor, which can be approximated by a Fourier series of two terms:

$$S(z)=s_0+s_1\cos\left(\left(\frac{2\pi}{\Lambda}\right)z\right), \quad (6)$$

where Λ is the period of the grating. The coefficient of the Fourier series s_0 and s_1 depend on the exposure function of the LPG writing process, we will consider $s_0=s_1=1$ in the following numerical analysis.

After the above approximations, the coupling coefficients can be expressed as

$$K_{0j,0k}=\left[s_0+s_1\cos\left(\left(\frac{2\pi}{\Lambda}\right)z\right)\right]\zeta_{0j,0k}, \quad (7)$$

with

$$\zeta_{0j,0k}=\frac{\omega\varepsilon_0}{2P_0}n_1 p_0\int_0^{2\pi}\mathrm{d}\varphi\int_{r=0}^{r_1}R_{0j}(r)R_{0k}(r)r\mathrm{d}r, \quad (8)$$

where n_1 is the refractive index of the core.