Spectral characteristics of cladding index modulated fiber grating

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A new class of fiber grating with only cladding index modulation is presented and analyzed theoretically. The calculation of the modes involved in this paper is based on a model of three-layer step-index fiber geometry. The transmission of a mode guided by the core through a cladding index modulated grating when evanescent field coupling occurs is analyzed with couple-mode theory. Lower attenuation and flexible spectral characteristics can be obtained in comparison with traditional fiber core index modulated grating.

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Since Hill *et al.* discovered the photosensitivity of germanium-doped-core optical fiber twenty years ago[1], photoimprinting grating in the core of optical fiber has been a primary method of fiber grating fabrication. However, this kind of doped-core photosensitive optical fiber always has inevitable great attenuation due to its heavy doped core. For example, the attenuation at 1550 nm of single-mode photosensitive fiber and radiation mode suppression photosensitive fiber of INO (National Optics Institute, Canada) are 63.6 and 53.2 dB/km respectively, while the attenuation of an ordinary single-mode fiber that is used in communication at the same wavelength is only 0.20 dB/km.

In order to mitigate the attenuation of a fiber grating, we propose a new type of fiber grating in this paper. The core of the new grating, the area that contains the dominating energy distribution of the core mode in a fiber, is unperturbed, while the index modulation is only in fiber cladding where the core mode is evanescent field. This new modulation scheme would minimize the attenuation of the grating greatly. Furthermore, we can modulate the cladding index in certain ways such as through exposing the fiber to periodic ultraviolet directly if the cladding is photosensitive. Although the field of fundamental core mode carries much less energy in the cladding region than the fiber core, the periodic index change still could affect the fundamental core mode through its evanescent field and couple it into the modes of the cladding when proper phase matching condition is met.

The structure of this new grating is analyzed under the model of three-layer step-index fiber geometry, which is shown in Fig. 1. The three layers are the core layer, the cladding layer, and the surrounding layer, respectively. The core of the grating is with the diameter of $2a_1$. The index is uniform in the core with the value of n_1. The cladding surrounds the core with the diameter of $2a_2$. The index of the cladding is not uniform. The index is modulated in a periodical way. The period of the modulation is Λ in distance. Therefore, the index in the cladding appears to n_2 and $n_2(z)$ alternatively. Both the core and cladding are immersed in the surrounding, which has the index of n_3. Usually the surrounding is air and n_3=1.

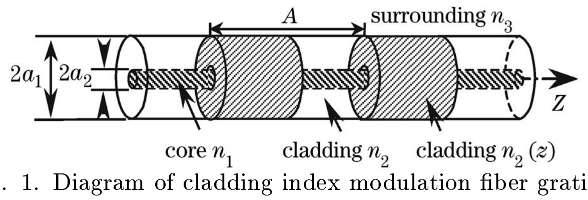

Fig. 1. Diagram of cladding index modulation fiber grating, showing the refractive index, grating period, and the radii of the core (a_1) and the cladding (a_2).

In our analysis we assume that, when a phase grating is induced in the fiber, it exits only in the fiber cladding, changing the cladding index to $n_2(z)$, but leaves the core and surrounding index unchanged, as follows:

$$n\left(r, zt\right)=\begin{cases} n_1 & r \leq a_1 \\ n_2\left(z\right)=n_2+\overline{\delta n}(z) & \\ \quad \left[1+m\cos\left(2\pi z/\Lambda\right)\right] & a_1 < r \leq a_2 \\ n_3 & r > a_2 \end{cases} . \tag{1}$$

Here, n_1 is the fiber core index, Λ is the period of the grating, m is the induced index fringe modulation, where $0 \leq m \leq 1$, $\overline{\delta n}(z)$ is the average induced index change.

The field expressions of fundamental core mode and cladding modes can be obtained by solving Maxwell's equations with proper boundary conditions. These modes transmit independently in the ordinary fiber. While in the grating periodical index is induced, this perturbation would cause coupling between the fundamental core mode and the cladding modes. Coupled-Mode Theory can be employed to analyze such interactions. According to the solving procedure of the Coupled-Mode Theory, all the necessary propagation constants and coupling coefficients need to be calculated first.

Propagation constants of both fundamental core mode and cladding modes can be obtained through solving dispersion relations in core and cladding respectively[2,3].Thus, the resonant wavelength can be determined by the phase matching condition, as well. Since fundamental core mode is so familiar and the exact field expressions of the cladding modes have been detailed in Refs. [2,3], we do not list the field components here. The following analysis follows Ref. [2], while the difference is the interaction between modes considered in this paper occurs in the cladding rather than in the fiber core. The transverse coupling coefficient between two modes ν and μ is thus

$$K_{\nu\mu}^{t}=\frac{\omega}{4}\iint\limits_{-\infty}^{+\infty}\mathrm{d}x\mathrm{d}y\Delta\varepsilon\cdot E_{\nu}^{t}\cdot E_{\mu}^{t^{*}}. \tag{2}$$

To calculate coupling coefficient, permittivity change $\Delta\varepsilon$ caused by the induced cladding index change should be obtained first. Because the grating considered is weak grating, $\overline{\delta n}(z)$ is in the order of 10^{-3}–10^{-4}, we can make the approximation $\Delta\varepsilon = \varepsilon_0\Delta(n^2) \cong 2\varepsilon_0 n\Delta(n)$. Combining with Eq. (1), we obtain

$$\Delta\varepsilon(r,z) \approx \begin{cases} 0 & r \le a_1 \\ 2\varepsilon_0 n_2 \overline{\delta n}(z) & \\ \quad [1 + m\cos(2\pi z/\Lambda)] & a_1 < r \le a_2 \\ 0 & r > a_2 \end{cases} . \tag{3}$$

Then the coupling coefficient can be written as

$$K^t_{\nu\mu}(z) = \kappa_{\nu\mu}(z)[1 + m\cos(2\pi z/\Lambda)]. \tag{4}$$

Then, we can deduce the coupling constant for core-mode-core-mode coupling and core-mode-cladding-mode coupling by Eqs. (2), (3), and (4) as follows:

$$\kappa^{\text{co-co}}_{01-01}(z) = \frac{\omega\varepsilon_0 n_2 \overline{\delta n}(z)}{2} \int_0^{2\pi} \mathrm{d}\phi \int_{a_1}^{a_2} r\mathrm{d}r\left(\left|E_r^{\text{co}}\right|^2 + \left|E_\phi^{\text{co}}\right|^2\right) , \tag{5}$$

$$\kappa^{\text{cl-co}}_{1\nu-01}(z) = \frac{\omega\varepsilon_0 n_2 \overline{\delta n}(z)}{2} \int_0^{2\pi} \mathrm{d}\phi \int_{a_1}^{a_2} r\mathrm{d}r\left(E_r^{\text{cl}} E_r^{\text{co}^*} + E_\phi^{\text{cl}} E_\phi^{\text{co}^*}\right) . \tag{6}$$

Using the expression for fundamental core mode in the cladding region, and performing the overlap integrals of Eq. (6), we obtain the coupling constant for core-mode-core-mode coupling:

$$\kappa^{\text{co-co}}_{01-01}(z) = \overline{\delta n}(z)\frac{2\pi}{\lambda}\frac{2u^2}{V^2}\frac{1}{K_1^2(w)}\frac{1}{a_1^2} \left\{a_2^2[K_0^2(wa_2/a_1) - K_1^2(wa_2/a_1)] - a_1^2[K_0^2(w) - K_1^2(w)]\right\} . \tag{7}$$

However, substituting the field expressions of both fundamental core mode and cladding mode in the cladding into Eq. (7), the analytical solution for the overlap integrals is not available. Coupling constant for core-mode-cladding-mode coupling must be evaluated numerically.

Provided that all the necessary propagation constants and coupling coefficients have been obtained, simple two-mode coupled-mode theory that involves constant-coefficient differential equations with slowly varying amplitudes can be employed. For a uniform grating considered in this paper, an analytical solution for the transmission is available.

Based on the theory described above we calculated the transmission spectra to demonstrate the cladding-mode coupling . The transmission spectrum of the new grating demonstrates the band stop filter characteristic.

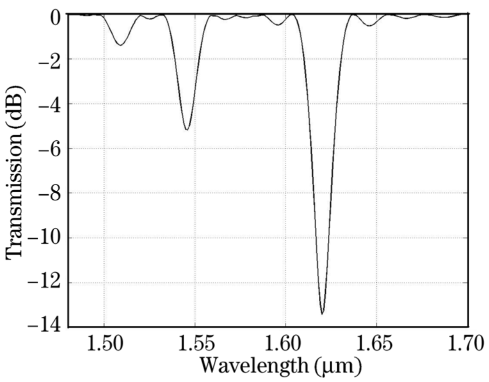

Fig. 2. theoretically calculated transmission spectra through a uniform cladding index modulation fiber grating.

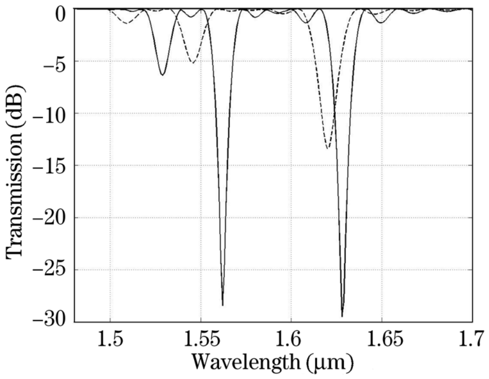

Fig. 3. Comparison of transmission spectra through a uniform cladding index modulation fiber grating and a uniform fiber core index modulation grating with the same parameters.

Figure 2 shows the theory value of the transmission spectrum of the cladding index modulation fiber grating. The parameters of the fiber grating under calculation is as follows: fiber core radius $a_1 = 2.625$ μm, cladding radius $a_2 = 62.5$ μm, fiber core index $n_1 = 1.458$, cladding index $n_2 = 1.45$, surrounding index $n_3 = 1$, grating period $\Lambda = 576$ $\underline{\mu\text{m}}$, grating length $L = 11.52$ mm, average index change $\overline{\delta n} = 5 \times 10^{-4}$, the induced index fringe modulation $m = 0.6$.

In order to compare the new grating with an ordinary grating, Fig. 3 gives the transmission spectra of a typical uniform fiber core index modulation grating with the same parameters (solid line). The transmission spectra of both gratings were presented simultaneously for the convenience of comprehension. We can conclude from Fig. 3 that under the same circumstances, the coupling in the cladding index modulation grating is much weaker than that in the core index modulation grating. It is reasonable because the part of the fundamental core mode in the cladding carries much less energy than the one in the fiber core. The interaction due to the induced perturbation between the evanescent field of the fundamental core mode and the field of cladding modes in the cladding is much weaker than the field in the fiber core.

However, this not means that the cladding index modulation grating cannot gain strong resonant coupling. It is well known that the spectral characteristics of the fiber grating are quite flexible, since practically one can vary numerous parameters to meet the various requirements. Both the induced index change and the grating length

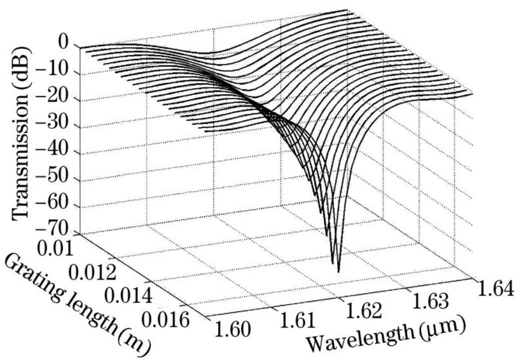

Fig. 4. Growth of transmission spectrum with the grating length.

affect the coupling strength. In this paper, we lengthen the cladding index modulation grating temperately and get a better coupling. Figure 4 shows the growth of the transmission spectrum with the increase of the grating length. When the grating length increases to 17 mm, the maximum transmissivity dip reaches −60 dB.

In conclusion, a new class of fiber grating with only cladding index modulated is presented and analyzed under a three-layer model with the coupling mode theory. The new grating demonstrates its reliable band stop filter characteristic. Furthermore, the configuration of the structure of the new grating is flexible. We can reconfigure the grating to meet various requirements. The new cladding index modulated fiber gratings may have lower attenuation.

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