Design of tunable metal-coated long-period fiber grating filter with dispersion consideration

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The design of a tunable metal-coated long-period fiber grating (LPFG) filter based on the material dispersion consideration is presented. The tuning of the resonant wavelength can be achieved by heating the metal layer. Based on the coupled mode theory, the influences of the material dispersion on the transmission spectrum of the metal-coated LPFG are studied. There is a special grating period for a specific cladding mode; when the grating period is less than or equal to the special grating period, the material dispersion has weak influence on the resonant wavelength. Under such condition, the attenuation band depth corresponding to the specific cladding mode has excellent stability while the temperature changes, thus improving the filtering performances of the tunable loss filter. Further, experimental results demonstrate the validity and feasibility of the proposed tunable filter.

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In recent years, long-period fiber gratings (LPFGs) have gained increasing research attention in the fields of optical communications and optical fiber sensors[1−4]. At the same time, LPFGs with metal coatings have also gained attention mainly due to their greater flexibility in tuning resonant wavelengths[2−5]. These metal-coated LPFGs have wide applications in optical communication, such as tunable band-stop filters[1−3].

Costantini *et al.*[1] reported a tunable loss filter based on metal-coated LPFG, in which the tuning of the resonant wavelengths could be realized by heating the metal layer. Such filter is considered ideal for fine tuning resonant wavelength; however, its attenuation band depth is proved unstable while heating the metal layer[1]. They thought that the instability might be due to non-uniform temperature distribution along the grating length. In our opinion, the influence of the material dispersion is an important factor; particularly, it is significant and cannot be ignored in optical communication waveband.

To our knowledge, the influence of the material dispersion on the transmission spectrum of metal-coated LPFGs has not been investigated. In this letter, a special grating period is proposed for design of the tunable metal-coated LPFG filter. When the grating period is less than or equal to the special grating period, the material dispersion exerts slight influence on the specific cladding mode, and the attenuation band depth corresponding to the specific cladding mode has excellent stability while heating metal layer. We present a design method of the improved metal-coated LPFG filter, and verify the proposed method by the experimental result.

A LPFG is a ultraviolet (UV)-induced period modulation of the refractive index of the core of a single mode fiber (SMF). Due to its longer period than that of the Bragg grating, the LPFG couples light from the fundamental core mode to propagating cladding modes if the phase matching condition is fulfilled[6]. This is expressed as

$$n_{\mathrm{eff,co}}(\lambda) - n^{\nu}_{\mathrm{eff,cl}}(\lambda) = \frac{\lambda}{\Lambda}, \nu = 1, 2, 3, \cdots, \qquad (1)$$

where $n_{\mathrm{eff,co}}(\lambda)$ is the effective refractive index of the fundamental core mode, $n^{\nu}_{\mathrm{eff,cl}}(\lambda)$ is the effective refractive index of the νth cladding mode, and λ is the resonant wavelength corresponding to the νth cladding mode.

Figure 1 shows the four-layer structural diagram of a metal-coated LPFG. The metal material is silver. The refractive indices of fiber core, cladding, silver film, and the surrounding area are n_1, n_2, N_3, and n_4, respectively; a_1, a_2, and a_3 are the radii of fiber core, cladding, and silver film, respectively; n_1, n_2, and N_3 are 1.4682, 1.4628, and $0.469 + 9.32\mathrm{i}$ in the wavelength of 1 550 nm, respectively; a_1 and a_2 are 4.15 and 62.5 μm, respectively; $a_3 - a_2$ is the thickness h_3 of the silver film, which is 50 nm. Moreover, the length of the grating is 1 cm, the grating period is Λ, and the modulation is σ with the amplitude of 10^{-4}.

A SMF consists of conventional GeO_2-doped SiO_2 core and pure SiO_2 cladding, the refractive index of the core is 0.0050–0.0055 higher than that of the cladding[7]. When the wavelength changes between 0.2 and 4.0 μm, the approximate calculation formula of the refractive index of the cladding is expressed by[8]

$$n_2^2 - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - (0.068403)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.89616)^2}. \qquad (2)$$

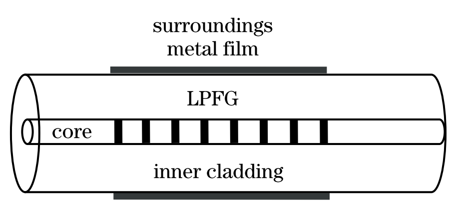

Fig. 1. Triple-clad LPFG model.

The refractive index of the core increases by σ after UV irradiation, and the approximate calculation formula of the refractive index of core is written as $n_1 = n_2+0.0052+\sigma$.

According to the discrete data[9], the approximate calculation formulas of the refractive index and the extinction coefficient of silver are derived through least squares fitting method and are respectively expressed as

$$n_3(\lambda) = -1.6578\times 10^{11}\cdot\lambda^2 + 9.430\times 10^5\cdot\lambda - 0.57721, \quad (3)$$

$$k_3(\lambda) = 2.967\times 10^{11}\cdot\lambda^2 - 3.083\times 10^{11}\cdot\lambda + 7.2079. \quad (4)$$

The resonant wavelength shift induced by the material dispersion was simulated. Figure 2 shows the relation curve between the resonant wavelength of the 10th cladding mode (EH_{15}) and the grating period. Curves B, C, D, and E represent the relation curve considering no dispersion, core dispersion, cladding dispersion, and the dispersions of three layers simultaneously, respectively. There is a special grating period, expressed by Λ_S, where four curves almost intersect at point R (Fig. 2). The special grating period corresponding to the EH_{15} mode is 295 μm. For a grating period of more than 295 μm, the resonant wavelength shifts toward the shorter wavelength while considering the material dispersion. A grating period of less than 295 μm shows a weak wavelength shift in comparison with the no dispersion case, wherein the resonant wavelength is almost immune to the influence of material dispersion. The special grating period is dependent on the cladding mode. Table 1 lists the special grating periods and the resonant wavelengths corresponding to the specific cladding modes. Obviously, the special grating period decreases with the cladding mode order.

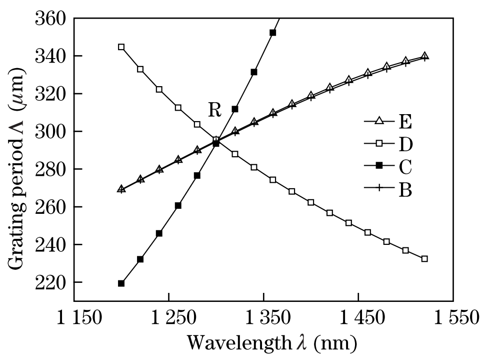

Fig. 2. Curves of the grating period and resonant wavelength.

Table 1. Special Grating Periods Corresponding to the Cladding Modes

Cladding Mode Order	7 (HE_{14})	8 (EH_{14})	9 (HE_{15})	10 (EH_{15})	11 (HE_{16})	12 (EH_{16})
Λ_S (μm)	323	314	306	295	286	274
Resonant Wavelength (nm)	1 230	1 245	1 276	1 304	1 330	1 350

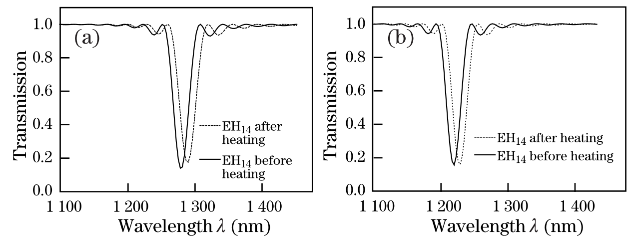

Fig. 3. Transmission spectra of the EH_{14} mode at different temperatures, Λ = (a) 320 and (b) 308 μm.

The working wavelength of the metal-coated LPFG filter is near the resonant wavelength. The wavelength tuning of these filters is obtained by heating the metal layer. The temperature change causes the change of the grating period and the refractive indices of the fiber and the metal layer. When the grating period is less than the special grating period, the influence of material dispersion on the specific cladding mode can be ignored; in other words, the change of the refractive index has nearly no influence on the specific cladding mode. Therefore, the resonant wavelength shifts while heating the metal layer, induced by the change of the grating period rather than the influence of the material dispersion; in addition, the attenuation band depth would not be influenced by the material dispersion. This is an advantage of designing a tunable metal-coated LPFG filter with excellent performance.

As the LPFG undergoes a temperature change ΔT, the refractive index of fiber can be written as[10,11]

$$n_T = n_0(\lambda)(1+\zeta\Delta T), \quad (5)$$

where ζ is the thermo-optic coefficient, and n_0 and n_T are the refractive indices of fiber at room temperature and T, respectively. When the temperature changes ΔT, the fiber radius is written as[10,12]

$$a_T = (1+\rho\Delta T)a_0, \quad (6)$$

where ρ is the thermal expansion coefficient of the fiber, and a_0 and a_T are the radii of the fiber at room temperature and T, respectively. In addition, the grating period is $\Lambda_T = (1+\rho_1\Delta T)\,\Lambda$, and Λ_T is the grating period at T.

Figures 3(a) and (b) show the transmission spectra corresponding to the 8th cladding mode (EH_{14}) of the silver-coated LPFG with the grating period of 320 and 308 μm at the temperatures of 20 °C (solid curve) and 175 °C (dashed curve), respectively. The material dispersion is taken into consideration during the calculation. The special grating period corresponding to the EH_{14} mode is 314 μm. Figure 3(a) shows that the attenuation band depth of the EH_{14} mode decreases with the temperature. This phenomenon has also been observed in the experimental result reported by Costantini *et al.*[1]. The attenuation band depth of the EH_{14} mode has excellent stability while heating the metal layer, as shown in Fig. 3(b). The results indicate that the filtering performances of the silver coated LPFG are highly improved when the material dispersion has slight influence on the specific cladding mode.

It is worth noting that the working range in Fig. 3(b) has changed, compared with that in Fig. 3(a). The

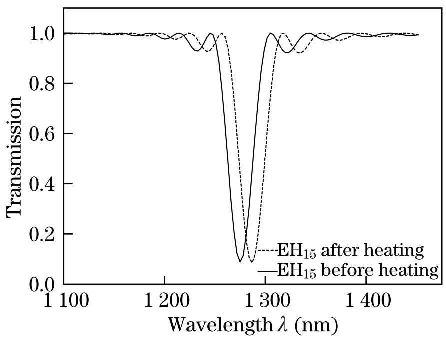

Fig. 4. Transmission spectra of the EH_{15} mode at different temperatures.

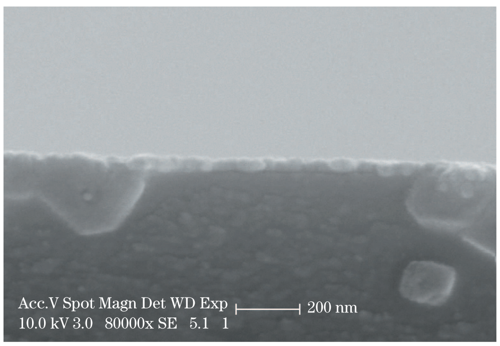

Fig. 5. SEM image of the cross-section of silver-coated optical fiber.

working range can be obtained by adjusting the grating period and choosing the appropriate cladding mode order to suffice for the optical fiber communication range of wavelength. The tunable wavelength range of the LPFG with the grating period of 320 μm is from 1 278 to 1 288 nm. The resonant wavelength decreases with the grating period (Fig. 2). When the grating period is chosen as 287 μm, the resonant wavelength corresponding to the EH_{15} mode is 1 278 nm. Under such condition, the required wavelength tuning range can be achieved (Fig. 4). The attenuation band depth has excellent stability before and after heating metal coating. Additionally, the working wavelength can be tuned by heating the metal layer. The working wavelength shift is about 30.9 nm in the temperature range of 20–500 °C, which is less than the erased temperature for grating in the fiber.

In order to validate the improved performance of the metal-coated LPFG filter, three kinds of silver-coated LPFGs with different grating periods and silver film thickness were fabricated, and their respective responses to the temperature were determined. The fiber used in the experiment was Corning SMF-28, which was hydrogen loaded for one month in 150 atm to enhance its photosensitivity. The LPFGs were fabricated using point by point exposure. Then, the fiber grating was annealed at 180 °C for 24 h to improve the temperature stability. The silver films were deposited on the three kinds of the LPFGs using a DC sputtering instrument (HV-Sputtering System-233). The SEM image of the cross-section of the optical fiber coated with silver film is shown Fig. 5. It is very obvious that the thickness of silver film is uniform.

The grating periods of the LPFGs and silver film thicknesses of samples 1, 2, and 3 are 300 μm and 50 nm, 270 μm and 50 nm, and 250 μm and 90 nm, respectively. The 10th cladding mode (EH_{15}) of sample 1 does not meet the previously mentioned design requirements, whereas the 12th cladding mode (EH_{16}) of sample 1 and the 14th cladding mode (EH_{17}) of sample 2 meet those requirements.

We monitored the transmission spectra by coupling the output from a SLED light source (OS310062) into the silver-coated LPFG and coupling the output from the distal end of the coated LPFG into an optical spectrum analyzer (AQ6370). The silver-coated LPFG was placed in a tubular electric resistance furnace (SK-2-6-12) to decrease the non-uniform temperature distribution along the grating length.

Figure 6 shows the transmission spectra of sample 1 at the temperatures of 20 °C and 140 °C, respectively. The attenuation band corresponding to the EH_{15} mode is also displayed. The working wavelength shifted to longer wavelength from 1 331 to 1 338 nm during heating. The decrease of the attenuation band depth from 9 to 7 dB is also observed. For sample 1, the grating period of 300 μm is larger than the special grating period corresponding to the EH_{15} mode. Under such condition, the filtering performance is not good. Moreover, the filtering performances of samples 1 and 2 are tested, which have been designed as mentioned previously.

Figures 7 and 8 show the transmission spectra of Samples 2 and 3 at the temperatures of 20 and 140 °C, respectively. The attenuation band corresponding to the EH_{16} and EH_{17} modes are also displayed, respectively. The working wavelength shifts towards the longer wavelength. The tunable wavelength range of sample 2 is

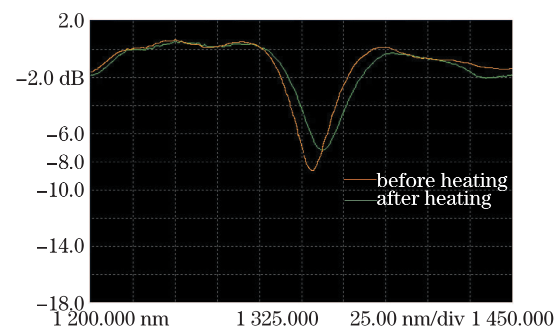

Fig. 6. Transmission spectra of the EH_{15} mode of the LPFG with the grating period of 300 μm and silver film thickness of 50 nm at temperatures of 20 and 140 °C.

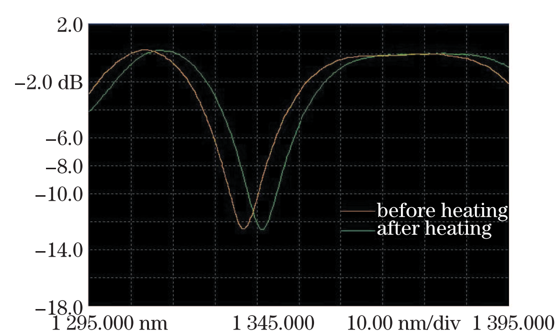

Fig. 7. Transmission spectra of the EH_{16} mode of the LPFG with the grating period of 270 μm and silver film thickness of 50 nm at temperatures of 20 and 140 °C.

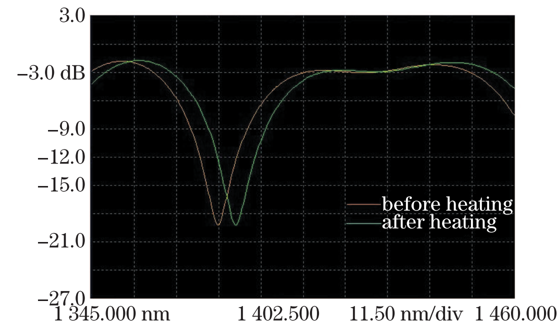

Fig. 8. Transmission spectra of the EH_{17} mode of the LPFG with the grating period of 250 μm and silver film thickness of 90 nm at temperatures of 20 and 140 °C.

from 1 332 to 1 339 nm, and that of sample 3 is from 1 379 to 1 385 nm. It is evident that the attenuation band depth has excellent stability during heating. For samples 2 and 3, the grating periods of 270 and 250 μm are less than the special grating period; under such condition, both have good filtering performances. Thus, the experimental observations are in agreement with the predicted results.

In conclusion, appropriate grating period and the cladding mode order result in greater flexibility of the tunable wavelength range and improve performance of the silver-coated LPFG filter. When the chosen grating period is less than or equal to the special grating period, the material dispersion exerts slight influence on the cladding mode. Under such condition, the attenuation band depth of the corresponding cladding mode has excellent stability while heating the metal layer. For the specific cladding mode, the resonant wavelength corresponding to the special grating period decreases with the cladding mode order. Experimental result shows the tunable filter based on the metal-coated LPFG with the special grating period has the advantage of fine tuning and attenuation band depth stabilization, thus corroborating the design method presented.

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