**Structural microfiber long-period gratings**

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**Abstract:** We experimentally demonstrate a novel structural long-period grating by helically coiling one microfiber onto another with the relatively thicker diameter. Owing to the strong periodic modulation of the coiled microfiber to the evanescent field of the straight microfiber, a resonance transmission notch of ~16.2 dB can be induced for a compact device length of ~450 µm only (4 helical periods). Moreover, the filtered light energy from the straight fiber can emerge again at the output of the coiled one, providing great flexibility in producing new device functions. The spectral response to external strain is investigated and wide wavelength tuning range of around 106 nm is discussed.

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**References and links**


1. Introduction

Long period gratings (LPGs) are attractive components in a wide variety of telecommunications and sensing applications. LPGs contain a periodic modulation of the modal propagation constant and allow power exchange between the guided modes that satisfy resonant condition. LPGs are used as gain-flattening filters for erbium-doped fiber amplifiers, mode convertors, dispersion compensators, and as strain, temperature, and chemical sensors.
Conventionally, LPGs were fabricated by periodically modifying the refractive index of a photosensitive fiber core through the UV radiation. This method can produce the grating with length in the level of centimeter due to the relatively small mode-field modulation strength. Some new fabrication methods including thermal shock of CO₂ laser [3] or electric arcs [4], mechanically microbending deformation [5] or periodic twist [6,7], and diffusion of the core dopant along the fiber axis [8], have also been proposed. However, for the previous LPGs in optical fibers, the coupled light is generally absorbed or radiated away from the fiber structure, restricting the grating to be used as no more than a band-rejection filter.

Recently, the subwavelength-size microfibers are increasingly used for fabrication of various miniature optical devices and sensors [9–11]. In this letter, we experimentally demonstrate a structural LPG by helically coiling one microfiber onto another with the relatively thicker diameter. The coiled microfiber can provide a strong modulation to the light field of microfiber, so that a resonance transmission notch of ~16.2 dB can be induced in a device length of ~450 µm (4 helical periods). Moreover, the coiled microfiber can resonantly lead out the light signal from the straight one, providing a great flexibility in producing new functions of the device.

2. Fabrication and characterization

Figure 1(a) shows the schematic of the proposed LPG, consisting of a straight microfiber surrounded by a coiled microfiber. In our experiments, both the straight and the coiled microfibers are obtained by adiabatically tapering a standard single-mode fiber with assistance of the conventional heating-and-stretching technique. Similar to the previous well-established bi-conical taper model, a tapered fiber consists of two transition regions and a central waist region [10,11]. In the adiabatic condition [12], light can be transferred from the core mode of the untapered single-mode fiber to the fundamental mode of the tapered fiber (microfiber) through the transition taper region with negligible transmission loss. The intermodal coupling can be suppressed [12]. In our experiment, the taper shape can be optimized through the control of the heating temperature and the stretching speed [10,11]. The transmission loss of the taper is smaller than 0.1 dB. Experiment shows that the transmission characteristics are insensitive to the bending of the microfiber. We use the uniform waist of fiber taper for fabrication of the LPG. From Fig. 1(a), the LPG is characterized by the diameters of \( d_1 \) for the straight microfiber and \( d_2 \) for the coiled microfiber, the helical pitch of \( \Lambda \), and the period number \( N \) (\( N = 6 \) in Fig. 1(a)), respectively. In this case the inclination angle of the coiled microfiber with regard to the structure axis is \( \theta = \tan^{-1}\left(\frac{\pi(d_1 + d_2)}{\Lambda}\right) \). Inset of Fig. 1(a) shows a typical cross-section of the structural LPG. The solid ellipse with widths of \( d_1 \) and \( d_2/\cos \theta \), representing the coiled microfiber, can rotate periodically around the circle.
with diameter of \( d_1 \), representing the central optical microfiber, along the axial direction of the straight microfiber. As induced by the coiled microfiber, modal coupling could occur when the intermodal beat length equals the helical grating period, with

\[
\beta_1 - \beta_2 = 2\pi / \Lambda,
\]

(1)

where \( \Lambda \) is the grating pitch and \( \beta_{1,2} \) represent the propagation constants of the modes that are coupled with each other. In the straight microfiber, the attenuation notch occurs when light is coupled from the fundamental mode of the straight microfiber to the higher order modes in the straight or to the guided modes in the coiled microfiber. In this paper, with experiments, we realize the modal coupling between the fundamental modes (LP01) of the two microfibers. \( \beta_1 \) and \( \beta_2 \) can refer to the LP01 modes for the straight and the coiled microfibers, respectively.

We adopt the straight microfiber with diameter of \( d_1 = 5-15 \mu m \) and the coiled microfiber with diameter of \( d_2 = 1-5 \mu m \), respectively. The helical period in the range 50-500 \( \mu m \) may induce the resonant light coupling at wavelength of \( \lambda = 1500nm \), subject to the phase-matching condition shown in Eq. (1).

The coupling strength depends on the modal overlap between the two microfibers. In our investigation, when we strengthen the mode interaction by decreasing the size of the straight microfiber (with the coiled microfiber unchanged), the coupling coefficient can be enhanced. In order to increase the resonant dip, the diameter of the central microfiber should be uniform in the grating fabrication region. The uniform length is optimized with control of the heat temperature and stretching speed in the fiber tapering process. Figure 1(b) gives the microscopic image of a fabricated LPG, where the bright spots correspond to the points when the coiled microfiber is bent behind the straight microfiber. Thanks to the strong van der Waals and the electrostatic forces between the two microfibers, the LPG device is quite stable and robust.

Figure 2(a) gives the measured evolution of transmission spectrum in the straight microfiber in respect of the period number \( N \) of a LPG, with \( d_1 = 7.05\mu m, \ d_2 = 3.1\mu m, \) and \( \Lambda = 120\mu m \); (b) \( d_1 = 5.8\mu m, \ d_2 = 3.4\mu m, \) and \( \Lambda = 112\mu m \). The transmission notches correspond to the coupling between the LP01 modes of the two microfibers.

![Fig. 2. Evolution of transmission spectra in respect of the period number \( N \), for the two LPGs with different parameters: (a) \( d_1 = 7.05\mu m, d_2 = 3.1\mu m, \) and \( \Lambda = 120\mu m \); (b) \( d_1 = 5.8\mu m, d_2 = 3.4\mu m, \) and \( \Lambda = 112\mu m \). The transmission notches correspond to the coupling between the LP01 modes of the two microfibers.](image)

For the period number increasing from 0 to 9, the attenuation notch at \( \lambda = 1426nm \) increases gradually until it reaches the maximum value of 16.4dB at the grating length of \( L = 1.08mm \). The resulted 3dB bandwidth is around 35nm. The strength of the attenuation notch decreases with the further increase of the grating period number, due to the back-coupling of light energy from the coiled microfiber to the straight microfiber. During the
variation of period number, the resonance wavelength keeps almost unchanged. The insertion loss of the device, including the transmission loss of the microfiber, is less than 0.5dB.

Figure 2(b) shows the evolution of transmission spectrum in the microfiber with an increase in period number for a LPG with $d_1 = 5.8\mu m$, $d_2 = 3.4\mu m$, and $\Lambda = 112\mu m$. The attenuation dip corresponds to the resonant coupling between the LP01 modes for the straight and the coiled microfibers. Comparison between Figs. 2(a) and 2(b) shows that when the straight microfiber diameter decreases, the outer microfiber coil can induce a much stronger refractive-index modulation through the increased evanescent fields. An attenuation notch of 16.2dB is achieved with 4 periods only, resulting in a compact LPG with length of 450\mu m. The grating length is much shorter than the conventional ones in normal size fibers [1].

Apart from acting as the index modulation in the composite LPG, the coiled microfiber itself can guide light with large evanescent fields. When light is resonantly coupled from the fundamental mode for the straight microfiber to that of the coiled microfiber, light can be readily dropped down at the coiled microfiber output. Figure 3 shows the transmission characteristics of the LPG with $d_1 = 5.8\mu m$, $d_2 = 3.4\mu m$, $\Lambda = 112\mu m$, and $N = 4$, where the green solid line is the transmission spectrum from A to D as shown in Fig. 1(a), the black dash-and-dot line denotes the transmission spectrum from A to C. It is clear that, the outputs from port C and port D are complementary to each other. One shows band-rejection characteristics and the other shows band-pass characteristics. The insertion loss from A to D is smaller than 0.3 dB, which may be attributed to the non-coupled mode remaining in the central microfiber.

As a broadband light is launched in the structure from port B, the light that satisfies the resonant conditions can be coupled into the central microfiber through the evanescent field interaction. The transmission spectrum from B to C, shown as the red dot line in Fig. 3, is similar to that from A to D, which is consistent to the reversibility of light since the coupling system is left-right symmetrical, as shown in Fig. 1(a). The insertion loss of transmission from port B to C is 0.8dB only. The small difference between the spectrum from A to D and that from B to C may be induced by the dissimilarity of leakage loss between the transition regions of microfibers near the respective input/output ports. Experiment also indicates that the transmission spectrum from B to D is a little bit similar to that from A to C. But the transmission loss from B to D is extremely large (>15dB, close to the background loss of the spectrum analyzer detection). The loss can be attributed to the radiation of light from the
coiled microfiber to the unguided modes of the straight microfiber. In a transmission system, if a signal power is attenuated by 15 dB, the signal is no longer deemed useful.

3. Spectral response to external strain

By stretching the straight microfiber but keeping the coiled microfiber in a free state, we measure the spectral responses of the LPG to the axial strain. Figure 4 gives the resonance wavelength as a function of the strain in the uniform microfiber, for the structure with \( d_1 = 8.6\, \mu m \), \( d_2 = 2.8\, \mu m \), \( \Lambda = 140\, \mu m \), and \( L = 1.62\, \text{mm} \). The dots in Fig. 4 are the experimentally measured results and the solid line is the linear fitting result. For the strain varying from 0 to 10300\( \mu \varepsilon \), the resonance wavelength shifts from 1580 to 1474nm, producing an average tuning efficient of around \(-10.6\, \text{pm} / \mu \varepsilon\). As the grating is stretched, the resonance wavelength, as determined by the phase-matching condition in Eq. (1), can be blueshifted (Fig. 4). The change of the grating pitch may affect the dissimilar propagation constants of the two microfibers via the inclination angle \( \theta \). On the other hand, it has been argued the waveguide dispersion can have a strong influence on the strain coefficient [13]. From [14, 15], the waveguide dispersion gives \( d\lambda / d\Lambda < 0 \) for the LPGs in microfibers, which may be extended to explain that the strain coefficient is negative for the present case.

The strain coefficient is similar to that of the resonance at the coupling of the higher order modes in the conventional long-period fiber gratings [13]. Compared with the conventional ones, the microfiber LPGs can have the larger wavelength tuning range thanks to the good stretchability of the micro-size fibers. The whole experiment has been carried out in over 30 minutes. At the beginning of the fiber stretching, the force associated with strain is weaker than that associated with surface forces. The dip wavelength can shift almost linearly with the change of the axial strain. After the strain is unloaded the spectrum can be recovered very well, as shown in Fig. 4, suggesting that the two microfibers are kept in good contact with each other in this process. But as we further increase the axial strain sufficiently, the force associated with strain become stronger than that associated with surface forces. As a result of this, both the grating pitch and the dip wavelength are unchanged as the fiber is stretched. Investigation shows that the maximum wavelength tuning range of the LPG is ~106nm. In order to widen the wavelength tuning range, the LPG should be packaged so that the relative position between coiled and the straight microfiber keep unchanged in the external strain loading.
Fig. 4. (a) Resonance wavelength as a function of the axial strain. (b) The transmission spectra corresponding to the strains: 0 µε (solid curve), 5150 µε (broken curve), and 10300µε (dashed curve).

4. Conclusion

In conclusion, we demonstrate a structural LPG by helically coiling a thinner microfiber on a thicker microfiber. Transmission notch of ~16.2dB is achieved in a device length of around 450µm only. The insertion loss of the device can be smaller than 0.5dB. Moreover, the coiled microfiber can resonantly lead out the light signal being transmitted in the microfiber. This novel LPG device has distinctive advantages of compactness and flexibility for future applications as optical filters and sensors.

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