Numerical and experimental analysis of long period gratings in wavelength scale elliptical microfibers*

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We report the fabrication of long-period gratings (LPGs) in elliptical microfibers with femtosecond laser. Based on the numerical analysis of the modes and the mode coupling condition of elliptical microfibers, an LPG is fabricated with a very short pitch of 10 μm by periodically modifying the fiber surface, which demonstrates very strong polarization-dependent resonances, a very low temperature sensitivity of a few picometers in air, and high temperature sensitivity of −1.62 nm/°C in refractive index oil.

Keywords: elliptical microfiber, long period grating, femtosecond laser, temperature sensitivity

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1. Introduction

Recently, micro/nanofiber (MNF) photonic devices have attracted significant attention. It has been suggested that MNFs could function as the basic element of micro–nano photonics due to their compactness.[1–3] The MNFs have a large evanescent field outside the fiber, allowing strong evanescent-wave coupling between MNFs and their environment, and hence the straightforward applications are evanescent-wave sensors,[4–6] which is important for chemical and biological sensing in medical, industrial, and environmental applications. MNF is typically taper-drawn from a conventional silica optical fiber and has a circular cross-section, and there have been investigations of LPGs on smaller size optical fibers, including surface-corrugated[7] and CO_2 laser-induced[8] LPGs on fiber taper with a diameter from 10 μm–15 μm, and recently, LPGs have been fabricated in thinner fibers (or micro/nanofibers) with a diameter of about a few micrometers with femtosecond laser[9] and CO_2 laser irradiation,[10] however the LPGs fabricated in elliptical microfiber and the sensing characteristics of small diameter microfiber-based LPGs fabricated with femtosecond laser are little reported.

In this paper, we report the fabrication of LPG in a microfiber with an elliptical cross-section with wavelength scale diameter by use of a femtosecond infrared laser. The first order LPG was fabricated with a grating pitch of ∼ 10 μm and 9 periods, which demonstrates polarization-dependent resonance and very low temperature sensitivity in air. The device length of the LPG is 90 μm, which is much more compact than the gratings fabricated in conventional fibers, about one or two-orders of magnitude shorter. This LPG demonstrates low temperature sensitivity of 15 pm/°C in air, and a higher temperature sensitivity of −1.62 nm/°C in oil with refractive index of 1.3.

2. Mode analysis

The model used to study the properties of the air-cladding elliptical microfiber is shown in Fig. 1.[11] It comprises an infinite air-cladding and an elliptical core made predominantly of silica with a tiny circular Ge-doped center region. The elliptical microfiber is featured with a semi-major diameter "a" and a semi-minor diameter "b", which are taken to be $a = 1$ μm and $b = 0.5$ μm, respectively. The refractive indices of the air-cladding, the silica and Ge-doped regions are set, respectively, to $n_{\text{air}} = 1$, $n_{\text{silica}} = 1.444$, and $n_{\text{Ge}} = (1+0.36\%)\cdot n_{\text{silica}}$. When the circular guide is made elliptical, the modes that are degenerate in the circular guide become non-degenerate in the elliptical waveguide because the circular symmetry is broken. According to the appropriate solutions of the wave equation for the elliptical waveguide, all modes on an elliptical dielectric cylinder are hybrid, for which neither field is purely transverse and there is a component of both electric and magnetic fields in the direction of propagation. It is therefore necessary to use the second system, calling EH or HE and putting the dominant field first. For instance, as the fundamental HE_{11} in circular guide splits into the oHE_{11} and eHE_{11}. The same applies to higher order modes. The pattern of the transverse electric fields and the power density distribution for the first few higher order modes are shown in Fig. 1.

The resonant wavelength of the LPG can be obtained

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through the following expression:

$$\Lambda = \lambda/(n_{\text{eff},0} - n_{\text{eff},\nu}), \tag{1}$$

where λ is the resonant wavelength, Λ is the grating pitch, and $n_{\text{eff},0}$ and $n_{\text{eff},\nu}$ are, respectively, the effective refractive indices of the fundamental and the ν-order mode. In the case of an elliptical MNF, the resonant wavelengths for which coupling condition (Eq. (1)) is satisfied are depending on the two principal input polarizations (two orthogonal polarizations aligned along the principal axes of the elliptical MNF). The birefringence causes each input polarization corresponding to each axis (slow or fast axis) to have different effective refractive indices of core and high order modes, which results in a splitting of the wavelength-dependent loss band and causes the codirectional mode coupling condition to be different at the two principal input polarizations.

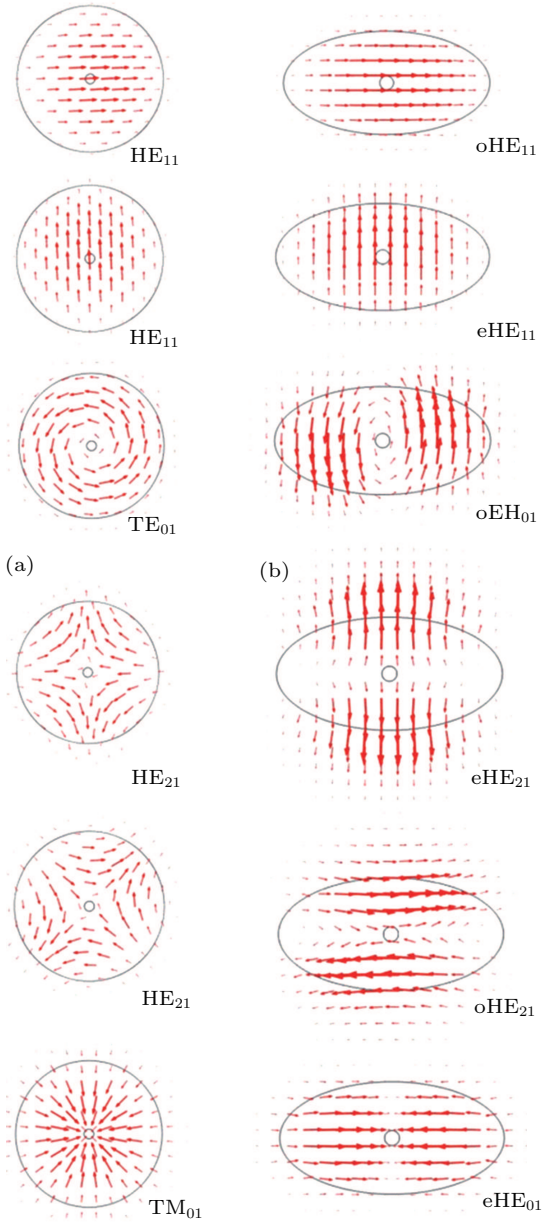


Fig. 1. (color online) Distribution of transverse electric field for modes in (a) MNF with circular cross-section, (b) MNF with elliptical cross-section.

Figure 2(a) shows the effective index of the modes in air clad silica elliptical MNFs as a function of a normalized fiber diameter $\sqrt{2a*2b}/\lambda$ for MNFs with $b/a = 0.5$ and $b/a = 0.9$, respectively. It is clear that, when the normalized diameter is larger than a certain value as denoted as the vertical dotted line in Figs. 2(a) and 2(b), the elliptical MNF is a multi-mode waveguide, which is the diameter of the MNFs used for fabricating the LPG, the elliptical MNF can support a few modes. Hence, by introducing an LPG satisfying the phase matching condition given in Eq. (1), resonant mode coupling devices may be implemented.

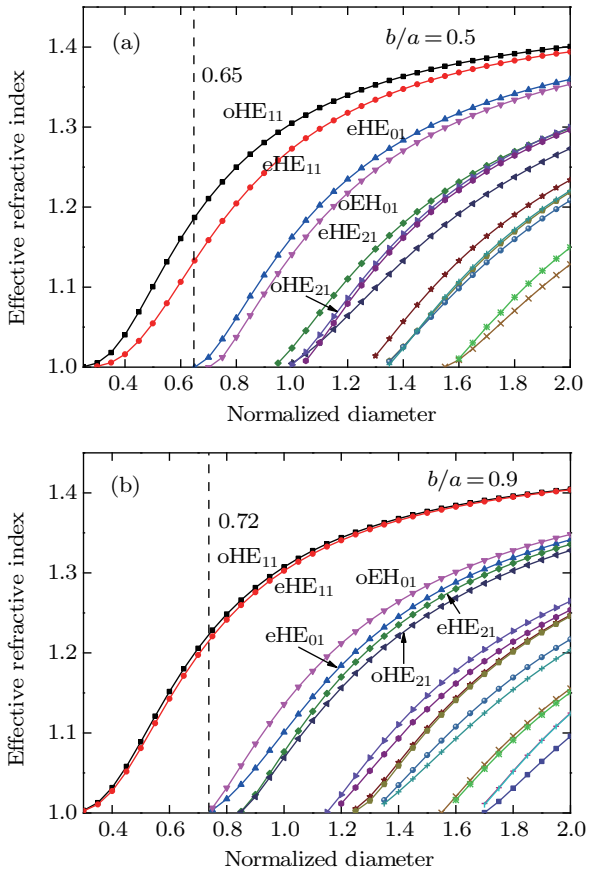


Fig. 2. (color online) Effective indices of lower-order modes as functions of normalized fiber diameter ($\sqrt{2a*ab}/\lambda$) for (a) $b/a = 0.5$ and (b) $b/a = 0.9$.

As can be seen from Fig. 2, the refractive index difference between fundamental and higher-order modes in an elliptical MNF is much larger than that in conventional SMFs. According to Eq. (1), this large index difference will require a much smaller grating pitch to achieve phase matching. Figure 3 shows the phase matching (Λ–λ) curves of elliptical MNFs with different diameters. The phase matching conditions between the two polarization states of the fundamental mode and the eHE$_{01}$ mode for the elliptical MNF with $b/a = 0.5$ and $b/a = 0.9$ are shown in Fig. 3, and the pitch that satisfied the resonance condition is much smaller than that of conventional fibers.

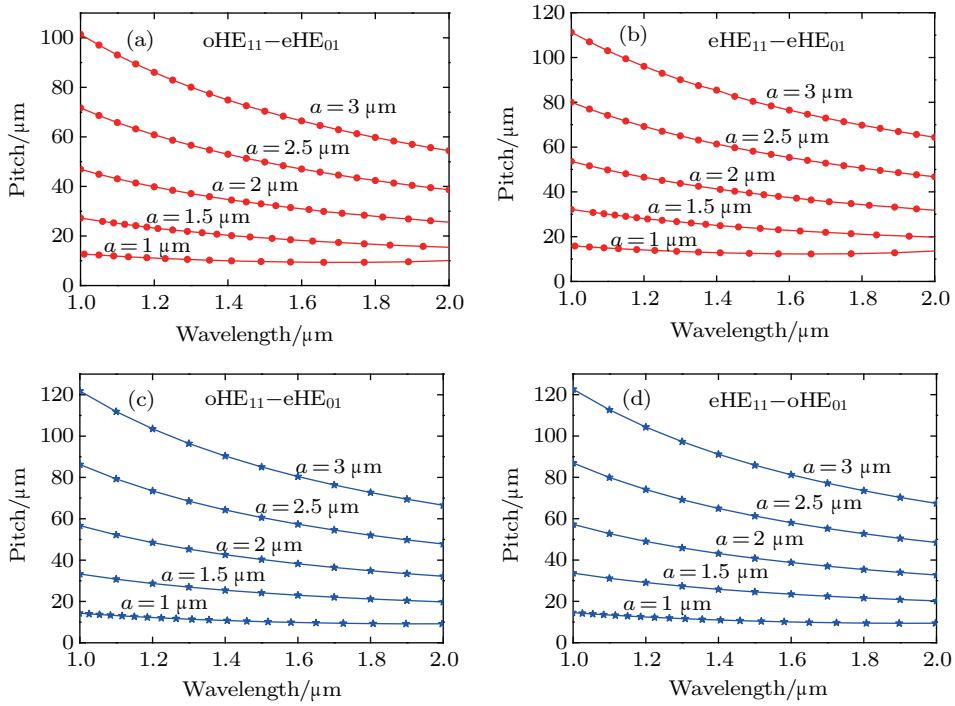


Fig. 3. (color online) Phase matching curves for MNFs with different sizes. (a) and (b) Coupling between oHE_{11}, eHE_{11} and eHE_{01} for $b/a = 0.5$; (c) and (d) Coupling between oHE_{11}, eHE_{11}, and eHE_{01} for $b/a = 0.9$.

3. Experimental results

The elliptical microfibers used in this investigation were fabricated from a commercial SMF-28 fiber by applying a technique described in Ref. [12] The elliptical microfiber obtained in this investigation has a uniform waist of ~ 1.7 cm in length, and a major-diameter of ~ 2 μm and an ellipticity of ~ 0.73. In such a small-size microfiber, the refractive index differences between fundamental and higher-order modes are much larger than in a standard-size optical fiber, as shown in Fig. 4, and the gratings pitches required to satisfy the phase matching condition are hence much shorter, about a few micrometers.

An LPG is written on the elliptical micro/nanofibers with a femtosecond laser by periodically modifying the surface along one side of the fiber to achieve the mode coupling,[10] as shown in Fig. 5. One pigtail is connected to a broadband source (BLS) covering a wavelength from 1450 nm to 1650 nm, while the other pigtail is connected to an optical spectrum analyzer (OSA) to record the transmission spectrum during the LPG fabrication process. During LPG fabrication, a polarizer was used to launch a linearly polarized light beam to the fiber to optimize the transmission dips.

With the assistance of an optical microscope, the laser focal position can be monitored and displayed on an LCD monitor, through which the location of the focal point on the MNF can be accurately adjusted via the computer-controlled translation stage. The LPG is fabricated by a point-by-point (PBP) process. The laser pulse with an irradiation intensity of 0.1 J/cm^2 is focused on the center of the upper surface of the elliptical MNF with an exposure time of 1 s, and the focal spot is then moved to the next point along the fiber by use of the three-axis translation stage. A polarizer is used to launch polarized light into the SMF pigtail of the elliptical MNF.

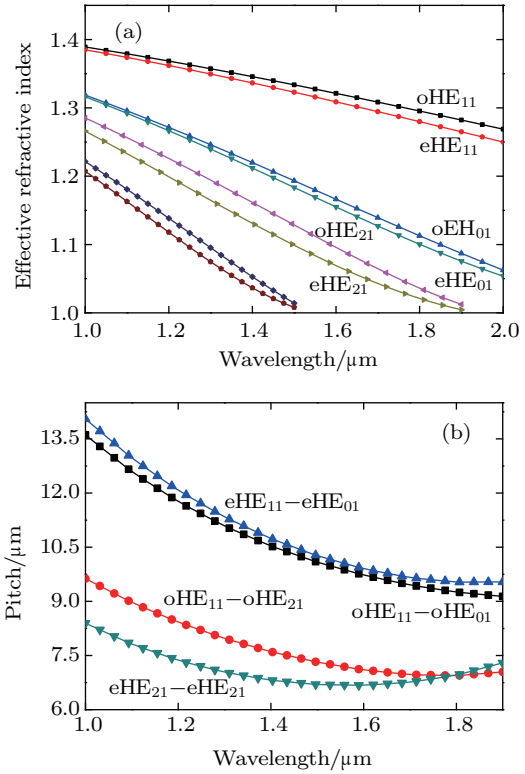


Fig. 4. (color online) (a) Modes transmission in the elliptical microfiber with diameter of 2 μm and ellipticity of 0.73. (b) Phase matching curves for MNFs with diameter of 2 μm and ellipticity of 0.73.

Figure 5 shows the transmission spectrum of an LPG fabricated on the elliptical MNFs with the diameter of the ma-

jor axis of ∼ 2 μm and a pitch of 10 μm. After inscribing 9 notches, the maximum coupling is realized with the resonance wavelengths for the two polarization modes of 1478.7 nm and 1604.7 nm, respectively, corresponding to coupling from oHE11 to oEH$_{01}$, eHE11, and eHE$_{01}$, respectively, and grating strengths of 18.6 dB and 23.2 dB, respectively.

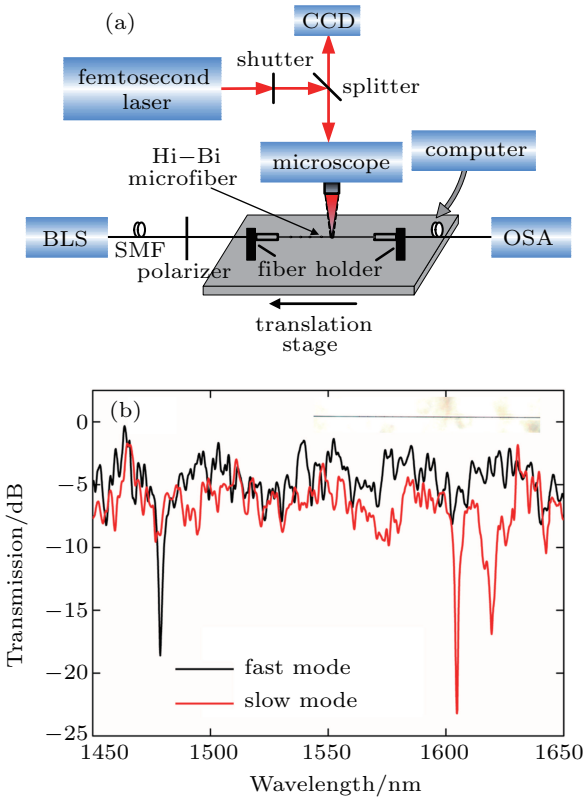


Fig. 5. (color online) (a) Schematic diagram of the femtosecond laser system for fabricating LPGs in elliptical micro/nanofibers. (b) Transmission spectrums of an LPG with a pitch ∼ 15 μm fabricated with a femtosecond infrared laser.

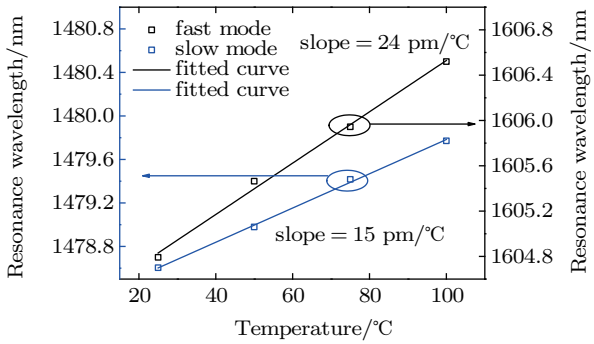


Fig. 6. (color online) The resonant wavelength as functions of temperature for the LPG fabricated by femtosecond laser.

For temperature response, the transmission spectrum of the two resonance wavelengths corresponding to the two polarization states were monitored when temperature surrounding the LPG was varied from 25 °C to 100 °C in steps of 25 °C by use of a digitally controlled oven. The measured temperature coefficients are 24 pm/°C and 15 pm/°C in air due to the low thermal-expansion coefficient of the silica fiber, as shown in Fig. 6, which is more stable than that of the conventional LPG.

To measure the response of the LPG to liquid temperature, the device was immersed into oil with a refractive index of 1.3, however, the original resonance dips disappeared because the mode coupling condition is not achieved when the refracitve index of the cladding material surrounding the small diameter microfiber changed a lot. The new resonance condition was achieved in the liquid surrounded elliptical microfibers, as shown in Fig. 7(a). The temperature test was carried out from room temperature (24 °C) to 34 °C by putting the LPG surrounded with refractive index oil into a digitally controlled oven. The resonant wavelength shifts toward a longer wavelength and follows an approximately linear relationship as shown in Fig. 7(b) and Fig. 7(c), corresponding to a temperature coefficient of ∼ −1.62 nm/°C, two orders of magnitude higher than that of the conventional LPG.

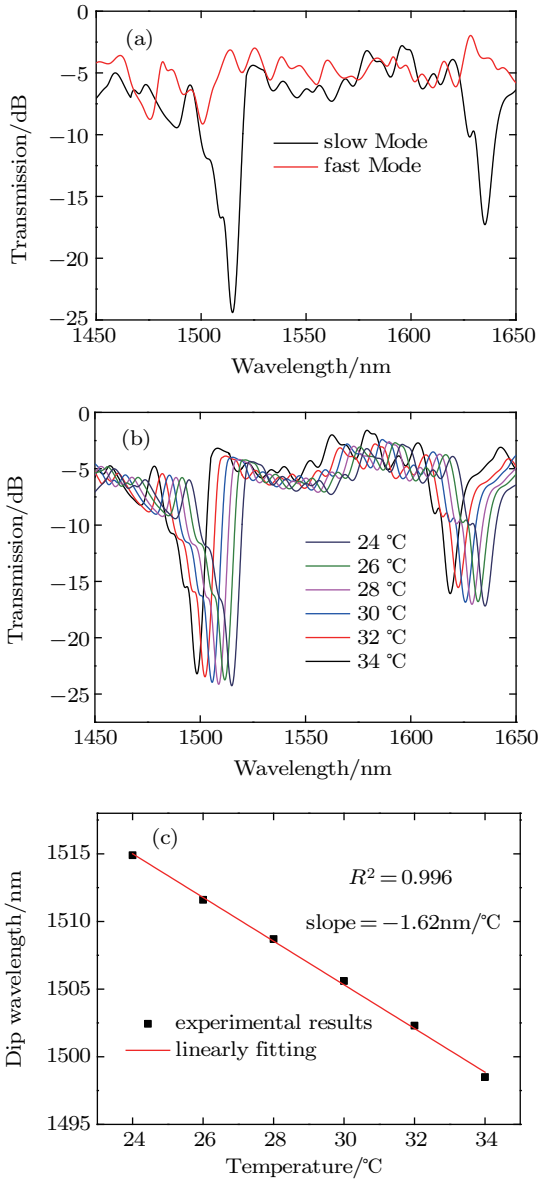


Fig. 7. (color online) (a) Measured transmission spectra when the LPG is immersed into oil with refractive index of 1.3. (b) Resonance wavelength of slow mode as a function of temperature.

4. Conclusion and perspectives

LPGs with grating pitches of 10 μm were fabricated in elliptical MFs by use of a femtosecond infrared laser. Very efficient, polarization-dependent resonant couplings were achieved with a very short device length of 90 μm, which is two orders of magnitude shorter than that of LPG fabricated in conventional fibers. This device demonstrates very low temperature sensitivity in air and a higher temperature sensitivity of -1.62 nm/°C in refractive index oil, about two orders of magnitude higher than that of conventional fiber-based LPG. These MF-based gratings may be used as wavelength selective polarization filters and sensors.

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