Long-period gratings in wavelength-scale microfibers

Haifeng Xuan, Wei Jin,* and Shujing Liu

Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
**Corresponding author: eewjin@polyu.edu.hk*

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We report the fabrication of long-period gratings (LPGs) in wavelength-scale microfibers with diameters from 1.5 to 3 μm. The LPGs were fabricated by use of a femtosecond IR laser to periodically modify the surface of the fibers. These LPGs have grating periods of a few tens of micrometers, much smaller than those in conventional optical fibers. A compact 10-period LPG with a device length of only ~150 μm demonstrated a strong resonant dip of >20 dB around 1330 nm. These microfiber LPGs would be useful in-fiber components for microfiber-based devices, circuits, and sensors. © 2009 Optical Society of America

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Long-period gratings (LPGs) have played very important roles in optical fiber communication and sensors [1]. LPGs have been fabricated in conventional single-mode fibers (SMFs) [1], index-guiding photonic crystal fibers (PCFs) [2], and solid-core photonic bandgap fibers (PBFs) [3], as well as hollow-core PBFs [4]. There have been reports on fabricating LPGs on tapered SMFs with diameters down to 15 μm [5]; these LPGs have a grating period of ~200 μm, not significantly different from that of the LPGs based on conventional SMFs.

Recently, there has been considerable interest in micro/nanofiber (MNF) photonic devices and applications. Optical MNFs can be taper drawn from standard optical fibers or glass rods and have potential to be used as low-loss microscale/nanoscale optical waveguides [6,7]. The MNFs have a high fractional evanescent field outside the fiber [8], allowing strong evanescent-wave coupling between MNFs and their environment, and hence the straightforward applications are evanescent-wave sensors [9] and waveguide couplers [10,11]. It has been suggested that MNFs could function as the basic element of micro–nano photonics, which focus on microphotonic circuits that are composed of MNFs [6,12,13]. However, most MNF devices reported so far are assembled by coiling (winding) or connecting (coupling), which intensively makes use of property of the large fractional evanescent field external to the fibers.

In this Letter, we report possibly the first in-fiber mode-coupling devices made directly on an optical microfiber (MF). The devices are LPGs made by periodically modifying the surface along one side of the MFs with a diameter from 1.5 to 3 μm. The MFs are made by tapering standard SMFs, and the LPGs have a period of 10 to 20 μm and demonstrate strong resonant coupling as high as 22 dB with only 10 periods.

The MFs were drawn by tapering SMFs with a commercial coupler fabrication station. As shown in Fig. 1, a commercial SMF-28 is held and pulled by two translation stages that can move with micrometer precision. The fiber is heated and softened by a hydrogen flame, whose dimension along the fiber is ~8 mm. The flame torch is scanned along the fiber with a speed $v_t \sim 1.0$ mm/s over a range of L, while the two translation stages are symmetrically moved apart at a speed of $v_s \sim 0.1$ mm/s. The scanning of flame improves the uniformity of the waist diameter as well as prolongs the length of effective taper waist [7]. With proper fabrication parameters, MFs with diameter from hundreds of nanometers to a few micrometers and effective waist length longer than ~15 mm can be fabricated.

Figure 2 is a schematic of the LPG fabrication setup. Laser pulses with wavelength of 800 nm, duration of 120 fs, and repetition rate of 1 kHz are produced by a Ti:sapphire laser. The laser pulses are focused onto the MF by a microscope objective, and the focal spot size is ~2.5 μm. The MF is mounted on the computer-controlled three-axis translation stage with a tuning resolution of 100 nm. Since the MFs are taper pulled from a commercial SMF, the MF (the waist of the taper) is automatically connected to the SMF pigtails. One pigtail is connected to a broadband source (BBS) covering a wavelength from 1200 nm to 1700 nm, while the other pigtail is connected to an optical spectrum analyzer to record the transmission spectrum during the LPG fabrication process. The BBS is composed of five separate superluminescent light-emitting diodes (SLEDs) with a center wavelength from 1260 nm to 1660 nm. They combined into a single-fiber output to produce a broad spectrum. The BBS source is polarized, because each of the SLEDs is polarized. However, the polarization characteristics for different wavelength ranges, corresponding to different SLEDs, may be

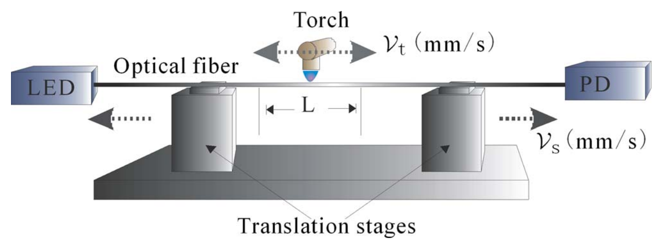

Fig. 1. (Color online) Experiment setup for fabricating MFs.

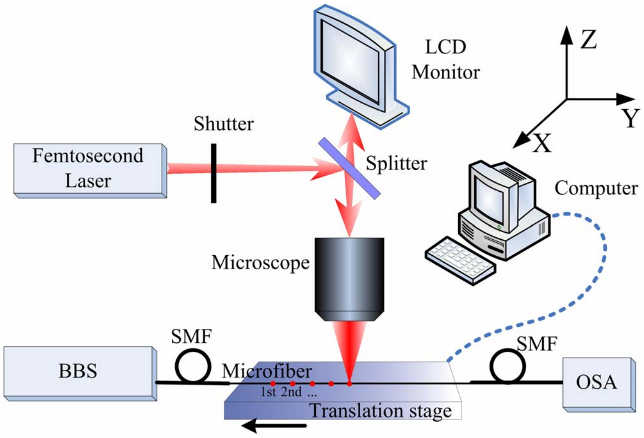

Fig. 2. (Color online) Schematic of the femtosecond laser system for fabricating LPGs in MFs.

different. During LPG fabrication, a polarization controller (PC) was used to adjust the polarization state to optimize the transmission dips, but the exact polarization states for different wavelength ranges are not known.

With the assistance of an optical microscope, the laser focal position can be monitored and displayed in a LCD monitor, through which the location of the focal point on the MF can be accurately adjusted via the computer-controlled translation stage. The LPG is fabricated by a point-by-point (PBP) process. Compared with the mask approach [1], the PBP process is more flexible, although it requires accurate control of the beam position with respect to the fiber. The laser pulses with an irradiation intensity of $\sim 0.2\ \mathrm{J/cm^2}$ are focused on the center of the upper surface of MF with an exposure time of ~ 1 s, and the focal spot is then moved to the next point along the Y direction by use of the three-axis translation stage as shown in Fig. 2. Figure 3(a) shows a typical image of the LPG observed from the LCD monitor, and the details of the surface modification can be seen from the scanning-electron-microscope (SEM) images in Figs. 3(b) and 3(c). The diameter of the laser-induced notch is $2-3\ \mu$m, comparable with the focal spot size of laser pulses. The depth of the notch is affected by the power of the pulses and the time of exposure and is a

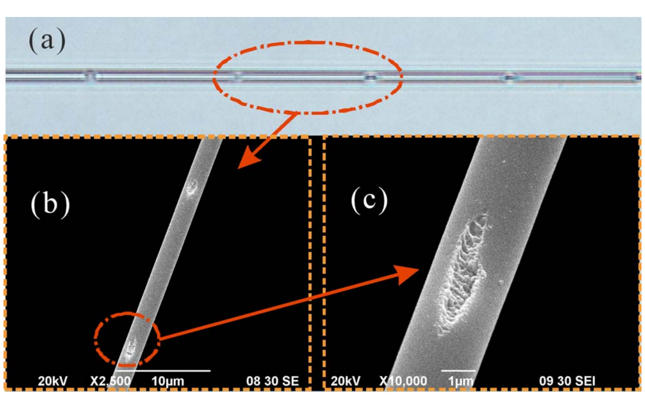

Fig. 3. (Color online) LPG fabricated in an $\sim 2.3\ \mu$m diameter MF. (a) Microscope image showing the periodic notches along the fiber. (b) SEM image showing two adjacent notches. (c) SEM image showing the details of a notch induced by femtosecond laser pulses.

couple of hundreds of nanometers for the LPG shown in Fig. 3.

Figure 4 shows the transmission spectrum of an LPG made on an MF with a diameter of $\sim 2.4\ \mu$m with increasing number of notches induced by the femtosecond laser pulses. The pitch or period of the LPG is $\sim 15\ \mu$m. The resonant dip at 1280 nm enhances significantly with increasing number of grating notches and reached ~ 25 dB after 11 notches. The 3 dB bandwidth of the attenuation dips are ~ 9 nm and ~ 6 nm, respectively, for the resonance at ~ 1280 nm and ~ 1360 nm. The multiple fringelike dips around the main dips could be due to the significant modification of the fiber induced by femtosecond laser, which excite higher-order modes. These higher modes would interfere with the fundamental mode and result in the unwanted fringes.

In an LPG, coupling between fundamental and higher-order modes is determined by the phase-matching condition [1],

$$\lambda_{\mathrm{res}} = (n_{\mathrm{eff},0} - n_{\mathrm{eff},v})\Lambda, \tag{1}$$

where λ_{res} is the resonant wavelength, Λ is the grating pitch, and $n_{\mathrm{eff},0}$ and $n_{\mathrm{eff},v}$ are, respectively, the effective refractive indexes of the fundamental and the v-order mode. The modal property of MNF has been studied previously by using a two-layer (i.e., a circular silica rod with an infinite air clad) step-index model [8]. By using the same model, we found that the MF is a single-mode waveguide for $D/\lambda < 0.73$, where D is the diameter of the fiber and λ is the optical wavelength. For $0.73 < D/\lambda < 1.8$, which is the range of our interest here, the MF can support several modes. Hence, by introducing an LPG satisfying Eq. (1), resonant mode-coupling devices may be implemented.

We also found that the index difference between fundamental and higher-order modes in MFs is much larger than that in conventional SMFs. For example, the index difference between HE_{11} and the first group of higher-order modes (i.e., TE_{01}, HE_{21}, and TM_{01}) is about ~ 0.1 for an MF with $D \sim 2\lambda$, while the differ-

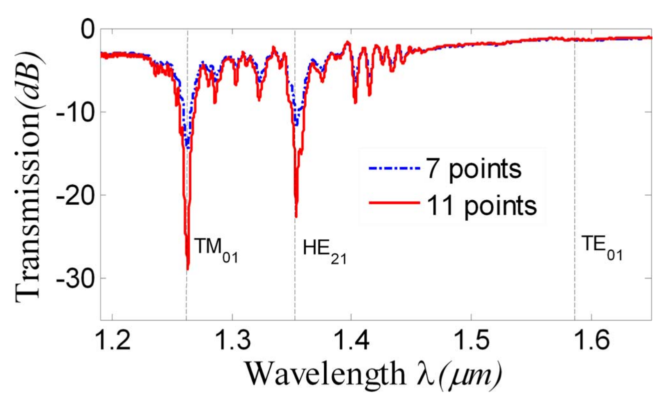

Fig. 4. (Color online) Transmission spectrum of an MF LPG with a different number of grating periods. The diameter of the MF is $\sim 2.4\ \mu$m, and the grating pitch is $\sim 15\ \mu$m. The dashed lines are the calculated resonant wavelengths corresponding to coupling to different higher-order modes for a fiber with $2.362\ \mu$m.

ence between HE_{11} and a cladding mode in a conventional SMF is about ~0.004. According to Eq. (1), this large index difference would require a much smaller grating period to achieve resonant mode coupling.

Based on Eq. (1), the phase-matching (Λ-λ) curve responsible for resonant coupling between the fundamental and the first group of higher-order modes is calculated for an MF with $D=2.6$ μm and shown in Fig. 5(a). For a grating pitch of 21 μm, Fig. 5(a) predicts that three resonance dips would be formed around 1270, 1390, and 1640 nm, corresponding to coupling from HE_{11} to TM_{01}, HE_{21} and TE_{01}, respectively. Figure 5(b) shows the measured transmission spectrum of an LPG with a grating period of 21 μm made in an ~2.6 μm diameter MF by use of the femtosecond laser. The vertical dashed lines are the calculated resonant wavelengths for an MF with $D=2.663$ μm. The transmission spectrum matches well with the calculated results for HE_{11}-TM_{01} (1274 nm) and HE_{11}-TE_{01} (1635 nm) coupling. The 3 dB bandwidths of the attenuation dips are ~ 14 and ~39 nm, respectively, for the resonance at ~1274 and ~1635 nm. The $HE_{11}-HE_{21}$ resonant did not appear for the sample shown in Fig. 5(b). However, $HE_{11}-HE_{21}$ coupling did appear for the LPG shown in Fig. 4 and matches with the theoretical prediction. The missing dip in Fig. 5(b) could be due to polarization-dependent mode coupling/overcoupling, since we did observe three dips during the fabrication process and the strengths of the dips can be changed significantly by adjusting the PC.

The response of the MF LPGs to temperature was measured by placing LPGs in a digitally controlled oven with temperature varying between 25 °C and 100 °C. Figure 6 shows the measured response for an LPG in an MF with a diameter of ~2.7 μm. The temperature coefficient is ~–5.1 pm/°C, about 10 times smaller than that of an LPG in traditional SMF and very close to LPGs in pure silica PCFs and PBFs [2,4]. The very small temperature coefficient may be explained as follows: the Ge-doped region of the MF taper drawn from the SMF-28 is so small that it can be considered as a pure silica fiber, and the LPGs in pure silica fibers have been shown to have smaller temperature sensitivity than Ge-doped fibers [2,4].

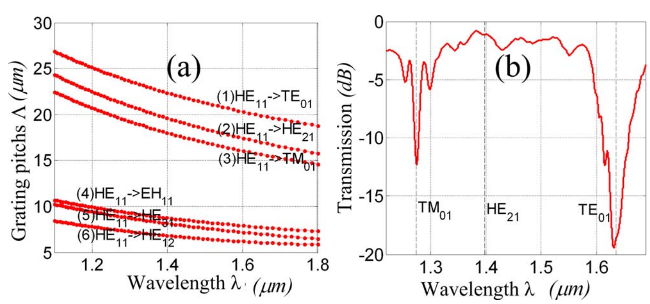

Fig. 5. (Color online) (a) Grating pitches as the function of wavelength for modes coupling between HE_{11} and the first group of higher-order modes for an MF with 2.6 μm diameter; (b) measured transmission spectrum of an LPG with a grating pitch of 21 μm fabricated in an ~2.6 μm diameter MF. The dashed lines in (b) are the calculated resonant wavelengths for a fiber with 2.663 μm.

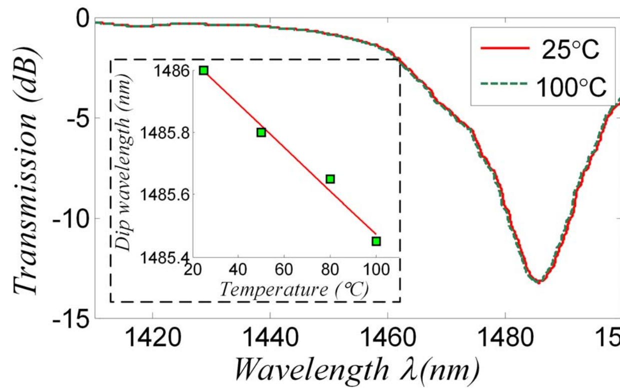

Fig. 6. (Color online) Spectral response of an MF LPG to temperature. Inset, measured dip (resonant) wavelength as a function of temperature.

Mode couplings in wavelength-scale MFs are realized by fabricating LPGs along the fiber. The LPGs are fabricated by periodically modifying the surface along one side of the fiber with a femtosecond laser. The periods of the LPGs in such MFs are on the order a few tens of micrometers, corresponding to coupling from the fundamental to the first group of higher modes. A strong resonant dip of ~25 dB was achieved with a 10-period LPG written on an MF of diameter 2.4 μm. Such an LPG has small temperature sensitivity and is truly a compact device with a grating length of only 150 μm. These LPGs would find applications in MF wavelength filters, gain equalizers for MF amplifiers, and wavelength-encoded evanescent-wave biosensors.

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