Leakage coupling of ultrasensitive periodical silica thin-film long-period grating coated on tapered fiber

Cheng-Ling Lee,[1,]* Zi-Yu Weng,[1] Chuan-Jung Lin,[1] and YuanYao Lin[2]

[1]*Department of Electro-Optical Engineering, National United University, Miaoli 360, Taiwan*

[2]*National Tsing-Hua University Institute of Photonics Technologies, Hsinch 300, Taiwan*

**Corresponding author: cherry@nuu.edu.tw*

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This investigation demonstrates leakage coupling between fundamental-mode and high-order mode resonance based on a periodical silica thin-film long-period grating (TFLPG) that was coated on a tapered fiber when wavelengths longer than the fundamental-mode cutoff were propagated. For the leaky guiding situation, these leakage modes still may exhibit strong mode coupling in the taper with the assistance of the TFLPG when the phase-matched condition is satisfied. An extremely high tuning efficiency of 62.9 nm/°C, which is equivalent to a measurement of sensitivity of approximately 168, 182 nm per refractive index unit, is achieved. To the best of our knowledge, this sensitivity is the highest achieved for a fiber sensor to date.

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A tapered fiber waveguide device can be regarded as a three-layer structure, and it has powerful applications in many advanced technologies [1–10], because the artificial rearrangement of a waveguide structure in a single-mode fiber taper has a modified and distinctive modal characteristic, which may give it more flexible and attractive properties. Tapered fibers can be further fabricated for novel, useful devices, such as sensitive sensors [1], especially those of the supercontinuum generation [2], long-period fiber grating (LPG) based on tapers [3–8], and short-pass fiber filters [9]. Among them, LPG-based filters using fiber tapers [3–8] differ critically from conventional UV-induced LPGs. The coupling mechanism of the latter is based on the core mode coupling to the co-propagated cladding modes, whereas the coupling modes in the tapers are all guided in the tapered core with a strong overlapping between the intermodal coupled modes, owing to the new artificial rearrangement of the fiber structure [3–8]. A mechanically induced LPG on a tapered fiber has been reported in [3]. Ding and Andrews developed another means of managing the configuration of a surface-corrugated LPG on a tapered fiber using contact optical lithography and wet etching [4]. Kakarantzas *et al.* elucidated two LPGs on tapered fibers formed by the deposition of low-loss porous sol-gel-derived silica films [5] and a periodic microtapering technique on a CO_2 laser beam [6]. The authors previously published an investigation of a fiber taper with a side-contacted metal grating that formed a taper-based LPG filter [7]. More recently, an important study of LPG fabricated by a Ti:sapphire laser on a wavelength-scale microtaper has been demonstrated [8]. However, the cited studies involve a highly complicated fabrication process with lower tunability and sensitivity to external variations because the mode-coupled mechanism of the above taper-based LPGs are all based on the intermodal guided modes coupling.

In this study, a silica thin-film long-period grating (TFLPG) coated on a tapered fiber by high-vacuum rf-magnetron sputtering is demonstrated. When the silica thin film is coated through an amplitude mask, a surface TFLPG can be formed on one side of the taper waist. In general, the fundamental mode is strongly confined in the taper and propagation along the taper is approximately adiabatic; nevertheless, a fundamental-mode cutoff (FMC) occurs when the tapered fiber is in an index-matched surrounding. This condition produces a sharp increase in spectral loss of the fundamental mode at wavelengths that exceed the FMC, because the modes are leaking out of the taper and not guiding anymore. However, at propagation wavelengths that exceed the FMC, the refractive index (RI) of the surroundings is higher than the effective indices of the modes. These leakage modes experience Fresnel reflection at the cladding–surrounding interface and may exhibit strong mode coupling in the taper with assistance of the TFLPG if the phase-matched condition is satisfied.

The developed device is based on tapering a SMF-28 fiber with a diameter of 30 μm, which causes the corresponding remaining core diameter to be less than 1.968 μm and enables the dopant germanium (Ge) in the core to diffuse out into pure silica cladding by the tapering processes [11]. After the fibers are tapered, the TFLPG is coated using the high-vacuum rf-magnetron sputtering technique with the same fabricated parameters of [12] with the ratio of $O_2/(Ar + O_2)$ to be 5% and working pressure of $\sim 10^{-2}$ mbar for 1 h deposition at room temperature. Figures 1(a) and 1(b) show a diagram and a scanning electron microscopic (SEM) micrograph of the TFLPG on the taper, respectively. The figure displays the fabricated TFLPG with a grating period of 200 μm. The average thickness of the SiO_2 thin-film grating is approximately 2 μm. Figure 2 presents the calculated effective index (solid curve) of the fundamental mode of the 30 μm tapered fiber in an index-matched liquid adopted in this investigation. The solid curve crosses the RI of the index-matched surroundings (dashed curve) at the cutoff wavelength of about 1.32 μm, and the fundamental mode cannot be guided in the taper beyond the FMC. Insets (a) and (b) in Fig. 2, respectively, show the calculated

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and experimental cutoff spectra of the fundamental mode of the original tapered fiber without the coated TFLPG. From the figures, the FMC gradually shifts to longer wavelengths when the temperature increases, because the RI of the surroundings is reducing (thermo-optic coefficient for liquid $dn/dT = -3.74 \times 10^{-4}$ °C^{-1}). The insets also reveal that use of the index-matched liquid, as the surroundings, yields a short-pass cutoff transmission spectra. Here, the above simulation works were accomplished by a numerical finite-difference-beam propagation method (FD-BPM) [13], and the attenuation region is defined as the spectral range in which the transmission is under −30 dB [10].

To investigate the resonant spectral responses of the leakage coupling in the proposed TFLPG on tapers at attenuation wavelengths, a Cargille index-matching liquid that is suitable for yielding a short-pass cutoff wavelength is used to fill the entire length of the TFLPG. As we can see in Fig. 3, LPG-like resonant peaks are achieved in the attenuation region of the spectrum as expected. The applied temperature T (°C) is controlled by a TE cooler and is increased from 25 °C to 30 °C to greatly reduce the RI of the liquid. The transmission spectra is shown in Fig. 3. In the figure, the spectral response in the attenuation region with a maximum extinction ratio of around 30 dB (at 26 °C) is achieved. By using the method proposed by [14], for the leaky guiding situation, and adopting the characteristic model in [7], the propagation constants and corresponding power attenuation coefficients for the leakage modes can be estimated. In general, a higher attenuation coefficient is expected for smaller RI difference across the interface between the cladding and the surroundings and for the high-order transverse modes owing to a shorter longitudinal distance between successive *Fresnel reflections* at the surrounding–cladding interface. It is observed that, with the TFLPG, the fundamental mode (M_{11}) can be coupled to high-order modes (M_{05}, M_{24}, M_{42}) at the phase-matching wavelengths, which yields discrete attenuation dips (calculated by the method in [7]) that are also identified experimentally. These resonant dips moved to the longer wavelength region, because the shifts are indeed dominated by the FMC shifts, although many factors may affect the sensitivity of wavelength shifts, e.g., the taper dimension, grating period of the LPG in which the

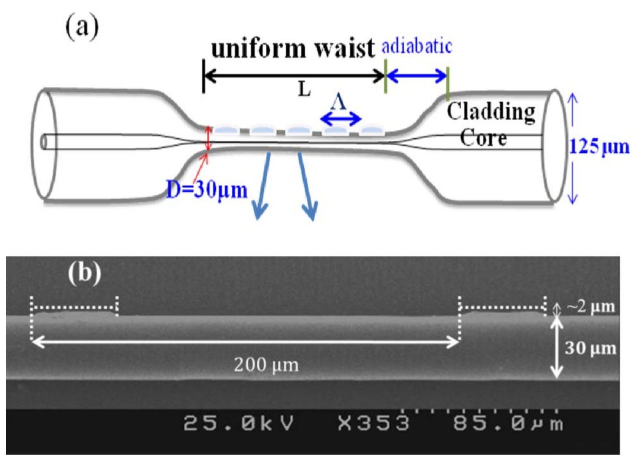

Fig. 1. (Color online) (a) Proposed TFLPG on tapered fiber and (b) SEM photograph of a portion of the uniform waist.

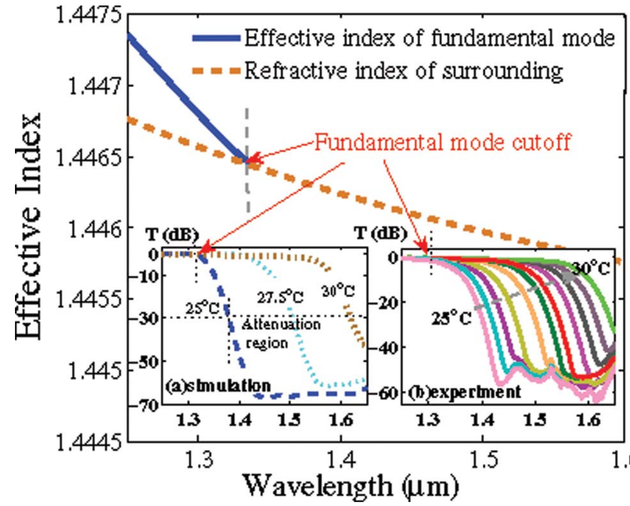

Fig. 2. (Color online) Effective index of fundamental mode (solid curve) of 30 μm taper with index-matched liquid (dashed curve) surroundings. Insets (a) and (b) present the simulated and experimental results of the cutoff spectra for the taper without TFLPG.

high-order mode is coupled and location resonant dips. When the temperature increases, the FMC gradually shifts to longer wavelengths that causes the fundamental mode to be survived at longer wavelengths with a broader mode field diameter. Therefore, a longer FMC can generate a less sharp spectral transition that has a broader resonance. Inset (a) of Fig. 3 reveals that the estimated average tuning efficiency is approximately 51.7 nm/°C, which is equivalent to a RI sensitivity of $51.7/(3.74 \times 10^{-4}) = 138{,}235$ nm per refractive index unit (RIU) (shown in the upper axis; the values are measured RI at 25 °C, sodium D line, 589.3 nm). Here, the thermal expansion coefficient ($\sim 5 \times 10^{-7}$ °C^{-1}) and thermo-optic coefficient (10^{-5}–10^{-6} °C^{-1}) of the silica fiber are neglected. In this Letter, the results obtained are much better than the experimental results in various published studies of fiber-based devices [1,15,16]. Inset (b) demonstrates a

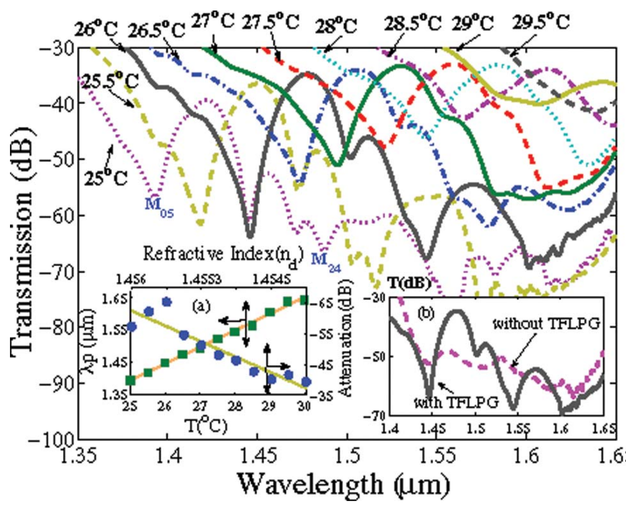

Fig. 3. (Color online) Transmission spectra of leakage coupling of the device with $\Lambda = 200$ μm and $L = 1.2$ cm in the attenuation wavelength region. Inset (a) shows shifts (■) and attenuations (•) of the resonant wavelengths associated with the first dip as the surroundings vary. Inset (b) presents the attenuation region for the taper with and without the TFLPG.

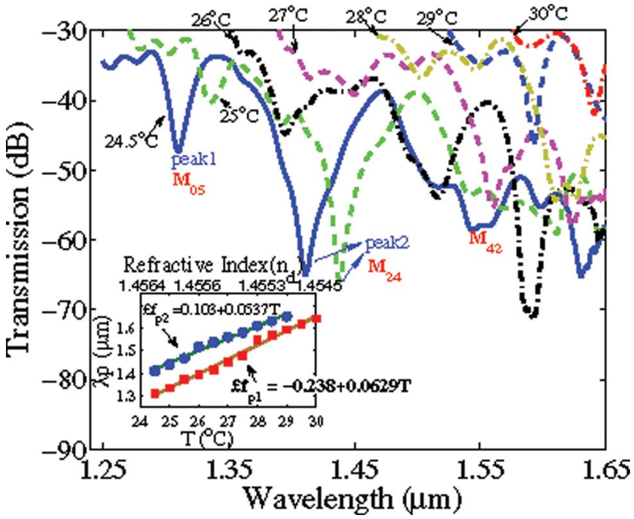

Fig. 4. (Color online) Transmission spectra of the device with $\Lambda = 240\ \mu$m and $L = 1.5$ cm in the attenuation region. Inset, shift of the first two resonant peaks as the surroundings vary.

strong leakage coupling in the attenuation region when the taper is with the TFLPG. More favorable results were obtained herein, because the TFLPG-based taper includes a modified fiber waveguide structure, causing the mode fields to interact directly with the surrounding liquid in a leakage-guiding way that further enhances sensitivity. Notably, in one study [15], the mode-coupling mechanism in the proposed CO_2-laser-ablated LPG with polymeric surroundings still involves the coupling of the core mode into the cladding modes, which may limit the improvement in sensitivity. Figure 4 concerns another case with the TFLPG with $\Lambda = 240\ \mu$m and $L = 1.5$ cm; as expected, all of the resonance peaks shift to longer wavelengths in a linear manner within the corresponding wavelength regions, yielding a best extinction ratio of about 33 dB (at 24.5 °C). The coupling strength in this case is higher than that obtained from the grating length of $L = 1.2$ cm because the longer length may enhance the transmission dip. The inset in Fig. 4 plots the linear curves fitted to the resonant shifts as the surroundings vary. The slope $0.0629\ \mu$m/°C of peak 1 indicates an extremely high tuning efficiency of 62.9 nm/°C (the RI sensitivity is 168,182 nm/RIU), which has excellent sensitivity because of the resonant wavelength of peak 1 possessing the highest order mode coupling and very near FMC resonance.

In conclusion, a successive periodical silica TFLPG coated on a tapered fiber by rf-magnetron sputtering and observation of leakage modes coupling in the device has been demonstrated experimentally for the first time (to our knowledge). The leakage coupling between the fundamental mode and high-order modes when light wavelengths exceed the FMC can be used in making ultrasensitive measurements of variations in the surroundings. The novel coupling characteristics, extremely high tuning efficiency, and excellent sensitivity may make the device effective in fiber-based ultrasensitive sensors.

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