Fabrication of a compact reflective long-period grating sensor with a cladding-mode-selective fiber end-face mirror

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Abstract: A long-period grating (LPG) based compact optical fiber sensor working in reflection mode is demonstrated. A technique to make a mirror on the cladding region of a fiber end-face to reflect only the cladding modes was realized by growing a polymeric microtip on the core region of the fiber end-face, by photopolymerization, followed by coating the fiber end-face with an aluminum film. Using the cladding-mode-selective fiber end-face mirror, the transmission spectrum of the LPG was "inverted" and reflected. Preliminary results of using the sensor to measure the refractive index of glycerol/water solutions were successfully demonstrated.

OCIS codes: (060.2370) Fiber optics sensors; (060.3735) Fiber Bragg gratings; (060.2340) Fiber optics components.

References and links

1. J. Dakin, and B. Culshaw, Optical fiber sensors (Artech House, Boston, 1988).
2. B. Lee, "Review of the present status of optical fiber sensors," Opt. Fiber Technol. **9**(2), 57–79 (2003).
3. A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele,"Fiber grating sensors," J. Lightwave Technol. **15**(8), 1442–1463 (1997).
4. I. Bennion, and L. Zhang, "Fiber Bragg grating technologies and applications in sensors," 2006 OSA/OFC, 2415–2417 (2006).
5. V. Bhatia, and A. M. Vengsarkar, "Optical fiber long-period grating sensors," Opt. Lett. **21**(9), 692–694 (1996).
6. X. W. Shu, L. Zhang, and I. Bennion, "Sensitivity characteristics of long-period fiber gratings," J. Lightwave Technol. **20**(2), 255–266 (2002).
7. S. W. James, and R. P. Tatam, "Optical fibre long-period grating sensors: characteristics and application," Meas. Sci. Technol. **14**(5), R49–R61 (2003).
8. H. J. Patrick, A. D. Kersey, and F. Bucholtz, "Analysis of the response of long period fiber gratings to external index of refraction," J. Lightwave Technol. **16**(9), 1606–1612 (1998).
9. M. P. DeLisa, Z. Zhang, M. Shiloach, S. Pilevar, C. C. Davis, J. S. Sirkis, and W. E. Bentley, "Evanescent wave long-period fiber bragg grating as an immobilized antibody biosensor," Anal. Chem. **72**(13), 2895–2900 (2000).
10. D. W. Kim, Y. Zhang, K. L. Cooper, and A. Wang, "Fibre-optic interferometric immuno-sensor using long period grating," Electron. Lett. **42**(6), 324–325 (2006).
11. J. L. Tang, S. F. Cheng, W. T. Hsu, T. Y. Chiang, and L. K. Chau, ""Fiber-optic biochemical sensing with a colloidal gold-modified long period fiber grating," Sens. Actuators B Chem. **119**(1), 105–109 (2006).
12. Z. Wang, J. R. Heflin, K. Van Cott, R. H. Stolen, S. Ramachandran, and S. Ghalmi,Biosensors employing ionic self-assembled multilayers adsorbed on long-period fiber gratings," Sens. Actuators B Chem. **139**(2), 618–623 (2009).
13. M. Dagenais, A. N. Chrysis, H. Yi, S. M. Lee, S. S. Saini, and W. E. Bentley, "Optical bio-sensors based on etched fiber Bragg gratings," Proc. SPIE **5729**, 214–224 (2005).
14. X. Sang, C. Yu, T. Mayteevarunyoo, K. Wang, Q. Zhang, and P. L. Chu, ""Temperature-insensitive chemical sensor based on a fiber Bragg grating," Sens. Actuators B Chem. **120**(2), 754–757 (2007).
15. L. Y. Shao, A. P. Zhang, W. S. Liu, H. Y. Fu, and S. He, "Optical refractive-index sensor based on dual fiber-Bragg gratings interposed with a multimode-fiber taper," IEEE Photon. Technol. Lett. **19**(1), 30–32 (2007).
16. G. Laffont, and P. Ferdinand, "Tilted short-period fibre-Bragg-grating-induced coupling to cladding modes for accurate refractometry," Meas. Sci. Technol. **12**(7), 765–770 (2001).

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17. T. Allsop, R. Reeves, D. J. Webb, I. Bennion, and R. Neal, “A high sensitivity refractometer based upon a long period grating Mach-Zehnder interferometer,” Rev. Sci. Instrum. **73**(4), 1702–1705 (2002).
18. P. L. Swart, “Long-period grating Michelson refractometric sensor,” Meas. Sci. Technol. **15**(8), 1576–1580 (2004).
19. J. Yang, P. Sandhu, W. Liang, C. Q. Xu, and Y. Li, “Label-free fiber optic biosensors with enhanced sensitivity,” IEEE J. Sel. Top. Quantum Electron. **13**(6), 1691–1696 (2007).
20. E. Davies, R. Viitala, M. Salomäki, S. Areva, L. Zhang, and I. Bennion,“Sol-Gel derived coating applied to long-period gratings for enhanced refractive index sensing properties,” J. Opt. A, Pure Appl. Opt. **11**(1), 015501 (2009).
21. J. F. Ding, A. P. Zhang, L. Y. Shao, J. H. Yan, and S. He, “Fiber-taper seeded long-period grating pair as a highly sensitive refractive-index sensor,” IEEE Photon. Technol. Lett. **17**(6), 1247–1249 (2005).
22. X. F. Chen, K. M. Zhou, L. Zhang, and I. Bennion, “Simultaneous measurement of temperature and external refractive index by use of a hybrid grating in D fiber with enhanced sensitivity by HF etching,” Appl. Opt. **44**(2), 178–182 (2005).
23. A. P. Zhang, L. Y. Shao, J. F. Ding, and S. He, “Sandwiched long-period gratings for simultaneous measurement of refractive index and temperature,” IEEE Photon. Technol. Lett. **17**(11), 2397–2399 (2005).
24. K. Shima, K. Himeno, T. Sakai, S. Okude, A. Wada, and R. Yamauchi, “Novel temperature-insensitivity long-period fiber grating using a boron-codoped-germanosilicate-core fiber,” OFC’97,” OSA Technical Digest Series 6, 347–348 (1997).
25. M. Jiang, Z. G. Guan, and S. He, “Multiplexing scheme for self-interfering long-period fiber gratings using a low-coherence reflectometry,” IEEE Sens. J. **7**(12), 1663–1667 (2007).
26. A. P. Zhang, X. W. Chen, J. H. Yan, Z. G. Guan, S. He, and H. Y. Tam, “Optimization and fabrication of stitched long-period gratings for gain-flattening of ultrawide-band EDFAs,” IEEE Photon. Technol. Lett. **17**(12), 2559–2561 (2005).
27. R. Bachelot, C. Ecoffet, D. Deloeil, P. Royer, and D.-J. Lougnot, “Integration of micrometer-sized polymer elements at the end of optical fibers by free-radical photopolymerization,” Appl. Opt. **40**(32), 5860–5871 (2001).
28. L. M. Xiao, W. Jin, M. S. Demokan, H. L. Ho, H. Y. Tam, J. Ju, and J. M. Yu, “Photopolymer microtips for efficient light coupling between single-mode fibers and photonic crystal fibers,” Opt. Lett. **31**(12), 1791–1793 (2006).
29. T. Erdogan, “Cladding-mode resonances in short- and long-period fiber grating filters,” J. Opt. Soc. Am. A **14**(8), 1760–1773 (1997).

1. Introduction

Optical fiber sensors have become one of the most important sensors because of their many advantages e.g. compactness, electromagnetic interference immunity, high sensitivity, passive operation, and multiplexing capabilities [1,2]. Fiber Bragg gratings (FBGs) and long-period fiber gratings (LPGs), in particular, have attracted much attention because they have self-referencing capabilities and flexible sensing schemes for the measurement of numerous physical parameters, e.g. strain, temperature, or external refractive index (RI) [3–23]. Fiber grating sensors have not only been widely extolled in research literature, but also achieved great success in real commercial industries.

Since the discovery of fiber gratings, the use of FBGs and LPGs for external RI sensing was proposed and demonstrated because of their potential applications as miniature biochemical sensors [8–23]. The detection of a specific antibody or antigen was demonstrated after immobilization of biological molecules or antibody on the surface of fiber grating [8–12]. An FBG needs some special post-processes for sensing of external RI [13–15], and has practical implementation limitations, including the reduction on the sensor’s mechanical strength. Tilted FBG was also utilized to measure RI sensing but its measurement resolution is only around 10^{-4} [16]. On the other hand, the measurement resolution of an LPG-type RI sensor is around 10^{-5} ~10^{-6} [17]. The reason that the RI measurement resolution of LPG is better than that of FBG is mainly because the resonant wavelength of an LPG depends on the difference of the effective indexes between the core mode and cladding modes, whereas the resonant wavelength of an FBG depends on the sum of the effective indexes of the two coupling modes.

Various designs of LPG sensors were proposed for RI measurement. For example, in-fiber Michelson interferometer based on a long-period grating was proposed for RI sensing [18]. The sensitivity of the sensor can be enhanced for bio-sensing applications, by decreasing its cladding thickness [19]. The improvement of RI sensor sensitivity was also demonstrated by applying sol-gel coating on an LPG [20] or introducing an LPG-based Mach-Zehnder interferometer with a taper in between [21], etc. In the case that the thermal effect has to be

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eliminated, one can utilize an FBG and LPG hybrid sensor configuration [22], sandwiched long-period grating structure [23], or LPG made in boron-codoped germanosilicate fiber with specific concentration [24].

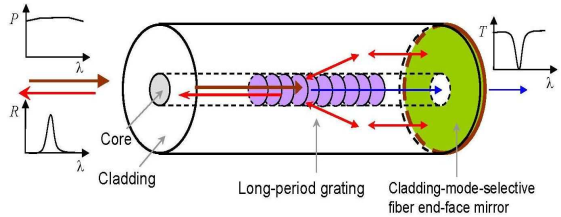

Fig. 1. Schematic diagram of the proposed reflective long-period grating sensor with a cladding-mode-selective fiber end-face mirror.

One of the limitations of LPG sensors that has not been adequately addressed is the transmission-mode operation of LPG, which is not desirable for many practical sensing applications. Although the LPG-based Michelson interferometer works in reflection, its interferometer nature makes the total length of the sensor, including the LPG and interferometer cavity, to be at least 4 ~5 cm [18,19,25], which might be too long for in vivo measurements. In this paper, we demonstrate a reflective LPG (RLPG) sensor based on a cladding-mode-selective fiber end-face mirror, as shown in Fig. 1, to overcome this limitation. In the proposed device, light coupled to cladding modes is reflected by the mirror and finally recoupled back to fiber core, whereas the light passing through the LPG will exit from the fiber core and lost. Basically, the proposed device is an LPG with "double" couplings, and the length of sensor is the same of conventional LPG sensor, which is normally 0.5 ~3 cm long which depends on the fiber parameters and the grating writing condition. The fabrication of such a RLPG sensor and preliminary results in using the sensor to measure external RI will be described.

2. Sensor fabrication

The procedure we proposed for the fabrication of the designed sensor is shown in Fig. 2. It mainly consists of four steps: 1) fabricate an LPG in an optical fiber; 2) make a polymeric microtip on the core of the fiber end-face through free-radical photopolymerization; 3) coat the fiber end-face with aluminum by sputter deposition; 4) break the microtip to form an escape channel for the core mode.

The setup used in our fabrication of LPGs is based on a point-by-point grating writing technique, which is a well-established method for the fabrication of complex LPGs [26]. The laser is a 248-nm excimer laser (TuiLaser Ltd., Germany). The grating fabrication is automated by a home-made software, which can simultaneously monitor the excimer laser and control the translation stages to make a grating with arbitrarily specified period, length and index modulation [26].

The fabrication of a microtip in the second step is critical since the microtip functions as a sacrificial mould to realize the cladding-mode-selective mirror. The microtip can be quickly fabricated by using a free-radical polymerization method [27,28]. The photopolymer formulation used in our experiment follows that reported by Backelot and associates [27]. It includes the multifunctional acrylate monomer: pentaerythrital triacrylate (Sigma-Aldrich Co., USA), amine cosynergist: methyldiethanolamine (Jinlong Ltd., China), and sensitizer dye: eosin Y (Sigma-Aldrich Co., USA). Eosin Y absorbs light and reacts with methyldiethanolamine to create radicals. The produced radicals initiate the polymerization of pentaerythrital triacrylate. Their concentrations in weight percentages are 91.5%, 8%, and 0.5%, respectively.

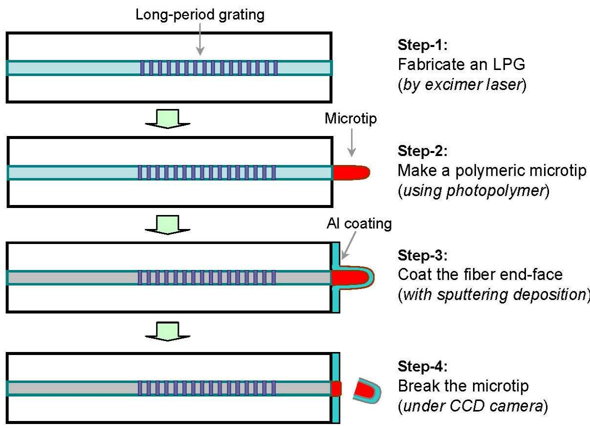

Fig. 2. Fabrication procedure for the reflective long-period grating sensor.

In the experiment, the freshly cleaved fiber end was cleaned by methanol and gently dried under nitrogen. A drop of the mixed formulation is directly deposited on the fiber end for photopolymerization. Light from a green LED with wavelength of 532 nm was coupled to the other end of the fiber to expose the photopolymer for polymerization. After exposure, the fiber end was cleaned again with methanol to remove the formulation. Figure 3 shows the microscope photos of three microtips fabricated with different exposure doses. The base diameters of the fabricated microtips shown in Figs. 3(a), (b), and (c) are 13.3 μm, 14.3 μm, and 20.9 μm, respectively. The power of the LED was increased from 20 to 30 μW, and the exposure time was 45 seconds. The effect of laser power on the size and shape of the microtips can be explained by the polymerization threshold at the air-formulation interface [27,28].

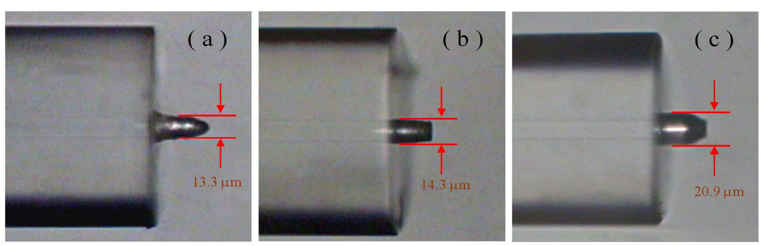

Fig. 3. Microscope photos of the fabricated microtips on the fiber end. 1) when the LED power is 20 μW; 2) when the LED power is 24 μW; 3) when the LED power is 30 μW;

It is worthwhile to note that special care has been taken when making the microtip after the fabrication of the LPG. The induced index modulation of LPG will scatter the green light from the fiber core to the cladding. Part of the light scattered to the cladding will reflect back from the air/cladding interface and propagates around the fiber in the form of cladding modes or radiation modes. Obviously, those light will become the "noise" source for the photopolymerization.

Figure 4 shows microtips formed on the end-face of bare fibers under different conditions. Typical microtips fabricated in the fiber without LPG and with LPG are shown in Fig. 4a and Fig. 4b, respectively. One can see that some residual polymerized material appears around the base of microtip. Since there are many cladding modes and the fiber itself is multimoded at 532 nm, the "noise" light resulting from both resonant and non-resonant scatterings cannot be suppressed by simply changing the period of LPG to shift the resonant wavelength. In order to eliminate such a residual base, we used some index matching gel to wrap around the LPG

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before the fiber end is deposited with the photopolymer for the fabrication of microtip. Therefore, the "noise" light scattered by the grating will dissipate in the index matching gel. After such a treatment, one can again make a regular microtip defined by the core mode of the fiber, as shown in Fig. 4.c.

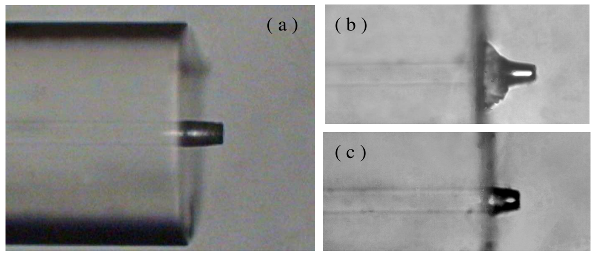

Fig. 4. Microscope photos of the fabricated microtips on the fiber end. 1) without LPG in the fiber; 2) with an LPG in the fiber (without index matching gel); 3) with an LPG immersed in the index matching gel;

After the fabrication of a microtip on the end of fiber with an LPG, the fiber end-face was coated with aluminum by using a magnetron sputtering system (SP-3, IME of CAS). In order to protect the side of the fiber from the sputtering, a polytetrafluoroethylene (PTFE) tube with inner diameter of 300 μm is used to enclose the fiber before the sputtering treatment. Aluminum is selected in the experiment because of its relatively good adhesion with silica. The sputtering treatment takes around 11 minutes and the coated aluminum film thickness is estimated to be ~700 nm.

The coated microtip was broken, as shown in Fig. 2, to form a microhole in the center of the mirror formed on the fiber end-face. Consequently, only light propagating in the cladding will be reflected back by the fiber end-face mirror. In the experiment, we utilized a freshly cleaved fibre to strike off the microtip under the observation of a CCD camera. It was found that the Al-coated microtip is mechanically quite strong although it has a diameter of just ~14 μm.

3. Spectral response of the sensor

The LPG used in our experiment was fabricated in a commercial boron co-doped photosensitive fiber (Fibercore Ltd. UK). The grating period was chosen to be 423 μm to excite the ninth order cladding mode at the wavelength of ~1550 nm. The gray curve in Fig. 5 shows the transmission spectrum of a fabricated LPG with length of ~2.6 cm, which was measured by directly connecting the LPG between a broadband amplified spontaneous emission (ASE) light source and an optical spectrum analyzer (OSA). One can see its coupling strength is around −16 dB at the transmission dip, which means that 97.5% of light is coupled from the core mode to the cladding mode at that wavelength. Then a cladding-mode-selective fiber end-face mirror close to the LPG was made using the procedure described above. The black curve in Fig. 5 shows the reflection spectrum of the fabricated RLPG, which was measured by an OSA after connecting an optical circulator between the ASE light source and the RLPG. A reflection peak with extinction ratio of ~10 dB was measured at the same resonant wavelength of the LPG. Therefore, we have fabricated a special LPG device based on co-directional coupling mechanism, but working in reflection mode.

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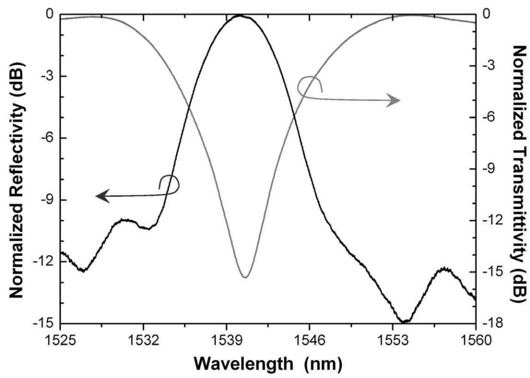

Fig. 5. The reflection spectrum of the fabricated RLPG sensor (black curve) and the transmission spectrum of the LPG used in the sensor fabrication (gray curve).

The fabricated RLPG sensor was tested in liquids with different RIs. The liquid was prepared by using glycerol mixed with de-ironed water with different mixture ratios. The experiment was carried out at constant room temperature (~23°C). Figure 6 shows the measured reflection spectra (left diagram) and wavelength shifts of the reflection peak (right diagram) of the sensor when the external RI changes from 1.333 to 1.428. The glycerol solutions with different volume concentrations of glycerol from 0 – 70% in increments of 10% were prepared, and their corresponding RIs are 1.33333, 1.34481, 1.35749, 1.3707, 1.38413, 1.39809, 1.41299, and 1.42789.

The reflection spectrum of the RLPG shifts to shorter wavelength and the side lobes of the reflection spectrum grow with external RI when the RLPG was immersed into the solutions. It is because the cladding mode expands into the liquid when the RLPG was immersed in the solutions. Both the coupling strength of the LPG and the reflectivity of the fiber end-face mirror decrease due to the reduction of the effective reacting mode area, resulting in a weakening of the main reflection peak and increase the side lobes. The reflection peak shifted 9.41 nm when the external RI was changed around 0.1 R.I.U, which is much more sensitive than normal FBG-type RI sensors. Numerical simulation of the spectral response of the LPG based on the three-layer fiber model and the coupled mode theory [29] confirms that the RLPG behaves as a conventional LPG sensor as expected, even though the light goes through the grating twice.

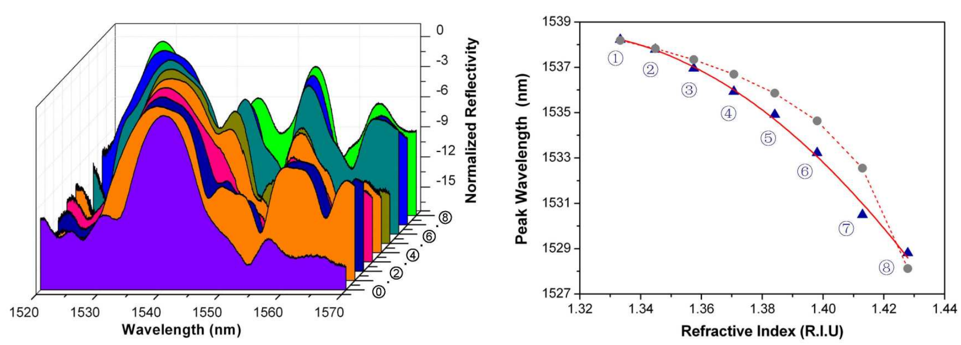

Fig. 6. The measured reflection spectra of the RLPG (left diagram) and peak wavelengths (blue triangles in the right diagram) of the RLPG sensor against external RIs. The calculated dip wavelengths (gray circles) of the LPG are given for comparison.

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4. Discussion and conclusion

We have proposed a new design of LPG sensor working in reflection mode and demonstrated a fabrication technique based on photopolymerization and sputtering coating to form a mirror on the cladding region of a fiber end-face. The transmission spectrum of the LPG is "inverted" to work in reflection mode, which offers a useful approach to make a practical in-fiber device based on cladding modes.

Elimination of core mode reflection was confirmed by experiment. However, reflection of the cladding modes was not very high in our preliminary experiments. Reflectivities of the fabricated RLPG sensors varied from around 8% to 11%, which depends on the fabrication process. Since the coupling between the core mode and cladding mode is quite high, as shown in the transmission spectrum of the LPG, the low reflectivity of the whole device might be caused by: 1) the relatively small amount of power of the cladding mode is reflected by the end-face cladding mirror because a large amount of the power of the ninth cladding mode locates in the fiber core. In order to reflect more light, one may have to reflect some of the core mode, or choose the lower order cladding mode; 2) the slightly larger base area of the microtip. It can be solved by optimizing the size of microtip through the control of laser power and the depression of higher-order modes (for green light) by a mode stripper; 3) fiber end-face not perfectly right-angled, and some defects might be formed on the fiber end-face during the fiber cleaving process. The issue can be solved by polishing the fiber end-face by using a commercial fiber end-face polishing machine. Although the reflectivities of the fabricated RLPGs are not very high, they were successfully used to measure the RI of glycerol/water solutions.

The main difference between the proposed RLPG and an LPG-based Michelson interferometer [18,19] is that the reflection of the core mode in the RLPG is avoided. Since the RLPG is basically an LPG with "double" couplings, it does not need an interferometer cavity and therefore allows a shorter sensor to be realized. Even smaller RLPG sensor can be made if shorter period or higher index-modulation LPG were used in the sensor fabrication. Furthermore, the sensor only needs single-end connection because it works in reflection mode and exhibits a clean reflection spectrum, permitting ease of demodulation. In addition to sensing, the technique proposed here can be utilized to measure cladding mode coupling and group delay which are necessary for LPG reconstruction using inverse scattering method. After preparing the fiber with such a cladding mode reflector before writing the LPGs, one can get physical insight of the photosensitivity mechanisms of LPG grow during the fabrication process.

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