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Mechanically induced long-period fiber grating in side-hole single-mode fiber for temperature and refractive sensing

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ABSTRACT

The inscription of a long-period grating in a side-hole single-mode fiber for sensing application is demonstrated. The grating is made by pressing a plate with a periodic groove against a short section of length of a side-hole single-mode fiber. Its strength and wavelength of the cladding-mode resonant can be tuned over 15 dB and 6.2 nm, respectively, by varying the ambient temperature of the grating. The refractive index sensitivity and the polarization dependence of the MPLG are also investigated.

1. Introduction

Long-period grating (LPG), which can couple light power between the fundamental guided mode and a set of forward-propagating cladding modes, used for a wide variety of applications, such as gain equalizers in fiber amplifiers [1], strain, refractive index, bending, and temperature sensors [2,3]. The characteristics of sensors based on LPG have been widely investigated over the past decade [4–7]. The LPG has been conventionally fabricated in an optical fiber by inducing periodic modulation on the fiber's core refractive index with a period of several hundred micrometers. So far, there is a variety of methods to fabricate it by using ultraviolet exposure through an amplitude mask [3], CO_2 laser with a point-by-point technique [4], electrical discharges [8] and mechanical pressure [9–12]. In particular, the mechanical pressure type long-period grating (MLPG) is more attractive since it can be fabricated in almost any type of fiber, such as any kind of conventional single-mode fiber (SMF) and photonic crystal fiber (PCF) [9,13,14]. Moreover, the mode coupling strength and the resonant wavelength of the MLPG can be tuned with high repeatability.

Owing to its simple structure and excellent characteristics, MPLG can be used for many applications, such as dynamic gain-flattening filter in fiber lasers or fiber amplifiers [15], fiber Mach–Zehnder interferometers [16], and temperature sensors [13,17].

In this paper, a MLPG in a side-hole single-mode fiber for sensing application is first demonstrated. The grating design and the sensing principle are presented in Section 2. The experiment results and discussion are shown in Section 3 and a conclusion is given in Section 4.

2. Working principle and sensor fabrication

The working principle of a LPG is that it can couple the light power between the fundamental guided mode and forward-propagating cladding modes inside the fiber. As a result, several of resonant modes are appeared in the corresponding transmission spectrum. The resonant wavelength of m-th order mode λ_m is defined by the phase-matching condition:

$$\lambda_m = (n_{core} - n_{clad}^m)\Lambda \tag{1}$$

where Λ is the grating period, n_{core} and n_{clad}^m are the effective indices of the fundamental guided mode and the m-th order cladding mode, respectively. The resonant wavelengths depend on the fiber characteristics through the effective indices of the core and cladding. Hence, the change of the grating period Λ and the effective index of the cladding mode will affect the resonant wavelength of the corresponding cladding mode.

The side-hole single-mode fiber was used in the experiment has two air holes in the cladding as shown in Fig. 1. The outer diameter of the fiber was the typical value of 125 μm. The air hole diameter was 24 μm, and its center was located from the center of the fiber of 28 μm. Two ends of the side-hole single-mode fiber were

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stripped, cleaved and inserted into a bare fiber adapter. Light from a supercontinuum (SC) source (KOHERAS SuperK) was guided by using a section of SMF-28 which in turn launched into the core of the side-hole SMF via the bare fiber adapter. The transmitted light from the side-hole SMF was guided by using another SMF-28 via the other same type bare fiber adapter again and then measured by using an optical spectrum analyzer (OSA, AQ6370). The SC source provided an ultra broad flat spectrum from 600 nm to 1700 nm which has the same wavelength range in the OSA.

The schematic diagram of the experimental setup is shown in Fig. 1. The MLPG was formed by pressing the side-hole SMF which was placed between a 5 cm long periodically grooved plate and a flat plate. The effect of the applied pressure on the section of fiber induced a periodic refractive index modulation on the core due to the photoelastic effect. Therefore, the resonant wavelength can be selected by using the different periodically grooved plate. The grating period ($\Lambda = 600\ \mu\text{m}$) was chosen in order to obtain the coupling wavelength near 1550 nm in a small order cladding mode. When the two holes in the cladding were filled with different refractive liquid by using capillary force, the effective index of the cladding mode would be affected. This effect would induce changes in the coupling conditions between the fundamental guided mode and the *m*-th order cladding mode. So this phenomenon can be used for refractive index sensing.

3. Results and discussions

The dips of the resonant wavelength in the transmission spectrum of the MPLG which were induced by the increasing of the applied pressure over the side-hole SMF are shown in Fig. 2. The pressure, applied on the grooved plate, induced a periodical strain on the fiber. From the photoelastic effect on the fiber, the strain induced a periodical index variation on the fiber core, which caused mode coupling between the guided mode and the forward-propagating cladding modes. Higher pressure induced higher index variation, which resulted in stronger mode coupling and thus generally in deeper dips in the transmission spectrum. Meanwhile, the corresponding resonant wavelength did not shift by the change of the applied pressure [13]. The 3 dB bandwidth was 17.8 nm with a depth notch of 14 dB, and the out-of-band loss of the LPG was about 1 dB due to the microbending loss. As the applied pressure on the fiber increased, the second dip near 1650 nm was observed in the transmission spectrum, due to the second order mode coupling of the MLPG in the side-hole SMF.

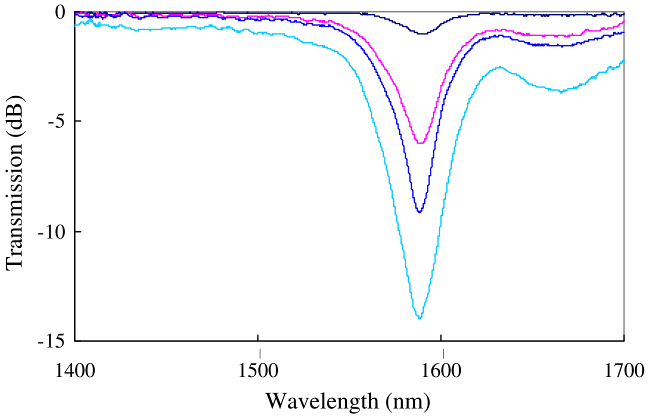

Fig. 2. Transmission spectra of the MLPG with different pressures.

In addition, the sensitivity of refractive index measurement was also investigated in the experiment. Firstly the transmission spectrum of the MLPG, which was formed by pressing the side-hole SMF with a fixed pressure, was recorded. Then one of the bare fiber adapters, which was connected to the OSA, was removed. The side-hole fiber was filled with refractive liquid by using capillary force. It took about 20 min to fill up a 30 cm side-hole SMF. Finally the bare fiber adapter was reconnected and the shift of the resonant wavelength was observed in the transmission spectrum as the index variation of the infiltration refractive liquid. The refractive index liquid samples (Cargille Labs) which have the refractive indices of 1.35, 1.37, 1.39, 1.41 and 1.43 were used to measure the shifts of resonant wavelengths of the MLPG in the same way. The corresponding calibrated refractive index accuracy for each liquid was ±0.0002 RIU. A new section of fiber was used for each refractive index liquid measurement in order to avoid the possibility of contamination which might affect the measurement accuracy. All the experiments were carried out in a controlled environment, where the effect of temperature variation can be ignored.

The transmission spectra of the MPLG taken after filling of different refractive index liquid samples are shown in Fig. 3. When the refractive index varied from 1.35 to 1.43, the measured resonant wavelength at 1588.6 nm exhibited a total blue shift of approximately 12.2 nm. It provides more resonant wavelength shift than that of the conventional long-period fiber gratings which is structurally induced by a CO_2 laser for the refractive index measurement of 8 nm [4], because the liquid samples inside the holes of the cladding region have influenced the effective index of the cladding modes more than the index of the surrounding material [6]. The resonant wavelength shift with different refractive index is shown in Fig. 4. The resonant wavelength exhibited a blue shift of 1.2 nm for the refractive index changed from 1.35 to 1.37, and a blue shift of 4.8 nm for the refractive index changed from 1.41 to 1.43. So the resonant wavelength shift increased as the liquid refractive index increased. The effective indices of the cladding modes became bigger gradually when the effective index of the liquid inside the two air holes of the cladding region increased [20]. So the resonant wavelength had a blue shift as seen in Eq. (1). Moreover, the radii of the side holes and the distance between the core and the side hole can change the effective indices of the

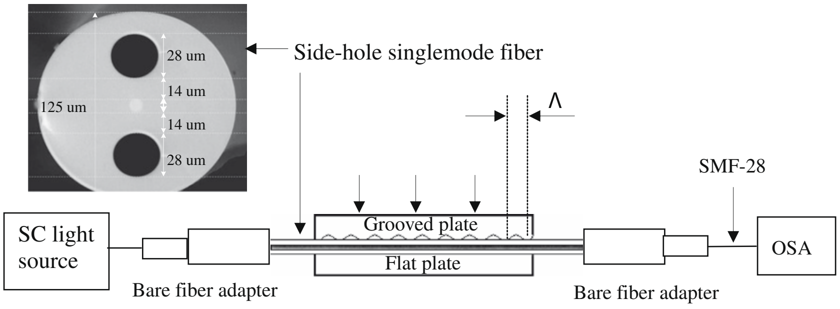

Fig. 1. Schematic diagram of the experimental setup. (SC light source: supercontinuum light source; OSA: optical spectrum analyzer).

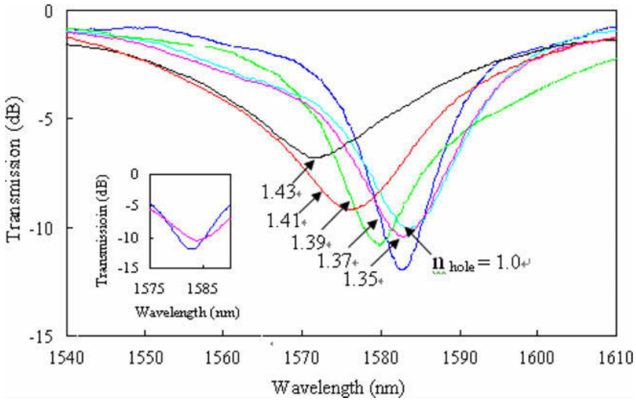

Fig. 3. Transmission spectra of the MLPG for different refractive indices in the hole with a fixed pressure. Inset: the transmission spectrum with refractive indices of 1.35 and 1.37.

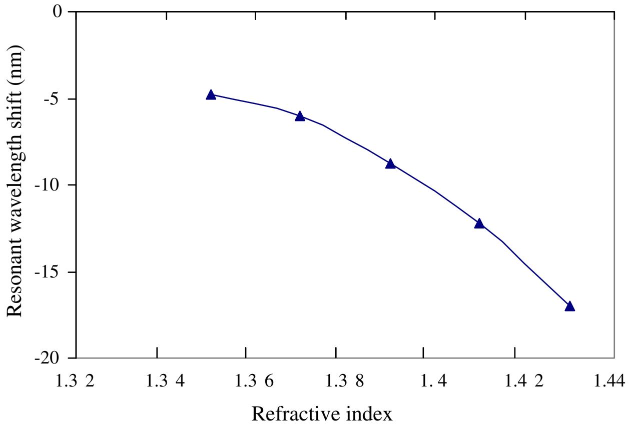

Fig. 4. Measured resonant wavelength shift of the MLPG with different refractive indices.

cladding modes, so the effective indices of cladding modes are smaller compared with smaller radii of side holes and longer distance between the core the side hole [20–22].

The resonant wavelength of a MLPG is anticipated to be varied with temperature because of the temperature dependence of the modes' effective indices. Another small contribution is expected from the variations in grating period Λ caused by thermal expansion of the grooved plate. Fig. 5 shows the measured transmission spectra with a fixed pressure with different ambient temperatures. As the temperature increased, the resonant wavelength exhibited a red shift, and the amount of attenuation also changed with different ambient temperature. The variations are attributed to the method of LPG fabrication. The same amount of attenuation could be obtained by adjusting the applied on the MLPG pressure [13]. As shown in Fig. 6, the resonant wavelength exhibited a red shift of 6.2 nm for the temperature changed from 20 °C to 100 °C, with a sensitivity of 77.5 pm/°C, which was similar to that of MLPG in silica fiber [9,13]. So there is a cross sensitivity for refractive index and temperature sensing, due to both the temperature and refractive index changes of the coupling conditions between the fundamental guided mode and the order cladding modes of the LPG. It can be addressed by using a simultaneous measurement technique, such as using a fiber Bragg grating, which is insensitive to the refractive index, as a temperature monitor and correcting for the inherent temperature effect of the LPG [23].

Finally, the polarization dependence of the MPLG was also analyzed by measuring the corresponding transmission spectra. A fiberbench polarization controller was used to adjust the polarization direction of the incident light. The corresponding transmission spectra of the MLPG for two orthogonal linear polarizations are shown in Fig. 7. The resonant wavelength of the MLPG for the two incident orthogonal linear polarization modes were split by as much as 4.8 nm, along with a corresponding peak attenuation variation of 0.5 dB. It is confirmed that the MLPG is polarization sensitive device [17,18]. These values are bigger than those reported in similarly induced LPG in conventional SMF of 4 nm [9]. And it can be increased through the increase of the radii of the side holes and/or decrease of the distance between the core and the

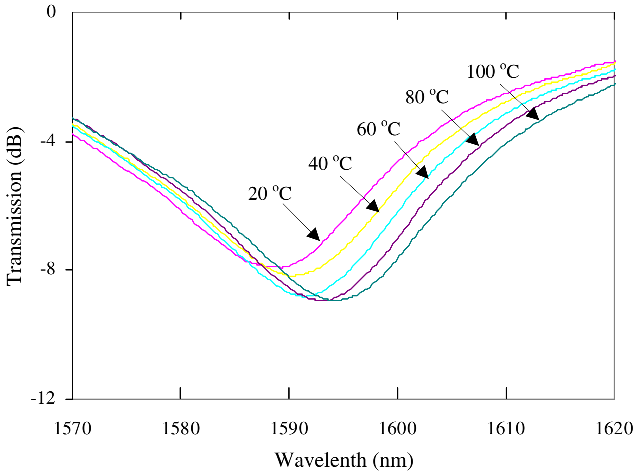

Fig. 5. Measured transmission spectra of the MLPG with different ambient temperatures.

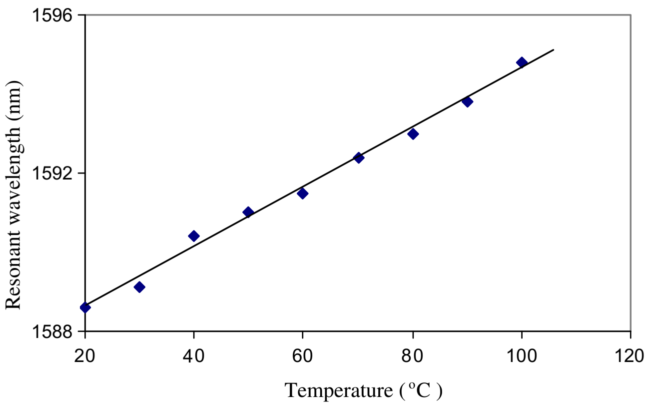

Fig. 6. Resonant wavelength of the MLPG vs. temperature.

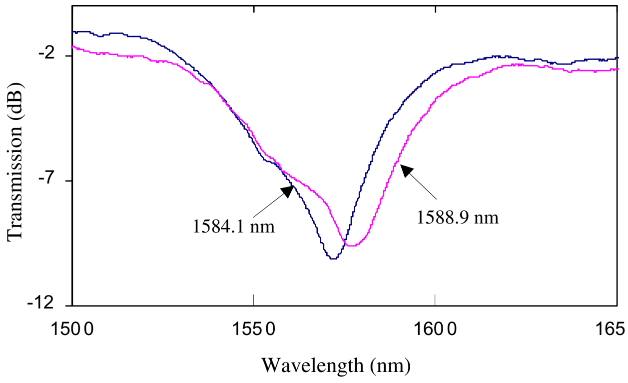

Fig. 7. Transmission spectra of the MPLG for two orthogonal linear polarizations.

side hole. The polarization dependency can be useful and beneficial for sensing applications, such as torsion, and twist sensor [10,19].

4. Conclusion

In this paper, a first mechanically induced LPG in a side-hole singlemode is presented. It is formed by pressing a side-hole SMF which is placed between a periodically grooved plate and a flat plate. The resonant wavelength of 1588.6 nm has a total blue shift of approximately 12.2 nm for refractive index ranging from 1.35 to 1.43, and a red shift of 6.2 nm for the temperature ranging from 20 °C to 100 °C, with a sensitivity of 77.5 pm/°C. The resonant wavelength of the MLPG for the two incident orthogonal linear polarization modes are split by as much as 4.8 nm, that is better than MLPG in conventional SMF. The MLPG in side-hole SMF is compact, simple and inexpensive, so it shows great potential for different sensing applications.

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