Long Period Fiber Grating Inscribed in Hollow-Core Photonic Bandgap Fiber for Gas Pressure Sensing

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Long period fiber grating inscribed in hollow-core photonic bandgap fiber for gas pressure sensing

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***Abstract*—In this paper, we have proposed and experimentally prepared an improved gas pressure sensing device. It is mainly constructed by a short hollow silica tube segment and a CO_2-laser-induced long period grating (LPG) in hollow-core photonic bandgap fiber (HC-PBF). To effectively enhance the interaction between light in the air-core of HC-PBF and external surroundings thus to achieve the best possible gas pressure sensitivity, a micro-channel is introduced in the middle of the hollow silica tube segment with the femtosecond laser processing technique. The corresponding gas pressure experiments demonstrate that the resonant wavelength of the LPFG shows a blue shift up to −1.3 nm/MPa. Moreover, the temperature response sensitivity of this sensor is as low as 5.3 pm/℃ and enable it possible as a temperature-insensitive gas pressure measure apparatus.**

***Index Terms*—pressure sensors, LPFG, HC- PBF, hollow silica tube**

I. INTRODUCTION

Long period fiber grating (LPFG) as a new type of optical device has been increasingly paid much attention since its appeared in 1996. Many publications have reported LPFG for measuring various physics parameters, including temperature [1-3], strain [4-6], and curvature [7, 8]. Since the first hollow-core photonic bandgap fiber (HC-PBF) was drawn successfully in 1999, it has been extensively applied in many areas due to its unique photonic bandgap light guide mechanism. Compared with traditional single mode fiber (SMF) or solid core photonic crystal fiber (PCF), the HC-PBF behaves some specific advantages. For instance, lower Rayleigh scattering, reduced nonlinearity, increased damage threshold and so forth. Although many LPFGs have been successfully inscribed in SMF and solid-core PCF, it is still a challenging work to fabricate a LPFG in HC-PBF. In 2008, Y. Wang et al. [9] first successfully fabricated a LPFG in hollow-core PBF , which effectively solved the problem of obstructing the development of photonic bandgap fiber gratings.

In recent years, a number of research on the fiber-optic gas pressure sensors have been conducted because of their intrinsic advantages of immunity to electro-magnetic interference. Many literatures have reported all kinds of optical fiber gas pressure sensors, such as those employing Fabry–Perot interferometers (FPIs) [10-13], Mach-Zehnder (M-Z) interferometers [14], and long period fiber gratings (LPFGs) [15, 16]. Among these, LPFG-based devices are relatively easy to obtain, and have thus attracted wide attention of researchers. For instance, the tapered LPFGs have been applied to monitor gas pressure variation in Ref. [16] and Ref. [17], where, although these devices exhibited somewhat low pressure sensitivities of only 51 pm/MPa and 112 pm/MPa, respectively, they clearly demonstrated the benefits of the approach. Thus far, the focus of most research is LPFG-based gas pressure sensors employing SMF or solid-core PCF [18, 19] and only fewer studies of gas pressure sensors employing LPFGs inscribed in hollow-core PBFs have been reported. This lack of development could be attributed to the fact that LPFGs cannot be easily fabricated in hollow-core PBFs. In Ref. [20], authors investigated the gas pressure sensing characteristics of LPFGs inscribed in hollow-core PBF by using arc discharge. The corresponding gas pressure response sensitivity was four times improvement over those LPFGs written in SMF. In 2015, we also fabricated a LPFG in HC-PBF by CO_2 laser inscription method and applied it to gas pressure sensing. The measured sensitivity was -137 pm/MPa, which is two times larger than that reported in Ref. [16]. However, it is worth noting that both studies just taken advantage of stress-induced elasticity effect of the LPFG to realize pressure monitoring. Due to this reason, the sensitivities are limited. Fortunately, an effective way to enhance the sensitivities of these sensors employing LPFGs written in hollow-core PBFs is to directly admit the ambient atmosphere into the air-core, and thus affecting its index of

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refraction, leading to a shift in the resonant wavelength of the LPFGs according to the mode coupling mechanism of the LPFG in the HC-PBF reported in Ref. [21].

In this paper, we fabricated a high-sensitivity gas pressure sensor based on a LPFG written in hollow-core PBF by CO_2 laser inscription method. A short hollow silica tube segment was spliced to the hollow-core PBF-inscribed LPFG. Using a femtosecond laser micromachining technique, we drilled a micro-channel in the hollow silica tube to facilitate equalization of the pressure in the air-core of the PBF with that of the surroundings, and thus to directly alter the air-core effective index of HC-PBF. Gas pressure experiment results shown that the sensitivity of the proposed PBF-inscribed LPFG device reach up to -1.3 nm/MPa, which is the highest sensitivity of the PBF-inscribed LPFG-based gas pressure sensor sensors at present. Furthermore, the temperature response of this sensor is as low as 5.3 pm/ ℃, which making it possible as a temperature-insensitive pressure sensor.

II. Fabrication of The PBF-Inscribed LPFG-Based Sensor

The HC-PBF (HC-1550-02) employed in the present study is from Crystal Fiber A/S, and lengths of ~80 cm were utilized for LPFG fabrication. The cross section of the hollow-core fiber was the same as in Ref. [9]. The fiber parameters are as follows: the core diameter is about 10.9 μm and the cladding pitch is 3.8 μm. The diameter of the cladding and the total diameter are 70 μm and 120 μm, respectively. As reported previously [15], we could achieve LPFGs in HC-PBF by periodically collapsing the inner cladding air-holes of the fiber along one side which facing the direction of CO_2 laser incidence. During the whole fabrication process, several critical parameters should be chosen appropriately, that is the power of CO_2 laser, the size of focused laser spot and the exposure time. Here, the adopted parameters were 0.20 W, 35 μm, and 200 ms, respectively. The grating pitch and grating numbers of LPFG are 400 μm and 30 in the present study. Each periodical heating along the fiber axis was called a scanning cycle K. In our experiment, this process was repeated 22 cycles until we obtain a desired LPFG. During the fabrication process, an optical spectrum analyzer (OSA) was used to monitor the transmission spectrum evolution of the achieved grating as shown in Fig. 1.

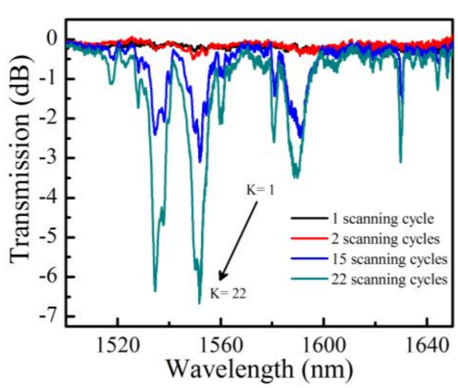

Fig. 1. Transmission spectrum evolution of a LPFG inscribed in HC-PBF by CO_2 laser irradiation.

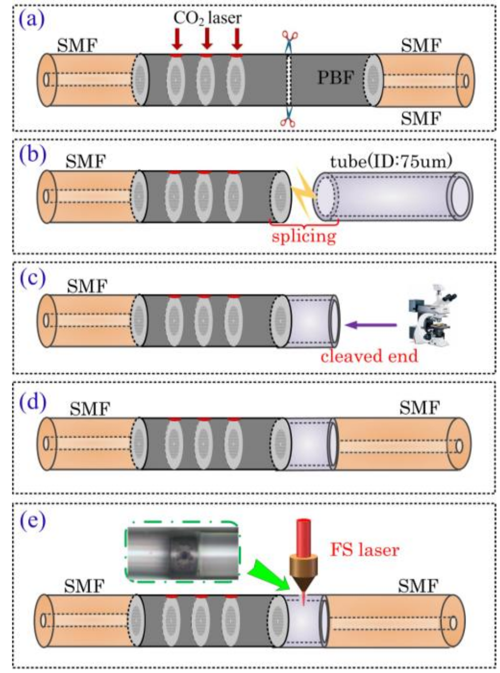

Fig. 2. The fabrication of the proposed gas pressure sensor employing the CO_2 laser beam-scanning technique, a commercial fusion splicer, and femtosecond (fs) laser micromachining.

Figure 2 describes the fabricating process of a LPFG-based gas pressure sensor in detail. Firstly, as illustrated in Fig. 2(a), using a CO_2 laser scanning technique we fabricated a LPFG in a long HC-PBF, then it was cut ~1 cm away from the end with the grating. This distance here is significant because we found that chaotic mode interference is more likely to be introduced if the distance is too short, which may negatively affect the grating transmission spectrum. Subsequently, we spliced the cut end of the LPFG to a short piece of hollow silica tube. Its inner diameter is 75 μm, which is slightly larger than the inner air hole cladding of HC-PBF(~70 μm). A manual splicing mode of the fiber splicer was selected to complete the splice operation, as shown in Fig. 2(b). In this process, two critical factors should be noted. one is that smaller inner diameter of the silica tube are more easily to introduce some uncontrollable interference between the silica tube and the optical fiber. Thus would further to deteriorate the grating transmission spectrum. The other is the arc discharge current and time of the splicer. Because inappropriate parameters may lead to the collapse of the air-core of the HC-PBF. Thus the outside gas cannot effectively go through into the air-core and alter its effective index. In our experiment, the optimized arc power and arc time were stander-60 and 400 ms, respectively. Thirdly, as shown in Fig. 2(c), we cut off a short hollow silica tube segment ~50 μm long, and observed the case of the collapse of air-core of HC-PBF by using a optical microscopy. In the experiment, we must make sure that the air-core does not collapse. After that, the cleaved end of the hollow silica tube was spliced to a SMF, thus we can obtain a closed air cavity, as illustrated in Fig. 2(d). After this operation, the completed LPFG-based sensor was well fabricated. To observe how the splicing operation affects the quality of the optical spectrum, we used an OSA to monitor the variation of the transmission spectrum in real-time. As illustrated in Fig. 3, it can be found that one of the grating spectrum resonant dips around 1538 nm (see Fig. 1) was deteriorated after the splicing operation. The reason for this could be attributed to the introduction of some uncertain interference modes between the HC-PBF and SMF owing to the presence of the hollow silica tube. Finally, to facilitate equalization of the pressure in the air-core of the HC-PBF with that of the surroundings, an open air-cavity was formed by drilling a micro-channel (about 12×10 μm) in the hollow silica tube whereby a femtosecond laser micromachining technique, as shown in Fig. 2(e). The inset of Fig. 2(e) shows a top view of the formed micro-channel. During the whole drilling processes, in order to observe whether this operation would affect the transmission spectrum properties or not, we should also monitor the sensor device in real-time using an OSA. Fig. 4 indicates that the spectrum exhibits negligible change after micro-channel fabrication.

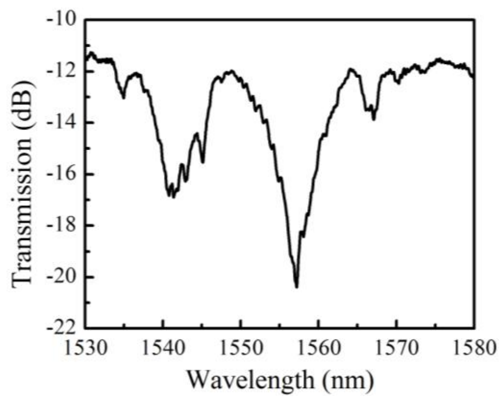

Fig. 3. Transmission spectrum of the LPFG after splicing with a short silica tube segment, corresponding to Fig. 2(c).

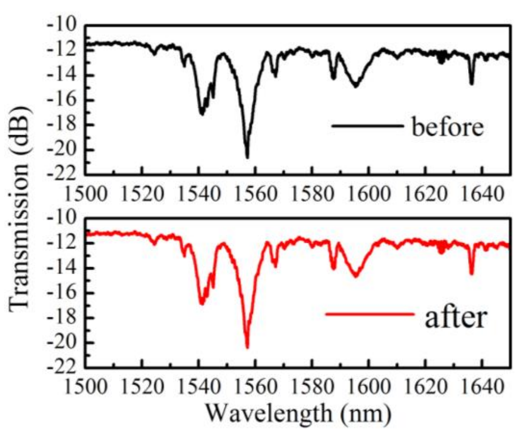

Fig. 4. Transmission spectrum of the LPFG before and after micro-channel fabrication through the sidewall of the silica tube, corresponding to Figs. 2(d) and (e), respectively.

III. Experimental Results

Fig. 5 shows the gas pressure measurement device we utilized in the experiments. First of all, we sealed the well fabricated LPFG-based pressure sensor in a closed gas chamber, where equipped with a air pump and a high-precision pressure meter (ConST-811). Then one end of the gas chamber pigtail fiber was connected to a broadband light source (BBS), another end was input to an OSA for monitoring the transmission spectrum variation of the LPFG under different gas pressure conditions. Lastly, it is worth noting that a polarization controller (PC) was employed in the present study. The reason is that LPFG fabricated by single-side CO_2 laser irradiation posses a relatively high polarization dependent loss [9], which may change with the light wave polarization state variation and further affect the accuracy of gas pressure measurements. Thus when we performed the gas pressure the measurements it was necessary to adjust the PC enable the resonant wavelength of the LPFG at the deepest position in advance.

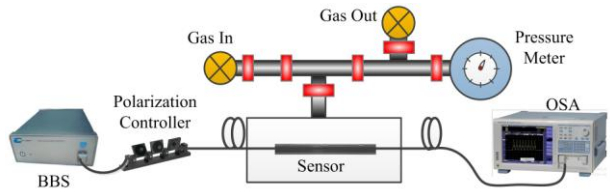

Fig. 5. The gas pressure measurement device used in the experiments

Our gas pressure experimental tests are done at atmospheric conditions. During the measurements, the gas pressure P was gradually increased to 0.6 MP from standard atmospheric pressure with an interval value of 0.1 MPa. At each measurement point, we stayed for ten minutes, and then recorded the data when the spectrum was in a steady state. From Fig. 6(a) we can find that λ shifted extensively toward shorter wavelengths with increasing P. The relationship between λ and P was shown in Fig. 6(b). The fitted line can be written as $\lambda = -1.3 * P + 1556.61$ (nm), it indicates that the sensitivity is −1.3 nm/MPa. The correlation coefficient $R^2 = 0.993$ implies that the proposed sensor exhibit an excellent linear gas pressure response.

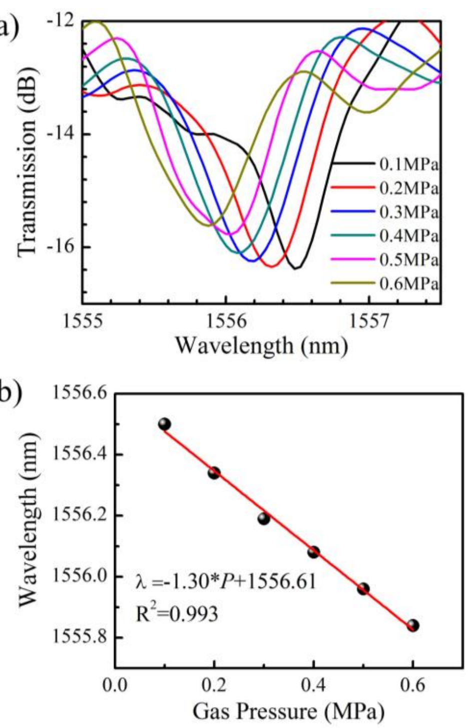

Fig. 6 (a) The resonant wavelength shift of the proposed sensor under different gas pressure condition; (b) Gas pressure response fitting curve of the proposed sensor.

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In order to investigate the gas pressure response property of an equivalent sensor without a micro-channel in the hollow silica tube, we also fabricate a PBF-inscribed LPFG-based sensor using the method as mentioned in Fig. 2 (a)~(d). Here, as shown in Fig. 7, the sensitivity is only −0.148 nm/MPa, which is similar to our previous reported results in Ref. [15]. These results show that the gas pressure sensitivity of the PBF-inscribed LPFG-based sensor was increased by nearly one order of magnitude (a factor of 8.7) by introducing a micro-channel in the hollow silica tube. As reported in Ref. [14], the refractive index of the air will increases as the increases of the air pressure. This also clearly demonstrates the significant impact on the resonant wavelength of the LPFG by directly altering the effective refractive index of the air-holes via the admittance of the surrounding gas.

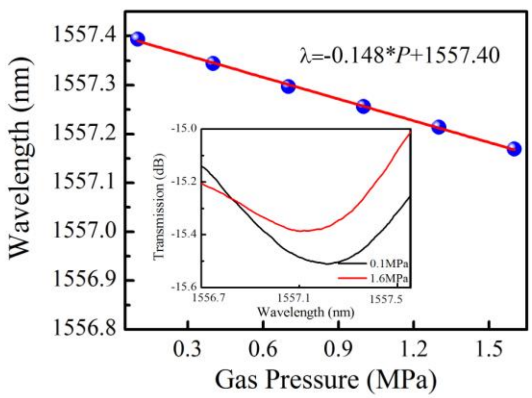

Fig. 7. Gas pressure response of a PBF-inscribed LPFG-based sensor without a micro-channel drilled in the hollow silica tube, and the resulting fitted line. The inset presents the resonant wavelength shift of the sensor under the changed gas pressure.

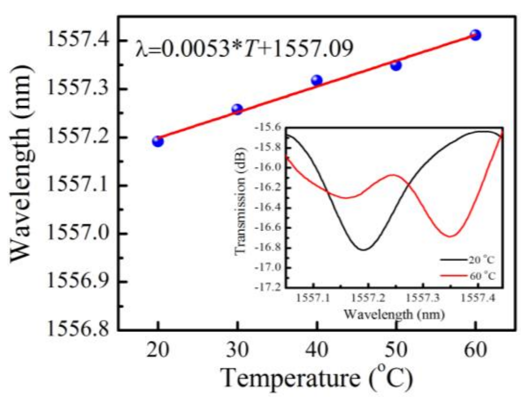

Fig. 8. Temperature *T* response of a PBF-inscribed LPFG-based sensor after micro-channel fabrication, along with the fitted line. The inset presents the transmission spectrum variation versus the temperature

In practical gas pressure sensing applications, we should consider the impact of ambient temperature on the PBF-inscribed LPFG-based sensor. Thus, we placed the sensor sample into an electrical oven to investigate its temperature response characteristic. As shown in Fig. 8, we can find that the resonant wavelength λ shift towards longer wavelengths when the temperature was gradually raised from 20 ℃ to 60 ℃ in 10 ℃ steps. The temperature response is as low as 5.3 pm/℃, indicating that the proposed PBF-inscribed LPFG-based pressure device is insensitive to moderate fluctuations in temperature. The reason for this is that the HC-PBF is constructed by pure silica with a low thermal expansion coefficient. According to the gas pressure and temperature sensitivities mentioned above, we can obtain a small cross-sensitivity of 4.1 KPa/℃. It means that the influence of ambient temperature on the gas pressure sensor may be ignored in practical gas pressure sensing application. Therefore, our proposed PBF-inscribed LPFG-based has the potential to be a temperature-insensitivity gas pressure sensor.

IV. Conclusion

We have reported a high-sensitivity gas-pressure sensor device based on a CO_2-laser-induced LPFG in HC-PBF. A short hollow silica tube segment was sandwiched between the LPFG and the SMF. Using the femtosecond laser micromachining technology, we drilled a micro-channel in the middle of the hollow silica tube to allow the air-core of the HC-PBF could be exposed to the external gas surroundings. In this way, we can effectively altered the effective index of refraction of the air-core as the external gas pressure was increased. The gas pressure sensitivity of the sensor is up to −1.3 nm/MPa, which is the highest sensitivity of gas pressure sensors based on LPFG in hollow-core PBF to the best of our knowledge. Moreover, the temperature sensitivity of the gas-pressure sensor is as low as 5.3 pm/℃. Therefore, our proposed design is suitable for developing a promising temperature-insensitive gas pressure sensor.

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