Parallel-Integrated Sapphire Fiber Bragg Gratings Probe Sensor for High Temperature Sensing

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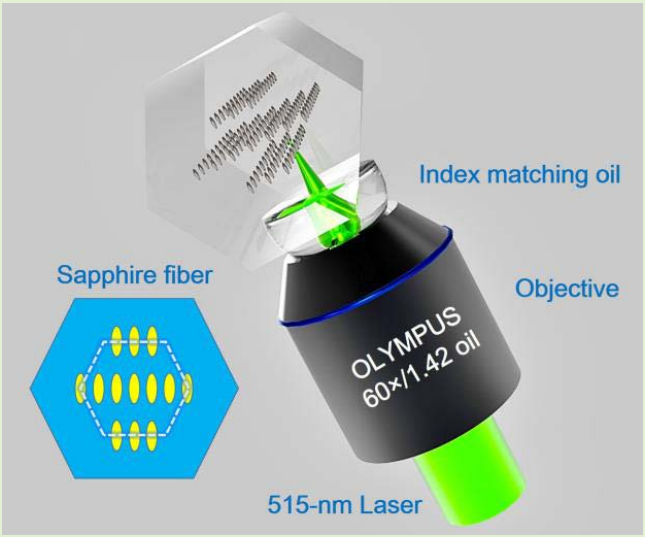
***Abstract*—This paper reports the fabrication of parallel integrated sapphire fiber Bragg gratings (SFBGs) probe sensor by the femtosecond laser point by point (PbP) method. The SFBGs probe sensor transmits optical signals through quartz multimode fiber, and takes an 8.5 mm sapphire fiber as the sensing probe, which can work stably for a long time at 1200 °C. This method can not only quickly prepare and obtain SFBGs with small bandwidth, but also obtain gratings with high reflectivity, which is about 15%. The mode field distribution in sapphire fibers with different lengths is studied by the beam quality analyzer. High-order modes are easily excited as the length of sapphire fibers increases. In addition, a spherical lens is prepared at the end of sapphire fiber, which effectively improve the signal-to-noise ratio (SNR) to 22 dB. The good spectral quality can still be maintained after holding at 1200 °C for 24 hours, and the temperature sensitivity can reach 30.19 pm/°C in the high temperature range, which is more than 2 times higher than that of quartz FBGs sensors. This parallel integrated SFBGs probe sensor overcomes the problems of doped quartz fiber element diffusion at high temperature and the instability of microstructure caused by material softening, and can be developed for long-term stable operation at 1200 °C high temperature and harsh environments.**



***Index Terms*—Sapphire fiber Bragg gratings, mode field distribution, high-order modes, spherical lens.**

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I. Introduction

HIGH temperature and harsh environments exist widely in many fields such as industry and aerospace [1], [2]. How to realize accurate and fast physical quantity sensing and measurement in these extreme environments is an important research topic. Optical fiber sensors have incomparable advantages over electronic sensors, such as anti-electromagnetic interference and chemical corrosion resistance [3]–[5]. The measurement of physical quantities such as temperature, pressure, torsion, angle and refractive index can be achieved through fiber sensors [6]–[10]. The traditional ultraviolet laser grating preparation technology has been widely used in various optical fibers, especially in photosensitive polymer fibers [11]–[13]. However, this preparation technology usually requires that the fibers have photosensitivity. In addition, it is easy to be thermally erased at high temperature, which is difficult to be stably applied in high temperature environment. In addition, with the development and maturity of silicon-based process technology, the sensors prepared also provide new methods for monitoring the physical quantities of the surrounding environment [14], [15]. Femtosecond laser micro-nano processing technology has been proven to

induce permanent refractive index changes in any transparent material, which is independent of the photosensitivity and chemical composition of the material [16], [17]. This is due to the nonlinear effect caused by the interaction between the ultra-high peak power femtosecond laser and materials [18]–[21]. This technology provides an efficient method for producing high-temperature resistant fiber gratings. A long-term stable high temperature sensor in the temperature range of 1200 °C is urgently needed in high temperature and harsh environments such as engine combustion chamber monitoring, petroleum cracking and metal smelting [22].

Limited by the doping elements in quartz fiber, element diffusion will occur at high temperature [23], [24], which will lead to the change of effective refractive index of fiber guide mode and spectral drift. This limits the long-term stable application of doped quartz fiber gratings above 1000 °C [25]–[27]. Although the microstructure fiber made of pure quartz material has no doped elements, the porous structure of the microstructure fiber makes the preparation of gratings difficult [28], [29]. In addition, due to the limitation of quartz softening point, the structure of submicron gratings in quartz fiber is unstable at 1200 °C for a long time, which will reduce the spectral quality and reflectivity. If the fiber Bragg gratings are prepared in the crystal fiber with high melting point, the problems of unstable grating structure and diffusion of doped elements at high temperature can be well solved. Single crystal sapphire fiber is undoubtedly a good choice because of its ultra-high melting point (2053 °C) and excellent optical properties [30].

In this paper, we report the fabrication of parallel integrated SFBGs in an 8.5 mm sapphire fiber by the femtosecond laser PbP method. The sensor composed of the SFBGs sensing probe and the quartz fiber can work stably at 1200 °C for a long time. The SNR of the spectrum is effectively improved by making a spherical lens structure at the end of sapphire fiber. The sensor has excellent high temperature stability, high temperature sensitivity, and high preparation efficiency. It can take advantage of the short sapphire fiber to improve the stable application range of quartz fiber in high temperature and harsh environments.

II. Sensor Fabrication and Principle

Figure 1 shows the mode field distribution of sapphire fiber end faces with different lengths tested by a beam quality analyzer (Ophir SP928). The 810 nm single-mode laser is first passed through the graded index multimode fiber (62.5/125 μm), and then passed into the sapphire fiber with the diameter of 60 μm and the lengths of 5 cm, 25 cm, 50 cm and 100 cm, respectively. The multimode fiber and sapphire fiber are fused together by a fusion machine. If the length of sapphire fiber is short, the mode field is mainly distributed in the center of the fiber. As the length of sapphire fiber increases, more high-order modes are excited, and the mode field is gradually distributed to the edge of the fiber. This will disperse the mode field in the sapphire fiber and reduce the energy density of the optical field, which also leads to the low reflectivity of SFBGs prepared by the femtosecond laser PbP method.

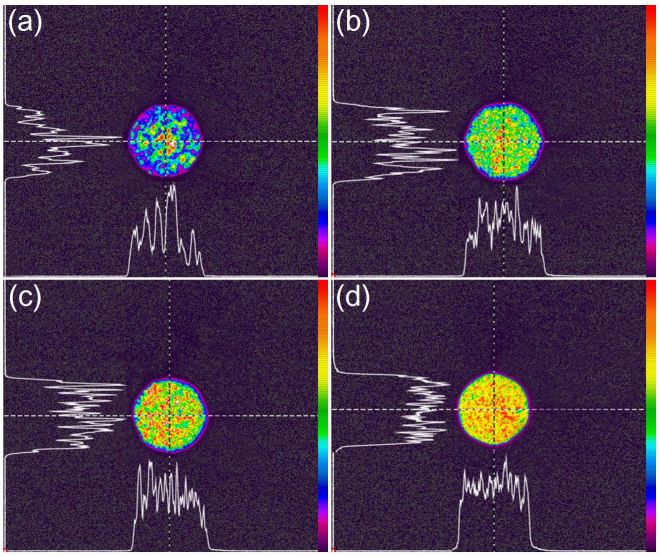

Fig. 1. The mode field distribution of 810 nm test light through sapphire fibers with lengths of 5 cm, 25 cm, 50 cm and 100 cm, respectively. The central region is the end profile of sapphire fiber, in which different colors represent different mode field intensity, and the edge curve represents the two-dimensional distribution of intensity.

Compared with line by line scanning method [31] or helical scanning method [32], the femtosecond laser PbP scanning method has the advantages of faster preparation speed and smaller FWHM [33]. The disadvantage is that the refractive index modulation region of single PbP scanning is small and the reflectivity of the prepared grating is low. Therefore, the SFBGs with high reflectivity and small FWHM can be prepared by PbP parallel-integrated method in short sapphire fiber. This method can expand the refractive index modulation region. In addition, the mode field distribution is concentrated in the center region of the short sapphire fiber, the excited high-order modes are less, and the periodic crosstalk between gratings is small, which is conducive to improving the reflectivity and reducing the FWHM.

Figure 2 (a) is a three-dimensional schematic diagram of preparing parallel-integrated SFBGs. The illustration is the two-dimensional distribution diagram of the end face of the prepared grating structure. The pulse width of the 515 nm femtosecond laser used is 290 fs, the single pulse energy is 160 nJ, and the repetition frequency is 400 Hz. The dotted line region is the main distribution region of short sapphire fiber mode field. By preparing SFBGs in parallel as shown in Fig. 2 (a), high preparation efficiency and coupling efficiency can be obtained. At the same time, there is no overlap between gratings and no crosstalk in grating period, which is conducive to quickly obtain SFBGs with high reflectivity and small bandwidth. The 515 nm femtosecond laser is focused into a 60 μm sapphire fiber (MicroMaterials Inc.) through a oil-immersed objective lens (Olympus, 60×/1.42). The single crystal sapphire fiber has a hexagonal lattice structure, and the femtosecond laser is focused vertically into the fiber from one side (A-Plane) of the sapphire fiber. The preparation of 7 parallel SFBGs in the middle layer is realized through PBP technology, and then 3 parallel SFBGs in the bottom layer are prepared. In order to obtain better grating quality

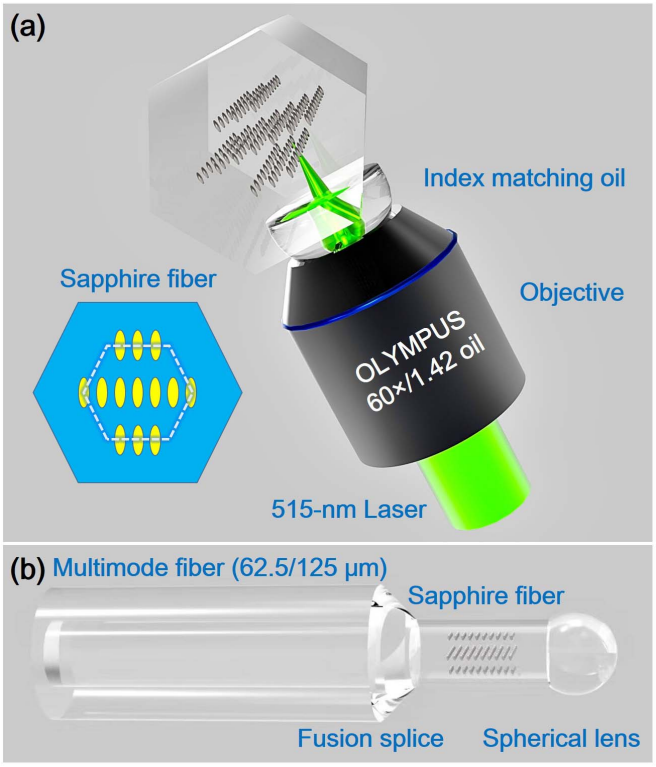

Fig. 2. (a) Schematic diagram of preparing parallel-integrated SFBGs. The illustration is the two-dimensional distribution diagram of the end face of the prepared grating structure. (b) Schematic diagram of high temperature fiber sensor integrated with quartz multimode fiber and sapphire fiber probe.

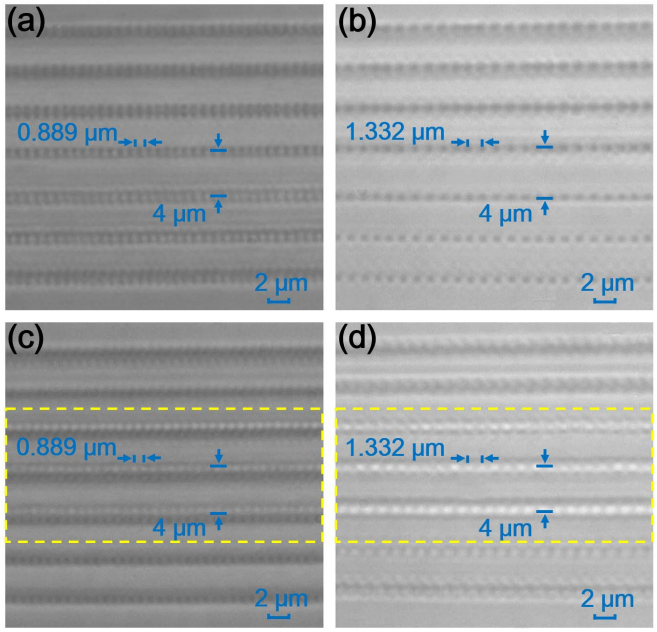

Fig. 3. (a) and (b) are micrographs of single-layer SFBGs prepared with grating spacing of 4 μm and grating periods of 0.889 μm and 1.332 μm, respectively. Fig. 3. (c) and (d) are micrographs of three-layer SFBGs prepared with grating spacing of 4 μm and grating periods of 0.889 μm and 1.332 μm, respectively.

and symmetry, when preparing the top-layer SFBGs, it is necessary to rotate the sapphire fiber coaxially by 180 degrees, and then continue to prepare SFBGs by the same method as the bottom layer. Fig. 2(b) is a fiber high temperature sensor integrated with a quartz multimode fiber (62.5/125 μm) and a sapphire fiber probe. The quartz multimode fiber and sapphire fiber are fused by a fusion machine (Ericsson, FSU975), which ensures the stability of coupling efficiency and high temperature resistance. The discharge current and time are 10 mA and 1.5 s, respectively. By continuously optimizing the discharge current and discharge time, the fusion quality of quartz fiber and sapphire fiber is the best under this current and time, and good mechanical strength and fusion quality are obtained. Due to the large refractive index of sapphire fiber (1.746 @ 1550 nm), the Fresnel reflectivity at the end face is high, which will greatly reduce the spectral SNR.

In order to improve the spectral SNR, the spherical lens is prepared by high current discharge through a fusion splicer at the end of sapphire fiber, in which the discharge current is 16.5 mA and the discharge time is 2 s. The sapphire fiber is melted by electrode discharge heating and aggregated into an approximate spherical lens structure. The diameter of prepared spherical lens is larger than that of sapphire fiber, and more high-order modes will be further excited inside this spherical lens. The high-order mode excitated is easy to scatter out, and some of the light will be reflected back into sapphire fiber. However, the optical power of this part is very small, so the spherical lens structure can significantly improve the SNR of the spectrum.

Figure 3 shows the micrographs of SFBGs with different periods and layers prepared by the femtosecond laser PbP method. Fig. 3 (a) and (b) are micrographs of single-layer SFBGs with grating periods of 0.889 μm and 1.332 μm and grating spacing of 4 μm, respectively. Fig.3 (c) and (d) are micrographs of the corresponding three-layer SFBGs. The interval between layers is 10 μm, and multi-layer superposition will make the image unclear. The grating spacing of 4 μm ensures no crosstalk and high discrimination between adjacent gratings.

III. Results and Discussion

Figure 4 (a) and (b) are the front and back ends of the sensor probe, and the illustration in Fig. 4 (b) is an enlarged view of the spherical lens area. After passing through the broadband light, part of the scattered light is clearly visible near the fusion point, grating and spherical lens regions. When broadband light passes through the spherical lens, most of the light will be scattered out. The overall length of the sapphire fiber probe is approximately 8.5 mm and the length of sapphire fiber at the front end of grating is 2 mm. The length of SFBG is 5 mm and the distance from the rear end of grating to spherical lens is 1.4 mm. The prepared spherical lens has a transverse diameter of 122 μm and a longitudinal diameter of 148 μm. Fig. 4 (c) shows the comparison of spectra before and after end face treatment, and the illustration is a partial enlargement of the spectrum in the wavelength range of 20 nm. By preparing a spherical lens at the end of sapphire fiber, the spectral SNR is greatly improved to 22 dB. The parallel

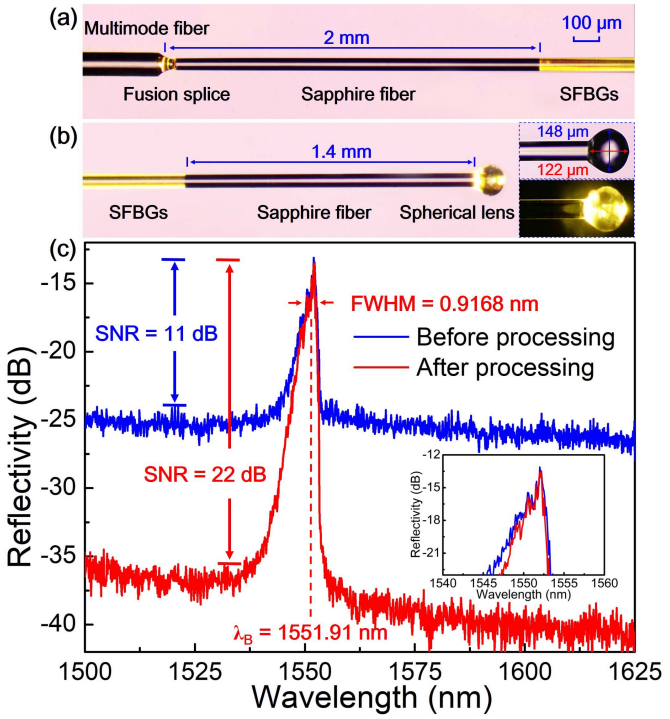

Fig. 4. (a) and (b) show the front and back ends of the sensor probe, and the illustration in Fig. 4(b) is an enlarged view of the spherical lens area. Fig. 4 (c) is the comparison of the spectrum before and after the end face treatment, and the illustration is a partial enlargement of the spectrum in the wavelength range of 20 nm.

integration of SFBGs prepared by femtosecond laser PbP method is helpful to increase the reflectivity of the grating and reduce the FWHM. The grating reflectivity is about 15%, and the FWHM is 0.9168 nm. If the FWHM is further significantly reduced, sapphire fiber can be coupled through single-mode fiber. However, due to the different mode field diameters of sapphire fiber and single-mode fiber, mode jump is easy to occur. This is also the reason why multimode fiber coupling sapphire fiber is used to prepare sensors.

By using high numerical aperture oil immersion lens to focus femtosecond laser, combined with PbP method, smaller period gratings can be prepared with high resolution. Fig. 5 is the spectral comparison of the prepared second-order and third-order SFBGs, and the illustration is the spectral comparison in the range of 20 nm. Compared with high-order SFBGs, low-order SFBGs with the same grating length have more cycles, higher diffraction efficiency and higher reflectivity, but this will also increase FWHM. The third-order SFBGs with smaller FWHM is selected in this experiment, which is conducive to improving the accuracy of spectral demodulation.

Remove the coating on the quartz fiber area of the sensor to be placed in the high-temperature area and wipe it clean with absolute ethanol. Put the sensor into a quartz tube sealed at one end. The inner diameter and outer diameter of the quartz tube used in this experiment are 1 mm and 2 mm. The purpose of this is to reduce the reaction between impurities and the surface of quartz fiber and sapphire fiber under high temperature and harsh environments, and thus reduce

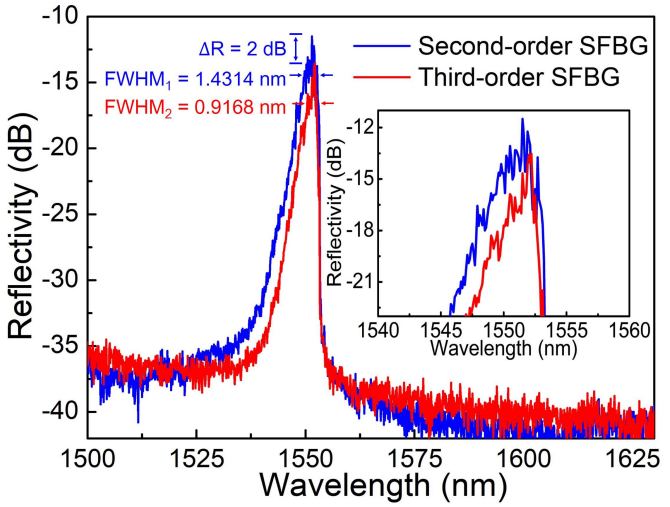

Fig. 5. (a) Spectral comparison of second-order and third-order SFBGs. The illustration shows a spectral comparison in the wavelength range of 20 nm.

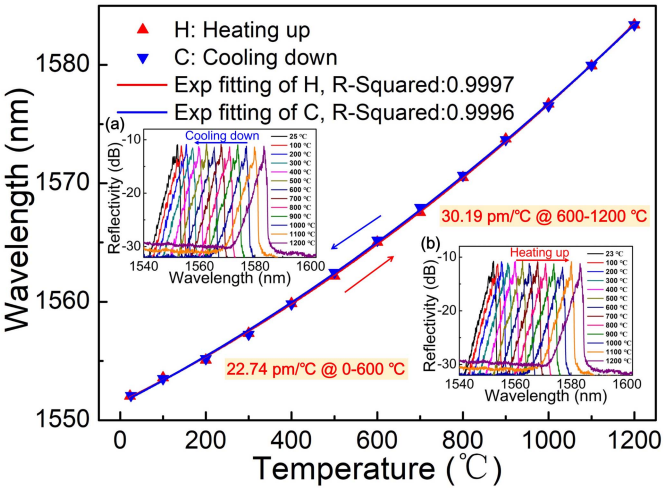

Fig. 6. The quadratic fitting curve of Bragg wavelength and temperature during the temperature cycling test from room temperature to 1200 °C. The illustration shows the variation of reflection spectra with temperature during cooling process (a) and heating process (b).

the performance of the sensor. Place the sensor in a high-temperature furnace, anneal it at 1000 °C for 3 hours, then cool it to room temperature to repeat the temperature cycle test. The maximum temperature is tested to 1200 °C, the temperature test interval is 100 °C, and each temperature point is held for 30 minutes. Fig. 6 is a quadratic fitting curve of Bragg wavelength and temperature during a temperature cycling test from room temperature to 1200 °C. The illustration shows the variation of reflection spectra with temperature during cooling process (a) and heating process (b). The quadratic fitting curve expression is: $\lambda = A + B \cdot T + C \cdot T^2$, The fitting parameters A, B and C are 1551.52022, 0.01785 and 7.31204×10^{-6}, respectively. The temperature sensitivity of 22.74 pm/°C (@0-600 °C) and 30.19 pm/°C (@600–1200 °C) can be obtained by piecewise linear fitting of different temperature ranges. This is also one of the advantages of using sapphire fiber as sensing probe to obtain high temperature sensitivity.

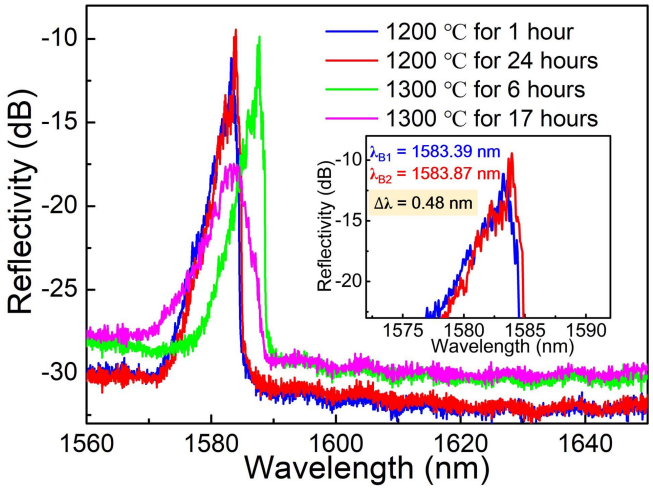

Fig. 7. Spectral comparison of long-time temperature stability test at 1200 °C and 1300 °C. The illustration is a comparison of spectral stability in the wavelength range of 20 nm at 1200 °C.

In order to further explore the long-term high temperature stability of the sensor, comparing the spectra of the sensor at 1200 °C for 24 hours and 1 hour, there is no obvious shift in the reflection spectra. The spectra remains relatively stable when the temperature rises to 1300 °C and remains for 6 hours. When the temperature is kept for 17 hours, the spectrum quality has obviously decreased. Fig. 7 shows the long-time spectral comparison at 1200 °C and 1300 °C, and the illustration shows the long-time spectral comparison in the wavelength range of 20 nm and holding at 1200 °C for 1 hour and 24 hours. Although the internal grating structure of sapphire fiber can remain stable at 1300 °C for a long time, the quartz softens obviously at this temperature, and the coupling region between quartz fiber and sapphire fiber changes, resulting in the reduction of coupling efficiency and the deterioration of spectrum. The long-time stability experiment shows that this sensor can work at 1200 °C for a long time and 1300 °C for a short time.

IV. Conclusion

In conclusion, we have prepared the three-layer parallel SFBGs with a 5 mm grating length in an 8.5 mm sapphire fiber by the femtosecond laser PbP method. The SFBGs probe and quartz multimode fiber constitute a fiber high temperature sensor, which can work stably at 1200 °C for a long time and 1300 °C for a short time. In order to reduce the problem of low SNR caused by Fresnel reflection, we fabricated a spherical lens on the sapphire fiber end face, which can effectively improve the SNR to 22 dB. In addition, due to the high thermal optical coefficient of sapphire material, the temperature sensitivity can reach 30.19 pm/°C in the high temperature range, which is more than 2 times higher than that of quartz FBGs sensors. The sensor overcomes the problems of doped quartz fiber element diffusion at high temperature and the instability of the microstructure caused by material softening, and can work stably in 1200 °C high temperature and harsh environments.

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