

Single-mode Sapphire Optical Fiber Temperature Sensor

Mohan Wang^{1,5}, Patrick S. Salter¹, Frank P. Payne¹, Adrian Shipley², Igor N. Dyson¹, Tao Wang^{3,4}, Kaihui Zhang³, Jian Zhang³, Zhitai Jia³, Stephen M. Morris¹, Martin J. Booth¹ and Julian A. J. Fells^{1,6}

¹Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

²Rolls-Royce Plc, Derwent Building, 5000 Solihull Parkway, Birmingham Business Park, Birmingham, B37 7YP, UK

³State Key Laboratory of Crystal Materials, Shandong University, 27 South Shanda Road, Jinan, Shandong 250100, China

⁴Jiangsu Jingying Optoelectronics Technology Co. LTD, 10 East Zhujiang Road Xuzhou Jiangsu 221116, China

⁵mohan.wang@eng.ox.ac.uk

⁶julian.fells@eng.ox.ac.uk

Abstract: Sapphire fiber is intrinsically multimoded, resulting in poor precision sensors. We demonstrate a 4-cm single-mode sapphire fiber with a Bragg grating temperature sensor and a standard-fiber tail, operating up to 1200°C. © 2023 The Authors.

1. Introduction

Sensors with robust monitoring capability under extreme environments are crucial for many applications in energy, space, and aerospace. High-quality monitoring of environmental parameter changes can help extend infrastructure lifetime, lower environmental impact, and prevent potential hazards at an early stage. Sapphire fiber is a promising candidate for extreme environmental sensing with a high melting point of over 2000°C and being intrinsically radiation hard. Sapphire fibers are single-crystal rods without a cladding, such that light is guided by the sapphire-air interface. The large refractive index and large diameter guiding region means that a pristine sapphire fiber contains many thousands of modes. Though it is possible to write fiber Bragg gratings (FBGs) within the multimode sapphire fiber, the different modes each have a different effective index and hence Bragg wavelength. This results in a broad and fluctuating spectrum, severely impacting the achievable accuracy. Attempts have been made to decrease the number of modes in a sapphire fiber by decreasing the diameter of the sapphire rod, either by using chemical and physical methods such as neutron irradiation [1] or hot acid etching [2]. However, the resulting fibers are still not single-mode.

Femtosecond direct laser writing has been widely adopted to fabricate sensors on both silica-core fibers and sapphire fibers. Optical and material property changes can be introduced at the laser focus, allowing three-dimensional fabrication and flexible design of optical devices. There have been extensive efforts to tailor the modal performances in sapphire fiber sensors using femtosecond laser direct writing. The designed sensors show an improvement in spectral performance but are still few mode [1-3]. Recently, we demonstrated a single-mode sapphire fiber Bragg grating on a commercial 425- μm diameter sapphire fiber [4]. However, the 1 cm device length was too short for practical application. Subsequently, a 2 mm single-mode helical FBG was fabricated in multimode sapphire fiber [5], but this is not a satisfactory solution as the coupling between the multimode fiber and the single-mode FBG will be extremely weak and wildly fluctuating.

In this work, we improve the laser-writing process and use high quality sapphire fiber growth to extend the length of the single-mode sapphire fiber. This has allowed sensors in fibers of sufficient length to be tested at ultra-high temperatures, opening up the possibility of practical deployment of these sensors.

2. Single-mode sapphire fiber sensor fabrication

The sensor was designed as a 4-cm single-mode sapphire fiber with a 1-cm Bragg grating at one end and spliced to single-mode standard fiber at the other. The sapphire fiber was grown using our custom laser-heated pedestal growth (LHPG) system. This system gives high purity sapphire fiber with precisely controlled diameter and crystal orientation [6]. A sapphire fiber of 104 μm diameter was grown with the *c*-axis along its length. This fiber was cut to a length of 4-cm for processing.

A regenerative femtosecond laser system (Pharos SP-06-1000-PP) delivering 170 fs pulses at 515 nm was used for fabrication. The linearly polarized laser beam was focused onto the substrate through a 63×1.25 NA oil objective. Immersion oil (Cargille Lab, $n = 1.7450$) was used to compensate for the rounded hexagonal sapphire fiber shape. The output beam was expanded using a telescope and projected onto a spatial light modulator. A pre-distorted phase pattern was applied to correct for aberrations inside the laser beam delivery system and projected to the pupil plane of the objective through a 4-*f* imaging telescope. The laser pulse energy was adjusted using a half-waveplate placed prior to a polarizer. An optimized pulse energy of 28 nJ was used in the sensor fabrication.

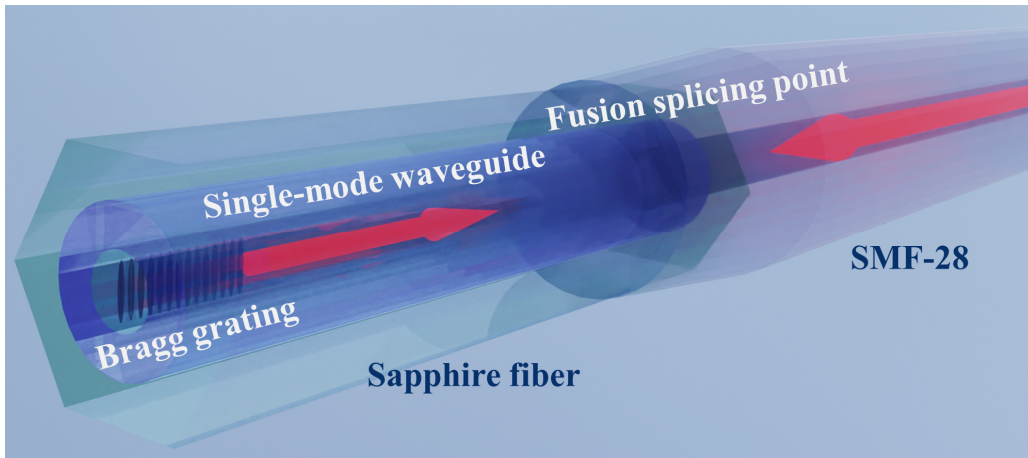


Fig. 1. Schematic of the sapphire sensor.

The sapphire fiber was mounted on a three-axis motion stage (x, y : Aerotech ABL10100L and z : ANT95-3-V), with the laser polarization perpendicular to the fiber central axis. The writing process within the sapphire material was first characterized and optimized by laser writing a series of individual tracks. Then a multilayer depressed cladding waveguide which supported only the fundamental mode was designed. Due to the elliptical shape of the laser modification region, extra tracks were added in the horizontal direction to make the waveguide circular. The process is described in more detail in our previous work [4].

A three-step fabrication process was used. Firstly, the bottom layers of the waveguide were written. Then a second order 1-cm long Bragg grating was embedded at the end of the fiber in the center of the cross-section, point-by-point. A pitch of 887.6 nm for a desired Bragg wavelength of 1550 nm was used. Finally, the top layers of the waveguide were added to enclose the grating inside a single-mode waveguide. A schematic of the sensor design is shown in Fig. 1. The writing speed and repetition rate were set to 2 mm/s and 50 kHz for the single-mode waveguide, and 0.1 mm/s and 50 kHz for the Bragg grating.

After laser-processing, the sapphire fiber was polished on both facets to a grit of 1 μm . Fig. 2(a) shows a microscope image of the waveguide cross-section. The design consists of 216 tracks, while the middle track contains the periodic refractive index modulation for the Bragg grating [Fig. 2(b) and (c)]. Two cracks can be seen at the outer side of the waveguide. However, they are confined to within close proximity of the fiber end facets, likely incurred by stress introduced during polishing. This is verified from the top view image in Fig. 2(b). No cracks were observed in or around the Bragg grating and waveguide region along the 4 cm sensor except for around the facets.

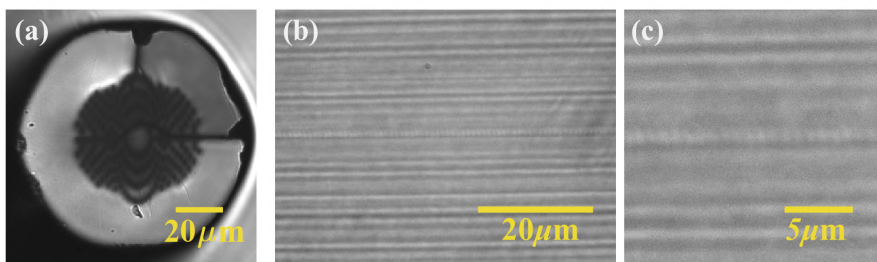


Fig. 2. Microscope images of (a) the cross-section of the 104 μm diameter sapphire fiber at the single-mode waveguide side, (b) top view of the waveguide and Bragg grating, and (c) a zoomed-in image of (b).

3. High temperature sensing

The 4-cm long sapphire sensor was placed inside a fusion splicer (Sumitomo Type-72C), together with a cleaved single-mode silica-core fiber (SMF-28). The Bragg grating was positioned the furthest from the silica-core fiber. An active alignment technique was used with the splicer in manual mode. Light from a tunable laser (Agilent 8164A Lightwave Measurement System) was injected into the single-mode fiber, and the reflected light was captured by a photodetector through a circulator. By using the fusion splicer positioning stages, precise alignment between the single-mode sapphire waveguide and the single-mode silica fiber core was achieved by an iterative process, using

the reflection spectrum as an indicator. Once the optimum position was identified, fusion splicing between the two fibers was performed. Though the splicing power between different fusion splicers are not directly comparable, we set the arc time to be 2 seconds and the pre-fuse time 0.15 seconds.

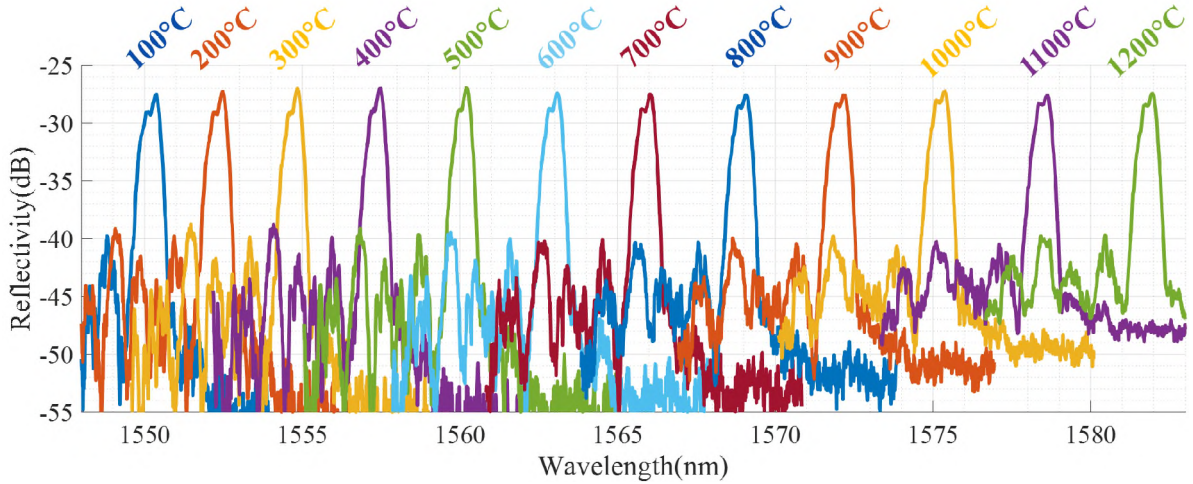


Fig. 3. The reflection spectra of the sapphire FBG during the third heating cycle at steps of 100°C.

After splicing, the sapphire fiber sensor with its lead-in silica fiber was inserted through a ceramic tube opening into a box furnace (Carbolite CF1200, maximum temperature 1200°C). A Type-K thermocouple with a resolution of 1°C was placed in the proximity of the temperature sensor (Eurotherm 2132). Light from a tunable laser (Agilent 8163A) was connected via a polarization controller and an optical circulator to the SMF-28 tail of the sapphire temperature sensor. The returned light was detected on the power meter of the 8163A.

Annealing was performed at 1200°C following three repeated heating and cooling cycles. The maximum temperature of 1200°C is beyond the vitrification temperature of the silica-core fiber. The sensor was taken to 1200°C in steps of 100°C in about six hours, then annealed at 1200°C for one hour. Fig. 3 shows the overlapped spectra for the third post-annealing temperature cycle. Each spectrum was taken with a wavelength range of 10 nm at a step resolution of 10 nm. The noise background increases as the temperature increases. At 1200°C, we still obtained an SNR > 16 dB.

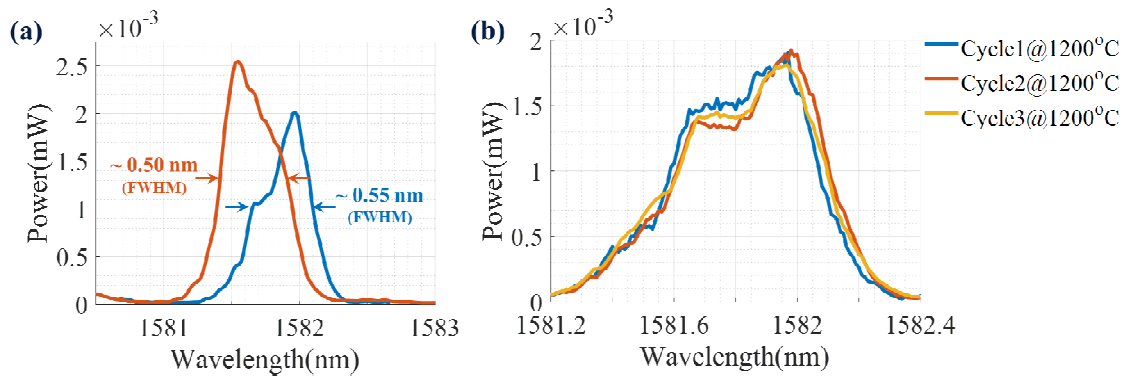


Fig. 4. (a) The spectra of two different polarizations, measured at 1200°C and (b) spectra at 1200°C for three temperature cycles.

The input polarization was adjusted to reveal two orthogonal polarization modes, shown in Fig. 4(a), recorded at 1200°C with a resolution of 20 pm. The birefringence was calculated to be 1.2×10^{-4} at room temperature. The full-width half-maximum (FWHM) bandwidths of the two polarization modes were measured to be 0.50 nm and 0.55 nm, respectively. While negligible birefringence was observed in our single-mode waveguide following a similar investigation method as described in [4], the existence of the birefringence is likely a result of the anisotropic refractive index distribution of the Bragg grating. Commercial interrogators typically have a polarization scrambler.

As the modes are distinct, it would be possible to determine the wavelength of both peaks with a scrambled input polarization and take a mean value.

Fig. 4(b) shows the spectra at 1200°C during the first, second, and third temperature cycles, showing good repeatability with only slight fluctuation recorded at a resolution of 10 pm. The accuracy is limited by the resolution of our tunable laser (10 pm ~ 0.5 °C), the fluctuation in the laser source power, and the Fabry-Perot fringes due to the reflection between the fusion splicing point and the sapphire fiber end facet, all of which could be improved through a better setup and improved sensor termination.

The Bragg resonance wavelengths were extracted from both polarizations and the characteristics curve were calculated. We used a quadratic fitting for the nonlinear thermal characterization curve using $\lambda_B = A + B \cdot T + C \cdot T^2$. The coefficients A , B , and C were calculated to be 1547.74 nm, 22.06 pm/°C, and 0.0053 pm/°C² for the polarization shown in red and 1548.01 nm, 21.87 pm/°C, and 0.0054 pm/°C² for the polarization shown in blue [Fig. 4(a)]. These numbers are similar to the previous research [3]. The fitted curve for the blue polarization was shown in Fig. 5. The single-mode operation of this sensor has led to exceptionally high precision and repeatability, not previously possible for fiber sensors operating at ultra-high temperatures exceeding 1000°C.

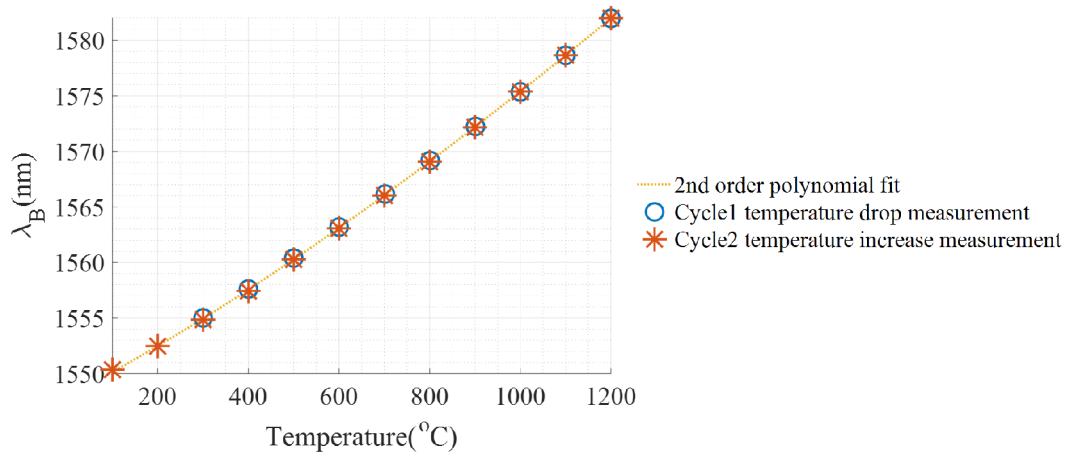


Fig. 5. The characteristic curve of the Bragg grating sensor.

4. Conclusions

We demonstrated end-to-end single-mode operation of a sapphire fiber Bragg grating temperature sensor up to 1200°C. The sapphire sensor was grown to high quality and a single-mode waveguide with a Bragg grating was inscribed using direct laser writing. The fabrication technique provides a promising solution for high-quality sapphire fiber sensors for extreme environment applications. The temperature sensor has demonstrated unrivalled precision and repeatability at ultra-high temperatures in excess of 1000°C, verified through repeated heating and cooling cycles.

5. References

- [1] J. T. Jones, A. Birri, T. E. Blue, D. Kominsky, K. McCary, O. J. Ohanian, and S. D. Rountree. "Light Propagation Considerations for Internally Clad Sapphire Optical Fiber Using the 6Li (n, α) 3H Reaction." *Journal of Lightwave Technology* 40, 1181-1187 (2021).
- [2] S. Yang, D. Homa, G. Pickrell, and A. Wang. "Fiber Bragg grating fabricated in micro-single-crystal sapphire fiber." *Optics Letters* 43, 62-65 (2018).
- [3] Q. Guo, S. Liu, X. Pan, B. Wang, Z. Tian, C. Chen, Q. Chen, Y. Yu, and H. Sun. "Femtosecond laser inscribed helical sapphire fiber Bragg gratings." *Optics Letters* 46, 4836-4839 (2021).
- [4] M. Wang, P. S. Salter, F. P. Payne, A. Shipley, S. M. Morris, M. J. Booth, and J. A. J. Fells. "Single-mode sapphire fiber Bragg grating." *Optics Express* 30, 15482-15494 (2022).
- [5] J. He, J. He, X. Xu, X. Yin, and Y. Wang. "Single-mode helical sapphire fiber Bragg grating for high-temperature sensing." In *European Workshop on Optical Fibre Sensors (EWOFS 2023)*, vol. 126433, pp. 23 (2023).
- [6] T. Wang, J. Zhang, N. Zhang, S. Wang, B. Wu, N. Lin, P. Kusalik, Z. Jia, and X. Tao. "Single crystal fibers: diversified functional crystal material." *Advanced Fiber Materials* 1, 163-187 (2019).