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High Temperature Stability of Femtosecond Written Ablation Fiber Bragg Gratings in Microstructured Optical Fibers

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Abstract—We examine the thermal lifespan of FBGs written in pure-silica microstructured optical fibers at temperatures of up to 1260°C, demonstrating that they are capable of performing measurements at this temperature for an extended duration.

Keywords—Fiber Bragg gratings; High temperature sensing; Microstructured optical fibers.

I. INTRODUCTION

Fiber Bragg gratings (FBGs) have found common use within structural health monitoring, but have also been employed in recent years for a range of temperature sensing applications [1]. Typically fibers written in conventional core:clad single-mode fibers (SMF) are limited to temperatures below 500°C, above which thermal annealing of the grating structure removes the refractive index modulations that make up the FBG [1, 2]. Specialty fibers or alternative grating writing techniques can expand this operating range, such as regenerated FBGs [3, 4], chiral gratings [5], or femtosecond written type II gratings [6], allowing for sensing between 1100-1295°C. Sapphire fibers show the best promise for sensing above this temperature range due to their increased material stability at higher temperatures. However, practical use of sensors based on FBGs in optical fibers is restricted either by the high loss of sapphire crystal fibers restricting the length or multiplexing capability, or from limitations in the high-temperature stability of conventionally written FBGs in silica fibers.

An alternative technology involves the use of microstructured optical fibers, in particular the suspended core fiber (SCF) fiber geometry, that consists of three evenly spaced holes within a fiber creating a glass core in which the light confinement comes from the glass:air index contrast (Fig. 1a). SCFs have found use in a range of applications in recent years, primarily in the biological and chemical sensing spaces [7, 8] due to the high capture of fluorescent light by the evanescent field [9]. Previous work on SCFs has shown that a variety of sensing methodologies can be employed using these fibers, with temperature sensing in particular being demonstrated either through multimode interference [10] and femtosecond written type II damage gratings [11]. These gratings have also been

demonstrated on exposed core fibers [12], allowing for direct contact of liquids or gases within the external environment. For temperature sensing applications however, the improved protection of the core and grating provided by the enclosed SCF geometry presents a more robust option than the exposed core fiber.

In this work we examine the thermal stability of gratings written in both flame fused silica (Heraeus F300), and electrically fused quartz (Heraeus LWQ / HSQ300). Typically optical fiber fabrication utilises F300 glass, as the higher purity and reduced OH content significantly improves transmission in the telecommunications band [13]. Recent work has also examined the use of high-OH content glass (Heraeus F100) for improved UV transmission, however for this work we look at lower-grade HSQ300 glass for the raw material for preform fabrication. HSQ300 possesses higher impurities than F300 or F100 glass, due primarily to the use of natural quartz glass rather than synthetic silica [13]. In the specific application of ultra-high temperature sensing these impurities act to increase the thermal stability of the gratings, resulting in a significant increase in sensor lifetime at the tested temperature of 1260°C.

II. METHOD

A. Fiber fabrication

Fabrication of the suspended core fibers (SCFs) was based on existing techniques described in detail in previous work [11, 14]. Briefly, 150 mm lengths of fused silica (Heraeus Quartzglas HSQ300 and F300) were drilled using an ultrasonic mill to create the triangular pattern of holes that comprises the structure (3 x 2.8 mm holes, 0.4 mm spacing between adjacent holes). Preforms were drilled from both ends to maximize the usable length. Previous work has shown that while the ultrasonic milling process creates a relatively rough surface during machining, this surface is fire polished during the draw resulting in losses in the order of 10-20 dB/km.

The preform was then pulled to fiber using a 6 m draw tower, controlling the pressure applied to the center structured region and the outer diameter of the fiber to create the desired structure.

Higher temperatures were used for the LWQ fibers such that the measured tension during the draw was comparable between both glass types. No coating is applied to the fiber during the fiber draw, as typical acrylate polymer coatings used on optical fibers are only rated to 80°C, with polyimide up to 300°C and metal coatings up to 700°C for long durations.

B. Grating writing and characterization

SCFs were spliced to conventional SMF28E single mode fibers for ease of integration with testing equipment using a Fujikura FSM-100P arc splicer. Due primarily to the mode mismatch between the SCF and SMF28E fibers measured splice losses were in the order of 2-3 dB. FBGs were written into the SCFs using a method based on that described previously [11]. Fibers were mounted in a groove on a flat aluminum block, taking care that the fiber lay flat in the groove with no curvature of the fiber, or rotation/torsion of the fiber along the length. A red alignment laser was coupled into the fiber, and the end-face of the fiber imaged on a screen to observe the rotational orientation of the fiber's structure. The fiber was then adjusted using a rotation mount such that one hole faced vertically out from the block.

In this technique the grating is written through the outside wall of the fiber, with the focal point of the femtosecond laser located on the side of the core itself. As the spot is expanded on the external cladding segments of the fiber no damage is caused to the cladding, with the ablation process of the FBG writing confined to the surface of the core, as shown in Fig. 1b. SEM images of an example FBG are shown in Fig. 1c&1d. The outer cladding acts as a cylindrical lens, with the elongated holes typically observed for FBGs written with the focus of the femtosecond laser on the surface of the SCF core.

The mount was then placed on a translation stage (Aerotech), and moved such that the front face of the core was located at the focal point of a 40 × long working distance microscope objective. Precise alignment was then obtained by firing single femtosecond pulses from the laser (Hurricane Ti:Sapphire, 800 nm) onto the core and monitoring the scattering of the red laser from damage points on the core. The FBG was then written by translating the stage 10 mm along a line between the two alignment points, monitoring the FBG spectra during the writing process. Spectra were recorded using a commercial FBG interrogator (Micron Optics sm125).

After writing, the gratings were packaged into fused silica capillaries for thermal testing. A commercial tube furnace (Across International TF1700) was used for analysis of the gratings. Gratings were annealed by cycling from room temperature to 1160°C twice prior to testing their thermal stability. An R-type thermocouple was co-located with the gratings at the center of the furnace, with the furnace profiled prior to measurements to ensure a uniform hot zone across the relevant region. The wavelength shift:temperature response was determined prior to this trial using 4 fibers which had been annealed with an identical profile, with the temperature increased in 50 or 100°C steps to obtain the response curve for the gratings.

For temperature stability trials the gratings were returned to room temperature, and the furnace ramped to 1260°C where the

temperature was held until the conclusion of the test (~13 hours). The reflected FBG signal intensity as well as the position of the FBG peak was recorded every 10 seconds during the trial for comparison to the reference thermocouple.

III. RESULTS & DISCUSSION

A scanning electron microscope (SEM) image of one the fabricated fiber structures is shown in Fig. 1a.

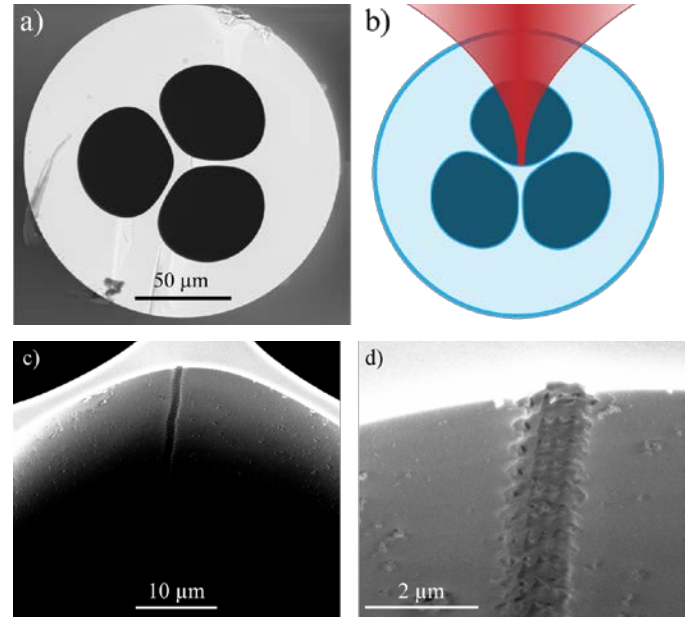


Fig. 1. a) Scanning electron microscope image of the SCF structure. Due to the high temperature application of these fibers no polymer coating is applied during the fiber draw, with the fibers drawn uncoated with diameters of 125-160 μm. b) Schematic of the femtosecond laser writing of FBGs on the core of the SCF. The femtosecond laser is focused onto the surface of the fiber core, through the outer cladding. c) SEM image of an example grating written into the core. The total length of the gratings used for the results shown in Fig. 2 is 10 mm. d) SEM image showing fine structure of type II grating features written on the SCF core.

Results from testing FBGs written in both F300 and LWQ are shown in Fig. 2 below at a measured temperature of 1260°C. From this we can see that the LWQ fiber shows a slower decay in peak height compared to the F300 fiber. The average decay rate for the LWQ fiber is only 1.2 dB/hour after the temperature reaches 1260°C, while the F300 fiber decays much more rapidly than the LWQ at a rate of 5.1 dB/hour. Once the signal intensity of the peak approaches the background noise level the peak tracking becomes unstable, and the temperature reading becomes unreliable.

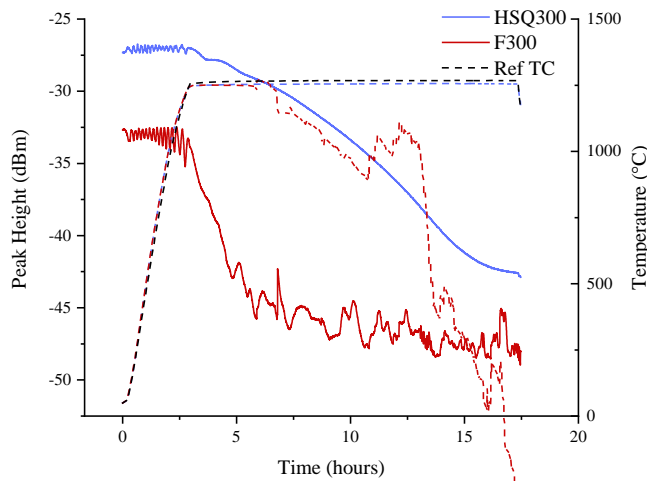


Fig. 2. Thermal testing of FBGs written in LWQ (blue) and F300 (red) SCFs. The peak heights are shown with solid lines, the temperature extracted from the FBG is shown with dashed lines. The reference temperature from an R-type thermocouple co-located with the FBGs is shown with a dashed black line.

At the temperature of 1260°C both the LWQ and F300 glasses are above their strain points (1125°C and 1070°C respectively) and annealing temperatures (1220°C and 1160°C respectively) [15]. The increased stability of the LWQ fiber compared with the F300 fiber is most likely due to the higher aluminum concentration (15 ppm [16]) within the LWQ glass compared to F300 (aluminum concentration below ICP-MS detection limit [13]), which acts to increase the annealing point and general thermal stability of the glass [15]. Literature shows that the viscosity of silica glasses increases with aluminium concentration, with a peak between 7-13 ppm before decreasing at higher concentrations [17, 18].

Further testing on fibers without FBGs written demonstrated that the fibers themselves experience an increase in loss at this temperature, with the transmission through an LWQ fiber dropping by only 0.54 dB/hour after the fiber reached 1260°C. This suggests that while some portion of the degradation in signal is due to an increase in the overall loss of the fiber, the majority of the degradation here related to the FBG. SEM imaging of fibers before and after heat cycling showed no measurable change in the fiber structure. SEM imaging of the gratings themselves showed evidence that the sharp edges of the gratings were partially rounded off thus decreasing the refractive index contrast. However, variability in the observed features between gratings makes this difficult to quantify.

IV. CONCLUSIONS

FBGs written in SCFs made from two different types of silica glass have been examined for their temperature stability. Results show that the electrically fused quartz glass (HSQ300) displays better stability at the testing temperature of 1260°C, with a 4× reduction in the rate at which the FBG peak decays compared to the flame fused silica (F300) typically used for microstructured fiber fabrication. Sensors made using these fibers present opportunities for measurements within a range of industrial and defense applications, as these femtosecond-written FBGs in SCFs show excellent performance at the

elevated temperatures required for metals processing applications.

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