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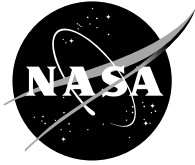
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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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The development of integrated fiber optic sensors for use in aerospace health monitoring systems demands that the sensors be able to perform in extreme environments. In order to use fiber optic sensors effectively in an extreme environment one must have a thorough understanding of the sensor's capabilities, limitations, and performance under extreme environmental conditions. This paper reports on our current sensor evaluation examining the performance of freestanding fiber Bragg gratings (FBG) at extreme temperatures. While the ability of FBGs to survive at extreme temperatures has been established, their performance and long term survivability is not well documented. At extreme temperatures the grating structure would be expected to dissipate, degrading the sensors performance and eventually ceasing to return a detectable signal. The fiber jacket will dissipate leaving a brittle, unprotected fiber. For FBGs to be used in aerospace systems their performance and limitations need to be thoroughly understood at extreme temperatures. As the limits of the FBGs performance are pushed the long term survivability and performance of the sensor comes into question. We will not only examine the ability of FBGs to survive extreme temperatures but also look at their performance during many thermal cycles. This paper reports on test results of the performance of thermal cycling commercially available FBGs, at temperatures up to 1000°C, seen in aerospace applications. Additionally, this paper will report on the performance of commercially available FBGs held at 1000°C for hundreds of hours. Various parameters of the FBGs performance were monitored and recorded throughout the evaluation process. Several test samples were subjected to identical test conditions to allow for statistical analysis of the data. Test procedures, calibrations, referencing techniques, performance data, and interpretations and explanations of results are presented in the paper along with directions for future research.

## I. INTRODUCTION

With the growing interest to use FBGs as temperature sensors in aerospace systems, the need to understand the performance and long term survivability of commercially available high temperature FBGs, up to 1000°C, has developed [1, 2, 3]. The survivability of FBGs up to and above 1000°C has generated interest [4, 5], but their per-

formance and long term survivability at these temperatures is not well published. This paper looks at, in great detail, the performance and long term survivability of FBGs up to 1000°C through more than 700 hours of thermal cycling and over 400 hours of continuous operation.

FBGs in standard telecommunications fiber were used throughout the evaluation. They were fabricated for use up to 400°C so it was expected that the FBG structure would completely dissipate. However, this was not what was observed. Degradation and loss of the signal from the FBGs was observed during the beginning of the evaluation but the signal eventually reappeared and stabilized. The results of the experiments are discussed below along with theories for the phenomena observed during the evaluation.

Additional experiments were performed to explain phenomenon seen during the optical portion of the thermal analysis. Sections of fiber were monitored for cracking using an acoustic emissions technique. Results of those experiments are also discussed.

## II. HIGH TEMPERATURE THERMAL CYCLING OF FBGS

All FBGs were commercially available and of a like construction and were evaluated to look at their suitability for use in aerospace applications. All had a polyimide jacket designed to withstand high temperature operation up to 400°C. High reflectivity, type I, gratings made using a Spectran fiber similar to Corning SMF28 were evaluated. They had a core diameter of 9 micron, a germanium doped core, and were hydrogen loaded. The gratings were produced with a 193nm Excimer laser. Prior to our evaluation the gratings were annealed to 400°C for about five minutes by the manufacturer. [6]

Evaluation of the FBGs consisted of four experiments all performed in ambient air; cycling to 750°C; cycling to 1000°C; long duration at 1000°C; and finally acoustic emissions monitor of the FBG during thermal cycling. During the thermal cycling experiments the gratings were subjected to repeated cycling to characterize the accuracy of temperature measurements made and their survivability. The experiments were designed to look at the long term survivability of the commercially available FBGs and determine their effectiveness as temperature sensors up to 1000°C. Throughout the evaluation process, performance of the reflected signal of the FBGs was recorded. The evaluation process was designed to help determine which missions, if any, FBGs might be appropriate as temperature sensors.

The test setup, as seen in Fig. 1, consisted of a thermally stabilized super-luminescent diode light source connected to a 90/10 coupler. The 10% output of the coupler was connected to a photodiode used to monitor the light source stability throughout the evaluation process. The 90% output port of the coupler was connected to the first port of a 3 port fiber optic circulator. The second port of the circulator was connected to a 4 port fiber optic switch. The four output ports of the switch were connected to up to 4 FBGs inside a box furnace. The reflected signal from the FBGs traveled back through the switch and circulator to an optical spectrum analyzer.

All equipment was controlled and monitored using LabVIEW. At the start of testing it was expected that the grating would degrade with increasing temperature until no measurable signal was detected. Additionally it was expected that there would be some devitrification of the fiber contributing to the loss in signal from the FBG [7]. Due to differences in the expansion coefficients of the core and cladding, it was expected that there would be cracking of the fiber.

### A. 750°C Thermal Cycling

The first evaluation of FBGs was a series of thermal cycles to 750°C in ambient air. In this test, four identical 1300nm FBGs were subjected to a series of slow thermal cycles designed to characterize the accuracy of temperature measurements made and their survivability. Various performance parameters of the FBGs were monitored

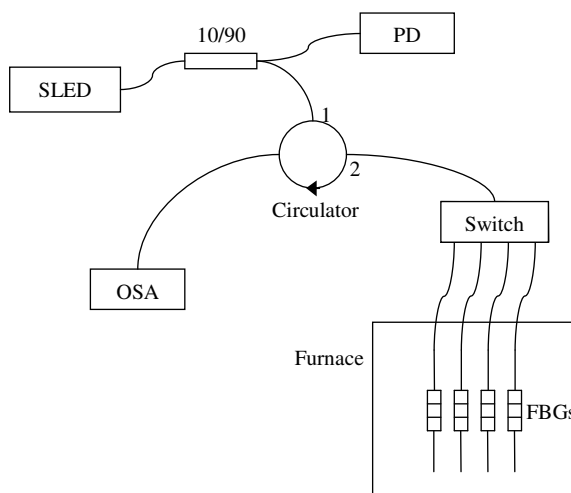


Fig. 1 Set-up for evaluating long term thermal stability of FBGs

throughout the test to allow for a statistical analysis of the lifetime of the FBGs under the test conditions. The temperature was also recorded using an s-type thermocouple.

The experimental configuration for the 750°C cycling used four identical FBGs placed in ¼ inch ID ceramic tubes inside of a box furnace. The fibers were placed in the tubes to give structural support for the fiber once the polyimide jacket evaporated. The fibers were positioned in the ceramic tubes such that there was no stress on the bare, unjacketed gratings. The experiment subjected the FBGs to 11 thermal cycles up to 750°C for a total of 66 hours at temperature. The thermal cycles were performed as follows: heat from ambient to 750°C at 1°C per minute; hold at 750°C for 6 hours; cool to 30°C at 1°C per minute.

### B. 750°C Thermal Cycling Observations

Throughout the 750°C evaluation, all four gratings exhibited very similar performance characteristics. All gratings had a shift of approximately 1.2nm per 100°C in Bragg wavelength with temperature as seen in Fig. 3. The magnitude of the shift in the Bragg wavelength is typical for 1300nm FBGs and while the shift was relatively linear, a 2<sup>nd</sup> order polynomial does seem to be a better fit through the temperature range studied in this paper as the response is not exactly linear.

As expected, the initial FBG dissipated relatively quickly taking only three thermal cycles to 750°C to completely dissipate as can be seen in Fig. 2. On average it took a total of 92.1 hours for the original FBG to dissipate equating to an average of 14.5 hours at 750°C. Once the original FBG had dissipated there was a period of about 40 hours in which no measurable signal was reflected from the FBG. However after approximately 40 hours of no signal, during the fourth thermal cycle, and after an average total test time of 132.1 hours, and 21.3 hours at 750°C, a new grating formed and a signal was detected. The newly formed Bragg grating, referred to as an oxygen-chemical composition grating or O-CCG [8], exhibited a response similar to the original FBG.

The original grating structure that dissipated was the result of a photoinduced change in the optical properties of the fiber. The O-CCGs that formed during our experiment are formed through a different mechanism. They are described by Fokine as a modulation of the chemical composition in the core of an optical fiber [8]. The thermal stability of the original photoinduced gratings is likely limited by the thermal stability of the induced birefringence whereas the thermal stability of the O-CCG is “limited by the fringe-to-fringe diffusion of the modulated concentration of ... dopants [5].”

The Bragg wavelength of the original FBG and the newly formed O-CCG exhibited somewhat opposite behaviors at temperature. While at 750°C, the original FBG exhibited a decrease in the Bragg wavelength of about 0.06nm. This initial shift to a shorter wavelength, also seen by Pal et al [2] and Brambilla [9], occurred through the

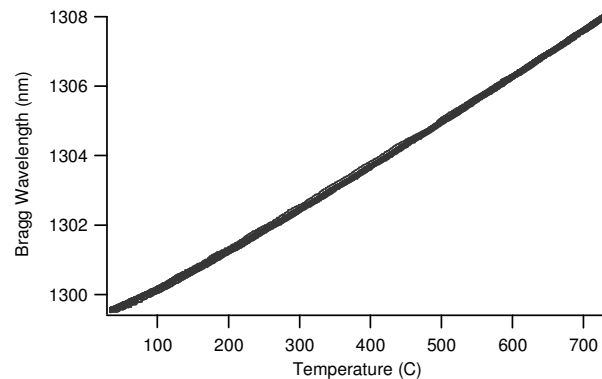


Fig. 3. Typical Bragg wavelength versus temperature response of an FBG during 750°C thermal cycling.

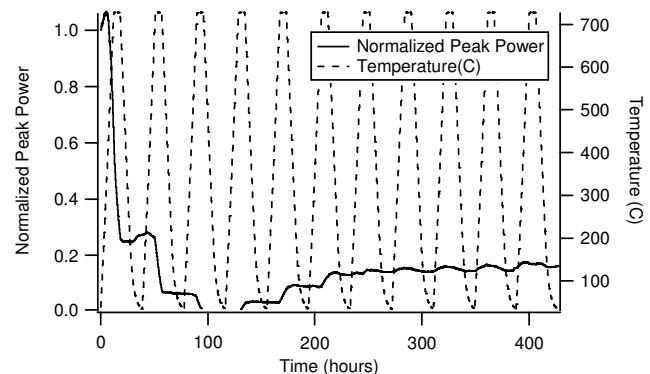


Fig. 2. Typical peak reflected power of an FBG during 750°C thermal cycling. The solid line is the normalized reflected power and the dashed line is the grating. The initial grating's dissipation is evident in the first 100 hours of the experiment followed by the formation of the O-CCG.

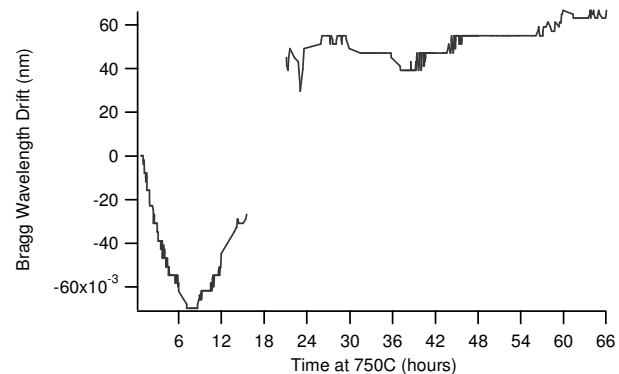


Fig. 4. Typical Bragg wavelength drift during only the 750°C portion of thermal cycling. The gap in the plot is when the original FBG had dissipated and the formation of the O-CCG.

first 6 hours at 750°C and into the first few hours of the next thermal cycle. After about 8 hours of decrease in Bragg wavelength at 750°C, the shift towards a shorter wavelength stopped and began to shift back to a longer wavelength. The Bragg wavelength continued to rise until the original FBG had dissipated. Once the new O-CCG formed, it exhibited far more stable Bragg wavelength characteristics at 750°C than the original FBG as can be seen in the last 45 hours of Fig. 4. The shift in the Bragg wavelength with temperature was still approximately 1.2nm per 100°C but was just offset by about 0.06nm at all temperatures.

With the formation of the new O-CCGs the power response began to increase as seen in Fig. 2 with the signal strength increasing each time the O-CCG was heated to 750°C. By the end of the test the O-CCG's reflected peak power had risen to an average of 13.4% of its original strength.

With a wavelength versus temperature relationship of approximately 1.2nm per 100°C and a drift in the Bragg wavelength of the O-CCGs of no more than 0.03 nm at 750°C, the Bragg wavelength has shown to be an indicator of temperature to within 1% full scale of that measured by the reference s-type thermocouple. This is within the accuracy range of the reference temperature measurement. A complete summary of the 750°C thermal cycling can be seen in See Table 1.

### C. 1000°C Thermal Cycling

The second experiment performed in the evaluation of FBGs was a series of thermal cycles to 1000°C in ambient air. As in the 750°C experiment, four identical 1300nm FBGs were subjected to a series of slow thermal cycles. The four FBGs were placed in ¼ inch ID ceramic tubes inside of a box furnace. The experiment subjected the FBGs to 16 thermal cycles up to 1000°C for a total of 96 hours at temperature. The thermal cycles were performed in a similar manner to the 750°C cycling: heating from ambient to 1000°C at 1°C per minute; hold at 1000°C for 6 hours; cool to 30°C at 1°C per minute. The temperature and various parameters of the FBG's performance were recorded throughout the experiment.

### D. 1000°C Thermal Cycling Observations

Throughout the 1000°C evaluation all four gratings exhibited very similar performance characteristics. As in the 750°C cycling experiment, all gratings had a shift of approximately 1.2nm per 100°C in Bragg wavelength. Similar to the 750°C cycling the shift in Bragg wavelength was relatively linear, however a 2<sup>nd</sup> order polynomial would provide a much better representation of the FBG's wavelength versus temperature response.

Similar to the 750°C cycling, the initial FBG dissipated relatively quickly. However the dissipation of the original FBG seemed to be accelerated by the higher temperature. Before the furnace reached 1000°C all four gratings had dissipated. On average, the original FBG dissipated by the time the furnace had reached 870°C, 14.3 hours into the test as seen in Fig. 5 and Fig. 8. As in the 750°C experiment, after the original FBG had dissipated an O-CCG formed in place of the original grating. This new grating formed an average of 0.2 hours after the dissipation of the original FBG at an average temperature of 888°C. The new O-CCG that formed exhibited very similar Bragg wavelength versus temperature response compared to the original FBG. However there was an initial shift in the Bragg wavelength that occurred mostly in the first six hours at 1000°C as seen in Fig. 6. This shift in the Bragg wavelength that was seen in the first cycle to 1000°C offset the temperature versus wavelength response of the gratings across the entire temperature range studied. This shift in Bragg wavelength from the first thermal cycle to the remainder of the

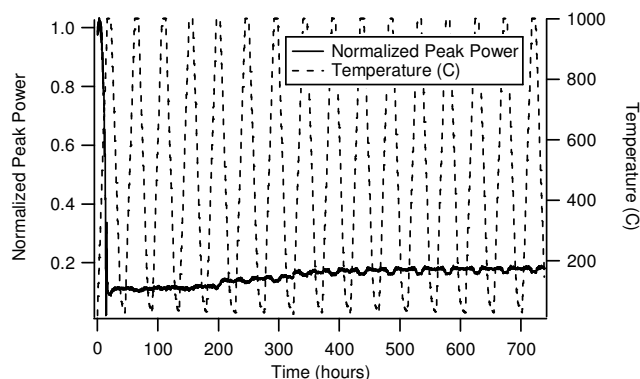


Fig. 5. Typical peak reflected power of an FBG during 1000°C thermal cycling. The solid line is the normalized reflected power and the dashed line is the grating temperature. As can be seen the peak power rises slightly after the O-CCG forms dropping a few percent as the FBGs are at heated.

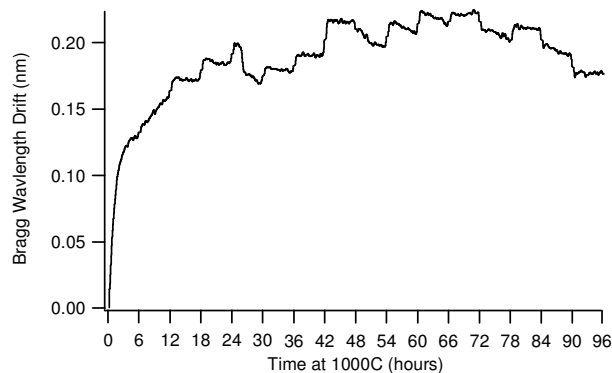


Fig. 6. Typical Bragg wavelength drift during only the 1000°C portion of thermal cycling. The plot shows the drift of a few tenths of a nanometer to longer wavelengths.

cycles can easily be seen in wavelength versus temperature plot of Fig. 7. The lower line in the plot is the grating's response on the initial heating to 1000°C. The break in the lower line is the time when the O-CCG was forming and no measurable signal was reflected. The upper, broader line is the temperature response of the grating through the remainder of the thermal cycling. After this initial shift of about 0.15nm to 0.20nm, the new O-CCG that formed in place of the original FBG had a stable Bragg wavelength at 1000°C as seen in Fig. 6. There was only a few hundredths of a nanometer drift for the remainder of the experiment.

The reflected peak power response of the new O-CCG exhibited a reversal of the degradation of the signal as seen in Fig. 5 with the reflected peak power increasing each time the new O-CCG was heated to 1000°C. By the end of the test, the O-CCG's reflected peak power had risen to an average of 11.8% of the original signal strength, nearly twice the starting level.

Allowing for an annealing time of two thermal cycles to 1000°C the Bragg wavelength of the O-CCGs proved to be an accurate representation of its temperature. With a drift in the Bragg wavelength of the O-CCGs of no more than 0.08 nm at 1000°C after two complete thermal cycles, the Bragg wavelength is an indicator of its temperature to within 1% full scale of that measured by the reference s-type thermocouple within the accuracy range of the reference temperature measurement. A complete summary of the 1000°C thermal cycling experiment can be seen in Table 1.

### III. LONG DURATION THERMAL EVALUATION OF FBGS

The third experiment performed in the evaluation of FBGs was a long duration evaluation at 1000°C in ambient air. In this experiment three identical 1550nm FBGs were held at 1000°C for 400 hours continuous. Despite these FBGs having a different Bragg wavelength, they were fabricated in the same manner and in the same fiber as the 1300nm FBGs used in the previous experiments. As in the previous experiments, the FBGs were placed in ¼ inch ID ceramic tubes inside of a box furnace. The FBGs were heated from ambient to 1000°C at 1°C per minute, the same in the previous experiments. Once at 1000°C, they were held there for 400 hours. The temperature and various parameters of the FBG's performance were recorded throughout the experiment.

#### A. Long Duration Thermal Evaluation of FBGs Observations

As in the 750°C and 1000°C thermal cycling, all three FBGs exhibited similar behavior. A shift of approximately 1.5nm per 100°C in the Bragg wavelength versus temperature was seen, slightly more than with

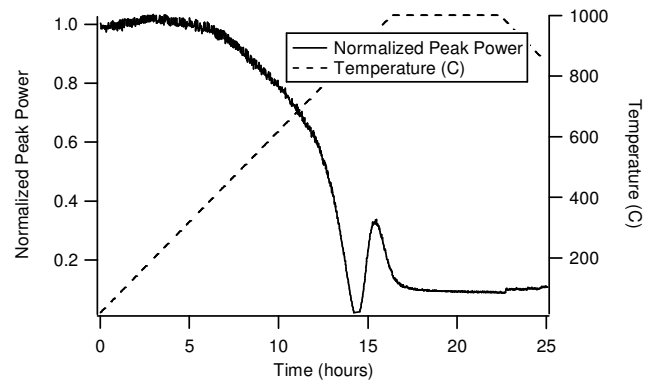


Fig. 8. A close-up of the peak reflected power shown in Fig. 5. The degradation of the original gratings and formation of the O-CCG are easily seen. The solid line is the normalized reflected power and the dashed line is the grating temperature.

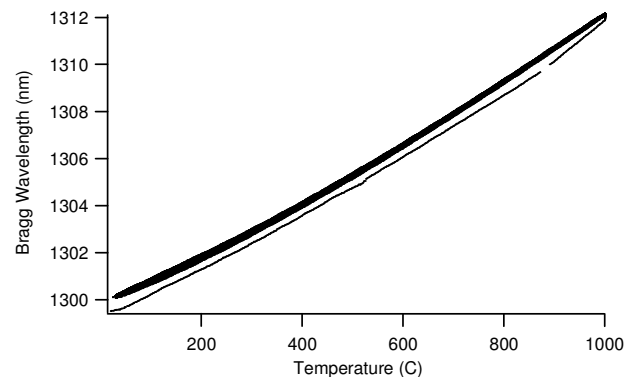


Fig. 7. Typical Bragg wavelength versus temperature response of an FBG during 1000°C thermal cycling. The plot shows two distinct lines. The lower line is the thermal response of the FBG during the initial heating to 1000°C. The upper, broader line is the response of the FBG over the remainder of the thermal cycling. The gap in the plot is when the original FBG had dissipated and the formation of the O-CCG.

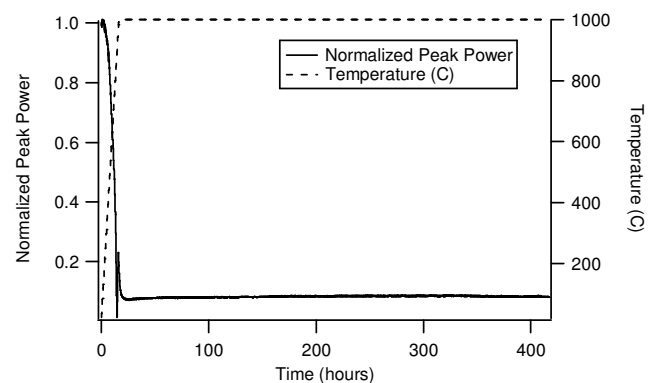


Fig. 9. Typical peak reflected power during long duration 1000°C evaluation. After the dissipation of the initial grating the power response from the reformed CCG is very stable, varying less than 1% over the remainder of the experiment.

the 1300nm gratings used in the cycling experiments. As in the thermal cycling experiments, the temperature versus wavelength response was fairly linear however a 2<sup>nd</sup> order polynomial is a better fit. The initial FBG dissipated at average temperature of 882°C, 14.3 hours into the test as seen in Fig. 9 and Fig. 11. This was about the same time to dissipation and temperature as seen in the 1000°C thermal cycling experiment using 1300nm FBGs.

As with the 1300nm FBGs, O-CCGs formed in the place on the original gratings. The new O-CCGs appeared at an average temperature of 913°C and after 14.8 hours of testing as seen in Fig. 11. The O-CCGs took 0.5 hours on average to form, an average of 0.3 hours longer to form than the 1300nm O-CCGs did during the 1000°C thermal cycling experiment.

Similar to the 1300nm O-CCGs in the 1000°C thermal cycling experiment, the Bragg wavelength of O-CCG exhibited a logarithmically shaped drift while at 1000°C, rising 0.48nm on average in the first 125 hours, then appearing to level off. This initial shift was almost twice the 0.28nm drift seen in the 1300nm gratings in the 1000°C thermal cycling experiment. After the quick rise in the first 125 hours of the experiment, the Bragg wavelength appeared to stabilize, however a slow downward, approximately linear, drift began that continued for the remaining 270 hours of the experiment. During this linear drift, the Bragg wavelength shifted 0.19nm on average down from its maximum. The complete response of the Bragg wavelength can be seen in Fig. 12.

The response of the reflected peak power was similar to that seen during 1000°C thermal cycling. The decay of the original grating was exponential then exhibited a slightly underdamped type of response with the formation of the new O-CCG. This can be seen in Fig. 11. After the formation of the O-CCG, the peak reflected power from the new grating rose to about 20% of the original power response then began to decrease. About 5 hours after the formation of the O-CCG the signal stabilized to about 7% of the original grating. The peak power response would remain stable throughout the remainder of the experiment, varying by no more than a percent for any of the three gratings evaluated.

After an annealing time of 25 hours at 1000°C, the Bragg wavelength of the O-CCGs proves to be an accurate representation of its temperature. With a drift in the Bragg wavelength of the O-CCGs of no more than 0.19 nm at 1000°C after 25 hours of annealing at 1000°C, the Bragg wavelength is an indicator of temperature to within 3% full scale of that measured by the reference s-type thermocouple. A complete summary of the long duration testing can be seen in Table 1.

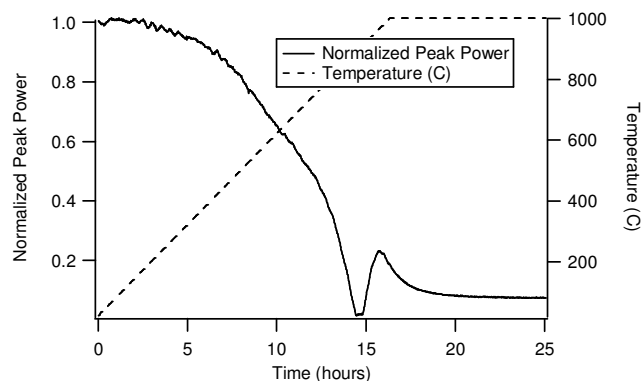


Fig. 11. A close up of the peak reflected power shown in Fig. 9. The degradation of the original gratings and formation of the O-CCG are easily seen. The solid line is the normalized reflected power and the dashed line is the grating temperature.

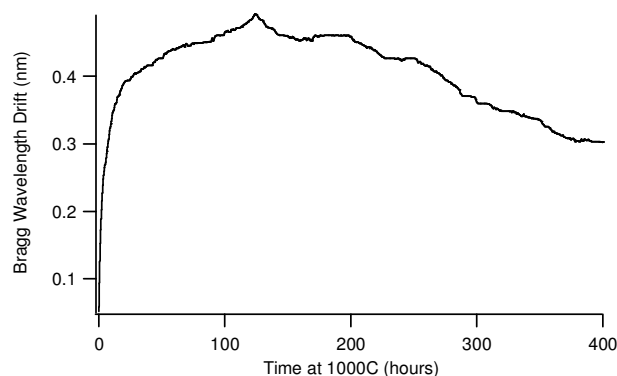


Fig. 12. Typical Bragg wavelength drift while at 1000°C during long duration testing. The relatively quick rise then gradual decrease in the peak wavelength was typical.

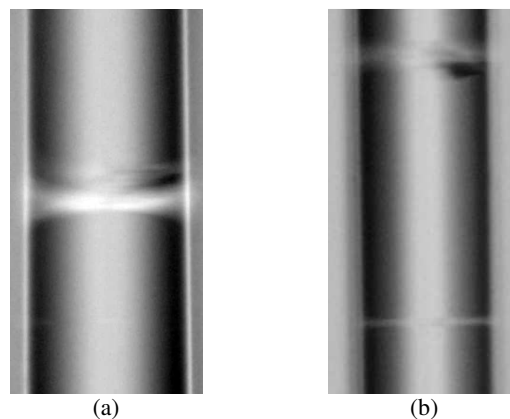


Fig. 10. Microscopic images of cracks formed in optical fiber during thermal cycling. Both fiber (a) and (b) are 9/125 fiber and are typical of the fiber used throughout the thermal evaluation process. Fibers are shown after the polyimide coating has burned off. Only the cladding is visible in the images.

## IV. MECHANICAL PROPERTIES OF THERMALLY CYCLED FBGS

The shift of the Bragg wavelength in the last two experiments presented in this paper exhibited a shift that was not initially explainable. To try and shed some light on this unusual behavior a closer examination of the fiber's material properties was undertaken. Work by Rose et al [7] had discussed the devitrification and resulting transmittance loss of optical fibers that were heated to temperatures as low as 850°C. Samples of our cycled fibers were examined for signs of devitrification but none were visible. However, during the examination of the fibers for signs of crystallization, small cracks were seen in the cladding of the fiber as seen in Fig. 10. (a) and (b). There were no cracks seen in the core.

### A. Acoustic Emissions Analysis

To further investigate the cracking seen in the fibers from the thermal evaluation experiments, samples of the similar fibers without a grating were thermally evaluated while monitoring the fiber for acoustic emissions. An acoustic emission from a fiber is equated to a crack forming somewhere along its length. The experimental setup used is shown in Fig. 13.

### B. Acoustic Emissions Analysis Observations

The results of the acoustic emissions evaluation can be seen in Fig. 14. The solid line indicates the temperature of the gratings and the line with the circles indicates the acoustic emissions count, or cracking. One immediately notices that the shape of the acoustic emissions curve resembles that of the Bragg wavelength drift in Fig. 6 and Fig. 12. The cracking events seemed to occur frequently through the beginning of the experiment but then tapered off. Although not easily seen in Fig. 14, the cracking events seem to occur most frequently during the cooling process. Upon inspection of the fiber the cracks seemed to be visible only in the cladding. No cracks were noted in the fiber core.

### C. Acoustic Emissions Phenomena Theories

As noted in the previous section the acoustic emissions seem to take on a similar shape to that of the peak wavelength drift. While there is only a circumstantial relationship between the cracking events and the drift of the Bragg wavelength, it seems plausible that the drift seen in the 1000°C experiments could be caused by cracking and an associated expansion of the fiber core due to the cracking of the cladding. However, this theory does not explain the reversal of the Bragg wavelength drift seen in the long duration 1000°C experiment. Further investigation is needed to confirm a relationship between the cracking events and the drift of the Bragg wavelength.

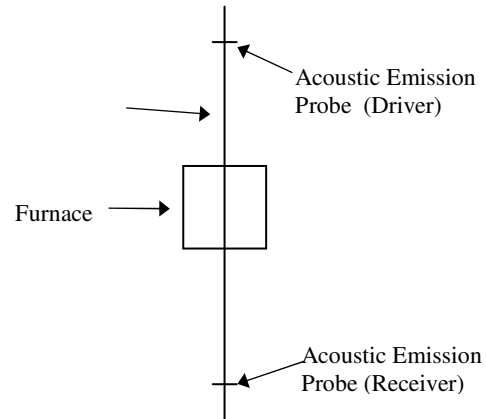


Fig. 13. Experimental set-up for monitoring of acoustic emissions of an optical fiber during thermal cycling.

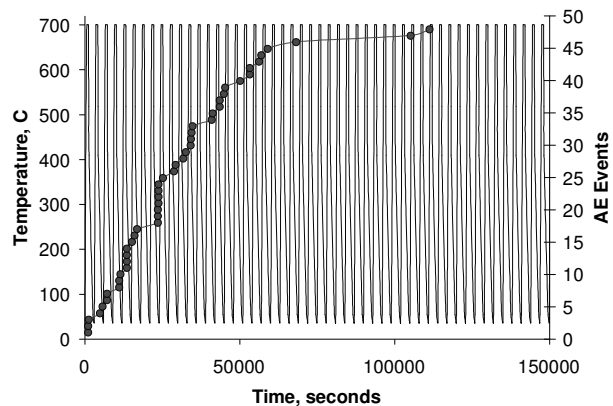


Fig. 14. Acoustic emissions in an optical fiber over a series of thermal cycles. The solid line is the temperature of the cycling while the plot with the circles indicates an acoustic emission count. The acoustics emissions equate to a crack forming somewhere along the length of the fiber.

Table 1. Summary of the performance of FBGs during thermal evaluation.

	1300nm Polyimide Coated		1550nm Polyimide Coated	
	750°C Cycling	1000°C Cycling	1000°C Hold	
<i>Time to initial dissipation of FBG</i>	Total time: 90.2-93.9 HR Avg.: 92.1 HR	Time at 750°C: 12.6-16.3 HR Avg.: 14.5 HR	14.2-14.3 HR Avg.: 14.3 HR @ 855-878°C Avg.: 870°C	14.2-14.4 HR Avg.: 14.3 HR @ 875-886°C Avg.: 882°C
<i>Time to appearance of O-CCG</i>	Total time: 130.3-136.1 HR Avg.: 132.1 HR	Time at 750°C: 20.0-24.0 HR Avg.: 21.3 HR	14.3-14.5 HR Avg.: 14.5 HR @ 880-892°C Avg.: 888°C	14.8-14.9 HR Avg.: 14.8 HR @ 911-915°C Avg.: 913°C
<i>Formation time of O-CCG*</i>	37-45.9 HR Avg.: 40.0 HR		0.1-0.3 HR Avg.: 0.2 HR	0.4-0.6 HR Avg.: 0.5 HR
<i>Standard deviation of Bragg wavelength at maximum temperature before formation of O-CCG<sup>†,‡</sup></i>	0.02-0.04nm Avg.: 0.03nm			
<i>Maximum Bragg wavelength drift at maximum temperature before formation of O-CCG<sup>‡‡, §§</sup></i>	0.07-0.13nm Avg.: 0.10nm			
<i>Standard deviation of Bragg wavelength at maximum temperature after formation of O-CCG<sup>‡‡, §</sup></i>	0.01-0.02nm Avg.: 0.01nm	0.03-0.06nm Avg.: 0.04nm		0.05-0.09 nm Avg.: 0.07nm
<i>Maximum Bragg wavelength drift at maximum temperature after formation of O-CCG<sup>‡‡, ***</sup></i>	0.05-0.09nm Avg.: 0.07nm	0.23-0.34nm Avg.: 0.28nm		0.45-0.52 nm Avg.: 0.48nm
<i>Total time at maximum temperature<sup>***</sup></i>	66 HR, 11 cycles	96 HR, 16 cycles		400 HR
<i>Final peak reflected power level as percent of original power level<sup>***</sup></i>	11.9%-15.8% Avg.: 13.4%	9.3%-17.8% Avg.: 11.8%		6.1%-8.4% Avg.: 7.5%

\* The formation of the O-CCGs occurred over two cycles during the 750°C evaluation. The time shown is the total experiment time for their formation.

† For 750°C testing the statistic shown is for Bragg wavelength at 750°C. For 1000°C testing the statistic shown is for Bragg wavelength at 1000°C.

‡ For the 1000°C cycling, the O-CCGs formed before reaching 1000°C, thus there are no statistics on the performance of the gratings before the O-CCG formed.

§ For the 1000°C cycling three gratings were cycled 16 times. The fourth grating was subjected to 7 cycles then evaluated for damage to the fiber.

## V. CONCLUSION

In conclusion, this work has demonstrated the long term survivability of commercially available oxygen-chemical composition gratings formed from fiber Bragg Gratings at temperatures up to 1000°C through many thermal cycles and also for continuous use at temperature up to 1000°C. For use up to 750°C it has been shown that, after the formation of an O-CCG, peak wavelength response is stable to within a few hundredths of a nanometer and could be used to measure temperature to within the accuracy of the reference measurement. This work has demonstrated that at temperatures up to 1000°C the stability of O-CCGs would allow temperature measurements to be made within 3% of the reference s-type thermocouple. This work has also demonstrated the long term survivability of O-CCGs formed in germanium doped silica fibers through over 400 hours of thermal cycling to 750°C and 700 hours of thermal cycling to 1000°C. The accuracy and stability of O-CCGs for use as temperature sensors for temperatures up to 1000°C has been demonstrated.

Throughout this work many similarities to the work of Fokine were observed including the formation O-CCGs [8], similar ratios of decay rate to heat rate in formation of O-CCGs [4], and similar gratings decay behavior [4, 5]. However we saw a trend of shifting to longer wavelengths at high temperatures whereas he indicated a shift to shorter wavelength [2].

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