High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors
• Goals and Objectives
Investigate the in-pile performance of sapphire optical fiber temperature sensors and to develop clad sapphire optical fibers for in-pile instrumentation. Evaluate the distributed sensing performance of the sensors through optical backscatter reflectometry under combined radiation and temperature effects, and high fluence.

– Objective 1: Fabricate sapphire optical fiber sensors.
– Objective 2: Evaluate the clad sapphire fiber to verify few-mode behavior and determine and characterize light modes supported by optical fibers.
– Objective 3: Characterize in-pile temperature sensing of sapphire optical fiber and combined temperature and irradiation effects.
– Objective 4: Evaluate the lifetime and sensing performance of the sensor under irradiation to high neutron fluence.

• Participants (2021)
– Idaho National Laboratory: Lead organization
  • Dr. Joshua Daw, Kelly McCary
– The Ohio State University
  • Dr. Thomas Blue, Josh Jones, NRL
– The Massachusetts Institute of Technology
  • NRL
– National Energy Technology Laboratory
  • Dr. Michael Buric
– Oak Ridge National Laboratory
  • Dr. Christian Petrie

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Technology Impact

• This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology with the potential to make measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors. This technology can also be applied to measurements other than temperature.

• This research will deliver modern optical fiber sensing techniques usable in multiple extreme environment applications. In the area of nuclear fuel/material testing, these fibers will enable access to operational data with excellent time and space resolution during irradiation testing.

• Commercialization is underway by Luna Innovations. This research represents the opportunity to close technology gaps and demonstrate the potential of sapphire optical fibers.
Accomplishments

• Sapphire fiber preparation:
  – Fiber procurement
  – FBG inscription
  – Fiber cladding irradiations
  – Annealing

• Out of pile furnace testing
• Heated irradiation at OSURR
Sapphire fiber cladding:
• Four one-day irradiations were completed with the purpose of cladding sapphire fiber
  • Cladding Irradiation #1: Completed January 24, 2019
    • 2 fibers, 100 um OD, with 2 FBGs inscribed by UPitt
    • 1 fiber, 100 um OD, without FBGs
    • 1 fiber, 75 um OD, with 13 FBGs inscribed by FemtoFiberTec
  • Cladding Irradiation #2: Completed March 13, 2020
    • 4 fibers, 100 um OD, each with 1 FBG inscribed by UPitt
  • Cladding Irradiation #3: Completed March 12, 2021
    • 2 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec
  • Clad Irradiation #4: Completed March 19, 2021
    • 4 fibers, 125 um OD, each with 4 FBGs inscribed by FemtoFiberTec

Post-Processing:
• Thermal annealing, polishing and splicing

Challenges: Annealing, Splicing
Sapphire optical fiber sensors were tested in a box furnace at up to 1500ºC prior to deployment in OSURR

- 8 in. heated region
- Interrogated with a Luna Innovations OBR 4600
- All the fibers were placed in alumina tubes that were closed on the heated end, then spliced to silica lead-out fibers
- When the furnace was heated past 1100ºC, the sensing mechanism failed

Results: Out of Pile Testing

Sensor 1: 75 um diameter – 13 FBGs inscribed by FemtoFiberTec
We believe this sensing failure was partially due to the wavelength range of the interrogator.

**Results: Out of Pile Testing**

Top: Backscatter profile of sensor #1 before, during, and after the out-of-pile heating from room temperature to 1500°C. Bottom: Top image zoomed in on the last three FBGs in the fiber.

Top: Frequency response of FBG #12 before, during, and after the out-of-pile heating from room temperature to 1200°C. Bottom: Frequency response of FBG #12 before, during, and after the out-of-pile heating from room temperature to 1500°C.
Results: Heated Irradiation

Sensor 1: 75 um diameter – 13 FBGs inscribed by FemtoFiberTec
  – Annealed to 1500°C in air, 23.5 in. long
Sensor 2: 100 um diameter – 2 FBGs inscribed by UPitt
  – Annealed to 1500°C in air, 13 in. long
Sensor 3: 100 um diameter – 1 FBG inscribed by UPitt
  – Annealed to 1200°C in air, 15.25 in. long
Sensor 4: 100 um diameter – No FBGs
  – Annealed to 1500°C in air, 9.25 in. long
Sensor 5: 100 um diameter – 1 FBG inscribed by UPitt
  – Annealed to 1500°C in air, 16.25 in. long
Results: Heated Irradiation

The heated irradiation was designed to test the fibers at various temperatures from ambient to 1600°C

- Total fluence: $3.2 \times 10^{17} \text{n/cm}^2$
- Thermal: $2.3 \times 10^{17} \text{n/cm}^2$

Backscatter profile of sensor #1, 75 um OD sapphire fiber featuring FBGs inscribed by FemtoFiberTec.

<table>
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<tr>
<th>Day</th>
<th>Hours</th>
<th>Power (kW)</th>
<th>Furnace Temp. (Celsius)</th>
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<tr>
<td>1</td>
<td>7</td>
<td>450</td>
<td>off/200</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>450</td>
<td>400/600</td>
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<td>3</td>
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<td>4</td>
<td>450</td>
<td>900</td>
<td>4 hours, some hours for another customer at 5 kw</td>
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<tr>
<td>5-1</td>
<td>0</td>
<td></td>
<td>1000</td>
<td>Fuse blow</td>
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<tr>
<td>5-2</td>
<td>7</td>
<td>450</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>7</td>
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<td>1100</td>
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</tr>
<tr>
<td>7</td>
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<td>7</td>
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<td>1.5 hrs at 800, 2 hrs at 1000, 2 hrs at 1200</td>
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<tr>
<td>11</td>
<td>7</td>
<td>450</td>
<td>1400 1 hr at 1500</td>
<td>Fuse blow during heating</td>
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<tr>
<td>12</td>
<td>6</td>
<td>450</td>
<td>1500 1 hr at 1600</td>
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The measurement was resolved at the locations of the FBGS.

Sensor 1 – 75 um OD – performed the best.

Sensor gets less noisy with higher temperatures.

Results: Heated Irradiation

Day 11

$2.9 \times 10^{17}$ n/cm$^2$
Results: Heated Irradiation

- Similar failure mechanism was observed at 1600°C in-pile as was observed in out of pile testing.
Results: Heated Irradiation

- After signal loss and amplitude reduction the FBGs recover as the fiber cools to room temperature.
- Similar amplitude reduction up to 1500°C that was seen in furnace testing.
Challenges:

- Procurement, inscription, and processing of sapphire
  - Non-commercial supplier of sapphire fibers experienced unforeseen issues
  - Inscription of sapphire fibers is not a trivial task
  - Splicing fibers can produce variable results
- Handling tritium-implanted fibers at INL
- Navigating through travel restrictions and shutdowns

Conclusions:

- Objectives 1-3 have been completed
- Heated irradiation indicates potential for sapphire fiber-based sensors to be used in extreme environments beyond silica fiber limits

Future Work:

- Further evaluation of un-clad sapphire fibers to determine source of attenuation in fiber
- High-fluence irradiation at MITR

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Questions?