Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure

FY2019 Progress for DOE SBIR Award DE-SC0017826
Luna Overview

We’re organized into two main business segments: **Products and Licensing** and **Technology Development**, which work closely together to turn ideas into products.

**Products and Licensing segment**

**Fiber optic instruments:**
Develop and commercialize breakthrough technologies for targeted industries
- Sensing products for the high growth aerospace, automotive, and energy markets
  - ODISI™-6000 Series
  - OBR™-4600
  - Hyperion™ si155 and si255
- Test & measurement solutions, primarily for the telecommunications industry
  - OBR™-4600
  - OVA™5000

**Terahertz solutions:**
Develop and commercialize disruptive sensing technologies for manufacturing applications
- Leading provider of industrial systems for quality control, inspection, and process control

**Technology Development segment**

**Applied research:**
Contract research ultimately focused on commercialization
- Focused areas: **Sensing & instrumentation**, Materials, Health sciences, Optical systems, Terahertz
Luna is a global company providing innovative products and solutions using proprietary fiber optic technologies.

- Founded 1990
- Corporate headquarters in Roanoke, VA
- 260+ Employees
- IPO in 2006 - NASDAQ: LUNA
- Reporting Segments
  - Technology Development
  - Products and Licensing
- Worldwide presence and support
- Strong, consistent growth
- Recent expansion
  - Micron Optics – 2018
  - General Photonics - 2019
The Problem

- Desire sensors that reduce containment vessel feedthrough count
- Combine fiber optic sensors to measure multiple properties
  - No electrical power requirements in vessel
  - Serial inline sensors reduce number of signal cables
- Targeting DOE Labs, Gen III & IV Commercial nuclear power, other high temperature harsh environments
Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure

Technology Summary

This project is working towards the advancement of multi-point temperature and pressure sensors toward commercialization of sensors for GenIV reactor environments. During Phase I sensors were successfully evaluated to 1000°C, combined temperature and pressure of 300°C and 2500psi, and to neutron fluence of 9E17 n/cm². Phase II has produced advancements in feedthrough fabrication, material compatibility studies, and testing of sensors to 2.54E18 n/cm². Temperature and pressure measurements are achieved by combining Fiber Bragg Gratings (FBGs) on the same fiber as one of Luna’s Extrinsic Fabry-Perot Interferometer (EFPI) sensors. This design utilizes recent advances in fiber chemistry and FBG manufacturing techniques resulting in radiation hardened sensors.

Technology Impact

Current temperature measurements utilize single point Type-K thermocouples, and to the PI’s knowledge, there exist no in-core pressure sensors. Luna’s sensor under development, will provide multipoint temperature readings with single point pressure at the fiber tip. This new class of sensor will provide for advanced monitoring while decreasing cable feedthroughs.

Project Summary

Period of Performance: Total Budget: $1,159,994
Start Date: 6/12/17 End Date: 8/26/2020

Key Milestones & Deliverables

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017 Sept.</td>
<td>Phase I Project Kickoff</td>
</tr>
<tr>
<td>2018 March</td>
<td>Phase I Final Report</td>
</tr>
<tr>
<td>2018 Sept.</td>
<td>Phase II Project Kickoff</td>
</tr>
<tr>
<td>2019 June</td>
<td>Sensor Operation in OSURR</td>
</tr>
<tr>
<td>2020 March</td>
<td>Sensor Operation in OSURR</td>
</tr>
<tr>
<td>2020 Summer</td>
<td>Long Sensor Operation in OSURR</td>
</tr>
</tbody>
</table>
Sensor Response for EFPI with Serial FBGs

- Change in temperature at FBG yields a wavelength shift directly proportional to temperature.
- Change in Pressure at the EFPI produces a change in cavity length which is measured by the change in fringe period.
Sample Data from Combined EFPI and fsFBG Sensor Using Luna Hyperion si155

Combined EFPI and fsFBG Sensor For Multiple EFPI gap distances

Data collected at room temperature using a translational stage to vary EFPI gap
Year 1 (Phase I) Accomplishments

Temperature sensing to 1000°C
FBG Temperature and EFPI gap sensing in radiation environment of:
  9.18E17 n/cm²
  2.6E7 rad-Si neutron dose
  1.3E9 rad-Si gamma dose
Temperature and pressure sensing to 300°C and 2500 psi
Year 2 (Phase II year 1)

The focus of Year 2 has been on:
1. Continuing analysis of phase I data
2. Developing moderate temperature high pressure feedthrough
3. Developing high temperature moderate pressure feedthrough
4. Advancing sensor development
5. Performing high irradiation tests
6. Publishing Phase I and Phase II results
Pressure Feedthrough Development

Phase I lower temperature feedthroughs acquired from external source.

Acquisition of Micron Optics (Luna-Lightwave, Atlanta) provided additional manufacturing capabilities

1. Feedthroughs are being developed at Luna-Lightwave, Atlanta.
   1. Glass to metal transition mechanical design complete
   2. Initial feedthroughs developed
   3. Thermal cycling from room temperature to 350°C
   4. Assembly cross-sections show no degradation
   5. Pressure and combined pressure and temperature sensor construction expected in early 2020.

Phase I pressure penetrator: Fiber optic pressure vessel feedthrough Rated for 300°C and 5000psi
Sensor compatibility studies

(a) SE and (b) BSE images showing oxidized salt fully cover fiber optic F103 immersed in MgCl2-KCl-NaCl after 24 hours

MgCl2-KCl-NaCl test
- Salt covered surface
- No salt penetrated the fiber

Surrounding Environment:
- O₂ : < 100 ppm
- H₂O : < 5 ppm

MgCl2-NaCl-KCl

Fiber

Alumina Crucible

<table>
<thead>
<tr>
<th>Material</th>
<th>SS 316</th>
<th>FLINaK</th>
<th>Pb-BI</th>
<th>PWR</th>
<th>MgCl2-KCl-NaCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Packaging</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hast. N</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Hast. X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Raw Fibers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F 101</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
<tr>
<td>F 102</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
<tr>
<td>F 103</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
<tr>
<td>F 105-1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
<tr>
<td>F 105-2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
<tr>
<td>F 106</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>n/a</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Legend
- ✔ Excellent
- ● Good
- ○ Moderate
- X Incompatible
- n/a Not Applicable
• fsFBG $\lambda$ shifts near linearly with respect to temperature
• The measurements shown are at room temperature and 100°C+ with the first fsFBG always at room temperature
• Proportionality constants vary depending on fiber with ranges of 8-16 pm/°C (62-125°C/nm)
Type-II Enhanced Rayleigh Scatter Tested in Rad-Hard Optical Fiber

• Similar to fsFBG’s the spectral data from Rayleigh scatter for a given region of fiber shifts as temperature changes.

• By writing scattering points we are able to raise the Rayleigh scatter level increasing the signal to noise ratio for such measurements.

• The graphs below show the FFT from the delay domain to the frequency domain for in regions with and without Enhanced Rayleigh Scatter Points.
OSURR Irradiation

Fiber Type F105 - FBG4

- TC4
- fbg4_λ_Ch5
- fbg4_λ_Ch11

Temperature (°C)

0E+0  5E+4  1E+5  2E+5  3E+5  4E+5

Time (s)

5.06E+17 n/cm²
1.86E+18 n/cm²
2.54E+18 n/cm²

Change in FBG Wavelength (nm)

0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1.0

OSURR AIF

Fiber optic leads to Sensor
Chassis deployed in OSURR AIF

Luna’s si155
Luna’s OBR 4600
DAQ Computers
Optical Switches
The Ohio State University Research Reactor

Spectral Shift (GHz)

-50  0  50  100  150  200  250

Time (s)

3E+4  8E+4  1E+5  2E+5  3E+5  4E+5
Publications and Conferences

• S. Derek Rountree, “Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure,” Advanced Sensors and Instrumentation Newsletter, Issue 9, Sept. 2018,
• Brian Risch, et. al, “Characterization of Fiber Optics with Femtosecond-Infrared Fiber Bragg Gratings for Extreme Applications,” SPIE OPTO 2019
• Steven Derek Rountree, et. al, “Multi-parameter fiber optic sensing for harsh nuclear environments,” SPIE Defense and Commercial Sensing, 26 - 30 April 2020 (Submitted)
Year 3 (Phase II Year 2)

1. Continue analysis of phase I data
   • 0-1000 °C at ambient pressure
   • 300°C @ 2500psi
   • 0 - 9.18E17 n/cm² with varying temperature 0-90°C
2. Publish Phase I results
3. Advance sensor development for 350°C @ 3500psi
   • Test sensors to 350°C @ 3500psi in noble gas
   • Test sensors to 350°C @ 3500psi water loop
4. Advance sensor development for 525°C+ @ 100psi
   • Test sensors to 537°C @ 100psi in noble gas
   • Test sensors to 537°C @ 100psi in molten salt loop
5. Advance sensor development for 750°C+ @ 100psi
6. Develop advanced analysis algorithms
7. Determine standard operating procedure for sensor calibration
8. Perform high temperature and pressure tests in irradiation environment
9. Perform high irradiation tests
The sensor development of the “Fiber-Optic Sensor for Simultaneous Measurement of Temperature and Pressure” project will:

- Provide never before available:
  - In-core single feedthrough multipoint temperature sensing
  - In-core pressure sensing
  - Multipoint temperature with endpoint pressure sensing

- Provide enhanced sensing capabilities for:
  - Reactor monitoring
  - GenIV fuel and fuel assembly studies
  - Solar salt loop monitoring

- Enable advanced instrumentation and controls

- Be Commercialized via Luna’s extensive network of commercial partners in the nuclear industry.
Energy Markets

- Gen IV Reactors
- Fusion Reactors
- Solar Concentrator Power Plants
- And More

Conclusion

Phase I Accomplishments:

– Temperature sensing to 1000°C
– Temperature and EFPI gap sensing in radiation environment of:
  • 9.18E17 n/cm2
  • 2.6E7 rad-Si neutron dose
  • 1.3E9 rad-Si gamma dose
– Temperature and pressure sensing to 300°C and 2500 psi

Phase II Goals:

– Sensor packaging for existing PWR fleet
– Sensor packaging for GenIV molten salt reactor environment
– Sensor packaging for GenIV molten metal reactor environment
– Sensor testing in combined temperature, radiation, and pressure environment
Luna – S. Derek Rountree, Matt Davis, Andrew Boulanger
Virginia Tech – Jinsuo Zhang, Amanda Leong
Pitt – Kevin Chen, Mohan Wang
Contact Information

Steven Derek Rountree, Ph.D.
Research Scientist
Luna Innovations, Lightwave Division
3155 State Street
Blacksburg, Va 24060
Main: 1-540-552-5128
Direct: 1-540-558-1667
rountreed@lunainc.com
www.lunainc.com

Open positions at:
https://lunainc.com/about-luna/careers/jobs/
This material is based upon work supported by the Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0017826."

Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.