Scaled Reduced Mode Sapphire Fiber Production (RMSF) Towards High Temperature Radiation Resilient Sensors

November 6th, 2024

Funding Agreement No: **DE-SC0022832**
Award Date: **8/11/22**

Principle Investigators: Steven Derek Rountree (Luna)
Tom Blue (OSU)

Luna Innovations Overview

Luna focuses on developing advanced optical technology and solutions that enable our customers to more efficiently design, manufacture and manage products, processes and assets.

History
Incorporated 1990
IPO 2006

Employees
+400

SENSING

Infrastructure, Energy, Automotive, Aerospace

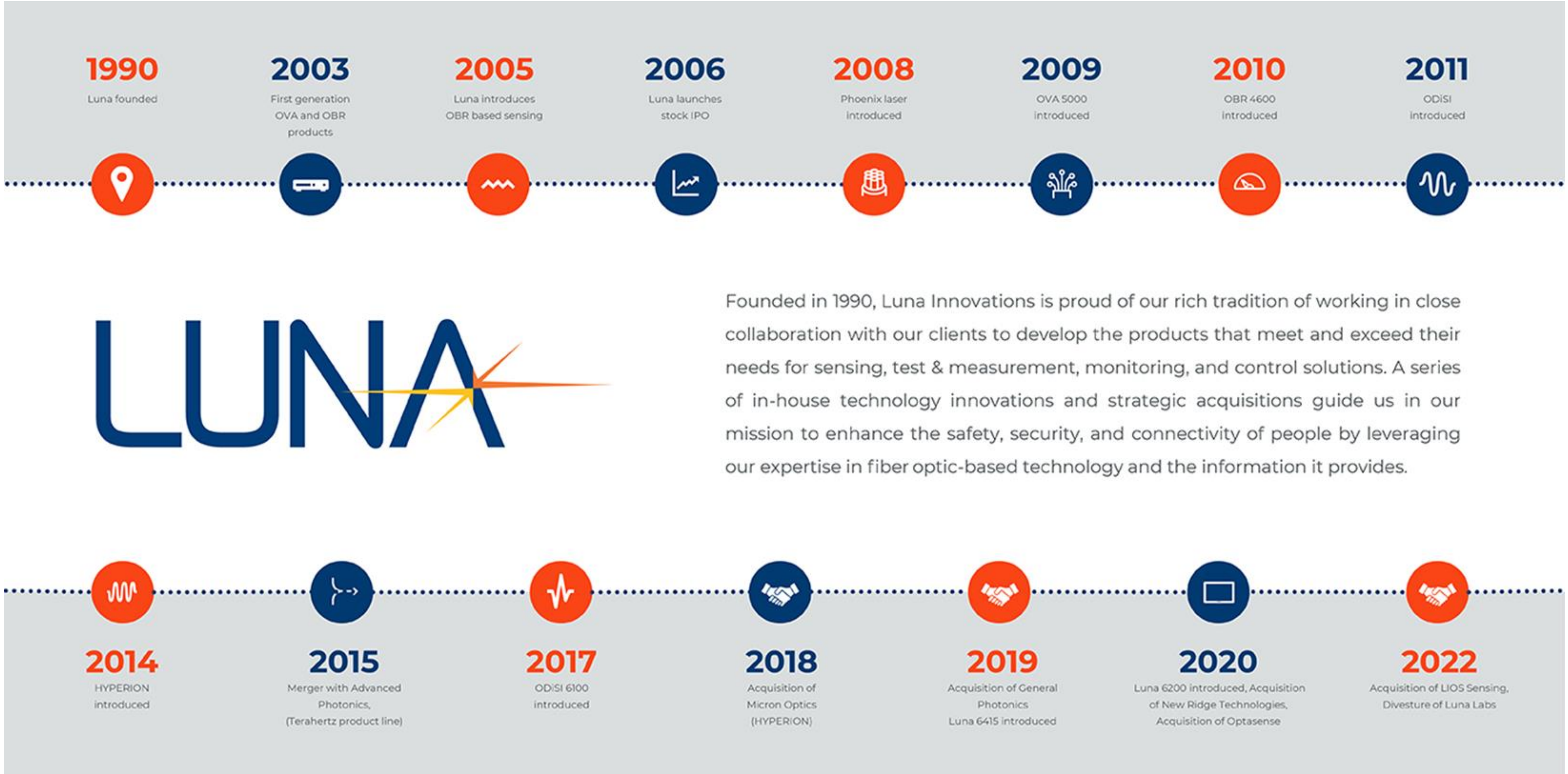
- Fiber optic sensing
- Terahertz gauging/imaging

PHOTONICS TEST & CONTROL

Telecom, Datacom, Aero/Defense

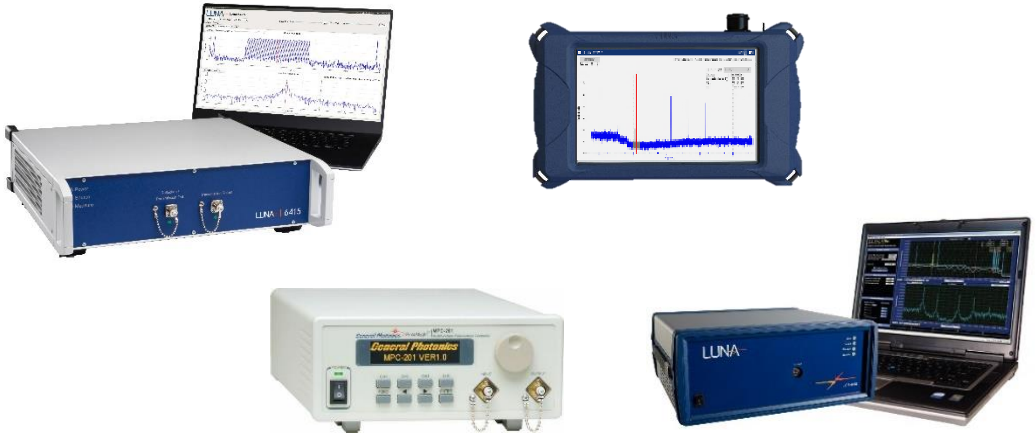
- Fiber optic test
- Component test
- Lasers, modules, components

Luna has a clear vision and established history



Communications Test and Control — Product Portfolio

Test & Measurement



- PIC / Component Test
- Fiber Optic Network Test
- Optical Backscatter Reflectometer (OBR)
- Polarization Analysis
- Polarization Management

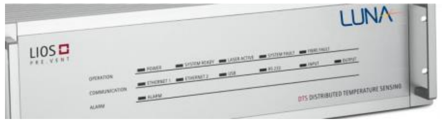
OEM Modules and Components

- Polarization Control
- Tunable Filters
- Delay/Phase Control
- Tunable Lasers
- Fiber Coils
- Narrow Linewidth Lasers

Fiber Optic Sensing: 4 Platforms, 4 Technologies

ODiSI

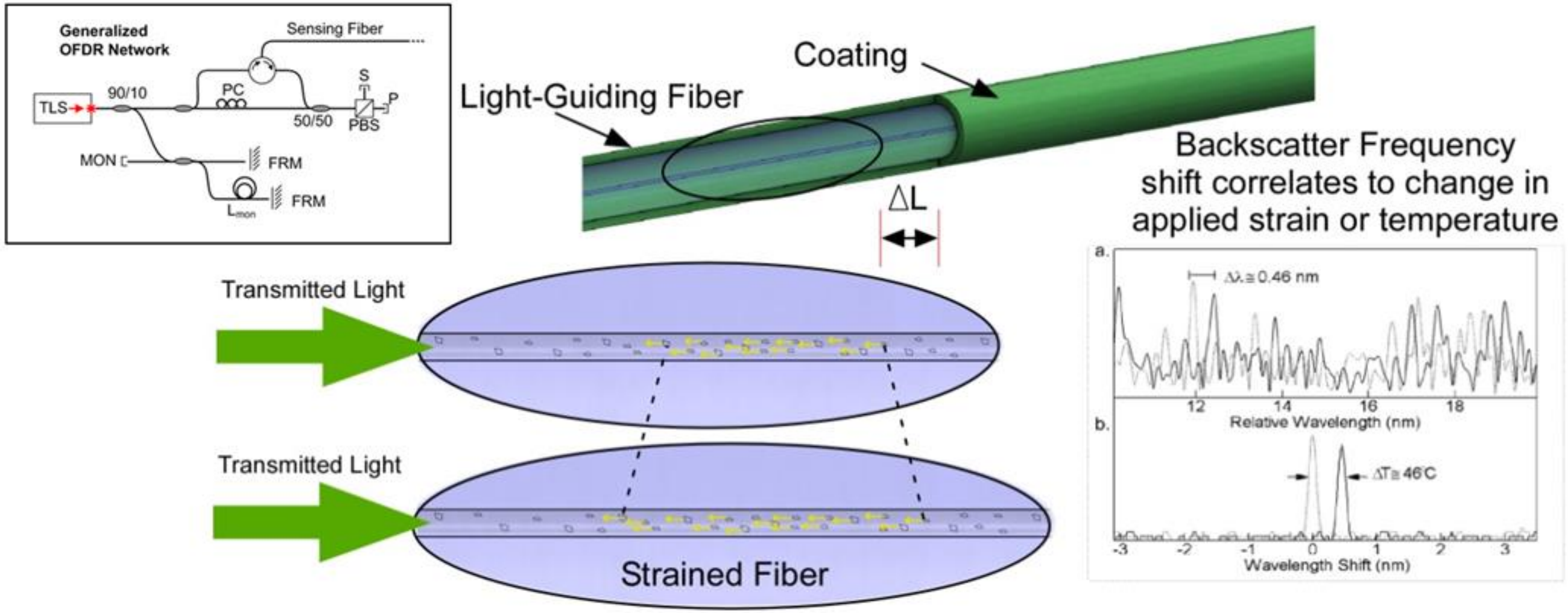
ODH/QuantX



	High-Speed Multipoint	High-Definition Distributed	Distributed Acoustic Sensing	Distributed Acoustic Sensing
FOS Technology:	**Fiber Bragg gratings (FBGs) and Fabry-Perot sensors**	**Rayleigh backscatter** ***Optical Frequency Domain Reflectometry (OFDR)***	**Rayleigh backscatter** ***Optical Time Domain Reflectometry (OTDR)***	**Raman backscatter**
Point/Distributed:	**Multipoint sensing**	**Distributed**	**Distributed**	**Distributed**
Sensor/gage spacing:	**FBG placement**	**Down to <1 mm**	**~1-10 m typical**	**0.25-10 m**
Sensor fiber length:	**Up to 10's of km's**	**100 m**	**Up to 50 - 100 km's**	**Up to 70 km**
Measurements:	**Strain, temperature, acceleration, displacement and pressure**	**Strain and temperature**	**Acoustics Strain, temperature**	**Strain and temperature**
Example applications:	Civil infrastructure monitoring Aerospace condition monitoring Wind turbine monitoring	Battery thermal analysis Structural and material test Precision process monitoring	Pipelines Transportation/rail Perimeter security Oil and gas	Fire Detection Power cables Pipelines Transportation/rail Perimeter security Oil and gas

OFDR Distributed Sensing Overview

Optical Frequency Domain Reflectometry (OFDR), the basis of the ODiSI platform, uses reflected light from minute differences in the local index of refraction of the fiber core to determine the degree to which the fiber is strained as a result of a thermal or mechanical stimuli.



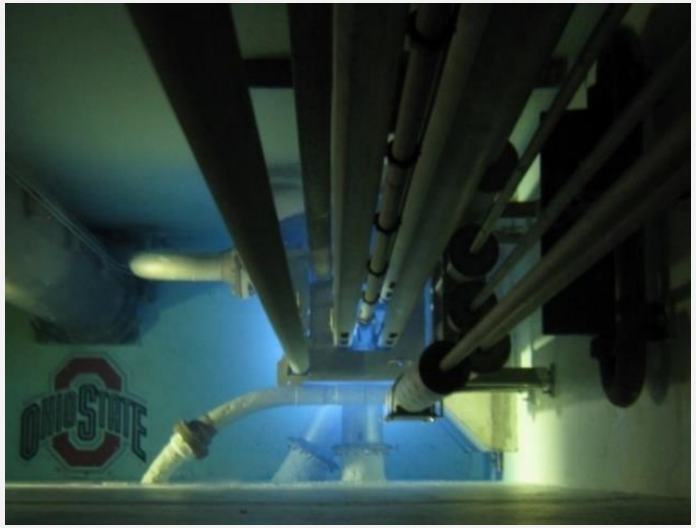
Basic Theory of Operation

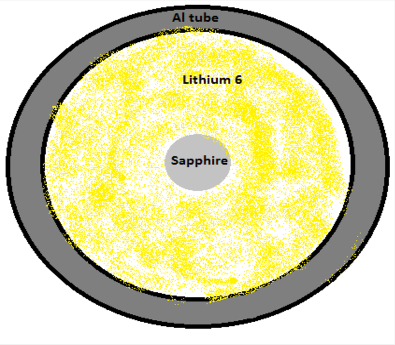
Creation of an Internal Cladding in Sapphire Fiber to Produce Reduced Mode Sapphire Fiber (RMSF)

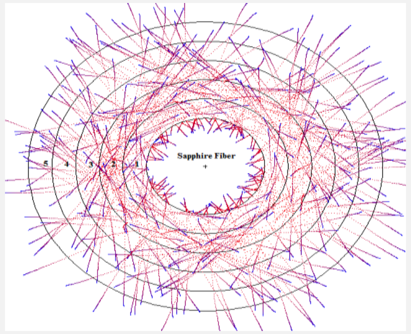
- The Ohio State University has developed a method for creating an intrinsic cladding in sapphire optical fiber
- By implanting ions into the periphery of a sapphire fiber, via the reaction below, a refractive layer forms in the sapphire with a slightly lower index of refraction that acts as an internal cladding

$$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{3}_{1}H + 4.8MeV$$

- The ions for implantation are created using Lithium-6 and the Ohio State Research Reactor reaction
- Using this method instead of an accelerator provides the benefit of creating large lengths of this cladded sapphire fiber in a short amount of time







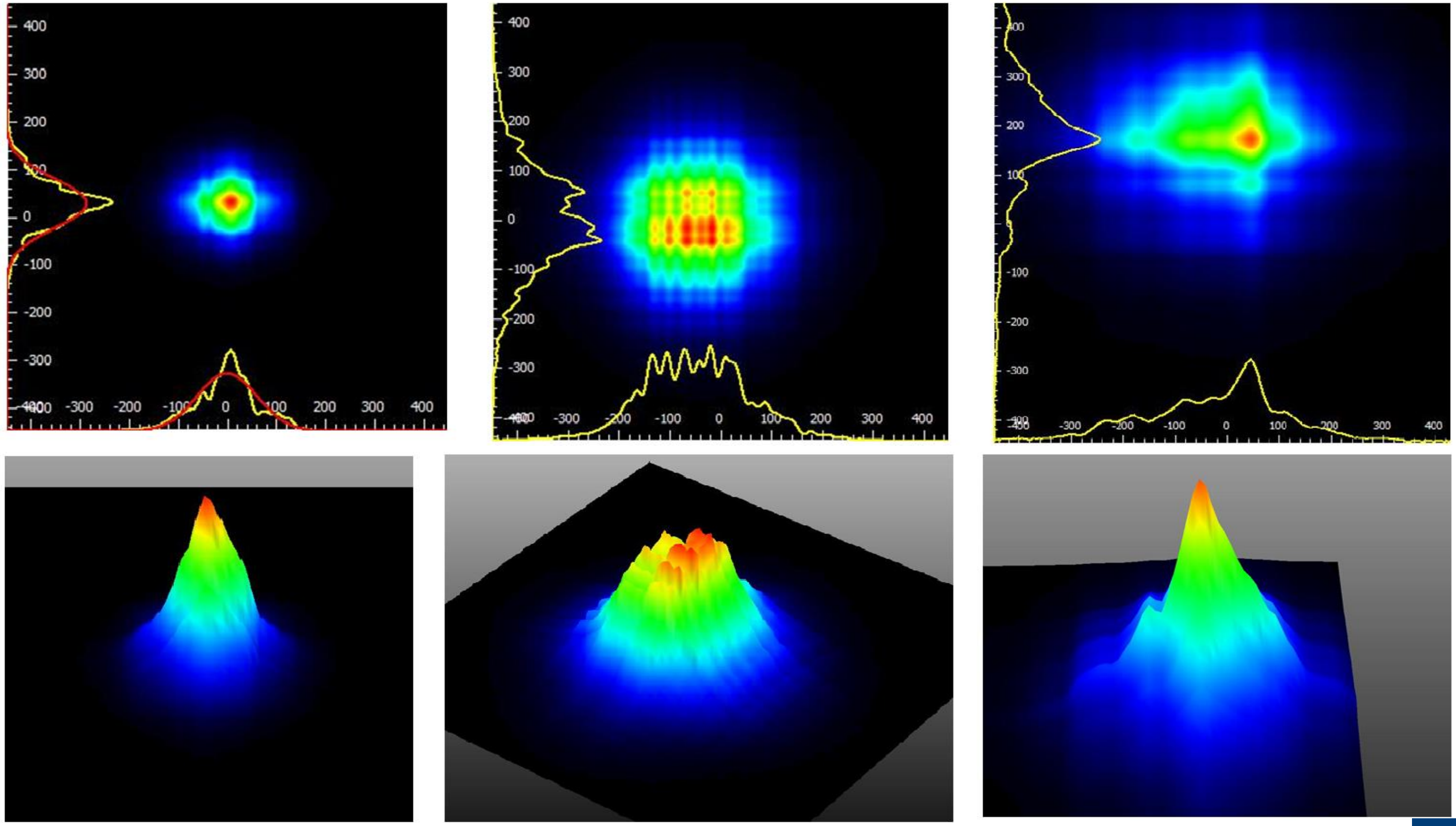
The work presented on this slide was performed at The Ohio State University prior to the current project

Wilson, Brandon Augustus, and Thomas E. Blue. "Creation of an Internal Cladding in Sapphire Optical Fiber Using the ^{6}Li(n, α)^{3}H Reaction." *IEEE Sensors Journal* 17, no. 22 (2017): 7433-7439.

Sapphire Cladding Results

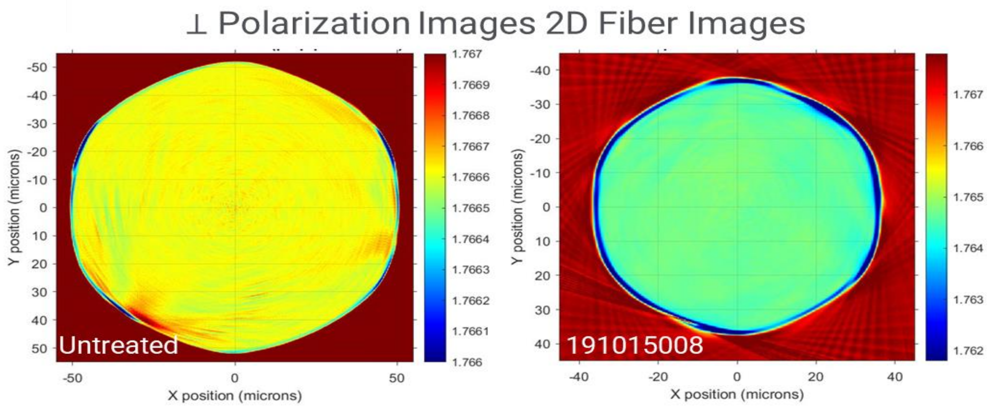
Measurements of various types of fibers using the OSU fiber transmission facility

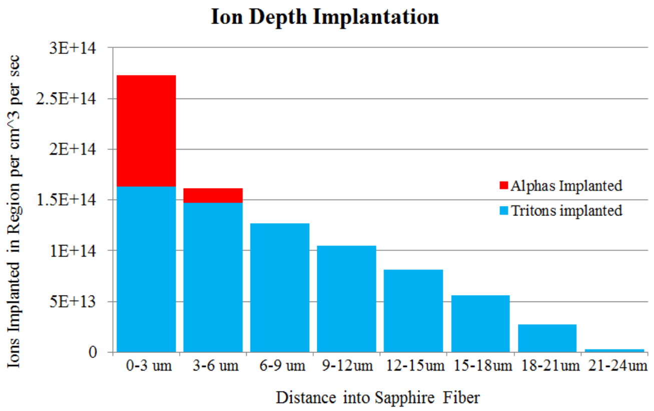
Single mode silica fiber | Unclad sapphire fiber | Sapphire fiber with cladding

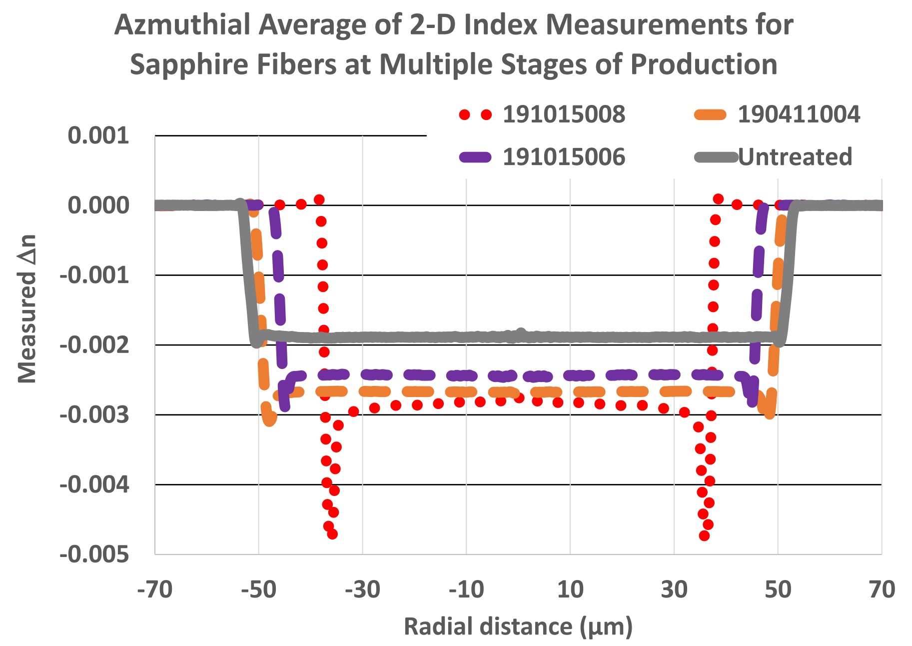


Cladding Profile

- Index profiles have been taken of an untreated fiber and fibers that underwent ion implantation via the method of the previous slide followed by annealing process described in the table with 632.8 nm light. The index contrast will be more significant at 1550 nm.





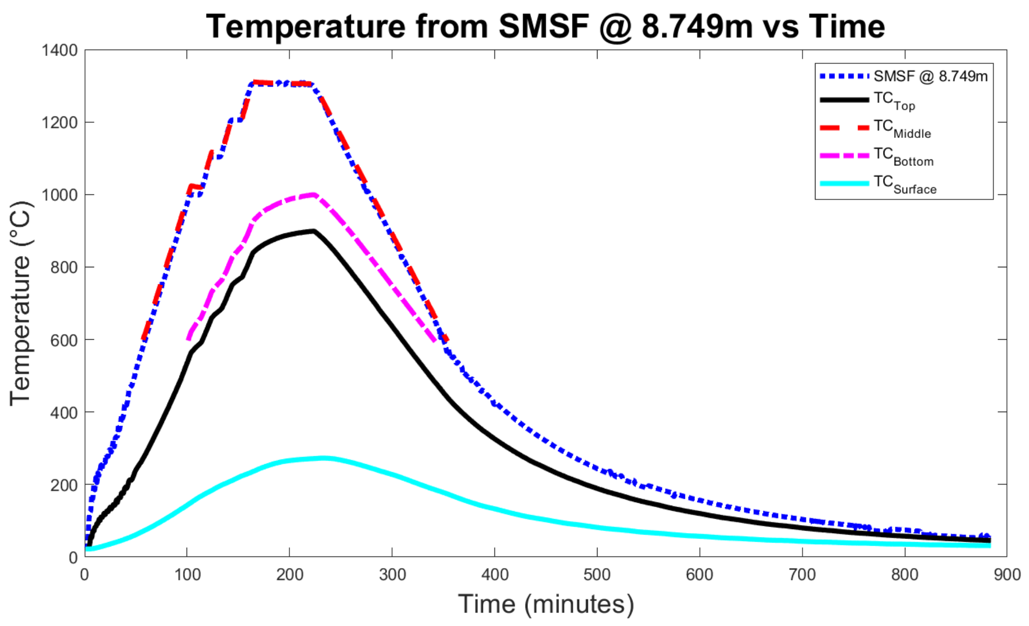


ID#	Diameter	Annealing method
Untreated	100 µm	N/A
191015008	75 µm	1200°C for 8 hours in 3 steps along the length
190411004	100 µm	1200°C for 8 hours
191015006	100 µm	1050°C for 1.5 hours followed by 1100°C for 8 hours

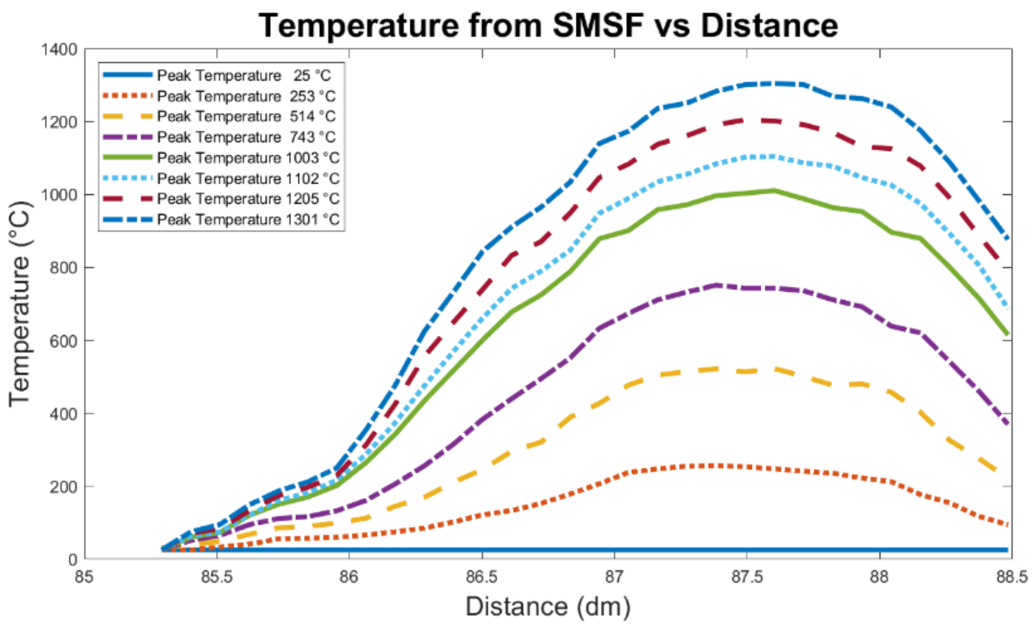
Furnace Test to 1300°C

Furnace test of Reduced Mode Sapphire Fiber (RMSF) to 1300°C interrogated with an OBR 4600

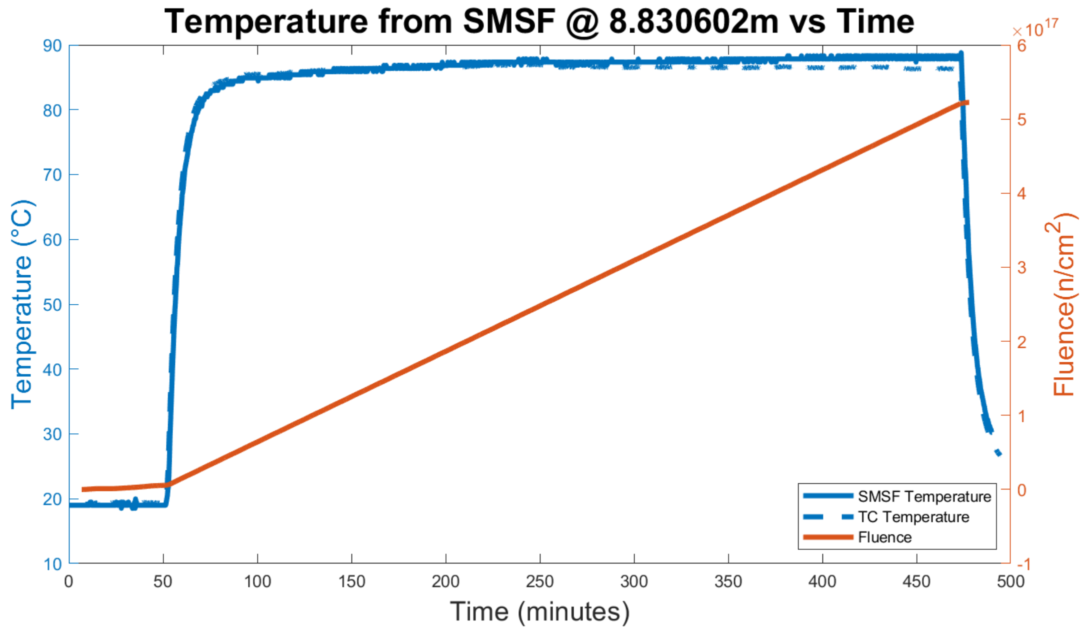
Single gage of SMSF

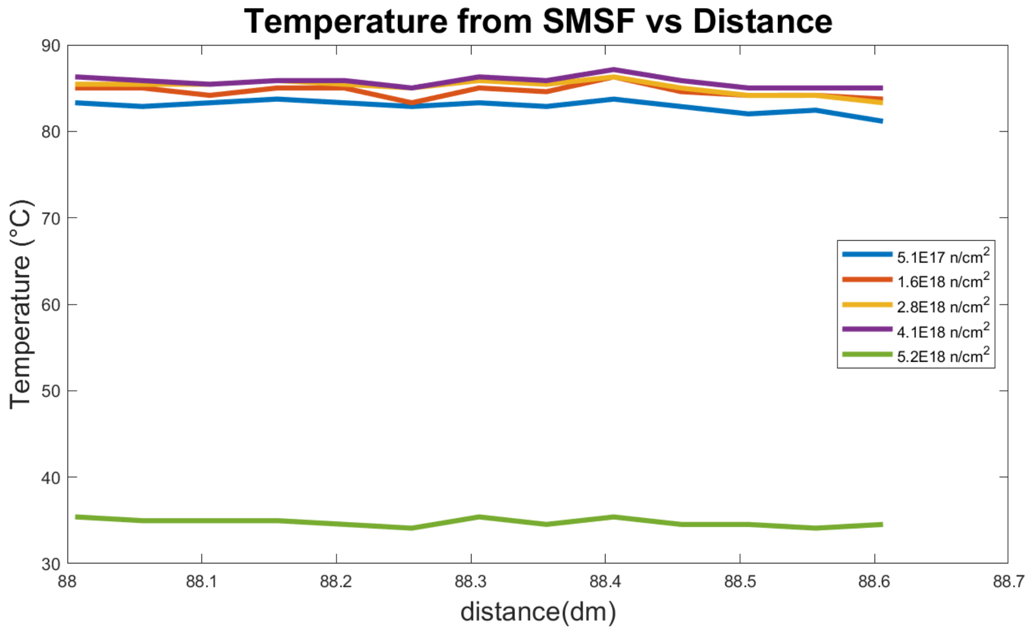


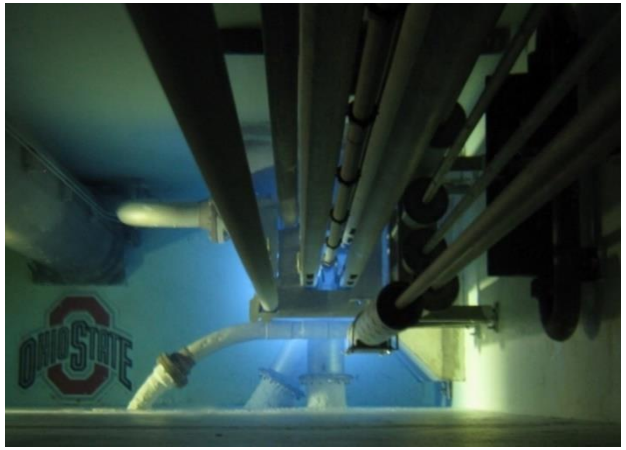
Full length SMSF at specific points in



Reactor Test to Neutron Fluence >5×10^17



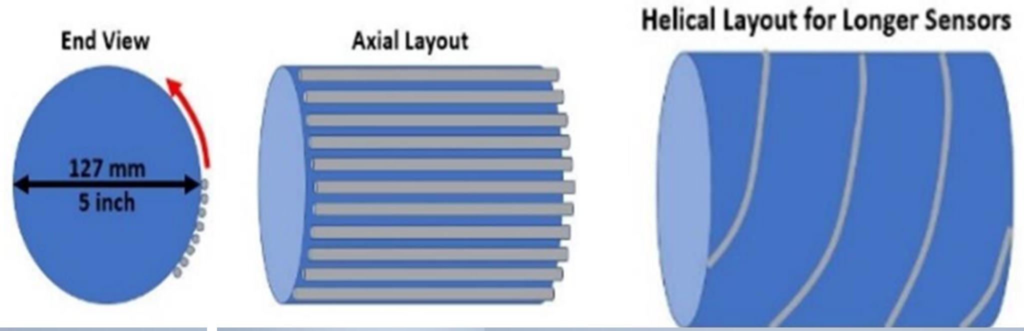


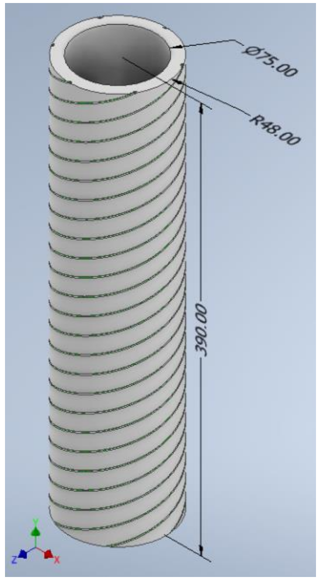


LUNA THE OHIO STATE UNIVERSITY

Cost reduction study and fixture design

Designs for RMSF transmutation rig



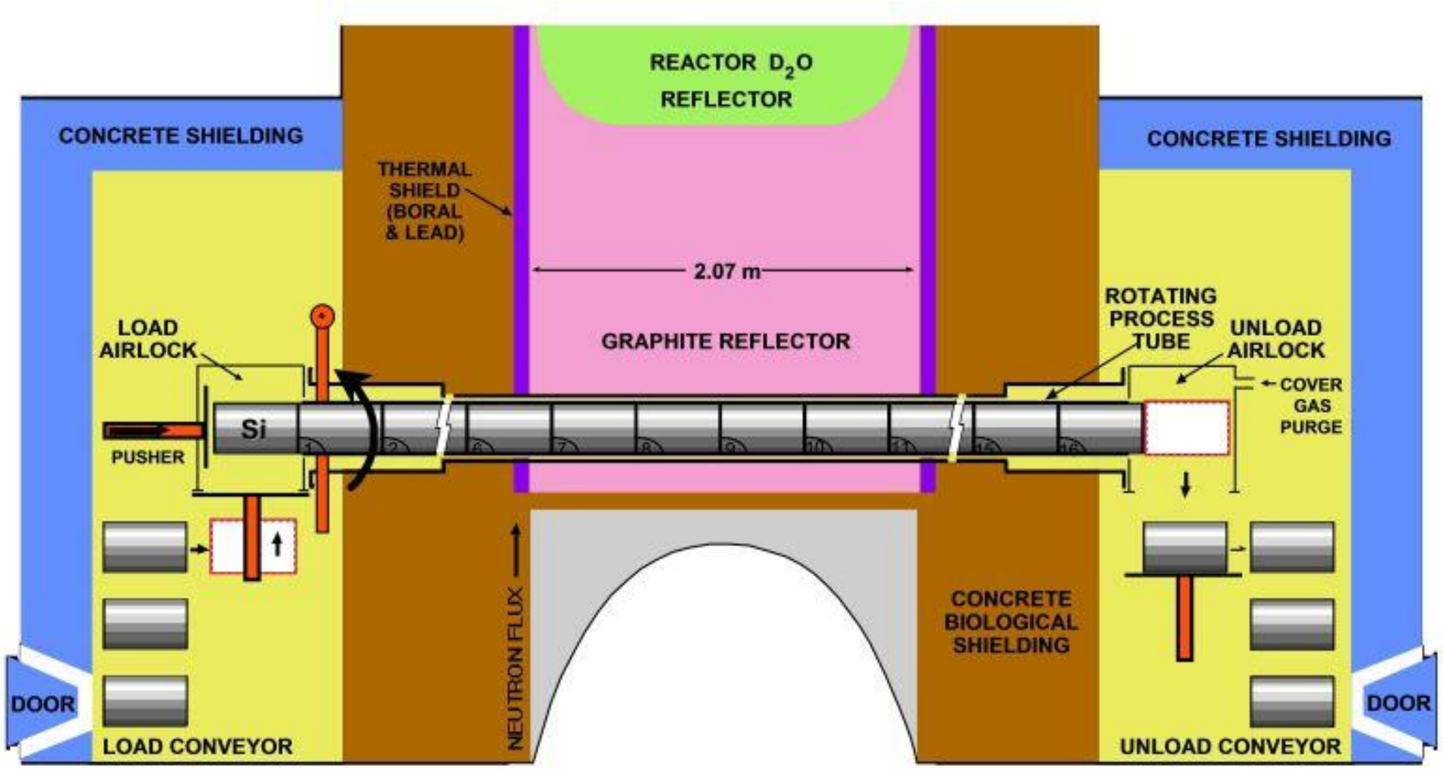


Fiber has been packed in a helical rig, shipped via UPS, returned, unpacked, and repacked with no breakage. These are the highest risk activities for the production process.

Cost reduction study via irradiation in MIT's 6TH1-2 horizontal through ports

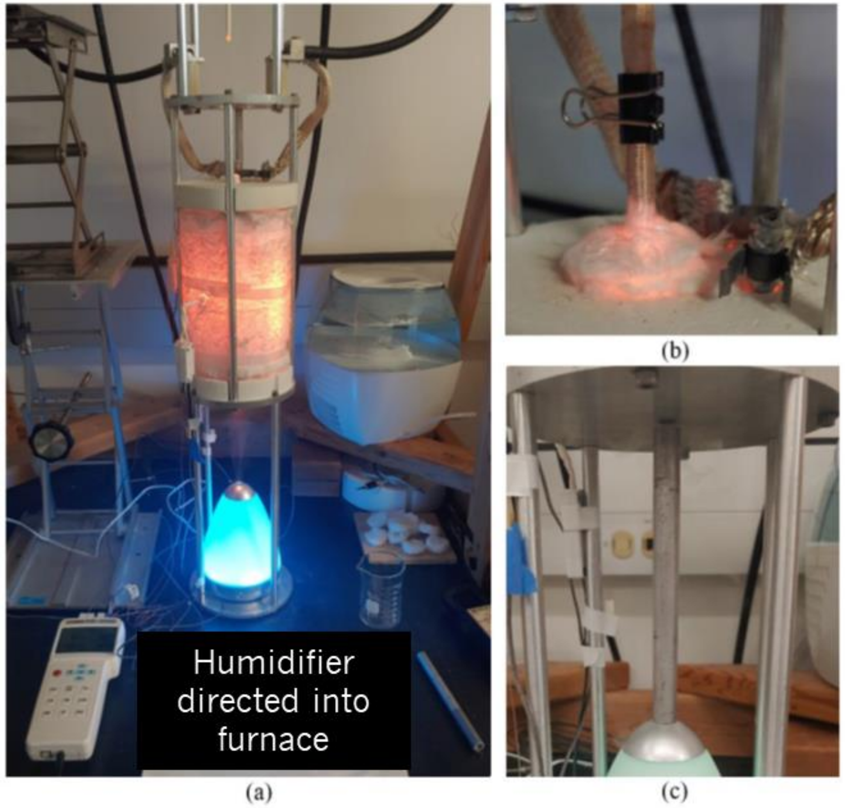
Awaiting irradiation of transmutation rigs.

Advantages
- Capable of irradiating longer length
- Continuous loading of material
- No effect on reactor criticality (no cost to the reactor)
- Industrial scale transmutation in place



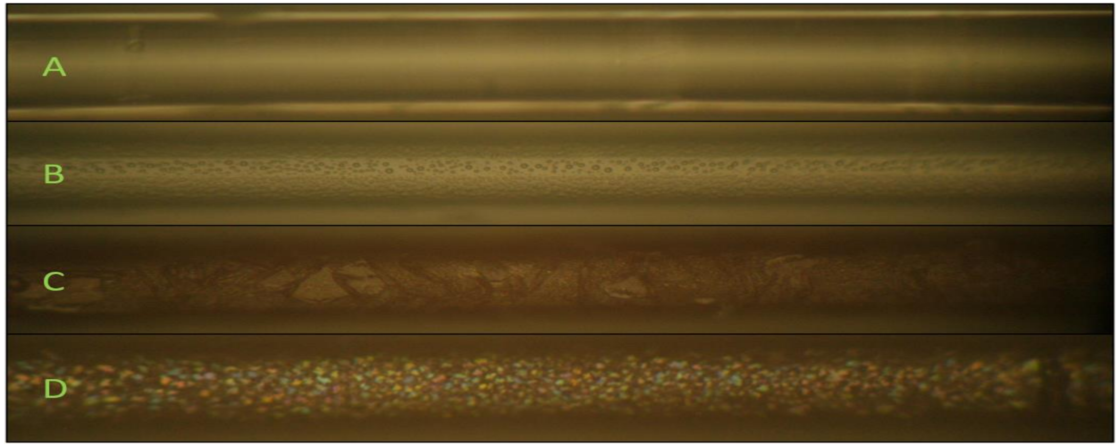
Cladding mode stripping mechanisms

- Aluminum Oxy-hydroxide added to clad surface to disrupt cladding modes
- PCT WO2021211195A1, Modification of internally clad sapphire fiber to attenuate cladding modes at high temperatures
- PCT based on work from DE-SC0019834 and DE-SC0018767
- Jones, Joshua T., Anthony Birri, Thomas E. Blue, Dan Kominsky, Kelly McCary, Osgar John Ohanian, and S. Derek Rountree. "Light propagation considerations for internally clad sapphire optical fiber using the 6Li (n, α) 3H reaction." Journal of Lightwave Technology 40, no. 4 (2022): 1181-1187.



Method of Stripping Cladding Modes

- Several methods of cladding mode stripping have been presented for clad sapphire fiber in PCT WO2021211195A1
- Luna and OSU are currently pursuing formation of aluminum oxyhydroxide crystals on RMSF surface that are formed in a high temperature steam environment. The sapphire's surface has different characteristics depending stream exposure as seen in the microscopy images.



Current Status

- Luna and OSU have pushed the transmutation cost of commercial-off-the-shelf sapphire fiber to RMSF from order $10,000/m to order $1,000/m over the last year.
- Demonstrated performance beyond 1300 °C
- Continued production optimization is needed along with testing to the melting point of sapphire, 2050 °C