Optical Fibers

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar
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Idaho National Laboratory

Project Overview

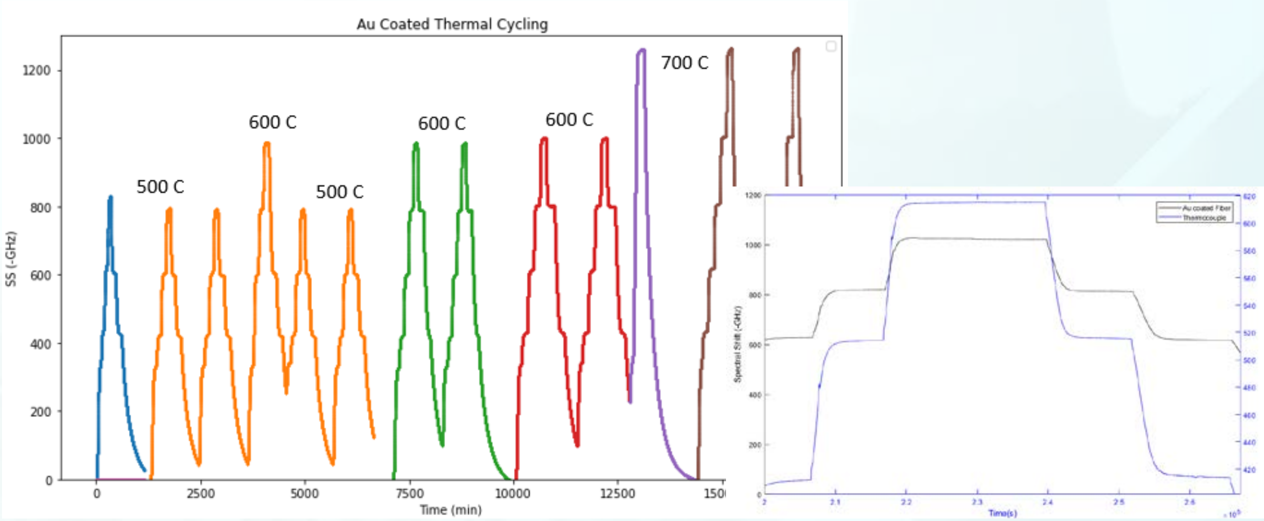
- Fiber optic technology has many sensing advantages, but few applications in nuclear environments.
- Fiber optic sensors have unique challenges associated with in-pile applications
  - Radiation Induced Attenuation
  - Radiation Induced Emission
  - Radiation Induced Compaction
  - These can result in a loss of signal or significant drift in many conventional fiber optic sensor designs
- The direct funded fiber optic activities under NEET-ASI focused on relatively high TRL items with the potential for high impact to the nuclear industry. These include the development and qualification of:
  - Fiber optic based pressure sensor
  - Distributed in-pile temperature sensing
  - In-pile imaging
  - Active Compensation/Drift correction for intrinsic temperature sensing
- An overview of these 4 activities will be given here

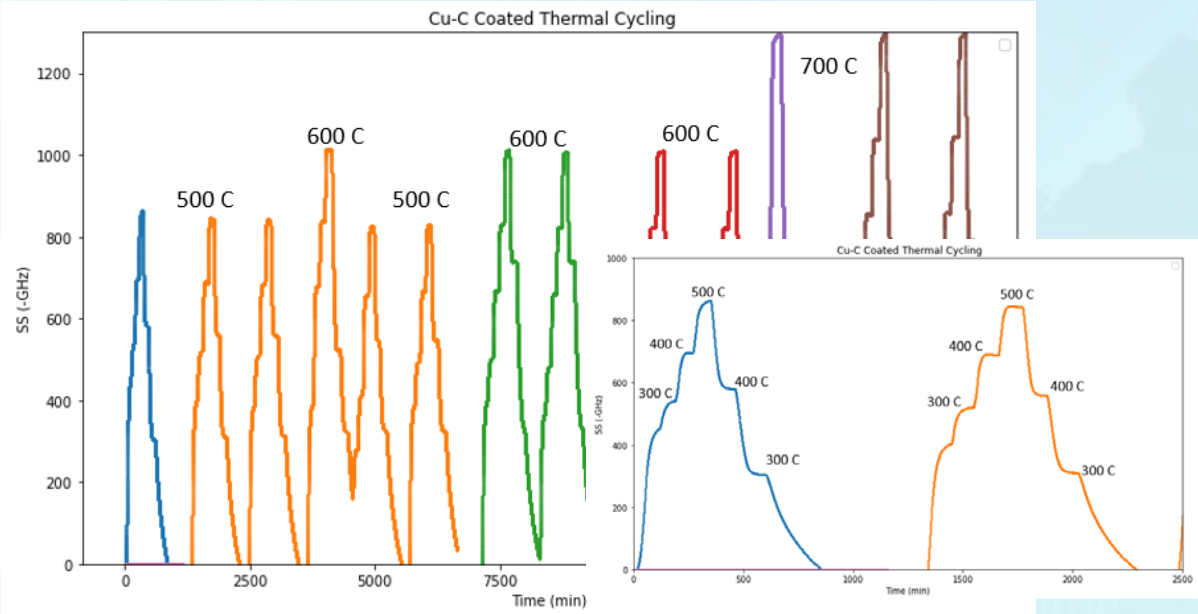
Project Overview (Intrinsic Temperature Sensor)

- Distributed temperature sensing using Rayleigh scattering (Optical Frequency Domain Reflectometry)
  - Commercially available systems
  - Unique considerations are required for in-pile work
- Much longer lead in lengths compared to other applications (often ~20-30m of fiber length with the *only* the last 1-2m providing data of interest.
- Multiple feed throughs, often multiple connections required.
- Unique considerations for fiber selection (minimize radiation effects)
- High temperature operations
  - Often bare fibers (coating is removed) are used for high temperature, but this makes fiber fragile
  - Sensor incorporation often requires robust sensors for experiment assembly (preferably with coating)

Project Overview (Intrinsic Temperature Sensor)

- Working towards extending high temperature measurement capability of distributed Rayleigh sensing by using metal coated fibers
  - Gold Coated, Copper coated, and Copper-Carbon coated fibers were all tested for Rayleigh backscatter response.
  - Au coated showed good performance and consistent response after initial thermal annealing up to 700 C
  - Cu and Cu-C coated fibers did not produce a consistent response even after initial thermal annealing

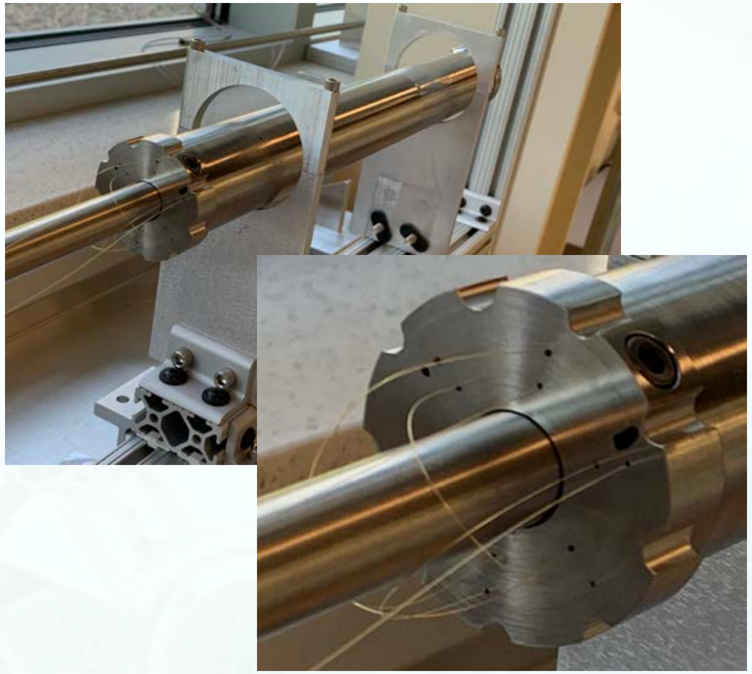




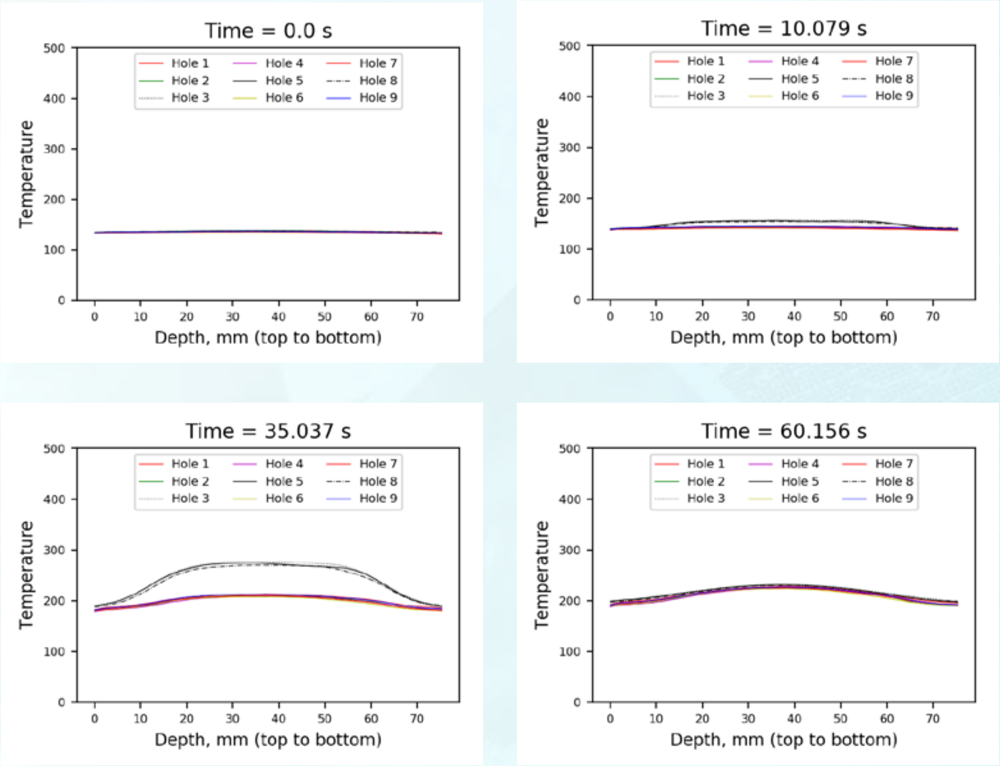
Project Overview (Intrinsic Temperature Sensor)

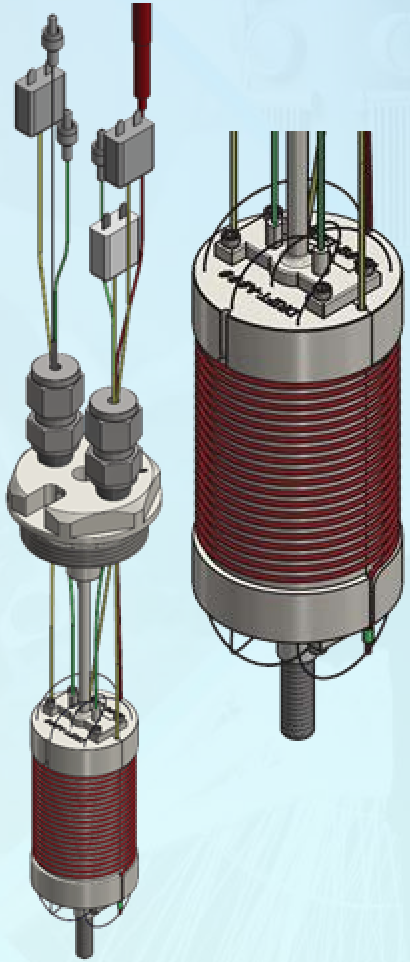
Technology Adoption

- Used previously in the DRIFT and TCR experiments (right)
- Currently being deployed in the THOR experiments



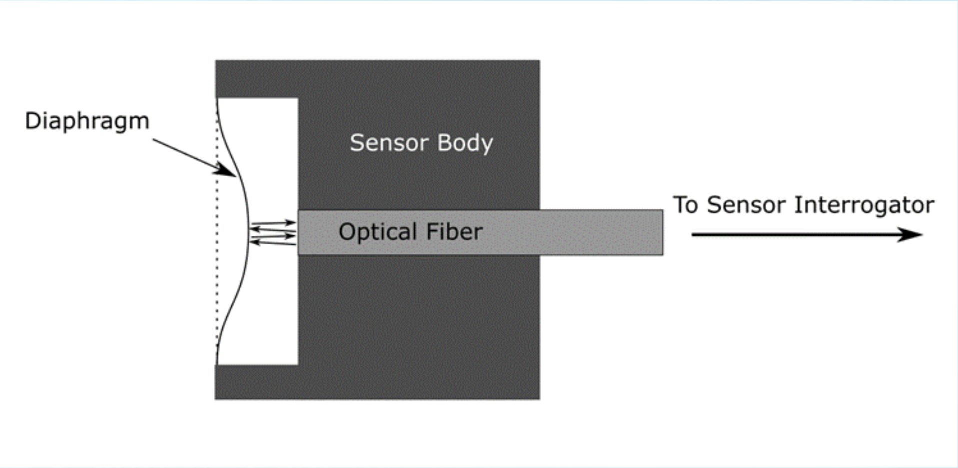
High optical fiber has been incorporated into the THOR experiment to meet the instrumentation needs for others





Project Overview (Fabry Perot Pressure Sensor)

- **Motivation:** Pressure is an extremely important parameter for thermodynamic and structural considerations
    - Heat Transfer
    - Phase Change
    - Structural Integrity (cladding/primary containment)
    - Coolant Flow (measurement/control)
- **Background:** Fiber Optic Fabry Perot Pressure Sensors
    - Widely documented in literature
    - Limited commercial availability
    - Based on light interference spectrum
    - Small Footprint
    - Relatively High Temperature
    - Customizable Pressure Range

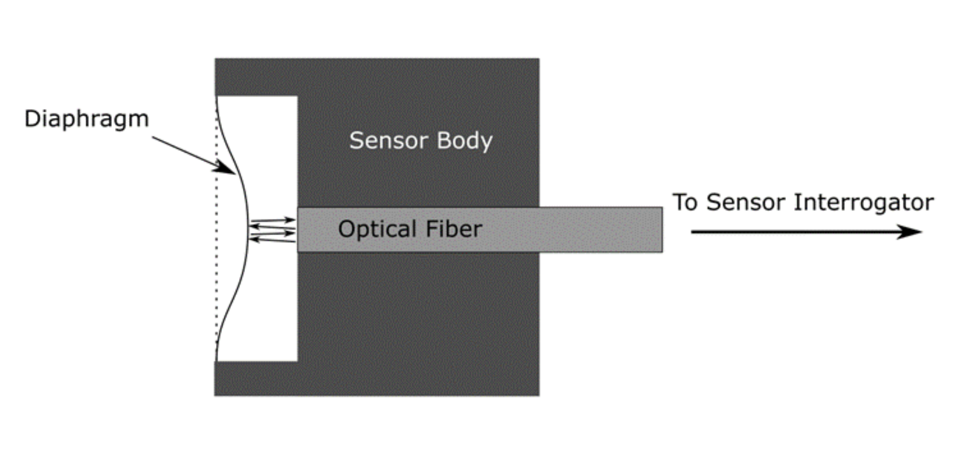


Project Overview (Fabry Perot Pressure Sensor)

- **Design Considerations:**
  - Diaphragm Diameter & Thickness
  - Sensor Material
  - Nominal Cavity Length
  - Fabrication Techniques
  - Design Rating
  - Desired performance
    - Drift
    - Hysteresis
    - Temperature compensation
    - Accuracy

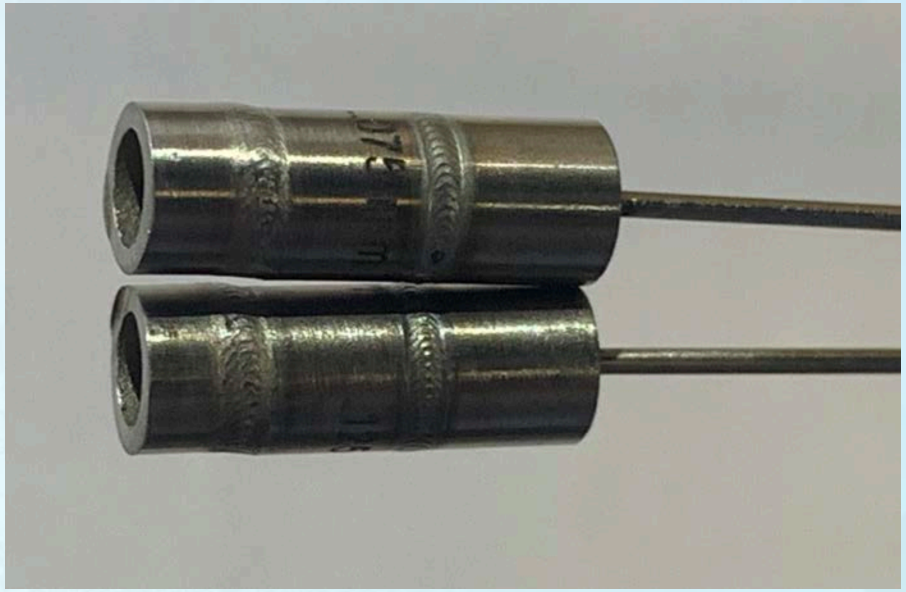
$$y_0 = \frac{3(1-\nu^2)P\, r_0}{16E\tau^3}$$

y_0 - displacement
ν - Poisson ratio
P - Pressure
r_0 - Diaphragm radius
E – Modulus elasticity
τ – Diaphragm Thickness



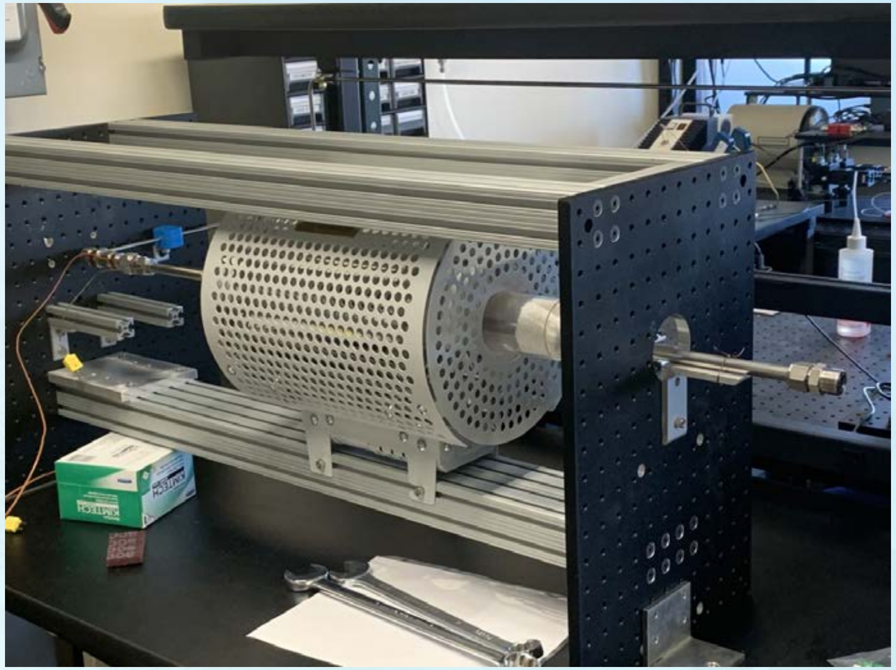
Project Overview (Fabry Perot Pressure Sensor)

- Fabrication Process
  - 3 component sensor head
  - Optical Fiber is brazed into sensor head
  - Fabry Perot cavity length is carefully controlled during the assembly process by using the optical interrogator
  - Assembly requires strict helium leak controls
    - Sensor drift will occur if cavity pressurizes due to a leak
  - Uses interchangeable diaphragms to customize Sensor pressure range. Current variations include:
    - 0-50 psi
    - 0-100 psi
    - 0-500 psi
    - 0-3000 psi



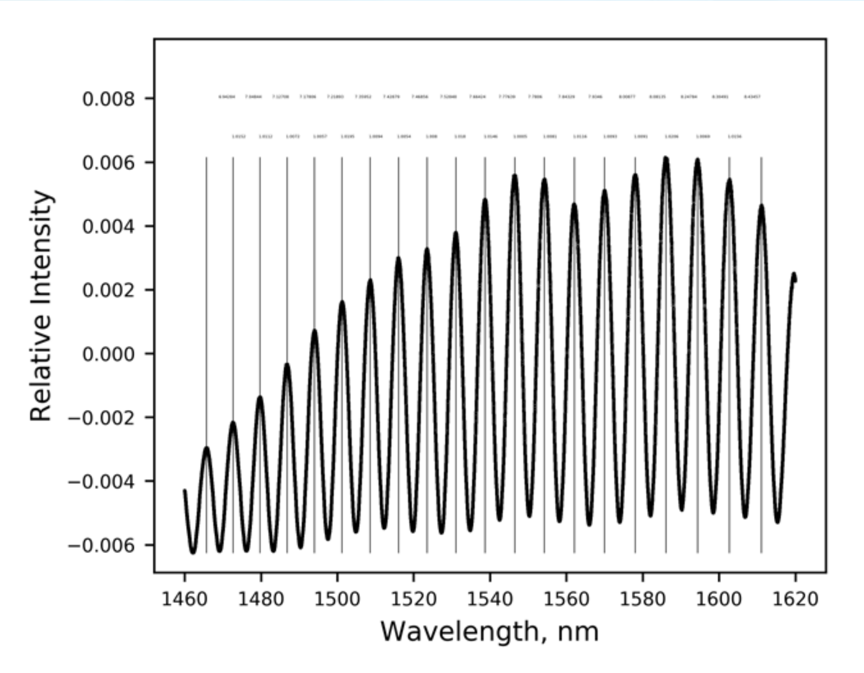
Project Overview (Fabry Perot Pressure Sensor)

- Calibration & Testing
  - Heated pressure chamber
    - 0-1250 psi
    - 20-600 C
  - Used to calibrate sensor, determine temperature cross sensitivity, hysteresis, sensor drift, and experimentally defining sensor operational range
  - Testing conducted to-date has focused on the 0-50psi, 0-100 psi, and 0-500 psi sensor versions
    - Calibration
    - Temperature cross sensitivity
    - Hysteresis
  - Future testing
    - Drift
    - Experimentally define operational range



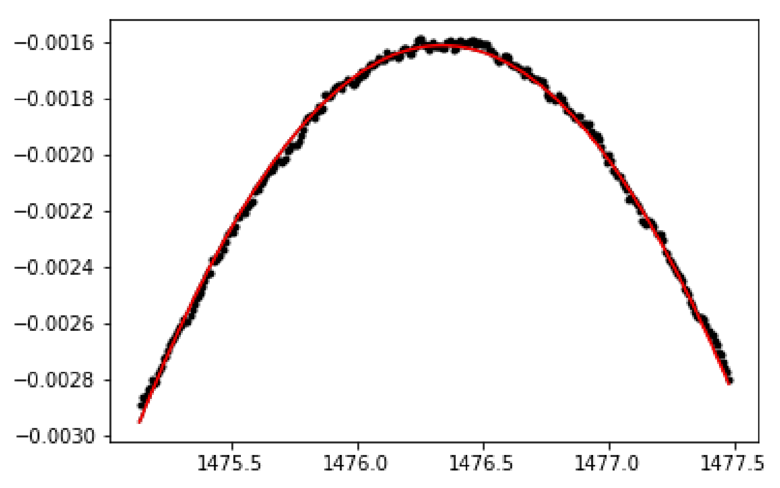
Project Overview (Fabry Perot Pressure Sensor)

- Results/Conclusions
  - Interference spectrum is collected
    - Peak location is determined by fitting a parabola for a small subset of data around each peach
    - Cavity length is calculated between all adjacent peaks
    - Mean & standard deviation are calculated with all cavity lengths to be used in uncertainty analysis



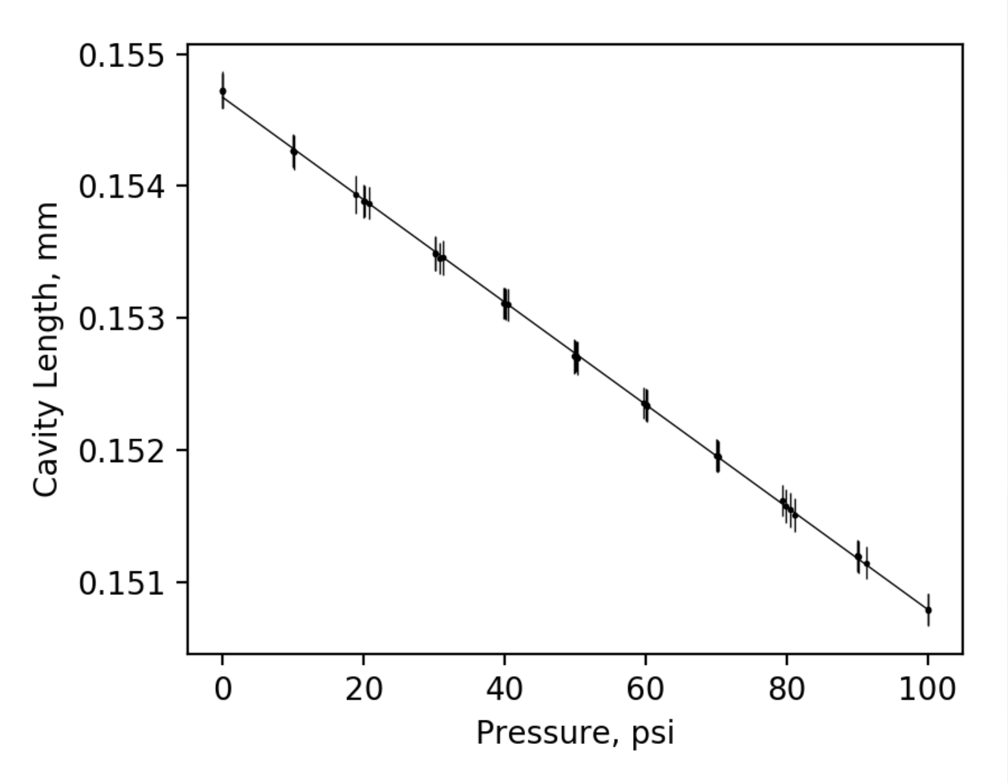
Interference spectrum from sensor with peak locations noted

$$L = \frac{\lambda_1 \lambda_2}{2n(\lambda_2 - \lambda_1)}$$



Project Overview (Fabry Perot Pressure Sensor)

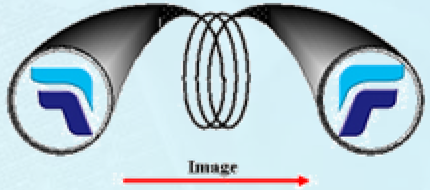
- Results/Conclusions
  - If sensor is operated within design range
    - Excellent linearity
    - Hysteresis is negligible
    - Very repeatable
  - Used to calibrate sensor, determine temperature cross sensitivity, hysteresis, and sensor drift
  - Recent work has focused on improving manufacturing process to improve yield, sensor performance, and durability

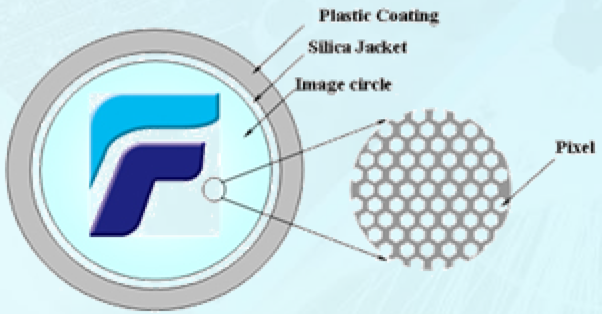


Hysteresis testing 100 psi sensor, 2 full hysteresis loops are shown. Error bars are 2σ

Project Overview (In-pile imaging)

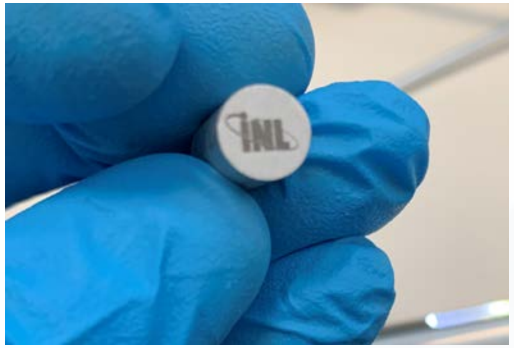
- Motivation:
  - Quantitative and qualitative information about in-pile conditions, properties or state
  - Diagnostics or control of systems
- Image bundles are commercially available “off-the-shelf” with up to100,000 fibers, the fiber bundle used in this demonstration had 10,000 fibers
- Fiber bundles have the potential to be compatible with various experiments, as their feedthroughs and footprints are similar to those of other sensor types
  - Diameter 0.5 mm - 2 mm
  - Would not require facility modifications



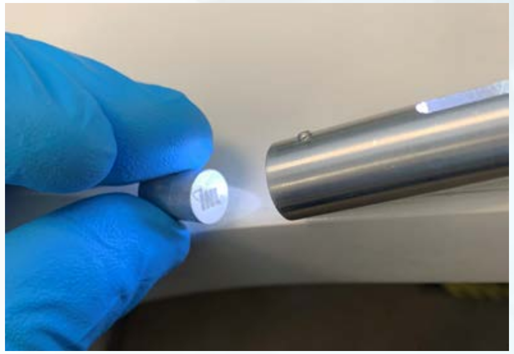


Cross Section Structure

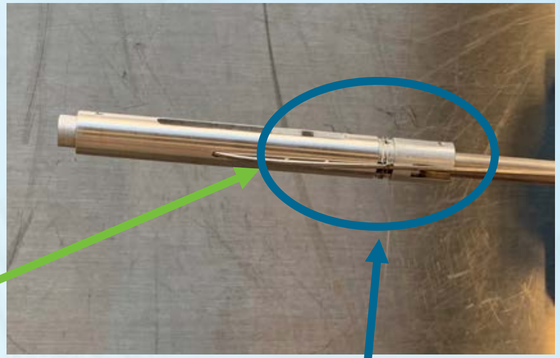
Project Overview (In-pile imaging)



INL logo target used for imaging



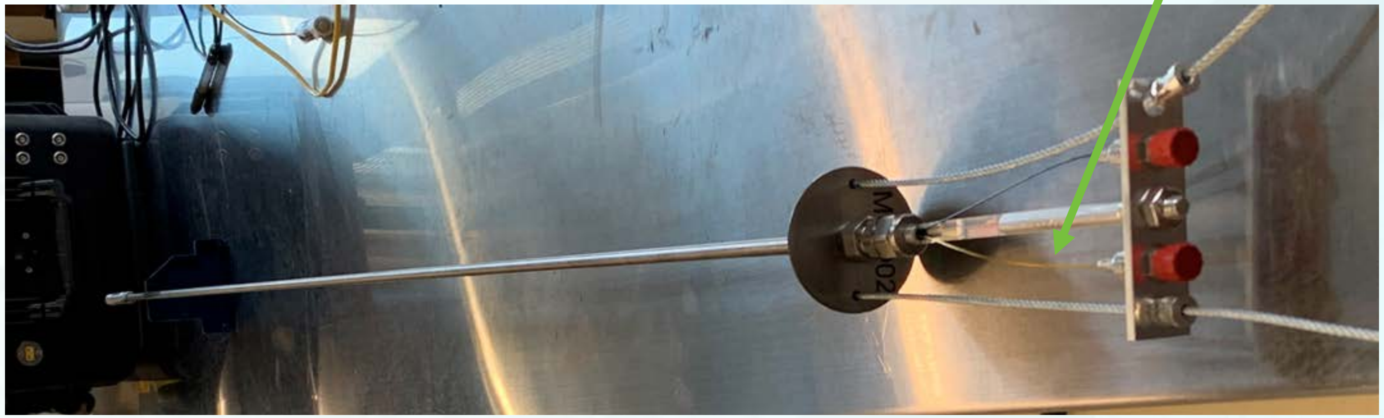
Target used for imaging

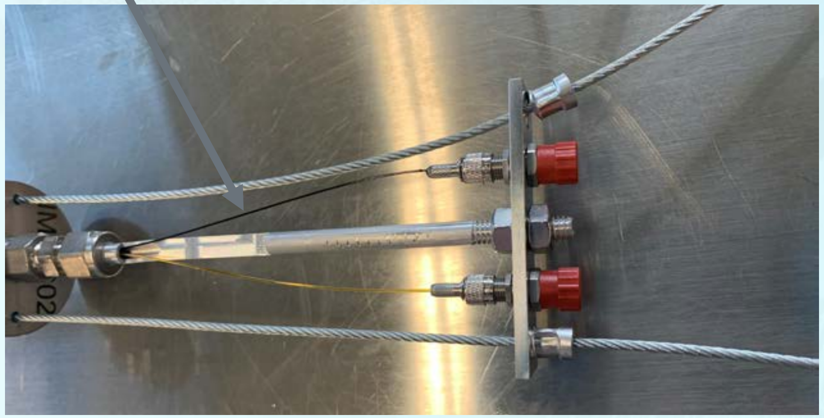


In-pile Lens assembly

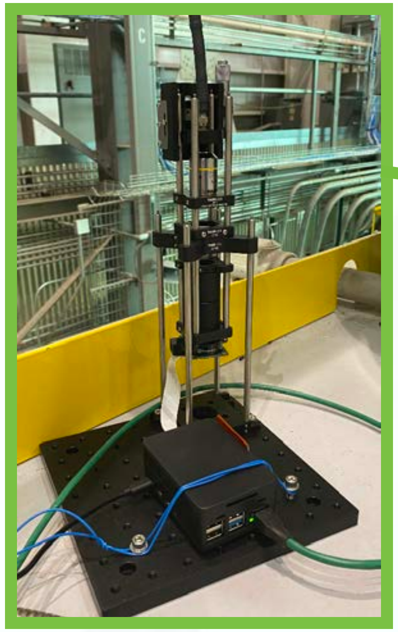
Illumination fiber

Image Bundle

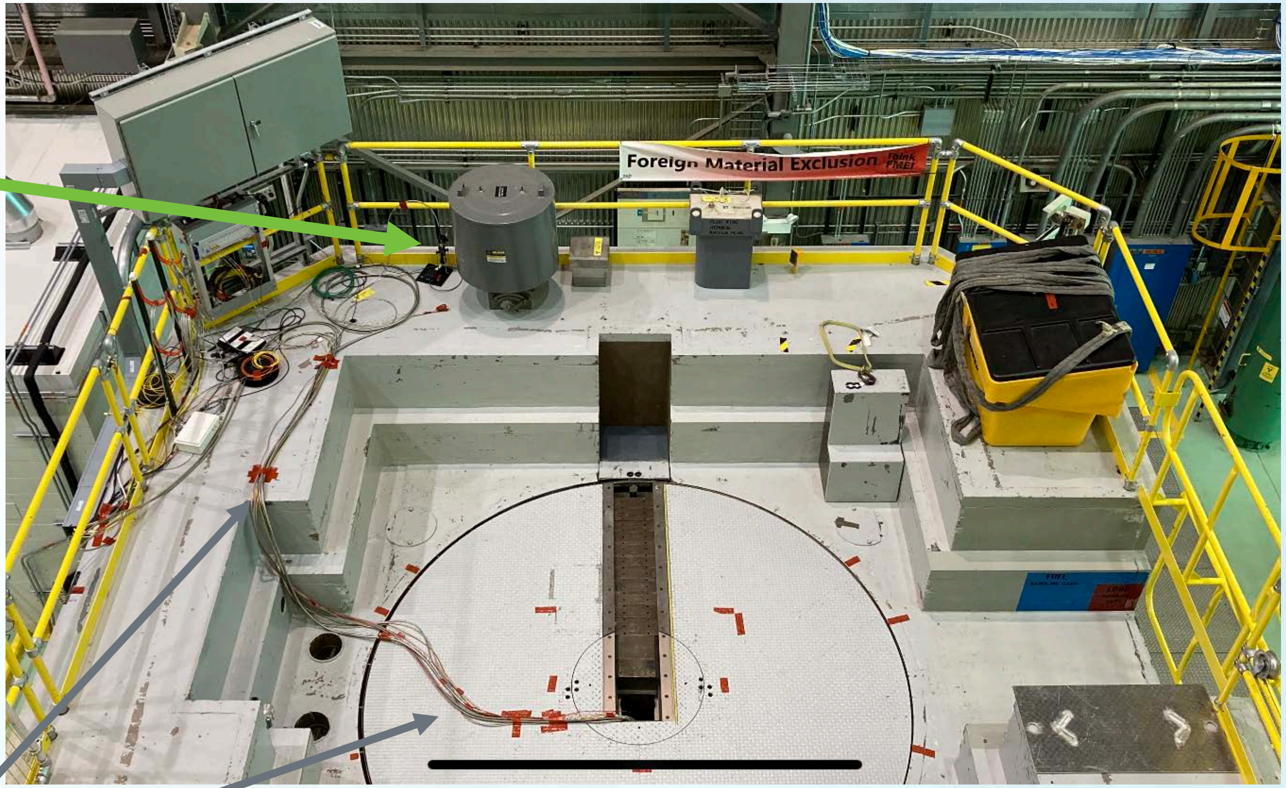




Project Overview (In-pile imaging)



Computer, camera, and lens system for capturing the image from the fiber bundle



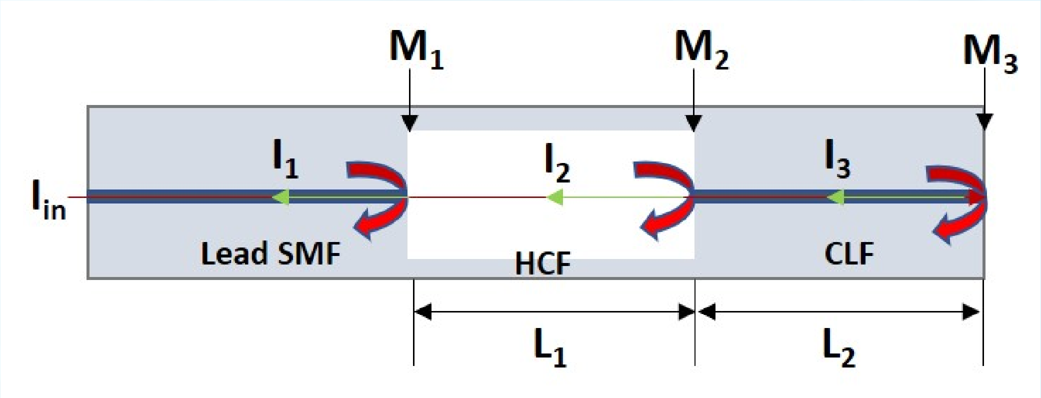
Armored imaging bundle running from camera to the test

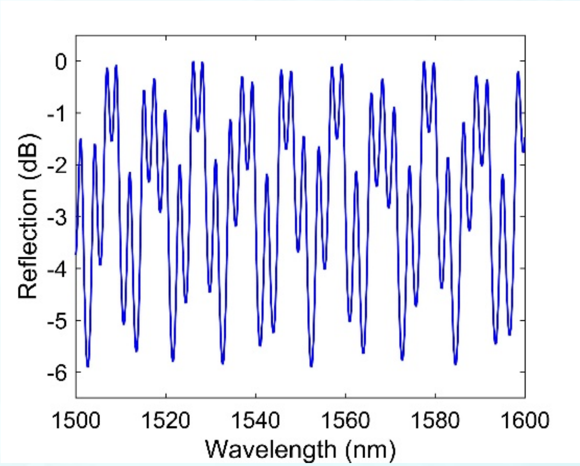
Image through fiber bundle

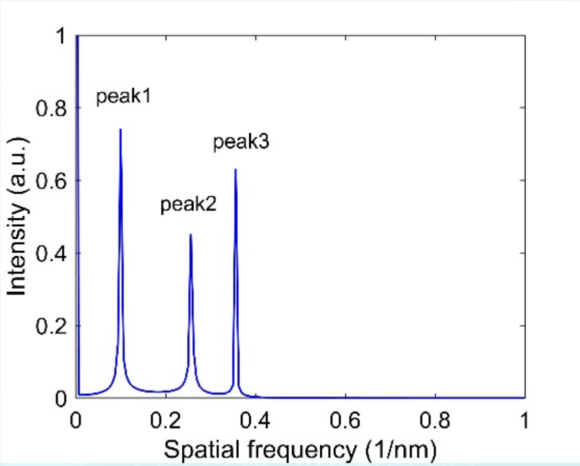
Project Overview (Active Compensation/Drift Correction)

- **Motivation:** It is well known that incoming radiation alters two of the driving parameters (refractive index and length) of optical fiber. It is extremely important to measure the radiation induced changes of these parameters to reduce the radiation induced signal drift in fiber optic sensors.

- **Background:** Fiber Optic Cascaded Fabry-Perot Sensors
  - Based on light interference spectrum
  - Easy to fabricate
  - Able to provide real-time information about refractive index and length changes caused by any physical parameters



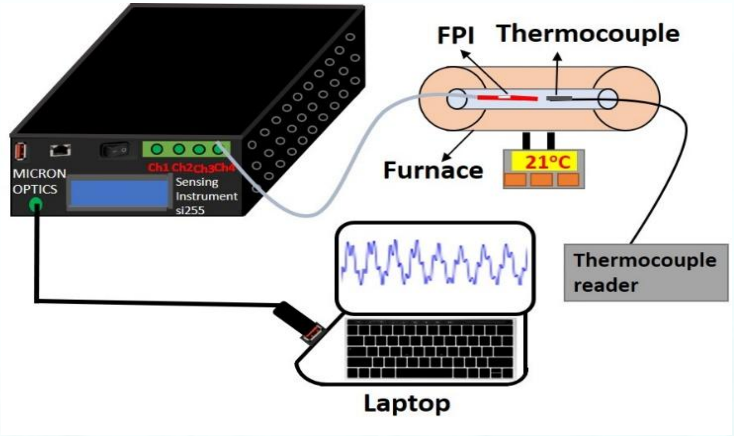


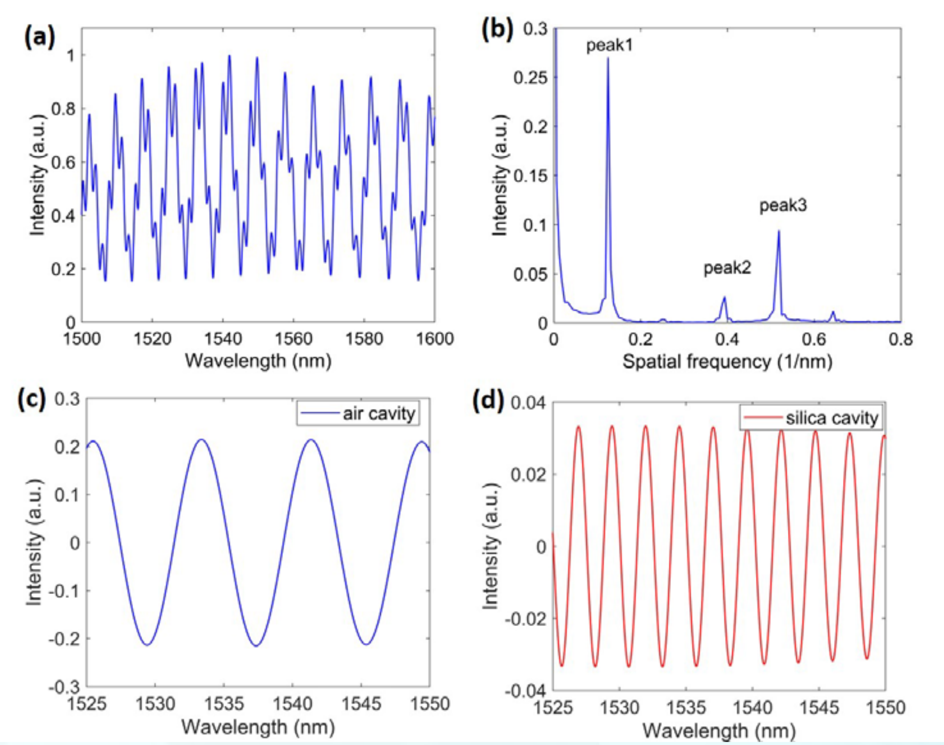


Active Compensation Prototype Sensor

Project Overview (Active Compensation/Drift Correction)

- Like radiation, temperature also alters the refractive index (RI) and length of fiber optic
- As a proof-of-concept, we experimentally demonstrate real-time monitoring of temperature effects on the RI and length and measure thermal expansion coefficient (TOE) and thermo-optic coefficient (TOC) using the cascaded Fabry-Perot.
- Temperature is increased from 21 to 486° C and data is monitored by optical interrogator





Linear compaction in air cavity,

$$C_a = \frac{L_{a,i} - L_{a,f}}{L_{a,i}}$$

Linear compaction in silica cavity,

$$C_s = \frac{L_{s,i} - L_{s,f}}{L_{s,i}} = C_a$$

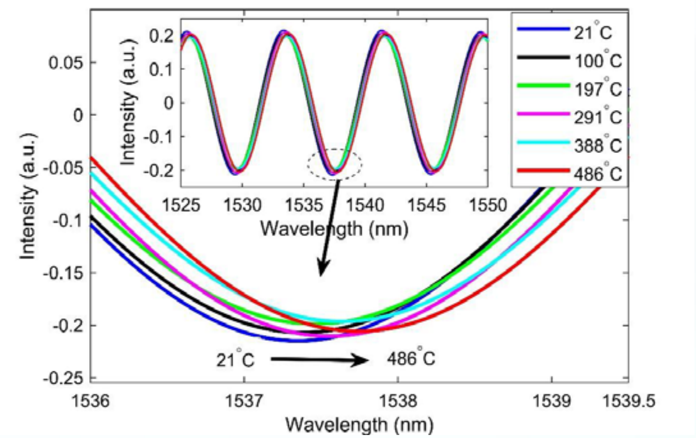
Final length of silica cavity,

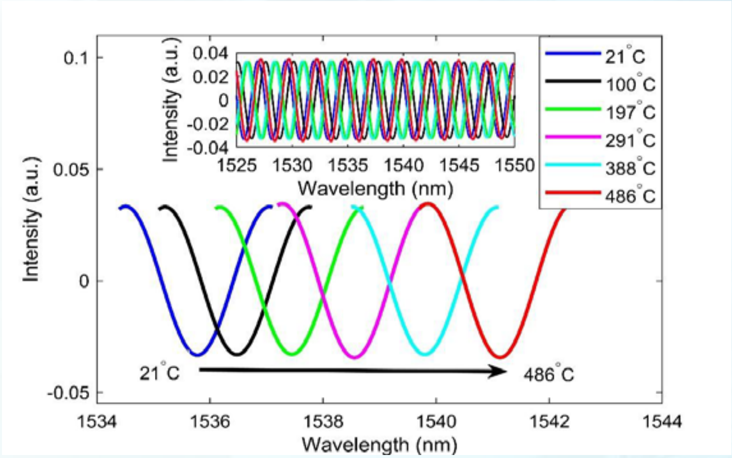
$$L_{s,f} = L_{s,i} - L_{s,i} \times C_s$$

Optical length of silica cavity

$$L_{s,opt} = n_{2f} L_{s,f}$$

Project Overview (Active Compensation/Drift Correction)





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Real-time measurement of parametric influences on the refractive index and length changes in silica optical fibers

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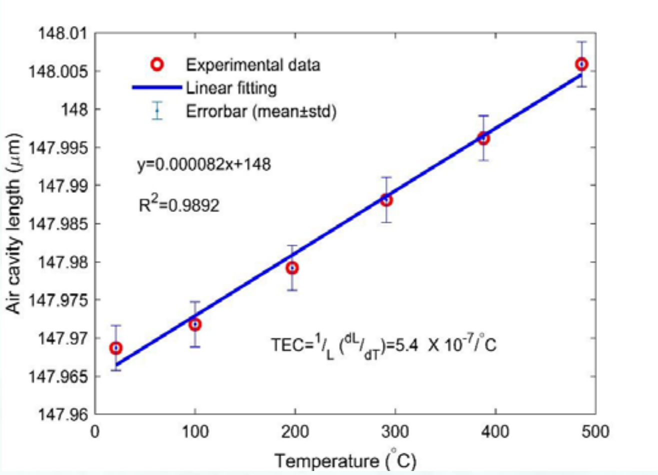
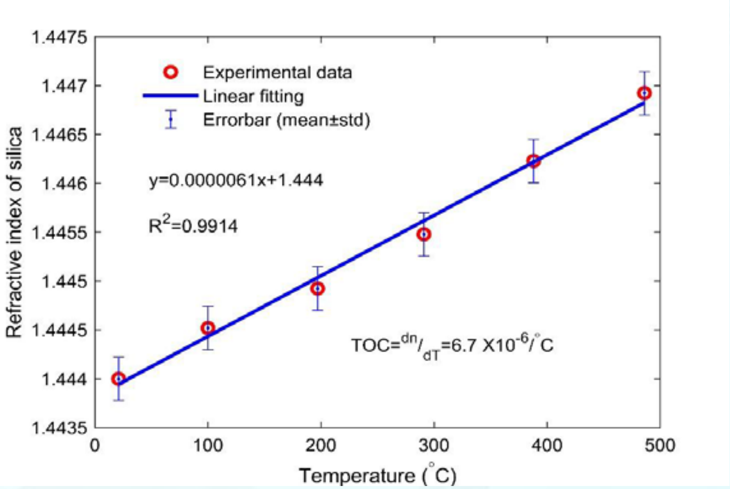


Measured air-cavity length as a function of applied temperature



Measured refractive index as a function of applied temperature

sensors MDPI

Article

Active Compensation of Radiation Effects on Optical Fibers for Sensing Applications

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Concluding Remarks

Technology maturation and adoption by end users is paramount goal for ASI activities

- Fiber optic pressure sensor and distributed temperature sensing has been adopted by other programs to meet their data needs. Specifically these include sensor deployments in:
  - UO2 DRIFT & TCR DRIFT (distributed temperature sensing)
  - THOR experiment series (high temperature distributed temperature)
  - HERA experiment series (Fiber optic pressure sensor)
  - BANNER & TWIST (planned use of fiber optic pressure sensor)
- Sohel Rana defended dissertation related to the fiber optic active compensation work has joined INL as a Post-Doc

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Thank You