Advanced Optical Techniques for Sensing and Imaging in Harsh Environments

Grigory (Greg) Adamovsky, Ph.D.

NASA Glenn Research Center, Cleveland, OH

and

Frederick W. Van Keuls, Ph.D.

Vantage Partners LLC, Cleveland, OH

Presented at PIWG Fall 2019 Conference

September 24-26, 2019

Skelton Conference Center

Blacksburg, VA

OUTLINE OF THE PRESENTATION

- Fiber Optic Bragg Grating Sensors for High Temperature Applications
  - Why Optics? Why Fiber Optics?
  - Advantages of fiber Bragg grating (FBG) sensors
  - Design, Manufacturing, and Testing of High Temperature FBG

- Fiber-based Sensors for Sensing & Imaging in Harsh Environments
  - Passive and Active Sensing and Imaging
  - Imaging through a Fiber Optic Conduit
  - Sensing Through a Fiber Optic Conduit
  - Combined Spectroscopic & Imaging Systems

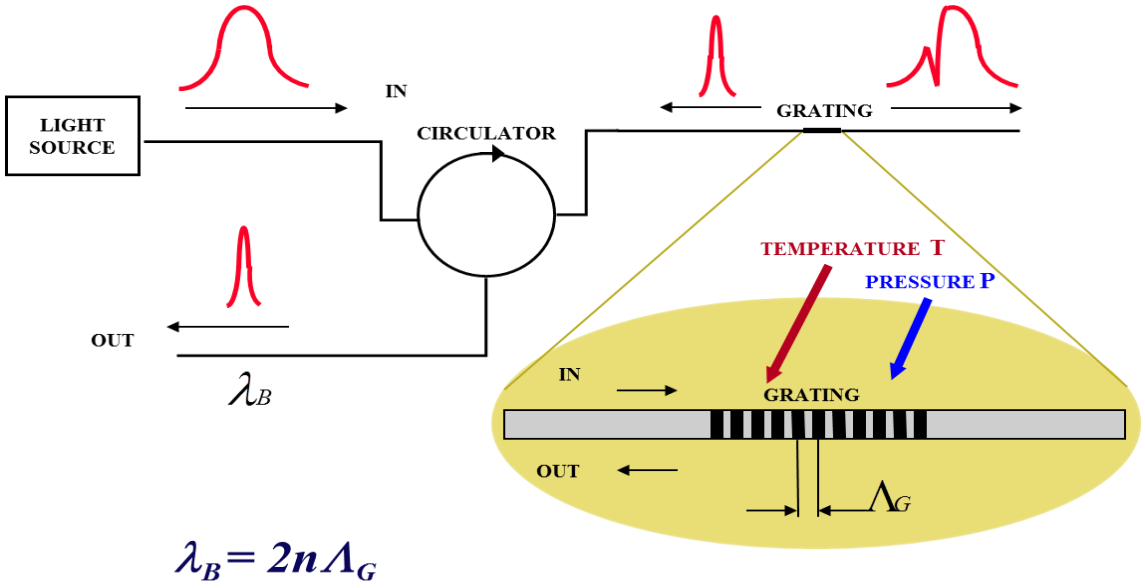
- Conclusions

FIBER OPTIC BRAGG GRATING SENSORS FOR HIGH TEMPERATURE APPLICATIONS

Why Optical? Why Fiber Optics?

- Immunity to electromagnetic interference
- Chemical stability
- Less weight and mass for signal harnesses
- Can be imbedded into structures
- No fire threats
- No explosive threats
- Multiplexing capabilities
- High bandwidth
- Ability to work at the distance

Fiber Bragg Gratings



$$\lambda_B = 2n\Lambda_G$$

EFFECTS OF HIGH TEMPERATURES ON FBGs

- **Thermal Expansion:**

The cladding, core, and buffer coating each have different thermal expansion coefficients. As a result, the thermal stability of an FBG at high temperatures fiber may be compromised.

- **Migration of Dopants :**

Diffusion and migration of dopants between the core and cladding; distortion of the light paths through the fiber (turning a step-index fiber into a distorted graded-index fiber); frustration of the total internal reflection.

- **Silica Devitrification:**

Crystallization of silica glass at high temperatures. Eventually the material becomes opaque.

- **Thermal Optic Decay:**

The index of refraction of fiber changes under high temperatures, which could change the numerical aperture of the fiber and ruin or weaken the FBG structural integrity and signal strength.

FBGs FOR HIGH TEMPERATURE OPERATIONS (>600 ºC)

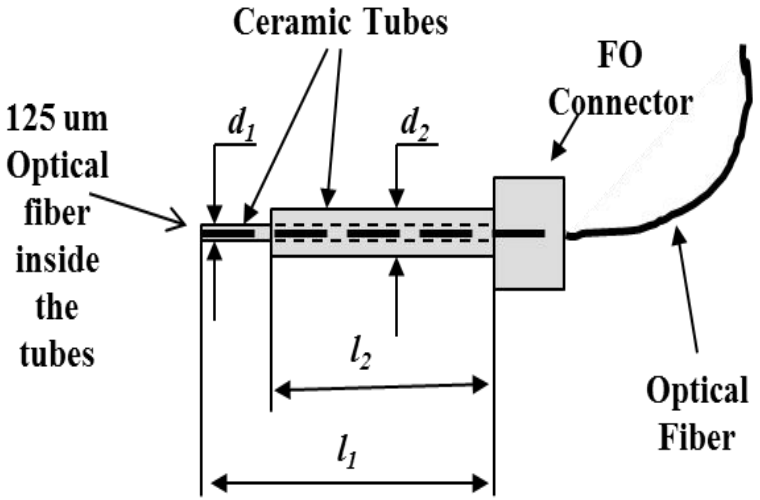
- **Type I Regenerated Gratings**

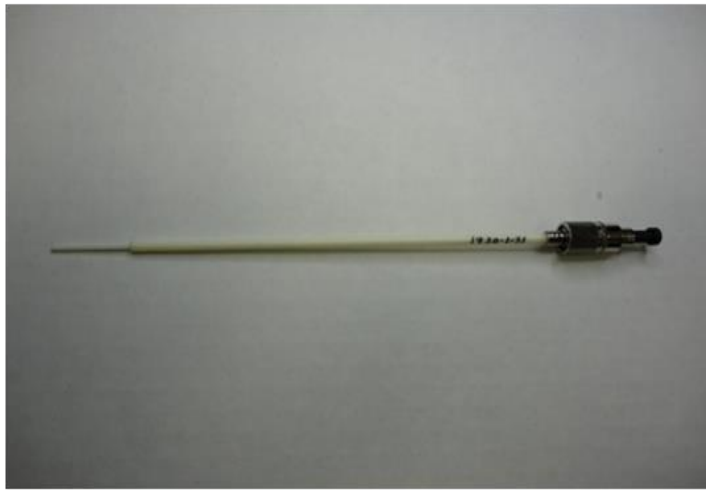
  - Hydrogen loading
  - In case of fluoride presence: formation of Chemical Composition Gratings
  - Utilization of special optical setups
  - Exposure to UV radiation (usually 244 or 193 nm)
  - Pulsed laser operation
  - Characteristic variations in grating reflectivity during annealing
  - Decrease in reflectivity after annealing

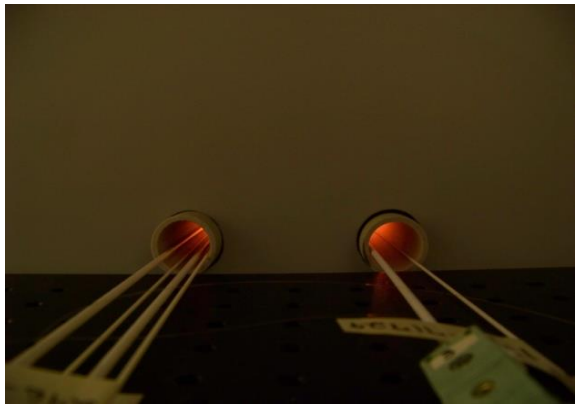
- **Type II Gratings**

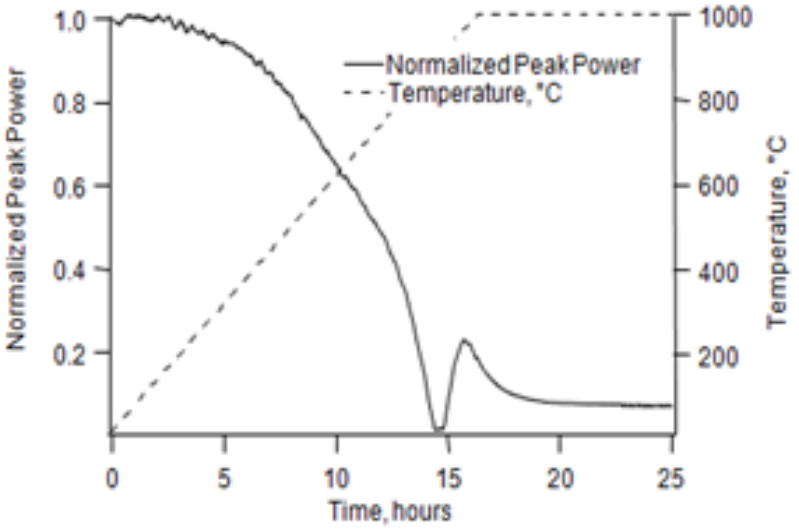
  - Near Damage Levels of Optical Radiation
  - Pulsed Mode of Operation (femtoseconds)
  - Various Wavelengths Used(from UV to IR)
  - Simpler Optical Setups
  - The Grating Reflectivity Stays High
  - May employ some features of Type I Regenerated Gratings

High Temperature Fiber Optic Sensor (HTFOS) Manufacturing Process



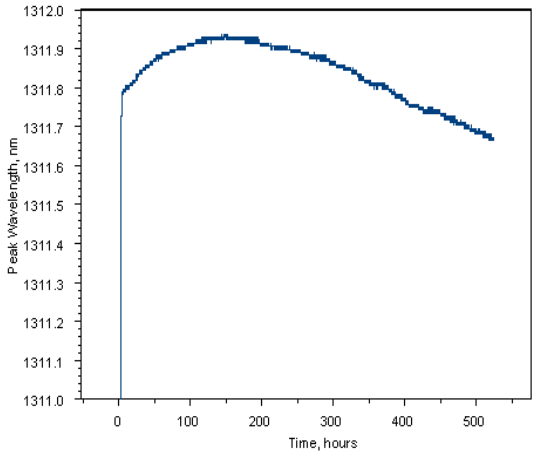




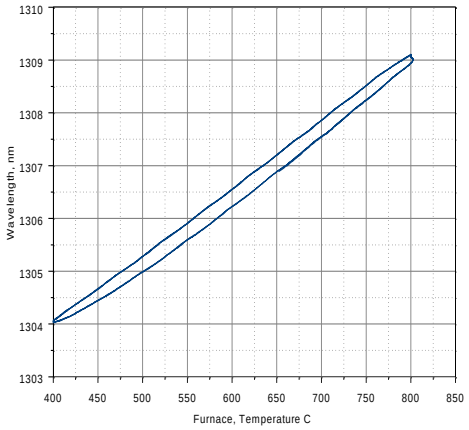


HTFOS Performance Evaluation

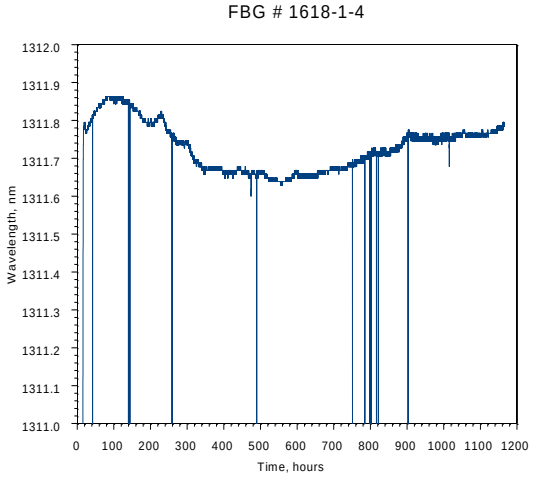
Wavelength Variations 500 Hours at 1000 °C



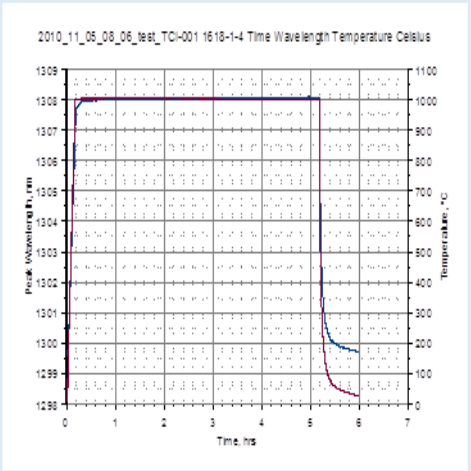
20 Cycles; 400-800 °C; 2 °C/ min Heating Rate; 2 Hrs Hold @ 800 °C

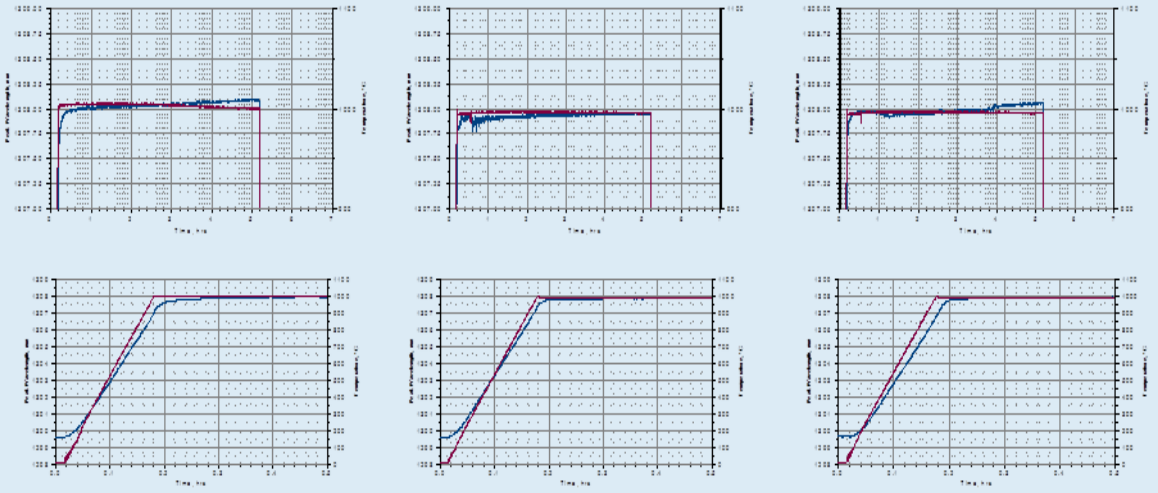


Wavelength Variations 1000 Hours at 1000°C

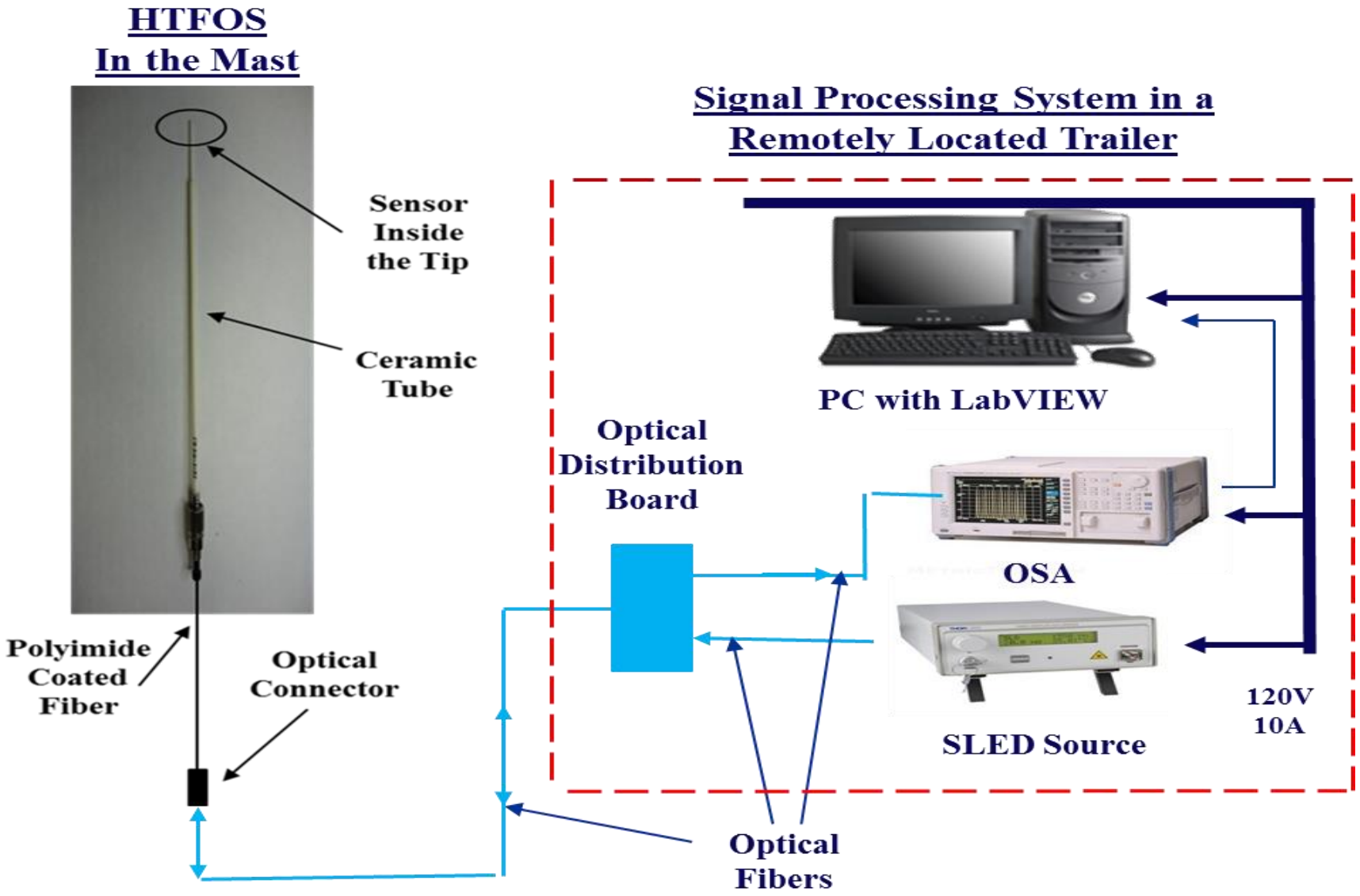


Rapid Heating to 1000 °C and Cooling at 100 °C/min Rates

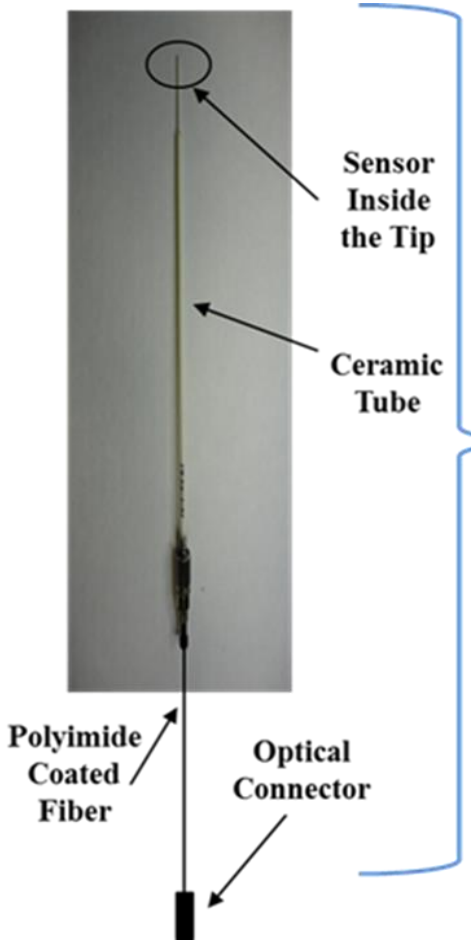


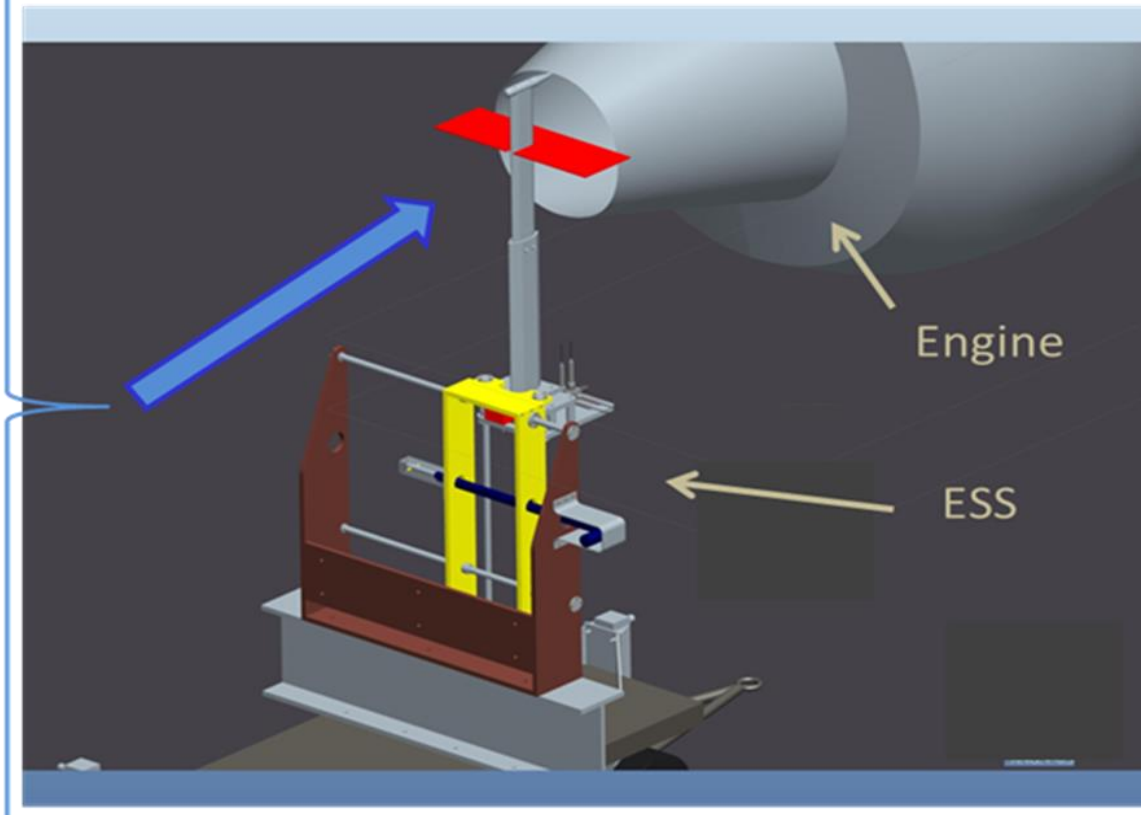


HTFOS with Signal Processing System



Schematics of HTFOS Installation in ESS





HTFOS Design Considerations:

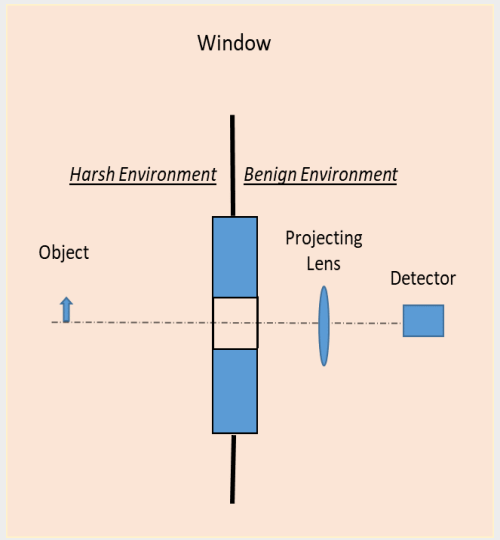
- The fiber optic connector attached directly to the ceramic tubes is outside of the hot zone (max. operating T~250^{o}C)
- The HTFOS tip protrudes above the ESS mast by 0.5” and withstand the effects of engine exhaust gases

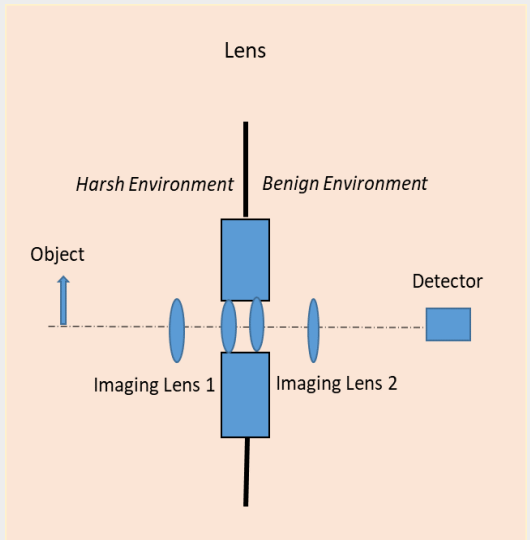
FIBER-BASED OPTICAL SYSTEMS FOR SENSING AND IMAGING IN HARSH ENVIRONMENTS

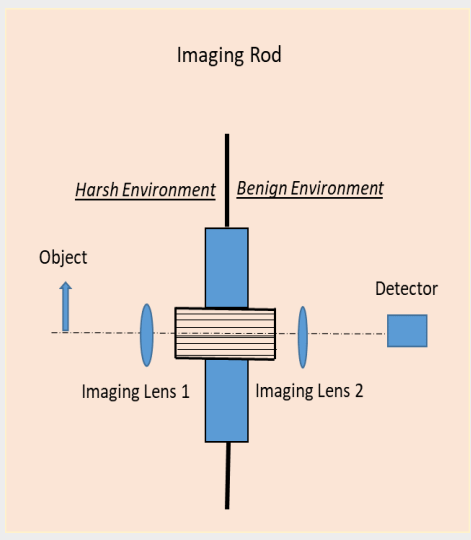
Optical Systems for Imaging and Sensing in Harsh Environments

IMAGING

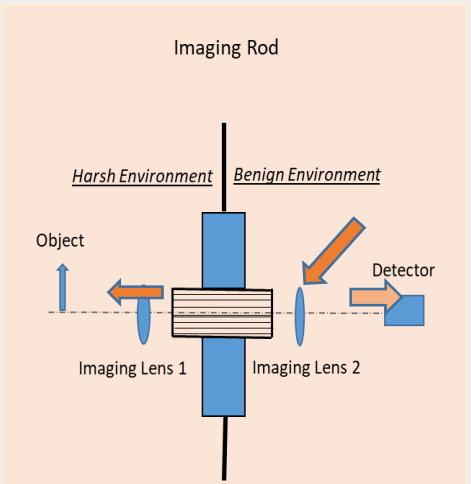
CONVENTIONAL (PASSIVE) IMAGING





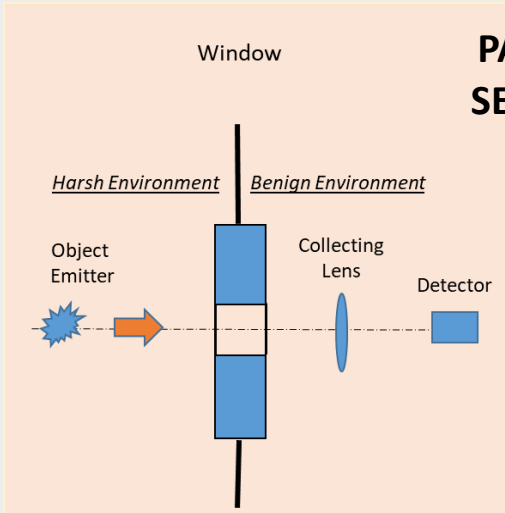


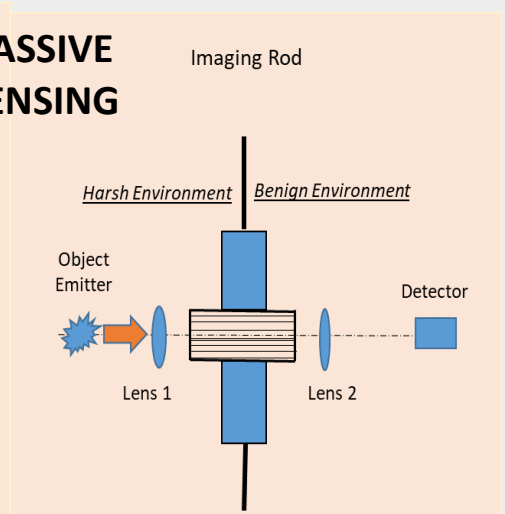
ACTIVE IMAGING
External Illumination



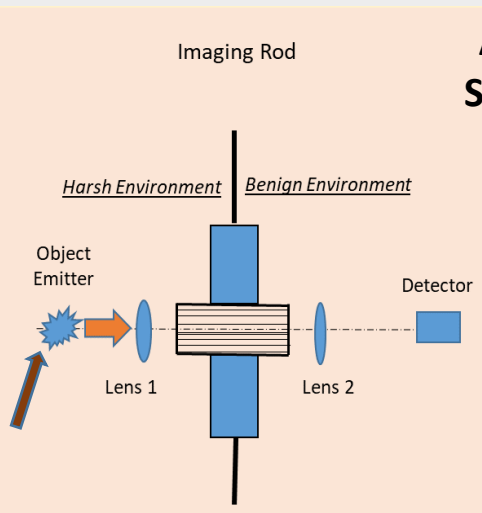
SENSING

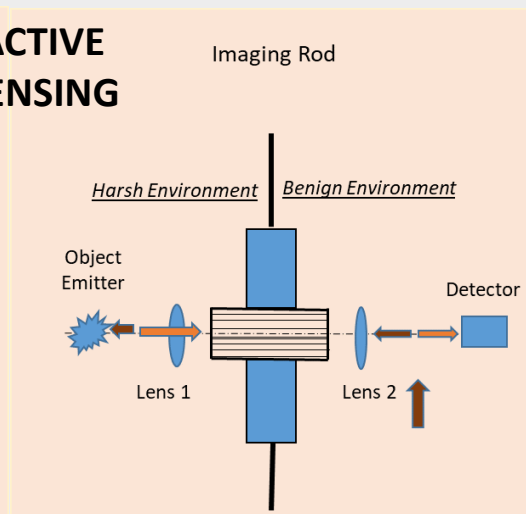
PASSIVE SENSING





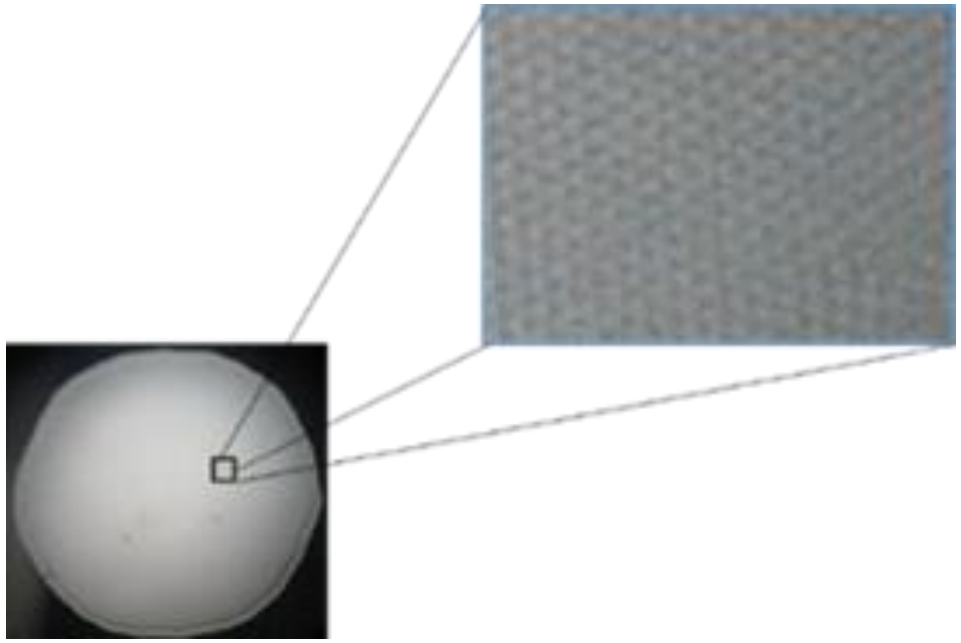
ACTIVE SENSING

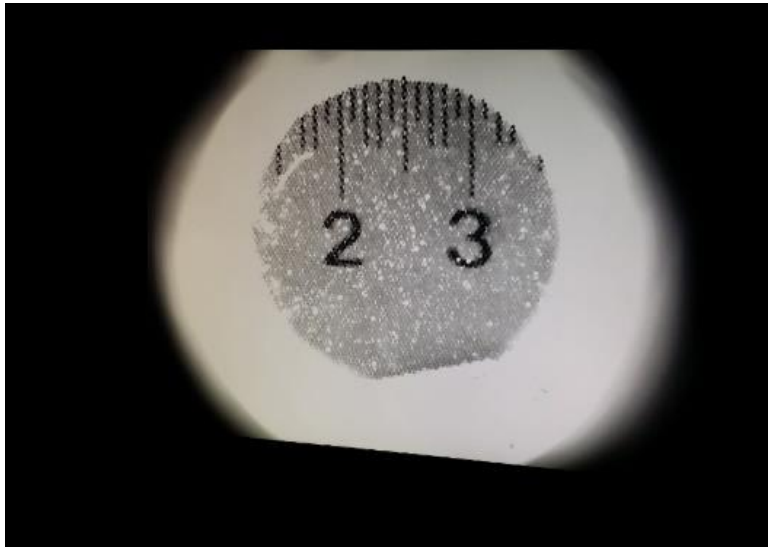




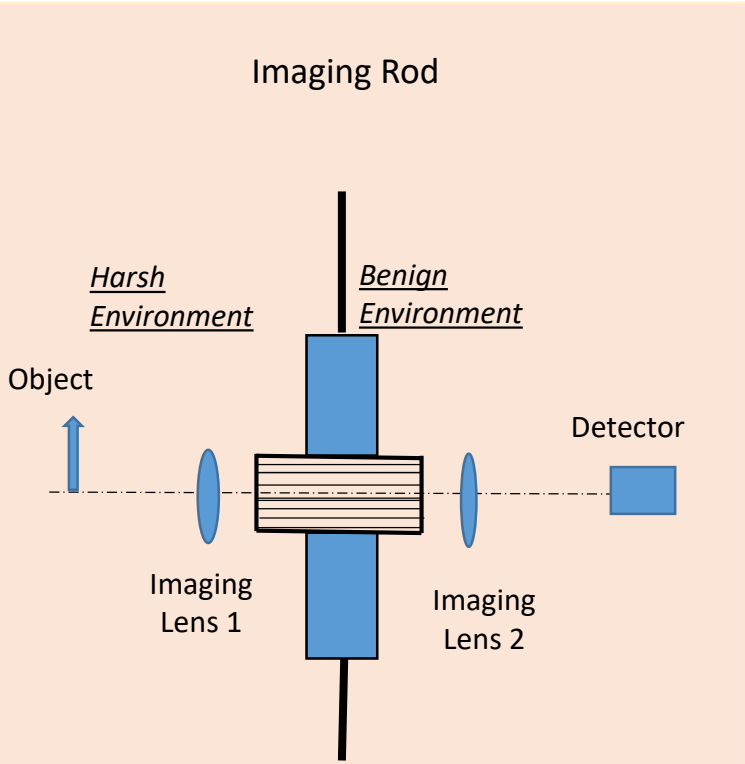
IMAGING THROUGH MULTI-FIBER RODS

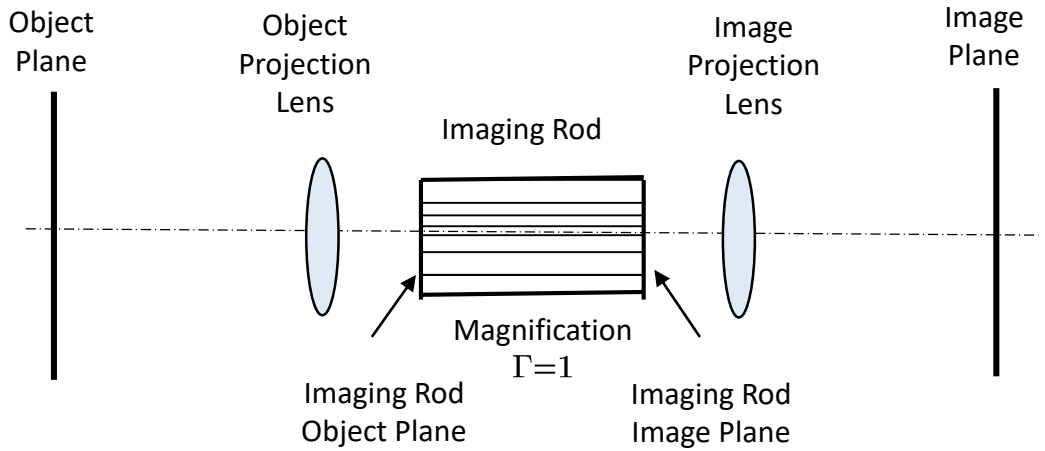
Multi-fiber rod is an optical waveguide consisting of thousands high refractive index cores fibers packed and fused together with lower refractive index cladding to form one large diameter multi-core optical fiber

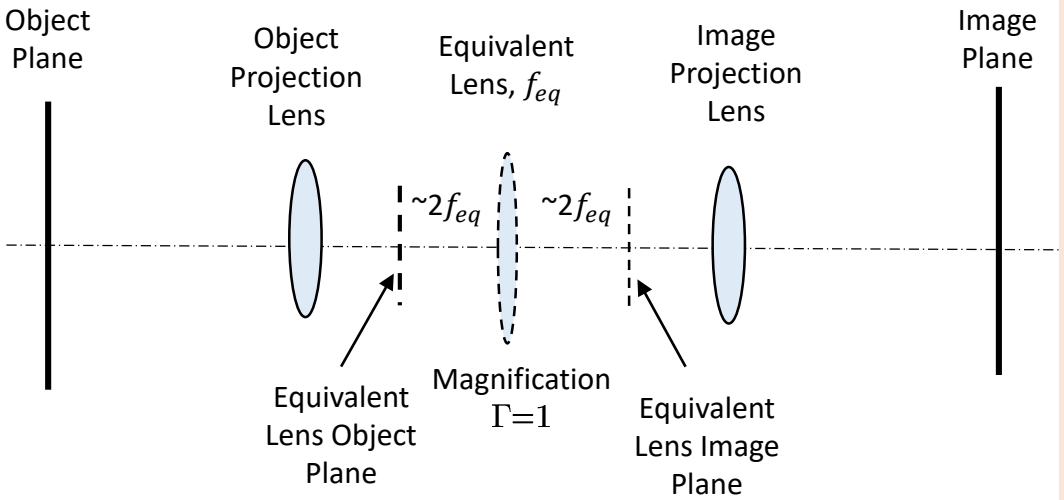


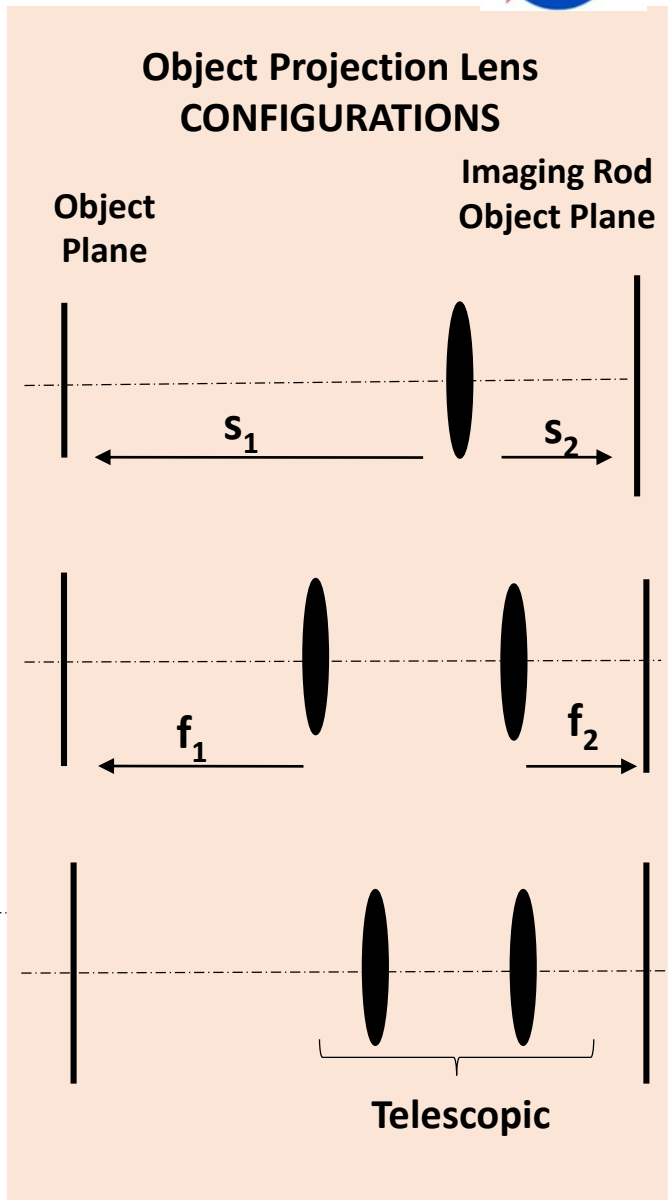


Imaging Through a Multi- Fiber Optical Rod



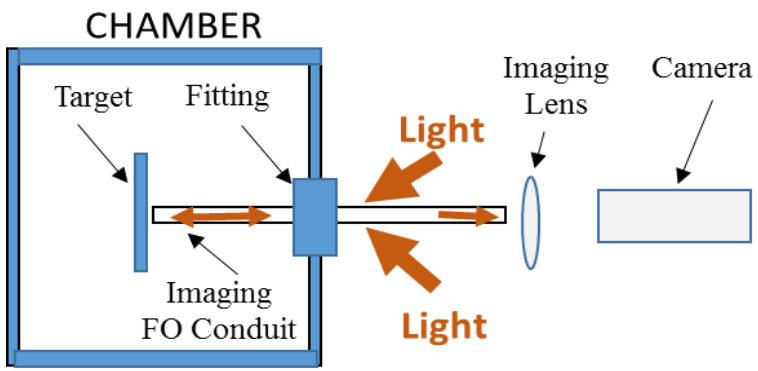




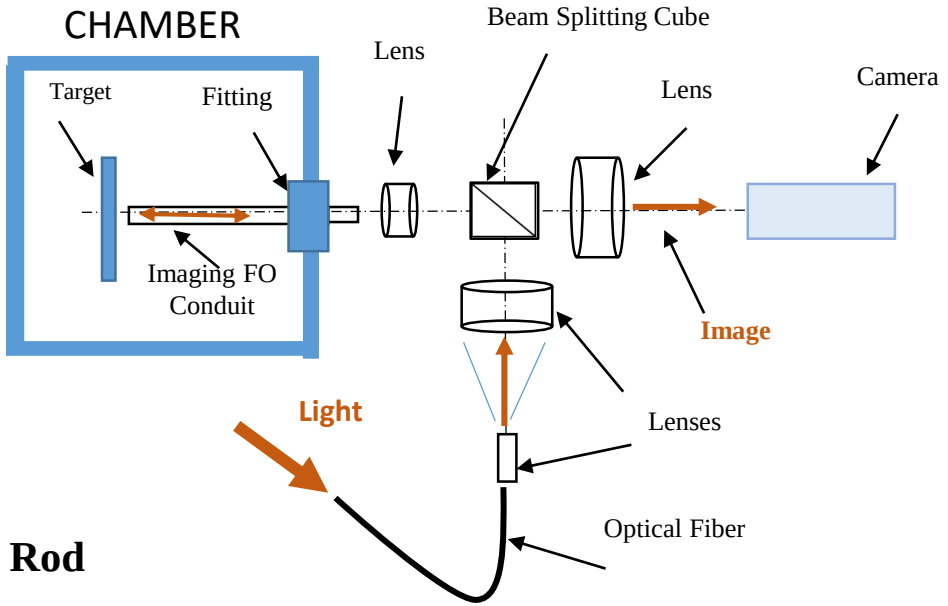


Configurations of Imaging System with External Illumination (Active Imaging)

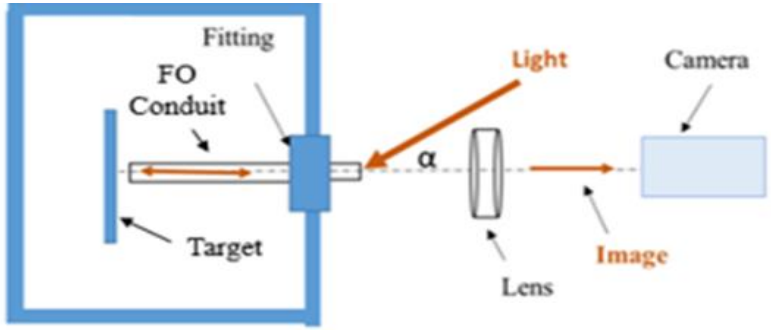
Side Coupling of Light through the Cylindrical Surface of the Rod

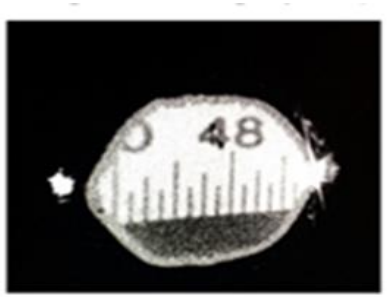


Direct Coupling of Light through the Face of the Rod Using Beam Splitter



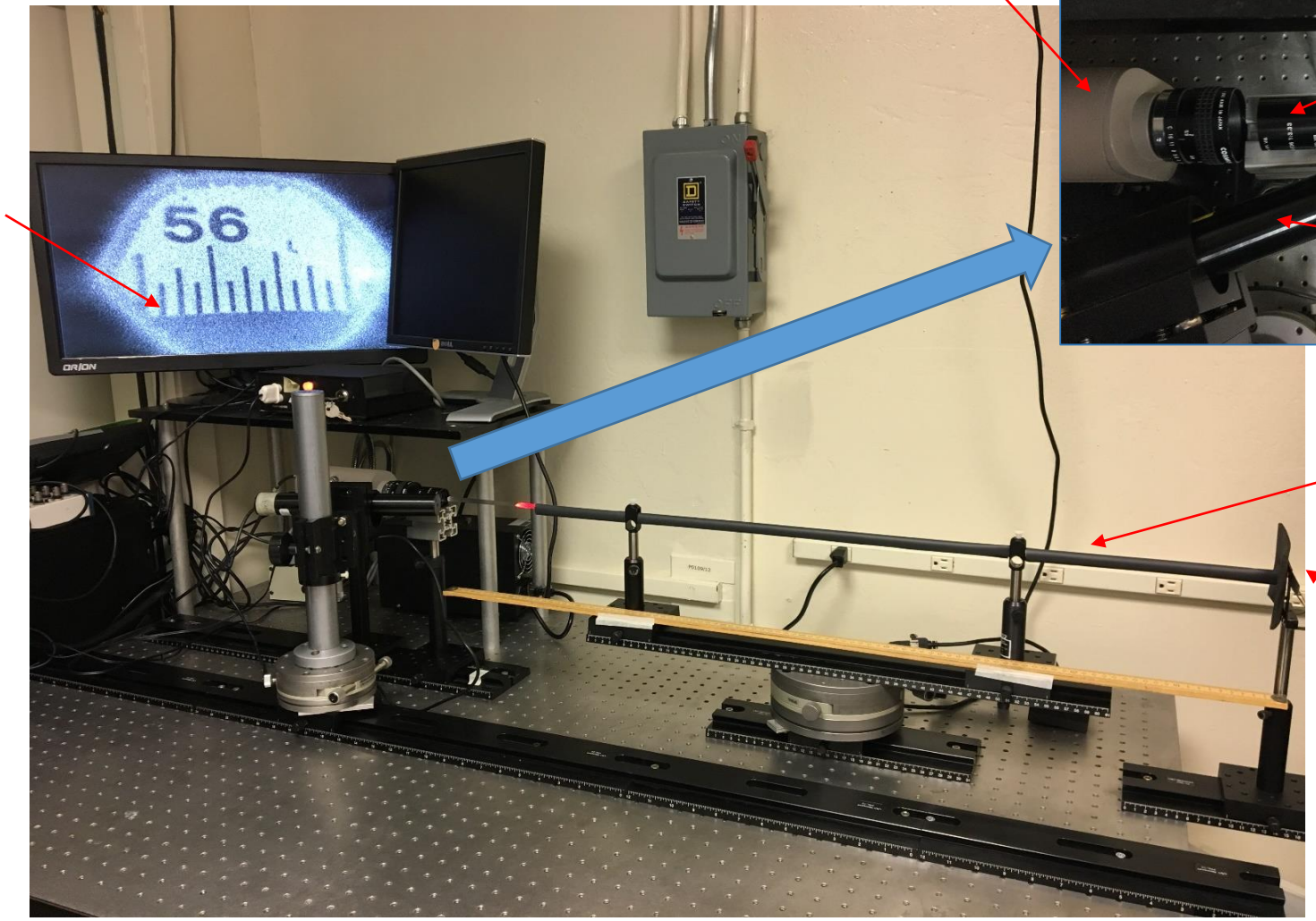
Angular Coupling of Light through the Face of the Rod



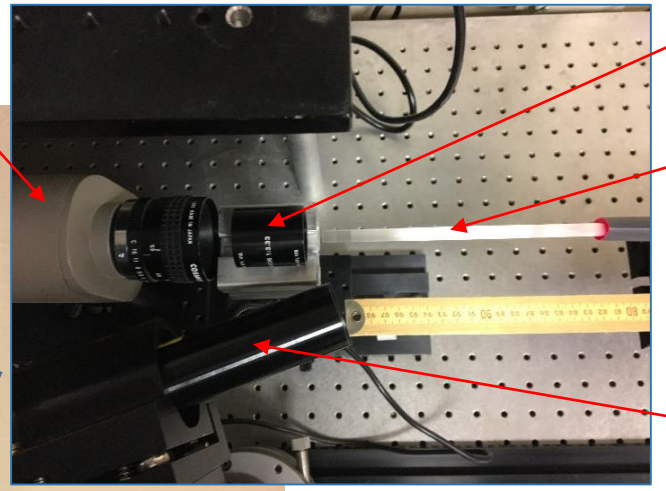


Imaging System with External Illumination: Experimental Demonstration

Imaging of 1/64” Scale through 1 Meter Long Imaging Rod with Laser Side Illuminator

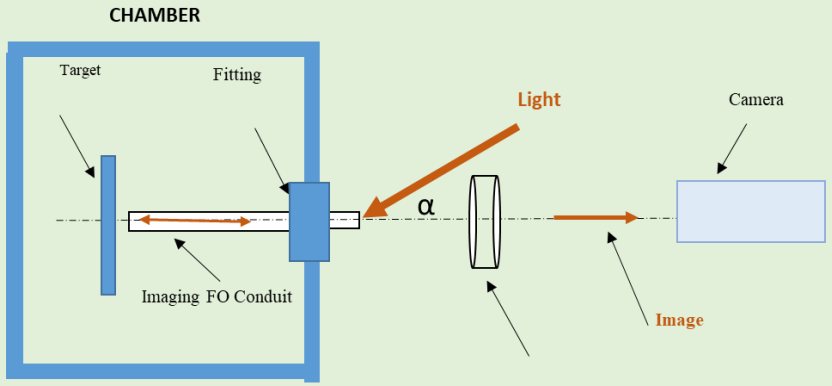


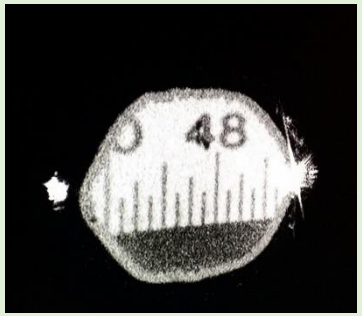
Top View

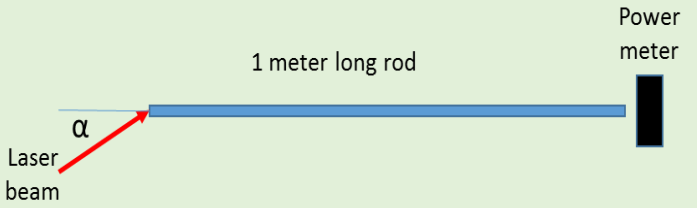


Scale Visualization Through a Rod

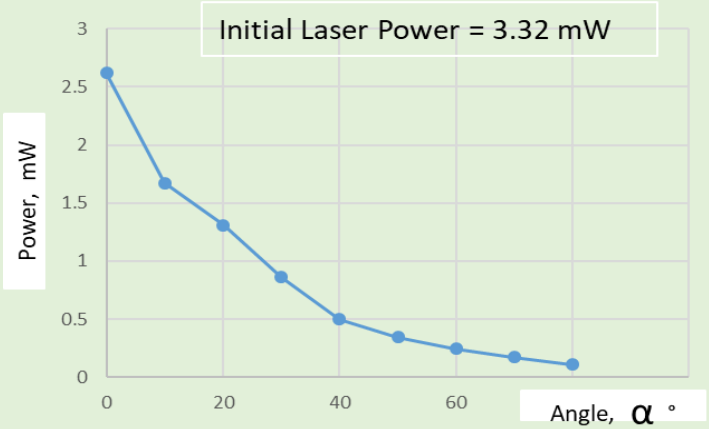
Angular Coupling through the Face of the Rod



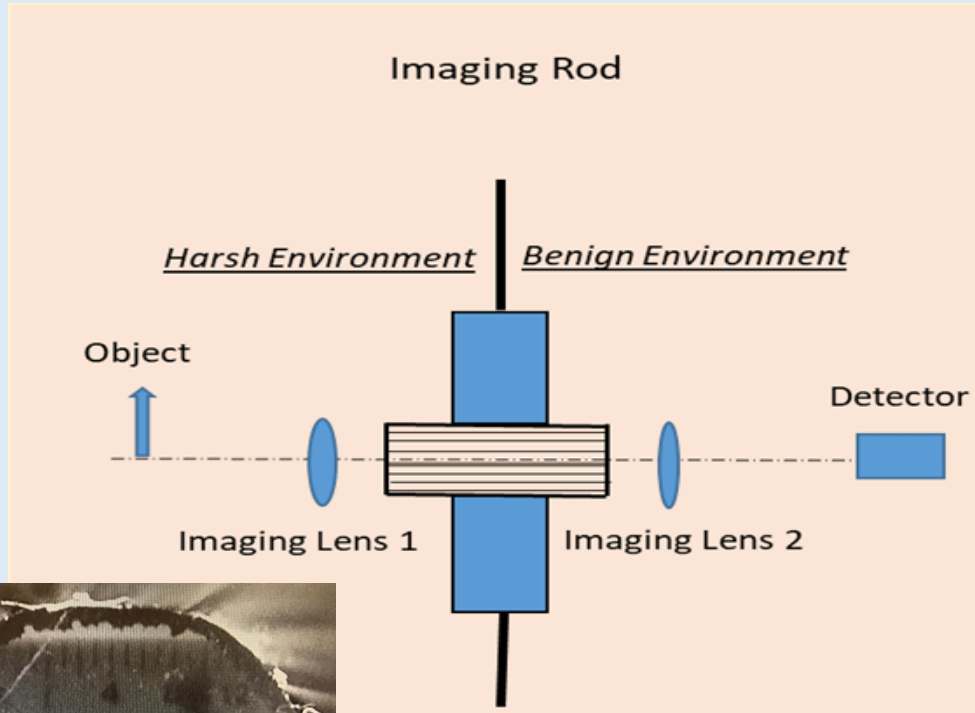




Laser Power Measured at the Other End of the Rod

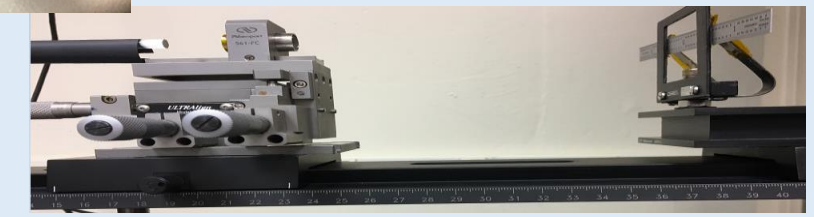


Magnification of the Scale



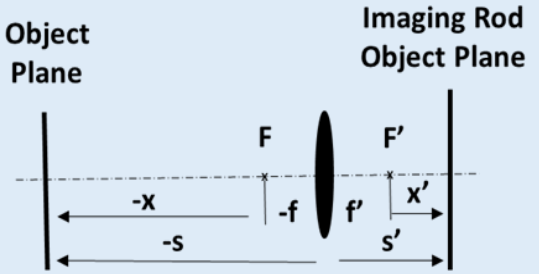
Imaging Lens 1

Object (Scale)



Lensed Fiber Optic Imaging Rod for Harsh Environments

Single Lens Configuration



Thin Lens Approximation
(with the sign convention)

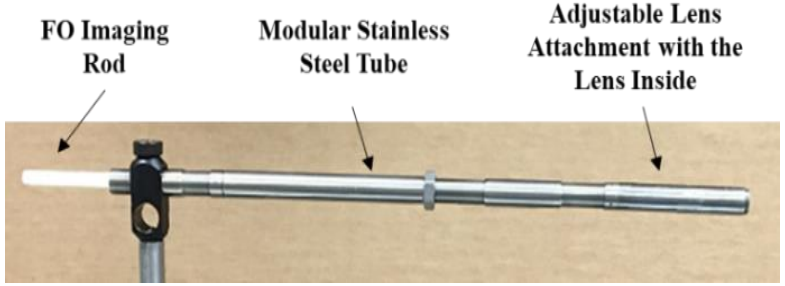
Newton's Formula: $xx' = -f'^2$

Gauss Formula $\frac{f'}{s'} + \frac{f}{s} = 1$

Linear Magnification

Angular Magnification $\gamma = \frac{s}{s'} = \frac{x}{f'} = \frac{f}{x'}$

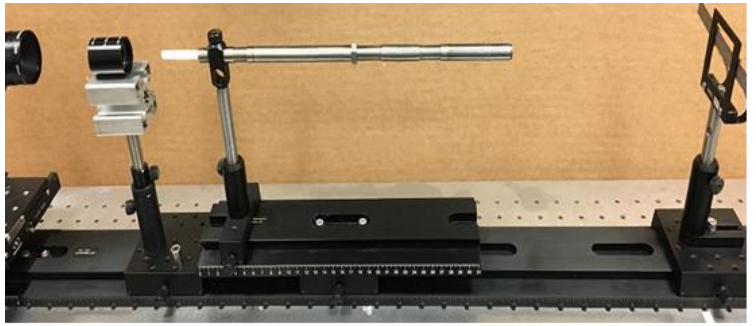
Preliminary Design of a Structure to hold the Fiber Optic Imaging Rod for Visualization in Harsh Environments

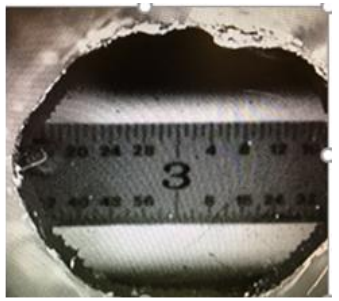


Diameter of the Imaging Rod: ¼ "

Resolution of the Scale: *1/64"*

Position of a 1/64" scale at various distances (left) and the corresponding images (right)

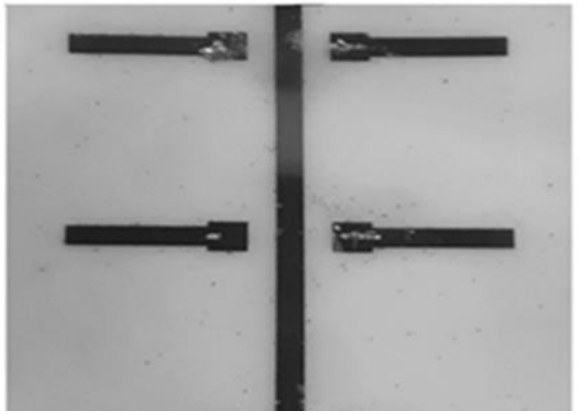




Images of a Target under External Illumination and Various Thermal Conditions

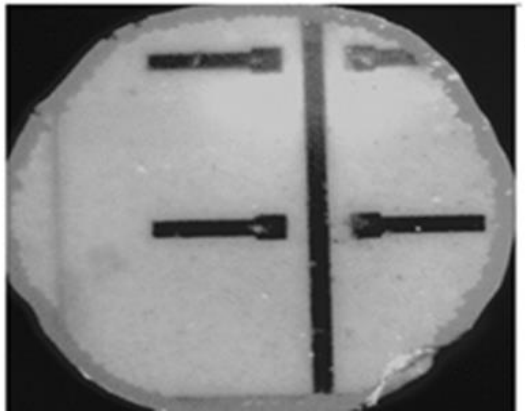
Initial Image under Microscope

a)



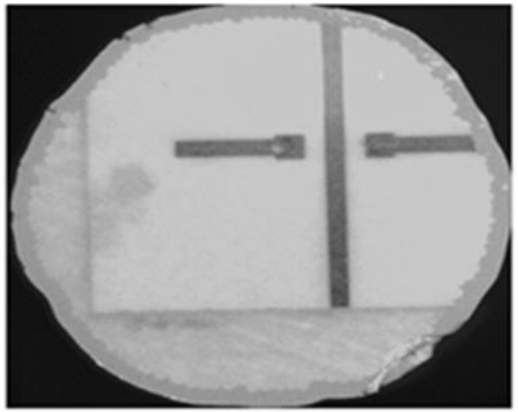
In the Furnace Room Temperature

b)



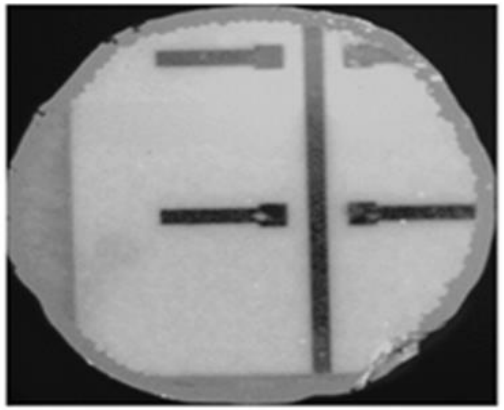
In the Furnace, After 2.5 hours @ 500 °C

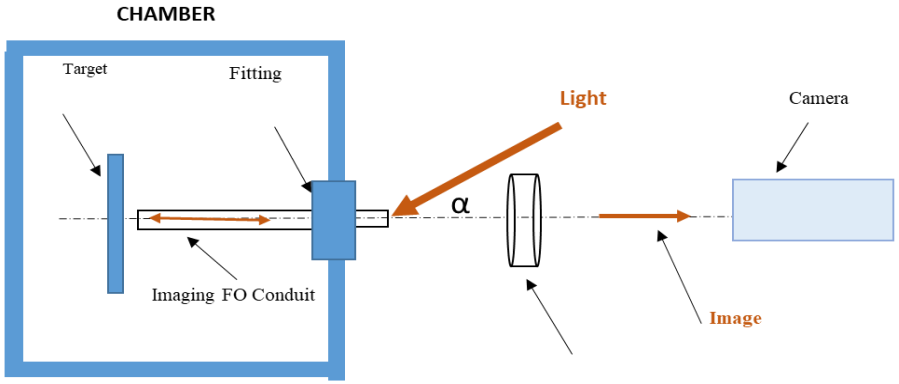
c)

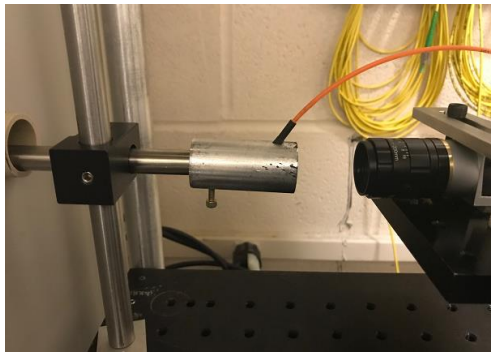


In the Furnace, After 3 cycles to 500 °C

d)



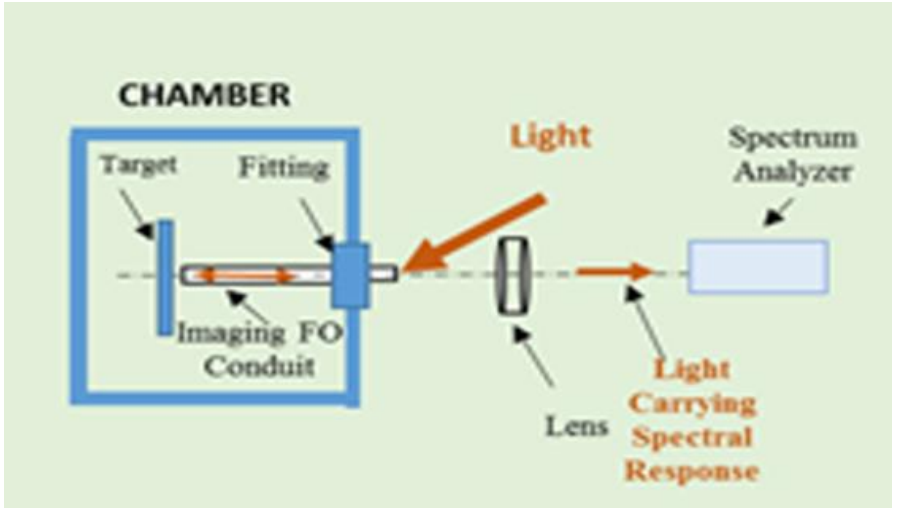


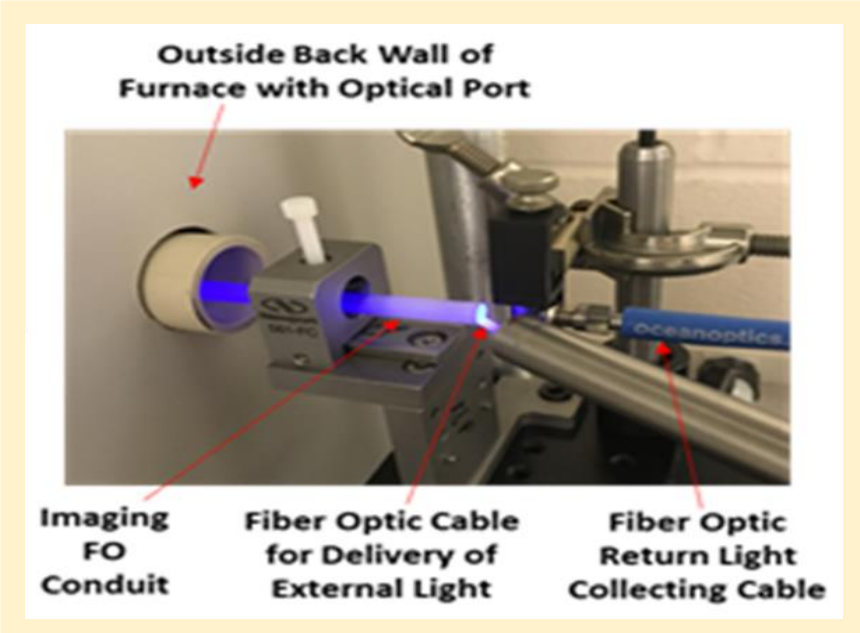


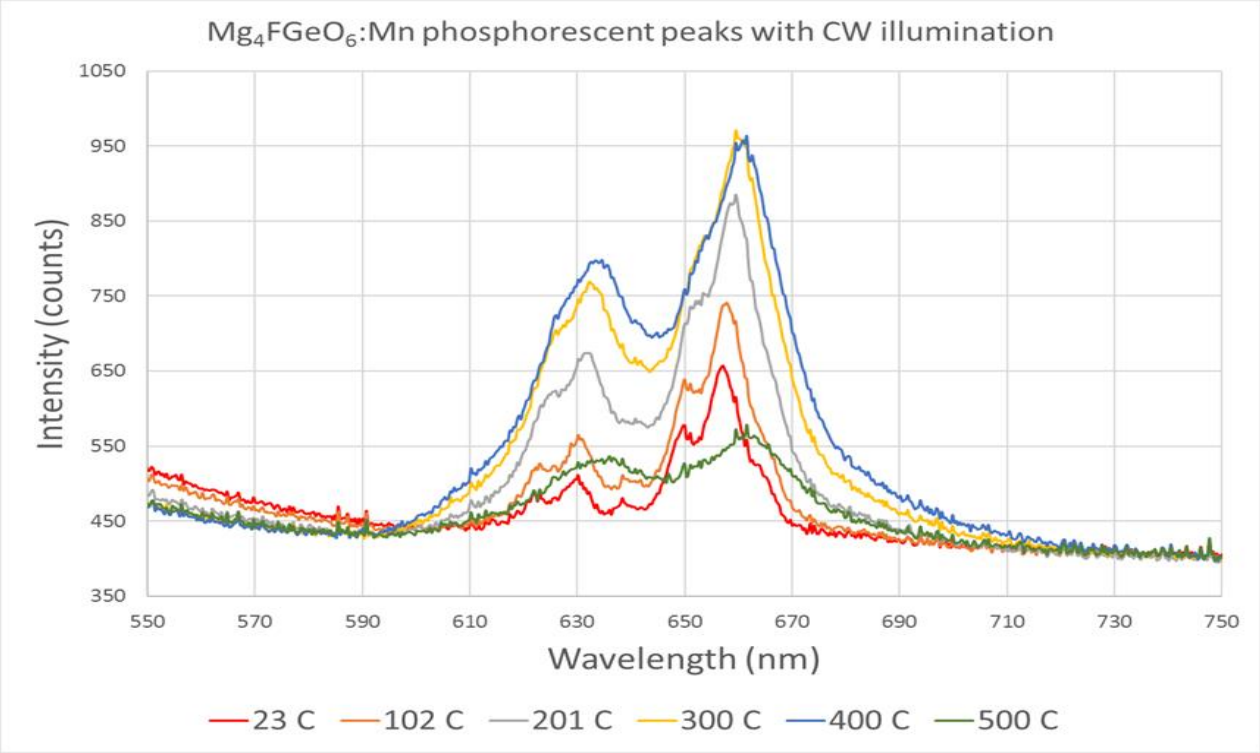
- **A 0.5 m long fiber optic conduit was used, 0.24 m of the conduit was exposed to 500 °C**
- **The illumination was injected through the conduit from an LED source**
- **The target was a gold circuit on an alumina substrate. The thickness of the traces on the circuit is 213 µm**
- **The image became slightly brighter after each cycle presumably because the FO conduit was annealed. Similar annealing effect of high temperature on light transmission through optical fibers have previously observed**

SENSING THROUGH MULTI-FIBER OPTICAL RODS

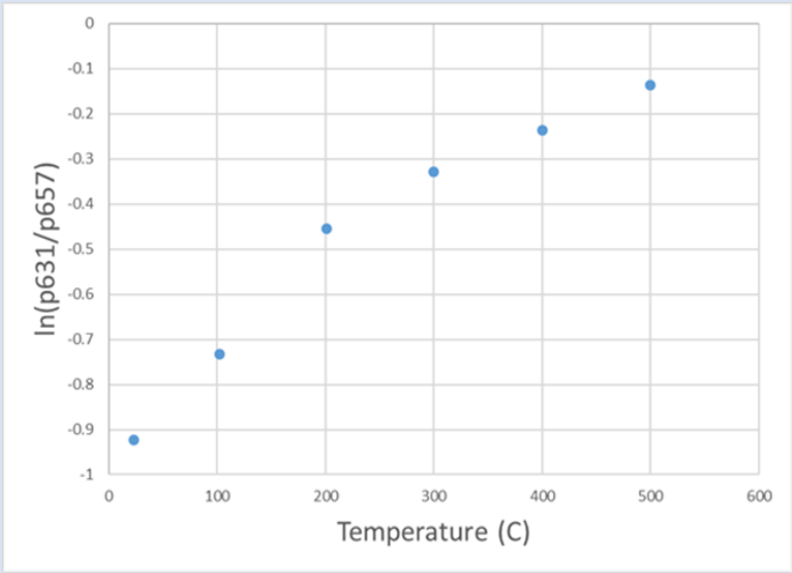
Sensing Through Fiber Optic Conduit





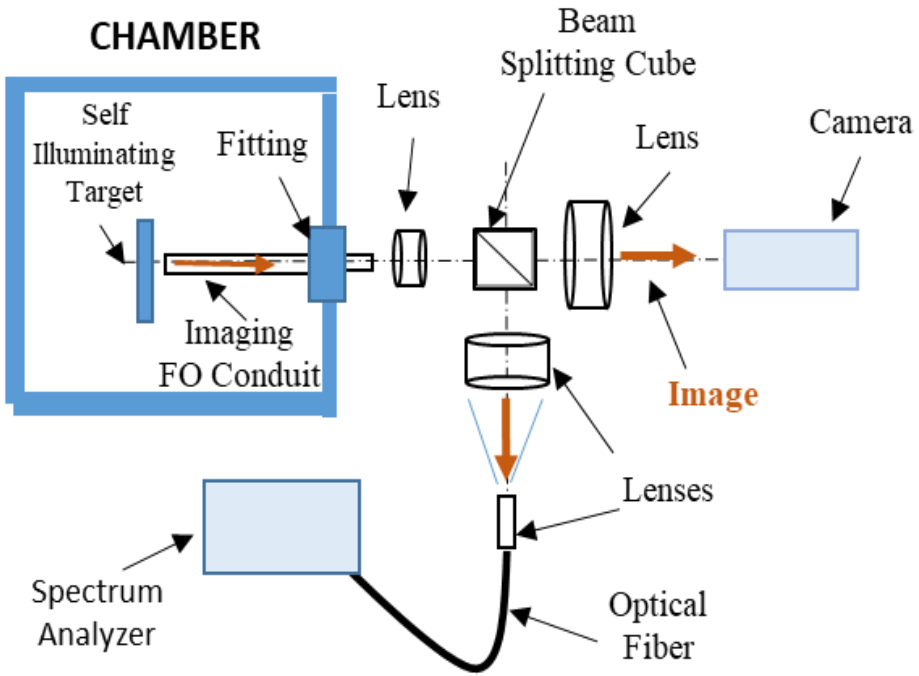


Natural logarithm of the ratio of peak intensities at two wavelengths (631 nm and 657 nm) emitted by Mg_4FGeO_6:Mn at various temperatures

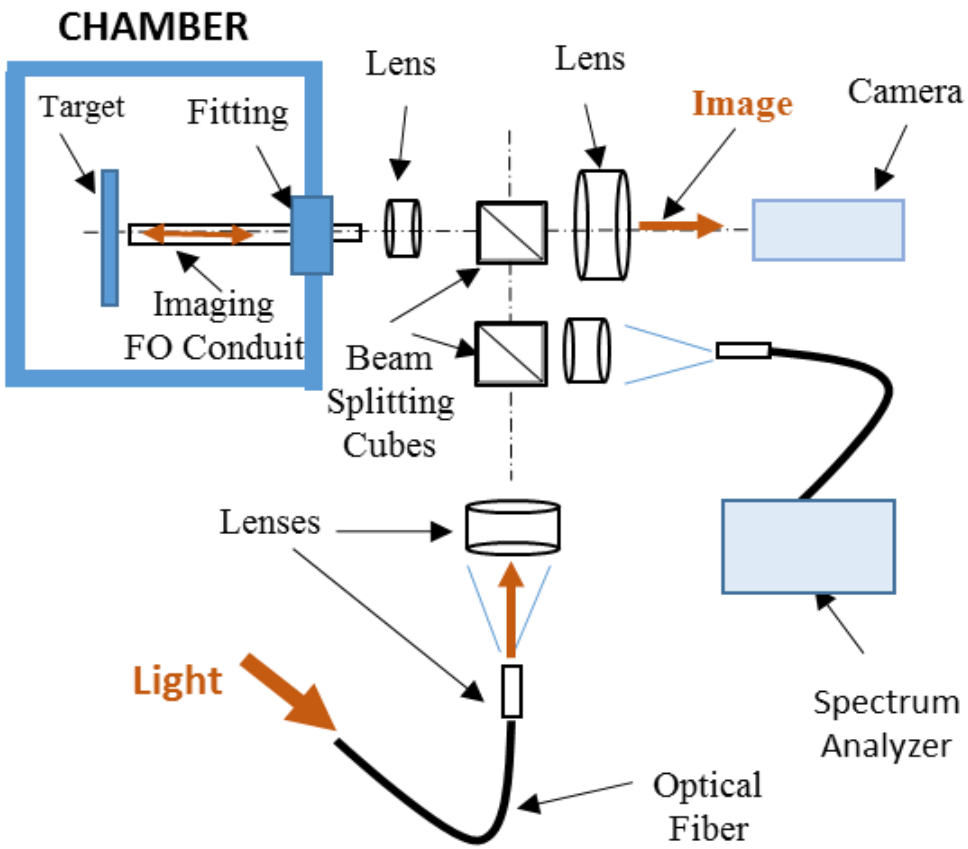


Combined Spectroscopic & Imaging Systems

Combined Spectroscopic & Imaging System with Internal Self Illumination



Combined Spectroscopic & Imaging System with External Illumination



Conclusions

Advantages of HT FBGs

- **Have small weight & are easily embeddable**
- **Chemically stable**
- **Insensitive to light intensity variations**
- **Depending on manufacturing process, have operability range up to 1000 C and above**
- **Provide repeatable results**

Advantages of Fiber Optic Conduits

- **Survivability in Harsh Environments**
  - Withstands high temperature and pressure
  - Exhibits chemical stability
- **In-Situ measurements and sensing**
  - Eliminates optical windows
  - Permits external illumination of targets for imaging
  - Permits implementation of active optical sensing
- **Modular Design**
  - Permits attachment of different lens systems to accommodate application requirements

NEEDS

- Optical fibers with flexible unexpansive protective coatings to withstand higher temperatures (up to 500 C and above)
- Optical fiber for extreme temperatures (perhaps, sapphire-based)
- Small factor signal processing hardware to process optical signals (wavelength-to-frequency converters, fast spectral readers, etc.)
- High temperature optical epoxies