“Protected, High Temperature Optical Fiber Sensors, Gauge Elements and Systems”

Fundamental Aero Program Workshop
New Orleans, 11/1/07

Fiber & Electro-Optics
RESEARCH CENTER

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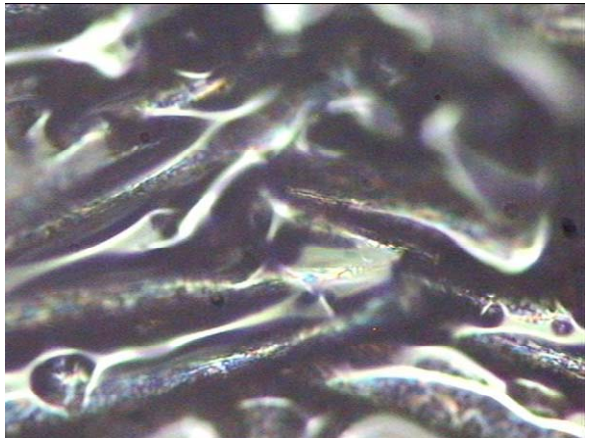
Program Overview:
"Protected, High Temperature Optical Fiber Sensors, Gauge Elements and Systems"

Objectives

- Develop High Temperature Coatings for Integrated Optical Fiber & Fiber Sensor Structures
  - Handling Resistant Coatings for: Sapphire/Zirconates/Hi Temp Silica
    - Carbon-Carbon (CC) & Carbon-SiC basis
    - Integration with Handling Resistant Gauge Structures
- Develop High Temperature Coupons & Integrated Gauges
  - Approach: "Fracture Release" structures
- Integration of Coated Fibers & Gauges in Connectorized Subystems



Pre-Pyrolysis Carbon-Carbon Fiber/Resin Coating on Optical Fiber

Approach

- Extension of successful Proprietary Sensor Concepts begun in a Prior NASA Program
- Collaboration with NASA Dreyden (Hypersonic testing) and Langley (Carbon-Carbon Materials) Laboratories
- Year 1: Progressive, Empirical Testing
- Observation….High temperature coatings using the materials of the mounting site (carbon-carbon) could have superior handling and utilization characteristics

FY 2007/08 Key Milestones

- Literature Review and Acquisition of Carbon-Carbon Materials/Processing Facilities
- Demonstration of Carbon-Carbon Coatings and Coating Potential/Performance
- Fabrication of High Temperature "Fracture Release" Sensors
- Advanced, Integrated, Protected Sensor Concepts & Capabilities Analyses

Virginia Tech

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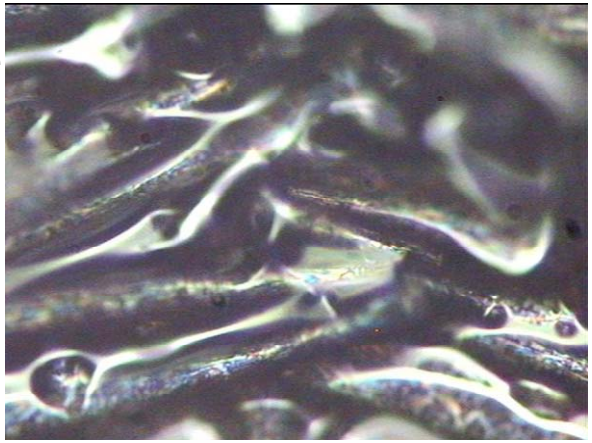
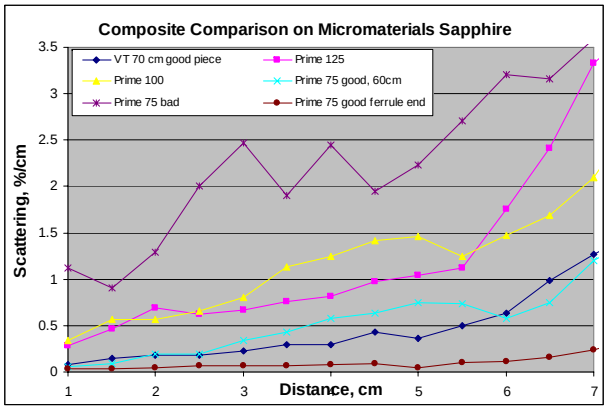
Status Overview

Status and Progress

- **Status: Program effort on schedule with positive progress**
- **Progress & Accomplishments:**
  - **Background work complete, materials in-house**
  - **Preliminary result: Viable, reduced temperature Carbon-Carbon coatings applied to Silica Fibers using milled fiber**
  - **Silica Fibers screened for temperature tolerance**
  - **New design for Fracture Release Sensor assembly tested in prototyping**
- **Highlight: Collaborative Program Effort well supported by DFRC & Industry supplied material**
- **Issues:**
  - **One US Source of Sapphire Fiber (2000°C)**
  - **Some Recent Sapphire Fiber not suited to sensors (highly scattering)**
  - **Carbon-Mesopitch compounds determined not suitable to the current program goals**
- **Plans for the remainder of the first year of effort**
  - **Continue development of coatings using milled and tow forms of Carbon-carbon fiber**
  - **Fabrication of Fracture Release sensors**



Pre-Pyrolysis Carbon-Carbon Fiber/Resin Coating on Optical Fiber



Scattering comparison of older and more recent sapphire optical fibers

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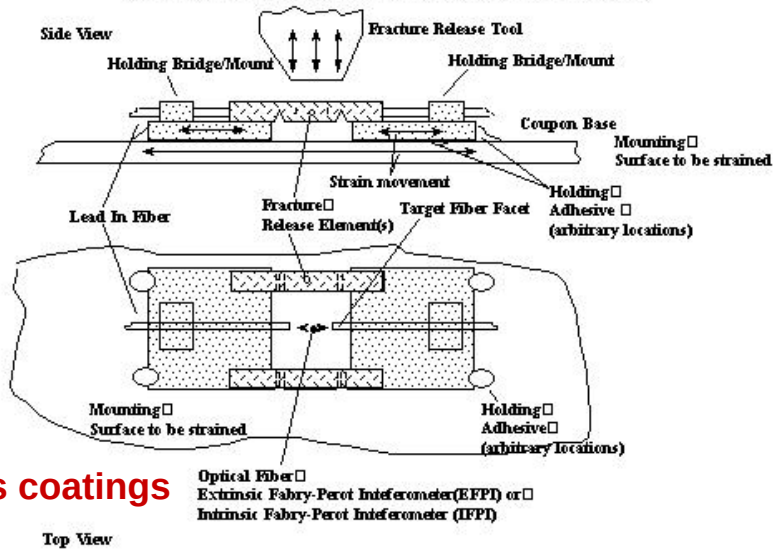
Concept Genesis: Fracture Release Sensor Concepts & Background

Fracture Release Assembly Concepts:

- Eliminates 6 Degree of Freedom Alignments
- Precision Alignment for:
  - Free-surface Gauges
  - Single or Multi-Mode Fibers
  - All Rigid Materials
- Ceramics, Carbon-Carbon/SiC, etc.

Fracture Release Coupon for Optical Fiber Strain Gauges



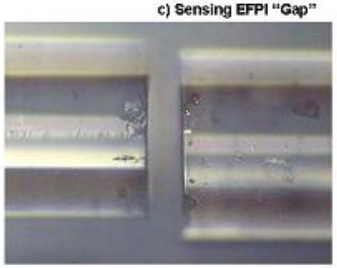
? Why not use the materials of the mounting site as coatings

Station Assembled, Non-Fracture Gauges

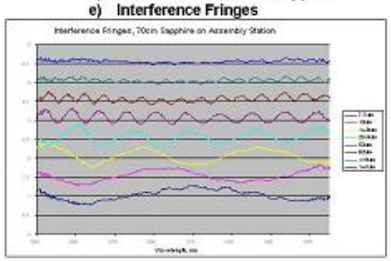
a) Sensor on Carbon-Carbon

b) Sensor on Ceramic Coupon

c) Sensing EFPI "Gap"



d) 100um dia Multi-Mode Sapphire
e) Interference Fringes

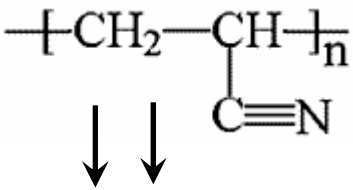


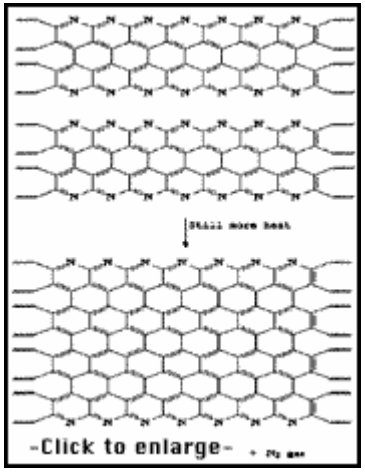
Assembly Station

Program Focus: Carbon-Carbon Coatings

- Chopped/Milled Carbon-Carbon Fiber mixed with standard Composite Resins
- Slurry Coating Precursor 95+% Carbon
- Fibers 7um Dia X 150um (L)
  - Processing continues Carbon Linkage
- Initial Feasibility Research:
  - Fabrication Process well suited to Fiber Coatings
  - Material bend radii should be suited to Fiber requirements
  - Industrial Consultations –
    - Good Support for Concept
    - Variety of Forms potentially achievable
- Current work is experiment with coating techniques
- Recipes from NASA Langley, Wallace Vaughn
- Patent Protection applied for

Polyacrynitrile Precursor



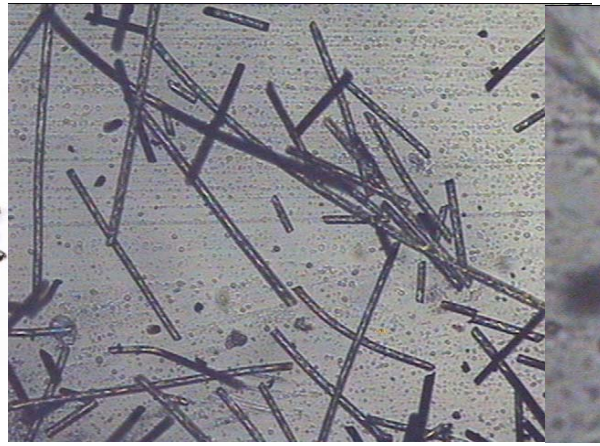


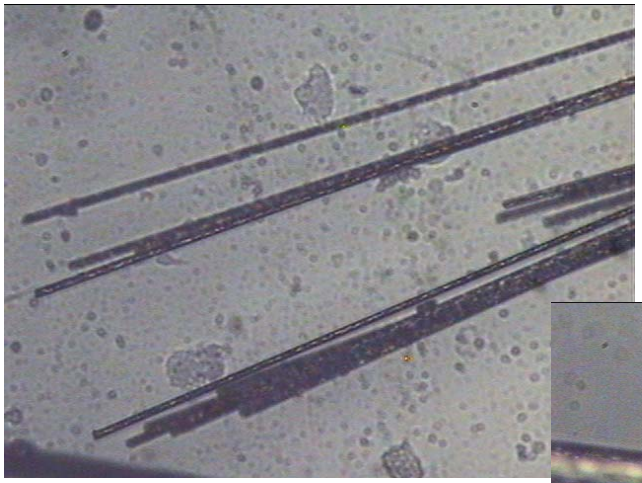
Source: ZOLTEK Inc., http://www.zoltek.com
Dan Shannon,Tim McCarthy, Dr. Long Gui Tang, 800-325-4409

Coating Efforts: Materials

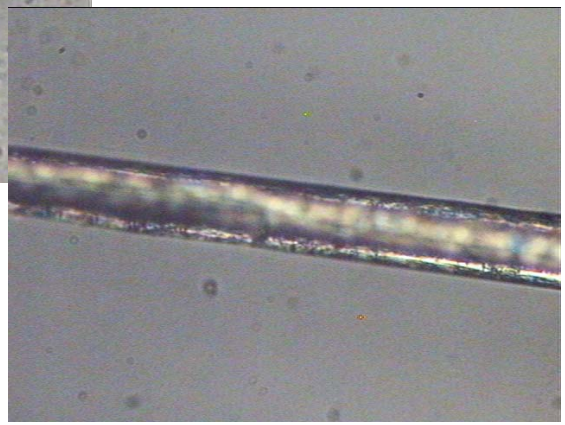
- Materials

Zoltek Milled Fibers





Zoltek & Hexcel Carbon Tows



Durite Phenolic Resole Resins (not shown)

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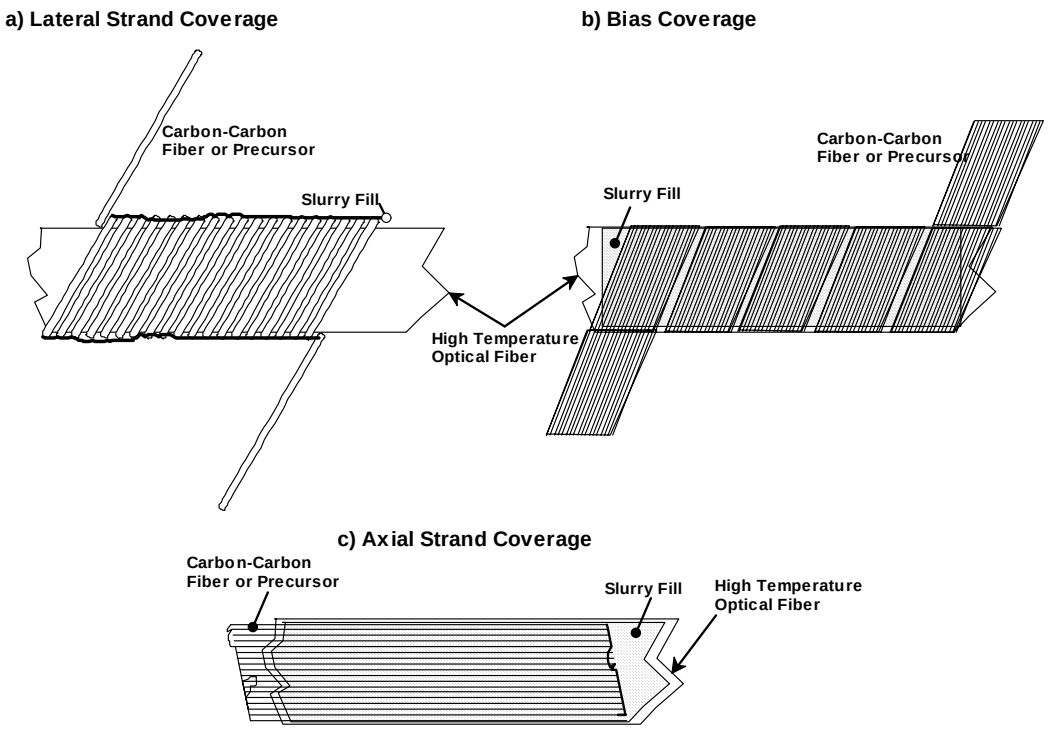
Application of Direct Carbon Fiber Coatings

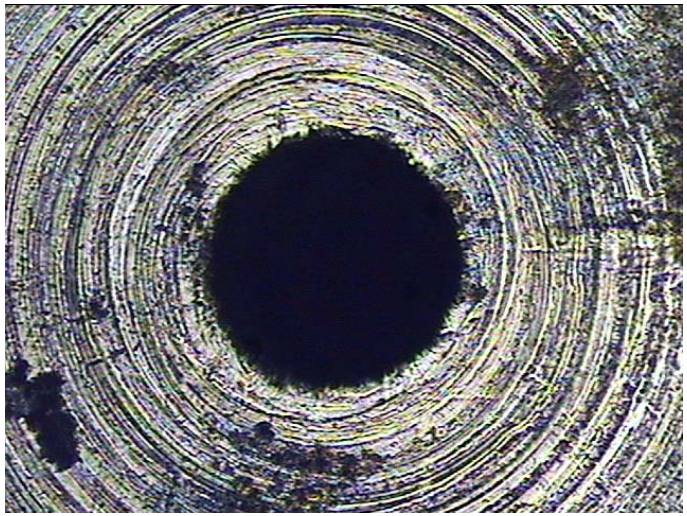
- **Carbon-Carbon Fiber:**
  - Bonded with standard Composite Resins
  - Impregnated with Milled Precursor Slurries
- **Fibers - 7um Dia**
  - Processing continues Carbon Linkage
- **Initial Research:**
  - <u>Feasible</u>
  - Fabrication Process suited to Fiber Coatings
  - Material bend radii < 1mm
  - Industrial Consultations –
    - Good Support for Concept
    - Variety of Forms potentially achievable

Source: ZOLTEK Inc., http://www.zoltek.com

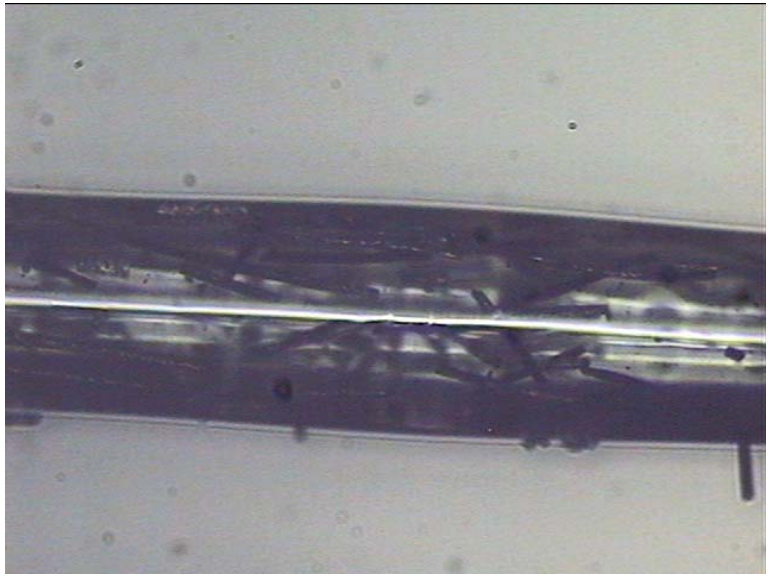


Results: Direct Extrusion of Slurry Coatings

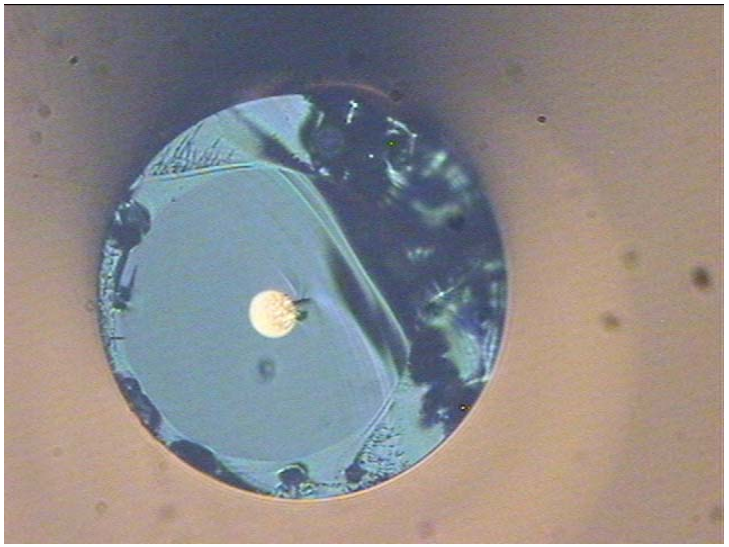
Extrusion Ferrule

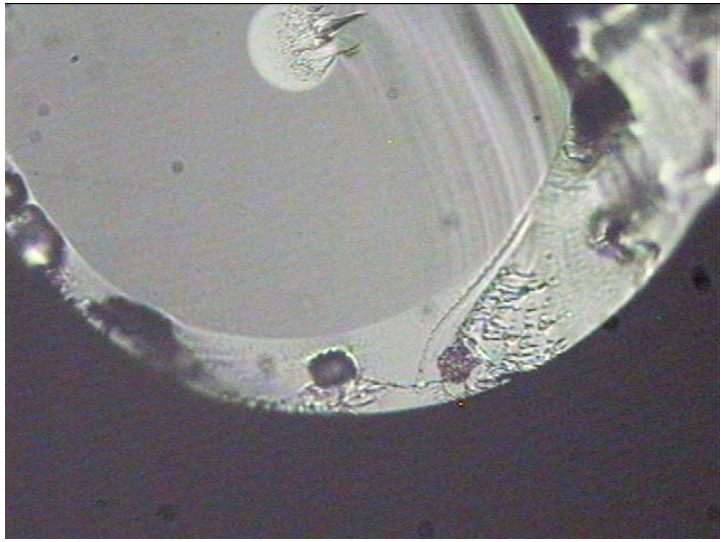


Coated Fiber



- **Initial Results Lacking in Fiber Density**





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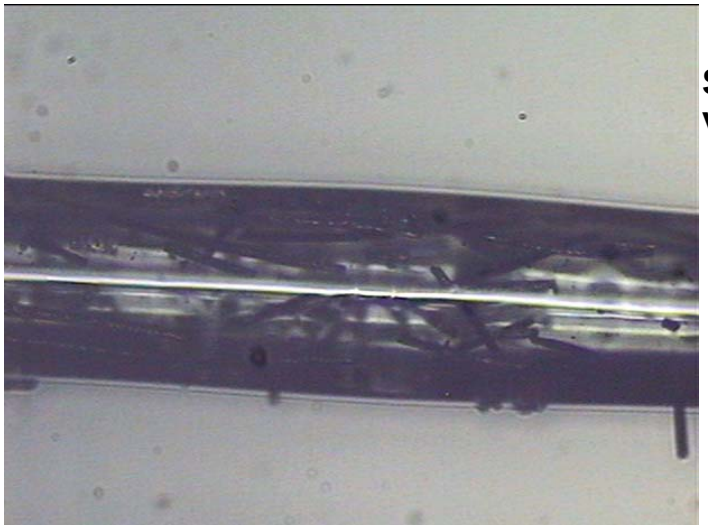
Slurry Coating vs “Powdered” on Coatings

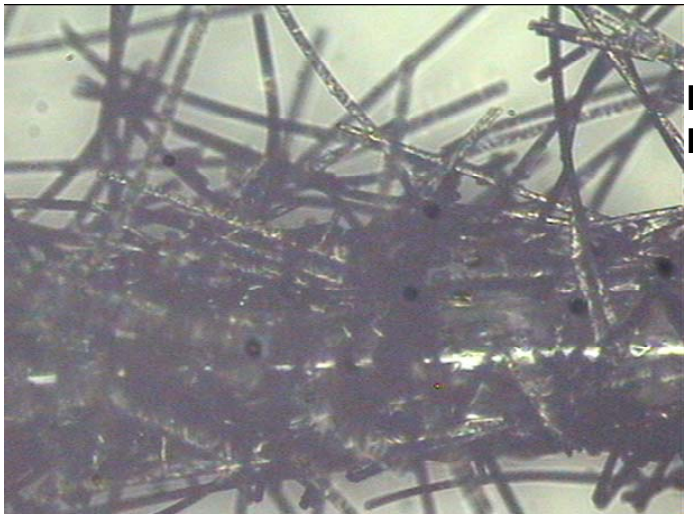
•Extruded Slurry Coating Results: Low CC Fiber Density



Side View

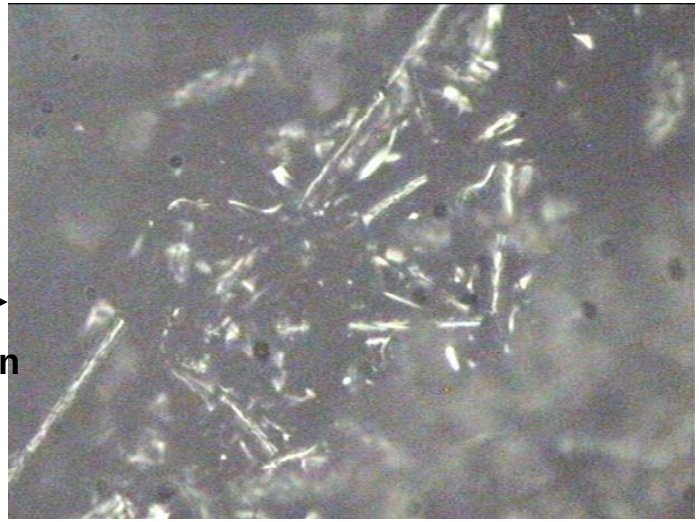
End View

•Initial “Powdered” Coating Results, milled CC fibers:
•High CC Fiber Density with good densification potential



Pre-Densification

Post Densification & Pyrolysis



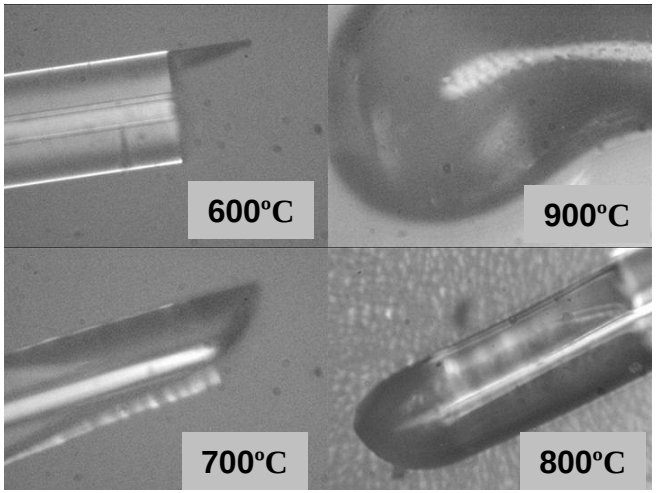
Pyrolytic Temperature Damage to Silica Fibers

- Silica Fiber Issues
  - Fictive Temperature and melt characteristics dependent on Silica and Dopants
  - Material, coatings and reduction atmosphere determine utility for current test sequences
  - Table shows relative temperature regimes for various fiber materials
- Sapphire
  - No Temperature issues
  - Expensive for initial feasibility testing

Optical Fiber Operational Temperatures

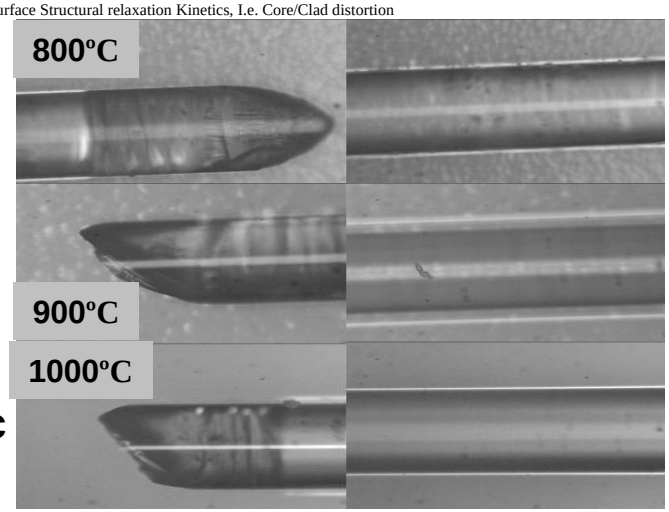
Fiber / Coating Type	High Temperature, deg. C Short Duration	High Temperature, deg. C Long Duration	Low Temperature, deg. C Short Duration	Low Temperature, deg. C Long Duration	
Silica					
Polymers					
Acrylate		85		-40	
UV-cured Acrylate		100		-40	
Polyimide	500	385-400		-190	
Polyimide + Copper		385-400			
Tefzel (Teflon deriv.)		160		-40	
Teflon		260			
Silicone		150		-40	
Nylon		100		-40	
Metals					
Aluminum*	500	450			
Copper	500				
Copper Alloy	600	400 / 600**			
CuBall	700	500 / 700**		-270	
Stainless Steel Braid		600			
Gold	900	700-900			
Fused Silica, unclad					
Silica Optical Fiber		850***			
Capillaries		1000			
Silica Fiber Material Limits					
Melting Point		1800			
Fictive (glass transition) limit					
Pure, Synthetic Silica		1450 -1660			
GeO2 Doped		1150 - 1300			
DeVitrification		800+		200	(crystallization onset)
OH Penetration		900 - 1200			
Annealing		850 - 1000			
Sapphire		2000			
Melting Point		2050			

*melting point 660 deg C
** Some alloys require Inert Atmosphere
***Limited by Surface Structural relaxation Kinetics, I.e. Core/Clad distortion



Original Test Fiber

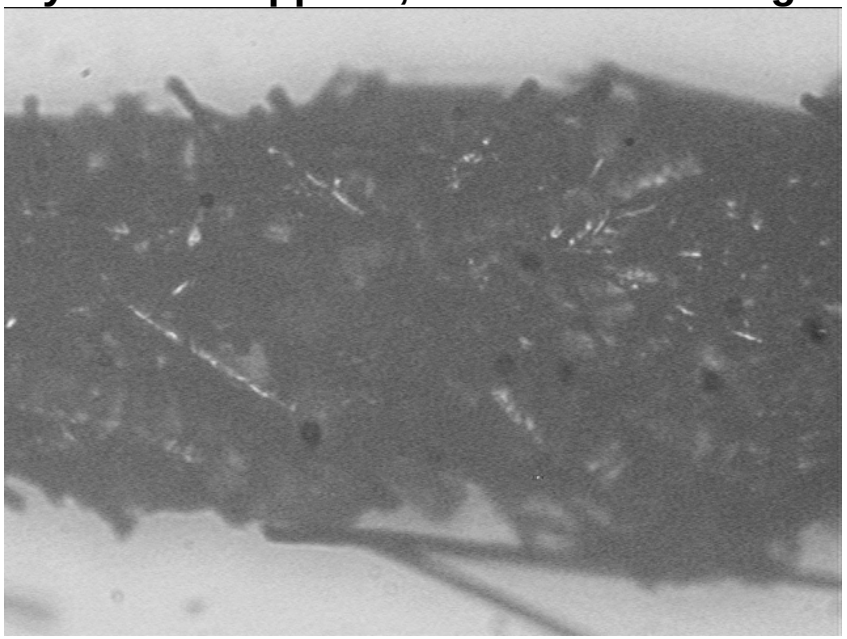
Synthetic Silica

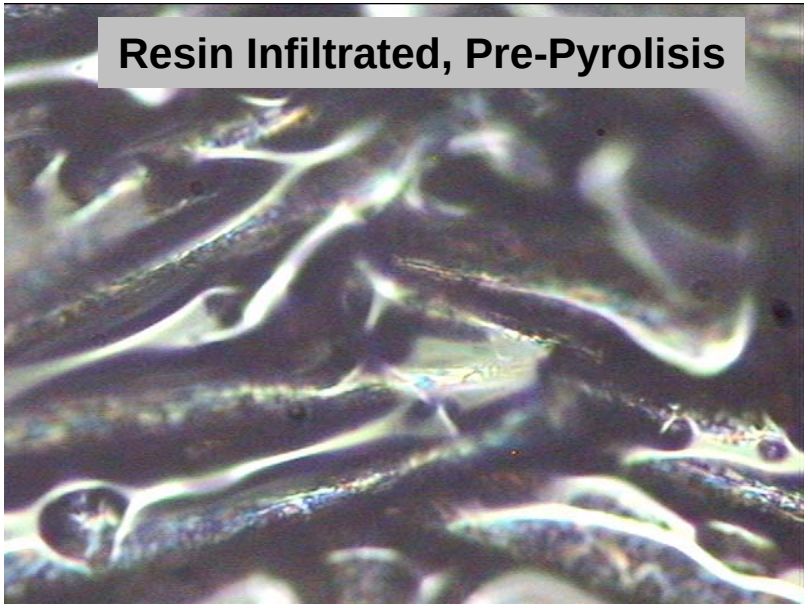


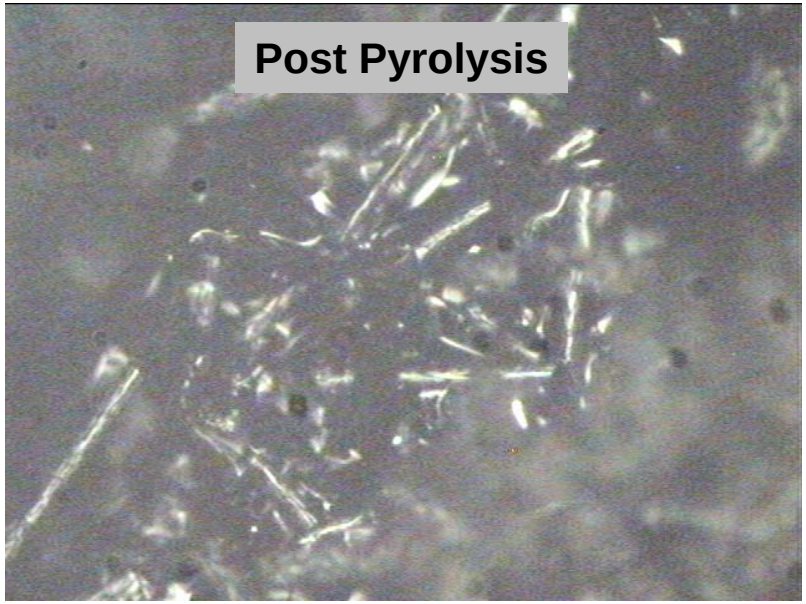
Current Results:
High Temperature Silica and Sapphire Powdered Coatings

- Useable Technique
- Coating Thickness > 200um
- Bendability: Adequate

Pyrolized Sapphire, Powdered Coating

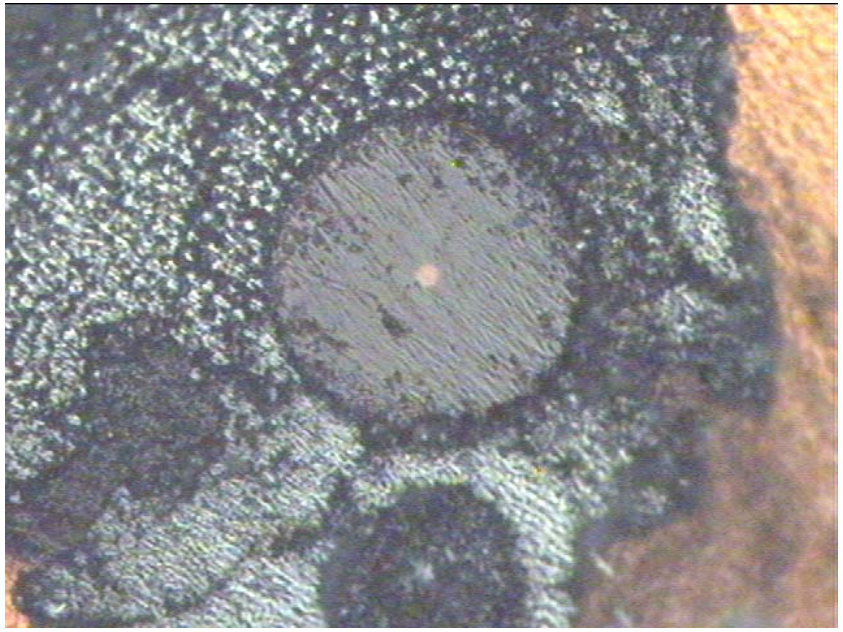




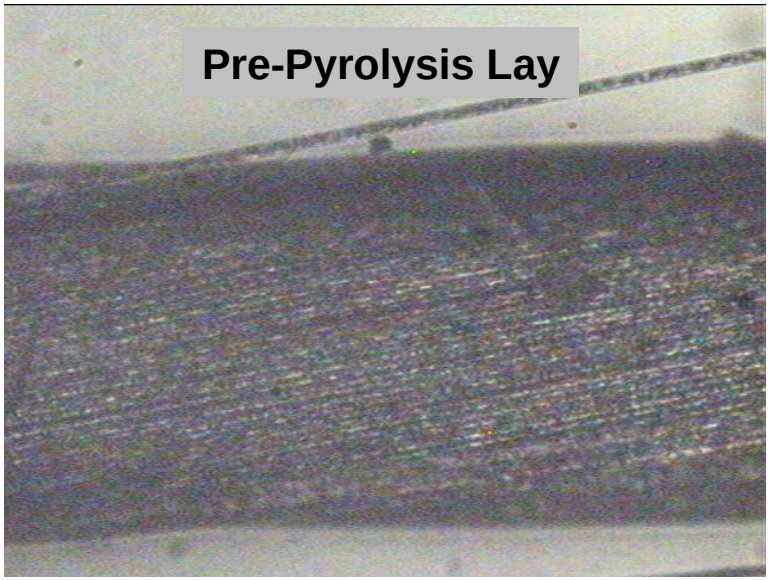


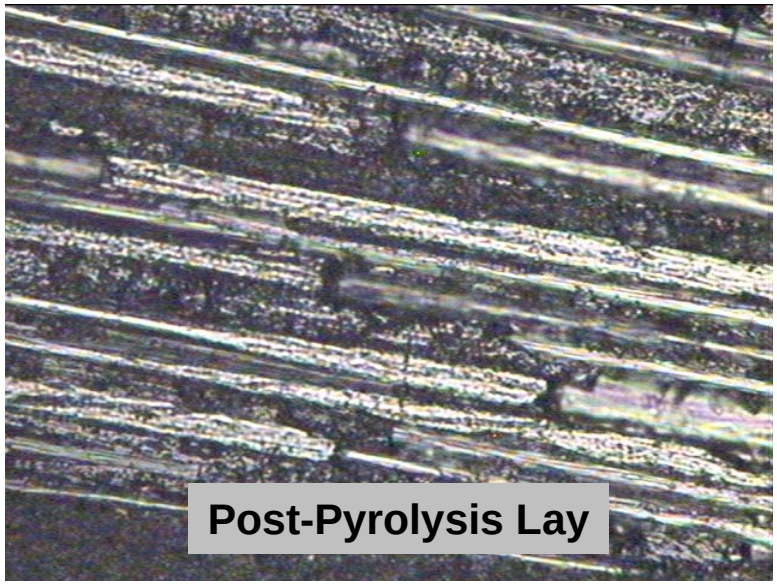
“Spiral” Wrapped Coatings with CC Tow

- Concept analogous to “Double Silk Covered, (DSC)” wiring insulation
- Coating Thickness < 50um
- Very Bendable



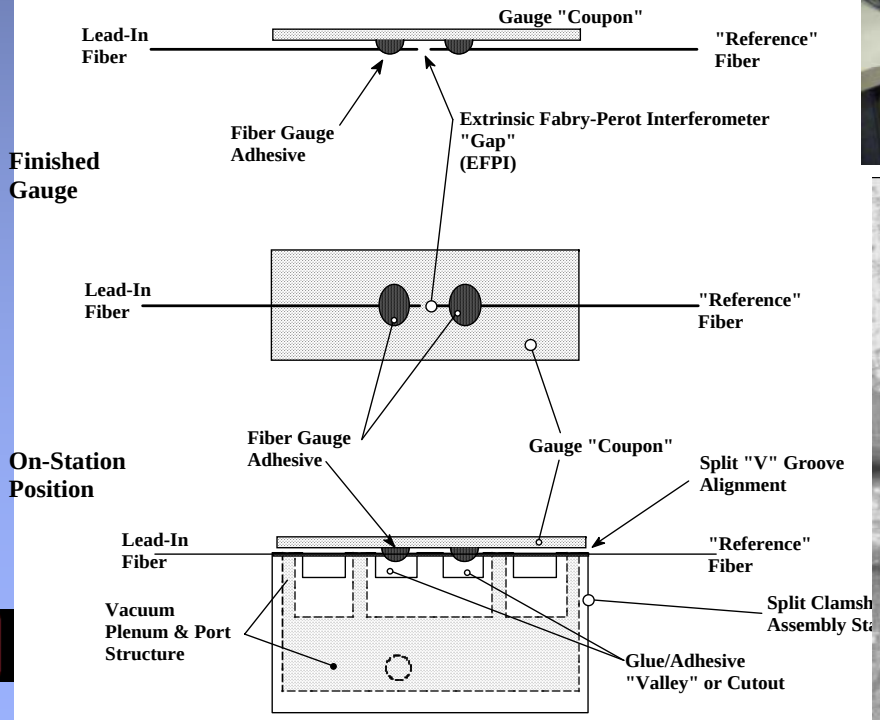
Pyrolized Cross-Section



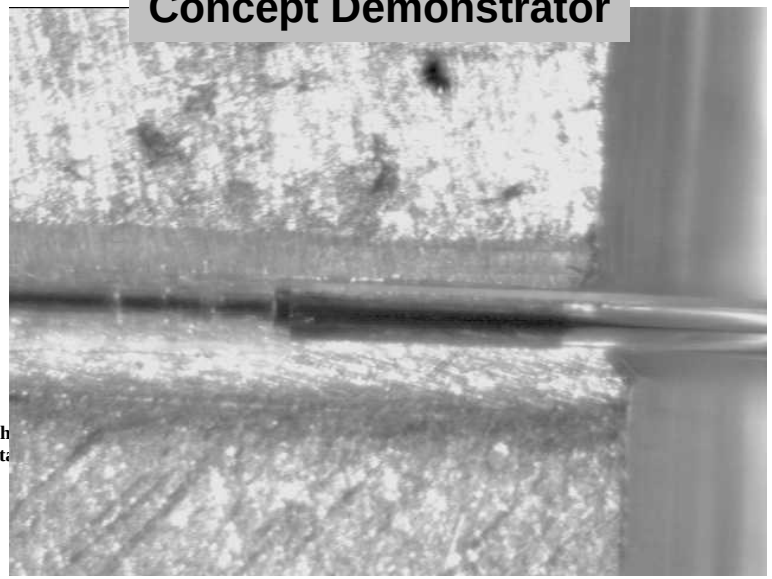


Fracture Release Sensors and Sensor Assembly

- Eliminates 6 Degree of Freedom Alignments
- Precision Alignment for:
  - Free-surface Gauges
  - Single or Multi-Mode Fibers
  - All Rigid Materials
- Initial Sensors Fabricated on non-Fracture Substrates
  - Patent Filings Submitted

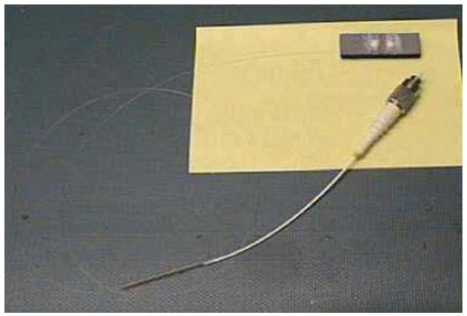


Concept Demonstrator



Prior Fabricated Gauges: Non-Fracture Release

Carbon-Carbon



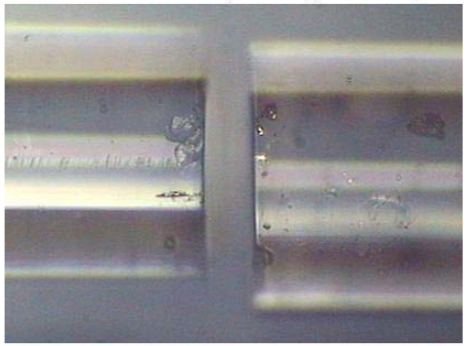
a) Sensor on Carbon-Carbon

b) Sensor on Ceramic Coupon

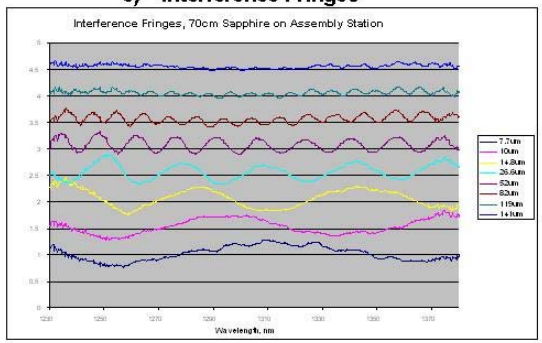
Sapphire (100um)

Glass

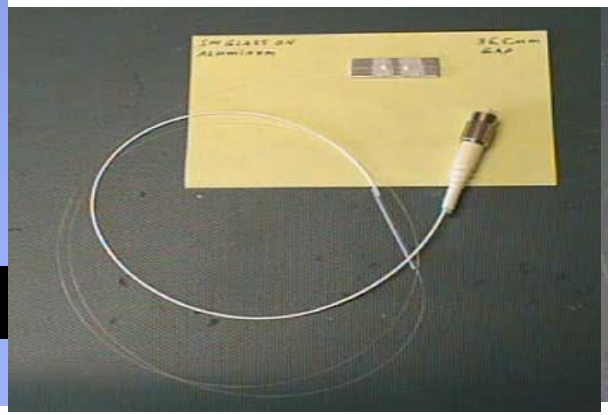
c) Sensing EFPI "Gap"



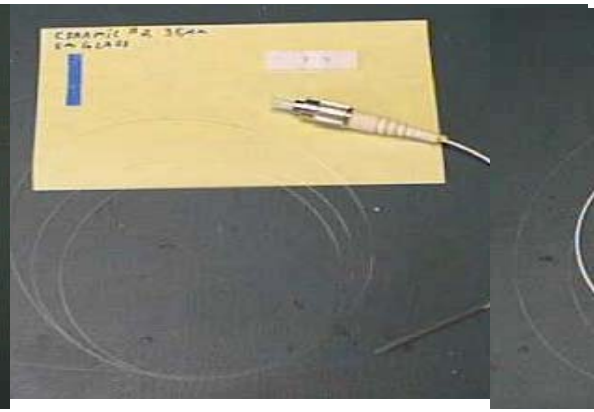
d) 100um dia Multi-Mode Sapphire
e) Interference Fringes



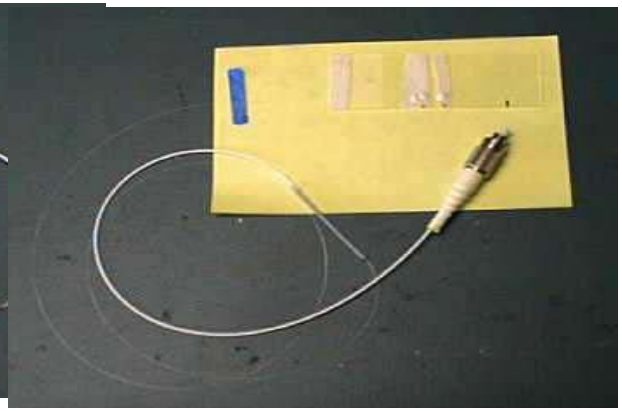
Aluminum



Ceramic



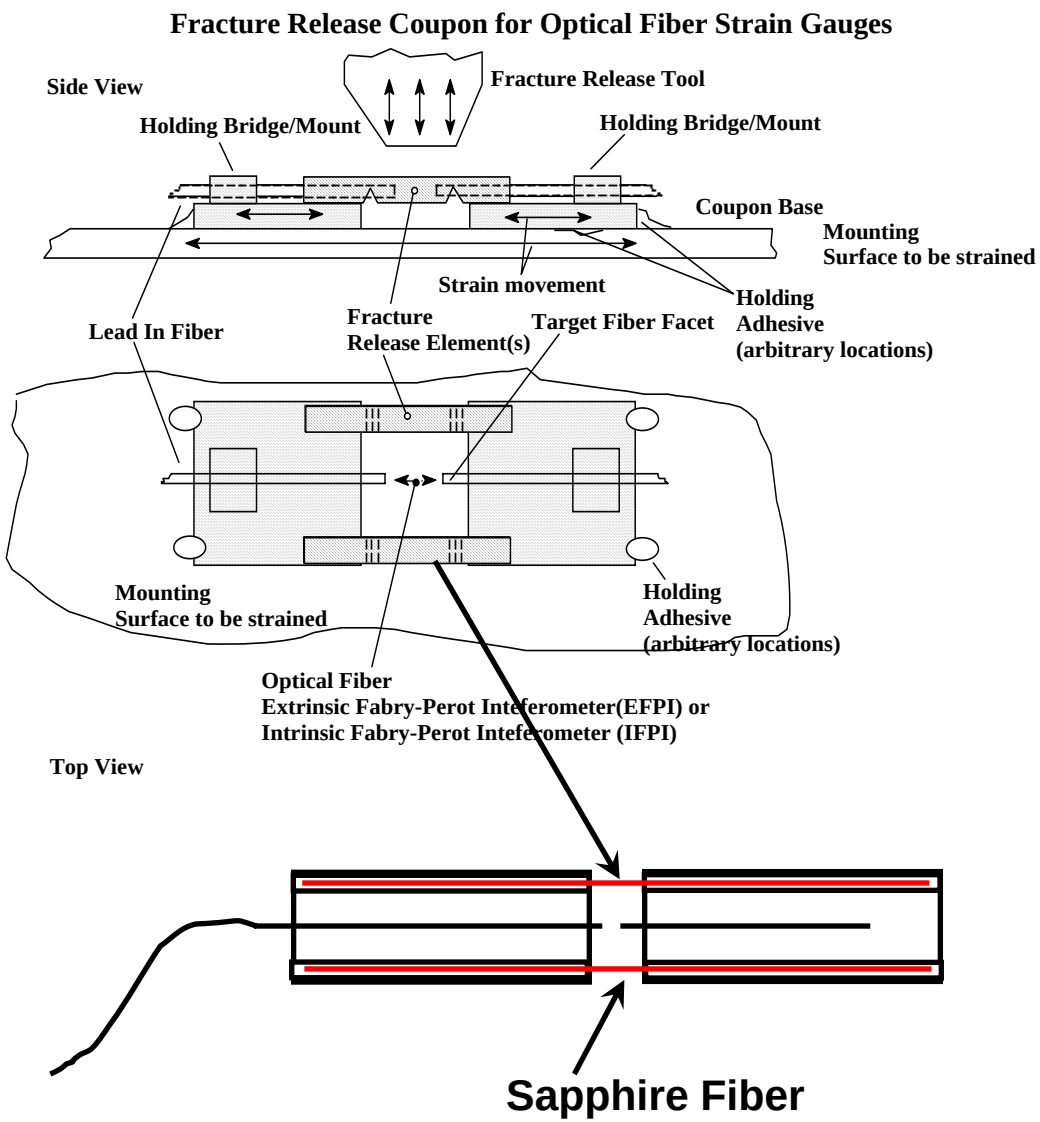
Glass



"Fracture Release" Coupon Structure Realizations

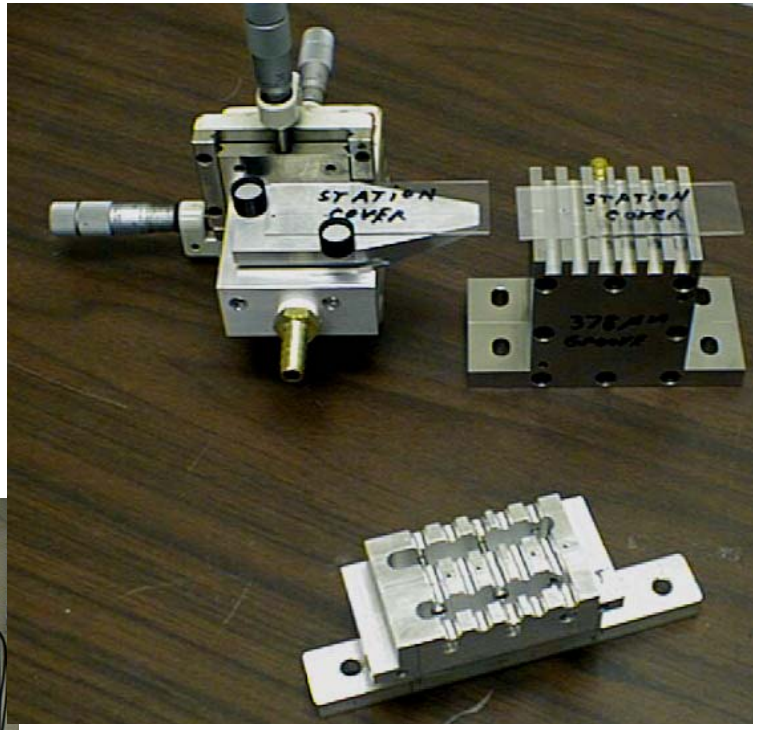
Initial re-Design Stages

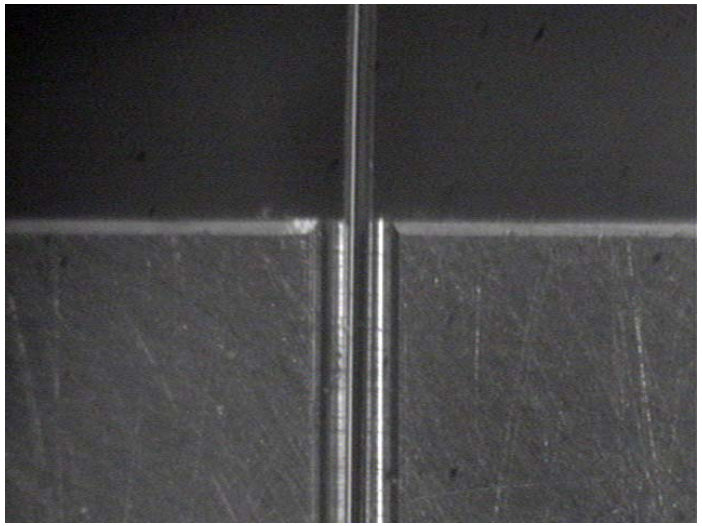
- Use Machinable Ceramics as basic Design Element
- Macor
- Cotronics 902
- Machined Bridges
- Cemented Fracture Bridges
  - Sapphire Fiber
  - Small Dimension Ceramics
- Machined Carbon-Carbon Materials



Gauge Station Redesign and Fabrication

- Stainless Steel Design for improved "Cleanability"
- Improved Vacuum
  - Added Vacuum Ports in alignment and maneuvering elements
- Multiple Units





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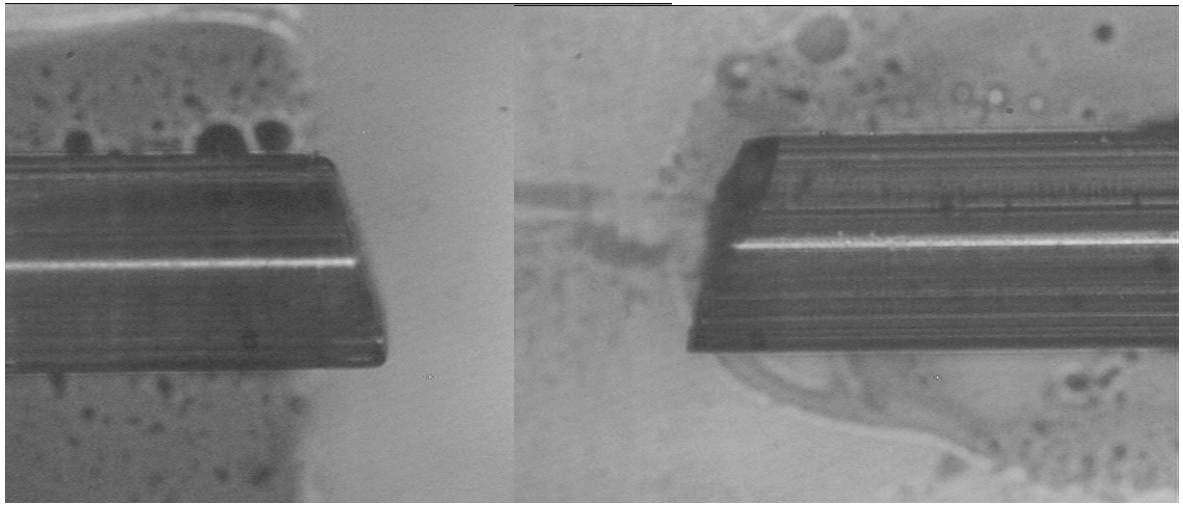
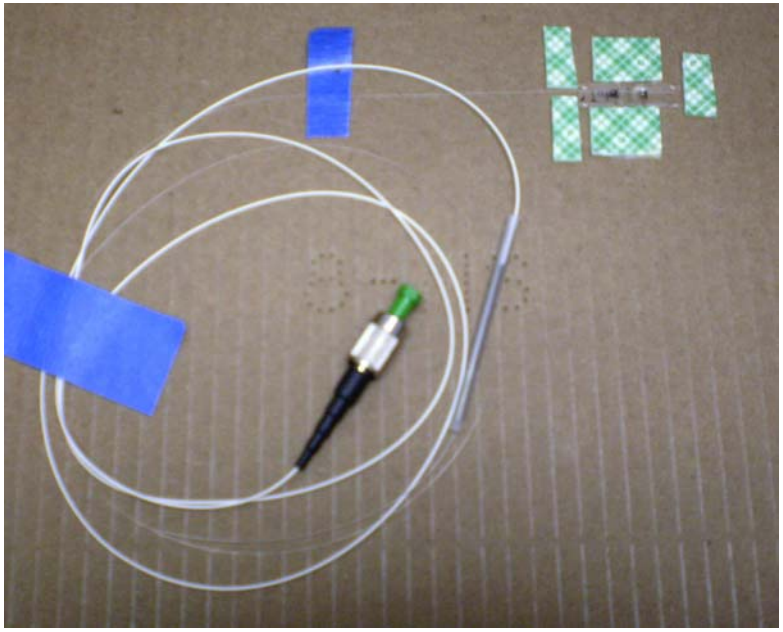
Discrete Silica-Sapphire Fracture Bridge(s)

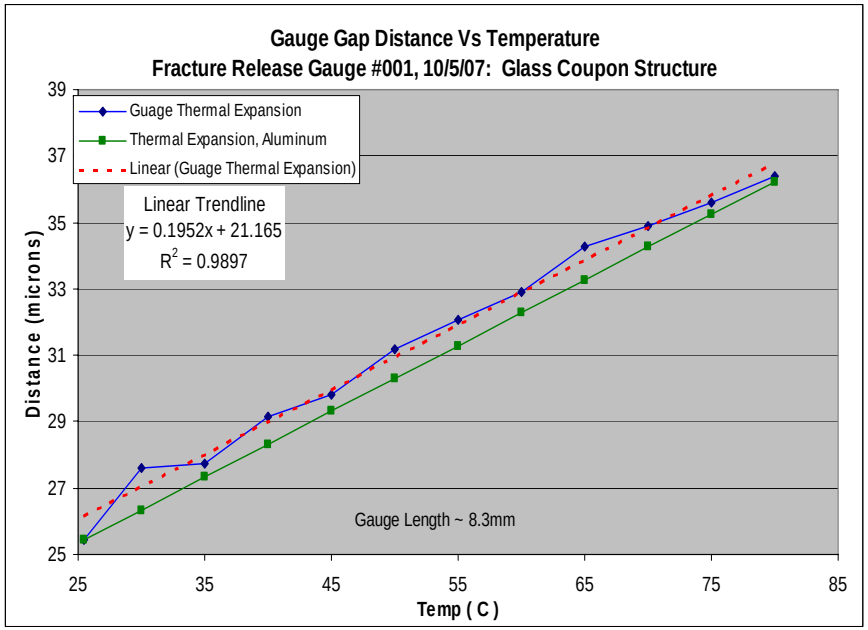
- Adhesively attached Fracture Bridges
  - Allow for rapid prototyping
  - Use Sections of easily scribed Silica and Sapphire Optical Fibers
- Initial test & assembly focused on Epoxy-Glass or Ceramic-Silica Prototypes
- Cross-Section of Silica fibers tested for Fracture Characteristics:
  - Scribe & Break
  - Fracture & Debris Clearance



Fracture Release Gauge Performance

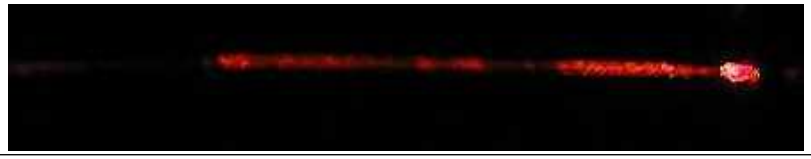
- **Initial Glass Substrate Gauges**
  - **Multiple Fabricated Units**
  - **Good "Fringe" Visibility & Contrast**
    - **Good Parallelism & Alignment**
  - **Temperature Tested for Strain Performance**

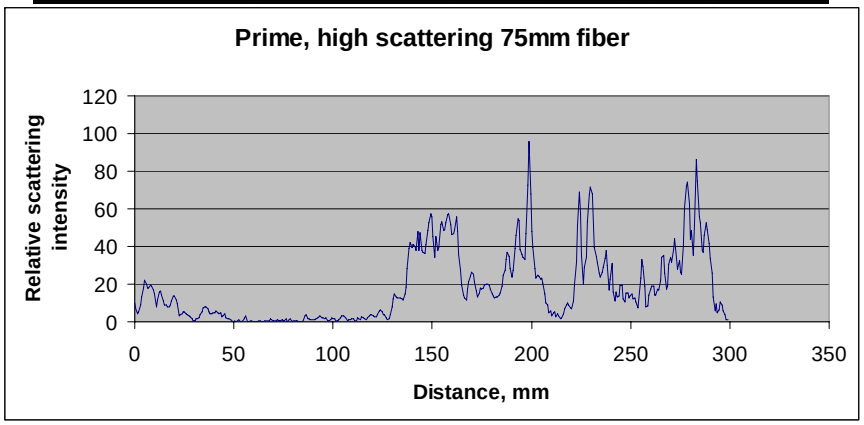


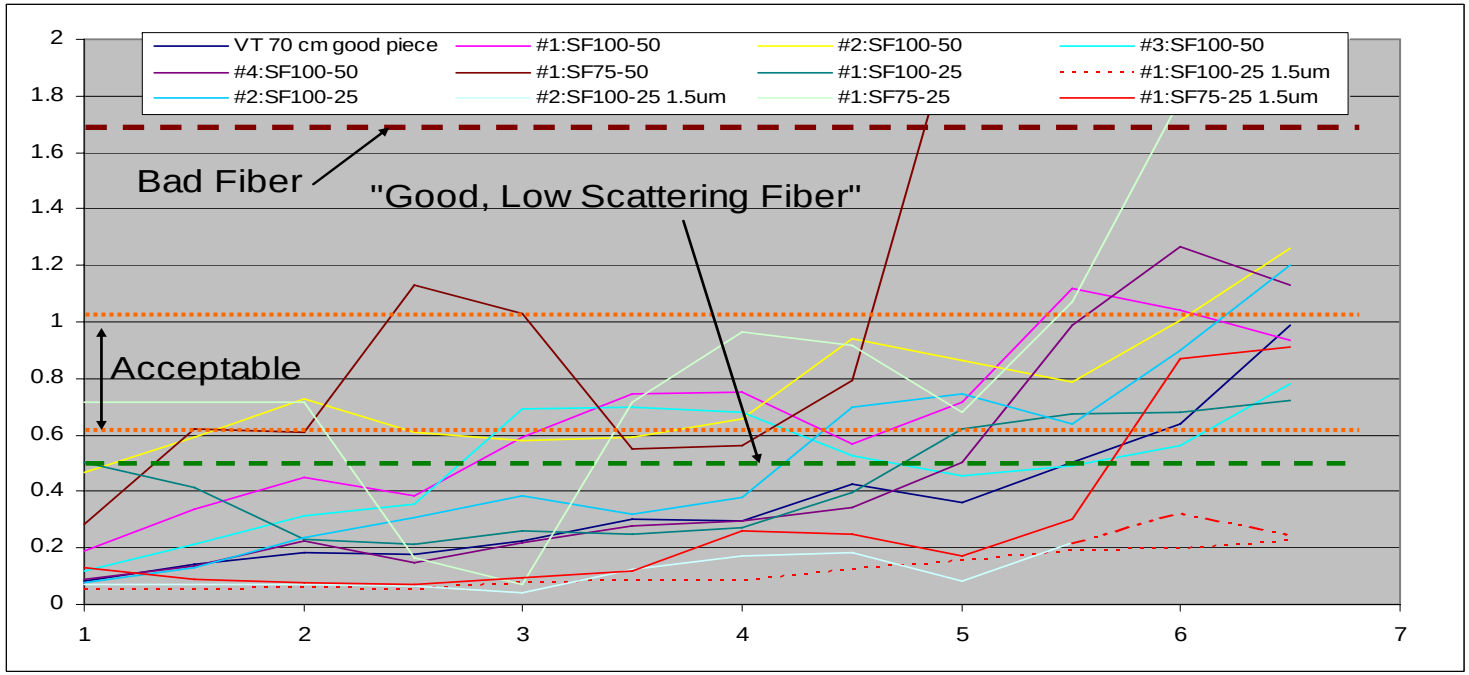


Sapphire Optical Fibers, Material Issues

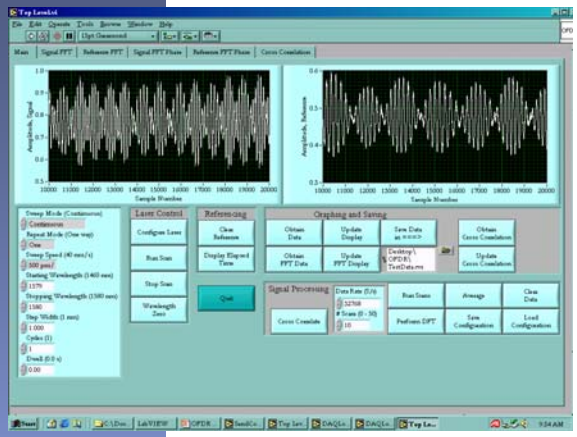
- 2 Current Suppliers:
  - MicroMaterials, Tampa, FL
    - Only supplier of fiber diameters under 150um.
    - Scattering levels in some recent deliverables preclude EFPI sensor function.
    - Manufacturer developing on High Temperature Sensor Product lines
  - Saphikon
    - Large Diameters
    - Supply response ?
  - University Labs ? (e.g. Rutgers, etc.)

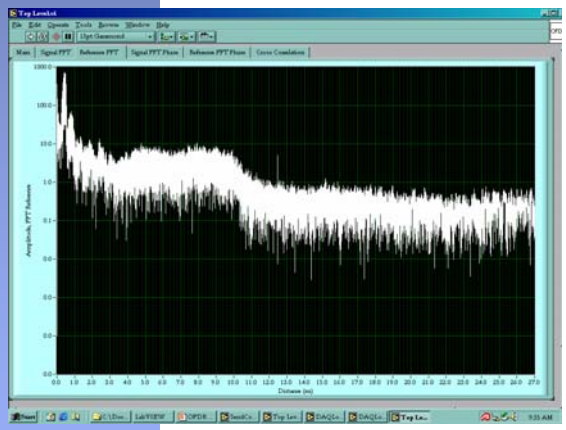






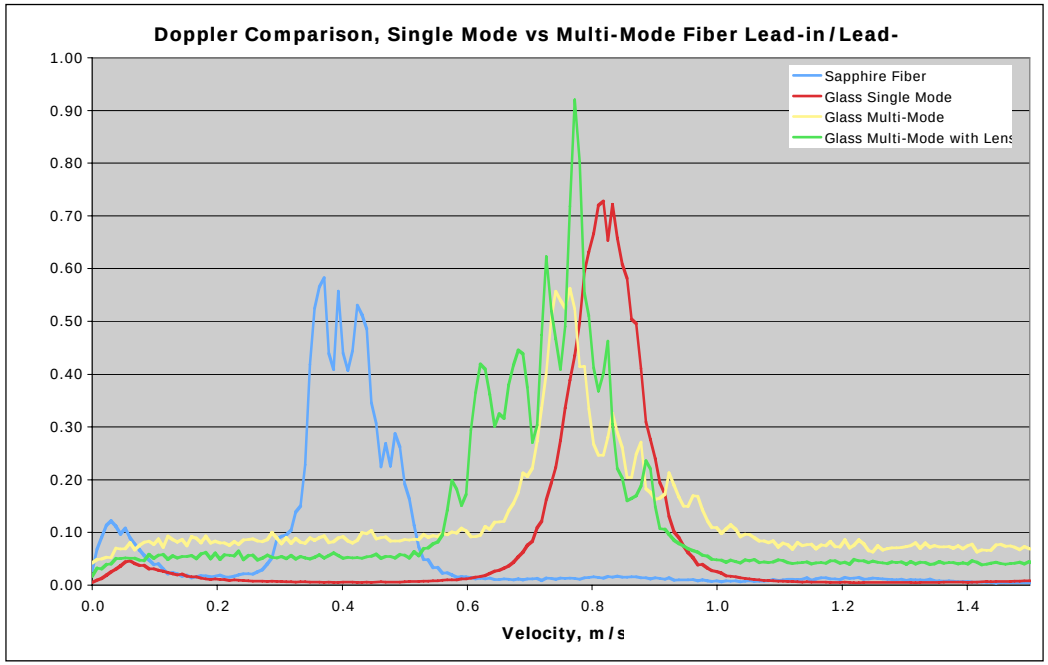
Extension(s) of Concepts, Auxiliary Program Investigations





OFDR Screens

- Laser Doppler Velocimetry demonstrated through Multi-Mode, High Temperature Sapphire Optical Fibers
- Enables Measurement of Vibration, Velocity, Displacement, Acceleration in Hypersonic test environment
- Compatible with Program's primary sensor focus
- Optical Frequency Domain Reflectometry (OFDR)



Velocity Spectra from a calibration target using an eye-safe, optical fiber lidar operating at 1.5um in FEORC's Lidar Laboratory (Virginia Tech)

Summary

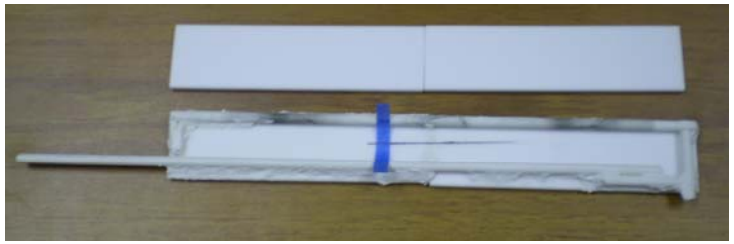
- **Conclusions:**
  - **Progress to date supports the successful development of Carbon-Carbon/SiC coatings on Sapphire fibers for handling and environmental protection.**
  - **Fracture Release gauge concepts continue to be viable for specialized applications.**
- **Issues:**
  - **Availability of Sapphire Fiber**
  - **Coating Application & Removal in Ingress-Egress/Transition Zones (e.g. connector to fiber, gauge exit to fiber, etc.**
- **Addendum: Visual Lab Tour in following slides**
  - **Purpose: Establish Science Connections to broader mission requirements in the Fundamental Aero Program**
  - **FEORC Facility**
  - **FEORC Tower**
  - **Center for Vehicle Systems & Safety Affiliation**
    - **Rail Technology Lab, Advanced Vehicle Development Lab, VIPER**
    - **Automotive and Vehicle Dynamics, incl Soil Terramechanics Lab**

FEORC Programs Spectra & Labs

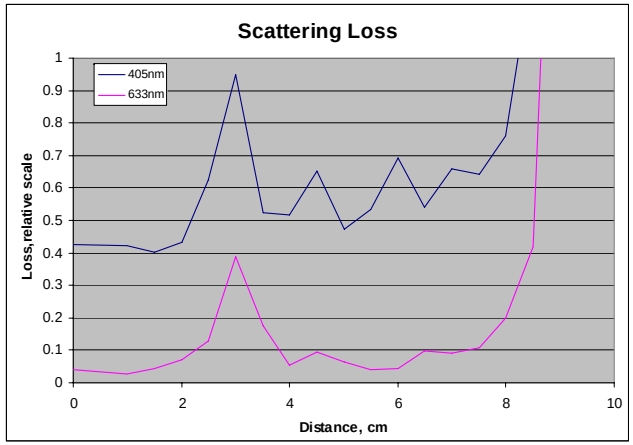
- Original Basis of FEORC Programs was Optical Fiber Fabrication
  - No Current Programs in this area
- Current Technologies
  - High Temperature Sensors
    - Protected Fibers: NASA Dreyden
    - Commercial Fracture Release Gauges (Prime Photonics/NASA Ames)
  - Fiber Sensors for Structural Health Monitoring (R. Claus, Air Force MURI)
    - Modal Sensors
    - Fiber Vibrometry
  - Optical Fiber Lidar
    - Meteorology (ONR)
    - Derived Parameter Sensing
      - Rail Friction & Train Dynamics (TTCI)
      - Wheel Lockup (Union Pacific)
  - Sensors in Stocastic Dynamics (NASA Langley)
    - Poly-chaos methods
    - Advanced Sensors: Non-contact (Lidar), RF Connected & MEMS
  - Exotic Fibers; Characterization (NucSafe)

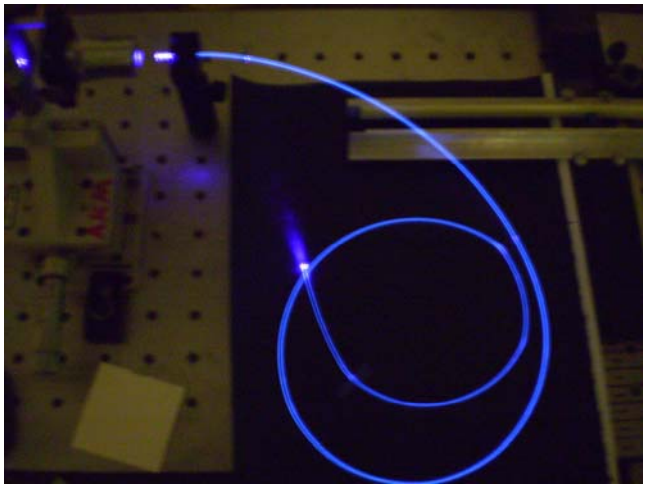
Coating Efforts: Facilities

Customized Inert Gas & Processing Fixtures



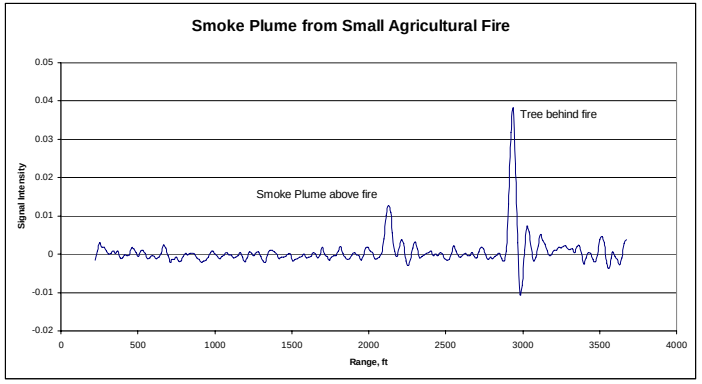
Fiber Characterization Lab



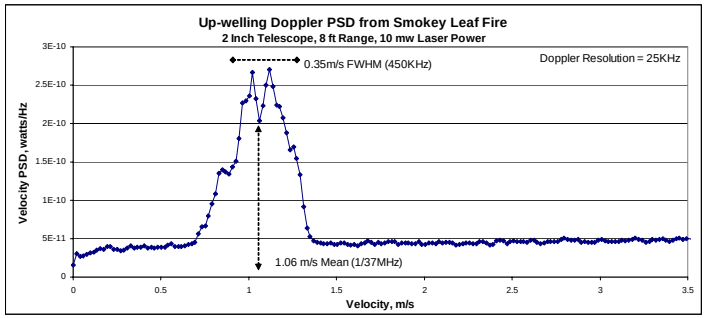


Lidar Lab

Range, Intensity, Density, Absorption



Velocity & Velocity Dynamics

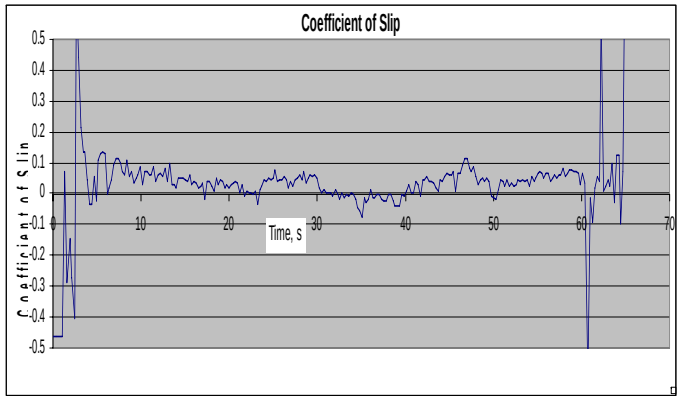


Fiber & Electro-Optics RESEARCH CENTER

Field Lab: Optical Fiber Velocimetry

- Derived Parameter Sensing
  - Velocity
  - Vibration
  - Acceleration
  - Displacement
- Parametric Derivation
  - Friction, Rotation, etc.

Coefficient of Slip, Wheel Dynamics



Structural Health & Monitoring Lab
Sponsor: US Air Force MURI Program, Hill AFB, UT

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Development Lab

- Supporting Measurements & Electronics
  - Microscopy
  - Optical Characterization
  - RF Electronics Development

Fiber & Electro-Optics RESEARCH CENTER

Supporting Facilities

- Fiber Optic Draw Tower
- Bragg Grating Lab
- Electro-Mechanical Shop
- Chemistry Lab
- CeVESS Affiliation