2016 NETL Crosscutting Research Review Meeting

Sheraton Station Square Hotel
Pittsburgh, PA

REDUCED MODE SAPPHIRE FIBER *AND* DISTRIBUTED SENSING SYSTEM

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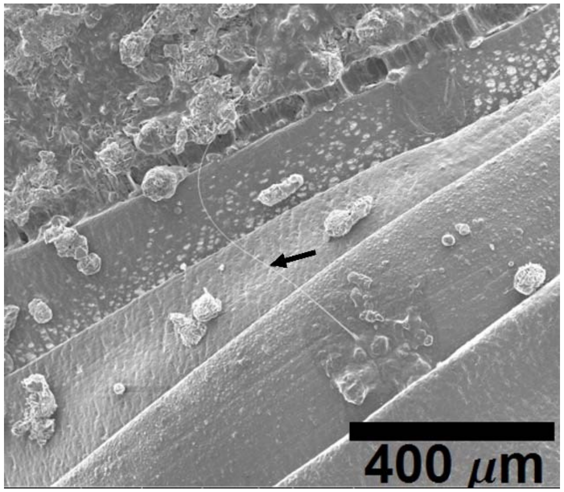
Overview

- Motivation, Objective and Impact
- Accomplishments and Research Products
- Technology and Approach
- Project Progress
- Next Steps



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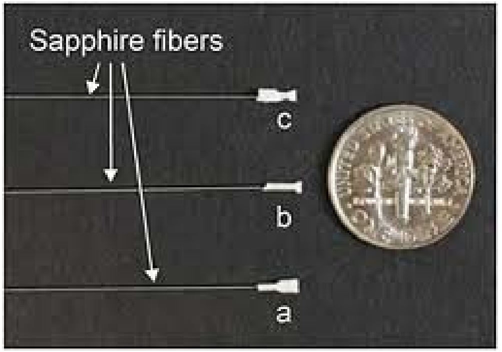
Motivation

- Eliminate barriers to the seamless integration of fiber optic sensing technologies in power plants



- Improve the operating efficiencies and safety of power plants via the real time and distributed sensing of temperature

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Project Objectives

- **Goal**: Develop a Raman scattering distributed temperature sensing system based on a low modal volume (LMV) sapphire fiber sensor.
- **Objective:** Design, fabricate and characterize a sapphire fiber that limits the number of guided modes.
- **Objective**: Develop a prototype, fully-distributed sensing system and evaluate its performance in a laboratory test environment for operation at temperatures over 1000ºC.
- **Benefit**: The proposed sapphire fibers and sensors will allow for the seamless integration of mature fiber optic sensing technologies in new power plant control systems.

Accomplishments & Products

- Student Support
  - Full: Cary Hill (Ph.D), Bo Liu, Yujie Cheng
  - Partial: Sunny Chang (M.S.), Elizabeth Bonnell (M.E.), Adam Floyd
- Peer Reviewed Publications
  - Hill, Cary, Daniel Homa, Bo Liu, Zhihao Yu, Anbo Wang, and Gary Pickrell. "Submicron Diameter Single Crystal Sapphire Optical Fiber." Materials Letters 138, no. 0 (2015): 71-73.
  - Bo Liu, Zhihao Yu, Zhipeng Tian, Daniel Homa, Cary Hill, Anbo Wang, and Gary Pickrell. "Temperature dependence of sapphire fiber Raman scattering." Opt Lett. 2015; 40(9):2041-4.
  - Cheng, Yujie, Cary Hill, Bo Liu, Zhihao Yu, Haifeng Xuan, Daniel Homa, Anbo Wang and Gary Pickrell. "Modal Reduction in Single Crystal Sapphire Optical Fiber." Optical Engineering 54, no. 10 (2015): 107103.
  - Three manuscripts submitted to peer reviewed journals are currently under review
- Intellectual Property
  - U.S. Patent Application No. 62/057,291; *Processing Technique for the Fabrication of Sub-micron Diameter Sapphire Optical Fiber*, G. Pickrell, D. Homa, W. Hill, filed Sept. 30, 2014.
  - Provisional Patent Application. *Distributed Temperature Sensing System Using Optical Sapphire Waveguide*, A. Wang, G. Pickrell, B. Liu, Z. Yu.
- Technical Achievements
  - Fabrication of sub-micron single crystal sapphire fiber
  - Observation of Raman Stokes *and* Anti-Stokes peaks in sapphire fiber
  - Measurement of fiber attenuation in the time domain in sapphire fiber
  - Distributed Raman temperature measurements in sapphire fiber
  - Demonstrated few to single mode operation in sapphire fiber

TECHNOLOGY & APPROACH

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Fiber Optic Sensing

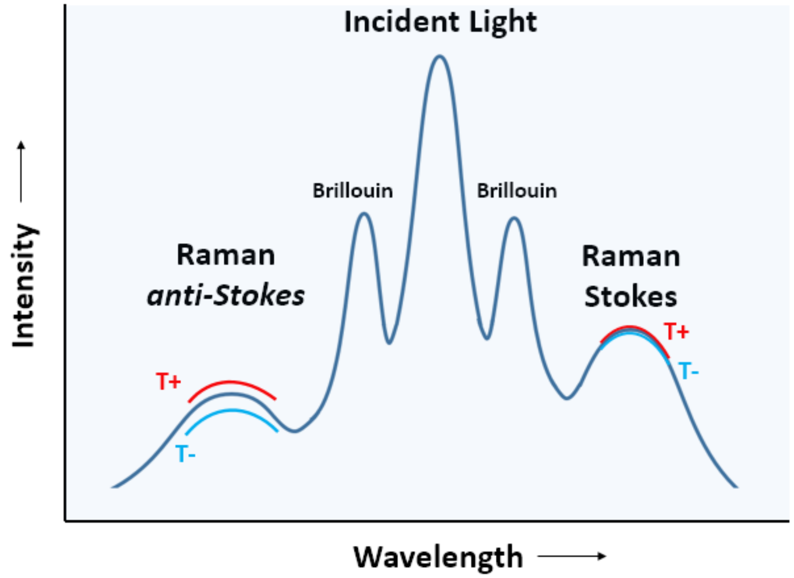
Single Crystal Sapphire Fiber

- Benefits of single crystal sapphire optical fiber
  - High melting point (~2072 ºC)
  - Chemical resistant and mechanically robust
  - Wide optical transmission window (0.15 µm – 5.5 µm)
- Drawbacks of single crystal sapphire optical fiber
  - Lack of traditional cladding material
  - Highly multimode
  - Limited commercial availability
- Single crystal sapphire fiber optic sensors
  - Inherent drawbacks limit achievable performance
  - Full benefits of the technology have yet to be realized

Fiber Optic Sensing

Distributed Raman Temperature Sensing

- Raman scattering based sensor
  - Intensity based
  - Fully distributed
- Temperature Sensing
  - Anti-Stokes: strong dependence
  - Stokes: weak dependence
- Raman spectra-sapphire fibers
  - Weak intensity
  - Narrow peaks
  - Complicated by impurities
  - Anti-stokes peak not well documented



Technical Challenges

- Performance of single crystal sapphire fibers
  - Large “core” diameters
  - High numerical aperture (NA)
  - High loss
  - Weak Raman signal in sapphire fiber
- High operating temperatures
  - Thermal radiation generated by the sapphire fiber
  - Thermal radiation coupled into the fiber end
- Achievable spatial resolution
  - Pulse width
  - Modal dispersion

Approach

- Design and fabricate a single crystal sapphire fiber with a modal volume optimized for sensor applications
  - Wet acid etching at elevated temperatures
  - Single crystal sapphire fiber growth via LHPG
- Design and construct a Raman scattering distributed temperature sensing system
  - Interrogation at 532 nm
  - Design and component optimization
- Integration of LMV sapphire fiber to improve the spatial resolution of the distributed sensing system

<u>RESEARCH PROGRESS</u>:
LMV SAPPHIRE FIBER

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LMV Sapphire Fiber

Theoretical Analyses

- *The numerical aperture (NA) in an optical fiber is given by*

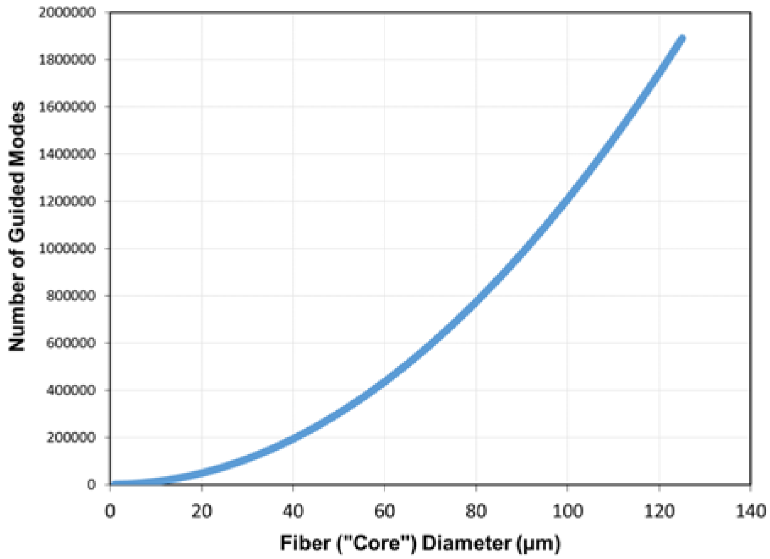
$$\mathrm{NA} = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

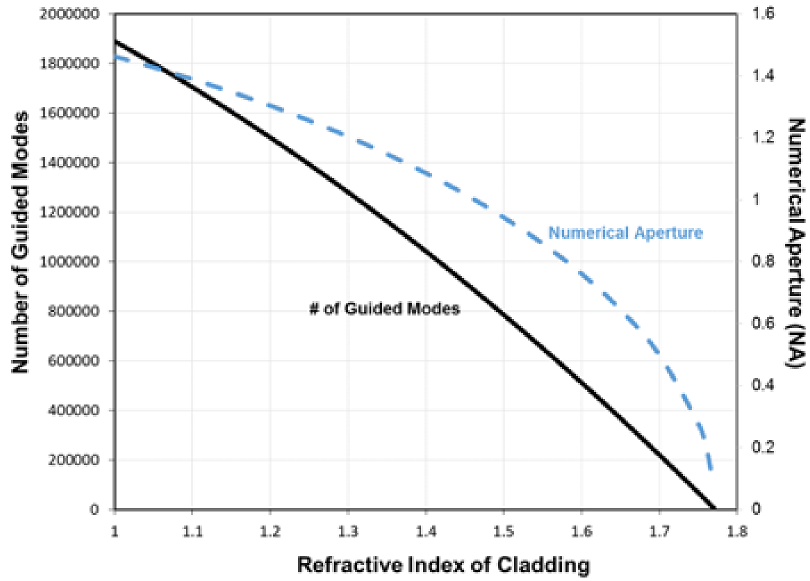
- *The normalized frequency, V number, is given by*

$$V = 2\pi \frac{a}{\lambda_0} \mathrm{NA}$$

- *The number of modes for fiber with large V parameters can be approximated by*

$$M \approx \frac{4}{\pi^2} V^2$$

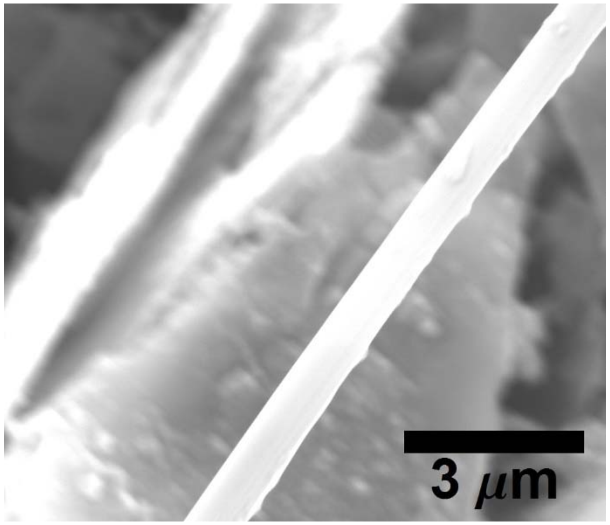


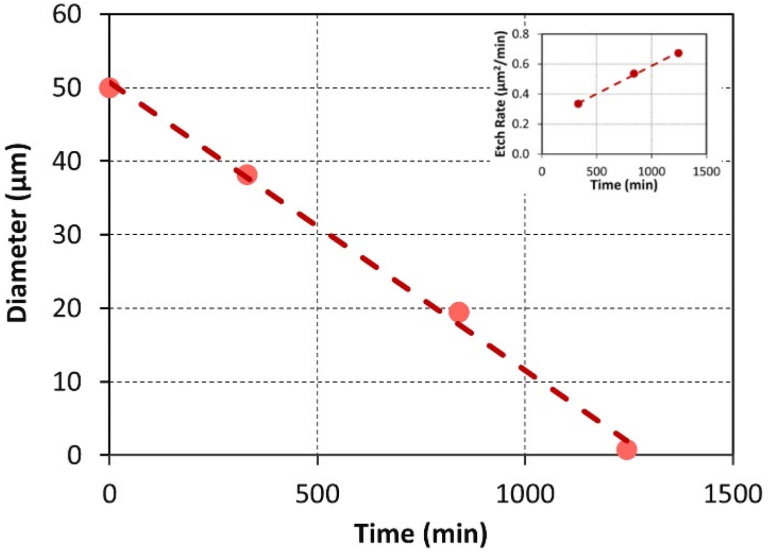


LMV Sapphire Fiber

Fabrication via Wet Acid Etching

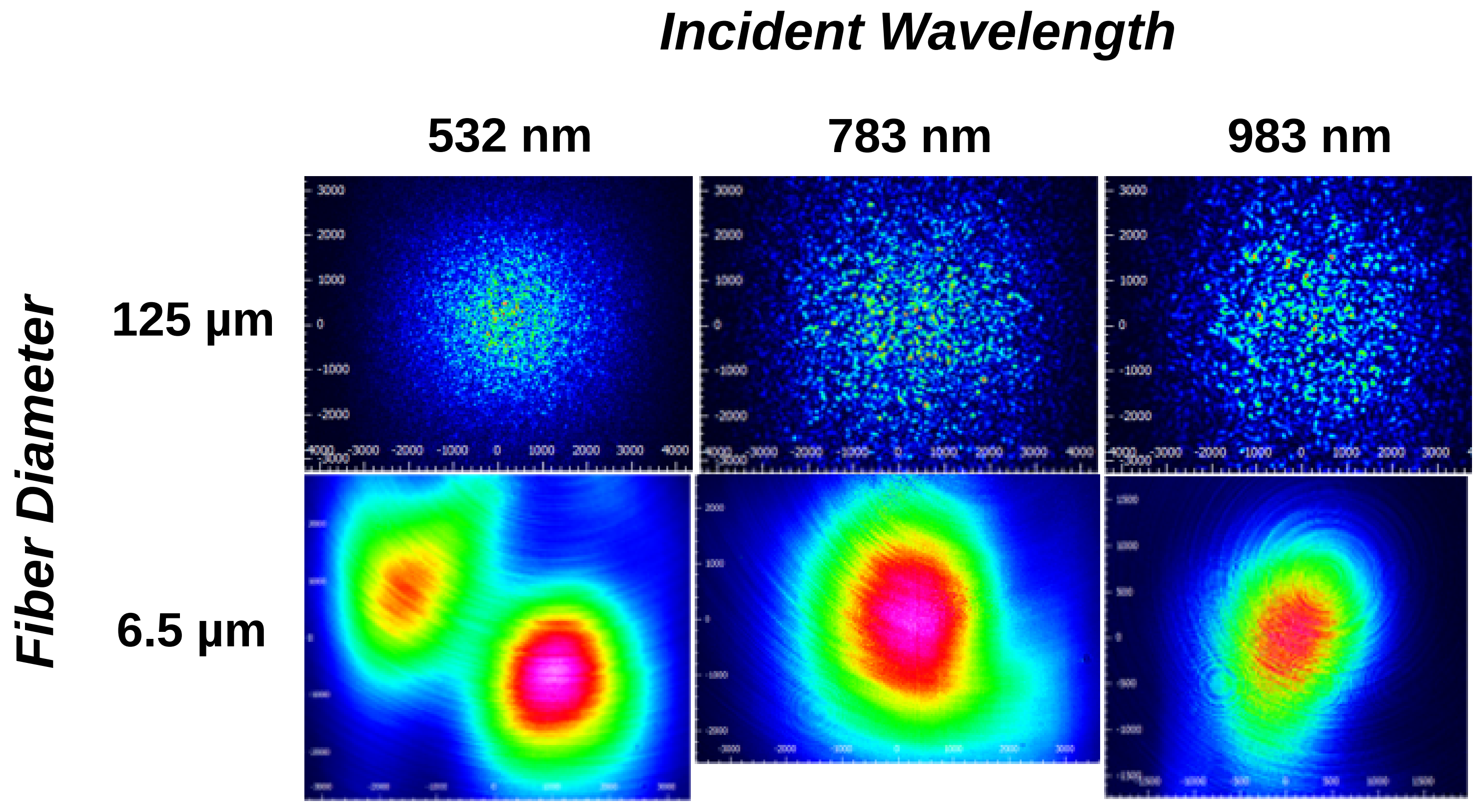
- Sulfuric/phosphoric acid solutions
  - Studied and optimized concentrations
- Elevated temperatures (>200˚C)
  - Determined etch rates
  - Determined activation energies
  - Studied a-plan vs. c-plan
- Extended lengths (~ 1m)
- Improved surface quality
  - Eliminated surface deposits
- Simple, cost effective, scalable





LMV Sapphire Fiber

Far Field Intensity Measurements



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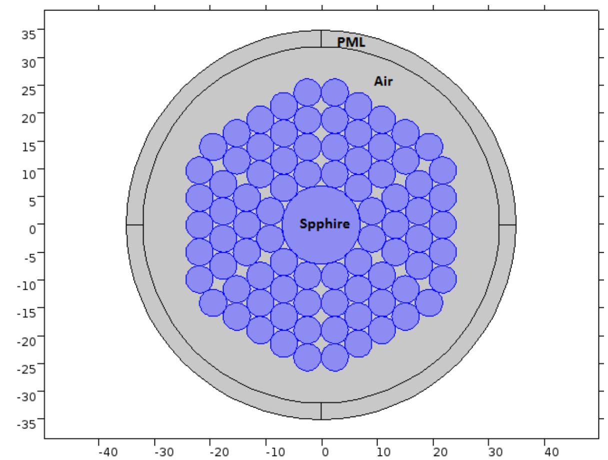
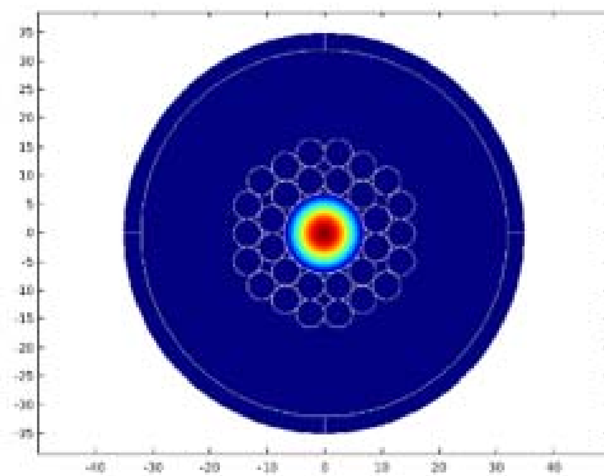
LMV Sapphire Fiber

"Bundled Photonic Crystal" Fiber Design

- Commercial single crystal (SC) sapphire "core"
- Bundled SC sapphire fiber fabricated via VT LHPG
- Reduction in effective cladding refractive index





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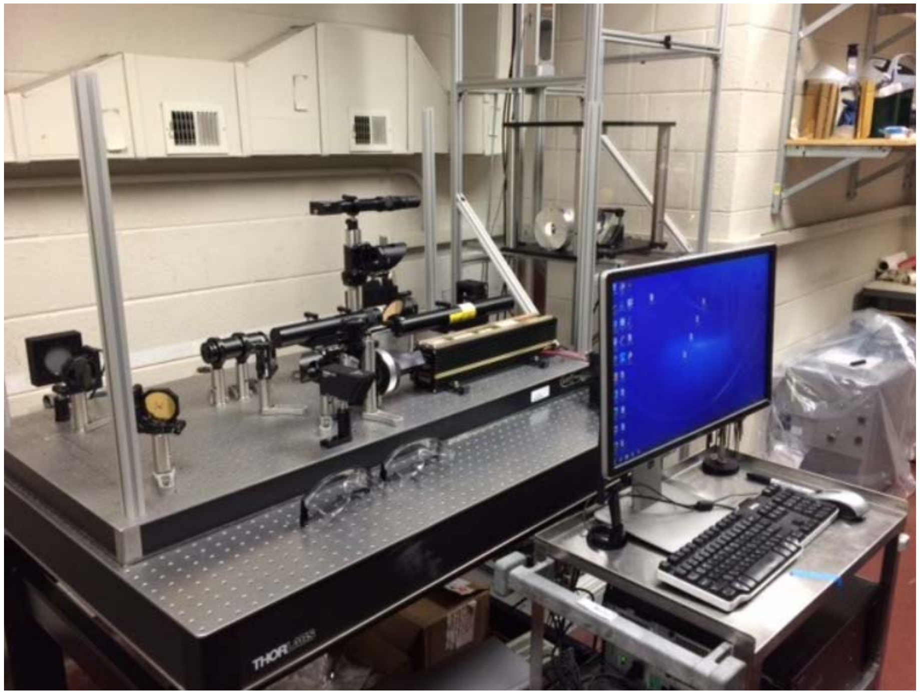
LMV Sapphire Fiber

Crystal Growth via LHPG

- Beam Steering Optics
  - HeNe Alignment Laser
  - Polarizer-Attenuator-Analyzer
  - Gold Coated Copper Mirrors
  - Top-Hat Optic
  - Beam Expander
- Growth Chamber Optics
  - Reflaxicon
  - Scraper Mirror
  - Parabolic Mirror
- Mechanical Drawing System
  - Synchronized Linear Stages



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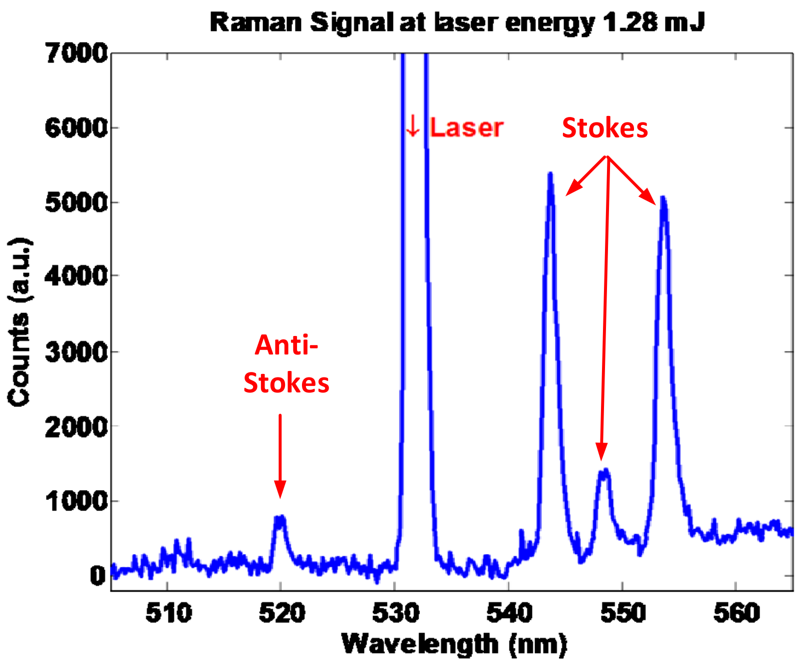
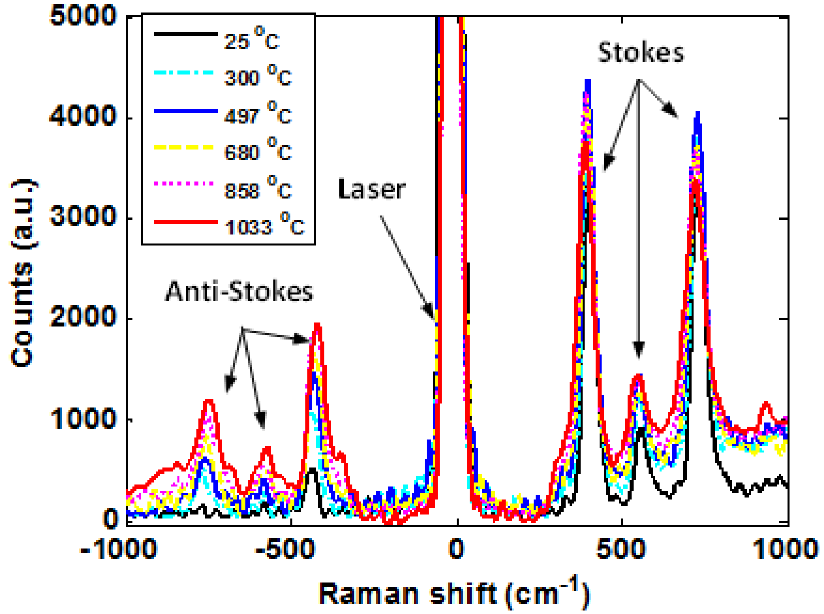
RESEARCH PROGRESS: *DISTRIBUTED TEMPERATURE SENSING SYSTEM*

Distributed Temperature Sensing

Characterization of Raman Spectra

532 nm Nd:YAG laser + spectrometer





B. Liu, Z. Yu, Z. Tian, D. Homa, C. Hill, A. Wang, and G. Pickrell, Temperature dependence of sapphire fiber Raman scattering. Optics Letters 40 (2015) 2041-2044.

DOI: http://dx.doi.org/10.1364/OL.40.002041.

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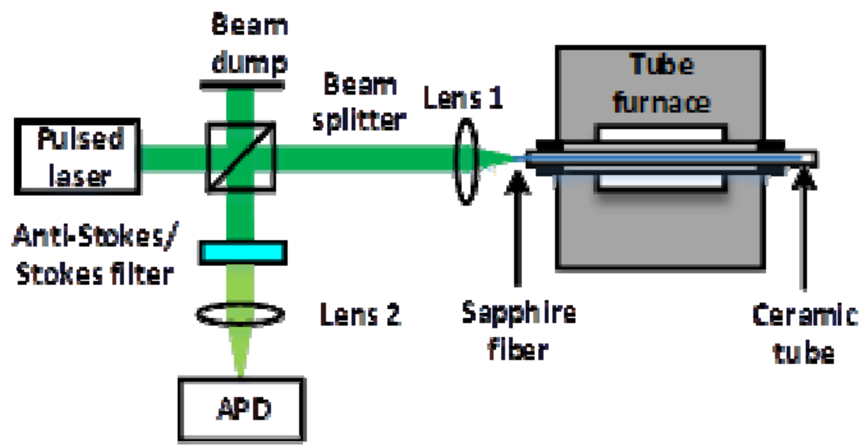
Distributed Temperature Sensing

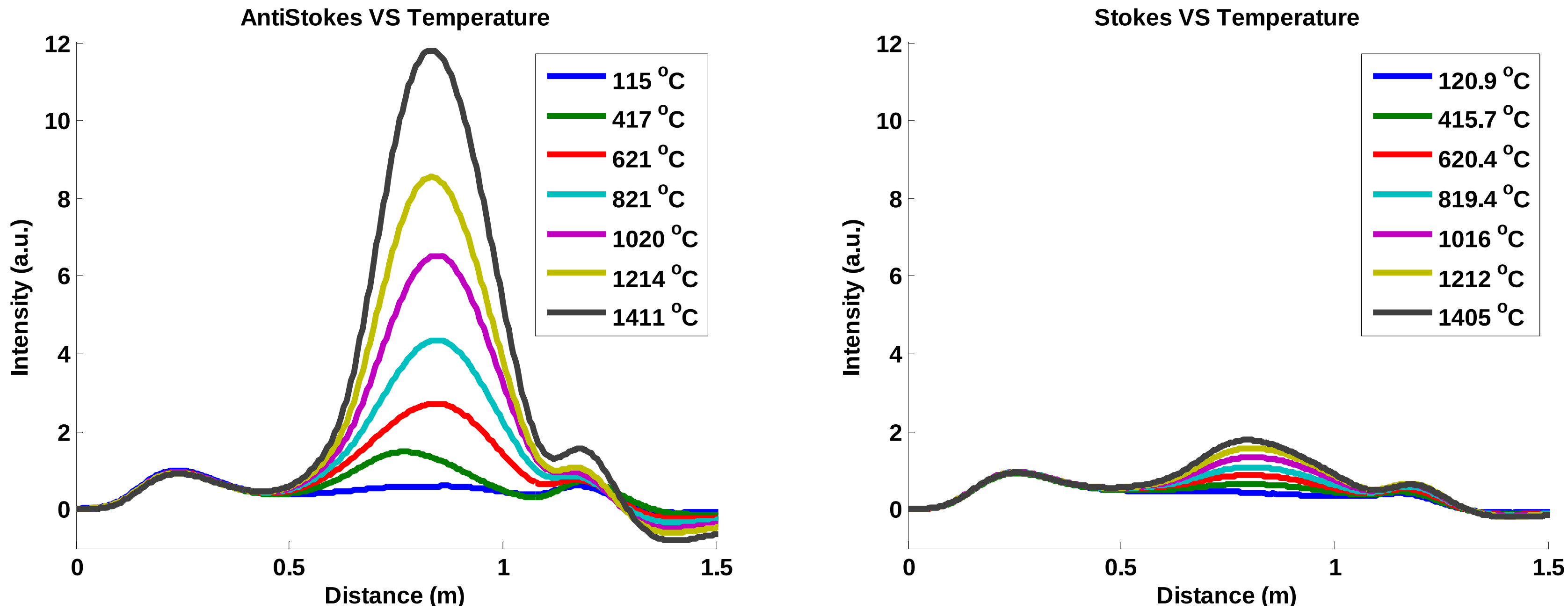
Preliminary Results with Sapphire Fiber

- Laser pulse width: 5 ps
- Sapphire fiber length: 1 m
- Sapphire fiber OD: 75 µm
- Heating position: 0.6 m



Distributed Temperature Sensing

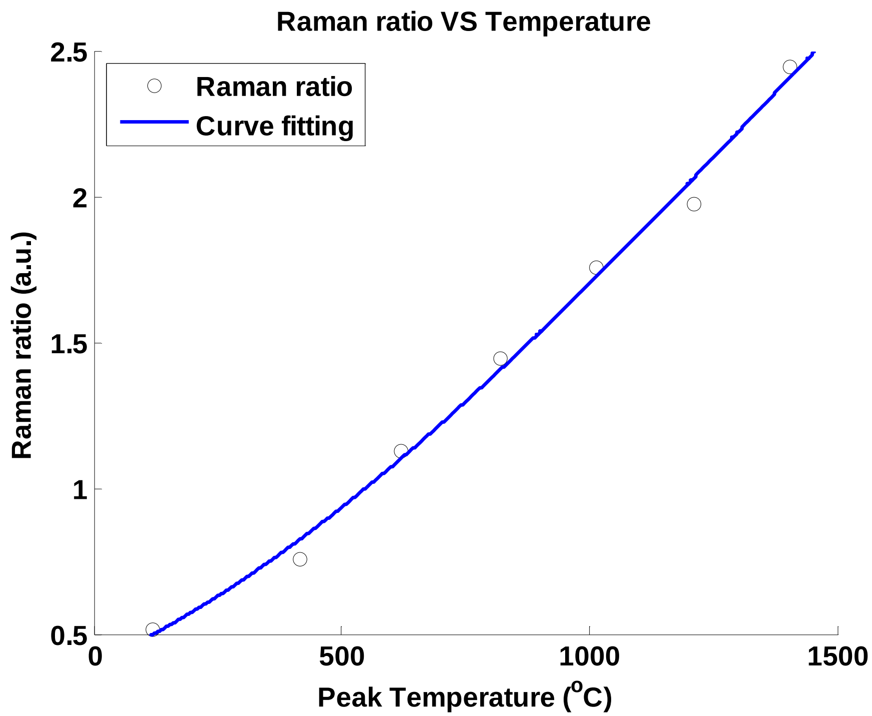
Preliminary Results with Sapphire Fiber



Distributed Temperature Sensing

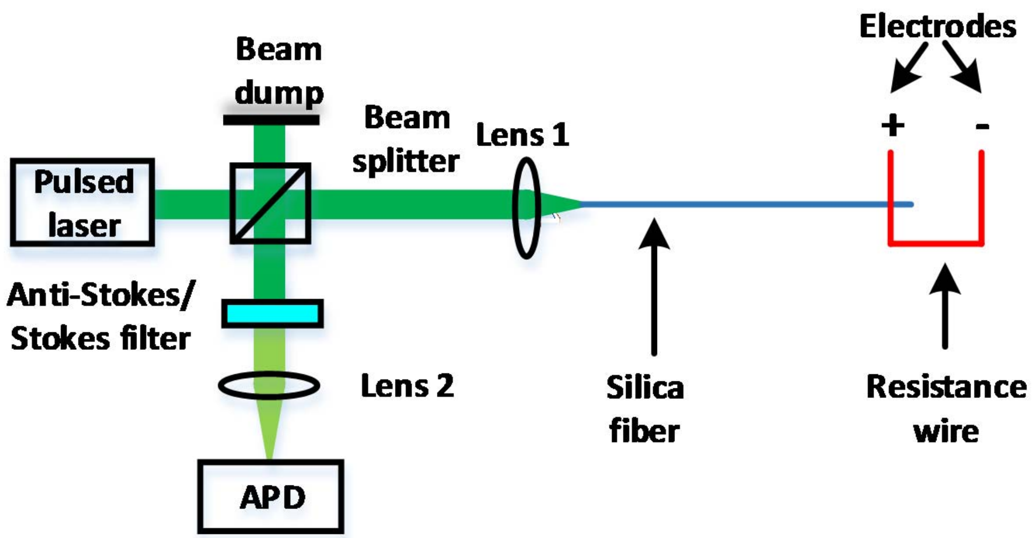
Preliminary Results with Sapphire Fiber

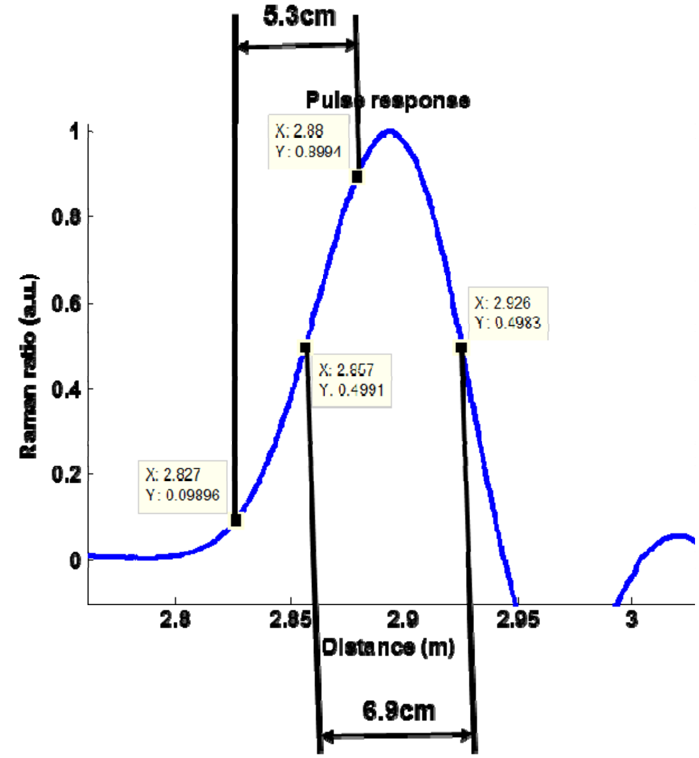
- Self-calibration
  - Laser intensity instability
  - Fiber attenuation and degradation
  - Coupling efficiency changes
- Temperature Sensing
  - Up to 1400 ºC (and higher)
  - Large range



Distributed Temperature Sensing

System Demonstration with Fused Silica Fibers

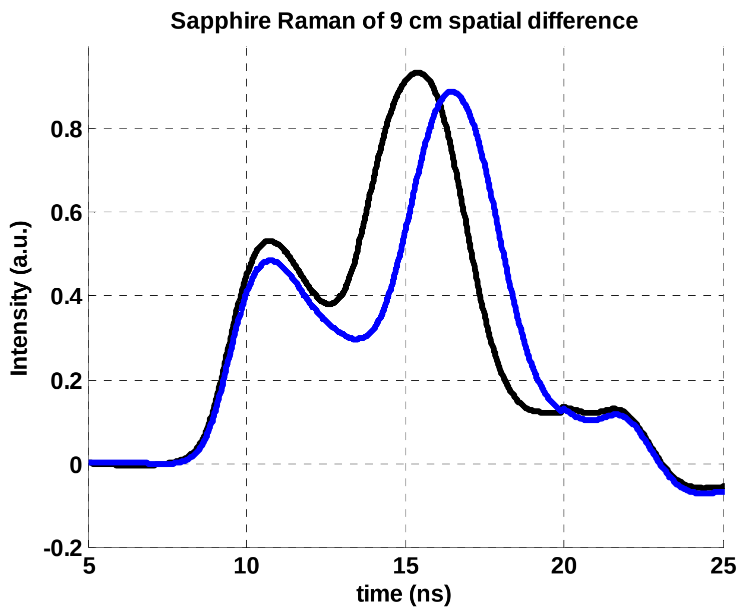


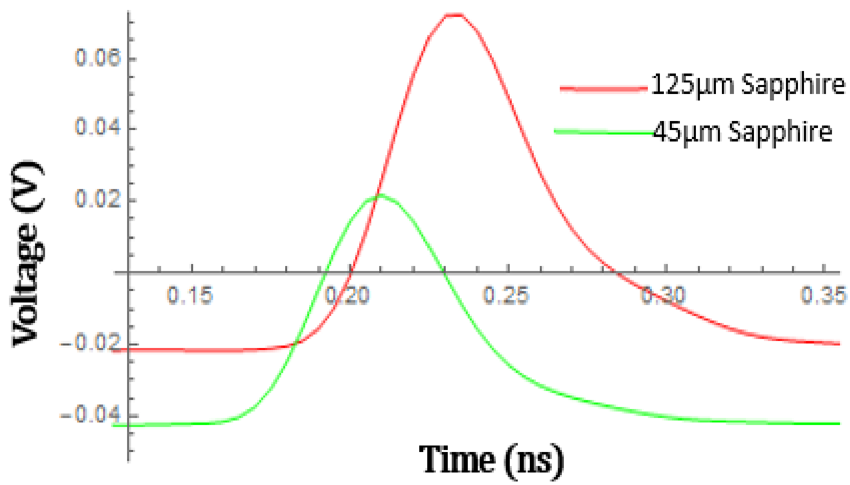


- Heating length ~ 2 mm
- Silica fiber 3 m
- Step-index MMF 50 um

Distributed Temperature Sensing

Preliminary Spatial Resolution with Sapphire Fiber





Reduction in pulse width → Increase in RDTS resolution

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Next Steps

- LMV sapphire fiber design, synthesis, and characterization
  - Develop protection schemes for reduced diameter fiber
  - Optimize LHPG system and fabrication processes
  - Fabricate “bundled photonic crystal” sapphire fiber
- Raman scattering distributed temperature sensing system
  - Characterize the maximum temperature measurement capability
  - Demonstrate the spatial and temperature resolution of the system
  - Demonstrate the maximum fiber sensing length (up to 3m)
  - Demonstrate system performance with LMV fibers

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