2015 NETL Crosscutting
Research Review Meeting
Sheraton Station Square Hotel
Pittsburgh, PA

REDUCED MODE SAPPHIRE FIBER *AND* DISTRIBUTED SENSING SYSTEM

DE-FE0012274

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Overview

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

Motivation

- Eliminate barriers to the implementation of fiber optic sensing technologies in power plants
  - Improved waveguide performance of single crystal sapphire fibers is needed to allow for the integration of mature optical fiber sensing technologies
- Real time monitoring of spatial and temporal distributions of temperatures in power plants
  - Increase operating efficiencies
  - Minimize environmental impact
  - Avoid catastrophic events

Project Objectives

- Develop a single crystal sapphire fiber with reduced modal volume.
  - Conduct theoretical and experimental evaluations of low modal volume (LMV) single crystal sapphire fiber designs
  - Demonstrate improvements in a wafer-based sensor system
- Develop a distributed temperature sensing system
  - Design, construct and evaluate integration system
  - Demonstrate performance improvements with the LMV single crystal sapphire sensing fiber
- Develop a prototype fully-distributed sensing system
  - Conduct performance testing in laboratory environment at temperatures in excess of 1000˚C.

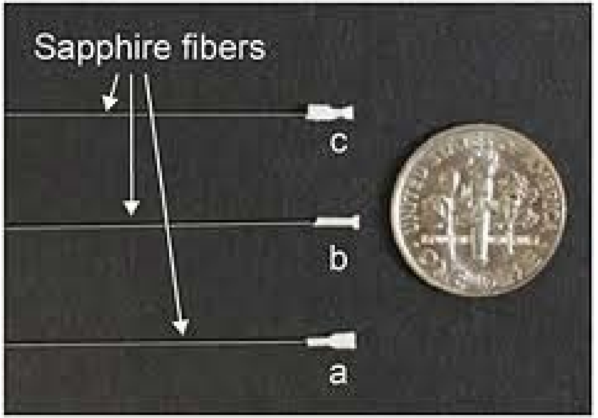
Project Impact

- Increased breadth of fiber optic sensing technologies deployable in fossil fuel power plants
- Acceleration of ongoing and future research in the field of high temperature fiber optic sensing
- Professional and scientific development of the next generation of scientists and engineers
- Deliver technologies and control systems that support efficient and clean energy production

TECHNOLOGY & APPROACH

Fiber Optic Sensing

- Interferometric Fiber Optic Sensors
  - Extrinsic Fabry Perot Interferometry (EFPI)
  - Intrinsic Fabry Perot Interferometry (IFPI)
- Fiber Optic Bragg Gratings
  - Long period Bragg gratings
  - Bragg gratings
- Scattering
  - Raman, Brillioun, Rayleigh
- Array of configurations
  - Measure temperature, pressure, strain
  - Single point, distributed, quasi-distributed



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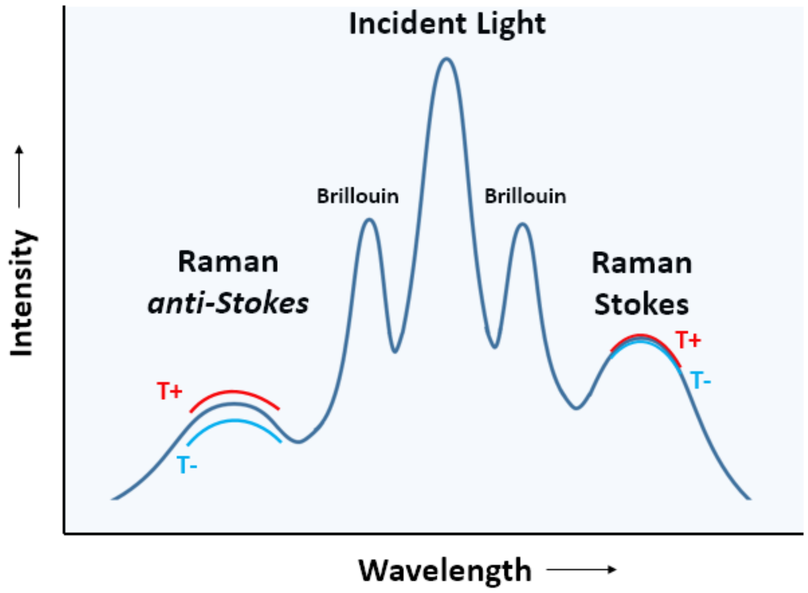
Sensing Mechanism

- Raman Scattering
  - Intensity based
  - Fully distributed
- Fused silica optical fibers
  - Graded Index Multimode
  - Germanium doped
- Temperature Sensing
  - Anti-Stokes: strong temperature dependence
  - Stokes: weak temperature dependence



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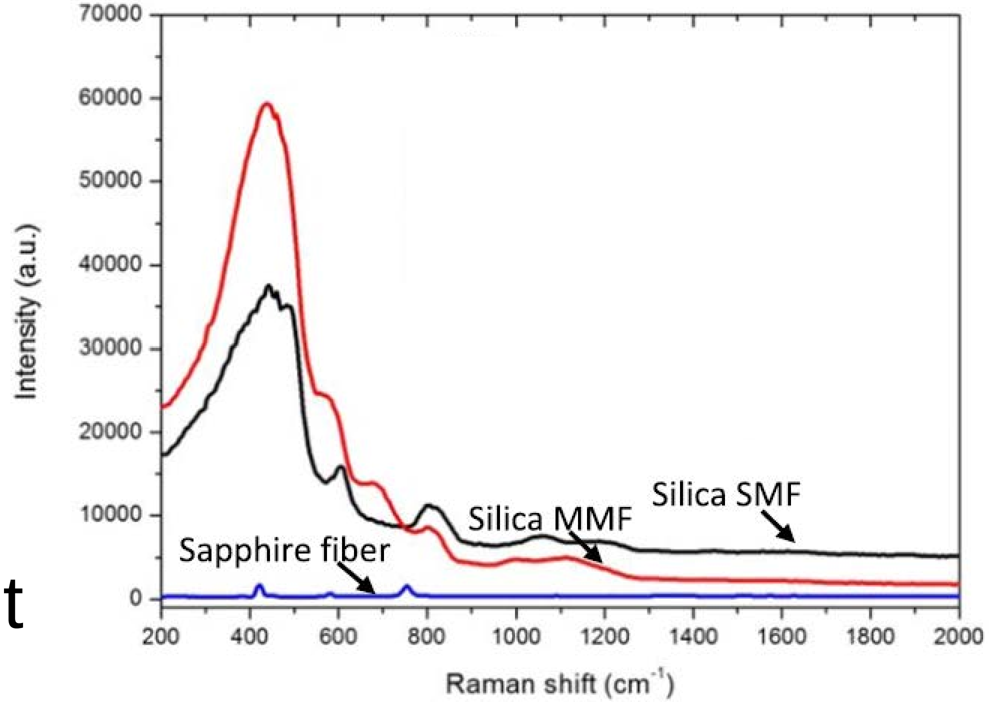
Raman Scattering in Sapphire

- Weak intensity
- Narrow peaks
- Complicated by impurities
- Anti-stokes peak not well documented



L. Yuan, X. Lan, J. Huang, H. Wang, L. Jiang, and H. Xiao, Comparison of silica and sapphire fiber SERS probes fabricated by a femtosecond laser. (2014).

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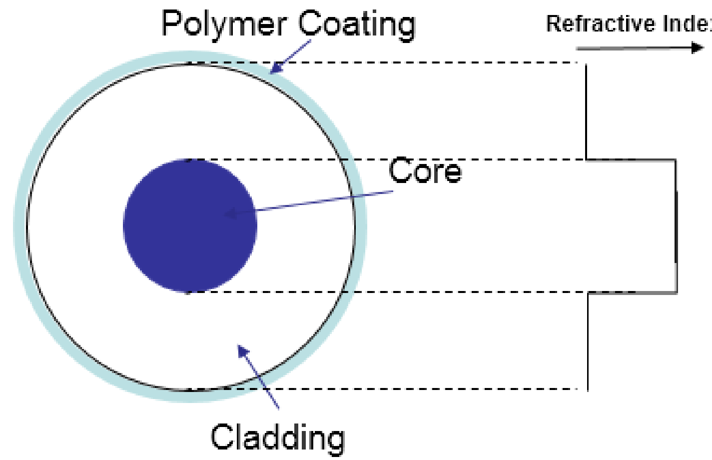
Optical Fiber

- Fused silica glass
  - Dopants: Ge, Al, Er, F…
  - CVD fabrication
  - Polymer coating
- Basic waveguide structure
  - Core / Cladding
  - $\Delta n_{core\text{-}clad} \approx 0.004 - 0.020$
- Fiber types
  - Step Index Single Mode
  - Step Index Multimode
  - Graded Index Multimode



V number

$$V = \frac{2\pi}{\lambda} a\, NA = \frac{2\pi}{\lambda} a \sqrt{n_{co}^2 - n_{cl}^2}$$

n_{co}: core index　　a: core radius

n_{cl}: clad index　　λ: wavelength

NA: numerical Aperture

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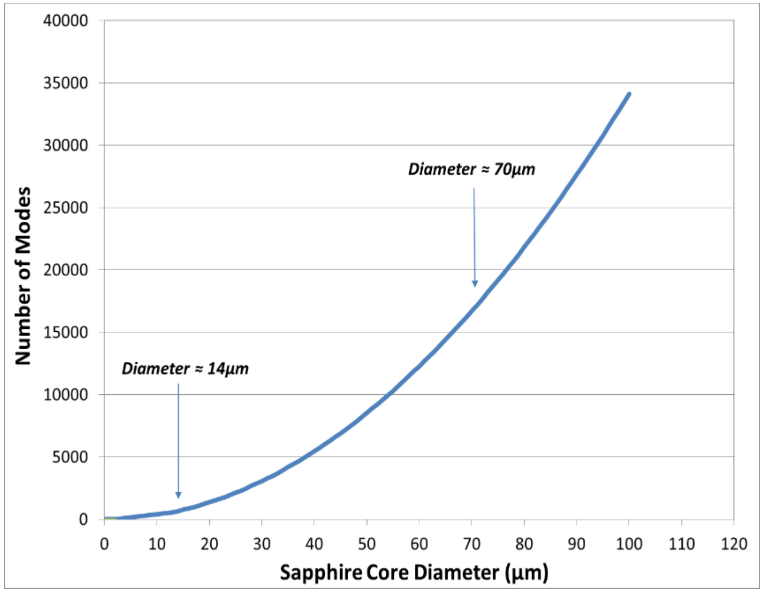
SC Sapphire Optical Fiber

- Single crystal growth
- Lack of cladding
  - Sapphire core: n ≈ 1.78
  - Air cladding: n ≈ 1
- Highly multimode
  - High numerical aperture
  - Large core
- Sensor Performance
  - High FO attenuation
  - Inherent EFPI challenges
  - Limits FBG opportunity

Mode Count Approximation

$$\uparrow M = \frac{V^2}{2} \uparrow$$



Technical Challenges

- Sapphire fiber
  - Large “core” diameters
  - High numerical aperture (NA)
  - High loss
  - Weak Raman signal in sapphire fiber
- High temperature
  - Thermal radiation generated by the sapphire fiber
  - Thermal radiation coupled into the fiber end
- Spatial Resolution
  - Pulse width
  - Modal dispersion

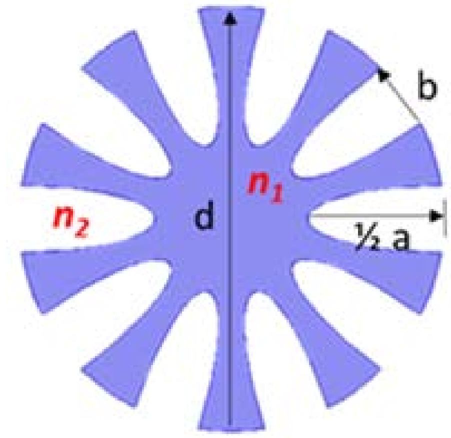
Approach

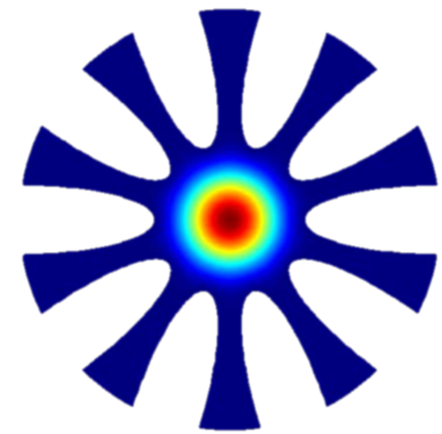
- Develop a “micro-structured” single crystal sapphire fiber with reduced modal volume.
  - Wet acid etching
  - Glass/Teflon masking
- Develop a Raman scattering distributed temperature sensing system
  - Interrogation at 532 nm
  - LMV single crystal sapphire sensing fiber
- Develop a prototype fully-distributed sensing system
  - Conduct performance testing in laboratory environment at temperatures in excess of 1000˚C.

RESEARCH PROGRESS:
LMV SAPPHIRE FIBER

LMV Sapphire Fiber Designs

- “Windmill” fiber design
  - Core region in the center
  - Alternating high (sapphire) & low (air) index region in the azimuthal direction
  - Uniform cladding in the radial direction
- “Sub/Few” micron fiber
  - Single mode @ diameter ~ 400 nm
  - Fewer modes @ diameter of few microns
- Theoretical optical modeling
  - Modal characteristics
  - COMSOL Multiphysics®





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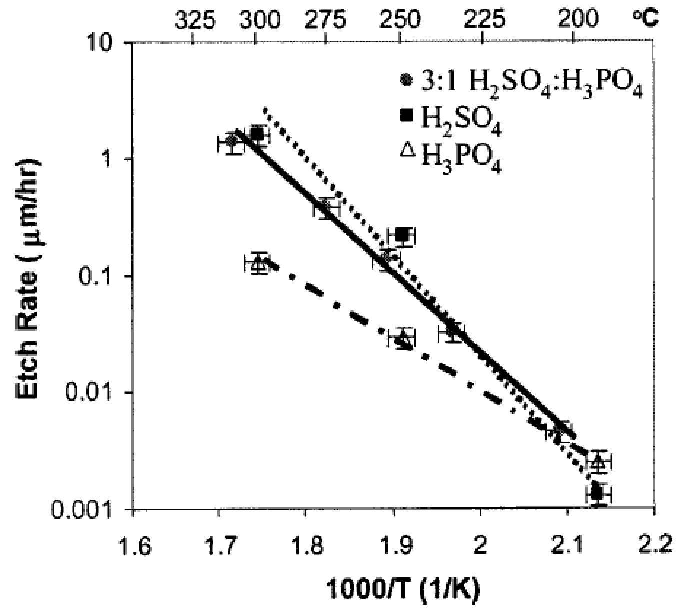
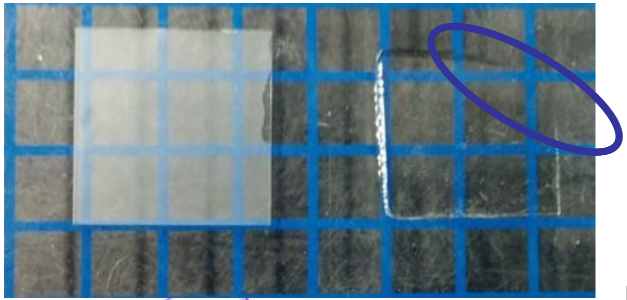
Wet Acid Etching

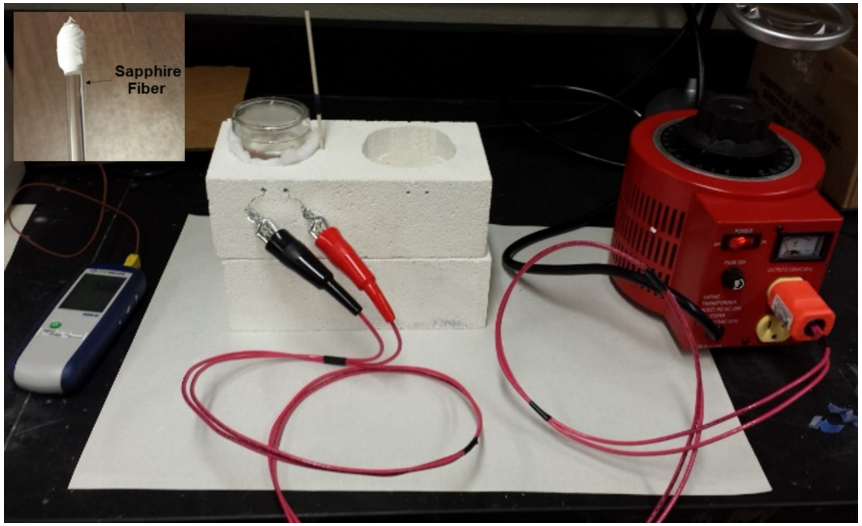
- Sulfuric/phosphoric acid solutions
- Elevated temperatures (>200˚C)
- Wafer etching
    - Surface cleaning and smoothing
    - ***Dwikusuma, F., D. Saulys, and T.F. Kuech. "Study on Sapphire Surface Preparation for III Nitride Heteroepitaxial Growth by Chemical Treatments". Journal of Electromechemical Society. 149 (11) G603-G608 (2002).***
- Repeatable and reliable
- Simple and cost effective



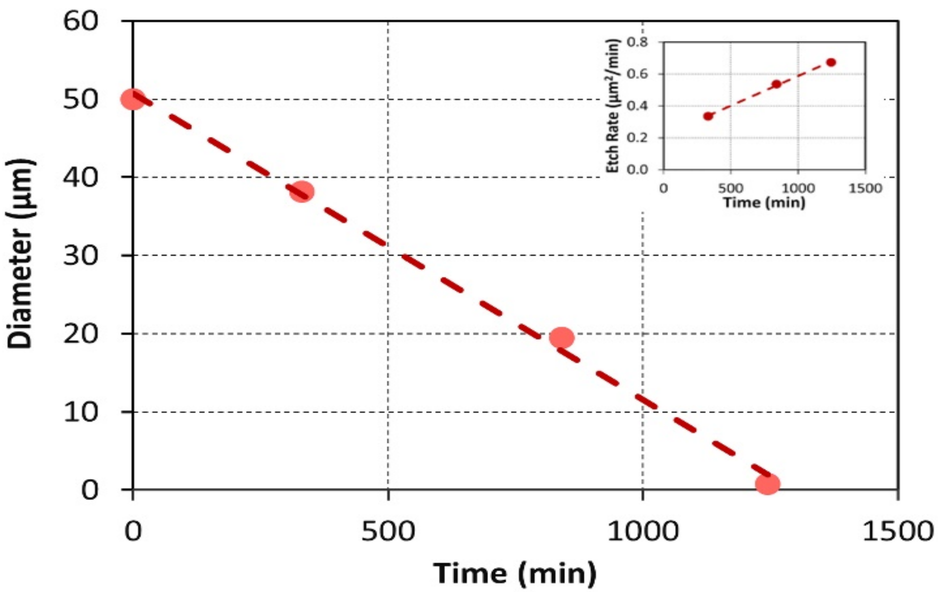
Completely Etched



Sapphire Fiber Etching



Wet acid etching system



Diameter reduction rate of sapphire fiber during etching at approximately 343˚C

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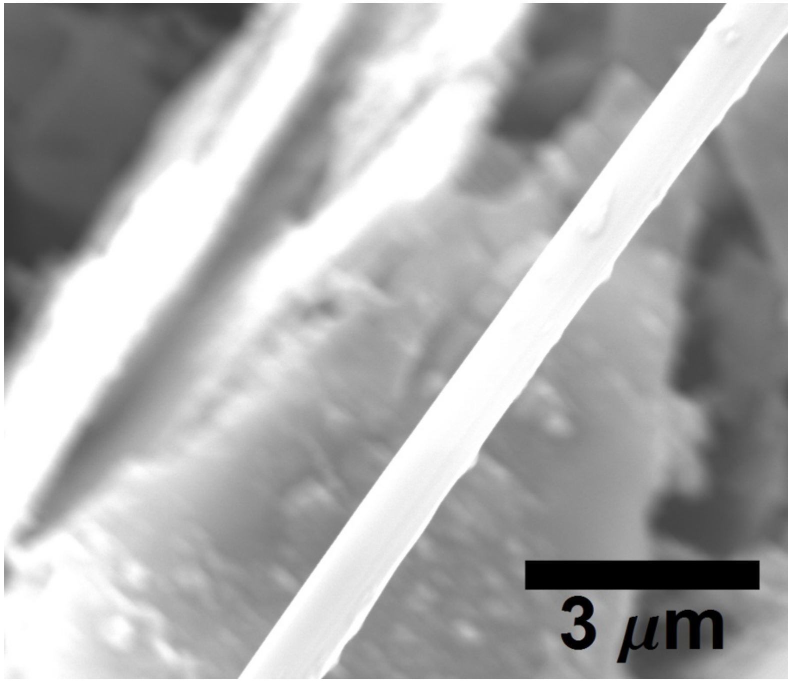
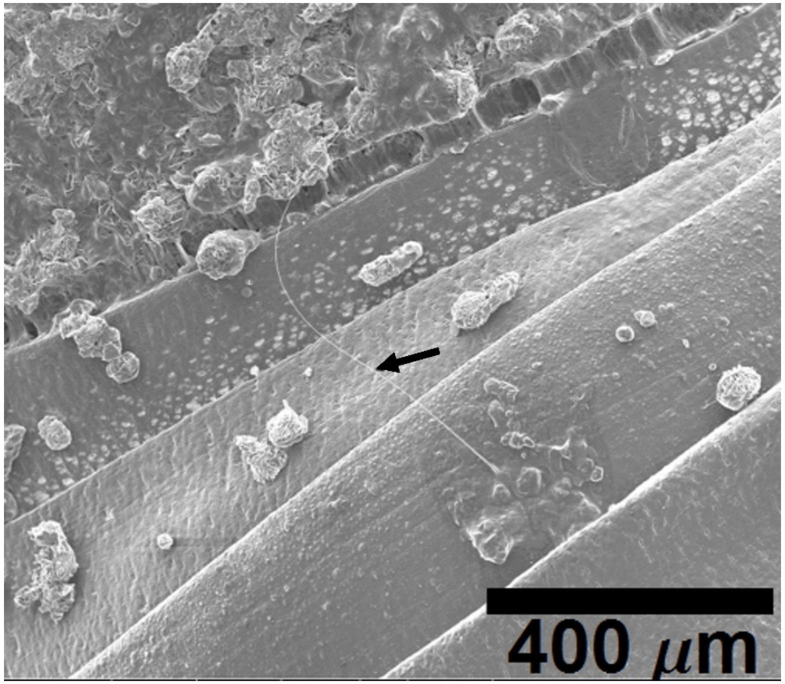
Submicron Diameter Fiber





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. DOI: http://dx.doi.org/10.1016/j.matlet.2014.09.105.

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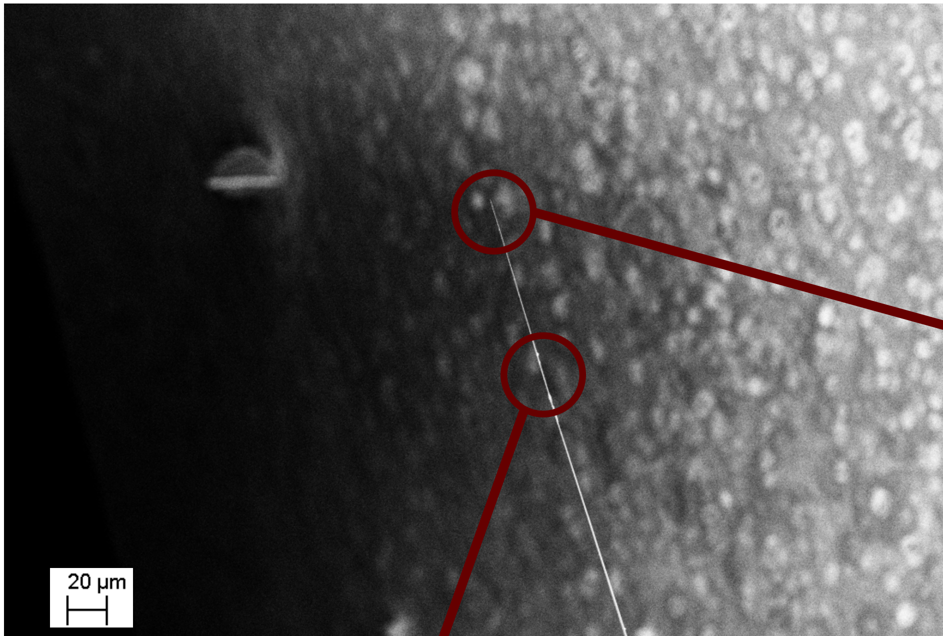
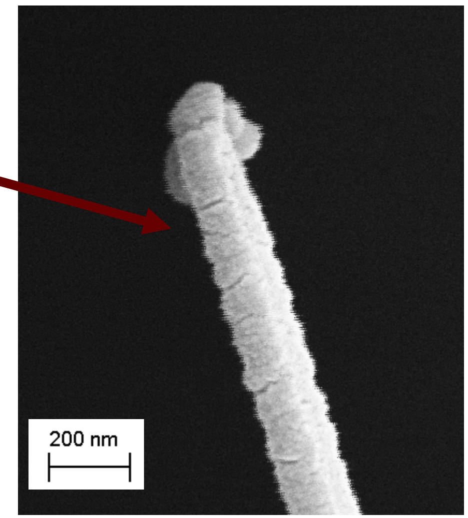
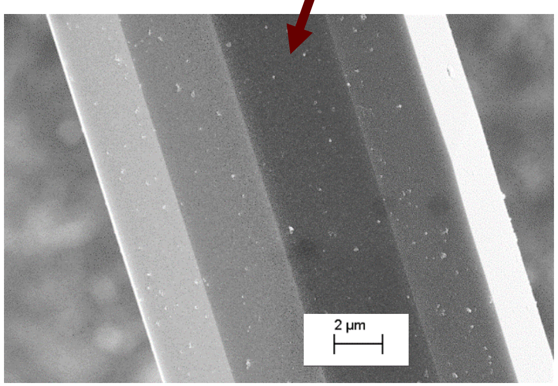
Sapphire Fiber Taper



Surface texture is Au-Pd coating

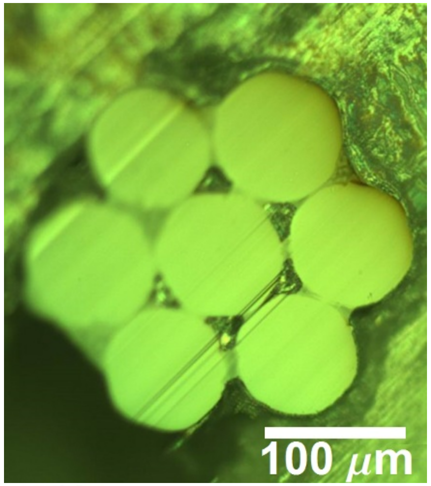




Base of tapered fiber demonstrates cleanly etched surface and preferential etching of r-plane (resulting in hexagonal cross-section)

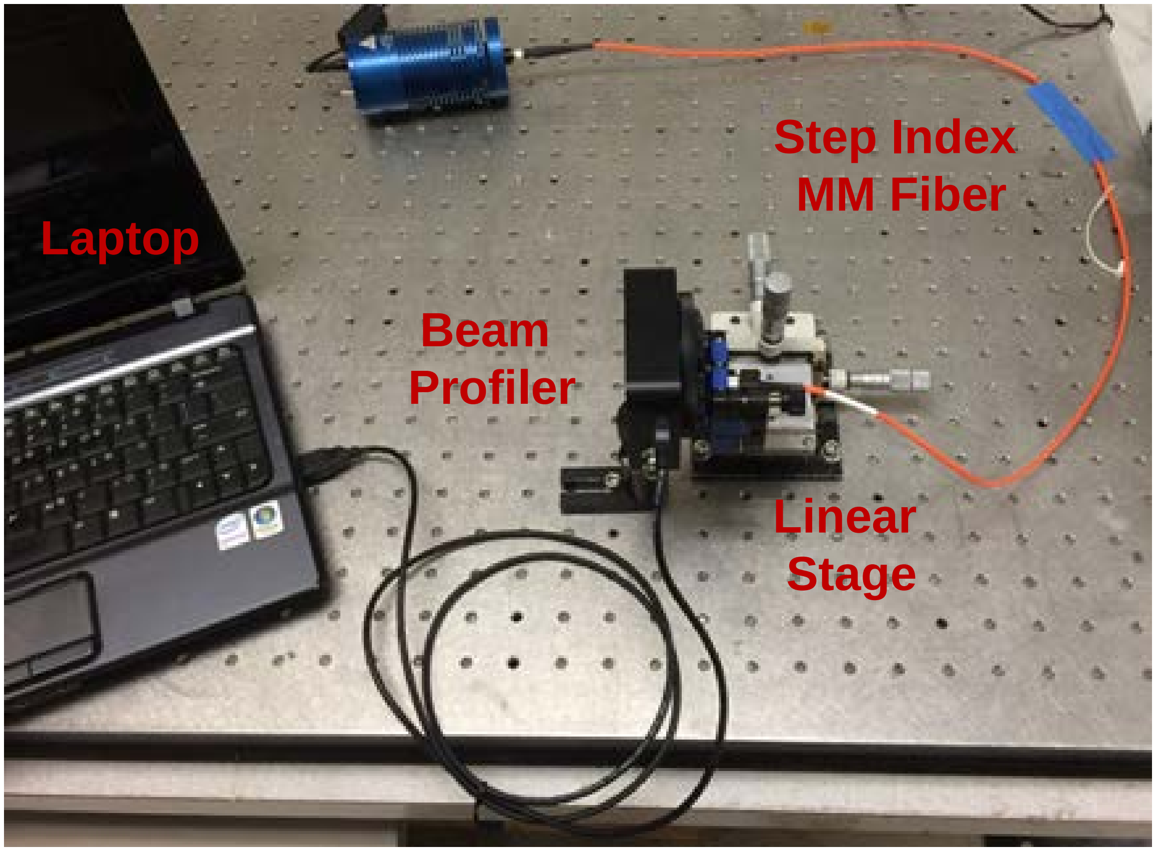
Fiber Masking

- Teflon™
- Glass
  - Vapor deposited silica coating
  - *Yet to be published technique*
- "Compositional" Masking
  - High temperature mullite conversion
- Silicon carbide deposition

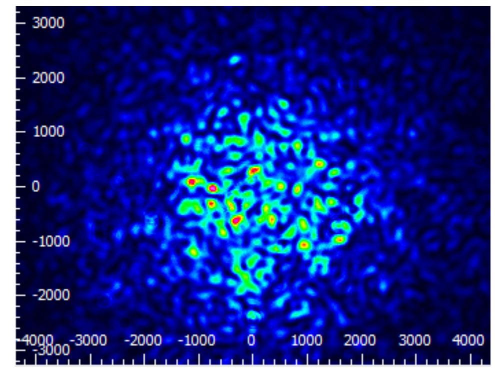


Optical Fiber Characterization

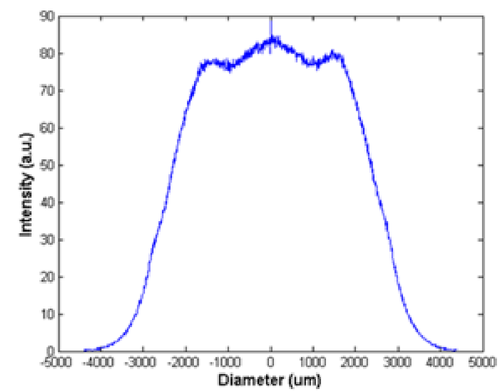
Halogen Light Source



Mode Field Pattern



Intensity Profile (X-direction)



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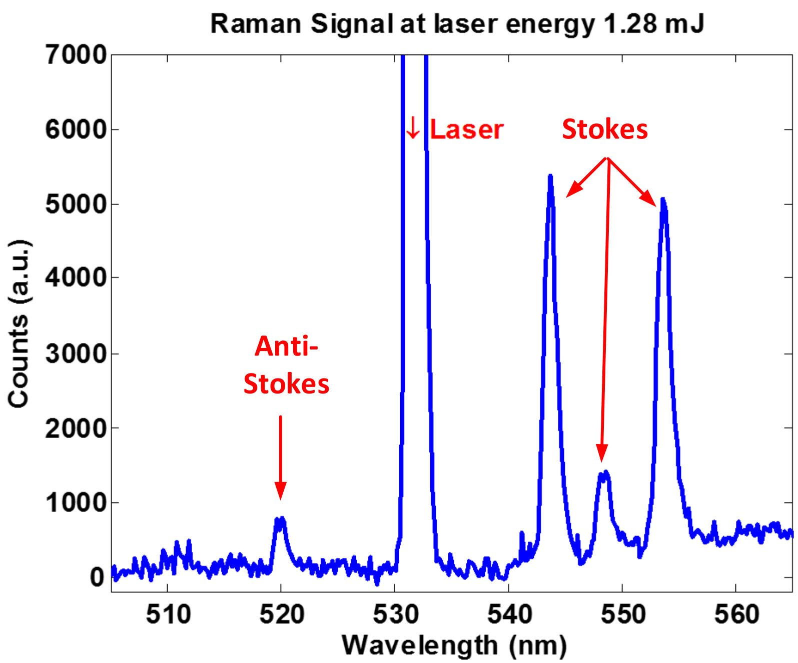
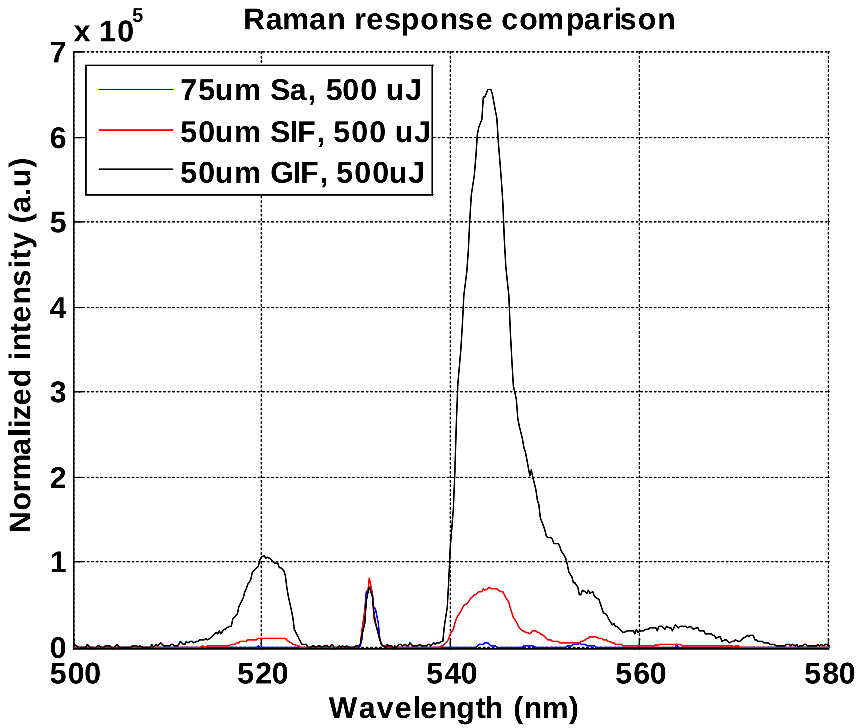
RESEARCH PROGRESS: *DISTRIBUTED TEMPERATURE SENSING SYSTEM*

Raman Scattering Spectra

532 nm Nd:YAG laser + spectrometer





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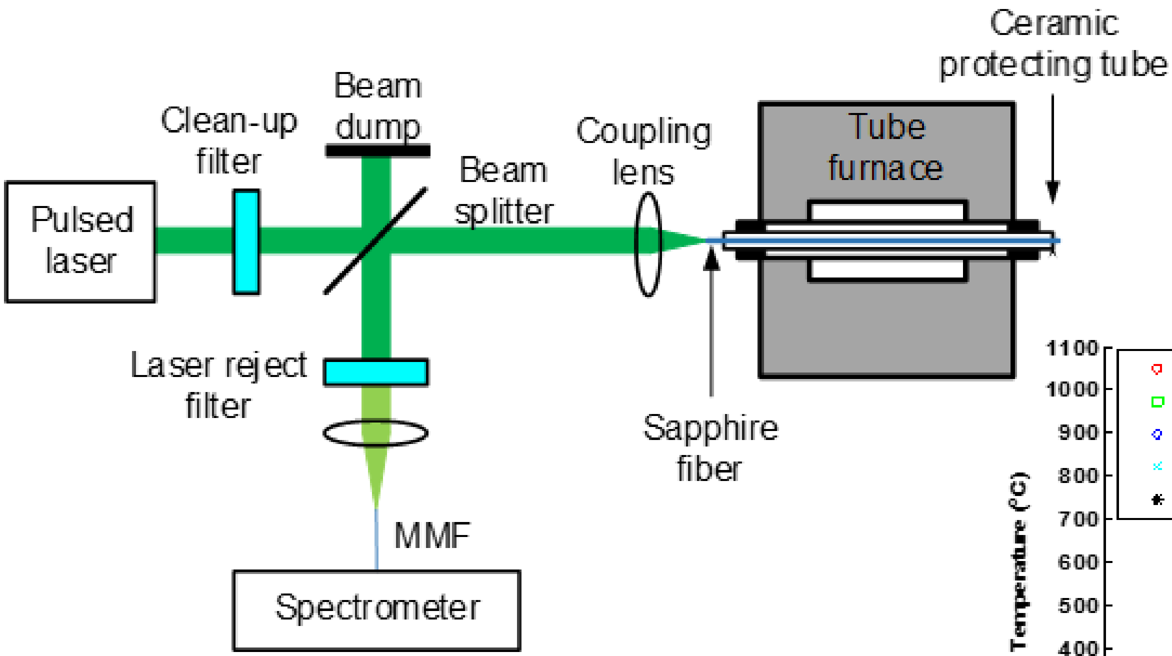
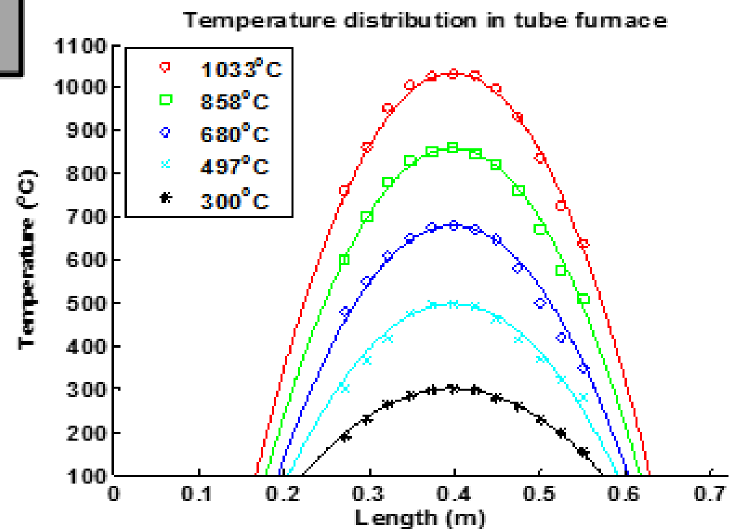
Thermal Response

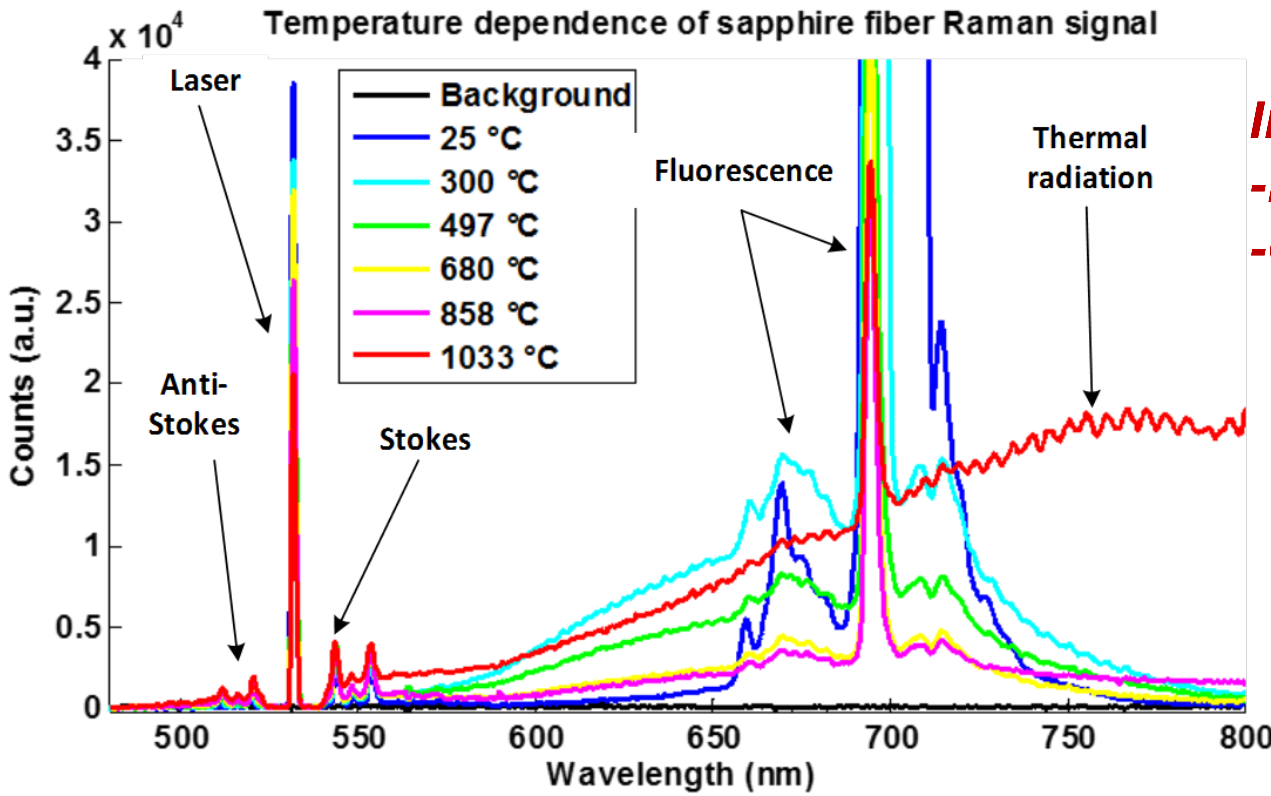
Test Setup





Thermal Response

Acquired Spectra



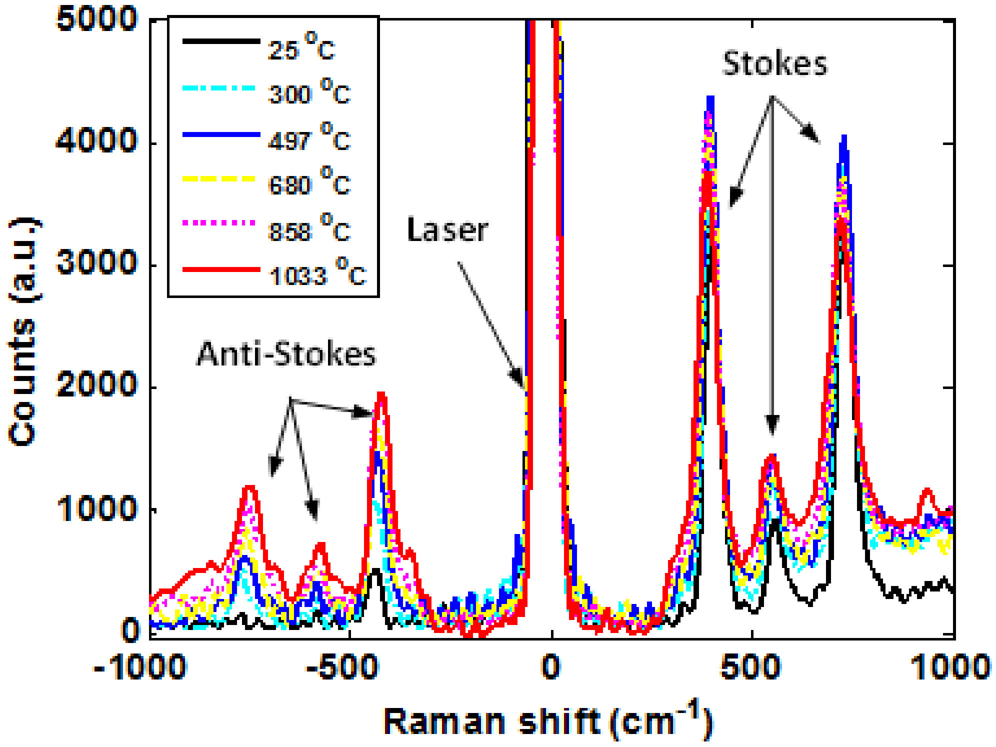
Includes:

-Blackbody radiation

-Cr^{+3} fluorescence

Thermal Response

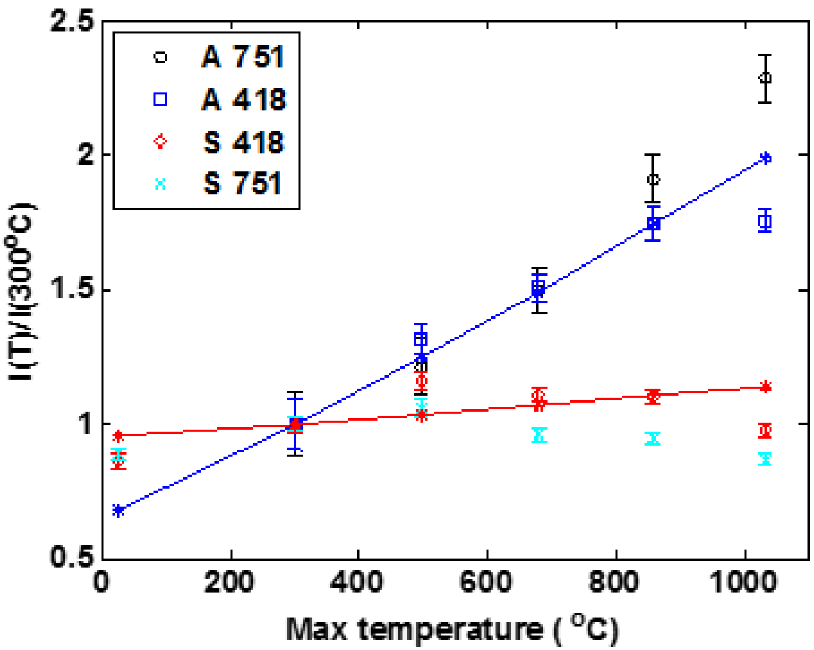
Processed spectra

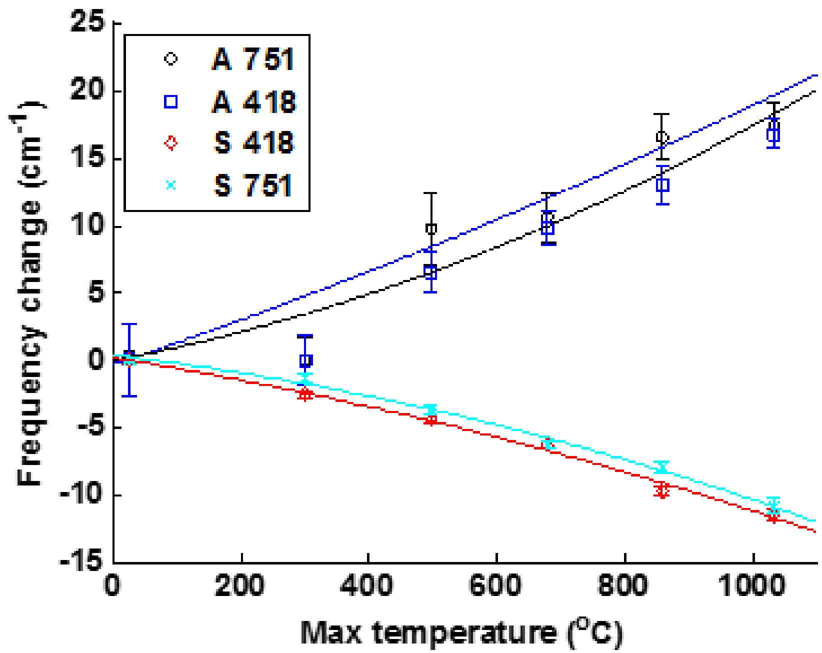


B. Liu, Z. Yu, Z. Tian, D. Homa, C. Hill, A. Wang, and G. Pickrell, Temperature dependence of sapphire fiber Raman scattering. Optics Letters 40 (2015) 2041-2044.
DOI: http://dx.doi.org/10.1364/OL.40.002041.

Thermal Response

Temperature Dependence





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Next Steps

- Design & optimize the distributed sensing system (light source and detectors)
- Demonstrate fully-distributed temperature sensing with fused silica fibers
- Synthesize and optimize “windmill” and submicron fibers
- Demonstrate mode reduction in selected LMV sapphire fibers
- Demonstrate fully-distributed sensing in standard and LMV sapphire fibers

THANK YOU FOR YOUR TIME