2018 CROSSCUTTING
Research Project Review
Omni William Penn Hotel
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REDUCED MODE SAPPHIRE FIBER *AND* DISTRIBUTED SENSING SYSTEM

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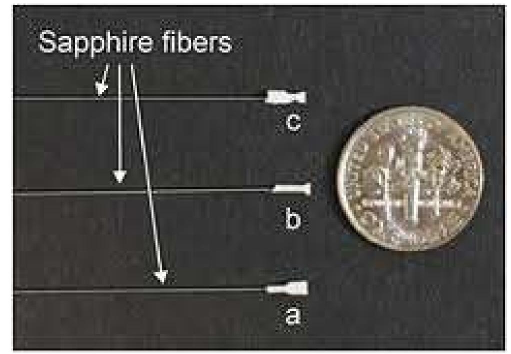
Overview

- Motivation, Objectives, and Technical Challenges
- Research Approach and Technology
  - LMV Sapphire Fiber Design and Fabrication
  - Distributed Temperature Sensing System
  - Field Deployable Fiber Optic Sensing System
- Milestones and Schedule
- Impact, Achievements and Next Steps

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, 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.

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

TECHNOLOGY & APPROACH

Research Approach

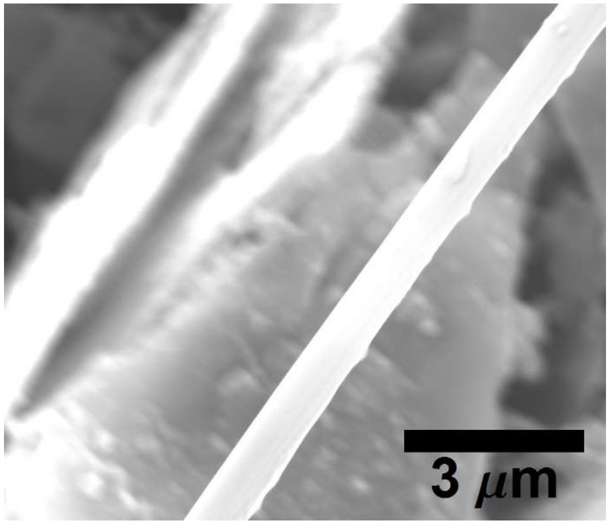
- Design and fabricate a single crystal sapphire fiber with a modal volume optimized for sensor applications
  - Perform waveguide analysis of fiber designs
  - Wet acid etching at elevated temperatures
- Design and construct distributed temperature sensing system(s)
  - Develop complimentary distributed sensing schemes
    - Raman backscatter
    - Fiber Bragg gratings
  - Conduct performance testing
- Field trails testing in operating environment
  - Design and fabrication of harsh environment sensor packaging
  - Sensor deployment and operation

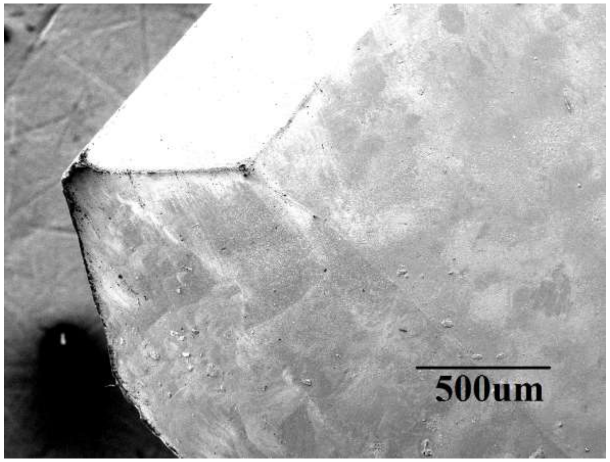
RESEARCH PROGRESS:
LMV SAPPHIRE FIBER DESIGN AND FABRICATION

LMV Sapphire Fiber Fabrication

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-plane vs. c-plane
- Extended lengths (~ 1m)
- Improved surface quality
  - Eliminated surface deposits
- Simple, cost effective, scalable
- Potential new applications
  - Gas sensing, inclined tip sensing





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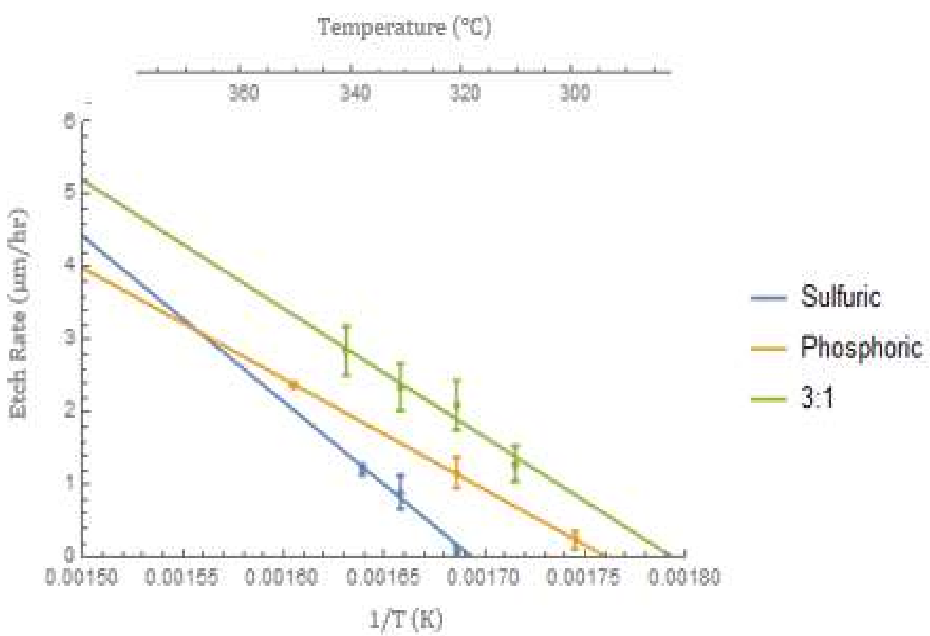
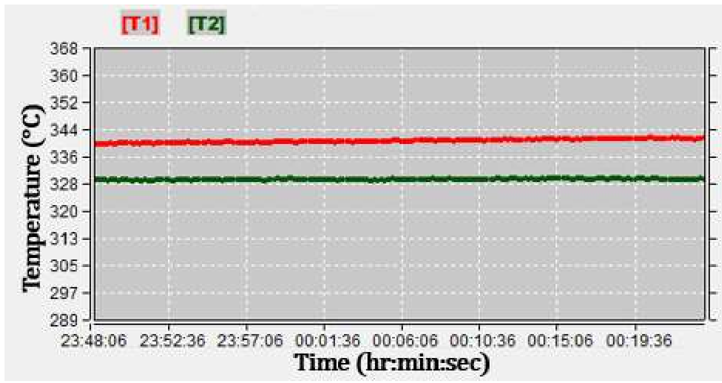
LMV Sapphire Fiber Fabrication

Optimization and Control





Sample	Top Diameter (μm)	Bottom Diameter (μm)
A	82.0	73.1
B	80.9	73.4
C	79.6	74.4
Average	80.8	73.6
Standard Deviation	1.2	0.7

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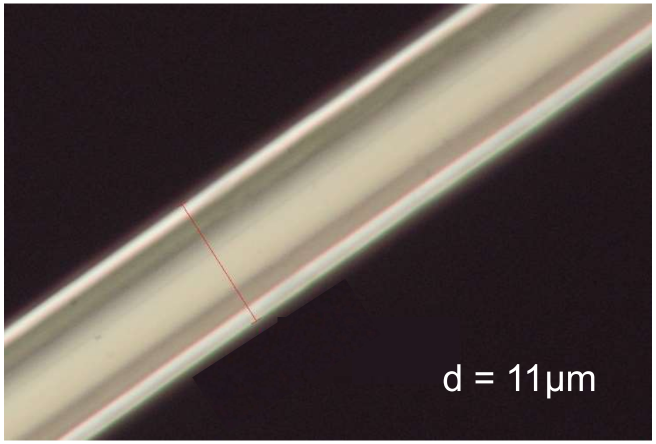
LMV Sapphire Fiber Fabrication

Characterization of Surface Quality

Optical Microscopy

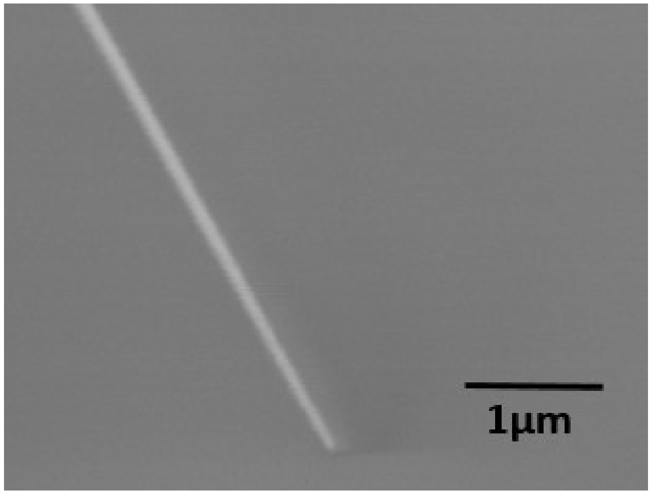
(fiber diameter, contamination, polarization states, non-uniformities)



Scanning Electron Microscopy (SEM)

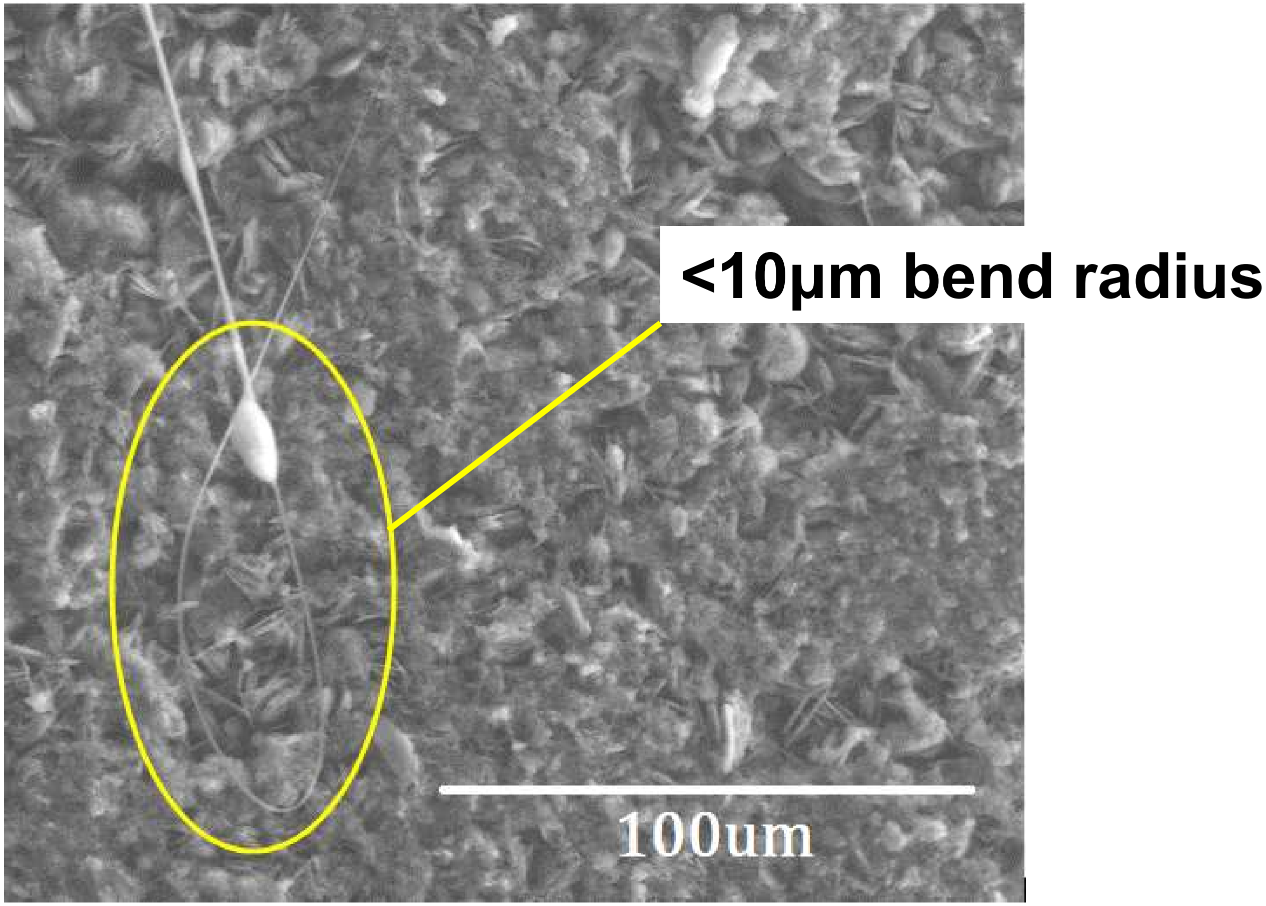
Energy-dispersive X-ray spectroscopy (EDAX)

(fiber diameter, contamination, composition/elemental analysis, defects, non-uniformities)



LMV Sapphire Fiber Testing

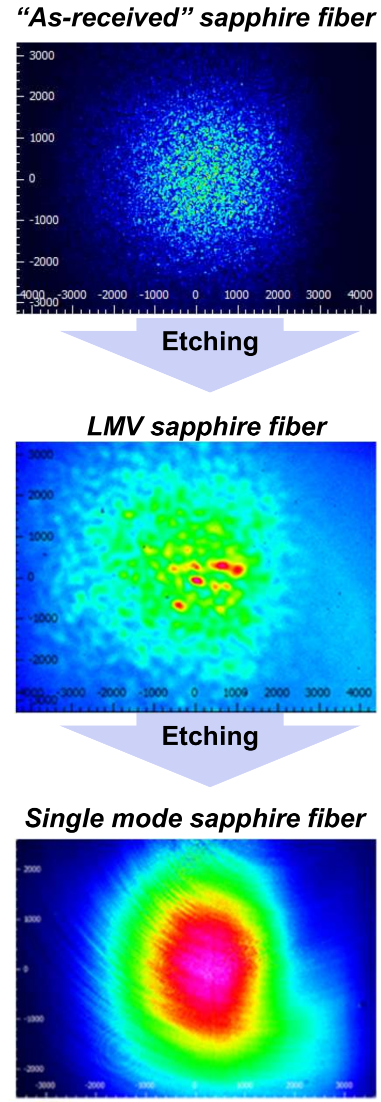
Mechanical Strength via Bend Radius



LMV Sapphire Fiber Testing

Far Field Analysis Method

- Far-field intensity patterns capture
  - Prior to etching
  - Post etching and polishing
  - Three different wavelengths (532nm, 782.9nm, 982.9nm)
- Modal interference and superposition yields a "speckled" appearance
- Reduction in diameter and modal volume
  - Number of power peaks (speckles) decreases
  - Relative diameter of individual speckles increases
  - Modal interference and superposition due a decrease in the number of supported modes
- Qualitative analysis of modal volume
  - Low order mode profiles are visible
- NA measurements performed via the beam width differential method



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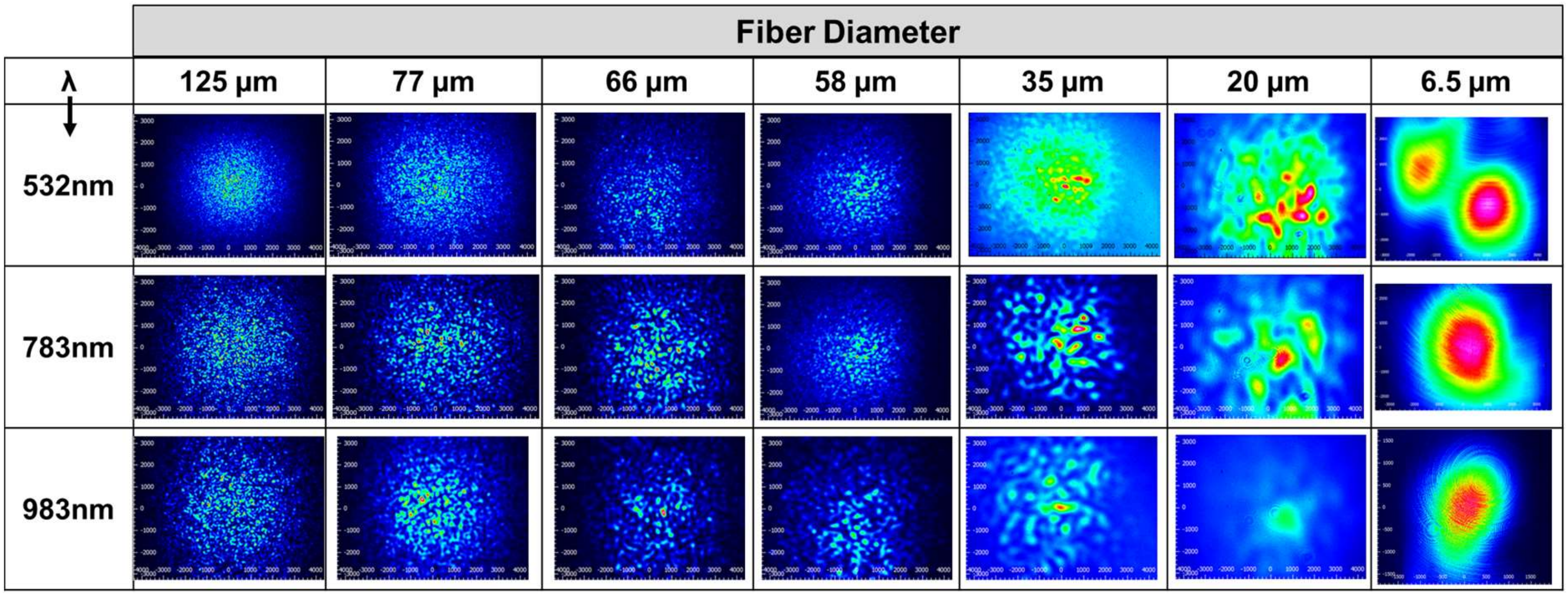
LMV Sapphire Fiber Testing

Far Field Analysis of RDSF



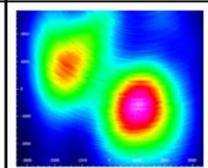
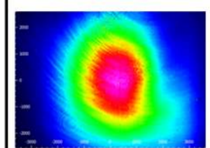
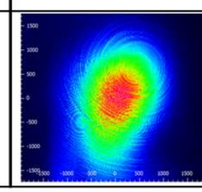
The trend in modal volume reduction for a reduction in fiber diameter and increase in wavelength agrees with theoretical predictions

LMV Sapphire Fiber Testing

Theoretical vs. Effective NA

- The measured ("effective") NA can deviate significantly from the theoretically calculated value
  - Non-ideal geometry (i.e. non-circular cross section)
  - Small core diameter
  - Inefficient coupling, surface scattering, angled end faces

- Beam width differential method
  - CCD camera beam profiler (Thorlabs BC106-VIS)

	Calculated Modal Volume		
Wavelength	**$NA_{Theor.}$=~1.4**	**NA_{eff}=0.09**	**6.5µm**
532nm	1614	2	
783nm	736	1	
983nm	461	1	

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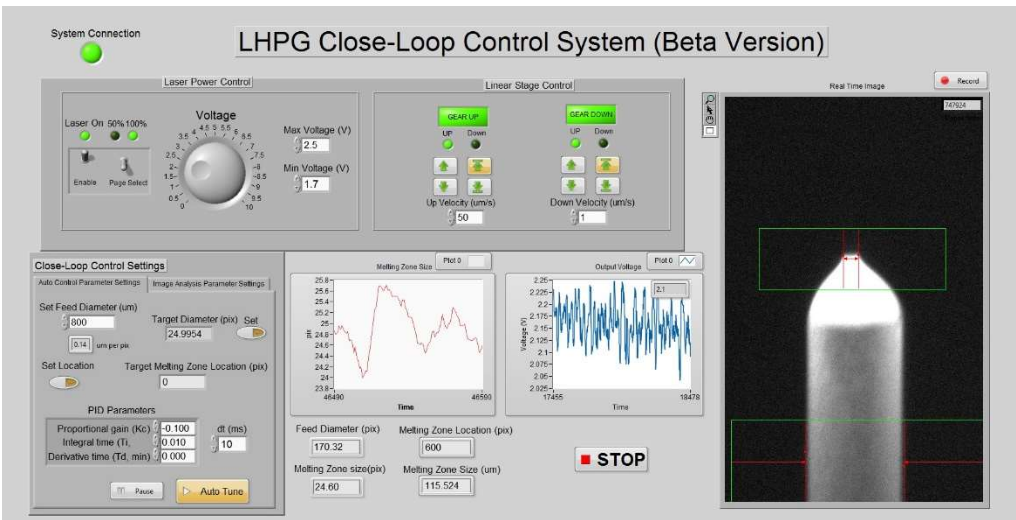
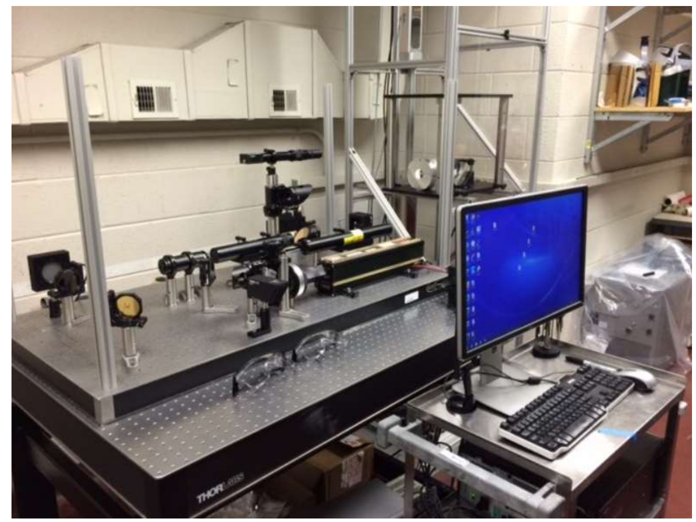
Laser Heated Pedestal Growth

Single crystal sapphire fiber fabrication





Diameter variations ~1.7% were readily achieved

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LMV Sapphire Fiber

Summary of Results

- **For the first time**, a submicron single crystal sapphire fiber for the propagation of lower order modes was fabricated via wet acid etching
- Few mode operation was demonstrated, for the **firsttime**, in a single crystal sapphire fiber
- Reduction of the “effective” NA and modal volume was verified via an array of characterization techniques and test parameters
- A fully operational LHPG system was designed and constructed in-house for the fabrication of unique sapphire fiber structures

RESEARCH PROGRESS: ***DISTRIBUTED TEMPERATURE SENSING SYSTEMS***

RAMAN BACKSCATTERING BASED TEMPERATURE SENSING

Operating Wavelength Selection

Signal Quality and Blackbody Radiation

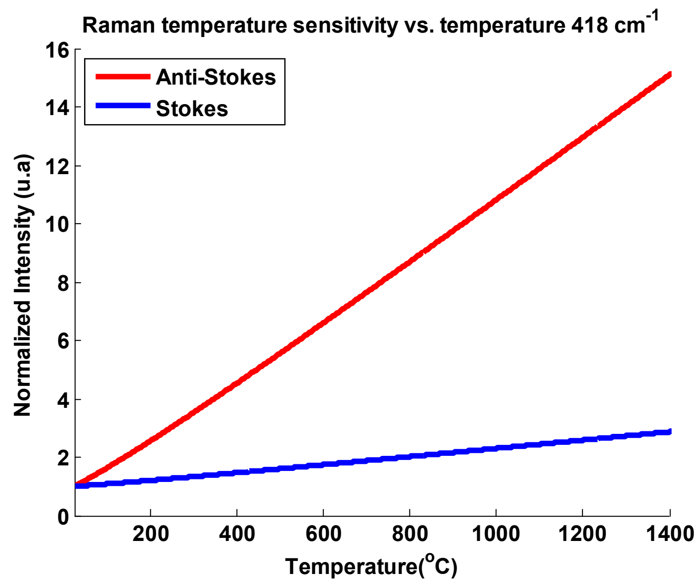
- The Raman intensity of the Anti-Stokes and Stokes components is proportional to its differential cross section given by *(M. Hobel, Applied Optics, 1995)*

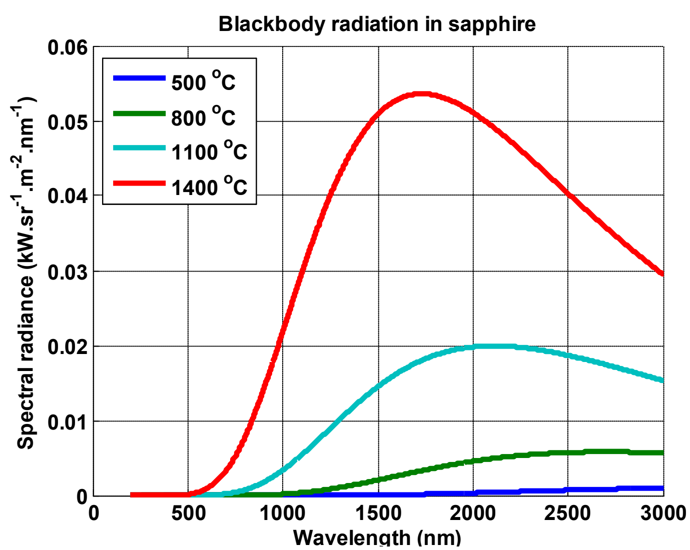
$$\left.\frac{d\sigma_{AS}}{d\Omega}\right|_x \cong \frac{1}{\lambda_{AS}^{\ 4}} \frac{1}{\exp\left[\dfrac{hc\Delta\upsilon}{K_B T(x)}\right]-1}$$

$$\left.\frac{d\sigma_{S}}{d\Omega}\right|_x \cong \frac{1}{\lambda_{S}^{\ 4}} \frac{1}{1-\exp\left[-\dfrac{hc\Delta\upsilon}{K_B T(x)}\right]}$$

- According to Planck's law, the radiation can be calculated as followed *(M. Planck, P. Blakiston's Son & Co, 1914)*

$$B(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}-1}}$$

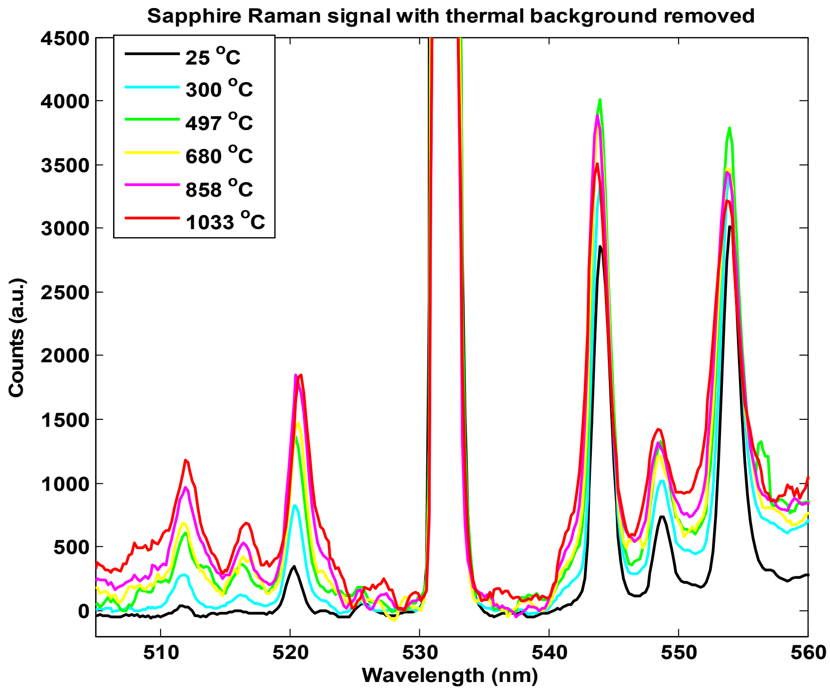




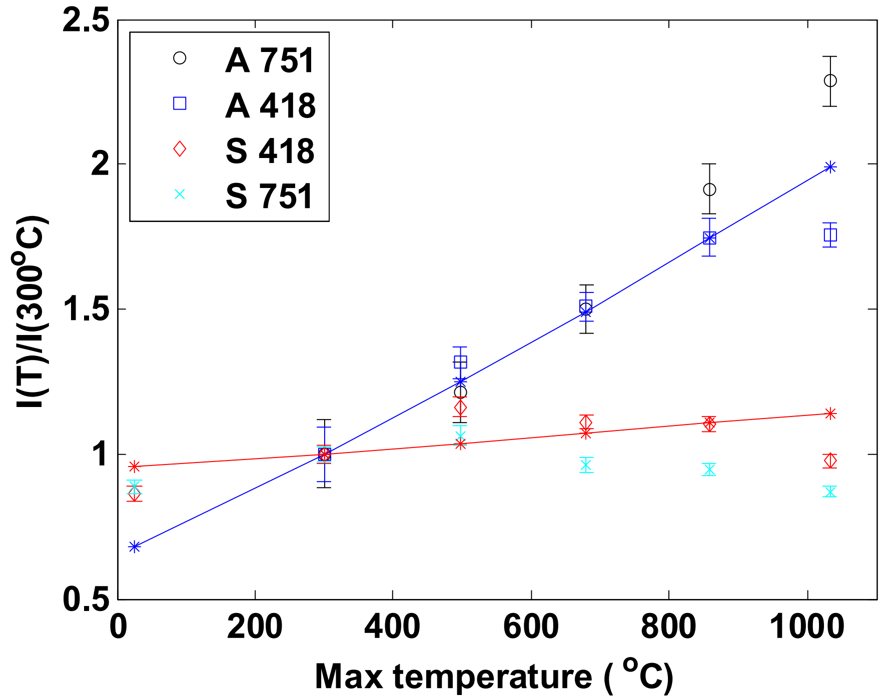
Scattering in Sapphire Fiber

Characterization of Raman Spectra

Spectrum



Peak Intensity



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.

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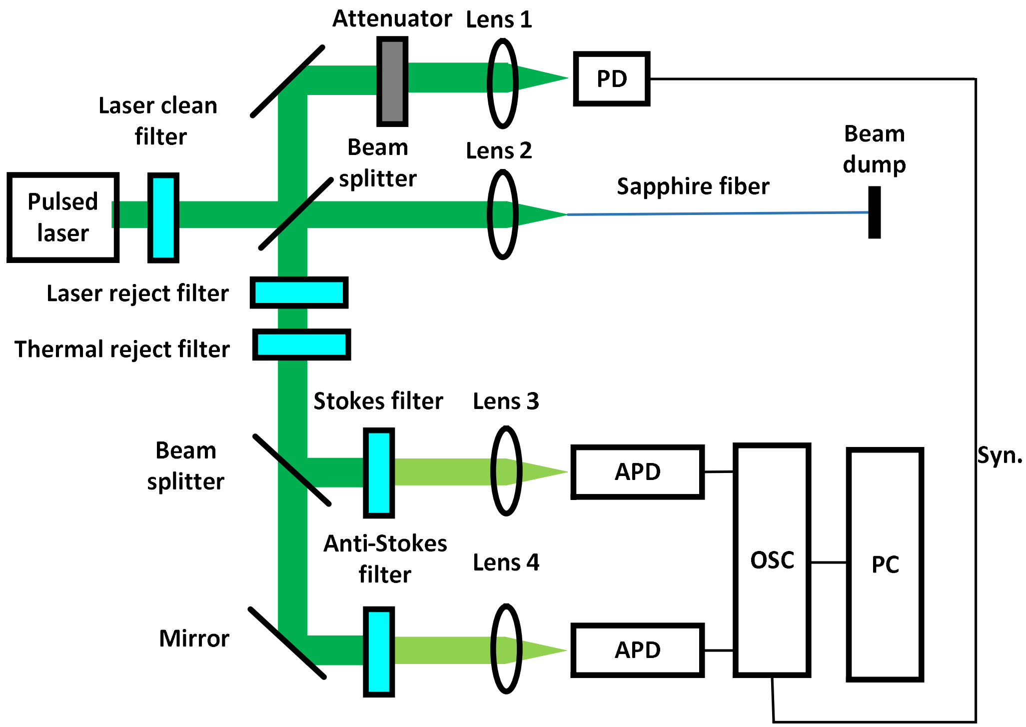
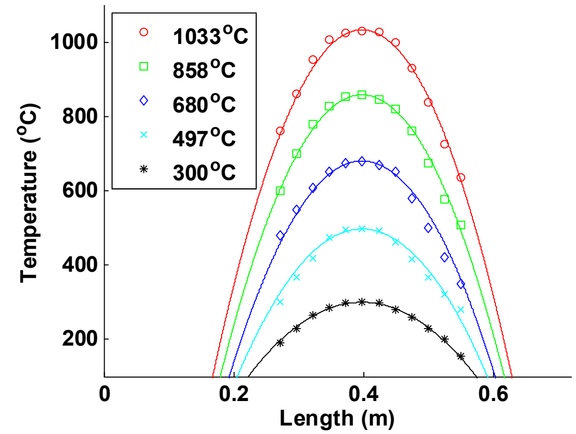
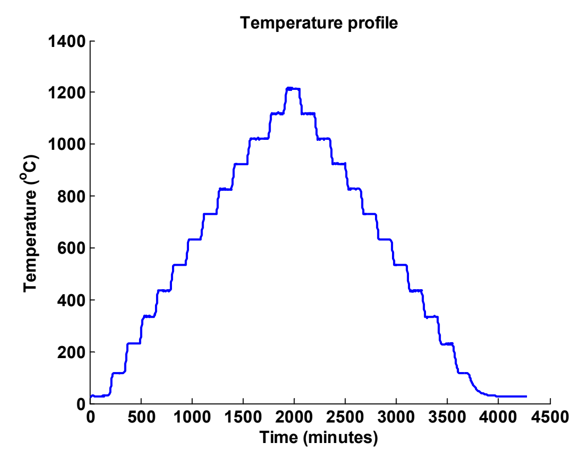
Raman DTS System Design

Experimental Set-Up



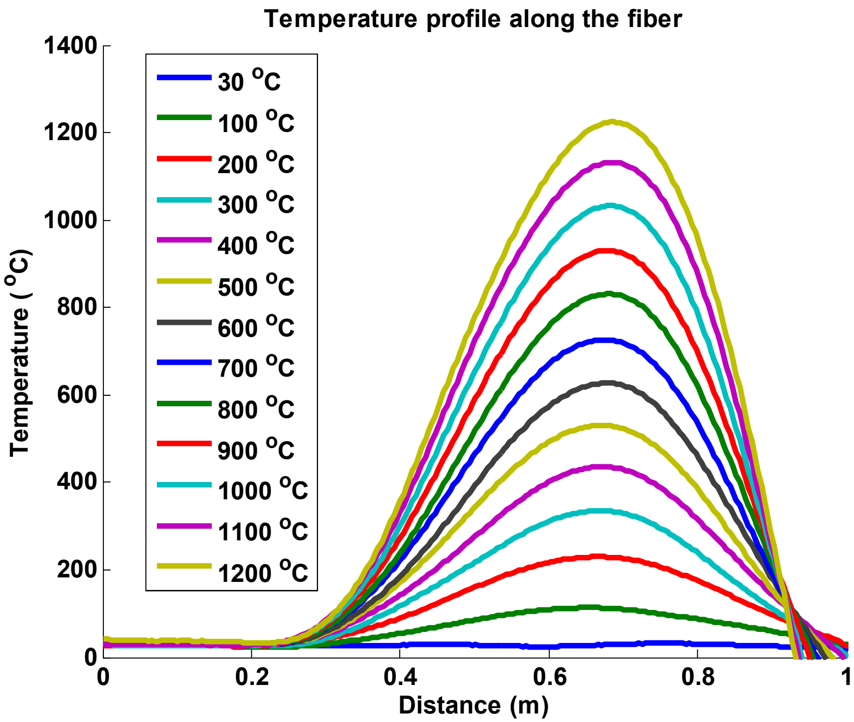


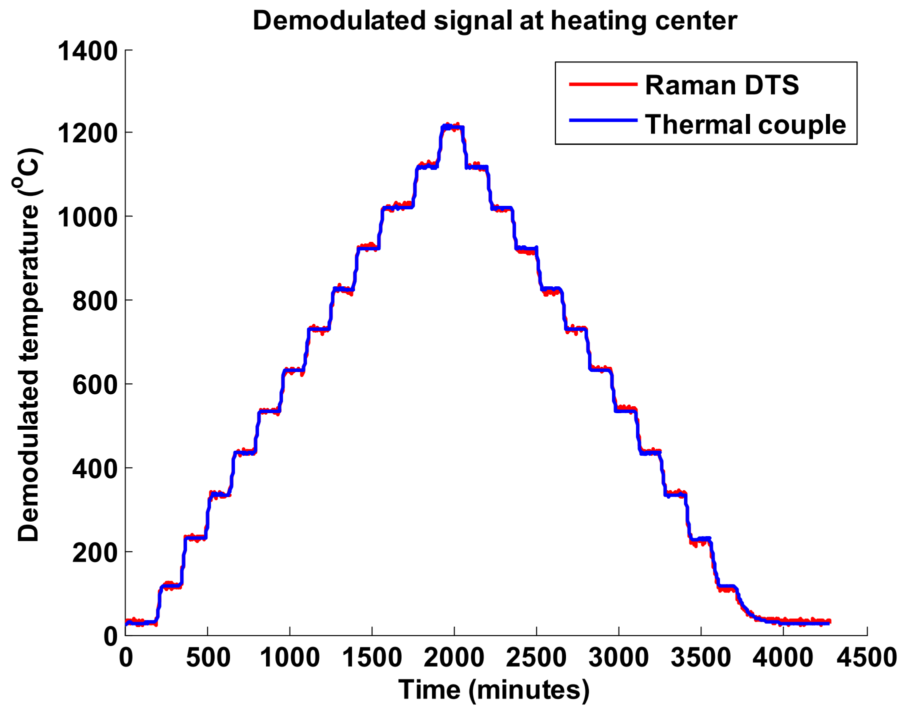


Liu, Bo, Zhihao Yu, Cary Hill, Yujie Cheng, Daniel Homa, Gary Pickrell, and Anbo Wang. Sapphire-fiber-based distributed high-temperature sensing system, Optics letters 41, no. 18 (2016): 4405-4408.

Raman DTS System Performance

1 meter Sapphire Fiber





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Raman DTS System Performance

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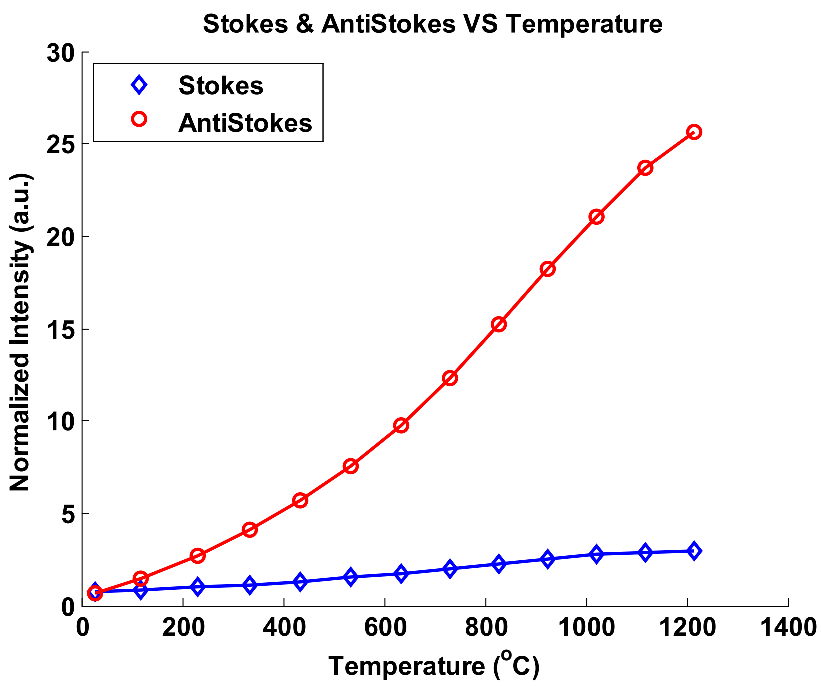

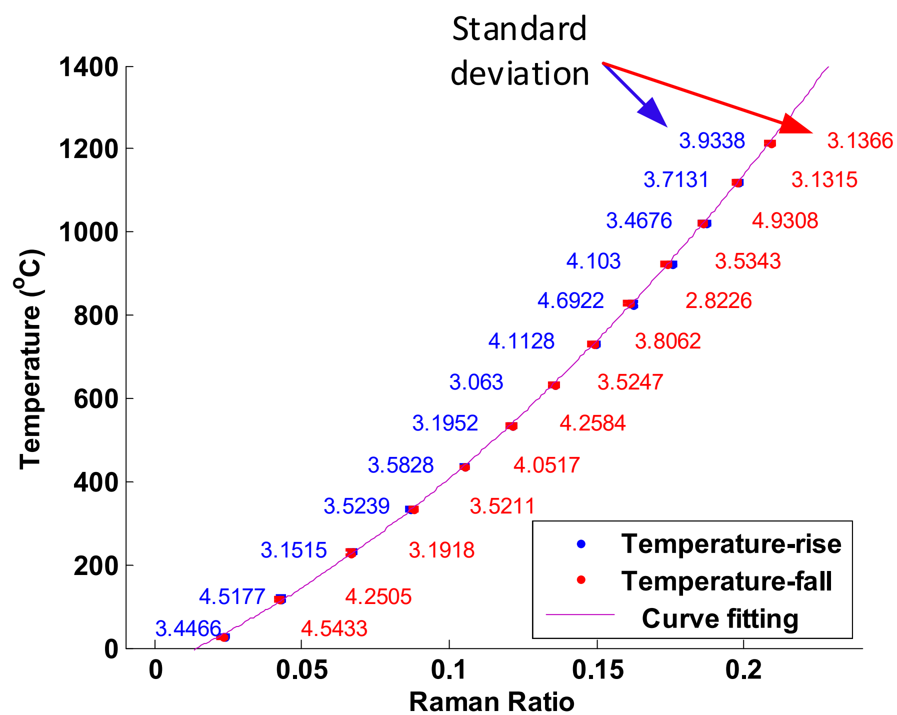

Standard Deviation: 3.7ºC (3.0ºC)

Liu, Bo, Zhihao Yu, Cary Hill, Yujie Cheng, Daniel Homa, Gary Pickrell, and Anbo Wang. Sapphire-fiber-based distributed high-temperature sensing system, Optics letters 41, no. 18 (2016): 4405-4408.

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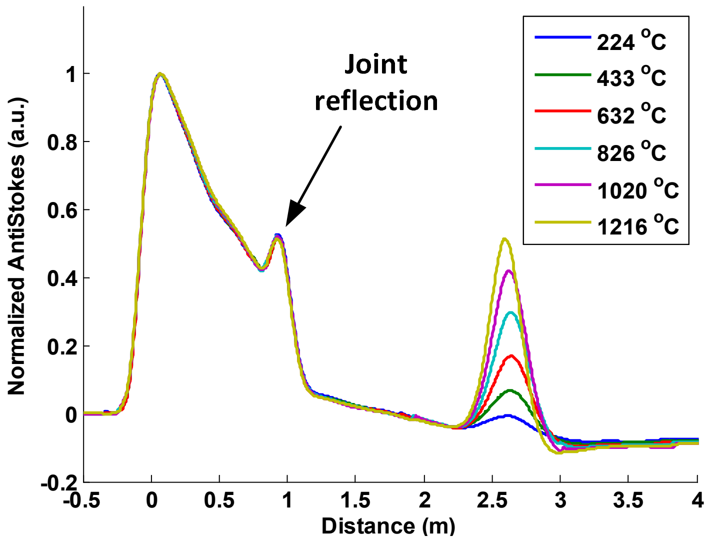
Raman DTS System Performance

Sensing Length, Temperature and Spatial Resolution

- Sensing length: 3 meters
- Temperature: 1400ºC
- Spatial resolution: 16.4 cm
  - Determined via 10% to 90% response distance



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FIBER BRAGG GRATING BASED TEMPERATURE SENSING

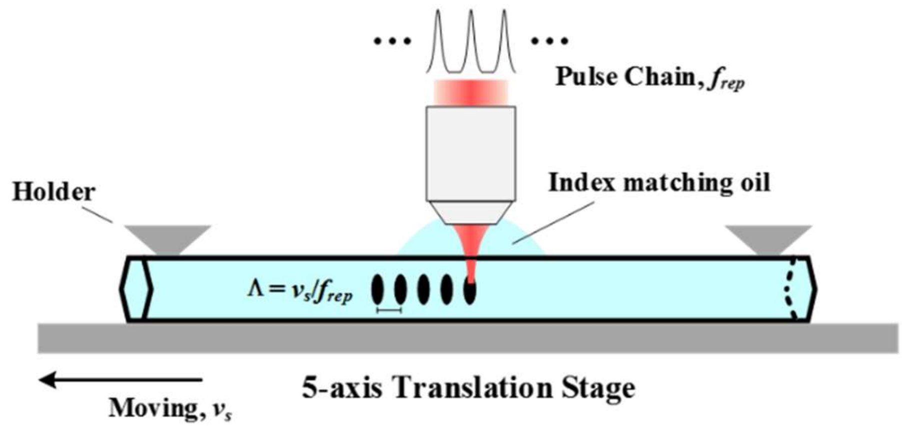
FBG Sensor Fabrication

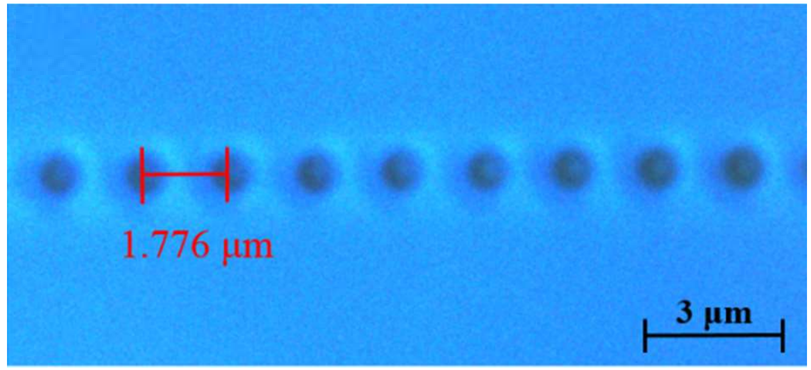
Point-by-Point Method

- FBG created by localized refractive index changes distributed along the fiber
  - Inscription via 780 nm (IR-fs) laser
  - Phase matching condition:

$$m\lambda_{Bragg} = 2n_{eff}\Lambda$$

- Pitch controlled by the relation between the moving speed and the repetition rate
- Length adjusted by the total number of laser pulses
- Unique advantages over phase mask method
  - Geometrical and design flexibility
  - Wavelength division multiplexing (WDM) can be readily implemented





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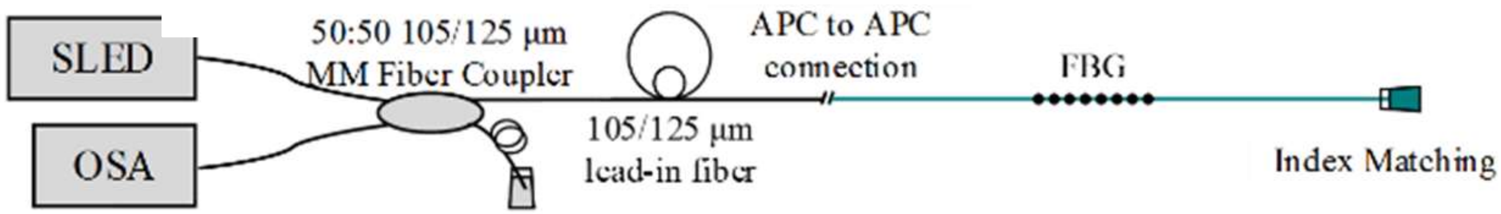
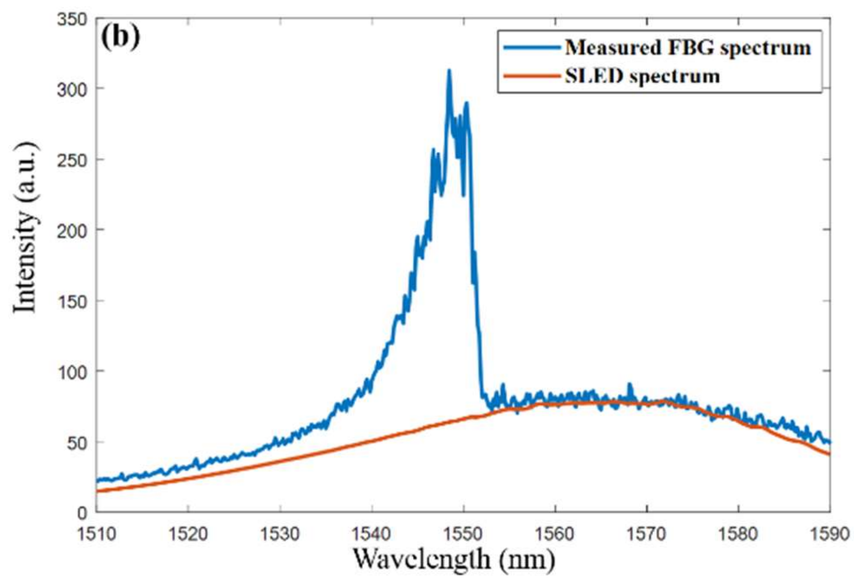
FBG Sensor Fabrication

FBG Interrogation Technique

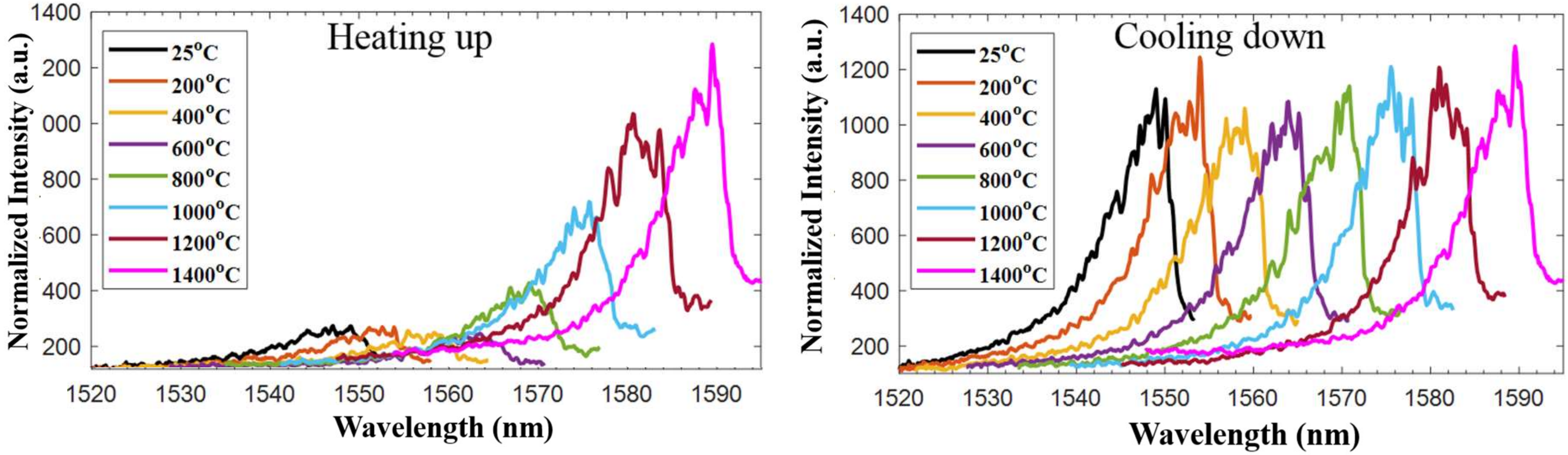




Yang, Shuo, Di Hu, and Anbo Wang. Point-by-point fabrication and characterization of sapphire fiber Bragg gratings, Optics letters 42, no. 20 (2017): 4219-4222.

FBG Sensor Fabrication

Enhancement of Reflectivity via Thermal Annealing

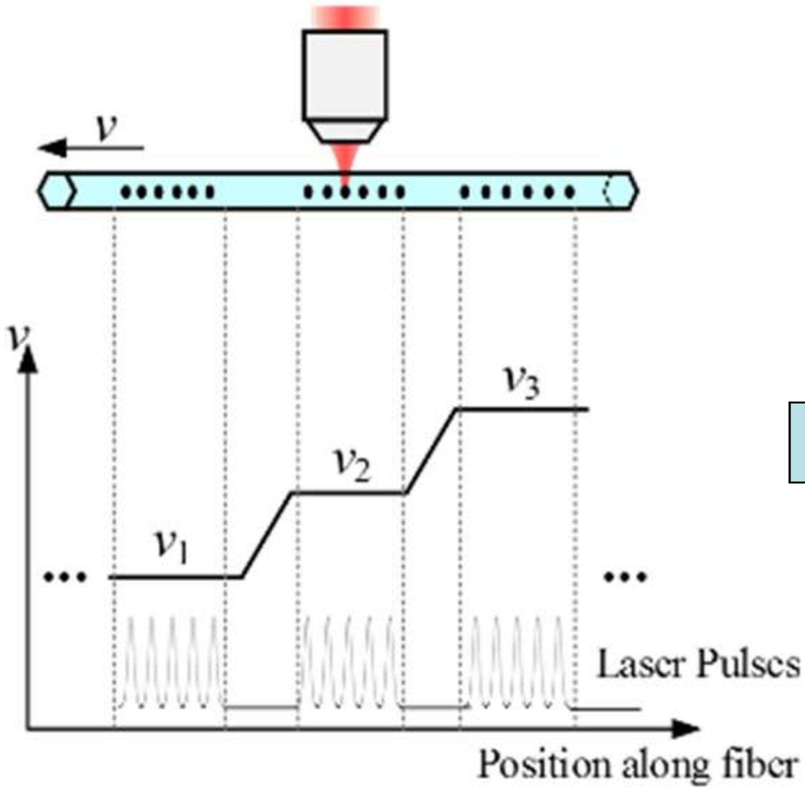


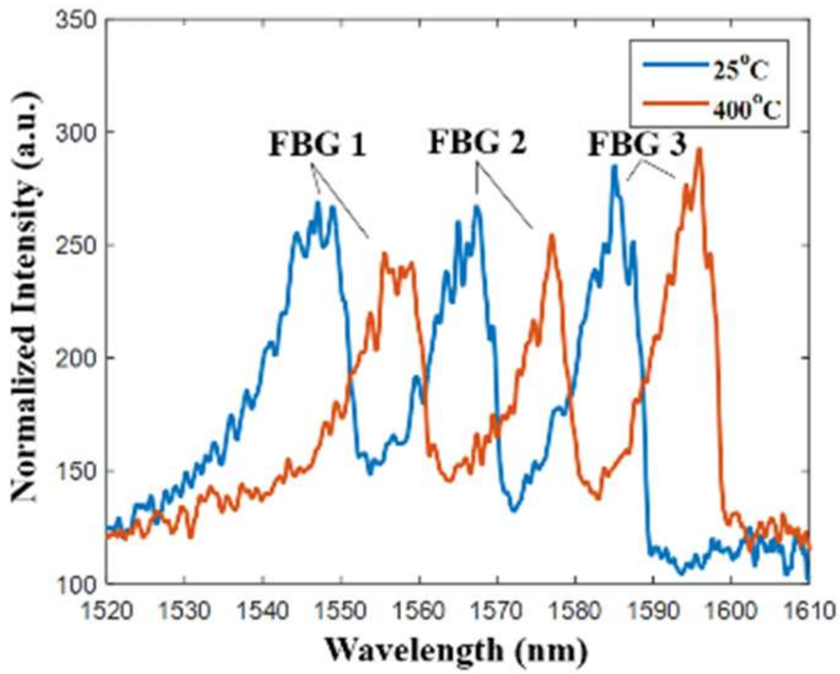
FBG reflectivity was permanently enhanced by about 5.5 times

Yang, Shuo, Di Hu, and Anbo Wang. Point-by-point fabrication and characterization of sapphire fiber Bragg gratings, Optics letters 42, no. 20 (2017): 4219-4222.

FBG Sensor Fabrication

Wavelength Multiplexed FBG Array





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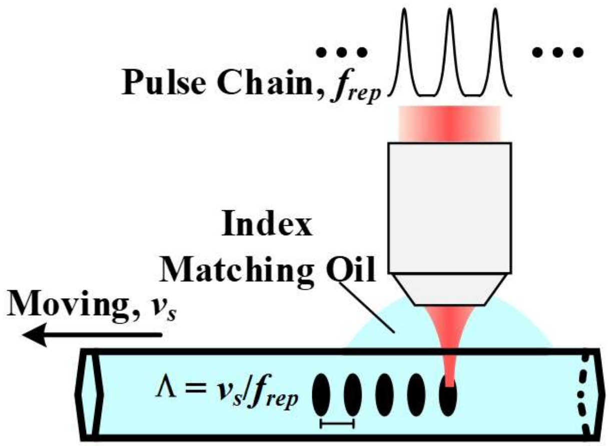
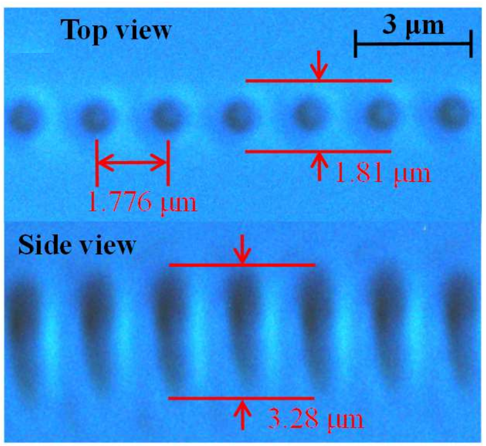
FBG Sensor Fabrication

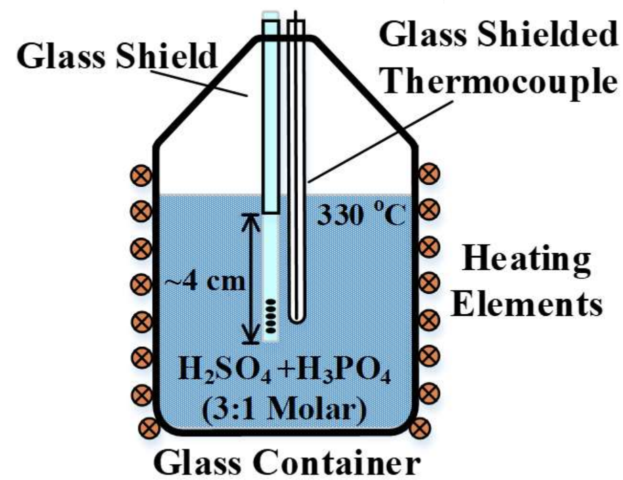
Reduced Diameter Sapphire Fiber Bragg Grating

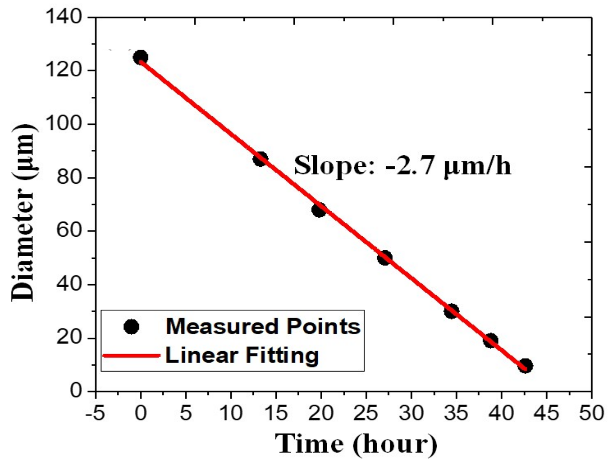
Step 1: Point-by-Point FBG Fabrication





Step 2: Hot-Wet Acid Etching

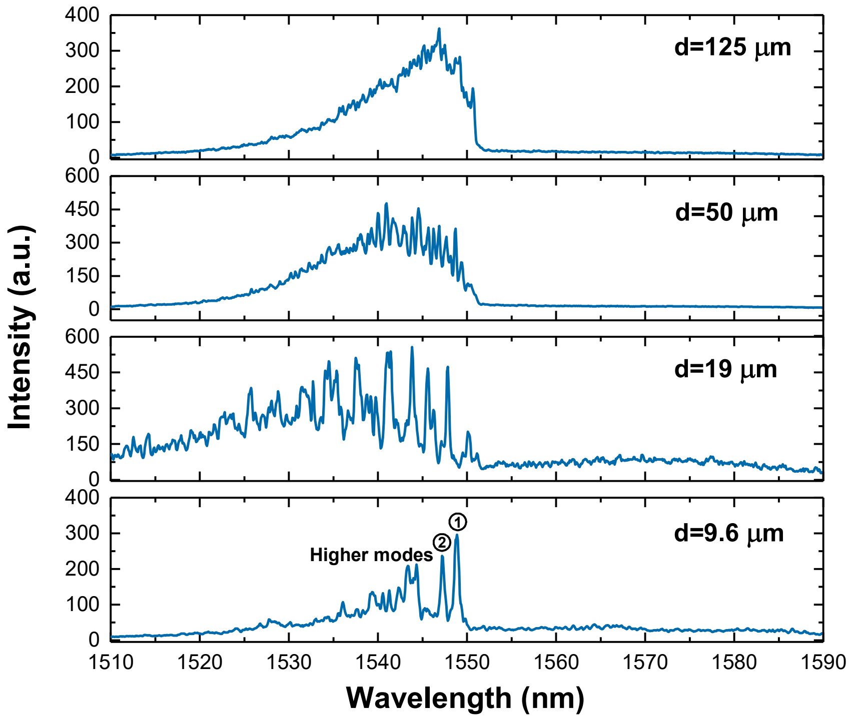




FBG Sensor Performance

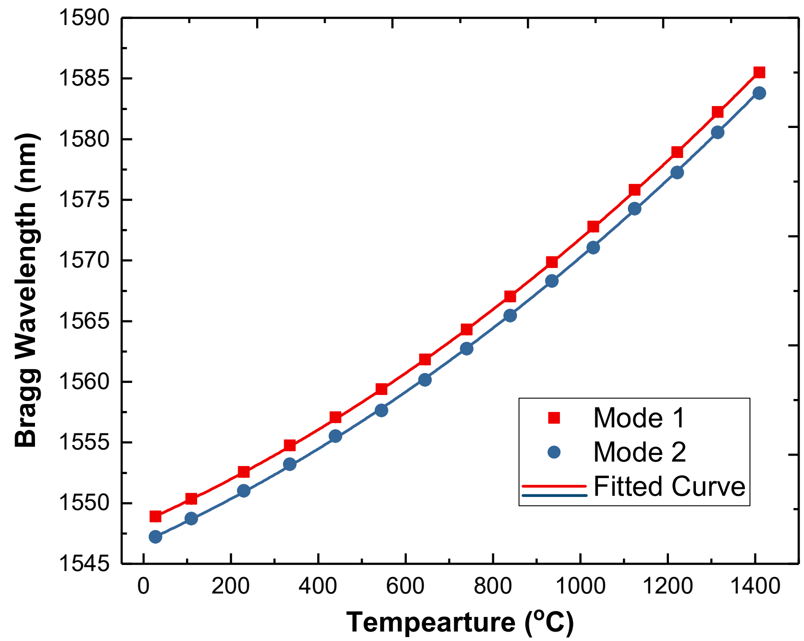
Reduced Diameter Sapphire Fiber Bragg Grating

FBG spectral response



Reduced modal volume improves FBG peak fidelity

Temperature dependence of λ_B



Demonstrated to temperature of 1400°C ; ~26.5 pm/°C

Yang, Shuo, Daniel Homa, Gary Pickrell, and Anbo Wang. Fiber Bragg grating fabricated in micro-single-crystal sapphire fiber, Optics letters 43, no. 1 (2018): 62-65.

Distributed Temperature Sensing Systems

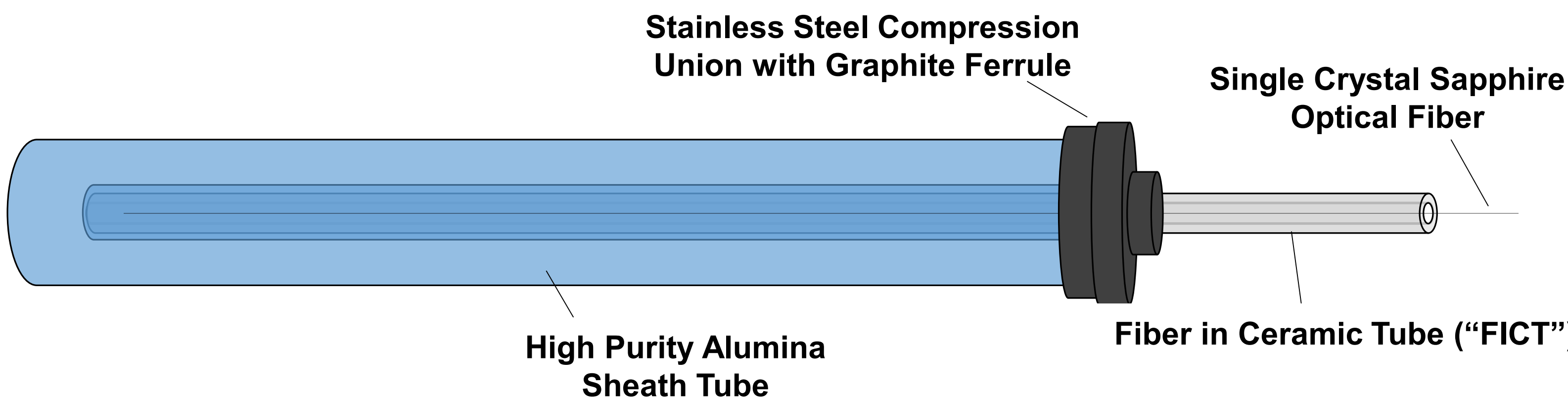
Summary of Results

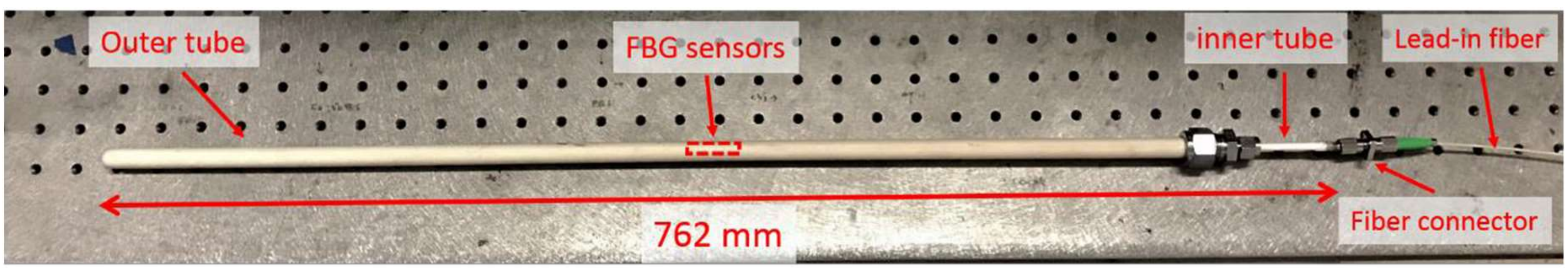
- Raman fully-distributed ultra-high temperature sensing technique, a **first-of-its-kind** technology, was successfully demonstrated
  - A temperature standard deviation of 3.0ºC (0.2% of full scale) was demonstrated in a 1 meter sapphire fiber.
  - A maximum operating temperature of 1400ºC was demonstrated (upper limit has yet to be determined)
  - A spatial resolution <20 cm was achieved with a fiber sensing length of 3 m
- Ultra-high temperature sensing was demonstrated, **for the first time**, with FBGs inscribed in single crystal sapphire fiber via the point-by-point method
  - FBG reflectivity enhancement and stabilization technique was demonstrated
  - A maximum operating temperature of 1400ºC was demonstrated (upper limit has yet to be determined)

HARSH ENVIRONMENT SENSOR PACKAGING AND DEPLOYMENT

Harsh Environment Packaging

Fiber in Ceramic Tube ("FICT")



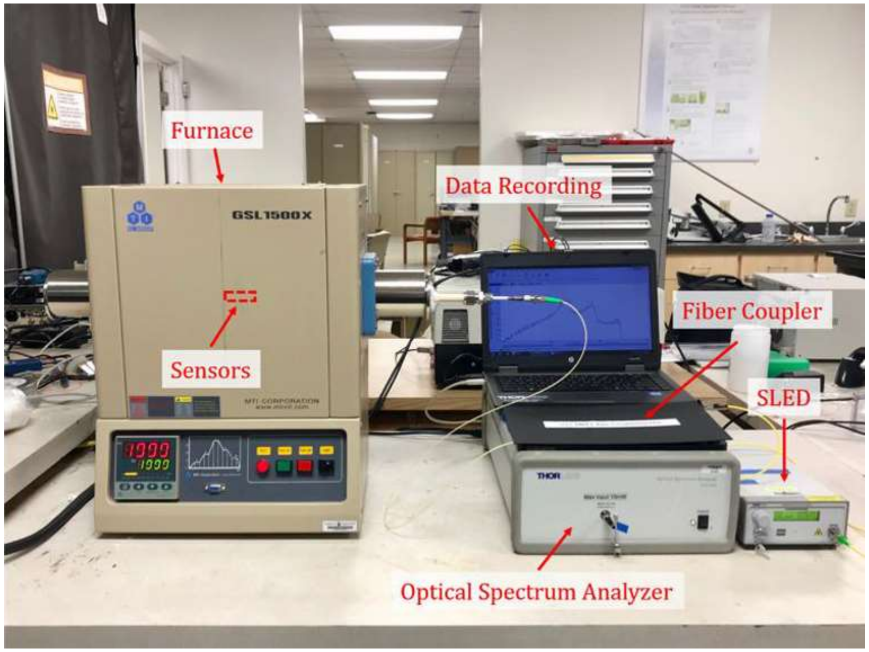


- *Inherent design and material flexibility for application specificity*
- *Constructed from commercially available "off-the-shelf" components*

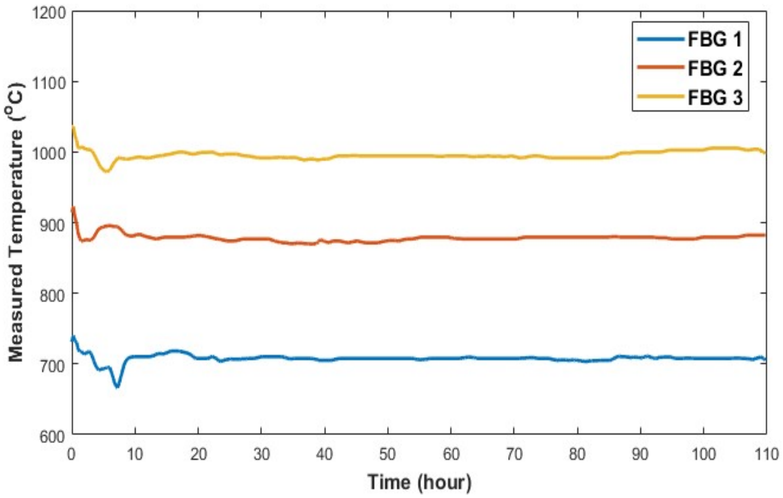
Performance Testing

High Temperature Exposure

Laboratory Scale Test Set-Up



Temperature Sensor(s) Response

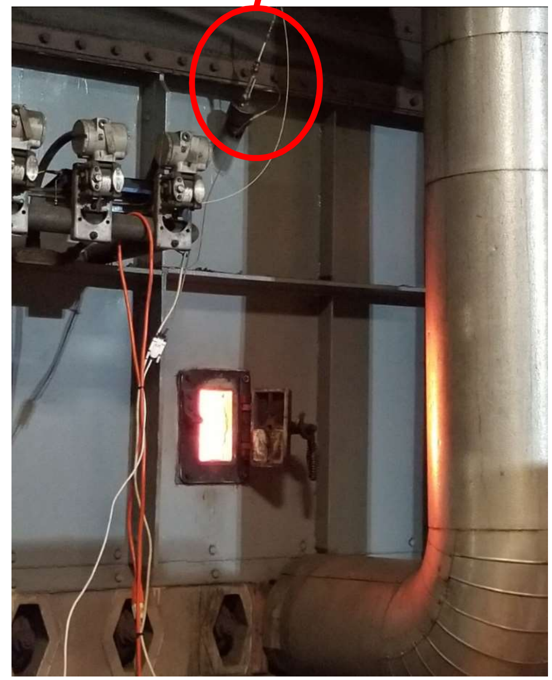


Field Trial Testing

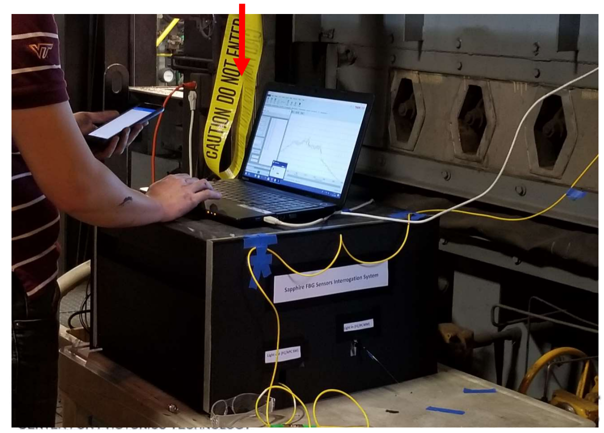
Virginia Tech Power Plant

- Virginia Tech Power Plant
  - Commercial entity that provides electricity to the residents of Blacksburg, VA, as well as steam for the Virginia Tech main campus
  - Annual steam output greater than 943 billion BTUs
  - A 6,250-kilowatt, 12,470-volt steam-turbine-powered generator produces nearly 27 million kilowatt-hours of electricity annually
  - Five boilers, each outfitted with superheaters rated at 80,000 or 100,000 lbs of steam per hour
- Successful sensor deployment
  - Coal-fired boiler (~1000ºC anticipated)
  - Installed during boiler operation
  - Operating for 2 weeks
  - Remote and mobile data access and monitoring

Installed Prototype Sensor



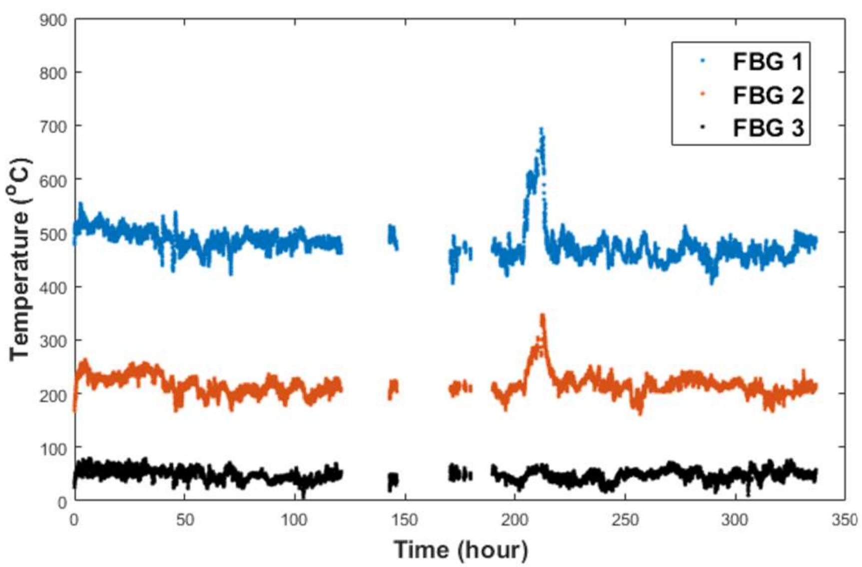
Sensor Interrogation System



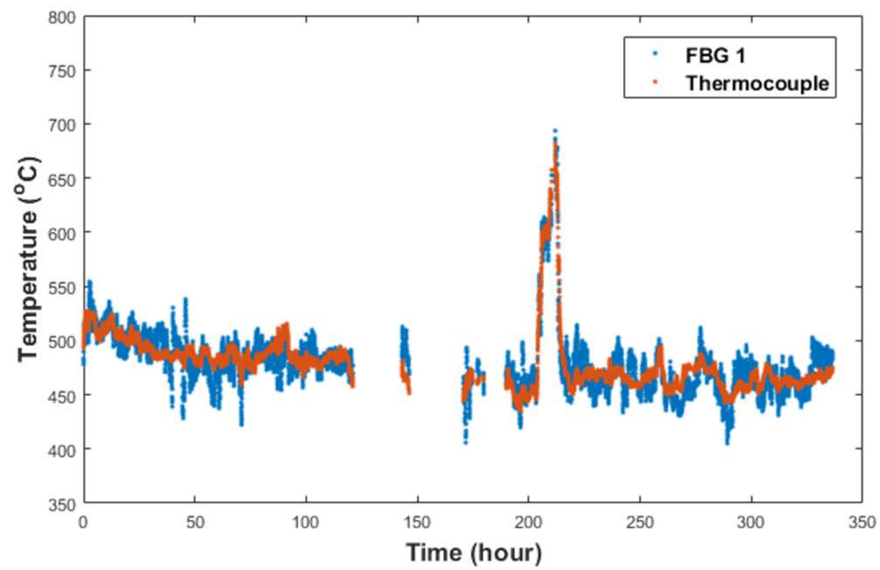
Field Trial Testing

Preliminary Results

Temperature Sensor(s) Response



FBG Sensor vs. Thermocouple



- Installed successfully and currently operating at 2 weeks
- Optical interrogator was "turned off" and caused observed data drops
- High operating temperatures anticipated in coming weeks

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MILESTONES AND SCHEDULE

Project Milestones

- LMV sapphire fiber
  - Demonstrated design feasibility
  - Developed fabrication processes
  - Demonstrated fiber performance
- Fully-distributed temperature sensing system
  - Demonstrated prototype FBG sensing system in single crystal sapphire fibers
  - Demonstrated prototype Raman distributed sensing system in single crystal sapphire fibers
- Field Testing
  - Demonstrated harsh environment sensor packaging
  - Performance tested prototype sensing system
  - Successful deployment and operation of sensing system

Milestone Number	Title/Description	Planned Completion Date	Actual Completion Date
1	Management and Qualification Plan	5/15/2014	5/15/2014
2	Modeling of LMV Sapphire Fiber & Sensing System	12/31/2014	12/31/2014
3	Demonstration of LMV Sapphire Fabrication	6/30/2015	6/30/2015
4	Demonstration of Sensing System	12/31/2015	12/31/2015
5	Prototype System Test Results	6/29/2016	6/29/2016
6	Project Management Plan	9/30/2017	9/30/2017
7	Optimized Sensing System	12/31/2017	12/31/2017
8	Harsh Environment Sensor Packaging	12/31/2017	12/31/2017
9	Field (or Performance) Testing of Prototype Sensor	12/31/2018	50%
10	Final Report	3/30/2019	60%

Milestone Success Criteria

- All Project Milestones Met On Time and On Budget
- All Success Criteria Met On Time and On Budget

ID	Title	Description	Result	M.S.	Planned Completion	Actual Completion
SC1	System Modeling	1. 50% modal volume reduction 2. Sensing length of 3 m 3. Resolution of < 20 cm	1. >> 50% modal volume reduction 2. Sensing length of 3 m 3. Resolution < 17 cm	M2	12/31/2014	12/31/2014
SC2	LMV Sapphire Fiber	1. 40% reduction in modal volume 2. Attenuation < 6 dB/m @ 355 nm 3. Minimum bend radius < 25 mm	1. > 50 % modal volume reduction 2. Attenuation < 8 dB/m @ 532 nm 3. Minimum bend radius < 4 mm	M3	6/30/2015	6/30/2015
SC3	Distributed Sensing System	1. Sensing length of 2 m 2. Resolution < 20 cm	1. Sensing length of 3 m 2. Resolution < 10 cm	M4	12/31/2015	12/31/2015
SC4	Prototype Test Results	Distributed Temperature Sensing: 1. Sensing length of 3m 2. Resolution < 20 cm	Distributed Temperature Sensing: 1. Sensing length of 3 m 2. Resolution < 17 cm	M5	6/29/2016	6/29/2016
SC5	Harsh Environment Sensor Packaing	1. Maximum Temperature: 1000°C 2. Testing Duration: 100 hours	1. Maximum Temperature: 1000°C 2. Testing Duration: 100 hours	M8	12/31/2017	12/31/2017
SC6	Temperature Sensing System	1. Maximum Temperature: 1000°C 2. Temperature Accuracy: < 5% F.S.	TBD	M9	12/31/2018	TBD

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Schedule

GANT CHART

BUDGET PERIOD 1: Project Year 1; BUDGET PERIOD 2: Project Year 2, Project Year 3, Project Year 4, Project Year 5, PY 6 (Q1–Q4 per year)

Task #	Task Name	Planned Start Date	Planned End Date
1	Project Management and Planning	1/1/2014	5/15/2014
2	Determine Technical Requirements	1/1/2014	5/15/2014
M1*	MILESTONE 1*	6/30/2014	
3	Optical Modeling of LMV Sapphire and Distributed Sensor System	2/3/2014	12/30/2014
3.1	LMV Sapphire Fiber Modeling	2/3/2014	12/30/2014
3.2	Sapphire Fiber Based High Temperature Distributed Sensing Modeling	4/1/2014	12/30/2014
M2	MILESTONE 2	12/31/2014	
4	Demonstrate Feasibility of LMV Sapphire and Distributed Sensing System	4/2/2014	12/31/2015
4.1	LMV Sapphire Fiber Fabrication	4/1/2014	6/26/2015
M3	MILESTONE 3	6/29/2015	
4.2	Distributed Sensing System Building and Demonstrating with Silica Fiber	5/1/2014	12/29/2015
M4	MILESTONE 4	12/30/2015	
5	Develop LMV Sapphire Fiber Temperature Sensing System	9/1/2015	6/30/2016
5.1	Construct Prototype LMV Sapphire Fiber	9/1/2015	1/4/2016
5.2	Demonstrate Distributed High Temperature Sensing with LMV Sapphire	1/14/2016	5/18/2016
5.3	Perform Sensor Calibration and	5/19/2016	6/28/2016
M5	MILESTONE 5	6/29/2016	
6	Construct & Evaluate Refined Prototype Sensing System	6/30/2016	11/30/2016
6.1	Fabricate Refined Version of LMV Sapphire Fiber	6/30/2016	8/22/2016
6.2	Construct Refined Version of LMV Sapphire Fiber Distributed Sensing	6/29/2016	9/15/2016
6.3	Test Sensor and Evaluate Performance	9/16/2016	1/28/2017
6.4	Project Management and Planning	1/16/2017	9/28/2017
M6	MILESTONE 6	9/30/2017	
7	Performance and/or Field Test Planning	7/1/2017	12/31/2017
8	Optimize the Optical Interrogator and LMV Sapphire Fiber	7/1/2017	12/31/2017
M7	MILESTONE 7	12/31/2017	
9	Develop Harsh Environment Packaging for FO Sensor	4/1/2017	12/31/2017
M8	MILESTONE 8	12/31/2017	
10	Performance (or Field) Testing of High Temperature Sensing System	1/1/2018	12/31/2018
M9	MILESTONE 9	12/31/2018	
11	Prepare and Submit Media-Ready Documentation of the Test Results	1/1/2019	2/15/2019
12	Prepare and Submit Final Report	1/1/2019	3/30/2019
M10	MILESTONE 10	3/30/2019	

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IMPACT, ACHIEVEMENTS, AND NEXT STEPS

Research Impact

- Technical Achievements
  - Fabrication of sub-micron single crystal sapphire fiber
  - Observation of Raman Stokes *and* Anti-Stokes peaks in sapphire fiber
  - Fabrication of FBGs in sapphire fiber via the point-by-point method
  - Measurement of fiber attenuation in the time domain in sapphire fiber
  - Distributed Raman temperature measurements in sapphire fiber
  - Quasi-distributed FBG based temperature measurements in sapphire fiber
  - Demonstrated few to single mode operation in sapphire fiber
  - Developed harsh environment fiber optic sensor packaging
- Student Support
  - Full Support: Cary Hill (Ph.D, '16), Bo Liu (Ph.D., '17), Yujie Cheng (Ph.D., '17)
  - Partial: Adam Floyd (Ph.D., '17), Jiaji He, (Ph.D., TBD), Hanna Heyl (Ph.D., TBD), Shuo Yang, (Ph.D., '19), Amiya Behera (Ph.D, '17), Chennan Hu (Ph.D., TBD), Sunny Chang (M.S., '16), Elizabeth Bonnell (M.E., '16), Logan Theis (Ph.D., TBD)
- Faculty Training & Development
  - Zhihao Yu (Post-doc)
  - Daniel Homa (Research Scientist)
  - Haifeng Xuan (Research Associate)
  - Chenyuan Hu (Post-doc)

Research Products

- 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.
  - Yujie Cheng, Cary Hill, Bo Liu, Zhihao Yu, Haifeng Xuan, Daniel Homa, Anbo Wang, and Gary Pickrell. ***Design and analysis of large-core single-mode windmill single crystal sapphire optical fiber***, Optical Engineering, 55 (2016) 066101-066101.
  - Liu, Bo, Zhihao Yu, Cary Hill, Yujie Cheng, Daniel Homa, Gary Pickrell, and Anbo Wang. ***Sapphire-fiber-based distributed high-temperature sensing system,*** Optics letters 41, no. 18 (2016): 4405-4408.
  - Hill, Cary, Dan Homa, Zhihao Yu, Yujie Cheng, Bo Liu, Anbo Wang, and Gary Pickrell. ***Single Mode Air-Clad Single Crystal Sapphire Optical Fiber***, Applied Sciences 7, no. 5 (2017).
  - Yang, Shuo, Di Hu, and Anbo Wang. ***Point-by-point fabrication and characterization of sapphire fiber Bragg gratings***, Optics letters 42, no. 20 (2017): 4219-4222.
  - Yang, Shuo, Daniel Homa, Gary Pickrell, and Anbo Wang. ***Fiber Bragg grating fabricated in micro-single-crystal sapphire fiber***, Optics letters 43, no. 1 (2018): 62-65.
- 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.
  - U.S. Patent Application No. 62/264,659. ***Distributed Temperature Sensing System Using Optical Sapphire Waveguide***, A. Wang, G. Pickrell, B. Liu, Z. Yu.

Project Performance

- All Project Milestones Met On Time and On Budget
- All Success Criteria Met On Time and On Budget
- “First of Its Kind” Technologies
  - Fabrication of sub-micron single crystal sapphire fiber
  - Fabrication and demonstration of single mode sapphire fiber
  - Point-by-point fabrication of single crystal sapphire fiber FBGs
  - 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
  - Quasi-distributed FBG based temperature measurements in sapphire fiber
- Dissemination of Findings
  - 8 peer reviewed publications
  - 2 provisional patents filed
- Graduate Student Support (12)
- Faculty Training and Development (4)

Next Steps

- Field trial of prototype sensor in coal-fired boiler
  - Continue operation until facility shut-down
  - Conduct full-scale data analysis
  - Review “lessons learned” and develop “action plan”
- Field trial of prototype sensor in natural gas-fired boiler
  - Implement action plan and improvements for sensor deployment
- Generate final report and “media-ready” documentation
- Evaluate additional research opportunities for fiber and sensing technologies

Acknowledgements

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Gary Pickrell

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Cary Hill

Di Hu

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Yujie Cheng

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Hanna Heyl

Zhiting Tian

Haifeng Xuan

Logan Theis

Amy Hill, Jiaji He, Shuo Yang, Amiya Behera, Chennan Hu, Cindy Purdue, Chenyuan Hu, Nevada Davis, Robert Blackwell

Department of Energy

National Energy Technology Laboratory

Project Manager: Jessica Mullen

Sydni Credle

Susan Maley*

**Now with Electric Power Research Institute*

THANK YOU FOR YOUR TIME

SUPPLEMENTAL INFORMATION

Review Panel Recommendations

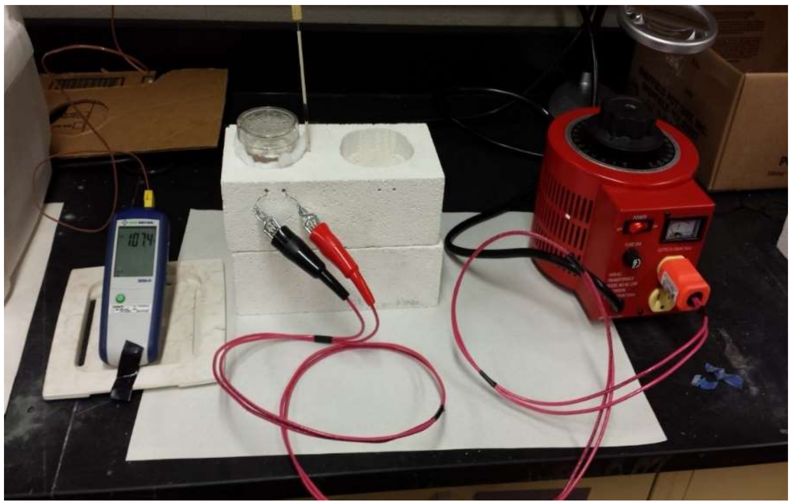
- All Recommendations have been addressed
- On schedule and budget

RPR #	Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments (progress toward achieving milestone, explanation of deviation from plan, etc.)
R1	Material Characterization of Pre- and Post- Etched Sapphire Fibers	9/30/2016	9/30/2016	DOE Approval	Completed
R2	"Back of the Envelope" Calculations to Predict Fiber and System Performance	3/30/2016	3/30/2016	DOE Approval	Completed
R3	Identify a "Back-up Approach"/Alternative Strategies	12/30/2016	12/30/2016	DOE Approval	On schedule
R4	Engage Crystal Growth Experts for LHPG	9/30/2016	9/30/2016	DOE Approval	Completed
R5	Evaluate Consistencies between Theoretical Anlyses and Experimentation/Manufacturability	12/30/2016	12/30/2016	DOE Approval	On schedule

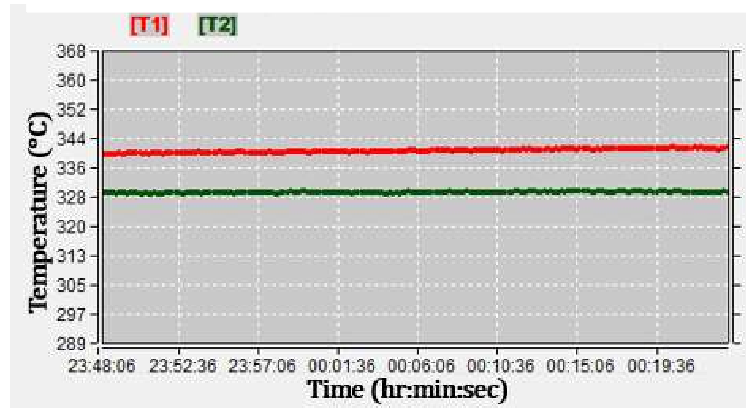
LMV Sapphire Fiber Fabrication

Equipment and Techniques

Custom Etching System



Excellent Temperature Control



Temperature and Etching Uniformity

Sample	Top Diameter (µm)	Bottom Diameter (µm)
A	82.0	73.1
B	80.9	73.4
C	79.6	74.4
Average	80.8	73.6
Standard Deviation	1.2	0.7

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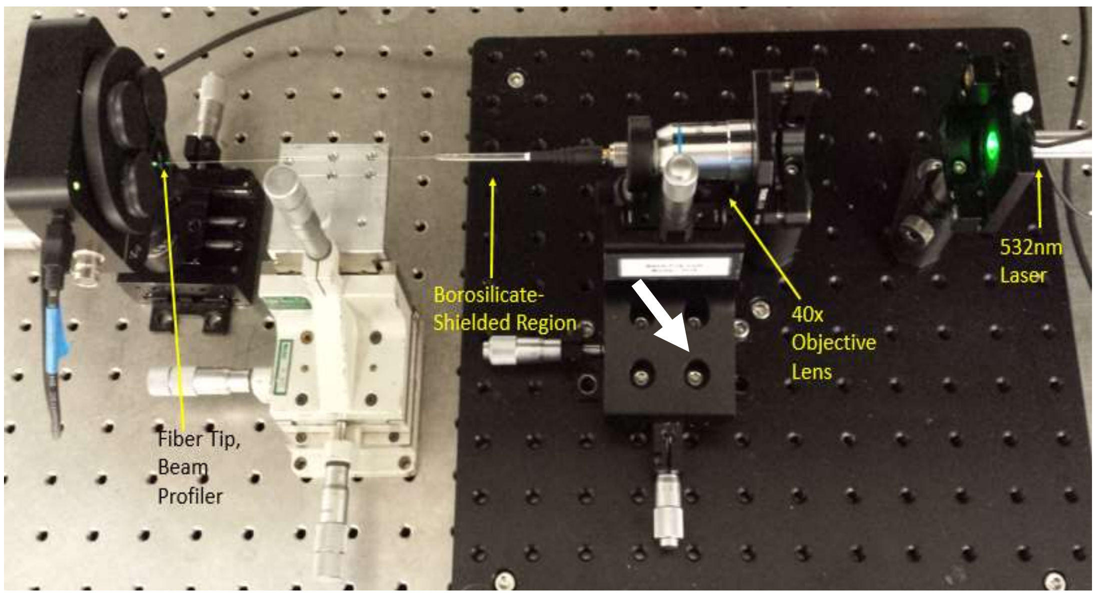
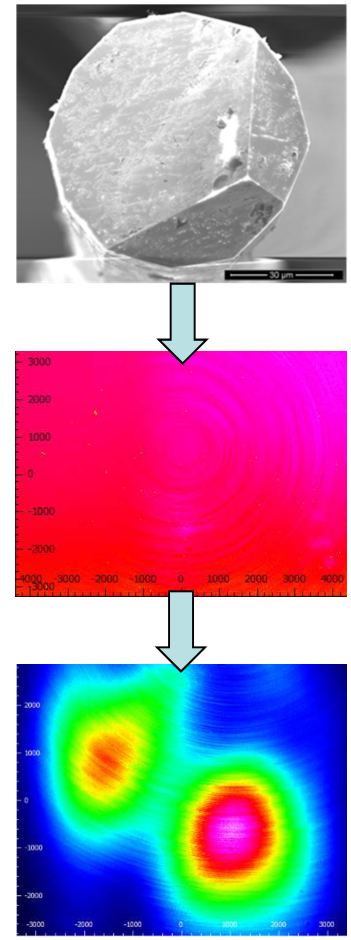
LMV Sapphire Fiber Testing

Modal Volume Measurement

- Three different wavelengths (532nm, 782.9nm, 982.9nm)
- Focused into connector using direct free-space coupling
  - Overfilled using objective lens with NA=0.66
- Sample mounted on 3-axis stage
- CCD camera beam profiler mounted on 3-axis stage
- Polished fiber tip (100 nm lapping film)





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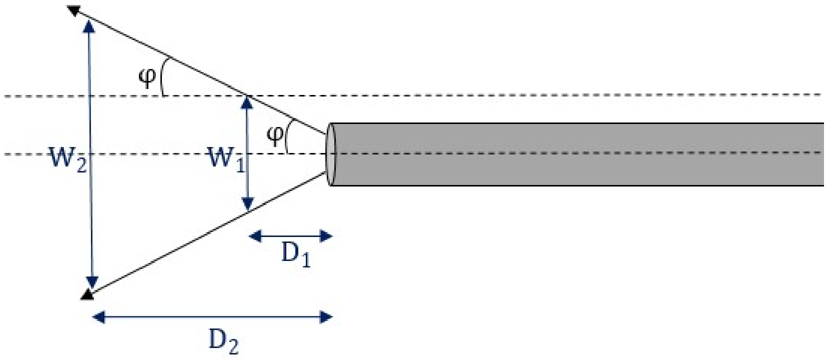
LMV Sapphire Fiber Testing

NA Characterization Techniques

- Vary angle of waveguide tip with stationary photodetector (TIA standard)
  - Requires both ends of fiber to be connected
  - Requires decent fiber length (>1/3m)
- Vary input NA and measure output power
  - Assumes all intensity effects are NA-dependent
- Beam diameter differential
  - Overfill fiber (all modes are excited)
  - Measure beam width twice with known distance between
  - Vergence angle calculated from beam width differential
  - Requires consistent beam projection to be accurate (single mode)



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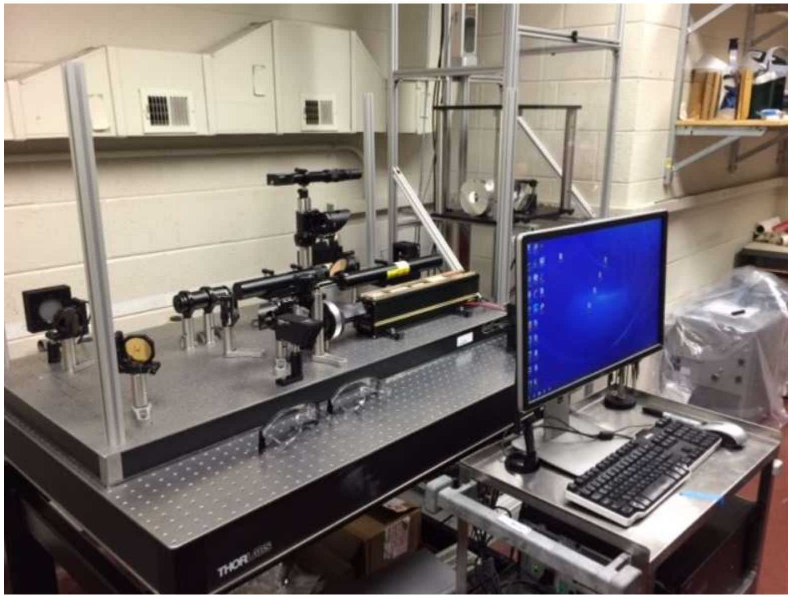
Laser Heated Pedestal Growth

Basic Components



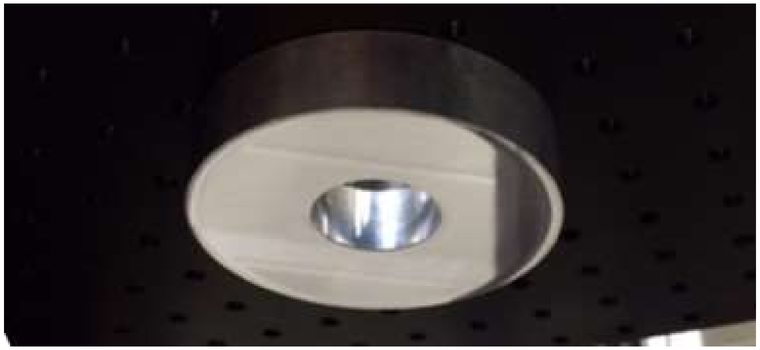
- Beam Steering Optics
  - Imaging System
  - HeNe Alignment Laser
  - Polarizer-Attenuator-Analyzer
  - Gold Coated Copper Mirrors
  - Beam Expander
- Growth Chamber Optics
  - Aluminum Optics
  - In-house design and polishing
  - Reflaxicon, Scraper Mirror, Spherical Mirror
- Mechanical Drawing System
  - Synchronized Linear Stages

Laser Heated Pedestal Growth

Growth Chamber Optics

Spherical (Parabolic) Mirror

(Focus beam to melt zone)

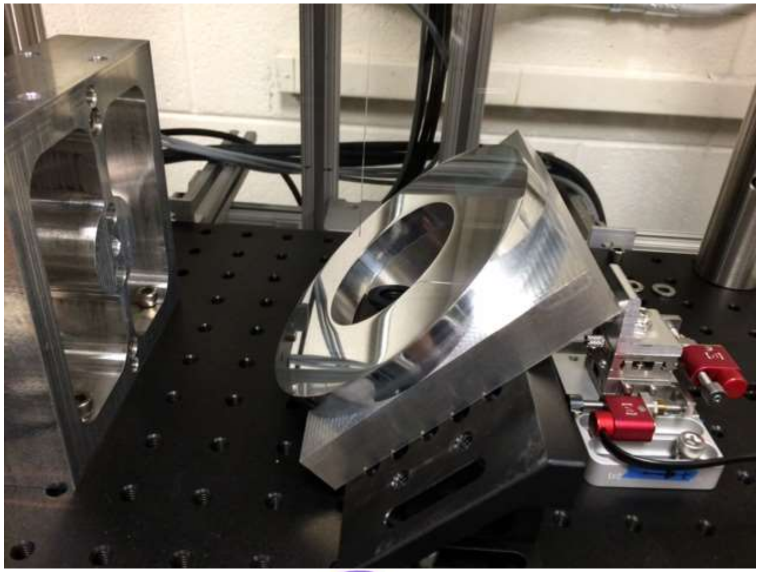


Reflaxicon

(Create "doughnut" shaped beam)

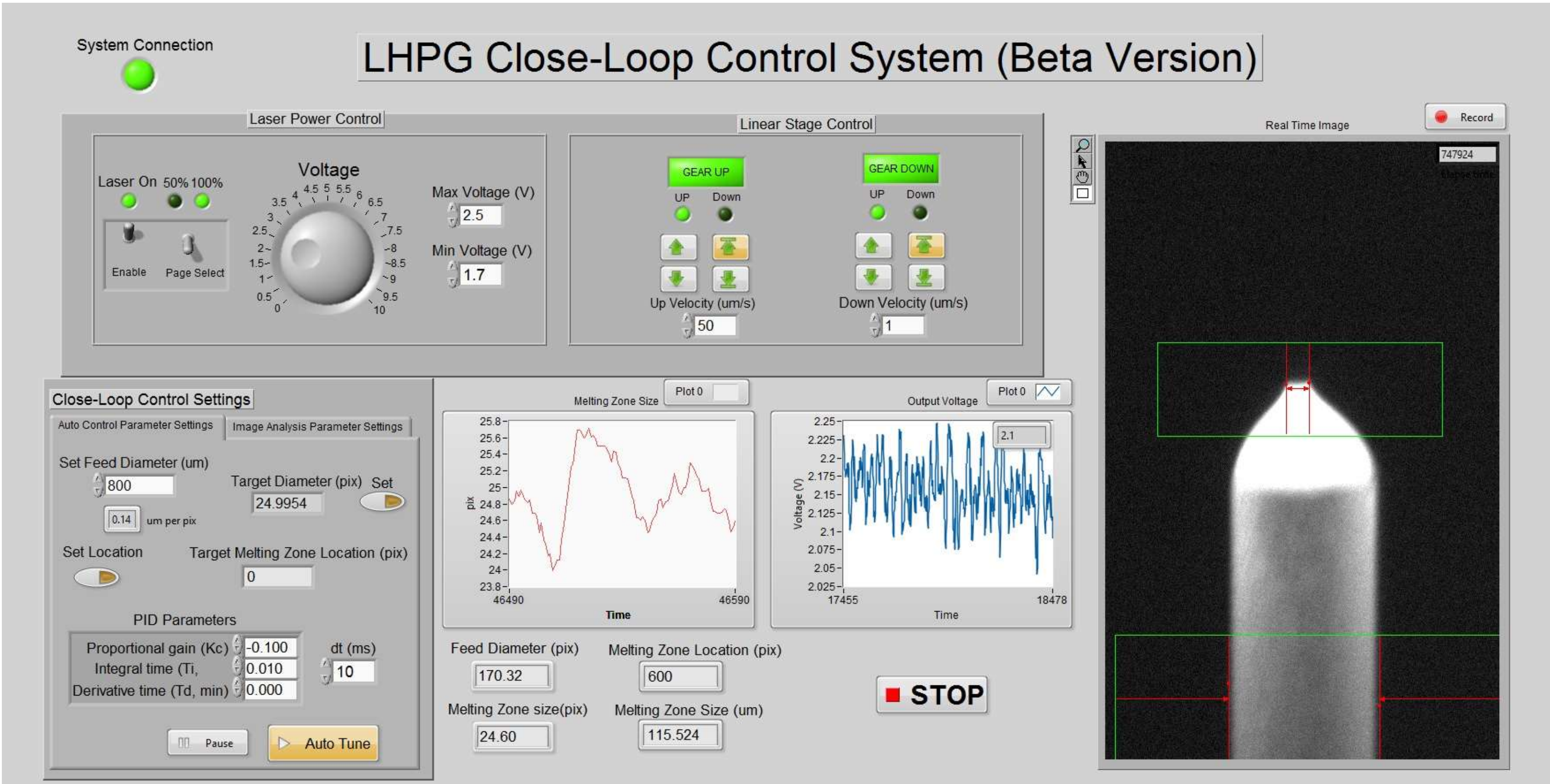
Scraper Mirror

(Reflect beam to spherical mirror)



Laser Heated Pedestal Growth

Automatic Diameter Control System



Diameter variations ~1.7% were readily achieved

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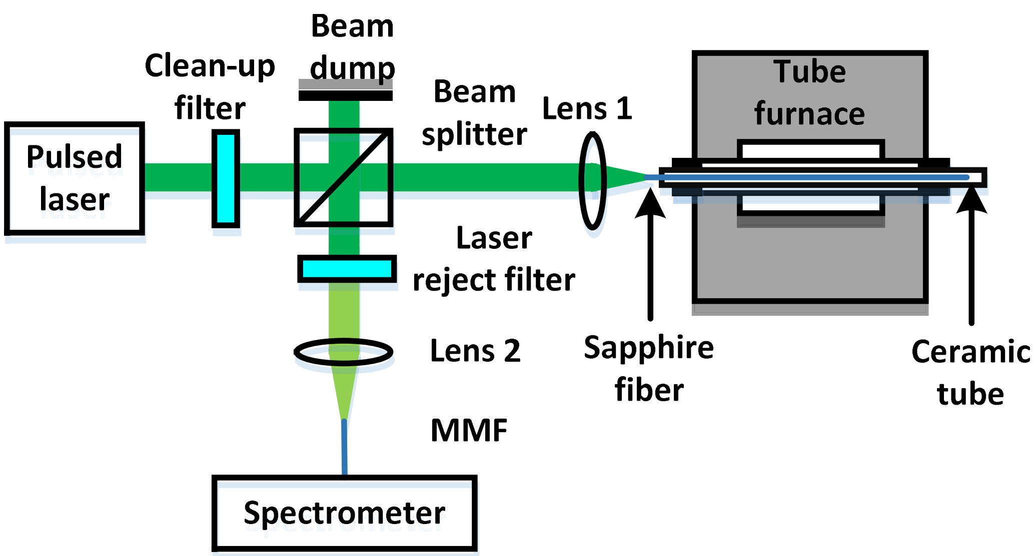
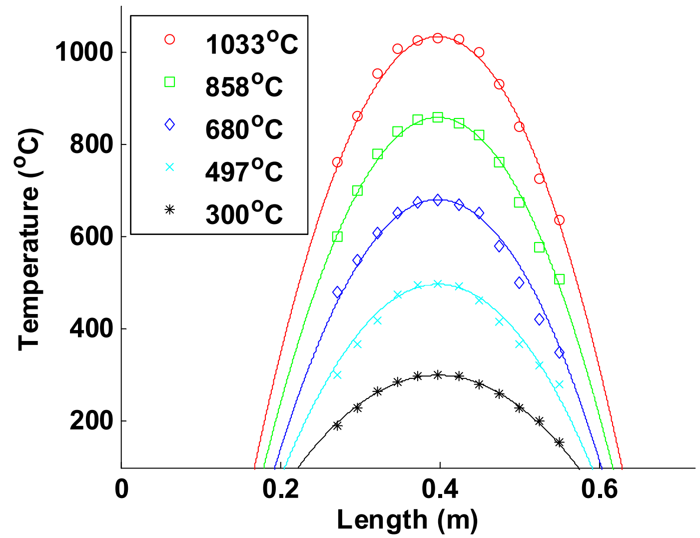
Scattering in Sapphire Fiber

Experimental Set-Up

- Experimental setup for Raman scattering detection.
- Temperature distribution along the sapphire fiber.





B. Liu et al, Optics Letters, 2015

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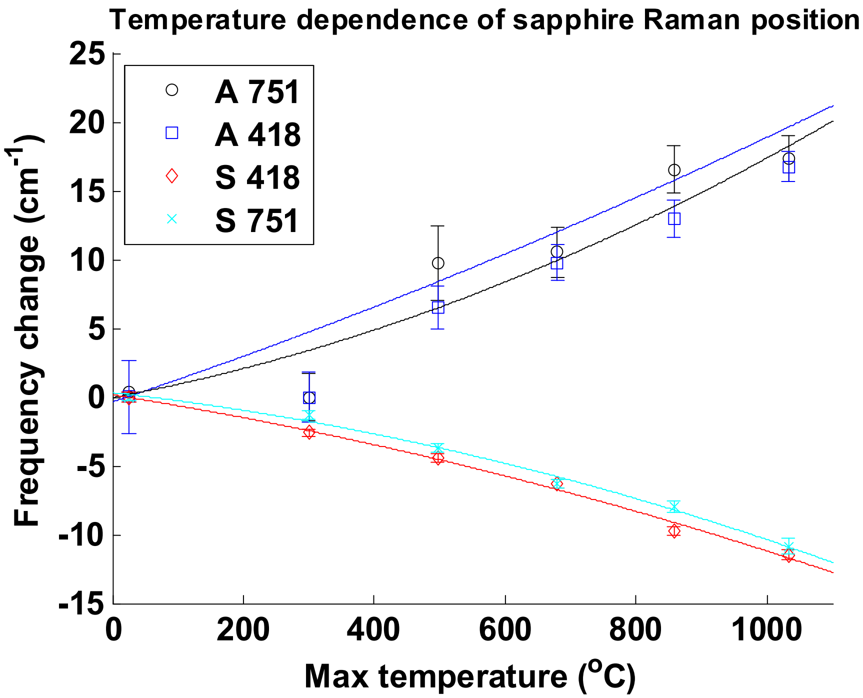
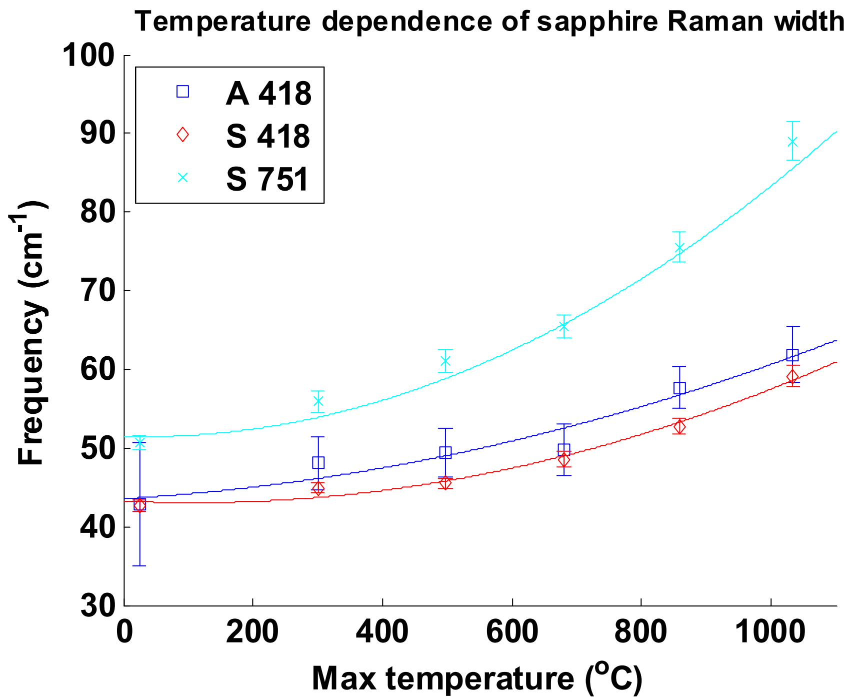
Scattering in Sapphire Fiber

Temperature Dependence

Peak Frequency



Peak Width



B. Liu, Optics Letters, 2015

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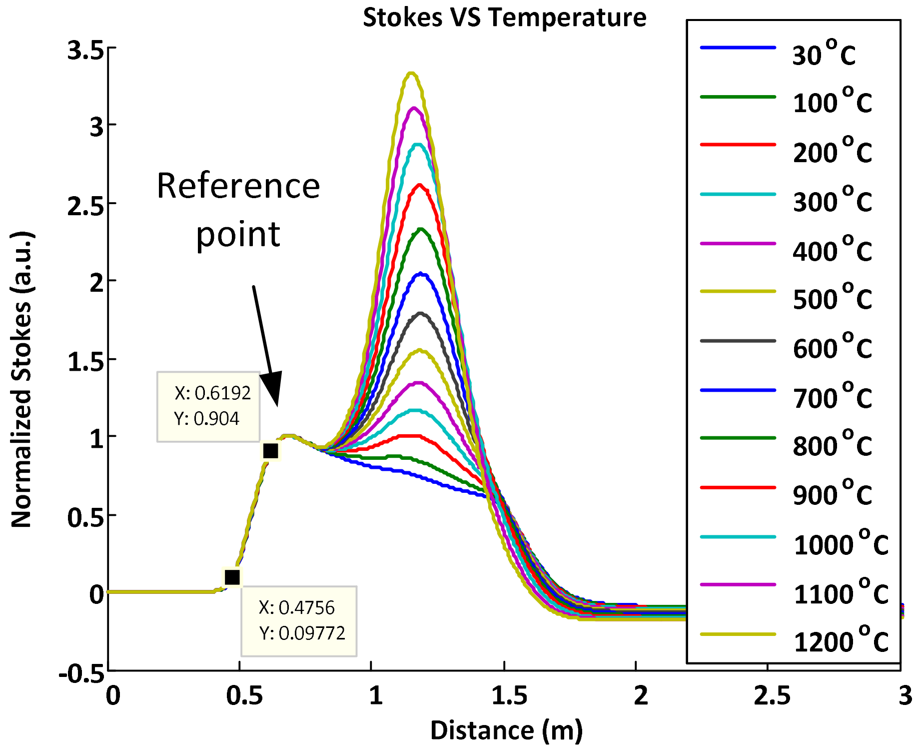
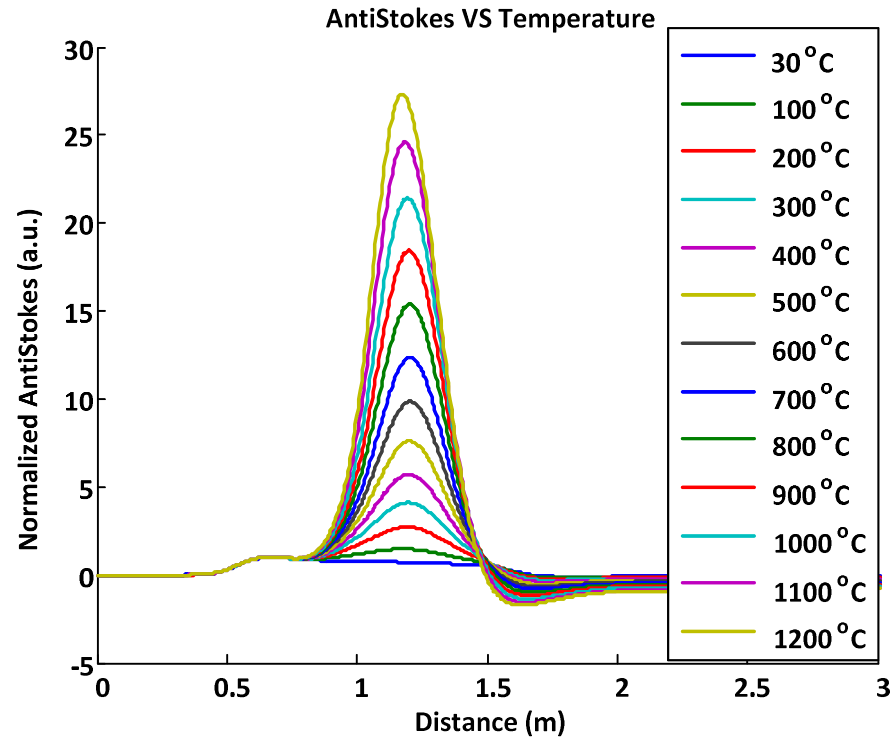
Raman DTS System Performance

1 meter Sapphire Fiber





B. Liu et al, Optics Letters, 2016, accepted for publication

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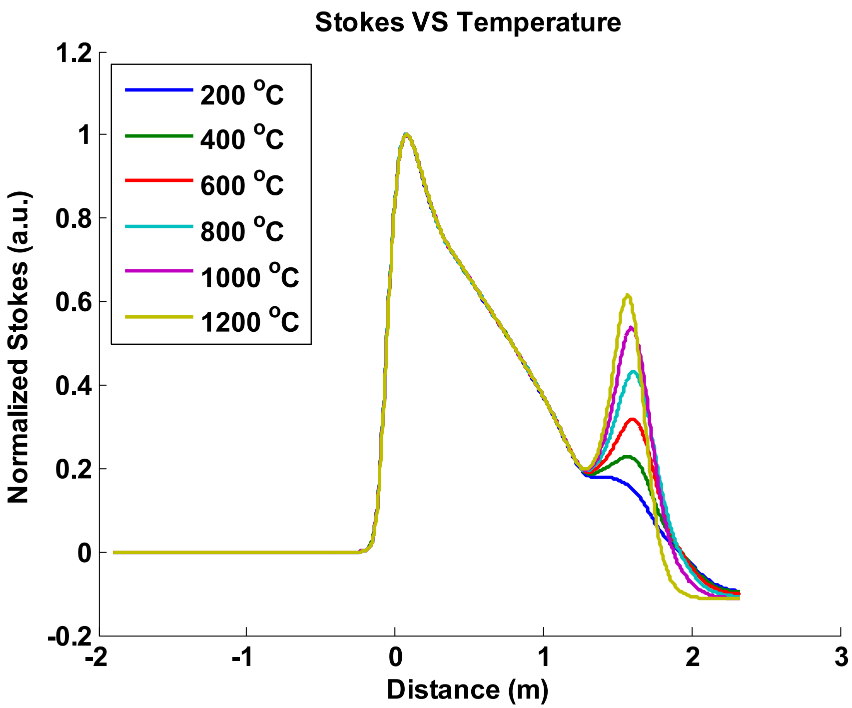
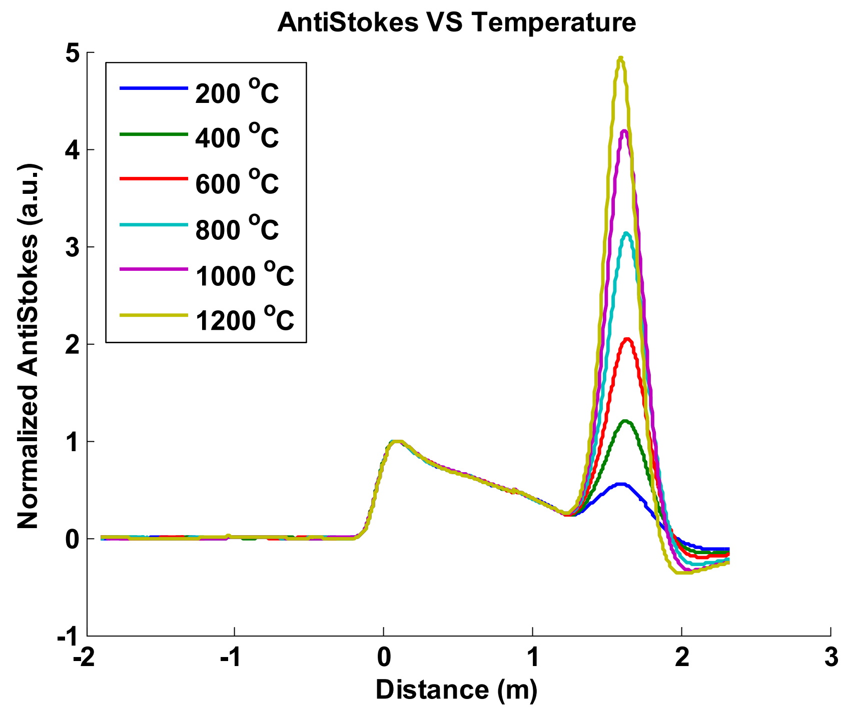
Raman DTS System Performance

2 meter Sapphire Fiber





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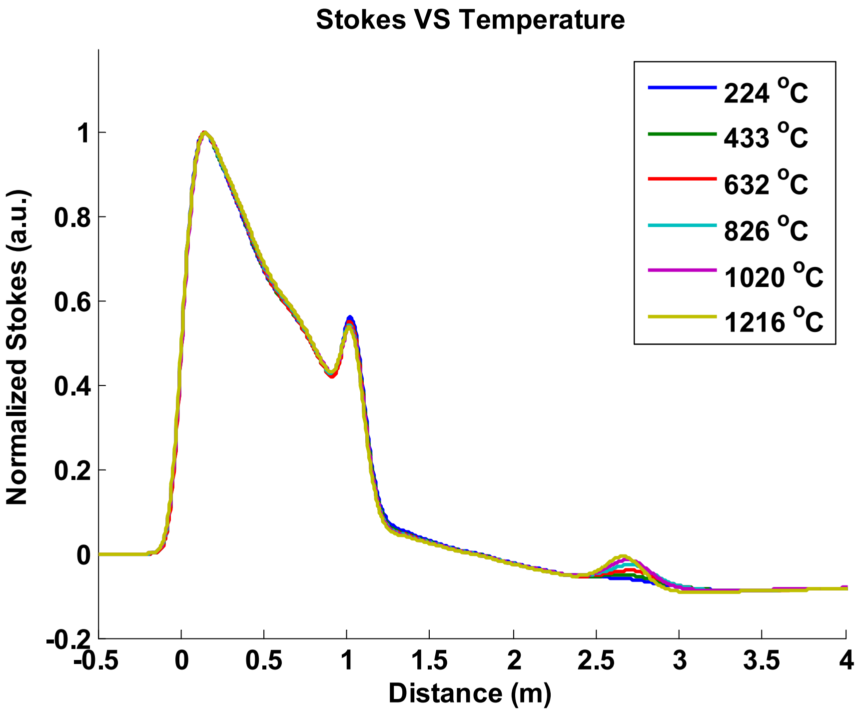
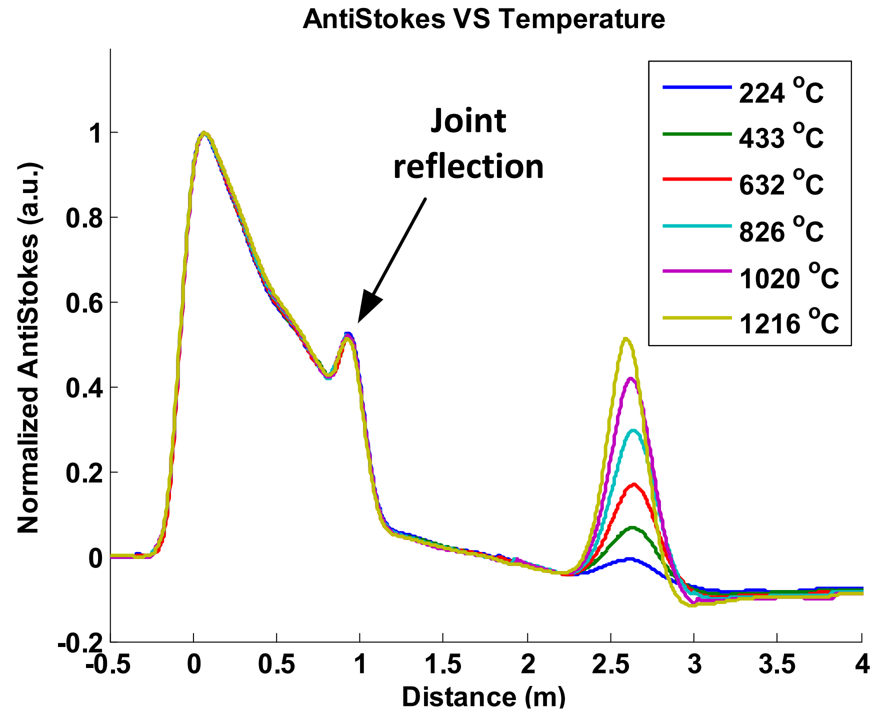
Raman DTS System Performance

3 meter Sapphire Fiber

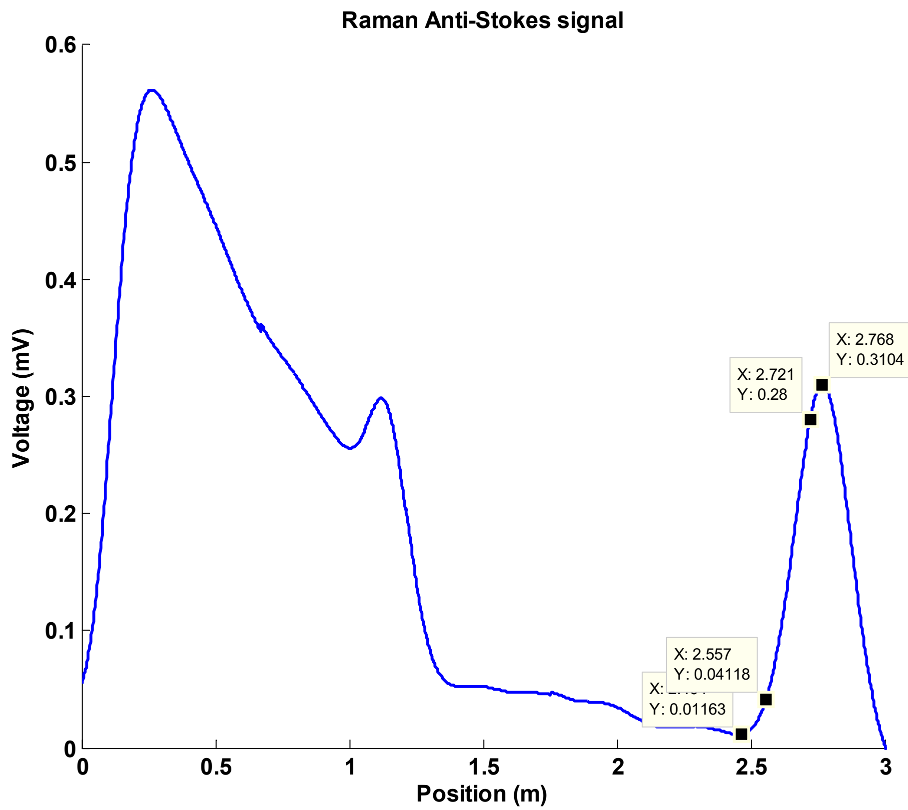




Raman DTS System Performance

Spatial Resolution

- Sensing length: 3 meters
- Temperature: 1400ºC
- Spatial resolution: 16.4 cm
  - Determined via 10% to 90% response distance



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