VIRTUAL WORKSHOP ON OPTIC SENSORS FOR ENERGY APPLICATIONS
March 2 – 3, 2023

OPTICAL AND ACOUSTIC SENSING IN HARSH ENVIRONMENTS

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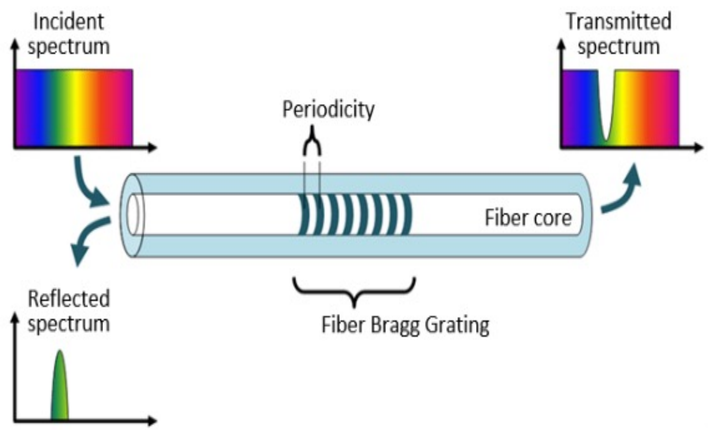
As a Broad Short Intro: There are many different types of optical fiber sensors which can be divided in many ways – some are:

Sensing Mechanisms

- **Scattering along fiber**
  - **Rayleigh scattering**
  - **Raman scattering**
  - **Brillouin scattering**
- **Light interference in fiber**
  - **Fiber Bragg grating**
  - **Long period grating**
  - **FP interferometer**
  - **MZ interferometer**
  - **Michelson interferometer …. etc.**

Optical sensors in SMFs and MMFs

❑ FBG and FPI sensors

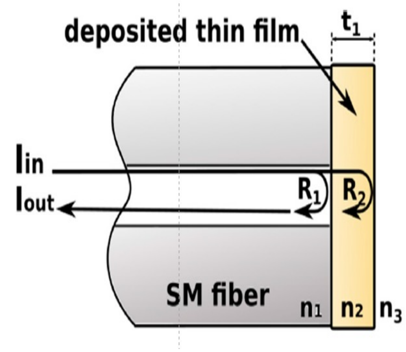


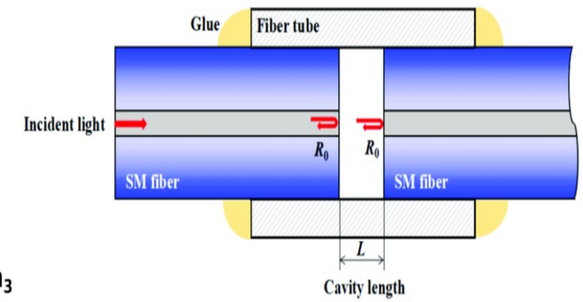
$$M \cdot \lambda_{\mathrm{Bragg}} = (n_i + n_j) \cdot \Lambda$$

M: grating order
λ_{Bragg}: reflection wavelength
n: effective RI, *i* and *j* are propagation modes
Λ: grating pitch

Advantages of FBGs and FPIs:

- Reflection mode, single fiber in;
- Multimodal analyte: sensing of RI, strain, temperature, etc.;
- Easy functional structure construction in normal fibers.





$$I(\lambda) = I_1(\lambda) + I_2(\lambda) + 2\sqrt{I_1(\lambda) \cdot I_2(\lambda)} V \cos\left(\frac{2\pi}{\lambda} \cdot \mathrm{OPD} + \phi_0\right)$$

I_1 and I_2: reflection from surface 1 and 2
OPD: optical pathlength difference
ϕ_0 : initial phase
V: fringe visibility

Why prefer SMFs:

- High signal coherence facilitates high SNR and sensitivity;
- Avoid cross coupling between modes, easy analysis and performance prediction.

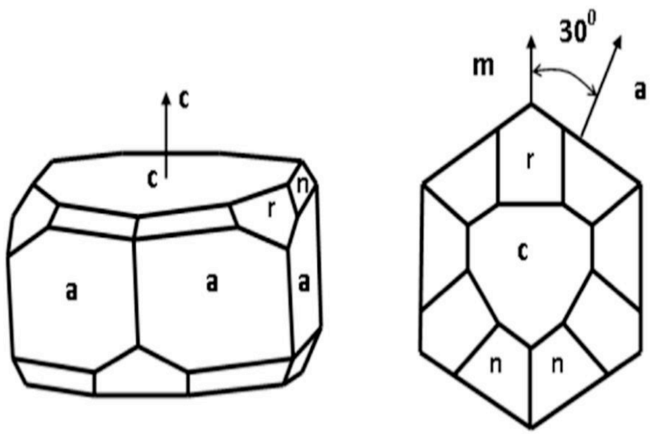
Challenges with SMFs:

- High light coupling loss due to small core size;
- Expensive interrogating system if using coherent light sources;
- Sensitivity to ambient fluctuations such as vibration.

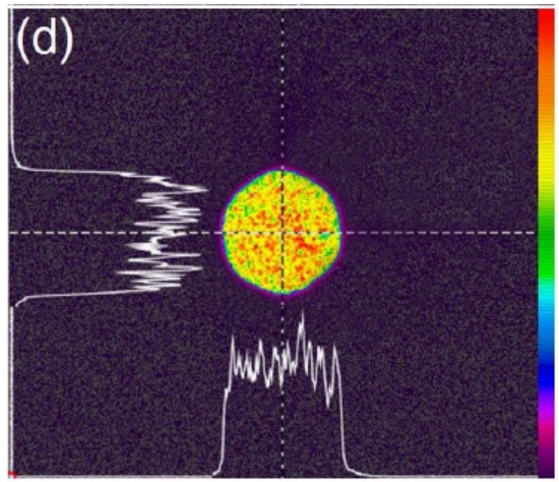
Hittech Corp., https://hittech.com/en/
Zhang, X., et al. Sensors, 19(1), p.36 (2018).
Hirsch, M., et al. Sensors, 17(2), p.261 (2017).

Sapphire fiber sensors

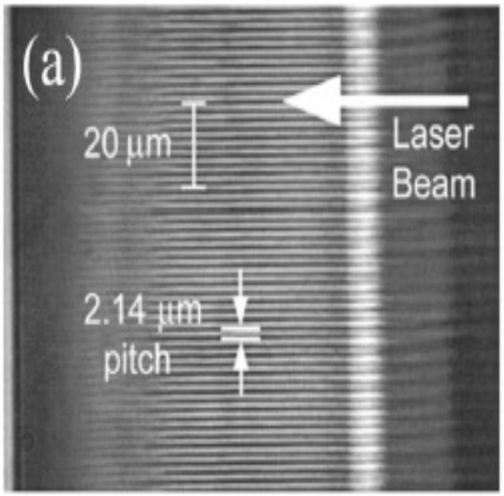
❑ Single-crystal sapphire fiber



Crystallography of sapphire[2]



Energy distribution in sapphire fibers[3]



Sapphire fiber FBGs[4]

Important properties: Ideal harsh environment sensor?

- High melting point (~2050° C);
- Excellent chemical etching and corrosion resistance;
- Light transmission window: 400 nm – 4 μm;
- Air cladding, highly multimode waveguide;
- Poor surface roughness, severe mode mixing.

Challenges of sapphire fiber sensors:

- Difficult connection with silica fiber-based components;
- Difficulty in construction of all-sapphire fiber sensors due to high melting point;
- Unclear coherence property that influence the sensor performance.
- Not stable for all sensor types in all environments

[2] Iskhakova, L.D., et al., Crystals, 6(9), p.101 (2016).
[3] Guo, Q., et al., IEEE Sensors Journal, 22(6), pp.5703-5708 (2022).
[4] Grobnic, D., et al., IEEE Photonics Technology Letters, 16(11), pp.2505-2507 (2004).

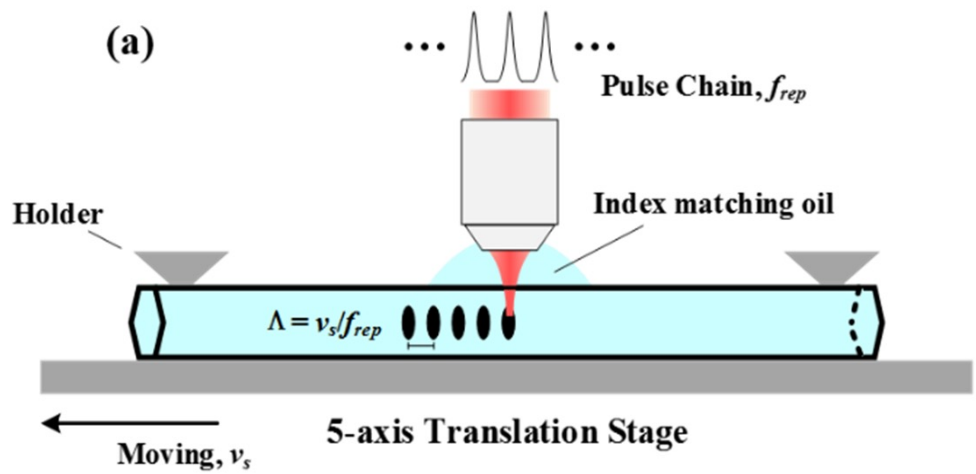
FBG Sensor Fabrication

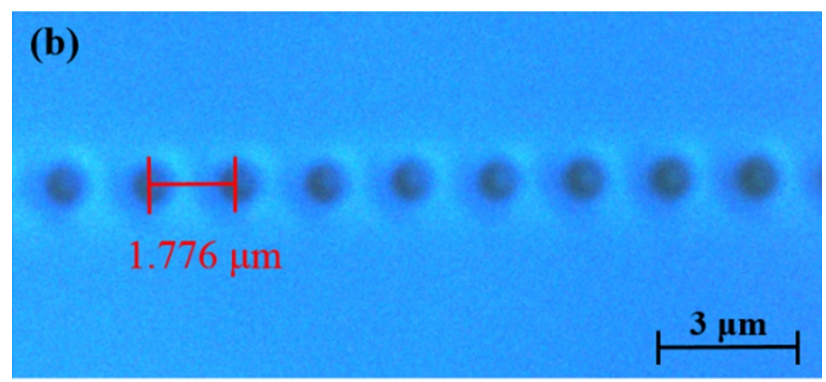
Point-by-Point Method with Femtosecond laser

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

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

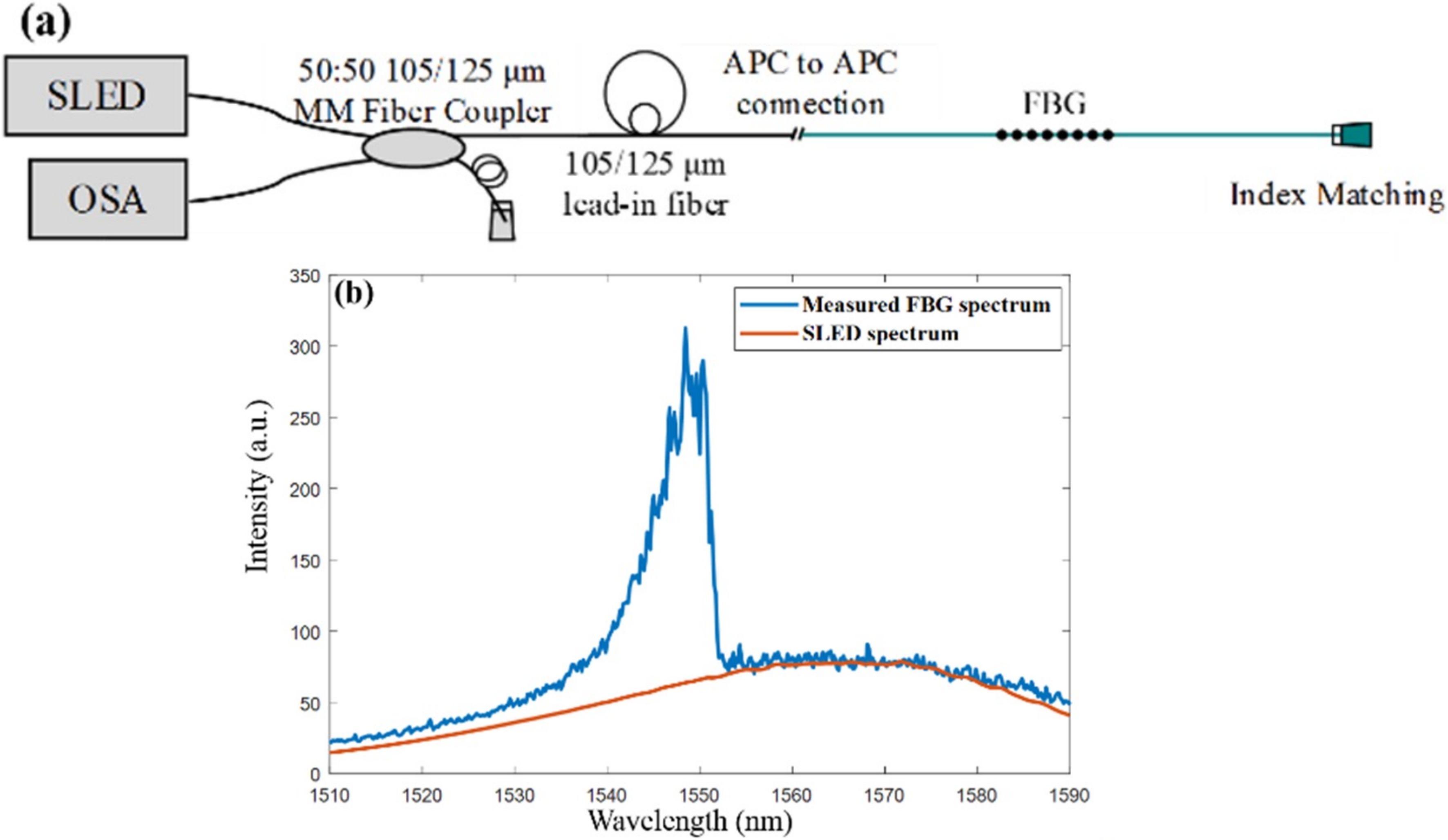
- Pitch controlled by the relation between the moving speed and the repetition rate
- Length adjusted by the total number of laser pulses
- Unique advantages over phase mask method
  - Geometrical and design flexibility
  - Wavelength division multiplexing (WDM) can be readily implemented





FBG Sensor Fabrication

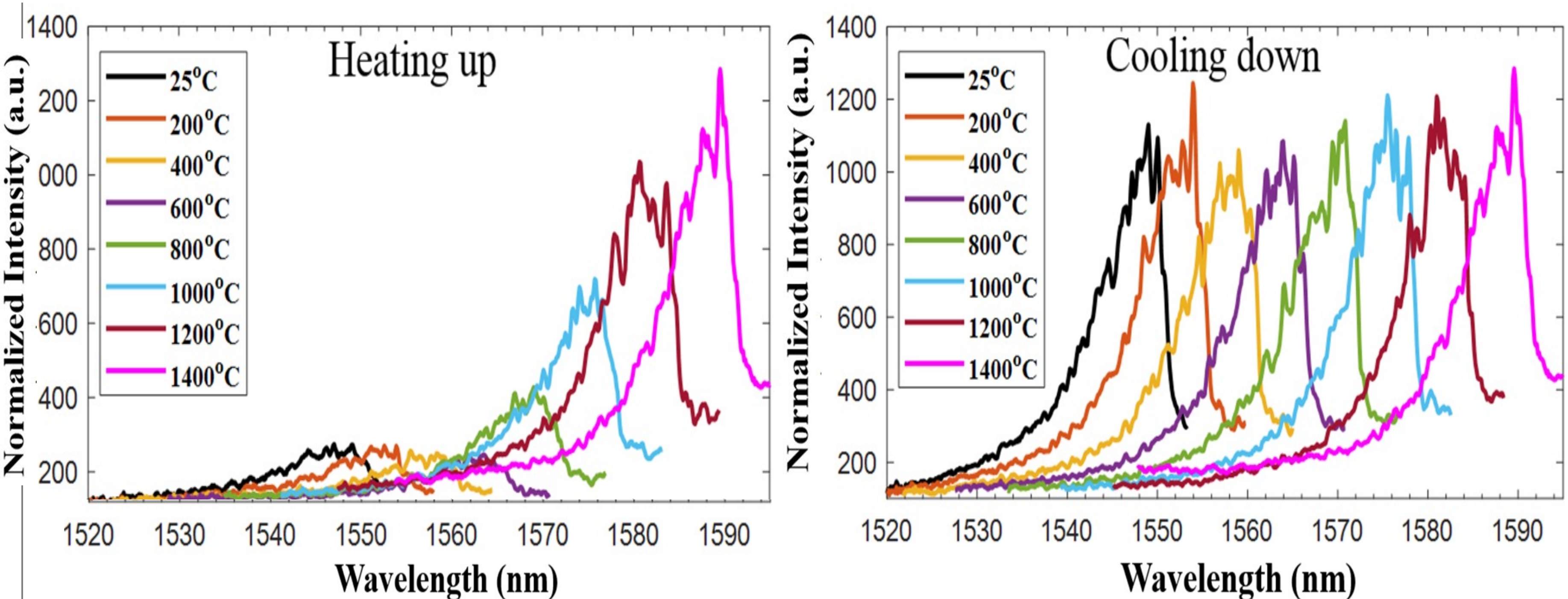
FBG Interrogation Technique



Shuo Yang, 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

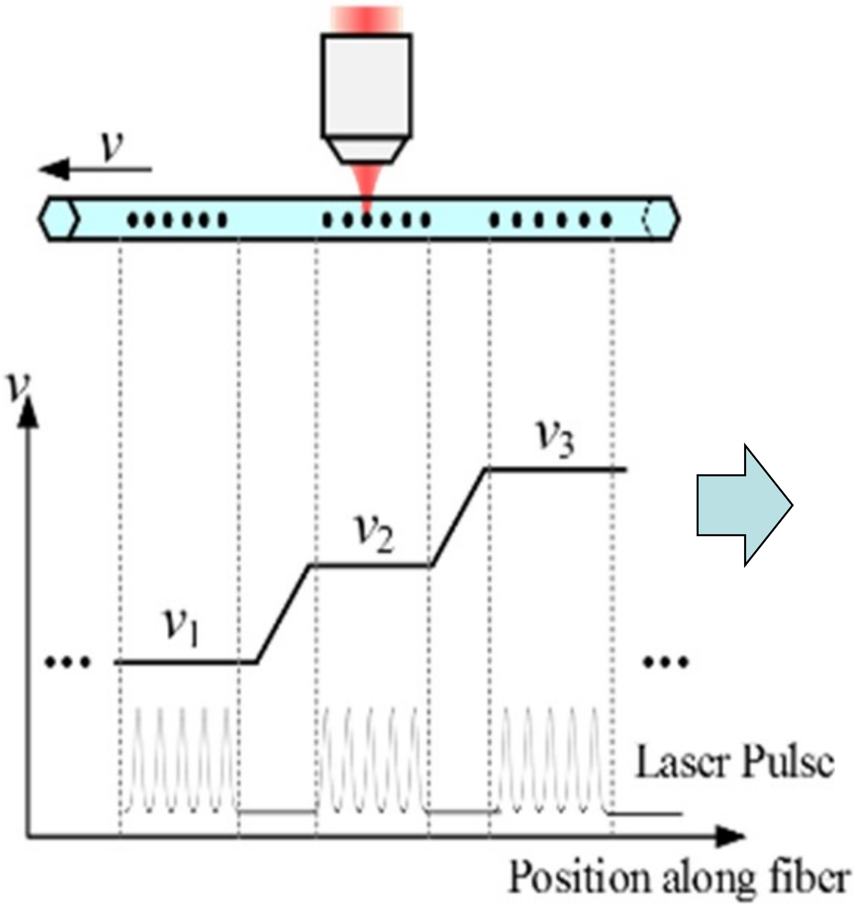
Enhancement of Reflectivity via Thermal Annealing

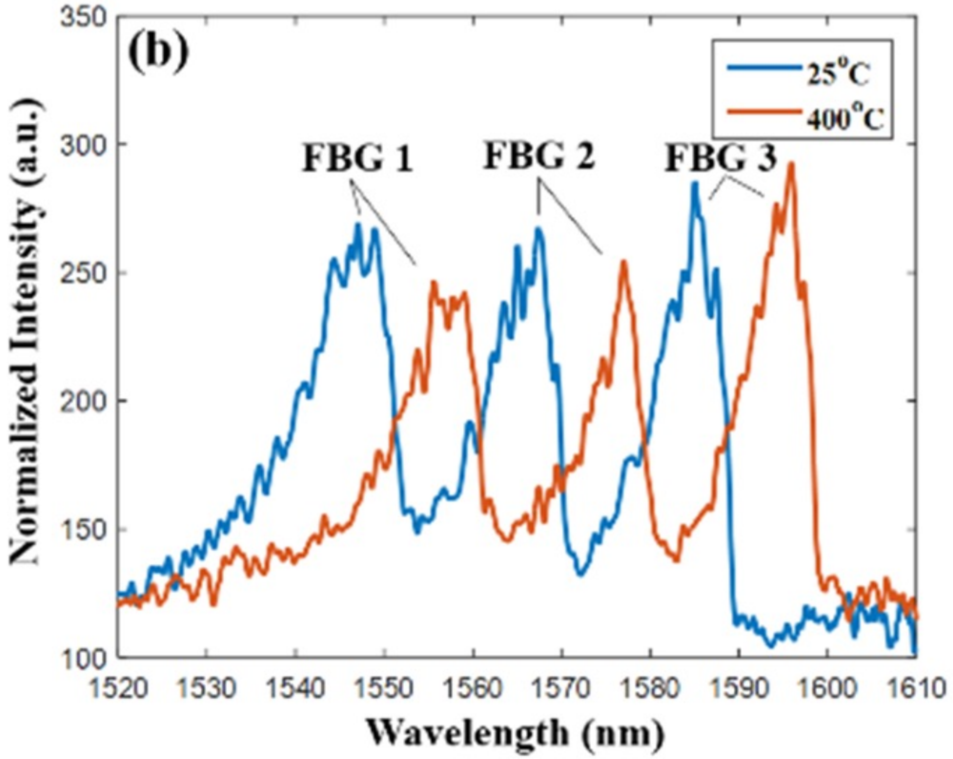


FBG reflectivity was permanently enhanced by about 5.5 times

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





Sapphire Fiber Bragg Grating Field Testing

The power plant, as shown in Figure 106, generates an annual steam output greater than 943 billion BTUs. The 6,250-kilowatt, 12,470-volt steam-turbine-powered generator produces nearly 27 million kilowatt-hours of electricity annually. To meet these demands, the plant operates five boilers, each outfitted with superheaters rated at 80,000 or 100,000 pounds of steam per hour. The Virginia Tech Power Plant ("Virginia Tech Electric Services") also sells electricity at retail prices to 6,000 residential customers in Blacksburg, VA.

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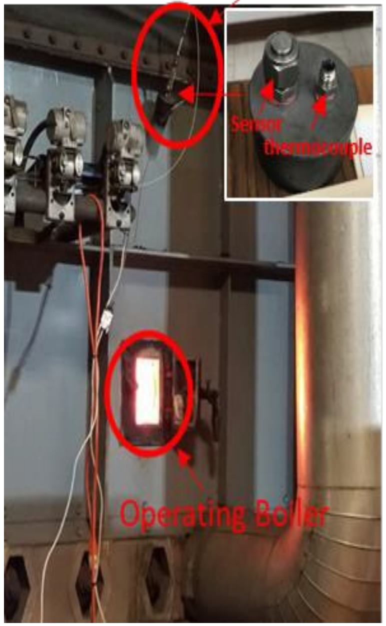
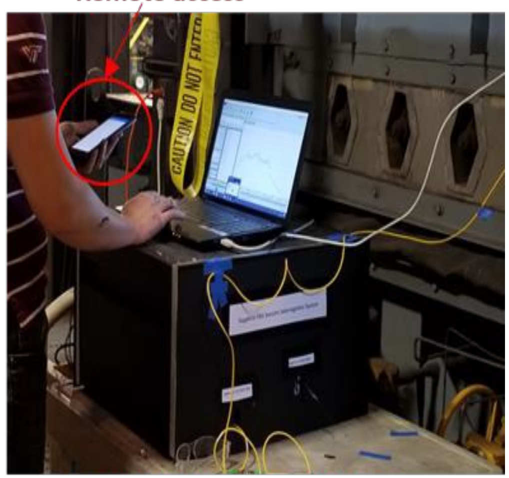
Coal Fired Boiler Field Testing

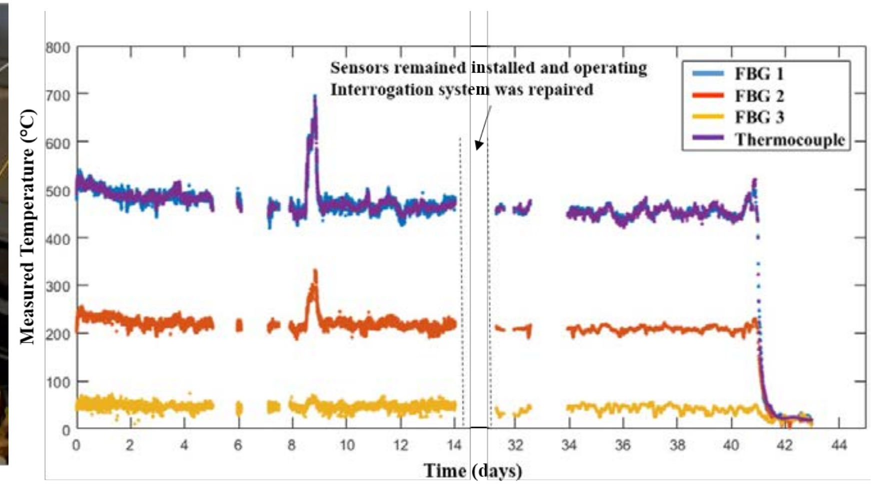
Installed Sensor

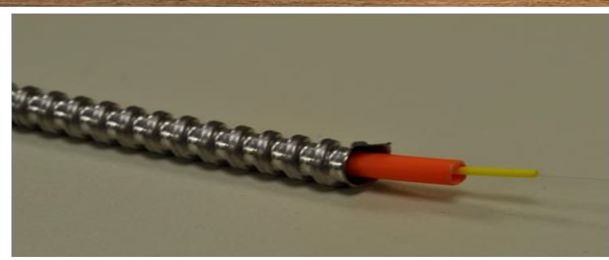


Remote access



Onsite Interrogation System





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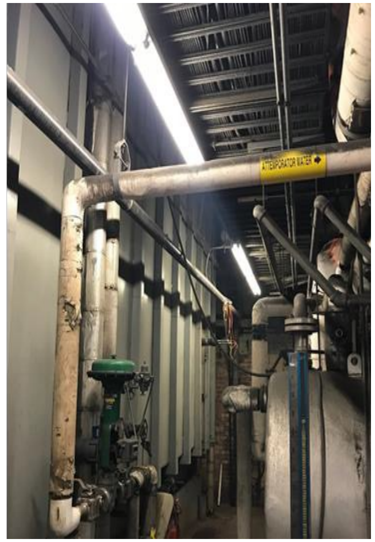
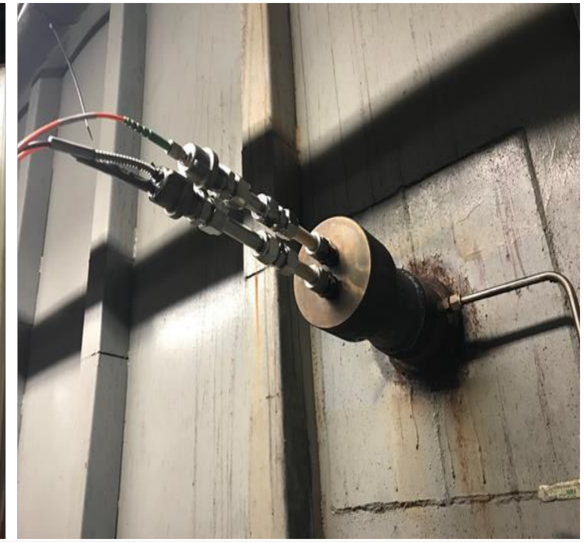
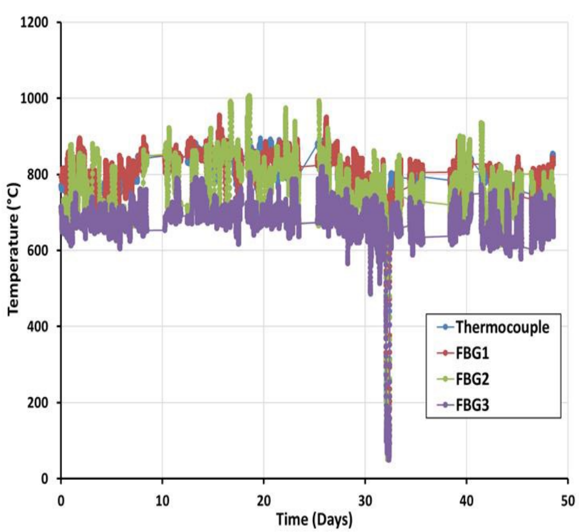
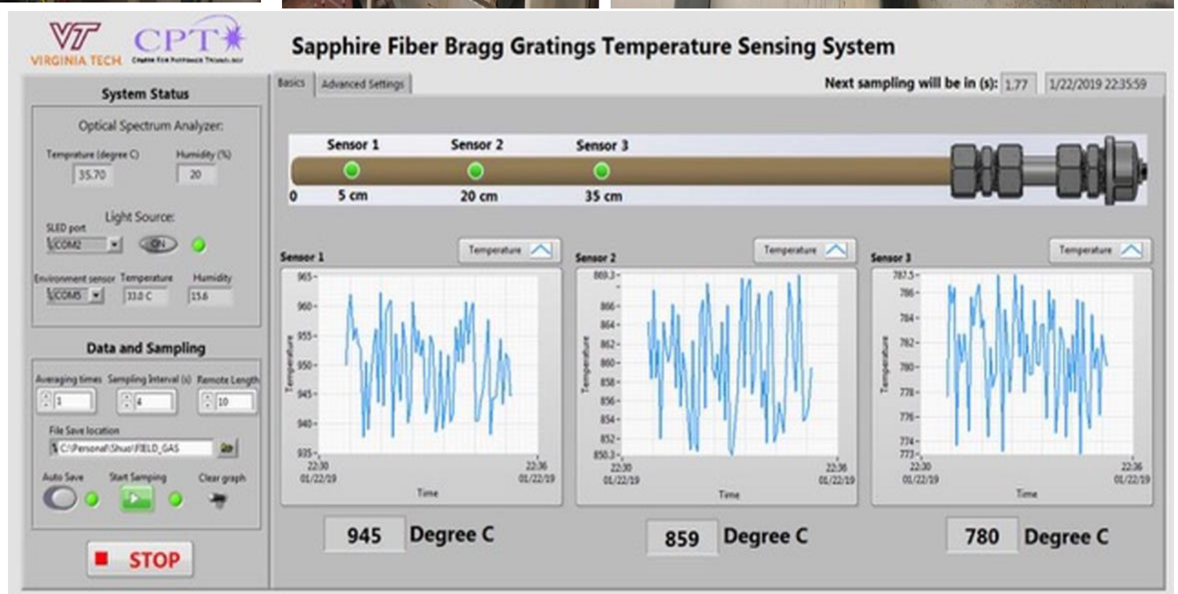
Natural Gas Fired Boiler Field Testing









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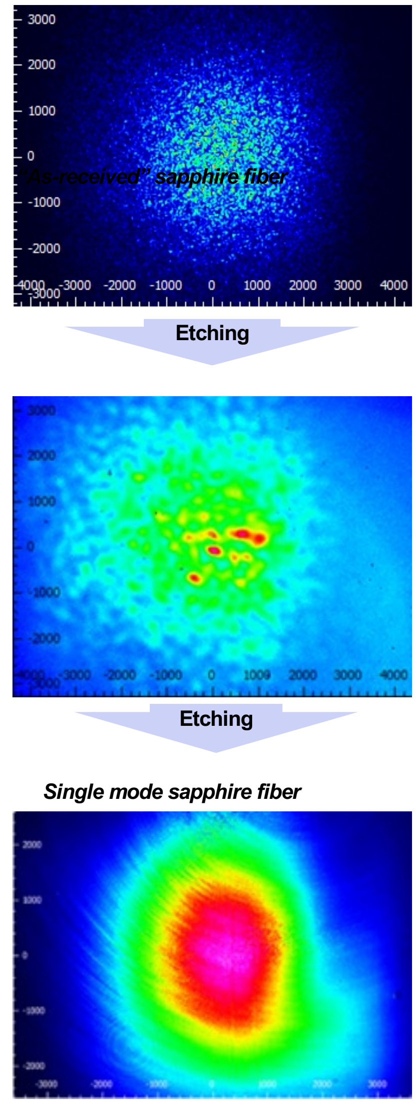
LMV Sapphire Fiber Testing

Far Field Analysis Method

- Far-field intensity patterns captured:
  - 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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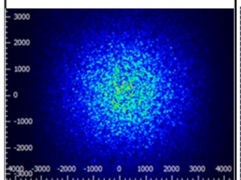
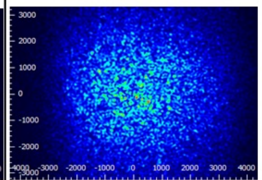
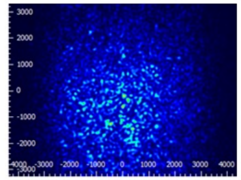
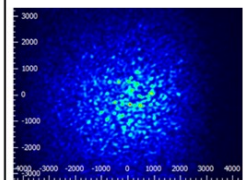
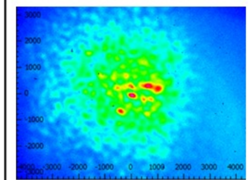
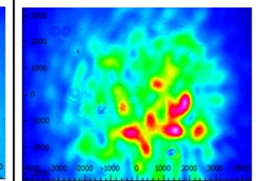
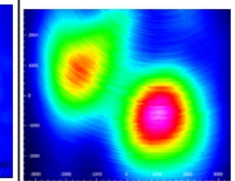
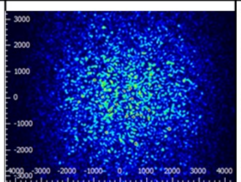
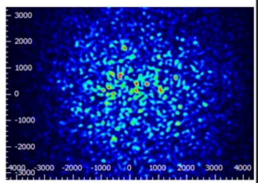
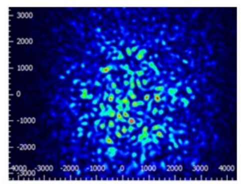
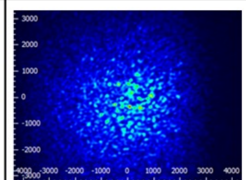
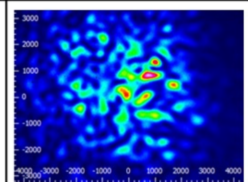
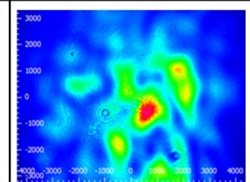
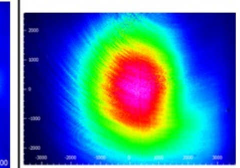
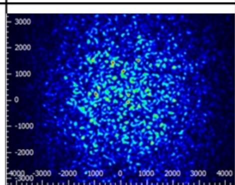
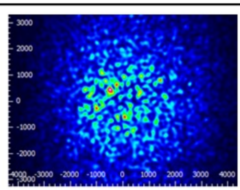
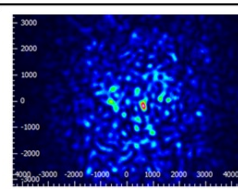
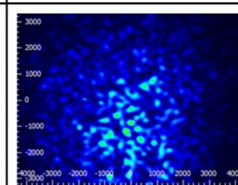
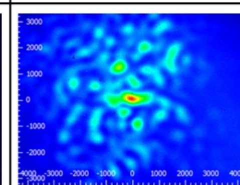
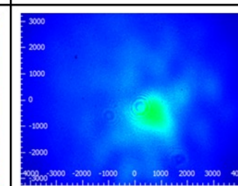
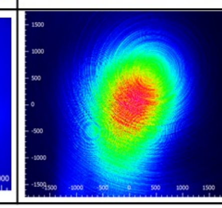
LMV Sapphire Fiber Testing

Far Field Analysis of RDSF

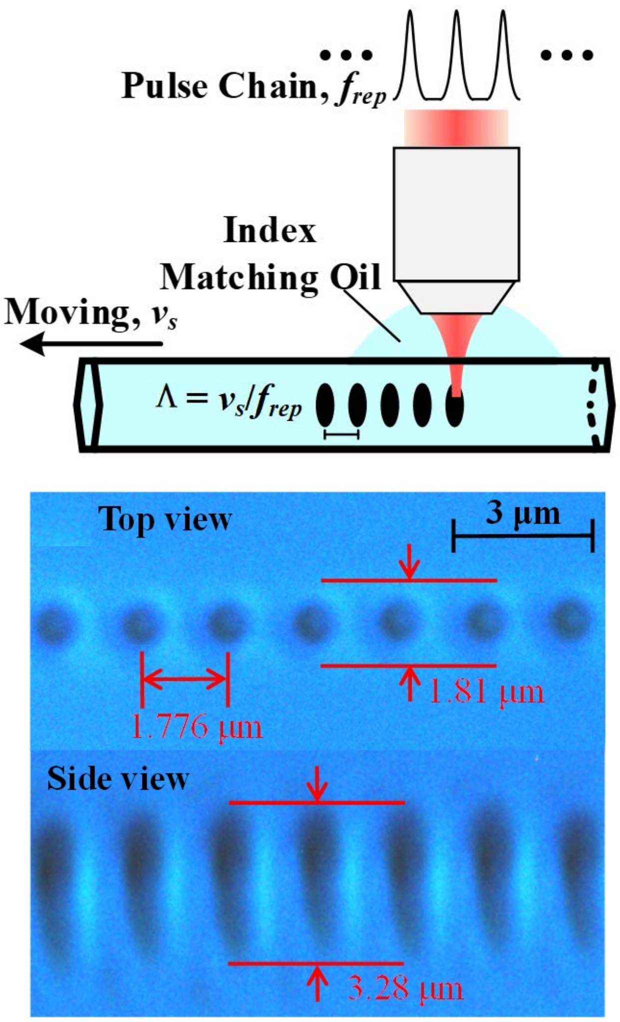
	Fiber Diameter						
λ ↓	125 µm	77 µm	66 µm	58 µm	35 µm	20 µm	6.5 µm
532nm							
783nm							
983nm							

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

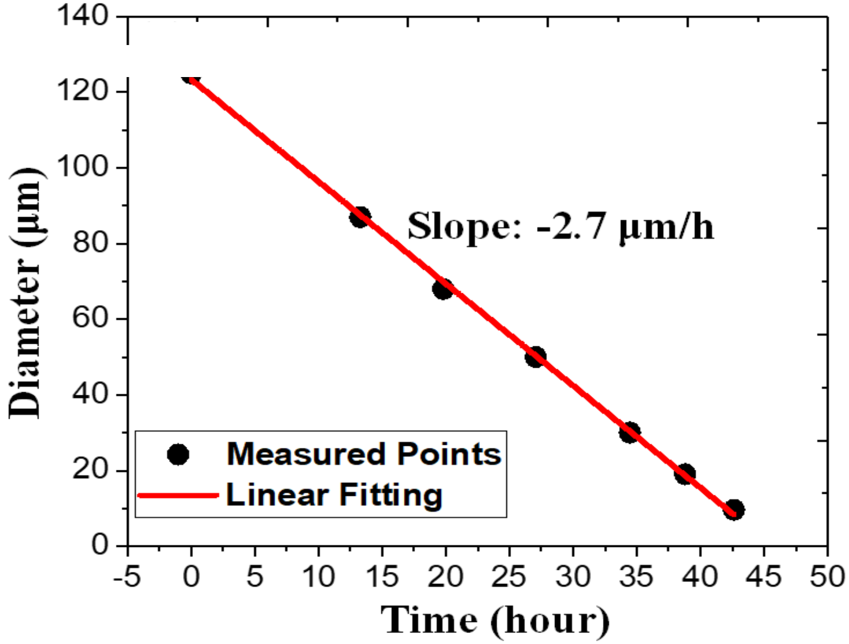
FBG Sensor Fabrication

Reduced Diameter Sapphire Fiber Bragg Grating

Step 1: Point-by-Point FBG Fabrication



Step 2: Diameter Reduction



Single mode air-clad sapphire optical fiber, C. Hill, D. Homa, Z. Yu, Y. Cheng, B. Liu, A. Wang, and G. Pickrell, Journal of Applied Sciences, 7 (5), 2017

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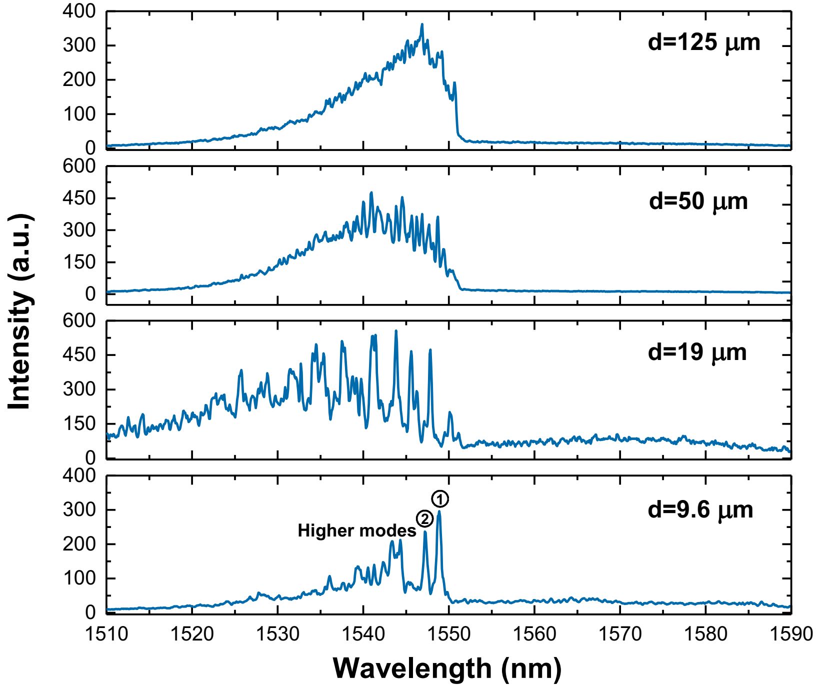
FBG Sensor Performance

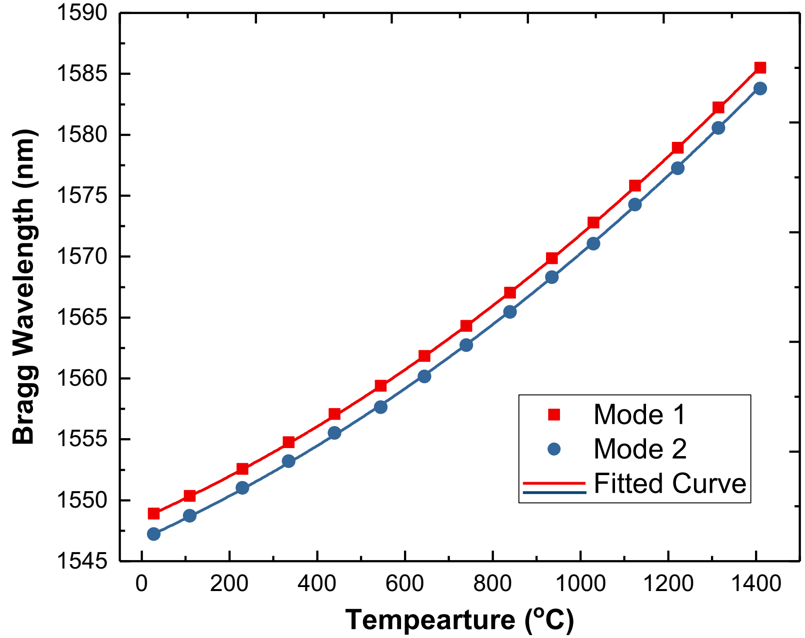
Reduced Diameter Sapphire Fiber Bragg Grating

FBG spectral response



Reduced modal volume improves FBG peak fidelity

Temperature dependence of λ_B



Demonstrated to temperature of 1400ºC ; **~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.

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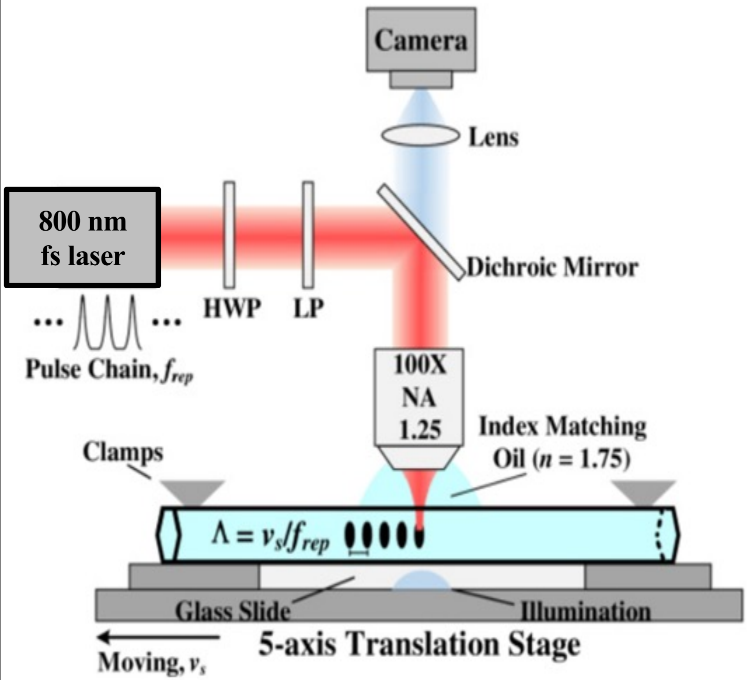
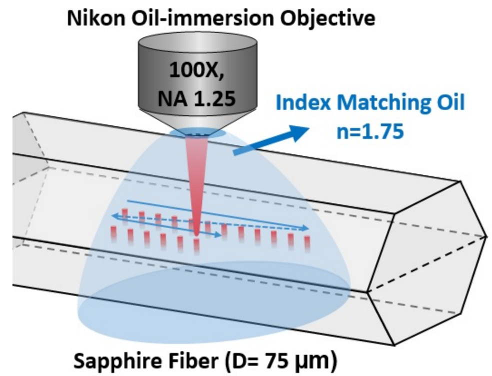
Parallel Fiber Bragg Grating (FBG) Sensors in Sapphire Fibers

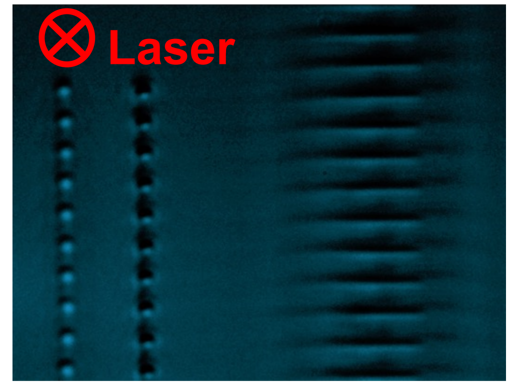
Design and fabrication of parallel FBGs

❑ Point-by-point inscription of pFBG



Fs laser point-by-point inscription system[5]





Inscribed in sapphire fiber with 75 µm diameter with an average power of 300 µW and repetition rate of 500 Hz, corresponding to single pulse energy of 600 nJ, takes 5.8 s to fabricate a 5-mm-long FBG with pitch size of 1.697 µm.

- ➢ Precise moving speed control of fiber via translation stage to control pitch size of FBG;
- ➢ 100x oil-immersion objective to focus laser energy higher than the damage threshold of single-crystal sapphire;
- ➢ Fabrication of each FBG at a time to maintain inscription point uniformity.

G.Shi, G.Pickrell, A.Wang, Y.Zhu **Opt Lett 2022 Sep 15;47(18):4724-4727.**

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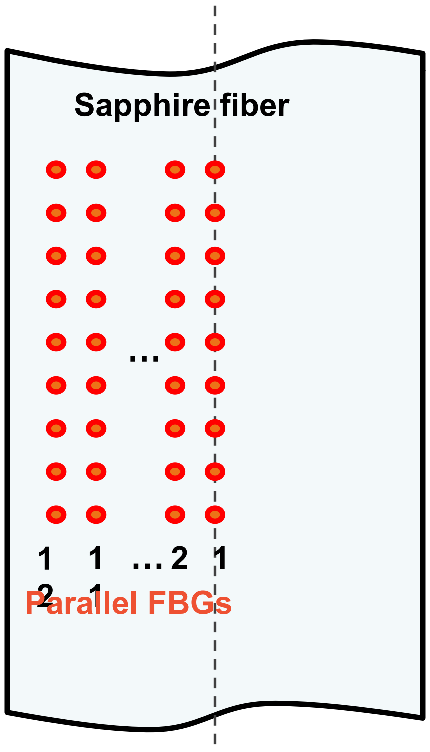
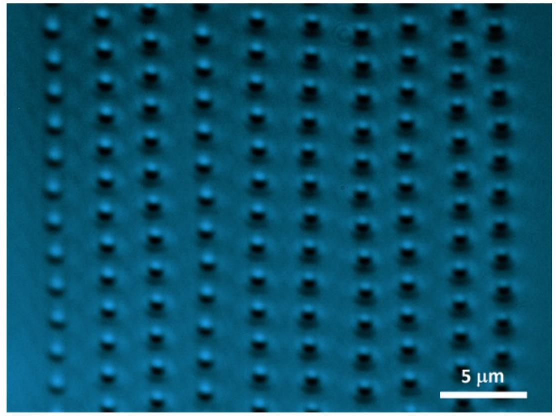
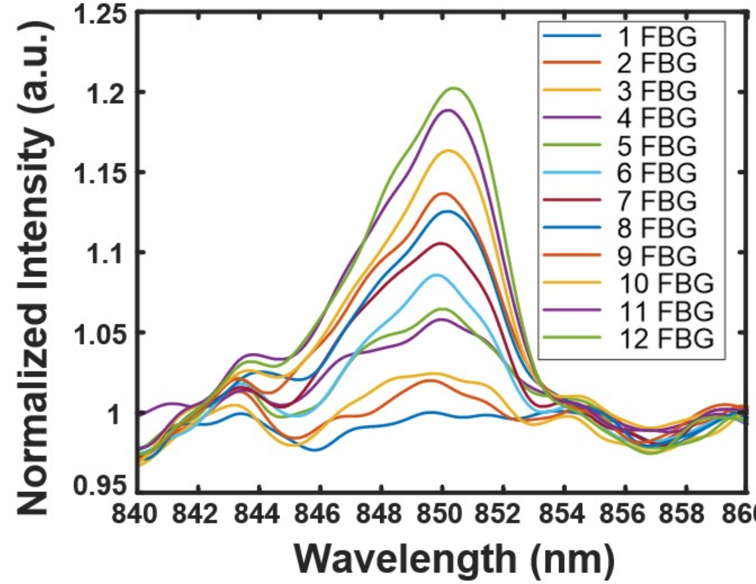
Design and fabrication of parallel FBGs

❑ Point-by-point inscription of pFBG







Parallel FBGs inscribed with same pitch size and length on the same longitudinal position, each with 3 µm lateral offset, with FBG1 along fiber axis and FBG12 4.5 µm away from the sapphire fiber edge.

- Fabrication of 12 identical FBGs with pitch size of 1.697 µm, corresponding to 7th order FBG in sapphire fiber;
- Parallel FBGs laterally distributed along radius with 3 µm offset;
- An 850 nm LED as light source for interrogation;
- NIR band light source, so the FBG order is higher, uses 7th order FBG
- Signal almost invisible before fabrication of 3 parallel FBGs, due to poor coherence and high mode capacity.

G.Shi, G.Pickrell, A.Wang, Y.Zhu OFS, Optica 2022

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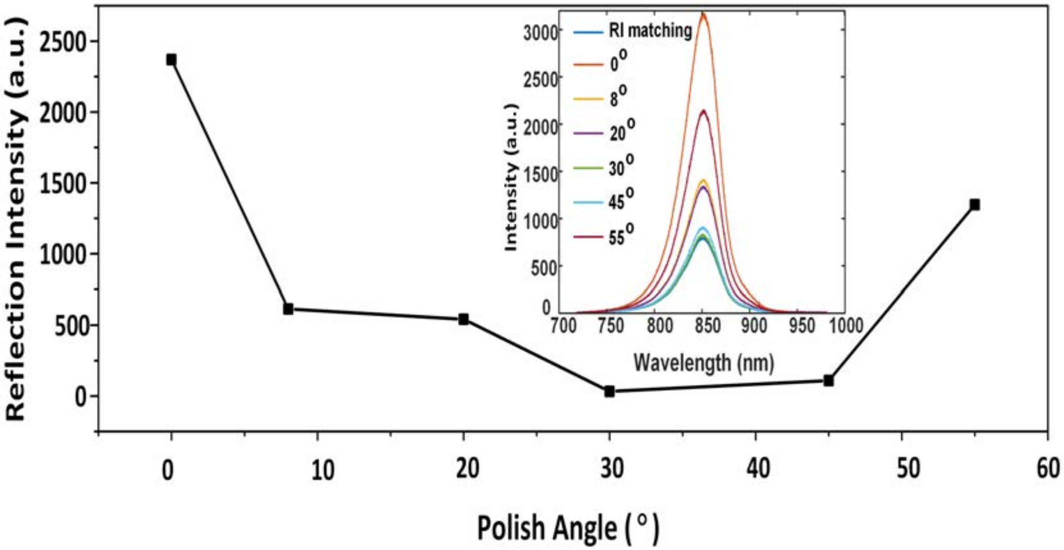
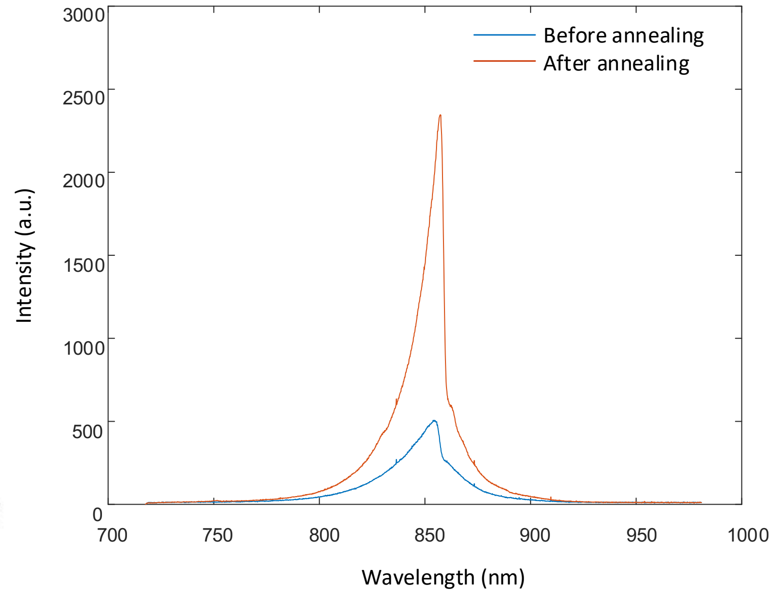
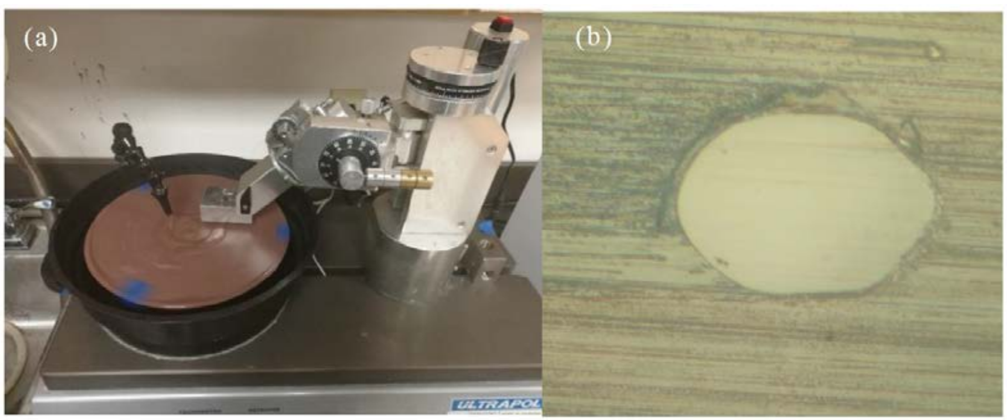
Design and fabrication

❑ SNR improvement via end reflection elimination and thermal annealing







SNR improvement of the pFBG sensor:

- Angle polish to eliminate end reflection, with multimode setting of sapphire fiber, 30° provides almost no reflection;
- Thermal annealing of sapphire pFBG improves surface morphology of inscription points, can effectively improve signal visibility.

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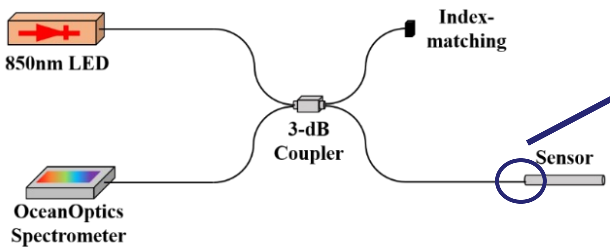
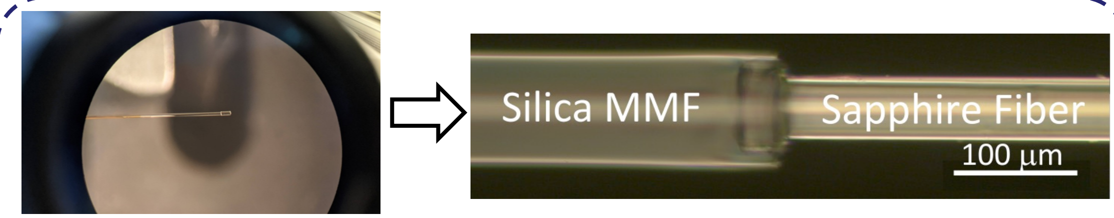
Cascaded pFBGs for temperature sensing

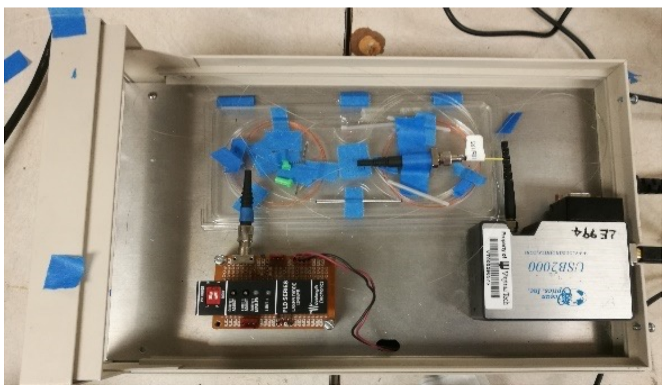
❑ Cascaded pFBGs with fully multimode interrogator

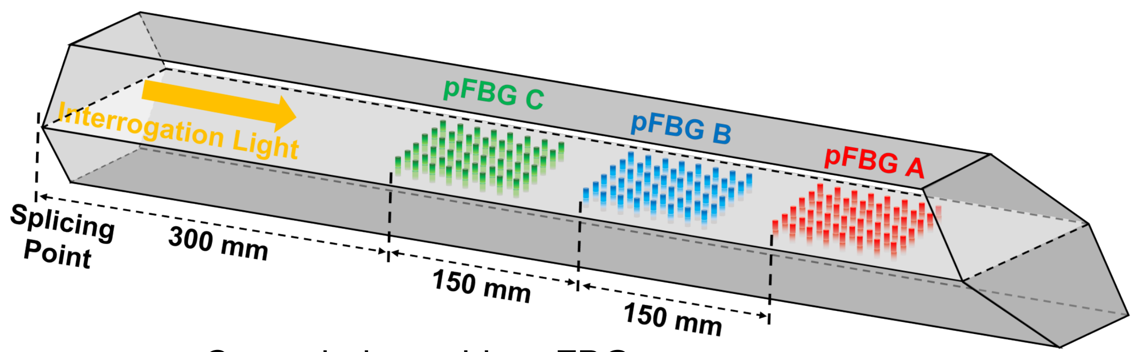


Fully multimode interrogator



Silica-sapphire fiber direct splicing

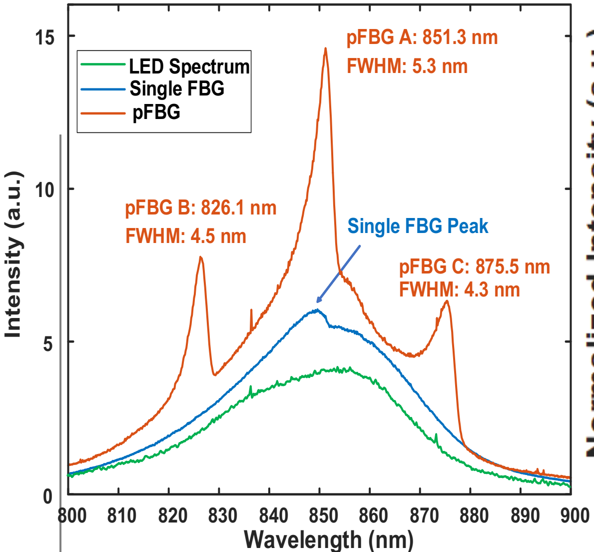


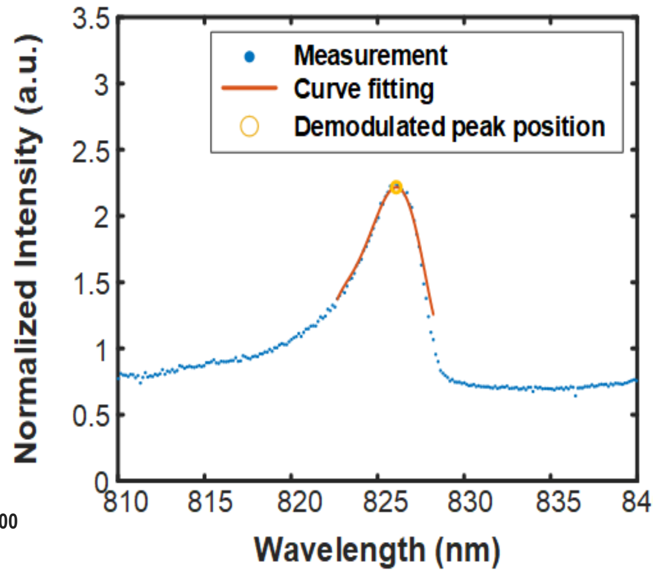


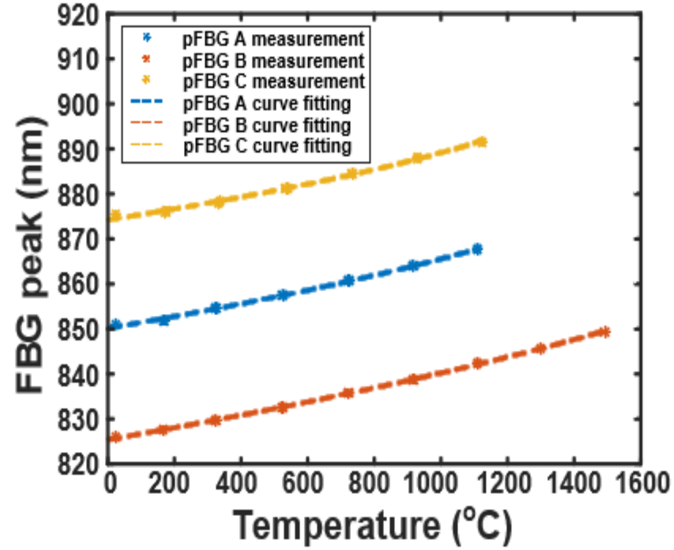
Cascaded sapphire pFBGs

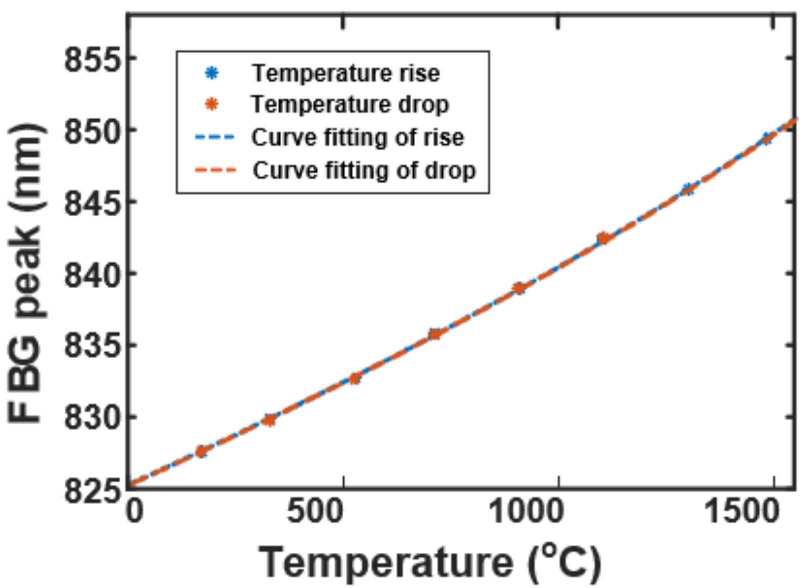
- Fully multimode interrogator at NIR band, with LED and CCD-based spectrometer;
- NIR band system requires high FBG order, which reduces the FBG signal intensity, thus pFBG technique and other SNR improvement methods are necessary.

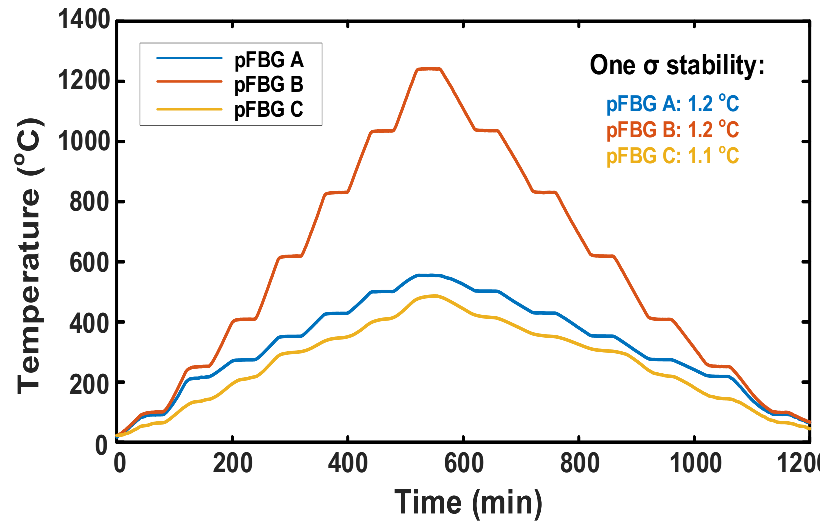
Cascaded pFBGs for temperature sensing











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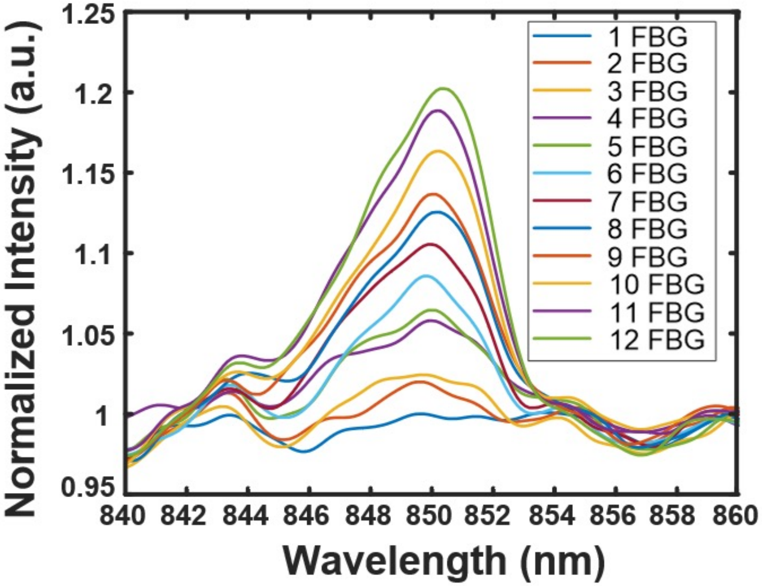
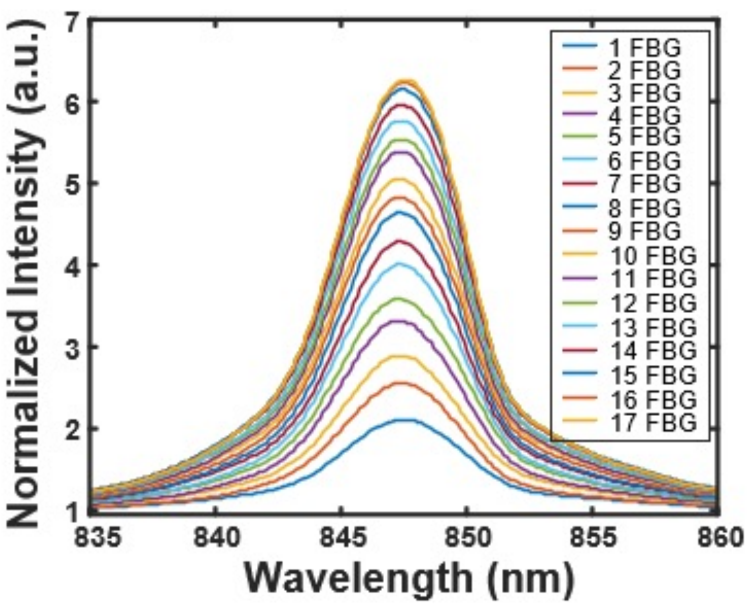
Design and fabrication Sapphire vs Silica Multimode Fibers

- FBG reflectivity with lateral position



Sapphire pFBG:

- Step index fiber (air cladding) with 75 μm core;
- Almost invisible signal until more than 3 FBGs;
- Peak FWHM ~6.5 nm.



Silica MMF pFBG:

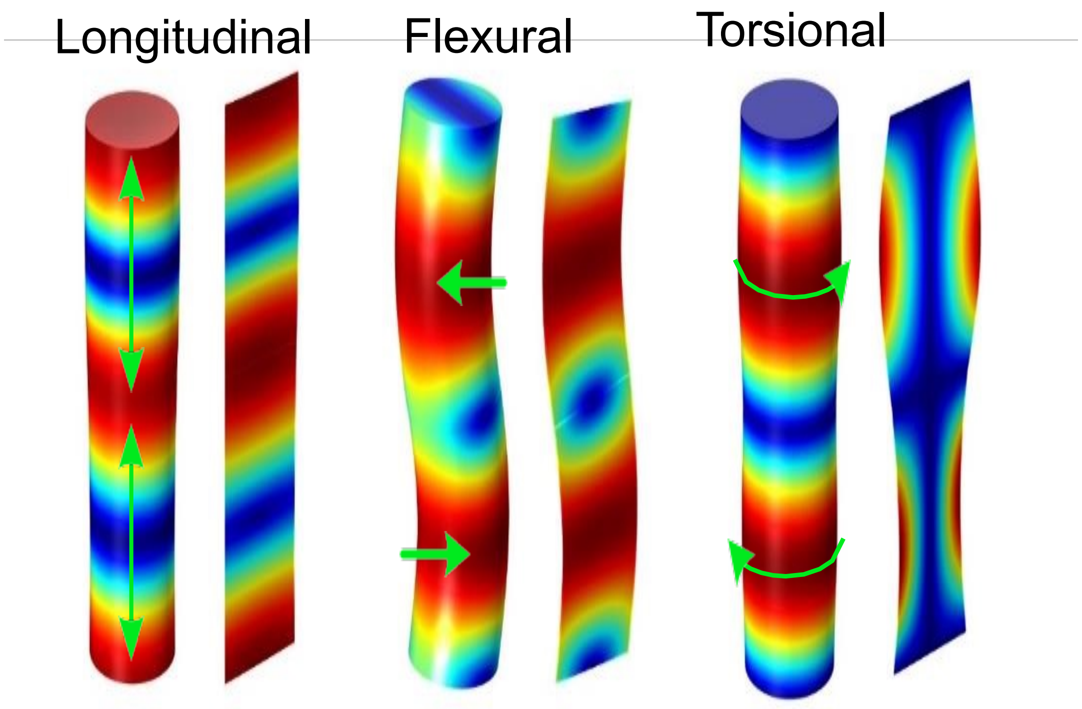
- Step-index 105/125 MMF;
- Visible FBG peak after one FBG fabrication;
- Peak FWHM ~5.5 nm;
- Slower reflectivity rise with larger lateral offset.

ACOUSTIC FIBER BRAGG GRATING SENSING TECHNOLOGY

AFBG Sensing Systems

Acoustic Fiber Bragg Grating – AFBG

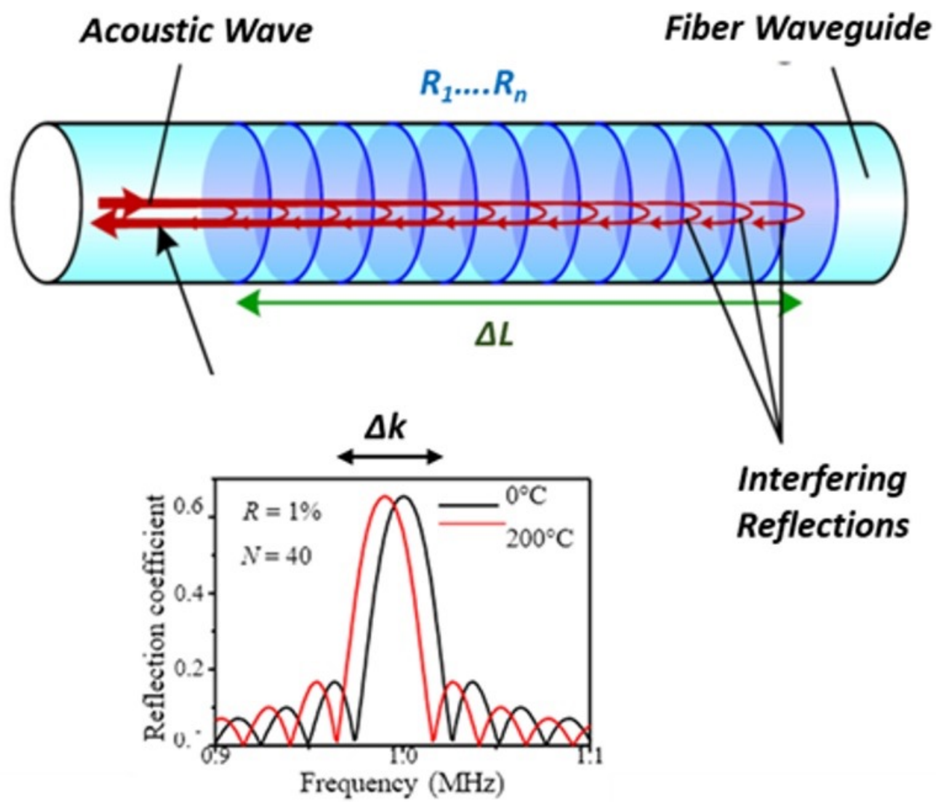
Many similarities in operation to optical FBG but in the acoustic domain. Modes of propagation:



Acoustic Fiber Bragg Gratings

Basic Overview

- Versatile sensing via fiber Bragg gratings (AFBGs) on an acoustic fiber waveguide (AFW)
  - Single mode operation
- Time-division spectral interrogation scheme is employed for fully-distributed sensing on a single fiber.
- AFBG central frequency position shifts proportionally to external perturbations such as temperature, strain, pressure and corrosion
- **Can be implemented on a wide array of materials!**



D. Hu., et al., IEEE Sensors Vol 18, #23 (2018).

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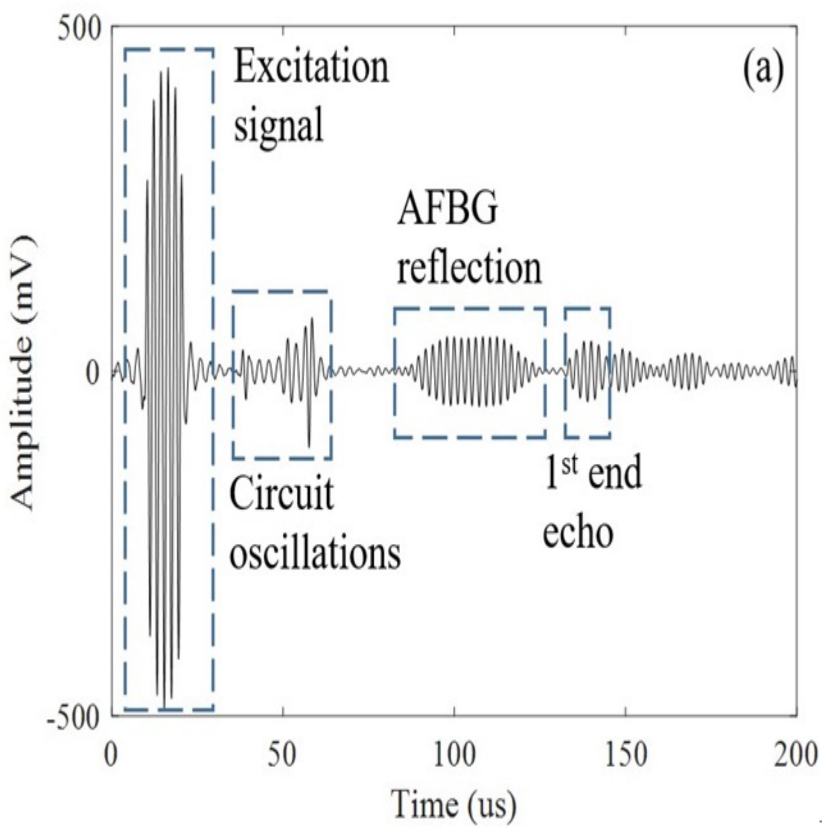
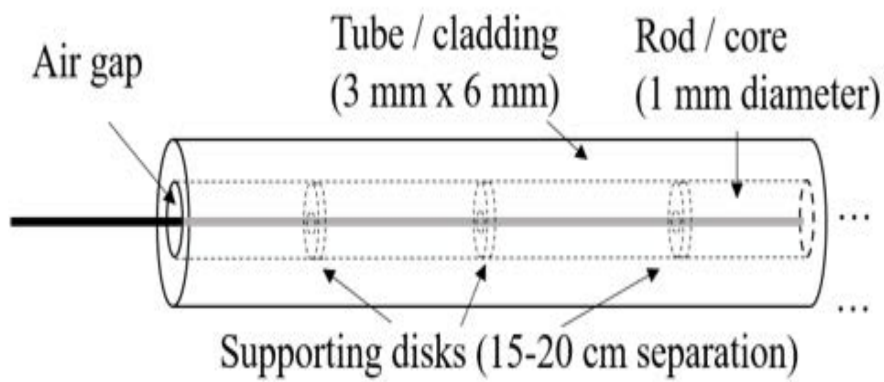
Fused Silica AFBG Sensors

FABRICATION, PERFORMANCE AND STABILITY

- Acoustically robust “Suspended-core” Silica AFW design
- AFBGs inscribed via CO_2 laser

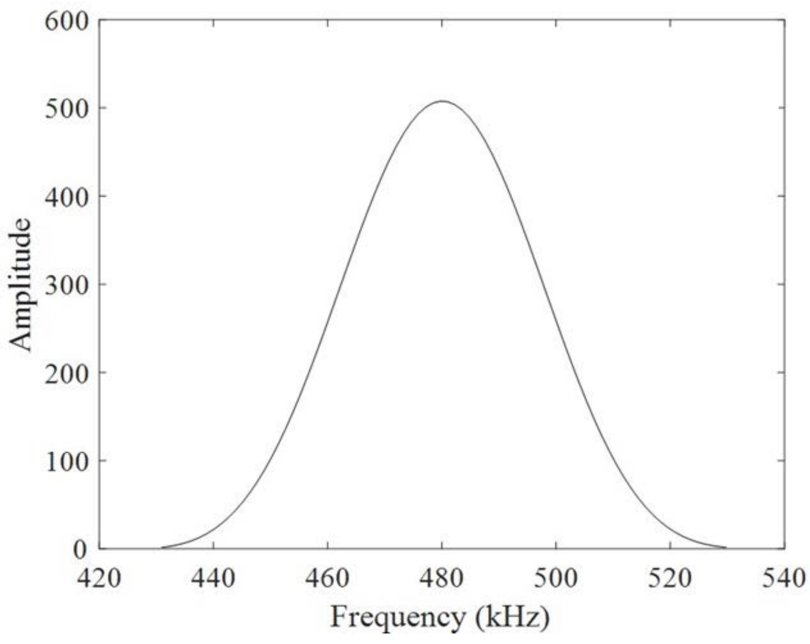


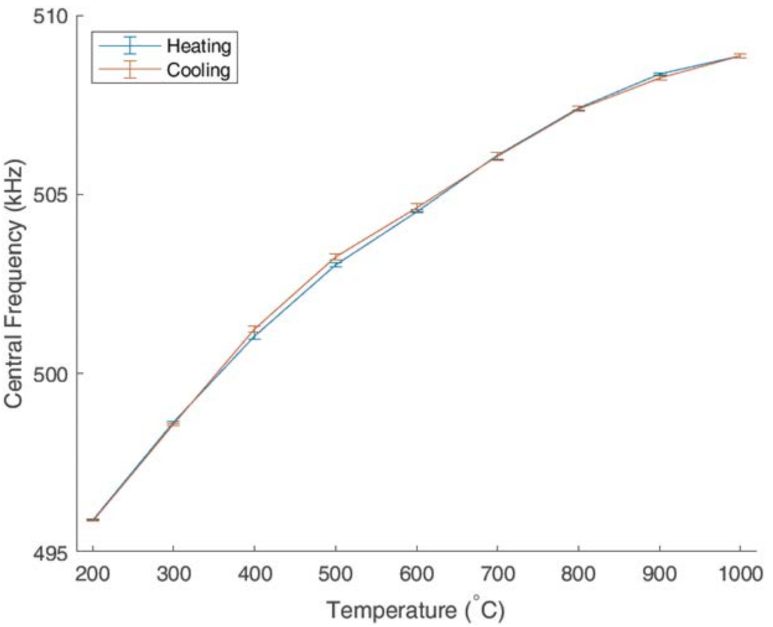


Fused Silica AFBG Sensors

FABRICATION, PERFORMANCE AND STABILITY

- Performance testing of AFBG temperature sensing system
  - Thermal cycling conducted to a maximum temperature of 1000ºC
  - ~1.3 kHz per 100 ºC / ~ 6 ºC resolution.
- Minimal thermal hysteresis

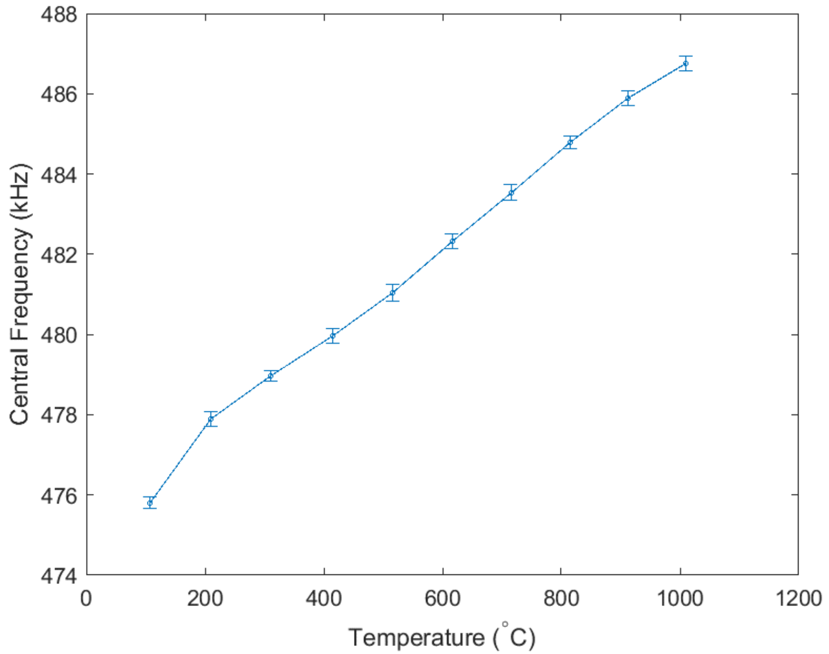




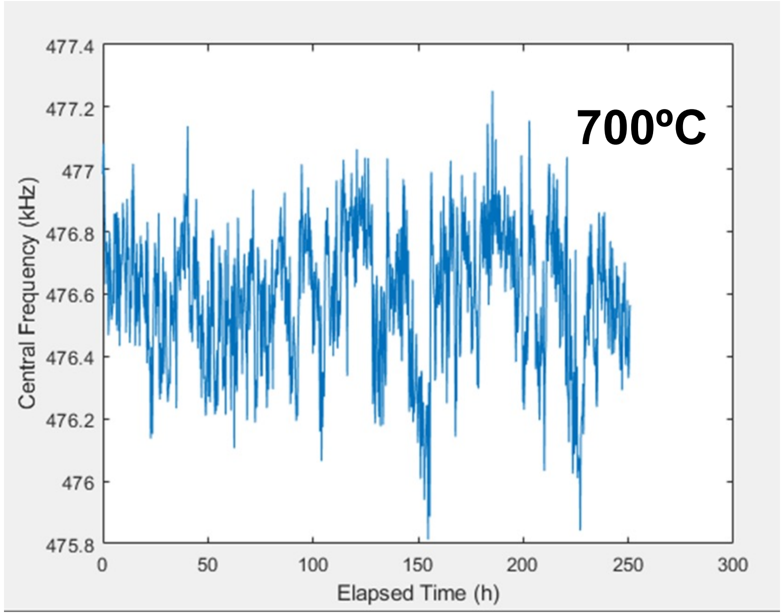
Fused Silica AFBG Sensors

Fabrication, Performance and Stability

- Full system integration and calibration up 1000ºC
- Long Term Stability Testing: 250 hrs @ 700ºC



Calibration of Fused Silica AFBG Sensor

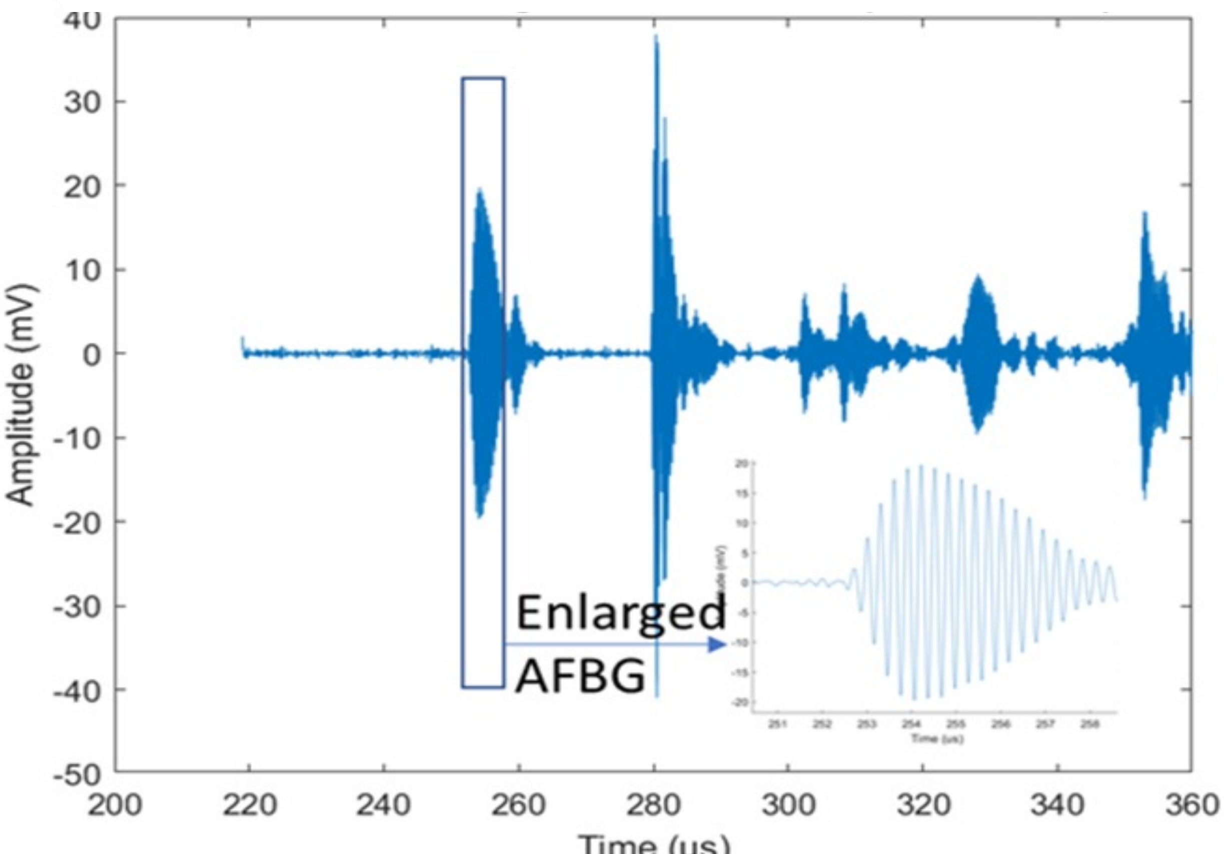


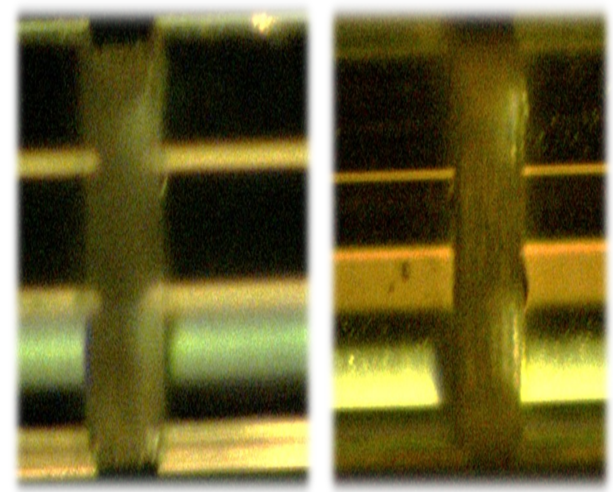
Long Term Stability Testing of Fused Silica AFBG Sensor

Single Crystal Sapphire AFBG Sensors

Fabrication, Performance and Stability

- High frequency (~3.4 MHz) SCS AFBG sensor
- AFBG was inscribed via a femtosecond laser
  - 250 μm SCS fiber; 20 nodes: period of 1.57 mm; Depth/width: 12 μm/60 μm



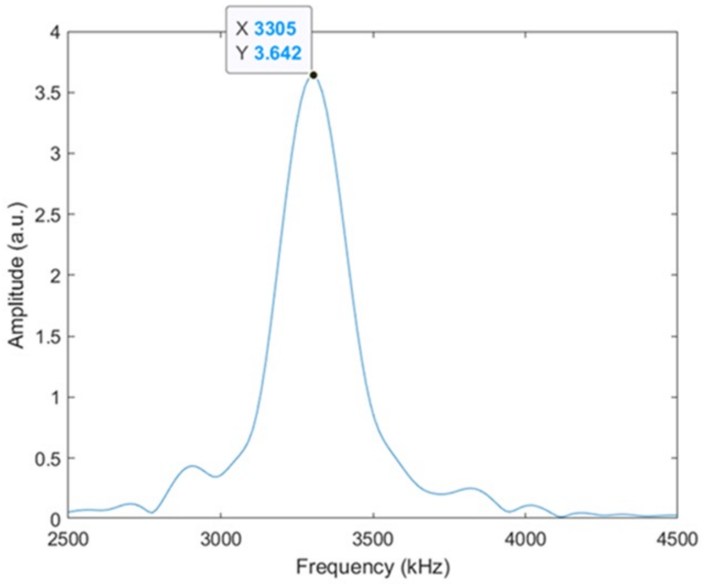


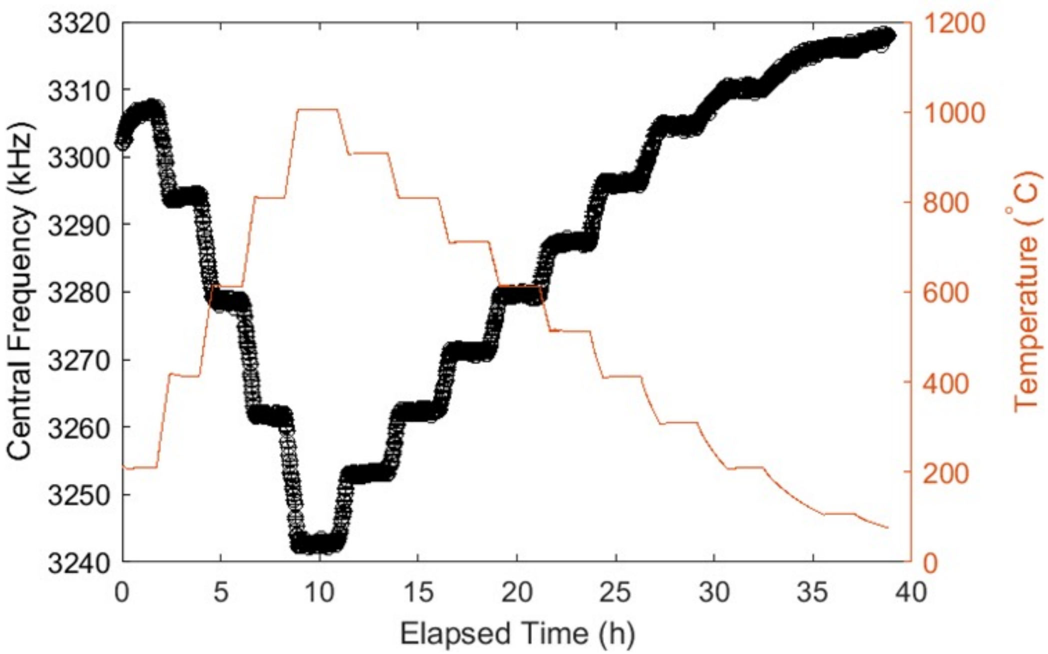
Micrographs of SCS AFBG

Single Crystal Sapphire AFBG Sensors

Fabrication, Performance and Stability

- Calibrated to 1200ºC (up to 1400ºC)
- Sensitivity: ~18 Hz/C

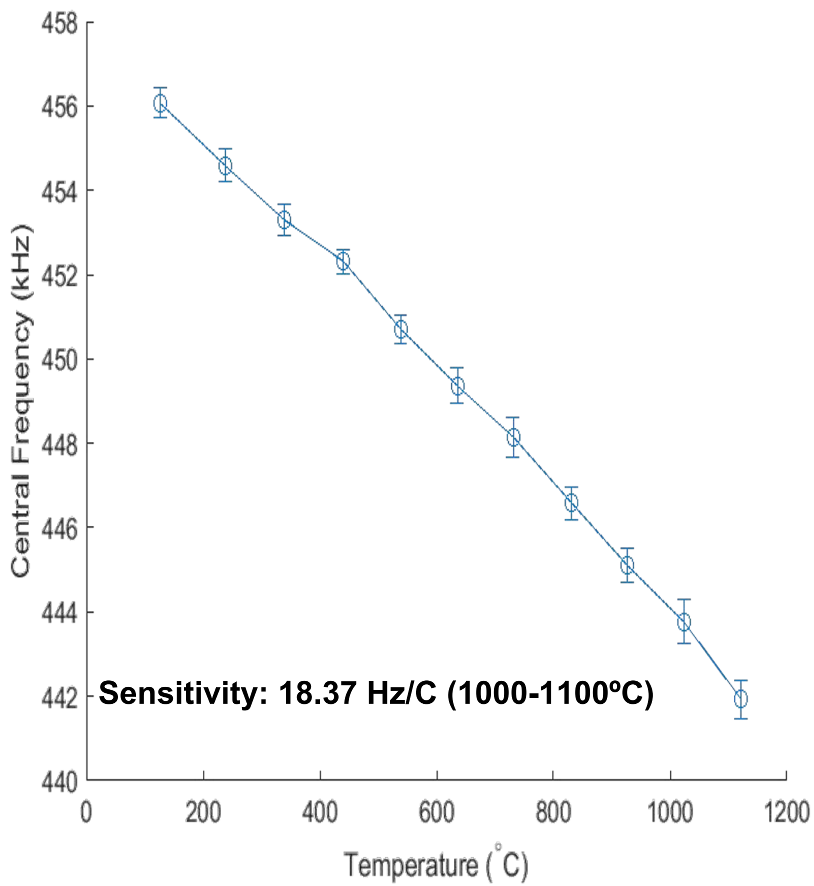




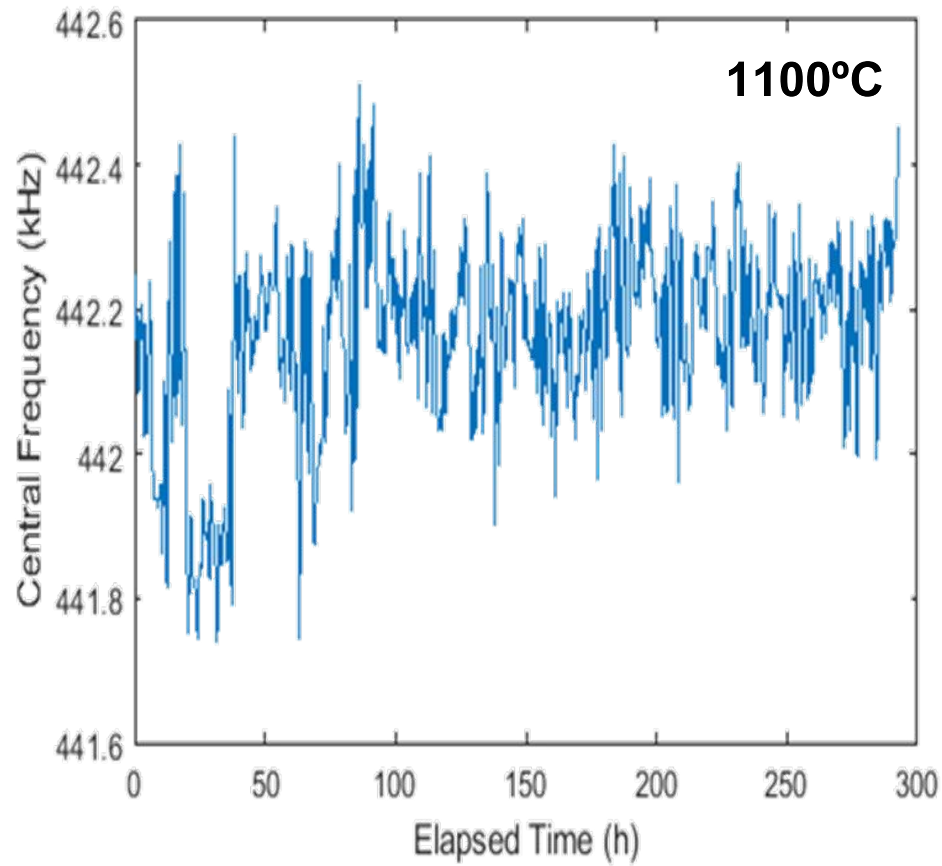
Single Crystal Sapphire AFBG Sensors

Fabrication, Performance and Stability

- Full system integration and calibration up 1100ºC
- Long Term Stability Testing: >250 hrs @ 1100ºC



Calibration of SCS AFBG Sensor

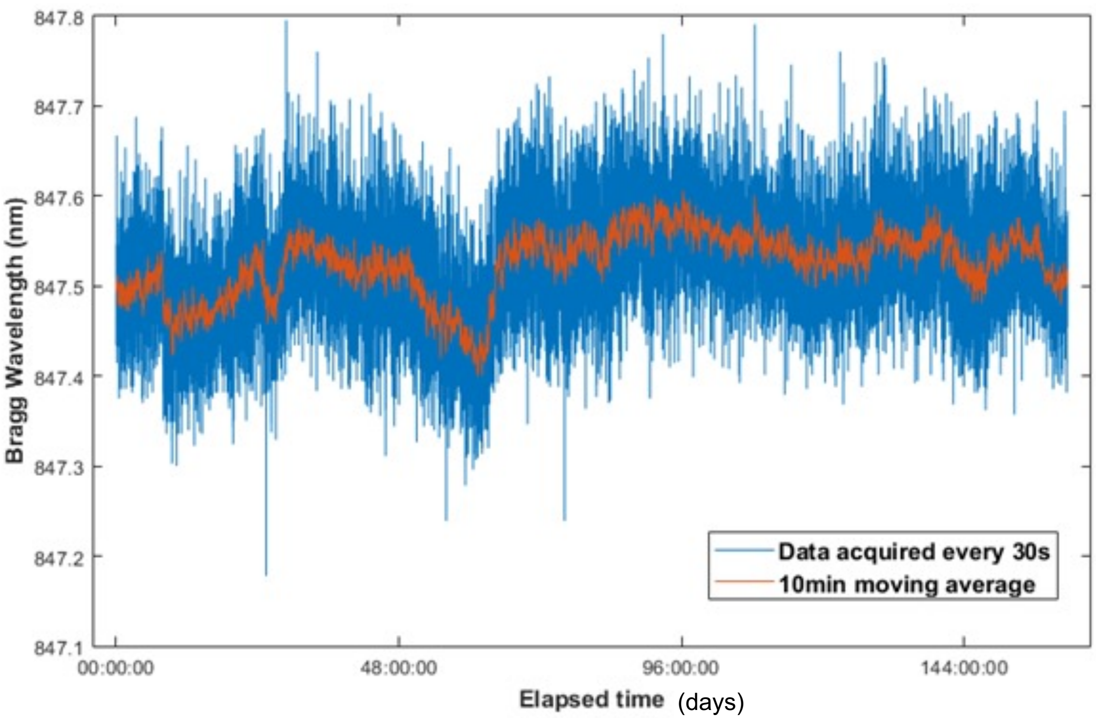


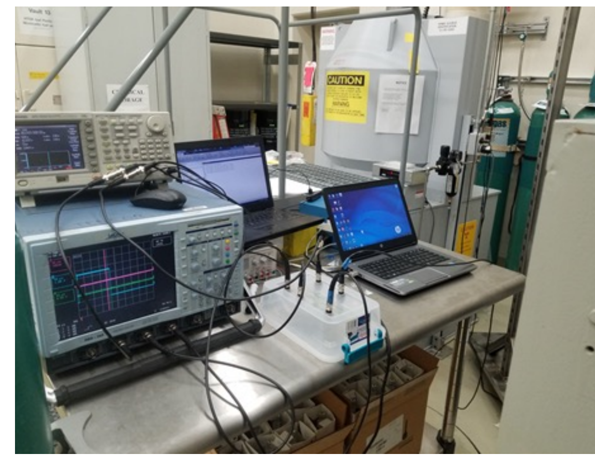
Long Term Stability Testing of SCS AFBG Sensor

Single Crystal Sapphire AFBG Sensors

FABRICATION, PERFORMANCE AND STABILITY

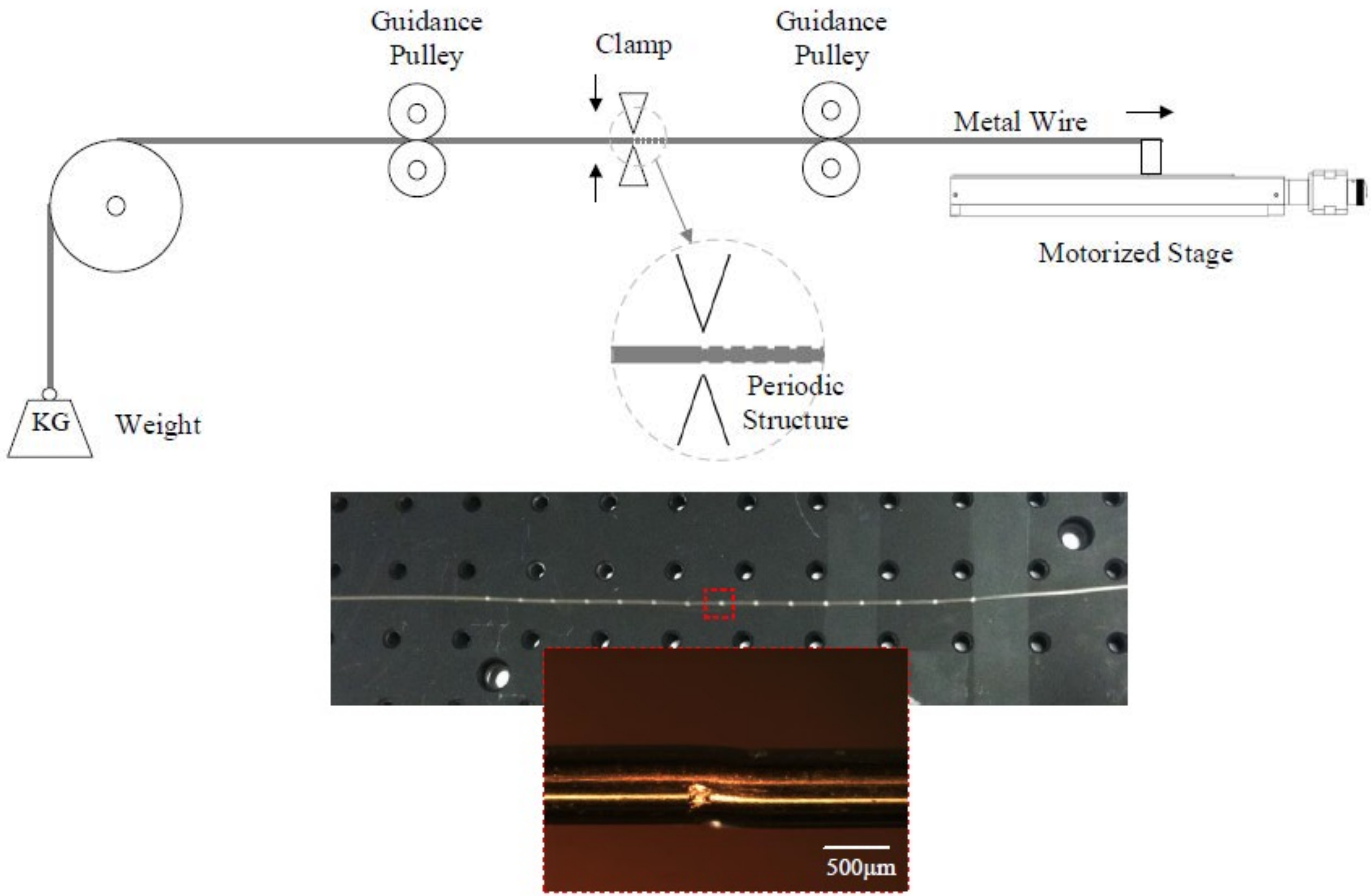
- Long term gamma radiation exposure testing at ORNL
  - Continuous, “hands-off” operation – Big Thankyou Alexander Braatz ORNL





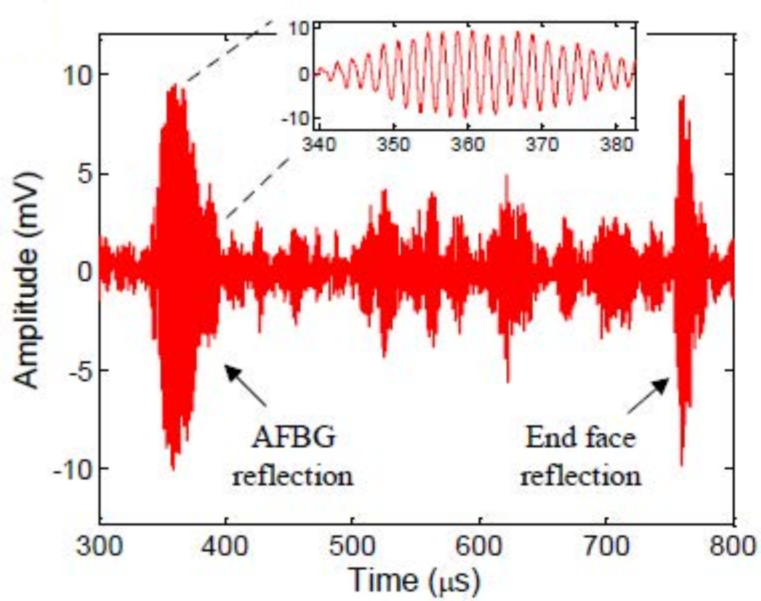
AFBG Fabrication in Metal Wire

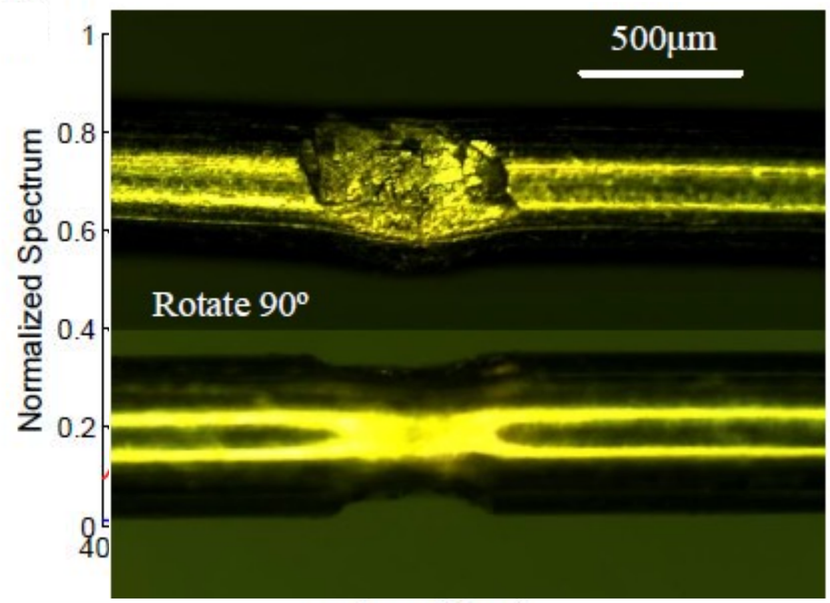
PELICAN ALLOY 785



AFBG in Metal Wire

PELICAN ALLOY 785

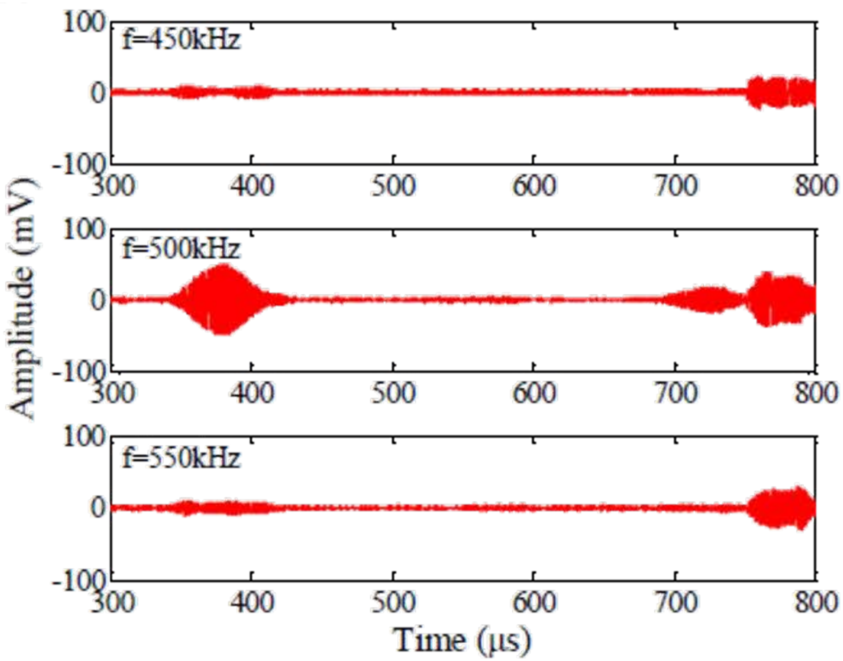


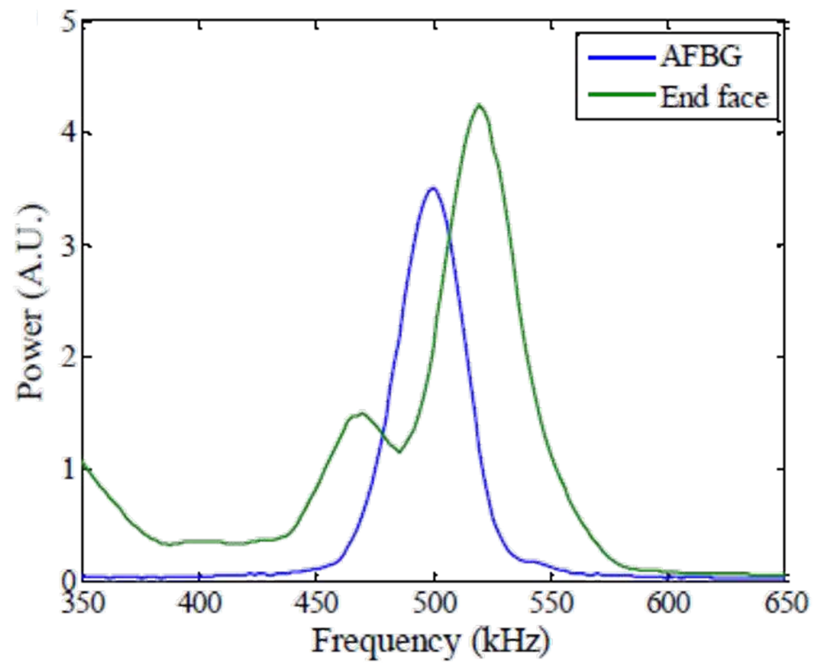


AFBG in Metal Wire

Pelican Alloy 785

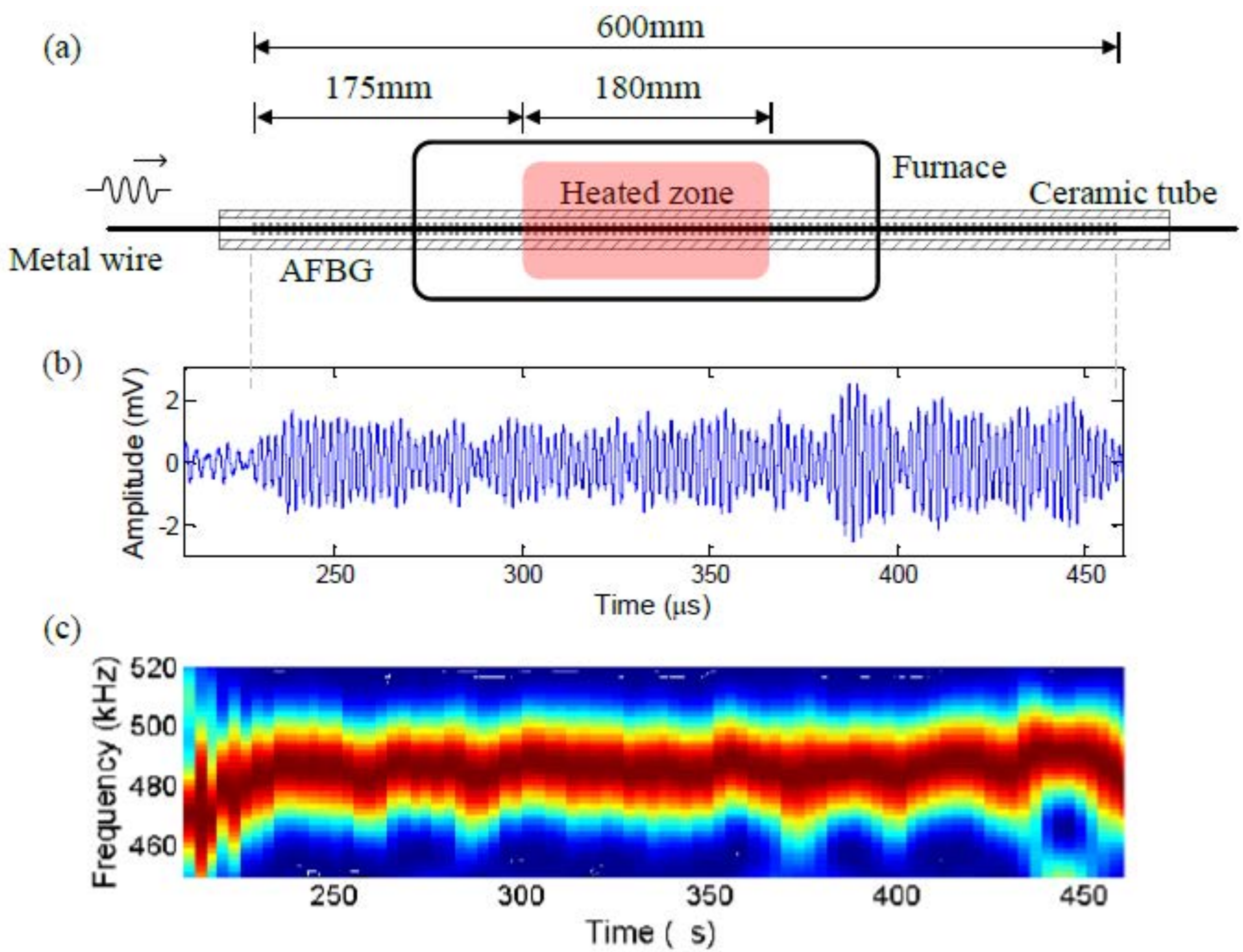
- AFBG designed for 500kHz interrogation





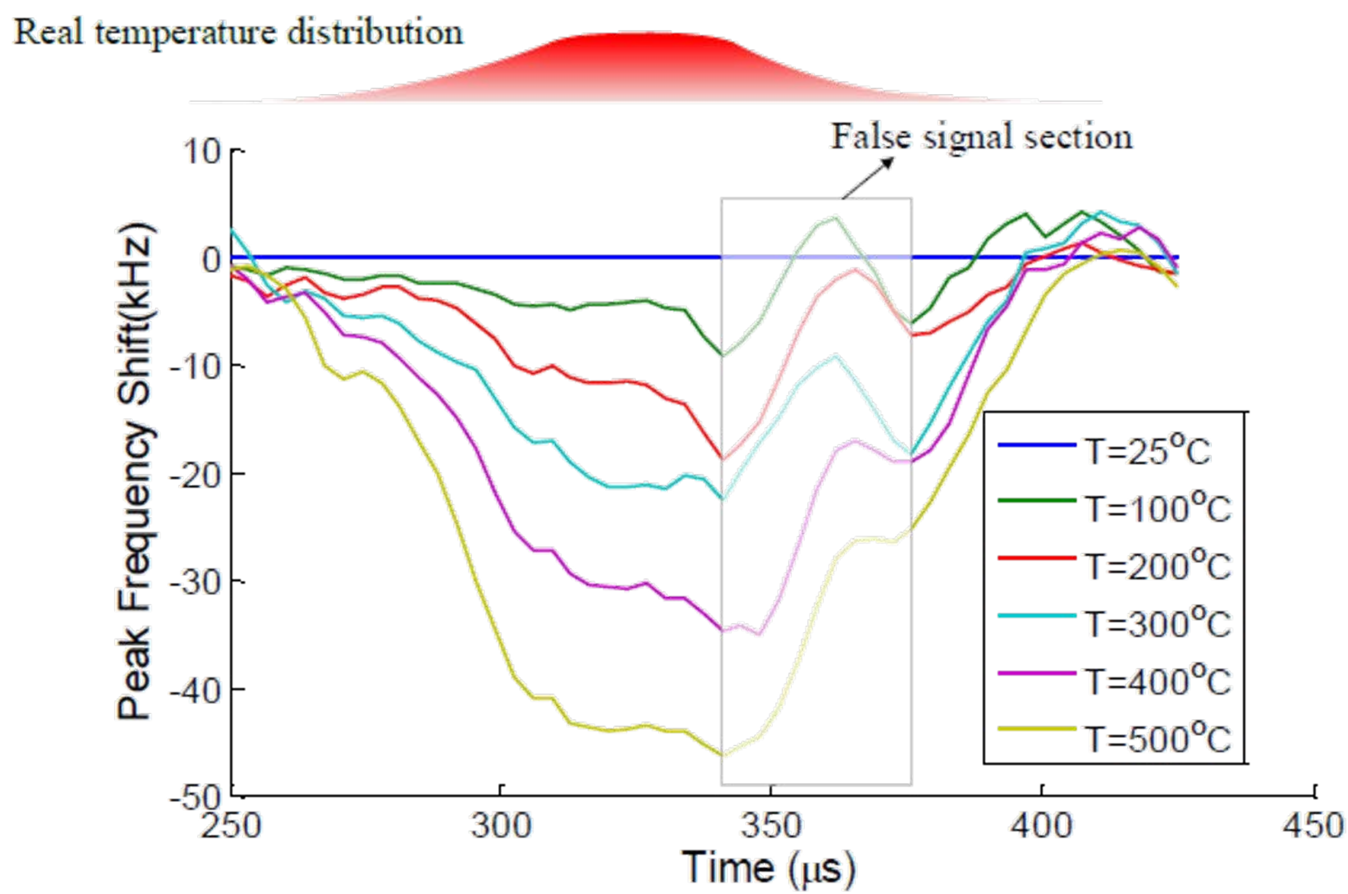
Continuous AFBG for Temperature Sensing

Metal Wire Waveguide: Pelican Alloy 785



Continuous AFBG for Temperature Sensing

METAL WIRE WAVEGUIDE: PELICAN ALLOY 785



- ***False signal caused by some systematic electrical noise and can be removed with improvement of electronic components***

Acoustic Fiber Bragg Grating (AFBG)

- Potential for opening the solution domain up with the development of AFBGs allows a much wider range of materials to be considered
- May relax the sensitivity to the effects of harsh environment variables due to the fact that optical property changes are not important, only the acoustic properties
- New sandbox of possible materials, structures and modes can be utilized

Thank You For Listening!