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Sandia National Laboratories

# State of Health Monitoring using Chirped Fiber-Optic Bragg Grating Sensing Technology

Garth Rohr, Roger Rasberry, Allen Roach

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Detection of Weak Bonds

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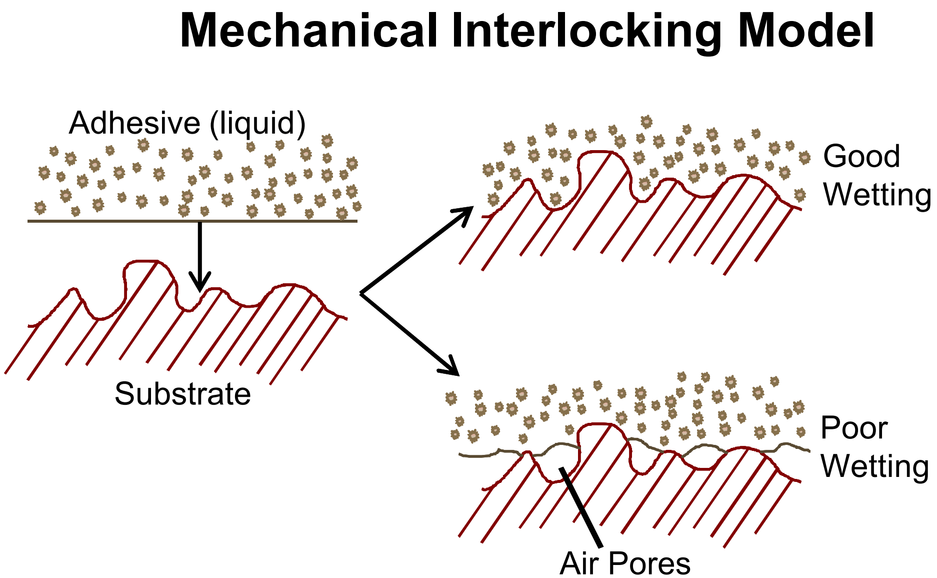
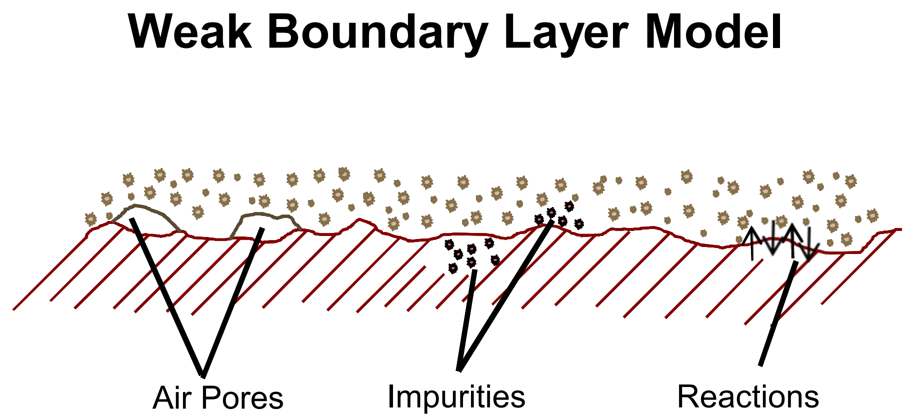



## Technical Problem

- **Debonds and adhesive failures at critical material interfaces are poorly characterized or identifiable**
- **Adhesive integrity between epoxy and alumina is not very well understood but essential to meeting breakdown strength requirements**


Yang, S.; Gu, L.; Gibson, R. F. *Compos. Struct.* **2001**, *51*, 63.
Nagy, P. B. *Journal of Nondestructive Evaluation* **1992**, *11*, 127.
Kumar, R. L. V.; Bhat, M. R.; Murthy, C. R. L. *Int. J. Adhes. Adhes.* **2013**, *42*, 60.
Vine, K.; Cawley, P.; Kinloch, A. J. *J. Adhes.* **2001**, *77*, 125.

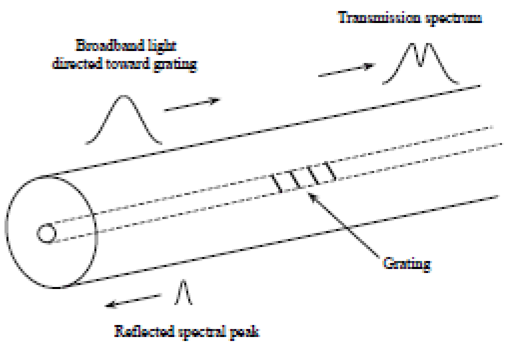
# NDI Inspection Methods

- **Time Domain Ultrasonics**: Monitor the ultrasonic echoes in the time domain.
  - If a defect exists, the local reflection coefficient will be changed. And so is the ultrasonic echo.
- **Ultrasonic Impedance and Spectroscopy**: Measures the characteristics of through-thickness vibration of a bonded structure.
  - Any changes in adhesive or adherend will result in amplitudes and resonance that are different from the undamaged structure.
- **Sonic Vibration**: Monitor vibration properties of a bonded structure.
  - Any defect will cause a local change in stiffness and thus vibration behavior to the whole structure.
- **Vibrothermography**: Monitor the surface temperature of a component as it is cyclically stressed.
  - A defect will cause a local rise in temperature due to either frictional heating at its internal surfaces or hysteretic energy dissipation. Use infrared thermal imaging camera.
- **Thermography**: Measure the response of the specimen to thermal transients created by an external heat source.
  - For example, heat the back surface of the structure and defects can be found by measuring temperature changes at front since defective areas are cooler due to the lower conduction through defects.

**Many advantages, however the ability to reliably detect weak bonds is debatable!!!**

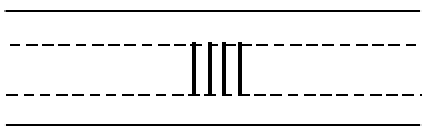
Hart-Smith, L. J. *J. Compos. Technol. Res.* **2002**, *24*, 133.
Yang, S.; Gu, L.; Gibson, R. F. *Compos. Struct.* **2001**, *51*, 63.

# Fiber Bragg Grating Sensor Design

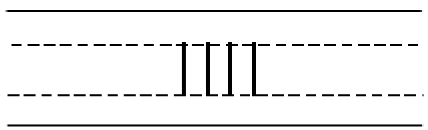


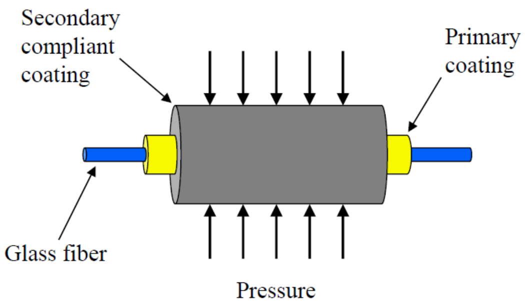

As the fiber undergoes tension & compression, the grating spacing changes

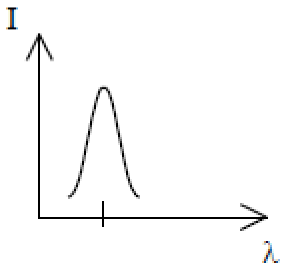
Grating spacing $d_1$



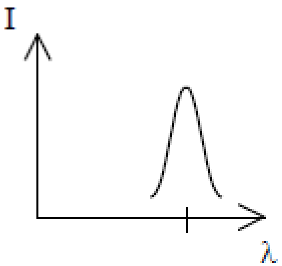
Grating spacing $d_2$






Reflected peak at lower center wavelength




Reflected peak at higher center wavelength

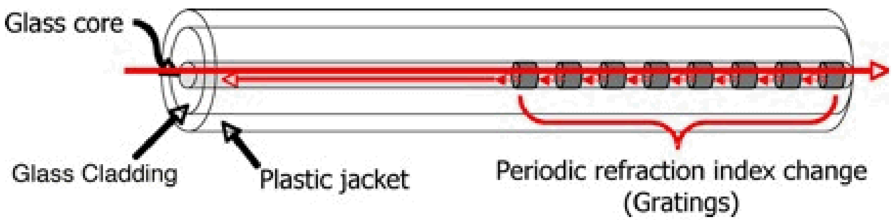
Grating spacing changes as the fiber goes through any tension or compression

**Advantages: 1) Inexpensive, 2) Facile, 3) Spatial dimension, 4) Regions/Area, 5) Continuous**

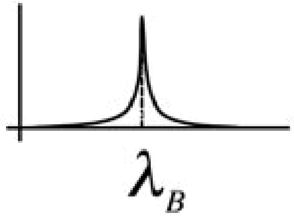
Udd, Eric. Review of Multi-Parameter Fiber Grating Sensors. Columbia Gorge Research, LLC.

# Grating Type

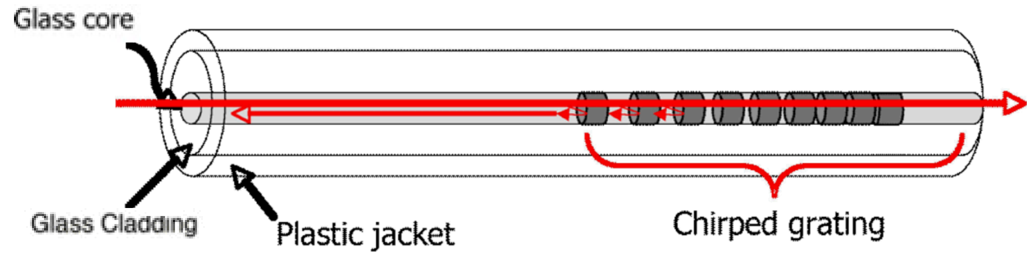
## FBG



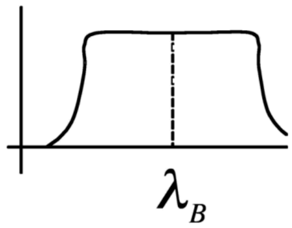

Narrow band reflection




## Chirped FBG




Broad band reflection




Fiber Bragg Gratings are periodic whereas chirped gratings are graduated and exhibit broadband reflectance.

Wang, Y.; Han, B.; Kim, D. W.; Bar-Cohen, A.; Joseph, P. *Exp. Mech.* **2008**, *48*, 107.
Udd, E.; Benterou, J.; May, C.; Mihailov, S. J.; Lu, P. In *Fiber Optic Sensors and Applications Vii*; Mendez, A., Du, H. H., Wang, A., Udd, E., Mihailov, S. J., Eds.; Spie-Int Soc Optical Engineering: Bellingham, 2010; Vol. 7677.

# Tension or compression are expressed in microstrain (με)

Basic Principle: Monitor the shift in wavelength of the reflected “Bragg” signal with the changes in strain or temperature.

$$\lambda_B = 2n\Lambda$$

n: effective index of the core
$\Lambda$: grating pitch

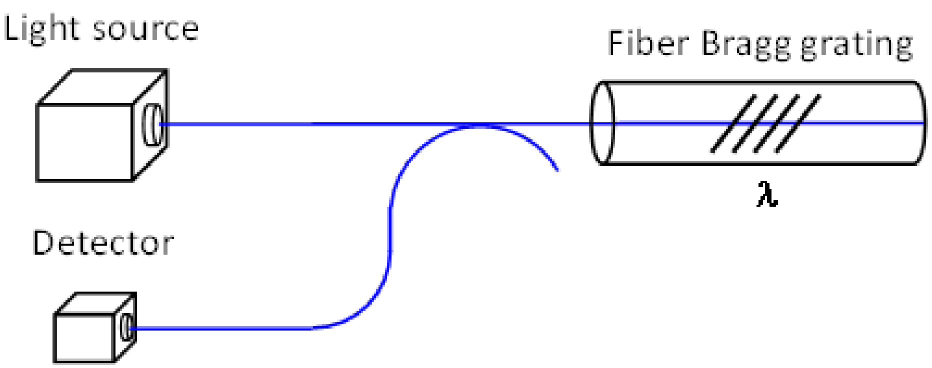
$$\Delta\lambda_B = 2n\Lambda\left(\left\{1-\left(\frac{n^2}{2}\right)[P_{12}-v(P_{11}+P_{12})]\right\}\varepsilon+[\alpha+\frac{\frac{dn}{dT}}{n}]\Delta T\right)$$

Rule-of-thumb (when $\Delta T = 0$): $\frac{1\ nm}{1000\ \mu\varepsilon}\ at\ 1.3\ \mu m \rightarrow \boldsymbol{\frac{1\ nm}{1200\ \mu\varepsilon}}\ at\ 1.55\ \mu m$

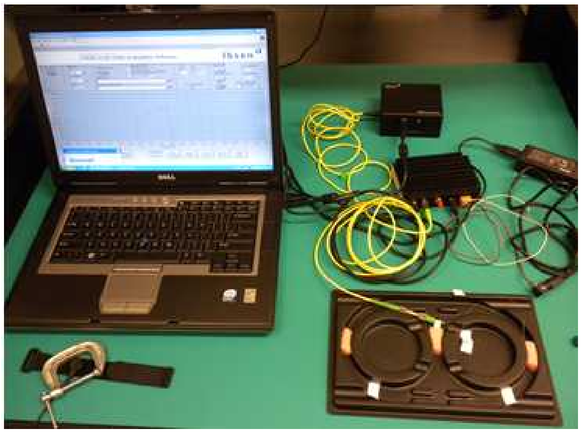
(when $\Delta T \neq 0$): $\frac{1\ pm}{0.1\ ℃}\ at\ 1.3\ \mu m \rightarrow \frac{1\ pm}{0.12\ ℃}\ at\ 1.55\ \mu m$

Kersey, A. D.; Davis, M. A.; Patrick, H. J.; LeBlanc, M.; Koo, K. P.; Askins, C. G.; Putnam, M. A.; Friebele, E. J. *J. Lightwave Technol.* **1997**, *15*, 1442.
Cusano, A.; Capoluongo, P.; Cutolo, A.; Giordano, M. *IEEE Sens. J.* **2006**, *6*, 111.

# Experimental Setup



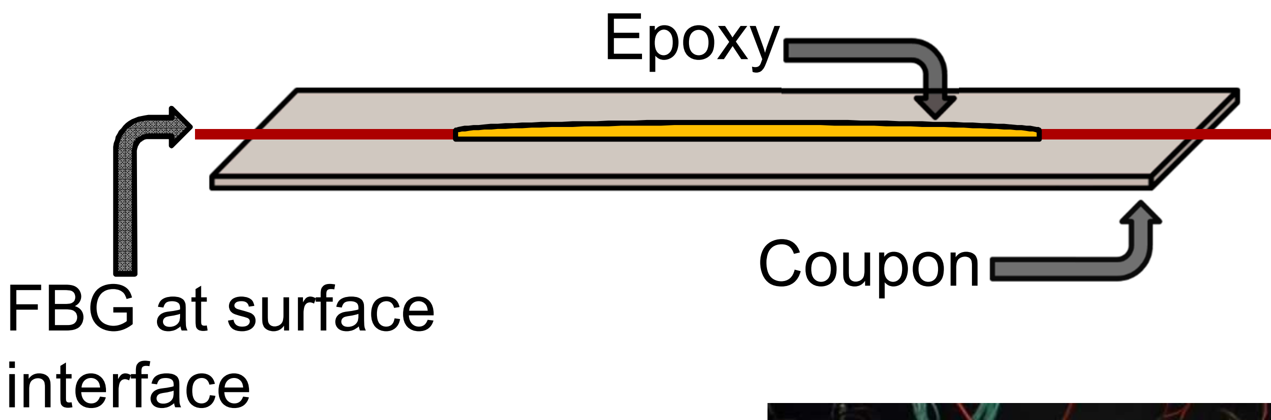

I-MON 512E-USB 2.0

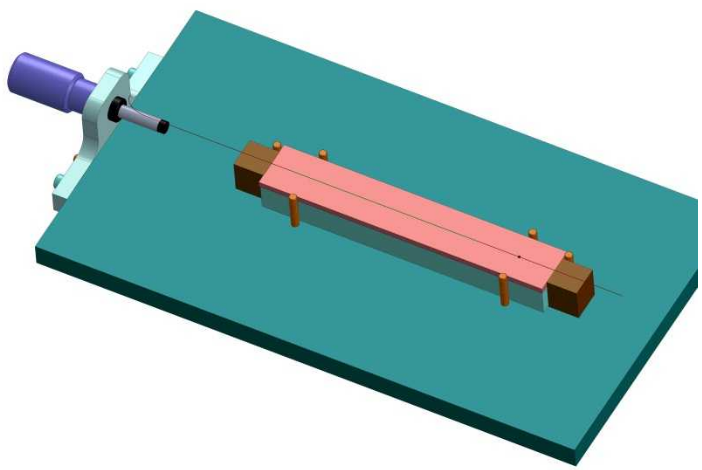


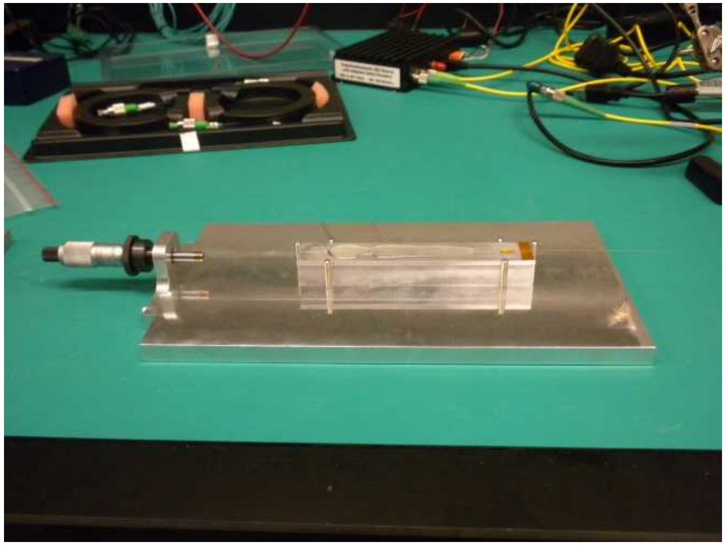
Micron Optics si255

- Basic FBG testing system
- Our current FBG system setup

# Embedded Fibers

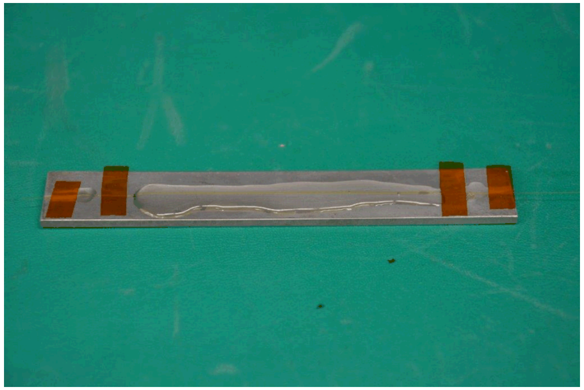


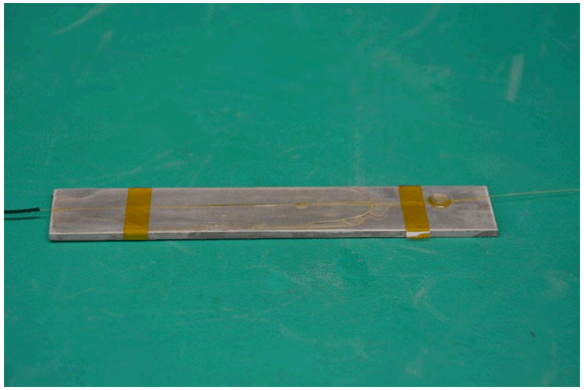





Rasberry, R. D.; Udd, E.; Rohr, G. D.; Miller, W. D.; Calkins D.; McElhanon, J. R. In Prep.

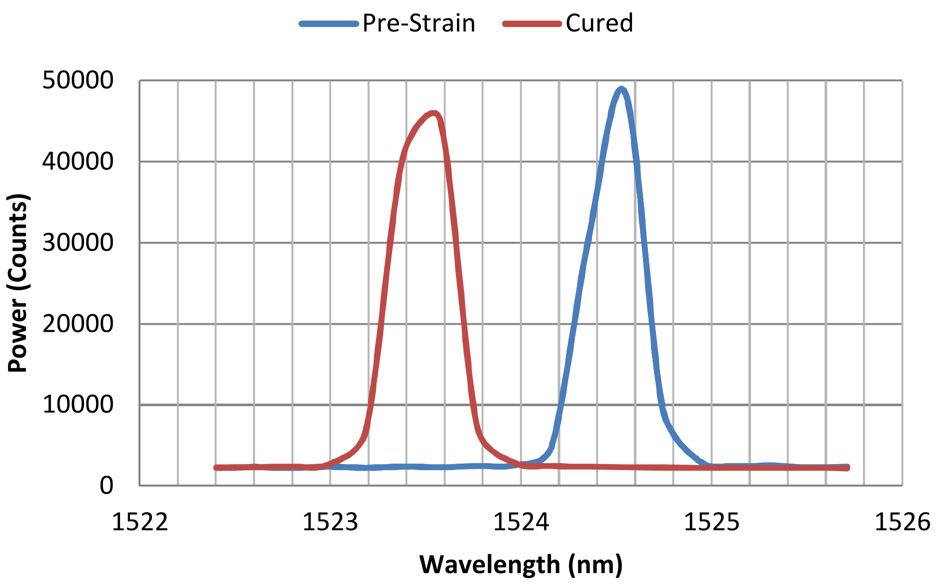
# Poor and Good Adhesion on Aluminum

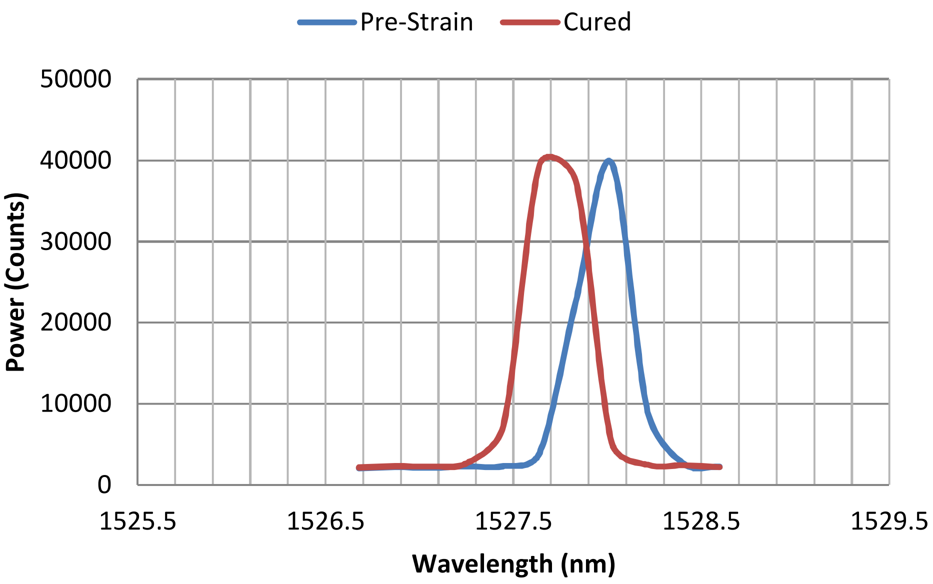




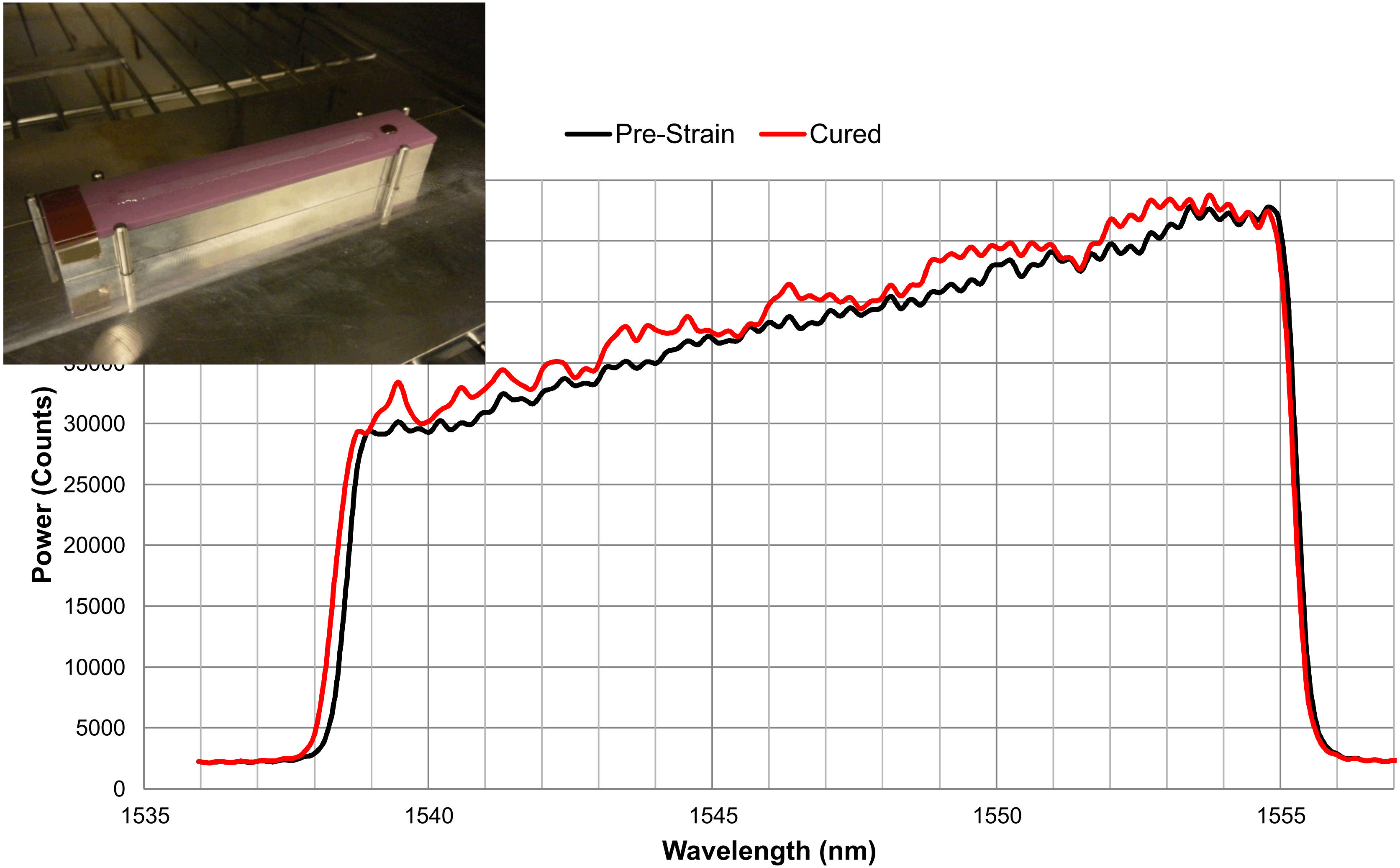
## Good Adhesion on Aluminum

## Ultra II on Aluminum



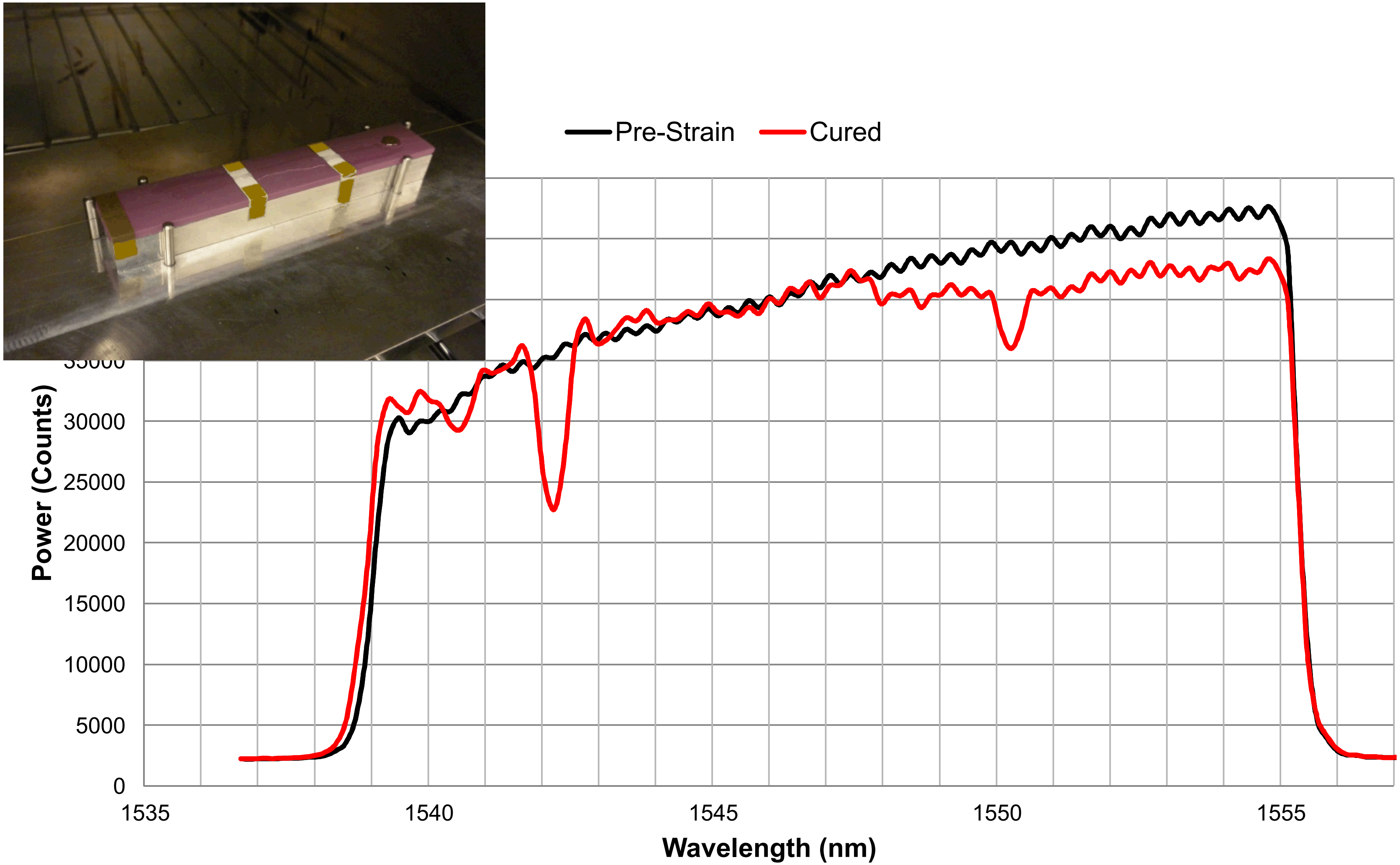



# Good Adhesion on Alumina



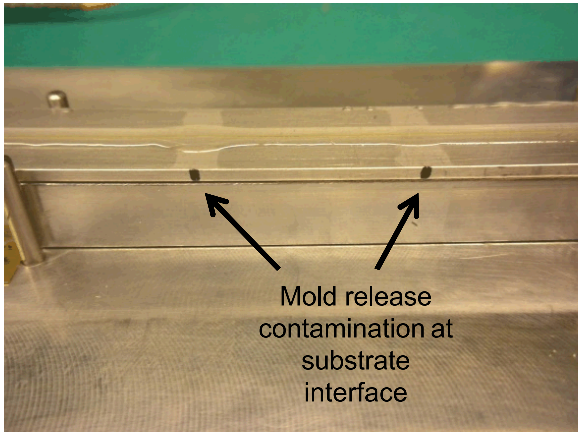

$$\Delta\lambda = 0.129\ nm\ \&\ \Delta T = 0 \therefore 154.8\ \mu\varepsilon$$

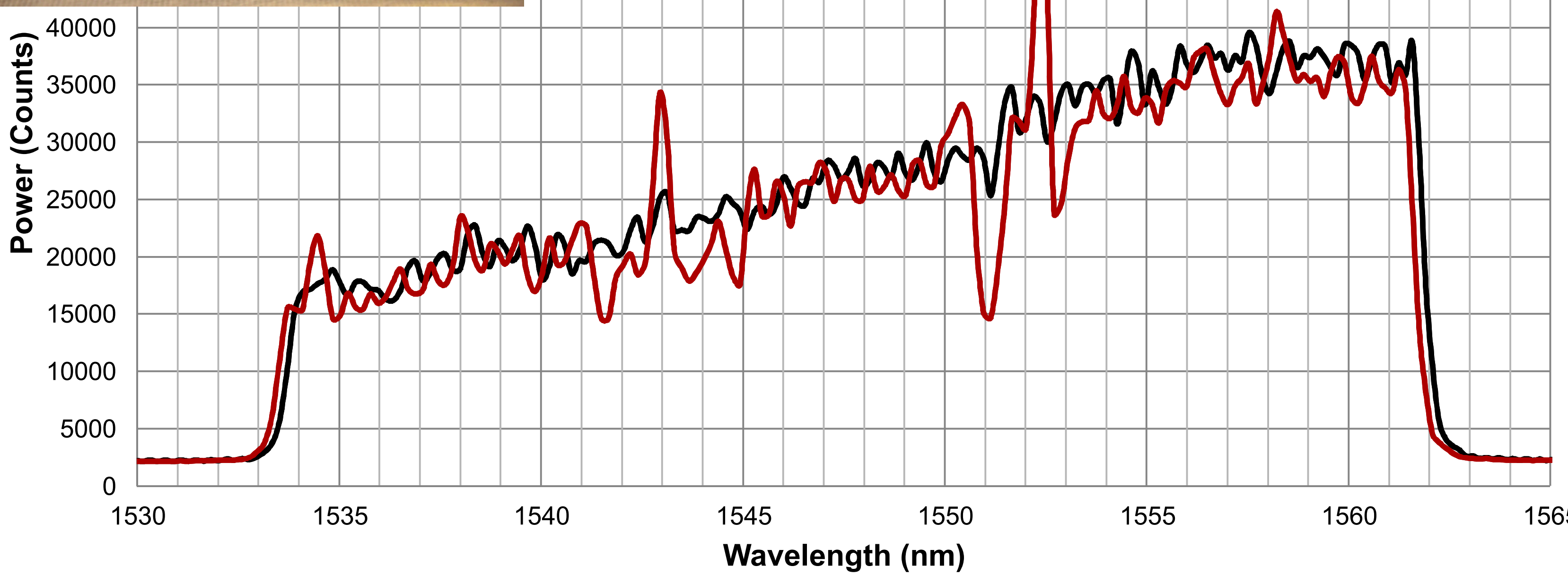
# Artificial Areas of Poor Adhesion




$$\Delta\lambda = 0.066\ nm\ \&\ \Delta T = 0 \therefore 79.2\ \mu\varepsilon$$

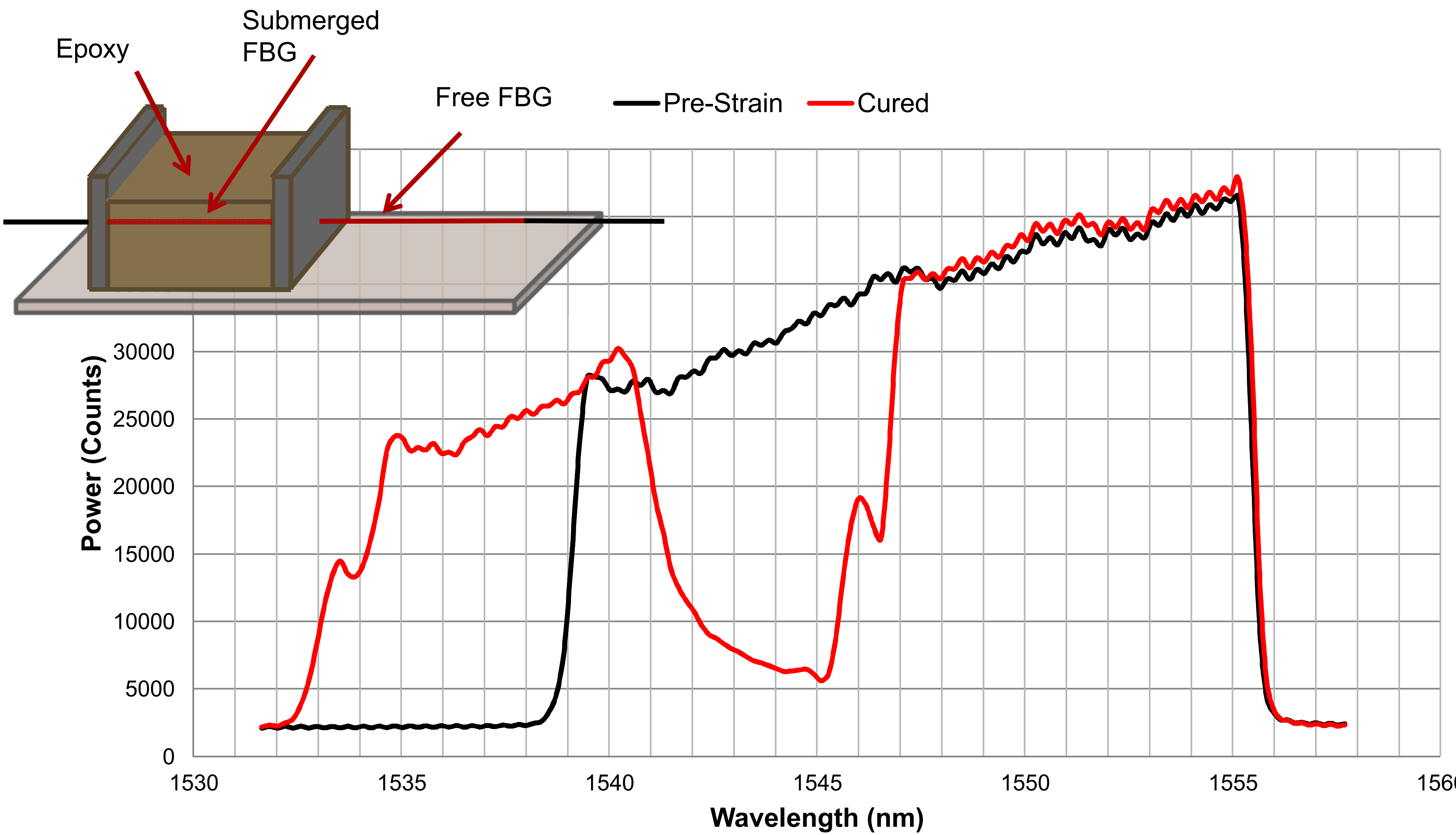
# Areas of Mold Release Contamination



# Half and Half Epoxy Body






$$\Delta\lambda = 4.925\ nm\ \&\ \Delta T = 0\ \therefore\ 5911\ \mu\varepsilon$$

# Attaching Fiber to Cone Geometry

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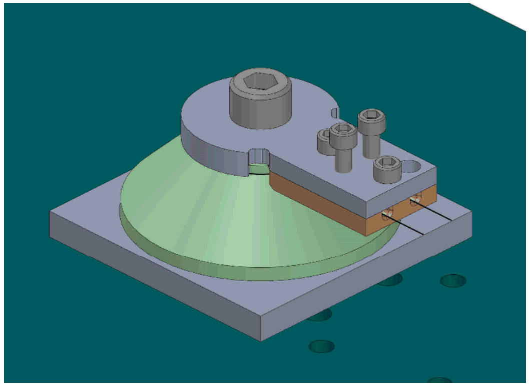
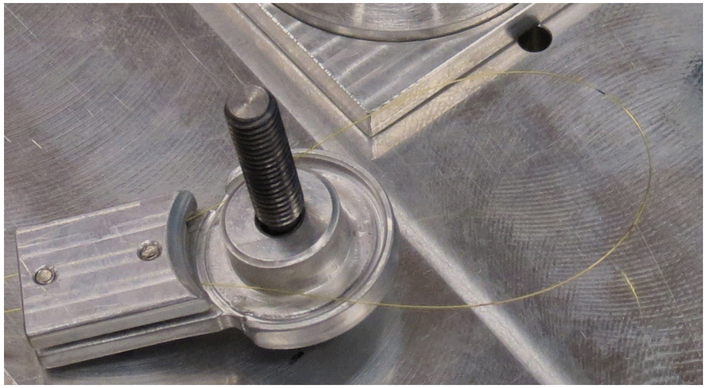
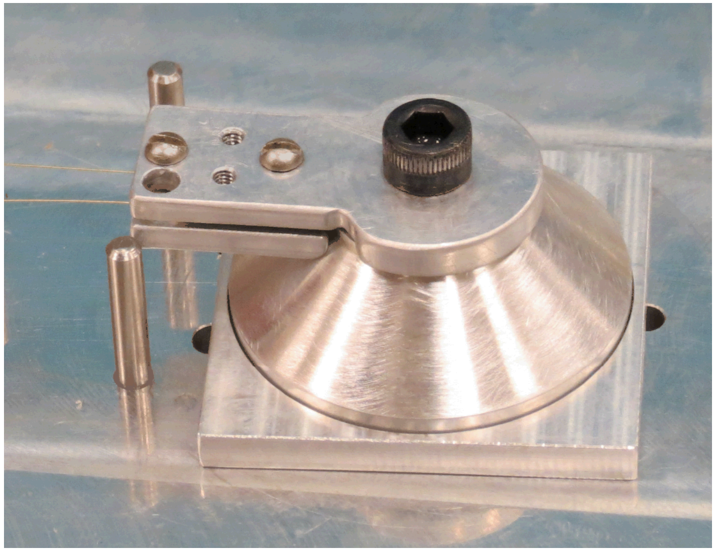


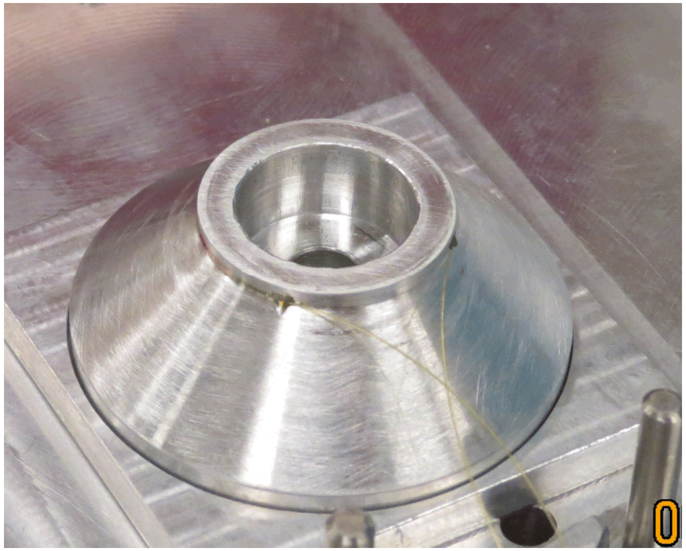
Fixture Design



FBG threaded through mounting fixture

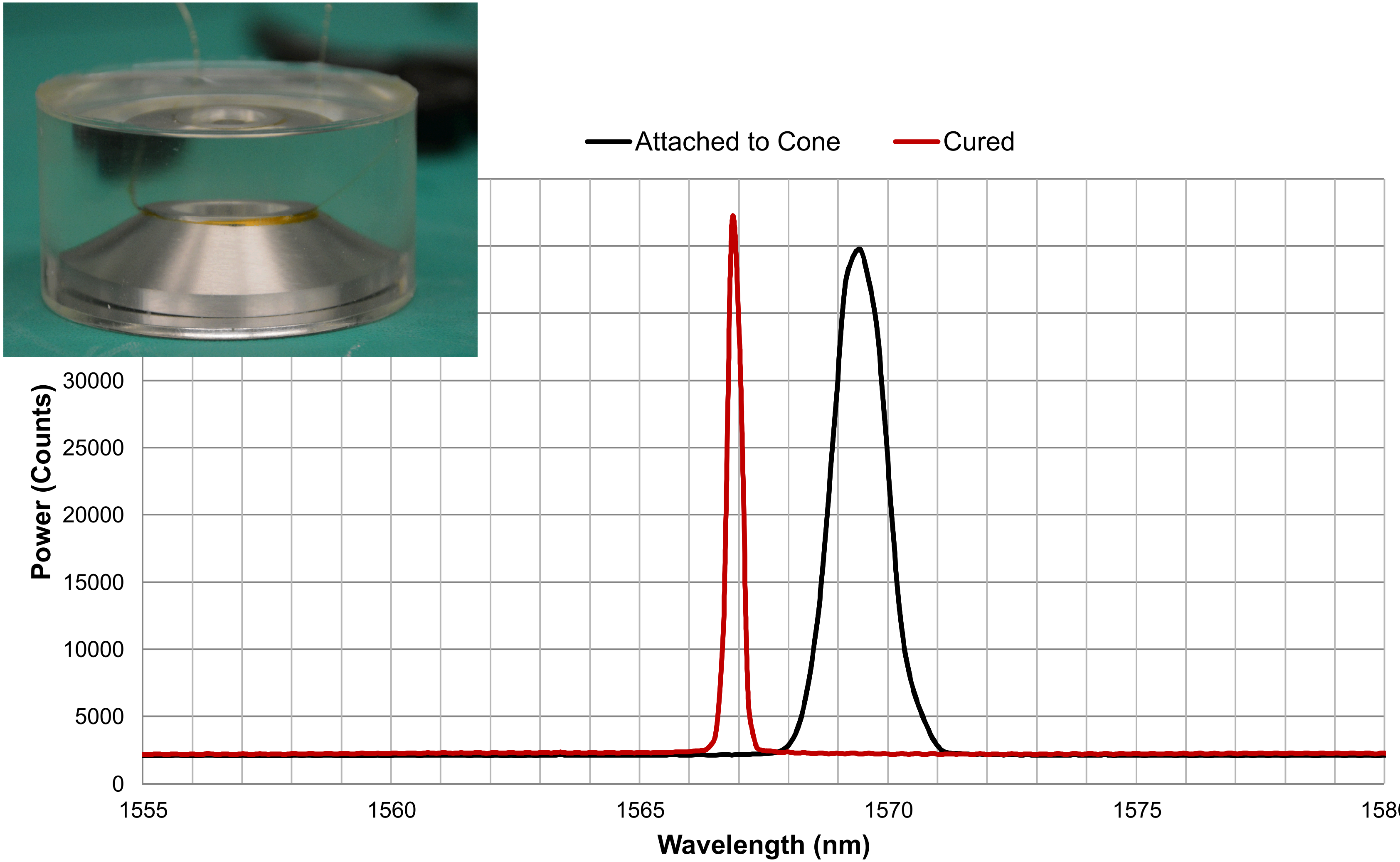


Fixture is placed on top of the cone



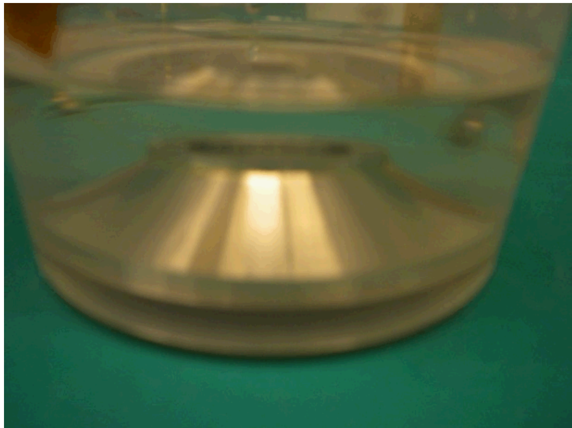
FBG epoxied to cone

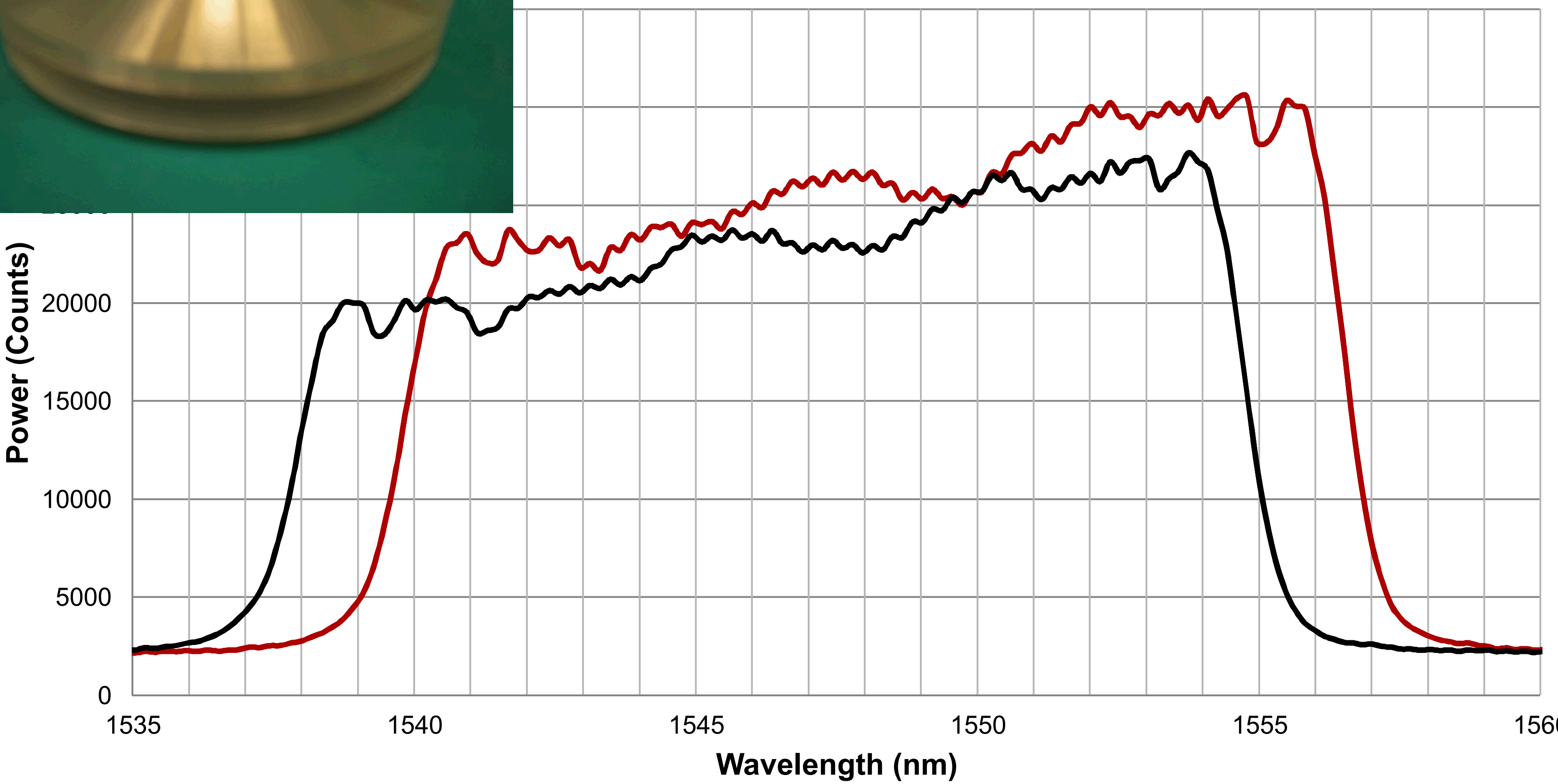
# FBG Attached to a Cone Geometry




$$\Delta\lambda = 1.745\ nm\ \&\ \Delta T = 0 \therefore 2094\ \mu\varepsilon$$

# Chirped FBG Cone Geometry






$$\Delta\lambda = 2\ nm\ \&\ \Delta T = 0 \therefore 2400\ \mu\varepsilon$$

# Chirped FBG Cone Geometry Filled

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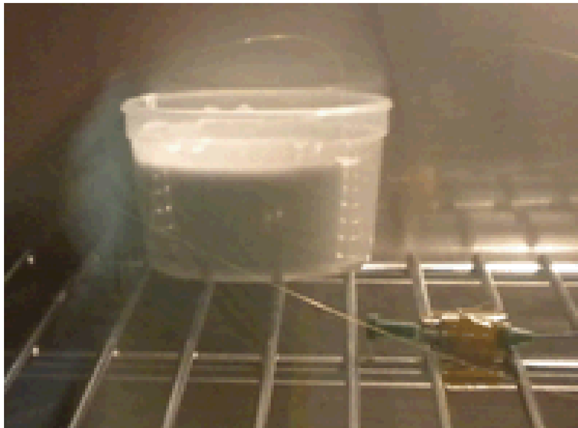
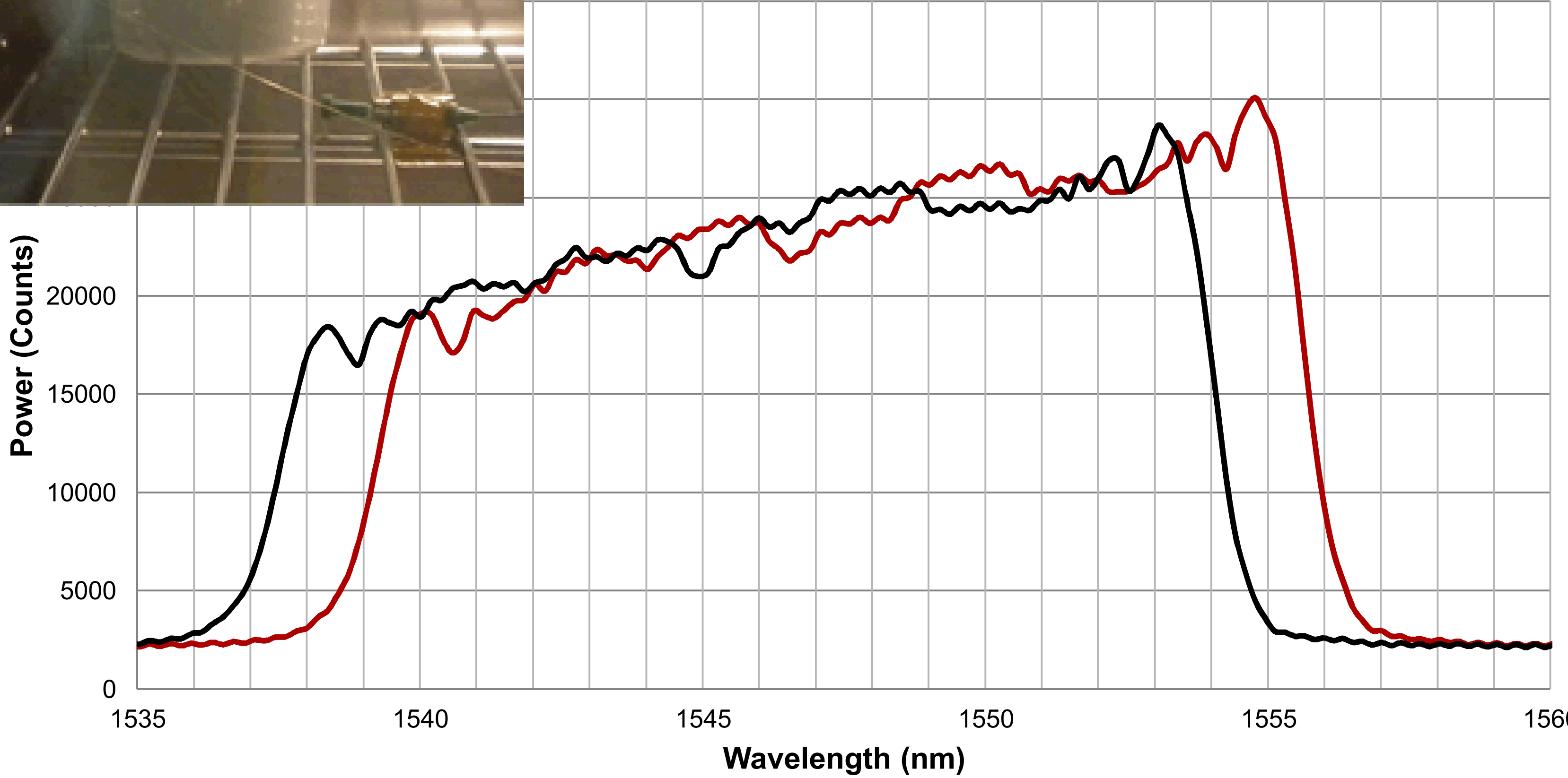
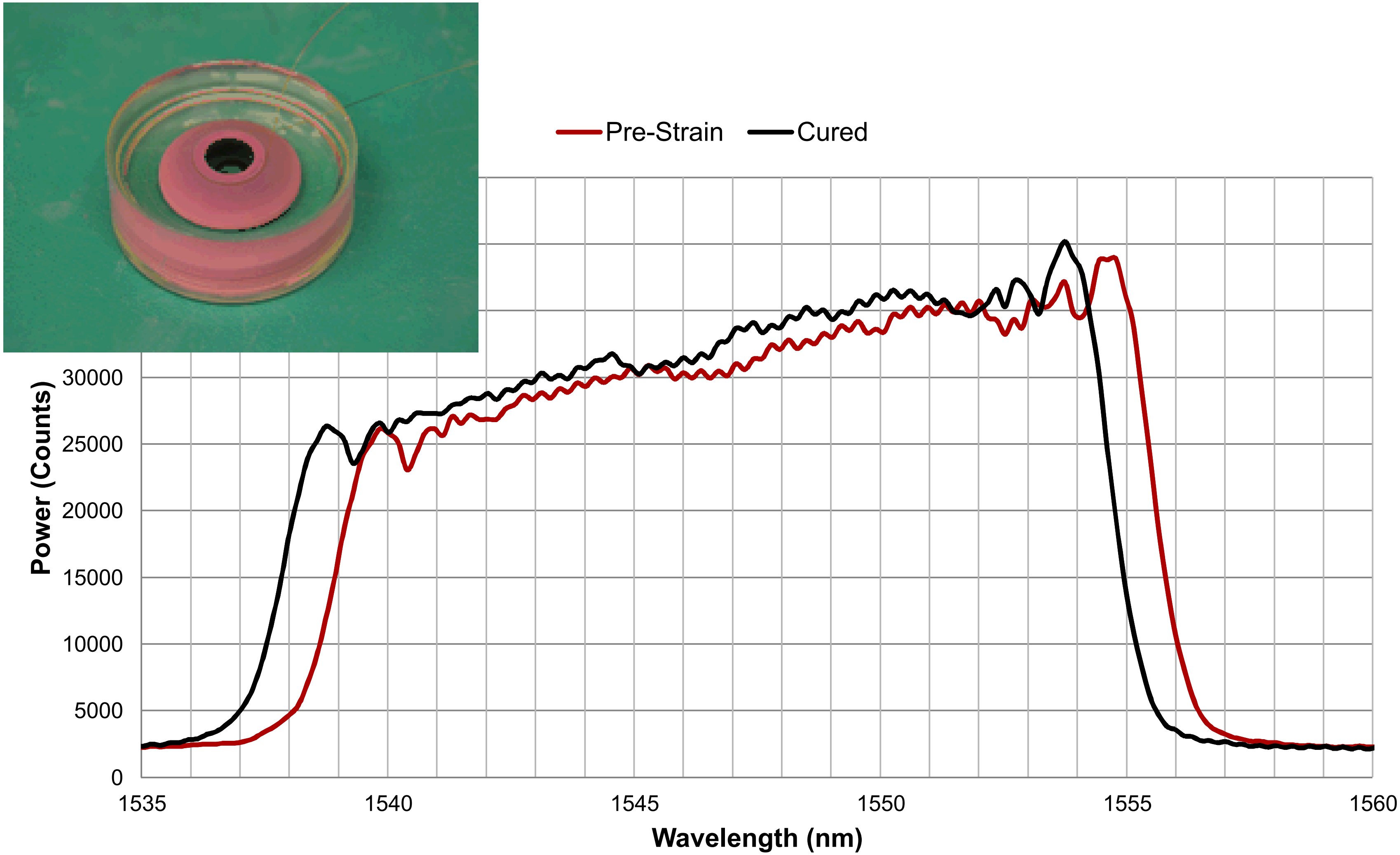




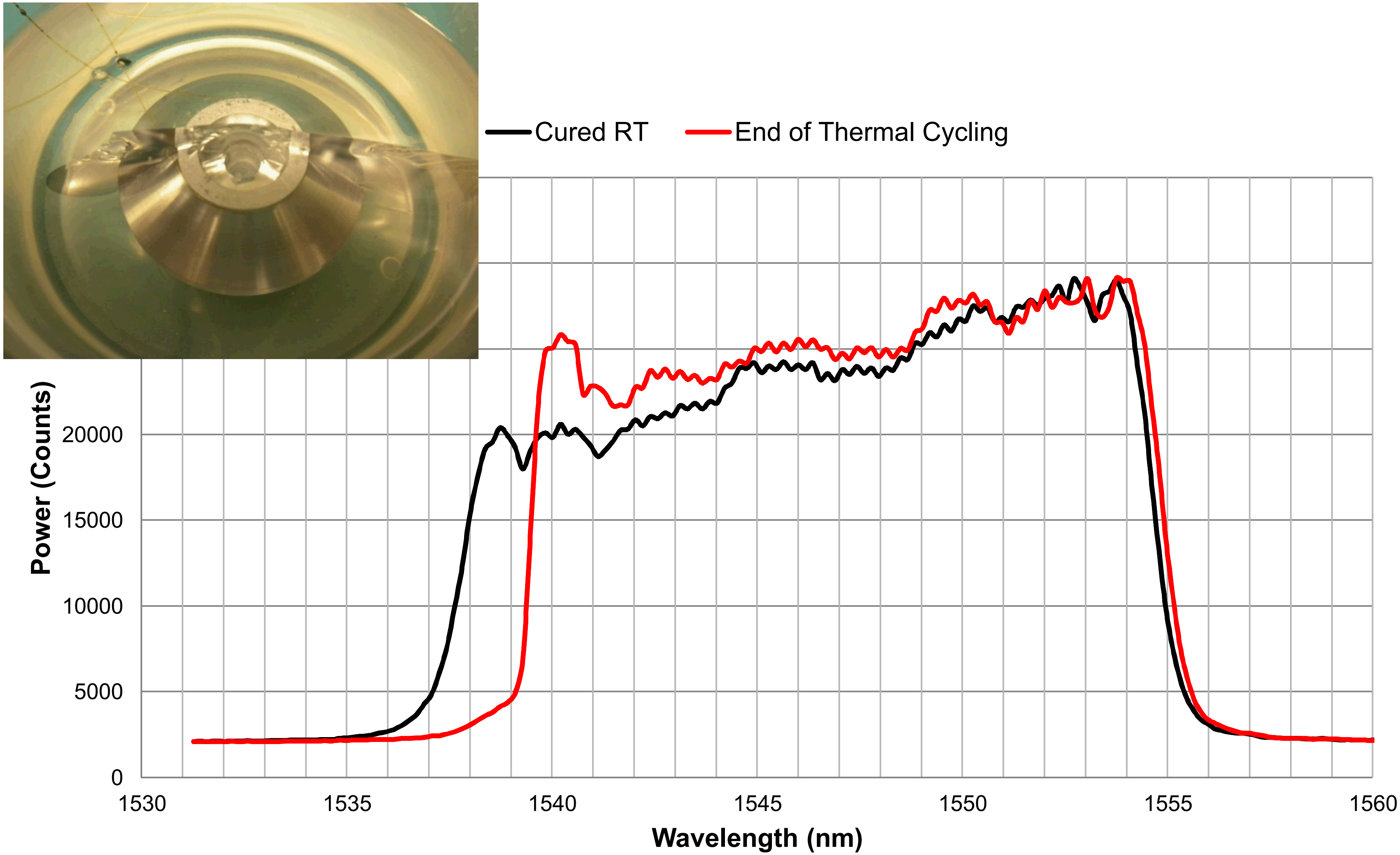

$$\Delta\lambda = 1.5\ nm\ \&\ \Delta T = 0 \therefore 1800\ \mu\varepsilon$$

# Chirped FBG Cone Geometry

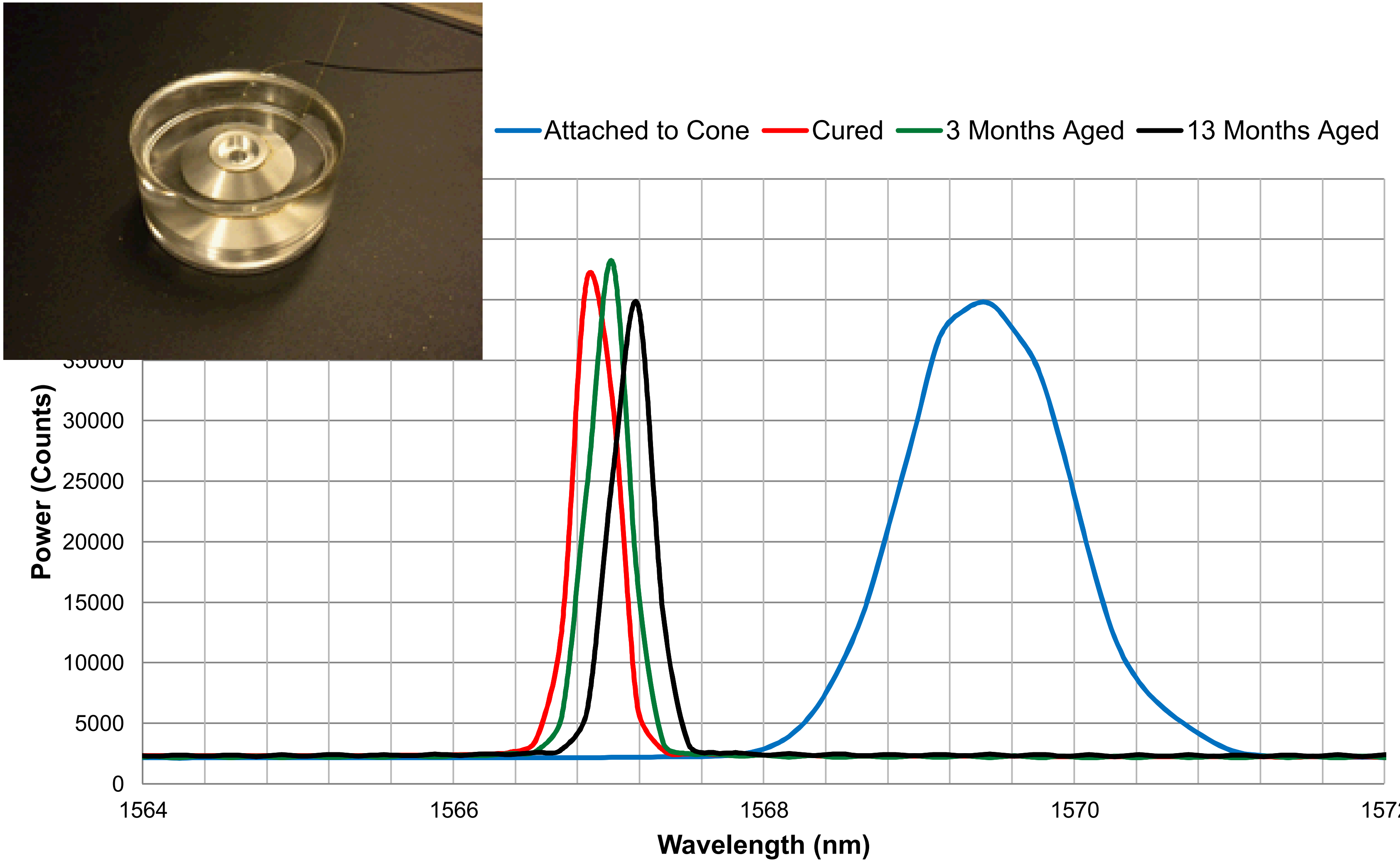



$$\Delta\lambda = 1\ nm\ \&\ \Delta T = 1200\ \mu\varepsilon$$

# Thermal Cycling



# Aging



Attached to Cone
Cured
3 Months Aged
13 Months Aged
Power (Counts)
30000
25000
20000
15000
10000
5000
0
1564
1566
1568
1570
1572
Wavelength (nm)

- Advantages

- Facile
- Spatial Information
- Regions/area of good adhesion
- Continuous/Real-time
- Inexpensive and mobile

- Future Variables

- Contaminate potted cone with mold release
- Statistical study
- Further aging

# Acknowledgements


- Noah Blach (Air Force)
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- Ryan Davis (Sandia)
- Trey Pinon (Sandia)
- Jim McElhanon (Sandia)
- Eric Udd (Columbia Gorge Research, LLC)


Thank you for attending!

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# Extra Slide

- Silica (cristoballite) hydroxyls = 4.6 $OH/nm^2$
- Alumina (alpha) hydroxyls = 2.4-4.2 $OH/nm^2$