SAND2016-3539C

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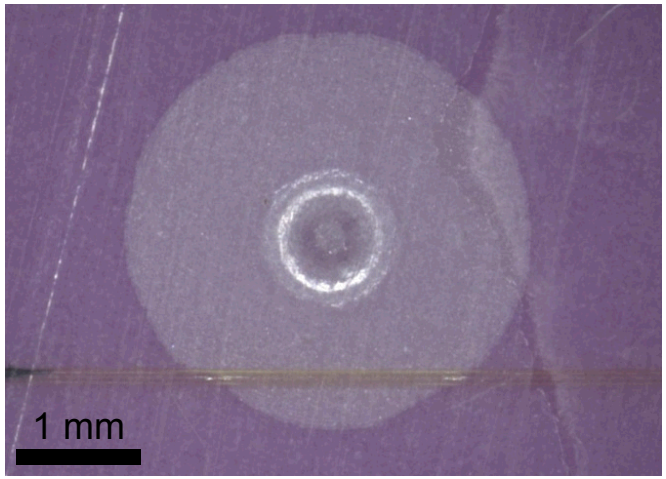

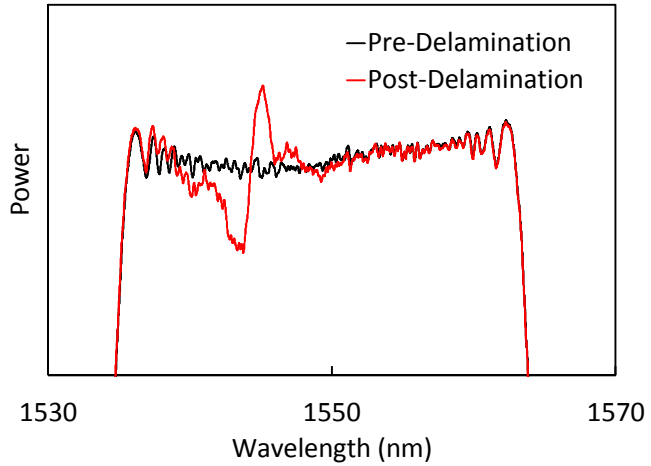

Sensing delamination in epoxy encapsulant systems with fiber Bragg gratings

Brad H. Jones, Garth D. Rohr, Amy K. Kaczmarowski

April 21, 2016

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Fiber Bragg Gratings

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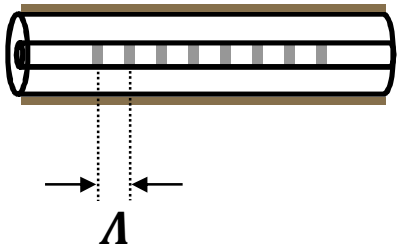
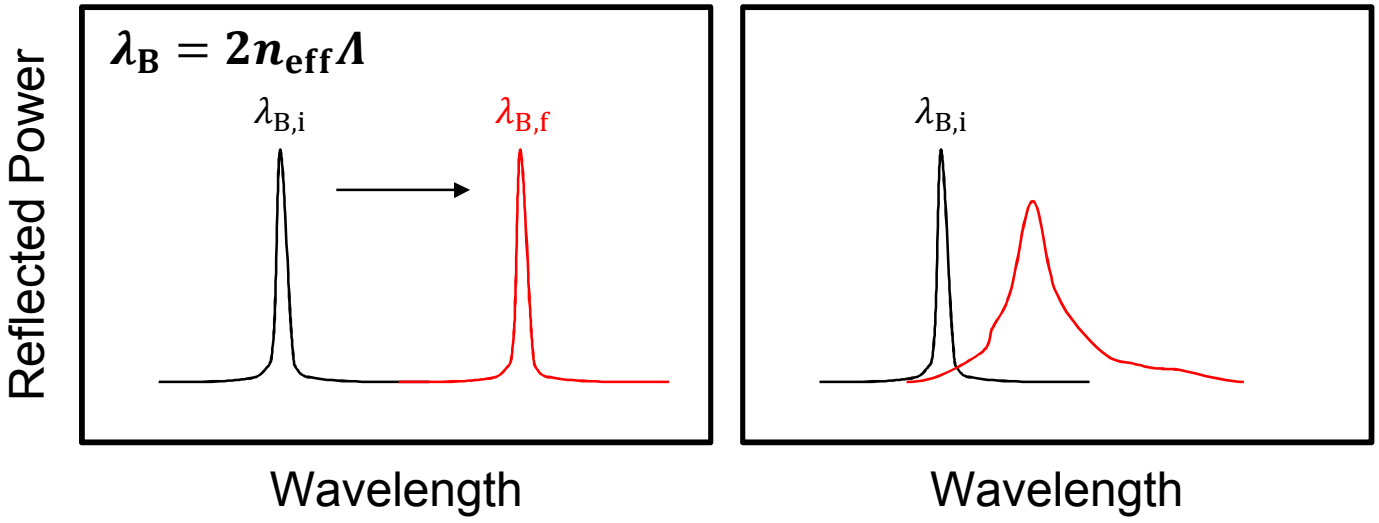
under uniform strain:

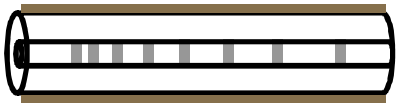
under non-uniform strain:

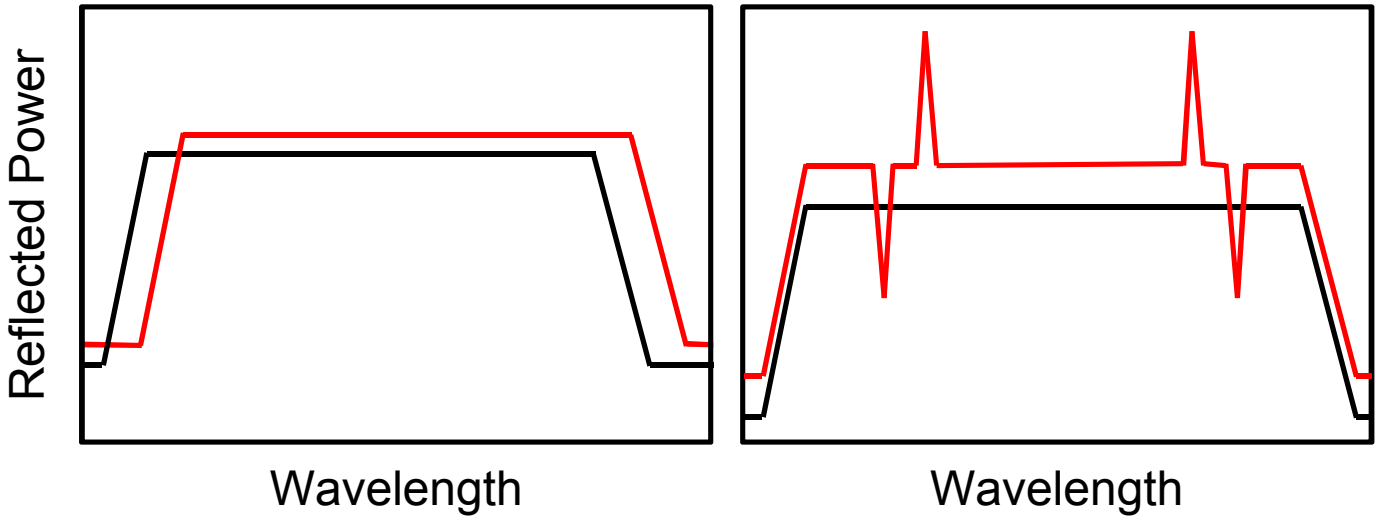
Uniform FBGs





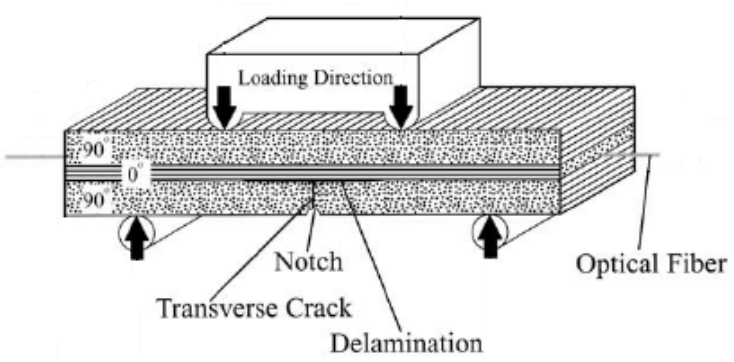
Chirped FBGs



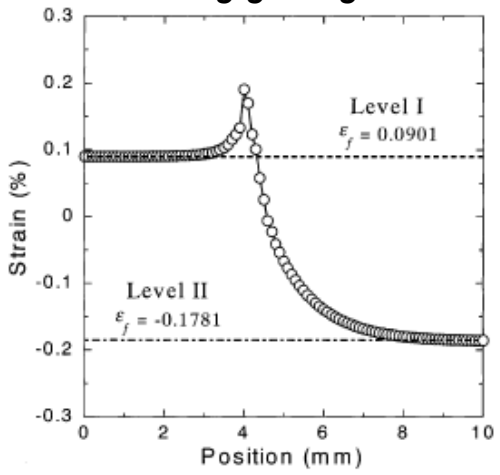


Fiber Bragg Gratings and Delamination

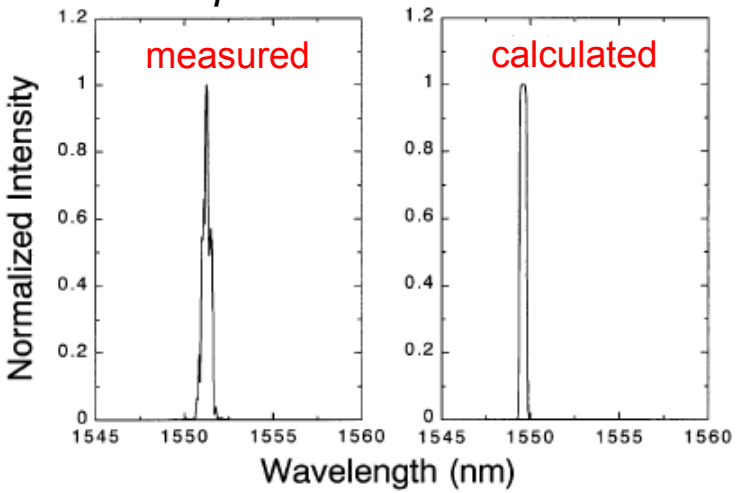
Past work with fiber-reinforced composites has shown non-uniform FBG axial strain distributions associated with delamination



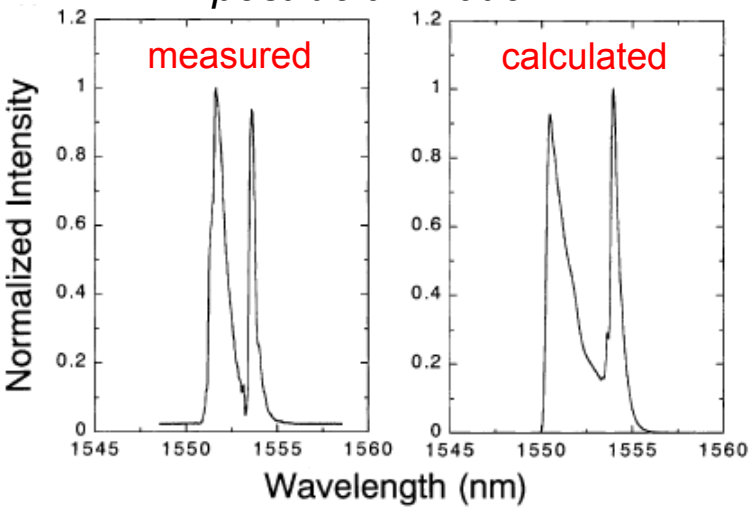
FEM-predicted strain distribution along grating



pre-delamination



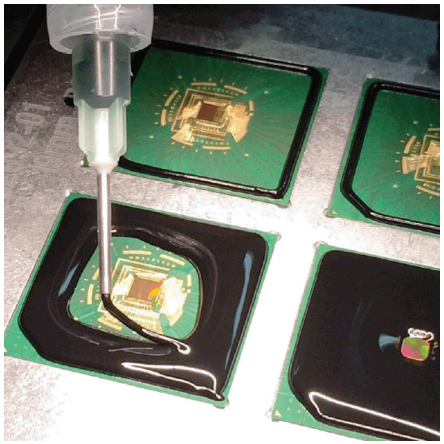
post-delamination



Takeda, S.; *et al. Composites A* **2002**, *33*, 971-980.

Our Objectives

Many encapsulated devices are at high risk for internal delamination that can only be diagnosed by device failure!



http://www.samtecmicroelectronics.com, retrieved Nov. 2015

- **Can we used embedded FBGs to passively sense the occurrence of delamination at interfaces between encapsulants and their encapsulated materials?**
  - **What are the local strain profiles associated with delamination?**
  - **Can we correlate FBG response with key interfacial properties (*e.g.*, delamination size, adhesive strength)**
- **Can we used embedded FBGs in complex and functional encapsulated devices to provide an indication of delamination-associated failure?**

Delamination at Planar Epoxy-Alumina Interfaces

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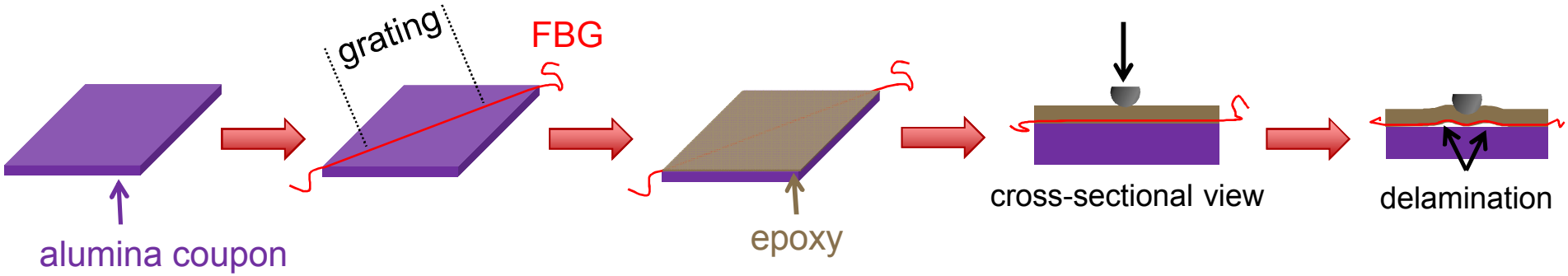
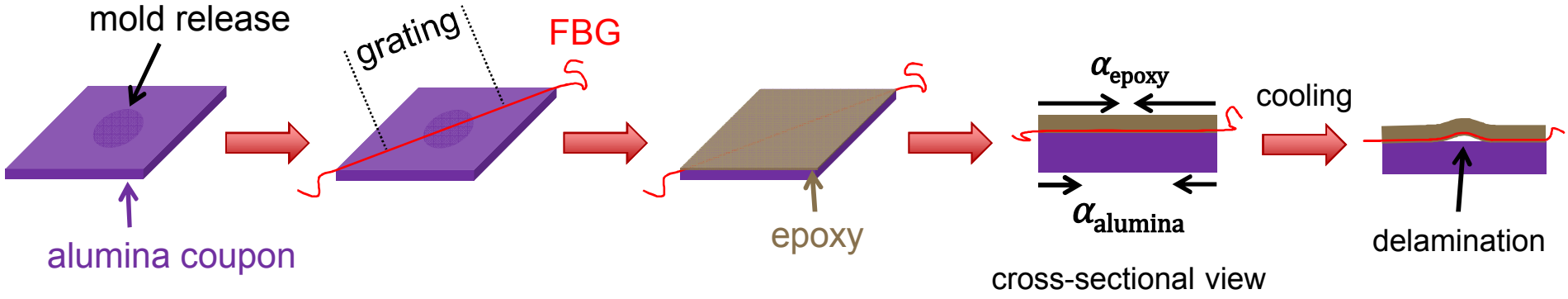
Method 1: Indentation-Induced Delamination



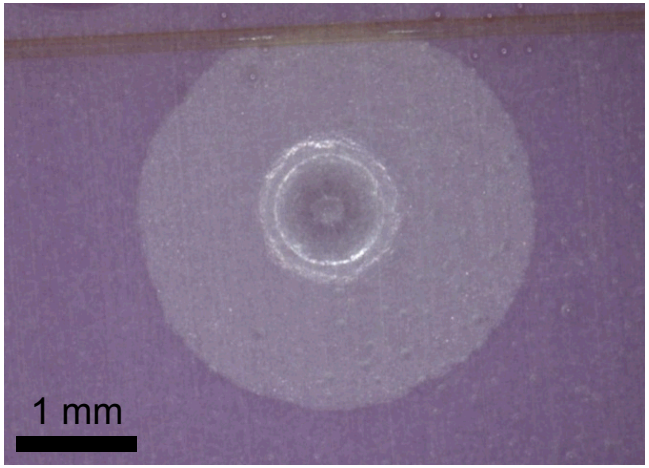
Method 2: Thermal Mismatch-Induced Delamination

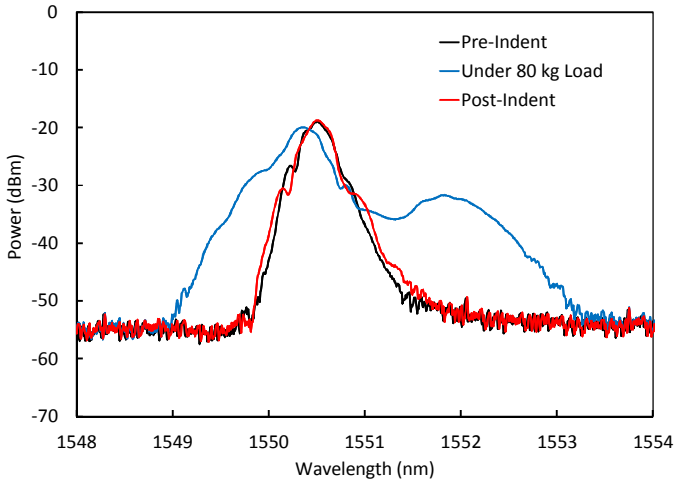


Indentation-Induced Delamination

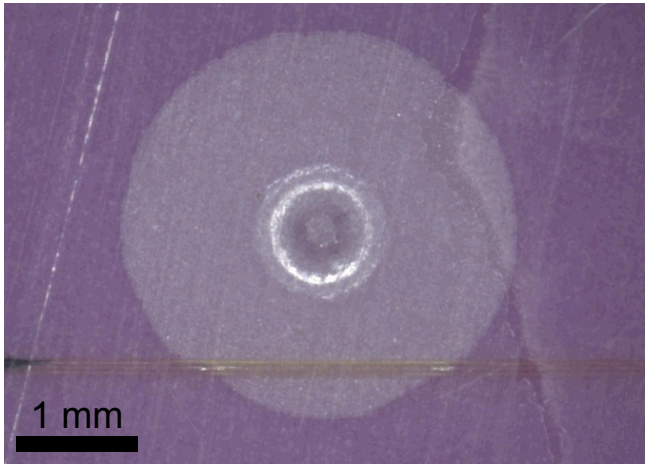
Embedded FBGs exhibit characteristics of non-uniform strain distribution during and after indentation and delamination

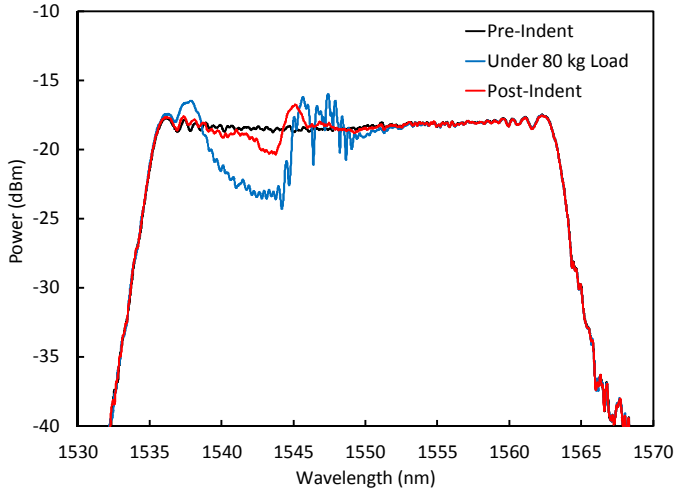
Uniform FBG





Linearly Chirped FBG

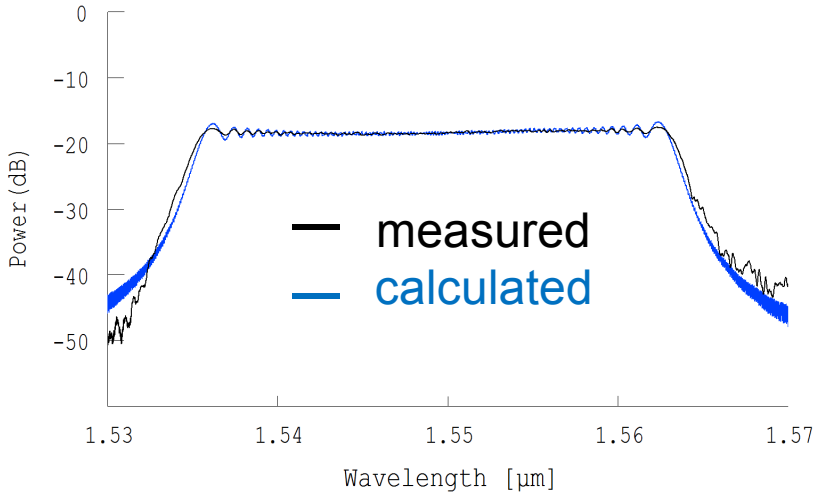




Residual Strain Distribution

OptiGrating simulation qualitatively captures residual perturbation in chirped spectrum using a Gaussian tensile strain distribution

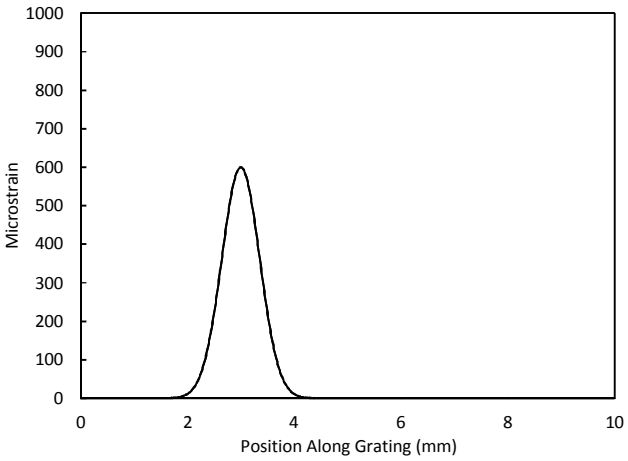
Pre-Indent

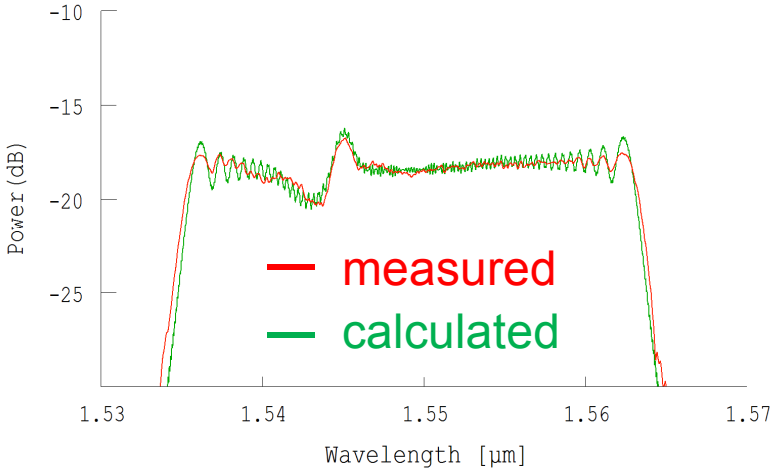


OptiGrating Inputs

- Core-cladding refractive indices (RIs) and dimensions of SMF-28 standard
- Sinusoidal core RI variation $1.15 \cdot 10^{-4}$
- 10 mm grating length
- 10 nm linear chirp function
- Center wavelength 1549.3 nm

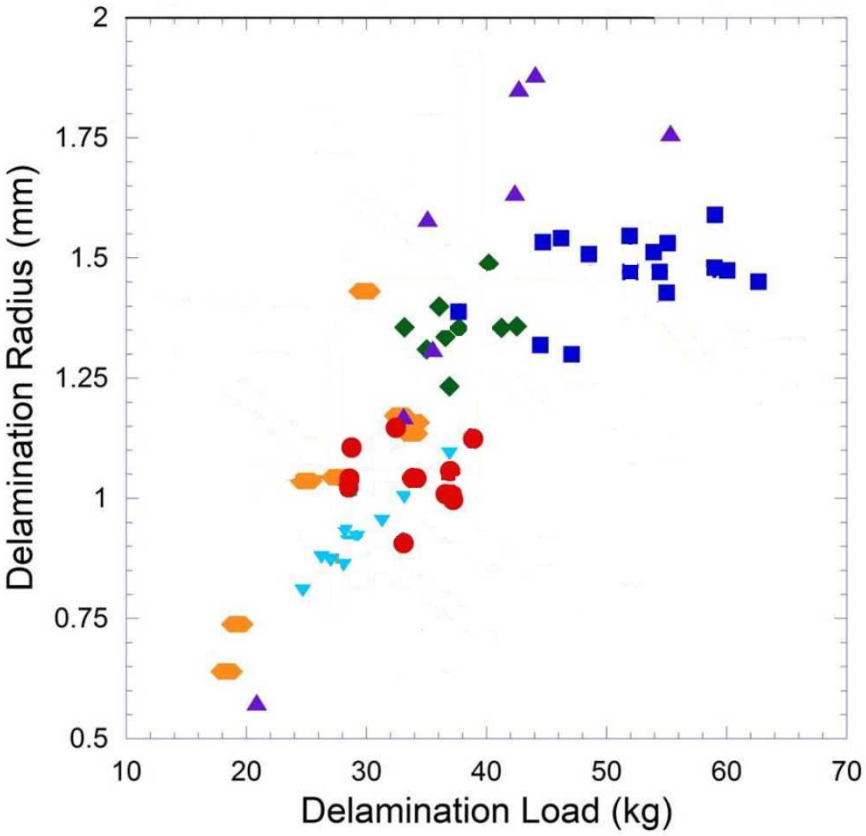
Post-Indent

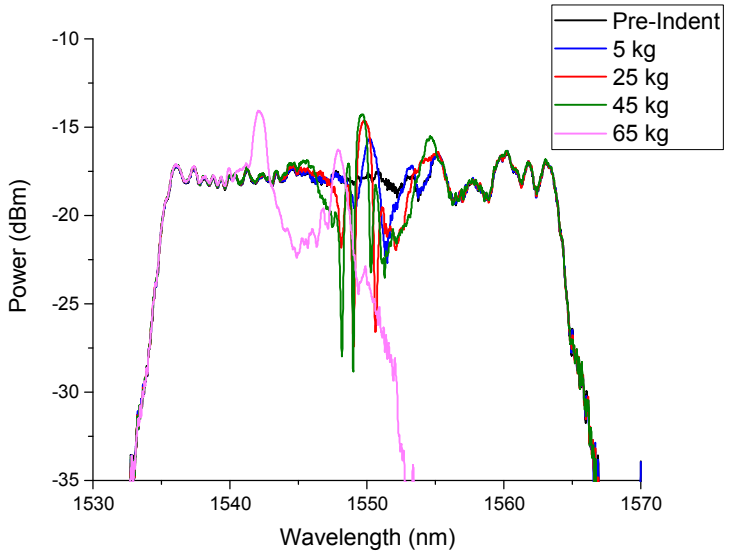


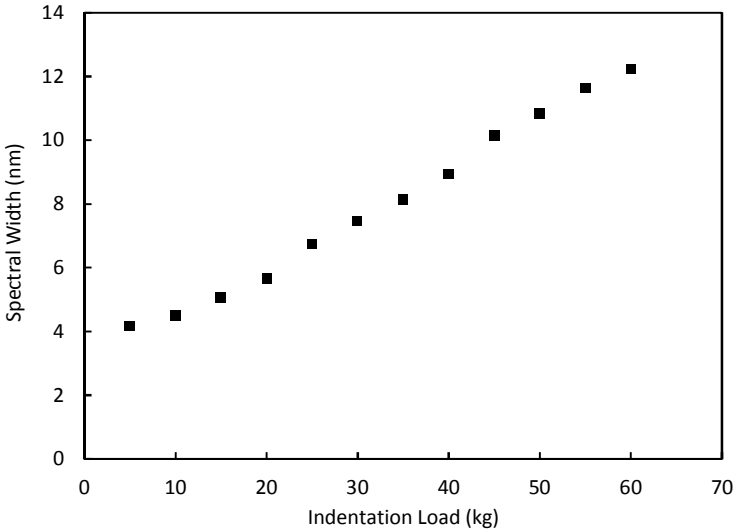


Indentation Load Scaling

The width over which a given spectrum deviates from its corresponding spectrum pre-indentation scales with indentation load



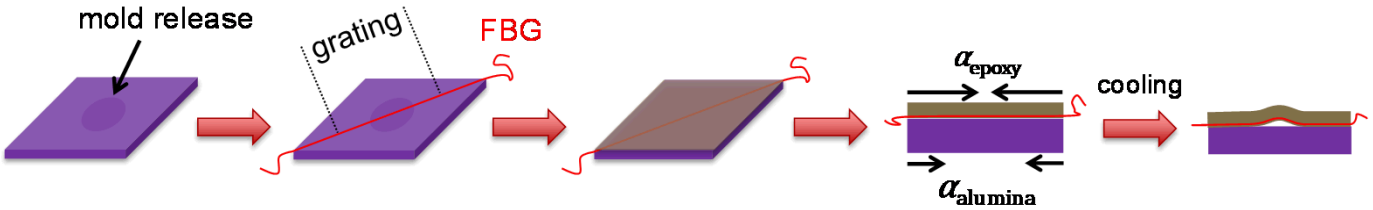




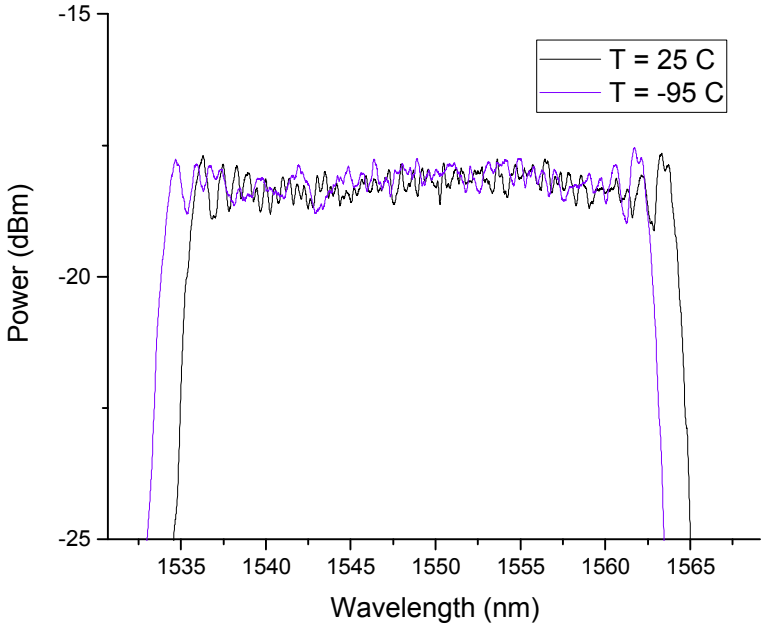
Adapted from K.I. Hutchins, *M.S. Thesis*, University of New Mexico **2015**.

Thermally-Induced Delamination

Embedded FBGs exhibit characteristics of non-uniform strain distribution concomitant with delamination

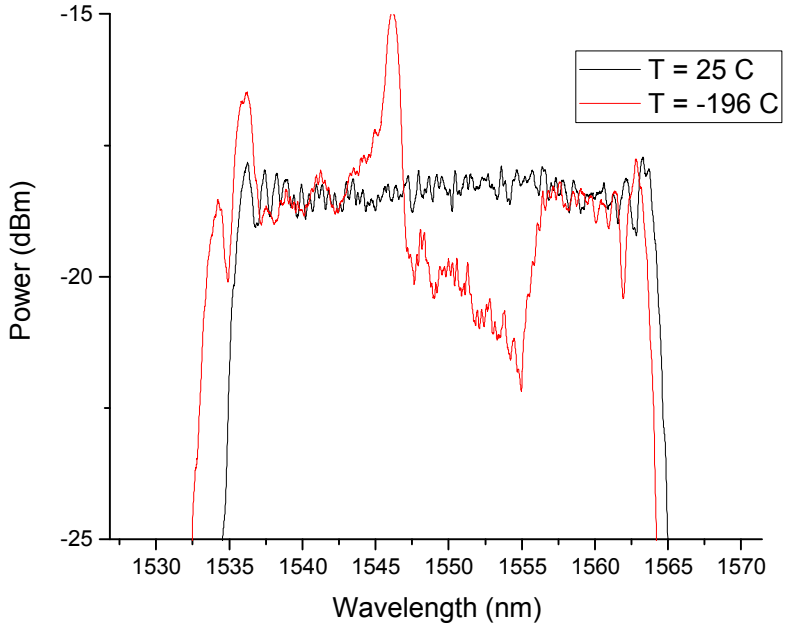


Cooling to −95 °C: No delamination



spectra indicate a uniform strain profile across the grating

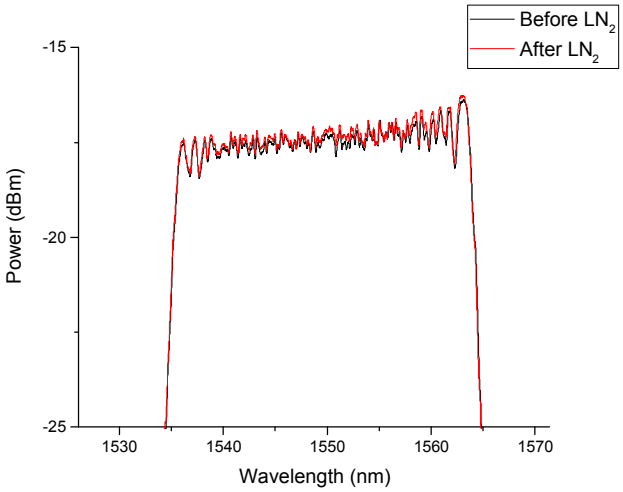
Cooling in LN_2 (−196 °C): Clear delamination



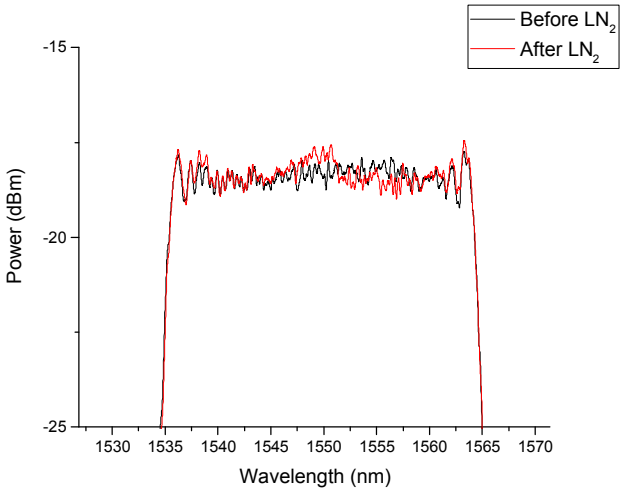
spectra indicate the development of a non-uniform strain distribution across the grating

Thermally-Induced Delamination

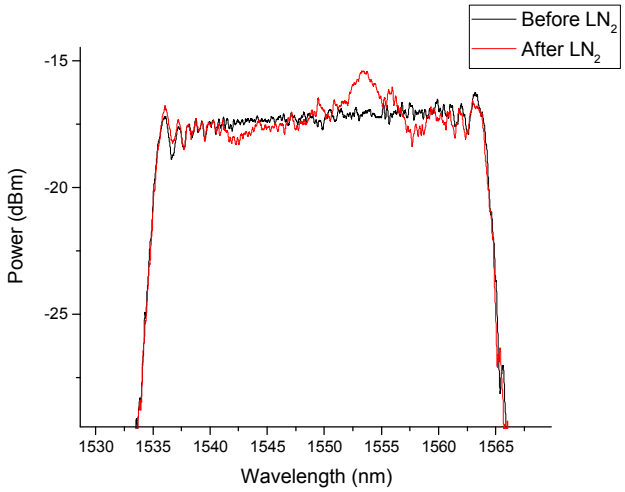
Again, the width over which a given spectrum deviates from its pre-delaminated spectrum is connected to delamination size



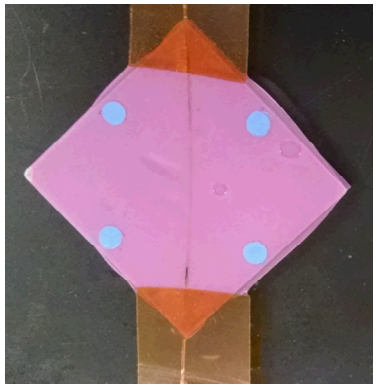
no mold release

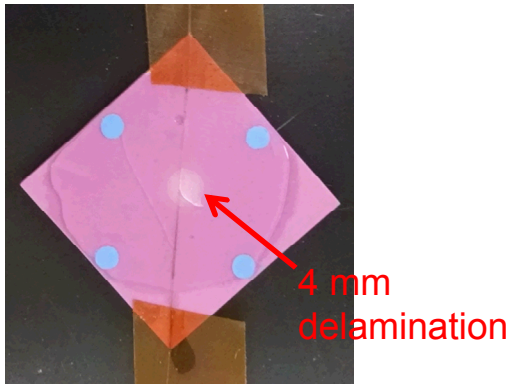


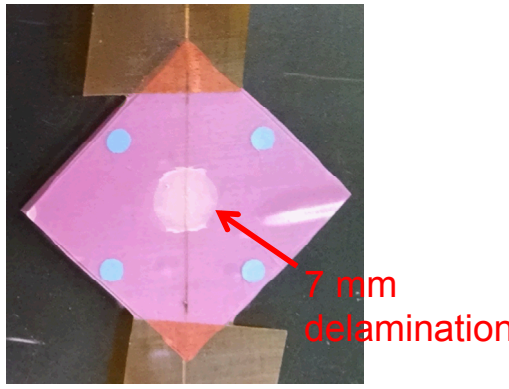
0.5 µL mold release



1.0 µL mold release

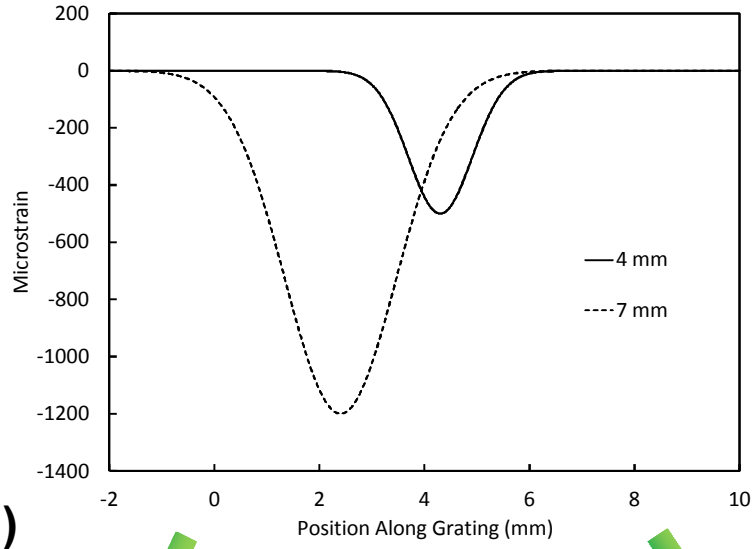




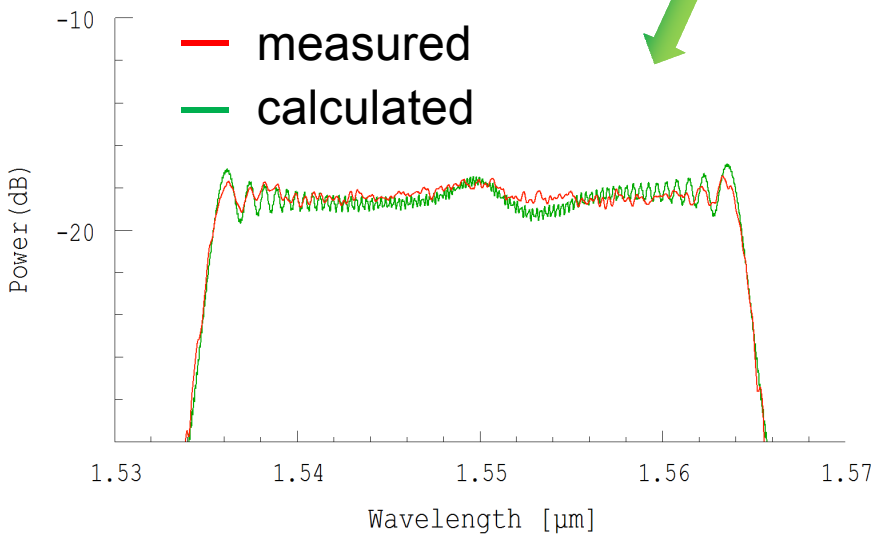


Residual Strain Distributions

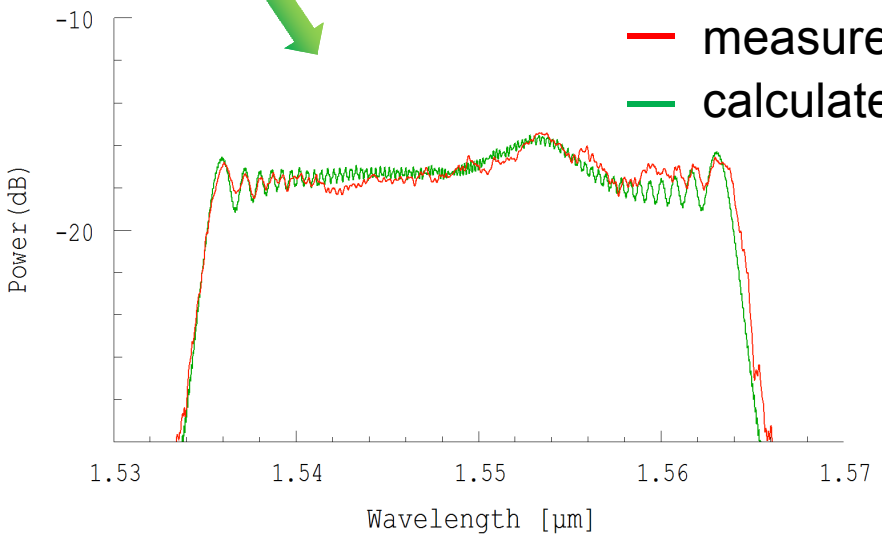
OptiGrating simulation roughly captures residual perturbation in chirped spectra using a Gaussian compressive strain distribution



0.5 µL MR (4 mm delam)



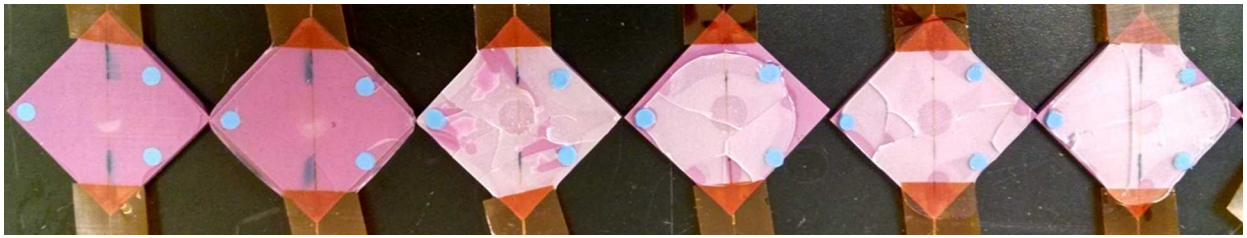
1.0 µL MR (7 mm delam)



Challenges in Scale

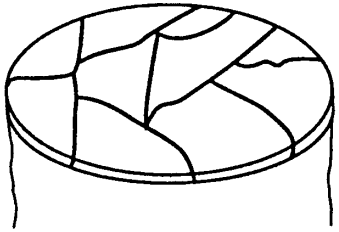
Cracking processes (including delamination) are activated at smaller temperature excursions as we move from film to bulk geometries

epoxy films of variable thickness cooled to −196 °C



413 µm → 1320 µm

channeling



delamination

$$\Omega = \frac{(1-\nu_f)\sigma^2 \boldsymbol{h}}{E_f} \qquad G = \frac{Z\sigma^2 \boldsymbol{h}}{E_f} \qquad \sigma = \frac{(\alpha_f - \alpha_s)\Delta T \cdot E_f}{1-\nu_f}$$

$\Omega \equiv$ stored strain energy

$G \equiv$ strain energy release rate

$\boldsymbol{h} \equiv$ **thickness**

$Z \equiv$ driving force

$\alpha_f \equiv$ film CTE

$\alpha_s \equiv$ substrate CTE

$T \equiv$ temperature

$E_f \equiv$ film modulus

Hutchinson, J. W.; Suo, Z. *Adv. Appl. Mech.* **1992**, *29*, 63-191.

Conclusions

- **Chirped FBGs embedded in epoxy encapsulants provide readily identifiable spectral signatures in response to delamination**
- **Spectral analysis suggests residual Gaussian axial strain distributions in embedded FBGs after indentation- and thermally-induced delamination**
- **Key spectral features scale with delamination dimensions**

Future Directions

- **Implementation of genetic algorithm methods for strain calculations**
- **Extend to filled encapsulants**
- **Extend to bulk, complex geometries**

Acknowledgements

- **Clay Newton and Thomas Buchheit** – indentation instrumentation
- **Thomas Buchheit, David Reedy, Patricia Sawyer, Mark Stavig, Eric Udd** – discussion and experimental support

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