



Guided Wave-based System for Cure Monitoring of Composites using Piezoelectric Discs and FBGs/PS-FBGs

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Student Spotlight

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Student Spotlight

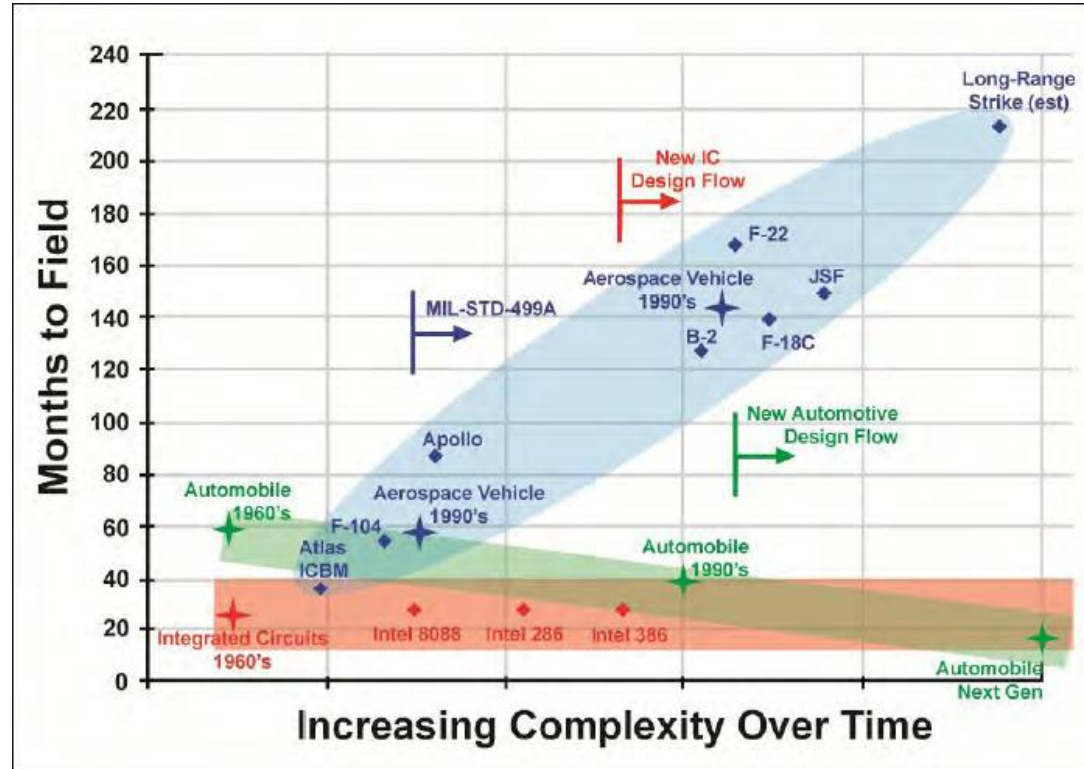
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- Reduce timeline required for development and certification of advanced composite structures by **30 percent**
 - 10-20 years, ~\$100s millions

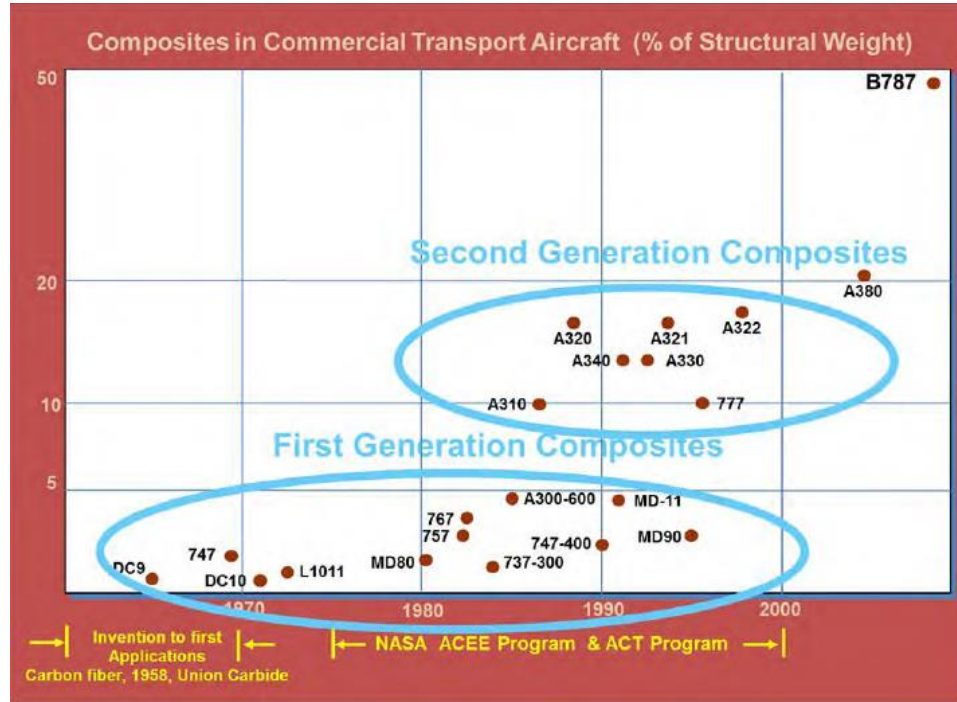
Design complexities in Aerospace Systems



Advanced Composites Project (Cont.)

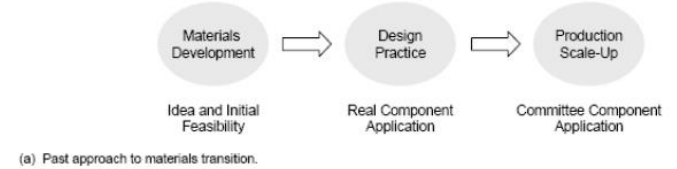


Evolution of Composites into Primary Aerospace Structures

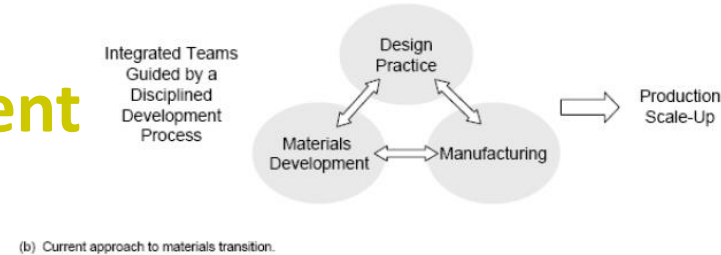


Analysis-Test Integration Validation

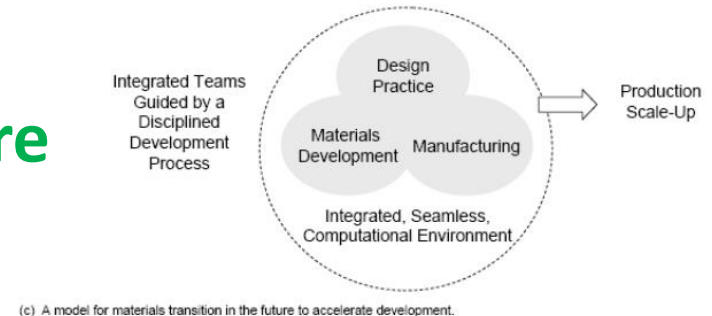
Past



Present

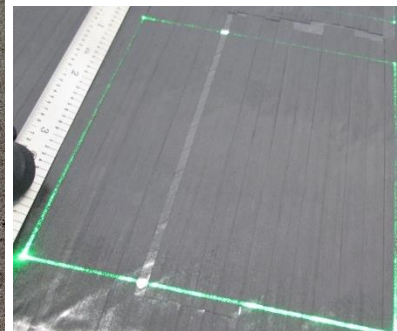


Future





- NASA Advanced Composites Project (ACP)
 - Reduce timeline required for development and certification of advanced composite structures by 30 percent
- Manufacturing Defects
 - Detrimently affect quality of parts
 - Lead to higher cost and cause significant delay
- Developed guided wave-based technique for detection of manufacturing defects in carbon fiber reinforced polymer (CFRP) composites
- **Extended guided wave-based technique for *in-situ* cure monitoring of composites using high temperature piezoelectric transducers**
- **Incorporated embedded fiber Bragg grating (FBG) sensors for guided wave sensing during cure**



Automated Guided Wave System for In-process Cure Monitoring of Composites using high temperature piezoelectric transducers



Objective: Develop guided wave-based technique for **in-situ** cure monitoring of composites

Accomplishments and Significance:

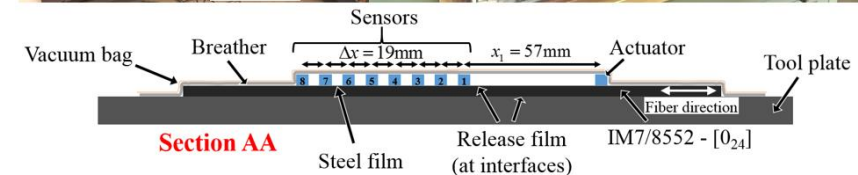
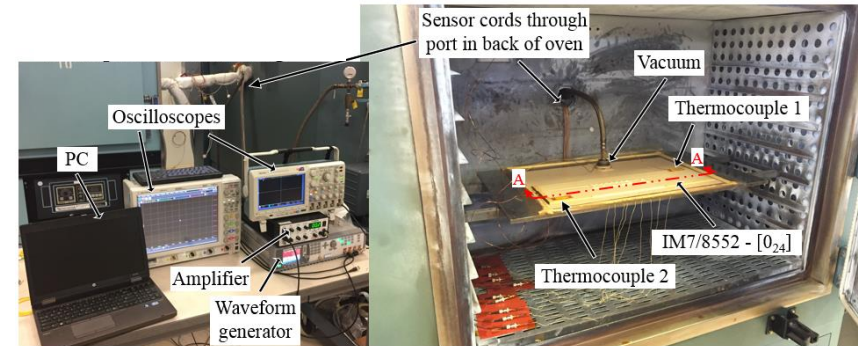
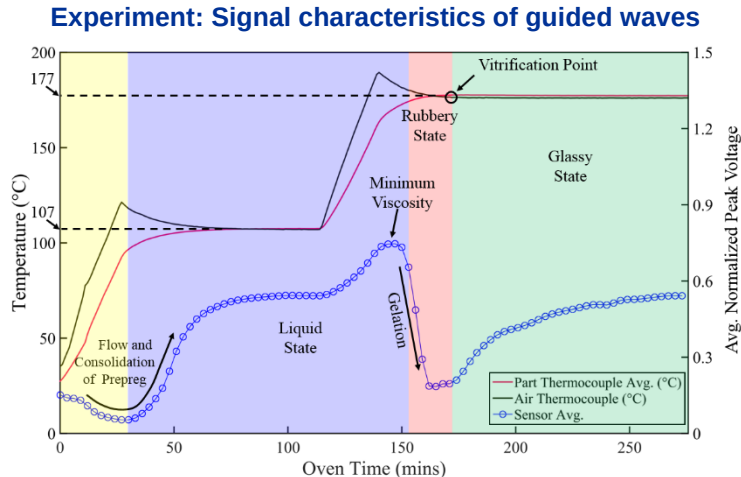
- Acquisition and analysis completed real-time during cure
- Experimental guided wave signal characteristics correlate with cure kinetic simulation
- Guided waves **throughout entire cure cycle** pushes the technology envelope forward
 - Guided waves typically applied to solid state structures
 - In-situ measurements during **liquid and rubbery states** at elevated temperatures

Key Milestones:

- **Non-provisional patent** application (LAR-18973-1), prepared July 2017*
- Journal publication (under review) and conference proceedings

*Non-provisional application has been prepared and is awaiting filing at the USPTO no later than September 20, 2017

Automated guided wave system for in-process monitoring



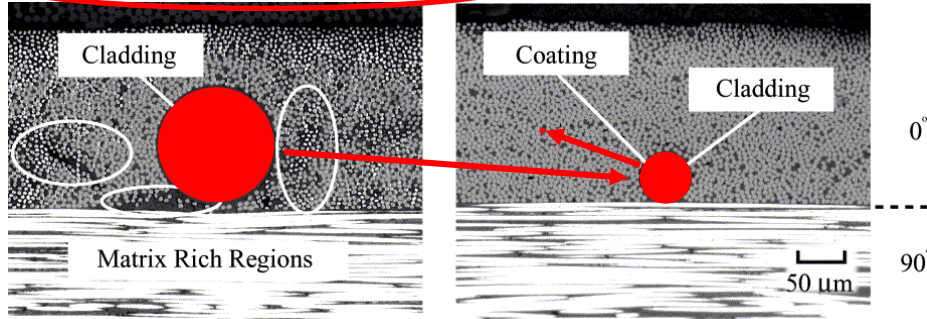
1. T.B. Hudson and F.G. Yuan, "Automated in-process cure monitoring of composite laminates using a guided wave-based system with high temperature piezoelectric transducers," Submitted to Journal of Composite Materials, 2017.
2. T.B. Hudson, B.W. Grimsley, and F.G. Yuan, "Development of a fully automated guided wave system for in-process cure monitoring of CFRP composite laminates." Proceedings of the American Society for Composites: Thirty-First Technical Conference, Williamsburg, VA, September 19-21, 2016.

Motivation and Recent Advancements



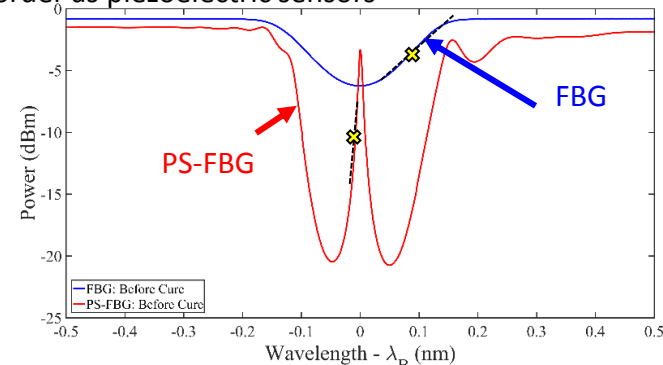
I. Small-diameter Fiber Bragg Grating Sensor (FBG)

Currently ~10% area of original fiber



II. High Sensitivity of Phased Shifted-FBG

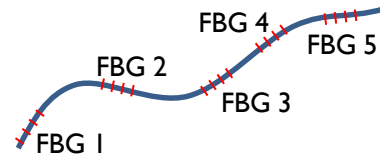
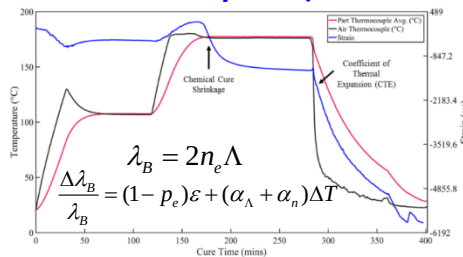
- Sensitivity two orders of magnitude greater than conventional FBG
- Same order as piezoelectric sensors



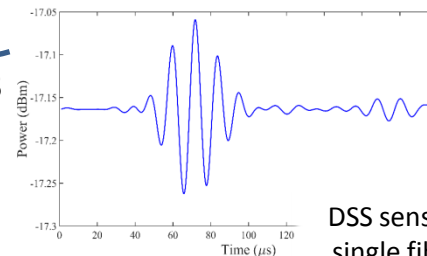
III. Usage Load Monitoring and Damage Detection/Acoustic Emission

- Strain (loads monitoring) measurement frequency (~Hz)
- Ultrasound (damage detection) measurement frequency (~MHz)
- Multiplexing

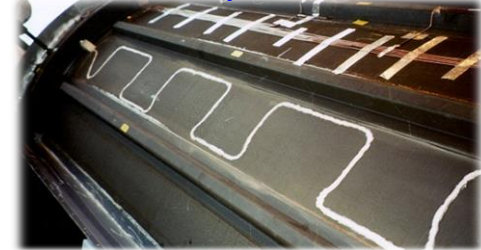
Strain Measured by FBG (Loads Monitoring)



Guided wave (Damage detection)

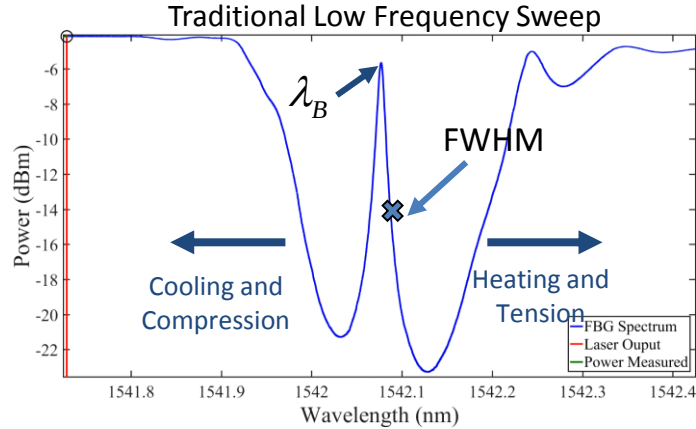


Previous Application of Fiber Optic Sensors at LaRC

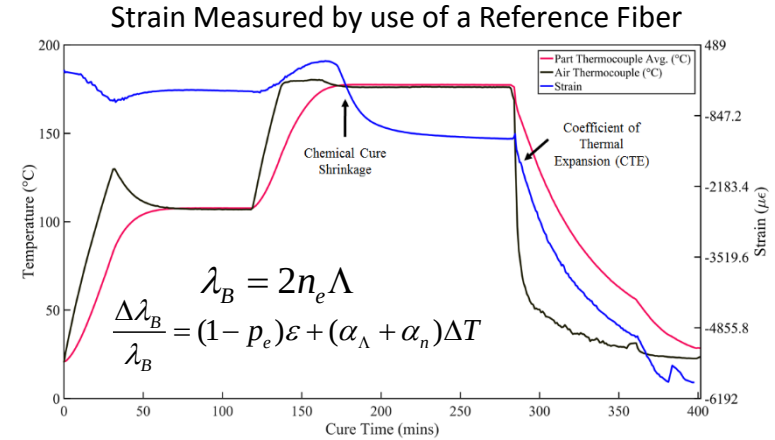


DSS sensor testing - 20 LaRC fiber strain sensors in a single fiber installed on X-33 composite test article.

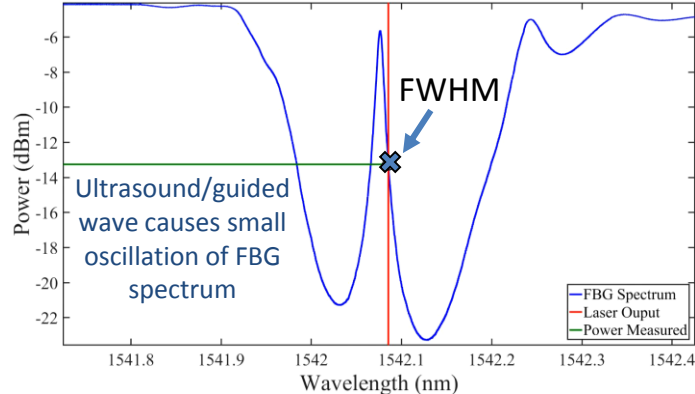
Sequential Strain and Guided Wave Cure Monitoring Measurement Procedure for PS-FBG



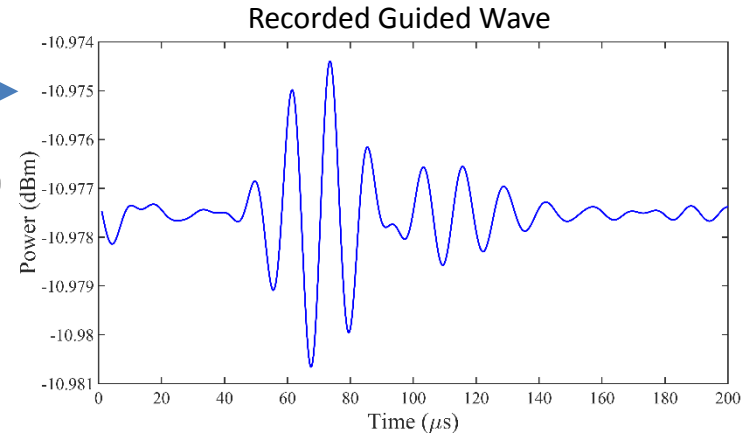
(~ Hz)



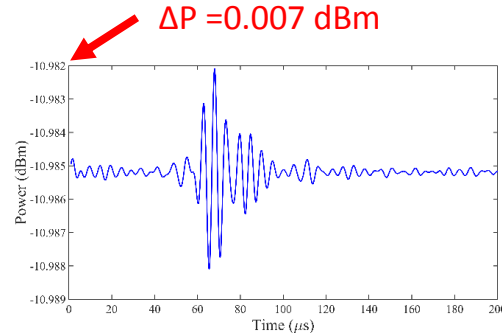
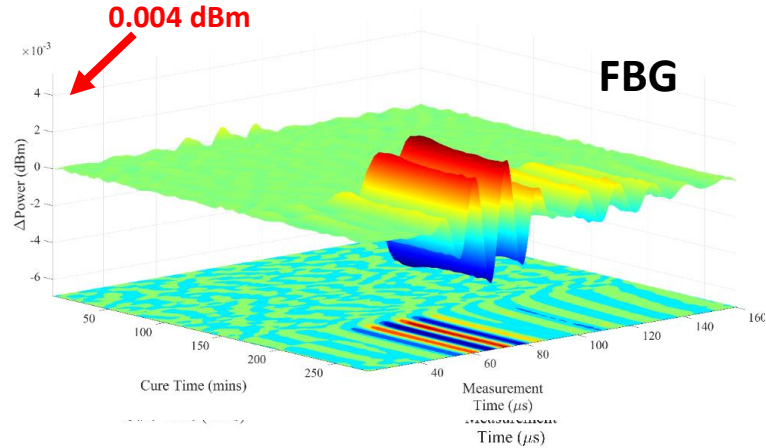
New High Frequency Guided Wave Measurement



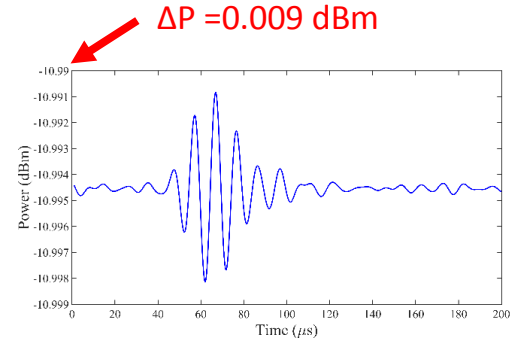
(~ MHz)



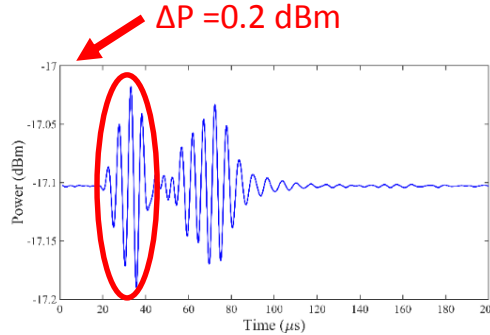
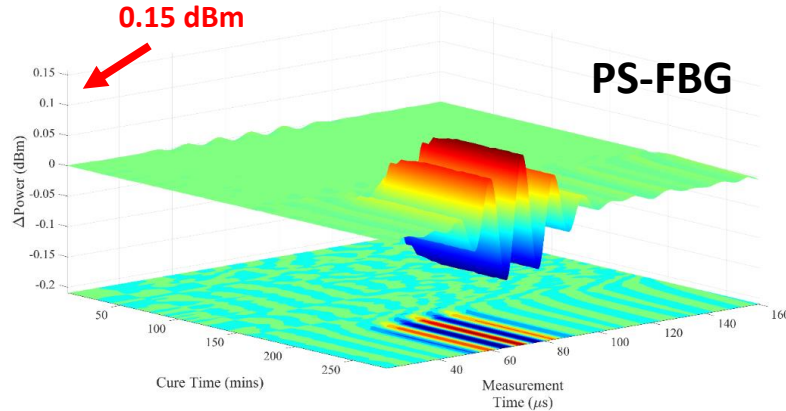
Comparison of Power Change (FBG vs. PS-FBG)



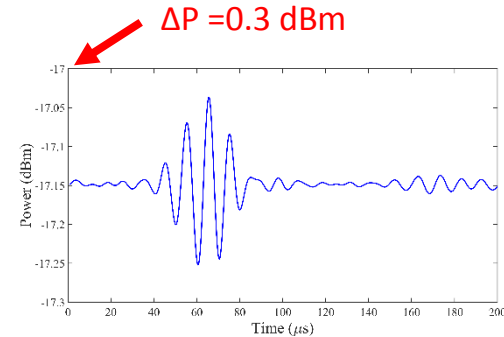
FBG 1, $f_c = 200 \text{ kHz}$



FBG 1, $f_c = 100 \text{ kHz}$



PS-FBG 1, $f_c = 200 \text{ kHz}$



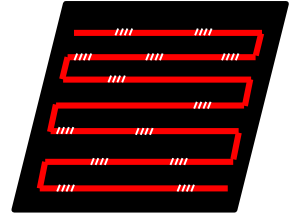
PS-FBG 1, $f_c = 100 \text{ kHz}$

Two order of magnitude increase in change in power
(~20 dB Gain)

Why guided wave-based ultrasonic sensing with embedded PS-FBG for cure monitoring?



- Guided wave sensing with piezoelectric sensors for cure monitoring have:
 - Inferred cure state (e.g., flow, gelation, vitrification)
 - Pushed technology envelope forward as guided waves typically applied to solid medium
 - In-situ measurements during all phases (**liquid, rubbery, and glassy**)
- Embedded FBG sensors can:
 - Perform strain based cure monitoring
 - **Life-cycle monitoring** of aircraft/other critical structures during service
- Integration: **Guided wave-based** ultrasonic sensing with **embedded PS-FBGs** for cure monitoring
 - Perform low frequency strain (**load monitoring**) based cure monitoring and high frequency guided wave sensing (**damage detection**) almost simultaneously during cure
 - PS-FBGs **100 times sensitivity** of FBGs and comparable to piezoelectric sensors
- Defect detection during cure with guided wave-based ultrasonic sensing
 - Unlikely with existing cure monitoring techniques
 - ACP goal of defect (porosity and fiber waviness) detection during cure





- **Patent Applications:**
 1. LAR-18973-1: "Automated Guided Wave System for In-process Cure Monitoring of CFRP Composite Laminates," T.B. Hudson, F.G. Yuan, and B.W. Grimsley (Provisional patent applications 62/397,180 Sep. 2016, 62/442,708 Jan. 2017, Non-provisional application prepared and awaiting filing at USPTO July 2017).
 2. LAR-19194-1: "Guided wave-based system for cure monitoring of composites using piezoelectric discs and fiber Bragg gratings (FBGs)/phase-shifted fiber Bragg gratings (PS-FBGs)," T.B. Hudson, F.G. Yuan, N. Auwajian, and F.L. Palmieri (New Technology Report filed July 2017).
- **Journal articles and conference papers:**
 1. T.B. Hudson, N. Auwajian, and F.G. Yuan, "Guided wave-based system for real-time cure monitoring of composites using piezoelectric discs and fiber Bragg gratings/phase-shifted fiber Bragg gratings," *To be submitted to Composites Science and Technology*, 2017.
 2. T.B. Hudson and F.G. Yuan, "Automated in-process cure monitoring of composite laminates using a guided wave-based system with high temperature piezoelectric transducers," *Submitted to Journal of Composite Materials*, 2017.
 3. T.B. Hudson and F.G. Yuan, "Detection and quantification of composite manufacturing defects using guided waves," *Submitted for NASA Internal TPSAS Approval*, 2016.
 4. T.B. Hudson, T. Hou, B.W. Grimsley, and F.G. Yuan, "Imaging of local porosity/voids using a fully non-contact air-coupled transducer and laser Doppler vibrometer system," *Structural Health Monitoring*, Vol. 16, pp. 164-173, 2016.
 5. T.B. Hudson, B.W. Grimsley, and F.G. Yuan, "Development of a fully automated guided wave system for in-process cure monitoring of CFRP composite laminates," *Proceedings of the American Society for Composites: Thirty-First Technical Conference*, Williamsburg, VA, September 19-21, 2016.
 6. T. Sreekantamurthy, T.B. Hudson, T.H. Hou, and B.W. Grimsley, "Composite cure process modeling and simulations using COMPRO® and validation of residual strains using fiber optics sensors," *Proceedings of the American Society for Composites: Thirty-First Technical Conference*, Williamsburg, VA, September 19-21, 2016.
 7. T.B. Hudson, T.H. Hou, B.W. Grimsley, and F.G. Yuan, "Detection of CFRP composite manufacturing defects using a guided wave approach," *Proceedings SAMPE Technical Conference*, Baltimore, MD, pp. 2096-2111, May 18-May 21, 2015.



- **Strong technical rigor**
- **Work on “real” problems as part of a team**
 - NASA projects
 - Collaboration with industry and academia
- **Develop connections inside NASA**
- **For success,**
 - Requires strong self-motivation
 - Requires a Langley professor willing to make the non-traditional relationship work (Dr. Yuan does that)
- **Carries the NASA affiliation**



➤ **Thank you to everyone who has contributed to this project. This work would not be possible without your help.**

- NASA Advanced Composites Project**
- Fuh-Gwo Yuan, Nick Auwaijan, Madison Maloney, Shane Campbell, Tan-Hung Hou, Brian Grimsley, Frank Palmieri, Roberto Cano, Hoa Luong, Sean Britton**



Questions?