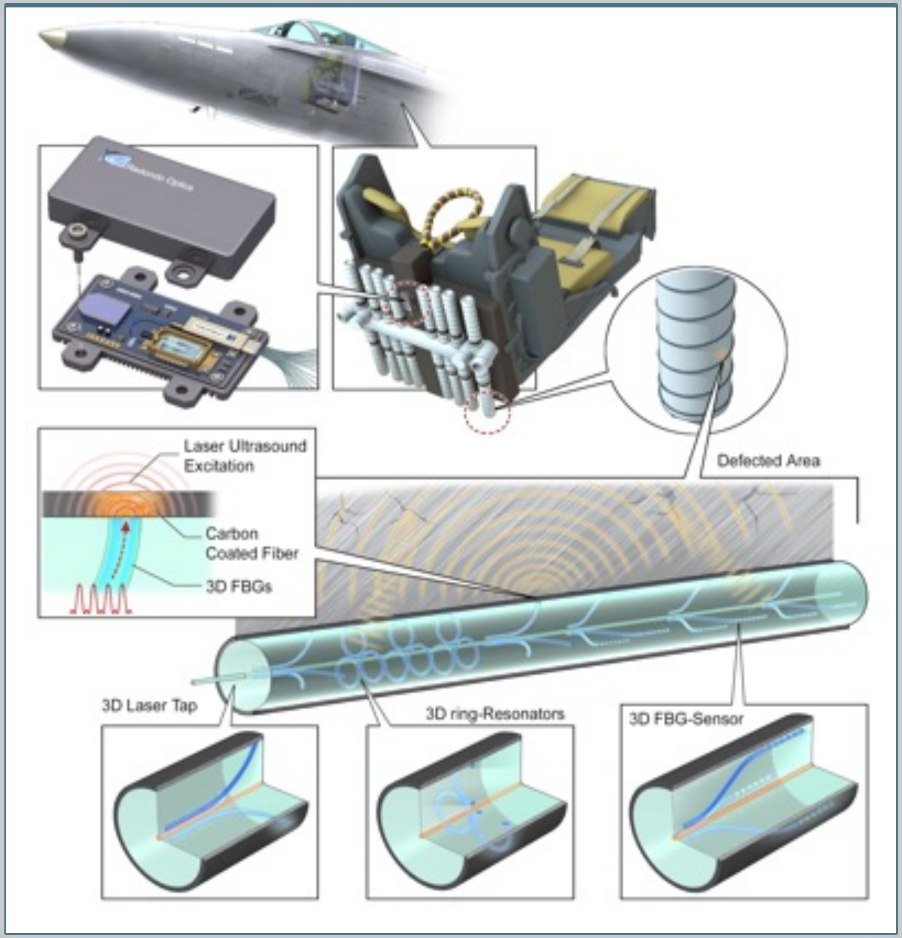
UN-INVASIVE FIBER OPTIC ACOUSTIC-ULTRASOUND SENSOR SYSTEM FOR THE DETECTION OF HIDDEN DAMAGE IN CAD/PAD ROCKET PROPELLANT STRUCTURES



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Acknowledgments

- Redondo Optics greatly acknowledges the financial support of the Navy SBIR Program under the technical program management of Magdy Bichay.
- Redondo Optics also acknowledges the technical advisory support of Nammo Defense Systems collaborating with ROI for the testing and demonstration of the FAULT Crack Detection Technology
- NAVY SBIR contract No (N68335-20-C-0361)

Redondo Optics Inc.

Revolutionizing
Smart Fiber Optic Sensors
for Applications Where
Weight, Size, and Power are
Critical for Operation

FBG Sensor Applications

Oil and Pipelines

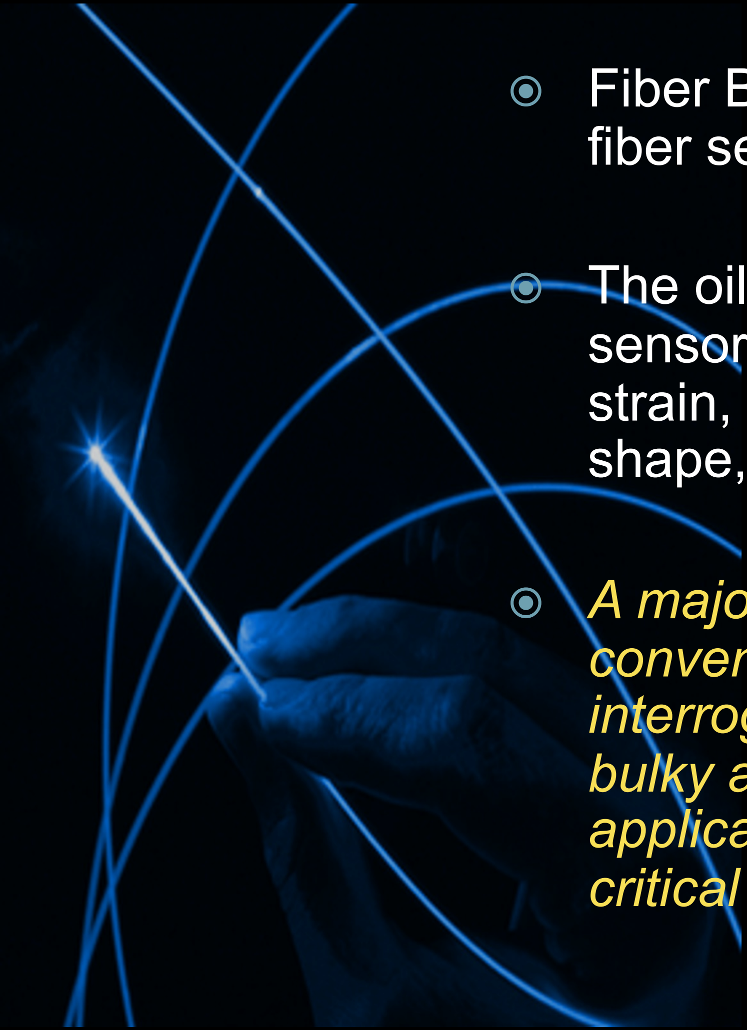
Buildings
and Civil Infrastructures

Wearable Heath-Med

Renewable Energy

Defense and Homeland Security

Fiber Bragg Grating Sensors



- Fiber Bragg Grating Sensors are the most widely used fiber sensor technology today.
- The oil and petrochemical industry routinely uses FBG sensors for multipoint distributed measurements of strain, temperature, pressure, vibration, acoustics, shape, and flow.
- *A major disadvantage of FBG technology is that conventional state-of-the-art fiber Bragg grating interrogation systems are costly, complex, and typically bulky and heavy bench top instruments not suitable for applications where cost, weight, size, and power are critical for operation.*

Photonic Integrated Circuits (PIC) Microchip Technology

- **ROI uses its patented PIC microchip technology to provide fiber optic sensor solutions for sensing applications where Weight, Size, Power, and Cost are critical for operation.**

- Developed on contract for applications with
  - **NASA**
  - **Department of Defense**
  - **Department of Energy**

ROI's Strategy

- Next Generation FBG SHM Systems Must be:
  - Cost Affordable
  - Low Weight
  - Small Size
  - Self-Power
  - Simple User Interface
  - Wireless Network Connectivity

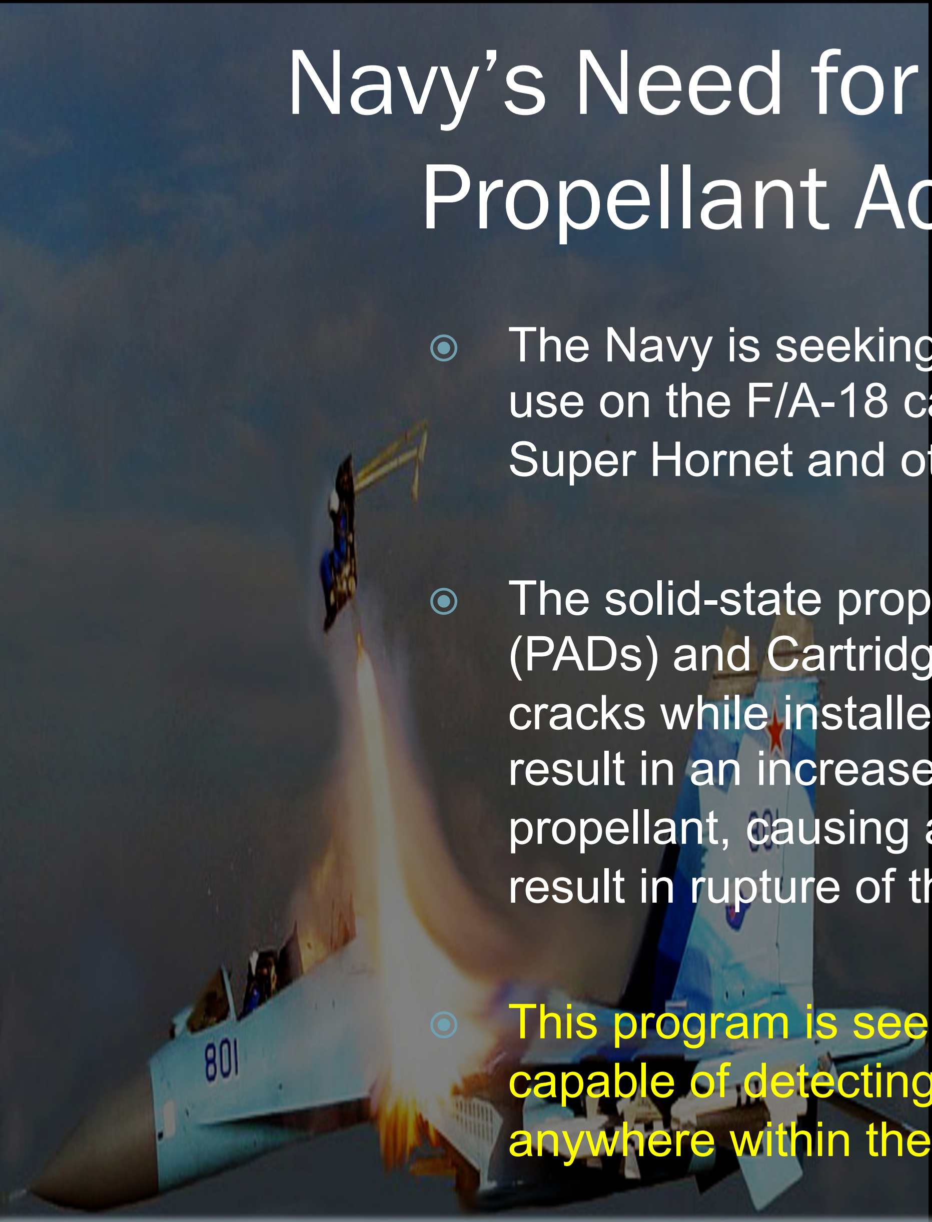
For Applications Where Weight, Size, Power, and Cost are Critical for Operation.

Project Goals

- This project seeks to develop an demonstrate an innovative multi-point fiber optic acousto-ultrasound sensor (FAULT™) SHM crack detection system suitable for the in-situ, real-time, un-intrusive detection of hidden damage associated with cracks in propellant actuated devices (PADs) and cartridge actuated devices (CADs) such as those used in aircraft (F-18) canopy rocket motors.

REDONDO OPTICS

Navy's Need for SHM Inspection of Propellant Actuated Devices



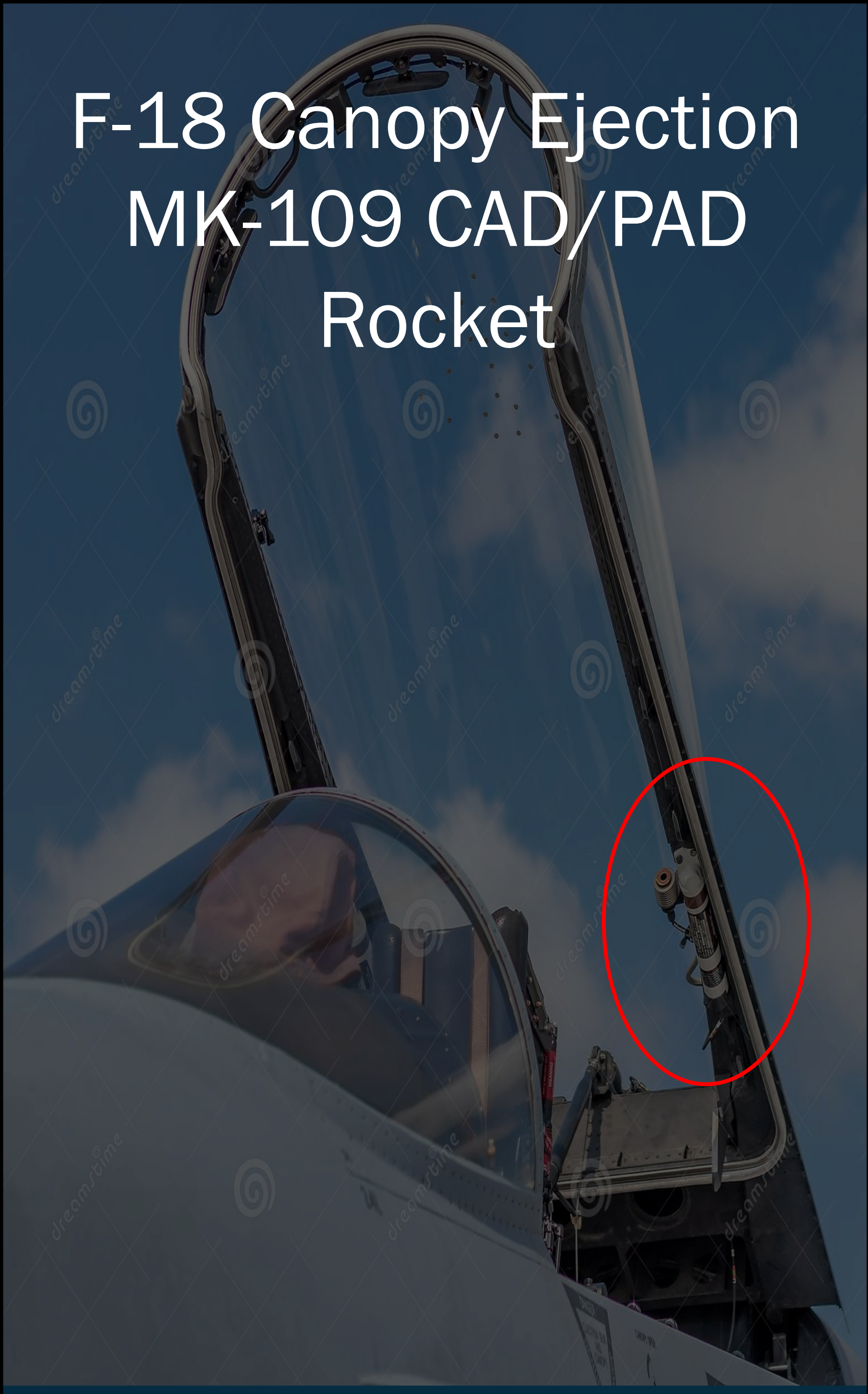
- The Navy is seeking to developed new sensor technologies for use on the F/A-18 canopy remover rocket motor (MK 109) Super Hornet and other propellant actuated devices.

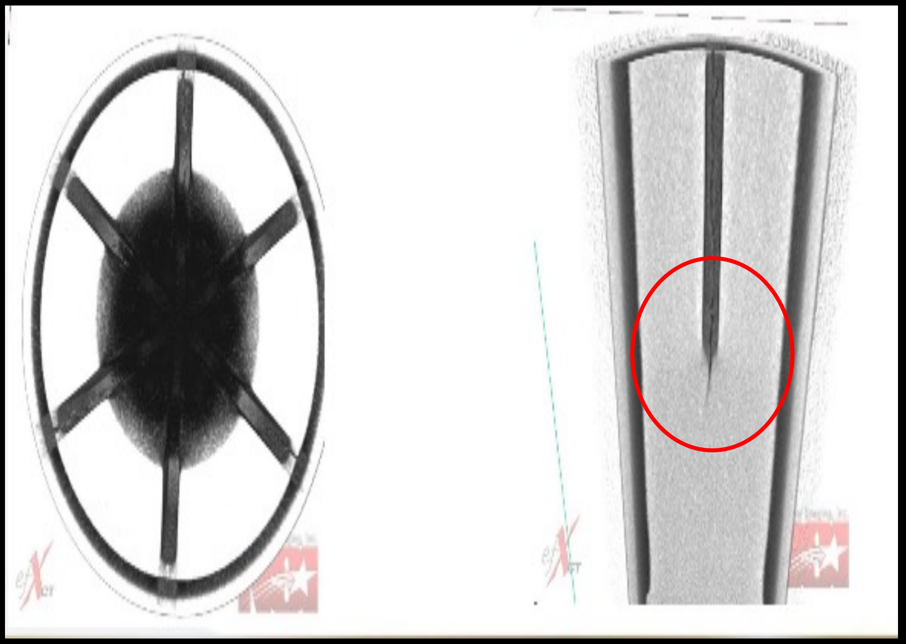
- The solid-state propellants used in Propellant Actuated Devices (PADs) and Cartridge Actuated Devices (CADs) can develop cracks while installed onboard an aircraft. the cracks would result in an increase of the burning surface area of the propellant, causing an increase in the gas production that may result in rupture of the device.

- This program is seeking to demonstrate a new sensor system capable of detecting the presence of cracks greater than 2-mm anywhere within the propellant grain

When developed, the FAULT SHM system can provide an early warning inspection of the presence of cracks within the CAD/PAD propellant grain and provide alarms via a visual and/or auditory to maintenance personnel.

F-18 Canopy Ejection MK-109 CAD/PAD Rocket



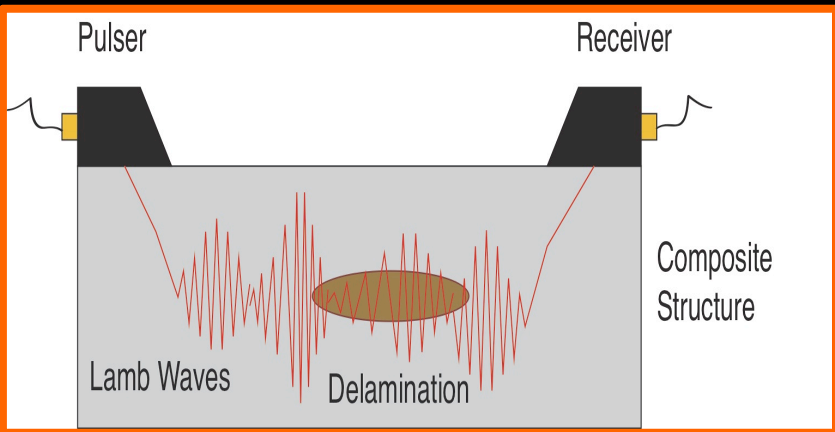


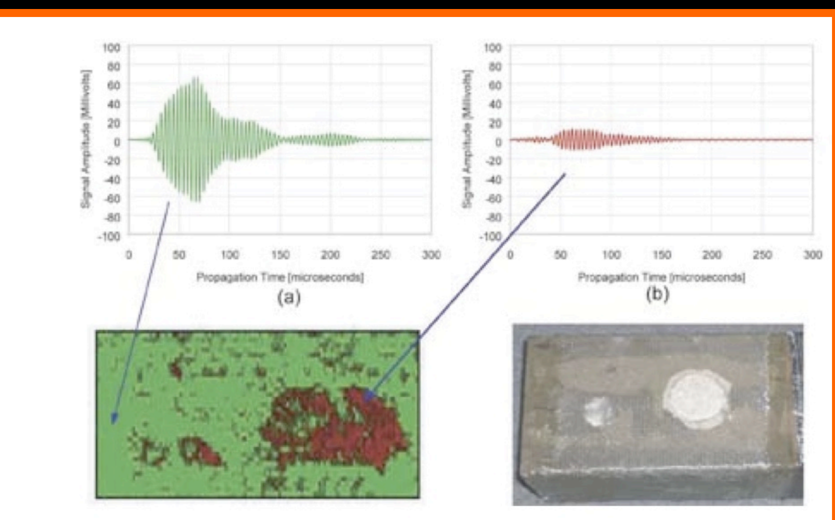
Acoustic-Ultrasound for Detection of Hidden Structural Damage in Large Structures

- Acoustic-ultrasound (AU) sensing is an effective, and powerful tool for the nondestructive testing and evaluation of composite and metallic material structures.

- Analysis of the detected acoustic-ultrasound waveform characteristics provides a clear representation of structural changes in mechanical state of a structure.

Acousto Ultrasonic Sensing

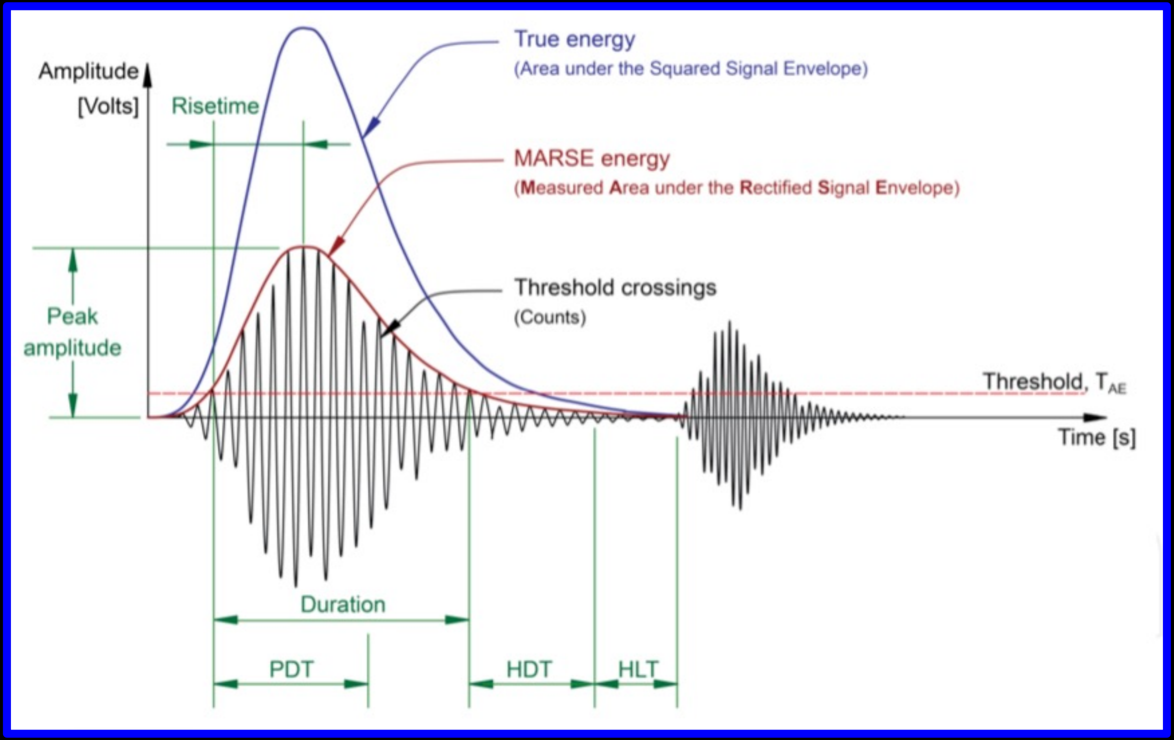


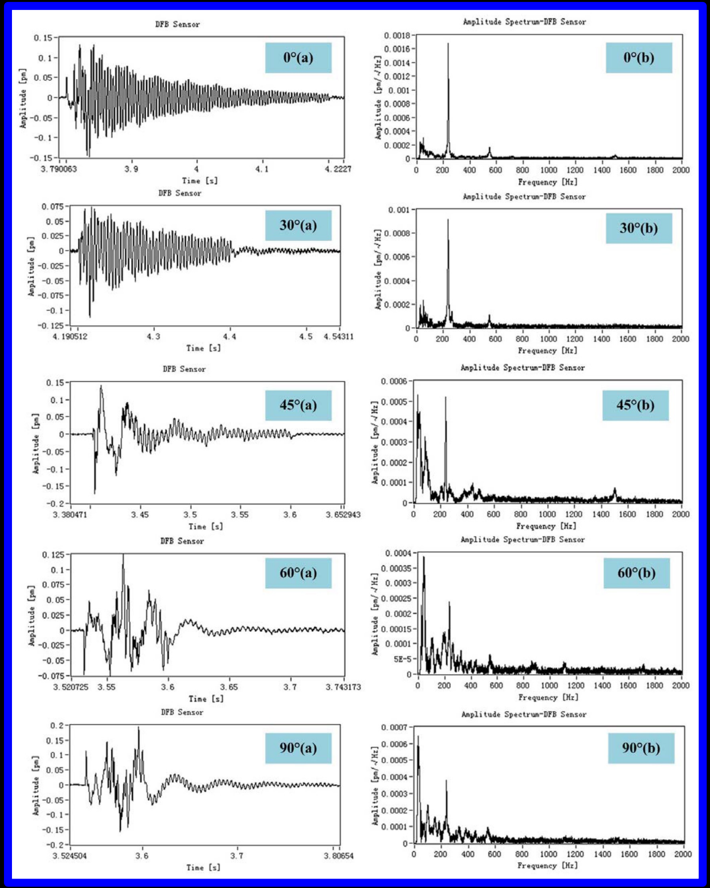


- The AU technology consists of sending low frequency acoustic pulses at a predetermined angle of incidence into a material under inspection.
- These acoustic energy pulses travel through the material and are reflected by the different interfaces inside the sample.
- If a discontinuity (fracture, crack, delamination, void, debonding etc.) is present inside the material, the reflected acoustic energy changes, revealing the presence of the discontinuity.

Acoustic-ultrasonics wave measurements include time-of-flight, path length, frequency, phase angle, amplitude, acoustic impedance, and angle of wave deflection.

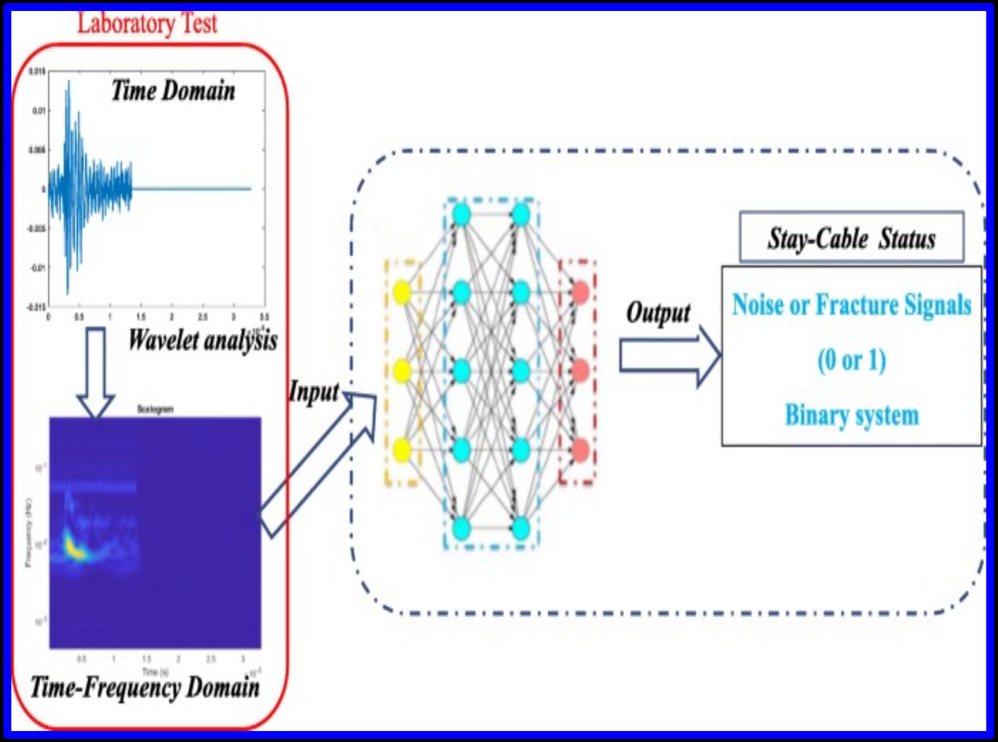
Acoustic Ultrasound Neural Networks and Wavelets For Signal Extraction



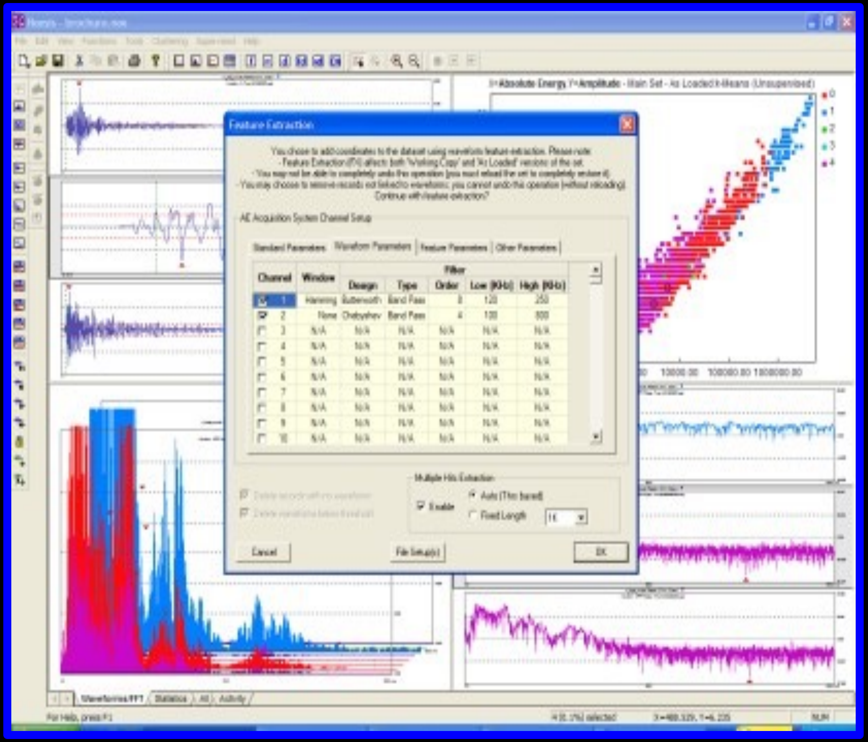


Acoustic-ultrasonics wave measurements include time-of-flight, path length, frequency, phase angle, amplitude, acoustic impedance, and angle of wave deflection.

Neural networks and Wavelets For Signal Extraction

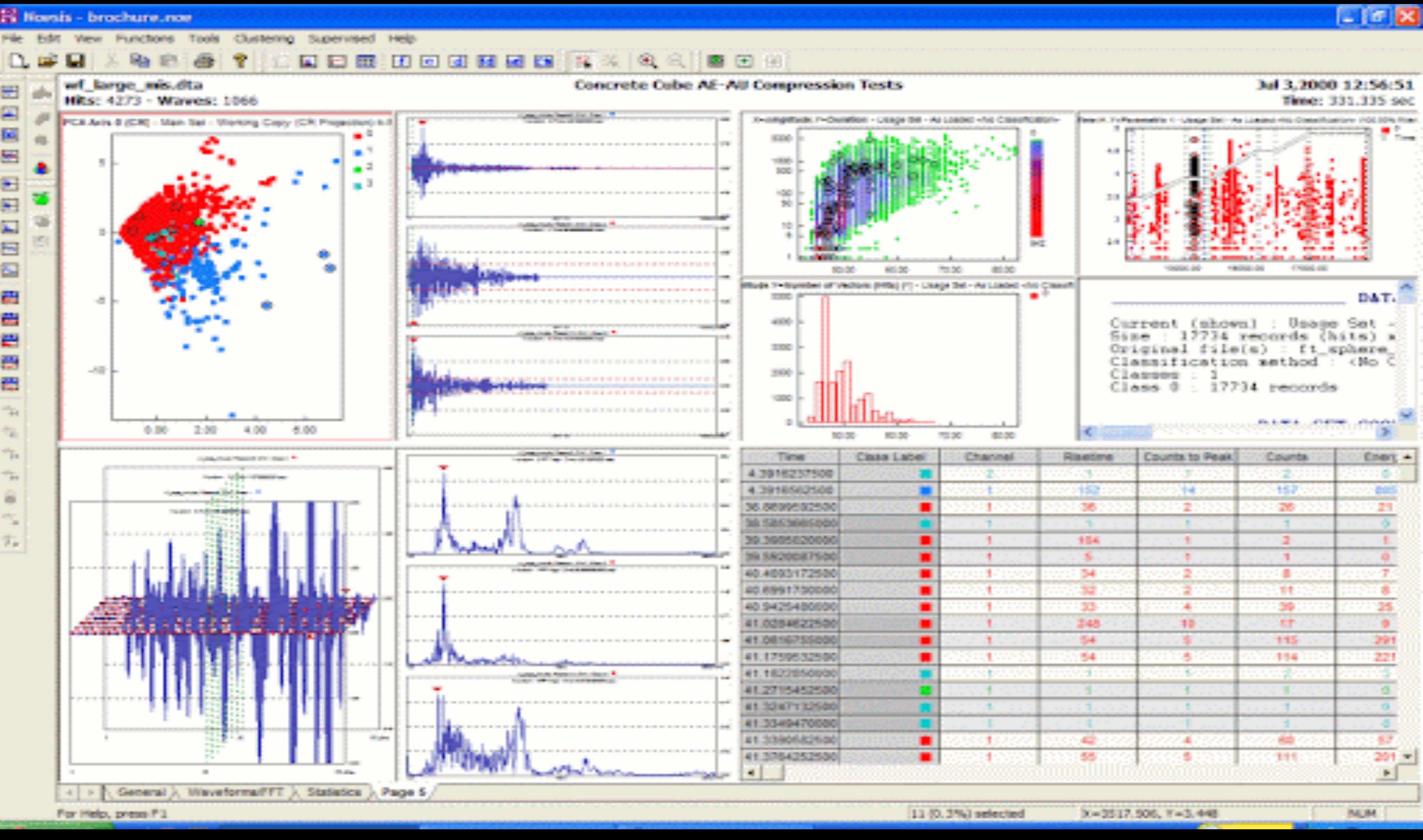


Trained Neural Network for CAD/PAD Propellant-Grain Cracks Signal Recognition

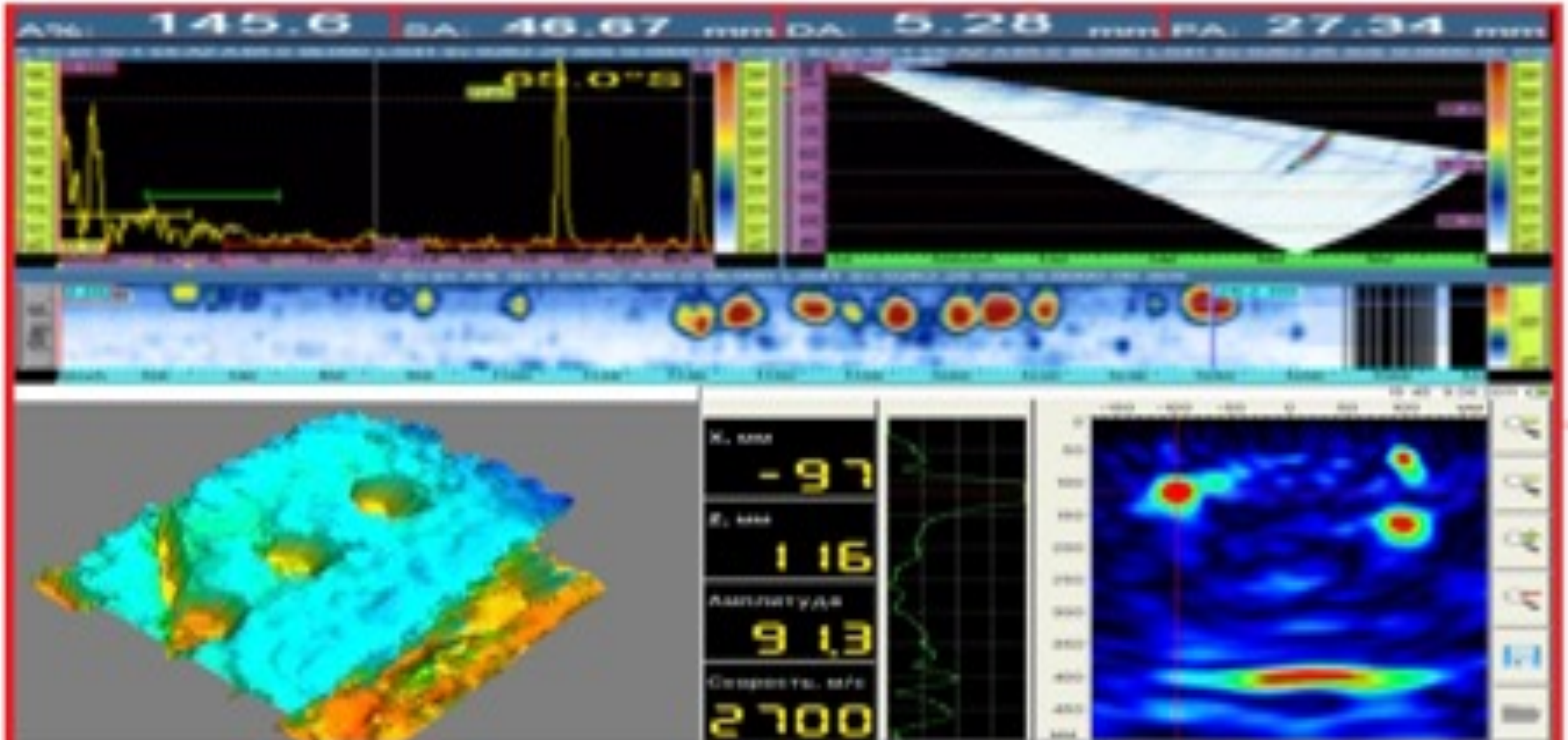


Feature Extraction and Prognostics Projections for Crack Damage Detection

Neural networks and Wavelets For Crack Detection, Localization and Damage Prognostics

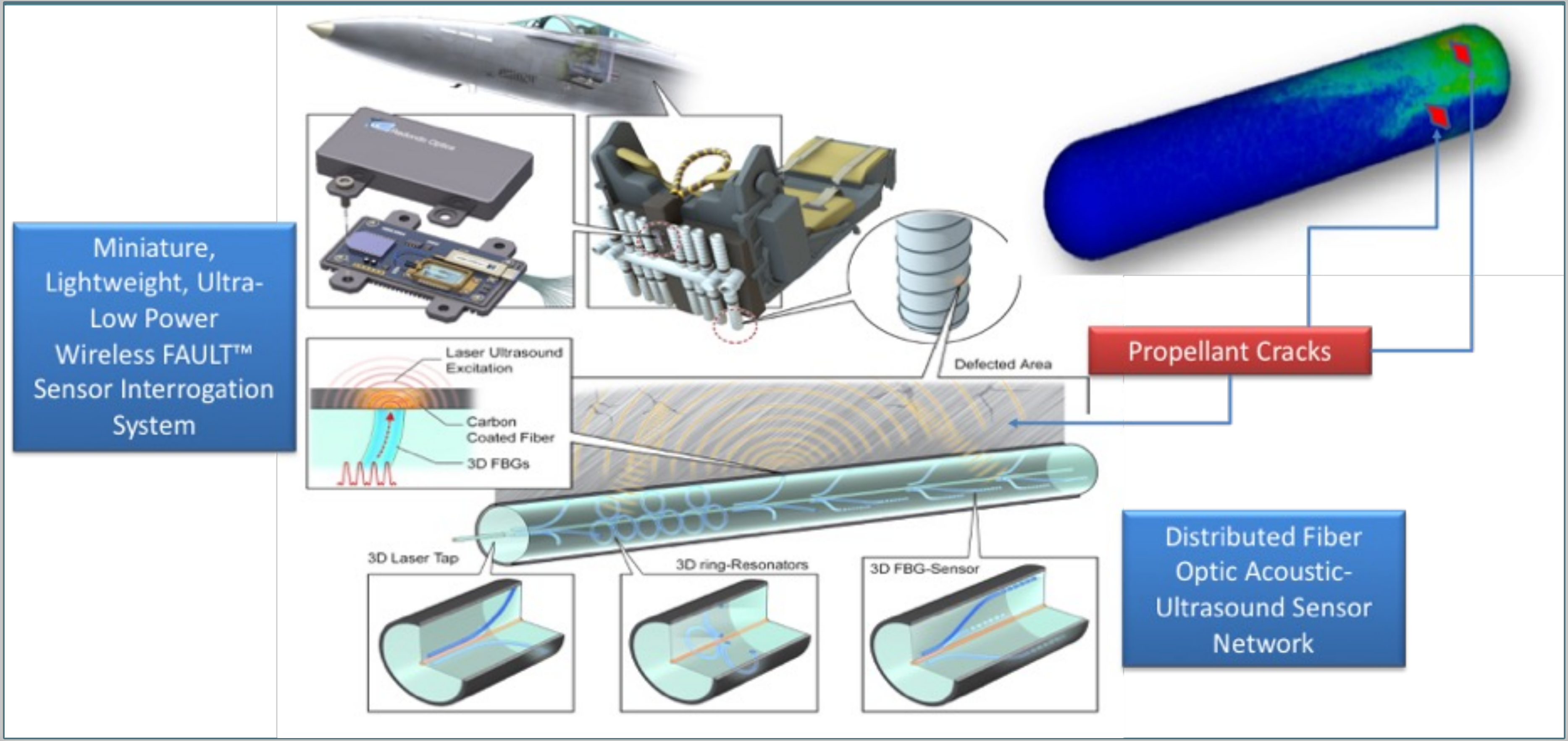


Neural networks and Wavelets For User Friendly Process Signal Visualization



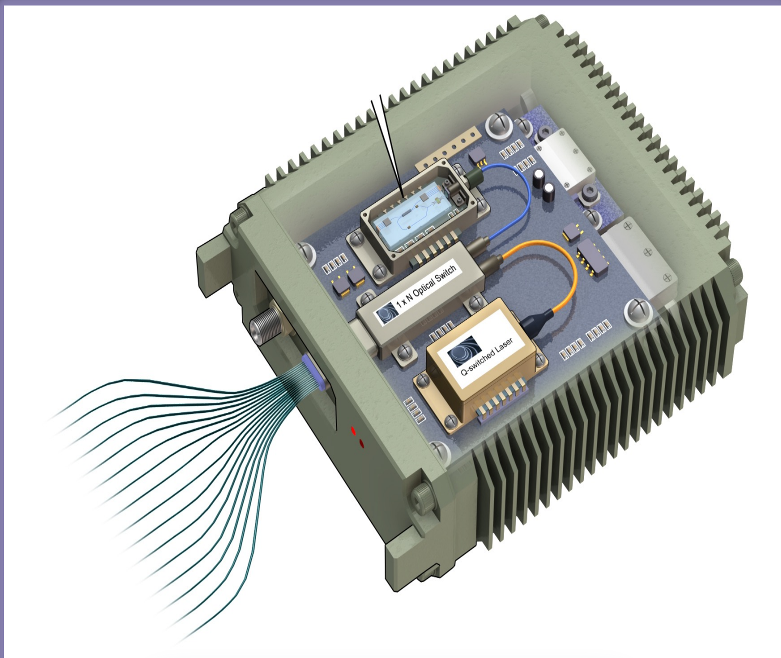
Acoustic Ultrasound Image of Structure Damage Assessment

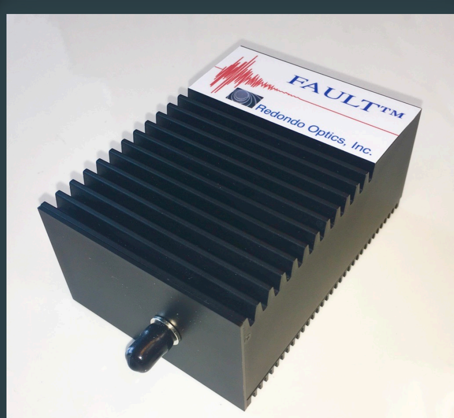
Fiber Optic acousto-ultrasound (FAULT™) crack detection SHM system



Miniature, Lightweight, Self-Power, Wireless Fiber Optic Acousto-Ultrasound (FAULT™) Crack Detection System

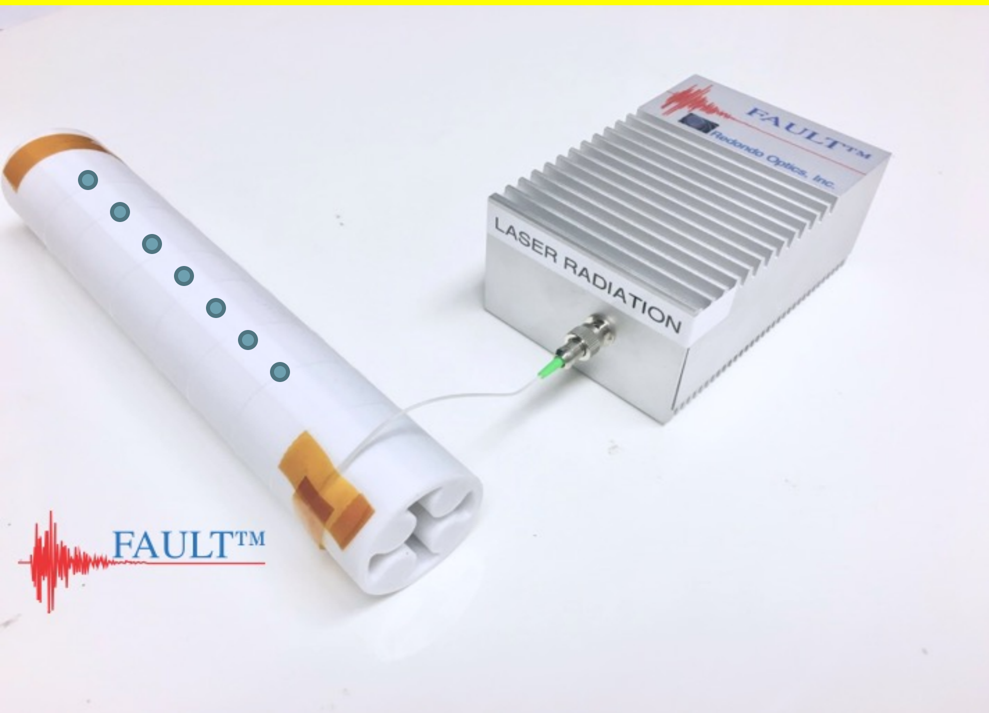
Fiber Optic Acousto-Ultrasound FAULT™ Crack Detection SHM System

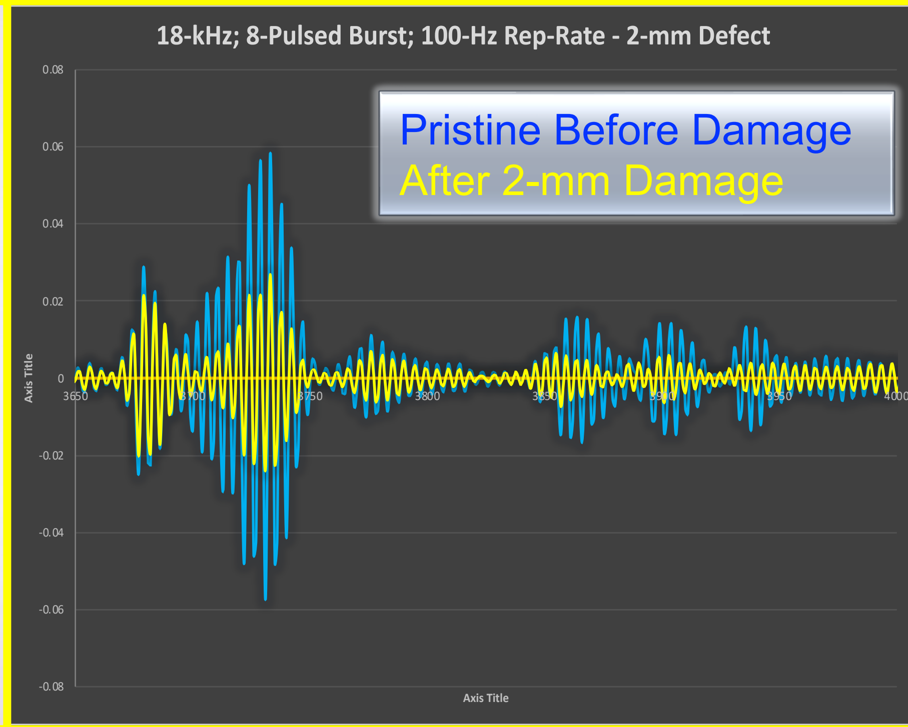




- Three-Dimensional Acousto-Ultrasound Fiber Optic Sensor Network
- Integrated Pulsed Laser Acousto-Ultrasonics Exciter
- PIC Microchip Technology Using TWM Interferometer FBG Sensor Signa Demodulator
- Integrated 1 x n MEMS Optical Switch for Global Monitoring
- Battery Power and Wireless Communication.

Phase I Demonstration FAULT™ SHM Crack Detection System





FAULT SHM Interrogation Transceiver System

Frequency Modulation Pulse Excitation

FAULT SHM crack detection sensor interrogation system packaged within a 2-in x 2-in x 4-in; 300-gr; 4-W Enclosure

FAULT™ SHM System Performance Specifications

Monitoring Mode	Adaptive Two-Wave-Mixing Interferometry
Sensing Elements	12-FBG sensors in one fiber
Sensing Fibers	MEMS Switch - 2, 4, 8, 12, 16, and 32-Fiber Channels
Strain Sensitivity	≤ 10 femto-strains
Strain Dynamic Range	± 2500-micro-strains
Frequency Range	7.5-MHz Total Bandwidth (625-kHz/FBG Sensor)
Frequency Sensitivity	0.1-micro-strain/Hz
noise-equivalent pressure NEP	≤ 25
Signal Processor	TI Digital Signal Processor (DSP-TMS320F2812PGF)
Data Communication	USB, Ethernet, Wi-Fi
Power Consumption	4-W @ 5-VDC
Poser Supply	5-V/6-A
Operating Temperature	(-)60°F to (+) 160°F

FAULT Crack Detection SHM System based on Innovative 3D fiber optic Acousto-Ultrasound sensor network and Silicon Phonics PIC microchip technology for applications were Weight, Size, Power, Performance, and Cost. are critical for operation

Key Engineering Components of Intelligent Wireless Fiber Optic Sensor (FAULT™) Network System

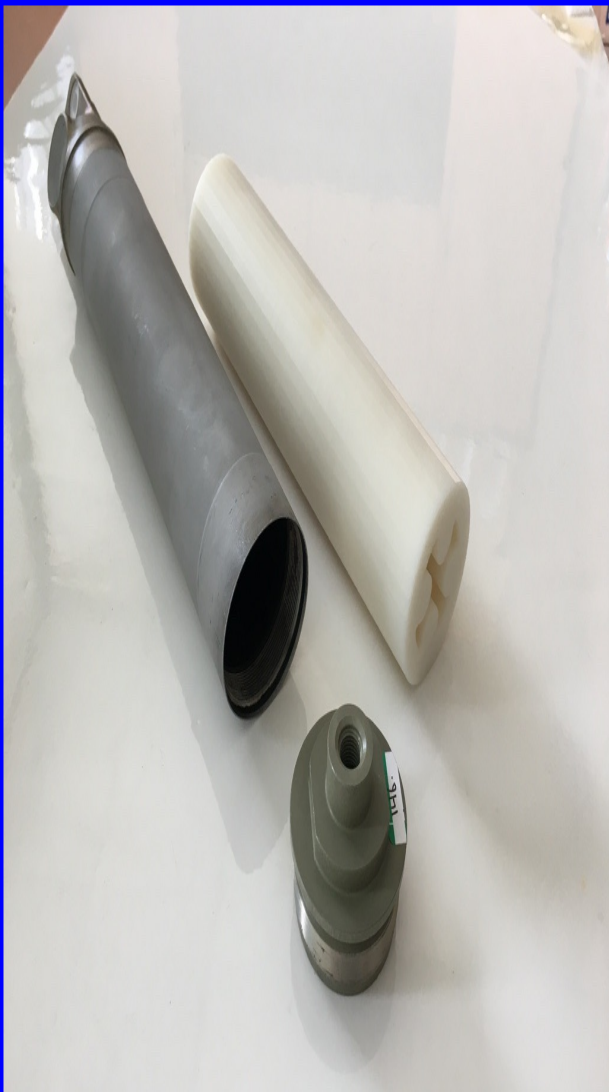
- Instrumentation of platform relevant MK-109 rocket motor test samples – inert and live - for unintrusive detection of propellant cracks and structural damage.
- Development and production of acousto-ultrasound fiber optic sensor networks.
- Development and production of miniature, battery power, wireless communication FAULT SHM Crack Detection System.
- Development and production of damage detection signal processing software

MK-109 Test Article Instrumented with Acousto-Ultrasound Fiber Optic Sensor Network

- ROI with the support of Nammo-Talley engineering group acquire several test samples of the MK-109 rocket motor shell for use in testing of the FAULT SHM crack detection system.

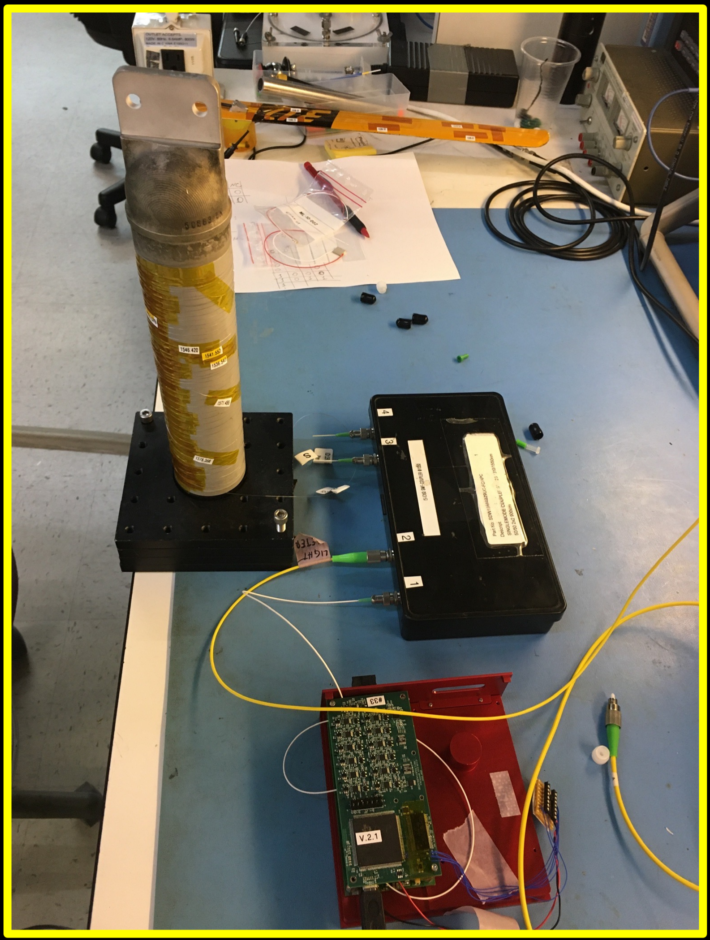
- The MK-109 rocket motor sample has been instrumented with an array of FBG sensors and currently used for testing and evaluation of the performance of the AU sensors for the detection of cracks and damage using a simulant propellant cartridge.

MK-109 Test Article Instrumented with Acousto-Ultrasound Fiber Optic Sensor Network



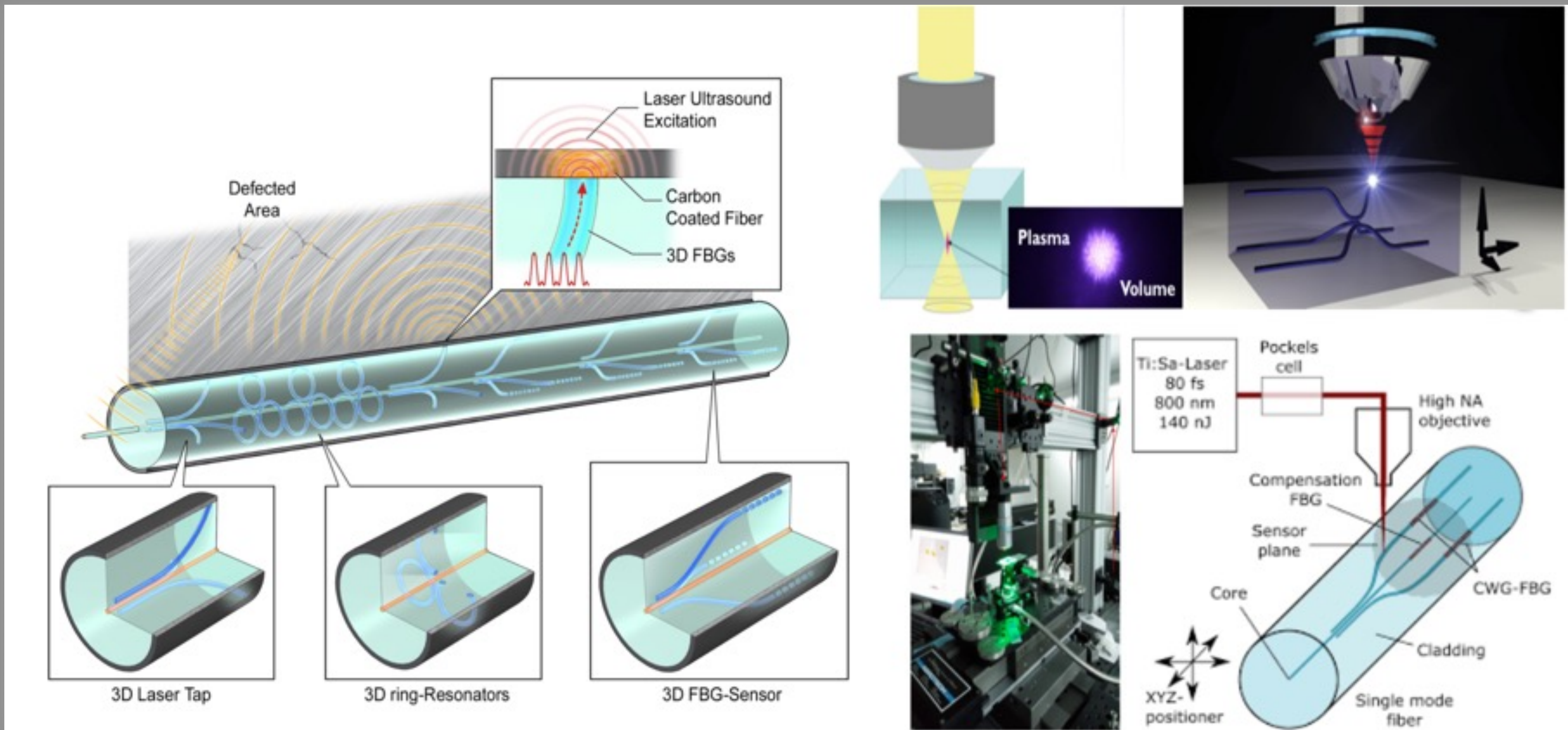
Ingredient	Function	T.I.M.S.	Parts by Weight		
			Nominal	Min.	Max.
*R-45M	Binder Constituent	15.01.10	67.565	66.00	72.00
AO-2246	Antioxidant	13.03.05	1.00	0.90	1.10
DHE	Bonding Agent	4.00	0.23	0.22	0.25
PDDP	Antiozonant	15.00	0.50	0.45	0.55
FeAA	Cure Catalyst	6.001	0.015	0.010	0.030
C-330	Filler (hydrated alumina)	8.80	19.40	19.00	21.00
*TMXDI	Curative	1.002	7.29	7.00	8.00
Carbon Black	Filler	3.02	4.00	0.00	6.00

MK-109 Inert Propellant Test Specimens



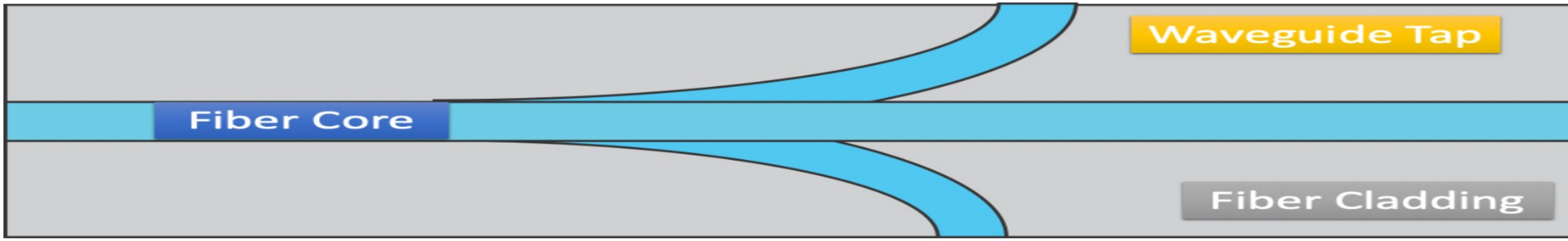
MK-109 Live Propellant Test Specimens

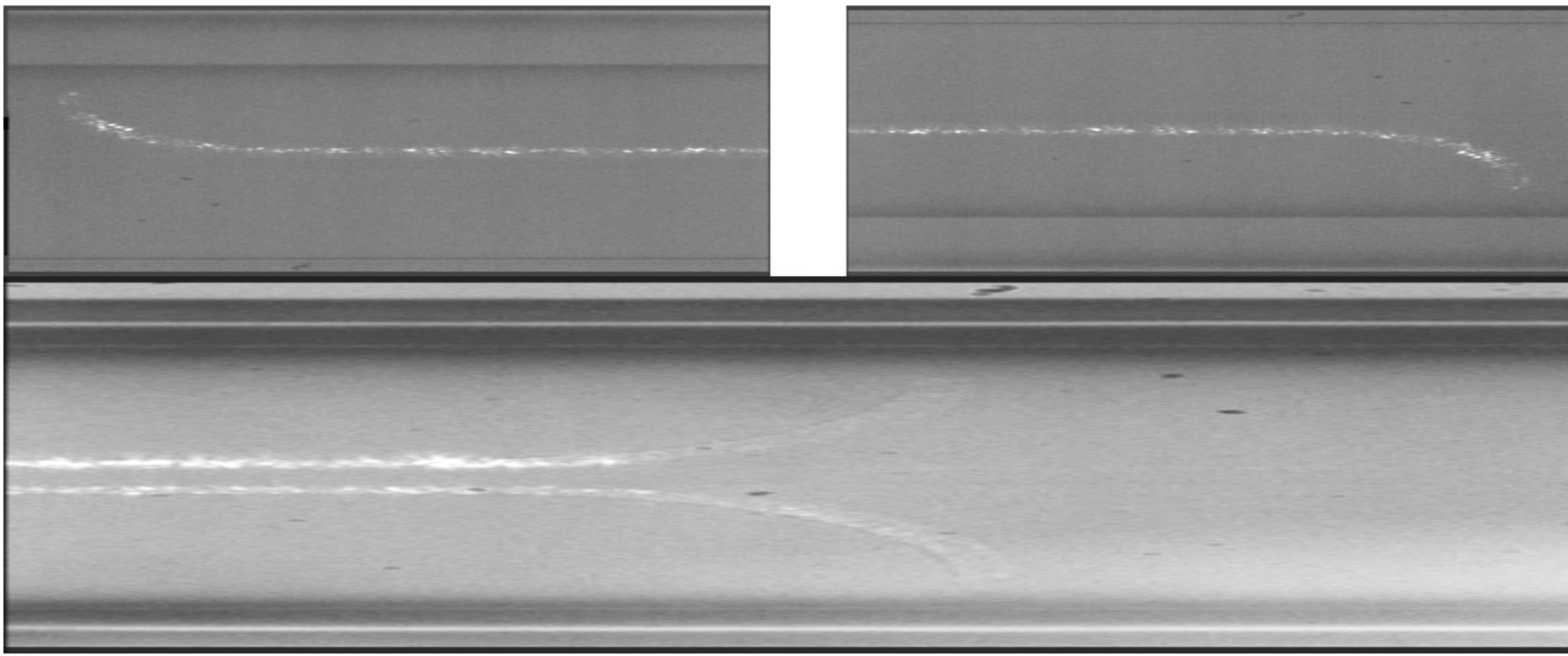
Production of Distributed Fiber Optic Acoustic-Ultrasound Sensor Network



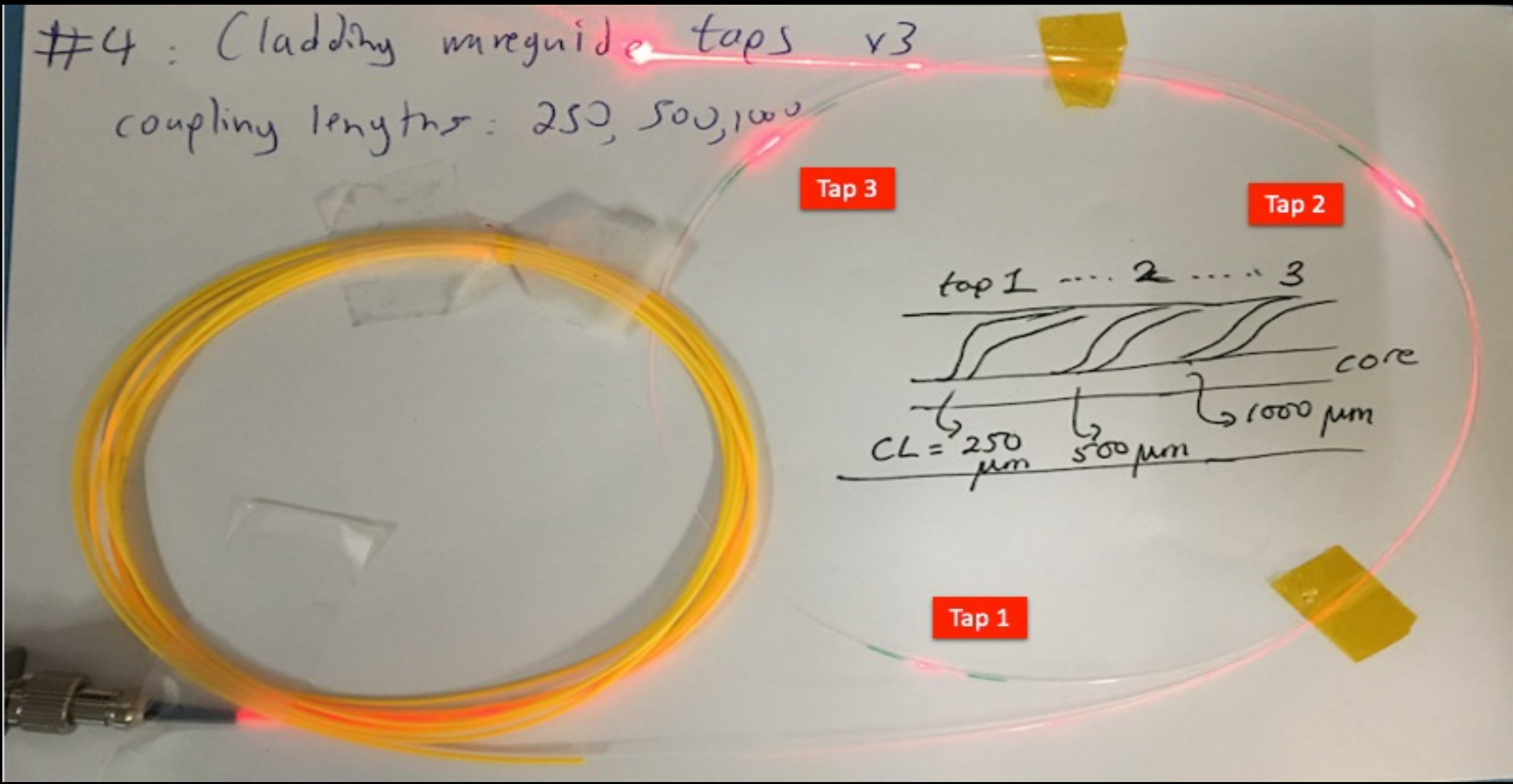
The FAULT™ SHM sensor network uses ROI's proprietary technology for the three-dimensional fento-second laser inscription of a distributed three-dimensional array of laser ultrasound excitation "hot-spot" tap points and an interleaved array (100's) of acoustic-ultrasound sensing receiver elements (FBGs and Ring-Resonators) produced within a single optical fiber

Fento-Second Laser Inscription Production of Laser "Tap" Excitation Points



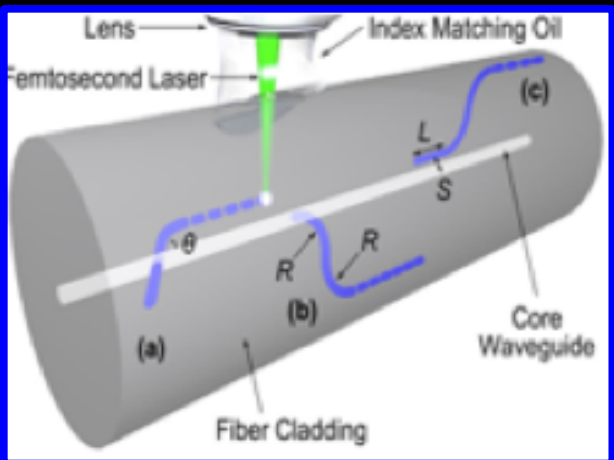


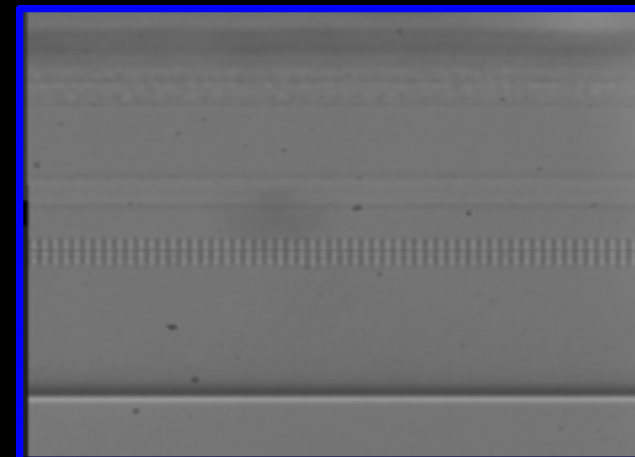
Fento-Second Laser Inscription Production of Laser "Tap" Excitation Points

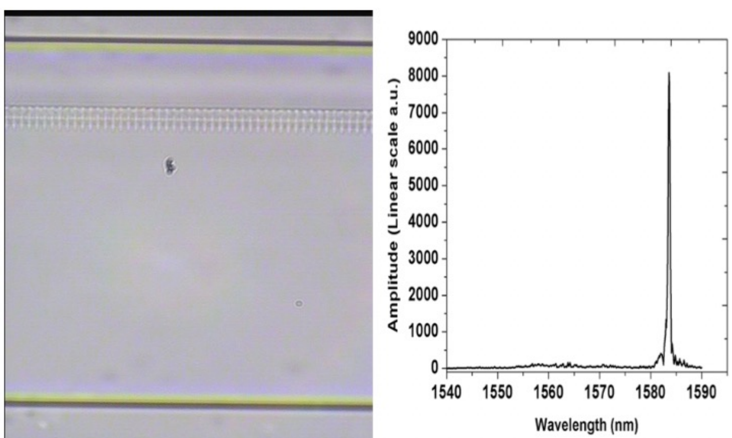


Radiative Optical Power from Laser Beam Launched onto Optical Fiber for Acousto-Ultrasonics Excitation of the Rocket Motor Test Structure

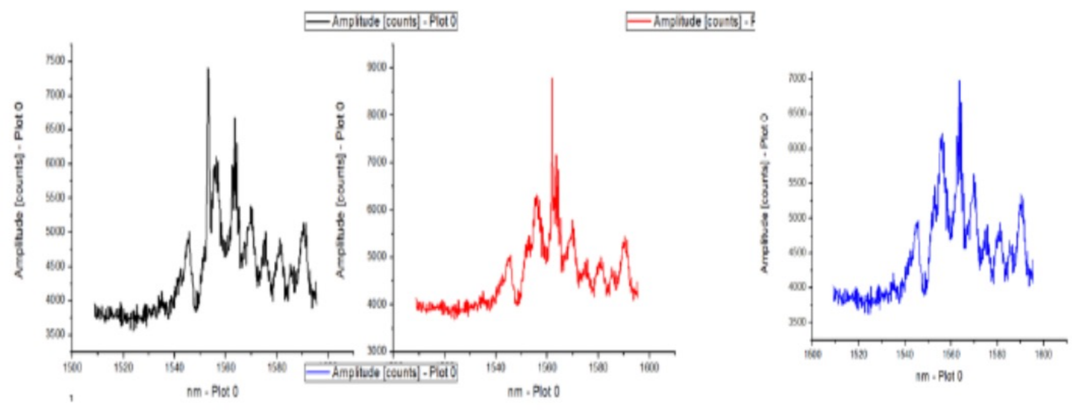
Fento-Second Laser Inscription for Production of 3D-Surface FBG Strain Sensors





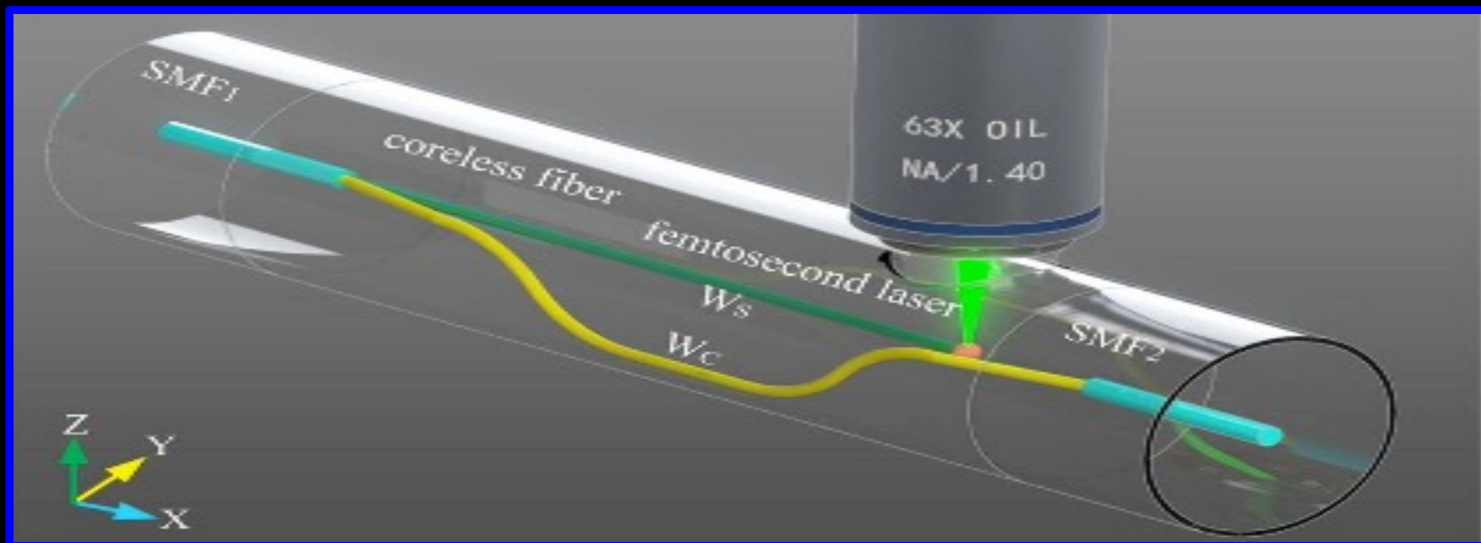


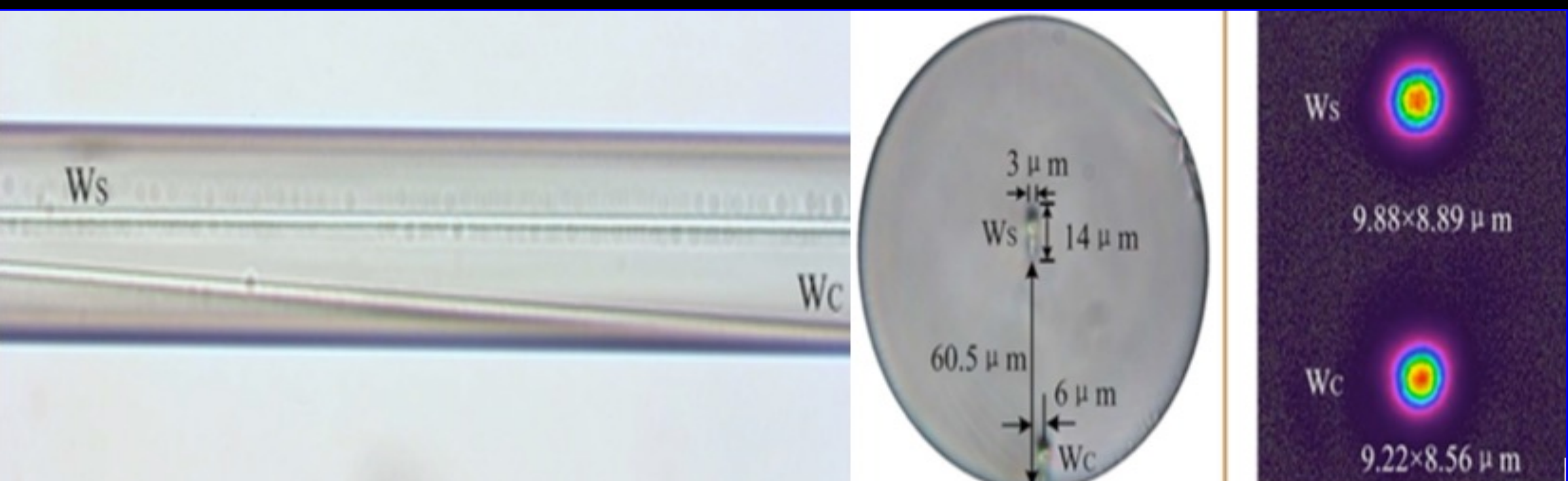
Single 3D FBG



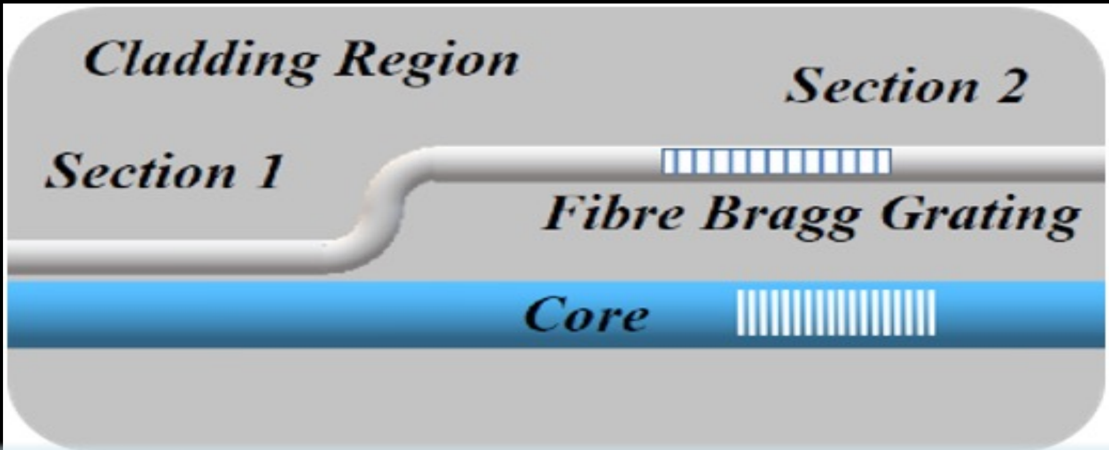
Array of 3D-FBGs

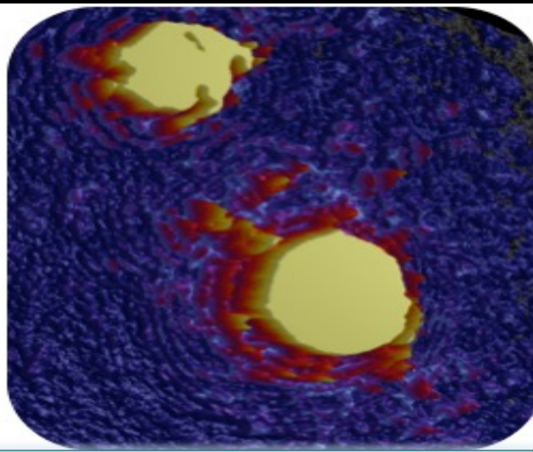
Femto-second laser inscription of three-dimensional waveguide structures



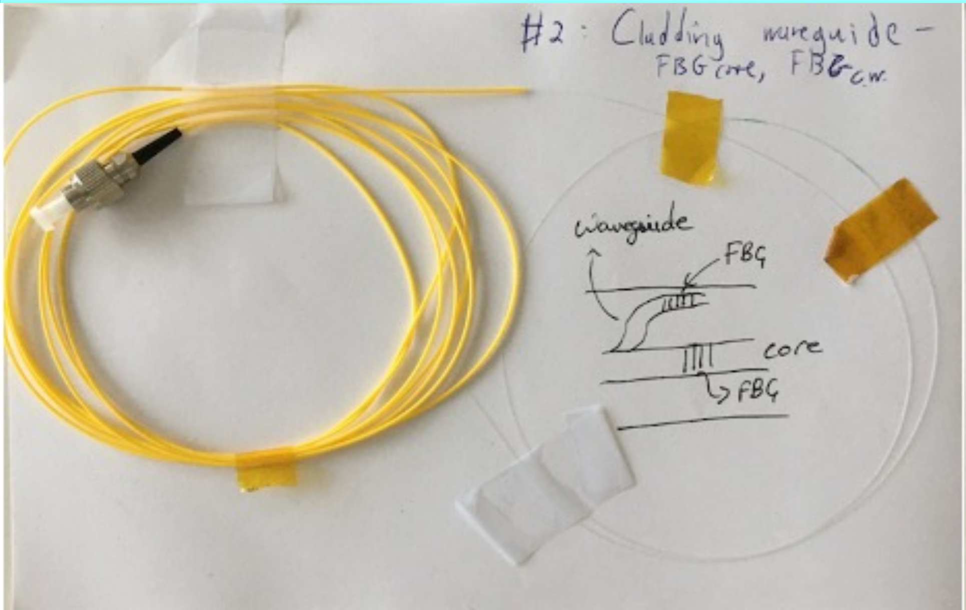


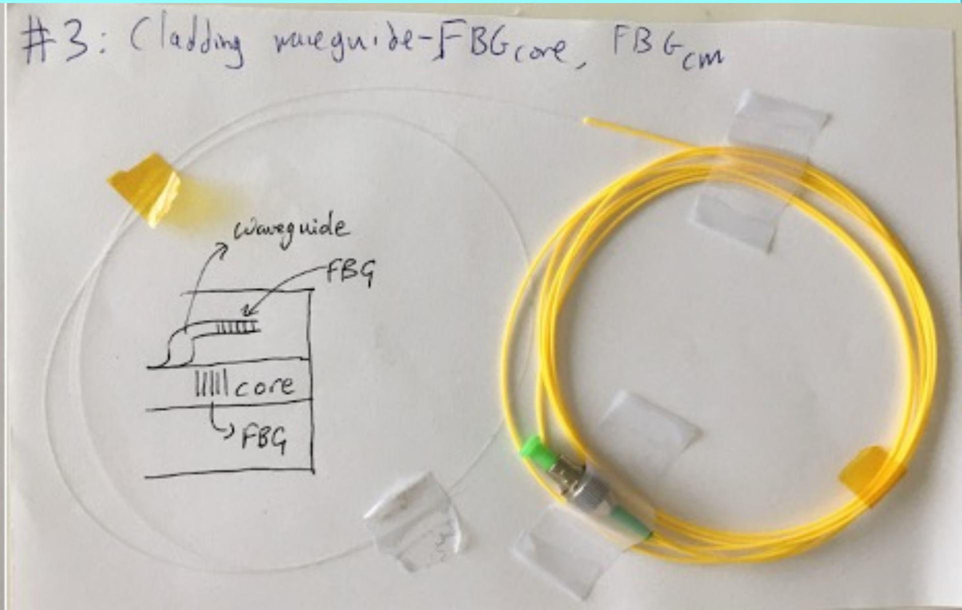
Fento-Second Laser Inscription for Production of 3D-Surface FBG Strain Sensors



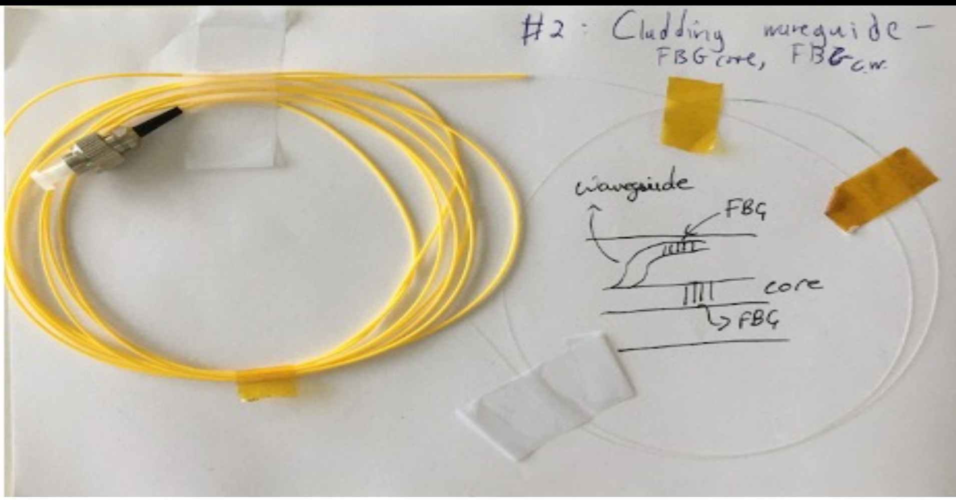


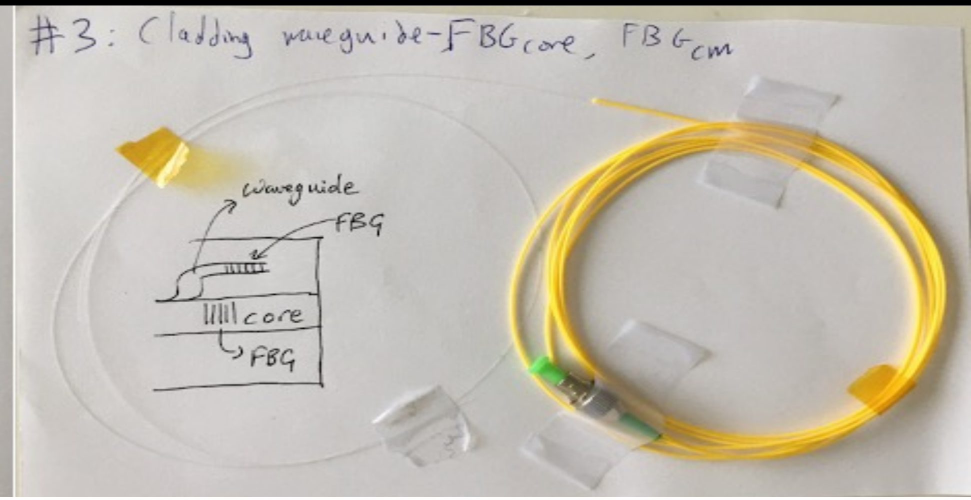
Dual FBG Sensor for Enhance AU Signal Detection

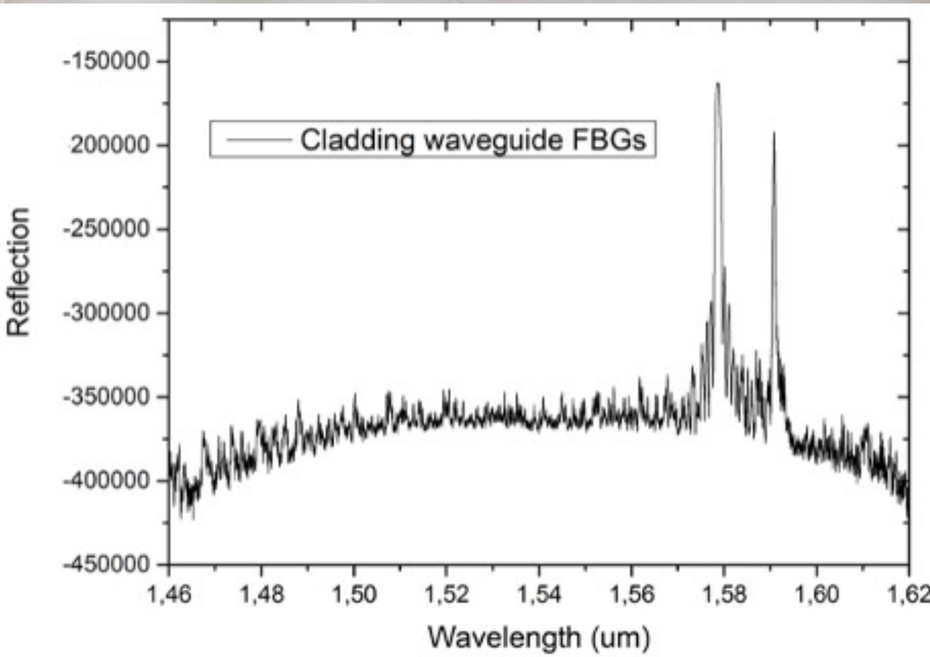


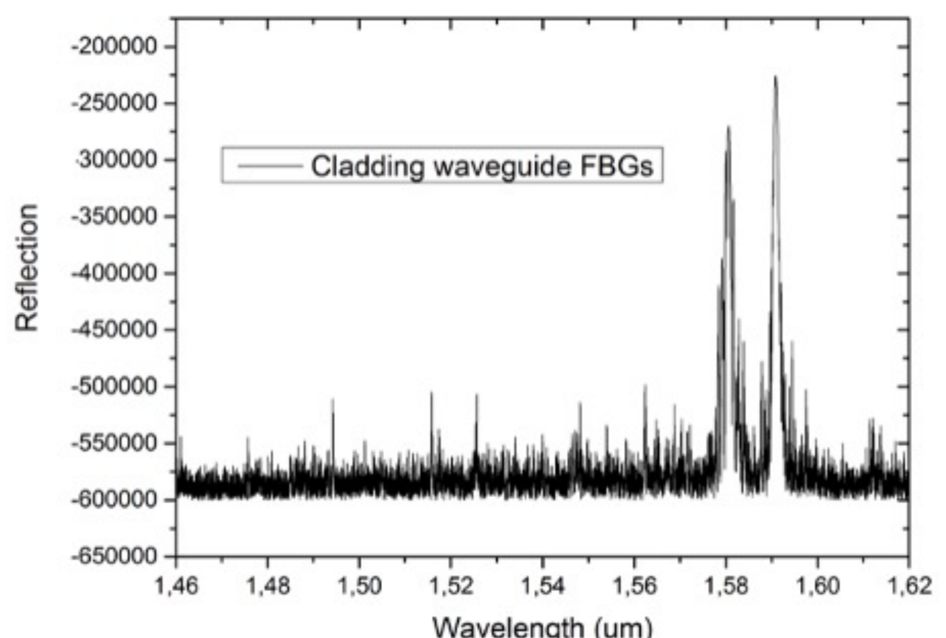


Fento-Second Laser Inscription for Production of 3D-Surface FBG Strain Sensors

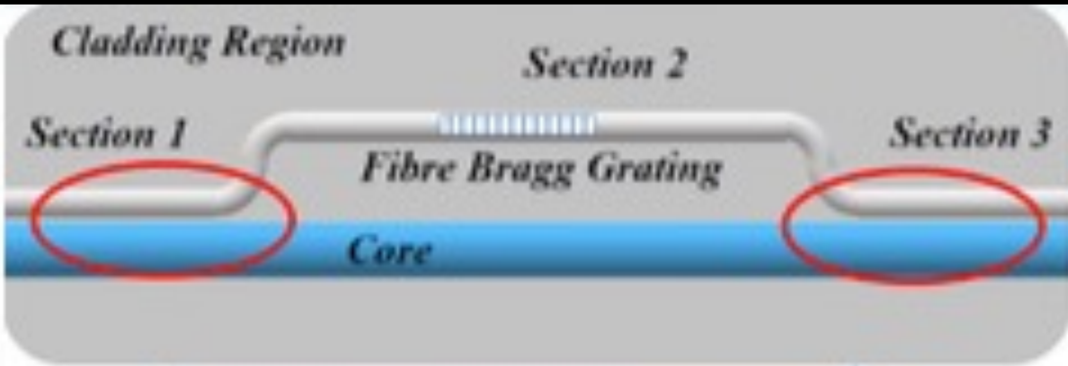


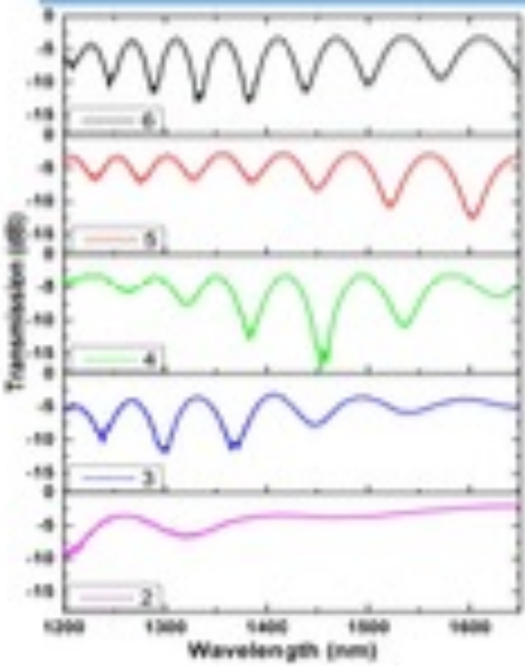






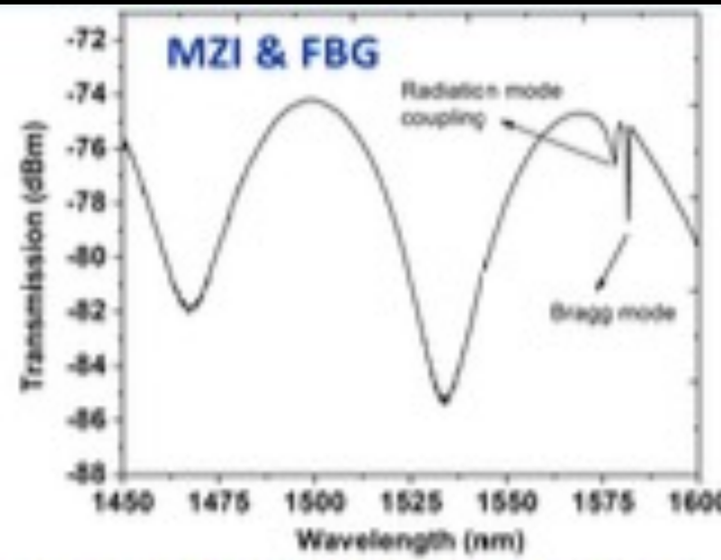
Femto-Second Inscription of 3D-Waveguide Mack-Zehnder Interferometers



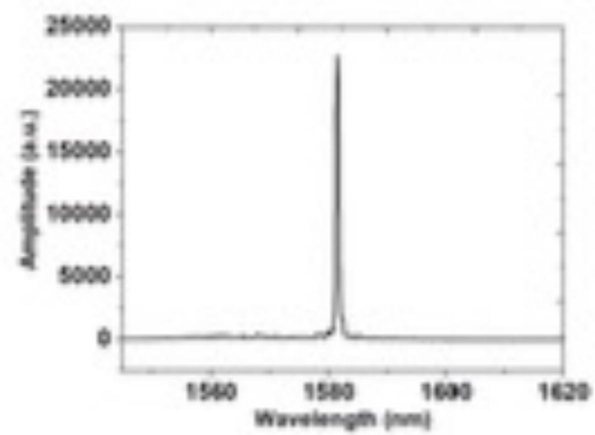


Wavelength shift Index~$4x10^{-3}$

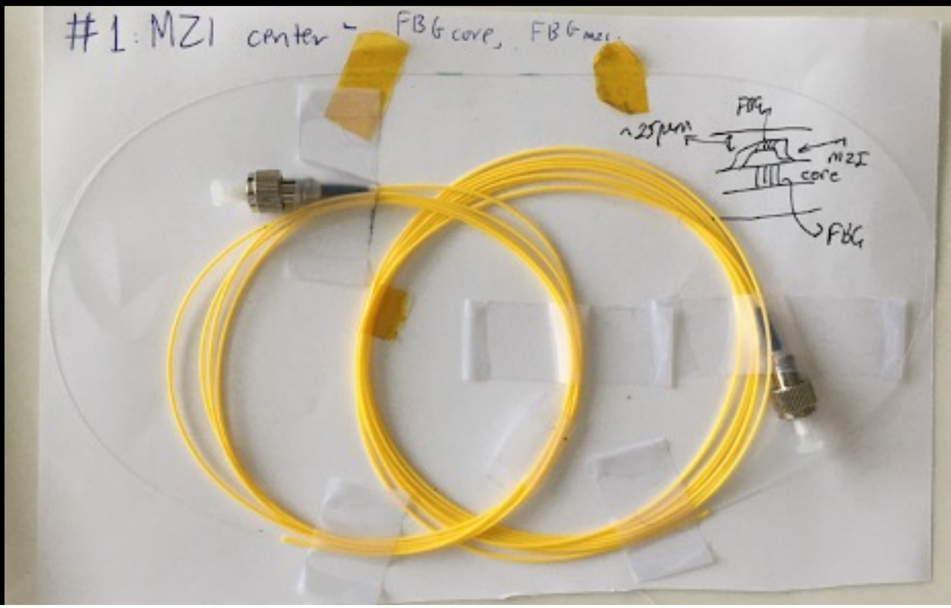
Spectrum vs increasing waveguide width – "Inscribe & Step"

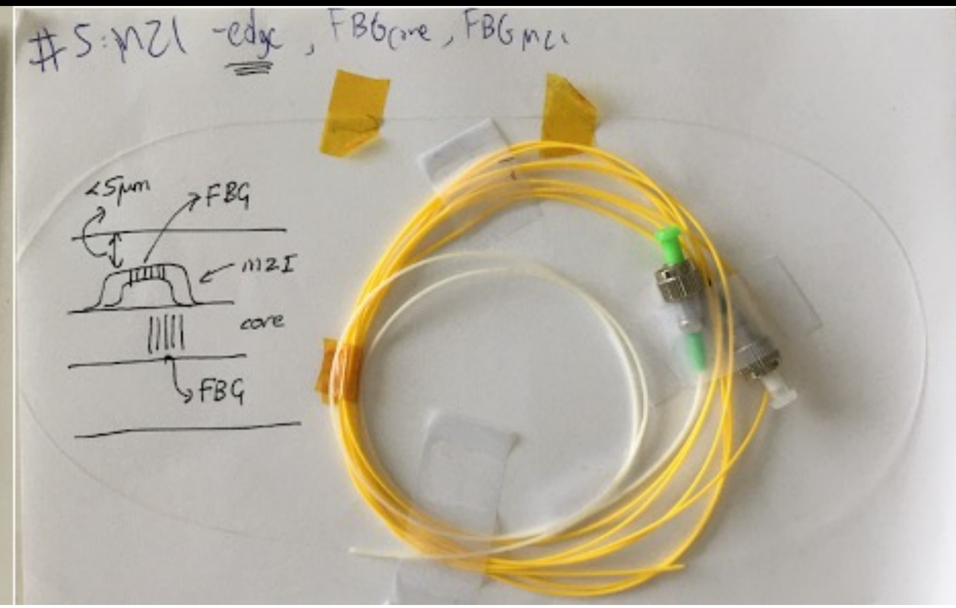


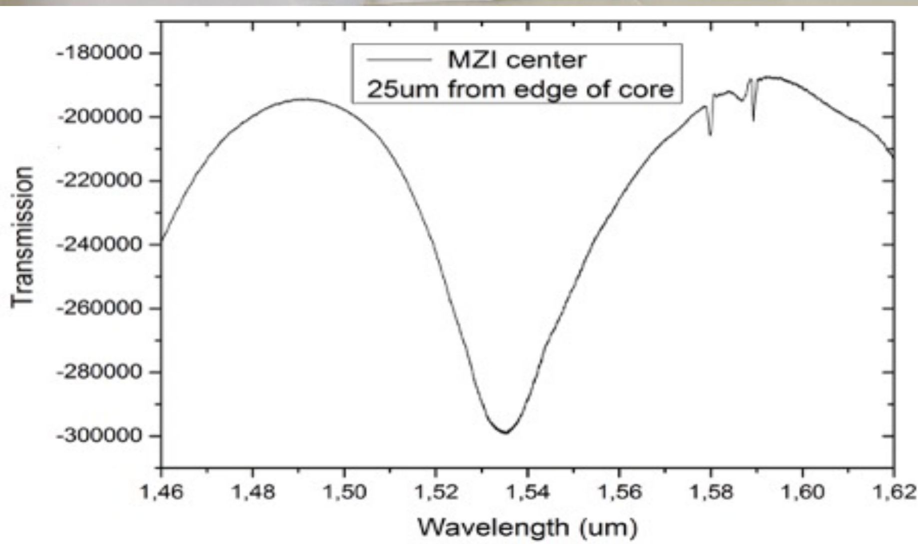
FBG in MZI – reflection spectrum

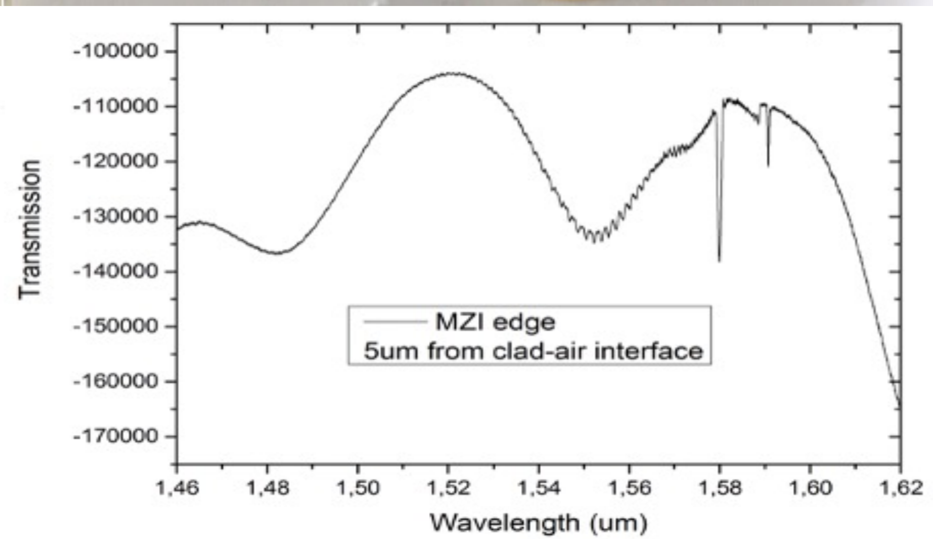


Femto-Second Inscription of 3D-Waveguide Mack-Zehnder Interferometers

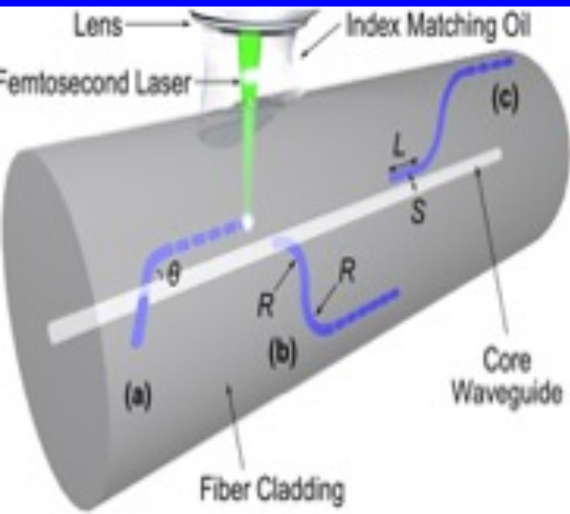


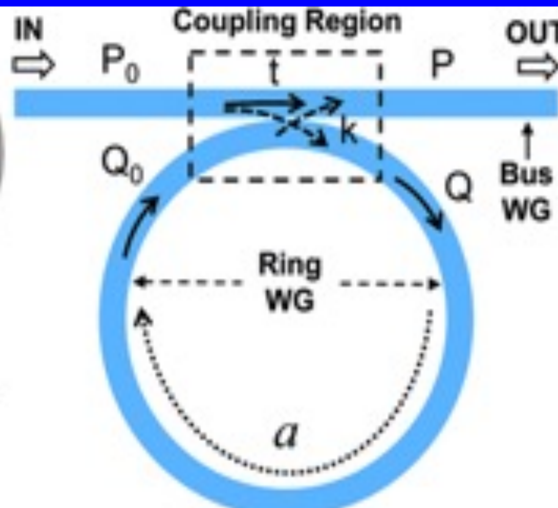


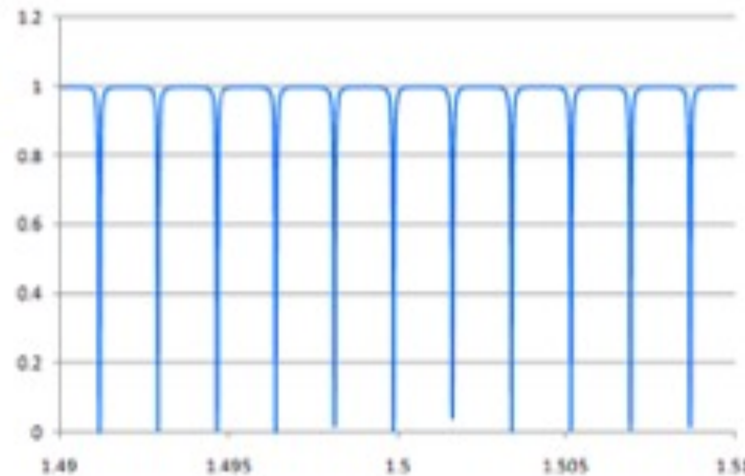


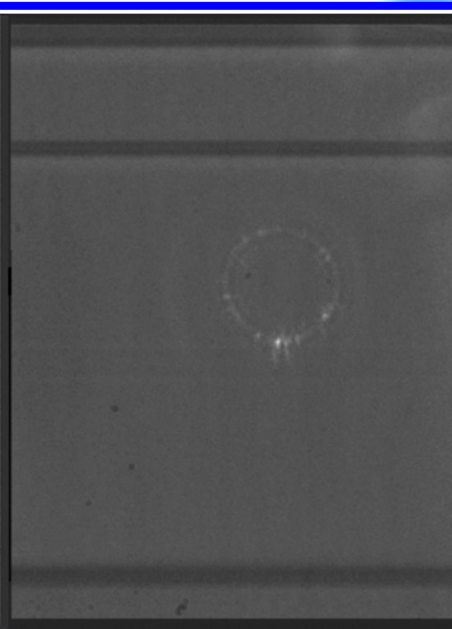


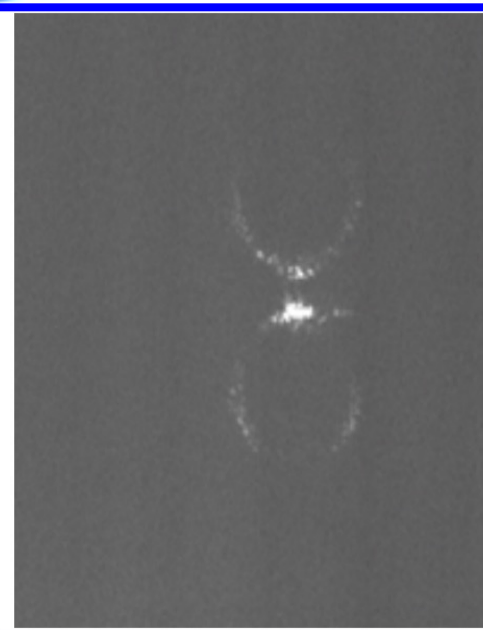
Fento-Second Laser Inscription for Production of Ring-Resonator Strain Sensors

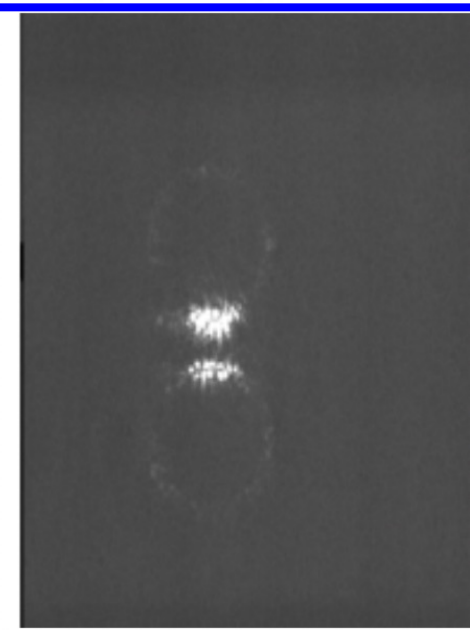




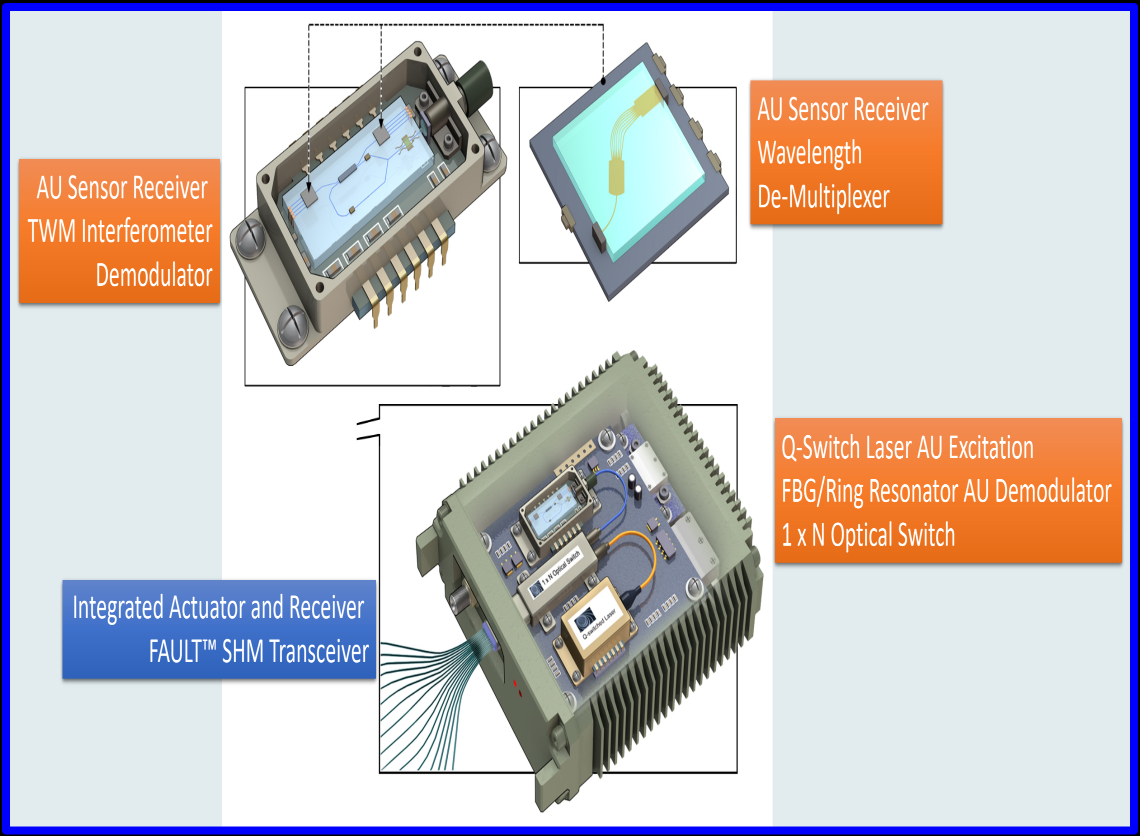


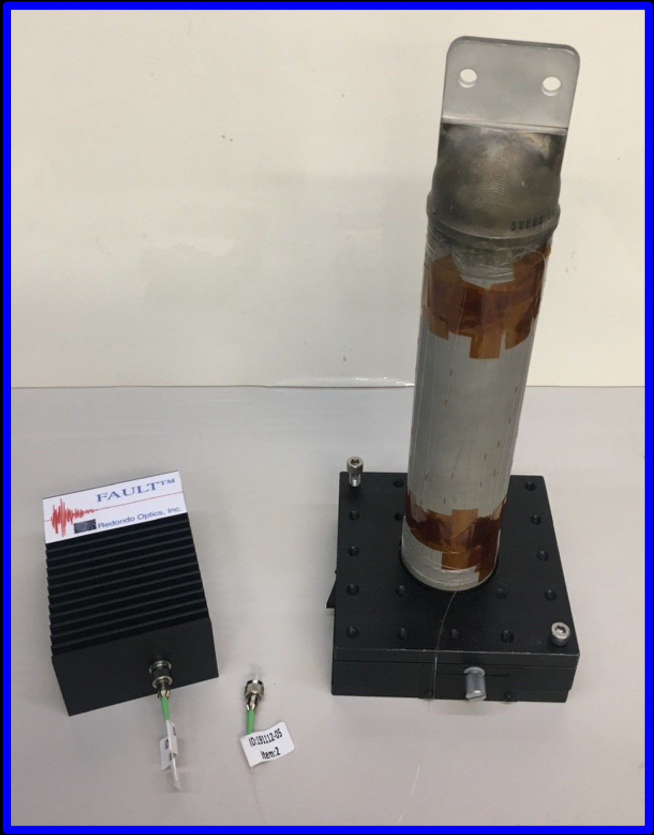






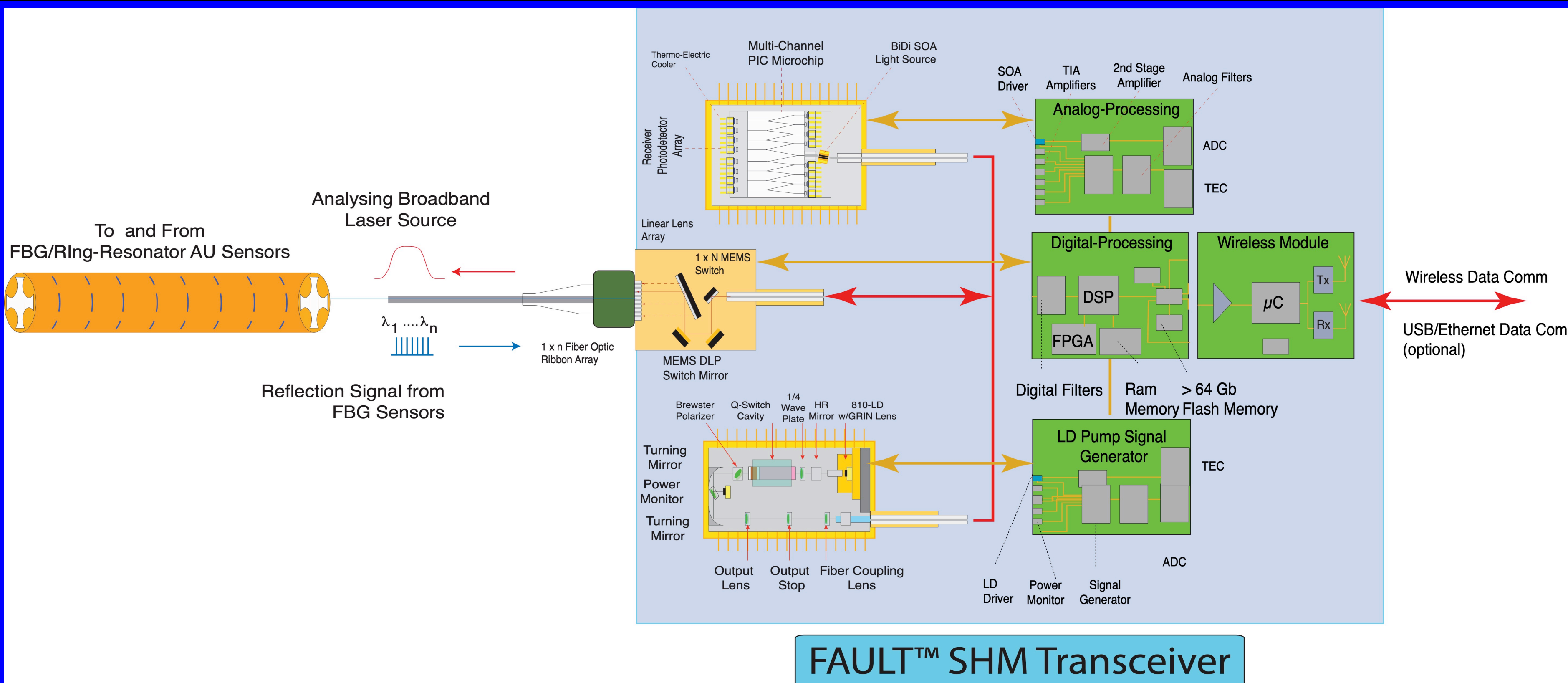
Engineering Development of FAULT™ Crack Detection SHM Transceiver System





Integrates the pulsed AU excitation laser source, multi-channel TWM PIC microchip demodulator; 12-ch WDM FBG sensor interrogation electronics; MEMS 1xn optical switch, high-speed signal processing electronics with wireless data communication

Block Diagram of FAULT™ SHM Transceiver Opto-Electronics



Integrates the pulsed AU excitation laser source, multi-channel TWM PIC microchip demodulator; 12-ch WDM FBG sensor interrogation electronics; MEMS 1xn optical switch, high-speed signal processing electronics with wireless data communication

FAULT System Signal Processing
Electronics On-Board Signal Processing

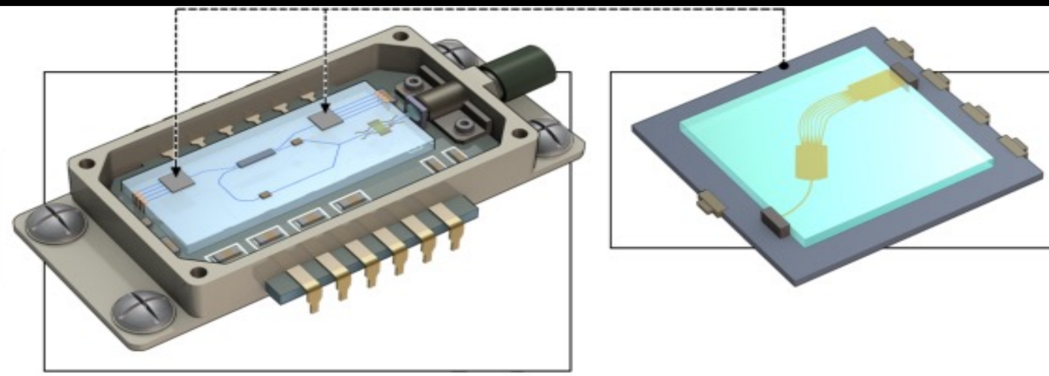
- Receives high sample rate (MHz) signals from analog/digital data logger board and reduces data using wavelet and neural network algorithms use for signal feature extraction.

- Reduced feature data is store on-board within high capacity (500-GHz) SD Card and transmitted using wireless (Wi-Fi or Bluetooth) data transmission protocols

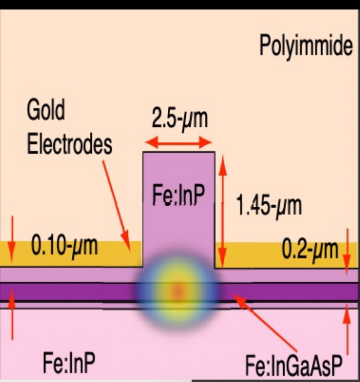
The FAULT System Uses a COTS High Performance Singe-Board Mini-Computer for On-Board Signal Processing, Data Discrimination, and Wireless Data Transmission

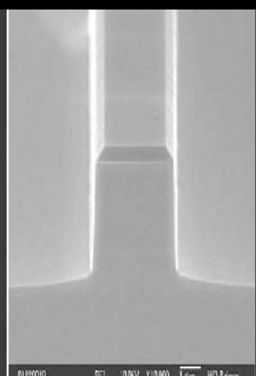
Design and Production of the FAULT SHM System Two-Wave-Mixing Interferometer PIC Microchip.

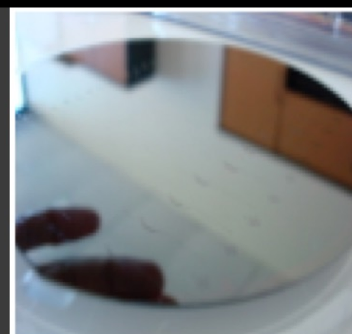
AU Sensor Receiver
TWM Interferometer
Demodulator



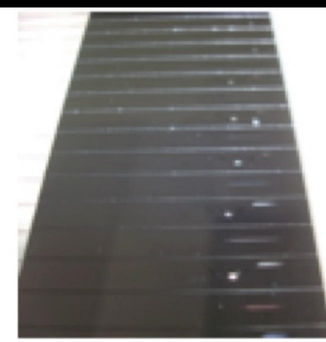
AU Sensor Receiver
Wavelength
De-Multiplexer



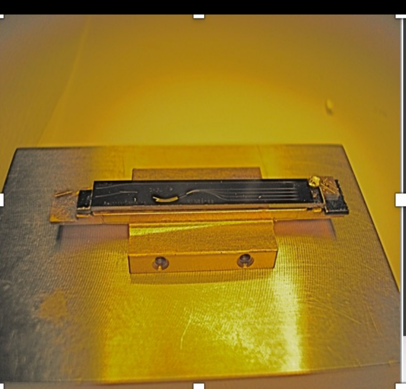


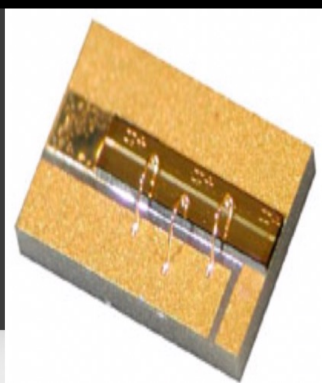


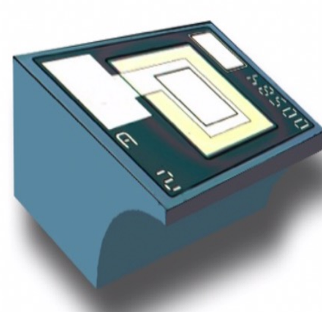
Produced Epitaxial Wafer

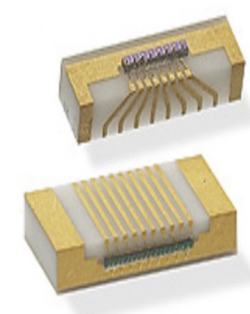


Diced PIC Chips



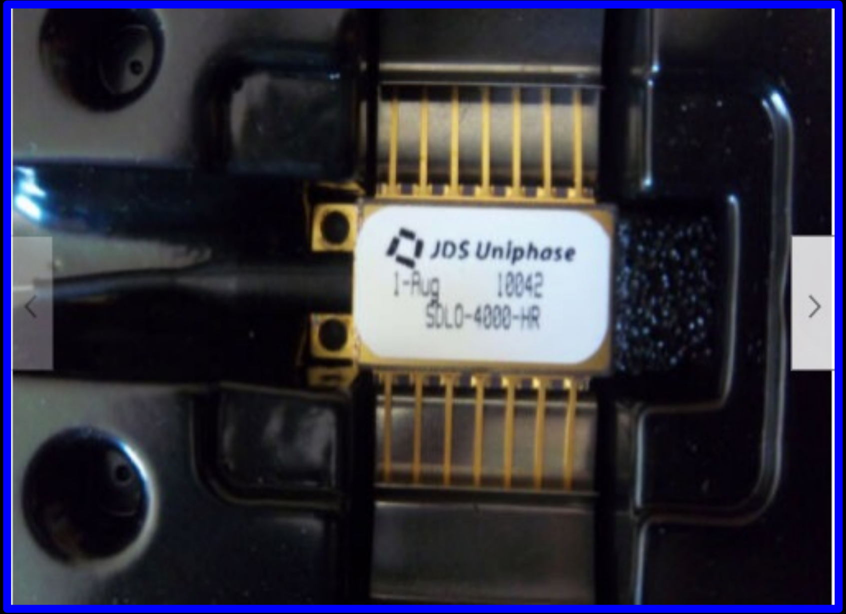


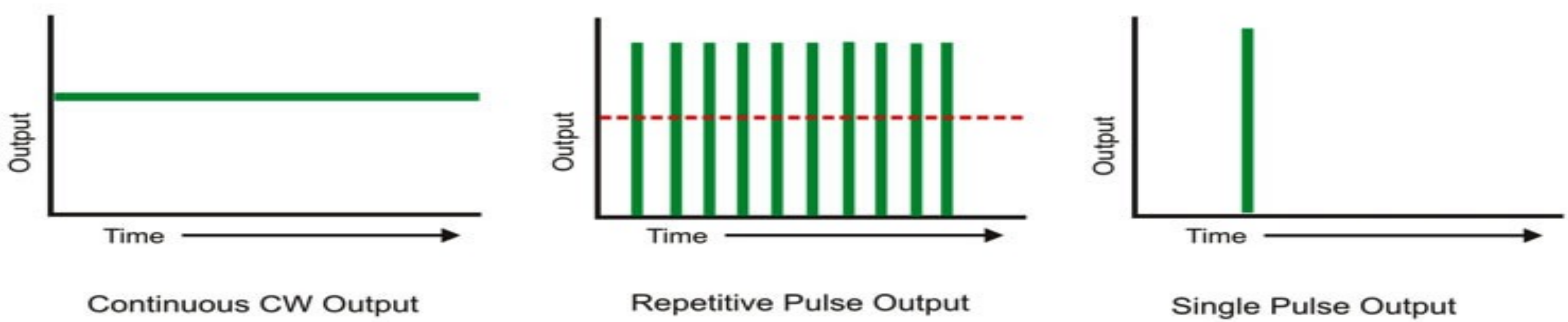




JDSU SDLO-4000 1000mW, 915nm Pump Pulsed Laser

- Semiconductor grating stabilized pulsed (nsec) pump lasers offers flexible capability for use with the FAULT SHM system for the acousto-ultrasound excitation of test structures.

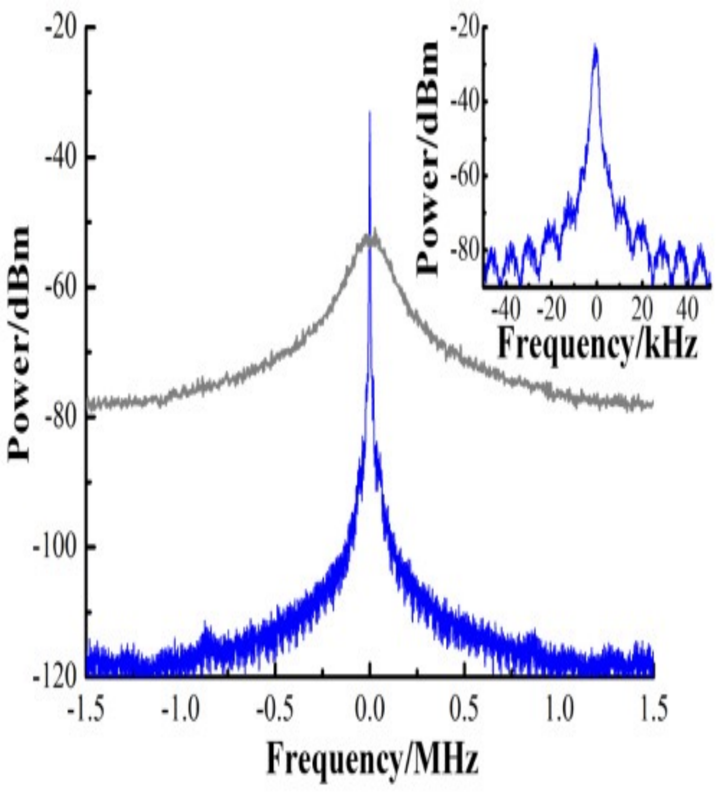




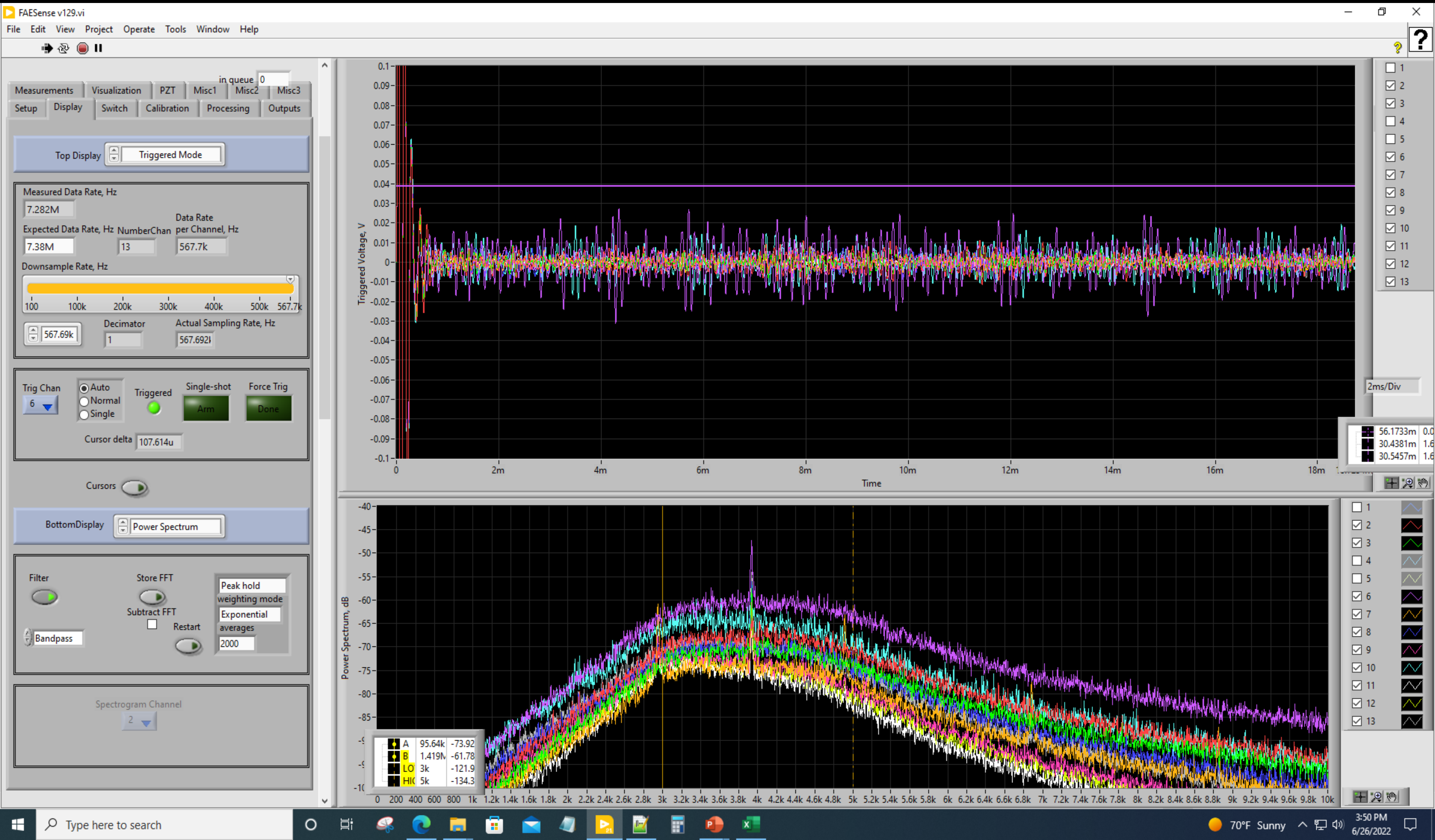
FBG Stabilized DFB Laser Spectrum 3-dB Linewidth ~ 2-nm

Table 4 Electro-Optical Performance[3]

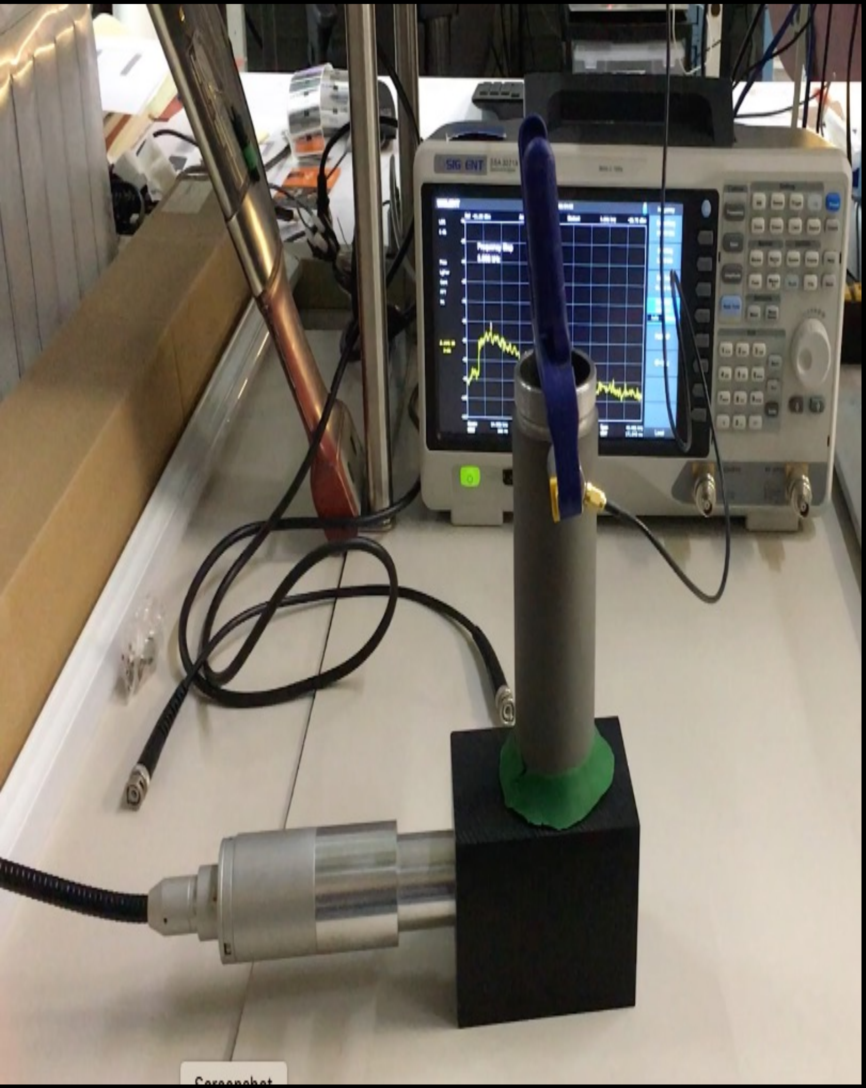
Parameter	Symbol	Test Conditions	Minimum	Maximum
Spectrum				
Target wavelength[4] (in vacuum)	λ_t	I_{op}	1420 nm	1510 nm
Power in band (λ_t ±2 nm)	P_{band}	$I(100\ mW) \leq I \leq I_{op}$	80%	–
Spectral bandwidth, RMS	$\Delta\lambda_{RMS}$	P_{op}, RMS	–	2.0 nm
Polarization extinction ratio	R_e	T_{case} = 25°C	13 dB	
Laser Diode				
Threshold current	I_{th}			200 mA BOL
End-of-lifetime operating current	I_{opEOL}		1.12 x I_{op} BOL	
Monitor Photodiode				
Monitor current	I_{MPD}	I_{op}, V_{rPD} = 5 V	0.5 µA/mW	5.0 µA/mW
Monitor dark current	I_d	V_{rPD}=5 V	–	300 nA
Monitor diode capacitance	C_{MPD}	$V_{r,PD}$ = 5 V, 1 kHz	–	20 pF
Front-to-rear tracking ratio	TR	I_m constant, 100 mW to P_{op}	0.85	1.15
Front-to-rear tracking error	TE	I_m constant, 100 mW to P_{op}	-15%	15%
Thermoelectric Cooler Operation				
Power consumption	P_{con}			12.5 W EOL
Thermistor resistance	R_{th}	25°C	9.5 kΩ	10.5 kΩ
Mean thermistor B constant	B	TC	3700 K	4100 K

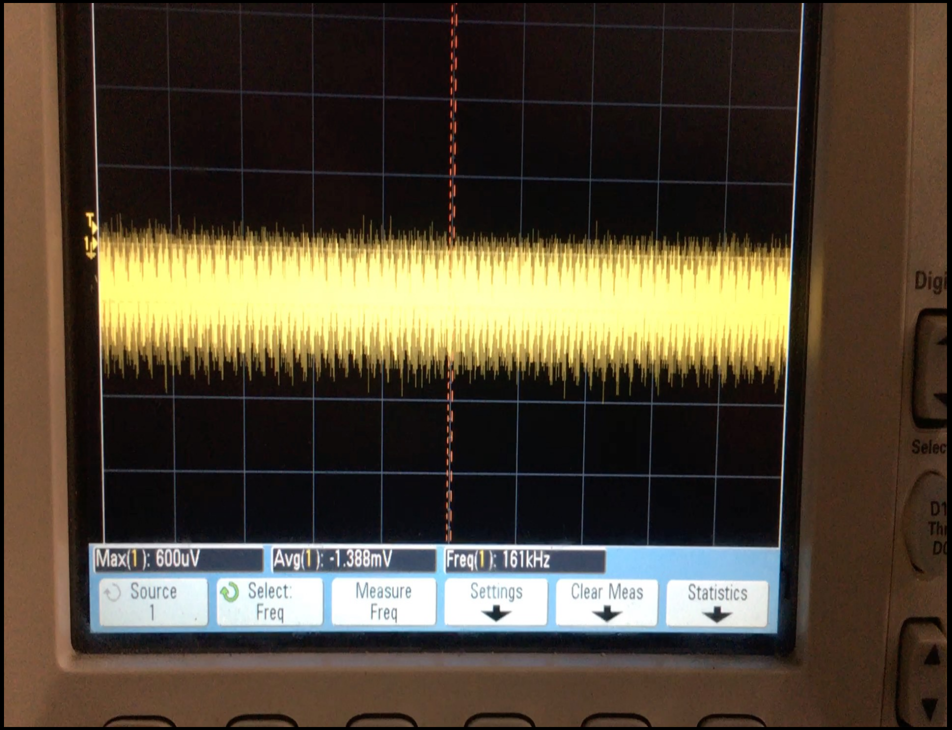


Laser Acoustic Ultrasound Excitation at Target Frequency Excitation

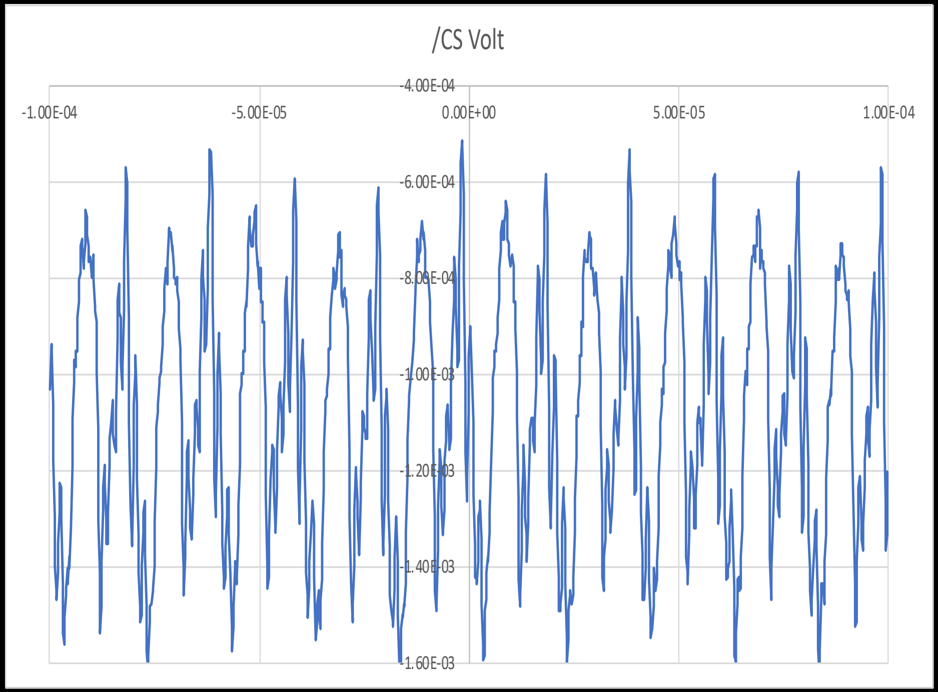


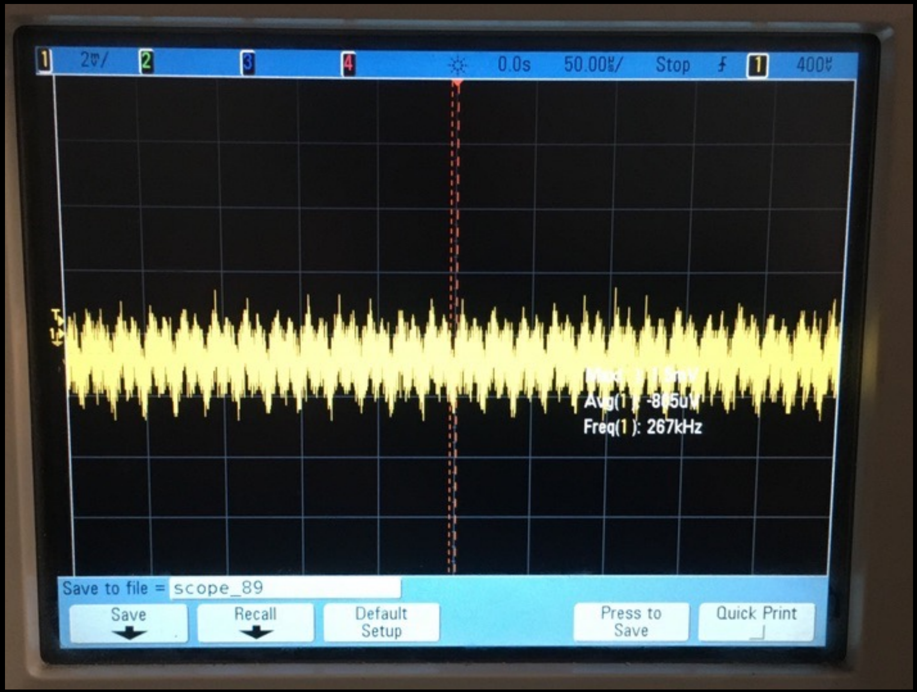
Fiber Optic Laser Acousto-Ultrasound Excitation



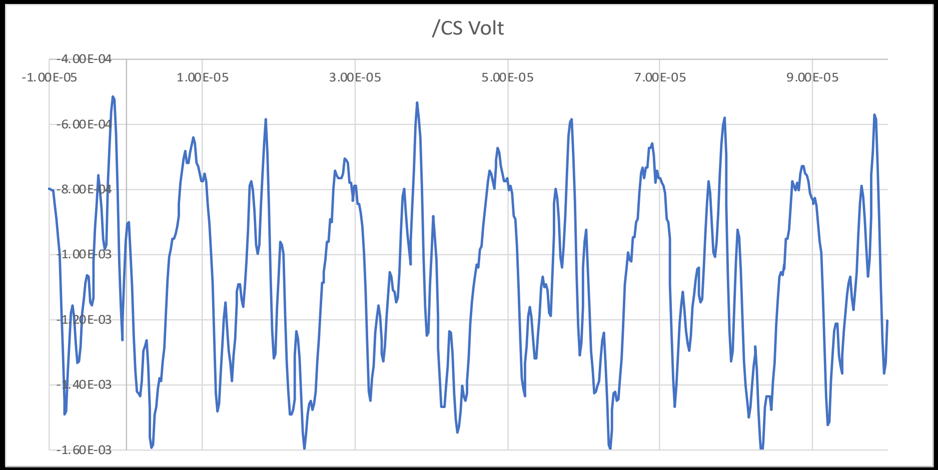


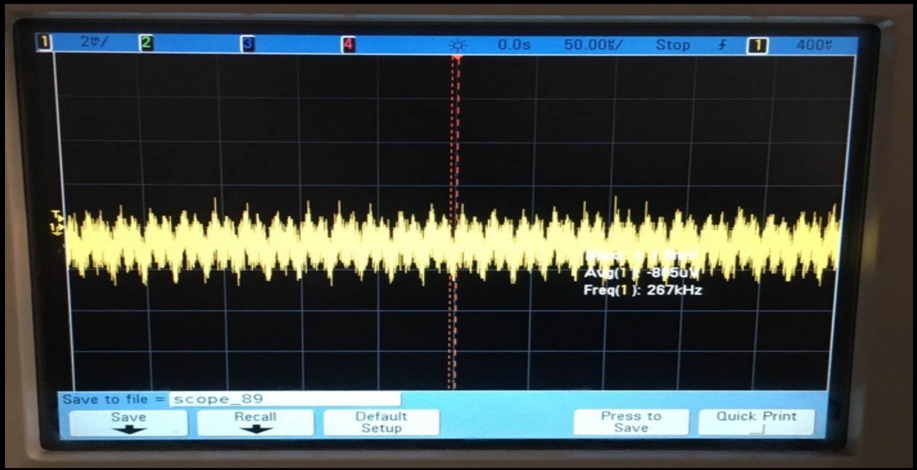
Fiber Optic Laser Acousto-Ultrasound Excitation (267-kHz Arbitrary Waveform)

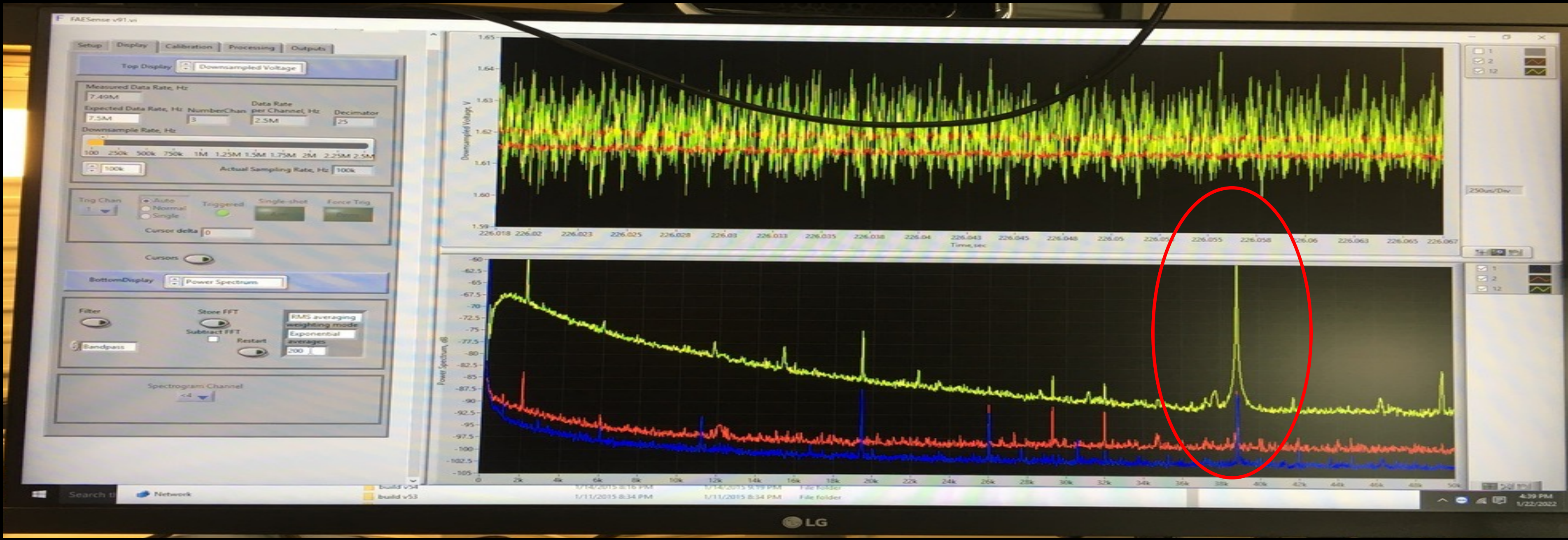




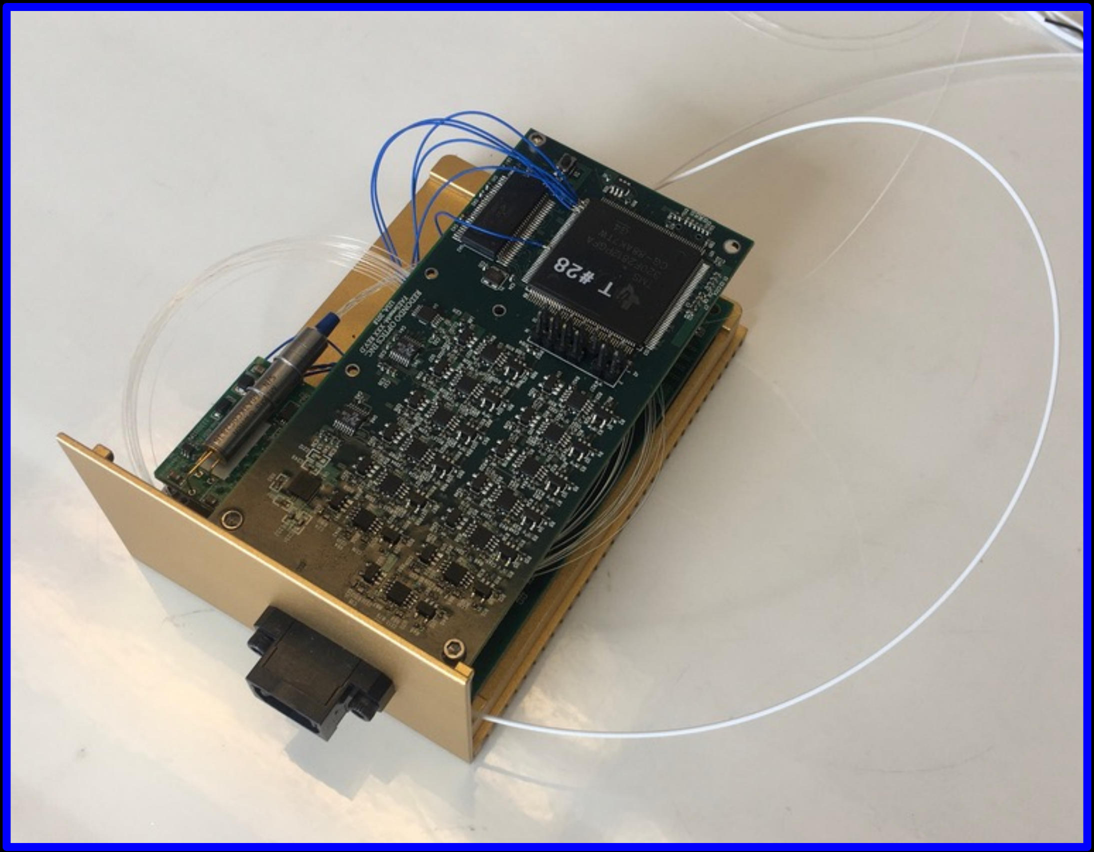
Fiber Optic Laser Acousto-Ultrasound Excitation (267-kHz Arbitrary Waveform)





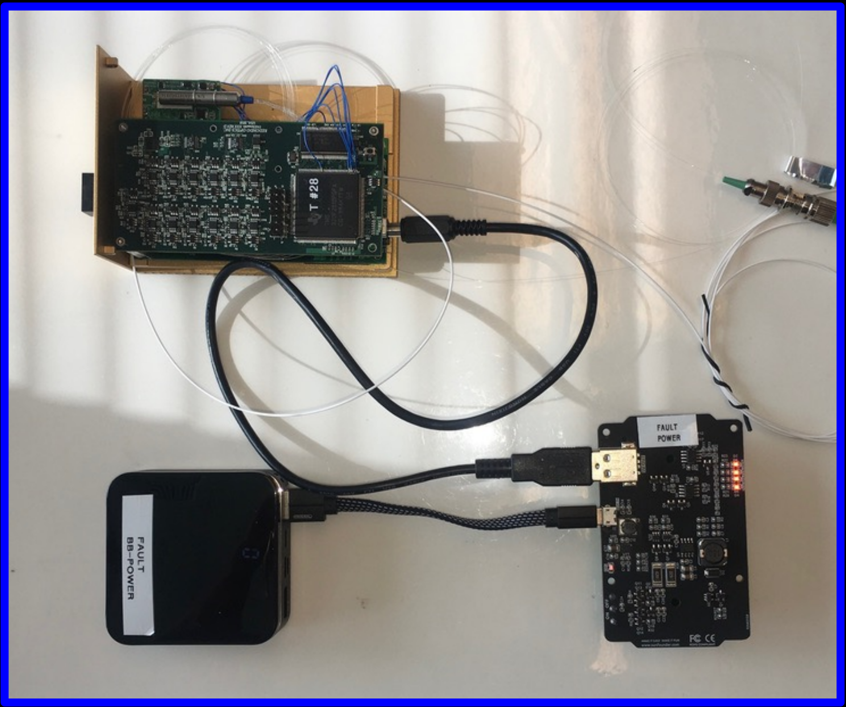


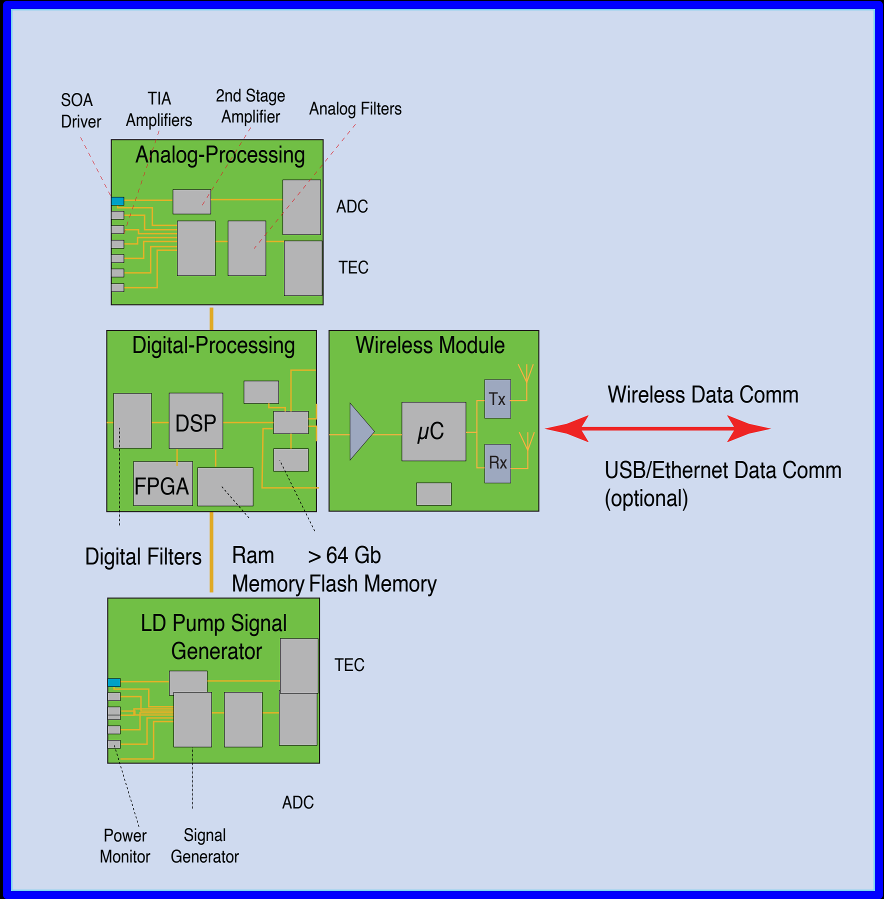
Integration of 1 x N MEMS Optical Switch to FAULT™ SHM Interrogation System



ROI Uses a COTS 1 x n MEMS Optical Switch Integrated to the FBG Sensor Interrogator for the High-Speed Multiplex Interrogation of the Flex Circuit FBG Receivers

FAULT System Self-Power Using Long-Lived Li-Ion Battery Packs

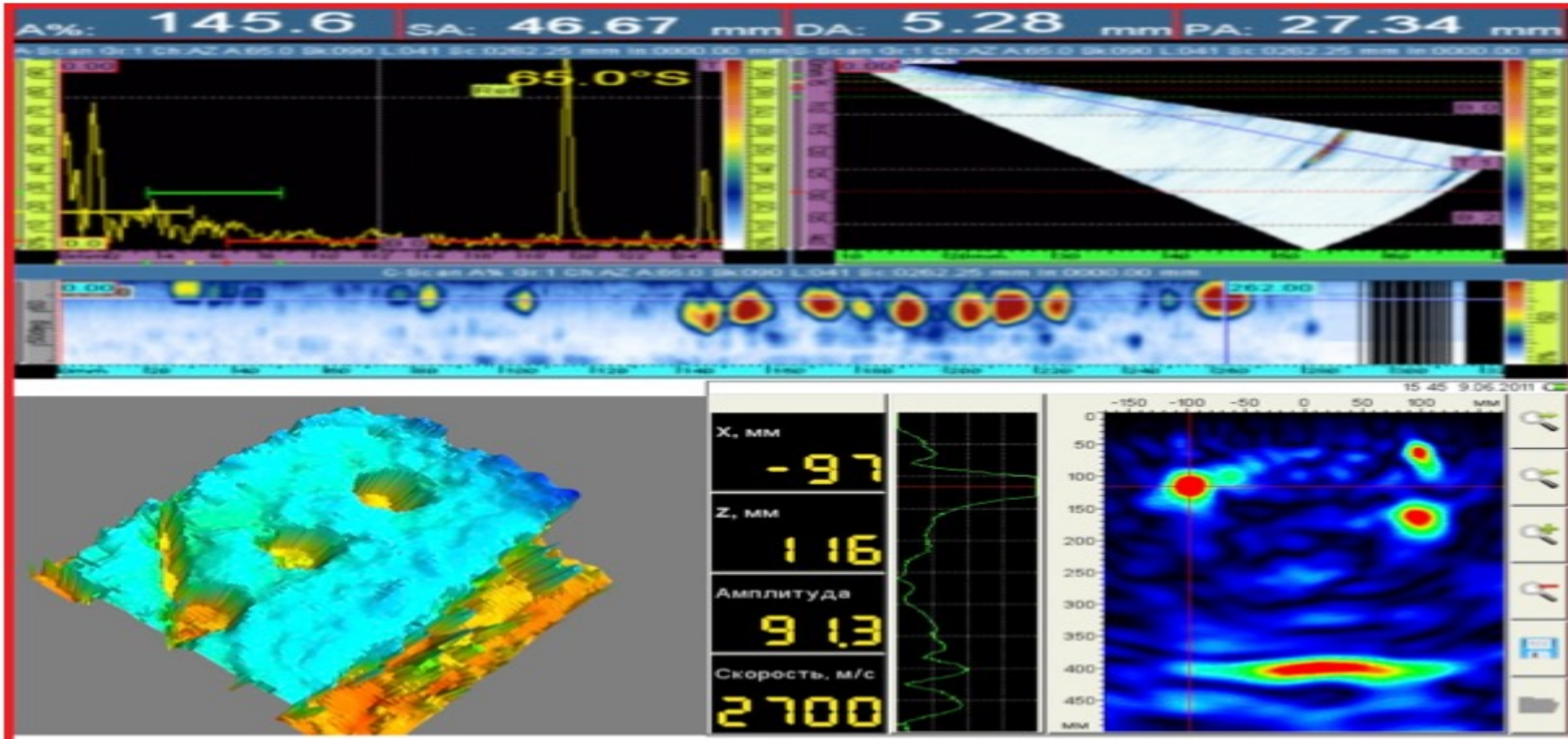




The FAULT System Uses a COTS Long-Lived Li-Ion Battery Pack, and Auxiliary Battery Recharging Module Used to Maintain Constant Power to System Over Prolonged Operating Periods of Time

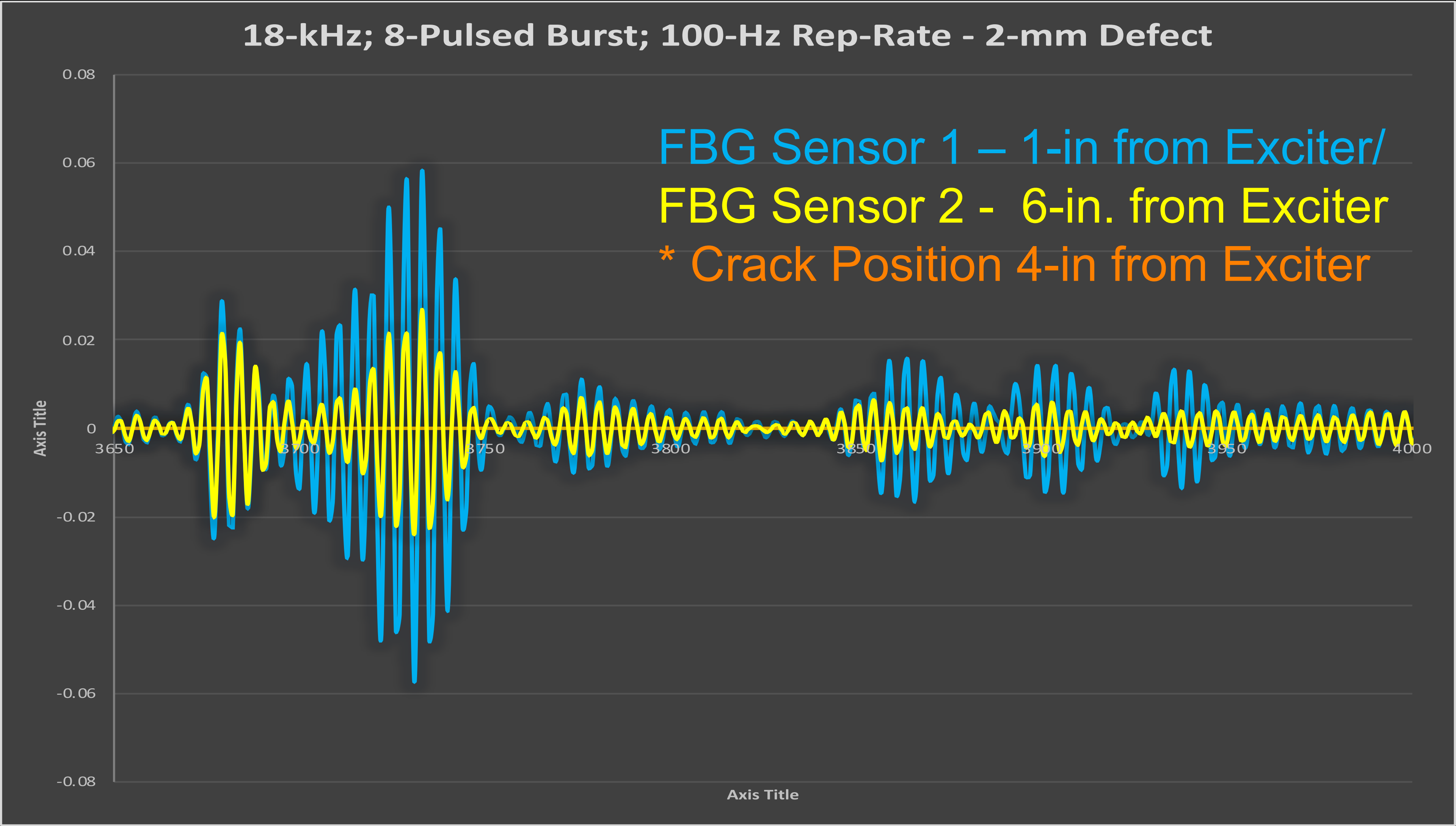
Real Time Signal Processing for Crack Detection Using Acoustic Ultrasound Signature Events.

Dynamic Events



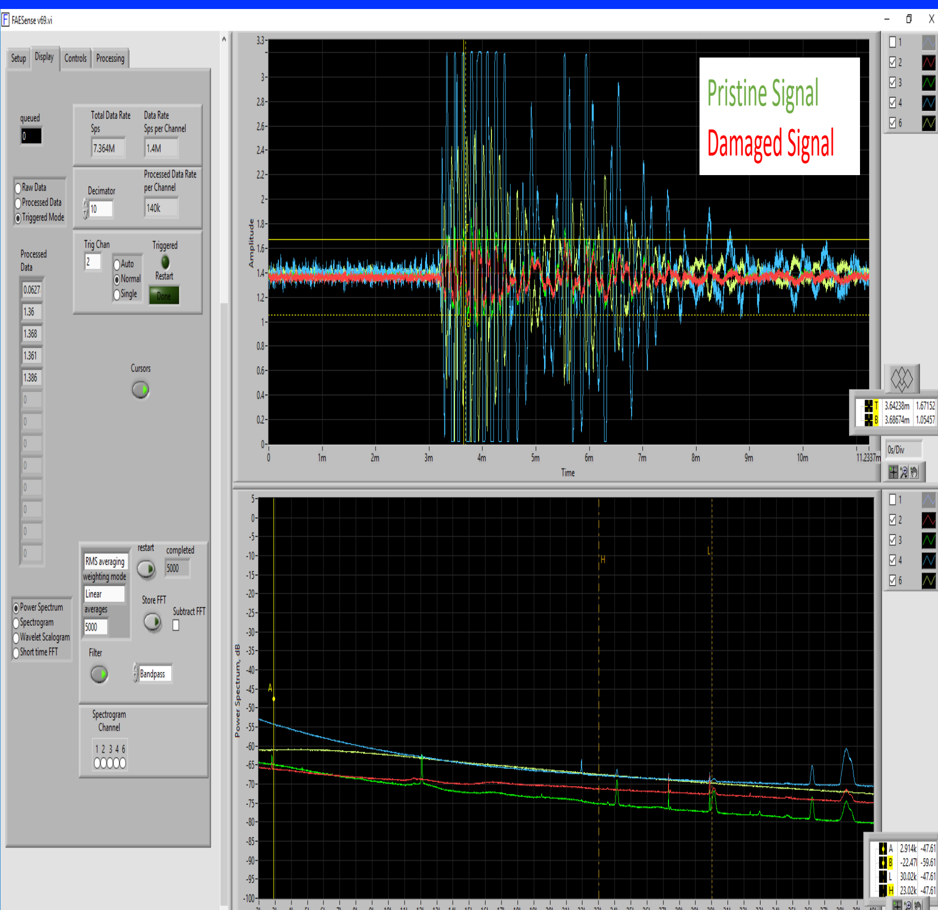
Acoustic Ultrasound Image
of Structure Damage Assessment

Acousto-Ultrasound Signal From Test Specimen with Induced 2-mm Crack Damage

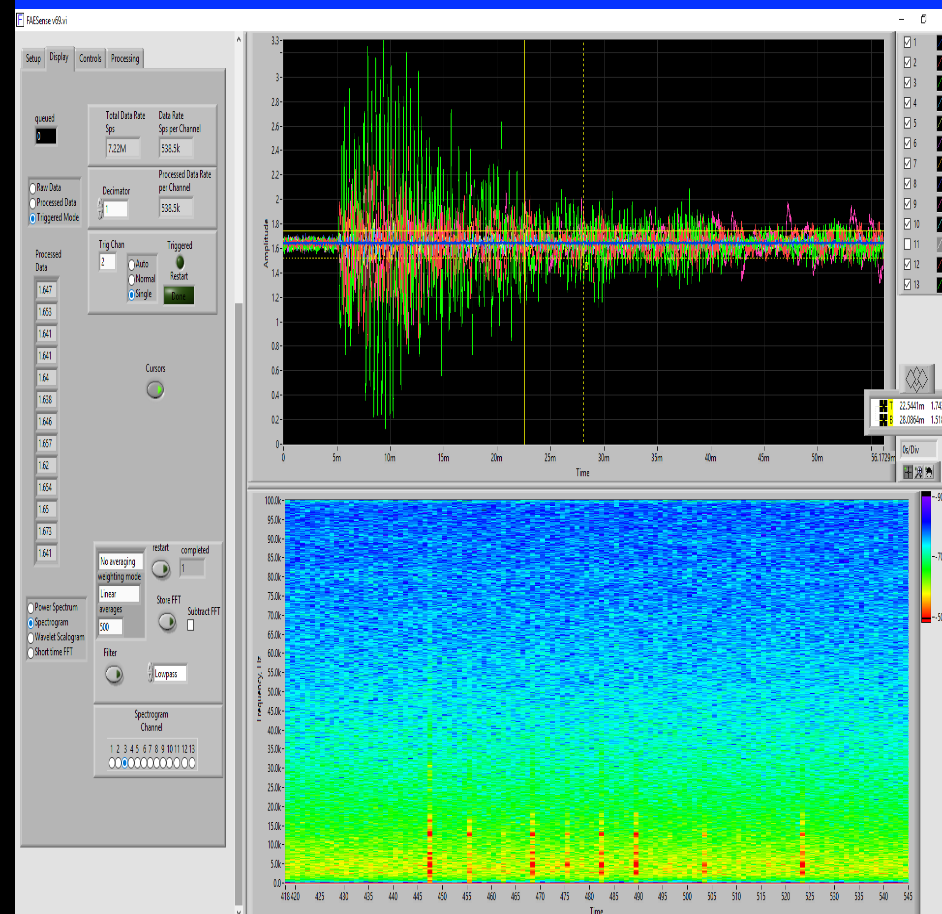


FAULT Lab-View based Software for system initialization, control, and data process

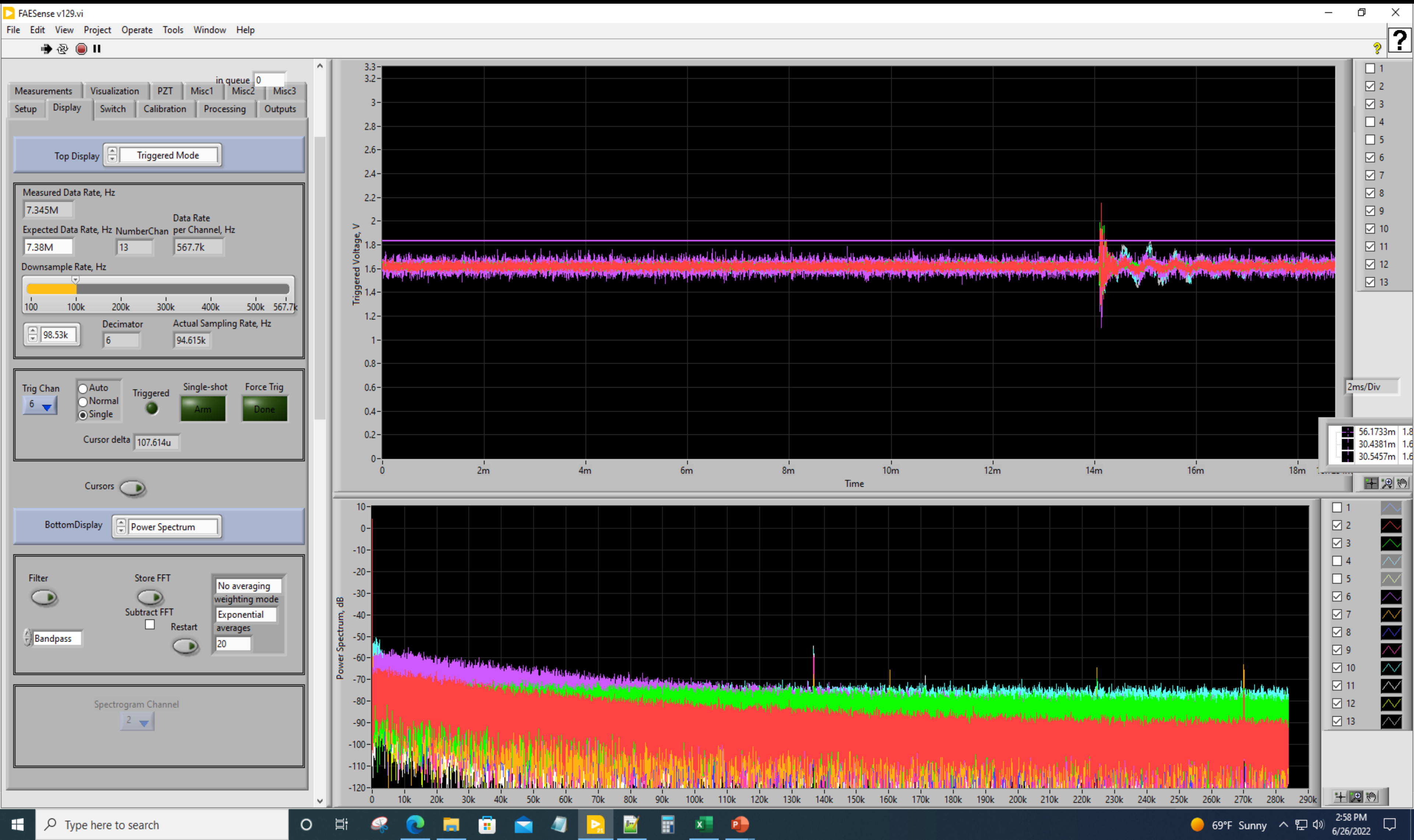
Acousto-Ultrasound Frequency Modulation for Structural Damage Detection



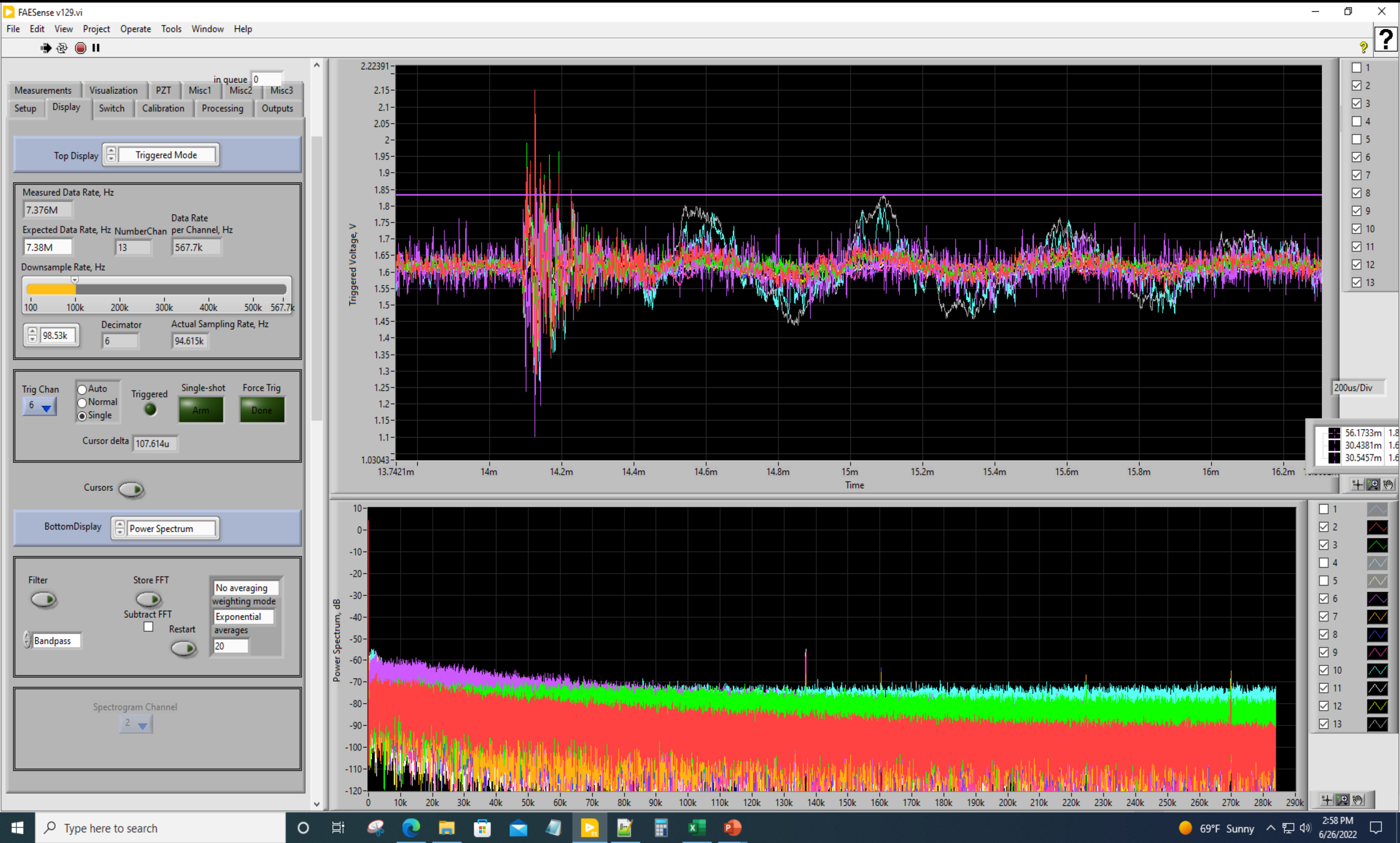
Time –Domain/Frequency Domain Single trigger & Spectrogram



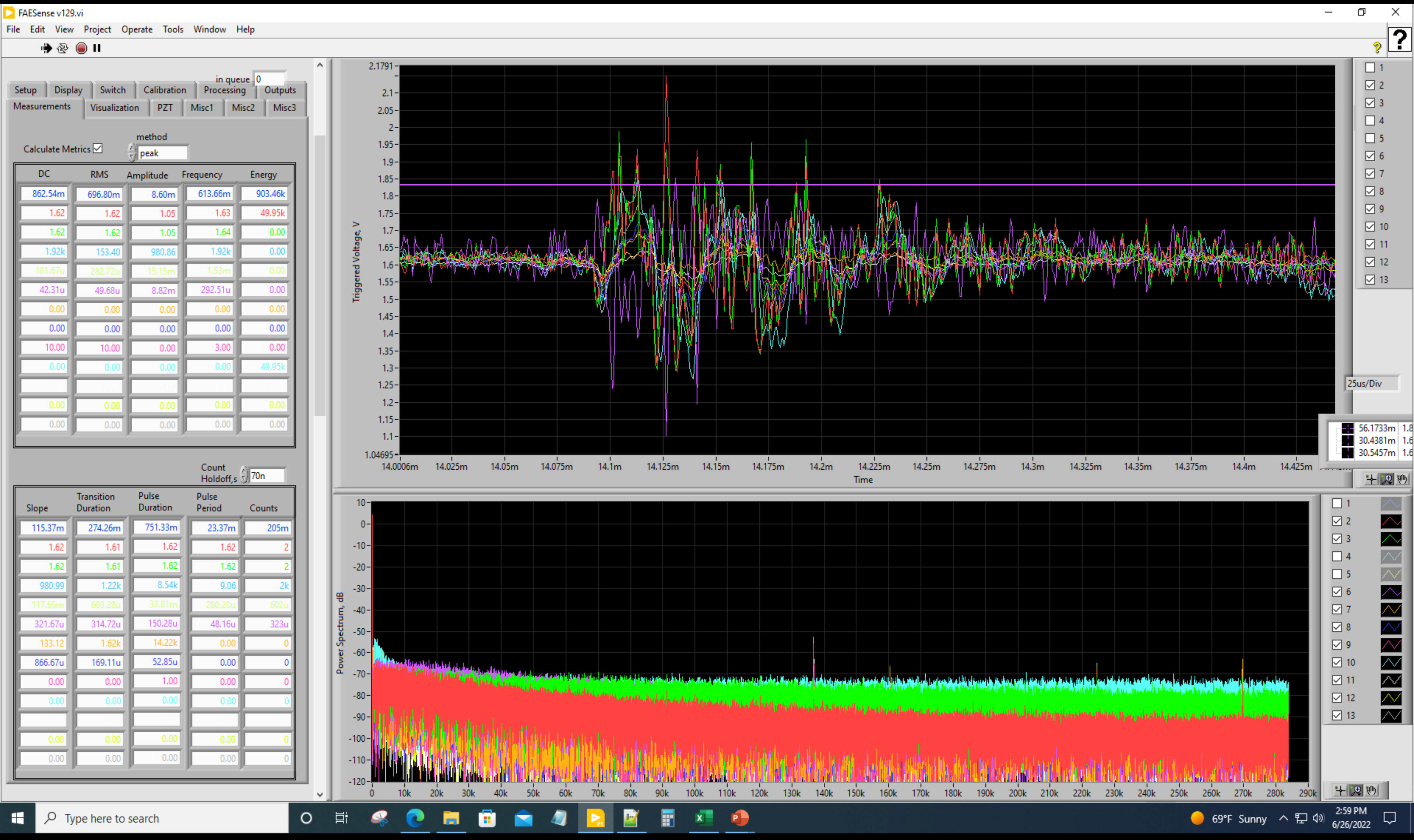
Detected Acoustic Ultrasound Signal Single Event Trigger Detection



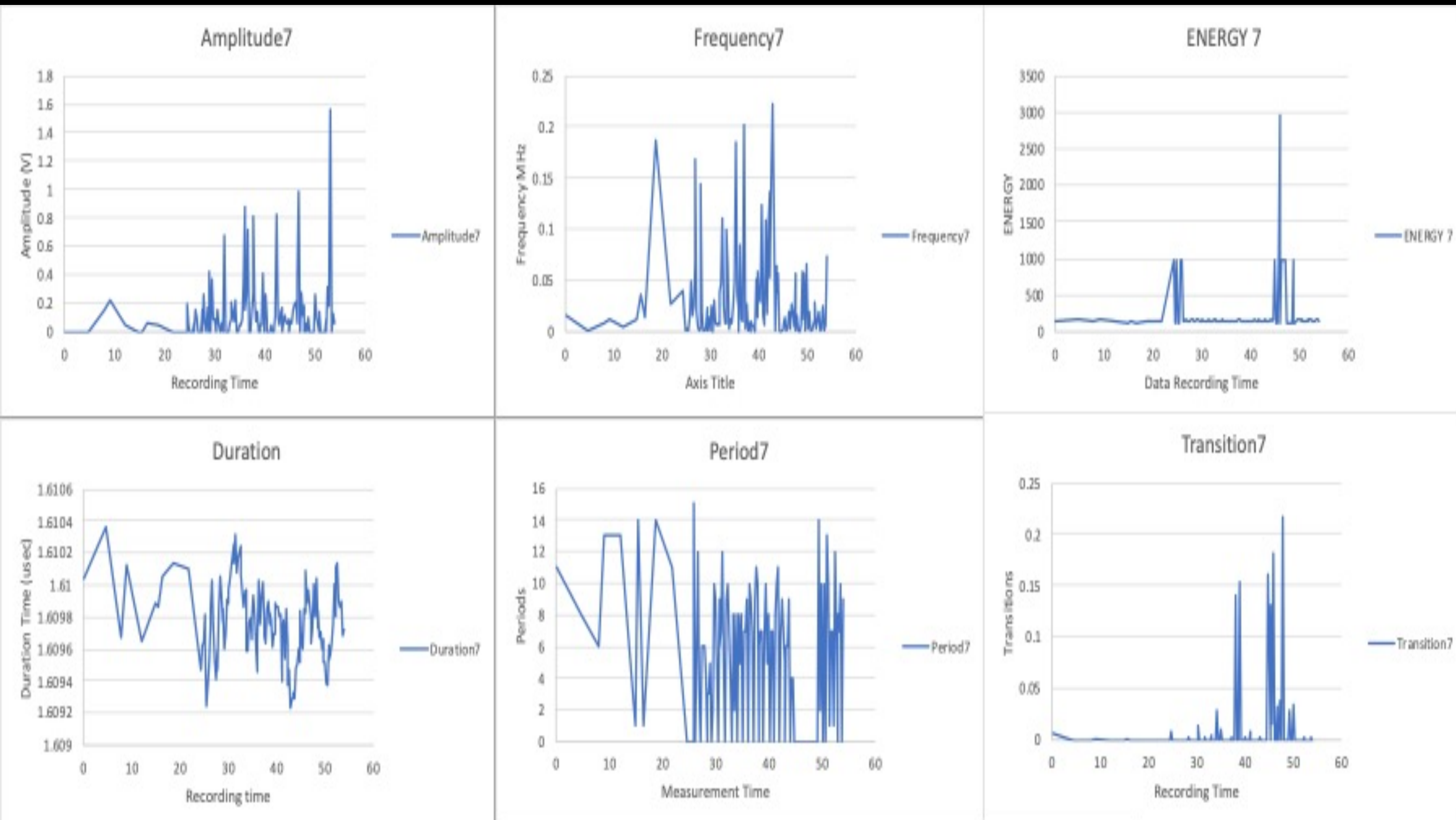
Captured AU Waveform
Single Event Trigger Detection



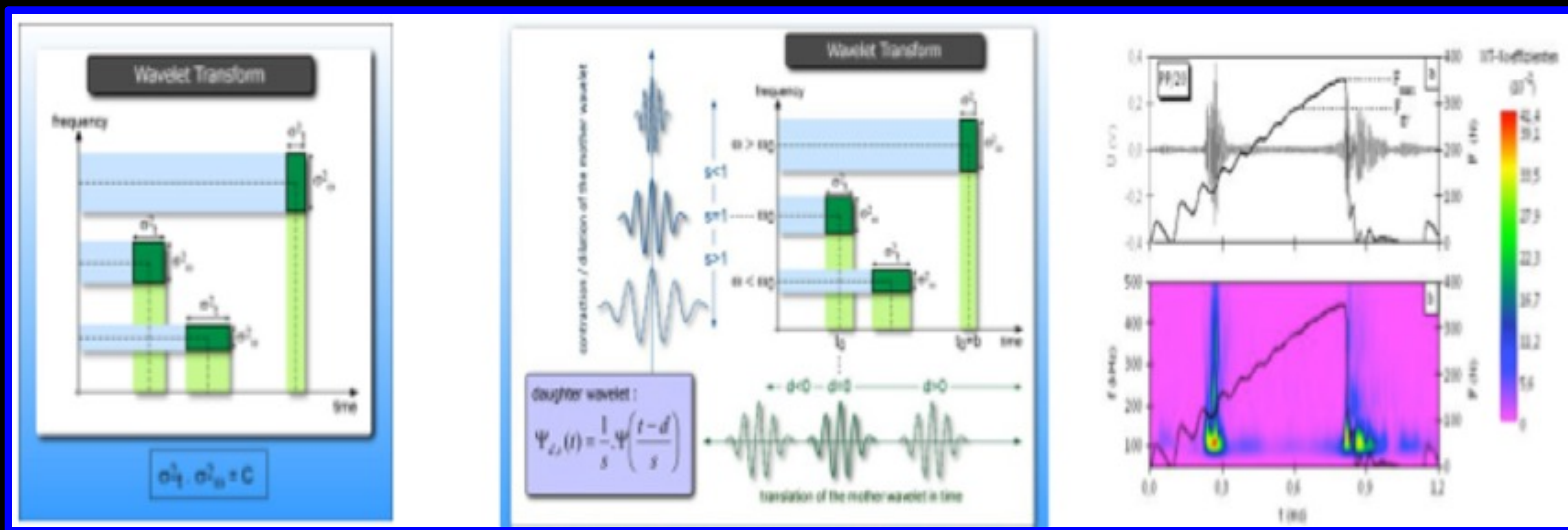
Real Time Feature Extraction Measurements from Acoustic Ultrasound Signals

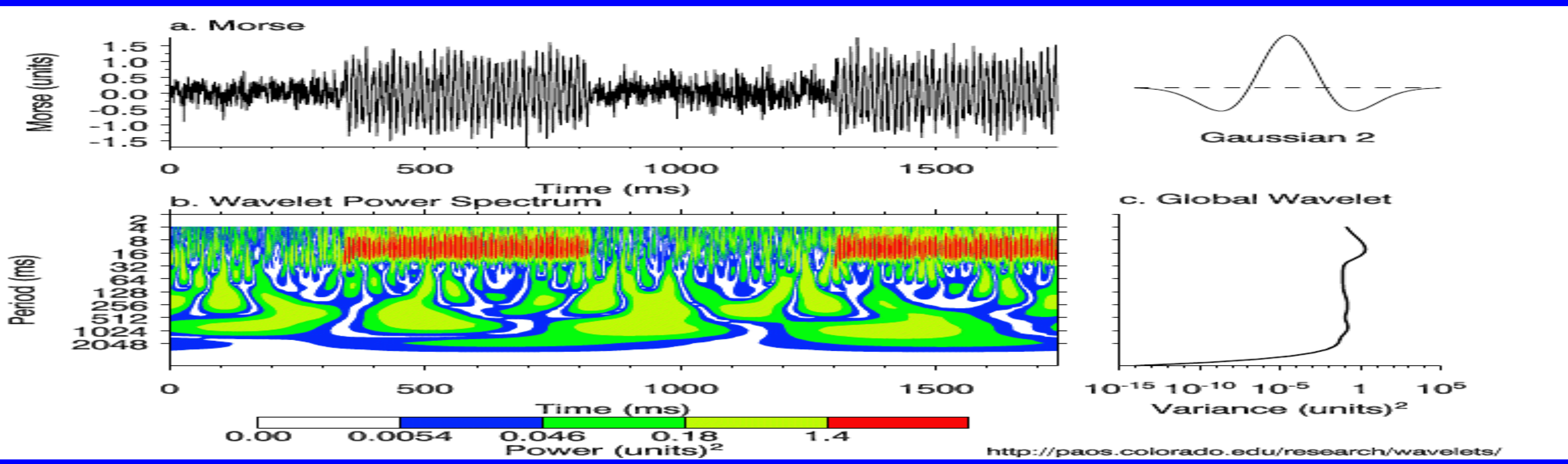


Trigger Waveform Data Extraction Measurements FBG-7

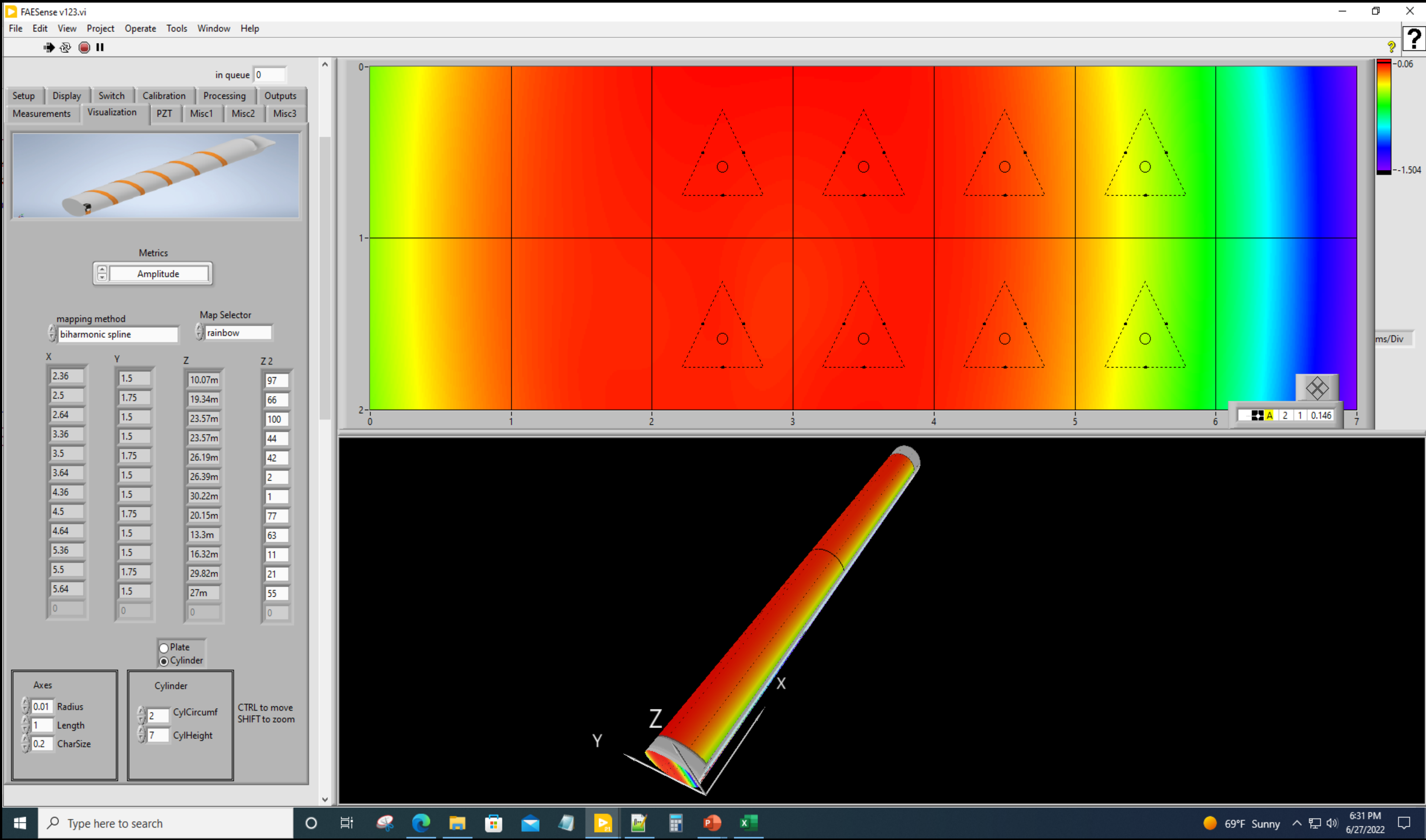


Wavelet and Neural Network Based Signal Processing

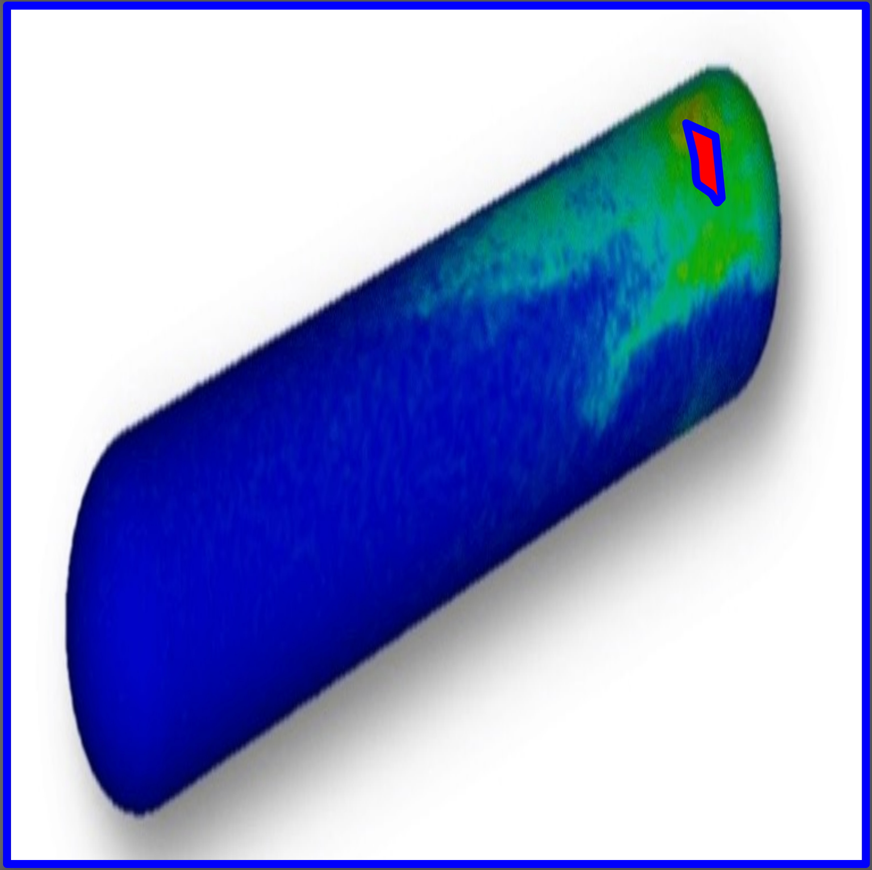




Real Time Visual Display of Time Sequence AU Measurements and Their Relation to FBG Sensors Location

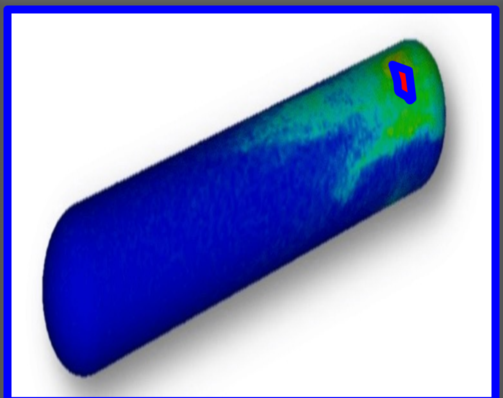


Acoustic Ultrasound Testing of Simulated Cartridge Actuated Devices using FAULT™ SHM system



Detect and localized structural damage within the test articles, and to classify the extent of damage (voids, fracture, cracks, delaminations) incurred in the PAD or CAD Device

Summary of Current Progress



- ***The Covid-19 pandemic severely affected ROI's time schedule for the development progress of the FAULT SHM Crack detection system.***

- ***Currently we are proceeding with the extensive testing of relevant platform MK-109 test surrogates that will lead to the training of the signal processing software feature extraction Neural Network algorithms leading to the real time detection, localization, and classification of hidden cracks and defects within the CAD/PAD propellant structure.***

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