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

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Redondo Optics Inc.

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

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Navy’s Need for SHM Inspection of Propellant Actuated Devices

- The Navy is seeking to develop 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 (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 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 crack detection sensor interrogation system packaged within a 2-in x 2-in x 4-in; 300-gr; 4-W Enclosure

FAULT™ SHM Interrogation Transceiver System

Frequency Modulation Pulse Excitation

Pristine Before Damage
After 2-mm Damage

18-kHz; 8-Pulsed Burst; 100-Hz Rep-Rate - 2-mm Defect
### FAULT™ SHM System

#### Performance Specifications

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

**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
MK-109 Inert Propellant Test Specimens
MK-109 Live Propellant Test Specimens
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
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

Cladding Region  Section 2
Section 1  Fibre Bragg Grating  Section 3
Core

Wavelength shift Index \( \sim 4 \times 10^{-3} \)

Spectrum vs increasing waveguide width – “Inscribe & Step”

MZI & FBG
Radiation mode coupling
Bragg mode

FBG in MZI – reflection spectrum
Femto-Second Inscription of 3D-Waveguide Mack-Zehnder Interferometers

![Image of fiber optic interferometers](image)

![Graphs showing transmission vs. wavelength](graphs)

- **MZI center**
  - 25um from edge of core

- **MZI edge**
  - 5um from clad-air interface
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
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
Design and Production of the FAULT SHM System
Two-Wave-Mixing Interferometer PIC Microchip.
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectra</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target wavelength</td>
<td>$\lambda$</td>
<td>$l_{\text{vac}}$</td>
<td>1420 nm</td>
<td>1510 nm</td>
</tr>
<tr>
<td>Power in band</td>
<td>$P_{\text{band}}$</td>
<td>$P_{\text{band}} = (100 \text{ mW}) \times l &lt; l_{\text{vac}}$</td>
<td>80%</td>
<td>–</td>
</tr>
<tr>
<td>Spectral bandwidth, RMS</td>
<td>$\Delta \lambda_{\text{RMS}}$</td>
<td>$P_{\text{RMS}}$, RMS</td>
<td>–</td>
<td>20 nm</td>
</tr>
<tr>
<td>Polarization extinction</td>
<td>$R_p$</td>
<td>$T_{\text{ext}} = 25^\circ \text{C}$</td>
<td></td>
<td>13 dB</td>
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<tr>
<td>Laser Diode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold current</td>
<td>$I_{\text{th}}$</td>
<td></td>
<td></td>
<td>200 mA BOL</td>
</tr>
<tr>
<td>End-of-life operating</td>
<td>$I_{\text{EOL}}$</td>
<td>$I_{\text{EOL}} = 1.12 \times I_{\text{th}, \text{BOL}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitor Photodiode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitor current</td>
<td>$I_{\text{MON}}$</td>
<td>$I_{\text{MON}} = V_{\text{ref}} = 5 \text{ V}$</td>
<td>0.5 \mu A/mW</td>
<td>5.0 \mu A/mW</td>
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<tr>
<td>Monitor dark current</td>
<td>$I_d$</td>
<td>$V_{\text{dd}} = 5 \text{ V}$</td>
<td>–</td>
<td>300 nA</td>
</tr>
<tr>
<td>Monitor diode capacitance</td>
<td>$C_{\text{MON}}$</td>
<td>$V_{\text{dd}} = 5 \text{ V}$, 1 kHz</td>
<td>–</td>
<td>20 pF</td>
</tr>
<tr>
<td>Front-to-rear tracking ratio</td>
<td>$TR$</td>
<td>$I_{\text{th}}$, constant, 100 mW to $P_{\text{opt}}$</td>
<td>0.85</td>
<td>1.15</td>
</tr>
<tr>
<td>Front-to-rear tracking error</td>
<td>$TE$</td>
<td>$I_{\text{th}}$, constant, 100 mW to $P_{\text{opt}}$</td>
<td>$-15%$</td>
<td>15%</td>
</tr>
<tr>
<td>Thermoelectric Cooler Operation</td>
<td>$P_{\text{cool}}$</td>
<td>$P_{\text{cool}} = 12.5 \text{ W EOL}$</td>
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<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>$P_{\text{EOL}}$</td>
<td>$P_{\text{EOL}} = 25^\circ \text{C}$</td>
<td>9.5 k\Omega</td>
<td>10.5 k\Omega</td>
</tr>
<tr>
<td>Thermistor resistance</td>
<td>$R_{\text{EOL}}$</td>
<td>$R_{\text{EOL}} = 25^\circ \text{C}$</td>
<td>3700 K</td>
<td>4100 K</td>
</tr>
<tr>
<td>Mean thermistor B constant</td>
<td>$B$</td>
<td>$B_{\text{TC}}$</td>
<td></td>
<td></td>
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</table>
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
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.
Acousto-Ultrasound Signal From Test Specimen with Induced 2-mm Crack Damage

18-kHz; 8-Pulsed Burst; 100-Hz Rep-Rate - 2-mm Defect

FBG Sensor 1 – 1-in from Exciter/
FBG Sensor 2 - 6-in. from Exciter
* Crack Position 4-in from Exciter
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

Pristine Signal
Damaged Signal
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

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a. Morse

Morse units

Time (ms)

b. Wavelet Power Spectrum

Period (ms)

Time (ms)

0 500 1000 1500

0 1024

Period (ms)

Variances (units)$^2$

Power (units)$^2$

0.00 0.0054 0.046 0.18 1.4

http://paos.colorado.edu/research/wavelets/
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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