DYNAMIC AND ADAPTIVE MULTI-POINT FIBER OPTIC ACOUSTIC EMISSION SENSOR (FAESENSE™) SYSTEM

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This paper describes progress towards the development and demonstration of a fully integrated dynamically reconfigurable, adaptive fiber optic acoustic emission sensor (FAESense™) system for the in-situ unattended detection and localization of structural damage caused by shock events, impacts, fractures, cracks, voids, corrosion, and delaminations in new and aging infrastructures found in the petroleum and chemical industries, solar and wind power plants, nuclear, coal, and gas utilities industries, in civil and geophysical engineering, biomedical engineering, aerospace and naval industries, transportation security. ROI's FAESense™ system is based on the integration of proven state-of-the-art technologies: 1) distributed multi-point array of in-line fiber Bragg gratings (FBGs) sensors sensitive to strain, vibration, and acoustic emissions, 2) adaptive spectral demodulation of FBG sensor dynamic signals using two-wave mixing interferometry on photorefractive semiconductors, and 3) integration of all the sensor system passive and active opto-electronic components within a 0.5-cm x 1-cm photonic integrated circuit microchip. ROI's FAESense™ system represents a next generation fiber optic sensing technology that is environmentally robust, reliable, and can be used for structural health monitoring and prognostics of new and aging commercial and military infrastructures. Its miniaturized package, low power operation, state-of-the-art data communications, and affordable price makes it a very attractive solution for applications where cost, weight, size, and power are critical for operation.

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ABSTRACT: This paper describes progress towards the development and demonstration of a fully integrated dynamically reconfigurable, adaptive fiber optic acoustic emission sensor (FAESense™) system for the in-situ unattended detection and localization of structural damage caused by shock events, impacts, fractures, cracks, voids, corrosion, and delaminations in new and aging infrastructures found in the petroleum and chemical industries, solar and wind power plants, nuclear, coal, and gas utilities industries, in civil and geophysical engineering, biomedical engineering, aerospace and naval industries, transportation security. ROI's FAESense™ system is based on the integration of proven state-of-the-art technologies: 1) distributed multi-point array of in-line fiber Bragg gratings (FBGs) sensors sensitive to strain, vibration, and acoustic emissions, 2) adaptive spectral demodulation of FBG sensor dynamic signals using two-wave mixing interferometry on photorefractive semiconductors, and 3) integration of all the sensor system passive and active opto-electronic components within a 0.5-cm x 1-cm photonic integrated circuit microchip. ROI's FAESense™ system represents a next generation fiber optic sensing technology that is environmentally robust, reliable, and can be used for structural health monitoring and prognostics of new and aging commercial and military infrastructures. Its miniaturized package, low power operation, state-of-the-art data communications, and affordable price makes it a very attractive solution for applications where cost, weight, size, and power are critical for operation.

1 INTRODUCTION

Advanced infrastructure systems are integral to the social, political, and economic well being of a nation. Facets of infrastructure systems affect the quality of buildings and structures, the air we breathe and the water we drink, our access to energy (e.g., electricity, oil, and gas), and communications, inter-modal transportation systems, and disposal of waste. Because these systems are so pervasive, complex, and inherent to our lives, and because of the continued and ever-increasing threats of environment and global terrorism, they need to be secured and made smart. In recent years, Fiber Bragg Grating (FBG) technology has been accepted as a new kind of sensing element for structural health monitoring (SHM) for the in situ monitoring of advanced structures in aviation, aerospace systems, civil structures, and the petrochemical industry. The cost of

FBG sensor production, the availability of high-quality FBG demodulation system, practical sensor embedding and packaging techniques are the cores for FBG sensors to be widely popularized for real time monitoring of infrastructure systems.

Worldwide critical infrastructures such as pressure vessels, piping systems, petrochemical reactors, bridges, railroads, tunnels, transportation systems, energy power plants (nuclear, gas, coal), wind turbines, solar pannels, and the human body among many others are routinely exposed to heavy stresses that required constant vigilant inspections. For those responsible for the safety and optimum operation of such structures Acoustic Emission (AE) testing provides a great valuable tool to detect damage, localized, and predict failure mechanisms of a structure way in advanced of the onset of structural damage.

2. DYNAMICALLY RECONFIGURE AND ADAPTIVE MULTI-CHANNEL FIBER OPTIC ACOUSTIC EMISSION SENSOR (FAESense™) SYSTEM

Redondo Optics Inc. (ROI) under a Navy SBIR contract [i] is in the process of developing an innovative next generation dynamically reconfigure and adaptive fiber optic acoustic emission sensor (FAESense™) system for the in-situ unattended detection and localization of structural damage caused by shock events, impacts, fractures, cracks, voids, corrosion, and delaminations in new and aging U.S. infrastructures commonly found in the petroleum and chemical industries, solar and wind power plants, nuclear, coal, and gas utilities industries, in civil and geophysical engineering, biomedical engineering, aerospace and naval industries, transportation security, and for DoD and homeland security support platforms.

ROI's FAESense™ system is based on the integration of three proven state-of-the-art technologies: 1) distributed array of in-line fiber Bragg gratings (FBGs) sensor transducers sensitive to small surface displacement perturbations such as those induced by acoustic emissions signals, 2) adaptive spectral demodulation of the FBG sensor acoustic emission dynamic signals using two-wave mixing interferometry on photorefractive photonic integrated circuit (PIC) architectures, and 3) monolithic integration of all the sensor interrogation system passive and active opto-electronic components within a miniature integrated optic microchip.

The FAESense™ system (see Figure 1) uses a cost effective, stand-alone, ultra-wide frequency interrogation system to monitor the status of a distributed array of in-line fiber Bragg gratings (FBGs), acting as strain, vibration, and acoustic-emission (AE) transducers to detect and localize the appearance and propagation of cracks, delaminations, creep, fatigue or failure in critical structures, such as pressurized bulkheads, rudders and propellers, wing attachment points, aircraft skins and fuselages, etc., that typically require costly periodic inspections to ensure optimum performance. The FAESense™ system uses a single thin (250-microns) optical fiber that incorporates an array of FBG sensors that can be conveniently surface mounted or embedded at multiple locations of the structure. The FAESense™ interrogation system uses ROI's proprietary photorefractive photonic integrated circuit (PIC) microchip technology to integrate at the optical chip level all of the passive and active functionalities of the system, such as, routing waveguide structures, couplers, semiconductor broadband light source, photodetector array, WDM filters, and a novel two-wave mixing (TWM) interferometer waveguide design that enables the dynamically reconfigure and adaptive ultra-wide frequency FBG sensor signal demodulation. The adaptive TWM demodulation methodology allows the measurement of dynamic high frequnency acoustic emission events, while compensating for passive quasi-static strain and temperature drifts.

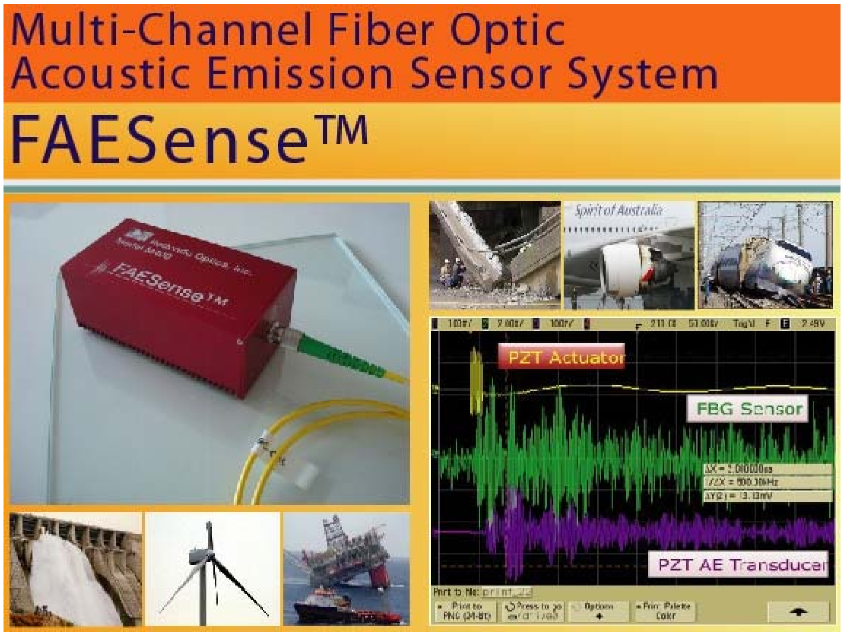

Figure 1. Next generation dynamically reconfigure and adaptive multi-point fiber optic acoustic emission sensor (FAESense™) system for condition based maintenance.

The multi-channel FAESense™ system features a compact, low power, environmentally robust 2-inch x 2-inch x 4-inch small form factor (SFF) package with no moving parts. The FAESense™ interrogation system is microprocessor-controlled using high data rate signal processing electronics for the FBG sensors calibration, temperature compensation and the detection and analysis of acoustic emission signals. The embedded software algorithms within the microprocessor are programmed to discriminate random noise from actual acoustic emission events using advanced waveform analysis and adaptive neural network pattern recognition functions, to enable detection, localization and triangulation of AE signals. It also offers the ability to transmit the processed FBG sensor data using ultrafast USB data communication protocols connected to a remote computer control station. A user friendly graphical user interface (GUI) controls the FAESense™ system initialization and data acquisition parameters and displays in real-time the detected acoustic emission event in either a time domain or frequency domain spectrum. The software GUI is equipped with user control alarm level warnings that provide information when a pre-selected signal target level has been exciding indication the appearance of unusual events of potential indication of structural damage.

ROI's miniature, non-intrusive, and cost efficient FAESense™ system is poised to revolutionize the field of acoustic emission structural health monitors and to gain a rapid acceptance into the structural health monitoring and nondestructive inspection (SHM/NDI) market, a well established, fast-growing, worldwide market. [ii]

Table 1-1. Performance Specifications of Multi-Channel FAESense™ System

Monitoring Principle	*Adaptive Two-Wave Mixing (TWM) interferometry*
FBG Sensor Channels	*2 to 4 acoustic-emission transducers per sensor fiber*
AE Frequency Range	*DC to 300-kHz*
Frequency Sensitivity	*0.1-microstrain/Hz*
Frequency Resolution	*1 kHz*
Frequency Accuracy	*± 1% of reading*
Frequency Bandwidth	*3 dB from 1-kHz to 300-KHz*
Graphical Interface Software	*Adaptive sensor fusion prognostic analysis (LabView)*
Data Communication	*Ultra-Fast USB, Ethernet, Wireless, Wi-Fi, Bluetooth*
Power Supply	*Main plug appliance NG 16, 12 V/500 mA @10-mA/Ch*
Weight	*≤ 250-g*
Dimensions	*2-inch (W) x 2-inch (T) x 4-inch (L)*

2. ACOUSTIC EMISSION FOR STRUCTURAL HEALTH MONITORING

Current structural health monitoring systems lack state-of-the-art acoustic emission sensors that are practically field deployable, specially for applications where weight, size, power, and EMI interference are critical for operation. Acoustic emission sensors are currently the only proven reliable method used for the detection of crack induced structural damage and prognostics indication of potential failure of a structure. However, current AE systems based on electronic PZT transducers suffer from various limitations to enable wide scale deployment. Conventional electronic AE transducers are bulky and complex to operate with need of near proximity pre-amplifiers and signal conditioning units for each sensor that results in a bulky set-up that requires an extensive electrical wiring infrastructure that often hinders their use in practical applications. Furthermore, conventional PZT based AE sensors can only be mounted to the structure using surface mount techniques with an extensive sensor wiring architecture that is extremely sensitive to EMI interference produced by the vast amount of instrumentation typically encountered on the majority of critical structures such as oil rigs, nuclear plants, wind and solar plants, railroads, aircraft, etc. For this reason, there is a need to develop next generation structural health AE sensing technologies where the sensor elements, without the need of preconditioning equipment, non-intrusively mounts to the structure using EMI insensitive wiring.

Redondo Optics has identified fiber Bragg grating sensors as a strategic technology to solve the shortcomings and limitations associated with conventional PZT AE sensors. In addition, recent advancements by Professor Shridar Krishnaswami from Northwestern University have demonstrated that adaptive FBG sensor demodulation techniques offer enhanced acoustic emission sensitivity for reliable structural damage detection. [iii]

3. DYNAMICALLY RECONFIGURE AND ADAPTIVE TWO-WAVE-MIXING ACOUSTIC EMISSION DEMODULATION SOLUTION

In the FAESense™ development program, ROI has expand on the use of its integrated optics microchip technology and incorporate at the microchip level a new dynamically reconfigured FBG sensor demodulation methodology based on the adaptive two-wave mixing (TWM) interferometry techniques demonstrated by Professor Krishnaswami, from Northwestern University, to expand the sensing capabilities of ROI's FBG interrogation systems from the detection and discrimination of passive, low frequency (DC) events (stress and temperature) from highly sensitive ultra-wide frequency (DC to 500-kHz) vibration and acoustic emission events.

The adaptive TWM interferometer shown in Figure 3 is a fast and effective method to demodulate the dynamic wavelength shifts of the peak reflectivity wavelength of the FBG sensors in the presence of passive quasi-static temperature and strain drifts. The reflected signals from the FBG sensor array is received by the microchip as they traverse unequal path lengths in the interferometer prior to mixing in the photorefractive cavity (PRC) of the interferometer. Any wavelength shift of the light reflected from the FBG sensor array results in an equivalent "phase" shift between the pump and the sample signals because they travel unequal optical paths. The relationship between the wavelength shift ($\Delta\lambda_B$) of the FBG sensor and the relative phase shift ($\Delta\phi$) induced by the unbalanced interferometer is given by:

$$\Delta\lambda_B = \frac{\Delta\phi(t)\lambda_B^2}{2\pi d} \tag{1}$$

where λ_B is the peak center reflectivity wavelength of the FBG sensor, and d is the optical path length difference (OPD) of a Mack-Zhender TWM interferometer. The expression shown in equation 1 shows that there is a direct linear relationship between the dynamic wavelength shift of the FBG sensor and the detected phase shift signal at the photoreceiver, as previously demonstrated by Professor Krishnaswami. [1]

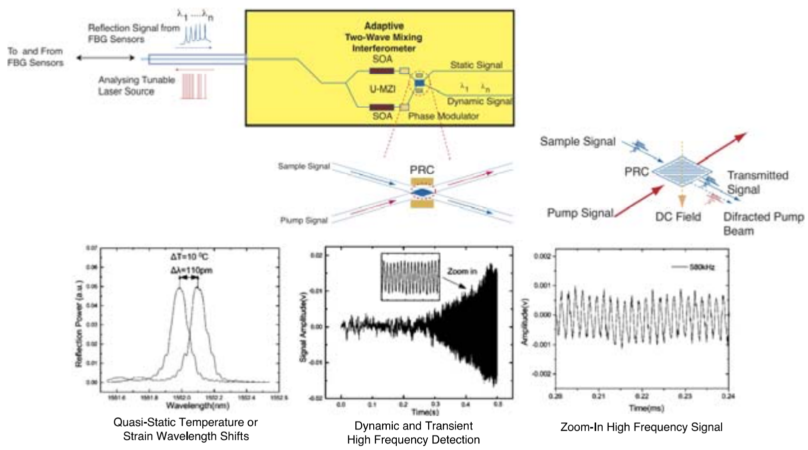

Figure 3. TWM interferometer for demodulation of dynamic high frequency wavelength shifts of FBG sensor spectral signature. [1]

5. DEMONSTRATION OF TWM PIC MICROCHIP PERFORMANCE FOR DETECTION OF HIGH FREQUENCY ACOUSTIC EMISSION EVENTS

Using the experimental AE test and data acquisition set-up shown in Figure 4, ROI has conducted a variety of acoustic emission tests aimed at demonstrating the capability of the multi-channel TWM PIC microchip to detect high frequency AE events in the presence of quasi-static strain. In the experimental set-up shown in Figure 4, an array of FBG sensors are surface mounted on a long cantilever beam. The test beam is equipped with a pair of PZT AE transducers, a pulse exciter and a receiver, to excite and detect AE events, as well as a low frequency speaker mounted at the edge of the cantilever beam used to excite low frequency strain events. The AE signature detected by the PZT AE transducers is time synchronized to the signal detected by the FBG sensor array. The scope trace results shown in Figure 4 show the trace signatures from the PZT pulse exciter (yellow), the PZT receiver (purple), and the FBG sensor (green). Comparison of the signatures detected by the PZT AE transducer and the FBG sensor show a similarity in the time trace characterstics of the detected AE signal. Analysis of the frequencies detected by the FBG sensor array show that we can clearly distinguish a 100-kHz and 500-kHz signatures.

6. SUMMARY.

The FAESense™ system is a cost effective, stand-alone, ultra-wide frequency interrogation system to monitor the status of a distributed array of in-line fiber Bragg gratings (FBGs), acting as strain, vibration and acoustic-emission (AE) transducers to detect and localize the appearance and propagation of cracks, delaminations, creep, fatigue or failure in Navy critical structures, such as pressurized bulkheads, rudders and propellers, wing attachment points, aircraft skins and fuselages, etc., that typically require costly periodic inspections to ensure optimum performance.

7. ACKNOWLEDGMENTS

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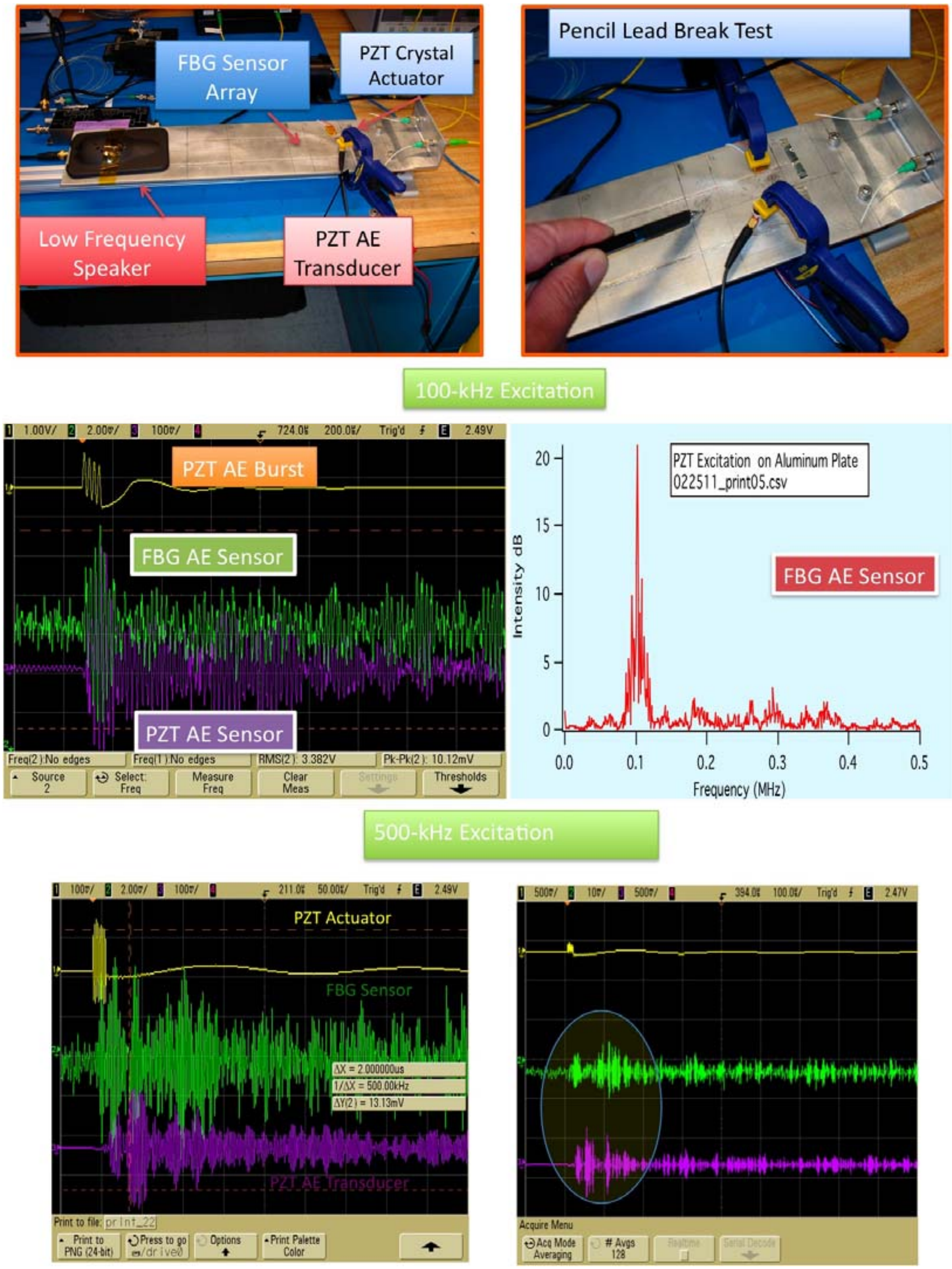

Figure 4.Demonstration of TWM PIC Microchip AE Detection Performance at dynamic modulation frequencies ≤ 500-kHz demodulation in presence of passive strain modulation.

[i] Mendoza, E. A., Principal Investigator, "Dynamically Reconfigure and Adaptive Multi-Point Fiber Optic Acoustic Emission Sensor System for Condition Based Maintenance," NAVY SBIR Phase II Contract No. N00014-10-C-0327, 2010

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