Piezo-optical measurements for guided wave and acoustic emission structural health monitoring

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ABSTRACT

This paper presents the application and validation of optical equipment suitable for high frequency guided wave and acoustic emission detection with fiber Bragg grating (FBG) sensors. Guided wave and acoustic emission (AE) measurements were compared between piezoelectric wafer active sensors (PWAS) and fiber Bragg grating (FBG) sensors embedded onto isotropic plates and beams with an emphasis on testing FBG ultrasonic wave propagation frequency characteristics.

The use of an acousto-ultrasonic FBG ring sensor to eliminate FBG directional dependence is also discussed. Since FBG sensors only detect strain longitudinal to the fiber, unlike PWAS they cannot serve as omnidirectional guided wave and AE sensors. To overcome this limitation, the use of an acousto-ultrasonic ring sensor, designed to augment and enhance the performance of FBG sensors, is tested. The ring sensor uses mechanical amplification principles to force in-plane vibration of the ring to occur at a specific resonance frequency. In this study, a ring sensor is bonded onto an isotropic plate; incoming guided wave and AE measurements from an FBG bonded to the ring sensor were compared to measurements from an FBG bonded to the plate. Preliminary results show the use of the ring sensor nearly eliminated the directional dependence of the FBG; concurrently the FBG on the ring sensor sensed incoming guided waves and AE events near its resonance frequency and rejected phenomenon occurring at other frequencies.

Keywords: SHM, PWAS, FBG, Bragg, Ultrasonic, Waves, Optical, Acoustic

1. INTRODUCTION

Structural health monitoring (SHM) is a field that seeks to monitor the health of mechanical structures through the use of structurally-embedded sensors. The ability of these sensors to serve as mechanical actuators and receivers allows for in-service structural interrogation, allowing for real-time assessment of a damage state and remaining useful life predictions. This methodology is comparable to the approach taken in nondestructive evaluation (NDE); however, the advantage is that in SHM diagnostic tools are permanently embedded onto a structure which eliminates the need to take a structure out of service for manual inspection. The potential benefits of SHM come with multidisciplinary technical challenges. Embedded sensors must be lightweight, reliable, and unobtrusive to be permanently attached to a structure; actuators are needed to mechanically excite structures through the use of vibration or guided waves, and receivers must be capable of detecting signals in the hundreds of kHz range and upwards for accurate signal representation.

A number of sensors have been proposed for SHM systems; one sensor that has shown a large amount of promise is the piezoelectric wafer active sensor (PWAS)\textsuperscript{1}. PWAS can be bonded onto the surface of a structure to send and receive mechanical vibrations and ultrasonic guided waves. PWAS are small, reliable, unobtrusive, and lightweight – ideal for embedding onto structures for SHM applications. For vibration-based SHM, PWAS can be used for electromechanical impedance spectroscopy (EMIS). For wave propagation-based SHM, PWAS can be used in pitch-catch, pulse-echo, and phased array techniques.

Fiber Bragg grating (FBG) sensors show great promise as SHM receivers. FBGs are able to sense quasi-static strain and strain at high frequencies below the microstrain level. They are corrosion resistant and immune to electromagnetic interference. They can also be multiplexed within a single fiber optic cable. FBG have been applied to SHM applications...
in spacecraft, aircraft repairs, highway and railway bridges, and nuclear reactors\(^2\). FBG function as strain sensors by introducing periodic variations in refractive index (Bragg grating) in the core of a fiber optic cable which causes that cable to serve as a wavelength-dependent filter. When the fiber is stretched along its longitudinal axis, the period of its gratings change, shifting the reflected wavelength. These shifts can be related to strain in the fiber. Although there has been research into high frequency FBG strain sensing, to date there are no commercially available FBG systems for ultrasonic SHM on the market\(^3\).

The purpose of this research is twofold: 1) to experimentally validate a tunable laser system (TLS) based ultrasonic FBG SHM system developed from a small number of modifications from commercially-off-the-shelf products, and 2) to discuss the performance of an acousto-ultrasonic FBG Ring Sensor designed to augment and enhance guided wave and acoustic emission FBG sensing. To validate the TLS, quasi-static strain and high-frequency Lamb wave propagation experiments for TLS FBG strain sensing were performed, followed by a number of FBG Lamb wave and acoustic emission experiments involving longitudinal and transverse excitation on an isotropic plate. To test the FBG Ring Sensor, the frequency characteristics were assessed for free and bonded rings, and the effect that the Ring Sensor had on the signal directional dependence was assessed.

2. FBG TUNABLE LASER SYSTEM ULTRASONIC SENSING

FBG strain sensing is performed by tracking wavelength shifts in the peak reflected wavelength and relating that to axial strain along the fiber by

\[
\frac{\Delta \lambda_B}{\lambda_B} = (1 - \rho_e) \varepsilon
\]  

(1)

where \(\lambda_B\) is the peak reflected wavelength (indicated in the example FBG reflected spectrum shown in Figure 1), \(\rho_e\) is the effective photoelastic constant for axial strain, and \(\varepsilon\) is the axial strain.

![Figure 1: Typical wavelength spectrum of power reflected from an FBG.](image)

Despite the simplicity of this approach, its disadvantage is that it is not a trivial problem to track the peak wavelength while maintaining the high sampling rate needed for ultrasonic strain sensing. To overcome this limitation, the intensity-based demodulation used by Norman\(^4\) was employed in this research. In the intensity-based demodulation approach, first the half-maximum of the rising or falling slope of the reflected FBG curve is found. Then, by using a TLS, the FBG is excited at a narrow-band wavelength. Shifts in intensity are related to the peak wavelength through the
slope of the linear portion of the curve. Thus, as long as intensity shifts remain within the linear portion of the curve, intensity shifts at a fixed wavelength can be related to FBG strain. This has the advantage that it can be performed by a high speed narrow bandwidth tunable laser source, which allows for high-speed data acquisition required for wave propagation SHM applications.

Since no commercially available FBG ultrasonic system was currently on the market, we have developed such a system using commercially-off-the-shelf products with as few modifications as possible (Figure 2). A Luna Phoenix 1400 Tunable Laser System was used as the narrow bandwidth laser source to excite the FBG. A circulator was incorporated into the system such that the reflected power from the FBG was not transmitted back towards the laser source, but was instead transmitted to another line. The reflected FBG power was output to a power meter, to a Tektronix TDS5034B Digital Phosphor Oscilloscope by way of a power to voltage converter, or to both by way of a power splitter.

**Figure 2: TLS hardware.** A tunable laser source is used to output power at a narrow-band wavelength to an FBG. The FBG reflects power back at an intensity that depends on its axial strain. This reflection is output to a power meter, an oscilloscope by way of a power to voltage converter, or to both by a power splitter.

### 3. FBG EXPERIMENTAL ANALYSIS VIA TUNABLE LASER SYSTEM

A cantilever beam setup was tested under quasi-static and high frequency conditions as a validation of FBG TLS strain measurement system. The beam had dimensions 60x2x0.2 cm, consisted of aluminum, and had sensor clusters #1 and #2 instrumented at 20 and 40 cm distance from the cantilevered end of the beam, respectively. PWAS, FBG, and strain gauges were bonded to the beam as shown in Figure 3. The FBG and strain gauge at sensor cluster #1 allowed for quasi-static strain testing. The PWAS and FBG setup allowed for pitch-catch wave propagation experiments, pitching from the PWAS at sensor cluster #2 and catching from the FBG at sensor cluster #1.

#### 3.1 Quasi-static strain characterization

The FBG TLS was tested under quasi-static conditions as a validation of the FBG FWHM strain detection method. The cantilever beam was held at a fixed displacement downwards at a known location along the beam, and the strain was measured at sensor cluster #1 by the FBG and the strain gauge shown on Figure 3.

The strain readings were compared to an Euler-Bernoulli beam theory analytical model and a finite element model of the bending beam. The analytical and finite element models predicted 33.8 µε and 33.5 µε respectively, whereas the FBG and strain gauge predicted 34.0 µε and 33 µε respectively (the strain gauge had a minimum reading of 1 µε). Since the strain detected by the FBG TLS system using the FWHM method was comparable to the strain detected by the strain gauge and the theoretical predictions, it can be surmised that the FBG strain detection functioned accurately under quasi-static predictions; this gave veracity to the strain measurements of the FBG TLS system.
3.2 High frequency wave propagation analysis

There has been a great deal of interest in high frequency wave propagation for the purpose of generating smaller wavelength guided waves capable of detecting damage at smaller sizes. To this effect, the ability of an FBG receiver to sense guided waves in the MHz range was tested using the beam shown in Figure 3.

![Figure 3: Experimental setup for quasi-static and high-frequency testing. a) A cantilever beam was instrumented with a PWAS, FBG, and Vishay strain gauge; b) the top of sensor cluster #1; and c) the bottom of sensor cluster #1.](image)

Guided waves were transmitted from a PWAS at sensor cluster #2 via a -50V to 100V 3-count tone burst generated by a Hewlett Packard 33120A function generator, amplified by an NF HAS 4014 high speed bipolar amplifier. The waves propagated through the beam and were received by an FBG receiver at sensor cluster #1, connected to a Tektronix TDS5034B Digital Phosphor Oscilloscope. The waveforms received by FBG and PWAS at 1 MHz and 2 MHz are shown in Figure 4.

The 1 MHz PWAS and FBG receiver signals show distinct incoming wave packets arriving at close to 45 µs. Visually, there appear to be similar trends and wave packets, although differences are expected due to the difference in sensing mechanism (in-plane sensing for PWAS vs. axial sensing for FBG). For 2 MHz excitation, the signal strength dropped dramatically. This was generally seen for the higher frequency excitation due to the power requirements necessary to drive the PWAS actuator. That said, at roughly 50 µs, the first wave packet arrives to the receiver PWAS. Also around 50 µs, an increase in voltage can be seen from the FBG receiver. However, the voltage is small compared to the noise level of the system, and a good representation of the signal could not be found. The high frequency excitation at 2 kHz was not necessarily the limit of the FBG receiver, but rather was limited by the amplitude of the signal delivered and the noise level of the FBG TLS system. Part of the future work is to eliminate noise present in the system from the power source, and re-approach these high frequency tests for a better representation of FBG upper frequency capabilities.
In this research, an acousto-ultrasonic FBG Ring Sensor previously developed by Roman is assessed. The purpose of the ring is to employ mechanical resonance amplification principles to enhance signals received by an FBG bonded to the ring. In the previous work of Roman, three FBG Ring Sensors were designed, with the fundamental design criteria requiring an axial resonance along the direction of the FBG installation hole at a desired frequency. Three Ring Sensors have been designed for resonance frequencies at 100 kHz, 200 kHz, and 300 kHz; the 100 kHz and 300 kHz Ring Sensors have been manufactured and are shown in Figure 5.

The ring sensors were made of 304 stainless steel; they have a flat top and bottom surface for increased contact area so they can be bonded to a flat structure. The major axis of the ellipse in the center of each ring is oriented along the direction of holes drilled in the ring for the fiber to force resonance in that direction.

The concept behind the Ring Sensor is that when it is subjected traveling waves at its in-plane resonance frequency, it will oscillate in-plane and elongate an FBG bonded to it. Resonances of the Ring Sensor that do not have a significant component in the direction of the FBG as well as frequencies at which the Ring Sensor does not resonate will be attenuated. Since the Ring Sensor’s mechanism of action is through mechanical resonance, it has the potential to exploit...
resonance effects such as signal amplification, such that it offers potential advantages as a receiver in terms of amplifying incoming waves.

![Figure 5: FBG Ring Sensors designed to resonate at 100 kHz (left) and 300 kHz (right).](image)

Previous work into the FBG Ring sensor has focused on its capabilities to resonate at a desired frequency and reject other frequencies. Roman assessed the frequency characteristics of the 100 kHz and 300 kHz Ring Sensors under free boundary characteristics through a linear chirp signal pitch-catch transmitted and received by PWAS on opposite sides of the ring. These experiments combined with laser vibrometry measurements identified in-plane resonance frequencies close to the designed resonance frequency of each ring.

The present work builds off of this foundation to test the in-service capabilities of the FBG Ring Sensor. The effect that the Ring Sensor has on an FBG is assessed. Its wave propagation and directional characteristics are also assessed by employing the Ring Sensor as part of a pitch-catch experiment across a plate.

### 4.1 Frequency analysis of a free Ring Sensor via linear chirp signal

To assess the effect that the Ring Sensor resonance characteristics have on a bonded FBG, a Ring Sensor was instrumented with PWAS on its top and bottom flat surfaces and with an FBG along the major axis of the ellipse on the side of the ring (Figure 6); the fiber was placed along the side of the ring and not through the hole in the center to simplify considerations regarding installation while still allowing for sensing of in-plane resonance.

Foam was placed underneath the ring to simulate free boundary conditions. A linear chirp signal was sent from the transmitter PWAS, such that a sinusoidal frequency from 50-150 kHz was swept over linearly in 100 milliseconds. The time-domain response and its single-sided amplitude spectrum are shown in Figure 7.

In addition to a resonance peak seen at 102.1 kHz, two additional resonance peaks are seen at 108.9 kHz and 119.3 kHz. This is in contrast to the work of Roman which saw only one resonance peak located near the Ring Sensor’s designed resonance frequency. One possible explanation for this is the use of an FBG receiver bonded to the side of the ring rather than a PWAS receiver bonded to the bottom. The fiber may be able sense additional resonance modes that the in-plane mechanism of the PWAS could not. The fiber located on the outer surface of the ring may also pick up additional resonance modes due to its off-centeredness that it would not if it were placed through the hole in the ring.
4.2 FBG pitch-catch experiments

A series of pitch-catch experiments were performed across the 120x90x0.2 cm aluminum 2024 plate shown in Figure 8 to test the wave propagation capabilities of the TLS system and the frequency and directional characteristics of the Ring Sensor. Two PWAS transmitters— one with a longitudinal excitation path and one with a transverse excitation path – were bonded 15 cm away from a cluster of receivers. The receivers consisted of a) a PWAS bonded to the plate, b) an FBG bonded to the plate, c) a PWAS bonded to the top of a Ring Sensor bonded to the plate, d) an FBG bonded to the side of the Ring Sensor.

A series of 20V peak to peak 3-count tone bursts were sent from the longitudinal transmitter PWAS to a) the PWAS on the plate, b) the PWAS on the Ring Sensor, and c) the FBG on the Ring Sensor. These tone bursts had excitation frequencies ranging from 30 kHz to 150 kHz in 3 kHz increments. The peak amplitude of the incoming A0 wave packet was extracted from these signals and the A0 tuning curve (i.e. peak wave packet amplitude vs. frequency) was generated over the frequency range for each receiver as shown in Figure 9.

The A0 tuning curve for the PWAS bonded to the plate was consistent with the work into PWAS tuning curves from previous literature. The A0 tuning curve for the PWAS bonded to the Ring Sensor was consistent with the Ring Sensor...
chirp test under free boundary conditions; near resonances at 100 kHz, antisymmetric waves are allowed to pass through the ring sensor. Away from the resonances near 100 kHz, Lamb waves are attenuated towards zero. The width of the peak near resonance is wider in these experiments is larger than for the chirp testing. This is because the tone burst involves not only its center frequency, but a frequency band surrounding its center frequency. In contrast, the chirp signal contained a harmonic component at only a single frequency at any single point in time. The tuning curve generated via longitudinal transmission to the FBG bonded to the side of the Ring Sensor (Figure 10) was similar in character to the tuning curve from the PWAS bonded to the top of the Ring Sensor. The primary difference is that the peak surrounding the resonance(s) is wider in the case of the FBG receiver; this is possibly due to the presence of additional resonance modes observable by the FBG on the Ring Sensor but not by the PWAS. Note that although the voltage scales are relatable between FBG and PWAS receivers, they are not directly comparable in value, as they both relate to strain differently based on each sensor’s sensing mechanism.

Figure 8: Experimental setup for pitch-catch wave propagation experiments across an aluminum plate.

Figure 9: Tuning curves for A0 wave packet over 30-150 kHz range. a) Tuning curve for PWAS bonded directly to plate. b) Tuning curve for PWAS bonded to Ring Sensor bonded to plate.
4.3 Directional dependence and ring sensor signal modification

Using the experimental setup shown in Figure 8, 20V peak to peak 3-count tone bursts were sent from both the longitudinal and transverse excitation PWAS to a) the FBG receiver on the plate and b) the FBG receiver on the Ring Sensor. The purpose of this was to assess the effect that the directionality of the incoming wave has on the received signal. Figure 11 shows the received waveforms at 99 kHz – near the resonance frequency of the Ring Sensor. The waveform received from longitudinal excitation showed higher amplitude than the waveform received from transverse excitation. This is expected, as the FBG senses strain only along the axis of the fiber. The waveform received from transverse excitation only showed incoming waveforms due to Poisson effects.

When the same 99 kHz longitudinal and transverse excitation signals were transmitted to the FBG bonded to the Ring Sensor, the directional dependence decreased as shown in Figure 12.
Figure 12: Effect of waveform directionality on signal received by FBG bonded to Ring Sensor: a) waveform received via longitudinal excitation along the axis of the FBG and Ring Sensor; b) waveform received via transverse excitation perpendicular to the axis of the FBG and Ring Sensor.

At 99 kHz, transverse excitation of the Ring Sensor produced a 27% drop in signal strength compared to longitudinal excitation. Compared to the FBG bonded directly to the plate, the Ring Sensor allowed an FBG bonded to detect signals transmitted from the most unfavorable orientation – transverse to the fiber’s axis. Since the FBG Ring Sensor is an omnidirectional sensor, an FBG bonded to it becomes omnidirectional.

Comparing Figure 11 and Figure 12, one result of note is that the S0 wave packet is nearly missing from the FBG Ring Sensor signal, while it is still present in the FBG signal. This is an additional characteristic of the Ring Sensor – it highly attenuates symmetric wave propagation modes while attenuating antisymmetric wave propagation modes to a much less degree. Conceptually, this is because out-of-plane motion is required to excite the Ring Sensor when it is bonded to a plate, and out-of-plane motion makes up a larger component of antisymmetric Lamb waves than symmetric Lamb waves.

One last factor that can be observed from Figure 11 and Figure 12 is a low frequency noise affecting some of the plots, causing the signal to shift up or down over time. This is a low frequency noise contribution from the TLS system. Since performing these experiments, efforts have been made to reduce this noise including analog and digital filtering. Part of the future work is to diminish or eliminate the effects of this noise.

4.4 Acoustic emission experiments

To test the capabilities of the TLS system and the Ring Sensor to sense acoustic emissions, the plate in Figure 8 was subjected to simulated acoustic emissions in the form of a pencil lead break. From a bird’s eye view, one pencil lead break was located 10cm to the right of the receiver cluster for longitudinal excitation, and one pencil lead break was located 10cm above the cluster for transverse excitation. The TLS system was connected to the oscilloscope, whose internal trigger was used to determine the point to begin recording the signal. The AE waveforms received by the FBG bonded to the plate are shown in Figure 13.

A clear, high-amplitude signal can be seen from the AE event in both cases for the FBG receiver bonded to the plate. The signal amplitude was not attenuated from the transverse excitation compared to the longitudinal excitation; this may be due to the observation of multiple reflections from the edge of the plate. The AE waveforms generated by pencil lead break received by the FBG bonded to the Ring Sensor are shown in Figure 14.
Compared to the signals seen on the FBG bonded to the plate, the Ring Sensor appeared to respond less favorably to the AE events. This may be due to the specific frequency range of the Ring Sensor; a 200 kHz, 300 kHz, or a Ring Sensor designed for another frequency may be more appropriate. Fourier analysis of the AE signals is the next step to improving the performance of the Ring Sensor for AE events. It should be noted that if the Ring Sensor can be designed to pick up AE events, it offers advantages in terms of isolation from other noise sources.

5 CONCLUSIONS AND FUTURE WORK

A TLS system for ultrasonic FBG strain measurement was described, created from a few modifications from commercially-off-the-shelf products. The guiding principle behind this system was an intensity modulation strain measurement. The performance of the system at a quasi-static state was validated by a cantilever beam, comparing with a strain gauge, analytical model, and FEM. A close comparison was obtained between FBG measurement, strain gauge measurement, and modeling. High frequency testing showed that waveforms were visually comparable between the
PWAS and FBG up to 1 MHz; differences between the two signals were observed and expected due to the difference in each sensor’s sensing mechanism. At 2 MHz and beyond, the low signal amplitude of the transmitter and the noise level of the receiver made strain sensing impractical. Given higher amplitude signals and efforts to reduce noise levels, the FBG is expected to be able to continue operating at 2 MHz above.

An acousto-ultrasonic Ring Sensor designed to augment and enhance the performance of an FBG was discussed. The frequency characteristics of the free Ring Sensor were tested under free conditions with FBG attached. Three major resonance peaks were found proximal to the designed resonance frequency, in contrast to research performed using a PWAS receiver for the same setup on another specimen that found only one resonance peak. This effect may be due to the placement of the FBG on the side of the ring, rather through a symmetric axis in the center; the FBG may also be able to sense other resonance modes due to its axial sensing mechanism. There may also be discrepancies between manufacturing tolerances between one specimen and the next. Part of the future work will be to test these effects by performing a chirp signal pitch-catch using a PWAS receiver on the specimen used in this study; the initial finite element models used for the Ring Sensor design will also be assessed to determine if any of the resonance modes near the resonances observed would be likely to excite the FBG, but not a PWAS.

Pitch-catch wave propagation studies were performed across an aluminum plate at frequencies ranging from tens to hundreds of kHz. Visually, tuning curves were very comparable between PWAS on the plate and FBG on the plate due to high similarity in received waveform from a longitudinal transmission direction. The tuning curves observed for the Ring Sensor demonstrate that the vibration principles applied in the design of the Ring Sensor function well for wave propagation methodologies. The Ring Sensor showed a high attenuation for in-plane excitation while allowing out-of-plane waves to excite the ring.

Proof-of-concept AE tests for the FBG on the plate and the Ring Sensor were performed. AE signals were received by an FBG on the plate and the Ring Sensor from both transverse and longitudinal directions. Although both cases observed incoming signals, the Ring Sensor showed significantly decreased amplitude. This may be due to high attenuation of frequency components outside the range of the Ring Sensor, or otherwise attenuation of in-plane excitation. More experimentation and analysis is necessary to determine how to proceed with Ring Sensor acoustic emission sensing.

Future work includes reduction and elimination of noise sources in this FBG TLS system. Analog and digital filtering has been approached to help eliminate sources of noise, and will be continued. The elimination of noise due to fluctuations in the power source will also be done by determining the fluctuations in the power source and subtracting its component as a reference.

Other future work will be to re-approach high frequency FBG testing with higher amplitude excitation and noise reduction techniques. Automatic multiplexing of FBG fibers is an issue of interest, and is a technical component of developing a practical piezo-optical FBG SHM system. Further work will be done in AE testing, with frequency analysis of AE signals and reapplication or redesign of the Ring Sensor to enhance the signal. The limit of FBGs to detect AE sources is also of interest, and future work will include the distances at which this system can detect incoming AE events. Improved bonding procedures for the Ring Sensor and FBG will be developed, including pre-stretching the fiber, and ensuring that the entire length of the FBG is bonded to the Ring Sensor.

Finally, the resonance effects of the Ring Sensor will be further investigated. Since the Ring Sensor was designed based on resonance principles, it is conceivable that it has the capability to amplify signals through resonance effects. If this proves to be the case, the Ring Sensor will greatly enhance the functionality of FBG sensors in their ability to sense guided wave and acoustic emission events.
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7 REFERENCES