Characterization and optimization of an ultrasonic piezo-optical ring sensor

Erik Frankforter, Bin Lin and Victor Giurgiutiu

Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29201, USA

E-mail: frankfor@email.sc.edu

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Abstract
A resonant piezo-optical ring sensor with both piezoelectric and fiber Bragg grating (FBG) sensing elements was assessed for ultrasonic wave detection. The ring sensor is an existing device that has been shown experimentally to exhibit a number of sensing features: omnidirectionality, mode selectivity, and frequency tunability. The present study uses finite element modeling to understand these features as a means to characterize and optimize the sensor. A combined vibration-wave propagation modeling approach was used, where the vibrational modeling provided a basis for understanding sensing features, and the wave propagation modeling provided predictive power for sensor performance. The sensor features corresponded to the fundamental vibrational mode of the sensor, particularly to the base motion of this mode. The vibrational modeling was also used to guide sensor optimization, with an emphasis on the FBG and piezoelectric sensing elements. It was found that sensor symmetry and nodes of extraneous resonance modes could be exploited to provide a single-resonance response. A series of pitch-catch guided wave experiments were performed on a thin aluminum plate to assess the optimized sensor configuration. Tuning curves showed a single-frequency response to a Lamb wave and mechanical filtering away from the dominant frequency; the sensor capability for mechanical amplification of a Lamb wave and mechanical amplification of a pencil-lead-break acoustic emission event were also demonstrated.

Keywords: piezoelectric, PWAS, FBG, AE, acoustic emission, ring sensor, SHM

1. Introduction

Structural health monitoring (SHM) is a field that seeks to detect damage for in-service structures through the use of permanently embedded sensors. The increasing age of our infrastructure, including the use of structures beyond their initial lifetime estimates, motivates a clear need for an in-service damage detection approach. By interrogating structures on demand, damage can be detected at an earlier stage for improved reliability, while simultaneously saving costs of unnecessary scheduled maintenance.

Guided-wave based SHM methods present significant advantages for SHM applications. In thin-walled structures like those commonly used in the aerospace and defense industries, ultrasonic guided Lamb waves are able to propagate over long distances for damage assessment. A Lamb wave interacts with damage to produce characteristic features embedded within the wave which can be analyzed to obtain information such as damage presence, location, type, severity, and eventually structural prognosis.

SHM can be performed in two main ways: active and passive. Active SHM can detect cracks and corrosion in metallic structures and delaminations in composites [1, 2]. Guided wave active SHM uses wave propagation techniques such as pitch-catch, pulse-echo, and phased-array to detect signal changes generated by the presence of structural damage. In contrast, passive SHM ‘listens’ to the structure. Conventionally in aerospace applications this is measuring flight parameters such as vibration levels, acceleration, strain, pressure, temperature, etc. More recent improvements include impact detection and acoustic emission (AE) detection [3]. AE detection is capable of monitoring crack initiation and
growth during corrosion or fatigue in metallic structures [4–6] and impact events and delaminations/disbonds in composites and bonded structures [7, 8].

1.1. SHM sensors

For guided-wave SHM, damage-containing information is embedded within a propagating wave [9]. This is an important distinction, as this means that an ultrasonic sensor capable of sensing a guided wave can be used for damage detection as long as the guided wave with its damage-containing information is accurately rendered. From the sensing perspective, an SHM sensor is suitable as long as it is sufficiently sensitive and capable of detecting wave modes at frequencies where damage information is present. To this end, permanently embedded SHM sensors must be able to detect high-frequency, low amplitude damage-related waves while being insensitive to extraneous noise. This is in addition to practical considerations limiting weight, bulk, and cost. Conventional transducers used in ultrasonic nondestructive evaluation and AE applications consist of a piezoelectric crystal connected to a wear plate and encapsulated into a protective casing. Although well established and widely available, they may not be appropriate for permanent attachment in an SHM system due to their size, weight, and cost. Hence, a number of SHM-specific sensors have been developed that are smaller, lighter, and often less expensive than conventional ultrasonic transducers and AE sensors. Common examples are piezoelectric wafer active sensors (PWAS) [10] and fiber Bragg grating (FBG) optical sensors [11]. PWAS serve as both transmitters and receivers of structurally guided waves, whereas the FBG sensors generally only act as receivers.

Both PWAS and FBG are capable of detecting AE events. However, the physical nature of an AE event provides an impetus for a more specialized sensor design. Since AE events are relatively broadband, the frequency characteristics of the sensor play an important role. AE sensors may be classified as wideband or resonant. The type of sensor used depends on the application; wideband sensors are useful when it is desirable to collect a large portion of the frequency spectrum, such as for investigation. Resonant sensors are useful for excluding noise and non-damage related signals at extraneous frequencies, providing signals that may be better for interpretation at the cost of a limited scope.

Conventionally, AE sensors have used a piezoelectric sensing element. However, there are advantages to instead using an FBG sensor—the principal advantage being the elimination of electromagnetic interference. Additionally, FBG offer fatigue resistance, corrosion resistance, multiplexing capability, self-calibration, and temperature sensing. Both surface-bonded and structurally-embedded FBG are capable of AE detection. A number of novel configurations have previously been developed. Strain-insensitive ultrasonic sensors have been developed which use an FBG glued to a small plate which could be coupled to a structure [12, 13]. An FBG accelerometer has been created using a pair of thin plates, a concentrated mass, and an FBG bonded to the plate [14]. Continuous structural strain-insensitive AE monitoring has been achieved by using a cantilevered FBG as an ultrasonic transmission line—bonding one end of the optical fiber to a structure with the other end, and the FBG between it, left free [15].

1.2. The piezo-optical ring sensor

In prior investigations, an ultrasonic sensor designed for permanent installation has been developed which incorporates both PWAS and FBG into a single resonant-type sensor [16–18], and a US patent application has been filed [19]. Shown in figure 1(a), it has been named a piezo-optical ring sensor due to its ring-like shape and both piezoelectric and fiber optic sensing elements. The characteristic feature of the ring sensor is a dominant ‘breathing’-type resonance mode where the ring expands and contracts along the major axis of the ellipse, exciting an optical fiber bonded through the smaller hole; (b) modal analysis shows the second breathing-type mode of the 100 kHz ring sensor at 268 kHz.

Figure 1. The piezo-optical ring sensor: (a) 100 kHz (left) and 300 kHz (right) ring sensors have been prototyped. (b) Modal analysis shows the fundamental breathing-type resonance of the ‘100 kHz’ ring sensor at 107 kHz. The elliptical hole expands and contracts along the major axis of the ellipse, exciting an optical fiber bonded through the smaller hole; (c) modal analysis shows the second breathing-type mode of the 100 kHz ring sensor at 268 kHz.
or slightly curved surface. A small hole, about the diameter of an optical fiber, runs centrally through the ellipse major axis. By modifying the dimensions, ring sensors have been developed with resonances at 100 and 300 kHz. Both aluminum and stainless steel have been used for the sensors; their similar wave speed keeps the natural frequency the same without changing the geometry. For brevity this paper restricts the focus to a 100 kHz ring sensor.

The dimensions of the 100 kHz ring sensor are $8.00 \pm 0.05$ mm diameter, $6.00 \pm 0.05$ mm depth, $5.00 \pm 0.10$ mm ellipse major diameter, $3.50 \pm 0.20$ mm ellipse minor diameter, $3.75 \pm 0.05$ mm from the center of the ellipse to the flat surfaces. The hole for the optical fiber is $0.30 \pm 0.05$ mm, running through the major axis of the ellipse within $\pm 0.05$ mm horizontal/vertical positioning. The flat faces should be parallel, with no more than $1^\circ$ difference in angle. See [16] for a drawing with dimensions and tolerances. The geometric tolerances relate directly to a tolerance on the fundamental frequency (in this case our design was to keep the sensor in the 90–110 kHz range). The aluminum 100 kHz ring sensor is 0.596 g in mass.

The emphasis of this work is on the fiber optic ultrasonic sensing capabilities of the ring sensor, as FBG sensors provide significant sensing advantages, and are not as well established compared to commercially available ultrasonic piezoelectric sensors. This ring sensor design may also have potential for lower frequency application as a vibration sensor or as an FBG accelerometer (e.g., simply scaling up the dimensions significantly lowers the resonance frequency). This is not addressed in this paper, but may be a promising avenue for future research. The breathing-type resonance frequency is surrounded by a quiescent range which allows the ring sensor to serve as a mechanical filter where excitation is rejected at undesired frequencies. Compared to surface-mounted FBG sensors, a number of sensing features have been identified:

- **Omnidirectionality.** The capability for the ring-mounted FBG to sense waves from multiple directions, compared to surface-mounted FBG which sense the wave component from only one direction.
- **Mode selectivity.** The capability to reject in-plane motion and accept out-of-plane motion, similar to a conventional AE sensor.
- **Frequency tunability.** The capability to respond to a frequency specified by design, and reject other frequencies. Ring sensor with different dimensions or material properties can be manufactured to hit a wide range of target frequencies, while geometric similarity ensures the sensing action remains the same.

### 1.3. Motivation and direction of the current investigation

Although the sensing features of the ring described in section 1.2 are a positive indicator, there are a number of obstacles that must be overcome for practical application:

- The sensing features have been identified, but are not well-understood, hindering optimization and redesign.
- The frequency response is not yet ‘crisp’—modes at extraneous frequencies complicate the response.
- Mechanical amplification and AE sensing have proven elusive, limiting the sensor application.

In this paper, we have addressed these shortcomings separately in each upcoming section. In section 2, ring sensor features are assessed by modeling its dynamic response. In section 3, extraneous modes are eliminated by optimizing FBG and PWAS placement. In section 4, we demonstrate the capability for mechanical amplification as a sensor feature. Frequency effects and pencil-lead break (PLB) AE sensing are explored in plate-guided wave experiments.

### 2. Assessment of the ring sensor features

#### 2.1. Finite element modeling (FEM) analysis overview

The ring sensor features were modeled using FEM software via a combined vibration-wave propagation approach. The three sensing features of the ring sensor from section 1.2 were investigated: frequency characteristics, mode selectivity, and omnidirectionality. In addition to these three, mechanical amplification was investigated.

Two types of analyses were used for vibration (modal analysis and harmonic analysis) and one type of analysis was used for wave propagation (transient analysis). The FEM modeling was performed using ANSYS Workbench Mechanical 15.0. Convergence was shown separately for the ring sensor and the plate. For the ring sensor, a sufficient number of quadratic tetrahedral elements were used such that the highest mode shape of interest was accurately represented. For the plate, ten quadratic hexahedral elements per wavelength, and six elements across the thickness was sufficient for convergence, measured by the convergence of maximum global amplitude.

#### 2.2. Combined vibration-wave propagation modeling approach

A combined vibration-wave propagation approach provided both simplicity in understanding, and precision in predictive power. The wave propagation modeling demonstrated the exact nature of the wave–sensor interaction; the vibrational modeling helped explore and understand why the interaction occurred. A few advantages to a vibrational approach to sensor modeling and design are:

- The resonance modes provide a basis for understanding sensor features.
- Extraneous frequency content may be eliminated by exploiting mode shapes.
- Resonance modes may be analyzed separately due to mode superposition, simplifying the design process.

The basis for a vibrational approach is derived from modal expansion, where the response of a linearly elastic
system is represented as a linear combination of its resonance modes. For a resonant sensor with a single-mode response, eliminating modes under a vibrational model can be simplified to the exploitation of mode shape nodes and symmetry. Understanding sensor features for a single-resonance response simplifies to understanding the action of the single resonance mode. However, a vibrational model is not sufficient to capture transient phenomenon such as a propagating Lamb wave—hence the need for a combined vibration-wave propagation approach.

2.3. FEM evaluation of ring sensor frequency characteristics

A 3D modal analysis was performed to assess the resonance frequencies and mode shapes under fully free boundary conditions. Since the dimensions of the final design were rounded for ease of manufacturing, the modal analysis showed the fundamental breathing-type resonance of the ‘100 kHz’ ring sensor was actually at 107 kHz, with a second breathing-type mode at 268 kHz (figure 1(c)). The term ‘100 kHz’ ring sensor is retained for simplicity. Proximal to the breathing-type mode, a number of additional modes were identified which may be capable of affecting the ring sensor. Two examples are given in figures 2(a) and (b): a ‘shear’ and a ‘torsional’-type mode. Seen in figures 2(a) and (b), there are nodes of these mode shapes along certain lines of symmetry—at the central hole for the optical fiber and at the top of the ring. This leaves these lines of symmetry as locations for bonding the PWAS and FBG to eliminate these modes.

A harmonic analysis was used to assess the steady state response of the ring sensor. Two 1 N harmonic line forces were oriented along the ellipse’s major axis, out-of-phase and at each side of the ring sensor’s top flat surface. This is analogous to a pin-force model, which approximates the excitation of a PWAS bonded to the top flat surface. The principal strain was calculated at the top surface, and the directional strain that an FBG would undergo was calculated by taking the differential displacement between the two holes and dividing by the major diameter of the ellipse. In each response (figure 3), there is a single dominant peak with no extraneous modes sensed.

From this result, a sensor with a single-resonance response is possible if the geometric tolerances of the ring sensor are acceptable and the bonded PWAS and FBG are
aligned with these nodes. The demonstration of a single-resonance response within the quiescent range is vital to the application of the ring sensor; if a single-resonance response was not possible in FEM, a superior result could not be expected in a prototype. The single-resonance result serves as a baseline for ring sensor implementation. It also demonstrates that the single resonance mode near 100 kHz is the only mode that must be investigated—provided frequency assessment of the prototype shows a single-mode response.

### 2.4. FEM Evaluation of ring sensor mode selectivity

A transient analysis of the ring sensor response to a Lamb wave was performed by modeling a ring sensor perfectly bonded to a 1.2 mm thick aluminum plate. Two point forces were applied to the plate at a location 10 mm away from the center of the ring sensor, on the top and the bottom of the plate. Only propagating Lamb wave modes were sensed, as this distance was sufficient for over 99% decay of the longest-wavelength Lamb wave evanescent mode at the frequency-thickness product used. The propagation path and direction of the forces were parallel and in-line with the central hole of the ring sensor. The excitations were 1 N peak-to-peak 3-count tone bursts, excited symmetrically/antisymmetrically via a pair of top/bottom nodes across the thickness. The symmetrically applied excitations gave rise only to the S0 Lamb wave mode, and the antisymmetrically applied excitations gave rise only to the A0 Lamb wave mode. The center frequency of the tone burst was lowered to 92 kHz, as the fundamental frequency of the ring sensor lowered to this frequency due to the plate-bonding.

A nonreflective boundary (NRB) approach was used to absorb the plate’s edge reflections and approximate an infinite plate [20]. This was done by placing damping elements along three orthogonal directions of all nodes through the thickness for three wavelengths of the longer-wavelength S0 mode. The damping coefficients were gradually increased following a quarter-sine wave profile from zero to a maximum value prescribed by the material properties and element sizes (see [20] for details). Compared to a control model without an NRB, there were no reflections off the beginning of the NRB itself. Strain energy was observed to dissipate across the span of the NRB by over two orders of magnitude by the time it reached the edge, even prior to a second pass through the NRB after edge reflection. Using this approach, edge reflections did not contribute to the overall model and an infinite plate was successfully approximated.

As seen in figure 4(a), the S0 mode was shown to excite shear-type motion in the ring sensor from a resonance mode close in frequency to the fundamental mode. The two holes of the ring sensor were almost entirely in-phase, and would not substantially excite an FBG stretched across them. A node is also present at the top of the ring sensor such that a PWAS bonded to the top would sense no significant strain component.

As seen in figure 4(b), the A0 mode excited both the shear-type motion and the breathing-type motion. The component from the breathing-type motion excited the two holes of the ring sensor almost entirely out-of-phase to substantially excite the FBG. Although shear-type motion is also present, it may be seen as a superposition onto the breathing-type mode, and did not substantially affect the FBG response.

The modal analysis provides the basis for understanding the mode selectivity. At the base of the ring sensor, the motion of the breathing-type mode is primarily out-of-plane. A much smaller component of the motion is in-plane. The A0 Lamb wave mode is sensed because it has predominantly out-of-plane motion which excites the breathing-type mode, and the S0 Lamb wave has predominantly in-plane motion which does not excite the breathing-type mode. The reason that the S0 mode is still somewhat sensed is twofold: (1) the ring sensor does not completely reject in-plane motion, and (2) the S0 Lamb wave still contains some out-of-plane motion.

### 2.5. FEM evaluation of ring sensor mechanical amplification

The antisymmetric excitation model from section 2.4 was used to assess the ring sensor mechanical amplification. The strain was calculated via differential displacement of the two holes in the ring sensor; this was compared to the surface strain 10 mm away from the excitation in a control model of a plate with no ring sensor. Seen in figure 5, a larger strain was sensed by the FBG on the ring sensor than by the plate itself. This result in itself does not necessarily reflect what would be seen in experiment; by leaving out the bonding layer with its viscoelastic effects, it is difficult to draw precise conclusions about the veracity of the amplitude. Moreover, this serves as a baseline that mechanical amplification is in principle attainable for a ring sensor. This will guide the later experimental development.

### 2.6. FEM evaluation of ring sensor omnidirectionality

Assessment of the ring sensor directional response followed the antisymmetric Lamb wave transient model from section 2.4. In each of seven models, the ring sensor was located 10 mm away from the excitation, rotated in plane from 0° to 90° in 15° increments. The differential displacement between the two holes was used to calculate the strain sensed by the FBG. The variation in maximum strain with incident angle is shown in figure 6. There is a harmonic nature to the variation in amplitude with angle of excitation, shifted upwards by a constant.

The mechanism of the ring sensor omnidirectionality is derived from the vibrational model, specifically looking at the base motion of the breathing-type mode. The largest component of the mode is out-of-plane. The in-plane sensitivity is larger along the major axis of the ring ellipse than transverse to it, which provides the slightly elliptical response. The harmonic nature of the variation in amplitude with incident angle is consistent with a constant out-of-plane component, and a trigonometric projection onto the two in-plane components. In future work, it should be determined if an elliptical directional response is desired, e.g. for source localization, or if it should be eliminated through an axisymmetric sensor design.
2.7. FEM evaluation of plate thickness effects

It was noted in section 2.4 that the resonance frequency of the ring sensor dropped when bonding to the plate. This can be conceptualized as the addition of an elastic constraint to the base of the sensor. However, it remains to be seen what effects plate thickness may have on sensor sensitivity. As the frequency-thickness product increases for thicker plates, parameters such as wave velocity, wavelength, and wave mode shape change. Also, for thicker plates, a lower sensor response is expected for a given excitation, since the energy is present throughout the thickness and less energy is available at the sensor base.

A full study would require the addressing of plate thickness/sensor frequency effects, wavelength effects, and sensitivity effects. To limit the complexity, we assess plate thickness/sensitivity effects. The transient analysis approach of section 2.4 was used, where two point forces were used to transmit an antisymmetric Lamb wave mode across a plate to the ring sensor. Three plate thicknesses were assessed: 1.2 mm, 3.0 mm, and 5.0 mm. The excitations were 1 N peak-to-peak 3-count tone bursts, excited antisymmetrically via a pair of top/bottom nodes across the thickness. The center frequency of the tone burst was set at the nominal 100 kHz resonance frequency of the ring sensor. This was done to intentionally not assess plate thickness/resonance frequency effects. Since the tone burst has a frequency spread about its center frequency, there is expected to be some overlap of the excitation frequency with the sensor resonance.

The out-of-plane displacement was obtained on a single node on the plate which joined with the center of the ring sensor base. The average longitudinal displacement was obtained for each ring sensor hole. As a simplifying approximation, the maximum/minimum displacement between the two holes was subtracted assuming the two holes were moving completely out-of-phase. The results, shown in table 1, show that for a given excitation, the out-of-plane deformation at the sensor base and the differential deformation of the sensor holes both decrease with increasing plate thickness. However, the normalized sensor response—the ratio between the two parameters—remains almost constant. This is striking due to the simplicity of the method and the simplifying assumptions made. If the wavelength started to diminish to the point that it was of the same length as the sensor or smaller, this would not necessarily hold, and plate thickness effects on sensitivity may become more prominent. It should be noted that these results are somewhat preliminary, and a more thorough study would be needed for a detailed understanding of the thickness effects across a broad range of thicknesses.

Figure 4. Mode selectivity feature of the ring sensor in capturing transient Lamb waves: (a) incoming S0 wave mode; (b) incoming A0 wave mode. The arrows represent the relative phase of the 1 N peak-to-peak 3-count tone bursts.
3. Optimizing the ring sensor configuration

Because the PWAS and FBG provide the sensing capabilities, their placement requires special consideration alongside the ring sensor dynamics to ensure an optimal response. To this end, an optimization was performed on a ring sensor under free boundary conditions.

The ring sensor did not have a ‘clean’ response under its original configurations; spurious modes at frequencies near the breathing-type mode were present. The presence of these modes complicates the sensing features. Since the ring sensor features identified in section 1.2 are related to the modes, a multi-modal response can cause the sensor to respond in an uncharacterized and undesired manner. The FEM evaluation from section 2.3 demonstrated the feasibility of a single-mode response by exploiting nodes along lines of symmetry. In the initial prototyping, exceeding the tolerances described in section 1.2, particularly when sensor symmetry is broken, do not necessarily degrade sensitivity but create spurious modes which cause the ring sensor to respond in an uncharacterized fashion. For example, a 3° variation in angle between the flat surfaces was sufficient in one prototype to generate spurious modes. After prototyping, while bonding the FBG and PWAS, careful attention to the symmetry of the sensor was used to eliminate confounding modes and produce a single mode response.

3.1. Initial ring sensor configuration

In earlier investigations of the ring sensor [16, 17], the FBG was bonded directly to the side of the ring (figure 7(a)). The side-bonding was used to provide a sufficiently large bonding surface. A slight prestretch was applied to the optical fiber by hand to ensure it did not buckle during use.

Two PWAS configurations with different grounding conditions were initially used. In one configuration, the PWAS was bonded flush with the top of the ring sensor; the PWAS had a wrap-around electrode, where the bottom electrode wrapped from the bottom to a section of the top surface so both electrical terminals could be wired to the top of the PWAS. A second configuration used a PWAS with top/bottom electrodes flush along the PWAS top and bottom surface. The electrode was left overhanging slightly so a wire could be soldered directly to the electrode for grounding. All of the sensor bonding was done using a cyanoacrylate adhesive (Vishay Micro-Measurements M-Bond 200 adhesive kit).

3.2. Setup of the FBG sensing

Turn-key commercially available FBG systems are generally not sufficient for ultrasonic guided wave-based SHM, as they are developed for high strains at low frequencies [21]. For ultrasonic FBG sensing, we used a custom bench-scale system based on an intensity demodulation approach [11]. A tunable laser source is first used to sweep across the FBG wavelength spectrum, and then fix upon the half-maximum of

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**Figure 5.** Ring sensor amplification of incoming A0 Lamb wave mode: (a) strain of FBG on ring sensor; (b) longitudinal plate strain in equivalent position of control model without the ring sensor.

**Figure 6.** Ring sensor directional dependence: the ring sensor shows a cosinusoidal-like directional dependence, shifted upwards by a constant.
the falling slope of the reflected spectrum. Strain in the sensor, related to wavelength shifts, is related to the reflected intensity through the falling slope. This allows ultrasonic strain sensing to be limited only by the speed of the photodetector and the data acquisition device.

The equipment used for FBG strain sensing consisted of a LUNA Phoenix 1400 tunable laser source, an optical circulator (AFW Technologies Pty, #Cir-3-15-L-1-2), a 50/50 optical splitter (AFW Technologies Pty, #FOSC-1-15-50-C-1-S-2), and an adjustable photodetector (New Focus 2053). Additional signal processing equipment included a function generator (HP 33120A) and an oscilloscope (Tektronix TDS5034B).

3.3. Experimental analysis—testing the ring sensor under free conditions

To assess the frequency response of the ring sensor, a 100 ms duration, 50–150 kHz, 0–50 V linear chirp excitation was transmitted from the PWAS and received by the FBG sensor. The chirp excitation has a linear time–frequency relationship, allowing a single-excitation sweep of the ring sensor’s frequency spectrum. Due to the linear time–frequency relationship, the frequency results can be observed directly from the time-domain signal.

Shown in figure 8(a), the ring sensor with a wrap-around electrode PWAS and side-bonded FBG showed two very prominent extraneous modes (the two higher frequency peaks). Shown in figure 8(b), two different extraneous modes are present at higher frequencies than the fundamental mode. It is interesting that all four extraneous modes are at different frequencies. Each of these modes can be seen in the modal analysis of the sensor, and correspond to non-breathing-type modes such as those shown in figure 2. The frequency could be used in conjunction with the modal analysis to identify the mode shape of the spurious mode to eliminate it in the response. In practice, the presence of spurious modes, regardless of which particular modes they are, indicate issues with both the PWAS and the FBG. The PWAS must be able to excite extraneous modes; otherwise they would not be present. The FBG must also be placed such that it was able to sense them.

3.4. Guiding sensor placement via FEM

To eliminate extraneous modes, the best prospect was to exploit lines of symmetry and the resonance mode nodes identified in section 2.3. All of the mode shapes other than the breathing-type mode shape have nodes along certain lines of symmetry. The FBG placement through the central hole was directly along a line of symmetry. The placement of the sensor along vibrational nodes is a stronger approach than attempting to ensure extraneous modes are not excited. In principle it is more difficult to ensure that base excitation via a
A guided wave does not excite the ring in a certain mode; this would require rejection of an excitation applied to the entire base of the sensor, which is a difficult condition to obtain in practice.

It was not as clear that the PWAS placement symmetrically about a line of symmetry would be sufficient to eliminate extraneous modes. However, it may be possible that placing the PWAS symmetrically about vibrational nodes may be sufficient. To explore this, a coupled field FEM analysis was performed (material properties from [22]), with a PWAS flush on top of a ring sensor under free boundary conditions. A frequency sweep via harmonic analysis with 1 V excitation was applied to the top of the PWAS, with the bottom of the PWAS used as a ground. Through the converse piezoelectric effect, the voltage applied to the PWAS caused a mechanical deformation, which excited the ring sensor. Using this approach, the effect of the PWAS could be assessed directly. The frequency response was sensed via differential displacement at the central holes for the FBG. Shown in figure 9(a), a single-resonance response was obtained via a PWAS bonded flush with the top flat surface. The lack of spurious modes indicates that this is the ideal configuration for the optimized ring sensor. In a separate FEM harmonic analysis of a PWAS left overhanging by 1 mm, two extraneous modes are sensed (figure 9(b)). The harmonic motion of these modes as excited by the PWAS can be displayed, but in principle they are not needed for this investigation. The results from the wrap-around electrode PWAS on top of the ring sensor in figure 8(a) can be justified in terms of asymmetry as well. Even though it is bonded flush with the top surface, the presence of the ground electrode wrapping around to a portion of the top surface creates an asymmetric excitation, which has a similar effect to asymmetric PWAS placement.

3.5. Optimized configuration of the ring sensor

Optimization of the sensor configuration was assessed separately in two experiments for changing the FBG and PWAS configurations. In the first experiment, an FBG was bonded centrally through the hole of the ring sensor and compared to
an FBG bonded to the side of the ring sensor. The chirp excitation was performed by a PWAS with top/bottom electrodes. The PWAS was left slightly overhanging for grounding considerations. As seen in figure 10(b), extraneous modes could be excited by the overhanging PWAS and sensed by the side-mounted FBG. Shown in figure 10(c), extraneous modes were still sensed by the central FBG, but were small in magnitude and largely overshadowed by the dominant resonance.

In the second experiment, a PWAS with a top/bottom electrode was bonded flush across the ring sensor flat surface. To avoid clamping a ground directly to the ring sensor, conductive epoxy (CircuitWorks CW2400) was used to bond the ground directly to the ring sensor (figure 11(a)). A chirp excitation was transmitted from the PWAS and sensed by an FBG directly in the center of the ring sensor. As seen in figure 11(b), the response is dominated by a single resonance; even the small-amplitude extraneous modes sensed by the central FBG are hardly present, if at all. This was considered a ‘clean’ response and taken as the optimized configuration. This same ring sensor was later bonded to a plate and used for the wave propagation experiments in section 4.

4. Evaluation of the ring sensor response to plate-guided waves

Testing the ring sensor under free boundary conditions was suitable for optimization, but its intended use is for a Lamb wave response. To this end, a series of pitch-catch and AE
experiments were performed across an aluminum plate. Of particular were three areas of interest:

- The plate-mounted frequency characteristics of the optimized ring sensor compared to original non-optimized configurations.
- The potential for mechanical amplification by the ring sensor.
- The capability of the ring sensor to sense AE events.

4.1. Experimental setup for testing the piezo-optical ring sensor

To assess the three areas of interest above, the optimized ring sensor from section 3.3 was bonded to a 1200 mm x 900 mm x 1.2 mm 2024-T3 aluminum plate using M-Bond 200 cyanoacrylate adhesive. The experimental setup can be seen in figure 12. Two transmitter PWAS are bonded 150 mm away from a sensor cluster, one with a propagation path longitudinal to the fiber axis, and one transverse to the fiber axis. The sensor cluster has four sensors: (1) a PWAS on the plate, (2) an FBG on the plate, (3) an aluminum 100 kHz ring sensor outfitted with the optimized configuration, and (4) a stainless steel 100 kHz ring sensor outfitted the non-optimized PWAS and FBG configuration. Corrosion-resistant modeling clay (McMaster # 6102T21) was used as a wave-absorbing boundary around the area of interest to reduce or eliminate edge reflections. A thin 90 mm wide layer was spread onto the plate on top and bottom. Using this technique, a 20 V peak-to-peak 3-count tone burst registered only one edge reflection, with its amplitude 96% lower than the initial incident wave. This was considered sufficient to significantly reduce the effect of standing waves across the plate for longer-duration excitations.

Figure 12. Experimental setup on the aluminum plate: (a) close-up of ring sensors bonded to the plate. The aluminum ring sensor in front had the optimized sensor configuration, and the stainless steel ring sensor behind had the side-bonded FBG and wrap-around electrode PWAS; (b) overall setup of the aluminum plate, with two transmitter PWAS and a single receiver cluster.
Figure 13. Tuning curves of the piezo-optical ring sensor: (a) measurement with the PWAS bonded to the plate; (b) measurement with the FBG optical sensor bonded to the plate; (c) measurement with the PWAS bonded to the non-optimized ring sensor; (d) measurement with the FBG optical sensor bonded to the non-optimized ring sensor; (e) measurement with the PWAS bonded to the optimized ring sensor; (f) measurement with the FBG bonded to the optimized ring sensor.
4.2. Pitch-catch experiments—response of the optimized ring sensor

A series of pitch-catch experiments were performed across the aluminum plate specimen to assess the ring sensor response to an incoming transient signal. The aluminum ring sensor, outfitted with the symmetrically placed FBG and PWAS, was compared to the stainless steel ring sensor (with side-bonded FBG and wrap-around electrode PWAS) and the FBG on the plate. 20 V peak-to-peak 3-count Hanning windowed tone bursts from were excited by the longitudinal transmitter PWAS. A tuning curve—the variation of amplitude with frequency—of the A0 Lamb wave mode was assessed over 30–150 kHz for the FBGs on both ring sensors and the FBG on the plate (figure 13).

The response of the FBG on the plate follows the tuning characteristics of the PWAS transducer. In comparison, the ring sensor tuning dominates, with a clear single peak near its designed frequency for both PWAS and FBG. As in the FEM simulations of the ring sensor on the plate, the resonance dropped, in this case to approximately 81 kHz for the optimized aluminum ring sensor. When comparing the aluminum and stainless steel ring sensors, the stainless steel ring sensor with the side-bonded FBG showed several distinct local maxima in the tuning curve indicating a multi-modal response. In contrast, the aluminum ring sensor with the centrally-bonded FBG shows a monotonic increase and decrease about a single peak. The tuning curves have a more gradual increase and decrease than the chirp excitation experiments performed on the free ring sensor; the plate-bonding may influence this. This effect is also explained by use of a Hanning windowed tone burst, which has a spread in its frequency content about its center frequency. This incorporates dynamic effects of the ring sensor in a neighborhood around its center frequency.

4.3. Mechanical amplification of a lamb wave

As seen in figure 13, the ring sensor did not amplify the response of a 3-count tone burst as predicted in section 2.5, possibly due to the adhesive layer damping effect. To assess the capability of the ring sensor to amplify an incoming signal, we varied the number of counts on a Hanning windowed tone burst, such that the excitation gradually approached the nature of a continuous harmonic wave. The longitudinal transmitter PWAS was used to transmit a wave across the plate to the FBG on the plate and the FBG on the ring sensor.

As the number of counts increased, the frequency spread about the center frequency narrowed and the signal length increased approaching a harmonic wave. For these experiments, the wave-absorbing clay was critical to eliminate the effect of standing waves on the plate. Ideally, the amplitude of the incoming waveform should asymptotically approach a fixed value associated with resonance as the number of counts increase. Since the exact excitation frequency was critical due to the narrowing frequency spread, a continuous sine wave was used to find the frequency which produced a maximum response on the ring sensor. This was found to be 82.1 kHz.

The variation in receiver strain for the FBG on the plate and the FBG on the aluminum ring sensor can be seen in figure 14. The voltage received was divided by the FBG falling slope so it was linearly related to strain, and the response was normalized by the amplitude of the continuous sine wave from the FBG on the ring sensor. The FBG on the plate had a larger strain for low-count tone bursts. After eight counts, the strain detected by the FBG on the ring sensor surpasses the strain from the FBG on the plate. That is, the ring sensor mechanically amplified the signal for tone burst excitations of eight-counts and above.

One interpretation is that the frequency content of the signal needed to fall sufficiently close to the resonance...
Figure 15. PLB AE events transmitted across the aluminum plate: (a),(b) longitudinally-excited AE sensed by the FBG on the plate, time-domain and frequency-domain results; (c),(d) longitudinally-excited AE sensed by the FBG on the ring sensor, time-domain and frequency-domain results; (e),(f) transverse-excited AE sensed by the FBG on the ring sensor, time-domain and frequency-domain results.
frequency of the ring sensor for a large enough amplification. Another possibility is that the additional boundary created by bonding the ring sensor to the plate added additional attenuation to the wave, which needed to be overcome by energy stored in the ring sensor from a longer duration excitation.

Although the mechanical amplification was not overly large in magnitude, roughly 20% at its maximum, this is nonetheless a positive indicator for future design. Now that it is clear that this approach can amplify a signal, optimization in the ring sensor design for amplitude is appropriate. An FEM parametric search over the ring sensor design features (wall thickness, ring diameter, etc.) can be used to optimize the sensor design for the greatest mechanical amplification.

4.4. PLB AE experiments on the aluminum plate

Experiments using PLB-generated AE (Hsu-Neilsen source) were performed to assess the ring sensor’s suitability to serve as an AE sensor. There are characteristic differences between a crack-generated AE and a PLB-generated AE in terms of frequency content, amplitude, and ratios between in-plane versus out-of-plane motion [23]. However, there have been efforts to characterize the PLB technique [24], and the resulting waveform produces motion sufficiently similar to a crack-generated AE that it is useful for characterizing normal AE sensor operation [25].

PLB AE signals were generated using 0.5 mm HB lead broken on the top surface of the aluminum plate in figure 12 at distances 100 mm longitudinal and transverse to the ring sensor. The response of the FBG on the plate and FBG on the ring sensor are shown in figure 15. The time and frequency domain response from the FBG on the plate to longitudinal PLB excitation is shown in figures 15(a) and (b) respectively. The time and frequency domain response from the FBG on the ring sensor to longitudinal PLB excitation is shown in figures 15(c) and (d). The time and frequency domain response from the FBG on the ring sensor to transverse PLB excitation is shown in figures 15(e) and (f). The case of a PLB exciting the FBG on the plate from a transverse direction is omitted, as the FBG could not sense a significant component of the wave. The response of the FBG on the ring sensor shown in figure 15(c) was significantly greater than the response of the FBG on the plate shown in figure 15(a) (this was true even when comparing strain values by taking the FBG falling slope into account). An interesting result is that the degree of amplification for the PLB AE was larger than the mechanical amplification from active Lamb wave transduction shown in section 4.3. This indicates the ring sensor may have a higher sensitivity for a more broadband source when multiple frequencies of the ring are excited. This effect would require further investigation.

The response of the FBG on the ring sensor showed the omnidirectionality feature, with the capability to sense Lamb waves with propagation paths in the longitudinal (figure 15(c)) or transverse (figure 15(e)) direction. The FBG on the plate could only sense the longitudinal component. When examining the FFT of the ring sensor PLB AE response in figures 15(d) and (f), the amplified frequency contents were the first and second resonances of the ring sensor at 82 kHz and 265 kHz. Surprisingly, the larger degree of amplification came from the second resonance. The reason why is not yet clear, and requires further investigation. Additionally, a low frequency component is clearly visible, interpreted as a flexural-type motion induced in the plate by the application and release of pressure from the pencil. However, upon examination of the time-domain signal, the initial sharp high-frequency peaks were still of a larger magnitude for the FBG on the ring sensor than for the FBG on the plate. From this result, we can conclude that the mechanical amplification of the ring was sufficient to amplify a PLB AE signal. It may be useful in future work to quantify the exact ring sensor sensitivity via ASTM E1106 [26]. Since PLB AE signals have similarities with crack-generated AE signals, we expect these results may be transferrable to crack-generated AE signals.

5. Summary, conclusions, and suggestions for further work

One of the original approaches adopted in this paper is a combined vibration-wave propagation assessment of sensor effectiveness. Vibrational modeling complements the wave propagation modeling to confer in-depth understanding of the sensor features. Each of the sensor features which relate to wave propagation phenomenon were understood through a vibrational modeling approach. The sensor vibrational modes were clearly discernable in transient FEM models with short-duration burst excitations—and these vibrational modes guided the understanding and optimization of the sensor under investigation.

Undesirable frequency components were eliminated by placing PWAS and FBG onto, or symmetrically across, nodes of the vibration mode shapes. This translated into a clearer wave propagation signal in pitch-catch Lamb wave experiments. The tuning curves were dominated by a single-resonance result for a clearer frequency response. Mechanical amplification was demonstrated for a Lamb wave signal. In the experimental analysis, mechanical amplification was not as pronounced as in simulations, possibly due the bonding layer effect. However, it was still a positive indicator for future redesign, as the sensor design was not optimized for mechanical amplification. PLB AE experiments showed the ring sensor was capable of detecting and amplifying PLB AE events compared to an FBG on a plate, which is a positive indicator for use of this sensor as a resonant-type AE sensor.

The understanding of the sensing features and the optimized ring sensor configuration provides a basis for future investigations. The next step is to take the ring sensor design and optimize it for size and mechanical amplification. There are indications that miniaturization is possible by changing the outer diameter and wall thickness separately; the wall thickness may also relate to mechanical amplification. The same combined vibration-wave propagation assessment will be used alongside the understanding of the sensing features presented herein for the optimization. Beyond the particular
shape of the sensor, future work will focus on novel geometries and sensing concepts for resonance-based sensors, such as features designed for energy concentration or tunable resonance frequency which incorporate a fiber optic sensing element.

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References