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# Studying the effect of strain induced birefringence on the sensitivity of FBG sensors for Guided wave measurements

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## ABSTRACT

To perform active structural health monitoring (SHM), guided waves (GW) have received great interest as they can inspect large areas with a few sensors and are sensitive to barely-visible structural damages. Fiber Bragg grating (FBG) sensors offer several advantages such as small size, low weight and ability to be embedded but their use has been limited for GW sensing due to their limited sensitivity while using spectrometers. FBG sensors in the edge-filtering configuration have overcome this issue with reasonable sensitivity and there is a renewed interest in their use. It is well known that when subjected to a transverse strain, the circular cross-section of the fiber deforms into an elliptical shape generating the birefringence phenomenon. This deformation, influences the coupling mode of the light inside the FBG and hence, modifies the resulting reflectivity spectrum. This paper investigates how controlled changes in the reflectivity spectrum can be introduced using different transverse loads. The effect of the modified spectrum on the sensitivity of the FBG for GW measurements is then studied. The study also investigates the effect of the transverse strain on the coupling of the GW from the structure into the fiber.

**Keywords:** plate, guided waves, fiber optic sensors, fiber Bragg grating birefringence, sensitivity

## 1. INTRODUCTION

Guided Waves (GW) based Structural health monitoring (SHM) is one of the most commonly used methods for SHM of large plate-like structures. GW can travel large distances and can allow inspection of large areas with few sensors. The problems of using GW for inspection of isotropic structures has been very well understood and thoroughly addressed.[1] The application of GW for composite structures is still a challenge. The key challenges for using GWs with composites is the material anisotropy and high damping. This damping can be overcome through the use of additional sensors albeit at an additional costs. In some applications such as aerospace, the increased weight of instrumentation results in reduced fuel efficiency. Hence the search for lighter sensors needing less wiring is still ongoing. Fiber Bragg grating (FBG) based sensors are small, light in weight and can be multiplexed[2] and are seen as an excellent solution to reduce the instrumentation weight. FBG sensors have been commonly used for SHM in the last two decades,[3–7] but due to their low sensitivity for GW sensing, their use has been limited. More recently, the use of FBG sensors in the edge filtering configuration has been shown to improve the sensitivity of FBG for GW sensing and hence is receiving a lot of attention.[8–11] The edge filtering approach is shown in Figure 1. A tunable laser or filter is tuned to the wavelength on the increasing or decreasing edge of the FBG reflectivity slope. The strain in the fiber shifts the Bragg wavelength. Instead of measuring the shift in the wavelength, the photodetector records the change in the intensity of the reflected light. As the slope of the reflectivity is steep, even a small horizontal shift leads to a large change in the amplitude of the photodetector response. Thus allowing a higher sensitivity. In addition to the higher sensitivity the photodetector can have very high sampling rates, thus leading to a very good temporal resolution of the signal.

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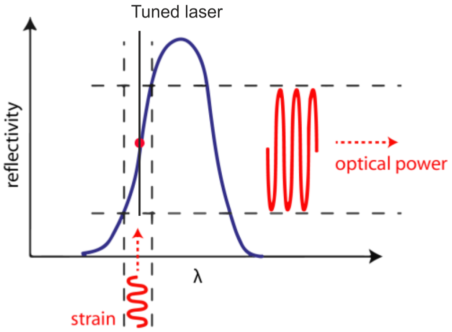

Figure 1: Edge filtering approach.[9]

The challenge of the complexity of the GW signal processing for composite structures, has not been overcome satisfactorily as yet. The most commonly used strategy for reducing the complexity is to restrict the frequency of the excitation to the regions where only the two fundamental modes (Antisymmeric A0 and Symmetric S0) are present. But even with this approach, in structures with several structural features, the signal processing is challenging due to many reflections and possible mode conversions. Thus more techniques for simplifying the signal processing need to be developed. One possible way is to restrict the modes excited in the structure through the use specially designed actuators,[12] special arrangements of actuators,[13,14] or co-axially located actuators.[15] The special actuators are costly and hence are not ideal for scaling to a large structure. Also, the special arrangement of the actuators limits the usable range of the network, as the actuator arrangement is optimized for one particular frequency.

Another solution is to identify the sensed mode through the use of special sensor arrangements. For instance placing sensors at two sides of the sample, may allow identifying the S and A modes. But this will need twice as many channels for interrogation which increases the cost significantly. The authors have recently presented an innovative strategy for mode separation using just one single FBG sensor.[16,17] This concept is based on the different mechanism of the transduction of the wave with the fiber. But this approach is only useful where the relative ratios of the wavelength of the GW and the length of the FBG are in different regimes.[18] Also in order to realize the mode filtering the time required for measurements is considerably longer, making it challenging to be used in real applications. A recent study by Rao and Duan[19] have shown that a polarization maintaining FBG sensor has selective sensitivity to S0 and A0 mode and has a potential to be used for mode separation. But the use of of polarization maintaining device needs specialized optical equipment including polarization maintaining optical fibers which increases the cost of instrumentation significantly. A solution to overcome this is to introduce birefringence by inducing a transverse strain on the FBG. The effect of transverse uniform and non-uniform strains on the FBG spectrum has been studied by several researchers.[20–22]

Hence, this paper investigates if strain induced birefringence may be used to enhance the sensitivity of the FBG sensors to the A0 and S0 mode. A piezo-FBG hybrid system is deployed on an aluminium plate. The FBG spectrum is manipulated through the addition of a uniform transverse force over the FBG to introduce birefringence. The edge filtering approach is then used to measure the GW in this birefringent FBG.

## 2. EXPERIMENTAL SETUP

In order to study the effect of strain induced birefringence on GW sensing in the edge filtering configuration, a square aluminium plate (50cm × 50cm × 0.1cm) was instrumented with sensors and actuators as shown in Figure 2. The FBG was attached using NOA61 glue cured using UV light. The sensor was located at the center of the plate based on engineering judgement. A PZT was attached at a distance of 12 cm in the direction of the optical fiber. The transverse load was applied by means of a linear actuator (Zaber NA23C60-T4). A load cell was included between the aluminium blocks and the linear actuator to allow measurement of the applied load. In order to ensure a uniform load, two aluminium blocks were used as shown in Figure 2. The FBG sensor and the steel block were placed one over the other, at the transverse midline of the aluminum plate. In addition to the glued FBG another supporting fiber (not glued) was placed parallel to the FBG. This allowed the load to be evenly distributed along the FBG.

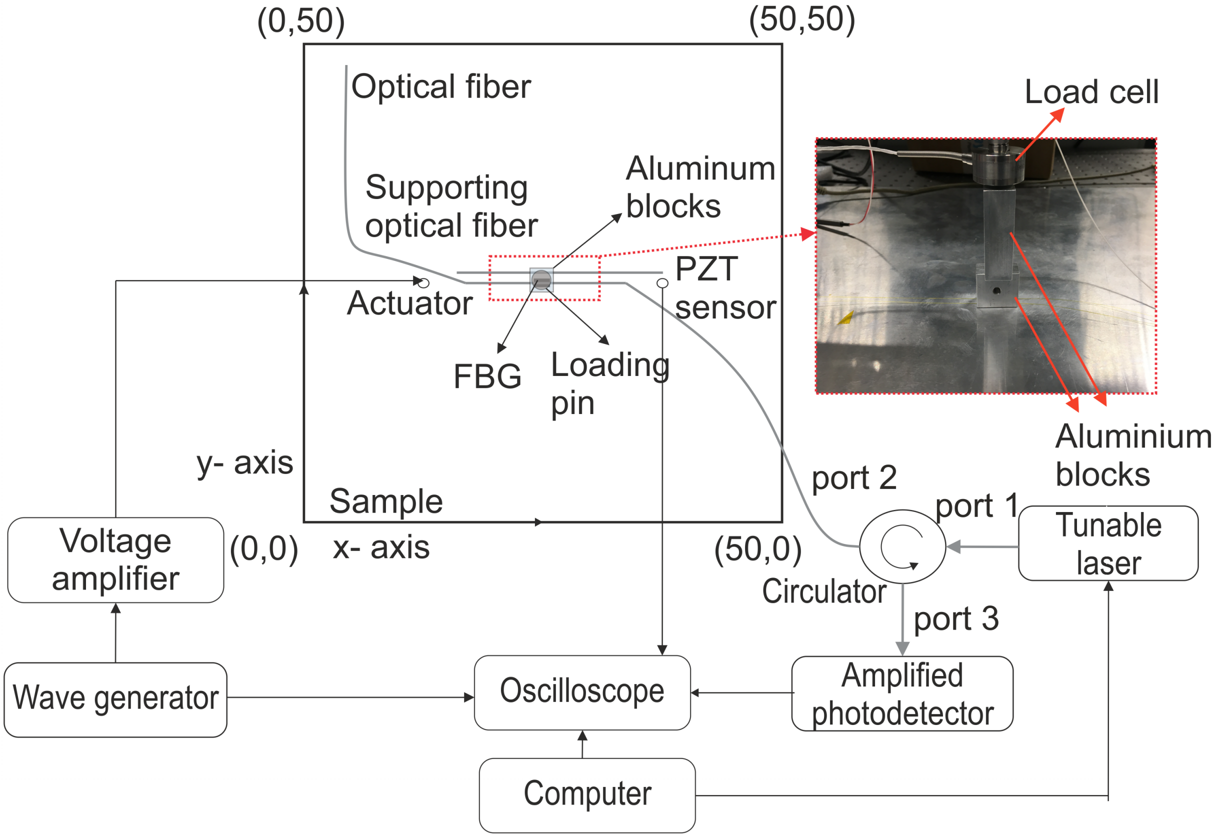

Figure 2: Schematic for the experimental setup

For the measurements, a tunable fiber coupled laser (Apex AP1000) was used for generating a chosen spectral band. The tunable laser can be synchronized with the oscilloscope (PicoScope 4424) and the waveform generator (Agilent 33500B). First the spectrum of the FBG was acquired in the loaded (8 N - 18 N) and unloaded conditions. In order to obtain the reflectivity spectrum, the tunable laser was connected through a circulator to the FBG and the reflected signal was recorded by the preamplified photodetector using the oscilloscope. The DC coupled measurements allow construction of the reflection spectrum. Once the birefringence was seen, wavelengths on the four slopes of the split peak spectrum were chosen and measurements at different excitation frequencies were realized. A 5 cycle Hann windowed signal at different frequencies in the range of 50 kHz to 250 kHz with a step of 50 kHz were used. In addition to the measurement using the FBG in edge filtering approach, the actuated signal was also captured with PZT sensor for comparison.

## 3. RESULTS AND DISCUSSION

### 3.1 FBG spectrum

Figure 3 shows the reflectivity spectrum of the FBG under no load, and with a transverse load (8 N - 18 N). The first thing we can notice is that there is a significant change in the maxima of the reflectivity peak. This indicates that the reflectivity is affected by the transverse load. Also apparent, is a distinct change in the spectral shape between the no load and transverse loaded conditions. In the no load conditions there is 1 distinct peak, while for transverse loads there are 2 peaks, and above certain loads the spectrum is distorted even more. For further study the 14 N loaded FBG was used as the magnitude of the reflectivity was the highest.

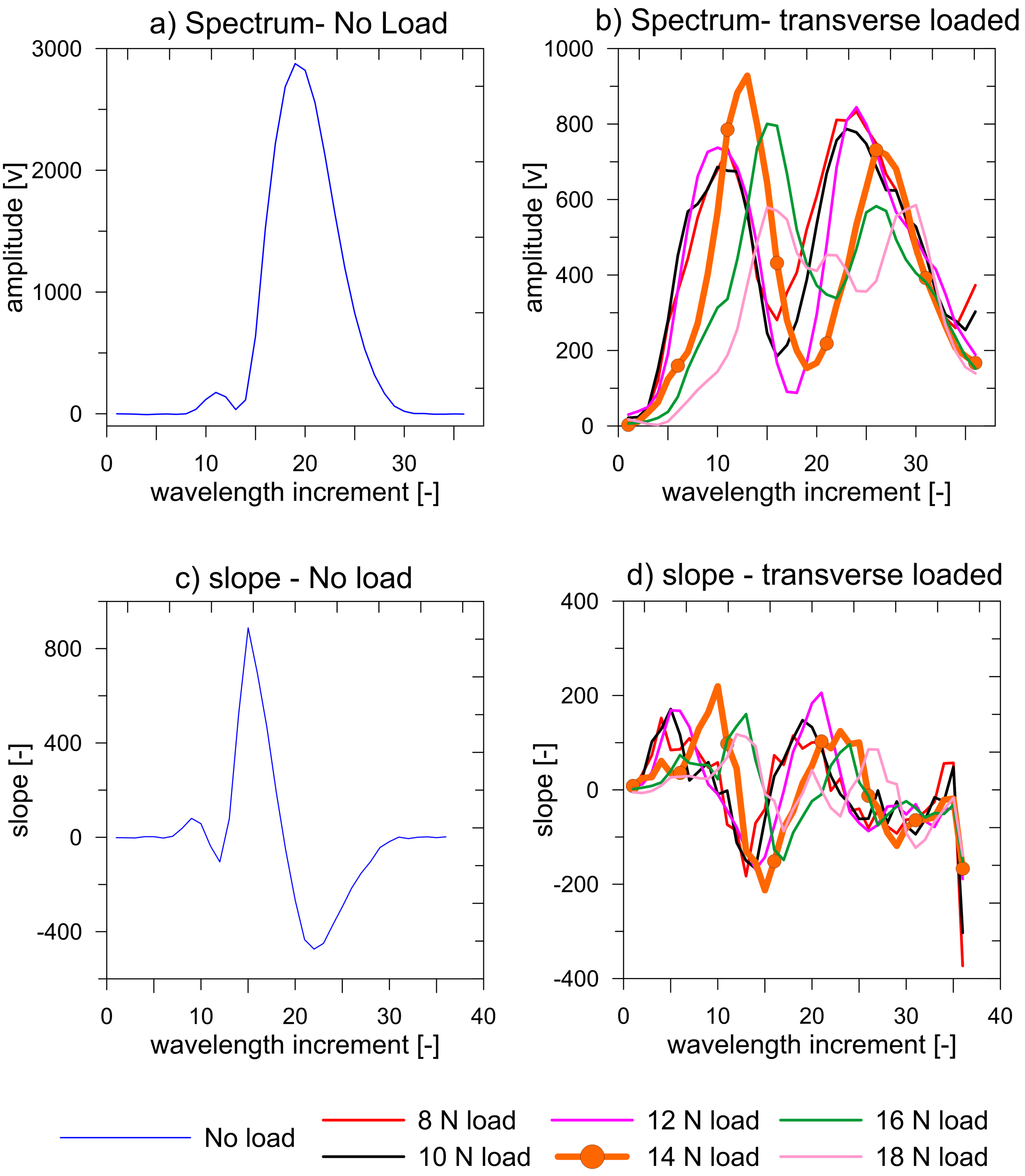

Figure 3: Plot for the FBG spectrum a) No Load b) under transverse loading c) slope of spectrum under no load d) slope of spectrum under transverse loading

The sensitivity of the sensor in the edge filtering configuration is proportional to the slope of the reflectivity as the slope acts like an amplification factor. Figures 3c and d show the slope of the reflectivity spectrum. In order to maximize the sensitivity the tunable laser should be tuned at the maxima or minima of the slope. Even here the slope for no load condition is considerably higher than for the transverse load, so it can be concluded that the sensitivity is adversely affected by the transverse load. But in spite of this effect, there might be a reason to use this if mode filtering or a selective sensitivity to a particular mode is achieved.

### 3.2 GW measurements in no load conditions

The PZT actuators were placed co-axially on both sides of the plate. By exciting them in phase and out of phase the two modes can be excited separately. Figure 4 shows this phenomena for the FBG without the transverse loading. It can be clearly seen that for single excitation both the S0 mode and A0 mode have comparable magnitudes (A0 mode is marginally better excited than S0 mode). But when the actuators are excited in phase, the S0 mode is excited better while the A0 mode is suppressed. Similarly when the actuators are excited out of phase, the S0 mode is suppressed while the A0 mode is amplified. Thus this phenomena can be used to selectively excite a particular wave and test the sensitivity of the FBG to the two modes.

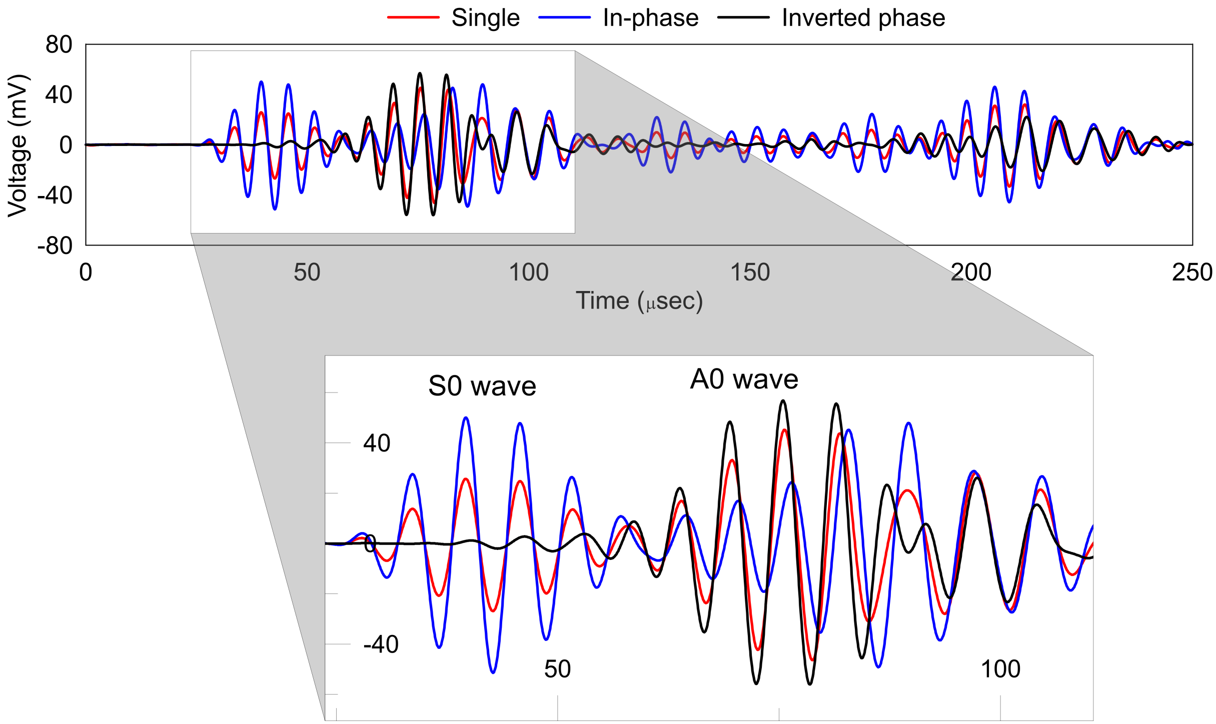

Figure 4: Measurements using an FBG without birefringence

### 3.3 GW measurements using FBG with transverse loading

In order to determine if the slopes of the two peaks seen in an FBG under transverse loading have different sensitivity, 4 points on the maxima and minima of the slopes of the reflectivity spectrum were chosen and measured in the edge filtering configuration. The points are labelled P1 and P2 for the increasing and Figures 5, 6, and 7 show the response recorded by the FBG at 250 kHz excitation for the 4 different wavelengths in 3 different excitation configurations.

A point to note that the amplitudes of the signals are proportional to the slope of the spectrum at that point. To allow the comparison of the four signals, they are normalized with respect to the slope. As can be seen points 3 and 4 have slightly higher magnitude for the A0 wave magnitude, than points 1 and 2. This seems to indicate that indeed, that peak shows slightly higher sensitivity to the A0 wave. This can be confirmed with the selective excitation of the A0 and S0 wave as shown in figures 6, 7. The slightly better performance of Points 3 and 4 for the A0 wave and Points 1 and 2 for the S0 wave can be seen.

This difference in the sensitivity can be used for identifying the wave modes and simplifying the signal processing. Unfortunately, the additional load imposed on the FBG changes the experimental boundary conditions of the plate. This additional constraint on the plate acts as a fixed node, and the propagation of the A0 mode

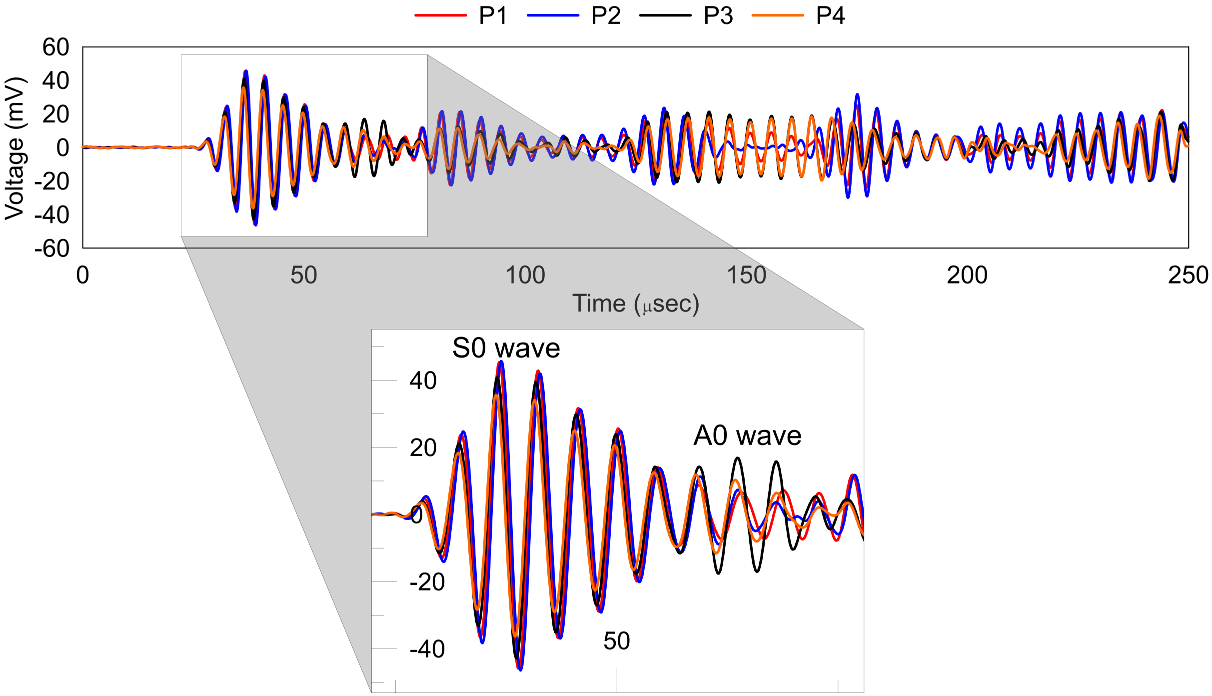

Figure 5: GW measurements at 4 wavelength with single excitation at 250 kHz

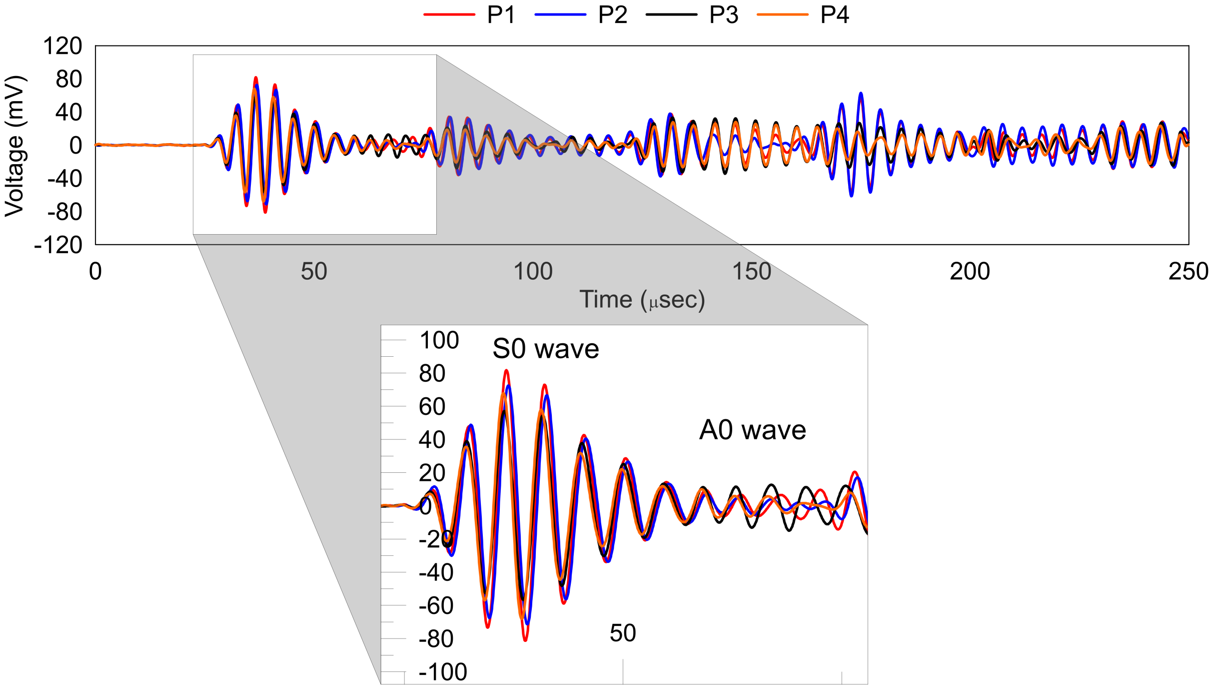

Figure 6: GW measurements at 4 wavelength with inphase excitation at 250 kHz

is affected especially at lower frequencies. At 100 kHz frequency the A0 wave is more dominant due to the out of plane resonance frequency of the PZT actuator. But as can be seen in Figure 8, the excitation for 4 different frequencies in the inverted phase configuration is shown. The inverted phase promotes the excitation of the A0 mode. But as can be seen, the 100 kHz signal has a considerably lower amplitude. To verify that indeed this was caused due to the change in boundary condition and not due to some systematic error in the measurement

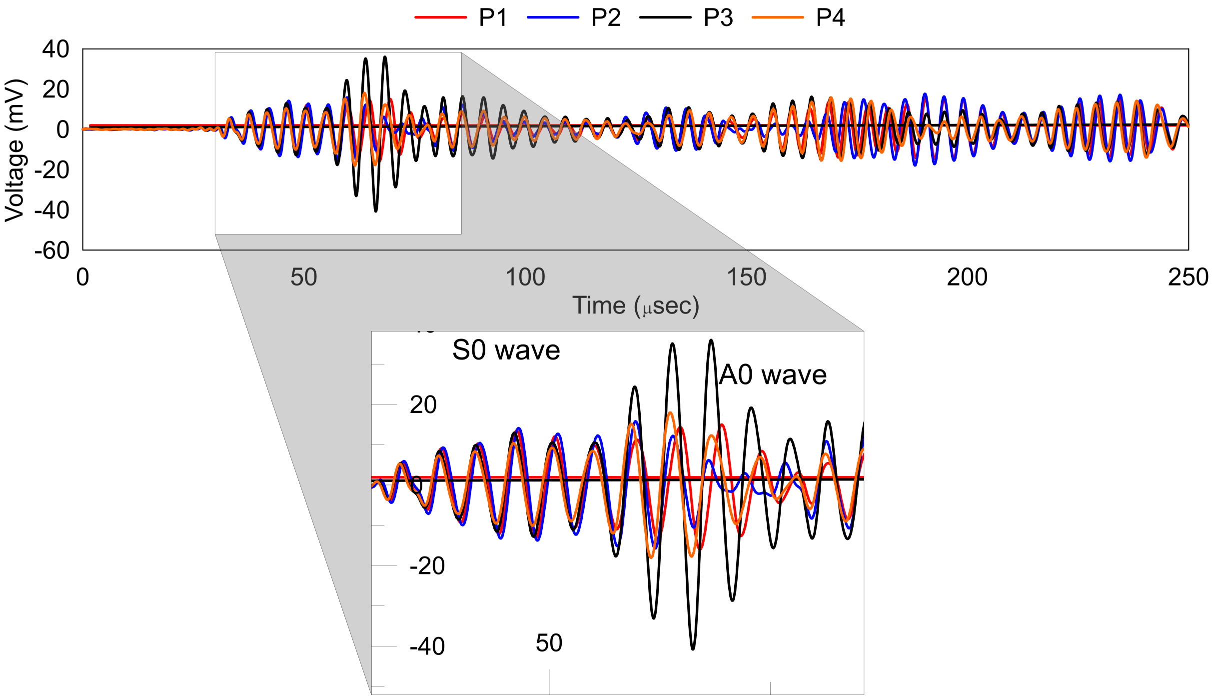

Figure 7: GW measurements at 4 wavelength with inverted excitation at 250 kHz

using FBG sensors, the time signal for the PZT sensor placed at the location indicated in Figure 2 is also shown.

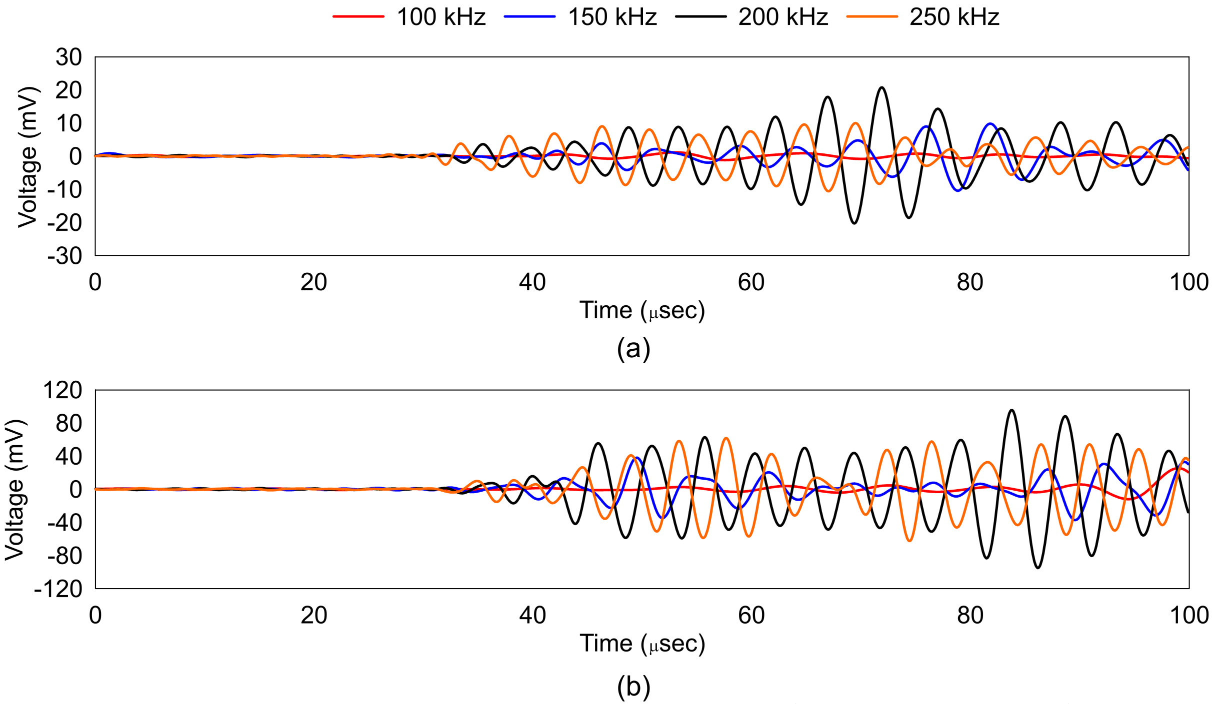

Figure 8: GW measurements at 4 frequencies with inverted excitation a) FBG measurements b) PZT measurements

As can be seen, the signal shows similar characteristics but is shifted in time due to the longer distance between the actuator and sensor. For 200 kHz, the A0 wave has the highest amplitude, this we believe is due to the lower wavelength of the A0 wave at higher frequency which may propagate beyond the point of the transverse loading. Additional studies need to be carried to gain further insight in this phenomenon.

## 4. CONCLUSIONS

This research undertaken investigated if the two peaks of a birefringent FBG have differential sensitivity to the antisymmetric and symmetric GW modes propagating in an aluminium plate. The birefringence is achieved by transverse uniform loading of the FBG. The initial results do indicate that there is a slight difference in the sensitivity of the peaks in the birefringent FBG. This may be utilized if not for mode separation, but for identification of the mode measured at the FBG. This may simplify the signal processing and improve the damage localization. The use of this differential sensitivity for damage localization is indeed the next step for research.

Although the results obtained support the hypothesis, the way in which the birefringence was achieved introduces systematic changes in the system. As a result the sample without the transverse loading and with transverse loading have marked difference in the wave propagation. So care needs to be taken while processing the data. This has been shown that lower frequency excitations are more affected by this introduced change. In order to gain more insight, numerical simulations needs to be performed and this is identified as future work. The systematic changes introduced in the system due to the external loading may be overcome using polarization maintaining FBG sensors, or FBG embedded in composite samples where the FBG is not aligned with the fibers of the composite. This too is an area which will be investigated closely in the future.

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