Experimental Investigation of an Active Sub-micron Acoustic Sensor Using Bandgap Materials

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Abstract

Acoustic bandgap (ABG) crystals are made of a periodic array of inclusions/scatterers embedded in a homogenous material. ABG crystals can be thought of as the mechanical analogues of semiconductors. In a semiconductor the electronic bandgap arises as the result of a periodic array in electronic potentials. In an ABG crystal a sonic bandgap arises as the result of a periodic array of differing acoustic impedances.

We suggest that acoustic bandgap crystals can be used as sensors to detect and quantify submicron damage in substrates by monitoring changes in their acoustic response. More interestingly, is the scalability of the proposed sensors as acoustic bandgaps can be observed in both low-audible frequencies (e.g. seismic waves) and terahertz frequencies (e.g. phonon waves). This article presents the ability of an ABG sensor made of an epoxy matrix loaded with Tungsten scatterers to detect and quantify submicron damage in composite material substrates adhered to the ABG sensor. A finite element simulation, coupled with acoustic wave analysis using finite difference in time domain, is used to present the ability of ABG crystals to be employed as submicron sensors.

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Introduction

This research examines the potential of using an acoustic bandgap (ABG) material as a sensor for sub-micron (nano) scale damage detection and quantification in composite materials. Acoustic bandgap is a physical phenomenon in which acoustic waves are prevented from propagating within a range of frequencies, therefore causing a 'gap' (Figure 1). This research exploits this observable fact to develop a novel sensor that can detect damage occurrence at scales not attainable using existing sensing technology. We demonstrate here the use of ABG materials to produce a scalable sensor. Scalability allows damage detection at various levels of damage ranging from micro- to macro-scale damage. This enables us for the first time to observe damage resulting in tens to hundreds of nanostrains, a scale never reported before in the literature.

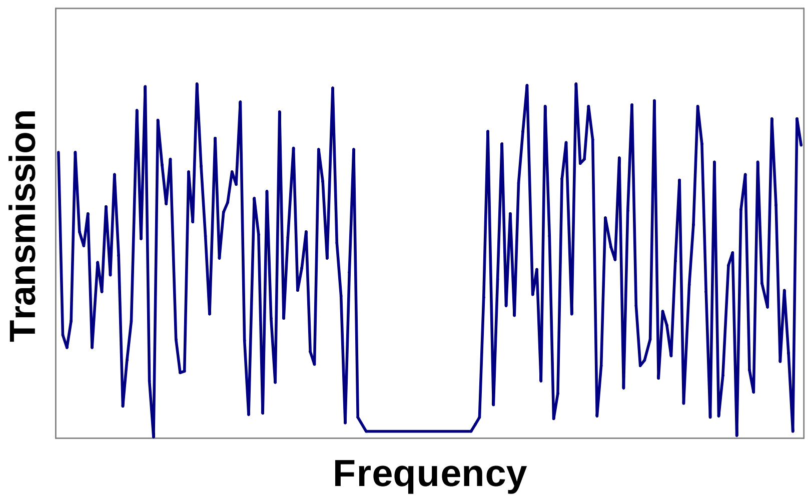

Figure 1. Acoustic Bandgap Schematic

Sensor Application

An ABG sensor is made of a polymer matrix (here epoxy) with cylindrical metal inclusions. The cylindrical inclusions are periodically spaced with a center-to-center distance known as lattice constant 'a'. The ABG material is sandwiched between two piezoelectric plates; one acting as an acoustic wave sender and one as an acoustic wave receiver. The sensor geometry including the lattice constant is designed to achieve a desired bandgap.

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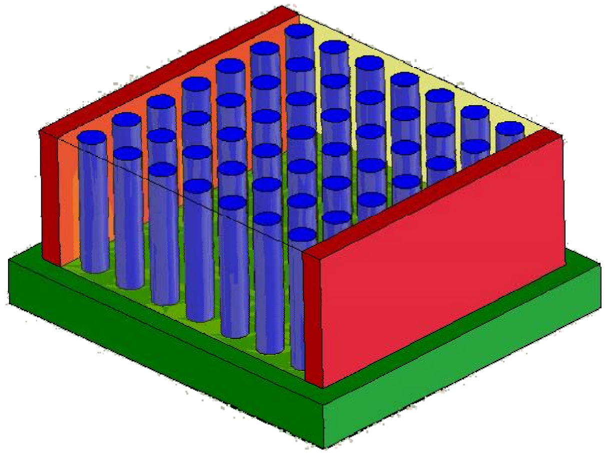

Figure 2. Three dimensional pictorial of an acoustic bandgap sensor showing the polymer matrix, the metallic scatterers and the piezoelectric plates

ABG sensors must be adhered to the substrate material to be able to identify damage in this substrate. We recommend using the ABG sensors for hot-spot monitoring of composite laminates at critical locations. The choice of the sensor polymer matrix is therefore governed by the needed ability to correctly represent the strains in the substrate material. The strain on the sensor will cause a dimension change in lattice constant 'a', creating a change in the acoustic transmission that can then be attributed to a specified damage case.

Theoretical and Experimental Analysis

Simulations using the finite difference time domain (FDTD) method were performed to demonstrate the significant change in the ABG sensor transmission of a mechanical pulse sent though the sensor when damage in the substrates take place. Two ABG sensors are simulated at two different scales: micro-scale and sub-micro scale sensors.

In order to develop the ABG sensor, a few experiments need to be developed. The experimental work is divided into five stages including:

1) Establishing a methodology to eliminate air bubbles from the epoxy matrix
2) Determine if stiffness required to enable acoustic transmission can be attained.
3) Develop a methodology for adhering the epoxy and the piezoelectric plates-to-transducer boundary
4) Cast epoxy with inclusions at specific period.
5) Observe the acoustic bandgap and its relation to multi-scale damage

Theoretical and Experimental Results

Figure 3 compares the signal response from an ABG sensor in case of an undamaged substrate and a substrate that has local damage of 45 mm. While an obvious acoustic bandgap can be observed in the case of an undamaged substrate (blue), the bandgap was completely deteriorated (red) when the local microdamage occurred in the substrate under the sensor.

Moreover, a second simulation case of a sub-micron damage detection using an ABG sensor with a lattice constant of 0.3 mm is demonstrated in Figure 4 (left). The sensor response for the undamaged

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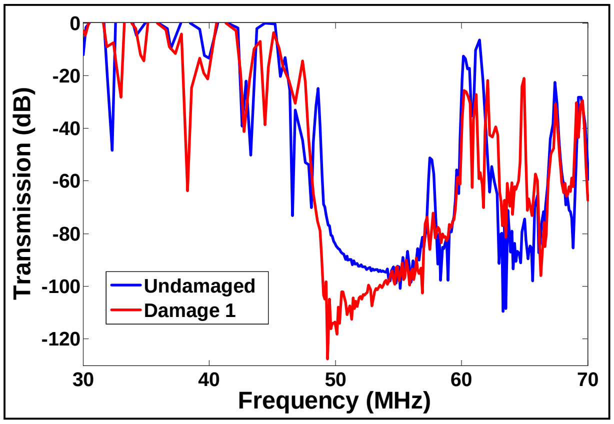
signal (blue) is compared to the sensor response due to a local damage of 75 nm width (red). It can be obviously observed that the sub-micron (nano) scale damage was able to deteriorate the bandgap observed in the undamaged case.



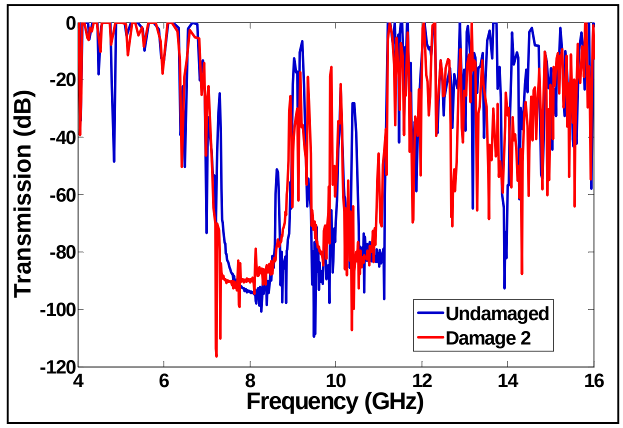


Figure 3. Acoustic signal response of ABG sensor for undamaged substrate (blue) and locally damaged substrate of 45 mm (red).

Figure 4. Acoustic signal response of ABG sensor for undamaged substrate (blue) and localized damage of 75 nm (red)

Conclusions

A novel sensor using ABG material is developed. The ABG sensor can observe micron and submicron damage in substrates adhered to the sensor. Differences between uniform stains and damaged cases due to cracking has been in the bandgap profile so that these cases are differentiated. Further work is needed to fabricate and test the ABG sensor. Research work is underway to correlate changes in the acoustic bandgap due to the level of damage.

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