An Experimental and Theoretical Investigation of Ultrasound Transmission in Bubbly PDMS Phononic Crystals

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M A T S

Abstract:

Phononic crystals are two- and three-dimensional structures with a periodic arrangement of two or more materials with different acoustic properties. Depending on the size, structure, and characteristics of the constituent materials, meta-materials with interesting acoustic properties can be formed. These crystals can be used to control the transmission of sound at selected frequencies, focus sound, or serve as waveguides. In this study, we investigated the transmission of ultrasonic waves through polydimethylsiloxane (PDMS) films with entrapped air bubbles. We examined how ultrasonic transmission through PDMS layers can be engineered by varying the dimensions, separation, and arrangement of air bubbles. We reproduced previously published data using two different theoretical models that describe ultrasonic transmission in air-PDMS crystals: (1) a simple scattering model for a series of partially reflective thin films, and (2) the code MULTEL, which calculates the transmission solution using multiple scattering theory. We then used these models to predict the performance of new phononic structures by scanning a large parameter space. To create these structures, we first fabricated arrays of micron-scale pillars on a silicon wafer. PDMS layers were then cast on these pillar templates and stacked to form air bubble arrays with two- and three-dimensional periodicity. A series of processes were developed to stack layers of the crystals with unprecedented alignment. Finally, we measured the ultrasonic transmission through the films using a transducer/receiver setup in a water bath and compared it to the theoretical results.

Modeling Ultrasound Transmission:

We used two theoretical models to fit published experimental data [1] of a single PDMS layer with a square bubble lattice (a = 300 μm) and a four-layer PDMS stack with a tetragonal bubble lattice (a_x = 300 μm; a_z = 350 μm). The first analytic approach treats each bubble layer as a partially reflective plane and then iteratively calculates the reflection and transmission through all layers [1, 2]. We also used a more rigorous multiple scattering theory (MST) approach [3] where each bubble served as a scattering source for incoming ultrasonic waves. We found excellent agreement with previously measured values and the theoretical approaches gave consistent results for much of the frequency range. We then used these models to explore a broad parameter space to determine the variation of transmission with the key parameters (e.g., number of layers, bubble radius and separation). Figure 1 demonstrates one such investigation, where we fixed the bubble separation and calculated the transmission up to 5 MHz as we varied the bubble radius up to 100 μm. Using a similar approach, we showed that the crystal can be tuned to block certain frequencies. The blocked frequency followed the isolated bubble Minnaert resonance [4]. However, due to the bubble periodicity, we could tune the blocked frequency away from the Minnaert resonance by adjusting the in-plane bubble separation.

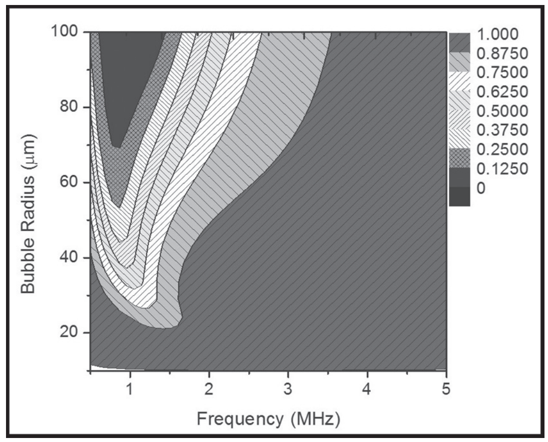

Figure 1: Contour plot of transmission for analytical model as a function of bubble radius and frequency. N = 1, a_x = 300 μm.

Phononic Crystal Fabrication and Measurements:

After establishing our theoretical models, we set out to build the crystals to measure the transmission experimentally. Contact lithography was used to pattern an array of pillars on silicon and we then etched the wafer down 50 μm. We then spun 350 μm of PDMS on the etched wafer, giving a flat, uniform film over the pillar array. PDMS was lifted off and stacked for ultrasonic measurements. Ultrasonic measurements were carried out in a

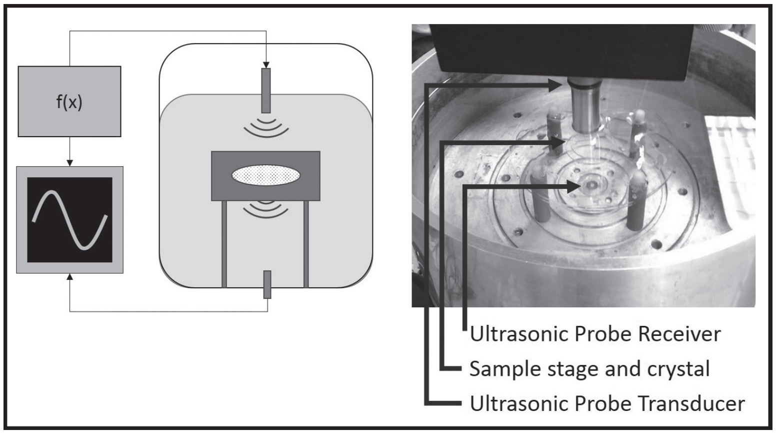

Figure 2: Schematic and image of the ultrasonic transmission experiments.

water chamber using a 10 MHz transducer positioned above the crystal (Figure 2). The ultrasonic waves were transmitted through the crystal, which was suspended on a sample stage, and the signal was then detected by a receiving probe at the bottom of the chamber.

Results and Conclusions:

A key challenge was the proper alignment of the bubble arrays in multi-layer films. Leroy et al. [1] described the alignment of the layers as, "a problematic issue" and their phononic crystal shows an offset between different bubble layers. Challenges include the inherent difficulties caused by the flexibility of the PDMS film, issues with entrapping errant air bubbles, adhering multiple PDMS layers, and perfectly aligning each layer. Figure 3 shows a top-down view of our well-aligned, two-layer film with the published two-layer film from Ref. [1] overlaid for comparison. Through a series of careful alignment procedures with a SUSS MA6/BA6 contact aligner, we were able to produce a two-layer crystal with no visible offset between bubble layers. After aligning two layers, we measured the ultrasonic transmission using the process described previously. Our transmission measurements for single- and two-layer films are plotted with our theoretical models in Figure 4. Overall, the measured transmission matches the trends expected from our theoretical models and from previously published data.

In this work, we have used two theoretical models to match published experimental data and also examine a broad parameter space for phononic crystals. We have fabricated single- and two-layer crystals and demonstrated better layer alignment than previously published work. Ultrasonic transmission measurements through these new crystals are comparable to our models and previous works.

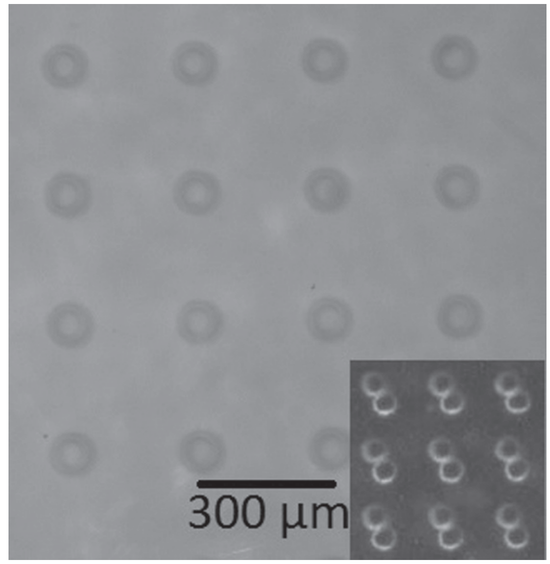

Figure 3: Micrograph of our two-layer film in comparison with previously published two-layer film [1] (inset).

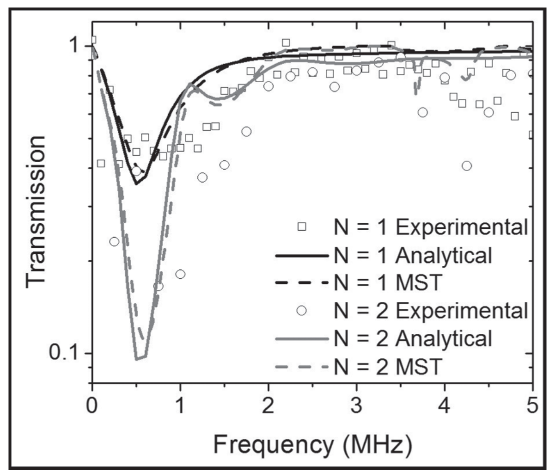

Figure 4: Transmission results for single- and two-layer films. R = 39 µm, a_x = 300 µm, and a_z = 360 µm.

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