Creating Personal Acoustic Spaces via Metasurfaces

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Abstract

In contrast to costly hardware and carefully choreographed phase shifting done at the source level, acoustic metasurfaces can play a significant role in the design of personal acoustic spaces. That is, by creating a 3D printed material to affix on top of the acoustic source, signal strength and gain can be maximized and steered towards a specific direction to create a spatial zone where it is the predominant noise. Ideally, metasurfaces alone can be used with an array of speakers to channel a given audio signal into a personal acoustic space and reduce noise being polluted into undesirable areas where that sound is not needed. This has great advantages as directing an audio signal towards only one desired location can reduce distractions to those affected otherwise by ejected noise pollution and can more efficiently generate signals as more power is not needed to increase gain in the intended zone. The project will carry out experiments involving speakers, microphones, and various 3D printed prototypes of metasurfaces to collect data on which design achieves the best goals in channeling signals and creating a personal acoustic space. Successful implementation of acoustic metasurfaces that can create personal acoustic spaces will be those that maximize gain towards the desired zone while reducing nose in adjacent spaces for noises within the audible frequency band.

Introduction and Motivation

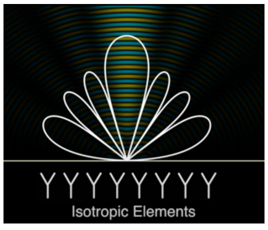
A personal acoustic space is defined as a spatial zone wherein the edge of the space is articulated by a sound wave rather than a physical barrier [7]. Creating one from a single or multiple sources is not as easy as simply pointing the source towards the intended direction. One could imagine that a speaker projecting sound in all directions, being isotropic, creates significant interference as sound bounces off walls and interacts with the direct signal to produce a cloudy and somewhat muffled tone to the listener. By creating a personal acoustic space, members of the space can experience the true signal with little interference as the source prioritizes its signal towards them and away from barriers that can potentially ricochet sound and increase noise. Additionally, personal acoustic spaces present many advantages over traditional means of engaging with sound. Rather than wearing bulky headphones or uncomfortable earbuds, personal acoustic spaces offer a zone where users can choose easily whether to engage with that sound by either walking into its boundaries or taking a couple steps out and leaving the auditory experience.

Acoustic metasurfaces present a low-cost and effective solution to creating personal acoustic spaces as they can reshape a reflected wavefront by offsetting its phase [11]. Doing so with an array of speakers and an affixed metasurface can overall re-channel the incident signal towards a specific direction while reducing noise towards other, unintended directions. By redirecting the signal with a 3D printed metasurface, we eliminate the need for physically moving or rotating a speaker to the target direction in order to create a personal acoustic space.

Research Question, Background, and Significance

By utilizing a metasurface, the propagation of acoustic waves can be manipulated in a way that prioritizes signal strength towards one particular direction as opposed to projecting the signal in all directions as in an isotropic fashion. In other words, by directing an acoustic signal towards a desired location, a personal acoustic space can be created as the bulk of the newly directed signal is being projected towards it, and locations adjacent to the source itself have a reduced set of noise from the source.

The technique used to focus transmitted signals to a specific location is known as beamforming [4] and it is used to improve the resolution of signals by amplifying the desired signal towards a given location. With regards to personal acoustic spaces, metasurfaces can manipulate acoustic waves within the near-field to beamform, and channel a signal towards a desired space. Figure 1A from [12] illustrates how an array of speakers, not in conjunction with a metasurface, behaves when projecting a signal, all equal strength. Waves created by one speaker interfere with its neighbors to produce a diffraction pattern; areas of constructive interference indicate where signal strength is strongest, and in the case without a metasurface, the major lobe rests in the middle. Figure 1B from [12] expands on this concept by introducing variations in the phase for each source. By offsetting the phase for each subsequent speaker, the speaker array turns to a *phased array* where the resulting diffraction pattern produces the major lobe with an offset of θ from the vertical. Figure 2 from [3] provides another visual reference of this, but with a wavefront drawn for each speaker source and a major lobe representing the area of greatest signal strength.



(A)

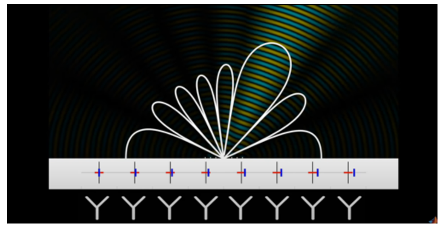

(B)

Figure 1A & 1B. Diffraction pattern for array of speakers all with same phase (left) and offset phase (right).

Source: [12]

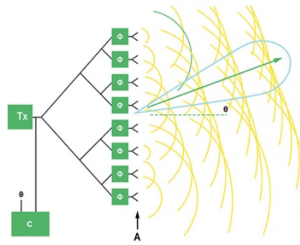


Figure 2. Resulting major lobe from a phased array of signal sources.

Source: [3]

Researchers in [1] designed a linear phased acoustic array to achieve such beamforming. Although they were able to achieve source localization, they did so through a rotating array of sensors. This has the drawback that keeping the sensor array fixed to one direction inhibits the source localization resolution from increasing. Additionally, phased arrays operating to produce a complex wavefront are challenging to synchronize and require costly speaker sources [9].

Alternatively, there has been substantial work done in utilizing metasurfaces to achieve beamforming. Rather than controlling the phase delays for each speaker, metasurfaces can be used to manually offset the phase of outgoing waves. A metasurface is a thin, often subwavelength, material designed to offset the phase of an acoustic wave incident on it [5]. Metasurfaces follow designs based on coiling up structures and principles of Helmholtz-resonator-like structures that utilize the phenomenon of air resonance in a cavity. In these designs, a tight, sub-millimeter distance of space between zig-zagged edges forms one cell of a resonator [8, 13]. By appropriately selecting the folding degree of these cells, the delay of phase for each wave incident on it can be achieved. Figures 3A and 3B from [5] and [2], respectively, illustrates the cross section for one unit of a metasurface cell that can achieve specific phase delay for incoming waves.

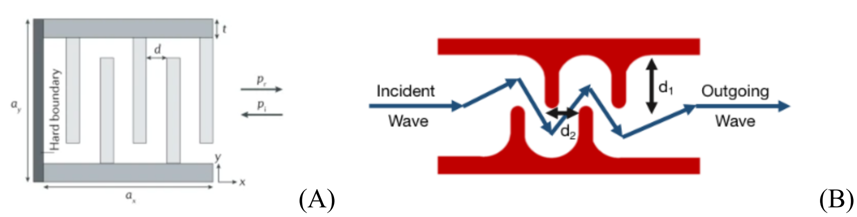


Figure 3A & 3B. Cross section design for one metasurface cell illustrating height and width properties.

Source: [5, 12]

Doing so with a collection cells, each affixed to the edge of a speaker source, can manipulate the propagation of the acoustic signals in the near-field and produce a complex wavefront to steer the major lobe of the beamformed result.

In [6], researchers designed a four-step phase metasurface to improve the transmission efficiency for ultrasonic waves. They, additionally, developed phase-optimized hybrid lenses for reducing side lobe amplitude; this, in effect, reduces the amount of signal noise ejected into spaces undesirable, and has potential applications in creating better, more defined personal acoustic spaces. Their experiments demonstrated accurate signal focusing on an arbitrary point; nevertheless, this study focused on acoustic waves beyond range audible to the human ear. As such, there is yet to be substantial work for signals within the audible spectra. Our project aims to manipulate the propagation of acoustic waves within the audible spectra towards a specific location with metasurfaces. In effect, by channeling an acoustic source within the audible range (sub ~15kHz) towards a specific location, a spatial zone wherein the edge that is articulated by an acoustic wave as opposed to a physical barrier can be created, also known as a personal acoustic space [7].

Existing studies have concluded that multifocal beamforming is possible with ultrasonic waves with applications in biomedical imaging and physical sensing [6] but is not conclusive of signals within the audible spectra for humans. Successful implementation of beamforming via acoustic metasurfaces allows for creating a spatial zone wherein most of the sound's energy is channeled; in effect, the sound will not be wasted on noise being polluted out into undesirable areas. This advantage could be extended to the fact that the signal source can then reduce its power if provided with a metasurface to channel the sound as compared to a source without a metasurface where more power is needed to project a stronger sound.

Methodology

With the goal of creating a personal acoustic space in mind, the research lies in designing a system to first project an audio signal from an array of speakers with a controlled amplitude and direction without moving the speaker sources. Doing so would require a microcontroller (MCU) to output a signal to a small speaker. Many microcontrollers currently available over the internet would suffice for this operation as we only intend to control minute properties of the outgoing sound wave, such as amplitude and/or phase. However, in order to accurately read acoustic data, a microcontroller with a good Analog to Digital Converter (ADC) is needed to sample signals at a high bit rate. The ESP32 will be a suitable choice for the project. Additionally, a small, 8 Ohm 1 Watt speaker would function for experiments because it becomes rather easy to then attach prototypes of metasurfaces onto an array of speakers.

However, using an array of speakers connected to one hobby microcontroller would likely draw far too much current rated for the general-purpose input/output (GPIO) pins of the MCU. In addition to the two hardware mentioned previously, a LM386 Audio Amplifier is needed to properly supply the speaker array with power and keep the microcontroller functional since directly connecting multiple speakers to a single microcontroller would likely burnout the MCU. Designing the metasurface will also be carried out by a CAD modeling software (Solidworks, Fusion360, GrabCAD, etc.) and prototyped using a 3D printer. Due to the sizing constraints and precision necessary to achieve the subwavelength nature of an acoustic metasurface, a resin printer will be advantageous as it can print materials with a <0.5mm layer height. An array of microphones affixed to the opposite side of the speaker array is needed to measure the power, or gain, of the incoming signals. We expect to see a higher gain measured on microphones pointed to by the major lobe of the beamformed signal as compared to the rest of the microphones in the array.

In addition to a physical apparatus for experimenting, there must be significant work done prior in simulations. For this, MATLAB & Simulink will be used to perform simulations with an antenna array and specific weights at each point in the array to simulate a change in phase with the ultimate goal to beamform.

Expected Outcomes

To properly create a personal acoustic space, the project expects to see significant gain in the direction of the personal acoustic space while simultaneously measuring little to no audio signal in adjacent spaces. Doing so through metasurfaces alone is our focus as it eliminates the need for costly phased array of speakers and provides an inexpensive solution. Acoustic metasurfaces should employ and improve on existing designs of coiling-up structures and Helmholtz resonator cells to accurately beamform and steer signal towards the desired space while also reducing power in areas adjacent to the zone, otherwise known as the side lobes of the complex wavefront. Users should have the choice whether to engage with an audio signal by simply walking in or out of the personal acoustic zone whilst hearing little to no ambient noise in the surrounding area.

Expected Timetable

- October 1st, 2024 – Perform simulations of linear beamforming
- October 8th, 2024 – Replace elements in simulation with a metasurface
- October 22nd, 2024 – 3D print metasurfaces
- October 29th, 2024 – Sine wave test with metasurfaces
- November 5th, 2024 – Evaluate issues with previous experiments
    - Issues in metasurfaces → redesign and reprint metasurfaces
    - Beamform for each signal such that the source only reaches a specific part of the room
- February 1st, 2025 – Assign different weights for different signals within the same set of speakers
- March 8th, 2025 – Investigate possibilities for personal acoustic spaces for wideband signals

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