Enhancing underwater acoustic surveillance and scientific monitoring by bio-inspired acoustic metamaterial device networks

PI: Nicholas Fang Co-PI: Jun Xu

Department of Mechanical Engineering, MIT

Introduction

Underwater acoustic surveillance has attracted great attention in the past several decades because of its wide applications in environmental monitoring, oceanography, marine commercial operations, assisted navigation, offshore oil industry, and defense for military [1,2]. The underwater acoustic methods provide a means of collecting a wealth of ocean ecosystem information with high space and time resolution [3], which makes a strong contribution to the healthy ecosystem from Boston harbor to the entire New England coast. Therefore, the underwater acoustic technique plays a key role in data acquisition, signal processing, and information exchange. There has been continued research on improving the performance and the robustness of the communication systems, which cover all layers of the underwater acoustic communications, including physical layer, data link layer, network layer, and transport layer [4]. Most research done to date has focused on the algorithm of signal modulation, noise filtering for increasing data exchange rate, as well as establishing 2D and 3D underwater sensor networks for broad coverage. However, there have been so far few studies addressing the performance of a single underwater detector or sensor for underwater signal launching and receiving.

Currently, most of the underwater transducers emit spherical waves, which are omni-directional. Therefore, acoustic waves undergo an quick attenuation in signal strength as they propagate. Previous studies showed around 60 dB acoustic signal attenuation for 1 km in sea water [5]. The typical transmission losses for different frequencies underwater are plotted in the inset of Fig. 1(left) [6]. The transmission intensity significantly attenuates when the distance increases, that induces a strong energy loss during the signal propagation. Consequently, in order to overcome the energy dissipation, high power transducers are needed for reasonable signal-to-noise ratio for long distance communications. In contrast, the collimated acoustic beam with small divergence angle shows great potential to carry the acoustic signal with low propagation loss, since the major loss due to the spherical spreading decay of the omni-directional wave is eliminated. Hence, underwater devices that can collimate acoustic wave are desired for wide underwater applications including environment monitoring, surveillance, and communication, as shown in Fig. 1(right).

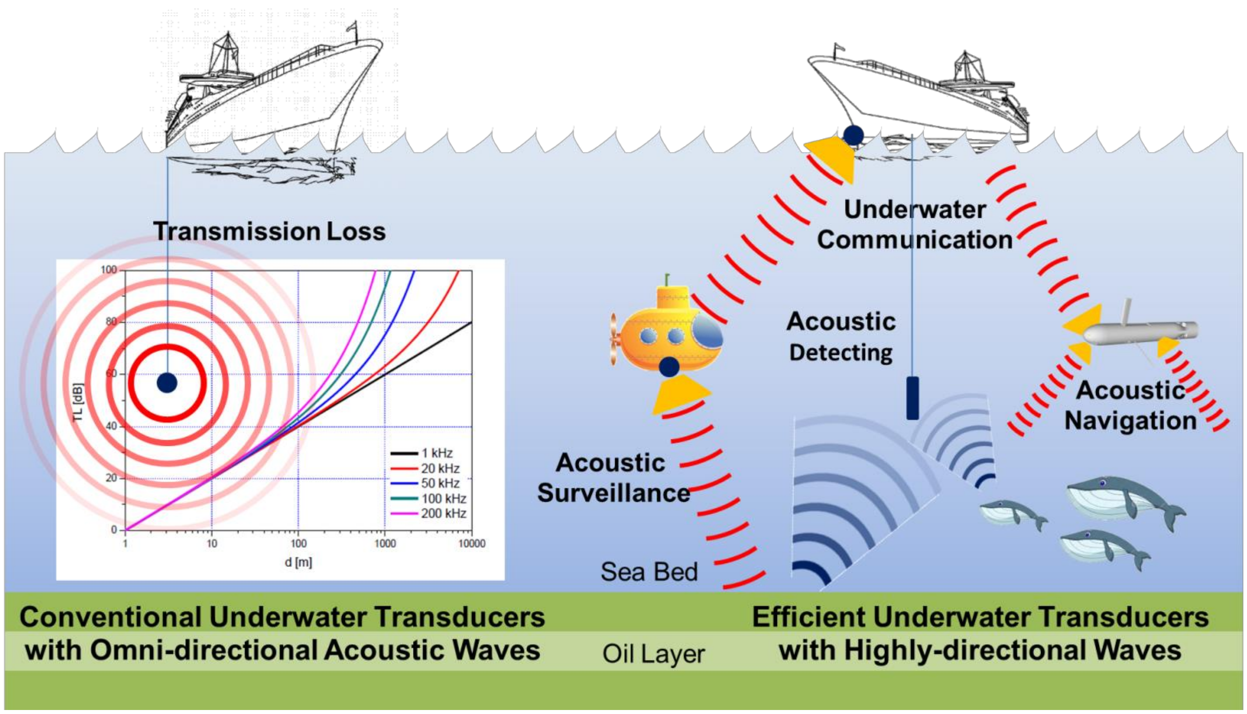

Fig. 1 Schematic view of proposed underwater acoustic devices for surveillance, tracking, and communications. Left: transmission loss of a spherical acoustic wave from a conventional transducer is significantly strong, as shown in the inset [6]. Right, promising applications of the collimated underwater acoustic waves using acoustic metamaterials for high-efficiency long distance communications.

Inspired by the melon acoustic lens in whales and dolphins, which can form sound beam into a cone-shaped beam, we propose to design **biomimetic underwater acoustic devices** to improve the performance of the underwater acoustic wave launching and receiving. The design strategy is based on our knowledge of **transformation acoustics and acoustic metamaterials**, which are expected to manipulate acoustics wave in a novel fashion. Uniquely, we will explore the enhanced interaction between the acoustic waves and artificial structures to design a compact underwater acoustic filter for desired frequency. Our proposed novel underwater devices are expected to significantly decrease the transmission loss of the underwater acoustic waves, and increase the signal-to-noise ratio for the acoustic wave detection.

The PIs Nicholas Fang (MIT) and Jun Xu (MIT) are leading researchers in the acoustic metamaterial design, fabrication and characterization. We have demonstrated the underwater ultrasonic focusing [7] and cloaking [8] effects by novel metamaterials, which have shown promising possibilities for guiding, harvesting, and filtering acoustic waves in both spatial and frequency domains. We have also explored extreme acoustic metamaterial properties, such as effective zero index material [9] to demonstrate unique wave manipulation capability. Our proposed work lies in investigating completely novel design strategies for underwater acoustic devices and developing exotic acoustic metamaterials to realize amazing performance. This research can lead to exciting pathways for the next-generation underwater acoustic devices for **marine sensing technologies**, which will benefit not only the **Healthy Coastal Ecosystems** of **MIT Sea Grant Strategic Plan**, but also the oceanography of industry and military.

Background

- Underwater acoustic communications

The development of the underwater communications has borrowed many design principles and tools from ongoing ground-based communication research. However, considering the nature of the transmission medium and physical properties of the underwater environments, neither radio frequency (RF) wave nor light is suitable for the underwater application because of their extremely limited propagation length. Therefore, acoustic wave, as a promising alternative form for the underwater communications, has been extensively studied and widely used in the past several decades. The information carried by the acoustic wave is launched by the acoustic transducer and received by the acoustic detector, which is similar to the antenna system used in RF communications. While the transition from RF to acoustics involves a change of the physics of communication from the speed of light (3×10^8 m/s) to the speed of sound (around 1500 m/s underwater), the five orders of magnitude difference in the wave speed significantly limits the bandwidth and speed of the underwater communications. In addition, high-speed communication in the underwater acoustic channel has been also challenging because of extended multipath, refractive properties of the medium, severe fading, rapid time variation and large Doppler shifts. There are several major factors that should be taken into account [4]: (i) propagation loss, including acoustic wave geometric spreading due to omni-directional point source and signal attenuation caused by the absorption/scattering in the medium [10]; (ii) noise, including man-made noise and ambient noise; (iii) multi-path; (iv) high-delay and delay variance, due to slow speed of sound; and (v) Doppler spread, due to the movement of the transducer/detector. So far, most of the investigations have been focused on the algorithm of signal modulation and noise filtering to minimize these effects during the underwater acoustic communications.

There is still a huge room to improve the performance of the hardware for the underwater acoustic communications by addressing some factors listed above. For instance, a spherical acoustic wave experiences a $1/R^2$ attenuation due to the spherical spreading, which limits the propagation length. The transmission loss can be described as $TL = 20\log d + \alpha \cdot d$, where d represents the distance between the source and destination, and α means the absorption coefficient depending mainly on the frequency [6]. In low frequency range (<10 kHz), the absorption coefficient is smaller than 1 dB/km. So the total transmission loss of an omnidirectional signal is dominated by the spreading loss. The absorption coefficient increases to several tens of dB/km for the frequency around 100 kHz, which is comparable to the spreading loss at the distance of 1 km (60 dB). Underwater acoustic communication systems usually operate at frequencies below 40 kHz, which have relative small absorption coefficient (<12 dB/km). Therefore, the spreading loss of an omnidirectional signal contribute the major part for the transmission loss when communication distance is smaller than 5 km. Furthermore, directional filter in front of the receiver can help to select the particular channel to avoid multi-path issue underwater. In order to achieve such functions, we need to manipulate the acoustic waves by specific devices. There are several options for ultrasonic acoustic collimation devices used in medical imaging techniques, which are based on multiple transducer configurations. However, due to the relative low frequency of the underwater acoustic communications (typically 300 Hz to 30 kHz), the active design of the transducer array appears to be large in size and high energy consuming, which leads to high costs. A compact and high efficient acoustic collimator is desired for wide applications, including underwater surveillance, marine environment monitoring, long range acoustic communication, which will benefit Healthy Coastal Ecosystems from Boston area to the entire New England coast.

- Collimation of acoustic waves

Collimated acoustic waves are widely used in medical imaging, mechanical detection, and underwater communication. The acoustic energy in collimated beam can be confined in a narrow divergence angle, which has well defined wave front and can be delivered to longer distance with low loss. However, the traditional collimated beam is generated by directional transducers. Some directional transducers, shown in Fig. 2 [11], have been proposed. The Tonpilz ring (Image Acoustics, Inc.) is considered too heavy for the underwater vehicles, while the directional 1-3 piezo composite (MSI) is too expensive. The Baffled ring (BTech) is not practical due to its excessively large dimension [12].

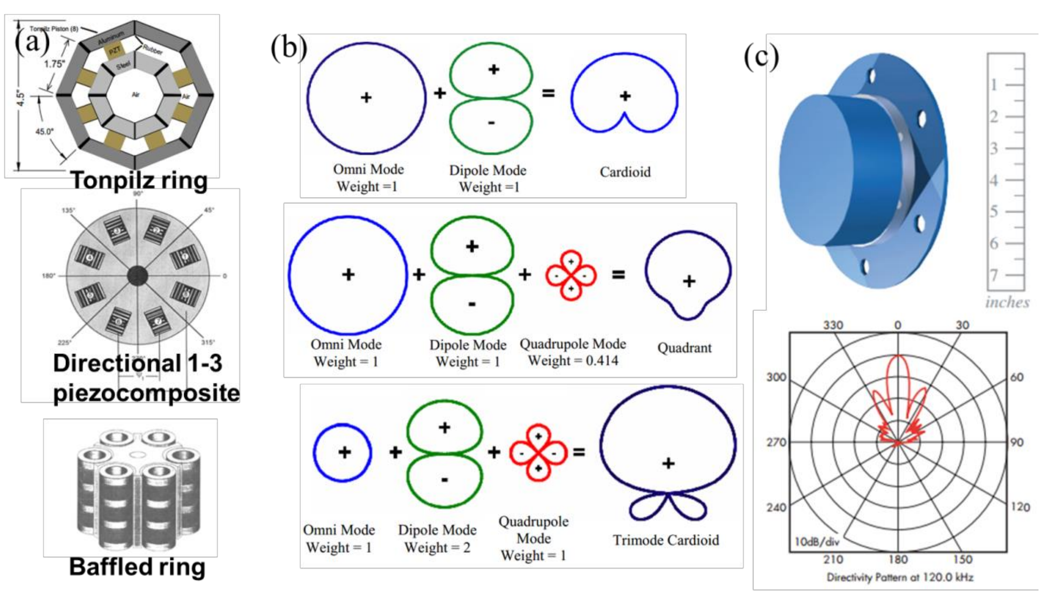

Fig. 2 (a) Some proposed directional transducers [11,12]. (b) Formation of cardioid beam pattern, trimode cardioid beam pattern, and quadrant beam pattern [11,13]. (c) Commercial available directional transducer ITC 3003D and its directivity pattern at 120 kHz.

The general idea of making directional transducer is the multimode beam synthesis [11,13]. The final emission pattern is the superposition of all excited modes from each transducer. It is obvious that the quality of the directionality highly depends on the numbers of the transducer, as described in Fig. 2(b). A few commercial underwater directional transducers are available, e.g. ITC 3003D (shown in Fig. 2(c)), which demonstrate an effective balance between the size and directionality. However, considering the working frequency (118 kHz), the device size is still quite large (4.5 inches, corresponding to 10 wavelengths). Therefore, an acoustic device which can convert an omni-directional acoustic wave to a collimated acoustic wave must generate a huge impact for the acoustics community. In addition, the compact size and low energy consumption are the key factors for the design and demonstration.

- Transformation acoustics and acoustic metamaterials

It is known that if light travels in a gradient index medium, where the refractive index changes as a function of position, the light ray will follow a curved path determined by the nature of the gradient. Therefore by controlling the permittivity and permeability distribution in space, the propagation path of electromagnetic wave can be controlled. The question is how to obtain the precise description of the medium property as function of position to achieve the desired redirection of optical rays.

Recently, a new design paradigm called conformal mapping and coordinate transformation provides the prescription of the gradient medium to control and manipulate wave propagation path. It was demonstrated that the arbitrary distortion of wave fields can be recorded as a coordinate transformation, which has inspired a series of key explorations to manipulate, store, and control the flow of energy, in the form of either sound, elastic waves, or light radiation [14,15]. In electromagnetism, because of the coordinate invariance of Maxwell's equations, the space for light can be bent in almost arbitrary ways by providing a desired spatial distribution of electric permittivity ε and magnetic permeability μ. Similar idea and mathematics are applied for the governing equations of acoustics as well. Based on the coordinate transformation of optics and acoustics, a set of novel optical devices as well as acoustic devices have been proposed [16,17]. Due to the space distortion and flow bending from the conformal mapping, these devices usually require complicated medium with anisotropic and spatially varying permittivity and permeability tensors for optics (density and compressibility tensors for acoustics) to accomplish the desired functionality. Recent advances in artificial structured metamaterial [18,19], whose properties are determined by its subwavelength structure, offer the possibility to physically implement these complicated media. Negative acoustic material properties, such as negative effective density [20] and compressibility [21] of the acoustic medium, have been experimentally realized for ultrasonic focusing [7], as shown in Fig. 3(b) and (c).

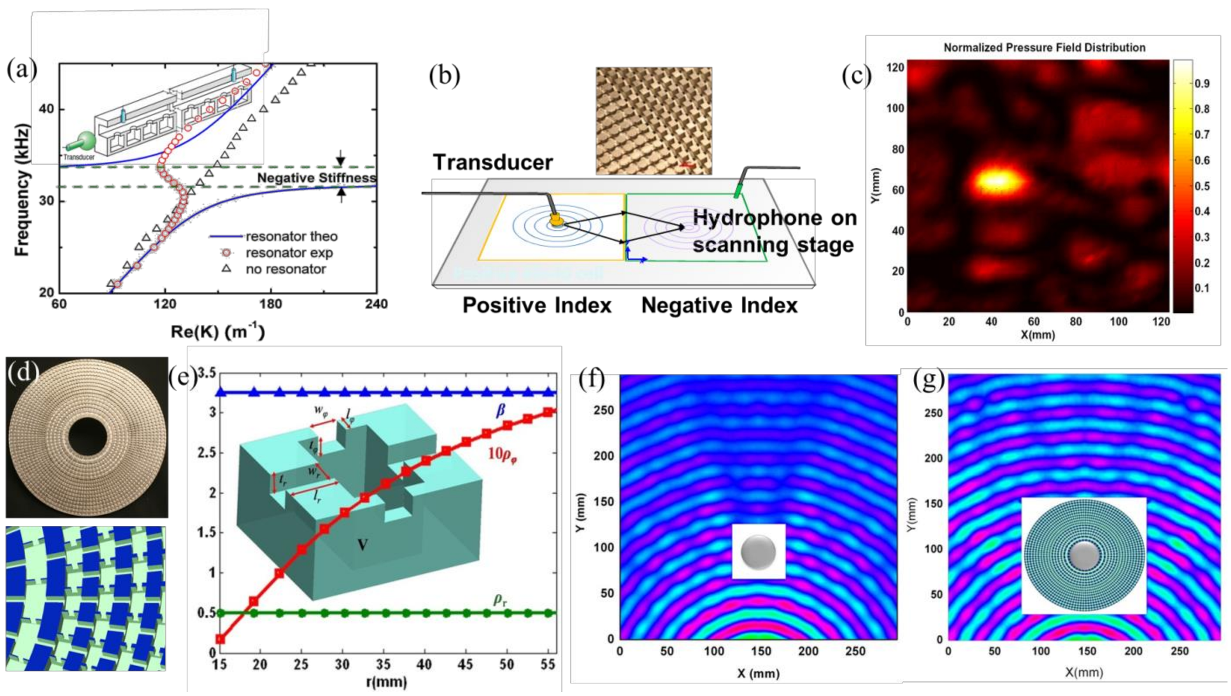

Fig. 3 Previous acoustic metamaterial related work carried out by the PI's group. (a) Simulated and measured compressibility of one-dimensional Helmholtz resonator array. The effective compressibility shows negative property near the resonance frequency [21]. (b) Configuration of the characterization system for acoustic superlens. The inset is the schematic view of both the positive and negative index region composed of two-dimensional Helmholtz resonator arrays [7]. (c) Measured intensity of a focused

point in the negative index acoustic metamaterial region. (d) Fabricated two dimensional acoustic cloak device. (e) Anisotropic effective properties of each building block. (f) Measured pressure field of a scatter illuminated by an ultrasound point source. (g) Measured pressure field of a scatter located inside the acoustic cloak illuminated by an ultrasound point source [8].

The most exciting example proposed by the transformation optics is a cloak that can render the objects invisible. The first experimental demonstration of such a cloak was reported in microwave using structured metamaterial composed of metallic resonant rings [22]. However, the invisibility effect was only obtained in a narrow frequency range because of the strong dispersion inherent to the resonant elements used to build the cloak. In addition, such resonances led to undesired material absorption in the cloak. The PIs are the pioneers of acoustic metamaterials, and were the first to experimentally demonstrate broadband underwater invisible cloak by anisotropic acoustic metamaterials [8], which is able to dramatically reduce the scattering cross section of underwater objects (shown in Fig. 3(g)). Fig. 3(d) and (e) illustrate the fabricated acoustic cloak device and the anisotropy of the building blocks. In addition, using the transformation acoustics, which can arbitrarily direct acoustic wave regardless of wave incidence, interesting acoustic wave phenomena have been proposed [23], such as acoustic illusion, energy harvesting, super-resolution imaging, etc. Therefore, the transformation acoustics and the acoustic metamaterials provide great opportunities to manipulate the underwater acoustic waves to improve the performance of underwater acoustic devices for surveillance and communication.

- Melon acoustic lens in whales and dolphins

Whales and dolphins in the sea are able to use a special kind of sonar called echolocation or biosonar for underwater communication and navigation. They have a mass of adipose tissue, called melon, in front of their head to focus the ultrasonic waves to achieve collimated acoustic beams, similar to a sound lens [24,25]. The melon is structurally a part of the nasal apparatus (the nose) and comprises most of the mass tissue between the blowhole and the tip of the snout, which functions as a bioacoustics component. The impedances of the melon’s tissue and the surrounding water are respectively similar, so acoustic energy can flow out of the whale's head and into the environment with the least loss of energy. The melon is a mixture of triglycerides and wax esters. Typically, the inner core of the melon has higher wax content than the outer parts and thus conducts sound more slowly. The exact composition varies throughout the melon, which generates a gradient index for focusing the acoustic waves as a sound lens. The transformation acoustics and acoustic metamaterials provide a great opportunity to realize an artificial acoustic lens, which can mimic the exotic performance by the sea animals.

Objectives and Intellectual Merit

According to the demands of the underwater acoustic applications and inspired by the melon acoustic lens in animals, we propose to develop a **passive and compact underwater acoustic collimator** designed based on transformation acoustics and acoustic metamaterials. The device placed in the front of an omni-directional transducer would be able to convert the spherical acoustic wave from a single transducer to a collimated beam, which can significantly increase the signal transportation length. In addition, we propose to design a **directional and frequency filter** to place in front of the receiver that can detect the signal only from the desired direction and frequency. All the design will match the currently available frequency range of underwater acoustic systems. And the proposed devices are passive, so that there is no additional energy consumption. Furthermore, due to the subwavelength structure of the metamaterial units and the wave control capabilities, the device size can be as small as a few wavelengths.

Intellectual Merit of our proposed research lies in (i) investigating the fundamental physics of the enhanced interaction between the underwater acoustic waves and the artificial structures to explore the exotic behavior by the acoustic metamaterials, (ii) optimizing the practical design for the compact and high-efficient devices, (iii) developing the advanced manufacturing techniques for the device fabrication; and (iv) characterizing the novel performance of the acoustic metamaterial based system. If successful, our demonstration would provide promising candidates for new underwater acoustic devices with the improved performance.

Technical Approaches

We propose to develop a novel high-performance compact underwater acoustic collimator based on acoustic metamaterials. Our efforts are dedicated towards the key components that will help to realize the overall approaches and goals. The details of the approaches for the components and the key novelties are described below:

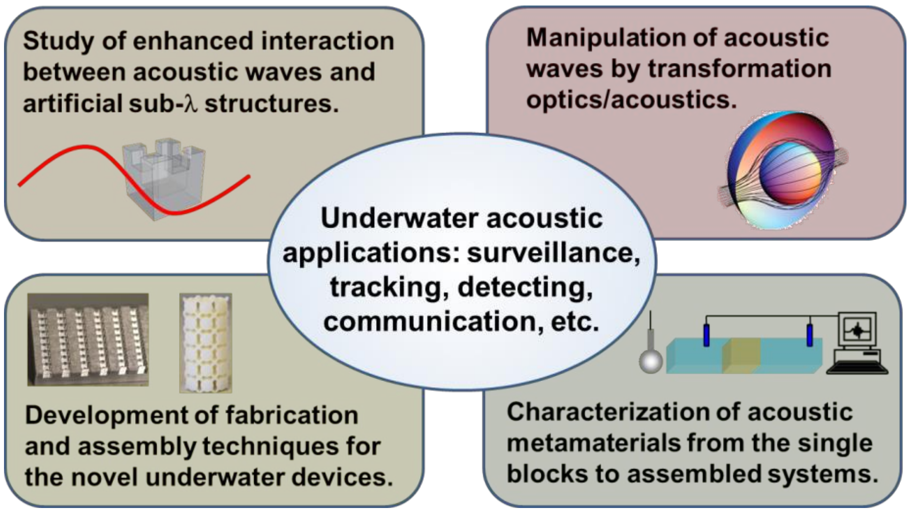

Fig. 4 The approach chart for the proposed acoustic underwater applications.

- Transformation acoustics for manipulating acoustic waves

Transformation acoustics can theoretically direct acoustic wave in any fashion by adjusting the spatial distributed metamaterials with desired effective properties. However, this might result in considerable anisotropic and inhomogeneous material properties, which cause the difficulty in the metamaterial structural design and manufactory. Mathematically, we will investigate the coordinate transformation to achieve practical material properties, and optimize the design for controlling the wave propagation.

Here, we apply the transformation acoustics to map a spherical region to a square region, as shown in Fig. 5(a). In 2D systems, the spatial mapping in cylindrical coordinate system can be written as:

$$r' = r / \cos\theta \qquad \theta' = \theta \qquad z' = z \tag{1}$$

It is noted that there are many transformations which can be chosen to achieve the goal. We choose one of them to reduce the anisotropy of the material properties in the new region. Since we only consider one quarter of whole region, θ here is varied from -π/4 to π/4. By applying the mathematics of transformation optics technique, the dynamic effective density and compressibility in new coordinates are written as:

$$\rho_\theta' = \frac{\rho_\theta}{\cos\theta} \qquad \rho_r' = \rho_r \cos\theta \qquad \beta' = \beta_0 \cos\theta \qquad (2)$$

where $\rho_\theta = \rho_r = \rho_0$, that means the original system is isotropic. From equation (2), we can see that the effective parameters in new coordinates are only function of azimuthal angle θ and independent of radius *r*, that reduces the fabrication complexity in real sample design and machining. The effective density and compressibility in terms of azimuthal angle are plotted in Fig. 5(b). Here, we want to emphasize that the coordinate transformation for this collimator design is not unique. However, some very complicated mappings, that might provide perfect collimation behavior, will induce quite anisotropic or rapidly changing effective parameters in transformed coordinate. It will be undoubted hard to fabricate such device since the effective parameters are realized by array of subwavelength structures. In this project, we try to reduce the complexity of the design to make our collimator to be easily realized.

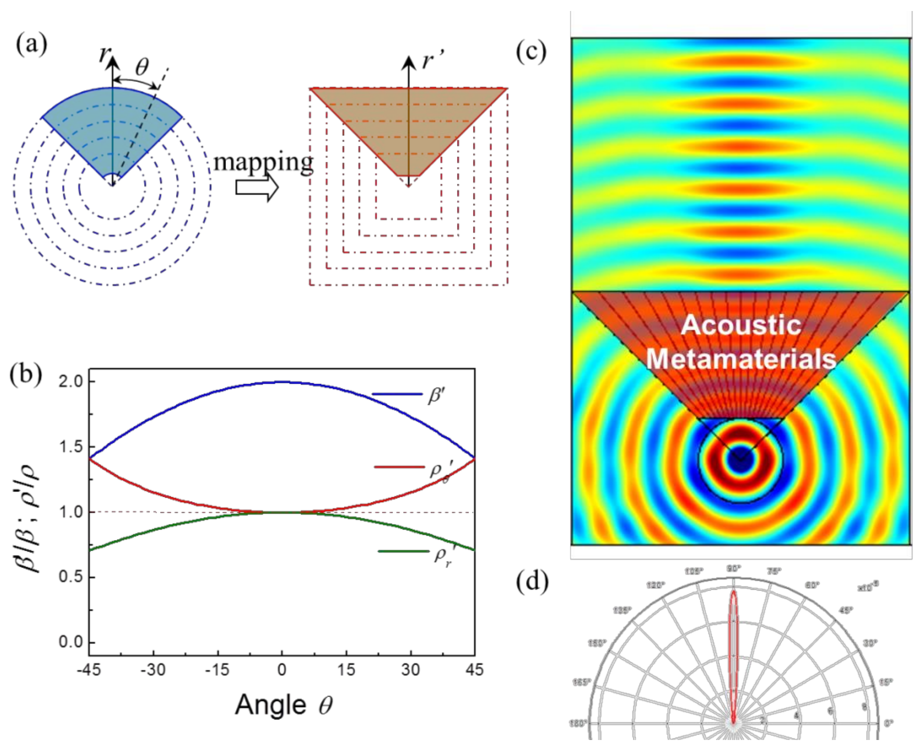

Fig. 5 (a) Spatial coordinate transformation for converting 2D cylindrical waves to plane waves by mapping the original polar coordinates to the transformed coordinate system. (b) Effective parameters of acoustic collimator based on the coordinate transformation results. (c) Simulated acoustic pressure distribution of the cylindrical wave converted to the plane wave by the acoustic collimator. (d) Polar plot of the radiation power.

We will use commercial software, e.g. COMSOL Multiphysics, as an integrated modeling platform to simulate the acoustic wave behavior based on the theoretical design. A preliminary simulation result of an acoustic collimator based on transformation acoustics is shown in Fig. 5(c). In the simulation, the background material is air and the working frequency is set at 10 kHz corresponding to the wavelength 3.4 cm in air. The acoustic collimator is constructed by metamaterials with angular dependent effective properties. The input length, output length and height of the collimator are 12 cm, 30 cm and 9 cm, respectively. The collimator region is equal-angularly divided into 18 segments from $-\pi/4$ to $\pi/4$ in the simulation. The simulated pressure field distribution plotted in Fig. 5(c) shows that the cylindrical wave propagating in air is effectively captured and converted into the plane wave by the collimator. The divergence angle of the collimated beam can be as small as 10 degree, as shown in Fig. 5 (d). In addition, the mathematics of coordinate transformation is frequency independent, which means that the effective parameters for the acoustic collimator design are suitable for broad band. Our simulation results also confirmed the latter by tuning the working frequencies from 5 kHz to 20 kHz.

We propose to apply the transformation acoustics method to design the underwater acoustic collimator. According to the previous research, the transformation acoustics can be applied to underwater acoustics, which has been demonstrated in our previous underwater acoustic invisible cloak. Therefore, the concept of the acoustic collimator in air can be extended to the underwater applications. Our device design will match the currently available underwater transducer frequency. Based on our preliminary results, the size of the collimator can be only a few wavelengths. So the underwater collimator based on the acoustic metamaterials can be as small as a few centimeters, which is compact to be installed in the current devices. Furthermore, the performance of the collimator is reversible, which is able to focus the plane wave to a single spot. This is also confirmed by our simulation results. So the similar device can be placed in the front of the detector to increase the sensitivity for the signal acquisition.

- Modeling of building-blocks for acoustic metamaterials

Based on the acoustic collimator design using transformation acoustics, the spatial dependent effective properties of the material are required. However, such material does not exist in nature. Therefore, we need to explore the interaction between acoustic wave and artificial structure to achieve the acoustic metamaterials with desired properties.

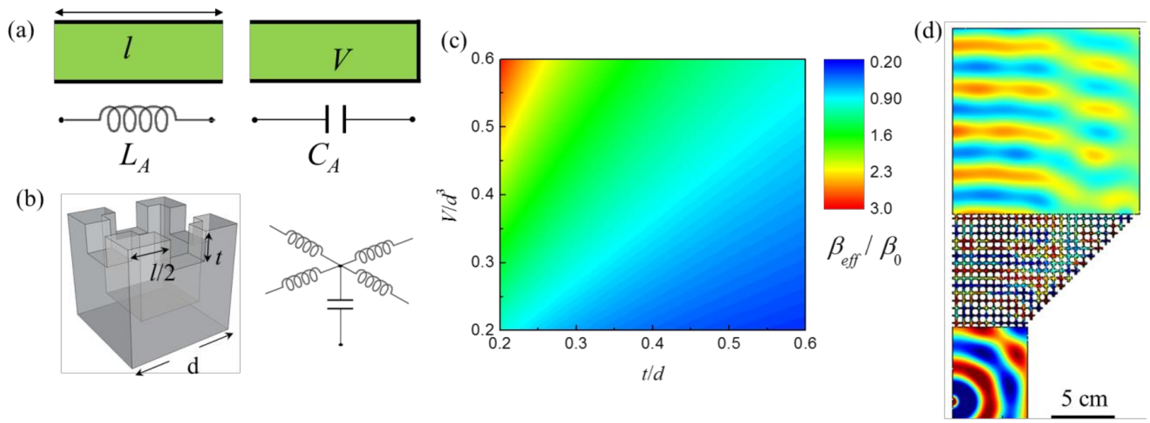

Fig. 6 (a) A pipe with open end and rigid end is analogous to an acoustic inductor and acoustic capacitor, respectively. (b) A Helmholtz resonator and its equivalent electronic circuit. (c) Various range of effective compressibility by changing both the channel height *t* and the cavity volume *V*. (d) Full-wave simulation for pressure field distribution of a cylindrical wave converted to a plane wave by an acoustic collimator.

According to a previous study in acoustics [26], a close analogy can be established between the propagation of acoustic wave in tubes or chambers and electronic circuits, as shown in Fig. 6(a). When the dimensions of the region where the sound propagates are much smaller than the wavelength, a lumped-parameter model is appropriate. By considering the pressure and velocity of the fluid inside the tube with rigid wall, the tube with open end and rigid end can be analogous to an acoustic inductor and acoustic capacitor with effective parameters: $L_A = j\omega \frac{\rho_0 l}{S}, C_A = \frac{V}{\rho_0 c_0^2}$, where ρ_0 is the density of the medium in the pipe and c_0 is the velocity of sound in the medium. A typical Helmholtz resonator can be presented as a series of inductance and capacitance. The fluid inside the cavity is much easier to be compressed compared with that in the neck part. Moreover, the pressure gradient along the open neck is much greater than that inside the large cavity. Therefore the cavity displays capacitive property and leaves the smaller neck as an acoustic inductor. Following the approach of EM circuit analysis [27,28], the effective mass density and compressibility as functions of the Helmholtz resonator geometric parameters can be written as:

$$\rho_{eff} = \rho_0 \frac{l}{d}, \qquad \beta_{eff} = \beta \frac{V}{S \cdot d} \tag{3}$$

where d is the unit size, l is the channel length, S is the channel cross section area, and V is the volume of the cavity, as shown in Fig. 6 (b). We can find that the effective properties of the Helmholtz resonator are only functions of the geometric parameters. The effective compressibility of the Helmholtz resonator by varying the channel height and cavity volume is plotted in Fig. 6 (c). It is observed that the effective compressibility can be tuned in a broad range. Thus, we can use the Helmholtz resonator as the building-block to construct the metamaterial based acoustic collimator. We also plan to apply the numerical simulation tools to test our building-block design, and optimize the structure for the acoustic metamaterials.

- Novel properties for acoustic metamaterials

A few remarkable material properties have been demonstrated in acoustic metamaterials, including acoustic superlens, hyperlens, invisible cloak, and so on. Here, we propose to construct a compact acoustic collimator according to our study of the transformation acoustics and the building-block of the acoustic metamaterials. We have demonstrated the behavior of an in-air acoustic collimator using an array of Helmholtz resonators. In order to reduce the complexity of design and manufactory, we further reduce the anisotropy of the collimator by choosing $\rho_\theta' = \rho_r' = \rho_0 / 2$ and $\beta' = \beta_0 / \cos^4 \theta$. Then we can vary the cavity volume of the Helmholtz resonator to achieve spatial distributed effective compressibility. We performed a 3D full-wave simulation to test the performance of our design, and plot the acoustic pressure field distribution in Fig. 6(d). In this demonstration, we choose our working frequency at 10 kHz in air, with corresponding wavelength 3.4 cm. The unit cell size d is set as 6 mm, which is smaller than $\lambda/5$. Besides, the effective density and compressibility are not achieved due to the resonant phenomena. Our design of the acoustic collimator can work in relatively broad frequency range.

We will extend the design strategies to the proposed underwater acoustic collimator. Due to the small impedance mismatch between water and construction material (typically around 10 to 20, which is a few orders smaller than the impedance mismatch between air and metal), the interaction between the fluid and solid may also be taken into account. Hence, we need to explore the fundamental physics of such interaction, and modify the model to obtain the effective properties for underwater acoustic waves.

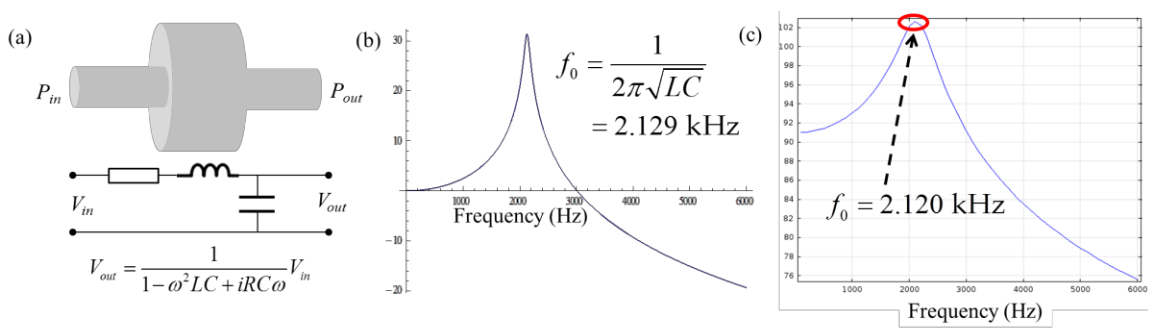

Fig. 7 (a) Schematic view of a Helmholtz resonator as an acoustic frequency filter and its equivalent electronic circuit. (b) Calculated transmission spectrum using LC circuit model. The effective capacitance and inductance are determined by the geometric parameters of the Helmholtz resonator. (c) Full-wave simulation result of the transmission spectrum.

In addition, the Helmholtz resonator can work as a high efficient frequency filter with a deep subwavelength. As discussed above, the Helmholtz resonator can be treated as a series of electronic inductor and capacitor. Inspired by the electronic circuit design, we are able to design the underwater acoustic frequency filter using the Helmholtz resonator. Fig. 7(a) shows the analogy between an LRC resonator and a Helmholtz resonator, which has a strong transmission peak due to the resonance. As such, we can match the resonance frequency by tuning the geometric parameters of the Helmholtz resonator. In Fig. 7(b) and (c), we compare the transmission of a Helmholtz resonator by full-wave simulation and the analytical calculation, which are in very good agreement. We also need to emphasize that the length of the resonator is only 1/5 of the resonant wavelength, so that the frequency filter devices can be very compact.

- Fabrication of acoustic metamaterials

Different designs from the previous stage will be fabricated using 3D techniques, e.g. 3D printing, direct metal laser sintering, etc. Both the home-developed projection micro-stereolithography technique and commercial 3D printer have been widely used for constructing acoustic metamaterials. However, most of the 3D printer compatible materials are plastics, which are too soft for underwater acoustic metamaterials. In our previous demonstration of the underwater acoustic cloak, we chose traditional digital controlled drilling machine to make the cavities and channels on an aluminum plate, which is a very time consuming process and high cost. Later, we developed a new technique by using metal microcasting process (described in Fig. 8(a)) with high resolution.

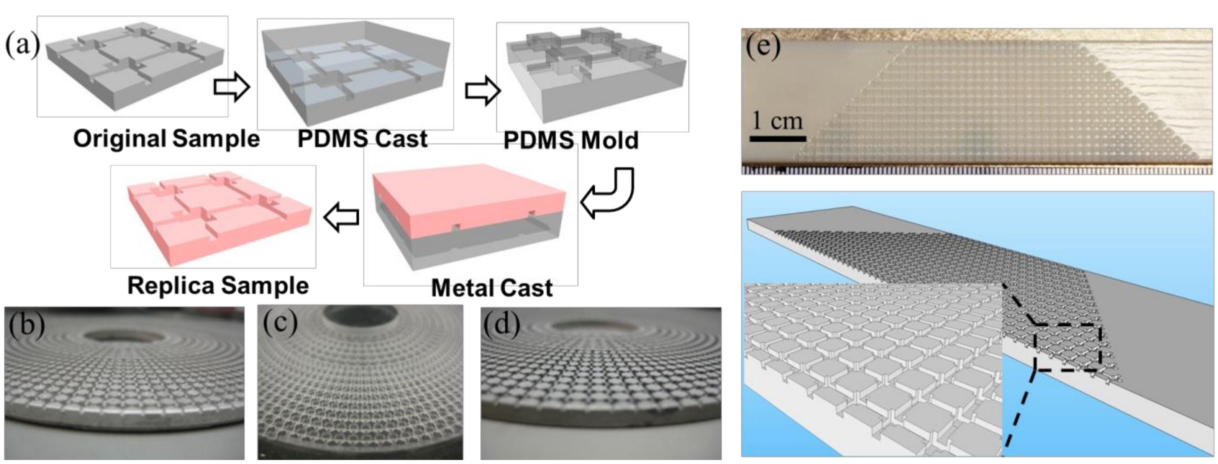

Fig. 8 (a) Detailed metal microcasting process. (b) Original acoustic cloaking device. (c) PDMS mold imprinted microstructures. (d) Replica of acoustic cloak made of CerroBend. (e) 3D CAD drawing of acoustic collimator designed based on transformation acoustics (bottom) and fabricated device by commercial available 3D printer (top).

The strategy for replicating the machined acoustic cloaking device is to make the silicone mold imprinted the original features of acoustic cloak and finally cast metal into the imprinted silicone mold. We make the silicon mold by pouring the polydimethylsiloxane (PDMS) silicone, Sylgard 184 by Dow Corning, onto the original acoustic cloak. The PDMS mold is created to cast the metal into the mold to achieve the replicated acoustic cloak. In our demonstration, the commercially available alloy, CerroBend was used as metal due to very low melting temperature 65°C. Fig. 8(b)-(d) show the corresponding original device, imprinted PDMS mold, and replica device, respectively.

Due to the similar mechanical properties of CerroBend alloy and aluminum, the behavior of the replica acoustic cloak device and the original one is almost identical. Thus, we propose to use the commercial 3D printing technique to fabricate the prototype device and apply this metal microcasting method to rapidly achieve underwater acoustic collimators. Fig. 8(e) illustrates the in-air acoustic collimator designed based on the transformation acoustics. The volume of each cavity varies as a function of the position to achieve gradient index. We fabricated a prototype sample by the 3D printer (Objet Connex 500), that can work as an original sample for the metal microcasting method.

- Characterization for novel acoustic wave performance

We have applied a set of acoustic characterization techniques to measure the behavior of the acoustic metamaterials from a single building-block to assembled devices. The transmission, reflection, absorption of the building-blocks can be characterized in acoustic impedance tube for deriving the effective properties. We will develop a new underwater impedance tube system for characterizing the building-blocks for the acoustic collimator. This system can test the frequency filtering properties of the acoustic metamaterials as well. We will also collaborate with the Experimental and Nonlinear Dynamics Lab

(ENDLab) at the Department of Mechanical Engineering, MIT to study the dynamic acoustic phenomena in the acoustic metamaterials over the broad frequency range.

In sequence, we will assemble the designed building-blocks to make the proposed underwater acoustic collimator, and test the performance. A 2D pressure field mapping system will be applied to capture both the intensity and the phase distribution of the collimated acoustic wave. This system as shown in Fig. 9(a) has been applied to map the pressure field of acoustic superlens and underwater acoustic cloak. We have also tested the in-air acoustic collimator (shown in Fig. 8(e)) and verify the performance of collimating the acoustic beam, which are plotted in Fig. 9(b) and (c). We propose to use this system to characterize our underwater acoustic collimators.

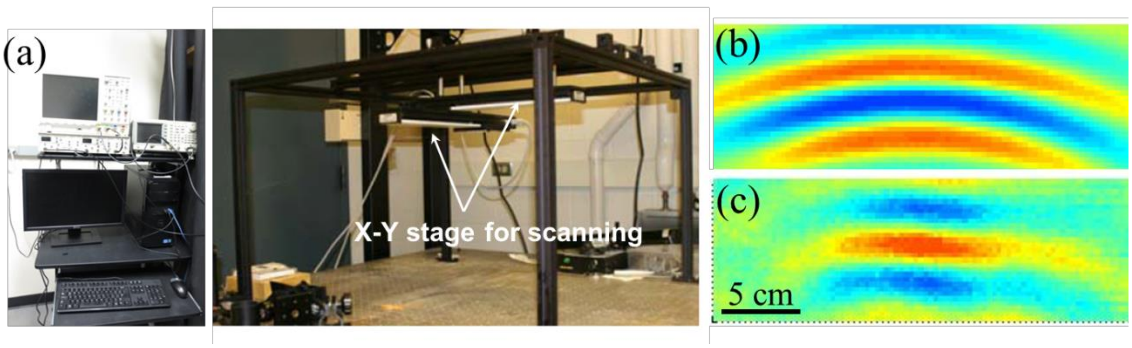

Fig. 9 (a) Experimental setup for acoustic wave measurement. Left: control station; right: 2D scanning system for mapping the pressure field. Measured acoustic pressure field distribution (b) without and (c) with the acoustic collimator. The acoustic wave is launched from a speaker placed at certain distance away from the device.

In addition, we will assemble the underwater acoustic collimator with the underwater transducer, and characterize the long range signal propagation capability in open water. The PI is currently involved in a MURI research program: Expanding the limits of acoustic metamaterials. We are collaborating with Prof. Haberman and Prof. Wilson (U.T. Austin) on the open water characterization of acoustic metamaterials covering the wide frequency range (0.5-100 kHz). The measurements are performed in Lake Travis test station (>500 Hz), large outdoor tank (>5 kHz), large indoor tank (>15 kHz), and ultrasonic tank (>50 kHz), respectively.

Proposed Timeline

	Year 1				Year 2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Transformation acoustics for manipulating acoustic waves								
Analytical design for acoustic collimator/filter								
Numerical simulation using effective parameters by COMSOL								
Optimization for practical material properties								
Modeling of building-blocks for acoustic metamaterials								
Theoretical investigation of acoustic waves interacted with artificial structures								
Design of building blocks working at 5 to 30 kHz for underwater acoustics								
3D full-wave simulation of designed building blocks by COMSOL								
Novel properties of acoustic metamaterials								
Optimization of building block design for proposed frequency								
Numerical simulation to verify the novel performance								
Fabrication of acoustic metamaterials								
Optimization of metal microcasting method								
Exploring new 3D manufacturing technique for prototype devices								
Fabricating building blocks and prototype devices								
Assembling prototype devices with omni-directional transducers								
Characterization for novel acoustic wave performance								
Testing the behavior of building blocks and optimizing design								
Small tank characterization of the collimation/filtering effect at proposed frequency								
Large tank or open water characterization for long-range underwater communications								

References

[1] M. Chitre, S. Shahabudeen, M. Stojanovic, *Marine Tech. Soc. Journal*, **42**, 103(2008).

[2] J. Heidemann, W. Ye, J. Wills, A. Syed, Y. Li, *IEEE Wireless Communications and Networking Conference*, **1**, 228 (2006)

[3] V. Trenkel, P. Ressler, M. Jech, *et. al*, *Marine Ecology Progress Series*, **442**, 285(2011).

[4] I. F. Akyildiz, D. Pompili, T. Melodia,, *ACM SIGBED Review - Special issue on embedded sensor networks and wireless computing*, **1**, 3(2004).

[5] J. Preisig, *Mobile Computing and Communications Review*, **11**, 2(2007).

[6] T. Won, S. Park, *Sensors*, **12**, 2309(2012).

[7] S. Zhang, L. Yin, N. Fang, *Phys. Rev. Lett.* **100**, 123002 (2008).

[8] S. Zhang, C. Xia, N. Fang, *Phys. Rev. Lett.* **106**, 024301 (2011).

[9] Y. Jing, J. Xu, N. X. Fang, *Physics Letters A*, **376**, 2834(2012).

[10] M. Stojanovic, *IEEE Journal of Oceanic Engineering*, **21**, 125(1996).

[11] G. Silva Sinerio, Master Thesis, *Naval Postgraduate School*(2003).

[12] J. A. Rice, J. L. Butler, & A. L. Butler, *Presentation at the NDIA Undersea Warfare Technology Conference*(2003).

[13] A. L. Butler, J. L. Butler, W. L. Dalton, & J. A. Rice, *Proceedings of the IEEE Oceans 2000 Conference*, 1289(2000).

[14] J. B. Pendry, D. Schurig, and D. R. Smith, *Science* **312**, 1780 (2006).

[15] U. Leonhardt, *Science* **312**, 1777 (2006).

[16] M. Rahm, S. A. Cummer, D. Schurig, J. B. Pendry, and D. R. Smith, *Phys. Rev. Lett.* **100**, 063903 (2008).

[17] M. Rahm et al., *Opt. Express* **16**, 11555 (2008)

[18] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, *Science* **305**, 788 (2004)

[19] A. Grbic, G. V. Eleftheriades, *Phys. Rev. Lett.* **92**, 117403 (2004).

[20] Z. Liu, X. Zhang, and Y. Mao et al., *Science* **289**, 1734 (2000).

[21] N. Fang, D. Xi, and J. Xu et al., *Nature Mater.* **5**, 452 (2006)

[22] D. Schurig, *et. al*, *Science*, **314**, 977(2006).

[23] H. Chen, C. Chan, *J. Phys. D: Appl. Phys.* **43**, 113001 (2010).

[24] T. Cranford, M. Amundin, K. Norris, *Journ. of Morphology*, **228**, 223(1996).

[25] C. Harper, W. McLellan, S. Rommel, *et. al*, *Journ. of Morphology,* **269**, 820(2008).

[26] L. E. Kinsler 1982 *Fundamentals of Acoustics* Wiley New York

[27] G. V. Eleftheriades *et al* *IEEE Trans. Microwave Theory Tech.* **50** 2702(2002)

[28] A. Grbic, G. V. Eleftheriades *Phys. Rev. Lett.* **92** 117403(2004)