Acoustic Leaky Wave Antennas: Direction-Finding via Dispersion

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Acoustic leaky wave antennas use an analog aperture coupled to an active transducer to steer acoustic energy using spatial-to-spectral coupling.

Introduction

The sound of a blaster in the classic *Star Wars* films is easily recognizable to many. It turns out that the wave phenomenon that produces that unique sound, something known as dispersion, is central to the operation of a new type of acoustic device known as a leaky wave antenna (LWA), which holds significant promise for use in acoustic navigation and imaging applications that require low-power operation. LWAs are mechanical structures that lead to direction-dependent radiation or reception of acoustic energy. In other words, when an acoustic LWA generates sound, it does not send out acoustic energy equally in all directions. Rather, the device has directionality and that directionality is dictated by its mechanical structure. Furthermore, the defining attribute of an acoustic LWA is the ability to change its directionality by simply changing frequency. This frequency-dependent directionality is a result of the LWA dispersion that is tailored by designing mechanical structures that make up the LWA. The design of the dynamic behavior of these subwavelength mechanical structures is central to the creation of the LWA and the primary focus of recent works on the topic of acoustic LWAs (Naify et al., 2013; Esfahlani et al., 2016).

So what is dispersion and how is it used to create an acoustic LWA? Furthermore, how can the LWA be engineered to create a compact, low-power acoustic-imaging or navigation device? This article provides a high-level overview of the physical phenomena underlying the desirable attributes of acoustic LWAs. It further traces the origins of acoustic LWAs to their analogues in electromagnetic LWAs, describes how concepts in acoustic metamaterials are used in the creation of LWAs, and provides examples and outlook on the future of this exciting technology.

Acoustic Beamforming and Direction Finding

To better understand the topic of acoustic LWAs, one must first understand the motivation for the study of such a device: the need for compact, low-power systems for navigation using acoustics. Acoustic waves have long been used to locate objects in space and to navigate. A classic example of the use of sound for navigation is echolocation employed by bats and marine mammals in which the animal emits an acoustic signal that then radiates out into the environment, primarily in front of the animal, until it encounters an object and some of the energy in the original signal is scattered back and received at the original location. If one knows the speed of sound in the medium carrying the wave (c), then the time elapsed between the generation and reception of the acoustic signal (Δt) provides an estimate of the distance (d) between the animal and the object that scatters the signal; $d = c\Delta t$. Although this is useful information, a single omnidirectional source-receiver pair will only tell the distance between the two with no information about direction.

The ability to localize objects in the environment using omnidirectional sources and sensors requires the use of either additional source-receiver pairs distributed in space, known as arrays, or structures that have an inherent directionality such as an acoustic lens like the melon of a dolphin. In man-made structures, the latter case is limited by the fact that its directionality cannot be changed once it is fabricated. For this reason, acoustic localization is most often performed using arrays of transducers such as hydrophones and microphones. As a simple example, humans partially localize objects by using time-of-arrival differences between our ears. Estimates of source location in arrays is achieved by array processing that uses knowledge of the location of each source or receiver and applies phase delays to electronically alter the directivity of the array through a process known as beamforming. **Figure 1** shows a cartoon of how beamforming works. In **Figure 1A**, an array of acoustic point sources are equally spaced along a line. If all of the sources are electronically coded to emit sound of equal magnitude at the same time, the resulting wave front propagates at an angle normal to the array. The red lines in all cases indicate acoustic phase fronts. If, instead of activating all of the sources simultaneously, we impart a phase delay of ϕ across each successive element in the array, the emitted wave front is steered at an angle θ. This phenomenon is shown in **Figure 1B**, with steering occurring at different angles.

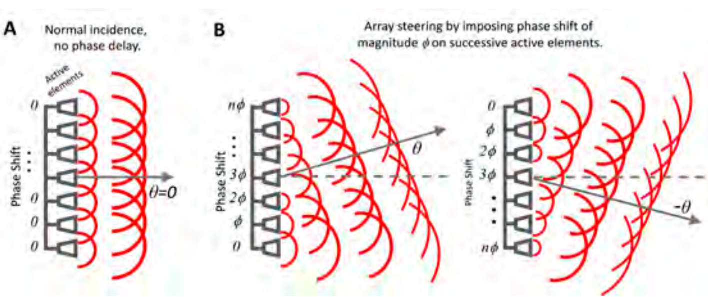

Figure 1. *Schematics of phase-delay steered active arrays. Active transducers (i.e., loudspeakers or hydrophones) are in in a uniform one-dimensional linear array. The transducers behave as point sources or receivers.* ***Red curve****, phase fronts radiating from each point source.* ***A****: when all active elements are excited simultaneously, with zero phase delay, the radiation direction is normal to the antenna (θ = 0).* ***B, left:*** *by imposing a phase shift increment of ϕ to each point source along the line array, it is possible to steer the phase front in a specific direction;* ***right****: by reversing the delay along the length of the antenna, the beam is steered in a different direction.*

Although highly useful, beamforming also requires complex electromechanical systems, postprocessing algorithms, and significant power. The explosion in recent years of autonomous systems for exploration requires navigation systems that are physically smaller, with reduced energy needs. LWAs have potential to fill all of these needs because they utilize very few acoustic sensors coupled to an analog aperture. Recent demonstrations by Esfahlani et al. (2016) and Naify et al. (2013) and subsequent development of acoustic LWAs have shown promise as a game-changing technique for acoustic sensing compared with array processing.

Waves That "Leak" and Spectral-to-Spatial Mapping

Fundamental to the operation of an acoustic LWA, as one might guess, is that sound must "leak" out of the device into the surrounding media in a controlled manner. In this context, leaking refers to the ability of a wave in one medium that is traveling parallel to the boundary with a second medium to lose some energy to an acoustic wave radiating into the second medium. According to Snell's law, this only occurs if the wave traveling at the interface between the media is faster than the wave in the second medium. An interesting example of this occurs when one throws a rock onto an ice-covered lake. Because the elastic wave at the point of impact travels faster than sound in air, some of the elastic wave energy leaks into the air, producing an audible sound reminiscent of the *Star Wars* blaster. The initial wave generated by the impact is a multifrequency, short-duration impulse. Due to dispersion, each frequency component propagates at slightly different speeds and thus the wave produced by the impact spreads out in time as it propagates in the ice sheet. An excellent demonstration and discussion of this phenomenon can be seen in this short National Public Radio video "Why Does a Frozen Lake Sound Like a *Star Wars* Blaster" (available at n.pr/2xHBiOW).

The dispersion that turns an impulse into a chirp is the same phenomenon that is exploited by an acoustic LWA to generate frequency-dependent directionality. Snell's law tells us that the angle of refraction [$\theta(f)$] depends on the ratio of the wave speed at an interface [$c_{int}(f)$] and the sound speed in the second medium (c_2) through the relationship $\theta(f) = \sin^{-1}[c_2/c_{int}(f)]$. In the icy lake example, $c_{int}(f)$ is the speed of elastic waves in the ice sheet and c_2 is in air. For the case of an acoustic LWA, $c_{int}(f)$ is the dispersive wave speed in the LWA and c_2 is the speed in the medium surrounding the LWA. If

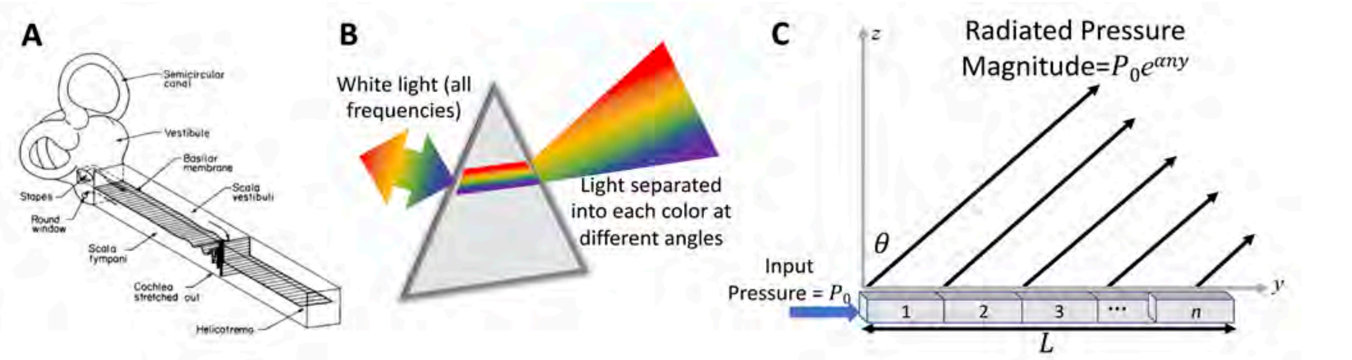

Figure 2. *Examples of spatial-to-spectral mapping.* ***A****: schematic showing unwrapped simplified model of the cochlea and basilar membrane (Zweig et al., 1974). The cochlea is an example of a spatial-to-spectral coupling device because discrete frequencies excite locations along the basilar membrane.* ***B****: a prism similarly performs frequency-spatial mapping by dividing a broadband signal, white light, into its frequency content as a function of space.* ***C****: acoustic leaky wave antenna (LWA) of length* L*, with n unit cells and input pressure* P_0*, radiating into the surrounding medium at angle* θ *according to the frequency of the signal. The coordinate system* y *and* z *defines the radiation and waveguide directions, respectively. The magnitude of the radiated pressure decreases exponentially along the length of the antenna as energy leaks out of the waveguide. The LWA displays a spatial-to-spectral mapping because each frequency travels at a different phase speed and thus radiates at different angles into the surrounding medium.*

one is able to tailor dispersion in a waveguide to create an acoustic LWA, it is possible to create frequency-dependent directionality of the LWA. Stated another way, a LWA enables the mapping from different frequencies (spectral components) to a particular radiated acoustic field (that is, a spatial acoustic pressure distribution). This spectrum-to-spatial mapping is important in other areas of acoustics as well, including our ability to hear. The place theory of pitch of the basilar membrane in the inner ear partially explains how the cochlea processes different frequencies (Zweig et al., 1974). In a simplistic model of the cochlea, the geometry and material properties of the basilar membrane (**Figure 2A**) result in each frequency exciting a different region of the membrane. Similar spatial-to-spectral mapping describes the physics behind an optical prism, as seen in **Figure 2B**, splitting the frequency components into different directions.

From Electromagnetic to Acoustic Leaky Wave Antennas

Electromagnetic LWAs have existed since the 1940s (Hansen, 1940). The direction and intensity of leaked acoustic or electromagnetic energy can be controlled in a similar manner to that of a far more complicated array of phased sources. Therefore, what would conventionally require tens or hundreds of active (i.e., powered) sources, each with electronics for precise phase control, can be achieved with a single simple source and a purely passive (i.e., unpowered, with no additional electronics) LWA. The simplest example of this is achieved by cutting a uniform, continuous slit in the side of a waveguide, as seen in **Figure 3, *top***.

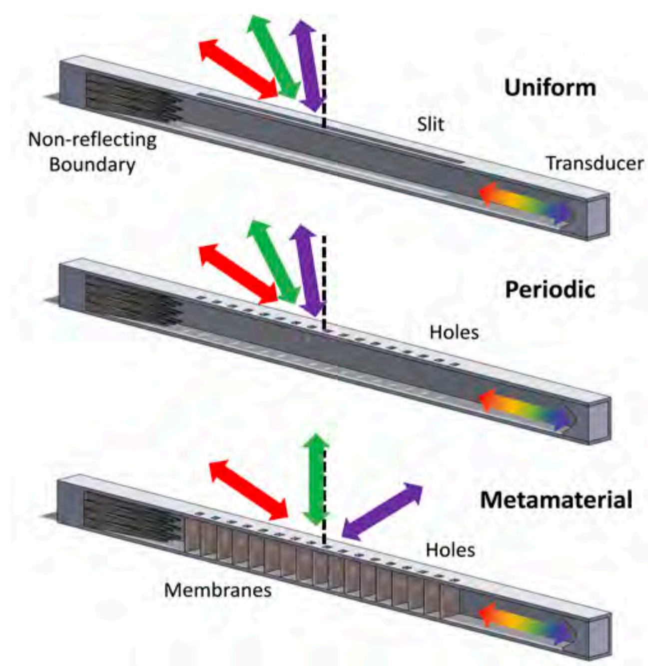

Figure 3. *Cross-sectional views of three basic types of acoustic LWAs. All of the LWA geometries have a single transducer (**right**) and a nonreflecting boundary (**left**) as well as a uniform cross section. In all cases, the **vertical dashed line** corresponds to broadside (0°). The uniform-slit structure (**top**) is the most straightforward realization, with a uniform slit cut in the side of the waveguide. Periodic perforations (holes; **middle**) can be included instead of a uniform slit to allow for more design tunability. By adding a periodic array of membranes (**bottom**) interspersed with the holes, a metamaterial structure is realized that allows for full forward (+90°) to backward (−90°) steering. **Purple, green**, and **red arrows**, different steering angles corresponding to low, middle, and high frequencies, respectively.*

LWAs as sensing instruments have been developed and improved in the subsequent decades by using a periodic modulation, such as an array of holes, instead of a continuous slit (see **Figure 3,** ***middle***; Monticone and Alu, 2015). This approach allows the antenna be divided into representative unit cells (repeating elements in a geometry such as a hole in the waveguide wall) to predict antenna directionality through the study of dispersion in a small section of the antenna rather than the entire array (Caloz and Itoh, 2004; Oliner and Jackson, 2007). Integrating metamaterial concepts, which are discussed in more detail in **Acoustic Metamaterials**, also provides additional degrees of freedom for LWA design (see **Figure 3,** ***bottom***; Liu et al., 2002).

So, how does the dispersion-beam steering relationship in LWAs work? Cutting a slit in the waveguide doesn't just allow power to leak out of the waveguide. Instead, it also alters the propagation of the wave *inside* the waveguide because the interaction of the wave with the slit is frequency dependent and, as a result, the waveguide is now dispersive.

To understand the dispersion-directionality relationship, we dig into some basic physics using the coordinate system defined in **Figure 2C** with a schematic of a LWA of length L, made up of n unit cell elements, which is excited by input pressure P_0 radiating at angle θ. **Equation 1**, in which all parameters are frequency dependent, defines the complex wavenumber, k_z, of the leaky mode inside the waveguide as it relates two important leaky-wave parameters (note that i denotes the imaginary component). The parameter β_z is known as the phase constant in the waveguide and α_z represents the leakage factor due to the slit or holes in the waveguide. Discussion of these parameters is described in greater detail by Caloz et al. (2004)

$$k_z = \beta_z - i\alpha_z \qquad (1)$$

When a wave at a given frequency propagates in the waveguide, the leaked power radiates at a frequency-dependent angle (θ), defined in **Equation 2** where k_0 is the wavenumber in the surrounding medium such as air or water. Note the similarity of this equation to the refracted angle of radiated acoustic energy of our ice-air interface example

$$\theta = \sin^{-1}\frac{\beta_z}{k_0} \qquad (2)$$

We then change the frequency inside the waveguide. When a wave at a given frequency (f) propagates in the waveguide, the leaked power radiates at an angle (θ) determined by the ratio of the wave speed in the waveguide to the wave speed in the surrounding medium, consistent with Snell's law as shown in **Equation 2**. In this way, the device behaves analogously to a prism, splitting the frequency components into different radiated directions. Several review articles provide comprehensive overviews of this steering behavior for electromagnetic LWAs (see Jackson et al., 2012; Monticone and Alu, 2015). Although the majority of research of LWA technology has been for use with electromagnetic waves, the idea was first realized in acoustics by Naify et al. (2013).

Acoustic Metamaterials

The topic of acoustic metamaterials has seen rapid expansion over the last two decades, in large part due to the promise of creating synthetic media whose properties surpass those of naturally occurring or currently available man-made materials with exotic capabilities for wave manipulation such as cloaking, lenses that exceed traditional resolution limits, and extraordinary absorption (Craster and Guenneau, 2013). These metamaterial arrangements behave just like any other material except that they have effective material properties (such as mass and stiffness) that are frequency dependent and can be positive or negative. This behavior is described in detail in recent review articles by Haberman and Guild (2016) and Haberman and Norris (2016). In its simplest form, negative inertia (mass) can be thought of as an out-of-phase time harmonic motion of a moving mass while negative stiffness requires that an increase in applied pressure yield a positive expansion. These unusual effective properties are impossible to create without exploiting dynamic effects at length scales much smaller than the acoustic wavelength, but have been shown to exist in certain frequency ranges for mass-spring-mass and side-branch resonator elements to induce negative dynamic density or stiffness, respectively.

The ability of metamaterials to enable negative effective mass and stiffness also has a significant impact on the wave propagation characteristics within the metamaterial. Because the phase speed is equal to the square root of the stiffness divided by the mass, the signs of the mass and stiffness terms must be the same (either both positive or both negative) for the phase speed to be real valued and therefore support wave propagation. When the dynamic density and bulk modulus are simultaneously negative, wave propagation is supported. However, in this case, the energy and phase velocities are in opposite directions, and we observe a very nonintuitive phenomenon known as negative refraction, where phase fronts bend in the opposite direction of the standard refractive index (see visualization at bit.ly/2Jun20A). This “backwards” refraction has led to wave phenomena being called “backward waves.” In the context of the acoustic LWA, these negative effective properties can be utilized to achieve a negative refractive index.

As we examine the concept of the LWA more closely within the context of acoustic metamaterials, it becomes apparent that the LWA configuration with an array of holes is a good starting place to incorporate metamaterial concepts. This geometry presents a classic configuration for analysis using a transmission line approach, which is a simple model developed to represent an infinite series of discrete, frequency-dependent elements. This approach can be used to analyze propagation and dispersion in several acoustic metamaterial structures. In this scenario, mechanical elements, such as acoustic ports, act as shunt inductances, or masses, and other elements, such as membranes, act as series capacitances, or compliances. The ability to create media that simultaneously displays a negative effective dynamic bulk modulus, and negative effective density was shown by Bongard et al. (2010) to generate a continuously variable index from positive to zero to negative values. This capability showed that it is theoretically possible to design a LWA geometry such that a single array can radiate continuously from positive through zero to negative angles like the array in **Figure 1**. This operational condition is referred to as a composite right-/left-handed structure, the development of which was a breakthrough in the field of electromagnetic LWAs by Caloz et al. (2008).

Improving Design and Performance: Using a Leaky Wave Antenna to Create an Acoustic Image

Like many acoustic transducers, an acoustic LWA can be operated in either source mode, where the antenna emits a sound (**Figure 4A**), or listening mode, where the antenna senses a sound field (**Figure 4B**). In the listening mode, external sources are localized in an angle by utilizing the frequency-angle mapping of the antenna as shown in **Figure 4B, *inset,*** where each angle of arrival couples to a discrete frequency within the waveguide.

In addition to passive localization, the LWA can be operated in a source mode, where the antenna emits a beampattern that can be steered (as in the case of the active array). Similar to the animal echolocation example, the reflected energy then returns to the LWA and gives location information as a frequency response read by the sensor. Multiple objects show up as multiple frequency peaks, as seen in **Figure 4C**, where the presence of two spatially separated scattered objects correspond to two peaks in the LWA-measured frequency response.

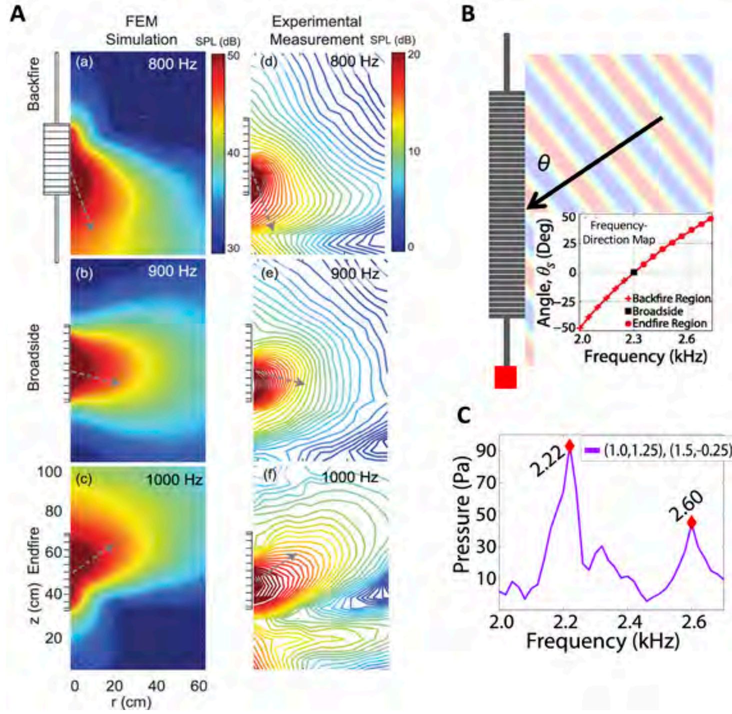

Figure 4. ***A****: LWAs can be used as a directional acoustic source, capable of sweeping in frequency across multiple angles (Naify et al., 2013).* ***a-c****: Sound pressure levels (SPL) of the sound field radiated by a LWA structure (line drawing at* ***top left****) predicted using finite element methods (FEM);* ***d-f****: experimentally measured radiation patterns from an antenna with identical geometry.* ***Dashed gray arrows****, direction of radiation; propagation direction inside the waveguide is in the positive z direction. Endfire refers to a radiated beam in the direction of the incident wave (inside the waveguide); backfire defines a beam radiating back to the direction of the incident wave.* ***B****: in a listening mode, the LWA receives incoming acoustic signals from sources emitting sound.* ***Red square****, location of the acoustic sensor.* ***Inset****: example of a frequency-angle map used to convert the directionality to a spectral profile of the scene, such as in* ***C****.* ***C****: the scattered field is recorded by the antenna as a frequency spectrum with multiple frequency peaks (****red diamonds****) corresponding to multiple features. These one-dimensional slices can be compiled into a two-dimensional scene.*

The ability to distinguish two adjacent targets or sources, or antenna resolution, is a critical problem for all antennas. The resolution of an antenna is often quantified by calculating a half-power beamwidth (HPBW), which is the angle subtended by these half-power angles. The HPBW is often reported in degrees and is determined by finding the angles on either side of the main lobe of the beam pattern at which the intensity is half that of the maximum value (a decrease in power of 3 dB). In fact, the resolution of an antenna and its size are inversely proportional, as seen in **Figure 5B** where a large antenna is needed to image very small objects.

Active arrays utilize beamform tapering by shading the signal using a variety of window tapers such as Tukey, hamming, and sine, to reduce side lobe levels (sensitivity peaks lower in magnitude and at different angles than the

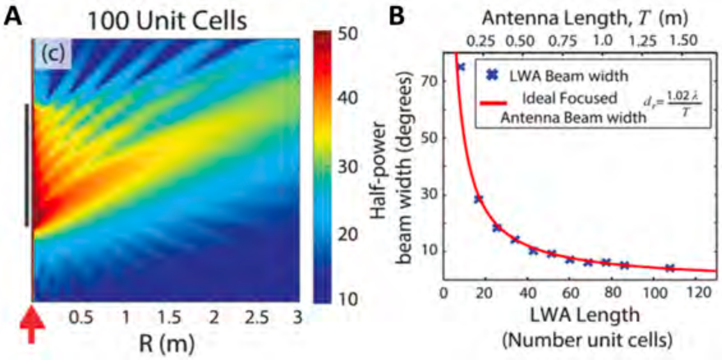

Figure 5. ***A***: *similar to arrays, the LWA has sidelobes in addition to the main radiating lobe, seen clearly in the 100-unit cell array, where the main lobe is not in the center of the antenna (**left black line**) but is instead biased toward the source end (**red arrow**).* ***B***: *resolution of the antenna, defined here as the half-power beamwidth, is improved by increasing the length of the LWA (Naify et al., 2016a).*

main beam) and improve image quality. **Figure 5A** shows a LWA beampattern with a significant side lobe profile in addition to the main lobe. It is, however, possible to taper the beampattern of a LWA by designing the taper into the radiation geometry (Siragusa et al., 2012).

Beyond the Linear Array

Until now we have limited discussion of LWAs to a one-dimensional, linear waveguide because many simple antennas are one-dimensional and for relative geometric simplicity. However, antennas come in many geometric configurations, and thus so can LWAs. The most obvious place to start is the extension from a one-dimensional to two-dimensional array (Naify et al., 2015). **Figure 6A** shows an example of a two-dimensional LWA able to steer in both elevation (angle from the *z*-axis, θ) and azimuth. Elevation steering is achieved by sweeping through frequency, as in the one-dimensional LWA. Azimuth steering is achieved by adjusting the relative pressure from multiple active elements, resulting in constructive interference of the beampatterns. Finite-element analysis-predicted radiation patterns of a two-dimensional acoustic LWA is seen in **Figure 6B** where the leftmost panel shows a beam generated using two sources of equal strength at a frequency of 1.2 kHz. As we increase the input frequency of both sources, the single beam moves along the dotted line (**Figure 6B, *middle***). If we instead change the relative input strength from each panel, the angle of the dotted line changes. It is worth noting that the transducer-reducing benefits for a two-dimensional LWA over a two-dimensional phased array are even more significant than with a one-dimensional array.

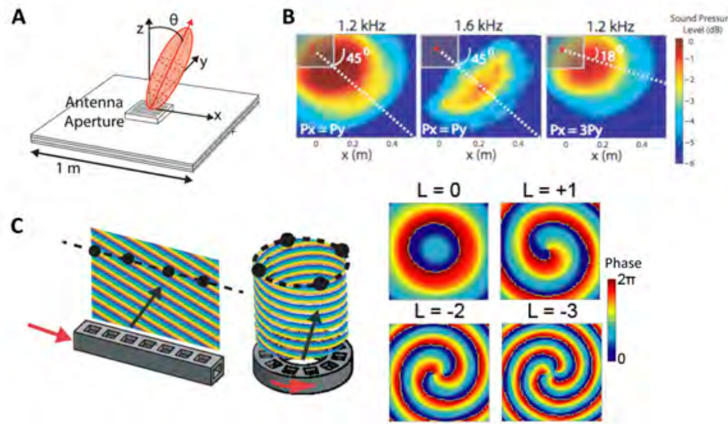

Figure 6. ***A***: *two-dimensional, positive-only index LWA can steer in three dimensions by coupling to two active transducers.* ***B***: *in this case, frequency is used to steer in elevation (**middle**). Relative magnitude of each transducer is used to steer in azimuth (**right**) as shown in Naify et al. (2015).* ***C***: *vortex waves, in which the phase of the wave is wrapped back on itself and which carries orbital angular momentum, can be generated by wrapping the LWA back on itself and steering through different vortex modes by varying the frequency of excitation. Experimentally measured vortex wave-phase profile using a LWA shows that a variety of vortex modes, L, are generated using a single antenna and varying the input frequency (Naify et al., 2016b).* ***Red arrow****, propagation direction inside the waveguide;* ***black arrows****, radiated directions.*

Another common configuration antenna array is to arrange transducers circularly to generate vortex waves, a type of structured wave in which the phase is twisted like a corkscrew around a central null (**Figure 6C**) for a range of applications from particle manipulation to acoustic communications. Until recently, acoustic vortex waves could be produced by two main methods: (1) using a fixed circular phase step, machined into a plate to introduce a fixed phase offset or (2) by using a electronic-heavy phased array of transducers (Hefner and Marston, 1999; Riaud et al., 2015). The practical limitations of these approaches are overcome by wrapping a linear acoustic LWA into a circle. This vortex wave antenna uses a single transducer while having the ability to tune the vortex mode by sweeping through, as seen in **Figure 6C**.

Looking Forward: Leaking What Comes Next

Looking forward, LWAs offer potentially game-changing ways for acoustically sensing and imaging the world around us. Although the potential savings in size, weight, and power might provide a more efficient approach to the current state-of-the-art arrays while maintaining the same functionality, in some cases, the LWA can open up entirely new avenues for acoustic imaging. One example is a biomedical ultrasonic imaging array and its associated electronics. The size and power required to operate and image with these arrays make imaging in limited spaces, like in intravenous applications, highly challenging. Alternatively, a micro-LWA achieved with a single active element and micromachined passive aperture can enable ultrasonic imaging in a small probe that can acoustically scan and image the interior walls of veins and capillaries (Rohde et al., 2017).

Another example in which LWAs offer a game-changing technological development is literally out of this world. It is for use on future NASA missions to explore liquid worlds such as Saturn's largest moon, Titan, and on Europa, one of the moons of Jupiter. These moons are believed to contain large subsurface oceans (Europa) or hydrocarbon seas (Titan), and exploration of these worlds requires acoustic arrays far more compact, lightweight, and low power than currently exists. LWAs offer a viable solution to meet these future space exploration needs. This would not be the first time acoustics has been used to explore extraterrestrial bodies as seismic experiments using arrays of geophones have measured quakes on the moon as described by Lynch (2017).

Despite these promising future applications of LWAs, current research challenges still exist. Due to the ease of fabrication and testing as well as implementation of the metamaterial components, all experimental realizations of the acoustic LWA have been demonstrated in air. Although typical structural materials such as plastics and metals have an acoustic impedance that is several orders of magnitude larger than that in air (and therefore tend to appear acoustically rigid), these same materials are much closer in impedance to water, with significantly more fluid-elastic coupling. As a result, the propagation of sound directly through the waveguide and the radiation via leaky compressional waves becomes far more complicated and challenging to control.

In addition to the added design challenges for a LWA operating in water, fabrication challenges remain. LWA designs require high-precision fabrication of unit cells be fabricated hundreds, or even thousands, of unit cells to produce a reliable device. Additive manufacturing (3-dimensional printing) offers a promising path forward in fabricating complex metamaterial structures such as those in a LWA. The ongoing development of new fabrication techniques and novel metamaterial structures suggest a very promising and exciting future for systems such as the LWA.

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BioSketches

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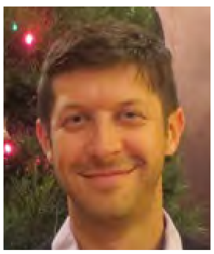

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