

Acoustic leaky-wave antennas from zero-index metamaterials

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We present an acoustic leaky-wave antenna based on zero-refractive-index metamaterials, offering significantly enhanced radiation efficiency and directivity compared to conventional designs. The zero-refractive-index metamaterial incorporates periodically distributed space-coiling structures, leveraging Dirac-like dispersion and accidental degeneracy to achieve vanishing effective density and compressibility simultaneously. The proposed acoustic Dirac leaky-wave antenna (ADLWA) achieves more than double the radiation efficiency of conventional antennas utilizing arrays with shunt ducts and membranes. It also exhibits superior directional control, enabling precise beam scanning through frequency tuning. Additionally, the ADLWA functions as a passive sonar system capable of detecting the direction of arrival of moving sound sources. This work expands the possibilities for acoustic wave control, with potential applications in acoustic sensing and communication technology.

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I. INTRODUCTION

Leaky-wave antennas (LWAs) are waveguiding transceivers that support wave propagation along the length of their structure with continuous radiation. Since their emergence in the 1940s, LWAs have attracted growing interest in the microwave community because of their intriguing features, including the capability of realizing high directivity and high gain, as well as dispersive beam-scanning without the need for complicated feeding networks [1]. Such an idea was also extended to acoustic wave systems. Conventional acoustic leaky-wave antennas (ALWAs) are composed of waveguiding materials with periodic shunt ducts, supporting only forward radiation [2]. Composite right-left-hand (CRLH) transmission-line (TL) metamaterials [3–5], which enable both right-hand and left-hand propagation to facilitate the transition of the main radiation beam from backward to forward radiation, have been subsequently integrated into ALWAs [6–14]. By incorporating periodic arrays of shunt ducts and

membranes along the waveguide, these CRLH TL ALWAs enable a continuous shift in the propagation constant from negative to positive, without the presence of a stopband. This acoustic beam steering was further exploited in different studies, such as acoustic dispersive prisms [14], acoustic vortexes [15], and single-microphone acoustic source direction detection [11,12]. More recently, heterostructures [12] and graded units were designed to achieve higher directivity [13]. However, ALWAs with shunt ducts and membrane arrays often suffer from a complex assembly process, difficult membrane tension control, high losses, and large sidelobes. For example, tuning the shunt duct size can control the radiation direction and the beam width, but the interplay between the duct and the membrane compromises the optimal directivity at a desired frequency, hence limiting the maximum radiation efficiency [6,14].

Zero-index metamaterials (ZIMs) are a class of unconventional materials, the refractive indices of which are vanishingly small [16–31]. In a ZIM, the phase velocity becomes infinite, resulting in no spatial phase change. This exhibits remarkable properties such as supercoupling [16,17,32,33], cloaking [19,20,34,35], and wave-front engineering [17,18,25,33,36]. A unique beam-collimating effect, demonstrated by a ZIM recently, is shown to produce highly directional beams in the far-field region [27, 28,37,38]. This indicates the potential of ZIMs for improving conventional leaky-wave antennas, where the directivity is typically constrained by the nonuniform spatial phase

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distribution across the radiation aperture. This advancement opens the opportunity for enhancing acoustic antenna technology by integrating ZIMs with ALWAs. Since the refractive indices are determined by the product of two parameters, i.e., permittivity and permeability in electromagnetism and mass density and compressibility in acoustics, there are two types of ZIMs: one is a single-zero-index material, in which one of the two parameters is zero, and the other is a double-zero-index material (DZIM), in which both parameters are zero. Compared to single ZIMs, DZIMs possess impedances better matched to the environment [39]. In electromagnetism, low-loss DZIMs are realized using photonic crystals comprising periodically arranged scatterers with high permittivity. They possess a Dirac-like cone at the Brillouin zone center induced by accidental degeneracy, at which frequency the effective permittivity and permeability approach zero simultaneously [25,29]. Similar strategies have been applied to waterborne acoustics [33] and elastic waves [32]. For airborne acoustics, despite some progress in realizing the DZIMs, such as using connected air cavities in three dimensions [40] and using high-order waveguide modes in planar waveguides [41], achieving DZIM in two dimensions is still challenging because finding stable scatterers supporting a wave velocity lower than that in air is difficult. Recently, a space-coiling structure was designed and demonstrated to be capable of increasing the sound travel time via a prolonged sound-propagation path, which behaves as a scatterer supporting a low wave velocity [42–51]. However, this structure usually exhibits highly anisotropic properties, resulting in multiply degenerate eigenmodes [50]. These unwanted degeneracies hinder the realization of the DZIM, in which accidental degeneracy of only monopolar and dipolar modes is desired.

Herein, motivated by the possibility to achieve highly directional radiation, we propose a design of an ALWA that leverages the DZIM effect, thus resulting in the so-called acoustic Dirac leaky-wave antenna (ADLWA). This device is realized via a space-coiling structure with variable channel spacing that effectively tailors the inherent multipole modes [50]. By tuning the geometric parameters of the coiling structure, we achieve a Dirac-like point at the center of the Brillouin zone in the subwavelength regime. The obtained DZIM is then embedded in a one-dimensional (1D) waveguide, forming an ADLWA. This ADLWA demonstrates the ability to radiate through the broadside while dynamically changing the directivity of the beam by altering the frequencies. The proposed antenna features a closed stopband, a matched response, and a consistent leakage factor around the broadside, significantly improving the directivity and more than doubling the radiation efficiency compared to conventional ALWAs. Last, but not least, this ADLWA can be used in a passive sonar system, effectively locating the direction of moving sound sources in space.

II. RESULTS AND DISCUSSION

A. Design of the DZIMs

The two-dimensional acoustic DZIM consists of a square array of space-coiling elements. A schematic of the unit cell is depicted in Fig. 1(a), where the light gray region represents air and the dark gray region indicates a solid material, such as aluminum or acrylonitrile butadiene styrene plastic—a common three-dimensional (3D) printing material. Because of the significant impedance mismatch with air, the interface between the solid and air is treated as a hard wall. The solid material forms thin walls with thickness t to construct the space-coiling structure. Each space-coiling structure comprises four identical channels connecting the inner hollow cavity with radius R_1 to the surrounding space. Each channel consists of two coiled regions: an inner coil with a narrow width, w_1 , and an outer coil with a large width, w_2 (i.e., $w_2 > w_1$). Unlike previous space-coiling structures discussed, for example, in Refs. [45,50], where all channels have a uniform width, the varying channel widths provide additional flexibility in controlling acoustic wave propagation, thereby enhancing

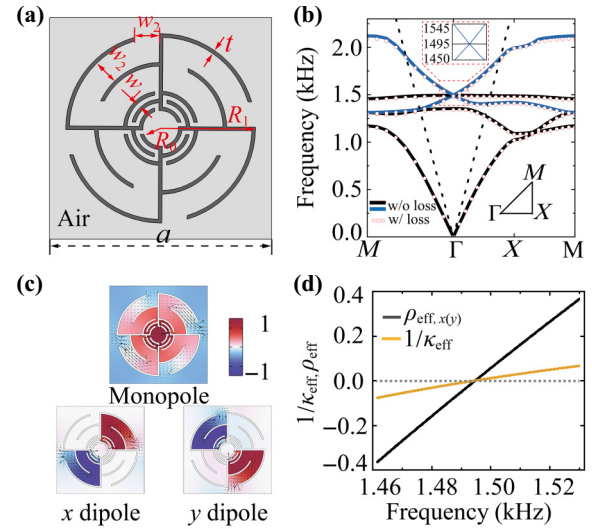


FIG. 1. Schematic of the designed space-coiling structure and the corresponding properties of the metamaterial. (a) Proposed structure with four zigzag channels. Solid material (thick solid dark gray lines) form zigzag channels with the outlet width identical to the outer channel width, $w_2 = 0.114a$; inner channel width is $w_1 = 0.02a$; wall thickness is $t = 0.016a$; inner and outer radii are $R_0 = 0.08a$ and $R_1 = 0.427a$, respectively. Light gray area represents air. (b) Band structure of the DZIM (solid lines). Dotted lines delineate the sound cone. Red open circles represent the case with loss. (c) Normalized acoustic pressure field distributions of the monopolar state and dipolar states near the Γ point (black arrows represent the particle velocity vectors). (d) Effective mass density, $\rho_{\text{eff}, x(y)}$ (black curve), and reciprocal of bulk modulus, $1/\kappa_{\text{eff}}$ (yellow curve), versus frequency. Dotted gray line depicts the Dirac point frequency.

the ability to tailor the effective medium properties. We use COMSOL Multiphysics 6.2 (a commercial package based on the finite-element method) to perform numerical simulations of the system. The interface between the solid and air is modeled as a hard wall due to the large acoustic impedance mismatch. The mass density and speed of sound in air are set to $\rho_0 = 1.21 \text{ kg/m}^3$ and $c_0 = 343 \text{ m/s}$, respectively. After fine-tuning the geometric parameters of the space-coiling structure, we obtain the Dirac-like dispersion relationship shown in Fig. 1(b), in which two linear bands (blue curves) intersect with a flat band (black line) at 1495 Hz [as further magnified in the inset of Fig. 1(b)]. This degeneracy is accidental, as demonstrated in the Supplemental Material [39], where varying the filling ratio leads to the splitting of this triply degenerate state into a doubly degenerate dipolar state and a single monopolar state. To understand the effect played by the intrinsic loss in air, we employ the built-in acoustic-thermoviscous interaction module and set the air dynamic viscosity to $\mu_d = 1.81 \times 10^{-5} \text{ Pa}\cdot\text{s}$. The resulting frequency response with loss (red open circles) almost resembles the one without loss (solid curve), as shown in Fig. 1(b), indicating that air loss does not significantly affect the Dirac-like point frequency in our case.

The three eigenstates near the degenerate frequency, ω_0 , are shown in Fig. 1(c), where a typical monopolar resonance and two orthogonal dipolar resonances are observed. From these eigenmodes, we calculate the effective medium parameters of the DZIM. These parameters are defined as in-plane quantities, i.e., within the x - y plane. Owing to the C_4 symmetry of the unit cell, the effective mass densities along the x and y directions

are identical (i.e., $\rho_{\text{eff},x} = \rho_{\text{eff},y}$). Using the field-averaging technique [39,52,53], we plot the effective mass density, $\rho_{\text{eff},x(y)}$, and the inverse of the effective bulk modulus, $1/\kappa_{\text{eff}}$ (corresponding to the compressibility), in Fig. 1(d). Both effective parameters cross zero at the Dirac-like point frequency, indicating the double-zero property of the meta-material. Additional evidence of the zero-index property of our designed material is provided in the Supplemental Material [39].

B. Acoustic Dirac leaky-wave antenna

The ADLWA proposed in this study features a top-perforated waveguide filled with the DZIM, as shown in Fig. 2(a). The size, shape, and position of each opening are all carefully selected to maintain the Dirac-like degeneracy of the eigenmodes while achieving the best leakage factor of the 3D leaking unit. For our structure, the geometric parameters are chosen to be $\phi_0 = 37^\circ$, $\phi_1 = 30^\circ$, $\phi_2 = 55^\circ$, $l_a = 0.354a$, $d_a = 0.07a$, $d_b = 0.343a$, $s_x = 0.0456a$, $s_a = 0.148a$, $s_b = 0.114a$, and $l_z = 0.656a$. As only 1D periodicity is assumed along the x direction and hard walls are enforced on the y and z directions, the y dipole, shown in Fig. 1(c), shifts to a different frequency and cannot be excited by the incident wave (propagating in the x direction). The remaining two eigenmodes become two leaky modes and have finite (due to radiation) quality factors, i.e., $Q_d = 150.6$ and $Q_m = 94.9$. Their quality factors are determined from the complex eigenfrequencies, ω , obtained via eigenmode analysis in COMSOL Multiphysics. Specifically, the quality factor is calculated using $Q = \text{Re}(\omega)/(2 \text{Im}(\omega))$, where $\text{Re}(\omega)$ is the real part of the

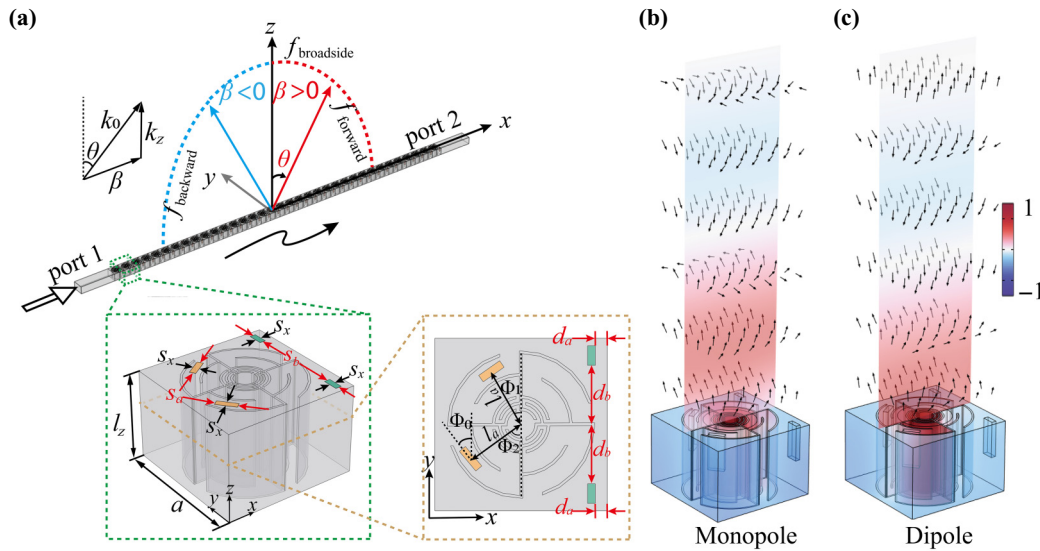


FIG. 2. (a) 3D view of the 35-cell ADLWA, constructed by cascading 35 unit cells along the x direction. Schematic of the unit cell is shown in the magnified views, where the four top perforations, denoted by yellow and green rectangles, are plotted. Normalized acoustic pressure field distributions of the leaky eigenstates of (b) the monopole and (c) the dipole (black arrows represent the particle velocity vectors).

eigenfrequency and $\text{Im}(\omega)$ is the imaginary part, corresponding to the energy decay rate due to radiation [54,55]. The ADLWA, shown schematically in Fig. 2(a), comprises 35 cells. As the frequency of the incident wave varies, the propagation constant, β , of the waveguide shifts from negative to positive. This property stems from the peculiar Dirac-like degeneracy [39], enabling continuous radiation scanning from the backward to forward direction in the x - z plane.

The perforations on the top surface of the waveguide are important in the design of our ADLWA. They allow leaky-wave radiation, yet they alter the Dirac-like dispersion and degeneracy. There are two pairs of identical rectangular slots, as shown in Fig. 2(a), highlighted in yellow and green, respectively. The yellow pair is precisely positioned at the nodal points (region of zero pressure) of the monopolar resonance shown in Fig. 1(c), thereby negligibly affecting this specific mode. However, since these slots are located at positions with different nonzero pressure field amplitudes of the dipolar mode, shown in Fig. 1(c), they selectively introduce losses to this mode [39]. Similarly, the green pair is located at positions where the pressure field is nearly zero in the dipolar mode but fairly large in the monopolar mode, resulting in a minimal influence on the dipolar mode while introducing loss to the monopolar mode [39]. The size of the slot determines the strength of induced losses. By carefully tuning the parameters of the slots, the two orthogonal Bloch modes of the original DZIM (monopole and x dipole) can be made degenerate again at 1554 Hz, allowing the ADLWA to match the impedance of the surrounding air, hence achieving an optimal leakage factor to support radiation.

C. Theoretical modeling

To gain a deeper understanding of the antenna operation, we employ both the transfer matrix method (TMM) and TL theory. For the TMM, the pressure and velocity fields at the boundaries of one unit cell ($x = 0, a$) can be related

through the following expression [56]:

$$\begin{bmatrix} P \\ V \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix}_{x=a}, \quad (1)$$

where $\mathbf{T}$ is the transfer matrix of the unit cell. By applying the Floquet boundary condition, the propagation constant, γ , can be obtained [57]:

$$\gamma = \frac{1}{a} \left[\text{arccosh} \left(\frac{T_{11} + T_{22}}{2} \right) \right] = \alpha + i\beta, \quad (2)$$

where α is the leakage factor of the ADLWA and β is its phase constant. The acoustic field above the antenna can be expressed as $P(x, z) = P_0 e^{ik_x x} e^{ik_z z}$. Here, $k_x(\omega) = \beta(\omega) + i\alpha(\omega)$ and $k_z(\omega)$ are the propagation constants along the x and z directions, respectively, where $\beta(\omega)$ is the phase constant. Due to the small leakage factor ($\alpha \approx 0$), the propagation constants satisfy the dispersion relationship, $\beta(\omega)^2 + k_z^2(\omega) = k_0^2(\omega)$, where $k_0(\omega) = \omega/c$ is the propagation constant in free space. Radiation (leaky-wave emission) occurs when $|\beta| < k_0$, allowing k_z to be real.

The radiation angle, θ , shown in Fig. 2(a), for the ADLWA is given by [57]

$$\theta(f) = \arcsin \left(\frac{\beta(f)}{k_0} \right). \quad (3)$$

Therefore, tuning the frequency changes the axial wave number and in turn steers the beam direction.

Alternatively, the ADLWA can also be modeled using TL theory [3]. As shown in Fig. 3(a), the unit cell can be modeled as a parallel connection of an impedance, Z_{se} , and a shunt admittance, Y_{sh} [3,57]. The transmission characteristics of this circuit structure can be connected to the transfer matrix, $\mathbf{T}$, given in Eq. (1), as follows:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} 1 + Z_{\text{se}} Y_{\text{sh}} & Z_{\text{se}} \\ Y_{\text{sh}} & 1 \end{bmatrix}. \quad (4)$$

The corresponding values of circuit elements in the TL model can be obtained by fitting [39]. As shown in

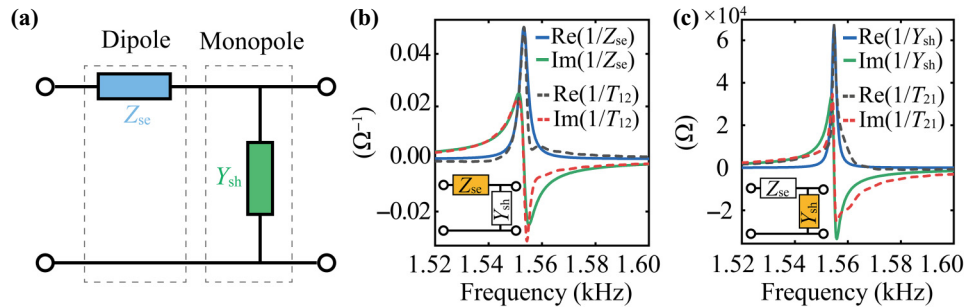


FIG. 3. (a) Equivalent transmission line model for ADLWA. (b) Extraction of the reciprocal of the T_{12} element from the unit transfer matrix (dashed line) and fitting the curve of the circuit model Z_{se}^{-1} (solid line). (c) Same fitting process for Y_{sh}^{-1} (solid line) using the T_{21} element.

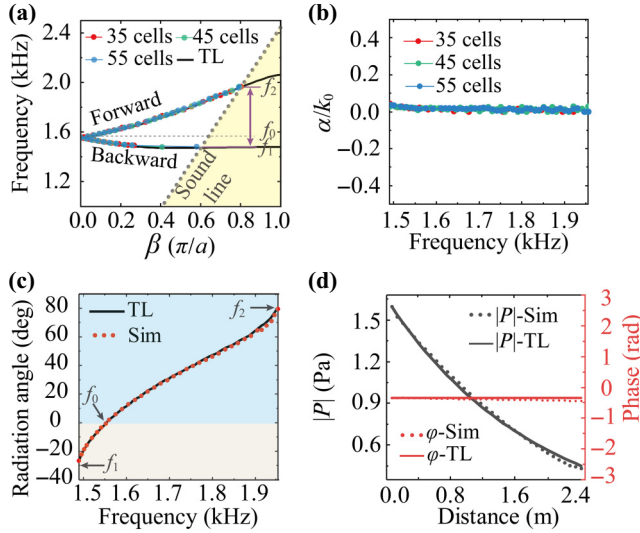


FIG. 4. (a) Dispersion diagram of the N -cell ADLWA calculated using acoustic TL (black solid line) analysis and simulation (dotted markers), where the sound cone is highlighted by yellow shading (dotted line represents the sound line). (b) Leakage factor, α/k_0 , for one unit cell, extracted from ADLWAs of varying lengths. (c) Radiation beam angle as a function of the incident frequency. Solid curves represent the TL beam angles, while dotted lines indicate the simulated beam angles for the 35-cell ADLWA. (d) Aperture field and phase distribution along the length of the antenna for broadside radiation.

Fig. 3(b), the fitted Z_{se}^{-1} are plotted as solid lines, exhibiting a strong correlation with T_{12}^{-1} extracted from full-wave simulations (dashed lines) for both real and imaginary parts across the frequencies of interest. Similarly, in Fig. 3(c), the agreement between Y_{sh}^{-1} and T_{21}^{-1} further validates the accuracy and robustness of the TL model, in predicting the metamaterial properties.

By combining Z_{se} , Y_{sh} , and Eq. (2), we obtain the dispersion relationship from the TL theory and plot it in Fig. 4(a) (black solid line). The radiation region of the ADLWA lies above the sound cone (highlighted in yellow and bounded by the gray dotted line) and is bounded by $f_1 = 1490$ Hz and $f_2 = 1955$ Hz. $\beta = 0$ (zero index) occurs at the Γ point, which corresponds to 1554 Hz (f_0), along with the nonzero group velocity, which provides the broadside radiation. The simulated dispersion for antennas of different lengths (dotted lines; 35, 45, and 55 cells) agrees well with the TL model. Figure 4(b) demonstrates that the normalized leakage factor, α/k_0 , is approximately 0.0267 and remains a constant over the frequency range of 1490–1955 Hz.

The propagation constant, β , is then used to determine the radiation angle of the ADLWA. The main beam angles, θ , at various frequencies are calculated for 35 cells and shown in Fig. 4(c), using both finite-element method (red dotted line) and TL theory, i.e., Eq. (3) (black solid line).

When excited at frequencies between f_1 and f_0 , the negative group velocity leads to backward radiation (as shown in the gray region), with a maximum angle of approximately -27.4° . In contrast, forward radiation (as shown in the blue region) occurs within the range of f_0 to f_2 , with a maximum radiation angle of approximately $+80.27^\circ$. A smooth gapless transition from the backward to the forward region is demonstrated.

In Fig. 4(d), we plot the phase and magnitude distributions of the pressure field along a ADLWA with 35 units at f_0 . The fields are measured at the center of the green slot located at the top-right corner, as shown in the Supplemental Material [39]. Clearly, we observe monochromatic decreasing behavior in the magnitude, but a nearly constant distribution for the phase. To understand these behaviors, we write φ_n and P_n , corresponding to the field (phase and amplitude, respectively) at the n th cell of the ADLWA array, as follows:

$$\varphi_n = -(n-1)\beta a, \quad (5)$$

$$P_n = P_0 e^{-\alpha(n-1)a}, \quad (6)$$

where P_0 is the pressure measured at the slot of the first unit cell. At f_0 , $\beta = 0$, the DZIM leads to zero-phase change along the length of the antenna, as confirmed in Fig. 4(d), resulting in broadside radiation. Additionally, the exponential decay of the field magnitude [Eq. (6)], depicted by the black solid line (TL model) and the black dotted line (simulation) in Fig. 4(d), further confirms the leaky operation characteristic of zero-index propagation.

D. Scanning characteristics and direction of arrival via ADLWA

The performance of our ADLWA in terms of its radiation efficiency, $\eta = 1 - r - t$, where r and t are power reflection and transmission coefficients, respectively, for different lengths (increasing number of cells) is demonstrated in Fig. 5(a). At the Dirac-like frequency (1554 Hz), due to impedance matching with air, the reflection is minimized and the radiation efficiency reaches its peak value of 82%. When operating slightly away from this point, the reflection increases marginally, and the average efficiency remains around 70% throughout the entire backward-to-forward scanning range (1490–1955 Hz). Moreover, our design features a nearly constant leakage factor, making the efficiency relatively insensitive to the antenna's length. This contrasts with conventional acoustic leaky-wave antennas, which typically exhibit a strong trade-off between efficiency and directivity and achieve only a few percent radiation efficiency [6,14]. In Fig. 5(b), the ADLWA's scanning properties and high directivity capabilities are further demonstrated. The sidelobe levels consistently stay well below the radiation power peak across all frequencies, reflecting its precise control over wave

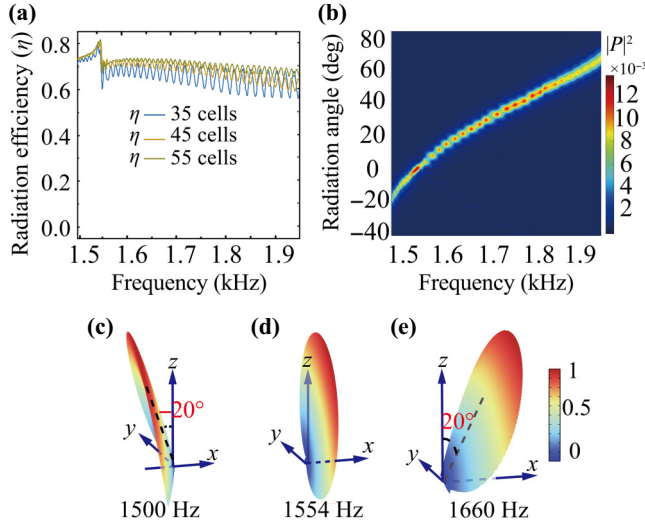


FIG. 5. (a) Radiation efficiency of the ADLWA with different lengths (35, 45, and 55 cells). (b) Scanning characterization of the ADLWA accompanied by significantly low sidelobes. Far-field radiation patterns of the ADLWA revealing (c) backward radiation at 1500 Hz, (d) broadside radiation at 1554 Hz, and (e) forward radiation at 1660 Hz.

directionality. Figures 5(c)–5(e) give the far-field radiation patterns (normalized power distribution) of the structure at three distinct frequencies: 1500, 1554, and 1600 Hz, corresponding to radiation in the backward, broadside, and forward directions, respectively.

Additionally, we demonstrate in the following that the DZIM offers diverse modulation capabilities. Traditional ALWAs are constrained by complex structural assembly issues, making them unadaptable to specific requirements in complex scenarios, such as customized radiation aperture design and/or robustness against interference. Leveraging the DZIM, we show that we can flexibly change the shape of our ADLWA to achieve various broadside radiation patterns [39]. Furthermore, even when some of the antenna’s elements are damaged, the DZIM still ensures stable operation of the antenna, as detailed in the Supplemental Material [39].

The frequency-dependent wave-steering property demonstrated earlier suggests a possible application of direction of arrival (DOA) detection. According to the reciprocity theorem [58] in the reverse operation (i.e., as a detector), the antenna exhibits a well-defined frequency-direction relationship. In other words, the ADLWA can be regarded as a passive sonar, which can detect the moving sound source in the space from the radiating side. As illustrated in Fig. 6(a), a microphone is positioned at the left end of the antenna. A sound point source, Q , emitting at frequency f , is located far away from the antenna. The polar angle of the source relative to the antenna’s normal is denoted by θ_{in} . It is important to ensure that the distance

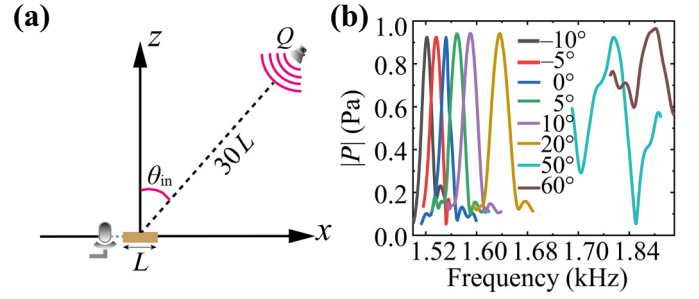


FIG. 6. (a) Schematic diagram of the ADLWA used for the direction of arrival detection. (b) Recorded sound-pressure spectra captured by the microphone probe in the ADLWA for various incident angles, θ_{in} .

from point Q to the antenna is set to 30 times the length (L) of the antenna and 420 times the shortest wavelength, so that the incident wave front can be reasonably approximated as a plane wave when it reaches the antenna. The antenna captures the sound-pressure spectrum as the angles between it and the sound source vary. During this process, the received sound-pressure spectrum is expected to exhibit a peak corresponding to a specific direction.

As depicted in Fig. 6(b), the sound-pressure spectra recorded at the microphone position for each incident angle reveal a lobe with maximal amplitude at a specific frequency. Using Eq. (3), angle θ can be determined, thereby confirming the DOA of sound source Q . Compared to traditional detection methods that depend on multisensor beam forming to efficiently pinpoint sound-source locations, the ADLWA detector enables directional sensing using only a single microphone, without the need for complex signal processing or sensor arrays, making it particularly suitable for low-power acoustic sensing systems.

III. CONCLUSION

We design an airborne DZIM, utilizing a space-coiling structure, and successfully verify its zero-refractive-index properties. By integrating this DZIM into a waveguide, we develop a highly efficient ADLWA, which enables continuous beam scanning from backward to forward radiation without a stopband. The ADLWA exhibits superior radiation efficiency (up to 82%) and enhanced directivity compared to conventional ALWAs. The designed ADLWA serves a dual purpose, functioning as both a radiating antenna and a passive sonar system for DOA, offering promising prospects for the development of multifunctional high-performance acoustic radiating and sensing devices.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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