DOI: 10.61782/fa.2025.0272

FORUM ACUSTICUM EURONOISE 2025

DESIGN AND FABRICATION OF AN ACOUSTIC LEAKY-WAVE ANTENNA FOR UNDERWATER APPLICATIONS

Alejandro Fernández-Garrido[1*] **María Campo-Valera**[2*] **Rubén Picó** [3]
Elena Abdo-Sánchez [2] **Rafael Asorey-Cacheda**[1,4]
[1] Department of Information and Communications Technologies,
Universidad Politécnica de Cartagena, 30202 Cartagena, Spain
[2] Telecommunication Research Institute (TELMA), Universidad de Málaga, 29071 Málaga, Spain
[3] Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC),
Universitat Politècnica de València (UPV), 46730 Gandia, València, Spain
[4] People Oriented Smart Technologies Laboratory (POSTLab), European University of Technology,
European Union

ABSTRACT

This work presents the design, fabrication and experimental characterization of an Acoustic Leaky Wave Antenna (ALWA) using low-cost materials. The antenna employs a single transducer coupled to a dispersive structure, allowing it to emit or receive acoustic energy from different directions depending on the operating frequency. It is designed to radiate in backward, forward and sideward directions, allowing versatile control of the acoustic beam. Finite element method (FEM) simulations were key to the geometry design and material selection, with experimental tests validating these results. Experiments confirmed the accuracy of the simulations and demonstrated the antenna's ability to scan the acoustic beam, providing a compact, high-performance solution suitable for technologies such as SONAR.

Keywords: *underwater acoustic, acoustic leaky-wave antennas, beam scanning, propagation.*

**Corresponding author: alejandro.fernandez3@upct.es, maria.campo@ic.uma.es.*

1. INTRODUCTION

Acoustic Leaky Wave Antennas (ALWAs) are an innovation in signal transmission and reception in underwater environments [1]. These devices are designed to emit or receive acoustic signals in a controlled manner through guided modes that progressively leak power along their structure [2, 3]. Their development has been driven by advances in transmission line metamaterials, inspired by their electromagnetic analogs [4].

Currently, these antennas have significantly improved their performance [5]. Recent advances have enhanced directivity, modal coupling, and efficiency in the propagation of acoustic energy along the antenna structure. This has been made possible by proper acoustic impedance matching of materials and modal leakage control, which has facilitated outward energy transfer and minimized unwanted emissions into the surrounding acoustic field [6, 7]. As a result, ALWAs could improve high-fidelity underwater communication, passive and active object detection applications, as well as advanced structure-borne and environmental noise management in complex marine environments [8].

This work focuses on the design and fabrication of an ALWA that employs membranes, enabling radiation in the angular space from backwards to forwards, for spatial location applications. The concept of ALWA is introduced in Section 2. Section 3 provides a detailed description of its structural design and the steps followed in its fabrication. Section 4 presents the experimental results, which are compared with analytical and numerical models to assess the device's proper functioning. Finally, Section 5 offers the conclusions.

2. CONCEPTUAL FRAMEWORK

ALWAs are defined as an open acoustic waveguide of length L propagating a leaky mode. These modes have a complex popagation constant since they radiate outward as they propagate through the open waveguide. The radiation pattern of these antennas is determined by the complex propagation wave number k [9], which is defined by the phase constant β and the attenuation constant α:

$$k_z = \beta - j\,\alpha \tag{1}$$

Specifically, α characterizes the leakage rate, which determines the beamwidth, while β determines the radiation angle.

The phase constant, β, is related to the main beam angle θ_r as:

$$\theta_r = sin^{-1}\left(\frac{\beta}{k_0}\right) \tag{2}$$

where k_0 is the wavenumber in free space. In addition, the half-power beamwidth $\Delta\theta$, for an ALWA of length L is estimated as follows [10]:

$$\Delta\theta \approx \frac{\lambda}{L\,cos\,(\theta_r)} \tag{3}$$

Since β is dispersive, the scanning angle θ_r also varies with it, allowing for a frequency scanning of the directive beam.

3. DESIGN AND MANUFACTURING

The design consists of a series of 32 stacked unit cells; each characterized by an inner radius r_{in} and a thickness t_{cell}, as shown in Fig. 1. A thin-film polyimide membrane is incorporated in the center of each conduit with a thickness of t_{mem}. This proposal is based on the design presented in [11], but with the particularity of including elastic membranes that allow radiation at negative angles [12], which broadens the angular response of the antenna.

To accommodate acoustic leakage, the cells are stacked with a small gap between them, having a width of w_{sh}. In addition, waveguides of length l_{wg} are placed at the ends of the stack to ensure proper acoustic matching. The geometric parameters used in the design and fabrication of the antenna are presented in Table 1.

Table 1: Geometric parameters of the proposed antenna.

Variable	Description	Value (mm)
l_{wg}	Input/output waveguide lengths	382
r_{in}	Inner cell radius	3
t_{cell}	Thickness of the unit cell	16.5
t_{mem}	Thickness of the membrane	0.04
w_{sh}	Width of the shunt	0.5
r_{out}	Length of the wall	17

Methacrylate (Polymethyl Methacrylate, PMMA) was used in the waveguides and unit cells. The membranes were made with thin-film polyimide thermal tape, chosen due to its elasticity and ability to return its original shape without permanent deformation.

The manufacturing process of the structure is carried out in the following stages:

1. Methacrylate cylinders are purchased [13], then cut and drilled according to the geometry shown in Fig. 2a.

2. Two methacrylate cylinders are obtained to serve as the initial and final waveguides, each with a length of l_{wg} as presented in Fig. 2b.

3. Wires are used as separating elements between the unit cells, as illustrated in Fig. 2c

4. Thin-film polyimide (Kapton material) [14] membranes are trimmed and placed next to each unit cell, ensuring proper fixation, as depicted in Fig. 2d.

5. All previously prepared parts are assembled, resulting in the complete structure, as seen in Fig. 2e.

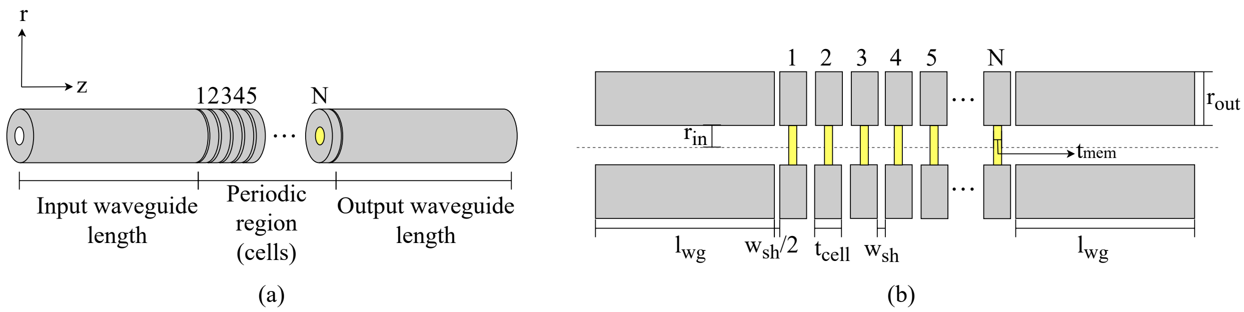

Figure 1: Geometry of the proposed design for the ALWA. (a) 3D view, (b) 2D longitudinal plane, where the discontinuous horizontal line represents the symmetry axis of the antenna.

4. ANALYSIS AND RESULTS

This section presents the results obtained from the analyses performed. In the experimental tests, the ALWA was measured in a real outdoor environment. It was configured in receiver mode by installing a microphone (model CMEJ-0627-42-P) in the input waveguide. As the emitting source, a loudspeaker (model NTi Audio TalkBox) was placed at 1 m. This device emitted white noise while rotating around the antenna, covering an angular range of $-90°$ to $90°$ with $5°$ increments.

The angular response of the ALWA is shown in Fig. 3, where the results of the studied methods are compared. It can be seen that the theoretical (presented in [11]) and numerical models are very similar, with only a small variation at higher frequencies (from $\sim$3000 Hz). This is because the numerical model takes into account the coupling of the unit cells, so the result is more accurate. On the other hand, the experimental measurements closely match the models studied, albeit with a slight deviation, probably caused by small imperfections in the antenna fabrication and the external environmental conditions in which it was measured.

Regarding the radiation patterns obtained in Fig. 4, an example is shown for the scanning angles of $-30°$, $0°$ and $30°$, considering the frequencies of 2530 Hz, 2800 Hz, and 3060 Hz, respectively. The numerical and experimental results exhibit a strong agreement, confirming the accuracy of the developed numerical model. In addition, the patterns show clear directivity and a well-defined beam scanning. Specifically, the half-power beamwidth of the main lobe is $30°$ at the frequency of 2530 Hz, $12°$ at 2800 Hz, and $16°$ at 3060 Hz. These results indicate a change in beam behavior as the operating frequency is varied, as expected.

5. CONCLUSION

In this work, the design of an ALWA capable of radiating in the angular space from backwards to forwards through broadside by varying the radiation frequency has been presented. The results were validated through numerical studies as well as experiments, demonstrating the practical functionality of this antenna design.

Although this study was conducted and validated for an antenna design in air, it highlights the disruptive potential of the ALWAs for the precise location of sound sources, which can open new opportunities, particularly in underwater acoustic communications.

6. ACKNOWLEDGMENTS

This work was the result of the ThinkInAzul and AgroAlNext programmes, funded by Ministerio de Ciencia, Innovación y Universidades (MICIU) with funding from European Union NextGenerationEU/PRTR-C17.I1 and by Fundación Séneca with funding from Comunidad Autónoma Región de Murcia (CARM). This work was also supported by the grants PID2023-148214OB-C21, TED2021-129336B-I00, PID2022-141193OB-I00 and PID2022-138321NB-C22 funded by MICIU/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR and FEDER/EU. This work was also funded by Fundación Séneca (22236/PDC/23). Alejandro Fernández-Garrido thank Omar Bustamante for his help in the beginning of this research.

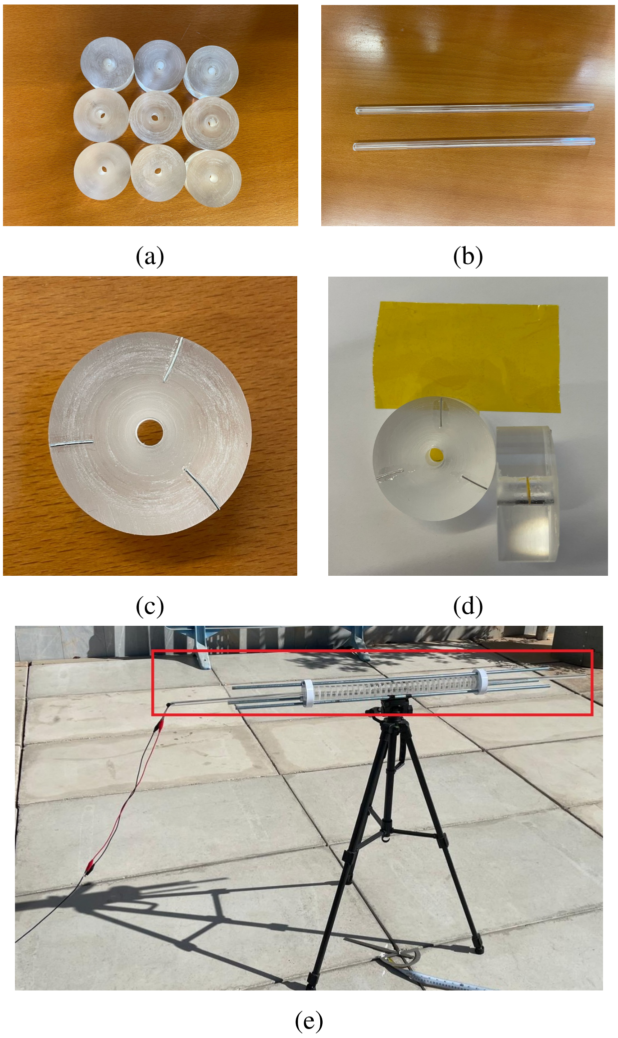

Figure 2: Steps of antenna fabrication. (a) Unit cells, (b) input and output waveguides, (c) wires for units cell separation, (d) cells with membranes, (e) full design.

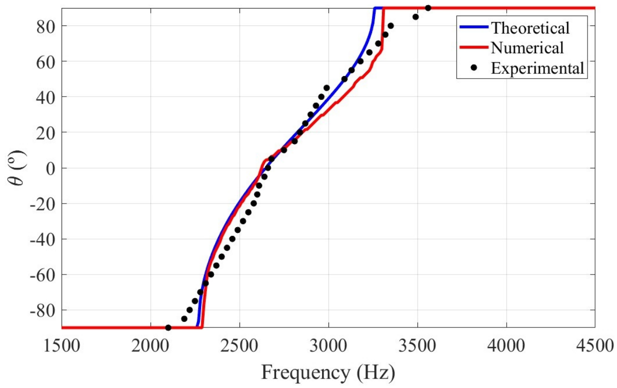

Figure 3: Theoretical, numerical and experimental comparison of the angular response of the ALWA.

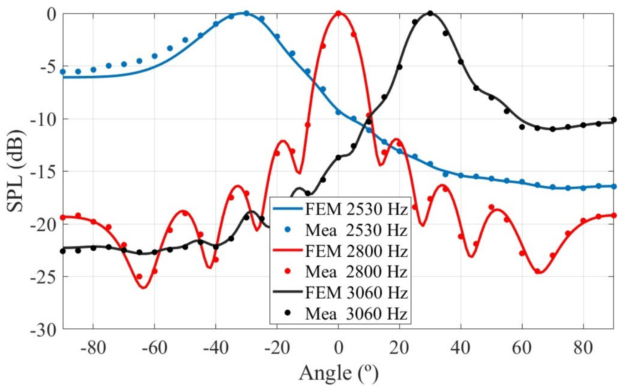

Figure 4: Radiation patterns obtained from the numerical and experimental models. The solid line represents the numerical model obtained by FEM simulation, while the dotted line corresponds to the measurements performed with the antenna.

7. REFERENCES

[1] I. Felis-Enguix, J. Otero-Vega, M. Campo-Valera, I. Villó-Pérez, and J.-L. Gómez-Tornero, "Practical aspects of acoustic leaky-wave antennas applied to underwater direction finding," *Engineering Proceedings*, vol. 2, no. 1, p. 93, 2020.

[2] F. Bongard, H. Lissek, and J. R. Mosig, "Transmission line based metamaterials for acoustic waves," in *2011 XXXth URSI General Assembly and Scientific Symposium*, pp. 1–4, IEEE, 2011.

[3] E. Romero-Vivas and B. Leon-Lopez, "Analogy of the dolphin jaw to a metamaterial leaky wave antenna for sound directional detection," *Journal of Sound and Vibration*, vol. 604, p. 118987, 2025.

[4] F. Monticone and A. Alu, "Leaky-wave theory, techniques, and applications: From microwaves to visible frequencies," *Proceedings of the IEEE*, vol. 103, no. 5, pp. 793–821, 2015.

[5] F. Bongard, H. Lissek, and J. R. Mosig,

"Acoustic transmission line metamaterial with negative/zero/positive refractive index," *Physical Review B—Condensed Matter and Materials Physics*, vol. 82, no. 9, p. 094306, 2010.

[6] H. Lissek, H. Esfahlani, S. Karkar, and J. R. Mosig, "Développement et validation d'une d'antenne acoustique à ondes de fuite," *Actes du 13e Congrès Français d'Acoustique*, pp. 623–629, 2016.

[7] Q. Wang, J. Lan, Z. Deng, Y. Lai, and X. Liu, "Acoustic source localization based on acoustic leaky-wave antenna with heterogeneous structure," *The Journal of the Acoustical Society of America*, vol. 153, no. 1, pp. 487–495, 2023.

[8] C. W. Broadman, C. J. Naify, M. J. Lee, and M. R. Haberman, "Design of a one-dimensional underwater acoustic leaky wave antenna using an elastic metamaterial waveguide," *Journal of Applied Physics*, vol. 129, no. 19, 2021.

[9] D. R. Jackson, C. Caloz, and T. Itoh, "Leaky-wave antennas," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2194–2206, 2012.

[10] A. A. Oliner, D. R. Jackson, and J. Volakis, "Leaky-wave antennas," *Antenna engineering handbook*, vol. 4, p. 12, 2007.

[11] A. Fernández-Garrido, M. Campo-Valera, E. Abdo-Sánchez, R. Picó, A.-J. Garcia-Sanchez, and R. Asorey-Cacheda, "Parametric study and experimental validation of acoustic leaky wave antenna in spatial localization," *IEEE Access*, vol. 13, pp. 10371–10385, 2025.

[12] C. J. Naify, M. Haberman, M. Guild, and C. Sieck, "Acoustic leaky wave antennas: Direction-finding via dispersion," *Acoust. Today*, vol. 14, no. 3, pp. 31–38, 2018.

[13] GUCOBA, "Methacrylate." `https://goo.su/v8S9`.

[14] Olimex LTD, "1188-KAPTON-TAPE40MM-ND." `https://goo.su/VLBfyk`.