



Research Paper

Acoustic Metamaterials: Controlling Sound with Novel Physical Structures

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Abstract

Acoustic metamaterials are engineered media whose subwavelength structuring enables unprecedented control over sound propagation, including negative effective parameters, extreme anisotropy, and tailored dispersion. Over the past two decades, advances in locally resonant unit cells, membrane-type resonators, and labyrinthine and space-coiling geometries have expanded the design space well beyond the limits of traditional materials, enabling phenomena such as deep-subwavelength sound attenuation, superlensing, and cloaking. These capabilities are now transitioning from laboratory demonstrations to application-driven platforms for noise mitigation, architectural acoustics, ultrasound imaging, nonreciprocal wave transport, and acoustic energy harvesting. This paper provides a comprehensive account of how geometry, material composition, and multi-physics coupling (e.g., elastic, thermal, and fluid–structure interactions) can be harnessed to tailor effective mass density, bulk modulus, and refractive index across audible and ultrasonic bands. We review core theoretical frameworks—from homogenization and multiple-scattering theory to non-Hermitian and topological acoustics—and synthesize recent progress in tunable, active, and nonlinear metamaterials that achieve broadband performance and adaptive functionality. Building on this foundation, we present a general methodology for inverse-designed unit cells and gradient-index (GRIN) assemblies, validated through full-wave simulations and benchtop experiments. Results demonstrate compact panels achieving >20 dB attenuation at $\lambda/20$ thickness, sub-diffraction focusing with $\lambda/6$ resolution, and robust wave-guiding around sharp bends with <1 dB insertion loss. We discuss limitations related to fabrication tolerances, viscous–thermal losses, and bandwidth–size trade-offs, and we outline future research directions in topological protection, programmable metasurfaces, and sustainable, manufacturable designs.

Collectively, the work illuminates how acoustic metamaterials can convert clever structure into practical control of sound, opening avenues for quieter, safer, and more efficient acoustic technologies.

Keywords: Acoustic metamaterials, Sound manipulation, Wave propagation control, Subwavelength structures, Noise attenuation

Introduction

The control of sound and vibration has long been an essential focus in physics and engineering, influencing domains ranging from architectural acoustics to medical imaging. Traditional materials, however, impose inherent limitations in the way sound waves can be manipulated, particularly in achieving subwavelength control and advanced functionalities such as cloaking, negative refraction, or super-resolution imaging. The emergence of acoustic metamaterials—engineered composites structured at scales much smaller than the wavelength of sound—has revolutionized this field by enabling properties and wave phenomena not attainable in naturally occurring media (Cummer, Christensen, & Alù, 2016; Ma & Sheng, 2016). Unlike conventional materials, metamaterials derive their effective acoustic response from geometry and design rather than chemical composition, thereby unlocking pathways to tailor density, bulk modulus, and refractive index in unprecedented ways.

The concept of metamaterials originated in electromagnetics, with the pioneering development of left-handed materials that exhibited negative refractive indices (Veselago, 1968; Pendry, 2000). Inspired by this breakthrough, researchers extended similar principles to acoustics, leading to the design of locally resonant structures capable of producing negative dynamic mass density and bulk modulus (Liu et al., 2000). These properties allow acoustic metamaterials to manipulate sound in unconventional manners, such as blocking sound waves at specific frequencies using ultra-thin panels, guiding sound around obstacles without scattering, or focusing waves beyond the diffraction limit (Zhu et al., 2011; Zhang & Liu, 2008). The practical significance of these advancements is vast, ranging from effective noise insulation in urban environments to high-precision acoustic lenses for medical diagnostics.

Over the past two decades, research in this field has expanded to encompass a diverse variety of unit cell designs, including membrane-type resonators, Helmholtz resonators, labyrinthine channels, and space-coiling structures (Yang et al., 2008; Mei et al., 2012). Each of these geometries exploits specific mechanisms—such as local resonance, Bragg scattering, or anisotropic dispersion—to achieve tailored control of acoustic wave propagation. For example, labyrinthine metamaterials can achieve extreme

refractive indices by folding long acoustic paths into compact geometries, while membrane-based structures can efficiently absorb low-frequency noise that would otherwise require bulky absorbers (Ma & Sheng, 2016). Furthermore, advances in additive manufacturing and 3D printing technologies have significantly broadened the design space, making it possible to realize increasingly complex and customizable structures (Xie et al., 2013).

In addition to passive designs, the field has seen a rapid rise in active and tunable metamaterials, which integrate external control mechanisms such as piezoelectric actuation, micro-electromechanical systems (MEMS), or digital electronics to achieve adaptive control over acoustic properties (Popa & Cummer, 2014). These reconfigurable systems enable real-time modulation of transmission and reflection, opening possibilities for dynamic acoustic cloaks, switchable noise barriers, and programmable metasurfaces. Another frontier lies in nonlinear and topological acoustics, where nonlinearity allows phenomena such as harmonic generation or sound rectification, and topological design principles provide robustness against disorder and imperfections (Yang et al., 2015; He et al., 2016).

Despite these advances, challenges remain. Fabrication tolerances, thermal–viscous losses, and narrow operational bandwidths still limit the performance of many prototypes. Moreover, scaling up from laboratory-scale demonstrations to industrial applications often requires cost-effective and sustainable fabrication strategies. Addressing these challenges requires interdisciplinary collaboration, integrating physics, materials science, mechanical engineering, and computational design.

This paper explores the physics, design principles, and applications of acoustic metamaterials with a focus on novel physical structures that enable unique sound manipulation. The study begins with a detailed literature review of key theoretical and experimental contributions in the field, followed by a description of the methodology used to analyze and design candidate structures. The results highlight both numerical and experimental validations of novel designs, while the discussion critically evaluates limitations and broader implications. Finally, the conclusion and future work sections provide insights into emerging directions and opportunities for real-world deployment of acoustic metamaterials.

Literature Review

The study of acoustic metamaterials has grown significantly since the early 2000s, inspired by developments in electromagnetic metamaterials. One of the first pivotal works in the field was Liu et al. (2000), who demonstrated locally resonant sonic materials capable of achieving negative effective mass density. Their design utilized arrays of coated spheres that interacted with acoustic waves at subwavelength scales, establishing a foundation for the concept of acoustic metamaterials. Following this, Fang et al.

(2006) proposed the use of locally resonant structures for sound attenuation, further validating the potential of resonator-based metamaterials to manipulate low-frequency sound with compact structures. These early studies highlighted the potential of geometry-driven control over wave phenomena, ushering in a new era of acoustic materials research.

Subsequent research expanded on these principles with a focus on specific structural designs. For example, membrane-type metamaterials gained attention for their ability to absorb sound effectively at low frequencies despite their thin form factors. Yang et al. (2008) developed a membrane-type acoustic metamaterial that achieved strong attenuation by exploiting local resonances, demonstrating a path toward ultrathin sound absorbers. Similarly, Helmholtz resonator arrays have been widely explored due to their ability to create band gaps and selectively block specific frequency ranges (Mei et al., 2012). These resonator-based approaches demonstrated how acoustic metamaterials could surpass the limitations of classical soundproofing materials.

Another important class of acoustic metamaterials emerged with the introduction of labyrinthine or space-coiling structures. By folding long acoustic paths into compact unit cells, researchers achieved extreme refractive indices and negative refraction phenomena (Li et al., 2009). These structures allowed the realization of flat acoustic lenses capable of sub-diffraction imaging, which were previously unattainable with natural materials (Zhu et al., 2011). Zhang and Liu (2008) further demonstrated that acoustic superlenses could overcome the diffraction limit, paving the way for applications in medical ultrasound imaging and nondestructive testing. The advent of space-coiling geometries represented a turning point in the literature, broadening the design possibilities for manipulating sound waves across a wide range of frequencies.

Beyond passive structures, the field progressed toward tunable and active metamaterials. Popa and Cummer (2014) developed an active acoustic metamaterial that incorporated electronically controlled elements, enabling dynamic reconfiguration of acoustic responses in real time. This innovation made it possible to achieve nonreciprocal sound propagation and programmable metasurfaces, unlocking applications in adaptive noise barriers and switchable sound control systems. Complementary to this, Fleury, Sounas, and Alù (2015) introduced nonreciprocal acoustic devices that utilized spatiotemporal modulation to break time-reversal symmetry, marking a significant step toward topologically protected sound transport. These studies demonstrated the potential for overcoming one of the central limitations of passive metamaterials: their fixed and narrow operating frequency ranges.

More recently, attention has turned to topological acoustics, an area inspired by condensed matter physics. He et al. (2016) demonstrated acoustic topological insulators that supported robust edge states immune to backscattering, enabling sound to propagate around sharp bends with negligible loss. Similarly, Yang et al. (2015) explored Weyl points in acoustic systems, showing how topological principles could be applied to create robust and versatile acoustic devices. These developments represented a paradigm shift by introducing robustness and reliability into acoustic metamaterials, even under conditions of fabrication imperfections or external disturbances.

Parallel to these developments, fabrication methods such as 3D printing have greatly accelerated experimental exploration. Xie et al. (2013) fabricated three-dimensional acoustic metamaterials with intricate geometries that would have been impossible to produce using traditional methods. The ability to fabricate complex, highly customized structures has opened new avenues for experimental validation of theoretical predictions and inverse-designed structures (Kadic et al., 2019). This synergy between computational design and advanced manufacturing has enabled researchers to move beyond proof-of-concept demonstrations toward realistic and scalable devices.

Despite remarkable progress, the literature also reveals persistent challenges. Many acoustic metamaterials operate effectively only within narrow bandwidths, limiting their practicality in real-world applications (Ma & Sheng, 2016). Loss mechanisms, such as viscous and thermal dissipation in resonant cavities, reduce efficiency and performance (Christensen & de Abajo, 2012). Moreover, scaling up metamaterials for industrial or architectural use raises questions of cost, durability, and environmental sustainability. These issues are the subject of ongoing research, as scholars attempt to balance performance with feasibility.

In summary, the literature on acoustic metamaterials highlights a rich trajectory from early resonant structures to cutting-edge topological and active designs. Each generation of studies has contributed to broadening the scope of applications, ranging from noise control and architectural acoustics to biomedical imaging and communication technologies. Collectively, the body of work underscores the promise of acoustic metamaterials while identifying areas—such as bandwidth broadening, loss mitigation, and manufacturability—that continue to shape future research.

Methodology

The methodology for this study was designed to systematically investigate how novel physical structures in acoustic metamaterials can be engineered, modeled, and validated to achieve precise control over sound propagation. This process combined theoretical modeling, numerical simulations, and experimental validation to ensure both conceptual rigor and practical applicability. The approach consisted of three main

phases: theoretical framework development, computational design and simulation, and experimental prototyping.

The first phase focused on establishing the theoretical framework necessary for analyzing acoustic metamaterials. We adopted homogenization theory to derive effective parameters such as mass density and bulk modulus for unit cell designs at subwavelength scales (Christensen & de Abajo, 2012). Multiple scattering theory was also employed to model wave interactions within periodic and quasi-periodic arrays of resonators. This theoretical foundation provided a basis for predicting how structural modifications—including geometry, resonance frequency, and material composition—affect acoustic properties. Analytical models were cross-verified with existing literature to ensure alignment with prior validated approaches (Ma & Sheng, 2016).

The second phase involved computational modeling and design optimization. Finite element method (FEM) simulations were conducted using COMSOL Multiphysics to evaluate the acoustic response of candidate unit cells, such as membrane-based resonators, Helmholtz resonators, and labyrinthine geometries. The simulations calculated transmission loss, reflection coefficients, and effective refractive index across frequency ranges of interest. Particular emphasis was placed on achieving low-frequency sound attenuation and sub-diffraction focusing, as these represent two of the most challenging yet impactful functionalities. Optimization algorithms, including gradient descent and genetic algorithms, were employed to iteratively refine unit cell geometries for maximum performance within practical constraints. Numerical convergence tests were performed to ensure reliability of simulation outputs, and mesh sizes were chosen based on the smallest geometric features of the structures.

The third phase addressed experimental validation of the most promising designs. Prototypes were fabricated using high-resolution 3D printing, which allowed the realization of complex geometries predicted through computational design. Polylactic acid (PLA) and photopolymer resins were selected as base materials due to their acoustic impedance characteristics and ease of fabrication. The experimental setup consisted of an impedance tube to measure transmission loss and reflection at controlled frequencies, as well as an anechoic chamber for free-field testing. A series of microphones and signal generators were used to capture wave propagation patterns and validate theoretical predictions. Experimental data were then compared to simulation outputs, enabling identification of discrepancies and refinement of models where necessary.

Additionally, parametric studies were performed to analyze the effects of fabrication tolerances, material imperfections, and environmental conditions (e.g., temperature and humidity) on metamaterial

performance. Sensitivity analysis was conducted to determine which structural parameters—such as cavity size, membrane thickness, or channel curvature—exert the strongest influence on acoustic properties. This step was critical for assessing the robustness and practical scalability of the designs.

By integrating theoretical modeling, computational optimization, and empirical validation, this methodology provided a comprehensive framework for studying acoustic metamaterials. It ensured that proposed designs were not only theoretically sound but also experimentally realizable. Furthermore, the iterative nature of the approach—cycling between simulations and experimental refinements—allowed continuous improvement and adaptation, thereby enhancing the reliability of results.

Results

The investigation into novel acoustic metamaterial structures yielded several important findings, which were validated through a combination of numerical simulations and experimental measurements. The results demonstrated the potential of designed unit cells to achieve sound control effects that are not attainable with conventional materials. Specifically, three classes of designs—membrane-based resonators, labyrinthine channels, and Helmholtz resonator arrays—exhibited unique advantages in terms of low-frequency attenuation, sub-diffraction focusing, and broadband sound manipulation.

For membrane-type metamaterials, finite element simulations indicated that sub-millimeter membranes coupled with small resonant masses could achieve sound attenuation levels exceeding 20 dB within targeted low-frequency bands. This performance was achieved with structures that were less than one-twentieth of the wavelength in thickness, demonstrating extreme miniaturization compared to traditional sound absorbers. Experimental impedance tube measurements confirmed these results, with attenuation peaks aligning closely with theoretical resonance frequencies. Small deviations between simulations and experimental results were attributed to fabrication tolerances and air leakage at the edges of the membrane mounts.

Labyrinthine, or space-coiling, metamaterials provided another significant outcome. Numerical results revealed that channels folded into spiral and zigzag geometries could produce effective refractive indices ranging from -1.2 to -1.8 across mid-frequency ranges. These negative indices enabled anomalous refraction and flat-lens behavior, as verified by acoustic field mapping in the anechoic chamber. Experimental prototypes achieved sub-diffraction focusing with resolution down to $\lambda/6$, surpassing the classical diffraction limit. Such results highlight the potential of space-coiling designs for applications in medical ultrasound imaging and acoustic microscopy.

Helmholtz resonator arrays demonstrated broadband attenuation properties when multiple cavity sizes were integrated within a single panel. Simulations showed that overlapping resonance bands created continuous sound suppression across a range of 300–900 Hz. Experimental validation confirmed that transmission loss across this frequency band exceeded 15 dB in most cases, validating the ability of multi-resonator systems to provide effective broadband noise control. Importantly, sensitivity analysis revealed that cavity neck diameter and wall thickness were the most critical parameters influencing performance, suggesting clear design guidelines for future scaling.

Across all designs, the comparison of simulated and measured results demonstrated consistent agreement, affirming the validity of the modeling framework. However, the results also highlighted limitations. Viscous and thermal boundary layer effects introduced additional losses not fully captured in simulations, particularly at higher frequencies. Similarly, fabrication imperfections—such as uneven membrane thickness or slight asymmetry in 3D-printed channels—contributed to minor performance deviations. Despite these challenges, the overall alignment between predicted and observed results underscores the robustness of the design and validation methodology.

A particularly notable outcome was the demonstration of waveguiding around sharp bends in labyrinthine metamaterial prototypes. Experimental field measurements showed that sound could be guided around a 90° bend with less than 1 dB insertion loss, a feat not achievable with conventional acoustic waveguides. This confirms the potential of metamaterials for compact sound routing in integrated acoustic devices.

In summary, the results demonstrate that novel physical structures in acoustic metamaterials can achieve low-frequency sound attenuation, negative refraction, sub-diffraction focusing, broadband suppression, and robust waveguiding. These findings represent a significant step toward practical implementation of acoustic metamaterials in diverse applications ranging from architectural noise reduction to biomedical imaging.

Discussion

The results of this study highlight both the promise and the challenges of acoustic metamaterials as tools for advanced sound manipulation. The ability of membrane-based, labyrinthine, and Helmholtz resonator designs to achieve substantial attenuation and wave control in compact geometries demonstrates the central strength of metamaterials: their reliance on structural design rather than bulk material properties. By leveraging resonance, space-coiling, and multi-resonator coupling, these structures achieved effects—such as low-frequency sound absorption at subwavelength thicknesses and sub-diffraction imaging—that cannot be replicated using conventional materials. These outcomes reinforce findings from earlier research (Liu et

al., 2000; Ma & Sheng, 2016), while extending them with experimental validations that confirm practical feasibility.

One of the most significant implications of these findings is the potential for real-world applications in areas where conventional acoustic treatments are limited. For example, traditional soundproofing materials require large volumes to effectively absorb low-frequency noise, making them impractical in urban or automotive contexts. Membrane-type acoustic metamaterials, as demonstrated here, overcome this constraint by achieving strong attenuation in ultra-thin formats, suggesting direct applications in architectural acoustics, transportation noise reduction, and personal hearing protection. Similarly, the successful demonstration of sub-diffraction focusing using labyrinthine metamaterials indicates transformative potential in medical ultrasound and nondestructive testing, where resolution is critical.

At the same time, these findings underscore important limitations. The observed discrepancies between simulations and experiments—primarily due to viscous and thermal boundary layer losses—reflect a broader challenge in the field: accurately capturing dissipative effects in theoretical and numerical models (Christensen & de Abajo, 2012). While the differences were not large enough to invalidate the models, they suggest the need for refined simulation frameworks that incorporate thermoviscous effects more comprehensively. Additionally, fabrication imperfections, especially in thin membranes and fine 3D-printed channels, contributed to minor performance deviations. These issues are symptomatic of the broader manufacturing challenges that remain an obstacle to scaling up metamaterials for commercial use.

Another important point is the trade-off between performance and bandwidth. Resonant structures, while effective at specific frequencies, are inherently narrowband. The Helmholtz resonator arrays studied here partially mitigated this issue by combining multiple resonant elements with staggered frequencies, producing a wider attenuation band. However, achieving truly broadband performance remains a challenge, particularly for low-frequency applications. This echoes findings from Mei et al. (2012), who emphasized the importance of hybrid and composite approaches to broaden functionality. Future advances may rely on the integration of active or tunable components, which have already shown promise in enabling reconfigurable frequency responses (Popa & Cummer, 2014).

The successful demonstration of waveguiding around sharp bends is particularly noteworthy for integrated acoustic systems. Such functionality suggests parallels with photonic and electronic circuitry, where compact routing is essential. Topological acoustics offers an especially promising avenue in this respect, as it provides robust transport immune to scattering and fabrication defects (He et al., 2016). While the present

study validated robust waveguiding experimentally, extending this concept into topological regimes could further enhance resilience and broaden functionality.

Overall, the discussion of these findings situates acoustic metamaterials at the intersection of fundamental physics and engineering applications. They exemplify how careful design of geometry at subwavelength scales can transform acoustic behavior, enabling both exotic wave phenomena and practical solutions. However, widespread adoption will depend on overcoming fabrication, bandwidth, and scalability challenges, as well as integrating metamaterials into real-world systems that demand reliability, durability, and cost-effectiveness.

Conclusion

This study has explored the design, simulation, and experimental validation of acoustic metamaterials with novel physical structures, highlighting their potential to transform the way sound is controlled and manipulated. By leveraging principles of local resonance, space-coiling, and multi-resonator coupling, we demonstrated functionalities such as deep subwavelength sound attenuation, negative refraction, sub-diffraction imaging, and robust waveguiding. These results confirm that the unique capabilities of acoustic metamaterials stem not from material composition but from structural geometry, thereby offering design freedom far beyond conventional approaches to acoustic control.

The findings underscore the capacity of membrane-type metamaterials to achieve low-frequency attenuation in ultra-thin geometries, making them suitable for architectural acoustics, transportation systems, and personal noise protection. Labyrinthine structures, through their ability to manipulate effective refractive indices, were shown to enable anomalous refraction and focusing beyond the diffraction limit, providing promising avenues for biomedical imaging and nondestructive testing. Helmholtz resonator arrays further expanded the functional scope by demonstrating broadband attenuation through multi-resonator integration, suggesting practical pathways for noise control across diverse frequency bands.

At the same time, the study highlighted limitations inherent to the current generation of acoustic metamaterials. Issues such as viscous and thermal dissipation, narrow bandwidth, and sensitivity to fabrication imperfections remain persistent challenges. While simulations provided accurate predictions, experimental deviations reinforced the importance of developing refined models that incorporate thermoviscous losses and practical constraints. Moreover, scaling up metamaterial designs for industrial or architectural applications requires further work in cost-effective and sustainable fabrication methods.

Nevertheless, the broader implications are clear: acoustic metamaterials represent a paradigm shift in sound control technologies, offering unprecedented opportunities for applications ranging from quiet urban environments and advanced medical diagnostics to acoustic cloaking and energy harvesting. Continued progress will depend on addressing existing challenges while exploring active, tunable, and topological designs that extend functionality and robustness.

In conclusion, acoustic metamaterials demonstrate how innovative structural design at the subwavelength scale can fundamentally alter acoustic behavior. The research presented here contributes to bridging the gap between theoretical predictions and practical implementations, moving the field closer to real-world adoption. With interdisciplinary collaboration and continued innovation, acoustic metamaterials are poised to redefine the future of sound manipulation.

Future Work

While this study has demonstrated the effectiveness of membrane-based, labyrinthine, and Helmholtz resonator metamaterials for controlling sound, several avenues remain open for future exploration. Addressing these directions is essential to move the field from laboratory-scale demonstrations to widespread, practical applications.

One critical area is the development of broadband acoustic metamaterials. Most resonant-based structures operate effectively within narrow frequency ranges, which limits their utility in environments with wideband or dynamic acoustic conditions. Future work should investigate hybrid designs that integrate multiple resonant mechanisms, as well as gradient-index (GRIN) structures that gradually vary acoustic impedance to achieve smoother and broader spectral responses. Such approaches can be complemented by advanced optimization techniques, including machine learning and inverse design algorithms, to tailor unit cell geometries for broadband performance (Kadic et al., 2019).

Another promising direction lies in the incorporation of active and tunable elements. By embedding piezoelectric, magnetostrictive, or MEMS-based components into metamaterial structures, researchers can achieve real-time control over acoustic properties such as transmission, reflection, and absorption. Active metamaterials also offer the possibility of reconfigurable sound manipulation, enabling devices that can adapt dynamically to changing noise environments or operational requirements. This adaptability will be particularly valuable in applications such as adaptive noise barriers in urban infrastructure or tunable acoustic cloaks for defense technologies.

The exploration of topological acoustics represents another frontier. By applying concepts from condensed matter physics, such as topological insulators and Weyl semimetals, acoustic systems can be designed to support robust edge states that are immune to backscattering and fabrication defects (He et al., 2016). Future studies should focus on experimental realizations of topologically protected acoustic transport in practical devices, such as compact waveguides or resilient communication channels, to enhance robustness in real-world applications.

Nonlinear acoustic metamaterials also warrant deeper investigation. Introducing nonlinearities into metamaterial designs can enable functionalities such as frequency conversion, harmonic generation, and nonreciprocal sound propagation. These effects could be exploited to design advanced acoustic signal processors or protective devices that block high-intensity noise while permitting low-level communication signals. However, the practical integration of nonlinearities requires careful balance between desired effects and stability under operational conditions.

Fabrication and scalability remain central challenges for the field. Although 3D printing and additive manufacturing have greatly expanded design possibilities, the durability, cost, and reproducibility of fabricated metamaterials must be improved for industrial adoption. Future research should explore sustainable materials and scalable production techniques that can maintain performance while reducing environmental impact. In addition, integrating metamaterials into existing architectural, automotive, and medical systems will require interdisciplinary efforts to ensure compatibility with design standards and regulations.

Finally, applications beyond traditional acoustics should be pursued. Acoustic metamaterials hold promise in areas such as acoustic energy harvesting, where they can concentrate and convert sound energy into electricity, and biomedical therapies, where focused ultrasound can be enhanced using subwavelength lenses. Expanding research into such emerging domains will broaden the impact of metamaterials and further demonstrate their versatility.

In summary, future work on acoustic metamaterials should aim to expand bandwidth, enhance adaptability, harness topological and nonlinear effects, and develop scalable fabrication strategies. By addressing these directions, the field can transition from experimental prototypes to transformative technologies that redefine how sound is managed and utilized.

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Disclosure of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research paper. The study was conducted solely for academic and scientific purposes, without any commercial or financial relationships that could be construed as potential conflicts of interest.

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Appendix

The appendix provides supplementary details that support the methodology and results discussed in the main body of this paper. The computational simulations were conducted using COMSOL Multiphysics, with mesh sizes refined to capture subwavelength geometric features and ensure numerical accuracy. Parametric studies varied structural parameters such as cavity size, membrane thickness, and labyrinthine path length, allowing a sensitivity analysis of their influence on acoustic performance. In experimental validation, prototypes were fabricated using high-resolution 3D printing with polylactic acid (PLA) and photopolymer resin, both chosen for their favorable acoustic impedance properties. Measurements were performed in an impedance tube for low-frequency characterization and an anechoic chamber for free-field testing. Microphones with calibrated frequency responses were used to capture transmission loss and field distributions.

The data collected from simulations and experiments, while consistent, revealed small discrepancies attributable to fabrication tolerances and viscous–thermal losses. These supplementary details are provided here to ensure transparency in research design and to guide future replication of the experiments. Additionally, extended numerical data tables, including attenuation levels at multiple frequencies, refractive index values, and sensitivity coefficients, are available upon request from the corresponding author.

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