Chinese Physics Letters **42**, 014301 (2025) **Perspective**

Active Acoustic Metamaterials

Xulong Wang(王绪隆)[1,2] and Guancong Ma(马冠聪)[1,3*]

[1]*Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong, China*
[2]*Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[3]*Shenzhen Institute for Research and Continuing Education, Hong Kong Baptist University, Shenzhen 518000, China*

(Received 10 October 2024; accepted manuscript online 4 December 2024)

DOI: 10.1088/0256-307X/42/1/014301 CSTR: 32039.14.0256-307X.42.1.014301

The history of acoustic metamaterials can be traced back to the turn of the 21st century, when the local resonances of subwavelength structures were leveraged for acoustic properties unavailable in natural materials.[1] Over a quarter of a century, acoustic metamaterials have continued to thrive as numerous novel acoustic effects have been investigated and realized.[2–6] However, acoustic metamaterials were entirely passive in their early days, thus indicating that their functionalities were singular and entirely determined at the fabrication stage. Additionally, even at the effective-medium level, such passive metamaterials must obey fundamental laws, such as time-reversal symmetry and causality. These limitations can be overcome by employing active components in metamaterial design. Thus, we surveyed the development, functionalities, and implications of active acoustic metamaterials.

Nonreciprocity via Moving Media. Linear time-invariant acoustic systems are time-reversal invariant and, therefore, obey reciprocity. This characteristic can be disrupted through the incorporation of moving media, which introduces the Doppler effect and breaks the time-reversal symmetry.[7] A notable demonstration of this principle is the acoustic circulator, which is an annular acoustic resonator with a constant circulating airflow.[8] The cavity sustains two degenerate acoustic modes that are counter-propagating traveling waves. The presence of circulating airflow introduces the Doppler effect, which increases (decreases) the resonant frequency of the mode traveling with (against) the airflow. This device functions as a three-port isolator and demonstrates nonreciprocal transmission among the ports. By modulating the hybrid junctions in a ring resonator, various nonreciprocal couplers, including rat-race couplers,[9] can be effectively implemented. Additionally, the moving medium (airflow) can be modeled as a static external magnetic field in the wave equation. This analogy offers essential insights into the quantum Hall effect and subsequently inspired a series of early adaptations of topological insulators in acoustics,[10–12] which were then experimentally confirmed.[13]

Nonreciprocity induced by moving media has become a productive approach for many innovative acoustic effects. Geometrically asymmetric structures introduce Willis coupling, which respects reciprocity and time reversal. Airflow can break time-reversal symmetry, thus enabling odd Willis coupling and nonreciprocal metagratings.[14] Furthermore, a resonant unit cell with a rotating inner core generates a bias through the circulating fluid, thereby allowing decoupled phase modulations. This approach enables Janus acoustic metascreens.[15] Collectively, the foregoing studies illuminate new pathways for compact asymmetric sound wave engineering, with applications in biomedical imaging, sonar technology, and wavefront engineering rooted in the principles of pressure-velocity coupling.

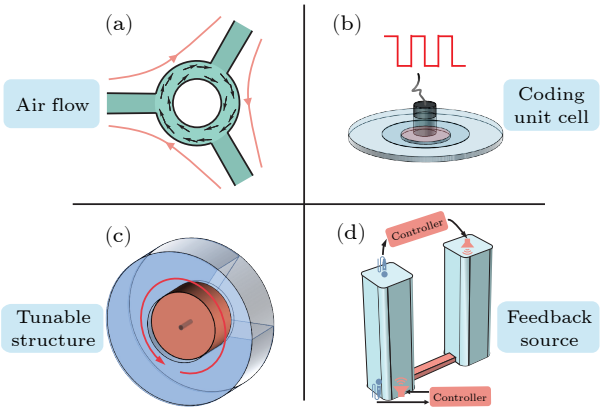

Fig. 1. Methods of active control in acoustic metamaterials. (a) Circulating airflow that breaks reciprocity in an acoustic cavity.[8] (b, c) Alternation of resonances via programmable electrical components, e.g., electromagnets[34] (b) and motorized structures[36] (c). (d) Programmable acoustic feedback.[57]

Actively Tunable Acoustic Resonances Enabling Reconfigurable and Programmable Metamaterials and Metasurfaces. Although acoustic metamaterials and metasurfaces have significantly expanded our wave-controlling capabilities, they cannot be altered after fabrication in the

*Corresponding author. Email: phgcma@hkbu.edu.hk
© 2025 Chinese Physical Society and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

early days. In contrast to the interference between the acoustic modes in a ring resonator influenced by airflow, the active tuning of resonant units provides a more direct method for wave manipulation. The incorporation of active reconfigurability or programmability is a sophisticated technique that not only enhances the adaptability of designs but also provides unprecedented possibilities for sound control. Active metamaterials transcend material-based limitations by incorporating electronically controlled elements that afford precise manipulation of their acoustic characteristics.[16–18] Consequently, they exhibit a broad spectrum of effective parameters, thus demonstrating their enhanced versatility and functionality. An initial experimental endeavor involved the integration of transducers and electronic circuits, which were designed to achieve negative refraction, negative effective mass density, and bulk modulus.[16] The coupling of sensing and driving transducers, along with the incorporation of electronic feedback loops, enabled the realization of advanced functionalities. Furthermore, the development of compact active meta-atoms has demonstrated their adaptability and potential for novel applications, and the incorporation of additional feedback control mechanisms has introduced a new approach for achieving acoustic nonreciprocal transmission.[19,20] Subsequently, researchers have shifted their focus to the programmability of resonant unit structures. Advanced programmable and coded acoustic metasurfaces have demonstrated remarkable adaptability to sound manipulation, proving to be instrumental in the modulation of the wavefront phase and amplitude.[21–25] By incorporating tunable structures capable of operating across a wide frequency range, researchers have expanded the novel functionalities of acoustic metamaterials, such as the continuous steering of acoustic beams and the precise modulation of acoustic energy flow.[26–31] A notable example of this capability is the fine tuning of acoustic cavity volumes, which enables precise and continuous control over the phase of acoustic waves transmitted through the associated metasurface. This versatility allows a single sample to perform various functions, including adjustments to focal distances, redirection of beam trajectories, and generation of tweezer-like beams.[32] Another significant example is the integration of programmable circuits to modulate the unit cell configuration in phononic crystals, which facilitates the realization of reconfigurable topological edge states. This advancement has substantially broadened the application scope of topological states.[33,34]

Additionally, actively reconfigurable metasurfaces are essential in extending the concept of adaptive wavefront shaping, which is a robust technology for controlling multiple scattering light, to acoustics. The central component of adaptive wavefront shaping is an optical device known as a spatial light modulator. A spatial light modulator typically comprises a liquid crystal array with individually controllable pixels, each capable of modulating the phase and/or amplitude of the transmitted light. Spatial light modulators are commercially available, ready-to-use devices. However, an equivalent acoustic technology did not exist until the emergence of actively reconfigurable metasurfaces. Two examples of acoustic metasurfaces are piezoelectric sheets and membrane resonators. The former employs thin piezoelectric sensors to create a flexible active array,[35,36] thus enabling precise sound field control and promising applications in ultrasound diagnostics, therapy, and underwater communications. The latter utilizes electromagnets to switch membrane-type resonators between distinct resonant modes, thereby enabling the modulation of the transmitted sound wave's phase between 0 and π. Metasurfaces with hundreds of individually controllable resonator units controlled by a feedback-driven optimization protocol showed that the reverberant sound field in a room can be locally shaped to generate quiet zones or hotspots.[37] Subsequently, researchers showed that this approach can alter the impulse response of a room, thus allowing the spatiotemporal profile of the sound field to be controlled successfully.[38] Recently, reflection-type metasurfaces based on tunable Helmholtz resonators with electrically variable volumes have been used to expand the functionality of complex sound field control by demonstrating crosstalk-free acoustic communication in rooms.[39]

Time Modulation. Whereas active or programmable acoustic metamaterials have significantly expanded the horizons of acoustic wave physics, the pursuit of novel wave–matter interactions has sparked interest in investigating time as a new degree of freedom within metamaterials. Facilitated by the application of explicit temporal modulations to the parameters of physical systems, recent investigations into wave phenomena in the time domain revealed numerous intriguing physical effects. Additionally, recent studies demonstrated the parallelism between temporally controlled acoustic resonance structures and tight-binding models in condensed matter physics. Acoustic non-Abelian braiding and logic gate operations have been realized by implementing flexible circuit designs that support adiabatic evolution.[40] Analogous to the concept of stimulated Raman adiabatic passage, these studies demonstrated robust and complete acoustic energy transfer along with nonreciprocal frequency conversion properties across different sites.[41] A unique class of strongly localized Floquet π modes has been observed in an acoustic temporal lattice featuring time-varying couplings. These modes are characterized by their gauge independence and can be effectively excited at frequencies within the nontrivial bandgap.[42] Furthermore, temporal modulation has emerged as a viable alternative for achieving nonreciprocity. This approach effectively replicates the effects of moving media while mitigating the associated drawbacks, such as extraneous noise, and is not limited to fluidic systems. For instance, dynamic adjustments to the bulk modulus in resonant cavity arrays have yielded promising simulation results, with acoustic isolation exceeding 40 dB while affording loss minimization concurrently.[43] This approach, which introduces a nonreciprocal effect by modulating cavity volumes to simulate circulating airflow, is frequency scalable and integrable to subwavelength devices. In sub-

sequent experiments conducted in two coupled acoustic cavities, a theoretical model based on a time-dependent Schrödinger-type differential equation was employed to demonstrate its capacity for nonreciprocal acoustic transmission. This finding underscores the universality of temporal modulation for achieving nonreciprocity in acoustic transmission.[44] In a waveguide model, an incoming acoustic wave interacts with a rotating elliptical blade, thus resulting in a scattering wave that undergoes harmonic frequency modulation. This interaction induces a frequency shift in a linear time-varying system. When combined with effective acoustic filtering, this mechanism facilitates unidirectional sound propagation at audible frequencies in two opposing directions.[45]

In addition to the aforementioned modulation of mechanical structures, rapid spatiotemporal modulations via actively controlled circuits provide a novel approach for the unidirectional amplification and suppression of scattering. The effective medium theory applied to temporally modulated acoustic metamaterials, along with the temporal averaging of constitutive parameters such as compressibility, density, and Willis coupling terms, enhances the control of time-varying metamaterials.[46,47] In related experiments, programmable dynamic control of acoustic impedance was implemented by spatiotemporally modulating the coupling between an ultrathin membrane and external biasing electromagnetic fields.[48] These experiments demonstrated a range of nonreciprocal mode transitions and steering capabilities for airborne sound waves. Moreover, the timely breaking of continuous translational symmetry introduces an additional dimension to the design of acoustic metamaterials. This development enables the exploration of nonreciprocity, directional amplification, and efficient frequency conversion, among other advanced functionalities.

Non-Hermitian Acoustics. Non-Hermitian systems are open systems that allow energy exchange with external reservoirs. Such systems do not conserve energy, thereby offering greater freedom for achieving new effects and phenomena that have no counterpart in Hermitian systems.[49–51] However, the realization and control of non-Hermitian effects require the control of energy flow, typically in the form of gain/loss or nonreciprocity, which poses significant experimental challenges. Owing to the development of active acoustics, acoustic-wave systems have become an invaluable platform for understanding non-Hermitian physics.[52,53]

Active acoustic components driven by feedback circuits are employed to modulate the non-Hermitian parameters of the system. For example, the instantaneous acoustic amplitude and phase measured using a small microphone are used to control loudspeaker emissions. The emitted sound can either supplement or counter the intrinsic losses in the system, thus effectively realizing gain and (additional) losses. This concept was initially demonstrated using invisible acoustic sensors based on parity-time (PT) symmetry, which comprises pairs of electro-acoustic resonators coupled with appropriately designed non-Foster electrical circuits, thereby forming a coherent perfect absorber-coupled acoustic device.[54] This approach was further validated experimentally via the observation of an exceptional point: a distinct non-Hermitian spectral singularity, where two states coalesced at an identical eigenvalue.[55] Another notable example is the experimental realization of a one-way invisibility acoustic cloak constructed from configurations of gain and lossy acoustic media; this cloak can conceal objects up to seven times larger than the acoustic wavelength.[56] The experimental approach can be similarly used to realize nonreciprocal coupling. For example, in a coupled-cavity configuration, the loudspeaker in a cavity can be set up to respond to the acoustic field in a neighboring unit, whereas a reverse response does not exist. This is an effective method for achieving long-range, complex-valued, and momentum-resolved couplings. Through the construction of a cavity-tube system, researchers have successfully demonstrated the existence of acoustic non-Hermitian Bloch braids and topological transition states.[57,58] The experimental realization of the non-Hermitian skin effect (NHSE) featuring twisted non-Hermitian windings has been successfully demonstrated in acoustic crystals through the design of long-range nonreciprocal couplings.[59] Additionally, the implementation of two-dimensional nonreciprocal acoustic metamaterials has showcased multipolar NHSE and hybrid skin-topological effects, thus facilitating the precise localization of sound fields at specific corners and boundaries in a frequency-selective manner.[60] Furthermore, researchers have investigated an approach for isolating the intrinsic NHSE from homogenous background loss.[61] Notably, extended topological zero modes have been experimentally observed using a one-dimensional non-Hermitian acoustic Su–Schrieffer–Heeger (SSH) model.[62] The results indicate that active acoustics are a convenient and effective method for exploring non-Hermitian physics. Furthermore, the integration of active acoustics with other forms of interaction, such as nonlinearity[63] and Anderson localization, is expected to foster significant advancements and vigorous development in the future.

Another interesting implementation of acoustic gain is the use of the thermoacoustic effect in carbon nanotube films. The thermoacoustic effect converts fluctuating Joule heating into sound. Based on this foundation, a whispering-gallery insulator incorporating a phononic crystal was developed, which demonstrated the ability to support dissipationless topological valley edge states along its interface.[64] Additionally, anti-PT symmetry in an acoustic context has been achieved by introducing gain and loss components into the SSH lattice, thus providing a valuable platform for investigating the topological properties within diverse PT-symmetric phases using sound.[65]

Outlook. In summary, through the smart application of a wide range of physical phenomena and various ingenious designs, active acoustic components have become an indispensable platform for fundamental physics research and an impetus for novel acoustic applications. Continued investigation into active acoustics is expected to yield substantial advancements in both theoretical understanding

and practical implementations, thus ultimately broadening the scope and impact of this field.

References

[1] Liu Z, Zhang X, Mao Y, Zhu Y Y, Yang Z, Chan C T, and Sheng P 2000 *Science* **289** 1734
[2] Cummer S A, Christensen J, and Alù A 2016 *Nat. Rev. Mater.* **1** 16001
[3] Ma G and Sheng P 2016 *Sci. Adv.* **2** e1501595
[4] Assouar B, Liang B, Wu Y, Li Y, Cheng J C, and Jing Y 2018 *Nat. Rev. Mater.* **3** 460
[5] Zangeneh-Nejad F and Fleury R 2019 *Rev. Phys.* **4** 100031
[6] Nassar H, Yousefzadeh B, Fleury R, Ruzzene M, Aù A, Daraio C, Norris A N, Huang G, and Haberman M R 2020 *Nat. Rev. Mater.* **5** 667
[7] Zangeneh-Nejad F and Fleury R 2018 *Appl. Sci.* **8** 1083
[8] Fleury R, Sounas D L, Sieck C F, Haberman M R, and Alù A 2014 *Science* **343** 516
[9] Zangeneh-Nejad F and Fleury R 2019 *J. Acoust. Soc. Am.* **146** 843
[10] Ni X, He C, Sun X C, Liu X, Lu M H, Feng L, and Chen Y F 2015 *New J. Phys.* **17** 053016
[11] Yang Z, Gao F, Shi X, Lin X, Gao Z, Chong Y, and Zhang B 2015 *Phys. Rev. Lett.* **114** 114301
[12] Chen Z G and Wu Y 2016 *Phys. Rev. Appl.* **5** 054021
[13] Ding Y, Peng Y, Zhu Y, Fan X, Yang J, Liang B, Zhu X, Wan X, and Cheng J 2019 *Phys. Rev. Lett.* **122** 014302
[14] Quan L, Yves S, Peng Y, Esfahlani H, and Alù A 2021 *Nat. Commun.* **12** 2615
[15] Zhu Y, Cao L, Merkel A, Fan S W, Vincent B, and Assouar B 2021 *Nat. Commun.* **12** 7089
[16] Popa B I, Zigoneanu L, and Cummer S A 2013 *Phys. Rev. B* **88** 024303
[17] Popa B I, Shinde D, Konneker A, and Cummer S A 2015 *Phys. Rev. B* **91** 220303
[18] Cho C, Wen X, Park N, and Li J 2020 *Nat. Commun.* **11** 251
[19] Geib N, Sasmal A, Wang Z, Zhai Y, Popa B I, and Grosh K 2021 *Phys. Rev. B* **103** 165427
[20] Wen X, Cho C, Zhu X, Park N, and Li J 2024 *Sci. Adv.* **10** eadm9673
[21] Xie B, Tang K, Cheng H, Liu Z, Chen S, and Tian J 2017 *Adv. Mater.* **29** 1603507
[22] Cao W K, Zhang C, Wu L T, Guo K Q, Ke J C, Cui T J, and Cheng Q 2021 *Phys. Rev. Appl.* **15** 024026
[23] Gong K, Zhou X, Ouyang H, and Mo J 2021 *J. Phys. Appl. Phys.* **54** 305302
[24] Zhang H, Xiao Y, Wen J, Yu D, and Wen X 2016 *Appl. Phys. Lett.* **108** 141902
[25] Chen X, Xu X, Ai S, Chen H, Pei Y, and Zhou X 2014 *Appl. Phys. Lett.* **105** 071913
[26] Fan S W, Zhao S D, Chen A L, Wang Y F, Assouar B, and Wang Y S 2019 *Phys. Rev. Appl.* **11** 044038
[27] Wang X L, Yang J, Liang B, and Cheng J C 2019 *Appl. Phys. Express* **13** 014002
[28] Fan S W, Zhu Y, Cao L, Wang Y F, Chen A L, Merkel A, Wang Y S, and Assouar B 2020 *Smart Mater. Struct.* **29** 105038
[29] Wang Y F, Wang Y Z, Wu B, Chen W, and Wang Y S 2020 *Appl. Mech. Rev.* **72** 040801
[30] Choi C, Bansal S, Münzenrieder N, and Subramanian S 2021 *Adv. Eng. Mater.* **23** 2000988
[31] Chen A L, Wang Y S, Wang Y F, Zhou H T, and Yuan S M 2022 *Appl. Mech. Rev.* **74** 020801
[32] Tian Z, Shen C, Li J, Reit E, Gu Y, Fu H, Cummer S A, and Huang T J 2019 *Adv. Funct. Mater.* **29** 1808489
[33] Xia J, Jia D, Sun H, Yuan S, Ge Y, Si Q, and Liu X 2018 *Adv. Mater.* **30** 1805002
[34] Ge Y, Shi B, Xia J, Sun H, Yuan S, Xue H, and Zhang B 2023 *Appl. Phys. Rev.* **10** 031403
[35] Shen Y, Zhu X, Cai F, Ma T, Li F, Xia X, Li Y, Wang C, and Zheng H 2019 *Phys. Rev. Appl.* **11** 034009
[36] Li P Q, Shen Y X, Geng Z G, Cao P C, Peng Y G, and Zhu X F 2020 *J. Phys. Appl. Phys.* **53** 155502
[37] Ma G, Fan X, Sheng P, and Fink M 2018 *Proc. Natl. Acad. Sci.* **115** 6638
[38] Wang Q, Del Hougne P, and Ma G 2022 *Phys. Rev. Appl.* **17** 044007
[39] Zhang H, Wang Q, Fink M, and Ma G 2024 *Nat. Commun.* **15** 1270
[40] Chen Z, Ma L, Ge S, Chen Z G, Lu M, Chen Y, and Lu Y 2024 *Phys. Rev. Appl.* **21** L011001
[41] Chen Z X, Peng Y G, Chen Z G, Liu Y, Chen P, Zhu X F, and Lu Y Q 2024 *Nat. Commun.* **15** 1478
[42] Chen Z, Chen A, Peng Y G, Li Z, Liang B, Yang J, Zhu X F, Lu Y, and Cheng J 2024 *Phys. Rev. B* **109** L020302
[43] Fleury R, Sounas D L, and Alù A 2015 *Phys. Rev. B* **91** 174306
[44] Shen C, Zhu X, Li J, and Cummer S A 2019 *Phys. Rev. B* **100** 054302
[45] Wang Q, Yang Y, Ni X, Xu Y L, Sun X C, Chen Z G, Feng L, Liu X, Lu M H, and Chen Y F 2015 *Sci. Rep.* **5** 10880
[46] Wen X, Zhu X, Wu H W, and Li J 2021 *Phys. Rev. B* **104** L060304
[47] Zhu X, Wu H W, Zhuo Y, Liu Z, and Li J 2023 *Phys. Rev. B* **108** 104303
[48] Chen Z, Peng Y, Li H, Liu J, Ding Y, Liang B, Zhu X F, Lu Y, Cheng J, and Alù A 2021 *Sci. Adv.* **7** eabj1198
[49] El-Ganainy R, Makris K G, Khajavikhan M, Musslimani Z H, Rotter S, and Christodoulides D N 2018 *Nat. Phys.* **14** 11
[50] Ashida Y, Gong Z, and Ueda M 2020 *Adv. Phys.* **69** 249
[51] Ding K, Fang C, and Ma G 2022 *Nat. Rev. Phys.* **4** 745
[52] Gu Z, Gao H, Cao P C, Liu T, Zhu X F, and Zhu J 2021 *Phys. Rev. Appl.* **16** 057001
[53] Huang L, Huang S, Shen C, Yves S, Pilipchuk A S, Ni X, Kim S, Chiang Y K, Powell D A, Zhu J, Cheng Y, Li Y, Sadreev A F, Alù A, and Miroshnichenko A E 2024 *Nat. Rev. Phys.* **6** 11
[54] Fleury R, Sounas D, and Alù A 2015 *Nat. Commun.* **6** 5905
[55] Shi C, Dubois M, Chen Y, Cheng L, Ramezani H, Wang Y, and Zhang X 2016 *Nat. Commun.* **7** 11110
[56] Li H, Rosendo-López M, Zhu Y, Fan X, Torrent D, Liang B, Cheng J, and Christensen J 2019 *Research* **2019** 8345683
[57] Zhang Q, Li Y, Sun H, Liu X, Zhao L, Feng X, Fan X, and Qiu C 2023 *Phys. Rev. Lett.* **130** 017201
[58] Zhang Q, Zhao L, Liu X, Feng X, Xiong L, Wu W, and Qiu C 2023 *Phys. Rev. Res.* **5** L022050
[59] Zhang L, Yang Y, Ge Y, Guan Y J, Chen Q, Yan Q, Chen F, Xi R, Li Y, Jia D, Yuan S Q, Sun H X, Chen H, and Zhang B 2021 *Nat. Commun.* **12** 6297
[60] Zhang Q, Leng Y, Xiong L, Li Y, Zhang K, Qi L, and Qiu C 2024 *Adv. Mater.* **36** 2403108
[61] Xiong L, Zhang Q, Feng X, Leng Y, Pi M, Tong S, and Qiu C 2023 arXiv:2312.11490 [cond-mat.other]
[62] Wang X, Wang W, and Ma G 2023 *AAPPS Bull.* **33** 23
[63] Guo X, Lissek H, and Fleury R 2023 *Commun. Phys.* **6** 93
[64] Hu B, Zhang Z, Zhang H, Zheng L, Xiong W, Yue Z, Wang X, Xu J, Cheng Y, Liu X, and Christensen J 2021 *Nature* **597** 655
[65] Hu B, Zhang Z, Yue Z, Liao D, Liu Y, Zhang H, Cheng Y, Liu X, and Christensen J 2023 *Phys. Rev. Lett.* **131** 066601