The Blossoming of Ultrasonic Metatransducers

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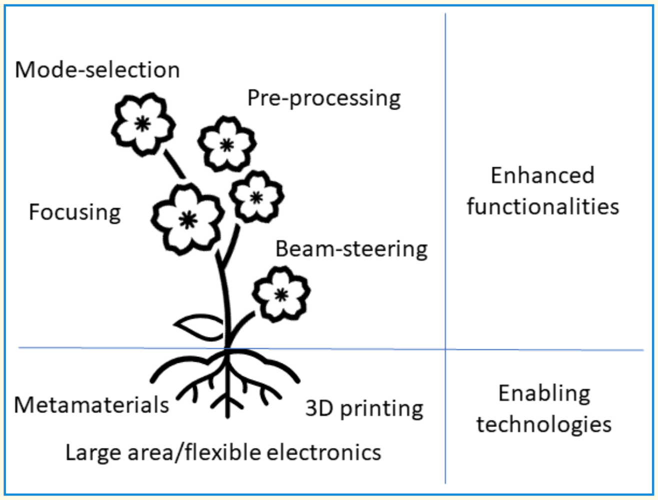
***Abstract*—Key requirements to boost the applicability of ultrasonic systems for in situ, real-time operations are low hardware complexity and low power consumption. These features are not available in present-day systems due to the fact that US inspections are typically achieved through phased arrays featuring a large number of individually controlled piezoelectric transducers and generating huge quantities of data. To minimize the energy and computational requirements, novel devices that feature enhanced functionalities beyond the mere conversion (i.e., metatransducers) can be conceived. This article reviews the potential of recent research breakthroughs in the transducer technology, which allow them to efficiently perform tasks, such as focusing, energy harvesting, beamforming, data communication, or mode filtering, and discusses the challenges for the widespread adoption of these solutions.**

***Index Terms*—Beamforming, focusing, metamaterials, mode selection, ultrasonic transducers (UTs).**



I. INTRODUCTION

PIEZOELECTRIC ultrasonic transducers (UTs), depending on their intended application, may come in a variety of shapes: disks, rings, plates, cylinders, and hemispheres. The shaping is instrumental in letting them resonate and efficiently convert mechanical and electrical energies to meet specific imaging needs, offering varying levels of resolution, penetration depth, and field of view [1]. The application of these devices in biomedical or material inspections has found increasing success, although there are also case studies in which traditional transducers have functional or cost limitations that prevent their use. For example, ultrasonic systems based on large phased arrays are bulky, stationary, and monofunctional, thus resulting to be impractical for the implementation of continuous health monitoring and on-demand medical therapy at the point of care [2]. To tackle this issue, the scientific community is investigating novel implantable or highly integrated systems suitable for long-term continuous imaging [3].

Ultrasonic inspections are also widely adopted for structural health monitoring (SHM) [4] due to the increasing demand for safer structures and infrastructures. Even in this field, the realization of permanently installed systems operating in real time on large structures poses major technical challenges, due to the severe requirements in terms of energy consumption, weight, and ease of installation [5].

Fortunately, recent manufacturing technology advancements are enlarging the conventional transducer design space. An extensive study on such advancements from the perspective of piezoelectric material strategies is presented in [6]. Here, it will be reviewed how the new degrees of freedom in terms of shapes may concur to lower the geometrical and energy footprint of inspection systems by incorporating additional functionalities beyond transduction.

In particular, the developments in 3-D printing and microfabrication technologies may foster the design of UT subcomponents made of *metamaterials*, i.e., artificial materials designed to control and manipulate waves in ways not found in natural materials, for example, by obtaining negative refractive index and cloaking [7]. Depending on their geometrical arrangement, or on their intended functionality, the terms *metasurfaces* or *metalens* have been used to describe the devices, which allow such flexible manipulation of wavefronts [8], [9]. By analogy, in this article, UTs, which utilize combinations of uniquely designed piezoelectric or passive materials, structures, and shapes to provide enhanced manipulation of acoustic waves and/or signal-processing capabilities at low cost and complexity, will be referred to as *metatransducers*. The main technological solutions that are paving the way to the blossoming of such ultrasonic metatransducers are discussed in Section II, while Sections III–VI will be dedicated to the principal functionalities that are deemed to

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Highlights

- **The UT design space is benefiting from numerous manufacturing technology advancements.**
- **Metatransducers with enhanced functionalities beyond the mere conversion are being conceived and are reviewed in this article.**
- **Metatransducers may pave the way to easily deployable and efficient ultrasonic systems.**

be suitable for integration in the transducers, i.e., focusing, mode selection, and beamforming. A discussion on possible, more advanced, integrable functionalities and the conclusions will end this article.

II. NEW TECHNOLOGIES FOR UT FABRICATION

Due to the usage of high processing temperature, hazardous materials, and expensive apparatus, piezo-transducer fabrication methods are typically characterized by low-volume production and poor versatility. However, new additive manufacturing and micromachining solutions are emerging that may overcome these limitations, making the manufacturing process more time and cost effective, and the transducer geometry design space more flexible.

For example, in [10], a strategy to fabricate piezoelectric films, arbitrary micropatterns, and nanoparticles is proposed. In [11], an optimized piezoceramic printing and processing solution is proposed, which allows the production of microtransducers with flexible geometries and complex architectures approaching the properties of pristine ceramics. Stereolithographic methods [12] can also be used to design complex-geometry piezoceramic transducers, overcoming the fabrication difficulty associated with the brittleness of such material. Laser additive manufacturing techniques are demonstrated in [13] to realize Langevin-type transducers, which can realize actuators, sensors, and energy harvesting devices. Additional progresses in the additive manufacturing of piezoelectric materials are reviewed in [14]. Among the achieved benefits brought by this fabrication method, we can include increasing the electromechanical conversion efficiency, and improving the sensitivity and the frequency range. These methods may also be used to modulate the piezoelectric constants, by properly designing the 3-D active topologies, and to make the electrical response dependent on the position, size, and direction of the stimuli. The mechanical response of the device may be changed as well, to simultaneously monitor and absorb impacts [15]. Also, the dual usage of piezo-transducers as sensors and energy harvesters has gained a lot of attention in the biomedical field. For example, [16] reviews how piezoelectric materials and their geometrical structure design can be engineered to optimize the mechanical and electrical performances of nanogenerators, including their flexibility and stretchability.

Guided wave (GW) transducers are typically realized with simple piezoelectric patches or diaphragms [17] operating as actuators and sensors and often directly bonded to the structure to be inspected. For this reason, a desirable feature for GW UT is conformability to the inspected medium [18]. To achieve this characteristic, the recent technological breakthroughs in **flexible** piezoelectric materials fabrications are certainly beneficial [19]. For example, in [20], conformable surface acoustic wave (SAW) devices are realized with an innovative aerosol jet printer. To overcome the brittleness of piezoelectric ceramic materials and the poor thermal stability of polyvinylidene fluoride (PVDF), it is also possible to resort to discontinuous piezoelectric ceramic powders dispersed in 3-D connected polymer matrices. As demonstrated [21], with this material, sensors conformable to curved structures, impact-resistant, and sensitive to GWs can be realized. Similarly, in [22], the applicability of tape-casted piezoelectric composite sensors for GW inspections is investigated, providing promising results.

Other technological solutions tackle the problem of **embedding** piezoelectric transducers in self-sensing smart composite laminates [23]. Fiber-optic and piezoelectric sensor embedding strategies are reviewed also in [24], with a specific focus on SHM applications. In this context, piezoelectric transducers are the only viable solution for active monitoring; however, the risk in the embedding process is to reduce the ultimate strength of the laminate [25]. As demonstrated in [26], the piezoelectric functionalization of composite laminates can be achieved by interleaving PZT micropowder between GFRP prepreg plies, without compromising the strength of the hosting material, and minimizing the risk of triggering the formation of delaminations. A similar approach is reported in [27], where the reinforcement of CFRP coupons with piezo-nanoparticles is used to achieve *self-powered* damage detection capabilities.

III. FOCUSING AND OMNIDIRECTIONAL TRANSDUCERS

In many application domains, ultrasound must be focused to improve image resolution and penetration [33]. The delivery of focused ultrasound to specific areas can involve the design of micrometer-scale transducer arrays for achieving finer spatial resolution and higher energy efficiency [34]. Novel technologies based on *time reversed acoustics* [35] may address the technical difficulties in designing arrays with hundreds of elements for ultrasound focusing. In [36], the ability of a 3-D time reversal cavity combined with a 1-MHz linear array transducer to focus ultrasound in shock wave therapy is demonstrated.

The reshaping of the transducer or the use of innovative *acoustic lenses* may also improve the capability to concentrate multiple intersecting US beams on a target. For example, oblong-shaped-focused transducers are proposed in [37] to reduce the diffraction spreading effect of ultrasound waves in intravascular ultrasound (IVUS) tissue harmonic imaging,

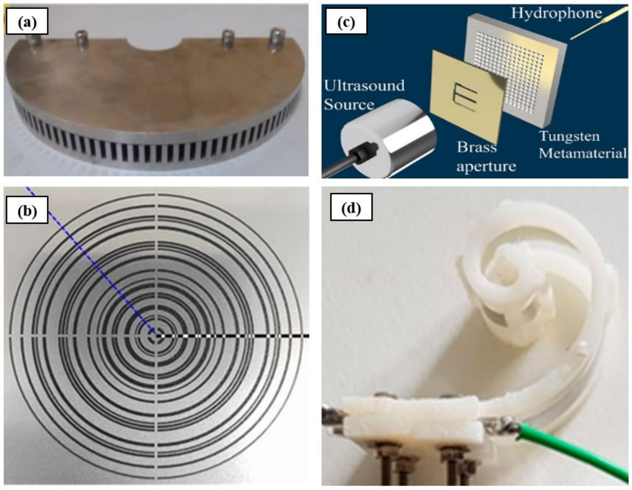

Fig. 1. Focusing subcomponents. (a) Hyperlens proposed in [28]. (b) Ultrathin super-oscillatory acoustic lens introduced in [29]. (c) Metasurface used in [30] to demonstrate subwavelength imaging performances. Conversely, subplot (d) represents an omnidirectional UT realized with a spiral-shaped 3-D-printed support [31]. Subplots (a)–(d) are used under CC BY 4.0 [32], cropped from the original.

while [38] presents a focused UT with double-parabolic-reflector waveguide that can achieve wideband (0–2.5 MHz), multiharmonic mode excitation. More recent works present the experimental realization of ultrathin acoustic lenses for subwavelength focusing [29] in the MHz range [see Fig. 1(b)], the use of polymer trapped-air lenses designed at 500 kHz for ultrasound focusing in water [39], and 3-D-printed acoustic lenses for improving the performance of ultrasound beams, such as those targeting the brain [40], or for row–column address transducers [41]. In [42], simultaneous acoustic energy transfer and communication for implantable medical applications are demonstrated, with a device whose focus can be adjusted by changing the geometry of a flexible base. Flexible piezoelectric UTs with adjustable curvature for achieving variable acoustic focus are shown in [43].

A large number of lens solutions are based on phononic crystals and acoustic metamaterials [44]. Such superlenses may enable far-field **super-resolution** imaging, allowing the magnification of subwavelength features and the achievement of super-resolution in the far-field. For example, in [45], the collimation effect was realized through the use of a 2-D phononic crystal made of stainless-steel rods. Another noticeable practical realization is presented in [28] [see Fig. 1(a)], while in [30], it has discussed the use of holey structure metamaterials [depicted in Fig. 1(c)] relying on Fabry–Pérot resonances to achieve ultrasonic imaging of subwavelength apertures in water. Holey structure metamaterials are used also in [46] where the ability to resolve features with sizes as small as $\lambda/25$ is demonstrated. Sharp autofocusing with a compact planar ultrasound metasurface and even a 3-D-printed acoustic metasurface capable of dynamically changing the focus by adjusting the operation frequency are presented in [47] and [48], respectively. It is worth noting that, indeed, recently presented metalens realizations are often fabricated through 3-D-printing [49], [50], or high-precision manufacturing processes, such as photolithography for high frequency (50 MHz) and small-size devices [51].

A different approach based on geometrically simpler, wavelength-scale, meta-atoms is proposed in [49], where it has shown the capability to arbitrarily focus the beam in the 3-D space. Besides defect and biomedical imaging, subwavelength ultrasound metalenses have the potential for practical therapeutic applications, such as tissue ablation and cardiac pacing [52]. Metamaterials with negative refractive index may also be used to enhance acoustic transmission [53] or for wave focusing in acoustic power transfer applications [54]; for example, [55] discusses the design and analysis of gradient-index (GRIN) lenses realized with shunted piezoelectric patches to focus flexural waves in thin plates, while [56] investigates the application of wave focusing and funneling to design metamaterial-based energy harvesters. To harvest energy from different acoustic sources, an array of graded locally resonant metamaterials can be arranged to realize acoustic rainbow trapping devices [57].

Most commonly, the geometry of the GW patch transducers is rectangular or circular. Circular transducers generate almost (see [58]) omnidirectional (radial) waves, while rectangular patches generate GWs with propagation preferentially oriented in the length direction, but with limited focusing capability. For GW focusing purposes, piezoelectric patches can be combined with elastic metamaterials, as discussed in [59].

The increased complexity of focusing transducers requires the parallel development of suitable *design-optimization* strategies; for example, the parametric optimization of the shape of acoustic lenses is discussed in [60], while a method to apply particle swarm optimization to the design of autofocusing metasurfaces to select different desired focal distances is proposed in [61], and Hur et al. [62] employ topology optimization to determine the design of a metasurface piezoelectric ring array.

In application domains requiring large coverage areas, wide opening angles [63] or even **omnidirectionality** rather than focusing are desired. To this aim, bio-inspired solutions can be introduced, as those presented in [31], where omnidirectional transducers emulating the shape of bats' cochlea [see Fig. 1(d)] and resonating at multiple frequency in the 20–80-kHz range are demonstrated. Similarly, the truncated conical geometry of the air-ultrasound transducer presented in [64] provides a wide bandwidth (25–36 kHz) with a wide vertical beam angle.

IV. MODE SELECTION, CONVERSION, AND FILTERING

The selection of the appropriate wave mode for ultrasonic inspection is a critical consideration that directly impacts the accuracy and effectiveness of the inspection process. For example, in Lamb wave inspections, the choice of mode can be influenced by the need to detect specific defects, by their dispersive behavior or by the damping effect of coatings.

There are multiple technological solutions to perform the mode selection task. Some of them have been thoroughly investigated, such as the usage of angle-beam (or *wedge*) transducers, which enable the transmission of ultrasound at a nonnormal angle into the surface of the inspected

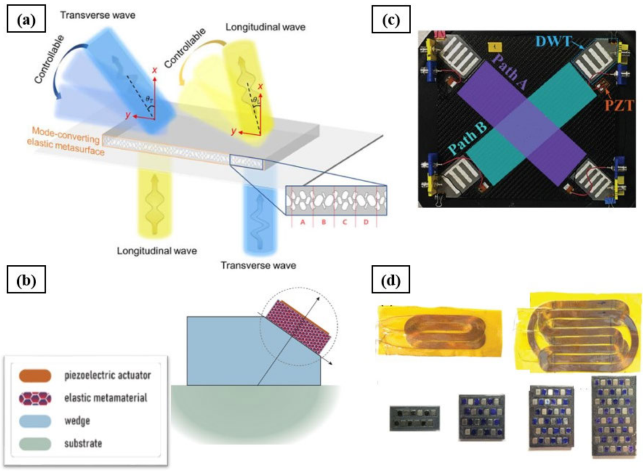

Fig. 2. Mode and polarization selection or conversion with (a) metasurfaces [65], (b) wedge transducers and metamaterials [66], (c) direct-write comb transducers [67] (© 2021 IEEE), and (d) EMAT with interleaved coil arrangements [68] (© 2022 IEEE). Subplot (b) is used under CC BY 4.0 [32], cropped from the original.

medium. Wedges can be used also for selective wave mode excitation and sensing. The efficiency of Lamb wave excitation by wedge-shaped UTs is investigated in [69]. Adjustable angle-beam transducers can be used to excite and receive single-mode Lamb waves by properly selecting mode-frequency combinations [70]. Shevtsov et al. [71] and [72] investigated the directivity of angle-beam wedge piezoelectric transducers that can be used to excite GWs in multilayered composite plate structures and CFRP plates, respectively. Ultrasonic signals traveling within the wedge can get reflected from its boundaries, causing interference signals called "ghost echoes" whose effect can be reduced with damping plates [73]. Angle-beam transducer can be combined with conformal piezoelectric-polymer-film sensors for monitoring surface cracks with Rayleigh waves, which are particularly sensitive to surface discontinuities [74].

Metamaterials are also suited to implement mode selection, conversion, and filtering tasks. For example, in [66], metamaterials are employed with wedge transducers [see Fig. 2(b)] to provide bulk wave mode conversion and a more efficient wave energy transfer. The development of an elastic metasurface that can convert a longitudinal wave into a transverse wave and vice versa is demonstrated in [65] [see Fig. 2(a)]. The 3-D-printed metamaterials suppressing unwanted ultrasound waves around 400 kHz while preserving subharmonic and ultraharmonic components and allowing the detection of weak microbubble emissions are discussed in [75]. The design and implementation of phononic arrays of microresonators to achieve frequency signal amplification and wave filtering are discussed in [76], also demonstrating selective wave filtering and polarization control in a 3-D elastic frame.

In GW inspections, selective wave mode generation can be achieved from the inherent relation that is established between the shape of the patch (or of the patch electrodes) and the wavenumber of the generated or received waves [77]. In particular, GW mode filtering can be realized with interdigitated transducers (IDTs), i.e., devices that consist of two interlocking comb-shaped arrays of metallic electrodes deposited on the surface of a piezoelectric substrate, forming a periodic structure. A summary review of different types of IDTs and their applicability in Lamb wave-based SHM systems is presented in [78], while [79] is about the design, fabrication, and characterization of transducers composed of a PVDF film with comb electrodes. **Directly write** (i.e., eliminating the need for bonding agent) comb-shaped transducers were presented in [67], introducing an innovative solution based on silver nanowires to realize a bottom electrode applicable on composite laminates [see Fig. 2(c)]. The radiation pattern of IDTs is influenced by the geometry and dimensions of the electrodes [80], and it can be designed to be asymmetrical [81] to provide a divergent beam on one side, while achieving a focusing effect in the opposite direction.

Besides Lamb waves, the usage of zero-order shear-horizontal (SH_0) GW mode for structural inspections has attracted many researchers, since these waves are nondispersive and less affected by leakage in surrounding media, resulting in reduced attenuation [82]. A solution to selectively excite pure SH GWs is presented in [83] and [84], exploiting the capabilities of face-shear d_{24} and d_{36} piezocomposite transducers, respectively. Piezoelectric fiber patch transducers capable of selectively exciting SH_0 and Lamb waves by properly multiplexing the input signals were presented in [85]. In [86], two thickness-shear d_{15} PZT wafers with opposite polarization directions are used to actuate generate SH_0 wave and suppress the unwanted Lamb waves. Further progress was introduced in [87], where a biodegradable and conformable transducer capable of obtaining a pure shear mode without requiring electrical poling is demonstrated. Conversely, in [88], it is demonstrated that high-order SH wave modes can be generated with IDT transducers.

As an alternative to piezoelectric transducers, electromagnetic acoustic transducers (EMATs) utilize the magnetostrictive effect to generate and receive contactlessly various types of ultrasonic waves in conductive materials even at high temperatures and on rough surfaces [89], [90]. This is achieved by using multiple coils that induce a magnetic field. Interestingly enough, despite the radically different transduction mechanisms, the coil arrangement can mimic the interdigitation of the piezoelectric transducer to achieve mode selectivity [see Fig. 2(d)]. This possibility was investigated in a series of recent papers [68], [91], [92], in which it is also shown that, with a suitable quadrature actuation, it is possible to generate distinct **unidirectional** wave modes, while, in [93], a diamond-shaped magnet array (assembled with the help of 3-D-printed formers) achieving sidelobe suppression was presented.

Unidirectionality via signal phase shifting is also possible by using piezoelectric wafers, as demonstrated in [94], basing on antiparallel d_{15} piezoelectric strips, and in [95], where the desired phase shifting is obtained with a time-delaying layer made of aluminum for SH_0 wave excitation.

V. BEAMSTEERING AND WAVEFRONT SHAPING

In bulk wave inspections, phased arrays allow for 2-D beam steering, enabling control of the ultrasonic beam in both azimuth and elevation by adding delays to the individual elements of the array. Similarly, GW phased array systems [100] are designed to generate ultrasound waves and direct them toward specific areas of a structure for effective inspection.

As a general rule, increasing the number of elements can enhance the overall performance of the phased array system. For example, by arranging piezoelectric elements as active metasurfaces, it is possible to minimize grating lobes [101]. However, a larger number of elements may also lead to higher power consumption and increased complexity in the system, which can impact cost and practical implementation.

Metamaterial bricks for zero-energy beam steering are demonstrated in [102]. However, for acoustic imaging purposes, it is necessary to have the possibility to rapidly **reconfigure** the steering direction. For example, in [103], a 3-D-printed metasurface is proposed, which can be reconfigured by controlling with a pumping system the cavity size of an array of Helmholtz resonators operating at 3 kHz. In [104], a report on 2-D and 3-D Lunenburg lenses designed for ultrasound actuation at 40 kHz is presented. In this case, the steering direction is varied by mechanically moving the speaker along the flat side of the lenses. Other solutions based on Lunenburg lenses are reviewed in [105]. A mechanically reconfigurable metasurface is also presented in [106], the actuation central frequency being again set to 40 kHz.

Actively controlled metasurfaces, capable of tuning their responses with programmable electronic circuits, may offer more rapidly reconfigurable solutions. For example, in [107], patterns of microbubbles controlled by a CMOS chip are shown to be effective in modulating plane acoustic waves for high-fidelity wavefront shaping.

GW beam steering with a metasurface made of shape memory (SM) alloy unit cells is proposed in [108]. In this case, the reconfigurability is achieved because of the variation of the elastic modulus of the unit cells induced by thermal loads. Reconfigurable ultrasonic wave propagation using thermal gradients induced on SM polymer films by a controlled laser source is demonstrated in [109]. Conversely, GW beam deflection under a single driving source is demonstrated in [110], by designing a metasubstrate that provides a suitable phase gradient. Further insights into the potential use of elastic metamaterials for beamforming functionalities in the context of GW inspections can be found in [59].

It is also possible to shape and arrange the electrodes, which are applied to polarize the material to achieve the capability of steering the ultrasonic beam by simply controlling the central frequency of the actuated pulse [96], [111] [see Fig. 3(a)]. In [97] [Fig. 3(b)], the same concept is used to realize a transducer capable of generating or sensing US waves along a reduced set of angles to minimize the effect of multipath interference for implementing GW-based communications. Finally, it has been recently demonstrated the capability to realize unidirectional frequency-steerable (FS) transducers with reduced sidelobes [98] [Fig. 3(c)]. The FS concept can be applied also to bulk waves UT and at higher frequencies with respect to those typically adopted for GW applications (≤500 kHz). However, just a few examples of this solution can be found in the literature [112], [113], [114]. In particular, in [114], the FS effect is achieved with a chessboard piezoelectric metasurface (driving frequencies up to 2 MHz).

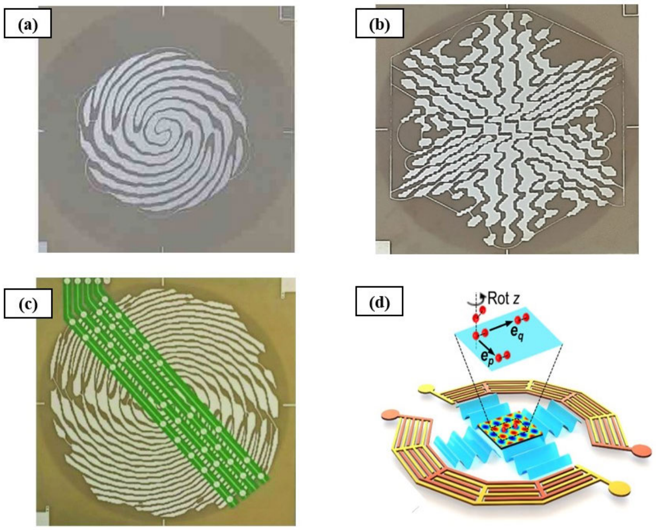

Fig. 3. Collection of UT, which can be controlled by tuning the spectral content of the actuating signal: the FS transducers presented in [96], [97], and [98] are depicted in subplots: (a) (© 2022 IEEE), (b) (© 2023 IEEE) and (c) (© 2023 IEEE), respectively, and (d) together with the wavenumber spiral tweezer presented in [99]. Subplot (d) is used under CC BY 4.0 [32], cropped from the original.

The design of new ultrasonic GW metatransducers based on electrode patterning may also draw inspiration from the diverse and expanding spectrum of SAW devices [115]. For example, in [116], a biosensor based on the combination of multiple IDT devices is introduced: one shear-horizontal-wave SAW and a second IDT used to generate Rayleigh waves. The research on transducers for *acoustofluidic* applications is particularly inspiring [117]: in [99], acoustic tweezers for cell and particle manipulation are presented, whose working principle is again based on the frequency content (spanning from 12.1 to 23.3 MHz) of the control signals, as for FS-UT [see Fig. 3(d)]. In [118], a spiral IDT is used to realize a laboratory-on-chip centrifuge. Similarly, equiangular and Fermat spiral shapes are used in [119] to generate vortices in the acoustic field.

It is worth noting that the performances of FS or IDT devices are tightly related to their physical dimensions. The wider the device, the finer can be the control on the wavelength of the sensed or actuated waves. Instead, the capability to fabricate small geometrical features in the transducers' shapes allows to actuate high-frequency (short wavelength) signals. For example, SAW devices may be operated even in the GHz range [115]. In this sense, advancement in high resolution and wide-area screen printing technologies may considerably extend the applicability of the FD-UT [120].

Other technologies are based on the intrinsic **anisotropic** behavior of certain transducers [121]. For example, strain sensors based on fiber Bragg gratings (FBGs) are characterized by a higher sensitivity when they capture waves directed along the grating length, and this feature can be used for directional sensing with the proper compensation [122].

VI. FUTURISTIC ADVANCED FUNCTIONALITIES

Functionalities that can be incorporated in metatransducers may go beyond the tasks that have been presented so far. Devices capable of performing various computational tasks begin to be devised [123]. For example, in [124], metamaterials that control the propagation of acoustic waves using magnetoelastic coupling have been proposed for wave computing and signal processing, while [125] discusses the creation of acoustic logic gates. In [126], a multiresonant acoustic sensor that mimics the basilar membrane in terms of biomimetic frequency band control is presented for biometric authentication applications. Randomized resonant metamaterials have been proposed for the source identification of elastic vibrations from the analysis of a single signal [127], while, in [128], a device designed to identify multiple broadband sound sources in noisy environments is presented. Finally, in a very recent work, speech recognition tasks are demonstrated [129].

Even if these solutions are meant to process audible signals, with a suitable scaling, they could be extended to the superacoustic regime. For example, [130] discusses the use of acoustic metamaterials combined with the concept of compressive sensing to improve ultrasonic imaging performance in the megasonic range.

VII. CONCLUSION

This article reviewed how UTs may serve as multipurpose devices beyond the mere conversion of electrical and mechanical energy. Such additional functionalities can be achieved with zero-energy (or extremely low-energy) solutions based on the proper engineering of the mechanical and geometrical parameters of the transducer subcomponents and may impact a wide range of application domains.

Despite these potential benefits, there are still factors that could limit the broad usage of these technologies. One of the main challenges for device developers is to handle the complexity of a very large design space. Especially for what concerns metamaterial-based subcomponents, finding the right arrangement may require long iterative procedures relying on multiphysics simulations. Besides developing dedicated fast (and possibly *open*) simulation tools, a possible solution to this issue may be in the adoption of AI-based design-optimization procedures [131]. Also, the technology of tunable metamaterials is somehow immature, despite being very promising to allow the implementation of easily reconfigurable devices. In this case, novel technological integration concepts based on large area and printed electronics may be needed.

Finally, the development of novel metatranducers will imply the parallel development of dedicated electronic interfaces and embedded signal-processing procedures. In this respect, Compressive sensing and tiny machine learning may improve the functionality, operational bandwidth, robustness, and efficiency of front-end systems to pave the way for a new generation of ultrasonic systems.

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REFERENCES

[1] C. S. Desilets, J. D. Fraser, and G. S. Kino, “The design of efficient broad-band piezoelectric transducers,” *IEEE Trans. Sonics Ultrason.*, vol. SU-25, no. 3, pp. 115–125, May 1978.

[2] A. L. Klibanov and J. A. Hossack, “Ultrasound in radiology: From anatomic, functional, molecular imaging to drug delivery and image-guided therapy,” *Investigative Radiol.*, vol. 50, no. 9, pp. 657–670, 2015.

[3] L. Jiang and J. Wu, “Emerging ultrasonic bioelectronics for personalized healthcare,” *Prog. Mater. Sci.*, vol. 136, Jul. 2023, Art. no. 101110.

[4] M. Ju et al., “Piezoelectric materials and sensors for structural health monitoring: Fundamental aspects, current status, and future perspectives,” *Sensors*, vol. 23, no. 1, p. 543, Jan. 2023.

[5] S. Patil, S. Banerjee, and S. Tallur, “Smart structural health monitoring (SHM) system for on-board localization of defects in pipes using torsional ultrasonic guided waves,” 2024, *arXiv:2403.11110*.

[6] J. Li, Y. Ma, T. Zhang, K. K. Shung, and B. Zhu, “Recent advancements in ultrasound transducer: From material strategies to biomedical applications,” *BME Frontiers*, vol. 2022, May 2022, Art. no. 9764501.

[7] S. Zhang, C. Xia, and N. Fang, “Broadband acoustic cloak for ultrasound waves,” *Phys. Rev. Lett.*, vol. 106, no. 2, 2011, Art. no. 024301.

[8] Q. Lu, X. Li, X. Zhang, M. Lu, and Y. Chen, “Perspective: Acoustic metamaterials in future engineering,” *Engineering*, vol. 17, pp. 22–30, Oct. 2022.

[9] A. O. Krushynska et al., “Emerging topics in nanophononics and elastic, acoustic, and mechanical metamaterials: An overview,” *Nanophotonics*, vol. 12, no. 4, pp. 659–686, 2023.

[10] X. Li et al., “Fast and versatile electrostatic disc microprinting for piezoelectric elements,” *Nature Commun.*, vol. 14, no. 1, p. 6488, Oct. 2023.

[11] H. Lu et al., “3D printing and processing of miniaturized transducers with near-pristine piezoelectric ceramics for localized cavitation,” *Nature Commun.*, vol. 14, no. 1, p. 2418, Apr. 2023.

[12] Y. Chen et al., “PZT ceramics fabricated based on stereolithography for an ultrasound transducer array application,” *Ceram. Int.*, vol. 44, no. 18, pp. 22725–22730, 2018.

[13] L. Wang, V. Hofmann, F. Bai, J. Jin, and J. Twiefel, “A novel additive manufactured three-dimensional piezoelectric transducer: Systematic modeling and experimental validation,” *Mech. Syst. Signal Process.*, vol. 114, pp. 346–365, Jan. 2019.

[14] C. Chen et al., “Additive manufacturing of piezoelectric materials,” *Adv. Funct. Mater.*, vol. 30, no. 52, 2020, Art. no. 2005141.

[15] H. Cui et al., “Three-dimensional printing of piezoelectric materials with designed anisotropy and directional response,” *Nature Mater.*, vol. 18, no. 3, pp. 234–241, Mar. 2019.

[16] W. Deng, Y. Zhou, A. Libanori, G. Chen, W. Yang, and J. Chen, “Piezoelectric nanogenerators for personalized healthcare,” *Chem. Soc. Rev.*, vol. 51, no. 9, pp. 3380–3435, 2022.

[17] L. M. Campeiro, D. E. Budoya, and F. G. Baptista, “Lamb wave inspection using piezoelectric diaphragms: An initial feasibility study,” *Sens. Actuators A, Phys.*, vol. 331, Nov. 2021, Art. no. 112859.

[18] L. Zhang, W. Du, J. Kim, C. Yu, and C. Dagdeviren, “An emerging era: Conformable ultrasound electronics,” *Adv. Mater.*, vol. 36, no. 8, Feb. 2024, Art. no. 2307664.

[19] Y. Wu, Y. Ma, H. Zheng, and S. Ramakrishna, “Piezoelectric materials for flexible and wearable electronics: A review,” *Mater. Des.*, vol. 211, Dec. 2021, Art. no. 110164.

[20] N. McKibben et al., “Aerosol jet printing of piezoelectric surface acoustic wave thermometer,” *Microsyst. Nanoeng.*, vol. 9, no. 1, p. 51, May 2023.

[21] S. Jiang, Y. Shen, S. Wang, W. Jiang, Y. Liu, and Q. Wu, “Flexible piezoelectric composite sensor for impact monitoring of curved structures,” *Sens. Actuators A, Phys.*, vol. 362, Nov. 2023, Art. no. 114655.

[22] T. Roloff, R. Mitkus, J. N. Lion, and M. Sinapius, “3D-printable piezoelectric composite sensors for acoustically adapted guided ultrasonic wave detection,” *Sensors*, vol. 22, no. 18, p. 6964, Sep. 2022.

[23] C. Tuloup, W. Harizi, Z. Aboura, and Y. Meyer, “Integration of piezoelectric transducers (PZT and PVDF) within polymer-matrix composites for structural health monitoring applications: New success and challenges,” *Int. J. Smart Nano Mater.*, vol. 11, no. 4, pp. 343–369, Oct. 2020.

[24] P. M. Ferreira, M. A. Machado, M. S. Carvalho, and C. Vidal, “Embedded sensors for structural health monitoring: Methodologies and applications review,” *Sensors*, vol. 22, no. 21, p. 8320, Oct. 2022.

[25] E. F. Crawley and J. de Luis, “Use of piezoelectric actuators as elements of intelligent structures,” *AIAA J.*, vol. 25, no. 10, pp. 1373–1385, Oct. 1987.

[26] M. E. Gino et al., “On the design of a piezoelectric self-sensing smart composite laminate,” *Mater. Des.*, vol. 219, Jul. 2022, Art. no. 110783.

[27] Y. Yu, Y. Shi, H. Kurita, Y. Jia, Z. Wang, and F. Narita, “Carbon fiber-reinforced piezoelectric nanocomposites: Design, fabrication and evaluation for damage detection and energy harvesting,” *Compos. A, Appl. Sci. Manuf.*, vol. 172, Sep. 2023, Art. no. 107587.

[28] M. S. Syed Akbar Ali and P. Rajagopal, “Far-field ultrasonic imaging using hyperlenses,” *Sci. Rep.*, vol. 12, no. 1, p. 18222, Oct. 2022.

[29] J. Hyun, Y. T. Kim, I. Doh, B. Ahn, K. Baik, and S.-H. Kim, “Realization of an ultrathin acoustic lens for subwavelength focusing in the megasonic range,” *Sci. Rep.*, vol. 8, no. 1, p. 9131, Jun. 2018.

[30] L. Astolfi et al., “Holey-structured tungsten metamaterials for broadband ultrasonic sub-wavelength imaging in water,” *J. Acoust. Soc. Amer.*, vol. 150, no. 1, pp. 74–81, Jul. 2021.

[31] A. S. Fiorillo, S. A. Pullano, M. G. Bianco, and C. D. Critello, “Ultrasonic transducers shaped in Archimedean and Fibonacci spiral: A comparison,” *Sensors*, vol. 20, no. 10, p. 2800, May 2020.

[32] *CC BY 4.0 Deed | Attribution 4.0 International | Creative Commons—Creativecommons.org*. Accessed: Jul. 3, 2024. [Online]. Available: https://creativecommons.org/licenses/by/4.0/

[33] D. S. Kwon, J. H. Sung, C. Y. Park, and J. S. Jeong, “Phase-inverted multifrequency HIFU transducer for lesion expansion: A simulation study,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 65, no. 7, pp. 1125–1132, Jul. 2018.

[34] H. S. Gougheri, A. Dangi, S.-R. Kothapalli, and M. Kiani, “A comprehensive study of ultrasound transducer characteristics in microscopic ultrasound neuromodulation,” *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 5, pp. 835–847, Oct. 2019.

[35] A. Sarvazyan and L. Fillinger, “Arbitrary shaped, liquid filled reverberators with non-resonant transducers for broadband focusing of ultrasound using time reversed acoustics,” *Ultrasonics*, vol. 49, no. 3, pp. 301–305, Mar. 2009.

[36] J. Robin, B. Arnal, M. Tanter, and M. Pernot, “A 3D time reversal cavity for the focusing of high-intensity ultrasound pulses over a large volume,” *Phys. Med. Biol.*, vol. 62, no. 3, pp. 810–824, Feb. 2017.

[37] J. Lee, J. Jang, and J. H. Chang, “Oblong-shaped-focused transducers for intravascular ultrasound imaging,” *IEEE Trans. Biomed. Eng.*, vol. 64, no. 3, pp. 671–680, Mar. 2017.

[38] K. Chen, T. Irie, T. Iijima, and T. Morita, “Wideband multimode excitation by a double-parabolic-reflector ultrasonic transducer,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 67, no. 8, pp. 1620–1631, Aug. 2020.

[39] L. Astolfi et al., “Optimised polymer trapped-air lenses for ultrasound focusing in water exploiting Fabry–Pérot resonance,” *Ultrasonics*, vol. 125, Sep. 2022, Art. no. 106781.

[40] S. Jiménez-Gambín, N. Jiménez, J. M. Benlloch, and F. Camarena, “Holograms to focus arbitrary ultrasonic fields through the skull,” *Phys. Rev. Appl.*, vol. 12, no. 1, Jul. 2019, Art. no. 014016.

[41] M. Audoin, A. Salari, B. G. Tomov, K. F. Pedersen, J. A. Jensen, and E. V. Thomsen, “Diverging polymer acoustic lens design for high-resolution row-column array ultrasound transducers,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 71, no. 1, pp. 202–213, Oct. 2024.

[42] P. Jin et al., “A flexible, stretchable system for simultaneous acoustic energy transfer and communication,” *Sci. Adv.*, vol. 7, no. 40, 2021, Art. no. eabg2507.

[43] C. Hou et al., “Active acoustic field modulation of ultrasonic transducers with flexible composites,” *Commun. Phys.*, vol. 6, no. 1, p. 252, Sep. 2023.

[44] F. Ma, Z. Huang, C. Liu, and J. H. Wu, “Acoustic focusing and imaging via phononic crystal and acoustic metamaterials,” *J. Appl. Phys.*, vol. 131, no. 1, Jan. 2022, Art. no. 011103.

[45] E. L. Walker, Y. Jin, D. Reyes, and A. Neogi, “Sub-wavelength lateral detection of tissue-approximating masses using an ultrasonic metamaterial lens,” *Nature Commun.*, vol. 11, no. 1, p. 5967, Nov. 2020.

[46] K. K. Amireddy, K. Balasubramaniam, and P. Rajagopal, “Deep subwavelength ultrasonic imaging using optimized holey structured metamaterials,” *Sci. Rep.*, vol. 7, no. 1, p. 7777, Aug. 2017.

[47] X. Jiang, Y. Li, D. Ta, and W. Wang, “Ultrasonic sharp autofocusing with acoustic metasurface,” *Phys. Rev. B, Condens. Matter*, vol. 102, no. 6, Aug. 2020, Art. no. 064308.

[48] Z. Hu, Y. Yang, L. Xu, Y. Hao, and H. Chen, “Binary acoustic metasurfaces for dynamic focusing of transcranial ultrasound,” *Frontiers Neurosci.*, vol. 16, Sep. 2022, Art. no. 984953.

[49] X. Jiang et al., “Three-dimensional ultrasound subwavelength arbitrary focusing with broadband sparse metalens,” *Sci. China Phys., Mech. Astron.*, vol. 65, no. 2, Feb. 2022, Art. no. 224311.

[50] G. Zuo, Z. Huang, and F. Ma, “A tunable sub-wavelength acoustic imaging planar metalens,” *J. Phys. D, Appl. Phys.*, vol. 56, no. 14, Apr. 2023, Art. no. 145401.

[51] Z. Li et al., “Piezoelectric metasurface for high-frequency ultrasonic transducer application around 50 MHz,” *Ceram. Int.*, pp. 1–9, Mar. 2024.

[52] Y. Zheng, C. Li, C. Zhang, J. He, X. Jiang, and D. Ta, “Distinct thermal effect on biological tissues using subwavelength ultrasound metalens at megahertz,” *iScience*, vol. 26, no. 10, Oct. 2023, Art. no. 107929.

[53] J. Wang, F. Allein, N. Boechler, J. Friend, and O. Vazquez-Mena, “Design and fabrication of negative-refractive-index metamaterial unit cells for near-megahertz enhanced acoustic transmission in biomedical ultrasound applications,” *Phys. Rev. Appl.*, vol. 15, no. 2, Feb. 2021, Art. no. 024025.

[54] G. Hu, L. Tang, J. Liang, C. Lan, and R. Das, “Acoustic-elastic metamaterials and phononic crystals for energy harvesting: A review,” *Smart Mater. Struct.*, vol. 30, no. 8, Jun. 2021, Art. no. 085025.

[55] K. Yi, M. Collet, M. Ichchou, and L. Li, “Flexural waves focusing through shunted piezoelectric patches,” *Smart Mater. Struct.*, vol. 25, no. 7, Jul. 2016, Art. no. 075007.

[56] M. Carrara, M. R. Cacan, J. Toussaint, M. J. Leamy, M. Ruzzene, and A. Erturk, “Metamaterial-inspired structures and concepts for elastoacoustic wave energy harvesting,” *Smart Mater. Struct.*, vol. 22, no. 6, Jun. 2013, Art. no. 065004.

[57] L. Zhao and S. Zhou, “Compact acoustic rainbow trapping in a bioinspired spiral array of graded locally resonant metamaterials,” *Sensors*, vol. 19, no. 4, p. 788, Feb. 2019.

[58] J. Moll, M. V. Golub, E. Glushkov, N. Glushkova, and C.-P. Fritzen, “Non-axisymmetric Lamb wave excitation by piezoelectric wafer active sensors,” *Sens. Actuators A, Phys.*, vol. 174, pp. 173–180, Feb. 2012.

[59] J. Lee and Y. Y. Kim, “Elastic metamaterials for guided waves: From fundamentals to applications,” *Smart Mater. Struct.*, vol. 32, no. 12, Dec. 2023, Art. no. 123001.

[60] G. P. L. Thomas, J.-Y. Chapelon, J.-C. Béra, and C. Lafon, “Parametric shape optimization of lens-focused piezoelectric ultrasound transducers,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 65, no. 5, pp. 844–850, May 2018.

[61] Z. Li et al., “Optimization design of autofocusing metasurface for ultrasound wave application,” *J. Adv. Dielectr.*, vol. 14, no. 1, Feb. 2024, Art. no. 2350001.

[62] S. Hur, H. Choi, G. H. Yoon, N. W. Kim, D.-G. Lee, and Y. T. Kim, “Planar ultrasonic transducer based on a metasurface piezoelectric ring array for subwavelength acoustic focusing in water,” *Sci. Rep.*, vol. 12, no. 1, p. 1485, Jan. 2022.

[63] M. Angerer, M. Zapf, S. Gebhardt, H. Neubert, and N. V. Ruiter, “Single-fiber transducer arrays for 3-D ultrasound computed tomography: From requirements to results,” *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 7, pp. 772–781, Jul. 2023.

[64] J. Chen, J. Zhao, L. Lin, and X. Sun, “Truncated conical PVDF film transducer for air ultrasound,” *IEEE Sensors J.*, vol. 19, no. 19, pp. 8618–8625, Oct. 2019.

[65] W. Lee, J. Lee, C. I. Park, and Y. Y. Kim, “Polarization-independent full mode-converting elastic metasurfaces,” *Int. J. Mech. Sci.*, vol. 266, Mar. 2024, Art. no. 108975.

[66] M. V. Golub, S. I. Fomenko, P. E. Usov, and A. A. Eremin, “Elastic waves excitation and focusing by a piezoelectric transducer with intermediate layered elastic metamaterials with and without periodic arrays of interfacial voids,” *Sensors*, vol. 23, no. 24, p. 9747, Dec. 2023.

[67] M. Philibert, S. Chen, V. Wong, K. Yao, C. Soutis, and M. Gresil, "Direct-write piezoelectric transducers on carbon-fiber-reinforced polymer structures for exciting and receiving guided ultrasonic waves," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 68, no. 8, pp. 2733–2740, Aug. 2021.

[68] L. M. Martinho, A. C. Kubrusly, L. Kang, and S. Dixon, "Enhancement of the unidirectional radiation pattern of shear horizontal ultrasonic waves generated by side-shifted periodic permanent magnets electromagnetic acoustic transducers with multiple rows of magnets," *IEEE Sensors J.*, vol. 22, no. 8, pp. 7637–7644, Apr. 2022.

[69] V. A. Nikolaevtsev, S. G. Suchkov, A. V. Selifonov, D. D. Suchkov, S. S. Yankin, and S. M. Suchkova, "Efficiency of Lamb wave excitation by wedge-shaped ultrasonic transducer," in *Proc. 13th Int. Sci.-Tech. Conf. Actual Problems Electron. Instrum. Eng. (APEIE)*, vol. 1, Oct. 2016, pp. 42–47.

[70] H. Mei, M. F. Haider, R. James, and V. Giurgiutiu, "Pure S0 and SH0 detections of various damage types in aerospace composites," *Compos. B, Eng.*, vol. 189, May 2020, Art. no. 107906.

[71] S. Shevtsov, V. Chebanenko, M. Shevtsova, E. Kirillova, and E. Rozhkov, "On the directivity of acoustic waves generated by the angle beam wedge actuator in thin-walled structures," *Actuators*, vol. 8, no. 3, p. 64, 2019.

[72] S. Shevtsov, V. Chebanenko, M. Shevtsova, S.-H. Chang, E. Kirillova, and E. Rozhkov, "On the directivity of Lamb waves generated by wedge PZT actuator in thin CFRP panel," *Materials*, vol. 13, no. 4, p. 907, Feb. 2020.

[73] O. Shapovalov, T. Heckel, M. Gaal, and S. Weiß, "External acoustical damping on a metallic angle wedge in a high temperature resistant ultrasonic probe," *Acoust. Aust.*, vol. 50, no. 3, pp. 343–353, Jul. 2022.

[74] X. Li et al., "Surface crack monitoring by Rayleigh waves with a piezoelectric-polymer-film ultrasonic transducer array," *Sensors*, vol. 23, no. 5, p. 2665, Feb. 2023.

[75] L. Nie et al., "A metallic additively manufactured metamaterial for enhanced monitoring of acoustic cavitation-based therapeutic ultrasound," *Adv. Eng. Mater.*, vol. 24, no. 4, Apr. 2022, Art. no. 2100972.

[76] F. Maspero et al., "Phononic graded meta-MEMS for elastic wave amplification and filtering," 2023, *arXiv:2306.12076*.

[77] M. Gawronski et al., "A semi-analytical approach to design of a transducer for selective wave generation," *Struct. Health Monitor.*, vol. 16, no. 5, pp. 583–593, Sep. 2017.

[78] T. Stepinski, M. Mańka, and A. Martowicz, "Interdigital Lamb wave transducers for applications in structural health monitoring," *NDT & E Int.*, vol. 86, pp. 199–210, Mar. 2017.

[79] T. Ding, Q. Wan, Y. Xiang, X. Qiu, M. Deng, and F.-Z. Xuan, "Selectable single-mode guided waves for multi-type damages localization of plate-like structures using film comb transducers," *Nondestruct. Test. Eval.*, vol. 38, no. 1, pp. 90–111, Jan. 2023.

[80] Y. Lugovtsova, A. Bulletti, P. Giannelli, L. Capineri, and J. Prager, "Characterization of a flexible piezopolymer-based interdigital transducer for selective excitation of ultrasonic guided waves," in *Proc. IEEE Int. Ultrason. Symp. (IUS)*, Sep. 2020, pp. 1–4.

[81] L. Capineri, L. Bergamaschi, and A. Bulletti, "Design of piezopolymer interdigital transducers with scaled electrode geometries based on FEM analysis," *Actuators*, vol. 11, no. 11, p. 326, Nov. 2022.

[82] H. Miao and F. Li, "Shear horizontal wave transducers for structural health monitoring and nondestructive testing: A review," *Ultrasonics*, vol. 114, Jul. 2021, Art. no. 106355.

[83] H. Miao, Q. Huan, F. Li, and G. Kang, "A variable-frequency bidirectional shear horizontal (SH) wave transducer based on dual face-shear (d_{24}) piezoelectric wafers," *Ultrasonics*, vol. 89, pp. 13–21, Sep. 2018.

[84] H. Miao, L. Xu, and H. Zhang, "SH guided wave excitation by an apparent face-shear mode (d_{36}) piezocomposite transducer: Experiments and theory," *Smart Mater. Struct.*, vol. 28, no. 11, 2019, Art. no. 115045.

[85] B. Köhler, Y. Kim, K. Chwelatiuk, K. Tschöke, F. Schubert, and L. Schubert, "A mode-switchable guided elastic wave transducer," *J. Nondestruct. Eval.*, vol. 39, p. 45, Jun. 2020.

[86] J. Cai, H. Zhang, and H. Miao, "Excitation of unidirectional SH wave within a frequency range of 50 kHz by piezoelectric transducers without frequency-dependent time delay," *Ultrasonics*, vol. 118, Jan. 2022, Art. no. 106579.

[87] Y. M. Yousry et al., "Shear mode ultrasonic transducers from flexible piezoelectric PLLA fibers for structural health monitoring," *Adv. Funct. Mater.*, vol. 33, no. 15, Apr. 2023, Art. no. 2213582.

[88] H. Qiu, M. Chen, and F. Li, "Selective excitation of high-order shear horizontal wave (SH_1) by using a piezoelectric interdigital transducer," *Mech. Syst. Signal Process.*, vol. 165, Feb. 2022, Art. no. 108390.

[89] R. B. Thompson et al., "Physical principles of measurements with EMAT transducers," *Phys. Acoust.*, vol. 19, pp. 157–200, Jan. 1990.

[90] G. Sha and C. J. Lissenden, "Modeling magnetostrictive transducers for structural health monitoring: Ultrasonic guided wave generation and reception," *Sensors*, vol. 21, no. 23, p. 7971, Nov. 2021.

[91] A. C. Kubrusly, L. Kang, and S. Dixon, "Optimal unidirectional generation of a dispersive wave mode with dual-array transducer," *Mech. Syst. Signal Process.*, vol. 177, Sep. 2022, Art. no. 109138.

[92] A. C. Kubrusly, L. Kang, and S. Dixon, "Selective simultaneous generation of distinct unidirectional wave modes in different directions using dual-array transducer," *Mech. Syst. Signal Process.*, vol. 187, Mar. 2023, Art. no. 109942.

[93] L. M. Martinho and A. C. Kubrusly, "A new diamond-shaped periodic permanent magnet electromagnetic acoustic transducer for side-lobe suppression of shear horizontal ultrasonic waves," *Sens. Actuators A, Phys.*, vol. 371, Jun. 2024, Art. no. 115290.

[94] M. Chen, Q. Huan, and F. Li, "A unidirectional SH wave transducer based on phase-controlled antiparallel thickness-shear (d_{15}) piezoelectric strips," *Theor. Appl. Mech. Lett.*, vol. 10, no. 5, pp. 299–306, Jul. 2020.

[95] Y. Du et al., "Time-delayed layer-based piezoelectric transducer for unidirectional excitation and reception of SH guided wave," *Mech. Syst. Signal Process.*, vol. 193, Jun. 2023, Art. no. 110268.

[96] M. Mohammadgholiha, A. Palermo, N. Testoni, J. Moll, and L. De Marchi, "Finite element modeling and experimental characterization of piezoceramic frequency steerable acoustic transducers," *IEEE Sensors J.*, vol. 22, no. 14, pp. 13958–13970, Jul. 2022.

[97] M. Mohammadgholiha, F. Zonzini, J. Moll, and L. De Marchi, "Directional multifrequency guided waves communications using discrete frequency-steerable acoustic transducers," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 70, no. 11, pp. 1494–1505, Nov. 2023.

[98] M. Mohammadgholiha, J. Moll, and L. De Marchi, "A new generation of piezoceramic frequency steerable acoustic transducers for the rapid inspection of large areas of metallic plate structures," in *Proc. IEEE Int. Ultrason. Symp. (IUS)*, Sep. 2023, pp. 1–4.

[99] Z. Tian et al., "Wave number–spiral acoustic tweezers for dynamic and reconfigurable manipulation of particles and cells," *Sci. Adv.*, vol. 5, no. 5, 2019, Art. no. eaau6062.

[100] T. Clarke, P. Cawley, P. D. Wilcox, and A. J. Croxford, "Evaluation of the damage detection capability of a sparse-array guided-wave SHM system applied to a complex structure under varying thermal conditions," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 56, no. 12, pp. 2666–2678, Dec. 2009.

[101] Y. Shen et al., "Active acoustic metasurface: Complete elimination of grating lobes for high-quality ultrasound focusing and controllable steering," *Phys. Rev. Appl.*, vol. 11, no. 3, Mar. 2019, Art. no. 034009.

[102] G. Memoli, M. Caleap, M. Asakawa, D. R. Sahoo, B. W. Drinkwater, and S. Subramanian, "Metamaterial bricks and quantization of metasurfaces," *Nature Commun.*, vol. 8, no. 1, p. 14608, Feb. 2017.

[103] Z. Tian et al., "Programmable acoustic metasurfaces," *Adv. Funct. Mater.*, vol. 29, no. 13, Mar. 2019, Art. no. 1808489.

[104] L. Zhao et al., "Ultrasound beam steering with flattened acoustic metamaterial Luneburg lens," *Appl. Phys. Lett.*, vol. 116, no. 7, Feb. 2020, Art. no. 071902.

[105] L. Zhao, C. Bi, H. Huang, Q. Liu, and Z. Tian, "A review of acoustic Luneburg lens: Physics and applications," *Mech. Syst. Signal Process.*, vol. 199, Sep. 2023, Art. no. 110468.

[106] H.-S. Kwon, B. I. Epureanu, and B.-I. Popa, "Reconfigurable large-scale bulk metamaterials for broadband ultrasonics," *Smart Mater. Struct.*, vol. 30, no. 8, Aug. 2021, Art. no. 085002.

[107] Z. Ma et al., "Spatial ultrasound modulation by digitally controlling microbubble arrays," *Nature Commun.*, vol. 11, no. 1, p. 4537, Sep. 2020.

[108] Y. Song and Y. Shen, "A metasurface radar for steering ultrasonic guided waves," *J. Sound Vib.*, vol. 538, Nov. 2022, Art. no. 117260.

[109] J. Rus and R. Fleury, "Reconfigurable ultrasonic media for spatio-temporal wavefront shaping," in *Proc. 16th Int. Congr. Artif. Mater. Novel Wave Phenomena (Metamaterials)*, Sep. 2022, pp. X-377–X-379.

[110] H. Miao and Y. Du, "Metasubstrate-based SH guided wave piezoelectric transducer for unidirectional beam deflection without time delay," *Smart Mater. Struct.*, vol. 33, no. 1, Jan. 2024, Art. no. 015038.

[111] M. Senesi and M. Ruzzene, "A frequency selective acoustic transducer for directional Lamb wave sensing," *J. Acoust. Soc. Amer.*, vol. 130, no. 4, pp. 1899–1907, Oct. 2011.

[112] S. T. Bachelor, L. Thompson, and J. Seawall, “Systems and methods implementing frequency-steered acoustic arrays for 2D and 3D imaging,” U.S. Patent 8 811 120 B2, Jul. 12, 2004.

[113] N. Testoni, L. De Marchi, N. Speciale, and M. Ruzzene, “Bulk wave FSAT for 2D optic fiber endoscopic echography,” in *Proc. IEEE Int. Ultrason. Symp. (IUS)*, Jul. 2013, pp. 162–165.

[114] Z. Li et al., “Coding piezoelectric metasurfaces,” *Adv. Funct. Mater.*, vol. 32, no. 47, Nov. 2022, Art. no. 2209173.

[115] P. Delsing et al., “The 2019 surface acoustic waves roadmap,” *J. Phys. D, Appl. Phys.*, vol. 52, no. 35, 2019, Art. no. 353001.

[116] W. Huang et al., “Integrated Rayleigh wave streaming-enhanced sensitivity of shear horizontal surface acoustic wave biosensors,” *Biosensors Bioelectron.*, vol. 247, Mar. 2024, Art. no. 115944.

[117] J. Rufo, F. Cai, J. Friend, M. Wiklund, and T. J. Huang, “Acoustofluidics for biomedical applications,” *Nature Rev. Methods Primers*, vol. 2, no. 1, p. 30, 2022.

[118] J. Huang, Z. Zhu, Y. Zhang, J. Tu, X. Guo, and D. Zhang, “On-chip centrifuge using spiral surface acoustic waves on a ZnO/glass substrate,” *Sens. Actuators A, Phys.*, vol. 347, Nov. 2022, Art. no. 113901.

[119] J. Cao, K. Yang, X. Fang, L. Guo, Y. Li, and Q. Cheng, “Holographic tomography of dynamic three-dimensional acoustic vortex beam in liquid,” *Appl. Phys. Lett.*, vol. 119, no. 14, 2021, Art. no. 143501.

[120] M. Aliqué, C. D. Simão, G. Murillo, and A. Moya, “Fully-printed piezoelectric devices for flexible electronics applications,” *Adv. Mater. Technol.*, vol. 6, no. 3, Mar. 2021, Art. no. 2001020.

[121] P. Kijanka, A. Manohar, F. Lanza di Scalea, and W. J. Staszewski, “Damage location by ultrasonic Lamb waves and piezoelectric rosettes,” *J. Intell. Mater. Syst. Struct.*, vol. 26, no. 12, pp. 1477–1490, 2015.

[122] R. Wang, Q. Wu, K. Xiong, J. Ji, H. Zhang, and H. Zhai, “Phase-shifted fiber Bragg grating sensing network and its ultrasonic sensing application,” *IEEE Sensors J.*, vol. 19, no. 21, pp. 9790–9797, Nov. 2019.

[123] F. Zangeneh-Nejad, D. L. Sounas, A. Alù, and R. Fleury, “Analogue computing with metamaterials,” *Nature Rev. Mater.*, vol. 6, no. 3, pp. 207–225, 2021.

[124] O. Latcham, Y. Gusieva, A. Shytov, O. Gorobets, and V. Kruglyak, “Hybrid magnetoacoustic metamaterials for ultrasound control,” *Appl. Phys. Lett.*, vol. 117, no. 10, 2020, Art. no. 102402.

[125] M. M. Indaleeb, H. Ahmed, and S. Banerjee, “Acoustic computing: At tunable pseudospin-1 Hermitian Dirac-like cone,” *J. Acoust. Soc. Amer.*, vol. 152, no. 3, pp. 1449–1462, 2022.

[126] H. S. Wang et al., “Biomimetic and flexible piezoelectric mobile acoustic sensors with multiresonant ultrathin structures for machine learning biometrics,” *Sci. Adv.*, vol. 7, no. 7, 2021, Art. no. eabe5683.

[127] T. Jiang, C. Li, Q. He, and Z.-K. Peng, “Randomized resonant metamaterials for single-sensor identification of elastic vibrations,” *Nature Commun.*, vol. 11, no. 1, p. 2353, May 2020.

[128] L. Wang, W. Li, Z. Huang, T. Jiang, and F. Ma, “A Nautilus bionic multi-information fusion compressed-sensing acoustic imaging device,” *Cell Rep. Phys. Sci.*, vol. 4, no. 12, Dec. 2023, Art. no. 101733.

[129] T. Dubček et al., “In-sensor passive speech classification with phononic metamaterials,” *Adv. Funct. Mater.*, vol. 34, no. 17, Apr. 2024, Art. no. 2311877.

[130] A. Ghanbarzadeh-Dagheyan, A. Molaei, J. Heredia-Juesas, and J. A. Martinez-Lorenzo, “A resonant metamaterial line array for ultrasound compressive imaging,” *J. Vib. Acoust.*, vol. 142, no. 2, 2020, Art. no. 021014.

[131] P. Kudela, A. Ijjeh, M. Radzienski, M. Miniaci, N. Pugno, and W. Ostachowicz, “Deep learning aided topology optimization of phononic crystals,” *Mech. Syst. Signal Process.*, vol. 200, Oct. 2023, Art. no. 110636.

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