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Microwave Acoustic Devices: Recent Advances and Outlook

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ABSTRACT This paper presents a short review of the microwave acoustics area, where exciting material innovations and performance advancements have been made in the past decade. The ever-growing demand for more sophisticated passive signal processing functions on-chip has fueled these developments. As a result, microwave acoustic devices have maintained performance leadership in mobile applications. By evaluating three fundamental parameters, namely electromechanical coupling (k^2), quality factors, and frequency scalability, of microwave acoustics, this paper aims to, extensively but not exhaustively, capture the rationales behind approaches achieving higher performance microsystems. Outlooks for different material systems and addressing their underlying challenges are also offered in hopes of establishing a balanced roadmap for future microwave acoustics development.

INDEX TERMS Microwave acoustics, resonators, filters, aluminum nitride, lithium niobate, lithium tantalate, electromechanical, quality factors, microsystems.

I. INTRODUCTION

Acoustic devices at radio and microwave frequencies have always received broad attention from research and commercial organizations for their profound applications in signal processing and sensing [1]–[3]. One can find their deployments dating back to the inception of many microwave systems in radars, broadcasting, and telecommunications [4], [5]. Their pervasiveness owes to several fundamental advantages of microwave acoustic systems over their electromagnetic counterparts. Acoustic waves travel about four to five orders of magnitude slower than electromagnetic waves [6], [7]. At radio frequencies (RF), their wavelength ranges from 100s of nm to several microns, while electromagnetic wavelengths are centimeters long. The micron-scale wavelength allows significant downsizing of passive structures that rely on waveguiding or manipulation to achieve their functions (e.g., resonators and transmission-line based components). Simultaneously, the chip-scale sizes permit the exploitation of semiconductor/micro-electromechanical systems (MEMS) fabrication techniques to achieve low-cost mass manufacturing. In addition, acoustic wave propagation in well-known low-loss materials has one to two orders of magnitude lower loss than electromagnetic waves in their respective low-loss waveguides at room temperature [8]. The low-loss leads to high quality factor (Q) and better frequency selectivity, responsible for attaining low phase noise frequency references/sources and high rejection/roll-off filters. As a result of the above advantages, adopting microwave acoustics can enable high-performance signal process functions (e.g., filters as the most prominent example) in a form factor that supports massively paralleled RF system compositions (e.g., heavily multiplexed RF paths to a shared antenna in a modern mobile transceiver) [9]. Such a feat so far cannot be delivered by any alternatives with comparable size, power, performance, and cost all at the same time.

Understandably, such technical prominence of microwave acoustic devices did not come easy. Many innovations and advances were made in the past few decades to keep the performance leadership of microwave acoustics in several application scenarios [10]–[12]. This paper aims first to review the more recent advances (in the past 5-10 years) and then give outlooks for what the future might hold for microwave acoustics.

II. MICROWAVE ACOUSTICS

Before reviewing advances, one has to establish a set of criteria for assessing microwave acoustic devices or microsystems. These criteria should be broadly applicable and agnostic to various material systems so that fair comparison can be made in the context of target applications. For future low-loss and wideband applications, the foremost parameter to mention should be the electromechanical coupling (k^2), as opposed to the quality factor. The rationale is simple. To benefit from technical advantages in the acoustic domain, any device or system has to access the acoustic domain first. A highly efficient electromechanical transduction mechanism that converts electrical signals into acoustic ones and vice versa is profoundly important as it determines bandwidth, loss, impedance, as well as other specifications for the system [3], [7]. Improving k^2 can often involve adapting new materials (or new configurations and growth methods of existing materials). A material or its composition is selected based on its potential to offer high coupling modes. However, the outcome for any given attempt to improve k^2 does not solely rest on the materials of choice but is also related to design and possible trades with other performance specifications.

The second metric is the loss in the acoustic device, captured by the Q and dependent on materials, operational mode, design, and fabrication. Often, many forces are at work setting the Q of an acoustic device. Thus, any attempt to improve Q has to address loss culprits comprehensively. Naturally, this is quite a complex subject of research. Advances are driven by the physical understanding of loss mechanisms that are either solely in acoustic or crosscutting acoustics and electromagnetics [13].

The last foundational metric is frequency scalability. The frequency range of operation can singularly determine a given technology's marketability. The early-day SAW vs BAW competition proves that frequency scalability can predominately drive market segmentation, with other aspects being assistant. Thus, frequency scaling is even more relevant in the age of 5G where band allocations are all over the spectrum and geographically diverse. Any technology (not limited to acoustic) that can offer adaption to vastly different frequencies is destined to play an essential role in future microwave systems.

Apart from probably k^2, Q, and frequency, often lumped as a product and dubbed as the different figures of merit (e.g., $k^2{\cdot}Q$, $f{\cdot}Q$, *or* $k^2{\cdot}f{\cdot}Q$), an assortment of secondary (not to say less critical) specifications, including temperature stability, power handling, nonlinearity, integration compatibility, and packaging, come into play in assessing the viability of a given acoustic technology. Generally, they are not as foundational as k^2 and Q in determining the material of choice and underlying trade space. However, they can, in some instances of applications, outweigh k^2 and Q. In this paper, we structure our review of the advances by categorizing them as targeting different fundamental parameters and discuss one target for each section. However, we carefully note that, like any complex engineering problem, these parameters are often interleaved. In practice, advances were made with a balanced goal of improving all parameters possible. With that said, we will also highlight the impact of enhancing one target on the others (including the secondary targets), although not in an exhaustive fashion. In some instances, we offer outlooks on potential challenges ahead while trying to be as nuanced as this complex subject deserves.

III. HIGHER COUPLING OPERATIONAL MODES

With the criteria set up, it is not surprising that foundational advances arise from materials and their supporting operational modes. It is particularly true for piezoelectric transductions, the most ubiquitous electromechanical method at microwave frequencies due to their balanced traits in the larger coupling, high linearity, and integration. Key materials that have been proven with commercial success include aluminum nitride (AlN) [14], [15], lithium tantalate (LT) [16], [17], and lithium niobate (LN) [18]–[20]. They have morphed into bulk acoustic wave (BAW) or surface acoustic wave (SAW) devices serving the filtering needs in handsets and other mobile devices.

Depending on the boundary conditions (suspended or solidly mounted), AlN can provide an electromechanical coupling of 4-6% for the thickness-extensional mode and 1-2% for lateral vibrating modes [zero-order symmetric (S0) Lamb wave] [21]–[24]. The former has been the workhorse configuration for film bulk acoustic resonator (FBAR) and solidly mounted resonator (SMR). The latter has been a research hotbed for infusing more lithography-driven frequency settings into AlN technology. To further enhance coupling in AlN, there are two prominent approaches. One relies on hybrid modes (2D mode, or cross-sectional Lamé) that harness both d_{33} and d_{31} to produce a larger coupling [25]. The enhancement here is 1-2% on top of a typical FBAR. The other approach requires scandium (Sc)-doping of AlN, a method proposed and validated a decade ago to increase d_{31} and d_{11} [26]–[30].

The first approach, primarily pioneered by university researchers, shows that the 2-dimensional (2D) nature of hybridizing thickness and lateral extensional modes can elegantly combine their respective benefits, namely large coupling and the ability to lithographically set frequency [Fig. 1(a)-(b)]. However, it inspires a complex design space where electrodes have been carefully designed to harvest the benefits and avoid the spurious modes. Fundamentally, making a cavity more prominent in 2D [i.e., making interdigital transducers (IDT) pitch and AlN thickness comparable] would increase eigenmode density (i.e., number of eigenmodes per unit frequency range) and boost the chance of inadvertent excitation of unwanted modes. They can be managed and more worthwhile provided with a more considerable boost of k^2 as

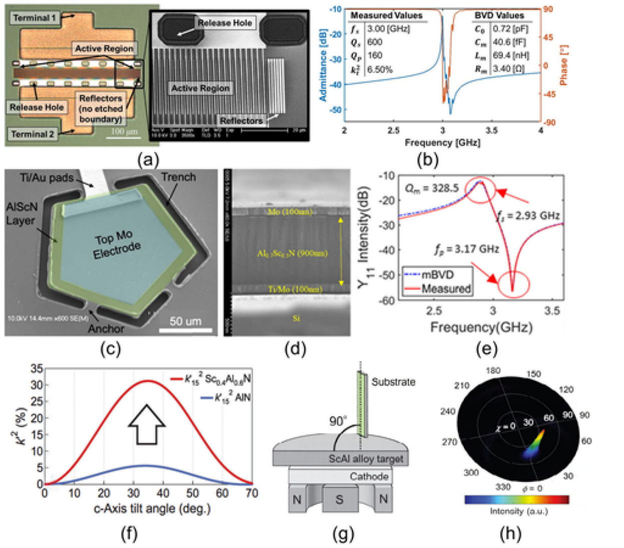

FIGURE 1. **(a) Optical and scanning electron microscope (SEM) images of a fabricated cross-sectional Lamé mode resonator. (b) Measured response with extracted Butterworth Van-Dyke values [27]. (c) SEM image for the fabricated FBAR. (d) Cross-section SEM image of the resonator stack. (e) Measured and modified-BVD fitted plots [28]. (f) Calculated k^2 of shear mode in tilted ScAlN. (g) Glancing angle sputtering technique. (h) X-ray diffraction of tilted ScAlN film [37].**

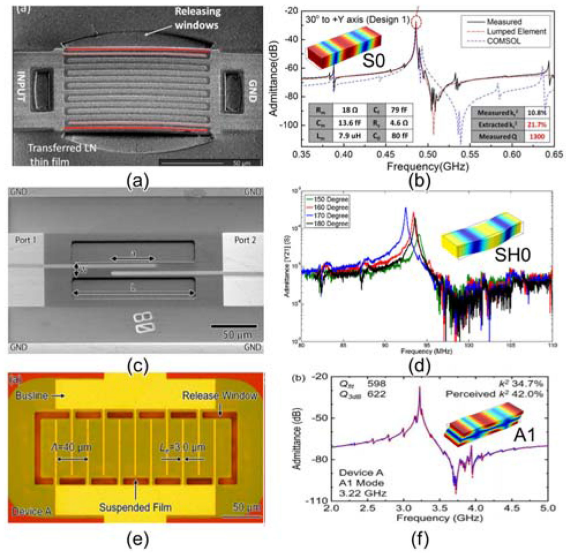

FIGURE 2. **(a) SEM and (b) measured admittance of S0 resonator in X-cut LN thin-film [40]. (c) SEM and (d) measured admittance of SH0 resonator in X-cut LN thin-film [41]. (e) Optical image and (f) measured admittance of A1 resonator in 128-Y cut LN thin-film [52]. Mode shapes for S0, SH0, and A1 are plotted.**

a reward. Therefore, it is expected to make more impact when applied to Sc-doped AlN for high-frequency applications [31], [32].

The second approach, Sc-doped AlN [Fig. 1(c)–(e)], since it was first introduced, has found its way into commercial products at moderate doping concentrations [30]. Extensive research has gone into reactive sputtering of Sc-doped AlN targets that can produce uniform doping concentration and stress across wafers [33]. Tradeoffs between doping levels and experimentally attainable Q have been renewed every year, producing higher and higher k^2 with nearly no sacrifice of Q [28]. It continues to encourage the researcher to push towards higher doping levels for larger k^2. In parallel, new film deposition techniques [e.g., metal-organic chemical vapor deposition (MOCVD) and molecular-beam epitaxy (MBE)] that had not been applied to AlN were exploited to control compositions more precisely and improve crystallinity [34]. New dopants [e.g., magnesium (Mg)] that promise comparable forming energy levels but lower-cost have also been attempted as an alternative to Sc [35]. However, several challenges, in addition to developing optimal physical vapor deposition (PVD) configurations, remain in reliably engineering targets of precisely controlled composition.

In addition to the above two approaches, the third approach, while still in the early stage, uses titled C-axis growth of AlN [doped or otherwise, Fig. 1 (f) - (h)] to gain access to shear modes in AlN [36], [37]. This technique is similar to producing different cut-planes in LT and LN but for AlN. By rotating the crystal axis, one can now customize the d_{ij} to the extent of tensor matrix rotation allowed by the titled growth. In this instance, the shear mode can produce higher coupling than the conventional thickness mode. So far, the experimental results show tilted grains have some detrimental effect on Q. It remains to be seen if such a bottleneck can be overcome.

In addition to AlN, the development in LT and LN is just as exciting in the past decade. Like AlN FBAR and SMR, conventional LT and LN SAW met the bottleneck in enhancing k^2 even though both materials are capable of higher k^2 if more advanced modes [zero-order shear horizontal (SH0) or S0 and first-order antisymmetric (A1) modes in Lamb wave family] are accessible [38]–[45]. To this end, plates and films of LT and LN have to be enabled, and reflective boundaries have to set for the surfaces of the films. This overarching approach has spun off numerous flavors of LT and LN thin film on substrate/insulator technology. They all similarly exploit the transfer technique to take a slice of the bulk LT and LN and bond to a carrier substrate for following device engineering [46]–[48]. Several vital benefits arise from such an implementation breakthrough. First, the film transfer techniques make any cuts available in bulk substrates available as single-crystal thin films on a bonding-compatible substrate. Designers now have comprehensive options, although not wholly boundless, in choosing d_{ij} of their liking for a given mode. Second, crystallinity and acoustic loss are superb in these thin films, free of typical crystallinity concerns in physical vapor deposited (PVD) films. Last, unlike the growth method where the film is highly dependent on the template film underneath, film quality enabled by transfer is far less contingent upon the carrier substrate, allowing better Q from the material point of view.

The modes that have been explored include S0 [Fig. 2(a), (b)], SH0 [Fig. 2(c), (d)], and A1 modes [Fig. 2(e), (f)] [38], [39], [41]–[45], [49]–[52]. The classification of these modes may vary depending on how strictly one treats and interprets the distortion of mode profile under different boundary conditions and their own branding purposes. Nonetheless, they display outstanding electromechanical couplings, in certain instances, 2 to 4 times of k^2 of conventional SAW modes, while featuring comparable Qs.

Their pros and cons are as follows. Besides their outstanding k^2, it is important to discuss the challenges that come along with high k^2. The large k^2 for the intended modes means that high d_{ij} in the cut plane of LT or LN can be inadvertently tapped by other eigenmodes residing in the nearby frequency range. It gets challenging to suppress some of these spurious modes, particularly for S0 and A1 devices [3], [52]–[56]. For S0, the cut plane allowing optimal S0 excitation also permits non-trivial SH0 excitation. Confinement schemes demonstrated so far for S0 also bound SH0 and other Lamb waves (e.g., A0) well. Considering the additional higher-order transverse or longitudinal S0 spurious modes, the problem is even more complicated. Nonetheless, with the faster velocity than S0 and its relatively non-dispersive nature, interest in S0 remains high for frequency scaling purposes, and the verdict is still out on if some of the challenges are too difficult to overcome.

On the other hand, A1 travels at a much faster phase velocity than any acoustic modes currently in use. It bears the 2D nature found in AlN cross-sectional modes, thus facing a similar change in having a high mode density. However, A1 in LN is more dispersive than the Lamé mode in AlN. LN also has much higher d_{ij}s overall than AlN. The combination of the two allows A1 to be excited without much k^2 variation over a much more extensive range of the pitch-to-thickness ratio [Fig. 2(e)–(f)]. Such flexibility works in favor of spurious suppression techniques that play with the electrode pitch values [44]. However, that is not to say A1 spurious modes are a solved problem. Transverse and other eigenmodes that cannot be addressed by adjusting pitch width would have to be overcome by more innovative methods (e.g., recessed electrodes [57] or periodically installed release windows [58], [59]). Perhaps, the large k^2 seen in the modes only serves as a motivator for addressing technical kinks in harnessing these modes.

One may say that competition between AlN and LN/LT-based technologies is shaping up. On the AlN side, enabling more doping while leveraging the existing manufacturing and design infrastructures is the key to the quick deployment of new devices for wideband applications. Given the large amount of know-how already accumulated with undoped AlN in design and fabrication, maturing the material is probably the main hurdle. However, as AlN doping levels get enhanced, design innovations will also follow, focusing on the best exploitation of a more complex and reconfigurable matrix of piezoelectric coefficients (examples already seen in Lamé and shear modes).

On the LN/LT side, ion-slicing or film transfer technique has made materials of single-crystal quality. However, fabrication still needs to be refined to attain finer thickness control, and wafer size should be increased to lower cost, both critical for competitiveness against doped AlN. Moreover, unlike AlN, designers are still battling spurious modes, power handling, temperature stability for these newly available modes in LN/LT thin films that were not accessible in LN/LT substrates. Solutions to these problems might require further structural innovation beyond electrode layout optimization. Luckily, the flexibility in transferring films onto various substrates and structures gives hope to overcome said issues eventually.

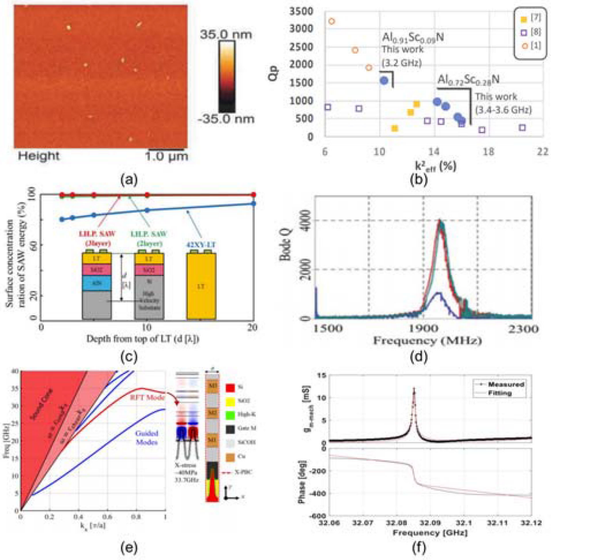

FIGURE 3. **(a) Atomic force microscopyof AlScN on Si, and (b) summary of *Q* and k^2 of AlScN at different doping concentration [62]. (c) Film stack and (d) measured Bode Q of the IHP-SAW at 2 GHz [66]. (e) Design and (f) measured transconductance of resonant-fin transistor at 32 GHz [74].**

IV. ENHANCING QUALITY FACTORS AND REDUCING LOSS

The efforts on enhancing the quality factors in acoustic resonators have been primarily on better material quality, advanced material bonding process, and new approaches for energy confinement. The piezoelectric films, e.g., ScAlN and AlN, have been extensively studied toward better film quality control for thinner piezoelectric layers [60]–[64]. The new epitaxial approach [65] and improved sputtering techniques [62] have shown a lower loss in piezoelectric films [Fig. 3(a)-(b)]. The improvement of thin-film transfer and bonding techniques is the other driver for higher Qs. These techniques have enabled structural innovations that were previously difficult to implement. More particularly, new film stacks leveraging solidly mounted piezoelectric thin films, e.g., incredible high performance (IHP)-SAW [66], have demonstrated higher Q and lower TCF at the same time. Researchers have investigated both the high-velocity substrates [67]–[69] and multi-layer substrates [70]–[72] for better energy confinement of acoustic wave devices [Fig. 3(c)-(d)]. Researchers have also demonstrated higher Q devices for free-standing thin-film devices by combining piezoelectric thin-films with low acoustic loss substrates [73]. Finally, the effort in studying the dispersion of acoustic structures and acoustic bandgaps through

TABLE 1. Comparison of Various Modes in LT and LN

Mode	Shear Horizontal [41], [49], [50], [70]	Longitudinal [39], [42], [56], [67]	Antisymmetrical [43], [45], [52]
Phase Velocity	3500 m/s	~6000 m/s	~8000 m/s
Range of k^2	~30%	~20%	~40%
Demonstrated Confinement Configuration	Suspended LN, LT on Si, LN on SiC, LN on SiO_2/Si	Suspended LN, LN on SiC, and LN on Mirrors	Suspended LN
Preferred Cuts in Demos	X-cut LN and 42Y LT	X-cut LN	128Y LN and X-cut LN
Challenges in Spurious Mode Suppression	Low to Medium	High	Medium to High

photonic crystal structures [Fig. 3(e)-(f)] is still pushing the limit of achievable acoustic resonators at RF [74]–[78].

Beyond the above improvements, which are driven by acoustic consideration, others tackle EM loss. Optimizations aiming to reduce dielectric loss use novel structures and strategic placement of low loss tangent dielectrics [79]. The results show substantial improvement not only in *Q*, but also in nonlinearity.

It can be forecasted that materials and fabrication are soon to be bottlenecks for *Q* as design advances exhaustively squeeze out all possible *Q* enhancements (e.g., anchor loss, mode confinements). For undoped and doped AlN microsystems at lower RF, *Q* is probably already hitting a glass ceiling collectively imposed by the AlN and metal materials, nonuniformity, roughness, and other fabrication imprecisions. LN/LT thin film-based devices, however, still have some room from the material imposed limit, at least for some of the modes.

Recently, extensive characterizations on acoustic wave propagation loss in thin-film LN have shown a material *Q* limit of 6000, while devices only display *Q* ranging from 300 to 1000. Such studies leverage a new group of devices, named acoustic delay lines (ADLs) [51], [80]–[82]. ADLs are two-port devices with a pair of piezoelectric transducers on the opposite end of the acoustic waveguide. Different from acoustic resonators, where various loss factors are intertwined (e.g., anchor loss, thermoelastic damping, and loss in the electrodes [83]–[85]), ADLs can have loss mechanisms more isolated. One can directly extract acoustic propagation loss [86] with the identical transducer design but different waveguide lengths [87]. Low-loss and wideband ADLs at GHz have been built using S0 in AlN thin films [82], S0 [87], SH0 [88], A1 [89], and higher-order Lamb waves [90] in LN thin-films, and SH-SAW in solidly mounted LN thin-films [91], [92]. The propagation loss reported for GHz acoustic waves in LN is around 0.005 dB/λ and 0.03 dB/λ [90], and S0 shows the lowest loss. Such propagation loss is equivalent to maximum *Q*s between 6000 and 1000 for GHz thin-film LN devices. Interestingly, the predicted maximum *Q*s are consistent with the highest *Q*s measured in LN lateral overtone bulk acoustic resonators (LOBARs) [93], [94], where the device is mostly unmetallized LN thin film. Such *Q*s are much higher than the reported resonator *Q*s, suggesting that the loss in the electrodes and anchor loss are the dominant loss factors for current LN resonators.

V. SCALING TO HIGHER FREQUENCIES

Increasing to high frequencies is probably the most exciting subject the microwave acoustic research community faces in the past few years. Somehow, acoustics have earned the reputation of being only good sub-3 GHz, beyond which *Q*s are meager and EM structures offer better. The crossover point, where EM waveguiding overtakes acoustics in having a lower loss for chip-scale passives, is hard to pin down and is a moving target as both platforms improve over time. At room temperature, it is safe to say that the crossover does not happen below 6 GHz currently [95], [96], i.e., acoustics still hold an edge in loss (without considering size advantages). Products based on FBARs and SMRs have been placed in market places for WIFI 6 and C-V2X bands with *Q* in 1000s. Questions start to emerge if one can push acoustics to even higher frequencies, well over 10 GHz, 20 GHz, and perhaps even 60 GHz [97]. The need for such higher frequency acoustic devices is definitely brewing as higher frequency and higher-order multiple-input multiple-output (MIMO) or phased arrays have been envisioned. All point to possibly more miniature filters as parallelism blows even further up in handsets. Although it is debatable where and how frequency-domain filtering should be or have to be applied in these future systems, having access to high-performance acoustic filters certainly would not hurt.

If one examines the wavelength vs. frequency chart in Fig. 4, a vast gap indeed exists in the size and frequency design space over the 6-60 GHz range between current EM and acoustic capabilities. Recognizing this deficiency, numerous works have targeted this problem with three different philosophies. The first type is based on brutal force scaling, namely reducing the dimension that predominately sets the resonant frequency [98]. In BAWs, that is the AlN thickness [99], and in SAW [Fig. 5(a)–(b)] or contour-mode resonators (CMRs) [i.e., S0 Lamb wave, Fig. 5(c)–(d)], that is the electrode pitch and lithography resolution [100]. In 2-dimensional modes [Lamé or A1, Fig. 5(e)–(f)], that is both the thickness and pitch. Such an approach is simple but facing challenges from multiple fronts. Maintaining precision in setting the thickness or pitch is difficult as the dimension reduces. It pushes closer

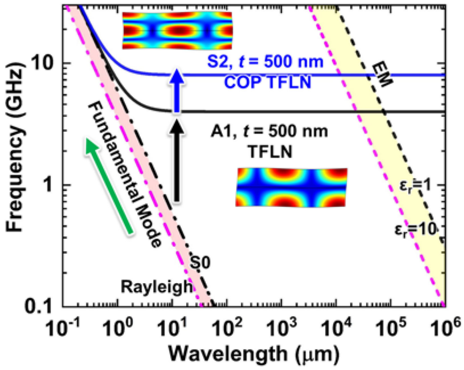

FIGURE 4. Operating frequencies of various EM and acoustic waves with different lateral wavelengths. The three frequency scaling approaches are labeled, including reduced dimension (green), higher-order mode in the thickness dimension (black), and further overmoding using bi-layer complimentarily oriented LN thin films (blue).

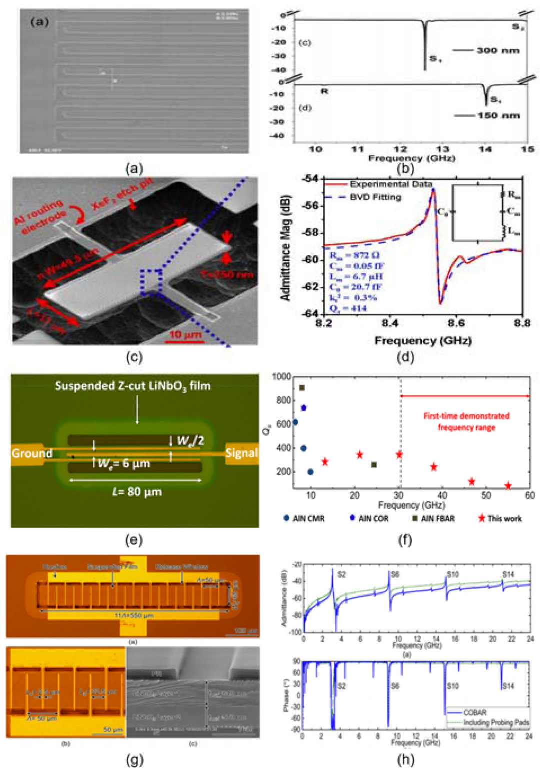

FIGURE 5. (a) SEM and (b) measured reflection of the high-frequency SAW [95]. (c) SEM and (d) measured admittance of AlN LVR [97]. (e) SEM and (f) measured responses of up to 60 GHz higher-order antisymmetric mode resonator in LN [94]. (g) Optical, SEM and (h) measured admittance of 21 GHz resonator using bi-layer complimentarily oriented LN thin films [86].

towards the limits of fabrication tools. Sputtered films also gradually lose crystallinity as thickness reduces. Other properties also degrade progressively (e.g., thermal conductivity). Moreover, metal thickness for BAW and metal width for SAW have to scale down accordingly, leading to exacerbated electrical loading. Power handling is also expected to diminish [101], requiring further quantitative studies.

The second type is to increase mode orders while keeping dimensions relatively unchanged to their low-frequency counterparts [97], [102]–[105]. Overmoding addresses the challenges of the prior approach but has to sacrifice k^2 at a pace of roughly 1/square of mode order. In order to scale frequency and end up with application-worthy k^2, one typically needs to start with a high k^2 mode. The higher the target frequency, the higher k^2 the fundamental should have for overmoding to suffice in k^2. Such an approach works well for the aforementioned A1 mode, although overmoding Lamé mode has also been attempted.

The third approach is a natural progression of the second, aiming to still overmode but with mitigated loss of k^2. It achieves such a goal by overmoding a composite structure. In one example [Fig. 5(g)-(h)], one can use a bi-layer complimentarily oriented device to double or triple the resonant frequency with no or little loss of k^2 [90]. In the other instance, one uses bimorph of piezoelectric on insulator to scale to third order, beating the pace of k^2 loss in conventional overmode and attaining temperature compensation in the process. Hopefully, all the above methods will find their place in implementing future high-frequency acoustic devices, particularly if the applications allow compensations schemes devised in the electromagnetic domain.

Roadmap for scaling towards high frequency is hard to depict as propagating acoustic waves beyond 10 GHz is a less traveled path. Physical understanding of loss with respect to frequency or mode orders is still significantly lacking, calling for more research and investigations. This area's uncertainty should be a hotbed for exciting discoveries for years to come.

VI. CONCLUSION

Despite being full of history, Microwave acoustics continue to spark innovations and exciting developments. As larger coupling, higher Q, and higher frequency microwave acoustic platforms mature, one should expect more complex microsystems with unprecedented signal processing capabilities.

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