Broadband Characterization of Near-Field Focusing With Groove-Structured Lens

YE HAN\(^1\), JIAN CHEN\(^1\), AND ZHENG FAN\(^2\)

\(^1\)State Key Laboratory of Fluid Power and Mechatronic Systems, School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China
\(^2\)School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798

Corresponding author: Jian Chen (mechejian@zju.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 52075486, and in part by the Ministry of Education Singapore under Grant MOE2019-T2-2-068.

ABSTRACT  Subdiffraction focusing of acoustic waves in the near-field can remarkably improve the signal-to-noise ratio in super-resolution acoustic imaging. Recently, we have successfully demonstrated the feasibility of near-field focusing with groove-structured lens. However, as a very critical step toward practical applications, the broadband characterization of the near-field focusing lens remains unexplored. In this study, we numerically and experimentally characterize the broadband performance of the near-field lens for subdiffraction sound focusing. The simulated and measured results agree well, both of which confirm that the near-field focusing works well over broadband. Furthermore, we find that the range and symmetry of the working bandwidth were largely influenced by the profound effect of groove depth on the excitation of evanescent waves. This study aims to advance the practical applications of the simple ultracompact lens in various areas of acoustics.

INDEX TERMS  Broadband characterization, near-field focusing, acoustic metasurface, evanescent wave.

I. INTRODUCTION

Super-resolution acoustic imaging of subsurface defects in opaque materials is of great importance in nondestructive evaluation as they are generally tiny, which are difficult to be perceived and could be easily missed. However, these shallow defects are easily to develop, thus becoming the potential origins of very server damages [1], [2]. Till now, this task is still very challengeable, and the research interest is seldom as well. On one hand, this is because conventional acoustic imaging devices operates with piezo-electric transducer, which has a blind zone in the near field. On the other hand, the spatial resolution of an acoustic imaging system is fundamentally restricted by the “diffraction limit” to half the wavelength of incident wave. To provide a detailed picture of the imaged scene, considerable works have been devoted to overcoming such limitation and exploring different approaches, such as superlenses [3]–[5], hyperlenses [6]–[8], time reversal techniques [9]. These works focus on detecting and restoring evanescent waves to achieve acoustic images with “super-resolution.” Nevertheless, the acoustic signal for super-resolution image formation is generally weak due to the exponentially decaying nature of evanescent waves. Recently, focusing and imaging beyond the diffraction limit in the far field were also realized by employing a unique phenomenon termed as superoscillation [10]–[2]. The key point to design a superoscillatory lens relies on the generation of delicate wave interference by specially optimizing mask structures. Similarly, the superoscillation phenomenon is usually featured with a very small fraction of power and constrained within a small region. To this end, another feasible approach commonly used in super-resolution imaging is to confine the acoustic energy into a small region beyond the diffraction limit to increase the intensity of scattered evanescent waves, improving the signal-to-noise ratio (SNR) of super-resolution imaging.

To do that, many theoretical and experimental attempts have been made over the past decades [13]–[15]. Among them, acoustic metasurfaces, planar artificial materials consisting of patterned arrays of subwavelength-sized scatterers, have broadened the horizon of acoustic wave and expanded the functionalities in acoustic wave manipulations, such as negative refraction [16], asymmetric transmission [17], perfect absorption [18], surface wave conversion [19], cloaking [20], and so on [21], [22]. Furthermore, considerable efforts have been made on superfocusing that obtained...
interesting results [23]–[27]. However, previous designs of acoustic metasurfaces mainly utilize periodic resonant array structures, which are commonly considered for their macroscopic properties by using the effective medium theory while ignoring the active control of the near-fields. Meanwhile, resonant array structures are sensitive to the operating frequency, and their functionalities deteriorate rapidly with small frequency shift. Nevertheless, broadband source is widely used in practical imaging scenarios. Therefore, the demonstration of the broadband response of an acoustic device is a crucial step toward the practical applications, but which is still largely unexplored. Moreover, the broadband response will also significantly alleviate the stringent constraints in device fabrication imposed by the fulfillment of resonance condition.

Recently, inspired by radiationless electromagnetic interference [28], we designed theoretically, confirmed numerically and demonstrated experimentally subdiffraction sound focusing by a near-field lens, which consists of an array of deep-subwavelength-sized and -spaced grooves. Interestingly, such type of aperiodic arrangements in deep-subwavelength scale may render the proposed lens inherently broadband. This expectation comes from the fact that the focusing action mainly arises from the diffractions and couplings between the deep-subwavelength structures. The focusing behavior could be effectively preserved as long as the wave dynamics arising from the groove units continue to operate on the deep-subwavelength scale. Although the broadband evidence of similar structures has been showcased for far-field focusing [29], [30], the broadband characterization of near-field focusing lens for the direct manipulation of evanescent waves remains unknown. To this end, this work aims to characterize the broadband performance of the groove-structured lens capable subdiffraction sound focusing through both numerical simulations and experimental measurements. The numerical and experimental results are in good agreement with each other, confirming the hypothesis on the broadband behavior. Given the importance of understanding the broadband response, we hope this work will benefit the simple, planar, and ultracompact acoustic lens for super-resolution imaging in industrial non-destructive evaluation and underwater communication.

II. SIMULATION AND DISCUSSION

A. DESIGN OF NEAR-FIELD GROOVE-STRUCTURED LENS

Figure 1(a) shows the schematic view of the reflective groove-structured lens for subdiffraction focusing in the near field. For simplicity while maintaining generality, a 2D metasurface is considered in this study, as sketched in Fig. 1(b).

To design the groove-structured lens for near-field focusing, we first should decide what image we desire to have at the focal plane. Based on the image, we then proceed to obtain the fields presented at the exit surface of the lens, which is also defined as aperture fields. Here, angular spectrum method is employed to yield the exact aperture fields. Firstly, the angular spectrum of the image \( p(x, z = L) \) at the focal plane is obtained by the Fourier transform:

\[
P(k_x, z = L) = \int_{-\infty}^{\infty} p(x', L) e^{j k_x x'} dx'
\]

Then, the angular spectrum of the image is back-propagated to the exit surface of the lens, located at \( z = 0 \), by multiplying a propagator function:

\[
P(k_x, z = 0) = P(k_x, L) e^{jL\sqrt{k_0^2-k_x^2}}
\]

where \( k_0 = \omega c \) is the wavenumber in the free space, \( \omega \) is the angular frequency, and \( c \) is the acoustic speed. Finally, the aperture field at \( z = 0 \) can be recovered via the inverse Fourier transform:

\[
p(x, z = 0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} P(k_x, L) e^{jL\sqrt{k_0^2-k_x^2}} e^{-j k_x x} dk_x
\]
desired aperture field at the near-field lens. Note that both groove width and depth could be optimized in the design process, here for simplicity, we assign the groove depth to a preset value in prior.

To facilitate the sample fabrication and experimental measurements, the operating frequency of the near-field lens was chosen to be 1715 Hz with a wavelength of $\lambda = 200 \text{ mm}$. As a concrete example, we design the near-field lens with a focal length of $L = 60 \text{ mm} (0.3\lambda)$ and a sub-diffraction focusing pattern of:

$$p(x, z = L) = 2 \exp\left(-\frac{1}{4 \ln 2} \left(\frac{x}{\text{FWHM}}\right)^2\right)$$

where FWHM represents the full width at half maximum, which was set to 70 mm (0.35\lambda). Note that a limited lens width is sufficient for the near-field focusing as the evanescent waves are exponentially decaying and the contributions from outer apertures decrease rapidly when they are far away from the lens center. For this reason, the geometrical parameters of near-field lens are preset to $h = \lambda/6 (33.2 \text{ mm})$, $s = 0.15\lambda (30 \text{ mm})$ and $N = 11$, as labelled in Fig. 1(b). Accordingly, the overall width and thickness of the groove-structured lens were $D = 360 \text{ mm}$ and $H = 50 \text{ mm}$. On this basis, we apply microscopic coupled-wave theory to tune the aperture field of the reflected waves on the surface of the near-field lens. The details of microscopic coupled-wave theory can be found in Ref. 31, which predicts that the aperture field can be effectively modulated by varying the groove widths. The groove widths are then optimized by using nonlinear least-squares inversion (Matlab 2013b) based on coupled-wave theory, which fit the calculated aperture field and that from Eqs. (1) – (4) at each groove center. The optimized results are listed in Table 1. On the basis of the derived results, the near-field lens was fabricated from an aluminum block through electrical discharge machining, as shown in Fig. 1(c).

**TABLE 1.** Groove widths of the fabricated metasurface.

| No | 1   | 2   | 3   | 4   | 5   | 6   |
|----|-----|-----|-----|-----|-----|-----|
| width | 1.0 mm | 1.0 mm | 1.2 mm | 20.5 mm | 20.0 mm | 3.4 mm |
| No | 7   | 8   | 9   | 10  | 11  |
| width | 20.0 mm | 20.5 mm | 1.2 mm | 1.0 mm |

**B. SIMULATION SETTINGS**

To primarily elaborate the broadband performance of the near-field lens for subdiffraction focusing, we firstly conducted finite element analysis by using COMSOL 5.4a. In the simulation model, physical modules of Pressure Acoustics, Frequency Domain and Solid Mechanics were adopted, which were coupled with Acoustic–Structure Boundary interface. The host (solid) and filling (background) materials were aluminum ($\rho_s = 2700 \text{ kg/m}^3$, $c_1 = 6300 \text{ m/s}$, and $c_s = 3100 \text{ m/s}$) and air ($\rho_l = 1.2 \text{ kg/m}^3$, $c_l = 343 \text{ m/s}$), respectively. A plane wave radiation boundary was applied on top of the simulation domain with the incident pressure field being unity amplitude (1 Pa) and normal incidence ($k_x = 0$, $k_z = k_0$). To reduce the computational burden, perfectly matched layers were added to other outer boundaries of the simulation domain, which mimic an anechoic environment to minimize unwanted scatterings. Meanwhile, Narrow Region Acoustics were assigned to deep-subwavelength grooves to account for the thermal and viscous losses.

**C. SIMULATION RESULTS**

As a representative illustration, the normalized intensity maps of the simulated pressure field at different frequencies, that are 1515, 1615, 1715, and 1815 Hz, are shown in Figs. 2(a) – 2(d) [upper panel]. As expected, the reflected waves were tightly focused in front of the groove-structured lens. In a qualitative sense, these results proved that the lens could work over a broad range of frequencies. Then, we further check the broadband focusing via a quantitative analysis. The amplitude profiles of the pressure field along $x$ and $z$ directions through the focal spot are plotted in Fig. 3(a) and Fig. 3(b), respectively. From Fig. 3(a), the simulated FWHM are measured to be 98, 86, 71 and 74 mm from 1515 Hz to 1815 Hz. After scaling to their respective wavelength, the normalized FWHMs are 0.43\lambda, 0.41\lambda, 0.36\lambda, and 0.39\lambda, respectively, all of which are below the diffraction limit, proving the assertion of broadband subdiffraction focusing. Similarly, from Fig. 3(b), the focal lengths are measured to be 0.23\lambda, 0.26\lambda, 0.29\lambda, and 0.42\lambda, respectively, which gradually increases with the frequency. Such focal length shift could be attributed to the dispersion effect [33]. For high frequencies, the converging waves tended to spread out, and consequently the focus moves away from the lens. Similar to the definition of $-3\text{dB}$ bandwidth of a signal at which the amplitude decreases by $3\text{dB}$ (about 29.3%) from its maximum value, here we consider the bandwidth as the FWHM deviates by 29.3% to that of designation, as illustrated in Fig. 3(c) inset. For that, the FWHM bound was calculated to be 0.453\lambda (FWHM_{max} = 0.35\lambda + 0.35\lambda*29.3%). From Fig. 3(c), it can be seen that the FWHM values were below the bound over the frequency range of [1420 Hz, 1850 Hz], which is about 25% of the operating frequency. This result indicates the broadband nature of the near-field lens. Although not very impressive, the working bandwidth outperformed many resonant devices. Meanwhile, it is obvious that the response is asymmetric over the frequency range. The low-frequency part (smaller than 1715 Hz) is found to be wider than its high counterpart. Besides, the incident and reflected energy were numerically computed by integrating the intensity over the domain ($-200 \text{ mm} \leq x \leq 200 \text{ mm}, 0 \leq z \leq 400 \text{ mm}$) in Fig. 2, which were 191.5 $\mu\text{W}$ and 123.5 $\mu\text{W}$, respectively. Thus, an efficiency of 64.5% can be obtained for the designed near-field lens.

**III. EXPERIMENT AND DISCUSSION**

**A. EXPERIMENTAL SETUP**

To confirm the broadband characteristic of the near-field focusing lens experimentally, we further carried out
experiments on the fabricated lens sample. Fig. 4 illustrates the experimental setup. The pressure field mapping was obtained by using a multifield microphone (4961, Brüel & Kjær, Denmark) and a 2D scanning stage in an anechoic room. A square sound shower (600 mm × 600 mm, Panphonics, Finland) was used to generate the plane wave incidence and placed 3 m away from the sample to minimize the bouncing between them. A sinusoidal signal was sent to the speaker through a USB sound card (sound blaster X-Fi, Creative Technology, Singapore). During the measurements, the microphone was raster scanned to record the pressure field in a 400 mm × 400 mm square area with a 2 and 5 mm step size in the x and z directions, respectively. The output signal of the microphone was 20 dB amplified by the signal conditioner (1704-A-001, Brüel & Kjær, Denmark) and then digitized by the sound card. The acoustic signal from the microphone and loopback signal from the speaker were recorded point-by-point in the virtual instrument software (Multi-Instrument 3.8, Virtins Technology) for further processing. Note that the pressure amplitude (A) and phase (ϕ) can be simultaneously recorded in the Multi-Instrument 3.8, and therefore the pressure field can be calculated as p = Aexp(−iϕ).

B. EXPERIMENTAL RESULTS
To obtain the reflected field from the near-field lens, the incident field without the lens and the total field with the lens were recorded in the measurement region. The resulting reflected field was calculated by subtracting the incident field from the total field. Following the same procedure, measurements were performed at different frequencies. The lower panels shown in Figs. 2(a) to 2(d) compare the normalized intensity maps of the measured pressure fields at the representative frequencies of 1515, 1615, 1715, and 1815 Hz. Also, the amplitude profiles of the measured pressure field across the focal spot and the measured FWHM values over the frequency range are plotted in Fig. 3. These measured results matched the simulated results well, thereby convincing the capability of broadband subdiffraction focusing. However, it is worth to emphasize that the measured spot size was smaller than that of the simulation when the frequency is below 1560 Hz, which is counterintuitive as the focal spot should be enlarged due to the convolution of the focusing pattern with the collection volume of the microphone. However, as mentioned above, the suppression in spot size can be attributed to the remarkable diffraction from the edges at the low frequencies. This also explains the causes of the differences between the simulations with measurements in Fig. 2.

IV. EFFECTS ON BANDWIDTH
Given the broadband characteristics of the near-field lens for subdiffraction focusing has been numerically and experimentally confirmed, we further showed that working bandwidth was remarkably influenced by the groove depth, which was narrowed down when the depth increased. Such limitation arises from the profound effect of groove depth on the excitation of evanescent waves. To prove that, Fig. 5 shows the reflection coefficient of groove units as a function of the depth. Intuitively, the reflection coefficient for smaller groove is larger, indicating the efficient excitation of higher spatial-frequency evanescent waves. Similarly, it also can be seen that the reflection increases with the groove depth ranging from 0 to 0.2λ, which means that the high-spatial-frequency evanescent wave can be efficiently
Y. Han et al.: Broadband Characterization of Near-Field Focusing With Groove-Structured Lens

FIGURE 3. The amplitude profiles of simulated (solid lines) and measured (cycles) pressure fields through the focal spot along (a) x and (b) z directions. (c) Simulated (squares) and measured (cycles) FWHMs of the focal spot. The threshold is denoted by the red dash line. The inset illustrates the bandwidth for broadband subdiffraction focusing.

generated. This also explained why a large depth \( h = 0.19\lambda \) was applied for tight focusing (FWHM = 0.17\( \lambda \)) in the previous study [32]. In this sense, the evanescent waves were more likely to change with deep grooves when the input frequency varies. Accordingly, the bandwidth that could preserve the desired focusing action was narrowed. To verify this proposition, we numerically examine the bandwidth of the previously developed near-field lens whose groove depth is 0.19\( \lambda \). For consistence, the operation frequency is also set to 1715 Hz, and the focal plane is 20 mm \( L = 0.1\lambda \) away from the lens. However, the sub-diffraction focusing pattern at the focal plane was \( p(x, z = L) = 2\text{sinc}(3k_0x) \), which yields a FWHM of 0.17\( \lambda \). Based on the same design procedures, the optimized groove widths are listed in Table 2. Fig. 6 shows the simulated FWHMs over a broad range of frequencies. According to the definition, the FWHM bound here was 0.23\( \lambda \). Note that, although the FWHM is far below the threshold at the high frequencies, the upper bound of the bandwidth is determined by the increasing sidelobes, and truncated at which sidelobes surpass the mainlobe, as shown in the inset of Fig. 6. Accordingly, the working bandwidth is determined to be only \( \sim 9\% \) of the operating frequency, less than half of the previous design. Meanwhile, this result also explained the formation of bandwidth asymmetry. For low frequencies, wavelength was comparatively long, and the effective groove

FIGURE 4. The schematic diagram of the experimental setup.

FIGURE 5. The reflection coefficient of groove with different widths as a function of the groove depth.
depth tended to remain unchanged. Therefore, the focusing behavior was more stable in the low-frequency band than its high-frequency counterpart. It is worth noting that the recent efforts on tunable structures also show great potential in broadband focusing [34]–[38]. We may further broaden the bandwidth by combining the inherent broadband characteristics with tunable geometrical parameters, i.e., the change of groove depth. This work would be concerned in the near future, but beyond the scope of this study.

V. CONCLUSION
To summarize, we numerically and experimentally characterize the broadband performance of the near-field lens for subdiffraction sound focusing. The simulated and experimental results are in good agreement, thereby indicating the broadband characteristic of the near-field lens with deep-subwavelength-sized and –spaced grooves. Furthermore, we show the effect of groove depth on the broadness and asymmetry of the working bandwidth. We expect the broadband characterization of near-field lens in this study would support the transfer of this simple ultracompact lens toward practical applications for various acoustics, including but not limited to, high-resolution acoustic imaging of subsurface defects in industrial NDE, compressed sensing in acoustic communication and high throughput in wireless power transfer.

REFERENCES
[1] A. Briggs and O. Kolosov, *Acoustic Microscopy*, Oxford, U.K.: Oxford Univ. Press, 2009.
[2] K. K. Amiridey, K. Balasubramaniam, and P. Rajagopal, “Holey-strutured metamaterial lens for subwavelength resolution in ultrasonic characterization of metallic components,” *Appl. Phys. Lett.*, vol. 108, no. 22, May 2016, Art. no. 224101, doi: 10.1063/1.4959067.
[3] J. I. Park, C. M. Park, K. J. B. Lee, and S. H. Lee, “Acoustic superlens using membrane-based metamaterials,” *Appl. Phys. Lett.*, vol. 106, no. 5, Feb. 2015, Art. no. 051901, doi: 10.1063/1.4907634.
[4] N. Kaine, F. Lemoutl, M. Fink, and G. Lerosey, “Negative refractive index and acoustic superlenses from multiple scattering in single negative metamaterials,” *Nature*, vol. 525, no. 7567, pp. 77–81, Sep. 2015, doi: 10.1038/nature14678.
[5] J. Zhu, J. Christensen, J. Jung, L. Martin-Moreno, X. Yin, L. Fok, X. Zhang, and F. J. Garcia-Vidal, “A holey-structured metamaterial for acoustic deep-subwavelength imaging,” *Nature Phys.*, vol. 7, no. 1, pp. 52–55, Jan. 2011, doi: 10.1038/nphys1804.
[6] J. Li, L. Fok, X. Yin, G. BartaI, and X. Zhang, “Experimental demonstration of an acoustic magnifying hyperlens,” *Nature Mater.*, vol. 8, no. 12, pp. 931–934, Oct. 2009, doi: 10.1038/nnmat2561.
[7] D. Lu and Z. Liu, “Hyperlenses and metalenses for far-field super-resolution imaging,” *Nature Commun.*, vol. 3, no. 1, p. 1205, Nov. 2012, doi: 10.1038/ncomms2176.
[8] C. Shen, Y. Xie, N. Sui, W. Wang, S. A. Cummer, and Y. Jing, “Broadband acoustic hyperbolic metamaterial,” *Phys. Rev. Lett.*, vol. 115, no. 25, Dec. 2015, Art. no. 254301, doi: 10.1103/PhysRevLett.115.254301.
[9] G. Lerosey, J. D. Rosnay, A. Tournay, and M. Fink, “Focusing beyond the diffraction limit with far-field time reversal,” *Science*, vol. 315, no. 5815, pp. 1120–1122, Feb. 2007, doi: 10.1126/science.1134824.
[10] D. Tang, C. Wang, Z. Zhao, Y. Wang, M. Pu, X. Li, P. Gao, and X. Luo, “Ultrabroadband superoscillatory lens composed by plasmonic metamaterials,” *Appl. Phys. Lett.*, vol. 109, no. 15, Oct. 2016, Art. no. 153501, doi: 10.1063/1.4959067.
[11] M. Berry et al., “Roadmap on superoscillations,” *J. Opt.*, vol. 21, no. 5, Apr. 2019, Art. no. 053002, doi: 10.1088/2040-8986/ab1091.
[12] Y.-X. Shen, Y.-G. Peng, F. Cai, K. Huang, D.-G. Zhao, C.-W. Qiu, H. Zheng, and X.-F. Zhu, “Ultrasonic super-oscillation wave-packets with an acoustic meta-lens,” *Nature Commun.*, vol. 10, no. 1, p. 3411, Jul. 2019, doi: 10.1038/s41467-019-11430-3.
[13] G. Ma and P. Sheng, “Acoustic metamaterials: From local resonances to broad horizons,” *Sci. Adv.*, vol. 2, no. 2, Feb. 2016, Art. no. e1501595, doi: 10.1126/sciadv.1501595.
[14] B. Assour, B. Liang, Y. Wu, Y. Li, J.-C. Cheng, and Y. Jing, “Acoustic metasurfaces,” *Nature Rev. Mater.*, vol. 3, no. 12, pp. 460–472, Oct. 2018, doi: 10.1038/s41578-018-0691-4.
[15] H. Ge, M. Yang, C. Ma, M.-H. Lu, Y.-F. Chen, N. Fang, and P. Sheng, “Breaking the barriers: Advances in acoustic functional materials,” *Nat. Sci. Rev.*, vol. 5, no. 2, pp. 159–182, Mar. 2018, doi: 10.1038/s42255-017-00154.
[16] L. Fok and X. Zhang, “Negative acoustic index metamaterial,” *Phys. Rev. B, Condens. Matter.*, vol. 83, no. 21, Jun. 2011, Art. no. 214304, doi: 10.1103/PhysRevB.83.214304.
[17] Y. Li, C. Shen, Y. Xie, L. Li, W. Wang, S. A. Cummer, and Y. Jing, “Tunable asymmetric transmission via lossy acoustic metasurfaces,” *Phys. Rev. Lett.*, vol. 119, no. 3, Jul. 2017, Art. no. 035501, doi: 10.1103/PhysRevLett.119.035501.
[18] Y. Li and B. M. Assour, “Acoustic metasurface-based perfect absorber with deep subwavelength thickness,” *Appl. Phys. Lett.*, vol. 108, no. 6, Feb. 2016, Art. no. 063502, doi: 10.1063/1.4941338.
[19] Y. Xie, W. Wang, H. Chen, A. Konneker, B. -I. Popa, and S. A. Cummer, “Wavefront modulation and subwavelength diffraction acoustics with an acoustic metasurface,” *Nature Commun.*, vol. 5, no. 1, p. 5553, Nov. 2014, doi: 10.1038/ncomms5553.
[20] C. Faure, O. Richoux, S. Félix, and V. Pagneux, “Experiments on metamaterial carpet cloaking for audible acoustics,” *Appl. Phys. Lett.*, vol. 108, no. 6, Feb. 2016, Art. no. 064103, doi: 10.1063/1.4941810.
[21] Y. Li, B. Liang, X.-Y. Zou, Li, J.-C. Cheng, “Extraordinary acoustic transmission through ultrathin acoustic metamaterials by coiling up space,” *Appl. Phys. Lett.*, vol. 103, no. 6, Aug. 2013, Art. no. 063509, doi: 10.1063/1.4817925.
[22] X.-D. Fan, Y.-F. Zhu, B. Liang, J. Yang, L.-L. Yin, J. Yang, and J.-C. Cheng, “Three-dimensional ultra-broadband focusing flat mirror for airborne sound,” *Appl. Phys. Lett.*, vol. 109, no. 15, Oct. 2016, Art. no. 153501, doi: 10.1063/1.4964605.
[23] S. Zhang, L. Yin, and N. Fang, “Focusing ultrasound with an acoustic metamaterial network,” *Phys. Rev. Lett.*, vol. 102, no. 19, May 2009, Art. no. 194301, doi: 10.1103/PhysRevLett.102.194301.

[24] Z. Lin, X. Guo, J. Tu, J. Cheng, J. Wu, and D. Zhang, “Acoustic focusing of sub-wavelength scale achieved by multiple Fabry–Perot resonance effect,” *J. Appl. Phys.*, vol. 115, no. 10, Mar. 2014, Art. no. 104504, doi: 10.1063/1.4868629.

[25] X. Zhou, M. B. Assouar, and M. Oudich, “Acoustic superfocusing by solid phononic crystals,” *Appl. Phys. Lett.*, vol. 105, no. 23, Dec. 2014, Art. no. 233506, doi: 10.1063/1.4904262.

[26] G. Ma, X. Fan, F. Ma, J. D. Rosny, P. Sheng, and M. Fink, “Towards anticausal Green’s function for three-dimensional sub-diffraction focusing,” *Nature Phys.*, vol. 14, no. 6, pp. 608–612, Mar. 2018, doi: 10.1038/s41567-018-0082-3.

[27] T. Liu, F. Chen, S. Liang, H. Gao, and J. Zhu, “Subwavelength sound focusing and imaging via gradient metasurface-enabled spoof surface acoustic wave modulation,” *Phys. Rev. A, Gen. Phys. Appl.*, vol. 11, no. 3, Mar. 2019, Art. no. 034061, doi: 10.1103/PhysRevApplied.11.034061.

[28] J. Chen, J. Xiao, D. Lisevych, A. Shakouri, and Z. Fan, “Deep-subwavelength control of acoustic waves in an ultra-compact metasurface lens,” *Nature Commun.*, vol. 9, no. 1, p. 4920, Nov. 2018, doi: 10.1038/s41598-019-50019-0.

[29] J. Chen, Z. Sun, and Z. Fan, “Groove-structured meta-surface for patterned sub-diffraction sound focusing,” *Appl. Phys. Lett.*, vol. 114, no. 25, Jun. 2019, Art. no. 254102, doi: 10.1063/1.5096258.

[30] A. Por, M. G. Nielsen, R. L. Eriksen, and S. I. Bozhevolnyi, “Broadband focusing flat mirrors based on plasmonic gradient metasurfaces,” *Nano Lett.*, vol. 13, no. 2, pp. 829–834, Jan. 2013, doi: 10.1021/nl304761m.

[31] J.-P. Xia, X.-T. Zhang, H.-X. Sun, S.-Q. Yuan, J. Qian, and Y. Ge, “Broadband tunable acoustic asymmetric focusing lens from dual-layer metasurfaces,” *Phys. Rev. A, Gen. Phys. Appl.*, vol. 10, no. 1, Jul. 2018, Art. no. 014016, doi: 10.1103/PhysRevApplied.10.014016.

[32] S.-W. Fan, S.-D. Zhao, A.-L. Chen, Y.-F. Wang, B. Assouar, and Y.-S. Wang, “Tunable broadband reflective acoustic metasurface,” *Phys. Rev. A, Gen. Phys. Appl.*, vol. 11, no. 4, Apr. 2019, Art. no. 044038, doi: 10.1103/PhysRevApplied.11.044038.

[33] Z. Chen, S. Shao, M. Negahban, and Z. Li, “Tunable metasurface for acoustic wave redirection, focusing and source illusion,” *J. Phys. D, Appl. Phys.*, vol. 52, no. 39, Jul. 2019, Art. no. 395503, doi: 10.1088/1361-6463/ab2abd.

[34] S. Pérez-López, J. M. Fuster, I. V. Minin, O. V. Minin, and P. Candelas, “Tunable subwavelength ultrasound focusing in mesoscale spherical mixtures using liquid mixtures,” *Sci. Rep.*, vol. 9, no. 1, p. 13363, Sep. 2019, doi: 10.1038/s41598-019-0019-0.

[35] J. Chen, J. Xiao, D. Lisevych, A. Shakouri, and Z. Fan, “Deep-subwavelength control of acoustic waves in an ultra-compact metasurface lens,” *Nature Commun.*, vol. 9, no. 1, p. 4920, Nov. 2018, doi: 10.1038/s41598-019-50019-0.

[36] J. Chen, Z. Sun, and Z. Fan, “Groove-structured meta-surface for patterned sub-diffraction sound focusing,” *Appl. Phys. Lett.*, vol. 114, no. 25, Jun. 2019, Art. no. 254102, doi: 10.1063/1.5096258.

[37] S. Pérez-López, J. M. Fuster, I. V. Minin, O. V. Minin, and P. Candelas, “Tunable subwavelength ultrasound focusing in mesoscale spherical mixtures using liquid mixtures,” *Sci. Rep.*, vol. 9, no. 1, p. 13363, Sep. 2019, doi: 10.1038/s41598-019-0019-0.