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ABSTRACT

Focusing of ultrasonic waves in water plays an important role in various scenarios ranging from biomedical imaging to nondestructive testing. Acoustic metasurfaces have been largely explored for acoustic focusing, but they are generally narrowband and mainly implemented for airborne sound because of their structural complexity. Nevertheless, our previous development of metasurfaces provides a great opportunity to solve the challenges. Here, we present numerically and experimentally the broadband focusing of ultrasonic waves in water with a metasurface lens consisting of an array of deep-subwavelength sized and spaced slots. The slot widths of the metasurface are optimized based on microscopic coupled-wave theory. Due to the non-resonant arrangement, the focusing effect is demonstrated over a broad band of frequencies. The metasurface lens with simplicity and an ultra-compact size provides a feasible means for the design of thin and lightweight ultrasonic devices and is suitable for practical applications in biomedical and industrial fields.

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Ultrasound is a powerful tool for the inspection of compositions and internal structures of opaque materials, and it is widely applied in various fields, such as biomedical imaging, non-destructive evaluation, and underwater seabed mapping.^{1,2} On this basis, manipulation of ultrasonic waves has attracted considerable interest in the acoustic community. As the basic and important means of wave manipulations, acoustic focusing, including ultrasonic focusing, has attracted considerable attention. Acoustic lenses based on refraction, which are usually constructed from a homogeneous material with a curved surface, have been widely employed to achieve acoustic focusing. However, the refractive lenses are generally bulky and expensive due to the limited acoustical materials, and the precise surface engineering of their cumbersome shape highly limits their throughput. In addition, the detachability of refractive lenses is poor due to their curved shape. Fresnel zone plates (FZPs) are introduced to focus acoustic waves by alternating the rigid and open apertures for constructive interferences of diffractive waves.^{3–7} FZPs are typically used in scenarios where curved refractive lenses are difficult to access owing to their planar profile. Meanwhile, FZPs are easy to fabricate. However, the low efficiency of FZPs impairs their practical applications.⁸ Furthermore, the focusing performance of either curved refractive lenses or planar FZPs is degenerated when their dimensions are reduced to wavelength scale.

In the last decade, the parameter space of acoustic materials has been vastly broadened with the rapid development of acoustic

metamaterials (AMMs).^{9,10} AMMs could yield diverse functionalities, such as negative refraction,^{11,12} extraordinary transmission,^{13,14} sub-wavelength imaging,^{15,16} extreme refractive index,^{11,17,18} perfect absorption,^{19,20} and others,^{21–25} through systematic engineering of their microstructures at a subwavelength scale. Among the functionalities, negative refraction and the gradient index are devised for the lens designs. Although promising results have been achieved, resonance-based AMM lenses experience narrow working bands and remarkable losses, which severely hamper their practical applications.^{12,18}

To overcome these deficiencies, planar AMMs with subwavelength thickness, namely, acoustic metasurfaces, have been applied for the design of acoustic lenses.^{26–30} Acoustic metasurfaces outperform bulk AMMs due to their compact footprint, low loss, and simple fabrication.³¹ Coiling-up-space-based acoustic metasurfaces (e.g., zigzag structure, labyrinthine structure, or helical structure) have proven their capability in acoustic focusing with substantially reduced thickness by controlling the effective path length. In addition, space-coiling elements render the lens to be inherently broadband. However, they are primarily realized for low frequency airborne sound due to their complex structures. Meanwhile, the thickness of these metasurfaces cannot be reduced to less than a quarter wavelength, in which the intrinsic losses in extreme narrow channels are remarkable. While the coiled space structures may be used for ultrasonic focusing, their practical realization is highly obstructed. More importantly, the routine design

rule based on effective medium approximation becomes invalid for underwater ultrasound. Recently, ultrasonic lenses with simple ring structures have been developed based on computational optimization algorithms.^{32,33} Although the results are satisfactory, such design processes are largely trial and the computational burden is intensive due to the large complexity of the optimization problems. For the same reason, the unit spacing and thickness of acoustic lenses cannot be reduced to be much smaller than that of the wavelength.

Very recently, our development of metasurfaces has provided a great opportunity to solve these challenges and the results demonstrate the great potential to apply this metasurface in the field of ultrasonic focusing. In this paper, we report an ultra-compact metasurface lens for broadband ultrasonic focusing in water based on microscopic coupled-wave theory.³⁴ The proposed metasurface consists of an array of deep-subwavelength spaced and sized concentric slots that are perforated in a thin plate. For convenience, the operating frequency is designated to be 100 kHz. The metasurface is optimized to focus a normally incident plane wave that is neither amplitude- nor phase-modulated at a given focal depth by tuning the slot widths. Moreover, the metasurface lens could operate over broadband due to the non-resonant units. Numerical simulations and experiments are conducted on the optimized metasurface to demonstrate the focusing action, and the results agree well. The proposed approach would provide a feasible means for the design of simple and ultra-compact ultrasonic lenses that are suitable in various scenarios.

The schematic of the proposed metasurface lens for ultrasonic focusing is depicted in Fig. 1(a). For clarity, the longitudinal section is shown in Fig. 1(b), in which the slot spacing and depth are denoted as s and h , respectively. As a concrete example but without the loss of generality, we use a metasurface lens comprising 10 concentric slots with $s = 2.5$ mm (0.17λ) and $h = 1$ mm (0.07λ). The focal length is specified as $f = 45$ mm (3.0λ). For a plane wave that is normally incident on the top of the metasurface, the ultrasonic wave experiences a phase shift when it passes through each slot. Following Huygens' principle, the transmitted waves diffracting from each slot should arrive in-phase for constructive interferences at the focal spot, which is expressed as follows:

$$\varphi(r) = \frac{2\pi}{\lambda} \left(f - \sqrt{r^2 + f^2} \right), \quad (1)$$

where r is the distance from the origin of the metasurface lens.

Traditionally, the phase shift passing through each slot is individually controlled by adjusting the slot width, depth, or filling material. However, the single-pass phase delay can be ignored in the context of deep-subwavelength thickness. The wave couplings between them are strong and impose a remarkable impact on the phase modulation, because the slots are closely spaced. On this basis, we apply microscopic coupled-wave theory to tune the phase profile of the transmitted waves on the output surface of the metasurface. The details of microscopic coupled-wave theory can be found in Ref. 34, which predicts that the phase can be effectively modulated by varying the slot widths. The slot widths are optimized by using nonlinear least-squares inversion based on coupled-wave theory, which fit the calculated phase and that from Eq. (1) at each slot. The optimized slot widths are listed in Table I.

We validated the analytical results by comparing them with numerical simulations. For simplification, a 2D simulation was performed by using a commercial finite element method (FEM) solver

FIG. 1. (a) Schematic of the metasurface lens for ultrasonic focusing. (b) The longitudinal section of the metasurface lens. It consists of 10 slots that are periodically perforated in a thin plate. The spacing, thickness, and width of the slots are denoted by s , h , and W_m , respectively.

(Comsol Multiphysics 5.1). The metasurface lens was axisymmetrically modeled with the structural parameters. The host material was steel ($E = 205$ GPa, $\rho = 7850$ kg/m³, and $\nu = 0.28$). The background (filling) medium was water with a density of 1000 kg/m³ and an acoustic velocity of 1500 m/s. Considering the fluid-structure interactions, modules of pressure acoustics and solid mechanics are incorporated and the acoustic-structure boundary interface deals with physical coupling. The slots were attributed to *narrow region acoustics* to account for the effect of thermal and viscous losses in the subwavelength regime. A plane wave radiation boundary was applied to mimic the plane wave incidence, which also serves as an absorbing boundary for the reflected

TABLE I. Optimized slot widths in the metasurface lens.

Slot	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}
Width (mm)	0.6	0.3	0.3	0.5	1.1	1.8	1.9	1.9	1.8	2.1

waves. To prevent unwanted reflections, perfectly matched layers were added to the outer boundaries of the simulation domain. For assurance, the mesh size was set to be smaller than $\lambda/10$, and a refined mesh was applied inside the slots to account for the fine features at the fluid-solid interfaces.

The intensity distribution of the simulated pressure field in the transmission domain is shown in Fig. 2(a), in which a typical cigar-shaped focal spot is clearly observed. For clarity, the intensity is normalized to the maximum value. To qualitatively assess the focusing performance, the normalized intensity profiles along the horizontal (x) and vertical (z) directions through the focal spot are plotted in Figs. 2(c) and 2(d), respectively. As shown in Fig. 2(c), the simulated full width at half maximum (FWHM) is measured to be 16.5 mm (1.1λ). On the basis of the Rayleigh criterion, the lateral spot size can be characterized by $0.61 \lambda/\text{NA}$, where NA denotes the numerical aperture of the metasurface lens that is determined by the lens radius and specified focal length as $\text{NA} = \sin[\tan^{-1}(r/f)]$. In our design, NA is calculated to be 0.48, and the theoretical spot size is predicted to be 19 mm (1.27λ). Obviously, the simulated FWHM is in good agreement with the theoretical prediction. The simulated focal length is 2.6λ by measuring the distance from the metasurface to the amplitude peak in Fig. 2(d), which is shorter than that of the designed focal length. This slight deviation can be attributed to two conditions, as follows. First, part of evanescent waves are incorporated because the acoustic focusing is close to the metasurface. This condition also causes the simulated FWHM to be tighter than that of the predicted FWHM. Second, the phase profile is only matched at a number of discrete points. Thus, the actual phase profile of the diffractive waves on the output surface may not coincide well with the theoretical profile. However, the simulated

FIG. 2. The intensity map of (a) simulated and (b) measured pressure fields in the transmission domain. The white dashed rectangle in (a) denotes the scanning area in experiments. The simulated and measured images are obtained at 100 kHz and 105 kHz, respectively. The profiles of normalized pressure amplitude through the focal spot along (c) horizontal and (d) vertical directions.

FIG. 3. (a) Schematic diagram of the experimental setup. (b) The fabricated metasurface lens. (c) The time-trace signal measured at the focal spot. The signals used for fitting and spurious reflections from the lens are marked by the red and black dashed rectangles, respectively.

results provide direct evidence on the ultrasonic focusing in water with the proposed lens, and the inaccuracies can be readily accounted through simulations. Meanwhile, we numerically estimate the focusing efficiency through the acoustic intensity integration. The incident power was calculated to be 1.55 nW over the working domain of $-24 \text{ mm} \leq x \leq 24 \text{ mm}$, $0 \leq z \leq 90 \text{ mm}$. Similarly, the focused power was 0.69 nW in the focusing area that is $-15 \text{ mm} \leq x \leq 15 \text{ mm}$, $0 \leq z \leq 90 \text{ mm}$. As a result, it is possible to render a focusing efficiency of 44.5% for the optimized metasurface lens.

To experimentally confirm the focusing behavior, we fabricated a sample lens from a 1 mm thick steel disk by electrical discharge machining. The experimental setup and a photograph of the fabricated lens are shown in Figs. 3(a) and 3(b), respectively. A round PZT transducer (Panametrics V1011, Olympus, USA) with a central frequency of 100 kHz was used to generate the normally incident plane wave and was placed at a distance of 300 mm from the lens to operate in the far field. The pressure field behind the metasurface lens was detected by using a Polytec laser vibrometer (Polytec GmbH, Germany) consisting of an OFV-505 optical sensor head and an OFV-5000 controller. The optical sensor head integrates a He-Ne laser with a power of 1 mW for the modulation of ultrasonic waves and an interferometer for the subsequent demodulation. The demodulated signal is then digitally decoded in an OFV-5000 controller with a bandwidth ranging from near DC to 24 MHz. A reflective strip was attached on the water tank to enhance the light scattering. During the measurements, the transducer was excited with a 5-cycle Hann windowed tone-burst signal at 100 kHz (RAM-5000, Ritec Inc., USA). The pressure field in a rectangular area with dimensions of $55 \times 108 \text{ mm}^2$ [white dashed rectangle in Fig. 2(a)] was scanned by using a lab-made 2D scanning system with a step size of 0.5 mm. The automatic acquisition process was

synchronized by a trigger signal from the motion controller. The time-trace signals were averaged 50 times to improve the signal-to-noise ratio and stored by using a digital storage oscilloscope (Lecroy HDO6054, Teledyne Technologies, USA). As an example, the time-trace signal at the focal spot, that is, $x = 0$, $z = 39 \text{ mm}$, is shown in Fig. 3(c). To avoid the spurious reflections from the metasurface lens (black dashed rectangle), we cut off the time-trace signal to obtain the first arrival wave according to the location of the detection point. However, this simple gating method does not work well for the pixels that are close to the lens. This is because the spurious reflection is partially overlapped with the first arrival wave. To solve this problem, we fit the first half of the gated signal (red dashed rectangle) to extract the actual waveform, and this treatment is applied to all pixels for the consistency of data processing.

Figure 2(b) shows the experimental result of the intensity distribution, in which a focusing pattern is clearly shown and coincides with the simulated image. Note that the intensity is derived from the pressure amplitude with $I = |p|^2/Z$, where Z is the acoustic impedance of water. Although nominated with 100 kHz, the measured central frequency is 105 kHz, and the bandwidth ranges from 95 to 125 kHz with tone burst excitation. The measured intensity profiles across the focal spot are plotted in Figs. 2(c) and 2(d). As shown in the figure, the measured and simulated results exhibit a fairly good agreement, which again validate the effectiveness of the proposed metasurface lens. However, the measured FWHM is larger than that in the simulation. This finding is mainly due to the edge diffractions arising from the finite size of the metasurface lens. Meanwhile, the spread of the acoustic beam from the transducer widens the focal spot. The simulation results are obtained by using the optimized parameters rather than the actual measured parameters from the sample lens. Therefore,

FIG. 4. Broadband ultrasonic focusing. Cross-sectional views of simulated (upper panels) and measured (lower panels) intensity patterns of the pressure field at (a) 95 kHz, (b) 115 kHz, and (c) 125 kHz. The white dashed rectangle marks the scanning area in experimental measurements.

the agreement effectively demonstrates the robustness of the metasurface design and its fabrication tolerance.

Interestingly, although the proposed metasurface lens is designed to operate a specific frequency, it could effectively focus ultrasonic waves over a broad frequency range, which is critically important for practical applications. The simulated (upper panels) and measured (lower panels) intensity maps of the pressure field at 95, 115, and 125 kHz are shown in Fig. 4. As expected, the ultrasonic waves are effectively focused at these different frequencies, which serve as a direct proof for the broadband focusing capability of the metasurface lens, which is over 25% of the central frequency. Actually, this broadband nature mainly arises from the aperiodic structure of the metasurface lens. From a microscopic viewpoint, the focusing behavior is dominated by the deep-subwavelength structures in terms of wave diffractions and couplings. Under this circumstance, the focusing effect can still hold when the input frequency changes as long as the lens structures are under the deep-subwavelength condition. As a result, it exhibits the observed broadband response.

Although the primary goal is achieved, several future studies should be conducted, which are beyond the scope of this work. In this study, the metasurface lens is optimized under a plane wave incidence. Therefore, the lens cannot be directly attached to the transducer at this stage. The emission wavefront on the transducer surface should be determined and considered to facilitate the integration. Meanwhile, a matching layer between the transducer and the lens is required to minimize the bouncing of reflected waves between them. The ultrasonic lens can be implemented in the megasonic regime to scale the metasurface to the desired sizes. The ultrasonic lens combined with the micro-electro-mechanical systems can remarkably reduce the cost and increase the throughput with massive production.

In conclusion, we theoretically designed, numerically proved, and experimentally demonstrated the broadband acoustic focusing in water by using a metasurface lens. Due to the non-resonant arrangement of the unit cells, the metasurface lens could work over a broad band of frequencies. Moreover, it offers the advantages of ultra-compact form, simple design, and ease-of-manufacture, which are particularly important for the implementation in the ultrasonic regime. Numerical and experimental evidence are in good agreement and thus validate the effectiveness of the proposed scheme. We anticipate that the proposed broadband lens could find potential applications in various fields of ultrasonics.

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