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ABSTRACT
Acoustic metasurfaces have largely been explored for acoustic field modulation, but because of their structural complexity, they are mainly implemented for airborne low frequency sound and generally located in the transmission medium, acting as a "passive acoustic field modulator." In this work, we present numerically the acoustic field modulation in water with a metasurface lens which consists of typical space-coiling structure units at high frequency (≥1 MHz). Four kinds of materials with different physical properties were utilized as lens materials, and the lens was set at the front surface of the ultrasonic transducers, acting as an "active acoustic field modulator." The proposed investigation could be extended to allow the metasurface lens for numerous waterborne high frequency ultrasound applications.

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INTRODUCTION
Ultrasound has widely been applied as a powerful tool in various fields such as diagnostic imaging, cellular stimulation, and microparticle manipulation. Manipulating ultrasonic waves is the key point for ultrasound applications and has attracted considerable interest. To achieve convenient acoustic field modulation, acoustic lenses no matter based on homogeneous material with a curved surface, Fresnel zone plates, or acoustic metasurfaces have been designed and developed. Among them, acoustic metasurface is the most notable one as it has the capacity to yield various functionalities, such as ultrahigh energy transmission, super-resolution beyond diffraction limitation, and anomalous refractive index conveniently at a subwavelength scale.

The normal principle behind these metasurface lenses which show a unique property of beam-steering is the generalized Snell’s law of refraction and reflection, where the wavefront can achieve a phase delay ranging from 0 to 2π by appropriately selecting the geometrical parameters. This unnatural functionality has been experimentally demonstrated by several standard artificial structures. In 2012, Li et al. reported a space-coiling structure that can force the waves to propagate through the passage which is much longer than the external dimension to achieve extra phase delay at 1734 Hz. After that, in 2014, Xie et al. proposed a labyrinthine material to control the surface phase distribution ranging from 2500 Hz to 3500 Hz. In 2016, Melde et al. used a reflection hologram to approach two trapping points by using a 100 kHz ultrasonic transducer in air. Conventional metasurfaces were primarily realized for low frequency airborne sound due to their complex structures and generally located in the transmission medium. Few research studies have been reported on the introduction of the metasurfaces to high frequency waterborne ultrasound.

The idea of extending the acoustic metasurface lenses from airborne sound to waterborne ultrasound has driven attractive attention but remains challenging. The first major limitation is the characteristic acoustic impedance contrast. In the traditional metasurface design, the characteristic acoustic impedance of the lens material is extremely higher with respect to air, which leads to the acoustic opaqueness of solids for airborne sound. The wave is assumed to propagate only in air, and thus, the phase delay can be calculated accurately. However, when the metasurface lens is located in water, the path formed by water may not modulate the wave propagation well due to the similarity of characteristic acoustic impedance. The wave may go through the metasurfaces directly rather than transport in the artificial coiling channels. The second problem is that with the frequency increasing to megahertz, ultrasound generated...
by transducers shows great directivity, which leads to the complexity of wave interference. Metasurface lenses can introduce the extra momentum at the surface, which attributes to the direction modulation at low frequency. Whether metasurface lenses can behave as theoretical prediction at high frequency is uncertain.

Compared to the “passive acoustic field modulator,” various advanced applications of the conventional metasurface lens can be achievable by setting the metasurface at the front surface of ultrasonic transducers, acting as the “active acoustic field modulator.” It is also worth noting that one can adjust the focal zone conveniently in experiment rather than complex operation. In this paper, a standard planar focus acoustic metasurface (PFAM) lens is designed and analyzed. Four materials with a significant characteristic acoustic impedance difference are chosen to analyze the approximate condition influence in water. A finite element simulation software (COMSOL Multiphysics 5.4a) is used to investigate the performance of passive and active metasurface lenses. Different simulation results are presented to verify the performance of metamaterial lenses for

**FIG. 1.** (a) The schematic diagram of unit cell of PFAMs. (b) Phase distribution along the x axis. (c) Simulation diagram of passive acoustic field control and dynamic acoustic field control.
choosing the most suitable materials for passive and dynamic application. This investigation pioneers a new path to developing a new application of metamaterial lenses for dynamic sound field control in water.

METHOD AND MODEL

The two-dimensional (2D) schematic diagram of the unit cells of PFAMs is shown in Fig. 1(a). The unit has a space-coiling structure which is capable of effectively generating an abrupt phase shift (0–2π). Hence, the phase shift due to the extra momentum of the incident wave in the coiled channel can cause the wave to refract at a specific angle. The total length of the channel is \( L \), and the phase response of the unit cell for fundamental frequency can be expressed as

\[
\phi = 2\pi L/\lambda. 
\]  

(1)

Figure 1(a) shows the phase difference diagram for \( f_1 \), and the extraordinary refraction angle is expressed as

\[
\theta_r = \arcsin \left( \sin \left( \theta_i + \frac{\lambda}{2\pi} \frac{d\phi}{dx} \right) \right).
\]  

(2)

where \( \theta_i \) is the incident angle and \( \lambda \) is the wavelength.

To analyze the potential of the metasurface lens applied in acoustic transducers, a planar focus acoustic metasurface (PFAM) was designed. As shown in Fig. 1(a), the unit cell is a coiling structure (green area) in the flat surface (blue area). The thickness of the unit cell is \( \lambda \), where \( \lambda \) is the wavelength corresponding to the operating frequency \( f_1 = 2 \) MHz. The transverse width of the unit cell is set as 192.5 \( \mu \)m, and the width of the coiling structure is \( a = 24 \) \( \mu \)m. The PFAM is integrated by a couple of units, where water forms the coiling space. The total length of the coiled channel \( L(x) \) is accurately designed to obtain the constant phase gradient. This assignment provides nearly linear distance difference among the neighboring outlets. Figure 1(b) shows that eight coiled channels are used ranging from \( \lambda \) to 2\( \lambda \) (\( L_0 \sim L_8 \)), and the corresponding phase varies from 0 to 2\( \pi \) with a step of \( \pi/4 \). The phase gradient and the

![Graphical representation](image)

FIG. 2. Analysis of passive acoustic field control: (a) transmission efficiency, (b) the acoustic intensity field, and (c) the foci point of four materials: epoxy 1500 \( \mu \)m; silicon 1300 \( \mu \)m; aluminum 1300 \( \mu \)m; steel 1300 \( \mu \)m. (d) The –3 dB beam width at foci points: epoxy 1424.38 \( \mu \)m; silicon 774.24 \( \mu \)m; aluminum 744.83 \( \mu \)m; steel 350 \( \mu \)m.

| Material | Density (kg/m\(^3\)) | Speed of sound (m/s) | Acoustic impedance (MRayl) |
|----------|----------------------|----------------------|---------------------------|
| Water    | 1000                 | 1540                 | 1.54                      |
| PZT-5H   | 8140                 | 4300                 | 35.00                     |
| Epoxy    | 1110                 | 2535                 | 2.81                      |
| Silicon  | 2329                 | 8433                 | 19.64                     |
| Aluminum | 2700                 | 6300                 | 17.01                     |
| Steel    | 5920                 | 7850                 | 46.72                     |
extraordinary sound refraction angle can be calculated theoretically. It is noted that traditional acoustic metasurface lenses are made of materials with significant acoustic impedance difference, such as air \((2 \times 10^6 \text{ Rayl})\) and epoxy \((2.81 \times 10^6 \text{ Rayl})\) and always applied in air. Few examples of the acoustic field control in water were proposed due to the acoustic impedance difference between water \((1.54 \times 10^5 \text{ Rayl})\) and epoxy \((2.81 \times 10^6 \text{ Rayl})\). The propagation of the wave in the coating structure can be affected, and the performance of the acoustic field control may be poor because of the wave cross talk in metasurface lenses. Four materials with different characteristic acoustic impedances such as epoxy, silicon, aluminum, and steel are chosen to analyze the performance of wave control. These four materials are commercially available, and some of them are used as matching layers for ultrasonic transducers usually.

To compare the dynamic performance of metasurface lenses with passive functionality of metasurface lenses, PZT-5H, a commercial piezoelectric material is selected to generate the Gaussian wave. The thickness of piezo-element is 800 μm, and the corresponding center frequency is about 2 MHz. Then, the metasurface lens is connected to the transducer directly and located in water. A finite element simulation software (COMSOL Multiphysics 5.4a) is used to investigate the performance of the dynamic metasurface lens. All material parameters used in the simulation were tested or from standard datasheet, which are shown Table I. It is observed that the sample is located in water. As plotted in Fig. 1(c), the sound source is set as a plane wave and Gaussian wave generated by the acoustic transducer, respectively, for further contrast investigation. The boundary condition of the medium is set sound free boundary, where the wave can go through without reflection. Several simulation results are presented to verify the performance of metasurface lenses. Criterions include transmission efficient, vibration mode of piezoelement, acoustic intensity field, focal point, and −3 dB beam width.

**RESULTS**

In Fig. 2(a), we present the numerical transmission spectra for “passive acoustic field modulator.” It is observed that the peak value of average conversion efficiency appears periodically within the frequency range. The first peak value shows the highest energy transmission efficiency, however, which may result from wave diffraction. Part of the wave can transport to the other side of PFAMs directly rather than in predicted passages, leading to less energy loss in coil- ing channels. Therefore, attention should be paid to the transmission efficiency around the designed frequency (2 MHz) to verify the acoustic modulation behavior of PFAMs. It is noted that epoxy (black line), of which the acoustic impedance is 2.35 MRayl, shows

![FIG. 3. Analysis of dynamic acoustic field control: (a) the acoustic intensity field, (b) the acoustic pressure field and phase profile, and (c) the foci point of four materials: epoxy 1900 μm; silicon 1600 μm; aluminum 210 μm; steel 1900 μm. (d) The −3 dB beam width at foci points: epoxy 610 μm; silicon 486.36 μm; aluminum 469.898 μm; steel 499.8 μm.](image)
good periodicity but poor transmission ability compared to other three materials. Due to the acoustic impedance similarity between epoxy and water, the performance of PFAMs may be poor and thus energy cannot be steered at foci point as predicted. Other three materials have significant impedance difference compared to water, which can suppress the cross talk in metasurface lenses. Thus, much more energy can be transferred to the medium. It is of interest that the frequency dependent conversion efficiency of aluminum and silicon (blue line and green line) has a consistent trend due to the similarity of acoustic impedance. This may cause the similar performance of wave modulation, and we will discuss it further. The PFAMs made of steel also achieve high transmission efficiency around 2 MHz after which it decreases with frequency.

In the investigation of the traditional metasurface lens application, the plane wave is set as the sound source. The simulation results of acoustic field and intensity magnitude along the y axis show good agreement with theoretical results. As predicted, the metasurface lens made of epoxy show the poor performance, while the metasurface lens made of steel shows significant performance in the wave control due to the biggest acoustic impedance, and it is interesting that the PFAMs have two focal points. For further investigation of this phenomenon, we assume that the wave propagates along a straight line, as shown in Fig. 1(a). By theoretically calculating, the refracted angle is 30° and the focal depth varies from 166.70 μm to 2833.60 μm. Due to the coherence and destructiveness, the focal points should appear one by one and the corresponding amplitude of intensity would decrease with distance. With the increase in frequency, varying from hertz to megahertz, the focal depth would be farther than theoretical prediction. Figure 2(c) shows that the first focal point is around 1500 μm and the corresponding focal depth is 730 μm. The PFAM made of steel (red line) has the maximum intensity value due to the biggest impedance difference. Moreover, at the first focal point, the ~3 dB beam width is investigated. As shown in Fig. 2(d), the beam width of steel (red line) is 350 μm, which shows the greatest capability of acoustic field control. It is obvious that steel may be the most suitable one among the four candidates for passive modulation behavior of the wave due to the significant acoustic impedance contrast of water.

Next, let us connect the PFAMs to the transducer directly. As we can see from Fig. 3(a), the effective wave steering behavior occurs at the frequency of 1.9 MHz. There is only one foci point which is around 2100 μm, and the corresponding focal depth is 1330 μm. Because the ultrasonic transducer is used to generate the Gaussian wave, the acoustic impedance matching is the considerable problem for high energy transmission. The generally accepted formula for the acoustic impedance of single matching layer is \( Z = (Z_0^2Z_l)^{1/2} \) (7.193 MRayl). Compared to the steel, aluminum and silicon have the lower acoustic impedance which are suitable to be the acoustic matching materials, and more energy is transferred to the water. To further investigate the wave modulation performance of the both, the detailed information is presented in Fig. 3(b). It is observed that there is a phase distribution along the x axis, and the wave modulation behaviors can be seen in the acoustic pressure field. The second foci disappeared because there is very little energy at the edge of pizoelement which transports through the PFAMs. It can also be demonstrated by the ~3 dB beam width in Fig. 3(d). Compared to the plane wave, the ~3 dB beam width of these four materials is smaller due to the disappearance of edge energy. Thus, steel and silicon may be the suitable materials for active wave control because they also play the role of bridges for energy transmission.

**CONCLUSION**

We have demonstrated the feasibility of a planar focus acoustic metasurface (PFAM) lens in water. Four different materials were analyzed by simulation, and the performance of wave control is investigated. Different materials are chosen due to the acoustic impedance contrast. Steel and aluminum show greatest performance in passive and dynamic wave control, respectively. However, it needs to be experimentally demonstrated by semiconductor process, and we will devote much effort to this work. Our work may lead to new ways of application of traditional metasurface lenses.

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