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Ultrathin coding metasurface for underwater wave focusing, branching and self-bending generation with one single actuator

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Abstract:

A novel metasurface is proposed that aims to generate underwater acoustic waves with various functions by only one actuator. Each metasurface unit consists of an air cavity sandwiched on one side by a vibration plate and connecting rubber supports. By properly selecting the ratio of the plate to unit lengths, a phase shift of π can be attained to constitute a binary coding metasurface. Three demonstrations, including focusing, branching and self-bending waves, are chosen to validate the functionality of the design. The design is also shown to work over a wide frequency range through changing the ratio. In addition, the design is extremely compact, with the thickness only about 1/100 of the target wavelength. Compared with commonly used phased array transducers that are utilized to generate underwater acoustic waves, this design offers has the advantage of needing only a single actuator as opposed to needing a lumped electrical control system.

I. Introduction

Acoustic metasurfaces, characterized by subwavelength thickness and functionally comparable to metamaterials [1-6], have shown astonishing abilities in controlling acoustic waves, abilities which cannot be found in natural materials [7-11]. These include, but are not limited to, providing asymmetric transmission [12-14], broadband operating ranges [15], cloaking [16-19] and high-efficiency manipulation [20-23]. Up to now, nearly all efforts in this area has put the metasurface as a passive interface in water, air or solids, including refractive, reflective or absorptive type[24-27]. This leaves the study of metasurfaces as an actuating part to be a barely developed field. On the other hand, the most popular way to currently generate underwater acoustic waves is the use of phased array transducer, which need multiple actuators and an electrical control system to coordinate them. This makes the systems complex and the design cumbersome.

Most metasurfaces require continuous 2π phase shift coverage to allow controlling the wave at will, which is not easy to obtain. An alternate is coding metasurfaces, which have attracted recent attention [28-35]. For instance, a one bit metasurface, or a binary metasurface, only needs 0 and π phase shifts, making it much easier to use when designing a structure. An ultrathin binary coding metasurface, nearly 1/100 of the target wavelength, is proposed here, which allows one to obtain underwater wave with phase shift of π by modifying the geometry of the metasurface. Three functions of the proposed metasuface are demonstrated. These include focusing, branching and self-bending wave generation, which are demonstrated through numerical simulation. In addition, the design allows tuning the function over wide operating frequency through slightly changing the geometry. This novel design opens a new avenue in metasurface research that has broad potential use in underwater wave applications.

II. Design

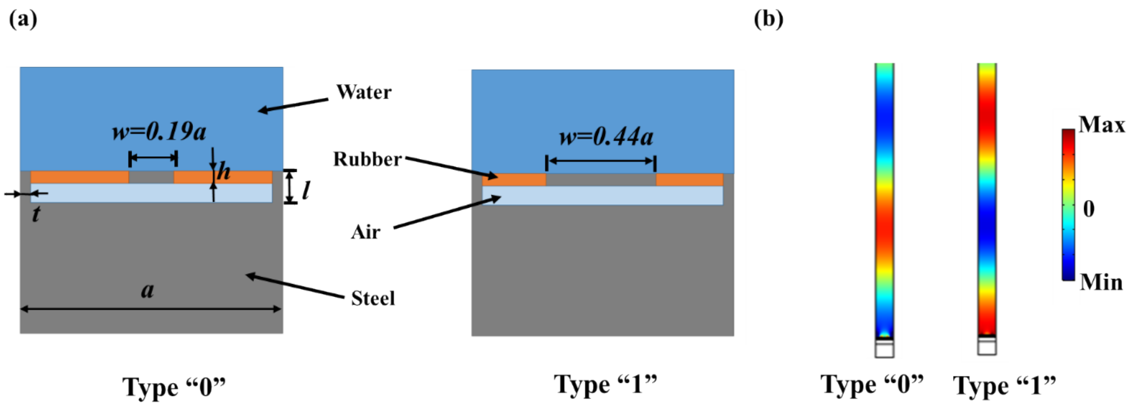

Figure 1.(a) Material and structure of the designed type “0” and “1” metasurface unit. (b) Acoustic fields of type “0” and “1” metasurface units under vertical displacement excitation at the bottom of 600Hz.

The material and structure of designed type “0” and “1” metasurface units is displayed in Fig.1a. A steel vibration plate of width *w* is connected to two steel supports by rubber spacers that hold the plate above an air cavity. The cavity provides space for the plate to vibrate. The metasurface functions when the bottom is excited by vertical displacement control to cause the plate to vibrate. Similar to the mechanism seen in membrane type metasurfaces, the wave phase in the water can be altered by changing the stiffness of the metasurface unit. The ratio *r*, which is equal to the ratio of the width *w* of the vibrating plate to the entire unit width *a*, is the chosen parameter used to modulate the phase.

Commercial finite element software Comsol Multiphysics is used to calculate the response of the unit. The Acoustic-Solid Interaction Module is utilized in the analysis. Periodic boundary conditions are imposed on the left and right sides. A Perfect Matched Layer is added to the top of the water region (not shown). The properties of steel and rubber are as follows. The associated Young's moduli are 205 GPa and 0.05 GPa, the associate densities are 7850 kg/m^3 and 1100 kg/m^3, and the associated Poisson's ratios are 0.28 and 0.4, respectively. The dimensions used in the design are: a = 0.2 m, t=0.008m, h=0.01m and l = 0.024 m, which are very compact compared to the target wavelength λ of 2.47 m. An input displacement excitation of 1×10^{-6} m at a frequency of 600 Hz is used on the bottom of the metasurface. It was found that selecting r = 0.19 and 0.44 resulted in identical transmitted amplitudes and a phase shift difference of π, as illustrated in Fig1.b. This indicates that the design produces the objective binary coding metasurface.

III. Demonstrations

To demonstrate the versatility of the design to generate underwater waves, three applications were considered. The first is acoustic wave focusing. With the help of the Airy function, the non-diffraction solution of the time-harmonic paraxial wave equation, Efremidis and Christodoulides [36] have achieved the focusing by setting the pressure along the metasurface as:

$$p_0(x) = Ai\left(\frac{x_0 - x}{\beta}\right)e^{\left(\alpha\frac{x_0 - x}{\beta}\right)}$$

where x is the position of the metasurface unit, x_0 is half-width of the metasurface, β and α are scaling factors, and $Ai(\cdot)$ is the Airy function. Jiang et al. [37] have recently shown a coding metasurface that successfully demonstrates focusing of acoustic waves by discretizing the Airy function in a binary manner. Here we discretize the function by selecting the units of the metasurface in the following manner. Along the length of the metasurface, a type “0” unit was selected when the Airy function was positive, and a type “1” unit was selected otherwise. The input excitation, as described in the design, is applied at the bottom surface and had a displacement amplitude of 1×10^{-6} m at a frequency of 600 Hz. Here β and α are chosen as 0.6 times the target wave length and 0.05, respectively. To discretize the signal, 144 metasurface units were used resulting in the intensity magnitude displayed in Fig.2a, which clearly indicates the focusing effect. To further validate this function, the intensity magnitude along the vertical and horizontal dash line in Fig.2a is plotted in Fig.2b and c. The full width at half maximum (FWHM), D, a scalar parameter used to describe the focusing extent, is also calculated and displayed in Fig.2c. In this case, D = 0.69λ, indicating that the uniform vertical motion of the solid structure under the metasurface is transformed and focused in the water by the coding metasurface.

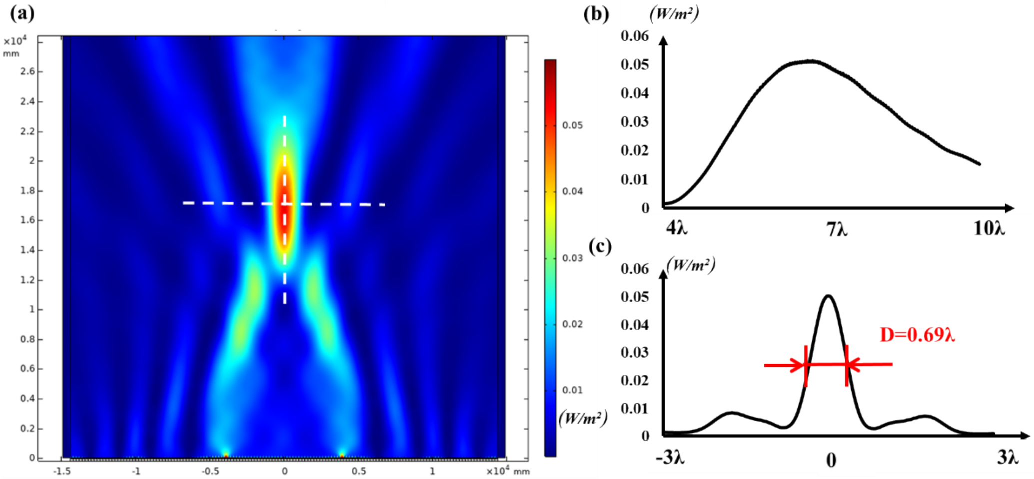

Figure 2. Focusing:(a) intensity magnitude distribution of the proposed metasurface under vertical displacement excitation. (b) and (c) intensity magnitude along the vertical and horizontal white dashed lines in (a). D is the full width at half maximum (FWHM).

The second demonstration is branching wave generation. By the Huygens principle, each metasurface unit can be treated as a line source and the acoustic field can be constructed by the superposition of all the units. Assume there are n_t units used and n_1 of them are type "1." Fang et al. [38] show that the pressure in the far field, written in a cylindrical coordinate system, is described by:

$$\mathrm{p}(r,\theta) = \frac{A}{k\delta\sqrt{r}} e^{-jk(\delta + r)}[\sin(kn_t\delta) - 2\sin(kn_1\delta)]$$

where $\delta = a\sin\theta/2$ is half the acoustic path of adjacent units and A stands for the pressure generated by a line source at one unit distance. Here we choose n_t=20 and n_1=10. Then directivity, $D(\theta)$, defined as square of the pressure at a constant radius over the square of the maximum pressure along all directions, is calculated and plotted in Fig.3a. The response of the proposed design is simulated and the result is displayed in Fig.3b. At a sufficient distance from the metasurface located at the bottom center of the figure, two branches of waves are found (i.e., in the far field) to closely match the theoretical prediction in Fig3.a, implying the possibility to use the proposed metasurface for branching wave applications.

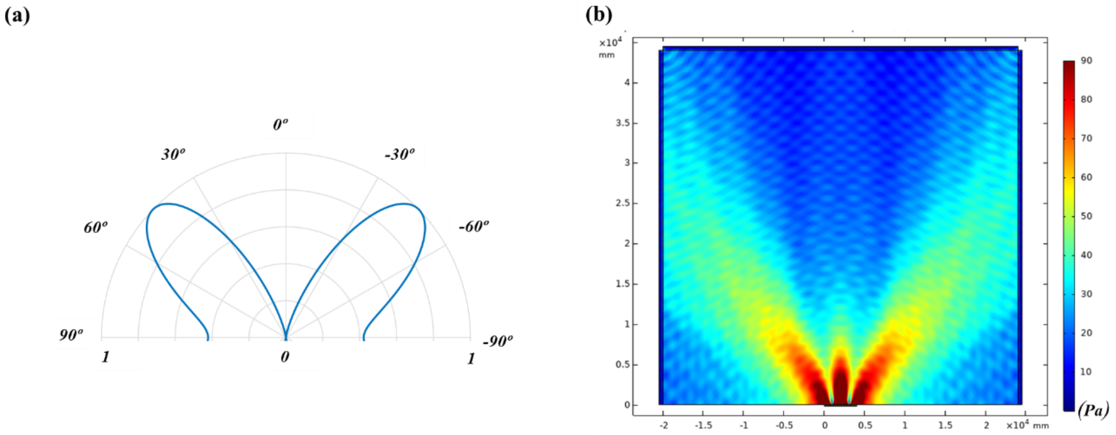

Figure 3. Branching: (a) theoretical value of directivity *D(θ)* with n_t =20 and n_l =10, (b) simulated pressure distribution of the corresponding metasurface.

Acoustic waves can be useful in underwater communication, since it is difficult for electromagnetic wave to propagate in water. Self-bending wave passing around obstacles may provide a pathway for communication when obstacles exist between the source and target. Here we show how our design can be used to easily form self-bending waves. As shown by Li et al. [39], a circular bending beam with radius R can be achieved by producing the following phase shift:

$$\varphi(x) =- k\left(x - 2Rk\sqrt{\frac{x}{R}}\right)$$

where k is the wave number and x is the position of the metasurface unit. For the demonstration R is chosen to be 6λ. The aforementioned binary discretization method is applied using 144 metasurface units. The pressure amplitude pattern for this metasurface is shown in Fig.4. We can see an obvious bending beam, and therefore our design for self-bending wave is verified.

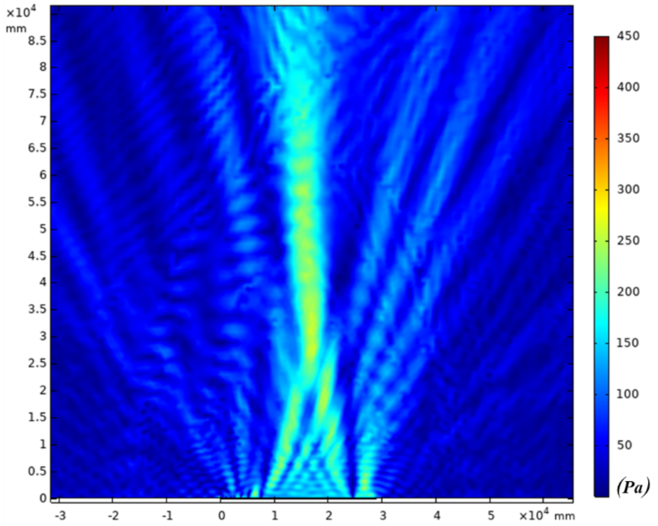

Figure 4. Self-bending: pressure distribution of the designed coding metasurface under vertical displacement excitation.

Although the working frequency of all the aforementioned demonstrations is 600 Hz, the design can be useful in a wide frequency band by altering the parameter *r*. Phase shift of one metasurface unit under different frequencies with *r* sweeping from 0.5 to 0.9 is calculated and plotted in Fig.5. By increasing the frequency from 300 Hz to 900 Hz, the phase shift function is moving but the difference of the two plateau of the same function is always close to π. This allows tuning of the metasurface to any frequency excitation from 300 Hz to 900 Hz by selecting the parameter *r*.

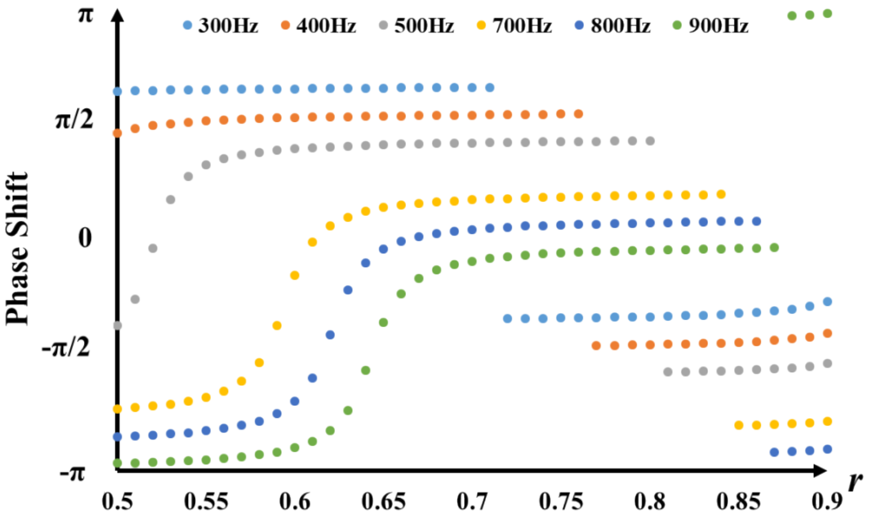

Figure 3. Phase shift of the designed metasurface unit under different frequencies with *r* from 0.5 to 0.9 in increment of 0.01.

IV. Conclusion

The work proposes an ultrathin metasurface which can create underwater acoustic wave with a controllable phase shift. The metasurface is made from steel and rubber units that should not be complicated to fabricate.

Wave focusing, branching and self-bending are demonstrated using solid-fluid coupled finite element analysis that show some of the functions the design can be used for. Also it is shown that the operating frequency can be switched over a large range by selecting the design parameter. This work has potential use in underwater acoustic wave generation and communication.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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