Manipulation of Electromagnetic and Acoustic Wave Behaviors via Shared Digital Coding Metallic Metasurfaces

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Introducing certain surface susceptibilities on the interface of boundaries is a well-known strategy to steer wave behaviors in different physical domains. However, most designs are thus far limited to engineer specific functionalities in a given physical application scenario. Herein, the approach manipulating electromagnetic (EM) and acoustic waves simultaneously on a shared digital coding metallic metasurface is described. The physical mechanism to realize the multiphysics digital coding is the equivalent governing equations behind wave behaviors as well as the boundary conditions with an identical mathematical model. Using split-ring resonators, 3-bit multiphysics digital coding elements are created, from which flexible wave-control devices are realized by simply designing coding sequences. As examples, multiple-beam generation, scattering reduction, beam steering, and beam forming are numerically demonstrated for both EM and acoustic fields. The anomalous reflection phenomena based on 3-bit multiphysics coding elements are experimentally performed to validate the design concept. The design strategy provides possibilities to manipulate multiwave behaviors in the shared metasurface, with a wide range of potential applications in the future.

1. Introduction

Metamaterials, arising from the pursuit of negative permittivity and permeability,\cite{1,2,3} have attracted tremendous interests in the past decades. With the greatly extended parameter space to the bulk design and large size make them cannot avoid the inevitable loss. Besides, the bulk design and large size make them difficult to realize in practice. As a way to reduce metamaterial dimensions, metasurfaces provide an avenue to tailor the EM wave behaviors through introducing abrupt EM changes on an ultrathin interface.\cite{13,14,15,16,17,18} Due to the capability to flexibly control multiple degrees of freedom of EM waves, such as transmitted/relected phases, polarizations, and working frequencies, most functions realized by metamaterials can be achieved with metasurfaces. The concept has been reported to design anomalous reflection and refraction,\cite{19,20} skin cloaks,\cite{21,22} flat lens,\cite{23,24} and even topological insulators.\cite{25} More recently, several attempts have been made to combine some other areas with metasurfaces, such as acoustic waves and remote quantum entanglement.\cite{26,27,28} A programmatic, software-defined approach has been introduced in the design process, enabling the functionalities of metasurfaces to be more intelligent.\cite{29}

Generally, conventional metamaterials are usually characterized by continuously macroscopic media with effective parameters. Similarly, metasurfaces are always treated as infinitesimal sheets with certain surface susceptibilities retrieved from generalized sheet transition conditions. The analytic models of the aforementioned metamaterials are derived from the physics level, i.e., Maxwell’s equations, which may bring considerable complexity to the design of wave manipulation devices. On the contrary, digital coding metamaterials brought discrete elements to realize various complicated functions, including steering, bending, focusing, and random scattering of EM waves.\cite{30,31,32,33,34,35,36,37,38,39} The basic elements are similar to the binary system of a computer, in which 1-bit coding elements “0” and “1” are represented by metamaterials with 0 and π reflected phases. For the 2-bit case, “00,” “01,” “10,” and “11” are represented by four specific phases of 0, π/2, π, and 3π/2, respectively. In
the same way, n-bit units can be conceived by dividing the phase response over \(2\pi\) by \(2^n\). In addition, the Shannon entropy has been introduced to measure the information of the digital coding metasurface.[24] Recent works about information processing with coding metasurfaces include convolution operations,[25] reprogrammable holograms,[26] multitasking-shared aperture,[27] and space–time-coding digital metasurface.[28]

Similar to the digital circuits design, the basic functionalities of the coding metasurfaces are determined by specific coding sequences. In other words, the function of a given coding pattern will not change with different types of coding particles, at different operating frequencies, and even under different kinds of waves. The researches about coding acoustic metasurfaces have been reported to reshape the acoustic wavefronts, render scattering diffusion, and control transmission,[29–31] Recently, Zhang et al. proposed a device that utilized four kinds of rigid pillars with various material properties to generate 1-bit reflection-type coding states for acoustic and EM fields, thus steering the propagation behaviors of multiphysical waves simultaneously.[32] However, the multiple-material (three dielectric materials and one metal) configuration makes it very difficult to fabricate and meet the mechanical requirements as well as request for high temperature resistance and good conformal property in practical applications. In addition, the 1-bit design restricts the possibilities of the apparatus to perform some complex wave controls, such as beam scanning, beam forming, etc.

Here, we present an approach to realize high-bit digital coding multiphysics metasurfaces for both EM and acoustic waves simultaneously. Only one metallic material is used in the design, which greatly reduces the fabrication complexity. In addition, the excellent mechanical and physical properties of metallic materials, such as large flexibility, good ductility, and high temperature resistance, enable the devices to have potential use in practical engineering applications. Using split-ring resonators, 3-bit digital coding states are created for dual physics waves, from which various functionalities, such as scattering diffusion, beam scanning, beam forming, and anomalous reflection, can be built just by encoding some simple digital sequences on the metasurfaces. For experimental verification, the anomalous reflection phenomenon is characterized as a proof-of-concept example, and the measurement results accord well with the numerical simulations, demonstrating the capabilities of manipulating both EM and acoustic waves simultaneously.

2. Results

2.1. Design and Methods

As shown in the schematic diagram of Figure 1, both EM and acoustic waves will be modulated on the proposed device. Previous works have shown practical insights on multiphysics metamaterials, which indicate that the same types of governing equations are required for different physical phenomena. It is well known that the thermal conduction equation and electric conduction equation are Laplace equations; hence, direct current (DC) and heat field can be manipulated using the same metamaterial structure.[33,34] The physical mechanism behind both EM and acoustic fields is Helmholtz equation,[35,36] which can be described as

\[
\nabla^2 \mu + k^2 \mu = 0
\]

(1)

If the condition is fit for EM waves, then \(\mu\) represents the transverse magnetic (TM) field \(H\); for acoustic fields, \(\mu\) is the pressure field \(p\), and \(k\) is the wave vector of the corresponding physical field, which is given by \(k = 2\pi/\lambda\), where \(\lambda\) is the wavelength of the material. When we choose the same working wavelength for both EM and acoustic fields, the wave vectors will be identical to each other, thus making the governing equations exactly equivalent. In addition to the governing equations, the boundary conditions with identical mathematical models have to be guaranteed. The boundaries between metal materials and air under the two fields are Neumann boundaries, which can be defined by a common formula, \(\mathbf{n} \cdot \nabla \mu = 0\), and corresponds to perfect electric conductor (PECs) boundaries \((\mathbf{n} \cdot \nabla H = 0)\) in microwaves and rigid boundaries \((\mathbf{n} \cdot \nabla p = 0)\) in acoustic fields, respectively. Thus, we can select metals as the material to construct Neumann boundaries for both EM and acoustic fields. In this work, aluminum is chosen as the basic material and the split-ring resonators are selected to generate the desired digital coding elements.

Figure 2a presents the typical structure of the proposed unit cells. As the mathematical models of the unit cells in both EM and acoustic fields are the same, i.e., the equivalent Helmholtz equation with Neumann boundary conditions set at the aluminum structures. Thus the field distributions of the two cases will be exactly the same, leading to identical phases and amplitude responses for both EM and acoustic waves. By changing the geometry of the cavity and split, the normal incident waves may encounter different oscillations and bounce back with specific phases. After thorough adjustments and optimizations, 3-bit coding structures are achieved. The detailed geometric parameters for each coding state can be seen in Table 1. Figure 2b,c
shows the responses of phase and amplitude of the unit elements. The unit cells operate at a wavelength of 75 mm, which corresponds to the working frequencies of 4 GHz and 4547 Hz in EM and acoustic fields, respectively. Clearly, the phase responses achieve significant phase coverage larger than 300°, with a large wavelength ranging from 50 to 100 mm, and present 45° gradient at the operating wavelength. The amplitude responses of the digital coding states are all above 0.99. It should be illustrated that the obtained reflected responses here are designed by considering a periodic expansion of each unit cell. In the practical design of metasurfaces, different unit cells may connect together, which will generate couples and cause disturbance to the reflective responses. To reduce the disturbance, the unit cells are always expanded periodically to construct the $N \times N$ supercells. Figure 2d shows the digital coding states and the corresponding structures. We point that higher-bit coding particles can be achieved by the proposed structures, which means that flexible controls of both EM and acoustic waves can be realized as desired.

2.2. Wave Manipulations by Multiphysics Coding Metasurfaces

As the most typical representative of reducing the complexity, 1-bit digital coding metasurfaces have shown strong abilities to generate multiple beams and steer scattering diffusions.

**Figure 2.** The phase and amplitude responses of the multiphysics digital coding elements. a) The basic structure of the proposed unit cell and the detailed geometric parameters of the cavity. b) The phase responses of the digital coding elements versus wavelength. c) The amplitude responses of the digital coding elements versus wavelength. d) Different digital coding states and the corresponding structures.
Here, we introduce the method to the multiphysics fields with the designed 1-bit coding elements. The coding states are supercells comprising $5 \times 5$ of identical “0” or “1” elements in Figure 2d. Under the normal incidence of EM and acoustic waves, the alternative coding sequence of “0000011111” can redirect the incident waves to two oblique directions in the upper-half space. Figure 3a,d shows the full-wave simulation results of EM and acoustic waves, which are performed using the commercial software CST Microwave Studio and COMSOL Multiphysics, respectively. Clearly, both EM and acoustic waves generate two beams with the reflection angles of $\pm 4.2^\circ$ in the upper-half space, and half-power beam width (HPBW) of each beam is about 3.5°. In fact, multiple beams can be designed using simple coding sequences. For example, three and four outgoing beams can be easily created by changing the coding sequences as “0000100000” and “0001000111.” The far-field scattering patterns of three beams are provided in Figure 3b,e. The reflected angles of the three beams for both EM and acoustic fields are $-8.4^\circ$, $0^\circ$, and $8.4^\circ$, respectively, and HPBW of each beam is about 3.2°. Figure 3c,f depicts the far-field scattering patterns of four beams, where the reflection angles are $\pm 3.5^\circ$ and $\pm 11.3^\circ$, respectively, and HPBW of each beam is about 3.5°.

A scattering reduction device, operating at multiphysics fields, can make radar and sonar systems confusing at the same time. In addition, benefiting from the inherent advantages of the metallic material, the device based on the aforementioned designed binary elements is free from thermal infrared detection. Here, the opposite phases are well known to design the scattering reduction equipment.[22,23,38] Here, we adopt the optimized coding pattern as that in studies by Cui et al.[22] and encode it with the 1-bit coding states, where each coding state is the $5 \times 5$ supercells. The 3D far-field scattering patterns of the compromised metasurfaces for EM and acoustic fields are presented in Figure 4a,b. It is very interesting to observe that the metasurface behaves like a rough surface to diffuse both waves to all possible directions in the upper-half space, which validates the correctness of our design. To evaluate the scattering reduction characteristics, we have provided the scattering patterns of the metallic plate with the same dimensions under the excitation of the plane wave of the two fields, as shown in Figure 4c,d. Figure 4e,f manifests the quantitative results of scattering reduction versus with wavelength, from which we can observe that the proposed metasurface presents a broadband property of $-10$ dB scattering reduction for both EM and acoustic fields. As a future prospect, many kinds of fascinating scattering signatures are promising to realize using numerical optimizations of 1-bit coding sequences for multiphysics metasurfaces.[137]

Two-bit coding metasurfaces have more freedom to design wave control devices. Beam steering is the most important function of a detection system. Previous researches have demonstrated that it is simple to realize beam steering by combining the convolution theorem with digital coding metasurfaces.[25] Introducing the method to this work, EM and acoustic beams can be manipulated to the desired directions simultaneously. Here, we aim to achieve multiple-beam controls with the 2-bit multiphysics metasurface. By adding the sequence “020202...” along the x axis with a gradient sequence “3210...” along the y axis, the two reflected beams in the x direction will be shifted in the y axis to the predesigned angle. Here, the coding states are the $5 \times 5$ supercells, comprising the 2-bit elements in Figure 2d. Figure 5a,b provides the simulation results of the EM and acoustic waves. The reflection angles of the two beams and the shift angles can be calculated by the generalized Snell’s law of reflection,[13]

$$\theta = \sin^{-1}\left(\frac{m\lambda}{\Gamma}\right)$$

(2)

where $\lambda$ is the wavelength of the working frequency in free space, $\Gamma$ is the period of the coding structures, and $m$ is the diffraction order. The period of the coding sequence “020202...” is $2\lambda$, and the diffraction period $m = \pm 1$, whereas the period of the gradient coding sequence is $4\lambda$, and $m = 1$. Based on Equation (2), the reflection and shift angles are calculated as $\pm 30^\circ$ and $14.5^\circ$, respectively. In simulation, the reflection angles for both EM and acoustic beams are $\pm 29.6^\circ$ and $15.1^\circ$, agreeing well with the theoretical prediction. The HPBW of each beam is about 4.3°.

![Figure 3](image-url)  
**Figure 3.** Multiple-beam generations based on the 1-bit multiphysics coding metasurfaces. a–c) for EM waves and d–f) for acoustic waves.
As an example of the 3-bit multiphysics device, the anomalous reflections for both EM and acoustic fields are investigated here. A gradient coding sequence "01234567..." can redirect a normal incidence plane wave to a specific reflection angle. The phenomena of 3D far-field scattering patterns are shown in Figure 5c,d, in which both EM and acoustic waves generate the oblique reflection beams in the upper-half space. In this design, the period of the metasurface is 1.6\(\lambda\), and \(m = -1\). The reflective angles of the two circumstances in simulation are all about \(-38.30^\circ\), which exactly fits the theoretical calculation as \(-38.68^\circ\) by Equation (2). The HPBW of the reflection beams for EM and acoustic beams are about 7.1°.

We should note that the high-bit digital coding metasurface is capable of achieving more complex wave-control devices. For example, multiphysics vortex beams, which carry the orbital angular momentum (OAM) mode with topological charges, can be generated. Recently, there has been great interest on OAM waves because of their potential applications in optical communication, detection of rotating objects, and super-resolution imaging. A vortex beam has an azimuthal phase dependence \(\exp(il\varphi)\), and the phase distribution can be expressed as

\[
\Phi(x, y) = l\varphi = l\arctan(y/x)
\]

where \(l\) is the topological charge and \(\varphi\) is the azimuth angle. To generate the vortex beam, the coding pattern should consist of a spiral-like phase shift. Figure 6a shows the digital coding pattern...
Beam-manipulation devices based on multiphysics digital coding metasurfaces. Multiple-beam steering for both a) EM and b) acoustic waves by the 2-bit multiphysics coding elements. Anomalous reflection for c) EM and d) acoustic fields by 3-bit multiphysics digital coding elements.

including eight sectors, where the coding states 0–7 are filled with each of them. Adding a gradient coding sequence “0011223344556677...” to the coding pattern of Figure 6a, the new coding pattern is shown in Figure 6b, which will make the vortex beam shift to a predesigned angle. Figure 6c,d displays the simulation results of 3D far-field patterns of the aforementioned coding metasurfaces for EM and acoustic waves, respectively. Note that a hollow occurs in the center of each beam, which corresponds to the character of vortex beams. And we clearly observe that the far-field beams are shifted to a predesigned angle for both EM and acoustic waves. The shift angle is $-18.7^\circ$, coinciding well with the calculated result of $-18.2^\circ$. Figure 6e,f presents the simulated phase maps of EM and acoustic fields, the main feature of the spiral phase distributions indicates that the vortex beams carry the OAM mode $l = 1$.

2.3. Experimental Verification

To validate the performance of the multiphysics digital coding metasurface, the anomalous reflection phenomenon based on 3-bit coding states is carried out in experiments. Figure 7a shows the measured environment of the EM field. A horn antenna (2–10 GHz) is utilized to generate the quasi-plane-wave illumination, and the metasurface sample and antenna source are placed on a long board, which is mounted on a rotary stage and can freely rotate in the horizontal plane. Another horn antenna, placed about 10 m away, acts as receiver to record the far-field scattering patterns. The measured result and the simulated result of the metasurface are depicted in Figure 7b. It is obvious that at the operating frequency of 4 GHz, the measurement result coincides well with the simulated result.

In the acoustic experiment, as Figure 8a shows, an array of eight speakers is used to excite the quasi-plane waves from the top. The metasurface is put on the bottom place, with anechoic cotton underneath. Right on the metasurface, a 1/4 in. microphone, which is connected to the stepping motor, serves as a sensor to receive the total sound pressures within the vertical scanning plane. The measured near field at the working frequency of 4547 Hz is shown in Figure 8c, which resembles the corresponding simulated result in Figure 8b. We derive the far-field scattering pattern using the near-to-far-field transformation, illustrated in Figure 8e. Due to the impact of the background field, a big sidelobe appears at an angle of 0°. The measured reflection angle agrees well with the simulation result in Figure 8d, verifying the correctness of the design.

3. Discussion and Conclusion

In this work, the selected material of aluminum is used to satisfy the Neumann boundary for both EM and acoustic fields simultaneously. If other materials (besides metals) are included in the materials design, the boundary conditions may not be equivalent for the two cases. For example, when the material FR-4 is chosen as the material to construct the unit structures, the rigid boundary condition is satisfied for the acoustic field; however, the PEC boundary for the EM field is not satisfied. In this way, the performance of the metasurface for the acoustic field will remain, whereas the EM effect may change. But, if we coat some metal coatings on the inner and outer surfaces of the unit structure made by FR-4, as long as the thickness of the metal coating is thicker than the skin depth, the PEC boundary will be satisfied, showing equivalence of EM and acoustic fields.

In summary, by constructing equivalent governing equations and the boundary conditions with the identical mathematic model, we have proposed 3-bit multiphysics digital coding metamaterials for both EM and acoustic fields simultaneously. The proposed metasurfaces exhibit great abilities to manipulate the wave behaviors. As examples, multiple-beam generation, scattering reduction, beam steering, and beam forming are demonstrated by numerical simulations for both EM and acoustic waves. Experimental results of the anomalous reflection based on the 3-bit digital coding elements verify the correctness of the designed metasurface, manifesting the capability to manipulate EM and acoustic fields at the same time. The single-metal material design greatly reduces the fabrication complexity and can meet mechanical requirements such as high strength, good ductility, and high temperature resistance. Furthermore, the proposed device can be regarded as the alliance of an EM reflect-array antenna and a sonar array, which may have potential use in safety detection or target exploration in some complex application scenarios.

4. Experimental Section

The sample with an outer dimension of $480 \times 480 \, \text{mm}^2$ was fabricated using the wire cut electrical discharge machining (WEDM) technology. In the far-field experiments, the metasurface sample and a horn antenna were placed at two ends of a 2 m-length board, which was mounted on a rotary stage and could freely rotate in the horizontal plane (Figure 7a). In addition, another wideband horn antenna, which was
Figure 6. Vortex beam generation and steering by the 3-bit multiphysics coding metasurface. a,b) The coding patterns of vortex beam generation and steering. c) The far-field scattering patterns of vortex beam and the beam steering for EM field. d) The far-field scattering patterns of vortex beam and the beam steering for acoustic field. e) The phase distribution of EM field. f) The phase distribution of acoustic field.

Figure 7. Experimental verification of anomalous reflection for the EM field. a) Experimental environment of EM far-field measurement. b) The comparison of the EM far-field measured result and simulated result.
connected to an Agilent N5245A vector network analyzer (VNA), acted as a receiver to record far-field scattering patterns. In the acoustic experiment, an array of eight speakers was used to excite the quasi-plane acoustic wave. A one-fourth-inch microphone (MAP416, BSWA Technology Co., Ltd.) (Figure 8a) served as the sensor to receive the total sound field within the scanning plane.

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Conflict of Interest
The authors declare no conflict of interest.

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all-metal metasurfaces, beam forming, multiphysics digital coding metasurfaces, multiple-beam generations, scattering reduction

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