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Switchable acoustic projection displays based on coding composite structures

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Projection display is of relevance for various applications, for example, information communication, encryption and storage. Although numerous optical projection devices have been reported in past years, the realization of switchable acoustic projection display without built-in circuits is a challenge. In this work, we propose a coding composite structure composed of a perforated plate and a coiling-up cavity with six interdigital rigid walls to achieve switchable acoustic projection displays. The configuration can be served as bits '0' and '1' by using forward and backward placements, respectively. The required projection can be displayed as long as the expected image regions are filled with bit '1' and other regions are filled with bit '0'. By switching control wave P_c , the projected image is able to be switched from 'Off state' to 'On state' accordingly. The underlying physical mechanism is the different scattering responses between two coding bits induced by coherent superposition. Our design provides an effective solution for the construction of acoustic projection displays with switchable feature, which may have potential applications in information encryption and storage.

KEYWORDS

composite structure, coiling-up cavity, switchable projection, coherent superposition, artificial structure

1 Introduction

As an effective approach to display required images or information, projection device plays important roles in many applications including light-emitting diode screens, electronic billboard signage and traffic light. Despite numerous achievements in optical projection displays [1–10], the similar devices in acoustic category have not been widely reported so far, especially for switchable fashion without built-in circuits. The realization of acoustic projection display is of great significant in information storage and communication. Given the advantages of subwavelength scale, flexibility and planer feature, the development of acoustic metasurface provides a possible solution for the design of acoustic projection device.

In past several years, acoustic metasurface (a composite structure with planer configuration) has been demonstrated to be good candidates to achieve various fascinating phenomena, such as beam deflection [11–13], beam focusing [14–19], vortex beam [20], splitting beam [21] and Airy beam [22] by utilizing Helmholtz resonators [23, 24], coiling-up cavities [25], or spiral particles [26]. Owing to the shifts of equivalent refractive index induced by resonance effect, arbitrary phase or amplitude response can be obtained by adopting ultrathin structural design, making it is suitable to be integrated in acoustic devices. To accurately fit the phase or amplitude profile, however, multiple discrete orders are required for designed units, which increases the complexity of the structure. In addition, some harsh parameters may be involved in discrete process, which are hardly to be

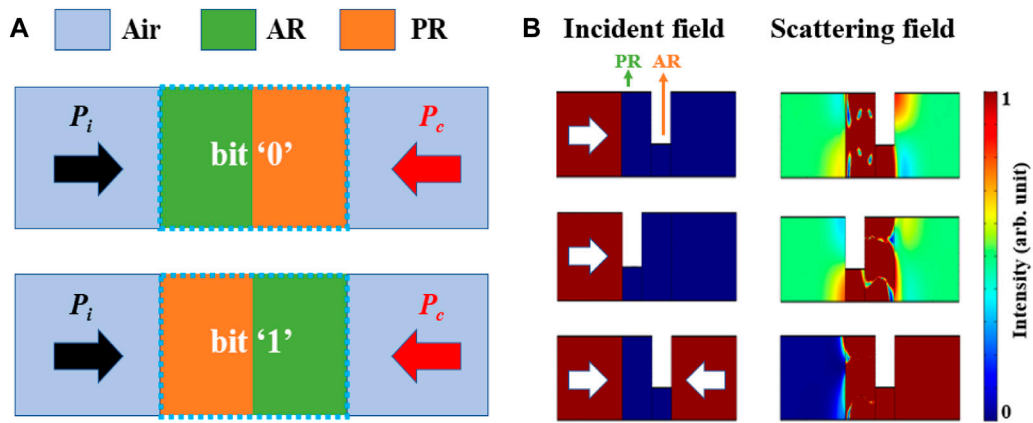


FIGURE 1 (A) Schematic diagrams of bits '0' and '1', where light blue region, green region and orange region are air background, AR and PR, respectively. The black and red arrows present the input wave P_i and control wave P_c . (B) The normalized incident and scattering fields of bits '0' and '1' for one side incidence and both sides incidence. The white arrows indicate the incident directions, and the operating frequency is 3,430 Hz.

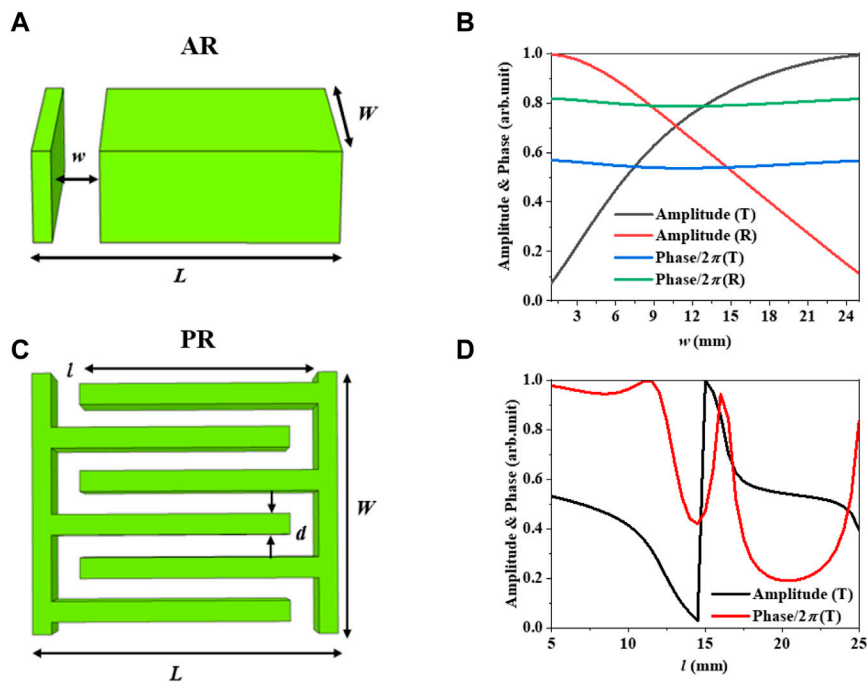
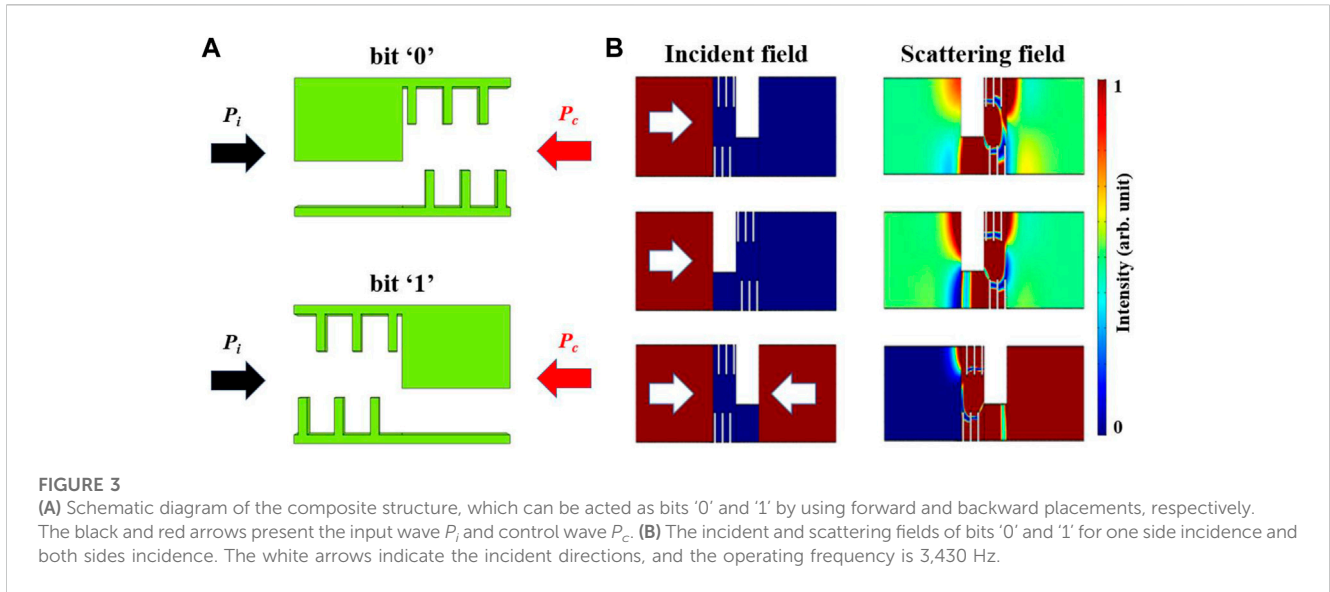


FIGURE 2 Schematic diagrams of (A) AR and (C) PR. AR is a perforated plate and PR is a coiling-up cavity with six interdigital rigid walls. The amplitude and phase responses of (B) AR and (D) PR with the change of w and l . The operating frequency is $f = 3,430$ Hz. The characters of 'T' and 'R' in legends of (B) and (D) present the transmission wave and reflection wave, respectively.

fabricated by 3D printing technology, and the thermal viscosity loss is non-negligible. Recently, the emergence of coding metasurface offers a simplified method for the realization of wavefront modulation [27–30]. Only two kinds of units with opposite phase responses (0 and π) are needed to serve as coding bit '0' and '1', and numerous beam-shaping behaviors can be achieved as well without complicated design philosophy. Hence, the combination between coding metasurface and acoustic projection displays is expected to be a valuable tool for advanced acoustic devices.

In this work, a composite structure composed of a phase regulator (PR) and an amplitude regulator (AR) is proposed to build switchable acoustic projection devices, through which arbitrary image can be projected by adopting corresponding coding sequences, and the 'On/Off states' are capable of switching by additional control wave P_c . To achieve desirable scattering responses for AR and PR, a perforated plate and a coiling-up cavity with six interdigital rigid walls are constructed to modulate the amplitudes and phases of scattering waves continuously. The composite structure can play the roles of bits '0' and '1' by using



forward and backward placements, respectively, due to their extremely asymmetric scattering responses induced by coherent superposition, greatly simplifying the design philosophy by using coding acoustic metasurface. The acoustic projection display illustrated in our work may have profound impact on exploring various acoustic information related devices.

2 Theory

To achieve switchable acoustic projection displays, we propose two kinds of unit and encode them as bits '0' and '1'. The transmission and reflection coefficients of bit '0' are assumed to be $T_0 = 1/\sqrt{2}$ and $R_0 = -1/\sqrt{2}$, respectively, while those of bit '1' are both desired to be $T_1 = R_1 = 1/\sqrt{2}$. In other words, bit '0' has the same transmission coefficient as bit '1', and the reflection coefficients between them have a phase difference of π . If two acoustic beams with opposite directions are incident on bits '0' and '1' simultaneously, the scattered acoustic pressures of 2 bits (S_0 and S_1) can be expressed as a matrix:

$$\begin{bmatrix} S_0 \\ S_1 \end{bmatrix} = \begin{bmatrix} T_0 & R_0 \\ T_1 & R_1 \end{bmatrix} \begin{bmatrix} P_i \\ P_c \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} P_i - P_c \\ P_i + P_c \end{bmatrix} \quad (1)$$

where P_i and P_c represent input wave and control wave, respectively. Following Eq. 1, it can be deduced that the normalized amplitude of S_0 and S_1 are 0.5 in the case of only P_i incidence owing to the identical transmission response for bits '0' and '1'. When input wave and control wave are incident on them simultaneously, however, the normalized amplitude of S_0 and S_1 are 0 and 1 owing to the existence of destructive interference in bit '0' and constructive interference in bit '1'. Therefore, switchable acoustic projection displays are expected to be obtained by utilizing coherent incident waves with opposite propagating directions.

Here, we intend to construct a model with an asymmetric configuration to act as bits '0' and '1' by using forward and backward placements, respectively, which needs the scattered pressures on both sides of the model agree with those on right

side of bits '0' and '1'. To achieve this goal, as shown in Figure 1A, we consider a composite structure composed of an AR and a PR. AR is placed on left and right sides of the PR for bits '0' and '1', respectively. Note that the phase (amplitude) response for AR (PR) is fixed when modulating the amplitude (phase) response continuously. For bit '0', the input wave P_i becomes $P_i^*t_A^*t_P$ after passing through AR and PR, and the control wave P_c becomes $P_c^*t_P^*r_A^*t_P$ because it first passes through PR, then is reflected by AR, and finally passes through PR again. t_P and t_A represent the transmittance of PR and AR, and r_A represent the reflection of AR. Therefore, the transmission and reflection coefficients of bits '0' and '1' can be expressed as follows:

$$\begin{bmatrix} T_0 & R_0 \\ T_1 & R_1 \end{bmatrix} = \begin{bmatrix} t_A t_P & t_P r_A t_P \\ t_P t_A & t_A \end{bmatrix} \quad (2)$$

From Eq. 2 it can be deduced that the phase difference between R_0 and R_1 is related to t_P , so the asymmetric phase response can be controlled by PR, and the exact values of scattering coefficients (T_0 , T_1 , R_0 , R_1) are capable of modulating by AR accordingly. When input wave and control wave are incident on composite structure simultaneously, the scattered pressures on left side of the bits '0' and '1' can be expressed as:

$$\begin{bmatrix} S_{00} \\ S_{11} \end{bmatrix} = \begin{bmatrix} t_A t_P P_i + t_P r_A t_P P_c \\ t_P t_A P_i + r_A P_c \end{bmatrix} \quad (3)$$

According to Eq. 1, Eq. 3, the relation of $S_{00} = S_0$ and $S_{11} = S_1$ can be obtained when the requirements of $t_P = \exp(i\pi/2)$, $t_A = 1/\sqrt{2} \exp(-i\pi/2)$ and $r_A = 1/\sqrt{2}$ are satisfied, which indicates that the composite structure can serve as bits '0' and '1' simultaneously once the AR and PR with proper scattering coefficients are designed.

To verify above deductions, as shown in Figure 1B, an equivalent medium meeting the conditions of $t_P = \exp(i\pi/2)$, $t_A = 1/\sqrt{2} \exp(-i\pi/2)$ and $r_A = 1/\sqrt{2}$ is proposed to numerically simulate the incident and scattering fields of bits '0' and '1'. The module of pressure acoustic is adopted in COMSOL Multiphysics software. The condition of plane wave radiation is applied to the left and right boundaries of waveguide to suppress the unwanted

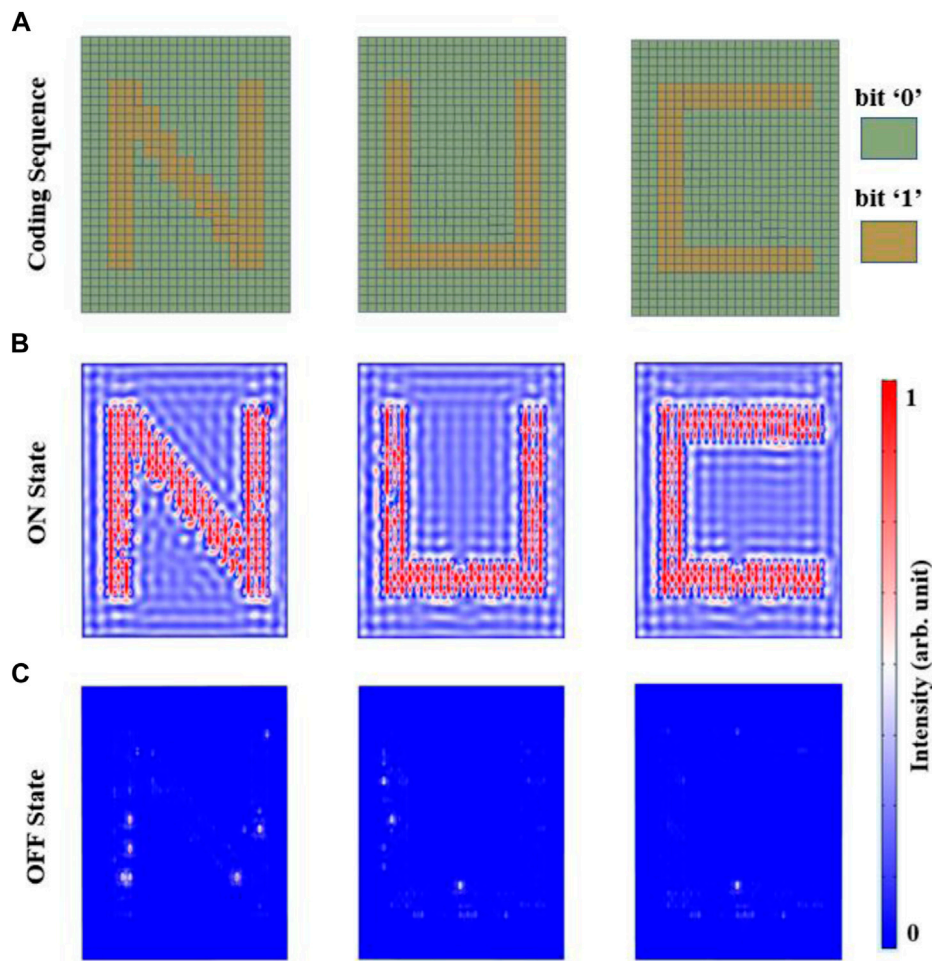


FIGURE 4

(A) Schematic diagrams of coding sequences adopted in projection acoustic devices for 'N', 'U', 'C'. The dark green region and dark yellow region represent bit '0' and bit '1', respectively. Acoustic scattering intensity fields of the projection devices with (B) input wave P_i incidence and (C) input wave P_i and control wave P_c incidence simultaneously.

reflection waves. The radiated acoustic pressure of the incident source is 1 Pa. Hard boundary condition is applied to the upper and lower boundaries of the waveguide to act as rigid material whose acoustic impedance is much larger than that of fluid background. In our simulations, the background medium is air ($c_a = 343$ m/s and $\rho_a = 1.21$ kg/m³). To ensure the desirable phase delay and perfect transmittance, the equivalent acoustic velocity and density of the PR is set as $c_e = 91.85$ m/s and $\rho_e = 4.8173$ kg/m³. The required amplitude response is achieved by adjusting the length of hard boundary between AR and scattering field. Three different incident cases, left side of bit '0' incidence, left side of bit '1' incidence, and both sides of composite structure incidence, are required to be considered. From the scattering fields of three incident cases, it can be observed that the intensity distributions in both sides of composite structure is almost identical for left side incident from bits '0' and '1', which shows that the normalized amplitude of S_0 and S_1 are 0.5 under this circumstance. For both sides of composite structure incidence, the intensity field in right side of bit '1' is strong, while that in left side of bit '1' is weak, illustrates an extremely asymmetric intensity response due to the coherent interference, and

the normalized amplitude of S_0 and S_1 are 0 and 1 in this situation. The simulation results fully confirm that the amplitude of scattering wave for bit '0' is the same as that for bit '1' with only input wave P_i incidence, but the amplitude of scattering wave for bit '1' is larger than that for bit '0' with input wave P_i and control wave P_c incidence simultaneously, which agrees well with our theoretical prediction. Thus, the required projection can be displayed as long as the expected image regions are filled with bit '1' and other regions are filled with bit '0'. By switching control wave P_c , the projected image is able to be switched from dark state to bright state accordingly.

3 Structural design

To construct desirable composite structure, a practical configuration with phase and amplitude modulation capability is required. Note that the phase (amplitude) response needs to be fixed when the amplitude (phase) response is modulated continuously by AR (PR), and the transmittance of PR should be as high as possible to

guarantee the projection quality. As shown in Figures 2A,C, we propose a perforated plate and a coiling-up cavity with six interdigital rigid walls to serve as AR and PR, respectively. The length and width of AR and PR are $L = 25$ mm and $W = 28$ mm, which are much smaller than the operating wavelength λ_0 ($L = 0.25\lambda_0$, $W = 0.28\lambda_0$), and have the advantage of subwavelength scale. To obtain amplitude modulation, the opening size of the perforated plate is a variable from $w = 5$ mm to $w = 25$ mm. With the reduction of w , as shown in Figure 2B, the transmitted (reflected) amplitude decreases (increases) gradually owing to the impedance mismatch induced by small opening size, while the transmitted and reflected phase responses are nearly fixed, exhibiting an excellent ability for amplitude modulation independently. As a special case, when $w = 10.8$ mm the transmitted amplitude is the same as reflected amplitude ($T = R = 1/\sqrt{2}$), and the phase difference between transmission wave and reflection wave is $\pi/2$, which meets the requirement of scattering coefficients for AR.

On the other hand, to achieve phase modulation by PR, the length of interdigital rigid wall in a coiling-up cavity is set to a variable from $l = 5$ mm to $l = 25$ mm. The thickness of interdigital rigid wall is a constant of $d = 2$ mm. It can be seen from Figure 2D that the transmitted phase shifts cover a wide range of $0-2\pi$ with the change of parameter l , and the transmitted amplitude of PR is over 0.9 when $l < 12$ mm. The desirable phase delay is attributed to the length change of propagation path in PR induced by labyrinth configuration, and the high amplitude is owing to the impedance matching induced by resonance effect in PR. Note that the transmitted phase and amplitude is $\pi/2$ and 0.95, respectively, in the case of $l = 8.6$ mm, satisfying the requirement of scattering coefficients for PR.

Next, we splice the AR and PR to integrate an asymmetric composite structure. As shown in Figure 3A, the configuration can be served as bits '0' and '1' by using forward and backward placements, respectively. To obtain expected scattering feature, the parameters of w and l are selected as $w = 10.8$ mm and $l = 8.6$ mm. Figure 3B illustrates the incident fields and corresponding scattering fields for left side of bits '0' incidence, left side of bits '1' incidence, and both sides of bits '0' and '1' incidence. Compared with Figure 1B, Figure 3B, the results of intensity field (the square of acoustic pressure) for composite structure designed by a practical configuration are identical with those for composite structure designed by equivalent medium. For input acoustic wave P_i incidence, the transmitted amplitudes of bits '0' and '1' are 0.5, while those are 0 and 1, respectively, for input wave P_i and control wave P_c incidence simultaneously, fully confirming the feasibility of our approach to achieve switchable control of scattering field via two coherent incident acoustic waves.

4 Switchable projection displays

Given the scattering feature of the composite structure, as shown in Figure 4A, we construct three acoustic projection devices with different coding sequences. The metasurface is composed of 24×32 coding bits, where the expected image regions are filled with bit '1' and other regions are filled with bit '0'. To avoid the coupling actions between two coding bits, the distance between two adjacent coding bits is set as $2W$. In addition, to observe the scattering fields conveniently, background pressure field is adopted in the incident field, and the plane acoustic waves are generated with a working frequency of 3,430 Hz. We define input wave P_i incidence as 'Off state' and input wave P_i and control wave P_c incidence simultaneously as 'On state'. For 'On state', as

illustrated in Figure 4B, three different characters ('N', 'U', 'C') are projected clearly in the scattering fields of three proposed devices owing to the extremely asymmetric intensity responses between bits '0' and '1' in this case. For 'Off state', as shown in Figure 4C, the scattering field is a uniform field, and no obvious projection images are able to be observed in this case due to the identical intensity responses between bits '0' and '1'. Therefore, arbitrary image can be projected by adopting corresponding coding sequences, and the 'On/Off states' are capable of switching by control wave P_c .

5 Conclusion

An approach is exhibited in this work for switchable acoustic projection displays by using two identical coding units (bits '0' and '1') with different placements. To obtain desirable scattering coefficients for acoustic waves, an AR (a perforated plate) and a PR (a coiling-up cavity with six interdigital rigid walls) are constructed to decouple the phase and amplitude modulations. The composite structure composed of AR and PR shows an extremely asymmetric scattering feature when two coherent acoustic waves incident simultaneously. The required projection can be displayed as long as the expected image regions are filled with bit '1' and other regions are filled with bit '0' due to the coherent superposition. As examples, three distinct characters ('N', 'U', 'C') are projected clearly by adopting three different coding sequences, and the projected images are able to be switched from 'Off state' to 'On state' accordingly by switching control wave P_c , confirming the feasibility of our approach. Given the advantages of simplified and passive design, the acoustic projection device proposed in our work may have numerous acoustic related engineering applications.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JH conceived the presented idea. RW performed the calculations and simulations and drafted the manuscript. All authors discussed the results and contributed to the final manuscript.

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Conflict of interest

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