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Bianisotropic acoustic metasurface for highly efficient wavefront transformation

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Abstract – Relying on the generalized Snells law (GSL), which defines a phase gradient along a surface, metasurfaces with subwavelength thickness have been demonstrated to achieve extraordinary control of the reflected and transmitted wavefronts. However, a fundamental limitation for GSL-based metasurfaces is their efficiency, especially at large deflection angles. Here we designed and fabricated the bi-anisotropic cells for a wavefront transformation acoustic metasurface that overcomes the fundamental limits of conventional designs, allowing us to steer the energy flow without parasitic scattering. Our discretized design is verified numerically and energy efficiency of over 90% is achieved for the transmitted wave into the desired direction of 60, 70 and 80 degrees, higher than the theoretical limitation of corresponding GSL based designs. Our design and its scattering-free property is experimentally demonstrated, showing good agreement with the theory and simulation. The proposed strategy offers a versatile platform for designing practical and highly efficient metasurfaces for wavefront transformation.

I. INTRODUCTION

The ability to fully control the classical waves has long been desired and is a highly active research area. Among many routes, metamaterials have been serving as the primary approach in recent years. In contrast to the bulky materials, the 2D version of metamaterials, or metasurfaces, offer an alternative solution for molding wave propagation within planar and compact geometries, which have opened up unprecedented possibilities for controlling waves at will. In current design of metasurfaces in both electromagnetic and acoustic communities, the generalized Snell's laws of reflection and refraction (GSL) is a typical way for wavefront transformation in both reflective and transmissive scenarios by packing the wavefront information into phase shift of the unit cells.

However, recent studies of conventional gradient metasurfaces have identified important limitations of GSL-based metasurfaces. It has been shown that they suffer from undesired scatterings which reduce the overall power efficiency [1]. Consider anomalous refraction as an example, which is the simplest functionality offered by gradient metasurfaces in transmission. The undesired scatterings originate from the impedance mismatch between incident and refracted waves, which are inherent to the design approach and do not depend on the cell topology.

Rigorous analysis of this problem has shown that the macroscopic impedance matching for theoretically perfect anomalous refraction of plane waves can be realized if the metasurface exhibits bianisotropy: magneto-electric coupling for electromagnetic metasurfaces [2] and Willis coupling for the acoustic counterpart [1, 3]. These results have been demonstrated in both electromagnetic and acoustic scenarios. In acoustics, an approach for perfect anomalous refraction was theoretically proposed using three membranes [1]. However, the surface tension, uniformity and durability, etc. of the membranes are extremely difficult to control, and it is questionable whether this design can be practically realized.

In this work, we propose a versatile platform for bianisotropic metasurfaces based on optimization of four independent resonators. Based on a systematic cell design process, we propose the first practical design for the realization of scattering-free manipulation of acoustic waves.

Fig. 1: (a) Schematic representation of the desired performance of perfect metasurface when $\theta_i = 0^\circ$. The inset illustrates the geometry of a unit cell. (b) Imaginary part of elements in impedance matrix along the metasurface for $\theta_t = 70^\circ$ and the achieved values by optimization. (c) Simulated pressure field for $\theta_t = 60^\circ, 70^\circ$ and 80° . (d) Comparison of the power efficiency, showing great advancement over GSL-based metasurfaces.

II. SYSTEMATIC DESIGN OF BIANISOTROPIC METASURFACES

In order to show the systematic design process of bianisotropic metasurfaces, we start with a simple design: a metasurface capable of redirecting the normally impinging wave ($\theta_i = 0^\circ$) into another direction defined by the angle θ_t . Figure 1(a) represents an illustration of the system under study. As it was demonstrated in [3], for avoiding parasitic scatterings, power conservation has to be satisfied, meaning that the amplitude of the transmitted wave has to be selected so that the normal power flow of the incoming wave and outgoing waves are equal.

After defining the input field and output field, we need to define the properties that need to be fulfilled by the metasurface. The inset in Fig. 1(a) is the illustration of the unit cell. By controlling the channel width and the height of the four resonators, full control over the bi-anisotropic response can be realized. The reader is addressed to [3] for more details about the analytical formulation of the problem.

With the theoretical requirement in mind and the versatility of the unit cells at hand, we apply the Genetic Algorithm (GA) for designing the detailed parameters for each cell. Figure 1(b) shows the comparison between theoretical requirements and achieved values of the elements in the impedance matrices in a show case where the metasurface steers a normal incident wave to a refraction angle of 70° . Excellent agreement can be found. Further discussion can be found in [3].

Here we designed three cases where the metasurface redirect the normal incident wave to 60° , 70° and 80° , respectively. The design is verified with numerical simulations performed by COMSOL Multiphysics. The results are shown in Fig. 1(c). We can see that the transmitted field does not contain undesired scatterings. The overall power efficiencies for the three designs are (93%, 96%, 91%), showing great advancement over conventional GSL-based designs (89%, 58%, 35%), especially at large deflection angles. Comparison between the theoretical limits of the GSL-based metasurfaces, discretized GSL-base metasurfaces, and our designed bianisotropic metasurfaces with same discretization is shown in Fig. 1(d). More details about the design parameters and the comparison will be given during the talk.

As we have demonstrated, this approach can provide a systematic methodology for the design of bianisotropic

Fig. 2: (a) Photography of the setup for the experimental validation. (c) Real part of the measured pressure field on both transmission side and reflection side. (d) Fourier transform of the line close to the metasurface.

metasurfaces for perfect wavefront transformation. The new strategy has three different stages: (i) definition of the fields for the desired functionality which ensure the total power balance (macroscopically the metasurface has to be lossless), (ii) evaluation of the impedance matrix profile along the metasurface, and (iii) optimize the parameters of the unit cells to fulfill the required response. The strategy can be easily adapted to other scenarios such as focusing, and generation of vortex beams with high angular momentum.

III. EXPERIMENTAL RESULTS

Here we chose the metasurface that steer the normally incident wave in to 60° at 3000 Hz for experimental demonstration. The sample was fabricated with fused deposition modeling (FDM) 3D printing. The printed material is acrylonitrile butadiene styrene (ABS) plastic. The fabricated metasurface consists of 8 periods, and is secured in a 2D waveguide for the measurement. A speaker array with 28 speakers sends a Gaussian modulated pulse normally to the metasurface and the transmitted field is scanned with a moving microphone with a step of 2 cm. Fig. 2(b) shows the real part of the pressure field where we can see that the normally incident beam is redirected into the desired direction without undesired scattering or reflection. A deeper analysis of the experimental data by performing Fourier transform along the transmission side close to the metasurface is shown in Fig. 2(c). The result shows that 97% of the energy goes to the desired direction and the reflected energy is less than 2%. Small discrepancies can be attributed to fabrication errors, discretization of the continuous profile of the metasurface, inevitable losses in the lab environment, and the use of a Gaussian beam instead of a perfect plane wave. More details concerning the experimental verification will be explained during the talk.

IV. CONCLUSION

In this work, a systematic and practical design of bianisotropic metasurfaces for wavefront transformation is presented and applied to the design scattering-free wave steering metasurfaces. Three examples for $\theta_i = 0^\circ$ and $\theta_t = 60^\circ, 70^\circ, 80^\circ$ are verified in simulation, showing great advancement over the conventional GSL-based metasurfaces. The 60° case is experimentally verified and good agreement between simulation and experiment is observed. The results can in principle be applied to other wavefront transformations and other disciplines.

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