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High-efficient Acoustic Anomalous Reflector Based on Power-flow Conformal Metamirror

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Abstract – In the last years, metasurfaces have attracted much attention due to the capability of tailoring the response in a sub-wavelength scale and their compact implementations. In the particular case of reflective metasurfaces, also called metamirrors, anomalous reflection is a fundamental transformation between two plane waves propagating in different directions. The analysis of this scenario is important for evaluating the potential use of engineered surfaces for more complex functionalities, such as lenses or holograms. Despite the apparent simplicity of this problem, current designs suffer from low efficiency or high complexity. In this paper, we present the analysis and design of an acoustic anomalous reflector device based on power-flow conformal metamirrors. The proposal is experimentally verified showing good agreement with the theoretical predictions.

I. INTRODUCTION

Control and manipulation of sound waves have been extensively studied in the literature using different approaches: precisely shaped materials acting as lenses, periodic distributions of materials forming phononic crystals, engineered artificial scatterers with exotic properties such as negative refraction index, also called metamaterials, or metasurfaces (the 2D version of metamaterials). Among the possible solutions, metasurfaces have attracted much attention due to their capability of tailoring the response in a sub-wavelength scale and their compact implementations. The minimalistic thickness of metasurfaces diminishes the propagation losses and facilitates integration into complex devices. The interest in metasurfaces revived with the formulation of the generalized reflection and refraction laws that proposed phase gradients as mechanisms for manipulating the wavefronts. Continuous phase gradients can be discretized into elements with finite sizes which can be locally – element by element – implemented by using coiled elements, Helmholtz resonators or resonant membranes. Deep studies of conventional gradient metasurfaces have underlined important limitations of this approach. It has been recently shown that gradient metasurfaces based on the generalized refraction and reflection laws suffer from undesired scattering which reduces the efficiency of devices [1].

In the reflection scenario, it was demonstrated that arbitrary control of the direction of reflected sound waves requires strong non-local response [1]. The non-local response can be understood as a mechanism for channeling the energy along the metasurface. Only retro-reflection and specular reflection functionalities do not require non-local response and can be implemented using conventional techniques with theoretical perfect performance [2]. For an anomalously reflective metasurfaces, non-locality can be implemented by controlling the interaction between different elements in one period [1] or even with one element per period [3]. However, if the wavefront transformation is more complex (beam splitters, holograms or lenses) non-local designs are difficult to find.

For the development of acoustic metasurfaces towards real applications, we must develop systematic tools for the design process. In this sense, locality of surface response presents important advantages in comparison with non-local designs. With local metasurfaces, one can find the required microscopic behavior of the individual elements by analyzing the desired macroscopic response and design the elements neglecting the interactions between neighbors. In this work, as an alternative to the known methods, we propose to use power-flow conformal metasurfaces which can be simply modeled as curved impedance boundaries, offering simple analytical solutions for the structure dimensions, which ensure the desired, theoretically perfect, operation.
II. POWER-FLOW CONFORMAL METASURFACES

In order to introduce the concept of power-flow conformal metasurfaces, we start with a simple design: a metasurface capable to redirect the normally impinging energy ($\theta_i = 0^\circ$) into another direction defined by the angle $\theta_r$. Figure 1(a) represents an illustration of the system under study. As was demonstrated in [1], for avoiding parasitic reflections power conservation has to be satisfied or, in other words, the amplitude of the reflected wave has to be selected for ensuring that it carries the same energy as the incident plane wave.

The origin of required non-locality of reflective metasurfaces is the power flow modulation due to the simultaneous propagation of multiple waves with different directions in the same medium [1, 4]. Figure 1(c) represents the intensity vector when both incident and reflected waves coexist in the medium. From this representation, it is clear that for any flat reflective boundary there will be points where the power enters through the metasurface (lossy behavior) and other points where the power emerges from it (active behavior). Under these circumstances, when we calculate the surface impedance which models the metasurface, we will find that the real part of the impedance takes positive and negative values [1]. It is important to notice that the overall response is lossless over a period because we enforce power conservation in the definition of the reflected wave amplitude.

If one wants to overcome the problem of the power flow modulation, the intensity vector should not cross the metasurface at any point. This can be ensured by using properly curved reflective metasurfaces. For example, Fig. 1(c) shows a surface profile which is tangential to the intensity vector. The surface impedance at this surface is everywhere pure imaginary, as it is shown in Fig. 1(b). Figure 1(d) shows the acoustic field scattered by the metasurface when it is illuminated normally. The numerical results are calculated using COMSOL and defining the metasurface as a surface impedance boundary. We can see that only the reflected wave in the desired direction is excited without any parasitic reflection.

As we have demonstrated, this approach can provide a systematic methodology for the design of perfect anomalously reflecting metasurfaces. The new strategy has three 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 power modulation and definition of the metasurface surface profile tangential to the intensity vector, and (iii) calculation of the surface impedance of the curved, power-conformal metasurface. In [4], it was demonstrated that the method can be easily adapted to other scenarios such as beam splitters. The reader is referred to [4] for more details about the analytical formulation of the problem.
III. EXPERIMENTAL RESULTS

The surface impedance of the designed curved metamirror can be realized using any kind of phase shifters. In this work, for simplicity, we use closed-ended tubes with different lengths. The input impedance of each tube is calculated as $Z_{s,i} = -j\eta_0 \cot(kl_i)$, where $\eta_0$ is the characteristic impedance of the medium, $k$ is the wavenumber in the media, and $l_i$ the length of the closed tube. Figure 2(a) shows a simulation of the metasurface implemented with such tubes. It is important to notice that, despite that the design approach is purely analytical and no optimization tool has been used, the performance is perfect.

The metasurface has been fabricated for working at the operational frequency of 3 kHz. The samples were fabricated with fused deposition modeling (FDM) 3D printing. The printed material is acrylonitrile butadiene styrene (ABS) plastic. The fabricated metasurface consists of 6 periods, and is secured in a two-dimensional waveguide for the measurement. A loudspeaker array with 28 speakers sends a Gaussian modulated beam normally to the metasurface and the reflected field is scanned using a moving microphone with a step of 2 cm [see Fig. 2(b)]. Figure 2(c) shows the real part of the pressure field where we can confirm that the normally incident beam is redirected into the desired direction (magenta solid line defines the direction $\theta_r = 70^\circ$ from the center of the incident beam). The results of a deeper analysis of the experimental data using a 2D-Fourier transform is shown in Fig. 2(c). Clearly, we can see that most part of the energy goes to the desired direction. Small discrepancies can be attributed to fabrication errors, 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, the concept of power-flow conformal metasurfaces is presented and applied to the design of perfectly reflective metasurfaces. An passive anomalous reflector for $\theta_i = 0^\circ$ and $\theta_r = 70^\circ$ is designed and experimentally verified for the first time. The results can be applied to other wavefront transformations and other disciplines (see [4] for the electromagnetic formulation).

REFERENCES