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Metasurfaces for perfect control of reflection

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***Abstract*—By controlling the surface reactance of impenetrable gradient metasurfaces it is possible to shape the phase front of reflected waves. This approach is similar to that used in conventional reflectarray antennas, where the phase of reflection from each array element is properly tuned. However, such phase-gradient reflectors always produce some parasitic scattering into unwanted directions. Here we present our recent results on non-local (spatially dispersive) gradient metasurfaces which do not have this drawback and demonstrate perfect anomalous reflection of incident plane waves into any desired direction.**

I. Introduction

Reflections of obliquely incident plane waves from uniform planar reflectors obey the simple reflection law: the reflection angle is equal to the incidence angle. However, if the reflector surface is not homogeneous, this law does not apply, and it becomes possible to shape the phase front of the reflected wave. The conventional design approach is based on the phase-array antenna principle. If the waves reflected from different points of the reflector have different phases, the phase distribution over the reflecting surface can be tuned so that the reflected waves interfere constructively in the desired direction. For example, if we want to reflect a plane wave at the incidence angle $\theta_{\rm i}$ into a plane wave propagating at the reflection angle $\theta_{\rm r}$ and the amplitude of the reflected wave is the same as in the incident wave, the reflection coefficient depends on the coordinate x along the reflector surface as $\exp[j\Phi_{\rm r}(x)] = \exp[j(\sin\theta_{\rm i} - \sin\theta_{\rm r})k_1 x]$. Here, k_1 is the wavenumber in the background isotropic medium, $\Phi_{\rm r}(x)$ is the phase of the reflection coefficient and we assume the time-harmonic dependency $e^{j\omega t}$. Obviously, there is a relation between the reflection angle and the gradient of the reflection phase profile

$$\sin\theta_{\rm i} - \sin\theta_{\rm r} = \frac{1}{k_1}\frac{d\Phi_{\rm r}(x)}{dx}, \tag{1}$$

and this simple relation is sometimes called the generalized reflection law [1]. Thus, it appears that in order to tilt the reflected plane wave into the desired direction, one needs to realize linearly-varying reflection phase profile.

However, if we realize a surface whose reflection coefficient equals exactly $R = \exp(j\Phi_{\rm r})$, in accordance to this recipe, the performance of this reflector will not meet our expectations. Locally at every point the reflector obeys the usual reflection law, meaning that the ratio of the tangential to the reflector surface electric and magnetic fields (the wave impedance) is the same for the incident and reflected waves. But in the desired field configuration these impedances must be different, because the reflection angle is different from the incidence angle. It is clear that the performance can be perfect only if the reflected wave has the same impedance as the incident angle, that is, only for simple uniform mirrors or for retro-reflectors. In all other cases, inhomogeneous reflectors (metasurfaces of reflectarrays) will produce parasitic reflections into other directions (see Fig. 1).

This problem of conventionally designed reflectarrays [2] and metasurfaces [3] has been recently recognized [4], [5]. It was shown that in order to realize perfect anomalous reflection (or more general perfect control of reflected wave front) one either needs active elements [5] or strongly non-local response of the metasurface [4]. Obviously, the use of active (gain) elements is usually not desirable and purely passive realizations are preferable. In this presentation we will review our recent results on design and experimental realization of perfect anomalous reflectors using inhomogeneous leaky-wave metasurfaces [6].

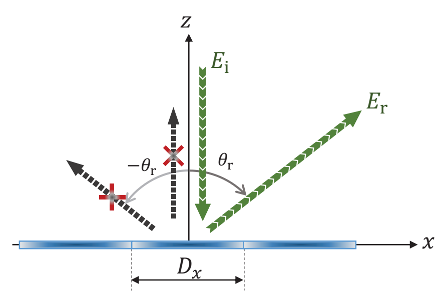


Fig. 1: Illustration of the desired performance of a perfect reflective metasurface when $\theta_{\rm i} = 0°$. Directions of the parasitic reflections are marked with grey arrows for $\theta_{\rm r} > 30°$.

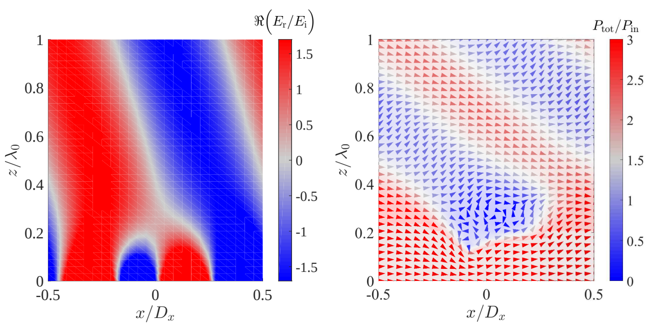
II. Results

Here we show how perfect anomalous reflection can be realized using lossless but non-local metasurfaces. Simple calculation of the ratio of the tangential electric and magnetic fields of the desired field distribution (the sum of the incident plane wave coming from the direction $\theta_{\rm i}$ and the anomalously reflected plane wave propagating in the direction defined by $\theta_{\rm r}$) gives the following result for the required surface impedance of an ideal reflector [4]:

$$Z_{\rm s}(x) = \frac{\eta_1}{\sqrt{\cos\theta_{\rm i}\cos\theta_{\rm r}}}\frac{\sqrt{\cos\theta_{\rm r}} + \sqrt{\cos\theta_{\rm i}}\,e^{j\Phi_{\rm r}(x)}}{\sqrt{\cos\theta_{\rm i}} - \sqrt{\cos\theta_{\rm r}}\,e^{j\Phi_{\rm r}(x)}}. \tag{2}$$

with η_1 being the wave impedance in the background medium. Equation [2] is a complex function, whose real part (surface resistance) takes both positive (loss) and negative (gain) values. Of course, the surface-averaged normal component of the Poynting vector is zero, and the surface is overall lossless [4], [5]. In paper [6], we proposed to realize such non-local gain-loss property by designing a leaky-wave planar waveguide, which would receive energy in the "lossy" regions, guide it along the surface, and radiate back into space in the "active" regions of the metasurface reflector, perfectly realizing the required non-local response.

First we consider a surface-impedance model of the anomalous reflector. Instead of modulating the reflection phase according to (1), we assume that the surface reactance has the same sign everywhere on the surface, to allow guidance of the surface wave of the working polarization. Next, we modulate the surface reactance in every period of the metasurface so that the surface mode couples to the incident plane wave in the "lossy" regions and to the reflected plane wave in the "active" regions. The calculated distribution of the Poynting vector is shown in Fig. 2(a) when $\theta_{\mathrm{i}} = 0°$ and $\theta_{\mathrm{r}} = 70°$. This result shows how the excited evanescent fields receive the energy from the incident plane wave and re-radiate it into θ_{r} direction, acting as a mechanism for energy channelling. Figure 2(b) shows the scattered field distribution, where we clearly see that all the energy is reflected into a plane wave with amplitude $E_{\mathrm{r}} = 1.7E_{\mathrm{i}}$.

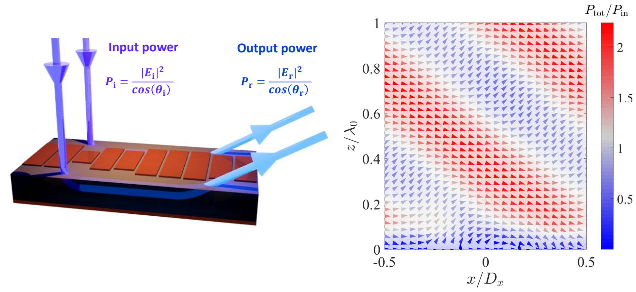


(a)

(b)

Fig. 2: Numerical simulations of a lossless metasurface for perfect anomalous reflection when $\theta_{\mathrm{i}} = 0°$ and $\theta_{\mathrm{r}} = 70°$. (a) Total power density flow distribution. (b) Real part of the normalized scattered filed.

Next, we realize the desired response designing an inhomogeneous high-impedance surface as an array of metal patches over a ground plane. The schematic representation of one unit cell is shown in Fig. 3(a). The length of the patches are designed for reflecting normally incident plane waves into plane waves at the reflection angle 70° at the frequency of 8 GHz. Numerical simulations which take into account dissipation losses in the metal and dielectric elements show that the expected power efficiency of this anomalous reflection is 94%. The measured value is 93.8% Detailed description of this work can be found in paper [6]. Figure 3(b) shows the Poynting vector in the xz-plane when $y = D_y/2$, with D_y being the period in y-direction.



(a)

(b)

Fig. 3: Proposed metasurface. (a) Schematic representation of one unit cell. (b) Total power density flow distribution in the xz-plane when $y = D_y/2$.

The proposed perfect anomalous reflector is lossless, so the reciprocity requirement has to be satisfied. In other words, a plane wave which impinges the metasurface at 70° will be completely reflected into the normal direction (see Fig. 4(a)). Moreover as a consequence of such reciprocal response, the metasurface will behave as a reto-reflector for $-70°$. The three different scenarios allowed in this system have been numerically studied. Figure 4(b) represents the field scattered by the metasurface when it is illuminated at $-70°$. The energy reflected into the retro-direction is 94% of the incident energy, 1% is distributed into other directions and 4% is absorbed in the structure. It is interesting to notice that in this case incident and reflected waves have the same amplitude. The second scenario corresponds to normal illumination and the results are shown in Fig. 4(c). Third scenario is studied in Fig. 4(d) and it shows how the metasurface carries the energy from 70° to the normal direction (92% of the incident energy). Perturbations in the wavefront of the reflected wave are produced by small parasitic reflections (2% of the incident energy). More details about this multi-channel analysis can be found in [8].

III. Conclusion

The presented results show that it is possible to overcome the fundamental limitation of reflectarrays and reflecting metasurfaces which locally fully reflect the incident power and fully control the reflection phase. Parasitic reflections can be completely eliminated by using non-local, waveguiding metasurfaces. The effective surface impedance of these structures perfectly emulates the gain-loss response which is necessary to ensure perfect operation of anomalous reflectors. We expect that the proposed approach can be generalized for the design of reflectarrays for general transformations of reflected waves, for example, for wave focusing. Finally, we note that an alternative multi-layer design was proposed in [7], and it appears that the physical principle of that solution is similar to what we have described here.

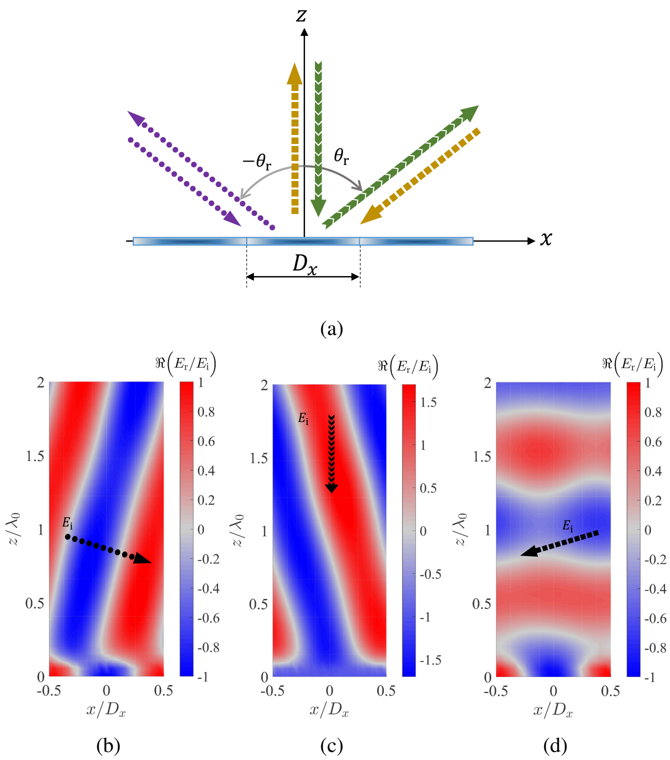


Fig. 4: (a) Schematic representation of the full functionality of the lossless anomalous reflector. Response of the metasurface under different illuminations: (b) plane wave at $-70°$; (c) plane wave at $0°$; (d) plane wave at $70°$.

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