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# Perfect Reflectarrays Elements Based on Non-local Metasurfaces

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***Abstract*—In this presentation we explain how reflectarrays can be made "perfect", in the sense that no power is scattered into unwanted directions. In particular, we present examples of impenetrable metasurfaces for anomalous reflection and beam splitting. We show that passive perfectly performing anomalous reflectors must be non-local and that this property can be realized by proper engineering the reactive impedance of the metasurface.**

## I. Introduction

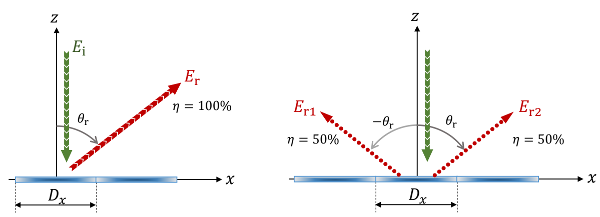
The planar configuration of reflectarrays [1] and possibilities to use low-cost manufacturing techniques make them attractive for many applications, especially in communication systems. Recently, the reflectarray principle has been widely used in the design of reflective metasurfaces, motivated by the formulation of the generalized Snell's law [2]. However, the conventional synthesis methods of reflectarrays and reflective metasurfaces do not ensure the perfect performance of devices due to inevitable parasitic reflections into undesired directions. This problem of conventionally designed reflectarrays [1] and reflecting metasurfaces [2], [3] has been recently recognized [4]–[6] specially for steep reflection angles. In this paper we explain how the fundamental deficiency of all conventional reflectarrays can be overcome on the examples of two different perfect reflectors: a gradient metasurface for reflecting an incident plane wave into an arbitrary desirable direction (anomalous reflector) and a metasurface which equally splits normally incident power into two different directions ( $50:0:50$ splitter). These two devices are schematically represented in Fig. 1. We call the performance "perfect" if the power efficiency $\eta$ is 100%, that is, all incident power is fully channelled into one (anomalous reflector) or two (splitter) plane waves.

## II. Results

For simplicity, we consider metasurfaces illuminated by a normally incident plane wave with TE polarization. If we want to reflect the wave into a certain direction, we fix the propagation direction of reflected waves, $\pm\theta_\mathrm{r}$, selecting the period of the metasurface $D_x = \lambda/\sin\theta_\mathrm{r}$, where $\lambda$ is the wavelength. The tangential electric field of propagating modes at the metasurface plane ($z=0$) can be expressed as

$$E_t(x,0) = E_\mathrm{i} + E_\mathrm{r1}e^{jk_xx+j\phi_1} + E_\mathrm{r2}e^{-jk_xx+j\phi_2}, \qquad (1)$$

where $k_x = k\sin\theta_\mathrm{r}$ is the tangential wavenumber of the reflected waves; $E_\mathrm{i}$, $E_\mathrm{r1}$, and $E_\mathrm{r2}$ are the amplitudes of




(a) (b)

Fig. 1. Schemtatic representation of the desired performance of perfect reflective metasurfaces when $\theta_\mathrm{i} = 0°$. (a) Anomalous reflection. (b) $50:0:50$ splitter.

the incident and two reflected waves, respectively; and $\phi_1$ and $\phi_2$ are additional phases of the reflected waves. The corresponding tangential magnetic field reads

$$H_t(x,0) = \frac{E_\mathrm{i}}{\eta_0} - \frac{\cos\theta_\mathrm{r}}{\eta_0}\left(E_\mathrm{r1}e^{jk_xx+j\phi_1} + E_\mathrm{r2}e^{-jk_xx+j\phi_2}\right), \qquad (2)$$

where $\eta_0$ is the impedance of the background medium.

The conventional design approach is based on ensuring that the incident power is fully reflected at every point of the reflector, that is, the absolute value of the reflection coefficient is unity. Furthermore, the phase of the reflection coefficient is modulated linearly [1], [2], so that the waves reflected from every point interfere constructively in the desired direction. However, in this case the desired field structure (1), (2) is not realized, because the corresponding surface impedance $Z_\mathrm{s}(x) = E_t(x,0)/H_t(x,0)$ is a complex number while the metasurface is assumed to be lossless at every point ($\Re(Z_\mathrm{s}) = 0$).

### A. *Perfect anomalous reflection*

Let us assume that we want to realize perfect anomalous reflection into only one plane wave ($E_\mathrm{r1} = 0$). For simplicity, we set $\phi_1 = \phi_2 = 0$. In this scenario, in order to satisfy the power conservation at every point of the reflective surface, the amplitude of the reflected plane wave has to be $E_\mathrm{r2} = E_\mathrm{r} = E_\mathrm{i}/\sqrt{\cos\theta_\mathrm{r}}$ [4]. By introducing this amplitude into Eqs. (1) and (2), the surface impedance can be written as

$$Z_\mathrm{s}(x) = \frac{\eta_0}{\sqrt{\cos\theta_\mathrm{r}}}\frac{\sqrt{\cos\theta_\mathrm{r}} + e^{-jk_xx}}{1-\sqrt{\cos\theta_\mathrm{r}}\,e^{-jk_xx}}. \qquad (3)$$

This impedance is a complex number whose real part takes positive and negative values. When the real part (surface resistance) takes positive values, it represents energy absorption (loss) and when it is negative, it represents radiation (gain). The average of the normal component of the Poynting vector over one period is zero. Figure 2(a) shows the real and imaginary parts of the surface impedance when $\theta_{\rm r} = 70°$.

### B. Beam splitter

Our second example is a 3-port perfect splitter which distributes the incident power into two reflected plane waves $(50 : 0 : 50)$ , so that $E_{\rm r1} = E_{\rm r2} = E_{\rm r}$. From the power conservation condition, the amplitude of the reflected waves reads $E_{\rm r} = E_{\rm i}/\sqrt{2\cos\theta_{\rm r}}$. As an example, we choose $\phi_1 = 0$ and $\phi_2 = \pi$. Following the same approach that in the previous example, the impedance which models the metasurface is

$$Z_{\rm s}(x) = \frac{\eta_0}{\sqrt{\cos\theta_{\rm r}}} \frac{\sqrt{\cos\theta_{\rm r}} + j\sqrt{2}\,\sin(k_x x)}{1 - j\sqrt{2\cos\theta_{\rm r}}\,\sin(k_x x)}. \qquad (4)$$

Figure 2(b) represents the surface impedance for the perfect splitter when $\theta_{\rm r} = 70°$. As in the previous case, we can see that the impedance is a complex number with a similar "lossy-active" behaviour.

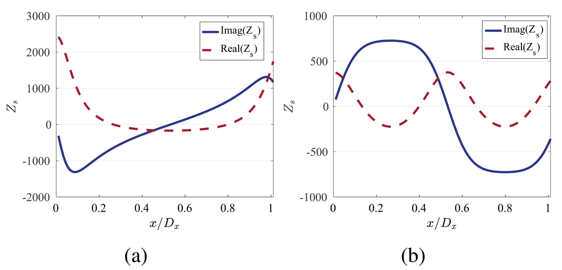



Fig. 2. Required surface impedance of metasurfaces when $\theta_{\rm r} = 70°$. (a) Anomalous reflection. (b) Beam splitter

### C. Energy channeling along lossless metasurfaces

In paper [7], we proposed to realize such effectively gain-loss property by designing the metasurface as an inhomogeneous, non-local leaky-wave waveguide, which would receive energy in the "lossy" regions, guide it along the surface, and radiate back into space in the "active" regions. We realize the desired response by designing an array of metal patches over a ground plane. Here, a combination of evanescent (surface waves) and propagating waves forms a required periodically modulated channel for energy transport along the reflector surface.

Figures 3(c) and 3(d) represent the views of both metasurfaces implemented with ten metal patches per period. Figures 3(a) and 3(b) represent the numerical verification of both designs. In the case of the anomalous reflector we see how a perfect plane wave is propagating in the desired direction. On the other hand, in Fig. 3(b) we can see the interference pattern generated by the two plane waves reflected from the perfect splitter.

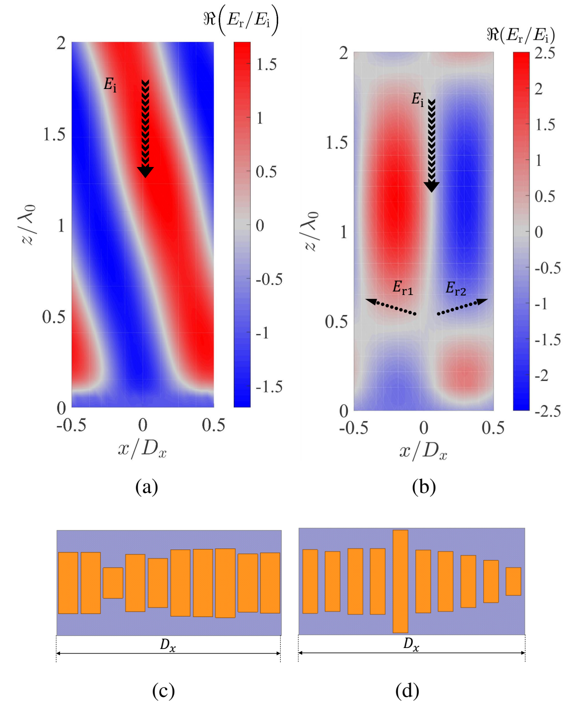



Fig. 3. Numerical simulations of lossless metasurfaces when $\theta_{\rm r} = 70°$: (a) perfect anomalous reflection and (b) 3-port splitter. Schematic view of the metasurface implemented with ten elements per period: (c) anomalous reflector and (d) 3-port splitter.

## III. Conclusions

In this work we have shown that it is possible to overcome the fundamental limitation of reflectarrays and reflecting metasurfaces with two examples of perfect reflectarrays. Here, parasitic reflections are completely eliminated and the perfect power balance between the incident and reflected waves is ensured. Experimental results will be shown in the conference presentation.


## ACKNOWLEDGEMENT

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