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Concept of an Asymmetric Metasurface Absorber

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***Abstract*—In this talk we show how to break the angular symmetry of electromagnetic response of thin absorbers. Based on our recent results on multichannel metasurfaces, we propose a new concept of asymmetric absorbers in which the absorption coefficient for waves impinging from a given oblique angle is extraordinarily different from that for waves incident from the oppositely tilted direction. The proposed asymmetric structure realizes controllable reflectance (from 0 to 0.99) for waves incident from one direction, exhibiting total absorption when the sign of the incidence angle is reversed. We provide a theoretical analysis for the asymmetric absorber as well as a numerical verification.**

***Index Terms*—asymmetric, multichannel metasurfaces, absorbers, surface impedances, Floquet harmonics.**

I. Introduction

Thin composite layers, known as *metasurfaces,* have been attracting significant attention due to their abilities to efficiently manipulate wave reflection and transmission [1]–[3]. By properly arranging meta-atoms, it is possible to implement a variety of devices such as polarizers [4], absorbers [5], anomalous reflectors [6], [7], and so on. However, integration of more than one functionality in a single metasurface is seldom reported. A recent work about multifunctional flat reflectors [8] opened up a blueprint for simultaneous manipulation of waves incident from multiple directions. In particular, a multichannel isolating mirror and a power splitter were demonstrated in [8]. By properly choosing the metasurface period (as compared to the wavelength) and the surface impedance profile, wave propagation into several different directions can be successfully controlled.

In this work, we exploit the idea of multichannel metasurfaces to create electromagnetic absorbers with angle-asymmetric properties. Known absorbers are designed to exhibit no diffraction lobes (the unit-cell size is smaller than the half-wavelength) [9]–[11] and the absorbing surface can be considered as uniform at the wavelength scale. In this case, specular reflections for waves incident from oblique angles θ_i and $-\theta_\mathrm{i}$ are always equal (due to reciprocity), and this forces the absorption coefficient to be an even function with respect to the angle of incidence. The situation becomes drastically different if we allow propagation of diffracted modes along desired directions, by increasing the unit-cell size compared to the wavelength. Now, the incident energy can be channelled to the diffracted modes in such a way that absorption coefficients are not anymore limited to even functions of the incident angle. In fact, it becomes possible to achieve arbitrarily asymmetric absorption without breaking reciprocity.

In this talk, we propose a possibility to integrate two extreme electromagnetic scenarios in a single planar and reciprocal device. Our designed metasurface exhibits full absorption for waves incident at a given angle and simultaneously nearly full retro-reflection for waves incident from the opposite direction. We also demonstrate that the reflectivity from the opposite direction can be arbitrarily engineered in a large scale from 0 to about 0.99.

II. Theory

A. Multichannel Metasurfaces

Let us first consider a periodical metasurface located in the xy-plane under the illumination of a TE-polarized plane wave (the incidence plane is the xz-plane) [see Fig. 1]. According to the Bloch–Floquet theorem, the reflected fields can be interpreted as a sum of space harmonics. The tangential wave number of the nth harmonic wave is related to the structure period D and the incident wave number k_i:

$$k_{\mathrm{r}x} = k_\mathrm{i}\sin\theta_\mathrm{i} + \frac{2\pi n}{D}, \tag{1}$$

where θ_i is the incident angle, n is the harmonic order (n can be any integer). The corresponding normal component of the reflected wave number is

$$k_{\mathrm{r}z} = \sqrt{k_\mathrm{i}^2 - k_{\mathrm{r}x}^2}. \tag{2}$$

From (2), we can see that if $|k_{\mathrm{r}x}|$ is larger than the incident wave number, $k_{\mathrm{r}z}$ becomes an imaginary value. This means that the wave is evanescent and cannot propagate to the far-field. For the harmonic wave satisfying $|k_{\mathrm{r}x}| < k_\mathrm{i}$, $k_{\mathrm{r}z}$ is real such that this reflected harmonic is propagating. It is can be seen from (1) that the propagating reflected waves are not limited to specular direction and the number of propagating waves can be increased if the structural period D is enlarged. By defining a proper periodic surface impedance of the metasurfaces, multichannel metasurfaces with various functionalities can be synthesized, as demonstrated in [8].

B. Asymmetric Absorber

For a structure with the period $D < \lambda_\mathrm{i}/(1+\sin\theta_\mathrm{i})$, only specular reflection is allowed, although the surface is not uniform. The electromagnetic response of this structure should be angle-symmetric due to reciprocity. As the period increases, more propagating channels open up, which offers possibilities to realize and engineer asymmetric reflections. Here, we utilize the principle of multichannel metasurfaces and develop the theory of asymmetric absorbers. The schematic of

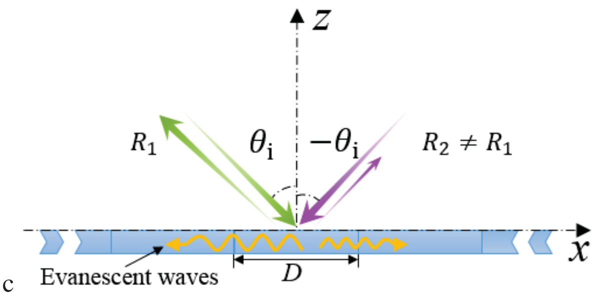


Fig. 1. Schematic of the asymmetric absorber.

the proposed structure is shown in Fig. 1. Considering oblique incidence from $\theta = \theta_i$ (shown as channel 1), only retro and specular reflection channels are open if $D = \lambda_i/(2\sin\theta_i)$. For illumination from channel 1, we can design a metasurface which does not reflect into the specular and no evanescent waves are induced. Denoting the desired reflectivity in the retro-direction by R_1, the tangential components of electric and magnetic field at the surface $z = 0$ can be written as

$$E_{1t}(x) = E_i(e^{-jk_0 \sin\theta_i x} + R_1 e^{jk_0 \sin\theta_i x}) \tag{3}$$

$$H_{1t}(x) = E_i \frac{\cos\theta_i}{\eta_0}(e^{-jk_0 \sin\theta_i x} - R_1 e^{jk_0 \sin\theta_i x}), \tag{4}$$

where E_i is the incident electric field amplitude. The impedance boundary condition relates the tangential electric and magnetic field. The surface impedance, $Z_s(x) = E_{1t}(x)/H_{1t}(x)$, which realizes these properties, reads

$$Z_s(x) = \frac{\eta_0}{\cos\theta_i}\frac{1 + R_1 e^{2jk_0 \sin\theta_i x}}{1 - R_1 e^{2jk_0 \sin\theta_i x}} \tag{5}$$

The spatially modulated surface impedances in one period $(-D/2 \leq x \leq D/2)$ with different retro-reflectivities are plotted in Fig. 2 (for $\theta_i = 45°$).

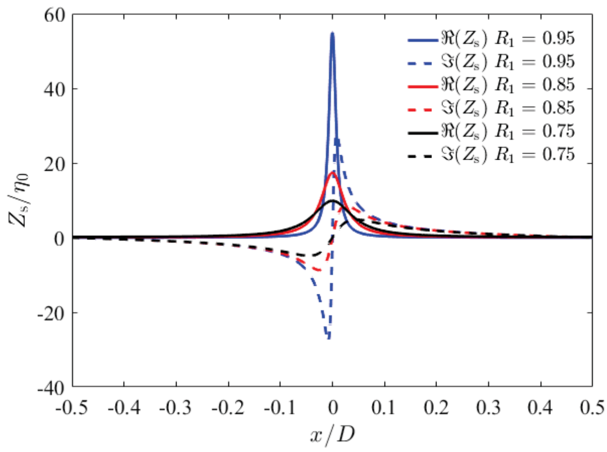


Fig. 2. The required normalized surface impedance within one period of the surface for R_1 =0.75, 0.85, and 0.95. The incidence angle is $\theta_i = 45°$.

We can see from Fig. 2 that the real part of the surface impedances is always symmetric and positive with a peak, which means that it is a lossy surface. The resistance peak tends to be squeezed as the retro-reflectivity increases. It also can be seen that the surface reactance is not symmetric and this asymmetry become more significant when the defined R_1 is larger. The asymmetric property of the surface impedance indicates its asymmetric electromagnetic response.

With the defined surface impedance $Z_s(x)$, we investigate the scattered fields when the TE-polarized wave illuminates from $\theta = -\theta_i$ (shown as channel 2 in Fig. 1). Since the period D is unchanged, the opened scattering channels in this scenario are still channel 1 (specular reflection in this case) and channel 2 (retro-reflection). However, due to the asymmetric $Z_s(x)$ and the altered phase distribution of the incident wave, the impedance boundary condition (5) is not satisfied with a sum of two propagating plane waves. In order to satisfy the boundary condition, evanescent waves are inevitably excited. The total reflected field can be represented as an infinite sum of Floquet harmonic modes:

$$\mathbf{E}_{\text{sca}} = \sum_{n=-\infty}^{\infty} A_n e^{-jk_{rz}z} e^{-jk_{rx}x}\mathbf{y}, \tag{6}$$

where A_n is the complex amplitude of the nth harmonic order. Note that the scattered field consists of both propagating and evanescent waves. The total tangential electric field at the $z = 0$ plane is written as

$$E_{2t}(x) = E_i e^{jk_0 \sin\theta_i x} + \sum_{n=-\infty}^{\infty} A_n e^{-jk_{rx}x}. \tag{7}$$

Thus, the total tangential magnetic field is

$$H_{2t}(x) = E_i \frac{\cos\theta_i}{\eta_0} e^{jk_0 \sin\theta_i x} - \sum_{n=-\infty}^{\infty} A_n \frac{k_{rz}}{\omega\mu_0} e^{-jk_{rx}x}. \tag{8}$$

By enforcing the boundary condition 5, that is, demanding that $E_{2t}(x)/H_{2t}(x) = Z_s(x)$, all of the harmonic modes can be uniquely determined.

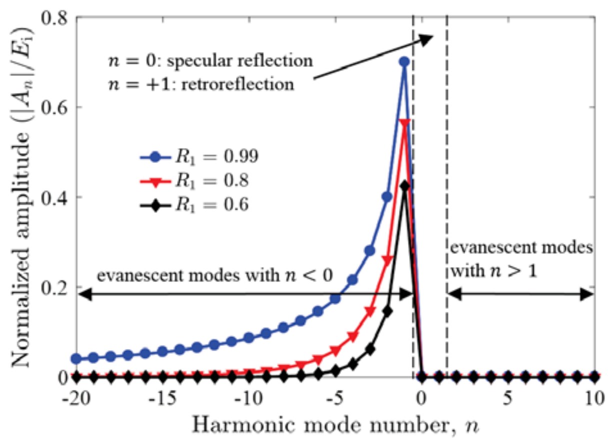
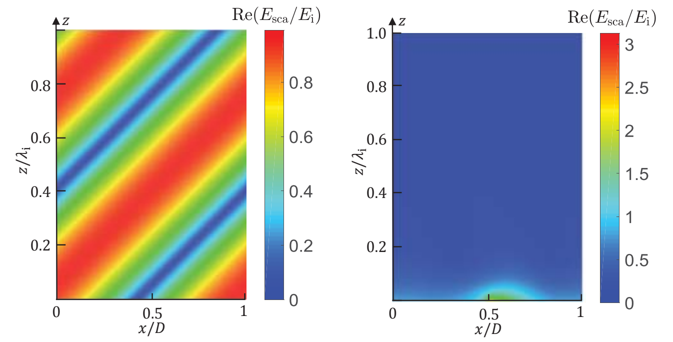


Fig. 3. Normalized absolute amplitude of reflection harmonics for $\theta_i = -45°$. Here, the surface impedances are defined by 5 for $R_1 = 0.6, 0.8$ and 0.99.

Figure 3 shows the solved amplitudes of harmonic orders (absolute values) from $n = -20$ to $n = 10$ for three different surface impedance profiles. For $Z_s(x)$ defined by $R_1 = 0.6$, the amplitude of specular refection ($n = 0$) is zero due to reciprocity. Interestingly, the retro-reflectivity ($n = 1$) is also zero. It means there is no reflected propagating waves when illuminating from channel 2. All of the incident energy is transformed into a set of evanescent waves ($n \leq -1$) and eventually dissipated in the lossy metasurface. As the pre-defined R_1 goes higher to $R_1 = 0.99$, still no propagating waves are allowed. The device still behaves as a perfect absorber when illuminated from channel 2. We can also observe that more evanescent modes are triggered if the surface is more reflective (R_1 is larger) when excited from channel 1.

III. Numerical Results

The surface impedance calculated from (5) is modelled in HFSS using impedance boundary conditions. Since HFSS is not able to model inhomogeneous impedance (spatially modulated), we divide one surface period into 300 discrete impedance strips to approximate the continuous and smooth impedance profile with a step-wise constant function.



(a) (b)

Fig. 4. Instantaneous values of the scattered electric field when incident from (a) $\theta_i = 45°$ and (b) $\theta_i = -45°$. The field value is normalized with the incident field amplitude. The surface impedance is defined for $R_1 = 0.99$.

For the surface impedance defined by $R_1 = 0.99$, the simulated scattered fields for two incidence directions at the oppositely tilted angles are displayed in Fig. 4. The simulated reflectivity for incidence at $\theta_i = 45°$ and $\theta_i = -45°$ are 0.99 and 0.04, respectively, which agree very well with the theoretical results. When the incident angle comes from the direction $\theta_i = 45°$, almost all the energy bounces back to the same direction. In this case, the device acts as a retro-reflector [see Fig. 4(a)]. For the incidence at $\theta_i = -45°$ [see Fig. 4(b)], the electric filed is confined in the vicinity of the impedance surface and decays exponentially along $+z$ direction. Apparently, the excited set of evanescent harmonics is automatically excited to satisfy the boundary condition which ensures the retro-reflection property for the opposite illumination. The far-field intensity is zero everywhere which means the incident wave is completely absorbed. Thus, at this illumination, the surface operates as a perfect absorber.

IV. Conclusions

In this paper, we have proposed a new concept of asymmetric absorbers where absorptions of waves coming from two incident angles are extraordinarily different. For a given retro-reflectivity at one incidence angle, the required surface impedance for implementing the asymmetric absorber is derived using the impedance boundary condition. We have shown that perfect absorption always takes place when illuminating from the opposite direction. This phenomenon is explained as the excitation of evanescent harmonics which are required to satisfy the boundary condition. In principle, using this concept, we can arbitrarily tune the reflectivity from two opposite incidence angles. Our theoretical predictions are shown to be consistent with numerically simulated examples.

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