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Diffraction Theory to Model Metasurfaces in Real-World Environments

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Abstract – It is expected that future mobile communication systems will exploit the possibilities of intelligent radio environments to enable the controllability, programmability, and optimization of the propagation channel. This technology will need reconfigurable and smart metasurfaces integrated into walls, ceilings, or facades. One challenge to be solved for development of this technology is to create a modelling tool for finite-sized metasurface panels that can be integrated into the models of the propagation channel. In this work, we study how to analytically characterize the far-field scattering properties of reflective metasurfaces mounted on a wall.

I. INTRODUCTION

Current wireless networks are designed by engineering and adapting the end-points of the network for a given propagation channel. Recently, a new perspective on wireless communication arose empowered by reconfigurable intelligent metasurfaces. In this new concept, the propagation channel can be engineered by integrating metasurfaces into the objects present in the propagation channel [1, 2]. How to realize and integrate tunable metasurfaces in actual environments is an active field of research with important technological challenges and practical aspects to be solved.

One of these important problems is the estimation of the far-field scattered from finite-sized metasurface panels. Current literature on metasurfaces focuses on the design and properties of infinite planar metasurfaces illuminated by plane waves. Approximate estimations of reflected power are usually based on the assumption of coherent summation of waves reflected by each individually controllable meta-atom, but this assumption is not valid for advanced anomalous reflectors [3]. Another aspect to investigate is the optimal size of the metasurface. For example, if we consider an environment where the distance between the transmitting antenna and the reconfigurable metasurface is several meters and the network operates in the millimeter frequency range, the size of the illuminated area is of the order of hundred wavelengths. A metasurface with an area of $100\lambda \times 100\lambda$ requires thousands of tunable meta-atoms what may results in unpractical and expensive metasurfaces.

In this talk, we will discuss our recent results on analytical models for scattering from finite-size metasurfaces. The proposed analytical method combines some approximations used in physical optics and diffraction gratings theory. Our model is applicable to both reflective and refractive metasurfaces. We will pay special attention to the size of the metasurface and its effect on the far-field scattering.

II. FAR-FIELD SCATTERING OF A REFLECTIVE FINITE-SIZED METASURFACES MOUNTED ON A WALL

In this section, we will consider scattering produced by a reflective metasurface with the size $a_1 \times a_1$ (the surface of the metasurface is denoted by Ω_1) located over an infinite and homogeneous reflective surface. We assume that the area $a_2 \times a_2$ is uniformly illuminated while outside of this area the incident fields are zero. Notice that $a_1 < a_2$ and there is a region, denoted by Ω_2 , where only the reflective homogeneous surface is illuminated. We use the Huygens principle and start the analysis by defining the total effective surface current densities in the illumination area as a combination of the incident and reflected fields. In general, the electric and magnetic current densities can be expressed in terms of the total magnetic and electric fields as $\mathbf{j}_e^+ = \hat{\mathbf{y}} \times \mathbf{H}^+|_{y=0}$ and $\mathbf{j}_m^+ = -\hat{\mathbf{y}} \times \mathbf{E}^+|_{y=0}$. Here, the superscript ‘+’ denotes the currents on the illuminated side of the wall. Notice that the Huygens currents at the shadow side of the wall are zero, $\mathbf{j}_e^- = \mathbf{j}_m^- = 0$, because we assume that fields do not penetrate through the wall.

Fig. 1: (a) Schematic representation of a reflective metasurface with the size $a_1 \times a_1$ mounted at an impenetrable wall. (b) Far-field scattering of an anomalous reflector designed to send the energy from 70° to normal direction for different sizes of the metasurface. The size of the illumination area is $100\lambda \times 100\lambda$. The reflection coefficient of the homogeneous wall is $R = 0.6$.

The electric and magnetic fields at the illuminated side of the wall can be defined using the following expression:

$$\Upsilon^+ = \begin{cases} \Upsilon_i + \Upsilon_{rm} & \text{if } (x, z) \in \Omega_1 \\ \Upsilon_i + \Upsilon_{rw} & \text{if } (x, z) \in \Omega_2 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where the operators $\Upsilon = (\mathbf{E}, \mathbf{H})$ denote both electric and magnetic fields.

In this definition, the incident fields $\mathbf{E}_i$ and $\mathbf{H}_i$ are present in the entire illuminated area $\Omega_1 + \Omega_2$ and, in the case of TE-polarization (electric fields oriented in z -direction), can be written as

$$\mathbf{E}_i = E_0 e^{-jk(\sin \theta_i x - \cos \theta_i y)} \hat{\mathbf{z}} \quad (2)$$

$$\mathbf{H}_i = -\frac{E_0}{\eta_0} (\cos \theta_i \hat{\mathbf{x}} + \sin \theta_i \hat{\mathbf{y}}) e^{-jk(\sin \theta_i x - \cos \theta_i y)} \quad (3)$$

with θ_i being the angle of the incidence of the illuminating wave. The reflected fields that define the electric and magnetic surface currents in the region Ω_2 can be written as

$$\mathbf{E}_{rw} = E_0 R e^{-jk(\sin \theta_i x + \cos \theta_i y)} \hat{\mathbf{z}} \quad (4)$$

$$\mathbf{H}_{rw} = \frac{E_0 R}{\eta_0} (\cos \theta_i \hat{\mathbf{x}} - \sin \theta_i \hat{\mathbf{y}}) e^{-jk(\sin \theta_i x + \cos \theta_i y)} \quad (5)$$

where R is the reflective coefficient of the homogeneous wall. Finally, the reflected fields in the area of the metasurface, Ω_1 , read

$$\mathbf{E}_{rm} = E_0 \sum_n r_n e^{-jk(\sin \theta_{rn} x + \cos \theta_{rn} y)} \hat{\mathbf{z}} \quad (6)$$

$$\mathbf{H}_{rm} = \frac{E_0}{\eta_0} \sum_n r_n (\cos \theta_{rn} \hat{\mathbf{x}} - \sin \theta_{rn} \hat{\mathbf{y}}) e^{-jk(\sin \theta_{rn} x + \cos \theta_{rn} y)} \quad (7)$$

where r_n are the reflection coefficients of the propagating Floquet harmonics and θ_{rn} defines the direction of propagation of each harmonic. More details on how to calculate the reflections coefficients of the Floquet harmonics can be found in [4].

In this work, we use the simplified far-field model that is valid under the following assumptions: $|\mathbf{r}| \gg \lambda$, $|\mathbf{r}| \gg a_2$, and $a_2^2/|\mathbf{r}| \ll \lambda$, where $\mathbf{r}$ is the position vector from the center of the illuminated area to the observation point. That is, the distance to the observation point is large compared to the wavelength and to the size of both the metasurface plate and the illuminated area. Under these assumptions, the reflected field can be found as

$$\mathbf{E}_{sc}(\mathbf{r}) \approx \frac{jk}{4\pi} \frac{e^{-jk|\mathbf{r}|}}{|\mathbf{r}|} \int_S e^{jk\hat{\mathbf{r}} \cdot \mathbf{r}'} \hat{\mathbf{r}} \times [\eta_0 \hat{\mathbf{r}} \times \mathbf{j}_e(\mathbf{r}') + \mathbf{j}_m(\mathbf{r}')] dx' dz' \quad (8)$$

where $\hat{\mathbf{r}}$ is the unit vector along $\mathbf{r}$, pointing from the center of the metasurface plate to the observation point [5].

Let us consider the scattered fields in the incidence plane ($\phi = \pi/2$). In this case, the reflected fields have only z -component and the expression of the scattered electric field can be simplified as

$$E_{scz} = \frac{jk}{4\pi} \frac{e^{-jk|\mathbf{r}|}}{|\mathbf{r}|} E_0 \left[a_2^2 ((1+R) \cos \theta - (1-R) \cos \theta_i) \text{sinc}(ka_{ef}) \right. \\ \left. + a_1^2 \sum_n (r_n - R\delta_n)(\cos \theta + \cos \theta_{rn}) \text{sinc}(ka_{efn}) \right] \quad (9)$$

where δ_n represents the delta function ($\delta_0 = 1$ and $\delta_{n \neq 0} = 0$).

Figure 1(b) shows the far-field scattering pattern of a perfect anomalous reflector designed to send the energy from 70° to normal direction for different sizes of the metasurface. In practice, this example describes structures such as non-local designs [6], power flow-conformal metasurfaces [7], or metagratings [8]. Because the metasurface is working as a perfect anomalous reflector, $r_1 = \sqrt{\cos 70}$ and $r_n = 0$ for any other mode. The size of the illuminated area is $100\lambda \times 100\lambda$ and the reflection coefficient of the wall is assumed to be $R = 0.6$. The upper panel shows the scattering properties of a metasurface that occupies all the illuminated area. Here, we can see that, as expected, energy is sent into the normal direction and the amplitude of the directivity is high because of the large area of the metasurface. The middle panel represents the far-field scattering of a metasurface with the area $50\lambda \times 50\lambda$. In this case we can see that a fraction of the incident energy is normally reflected and the rest of the energy is sent into the specular direction. Finally, for comparison, in the bottom panel we plot the scattering pattern produced without the metasurface. Following the same principle, one could consider a multi-metasurface scenario where different parts of the structure are designed to scatter the energy into different directions, acting as routers.

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