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Analytical Models of Link Budget in the Presence of Reflection-shaping Metasurface Panels

S. Kosulnikov*, A. Díaz-Rubio*†, S. Tretyakov*
*Department of Electronics and Nanoengineering, Aalto University, Espoo, Finland, email sergei.2.kosulnikov@aalto.fi
†Nanophotonics Technology Center, Universitat Politècnica de València, Valencia, Spain, email andiaru@upv.es

***Abstract*—The use of reconfigurable intelligent surfaces (RIS) for optimization of propagation channels is one of the currently actively studied techniques for improving the efficiency of the next generation of communications systems. In this work, we combine the physical optics approximation and the theory of diffraction gratings to derive simple analytical formulas for far-zone fields reflected and scattered by anomalously reflecting metasurface panels mounted on walls. In the talk, we will present numerical examples, illustrating the difference in performance of conventional phase-gradient reflectors (reflectarrays) and optimized nonlocal metasurface reflectors.**

***Index Terms*—reconfigurable intelligent surface (RIS), metasurface, scattering, diffraction.**

I. Introduction

Potential improvements of wireless telecommunication systems with the use of reconfigurable intelligent metasurfaces (RIS) [1] are studied in many research groups. However, known estimations of fields reflected and scattered from anomalous reflectors, especially from finite-sized panels, are based on various approximations and assumptions, whose validity is not always justified. In the vast majority of works on reconfigurable intelligent surfaces the classical reflectarray theory [2] is used. That theory is based on the assumption that every "point" at the metasurface plane is characterized by a certain plane-wave reflection coefficient. This is equivalent to the locally periodic approximation used in the theory and design of reflectarray antennas: the local reflection coefficient is calculated as a reflection coefficient of a regular infinite periodical array formed by identical cells. This model takes into account interactions of unit cells assuming that the cell properties vary slowly on the wavelength scale. This approximation has been used in many works with various modifications, see e.g. recent papers [3], [4].

In this presentation, we will discuss our recent results on finding analytical solutions for fields scattered by finite-size anomalous reflectors mounted on walls, using models that are not based on the locally periodic approximation. Here, we take into account periodicity of the metasurface and scattering into multiple propagating Floquet harmonics.

II. Theory

Here, our main interest is in millimeter-wave communications scenarios. In this frequency range, directive antennas are usually used. Thus, the most common situation with the use of reflection-shaping metasurfaces is a metasurface panel with the area Ω_1 illuminated by a directive beam, as is illustrated in Fig. 1.

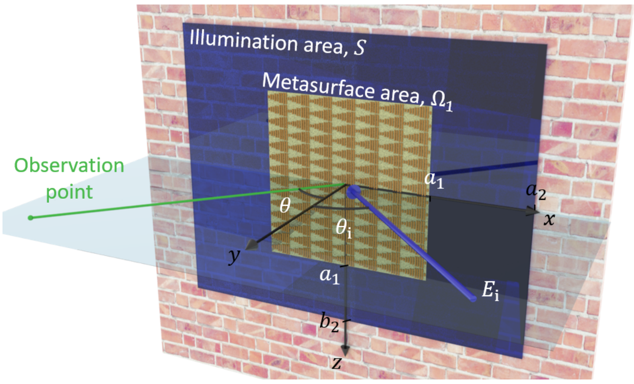

Fig. 1. Schematic representation of a reflective metasurface of the size $a_1 \times b_1$ mounted over an impenetrable wall. The source (a directive antenna), positioned at a distance r_0, illuminates area S of the size $a_2 \times b_2$. The incident angle is $\theta_{\rm i}$.

For normal illumination ($\theta_{\rm i} = 0$), the illuminated area of the wall can be estimated as [5]

$$S = \pi r_0^2 \left[\left(\frac{G}{G - 2\varepsilon_{\rm a}} \right)^2 - 1 \right] \tag{1}$$

where G is the gain of the illuminating antenna, and $\varepsilon_{\rm a}$ is its efficiency.

To calculate scattered fields, we make use of the Huygens principle, introducing equivalent Huygens surface current densities based on total fields at a closed surface fully enclosing the scattering object (e.g., [6]):

$$\mathbf{j}_{\rm e}^+ = \hat{\mathbf{y}} \times \mathbf{H}^+|_{y=0}, \qquad \mathbf{j}_{\rm m}^+ = -\hat{\mathbf{y}} \times \mathbf{E}^+|_{y=0} \tag{2}$$

Here, the superscript '$+$' marks the total fields and the surface currents on the illuminated side of the wall and the metasurface. The Huygens currents at the shadow side of the wall are zero, because fields do not penetrate the wall, assumed to be of the infinite extent. The electric and magnetic fields on the illuminated side of the wall can be defined using the following expression:

$$\boldsymbol{\Upsilon}^+ = \begin{cases} \boldsymbol{\Upsilon}_{\rm i} + \boldsymbol{\Upsilon}_{\rm rm} & \text{if } (x,z) \in \Omega_1 \\ \boldsymbol{\Upsilon}_{\rm i} + \boldsymbol{\Upsilon}_{\rm rw} & \text{if } (x,z) \in \Omega_2 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

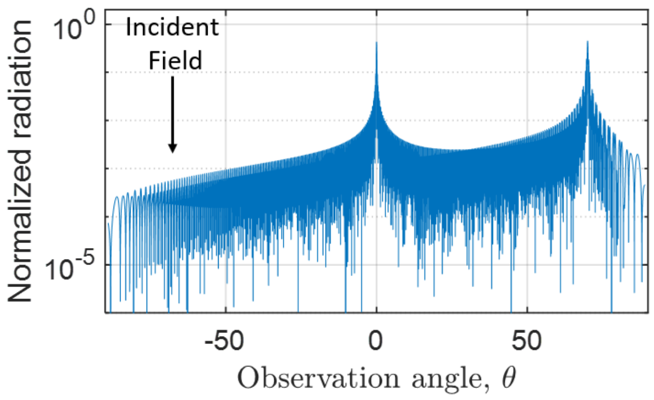

Fig. 2. Numerical study of the far-field scattering produced by a metasurface designed to produce perfect anomalous reflection for an illumination angle $\theta_\mathrm{i} = 70^\circ$ and a reflection angle $\theta_\mathrm{r} = 0^\circ$, when the illumination area is $100\lambda \times 100\lambda$. The size of the metasurface $50\lambda \times 50\lambda$.

where the six-vector $\boldsymbol{\Upsilon} = (\mathbf{E}, \mathbf{H})$ contains the components of the total electric and magnetic fields, incident $\boldsymbol{\Upsilon}_\mathrm{i}$ and reflected $\boldsymbol{\Upsilon}_\mathrm{rm}$ by the metasurface and by the illuminated area of the wall $\Omega_2 = S - \Omega_1$. The field over the illuminated area where there is no metasurface is a combination of the incident field and the field reflected by the wall, denoted by $\boldsymbol{\Upsilon}_\mathrm{rw}$.

For plane-wave illumination, the fields reflected from the uniform wall (region Ω_2) are also plane waves (in the physical-optics approximation) and can be written as

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

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

where R is the reflection coefficient of the homogeneous wall. Importantly, the fields reflected by the periodically modulated metasurface are sums of the correponding Floquet harmonics [7]:

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

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

where r_n are the complex macroscopic reflection coefficients of the propagating Floquet harmonics, and angles $\theta_{\mathrm{r}n}$ define the directions of propagation of each reflected plane-wave harmonic.

Calculating the fields created by the equivalent Huygens currents in the far zone, we find [5]

$$\begin{aligned} E_{\mathrm{sc}z} = & \frac{jk}{\pi} \frac{e^{-jk|\mathbf{r}|}}{|\mathbf{r}|} E_0 \\ & \Big[a_2 b_2 \left((1+R)\cos\theta - (1-R)\cos\theta_\mathrm{i} \right) \mathrm{sinc}(k a_\mathrm{ef}) \\ & + a_1 b_1 \sum_n (r_n - R\delta_n)(\cos\theta + \cos\theta_{\mathrm{r}n}) \mathrm{sinc}(k a_{\mathrm{ef}n}) \Big] \end{aligned} \tag{8}$$

where δ_n is the Kronecker delta ($\delta_0 = 1$ and $\delta_{n\neq 0} = 0$). The parameters $a_\mathrm{ef} = (\sin\theta - \sin\theta_\mathrm{i}) a_2$, and $a_{\mathrm{ef}n} = (\sin\theta - \sin\theta_{\mathrm{r}n}) a_1$ represent the effective size of the metasurface for each reflected propagating Floquet mode.

Figure 2 shows an example calculation of the scattering pattern (normalized to the pattern of a PEC plate of the same size as the metasurface panel) for a perfect (nonlocal design [8]) anomalous reflector designed to reflect waves from $\theta_\mathrm{i} = 70^\circ$ into the normal direction. The two main beams correspond to the anomalous reflection into the normal direction and to the specular reflection from the uniform wall.

Knowing the amplitude of the reflected field in the far zone, we immediately find an estimation of the link budget. To do that, we write the amplitude of the incident field in terms of the transmitter power, transmitter antenna gain, and the distance from the transmitter to the metasurface. Finally, we find the receiver power by multiplying the Poynting vector amplitude at the receiver position (corresponding to the electric field amplitude in (8)) by the effective area of the receiver antenna.

III. Conclusion

The described approach is based on the use of the Huygens principle, modified physical optics, and the theory of diffraction gratings. The main idea of the physical optics was used solving the problem for induced currents in the approximation of an infinite periodic surface. In contrast to the conventional use of physical optics, we do not assume that the reflecting surface is smooth on the wavelength scale. In our solution, the surface can be strongly inhomogeneous, we only assume that the reflected field is approximately the same as for the same periodical surface of infinite extent. That is, we neglect the edge effects, while we do not assume that the surface properties vary slowly over the reflector area. Thus, the results are applicable to metasurfaces designed for any periodical metasurface (for example, anomalous reflectors and beam splitters). We hope that these results will be useful for design and optimization of reconfigurable metasurfaces and developing models of propagation channels in presence of such new devices.

More details of this work, including modeling of transmitarrays, can be found in preprint [5].

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