

Exploring Low Back Reflection in Layer-Limited Metasurfaces: A Comparative Analysis of Various Simulation Techniques

Wenman Hu and Yahya Rahmat-Samii

University of California, Los Angeles, CA 90095, USA

wenmanhu221@ucla.edu, rahmat@ee.ucla.edu

The rapid development of metasurfaces has significantly advanced the ability to control the behavior of electromagnetic (EM) waves within these structures, enabling various functionalities critical for future communication and sensing systems. Metasurfaces offer several key advantages, including low cost, ease of fabrication, and a planar profile, making them highly attractive for practical implementations. These attributes have led to widespread applications in antenna design, such as metalenses and reflect/transmitarrays, to enhance high-gain performance for millimeter-wave (mmWave) applications. Additionally, metasurfaces can enable desirable design objectives, including wide-angle beamsteering and reconfigurability.

Transmissive designs benefit from simpler feeding networks and the absence of feed blockage, but a key challenge remains to mitigate back radiation, which degrades feed performance, creates undesirable back-lobe, and consequently reduces overall antenna efficiency. Multilayer designs can address this issue by wideband impedance matching, as demonstrated in prior works (Y. He and G. V. Eleftheriades, 2018; A. Papathanasopoulos *et al.*, 2020; in *IEEE Transactions on Antennas and Propagation*). However, fewer studies have explored single- or double-layer designs to consider design considerations for suppressing backlobes and improving overall efficiency. Additionally, it is common practice to design and optimize metasurfaces under normal incidence while neglecting oblique incidence effects for design simplicity. This assumption poses a challenge for satellite applications where limited stowage volume may require the feed to be positioned close to the metasurface aperture, generating a wide subtended angle. In such cases, accommodating wide-angle incidence becomes very critical to minimize performance degradation at large incident angles. To address the aforementioned challenges, this work revisits three EM analysis methods and validates an analytical formula that relates the oblique incidence angle to the element's reflection and transmission characteristics using a single-layer effective dielectric model. The methods include the ray-tracing technique, boundary conditions, and transmission line impedance matching. The incident wave, consisting of both TE and TM components, propagates through free space, interacts with a dielectric medium, and transmits back into free space. In the ray-tracing method, the rays undergo multiple transmissions and reflections, with the total reflection expressed as a series summation of all reflecting terms. The second method employs boundary conditions to form a matrix equation, which can be solved numerically to determine the unknowns. Finally, the third method uses transmission line theory to express the impedance of each region analytically. By canceling out the total reflection coefficient, these methods all arrive at the same equation as follows

$$\epsilon_r = \left(\frac{m\lambda_0}{2t}\right)^2 + \sin^2\theta_i (m = 1, 2, 3, \dots) \quad (1)$$

where λ_0 is the free-space wavelength, t is the dielectric thickness, and θ_i represents the incident angle. To connect this equation with metasurface design analysis, the S-parameters of a metasurface can be used to retrieve the effective refractive index ($n = \sqrt{\epsilon_r}$) as described by D. R. Smith *et al.* (*Physical Review*, 2005)

$$n = \frac{1}{kt} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{21}^2) \right] \quad (2)$$

where k is the free-space wave number, S_{11} and S_{21} are complex reflection and transmission coefficients. Although this standard equation assumes normal incidence, relevant parameter retrieval studies have been extended to oblique incidence (C. Menzel *et al.*, *Physical Review*, 2008). These equations offer valuable insights for developing design guidelines for low-reflection metasurfaces and for characterizing the effects of oblique incidence and back radiation in high-efficiency, reduced-layer metasurface antenna. This approach enables the development of advanced mmWave communication and sensing antennas.