

Extension of Implicit IE-GSTC Metasurface Forward Solver to Three-Dimensional Problems

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Metasurfaces are sheet-like engineered materials that allow for the systematic manipulation of electromagnetic (EM) waves. By the careful design of their subwavelength constituents known as unit cells, engineers can tailor the scattering properties of the metasurface. When optimizing these unit cells, it is critical to simulate the scattering performance of the metasurface, either once as a final design check or repeatedly as part of an iterative design process. The formulation and implementation of these metasurface forward solvers is therefore an important research area in the domain of metasurface design.

Metasurface forward solvers can broadly be classified by the metasurface models and fundamental numerical techniques employed by the algorithm. Both of these choices will result in consequences for the accuracy, speed, and difficulty of implementation of the forward solver. For maximum accuracy, full-wave solvers relying on the exact metasurface structure can be used to great effect, e.g., commercial solvers such as Ansys HFSS. However, due to the complexity of most metasurface structures, the simulation of these devices becomes a multi-scale problem with a large computational cost. This cost is further compounded when considering *reconfigurable* metasurfaces whose unit cell properties can be controlled via auxiliary electronic circuitry (Pitilakis et al., *IEEE Trans. Antennas Propag.*, vol. 69, 2021). A complete characterization of a reconfigurable metasurface with N binary unit cells would require 2^N simulations, a prohibitively large number even for modest choices of N .

More efficient metasurface forward solvers can be obtained by utilizing effective (or homogenized) metasurface models, e.g., replacing complex metallic trace layers with homogenized impedance sheets (J. Budhu et al., *IEEE Journal of Microwaves*, vol. 2, 2022). The resulting forward solver trades a small degree of accuracy for greater computational efficiency and ease of implementation. Even greater efficiency can be obtained by replacing the entire finite-thickness metasurface with a zero-thickness homogenized sheet characterized by surface parameters. This action is commonly done through the use of the Generalized Sheet Transition Conditions (GSTCs), which characterize the metasurface through homogenized surface susceptibility tensors (Achouri et al., *IEEE Trans. Antennas Propag.*, vol. 63, 2015). The GSTC equations can then be coupled with numerical techniques in order to obtain very efficient metasurface forward solvers. For many metasurface problems, the use of field integral equations (IE) is particularly useful as it only requires the numerical meshing of the (compact) metasurface itself and any other scattering objects. (This is in contrast to other numerical methods, e.g., finite-element techniques, which mesh the entire problem domain.) A combination of IEs with the GSTCs leads to the so-called IE-GSTC metasurface forward solvers (Smy et al., *IEEE Trans. Antennas Propag.*, vol. 70, 2022).

To date, the vast majority of zero-thickness IE-GSTC works only consider two-dimensional (2D) problems. To the best of our knowledge, only one research group has extended a 2D IE-GSTC solver to three-dimensions (3D) (Sierra et al., *2023 IEEE AP-S/URSI Conference*, 2023). In this presentation, we consider the 3D extension of the authors' own IE-GSTC method known as the implicit IE-GSTC (Phaneuf et al., *XXXVth URSI GASS Conference*, 2023). Our work differs from the other 3D IE-GSTC method by considering practical discrete unit cells (e.g., squares) as opposed to a continuously varying metasurface model. This must be addressed carefully when defining the basis functions of the problem, e.g., Rao-Wilton-Glisson basis functions. In addition, we will show how the unique formulation of the implicit IE-GSTC results in a reduced number of total unknowns, irrespective of the choice and density of basis functions. Several practical test cases will be presented, with a focus on the accuracy and speed of the extended solver.