

# A New Homogenization-Free Boundary Condition Towards Aperiodic Metasurface Design Using Full-Wave Surrogate Models of Printed Circuits

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Traditionally, metasurfaces—engineered surfaces that manipulate electromagnetic waves—are designed using the Generalized Sheet Transition Condition (GSTC). For metasurfaces invariant in one dimension which support only electric currents driven by electric fields, the GSTC reduces to the scalar impedance boundary condition  $E_{tan}^{tot} = \eta_s J_s$ . This boundary condition relies on homogenization, where the complex geometry of metasurface components (meta-atoms) is simplified into average values, like impedances, between induced currents and averaged fields (in the scalar case above,  $\eta_s$ ). This way the metasurface can be described, analyzed, and designed in a reduced dimensional space. After a design is completed in the reduced dimensional space, the proportionality constants must be translated back to complex geometries by way of an extraction method to realize the metasurface. While effective for simplified modeling, homogenization often fails to translate into feasible physical designs without additional costly and time-consuming adjustments, such as adding structures like baffles (G. Xu, S. V. Hum and G. V. Eleftheriades, "Augmented Huygens' Metasurfaces Employing Baffles for Precise Control of Wave Transformations," in *IEEE Trans. Antennas Propag.*, vol. 67, no. 11, pp. 6935-6946, Nov. 2019) or conducting further optimization (J. Budhu and A. Grbic, "Fast and Accurate Optimization of Metasurfaces With Gradient Descent and the Woodbury Matrix Identity," in *IEEE Trans. Antennas Propag.*, vol. 71, no. 9, pp. 7679-7683, Sept. 2023). One approach which attempts to solve the duplication problem is described in (J. Budhu, N. Ventresca and A. Grbic, "Unit Cell Design for Aperiodic Metasurfaces," in *IEEE Trans. Antennas Propag.*, vol. 71, no. 9, pp. 7387-7394, Sept. 2023) for metasurfaces modeled using matrix equations. However, this approach is costly as each unit cell must be designed one-at-a-time using full-wave simulation-based optimizations. Furthermore, the optimizations themselves may not always converge. To address these challenges, we propose a homogenization-free approach that incorporates the physical response of printed circuits directly into the design process. Rather than attempting to recreate the performance of the homogenized metasurface using printed circuits *post-design*, here we present an approach to incorporate the printed circuits response *intra-design*. Using full-wave data-driven surrogate models, which accurately represent the underlying physics of printed circuits, we create a novel boundary condition that replaces the GSTC. This eliminates the need for homogenization altogether, enabling metasurfaces to be designed in their true physical form from the outset. Thus, the new design approach can be described as homogenization-free. Our method provides significant advantages: it reduces the design-to-realization gap, avoids iterative post-design adjustments, and enables the efficient creation of aperiodic metasurfaces at scale. In this talk, we will present recent results and provide compelling evidence of the utility of our approach.