Modeling Reconfigurable Intelligent Surfaces with the Finite Element Method

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Abstract— Metasurfaces are complex electromagnetic structures with subwavelength thickness and intricate scattering features; they have emerged as a cornerstone of modern science and technology. Their design and analysis demand a holistic approach that integrates advanced synthesis and computational techniques grounded in robust theoretical models. The generalized sheet transition conditions (GSTCs) with bianisotropic surface susceptibility functions, provide a comprehensive framework for modeling and designing sophisticated reconfigurable intelligent surfaces (RISs). In this work, the design of a RIS is evaluated in a realistic scenario by considering its finite size through a robust computational approach. The absence of periodic conditions at the edges introduces a broader spectrum of diffracted waves, necessitating accurate representation through the calculation of the scattered field pattern [1]. This analysis is essential for assessing the RIS performance, as it enables the validation of the periodic design's functionality by examining the occurring scattered field patterns across different frequencies and angles of incidence. To achieve this, we develop a numerical tool based on the finite element method (FEM) incorporating an equivalent bianisotropic GSTC sheet of zero thickness to reduce computational complexity, while maintaining the physical accuracy of the solution. A 2.5D total field–scattered field (TF-SF) formulation with combined vectorial and nodal elements is employed to integrate the RIS into the total field domain, facilitate its interaction with the incident field, and enable the use of an uniaxial perfectly matched layer (UPML) to calculate radiation patterns. The discontinuities of electric and magnetic fields across the RIS are incorporated into the FEM framework by assigning distinct degrees of freedom to each side of the GSTC boundary. A closed boundary within the scattered field domain is chosen, and the magnetic field is derived from FEM electric field solutions on it. By combining the electric and magnetic field data with Love's equivalence principle, the far-field scattering pattern of the RIS is accurately calculated, providing insights into RIS performance in realistic operating conditions.

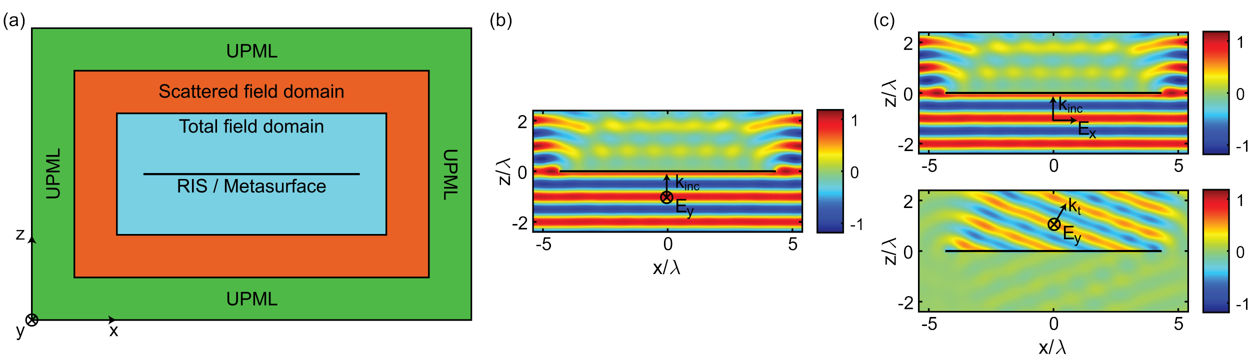

Figure 1: Bianisotropic RIS modeling with FEM and GSTC for a set of two field transformations: (a) 2D geometry of domains, (b) perfect absorption of a y-polarized incident plane wave (first transformation), and (c) anomalous full transmission at $\theta_t = 30^o$ with polarization rotation of a x-polarized incident plane wave (second transformation).

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