

A Time-Domain Method of Auxiliary Sources for Analyzing Transient Electromagnetic Interactions With GSTC-Modeled Metasurfaces

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Abstract—This article presents a time-domain (TD) formulation for modeling the transient electromagnetic (EM) response of 2-D metasurfaces using the method of auxiliary sources (MAS) combined with the generalized sheet transition condition (GSTC). In the proposed approach, the frequency-domain (FD) impedance-type GSTC is transformed into a causal, convolution-based TD representation and integrated within the MAS formulation. The method supports both TM_z and TE_z polarizations and accommodates general transient excitations, including pulsed plane waves and localized sources. Numerical experiments are presented for several representative cases—anisotropic graphene, black phosphorus (BP), and an artificial Lorentzian metasurface—demonstrating the method’s accuracy, stability, and versatility. Validations against both an FD MAS solver and full-wave simulations performed in commercial software confirm the correctness of the results, establishing the proposed TD–MAS–GSTC formulation as an efficient meshless tool for broadband TD analysis of metasurfaces.

Index Terms—Anisotropic graphene, black phosphorus (BP), generalized sheet transition conditions (GSTCs), Lorentzian metasurfaces, metasurfaces, method of auxiliary sources (MAS), time-domain (TD) electromagnetics (EMs), transient analysis.

I. INTRODUCTION

TIME-DOMAIN (TD) electromagnetics (EMs) has become increasingly important owing to a broad range of applications in radar systems [1], [2], geophysical exploration [3], [4], nondestructive testing [5], and biomedical imaging [6]. In recent years, it has also emerged as a powerful tool for investigating EM metasurfaces—2-D arrays of subwavelength features designed to control the behavior of EM waves [7], [8]. TD modeling of such structures is of growing relevance, as metasurfaces need to be designed for broadband and transient wave manipulation in applications like dynamic beam steering [9], pulse shaping [10], and temporal modulation [11], [12]. TD techniques are advantageous in this context, as they rely on short pulses exciting a wide frequency range, enabling the broadband response of a metasurface to be captured in a single simulation or experiment. The pulse duration

governs the spectral bandwidth, with shorter pulses yielding broader frequency coverage; this is essential for analyzing metasurfaces under realistic, time-varying excitations.

A broad range of numerical techniques have been proposed for solving TD EM problems [13], encompassing applications from transient scattering to the modeling of dispersive and anisotropic materials. Among the most established approaches, the finite-difference TD (FDTD) method remains a popular choice owing to its straightforward formulation and ability to capture broadband dynamics in complex geometries [14], [15]. The TD finite element method (TD-FEM) represents another mature option and is widely available in commercial solvers such as COMSOL Multiphysics [16]. Additional alternatives include Galerkin-based TD formulations [17], [18], as well as TD surface- and volume-integral-equation methods [19], [20], all of which have been extensively developed for transient EM analysis. However, these schemes typically require volumetric or surface meshing, which can lead to significant computational overhead—particularly when modeling electrically thin, spatially dispersive layers such as metasurfaces. The method of auxiliary sources (MAS) [21], [22], also referred to as the method of fundamental solutions (MFS) [23], [24], or the source model technique (SMT) [25], [26], offers a meshless alternative circumventing this limitation. It has demonstrated adequate accuracy and efficiency in TD modeling of 2-D EM structures [27], [28], [29], [30]. More recently, a TD-MAS implementation was developed incorporating the standard impedance boundary condition (SIBC) in [31], and the impedance matrix boundary condition (IMBC) in [32], providing foundations for analyzing more general metasurfaces.

The *generalized sheet transition condition* (GSTC) gives a rigorous theoretical framework for modeling metasurfaces by relating the discontinuities of the tangential EM fields across an infinitesimally thin sheet to its effective electric and magnetic surface susceptibilities [33]. With this approach, a physically thin but volumetric metamaterial layer is replaced by an equivalent zero-thickness sheet, reducing modeling complexity and avoiding the dense meshing requirements typically associated with volumetric representations. The GSTC framework has been extensively implemented in the frequency domain using several numerical schemes, including the finite element method (FEM) [34], integral equation methods [35], [36], and the MAS [37], for planar and cylindrical geometries. In parallel, TD GSTC-based techniques have also been developed—most notably using the FDTD method [38], [39],

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