

Coupled Solution of Time-Domain Volume Integral and Hydrodynamic Equations for Analysis of Scattering from Nanostructures

S. Celis Sierra⁽¹⁾, M. Khamitova⁽¹⁾, D. Aibek Uulu⁽²⁾, R. Zhao⁽³⁾, and H. Bagci⁽¹⁾

⁽¹⁾ Electrical and Computer Engineering (ECE) Program
Computer, Electrical, and Mathematical Science and Engineering (CEMSE) Division
King Abdullah University of Science and Technology (KAUST)
Thuwal 23955-6900, Saudi Arabia

⁽²⁾ Department of Cyber Security
Light Academy College of Engineering, Bishkek, Kyrgyzstan

⁽³⁾ School of Electronic Science and Engineering
University of Electronic Science and Technology of China (UESTC), Chengdu, China

Plasmonic nanostructures are widely used in various applications of engineering because of their ability to confine electromagnetic fields within subwavelength dimensions. This field confinement occurs on the surface of a metallic nanostructure as result of the strong interaction between electromagnetic fields and free conduction electrons of the metal (S. A. Maier, 2007, Springer, New York). In the ultraviolet frequency regime, this interaction cannot be accurately modeled using the standard constitutive relations that are valid at the lower frequencies. More specifically, free electrons within a metal exhibit nonlocal behavior, rendering the classical Drude model inadequate for describing the electron motion (F. Forstmann and R. R. Gerhardt, 1986, Springer, Heidelberg). This nonlocal response of free electrons can be modeled as collective oscillations of an electron gas using the hydrodynamic equation (HDE) (N. A. Mortensen, *Phot. Nanostr.*, 11, 303-309).

Transient electromagnetic field interactions on a metallic nanostructure can be accurately described by the coupled system of the time-domain HDE and the time-domain Maxwell equations. Several numerical methods have been proposed to solve this coupled system of equations: finite-difference time-domain (FDTD) method (M. Fang, et al., *IEEE J. Multiscale Multiphysics Comput. Tech.*, 2017, 2, 194-201), discontinuous Galerkin time-domain (DGTD) method (N. Schmitt, et al., *J. Comput. Phys.*, 2018, 373, 210-229), and the hybrid DGTD and time-domain finite element method (DGTD-TDFEM) (A. C. Gungor, et al., *IEEE Trans. Magn.*, 2021, 57, 1-5). These differential equation solvers require the entire computation domain to be discretized, and approximate absorbing boundary conditions (ABCs) to be enforced on the boundaries of this computation domain. These requirements significantly increase the computational cost of these solvers, especially when a high level of accuracy is desired in the solution.

To overcome these limitations, one can couple the HDE with surface integral equations (SIEs) (X. Zheng, et al., *IEEE Trans. Antennas Propag.*, 2018, 66, 4759-4771) or volume integral equations (VIEs) (D. A. Uulu, et al., *IEEE Trans. Antennas Propag.*, 2023, 71, 3418-3429). The formulation of the coupled SIE-HDE requires the derivation of a new Green function for every type of boundary condition enforced by the HDE for the free electron polarization current, while also requiring the nanostructure to have homogeneous or piece-wise homogeneous material properties. Coupled VIE-HDE formulation does not suffer from these limitations, however this formulation is developed only in frequency domain.

In this study, the frequency-domain VIE-HDE solver is extended to time-domain. More specifically, time-marching schemes are formulated and developed to solve the coupled system of the time-domain VIE and the time-domain HDE. Use of explicit and implicit time updates are investigated for efficient coupling of these two equations with different time scales. Numerical examples will be presented to demonstrate the accuracy and validity of these time-marching schemes in analyzing scattering from composite nanostructures.