Butterfly-Accelerated Solution of Coupled Volume Integral and Hydrodynamic Equations

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In recent years, advancements in plasmonic devices have enabled the localization of electromagnetic fields at subwavelength scales, contributing to breakthroughs in various scientific and engineering fields (J. C. Ndukaife, et al., ACS Nano, 2014, 8, 9, 9035–9043). These structures are often made of metals and their electric properties are typically represented by the classical Drude model (S. A. Maier, 2007, Springer, New York). As the size of the plasmonic structures approaches the nanoscale, the classical Drude model falls short in explaining the collective movement of free electrons in metals. The interaction between moving charges and the electromagnetic fields can be described by a coupled system of the Maxwell and hydrodynamic equations (X. Zheng, et al., IEEE Trans. Antennas Propag., 2018, 66, 9, 4759–4771).

To numerically solve the coupled system of Maxwell and hydrodynamic equations, discontinuous Galerkin time-domain schemes (N. Schmitt, et al., 2016, J. Comput. Phys, 316, 396-415) and finite element methods (K. R. Hiremath, et al., J. Comput. Phys., 2012, 231, 17, 5890–5896) have been developed. However, differential equation solvers require the discretization of the whole computational domain and the inclusion of error-inducing artificial absorbing boundaries. To avoid these limitations, the combined solution of volume integral with hydrodynamic equations (VIHDE) has recently been proposed (D. A. Uulu, et al., IEEE Trans. Antennas Propag., 2023, 71, 4, 3418-3429). Above the plasma frequency of a given material, however, the solution of the coupled VIHDE system requires very dense discretization, resulting in a large number of unknowns and, thereby, a large memory requirement and computational cost. Additionally, at these frequencies, the coupled VIHDE system's iterative solution exhibits slow convergence, requiring excessive time to reach the desired error tolerance.

This study presents a butterfly-accelerated solution of the coupled VIHDE. The proposed scheme compresses the dense matrix blocks in the VIHDE system via various butterfly-enhanced hierarchical matrix schemes. Then, the compressed representations are used to perform fast matrix-vector multiplication during the iterative solution of the coupled VIHDE. By doing so, the scheme drastically reduces the computational time and memory requirements of the combined solution of the VIHDE. The accuracy and efficiency of the proposed scheme will be demonstrated via its application to the analyses of finely discretized plasmonic structures at high-frequencies. Furthermore, preconditioning strategies leveraging butterfly-based inversion of the system matrices will be discussed during the talk.