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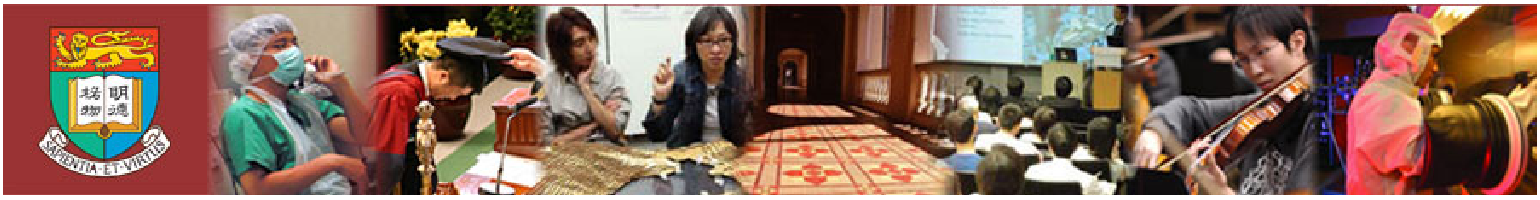

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Recent Development of Surface Integral Equation Solvers for Multiscale Interconnects and Circuits

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***Abstract*—This paper presents a brief review and recent development of surface integral equation solvers for multiscale interconnects and circuits modeling. As the future production processes down to 5 nm and the operating frequency increases, both multi-scale and large-scale natures should be taken into account in the electromagnetic simulations. Fast, efficient, stable, and broadband integral equation based solvers become indispensable when millions or tens of millions of unknowns might be involved in the simulation of the integrated circuit. Recent progress and our latest researches in the development of broadband fast electromagnetic solvers will be demonstrated.**

***Keywords*—computational electromagnetics, integral equation, interconnects, multiscale, circuit modeling.**

I. INTRODUCTION

Following the trend of production process, the Intel's manufacturing cadence has suggested 5 nm product will arrive in 2019, while the previously announced 20nm technologies has been extended to 14 nm for the next-generation products. Hence, the simulation and modeling of on-chip interconnects and circuits become more challenging, as the operating frequency and the number of unknowns keep increasing [1], [2]. A typical on-chip interconnect structure is shown in Fig. 1. Previous quasi-static analysis tools are inadequate as the frequency increases, where both the wave physics and the circuit physics inherent need to be captured in the electrical design of computer-chip design [3]. The surface integral equation (SIE) method has proven to be a powerful tool in electrodynamic analysis. It usually requires less unknowns than volume discretization methods. However, the traditional SIE methods have a well-known breakdown problem, when it applied to on-chip circuit analysis. The dimensions of most interconnect, packaging, and on-chip circuit elements are just a tiny fraction of the wavelength. This will lead to two imbalanced frequency-dependent potentials in the formulation of integral equations, which is so-called low-frequency breakdown problem. In the past years, a lot of research efforts have been carried out in order to make the fast solvers stable from static to microwave ranges [4]-[11].

II. METHODS BASED ON HELMHOLTZ DECOMPOSITION

To overcome the low-frequency breakdown problem and capture the physics correctly, loop-tree or loop-star basis based on Helmholtz decomposition are usually used together with proper frequency normalization and basis rearrangement schemes [4]. By doing so, the electrostatic and magnetostatic physics can be well separated. However, the loop-tree based method is always burdened by the need to search for loops. It will be very difficult for complicated geometries which have many inductive long loops. At higher frequencies, the wave effects across the whole structure also cause the representation of loops and trees physically improper [5].

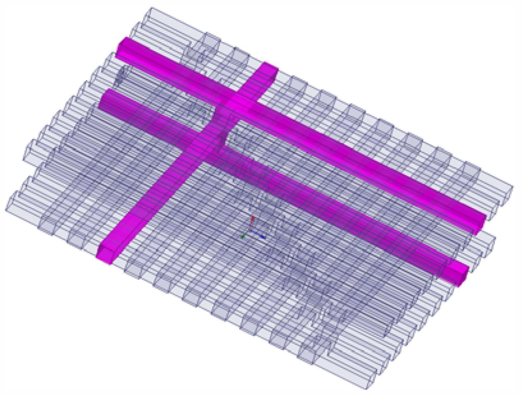

Fig. 1. A typical three dimensional on-chip interconnect structure.

III. AUGMETNED EFIE-BASED METHODS

Recently, an augmented electric field integral equation (A-EFIE) was proposed to model large-scale and complex multiscale structures [6]. Both the charge and the current are considered as unknowns to avoid the frequency imbalance in the original EFIE formulation. By extending A-EFIE method with augmented equivalence principle algorithm (A-EPA) [7]-[8], the multi-scale physics of complex structures can be effectively modeled. Fig. 2(a) shows the simulated current distribution for a differential via-hole structure. A pair of coupled striplines start from the upper layer, go through the via-holes to the second layer, and then return to the first layer. This kind of differential vias with holes are frequently used in integrated circuits. Another example is to simulate and model a packaging ball grid array (BGA), as shown in Fig. 2(b). Due to the geometry similarity of all the balls, A-EPA with A-EFIE

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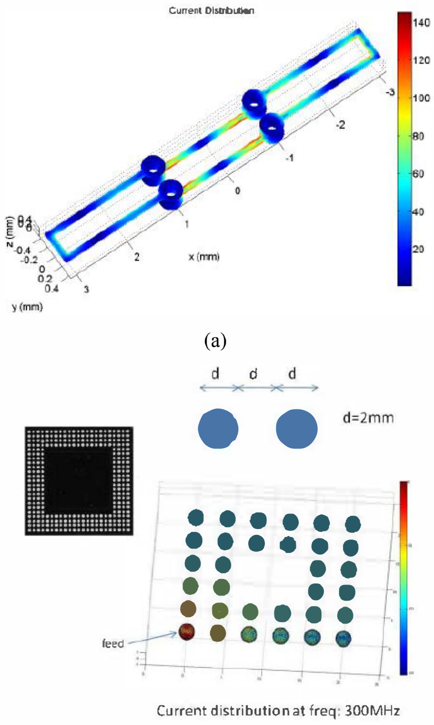


(a)

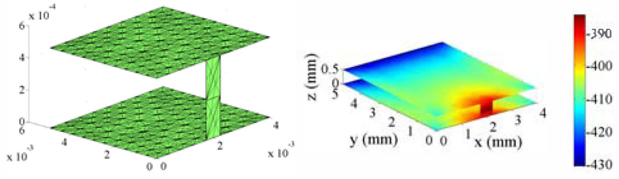
(b)

Fig. 2. (a) Current distribution of via-hole structure. (b) BGA ball array analysis: top view, geometry specification and current distribution [8].

only one scattering operator is solved and reused for coupling interactions.

IV. CALDERÓN PROJECTION METHODS

However, we observed that A-EFIE loses accuracy of current for certain capacitive problems. Hence, the perturbation method was further proposed as a remedy [9]. Similar inaccuracy problem also exists in Calderón projection based methods. As detailed in [10], the Calderón multiplicative preconditioner (CMP) was proposed based on the self-regularizing property of the EFIE operator and Calderón identities, which results in a well-conditioned second-kind Fredholm integral equation operator. With the help of perturbation method, CMP-EFIE can compute the electric currents on both closed and open surfaces accurately at very low frequencies [11]. As shown in Fig. 3(a), a parallel-plate capacitor is discretized into 394 triangle patches, equivalent to 553 internal edges. A delta-gap voltage source is assigned in the middle of the strip connecting the two plates. Fig. 3(b) shows the current distribution at 10^{-11} Hz on the capacitor surface. Without the perturbation method, the magnitude of the solved current is wrong and the extracted capacitance diverges from the right value at 0.4716 pF. Because the frequency order of the capacitive current is always higher than inductive current. With the perturbation method, the electric current at different frequency orders can be accurately captured at arbitrarily low frequencies.



(a) (b)

Fig. 3. (a) Geometry of the capacitors. Unit: m. (b) Surface current density at 10^{-11} Hz by the CMP-EFIE with perturbation method. Unit of current density: A/m [11].

V. CONCLUSION

In this paper, we briefly reviewed our progress in developing integral equation based solvers for multi-scale on-chip circuit modeling. The proposed methods can solve the complicated circuit structure over millions of unknowns over a wide frequency range efficiently and accurately.

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