

# Session 1A4

## Robust and Efficient Electromagnetic Solutions for Large-scale Problems

On the Frequency Barrier of Surface Integral Equations from a Circuit Point of View	46
<i>Lijun Jiang, Albert E. Ruehli, .....</i>	
Fast Integral Equation Solution Techniques for Planar-3D Structures in Multilayered Media	47
<i>Thomas Vaupel, .....</i>	
A Surface Absorber Approach with the Boundary Element Method to Terminate Nanophotonic Devices	48
<i>Lei Zhang, Steven G. Johnson, Jacob K. White, .....</i>	
A Hybrid PMM-MOM Method for Analyzing Electrically Large and Finite Frequency Selective Surface	50
<i>Jianxun Su, Xiaowen Xu, .....</i>	
The Discontinuous Galerkin Method for Highly Inhomogeneous Media	51
<i>Christoph Schwarzbach, Eldad Haber, .....</i>	
Multi-region Pseudospectral Time Domain (MR/PSTD) Modeling of Electromagnetic Wave Propagation	52
<i>Lanbo Liu, Benjamin Barrowes, Zhao Zhao, Zijian Liu, .....</i>	
Simplified Integral Equation Modeling of Low-frequency Electromagnetic Scattering from a Resistive Underground Target	53
<i>Shaaban Ali Bakr, Trond Mannseth, .....</i>	
A Three-dimensional Inversion Approach for Cross-well Electromagnetic Field Data	54
<i>Jianguo Liu, Guangdong Pan, Aria Abubakar, Tarek M. Habashy, Mikhail Zaslavsky, Vladimir L. Druskin, .....</i>	
Computation of Casimir Forces in Arbitrary Geometries and Materials via the Finite-difference Time-domain Method	55
<i>Alejandro W. Rodriguez, Alexander P. McCauley, John D. Joannopoulos, Steven G. Johnson, .....</i>	
Spectral Element Method for 2-D and 3-D Photonic Crystals with Dispersive and Anisotropic Materials	57
<i>Ma Luo, Qing Huo Liu, .....</i>	

## On the Frequency Barrier of Surface Integral Equations from a Circuit Point of View

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**Abstract**— The failure to provide an accurate low frequency and even DC solution has been a key issue of research for integral equation based formulations. Loop-star techniques were conceived to extend the low frequency limit of SIEs such as EFIE methods. It has successfully improved the low frequency conditioning, but requires complicated graph oriented algorithm. In addition, this approach does not work for DC.

At the same time, the Partial Element Equivalent Circuit (PEEC) approach has been used to solve similar electromagnetic problems for packaging and interconnect applications. It uses the Modified Nodal Analysis (MNA) circuit solver formulation, which is employed in most of Spice circuit solvers. PEEC+MNA not only provide a well conditioned low frequency solution, but also a dc solution. The attached figure shows an equivalent circuit for this simplest PEEC model. Both PEEC and EFIE approaches separates the MoM impedance  $Z_{ij}$  into a separate inductance and a capacitance part for the electromagnetic solution. In fact, most important low frequency issues can be observed from this simple circuit. The capacitances will represent open circuits at low frequencies such that the MoM impedances will go to infinity. EFIE mixes the capacitance contribution with that of the inductance, which causes the underflow of the inductance effects. The PEEC method uses Kirchoff's Current Law (KCL) in MNA to enforce the continuity of the current. Both nodal potentials and currents are included as unknowns in PEEC. Hence, PEEC demonstrates much better conditioning than EFIE at the low frequency regime (not DC).

For a meaningful DC solution, two conditions are necessary. First, the losses must be included in the model. This is symbolized by the resistance in series to the inductances. Clearly, at DC, the inductances will become short circuits and the remaining circuit only consists of resistive losses. Second, the solver formulation must be separate the capacitive and inductive circuit such that a solution can be found in spite of the open circuited capacitances. It corresponds the Helmholtz decomposition between the electric field and the magnetic field. For this reason, PEEC use the MNA approach in solving the equations. Again, the key issue is that both the currents and the potentials must be included as unknowns. EFIE completely breaks at DC due to the decomposition.

In the presentation we will include example solutions and matrix condition numbers to support the discussion. Also, we consider the use of RWG basis functions to show that the popular approach can be formulated such that some of the properties of the PEEC method can be inherited to improve EFIE, such as the Augmented EFIE developed by Qian and Chew.

