Physics-Intuitive Micro-Modeling Circuits (MMC) Inspired by PEEC Models for Emerging Electromagnetic Problems

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Abstract—**Many electromagnetic (EM) problems arise as emerging electronics develops, such as the significant increase of radiation and coupling effects, usage of complicated heterogeneous dielectrics and metasurfaces structures, and drastic growth of circuit size. To efficiently analyze these challenging EM problems, figure out the working mechanism, and inspire new design methods, the comprehensive theories of the physics-intuitive micro-modeling circuit (MMC) that are derived from the dedicated physically-meaningful partial element equivalent circuit (PEEC) models have been developed. This paper will present a review of these works.**

Keywords—Circuit Model, EM problems, Micro-Modeling Circuit (MMC), partial element equivalent circuit (PEEC)

I. INTRODUCTION

The partial element equivalent circuit (PEEC) is first derived by Dr. Albert E. Ruehli in 1973. It provides a comprehensive interpretation of the relations between circuit theory and field theory [1], which can be simulated simply by SPICE-like solvers for both time- and frequency-domain. PEEC has been successfully used for signal integrity analysis or field analysis in electronic systems with muticonductor arrangements. For the emerging electronic systems in the post-Moore law period, radiation and coupling effects increase significant, complicated heterogeneous dielectrics and metasurfaces structures are used, and circuit size increase drastically. Hence, the comprehensive theories of the physics-intuitive micro-modeling circuit (MMC) are derived from the PEEC models, which can efficiently analyze these challenging EM problems, figure out the working mechanism, and inspire new design methods. This paper will present a review of these works.

The generalized partial element equivalent circuit (GPEEC) model incorporating the complex-valued generalized inductance and real-valued capacitance is introduced first in [2][3], to which the radiation effect is not negligible. By employing the concept that the capacitor is defined by the electric potentials in a conservative field domain, it is proven that the imaginary part of the generalized complex inductance for a short dipole exactly reflects the radiation resistance of the dipole. More importantly, the radiation resistances in the GPEEC model are guaranteed to be passive [4], which solves the problem of negative self-radiation resistances in the traditional full-wave PEEC model.

Modern integrated circuit (IC) packaging for high-speed systems, dielectric resonance antennas (DRA), and reconfigurable intelligent metasurfaces involve heterogeneous unstructured dielectrics of finite size, which requires sophisticate sub-circuit to describe the unstructured dielectrics in conventional PEEC models. Hence, we developed both quasi-static PEEC models and fullwave PEEC models for 3D dielectric problems. First, we proposed the concise PEEC models via the quasi-static approximation, namely the quasi-static PEEC models [5][6], and the compact PEEC (c-PEEC) model [7]. For general heterogeneous problems, the passivity-guaranteed full-wave GPEEC [8] models are established based on the surface equivalence principles. By manipulating the periodic Greens' function with the concept in GPEEC, a full-wave periodic-GPEEC [9] and its corresponding quasi-static form [6] are proposed for modeling and designing metasurfaces in the form of two-dimensional (2D) periodic structures.

Since the PEEC model requires massive distributed partial RLC elements that depends on the mesh number, it will be both time- and memory-prohibitive to simulate PEEC model. Moreover, it is lack of physical intuition for design. Therefore, a unique and complete theory of micro-modeling circuits (MMC) is proposed [2][10]–[12], which can reduce the size of original PEEC models as small as the set criterion. Because MMC is derived based on the physics-based equivalent circuit transformation, it doesn't need any matrix inversion and can retain the correspondence to the physical layout, which solves two critical issues of the mathematic-based model order reduction (MOR) methods for large-scale EM problems. What's more, over 99% operations of MMC derivation are the outer product, which is very suitable to be accelerated by GPU parallel computation technique [13].

In order to speed up the signal integrity analysis of large-scale interconnect and packaging circuit, a passive quasi-static MMC [11], a fullwave MMC [4] and transient analysis methods of fullwave circuit [12] are developed. Usually, the model order of MMC is 10 times smaller the PEEC model, which can accelerate both time- and frequency-domain simulation by 1000 times. The superior efficiency of the MMC serves as a promising candidate to leverage artificial intelligence in solving inverse EM problems.

The MMC also paves a new way of understanding EM radiation problems and optimizing antenna design. Based on the physically-meaningful MMC model, it is discovered theoretically and validated experimentally in [14] for the first time that the radiation efficiency decisively depends on mutual radiated power associated with partial segments of the antenna. A circuital figure of merit for describing the total positive or negative mutual radiated power is introduced to quantify the measure. In addition, the MMC circuit is very flexible to connect external lumped elements. Therefore, it can well reveal the working mechanism of antennas utilizing external lumped elements and improve the design, such as the self-curing decoupling technique of MIMO antennas [15] and the characteristic mode manipulation technique for 5G wireless terminal antennas [16].

II. PEEC Models

A. *Generalized PEEC Models for Radiation Problems*

For radiation problem, the self-radiation resistances derived in the traditional full-wave PEEC model is negative, which will cause the failure of time-domain simulation. The negative self-radiation resistance only represents the partial radiation effect of the current flowing on one inductive mesh. Hence, we incorporate the radiation effect (imaginary part) of the complex-valued capacitance by its complex-valued generalized inductance [2][3]. It is proven that the imaginary part of the generalized complex inductance for a short dipole exactly reflects the radiation resistance of the dipole. More importantly, the radiation resistances in the GPEEC model are guaranteed to be passive [4]. The normalized passivity violation (NPV) factor [4] is defined to evaluate the passivity of two models for a multilayer interconnection as shown in Table I. As compared with PEEC model, the NVP of the radiation resistance in GPEEC model can be negligible, which is caused by numerical calculation and can be solved by the passivity enforcement method in [4].

TABLE I. NPVs of PEEC and GPEEC Models

Element matrix	PEEC model	G-PEEC model
C	0	0
M	0	1.52×10^{-5}
R in series with **M**	0	3.36×10^{-5}
R in series with **C**	0.612	N/A

B. *PEEC Models for Heterogeneous Dielectrics*

For EM problems involving heterogeneous unstructured dielectrics of finite size, the model size of the conventional PEEC model becomes large because the sophisticate sub-circuit to describe the unstructured dielectrics are used. The concise PEEC models via the quasi-static approximation, namely the quasi-static PEEC (QS-PEEC) models [5][6], and the compact PEEC (c-PEEC) model [7] are proposed. The quasi-static PEEC [5] that enforces the tangential null field condition in the null field regions can significantly reduce the number of unknowns of the traditional Surface-PEEC. Building upon this study, a novel null-field boundary integral equation (n-BIE) system is developed for the c-PEEC [7], which can effectively describe the heterogeneous integrated systems by using the conducting sub-circuit only. The model orders of S-PEEC model, QS-PEEC, and c-PEEC are compared in Table II.

TABLE II. Comparision of Model Orders
(M_C, M_D, N_C, and N_D are number of branches on conductor, branches on dielectric, nodes on conductor, and nodes on dielectrics)

No. of	S-PEEC	QS-PEEC	c-PEEC
Inductive branches	$M_C + 2M_D$	M_C	M_C
Capacitive branches	$N_C + 2N_D$	$N_C + N_D + M_D$	N_C
Unknown currents	$M_C + 2M_D$	$M_C + M_D$	M_C
Unknown potentials	$N_C + 2N_D$	$N_C + N_D$	N_C
Unknown voltages	0	M_D	0
Total unknowns (n)	$n_S = N_C + M_C + 2N_D + 2M_D$	$n_{QS} = N_C + M_C + N_D + 2M_D$	$n_C = N_C + M_C$

For general heterogeneous problems, the passivity-guaranteed full-wave GPEEC [8] models are established based on the surface equivalence principles. As validated in [8], the NPV of the resistance in the S-PEEC is 1, meanwhile, that of the GPEEC in [8] is only 9.43×10^{-4}. PEEC model is also efficient on solving metasurfaces in the form of two-dimensional (2D) periodic structures [6][9]. By proposing a novel quasi-static PGF that approximates the full-wave PGF by a second-order polynomial in frequency, the quasi-static PEEC model [6] shows excellent efficiency in modeling EM problems that require swapping in the frequency- and time-domains. This is because the coefficients of the proposed quasi-static PGF for both propagating and evanescent modes are frequency-independent.

III. Micro-Modeling Circuits

A. *MMC for Accelerating Signal Integrity Analysis*

The modern interconnections requires more layers and more complicate structures, whose model order significantly increase. Analyzing their signal integrity with cubic computation complexity becomes both time and memory prohibitively. Therefore, the theory of a concise MMC model, including a passive quasi-static MMC [11], a fullwave MMC [4] and transient analysis methods of fullwave circuit [12], are developed. When comparing the traditional model order reduction (MOR) method, the MMC doesn't need any matrix inversion because it is derived based on a physics-inspired circuit transformation as shown in Fig. 1 to absorb insignificant nodes rather than a mathematic equivalent circuit transformation. This physics-based transformation brings another superiority. the dominant arithmetic operation deriving MMC is the outer product, which is very suitable to be speeded up by GPU parallel computation.

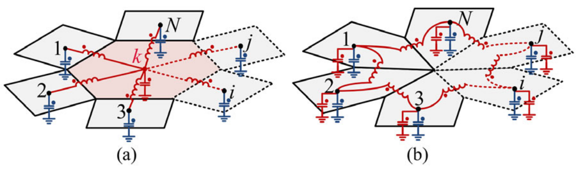

Fig. 3. Physics-inspired circuit transformation for absorbing an insignificant node . a) Meshes and circuit prior to transformation. b) Equivalent meshes and circuit posterior to transformation.

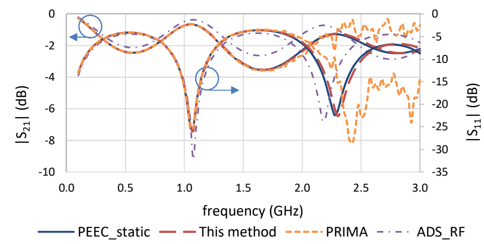

Fig. 1. Simulated S-parameter obtained by PEEC, MMC, PRIMA, and ADS software.

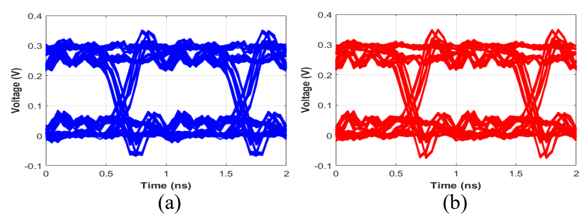

Fig. 2. Simulated eye-diagram obtained by PEEC and MMC. a) eye-diagram obtained by PEEC. b) eye-diagram obtained by MMC.

Usually, the model order of MMC is 10 times smaller than PEEC model. For a multilayer interconnect in [11], the number of nodes and inductor branches are reduced from 7542 and 12120 to 859 and 1711, respectively. Fig 2 and 3 compares the simulated S-parameter and eye-diagram obtained by PEEC and MMC. The frequency- and time-domain simulation time are decreased from 1598 min and 14942 min to 4 min 39 s and 34 min 15 s, respectively.

B. MMC for Antenna Designs

The MMC also paves a new way of understanding EM radiation problems and optimizing antenna design. It is discovered theoretically and validated experimentally in [14] for the first time that the radiation efficiency decisively depends on mutual radiated power associated with partial segments of the antenna. The ratio of self-radiated power to total conductor loss for every segment are same positive value, which is defined as factor α. But the ratio of mutual radiated power to total conductor loss for every pair of segments can be positive or negative, which is evaluated as factor β. The distribution of mutual radiated power is visualized as holographic radiation diagram.

Take a commonly used loop antenna (design 1) in Fig. 4(a) as an example. Its holographic radiation diagram in Fig. 4(c) shows the negative mutual radiated power in blue color is comparable with the positive mutual radiated power in red color. Therefore, its simulated and measured radiation efficiency is only 66% and 57%. Then the loop antenna is revised based on the proposed principle to reduce the negative mutual radiation power as design 2 in Fig. 4(b). Its holographic radiation diagram is plotted in Fig. 4(d), which indicates that the positive mutual radiation power become dominant. Hence, the simulated and measured radiation efficiency increase to 99% and 91%.

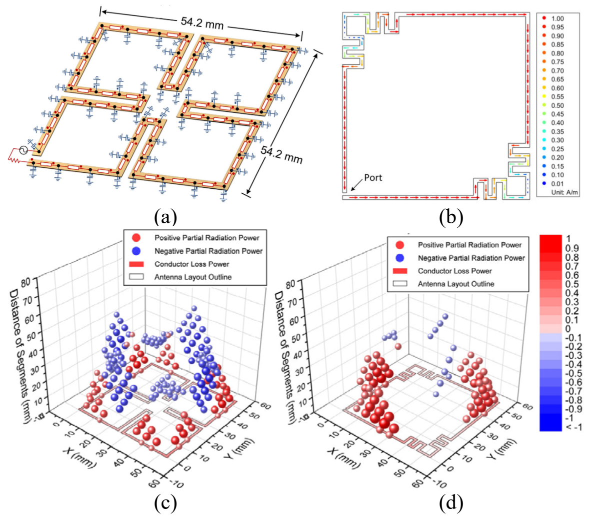

Fig. 4. Loop antena structures and their holographic radiation diagram. a) loop antenna design 1. b) loop antenna design 2. c) holographic radiation diagram of design 1. d) holographic radiation diagram of design 2.

Since MMC can well reveal the working mechanism of antennas utilizing external lumped elements, it can also be used to improve the antenna design by the self-curing decoupling technique of MIMO antennas [15] and the characteristic mode manipulation technique for 5G wireless terminal antennas [16].

IV. Conclusion

In summary, a number of PEEC models and the concise MMC models are rigorously developed while retaining the physical meaning. These models can accurately analyze emerging problems with complicate EM effects or inhomogeneous unstructured dielectrics, and significantly speed up large-scale problems. Most importantly, their physics-intuitive characteristics can provide deep physical insights to understand the mechanism of EM problems, further promoting new methods for electronic design.

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