Advanced Multi-Level Electromagnetic Modeling and Design with MEFiSTo

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Abstract: This paper describes three advanced modeling features of the time-domain EM simulator MEFiSTo-3D. These include a general boundary modeling framework for coupled field/circuit modeling, a text-based import/export and external control capability enabling Space Mapping and surrogate generation for fast optimization, and an inter-cell modeling framework for complex materials such as metamaterials.

Keywords: MEFiSTo Electromagnetic Simulator, Field-Based Design, Circuit Embedding, Optimization, Space Mapping, Metamaterials, Neural Network Surrogates, Optimized Prony Predictors.

1. Introduction

MEFiSTo-3D is a Multipurpose Electromagnetic Field Simulation Tool based on the Transmission Line Matrix (TLM) method [1-2]. Its numerically robust, high-performance TLM engines provide second-order accuracy and have superior dispersion properties. TLM uses an unconditionally stable scattering formulation rather than finite differences to model Maxwell’s equations such that electric and magnetic fields remain fully coupled down to DC. Field data can be co-processed on-the-fly and visualized in real solution time, or post-processed. MEFiSTo has a number of features that allow it to work in synergy with other software tools, such as MATLAB, SPICE, SciLab, NeuroModeler and Space Mapping Framework (SMF). This opens a considerable range of multi-level modeling, design and optimization capabilities that make MEFiSTo a truly outstanding software tool for advanced research, development and education. In this paper, the most important features will be described and demonstrated by typical applications.

The three key features that allow MEFiSTo to interact with other software tools and programs in a seamless fashion are: a) the specific boundary modeling framework, b) the parameterization of the geometric modeler, and c) the text-based import/export capability associated with the batch command feature.

2. Multi-Level Simulation Through TLM Boundary Framework of MEFiSTo

The TLM boundary framework is a general procedure that allows a TLM mesh to be terminated by subdomains of arbitrary time or frequency behavior [3-4]. Fig. 1 demonstrates a number of ways in which a TLM boundary cell can interact with an adjacent boundary, device, or subdomain. A TLM impulse traveling from the boundary node towards the boundary will cause one or more impulses to be returned. If the boundary is non-dispersive, only a single impulse is returned into the TLM cell, so the boundary is characterized by a single real number (impulse reflection coefficient). However, the boundary response can be a sequence of impulses, indicating dispersive as well as nonlinear properties of the boundary. This can be the result of a regular or a recursive convolution, or the response computed by a SPICE or MATLAB model of a circuit, device or material.

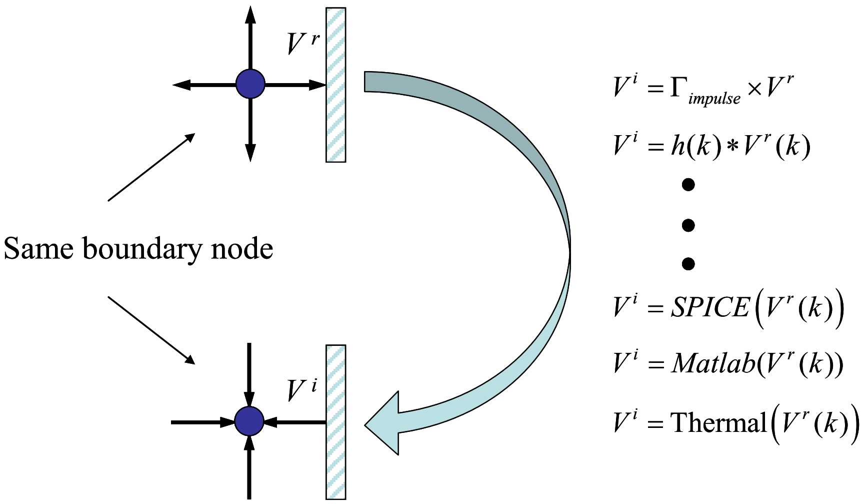


Fig. 1 TLM Boundary Modeling Framework of MEFiSTo.

When the boundary is a perfect conductor, its impulse reflection coefficient $\Gamma_{impulse}$ is –1; in this case, $V^i = -V^r$. In the cases of lossy and super-conducting boundaries, the function $f(V^r(k))$ can represent finite difference equations that approximate the differential equations governing the boundary response, or a stored boundary impulse response $h(k)$. The framework can also model a closed surface that contains a lumped or distributed device. In this situation, $\boldsymbol{f}(V^r(k)$ models a device equation described either by an internal function of MEFiSTo or by an external device solver such as SPICE or MATLAB.

Two simulation examples demonstrate the versatility of this TLM boundary framework. Fig. 2 shows the transient response of an amplifier embedded into a 3D microstrip test jig. The amplifier is modeled by SPICE, and the surrounding microstrip is modeled by TLM. Both subdomains are connected in real time by the boundary framework. The second example is a Gunn diode oscillator in which both the active device and the dispersive waveguide load have been realized using the TLM boundary framework. The Gunn diode has been modeled by a nonlinear finite difference device equation, while the wideband dispersive waveguide absorbing boundary is modeled through convolution of the incident impulses with the impulse response of a semi-infinite rectangular waveguide.

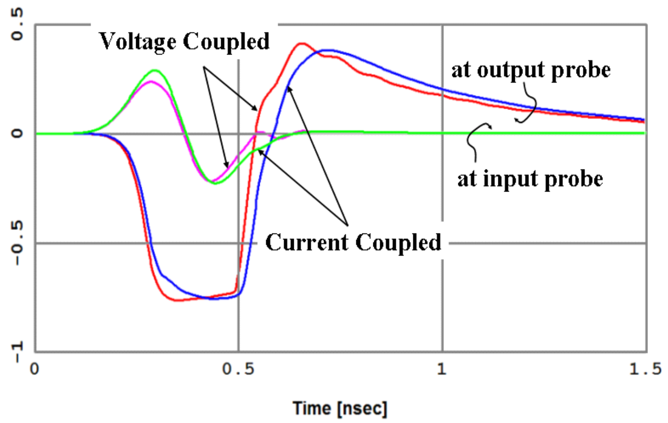


Fig. 2 Transient response of a microstrip amplifier (Coupled SPICE/TLM simulation with MEFiSTo).

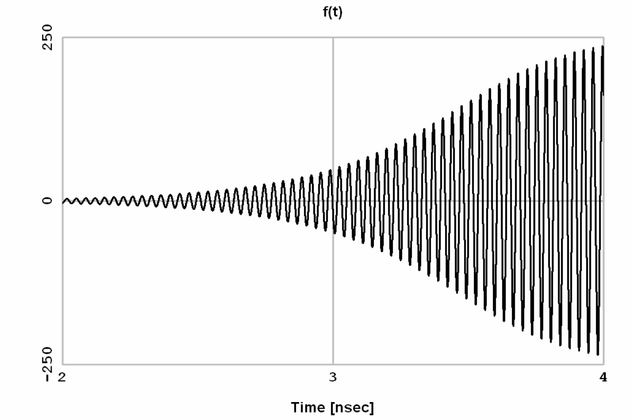


Fig. 3 Start-up of a waveguide Gunn oscillator (Build-in MEFiSTo active device model and waveguide convolution ABC).

3. Field-Based Optimization and Surrogate Model Generation with MEFiSTo

A key requirement for field-based optimization and surrogate model generation is the ability to parameterize the geometry and electromagnetic properties of a structure, and to control these parameters with an external program, preferably through a text-based interface. Fig. 4 shows a typical scenario of field-based optimization in which MEFiSTo is controlled by a MATLAB script invoking the MATLAB Optimization Toolbox [5-6].

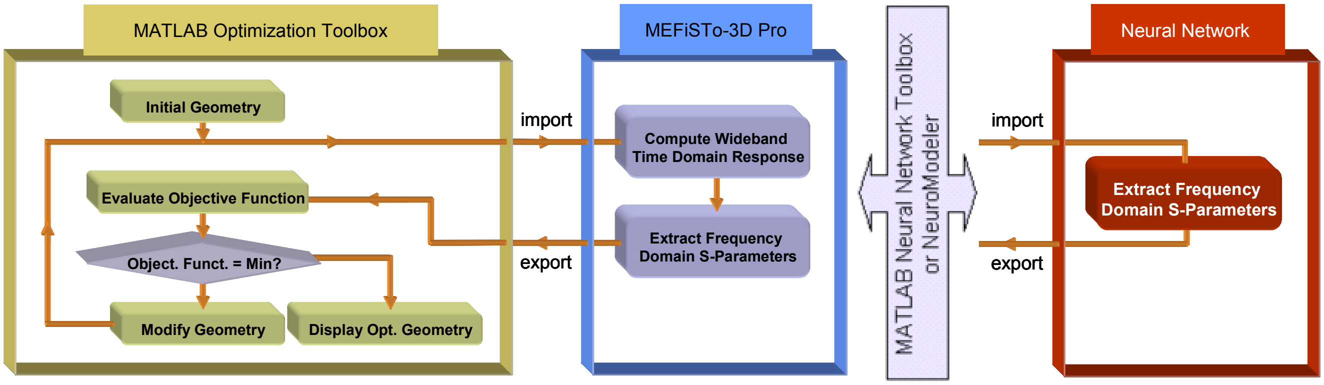
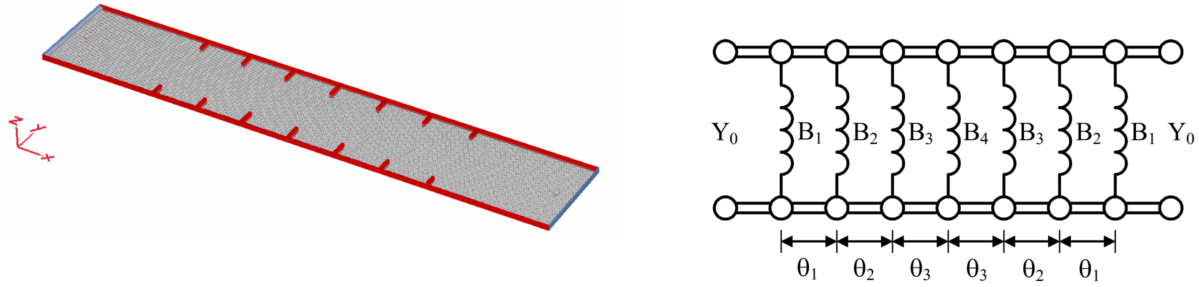


Fig. 4 Field-based and surrogate-based optimization scenario. Parameter values and simulation results are exchanged between the MATLAB Optimization Toolbox and MEFiSTo through the text-based import/export feature of MEFiSTo, while MEFiSTo is controlled by MATLAB through batch commands. Significant speed-up is achieved by using a Neural Network surrogate generated with MEFiSTo.

The direct optimization using MEFiSTo as a finely discretized field model is only practical for small- to medium-sized structures where the time required for a full analysis does not exceed a few minutes. For larger optimization problems it is preferable to create a parameterized surrogate model, either in the form of a neural network model, an equivalent lumped element network model, or a coarse field model requiring significantly reduced computational resources. The first option involves the creation of a neural network using the MATLAB Neural Network Toolbox or NeuroModeler [7], which is trained using field responses generated with MEFiSTo. The creation of a surrogate model in the form of an equivalent network or a coarse field model involves so-called Space Mapping [8-9]. In this approach, a mapping or projection is established between the parameters of the coarse and fine models in such a way that for a desired range of parameter values a suitably scaled coarse model – the surrogate - can be substituted for the fine model, yielding the optimal results in a fraction of the time.



(a) (b)

Fig. 5 Space Mapping optimization of a six-section H-plane waveguide filter [9].
a) Fine MEFiSTo field model, b) Coarse MATLAB model in the form of a ladder network.

In all cases of surrogate modeling, MEFiSTo can be used as the fine model to generate a validation data base under the control of the program that generates the surrogate model. Fig. 5a shows an example, the fine MEFiSTo model of a six-resonator H-plane waveguide bandpass filter. The discretization of this model is so fine that the mesh appears as a uniformly gray area. Fig. 5b shows the coarse model of the filter that consists of eight sections of transmission lines and seven shunt susceptances. Once the mapping between the geometrical parameters of the structure and the network parameters of the surrogate have been established, the coarse model can be optimized in a time that is several orders of magnitude shorter than direct field optimization. The optimal parameters of the fine model are then determined from the optimal coarse model parameters using the Space Mapping transformation.

4. Simulation of Complex Metamaterials using TLM Inter-Cell Framework Modeling

Research in metamaterials has opened exciting new engineering applications that require suitable modeling capabilities for development and design of novel components. Negative dielectric and magnetic constitutive parameters can be achieved over a wide frequency range by creating periodic transmission line structures with embedded series capacitors and shunt inductors [10-14]. It is thus natural to emulate such periodic structures by TLM networks and embed additional reactive elements into each TLM cell. The Inter-Cell Framework of MEFiSTo allows such a systematic embedding by introducing additional scattering networks at the boundaries between TLM cells, as shown in Fig. 6.

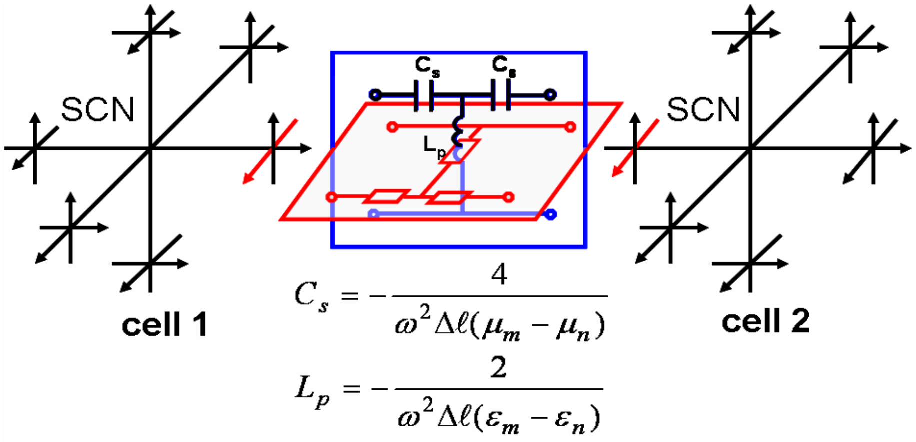


Fig. 6 Modeling of 3D metamaterial properties by reactive inter-cell networks inserted between TLM nodes. The inter-cell network produces additional scattering of impulses exchanged between neighboring TLM nodes. C_s and L_p are determined at the design frequency ω.

Fig. 7 demonstrates the application of this modeling feature. It shows the focusing of a 10 GHz monochromatic wave emitted by a Hertzian dipole placed in air at 5.5 mm from a 11 mm thick slab of metamaterial with $\mu_m = \varepsilon_m = -1$ (Pendry lens). The dipole is vertically polarized. The contours of the magnetic field tangential to the slab surface are shown in the azimuthal plane. The plasmon resonances along the metamaterial-air interfaces, and the focusing of the spherical wave by the Pendry lens are clearly visible. The dynamic display of the field distribution in the metamaterial provides considerable insight into the physical behavior of the material and allows to observe the transient build-up of the surface wave regime responsible for the sub-wavelength focusing properties of the planar metamaterial lens.

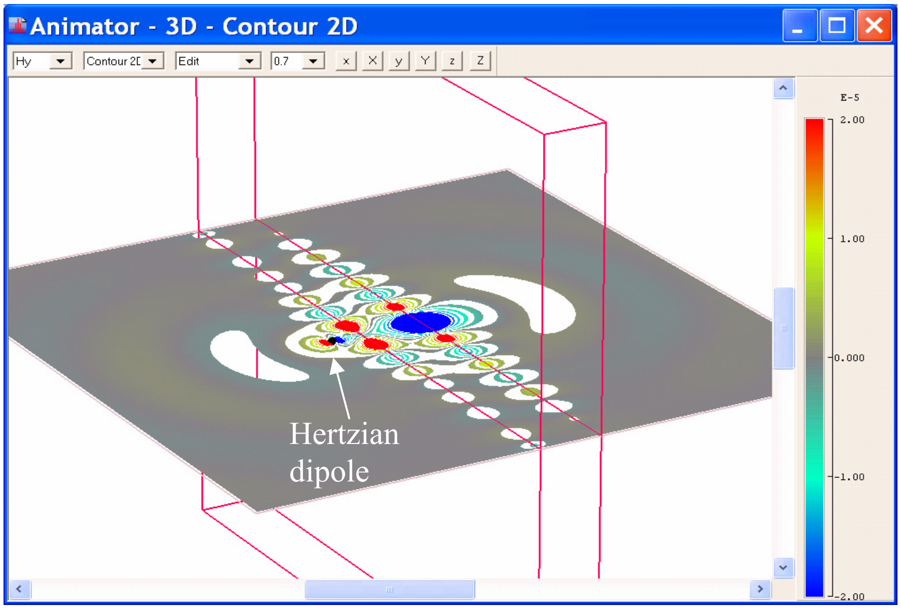


Fig. 7 A spherical 10 GHz wave is focused by a planar Pendry lens made of metamaterial with a refractive index of $n = -1$. MEFiSTo simulation using the 3D TLM Inter-cell modeling framework. (After [15].

5. Conclusions

Three advanced features of MEFiSTo EM Simulators have been described in this paper. The general boundary modeling framework for coupled field/circuit modeling, a text-based import/export and external control capability enabling Space Mapping and surrogate generation for fast optimization, and an inter-cell modeling framework for complex materials such as metamaterials, have been discussed and illustrated by typical simulation results. These features provide MEFiSTo, which is an autonomous EM CAD tool, with unprecedented interconnectivity with external simulation/data processing/control software. As a result, the user has considerable freedom to create a personalized, sophisticated modeling environment and to expand the range of modeling capabilities beyond the bounds of mainstream EM solvers with restricted user access. Relevant simulations will be run live during the presentation of the paper.

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