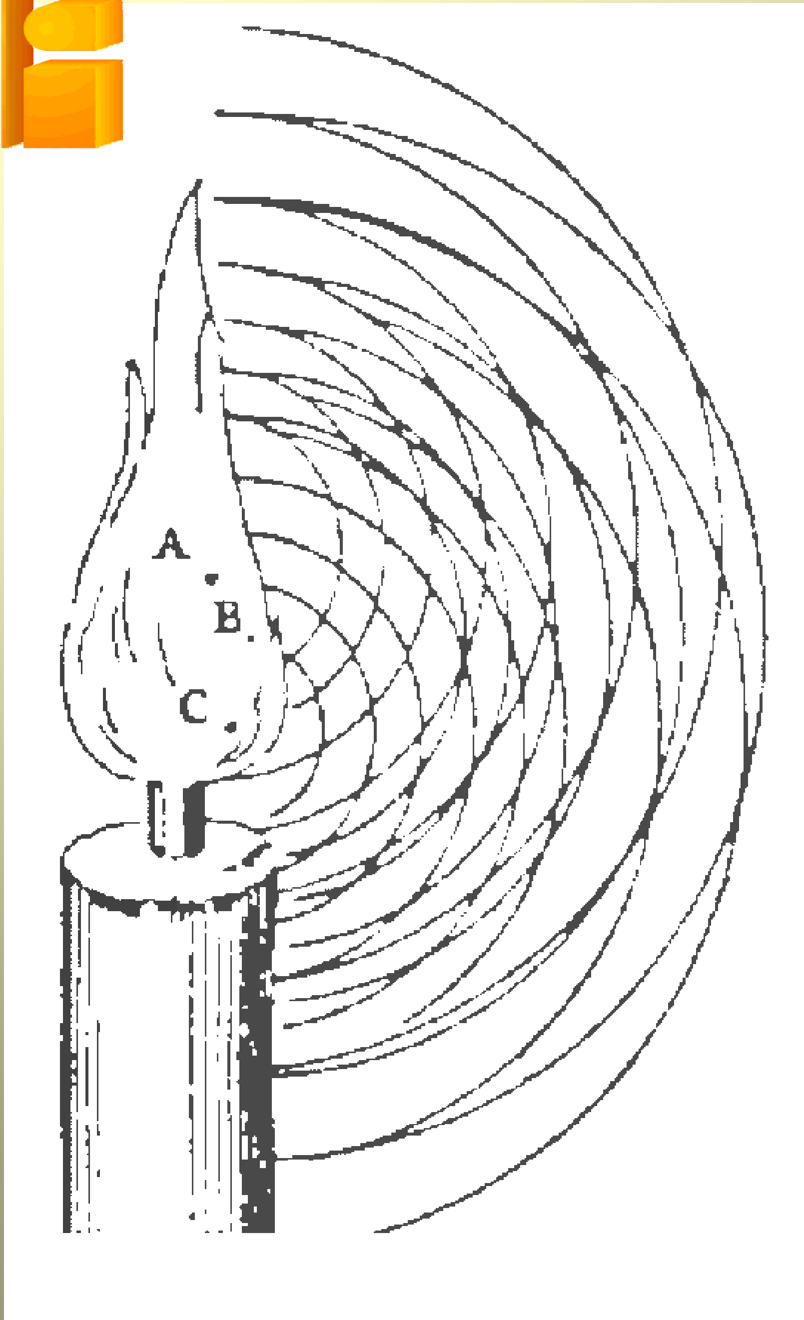


Multi-Level Modeling of Complex Systems and Advanced Materials with MEFiSTo

Wolfgang J.R. Hoefer

Faustus
Scientific Corporation

Contact Information

Faustus Scientific Corporation
1256 Beach Drive
Victoria, BC, V8S 2N3
Ph. (250) 592-6554
Fax: (250) 592-6557
Email: hoefer@faustcorp.com
http://www.faustcorp.com

Outline

- Introduction
- MEFiSTo – The Tool and its Architecture
- Principal and Unique Features
- Modeling Examples
- Benchmark: Potato in a MW-Oven
- Summary

Presentation of MEFiSTo

Multipurpose Electromagnetic Field Simulation Tool

- Simulation Engine: TLM in Time Domain
- Object-Oriented Program, C++
- Multi-Thread Architecture
- Real-Time links to other tools enabling multi-level field/circuit/neural network/ thermal/mass transfer simulations

Frequency vs. Time Domain

Frequency Domain Simulators	Time Domain Simulators
Time Harmonic (single frequency)	Transient (wide bandwidth)
Implicit algorithm	Explicit algorithm
$[M][x] = [g]$	$[x_{n+1}] = [S][x_n]$
(FEM, MoM, FD, FIT)	(TLM, FDTD, TDFEM, TDFIT)

↓

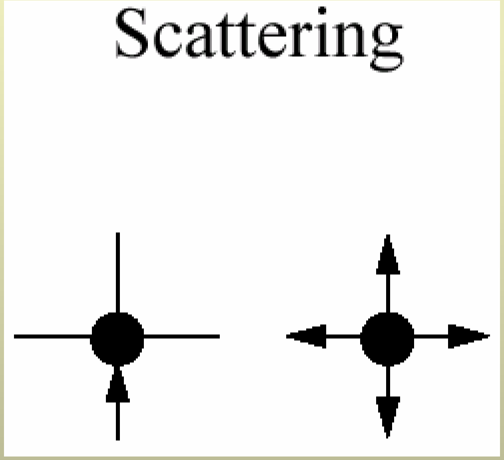
MEFiSTo

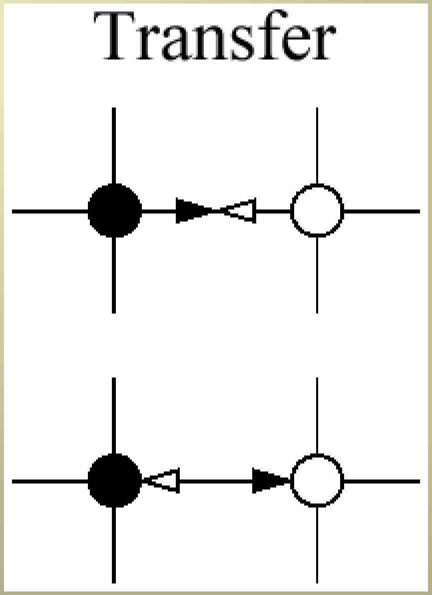
TLM Modeling Environment

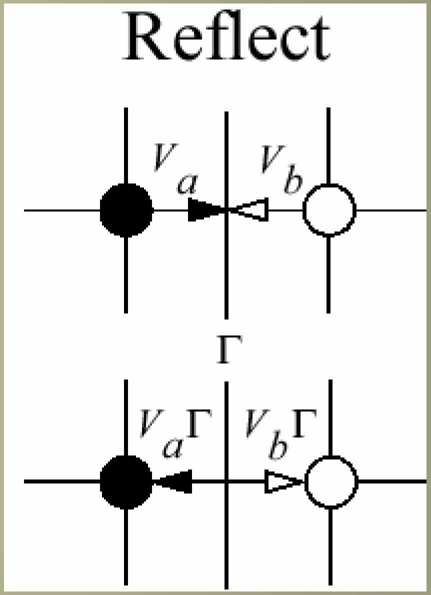
- TLM is a discrete network model of the 3D Maxwell Equations;
- It can be operated either in the time or in the frequency domain;
- Time domain modeling with TLM involves a sequence of impulse scattering and transmission (connection) operations.

The TLM Algorithm

The three basic TLM operations:





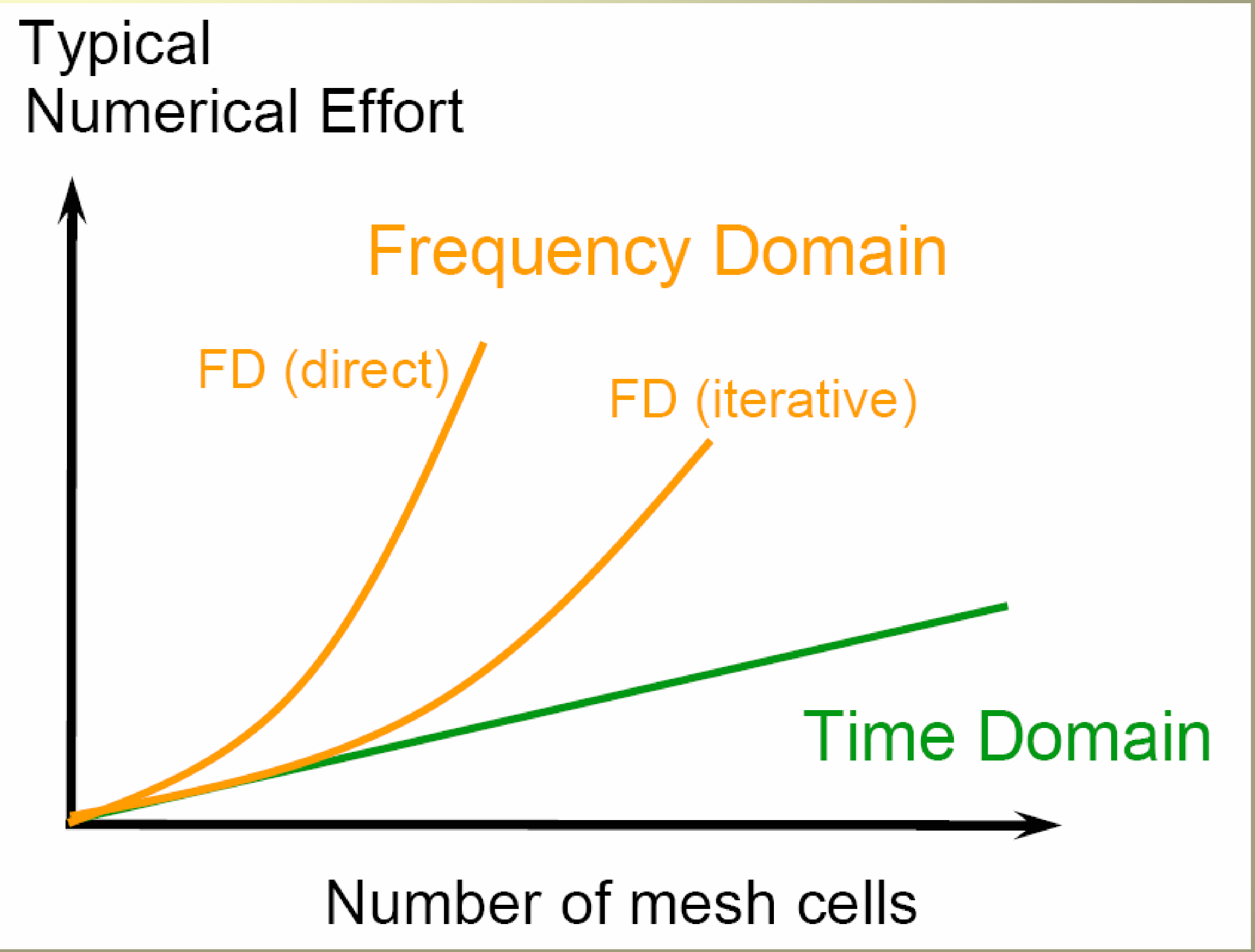


MEFiSTo operates exclusively in the time domain

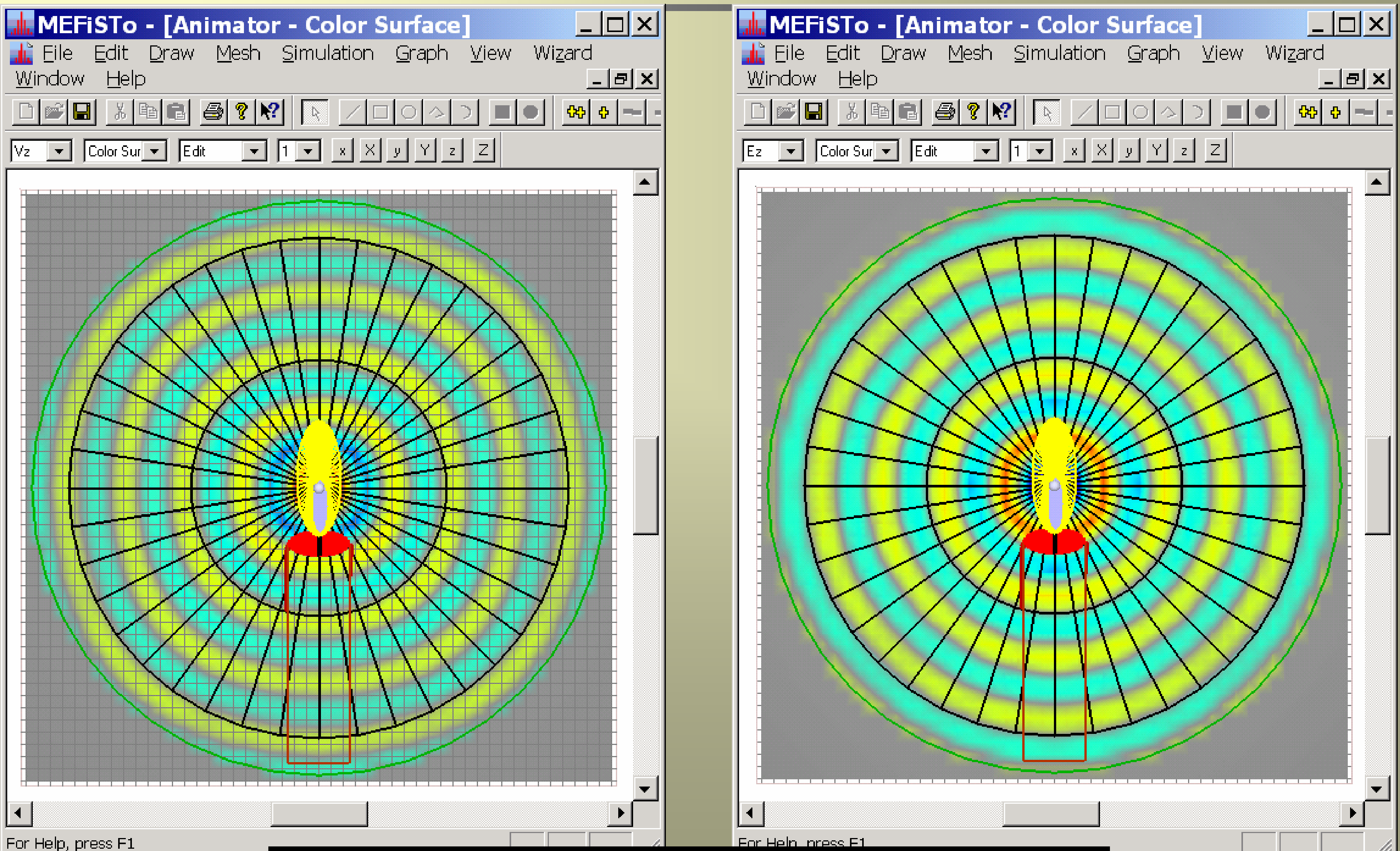
Advantages of TLM

- Less dispersive than other time discrete schemes.
- Passive network model is always unconditionally stable.
- Scattering algorithm is numerically more robust than finite difference formulations [Fettweiss].
- Due to co-location of electric and magnetic fields it is easy to connect devices and implement boundaries. (SPICE-EM-bed, MatLab Link, Thermal Engine)
- TLM modeling invokes expertise in field theory, network and circuit theory, and signal processing. It is a "physical" field model.

Computational Burden



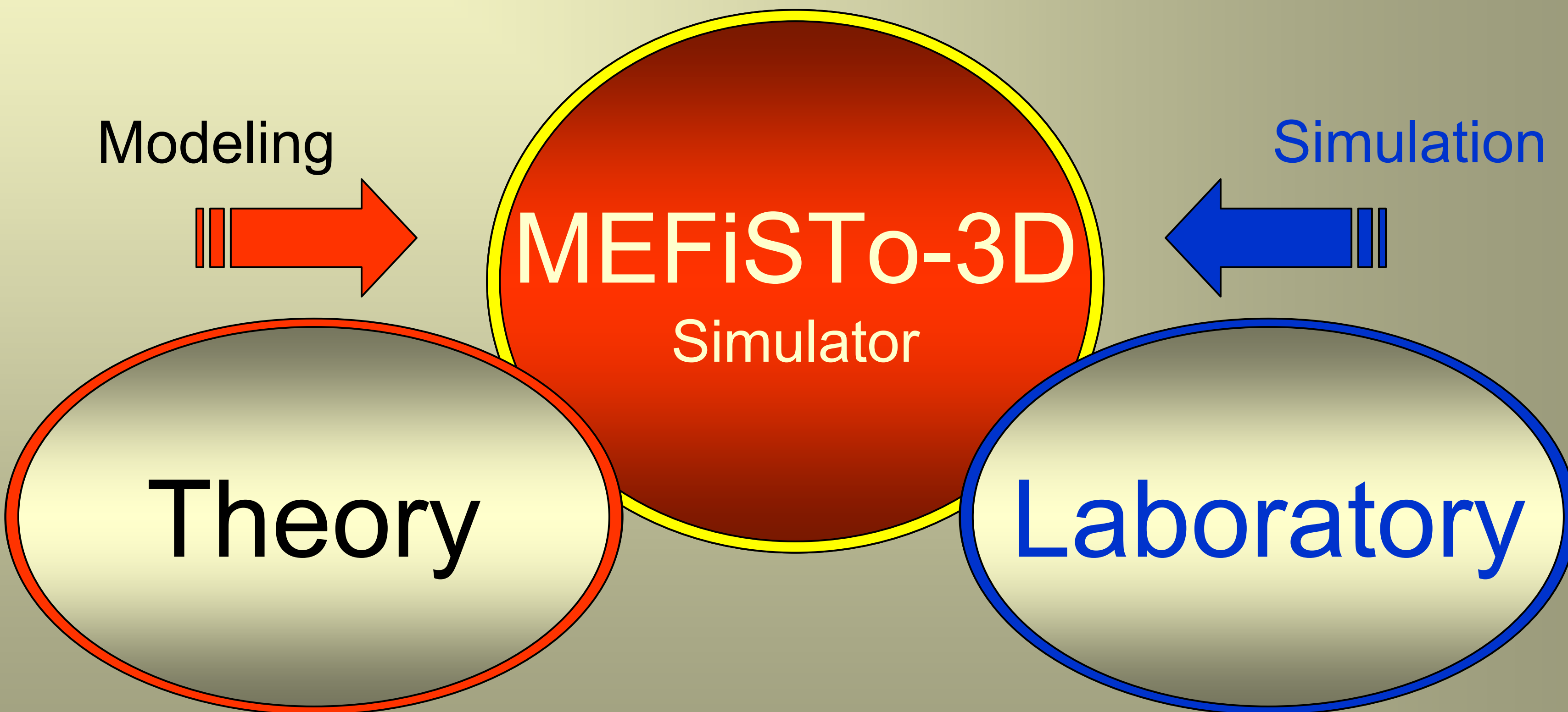
FDTD vs. TLM



f= 60 GHz ; Δl= 1 mm =λ/5

Theory and Laboratory

MEFiSTo builds on traditional theory and laboratory practice and extends them through modeling and simulation



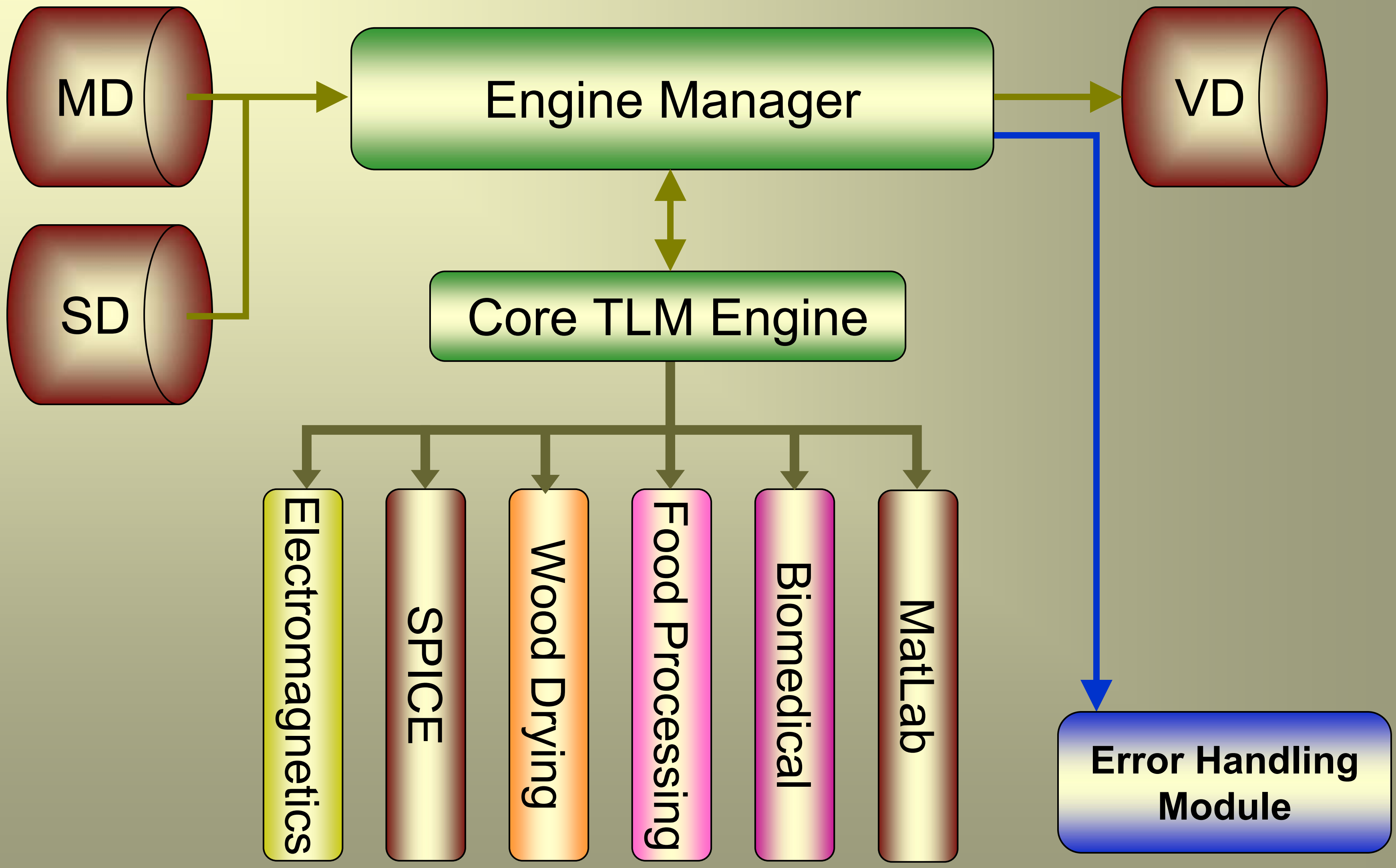
Transmission Line Theory, Maxwell's Equations

Network Analyzer, Spectrum Analyzer, Oscilloscope, etc.

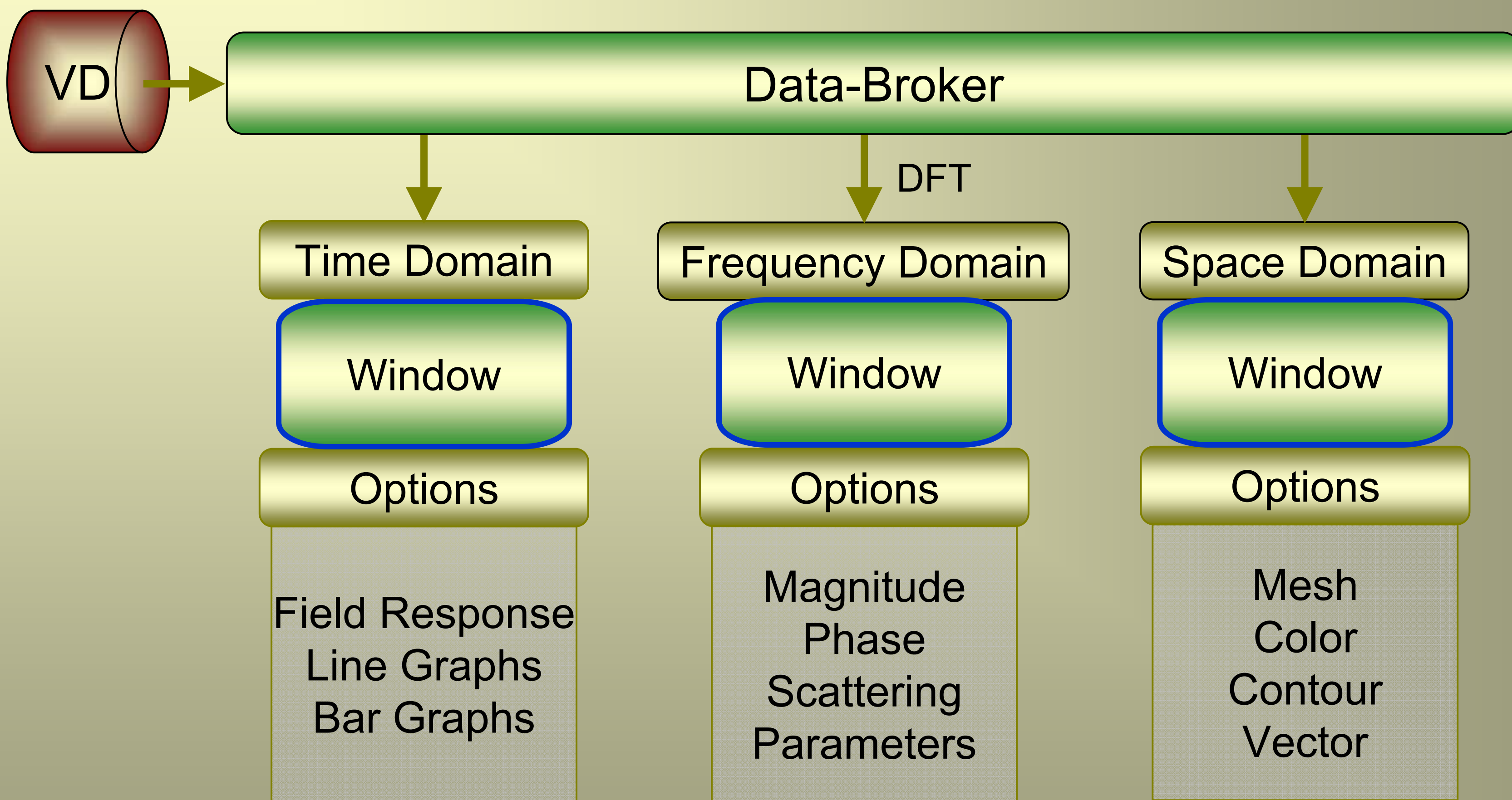
How does MEFiSTo work?

- Enter/import geometry & el.-mag. properties,
- Set up source(s), probes, reference planes,
- Set discretization parameters and mesh,
- Specify source waveform,
- Extract time response at probes or bounds,
- Extract S-parameters, radiation pattern,
- Visualize fields, responses, characteristics,
- Analyze, optimize, export, store, print data, graphs, field plots, results.

The Modeling Engines



The Signal Co-Processor



All data can be displayed dynamically as they are generated

Features of MEFiSTo-3D

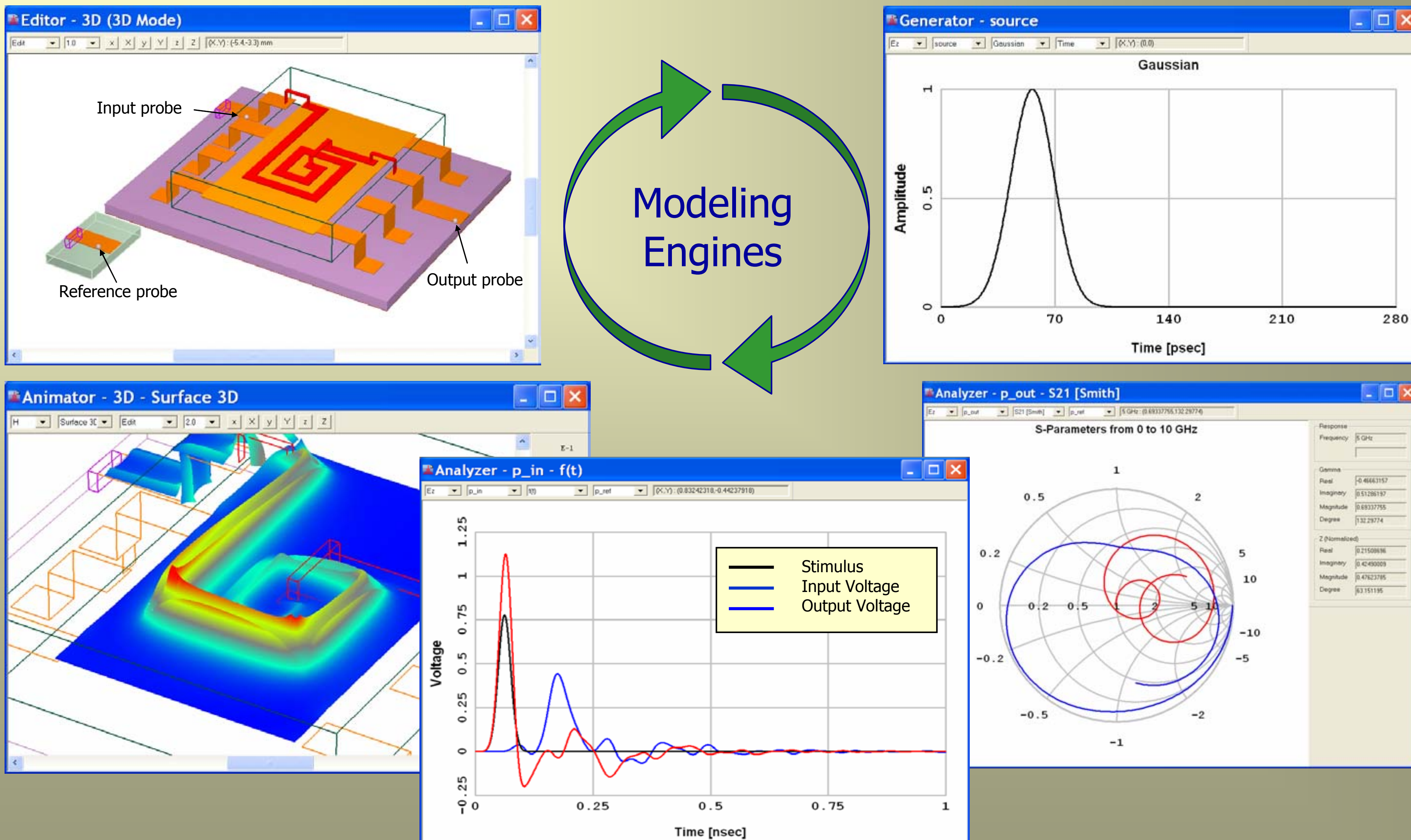
- Electromagnetic modeling software tool with transient and time-harmonic capability;
- Accuracy, ease of use, versatility, speed;
- User-friendly lab-inspired graphical interface, fully parameterized, controllable externally;
- Runs under all current Windows operating systems, 64-bit version in preparation;
- Dynamic field visualization in space and time;
- Automatic window capture for movie creation;
- Co-processing instead of post-processing provides unprecedented interactivity.

… continued

Features of MEFiSTo-3D

- Multi-threaded architecture for multiple platforms; smart memory allocation;
- Text-based data import and export;
- Customized library of user-defined structure elements;
- SPICE-EM-bed capability allows coupled circuit-field simulation and circuit embedding;
- MatLab link for multi-level processing;
- Batch processing capability for automatic data base and reduced order model (SPICE modules, neural networks) generation;
- 2D and 3D metamaterial modeling capability.

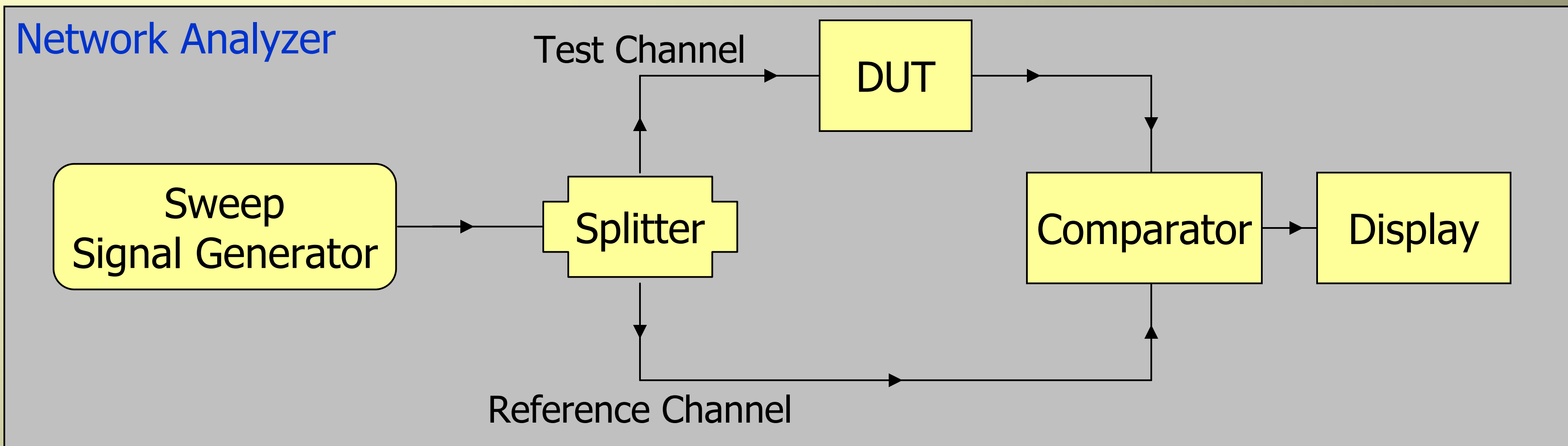
MEFiSTo - A Virtual Laboratory

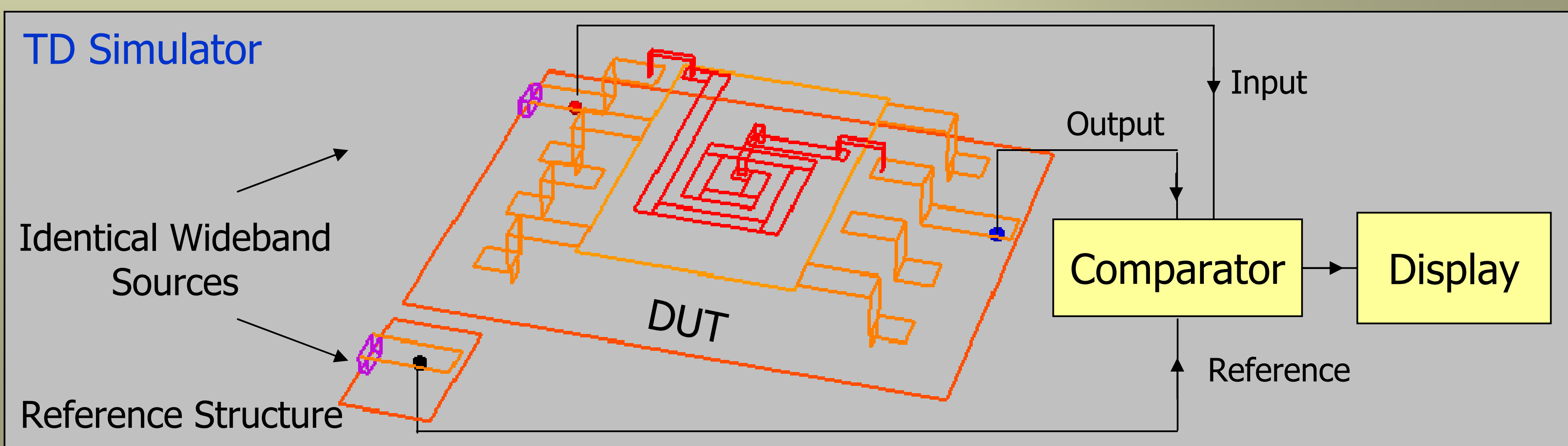


Typical MEFiSTo Applications

- MEFiSTo as a Virtual Network Analyzer (VNA) and design tool;
- MEFiSTo as a Virtual Time Domain Reflecto-meter (VTDR), Signal Integrity & EMC tool;
- MEFiSTo as a virtual kiln, food pasteurizer, or microwave oven;
- MEFiSTo as a virtual design and test environ-ment for advanced materials and components;
- MEFiSTo as a virtual teaching and training laboratory providing physical insight into the relationship between field behavior and circuit or system properties.

MEFiSTo as Virtual Network Analyzer





Modeling of Wood Drying

- Electromagnetic Fields: TLM
  - 3D Spatial Transmission Line Network, Cartesian
  - Diagonal tensor permittivity
  - Time-dependent ε' and *tan*δ (functions of moisture content and temperature.
- Heat Diffusion: FDTD
  - FDTD mesh overlaps TLM mesh
  - Forward Time Central Space (FTCS) Scheme)
  - Temperature and moisture dependent diffusivity tensor (diagonal)
- Mass Transfer: FDTD
  - Same as Heat Diffusion

The Coupled Kiln Model

Reach steady state
after material changes

E/M Field in the Kiln

TLM

$\varepsilon_r, \tan\delta$

Q

FDTD

RF Energy deposited in Wood

Moisture and Heat Transfer

Compute until proper-
ties change by 1 %

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu_r H)$$

$$\nabla \times H = J + \frac{\partial}{\partial t}(\varepsilon_r E)$$

$$\frac{\partial M}{\partial t} = \nabla(D_M \nabla M)$$

D_M: moisture diff. coeff.

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + Q$$

ρ: wood density; c_p: specific heat; λ_T: heat diffusion coeff.; Q: energy

Modeling of Food Pasteurization

- Electromagnetic Fields: TLM
  - 3D Spatial Transmission Line Network, Cartesian Diagonal tensor permittivity
  - Time-dependent ε' and $tan\delta$ (functions of temperature.
- Heat Diffusion: FDTD
  - FDTD mesh overlaps TLM mesh
  - Forward Time Central Space (FTCS) Scheme)
- Mass Transfer: not considered (sealed food packages)

Coupled Food Pasteurization Model

Reach steady state
after material changes

E/M Field

TLM

$\varepsilon_r, \tan\delta$

Q

FDTD

RF Energy deposited in Food

Heat Transfer

Compute until proper-
ties change by 1 %

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu_r H)$$

$$\nabla \times H = J + \frac{\partial}{\partial t}(\varepsilon_r E)$$

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + Q$$

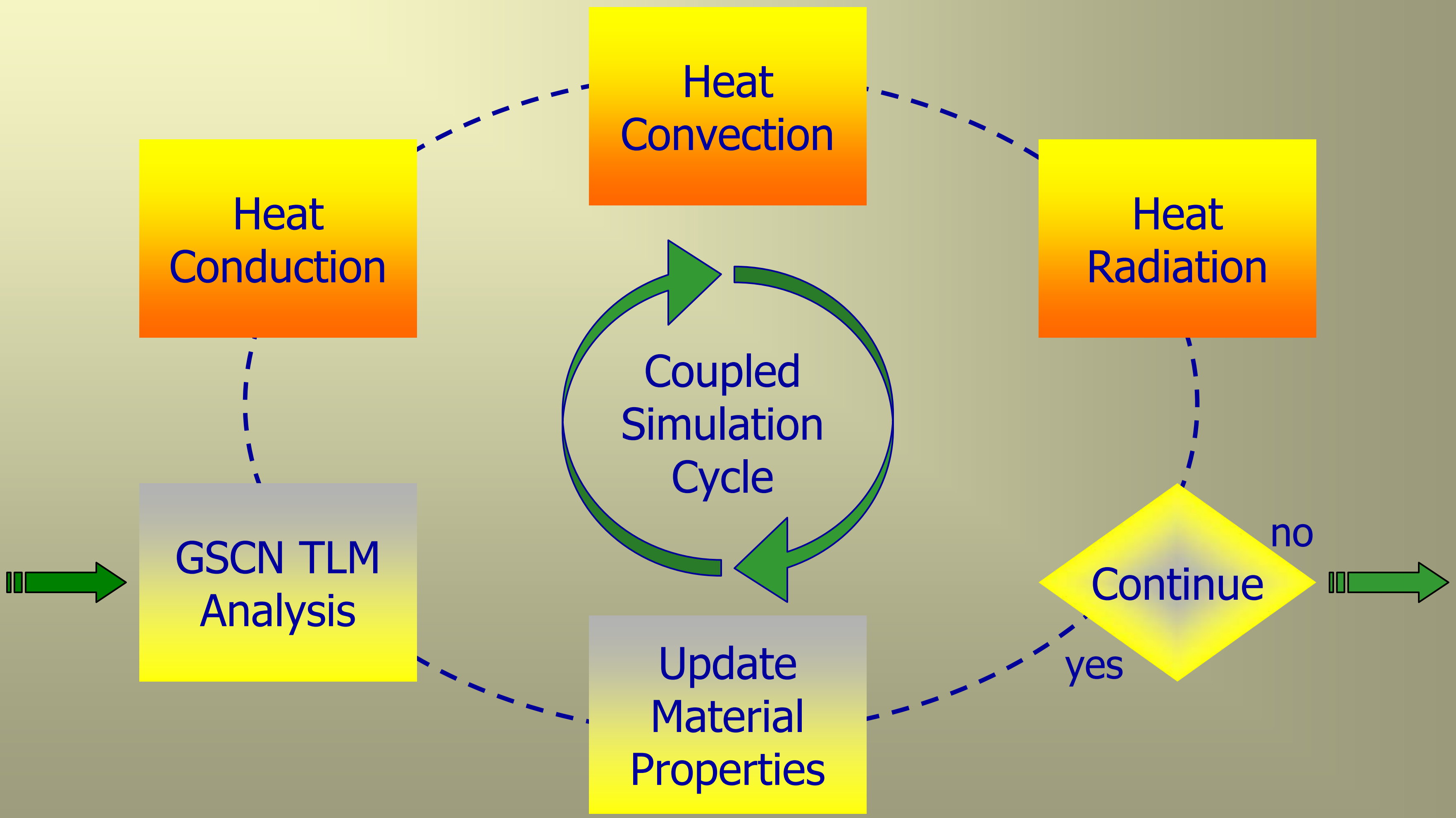
food density

specific heat

heat diffusion coeff.

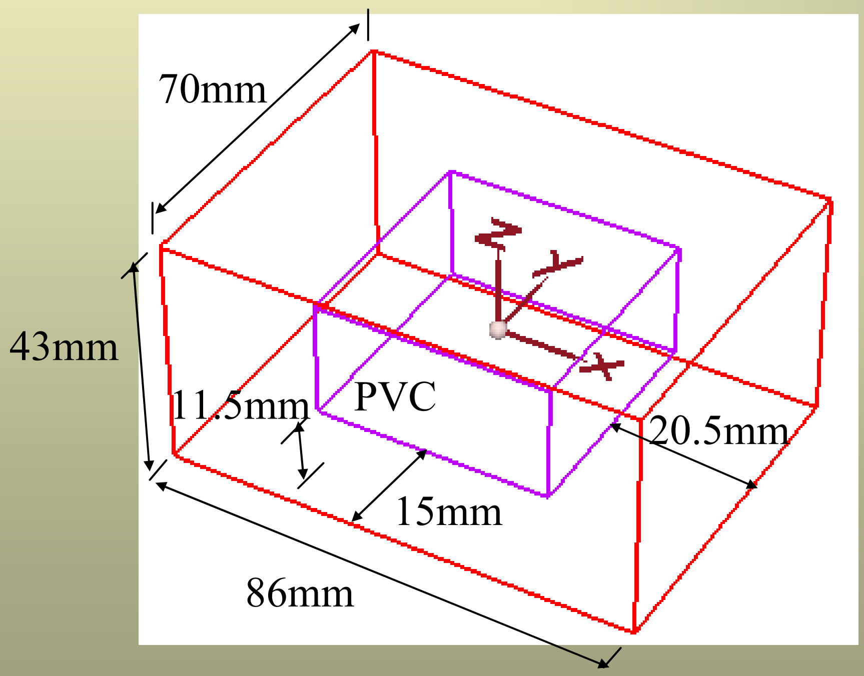
energy

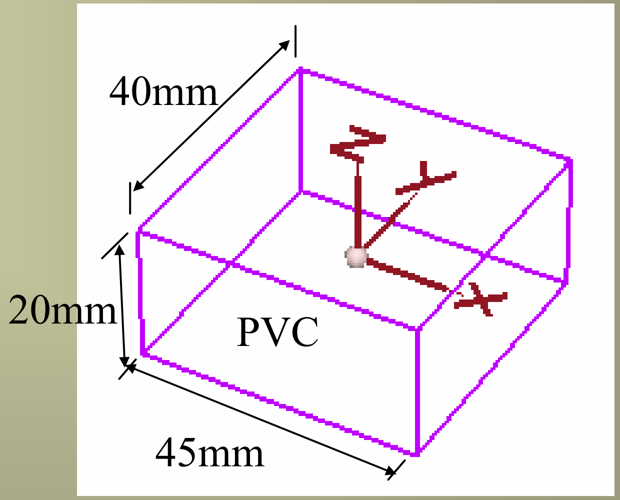
Coupled EM-Thermal Engine



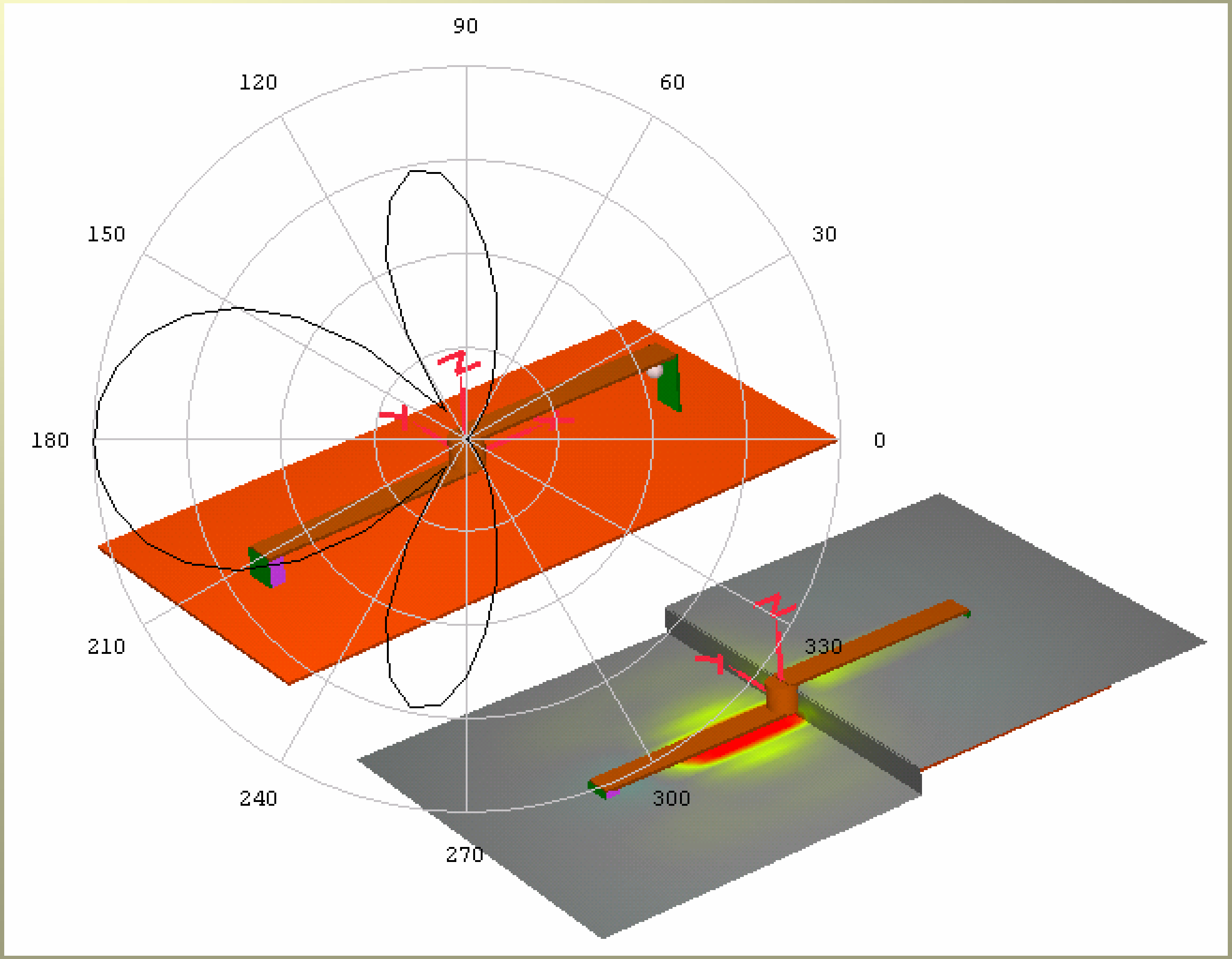
Simulation Example

- PVC Block in a Rectangular Cavity

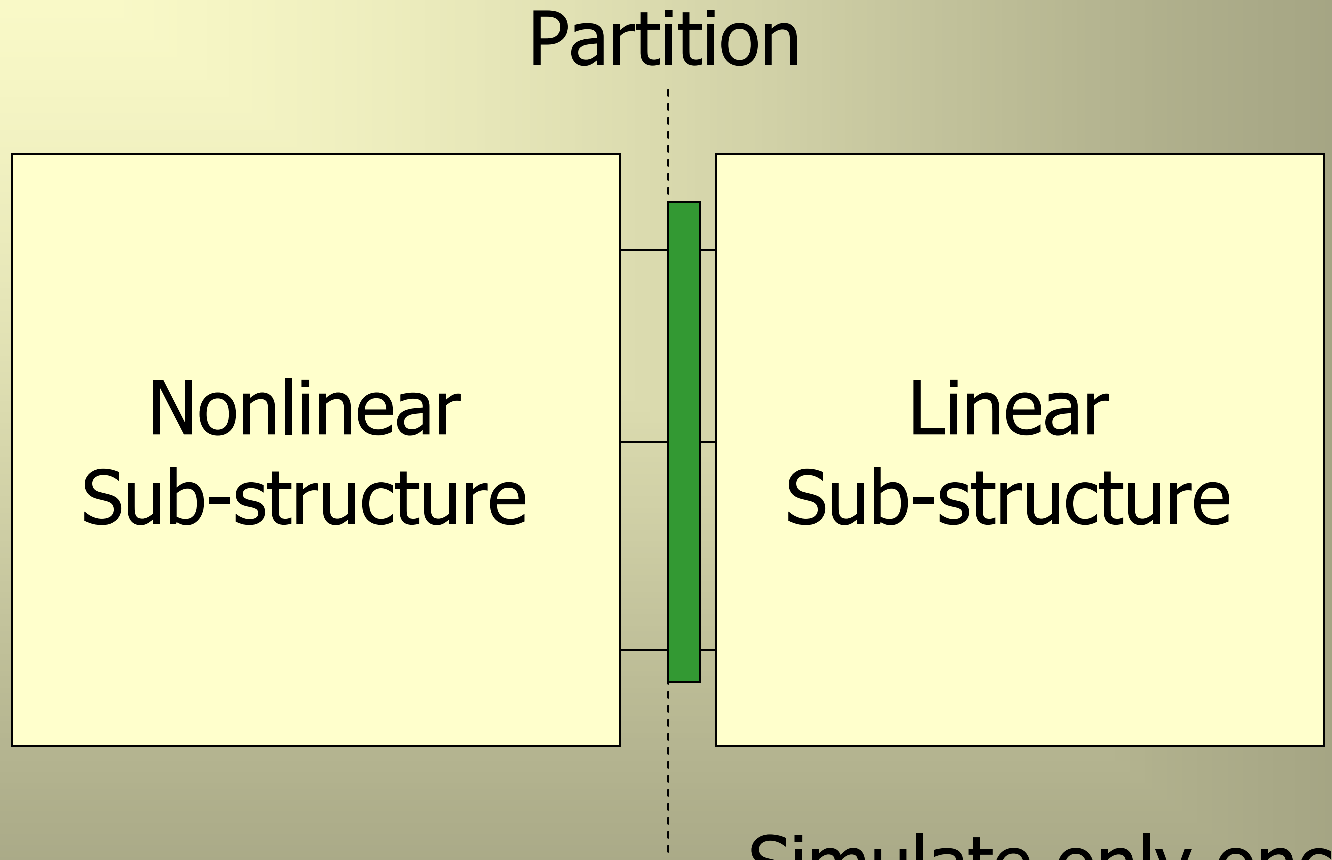




Transient Radiation from Circuits



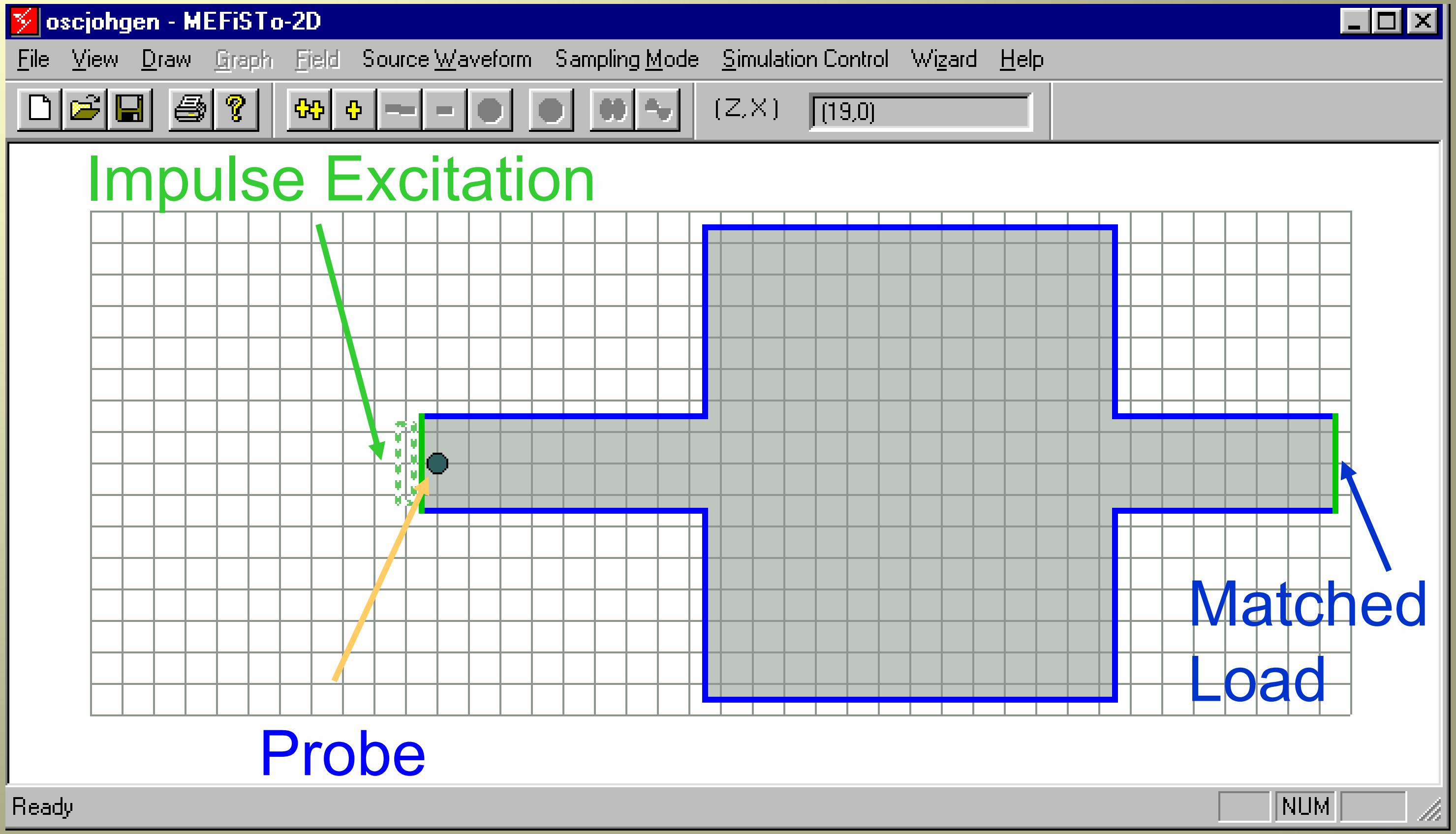
Application of Diakoptics



Simulate only once,
Store impulse response

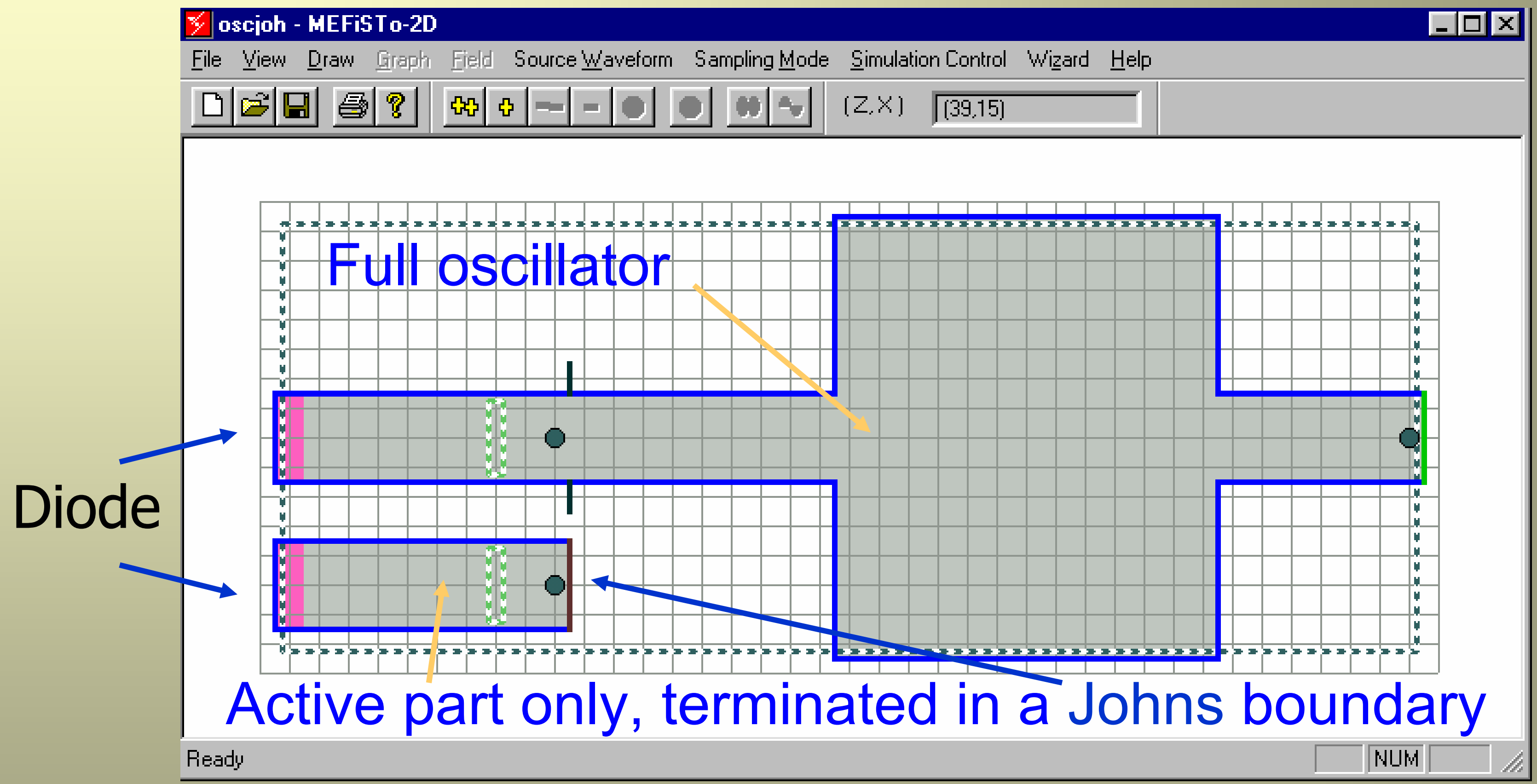
Reconnect by convolution

Response of Passive Circuit



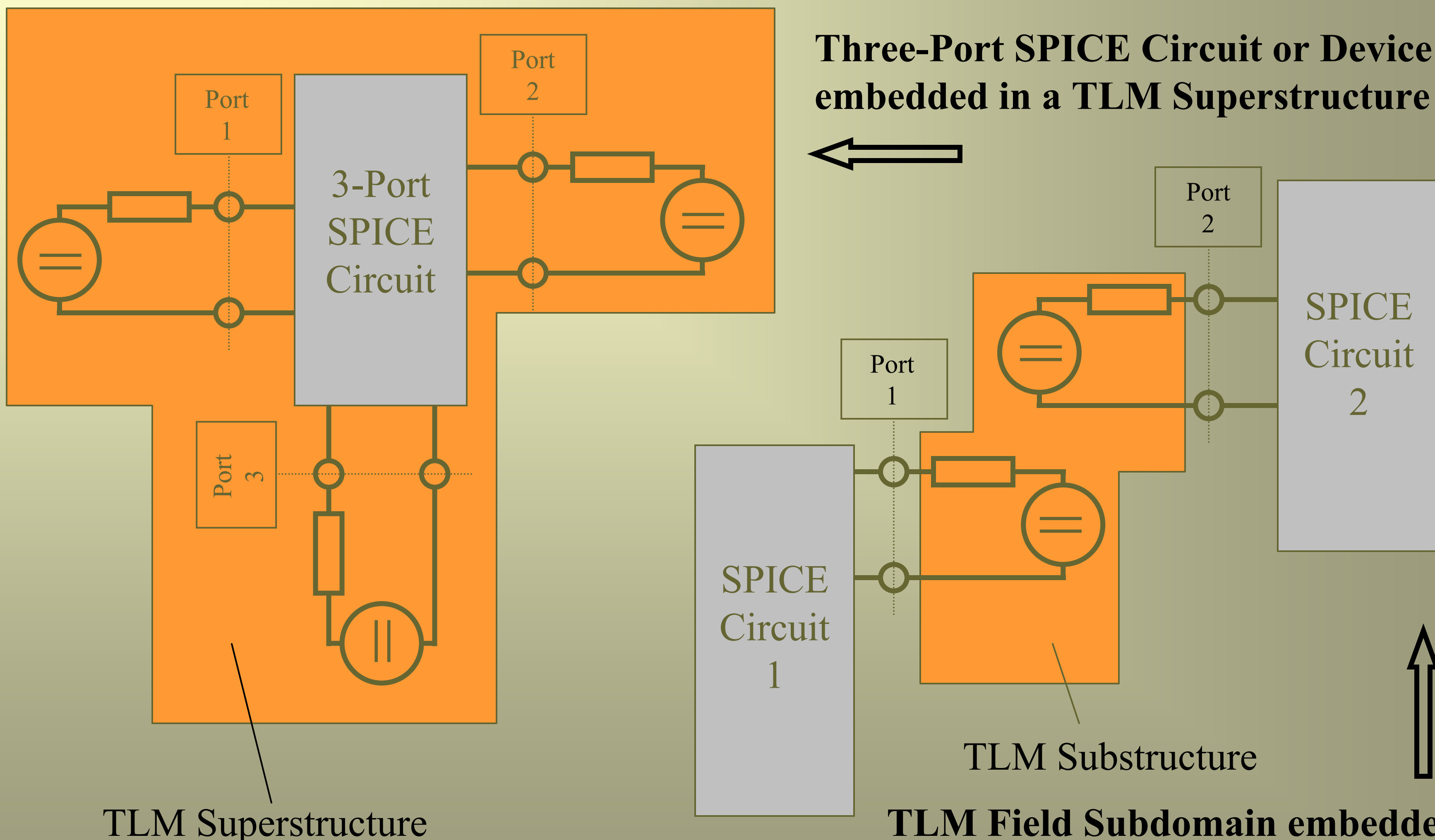
The impulse response of the passive part of an oscillator is computed, picked up by the probe and stored

Connection to the Active Diode



The active part of the oscillator is terminated by convolution in a Johns boundary characterized by the impulse response of the passive part. It behaves exactly as the full oscillator

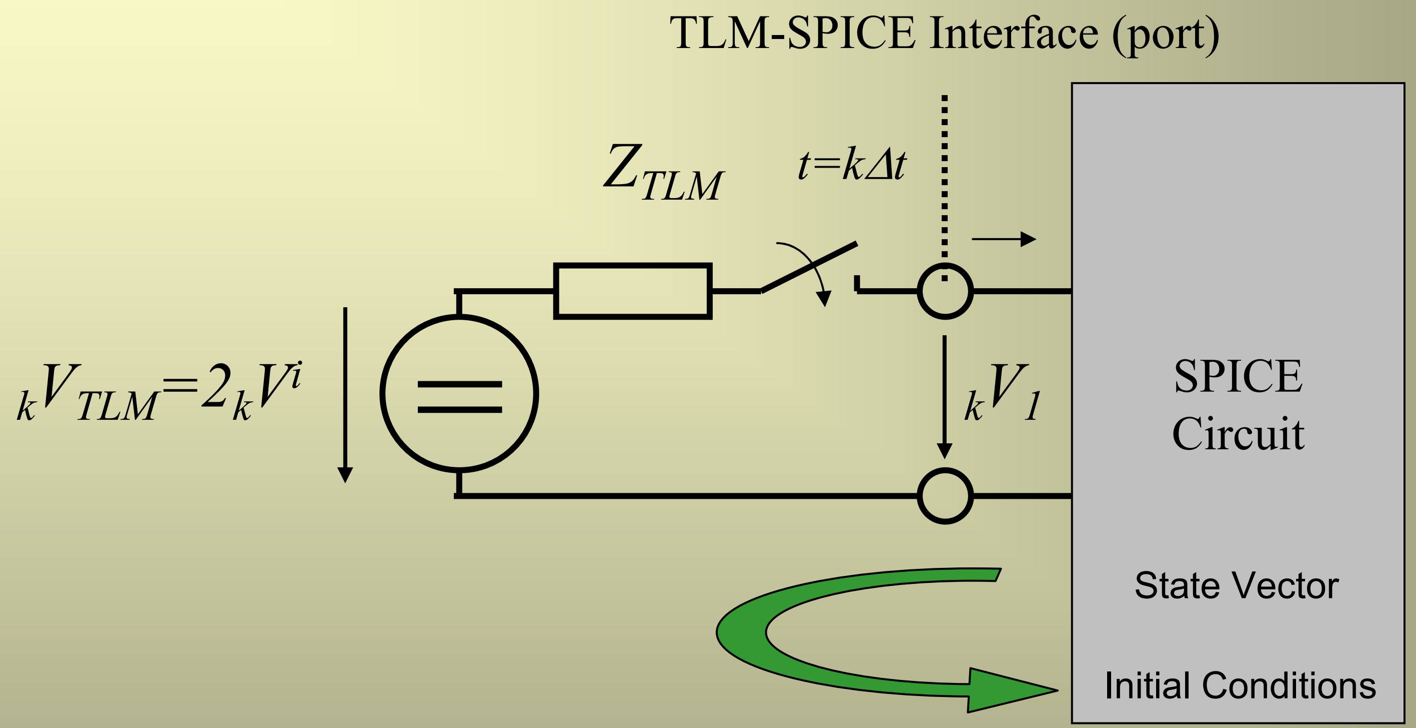
General SPICE-TLM Interface



Three-Port SPICE Circuit or Device embedded in a TLM Superstructure

TLM Field Subdomain embedded between two external SPICE Circuits.

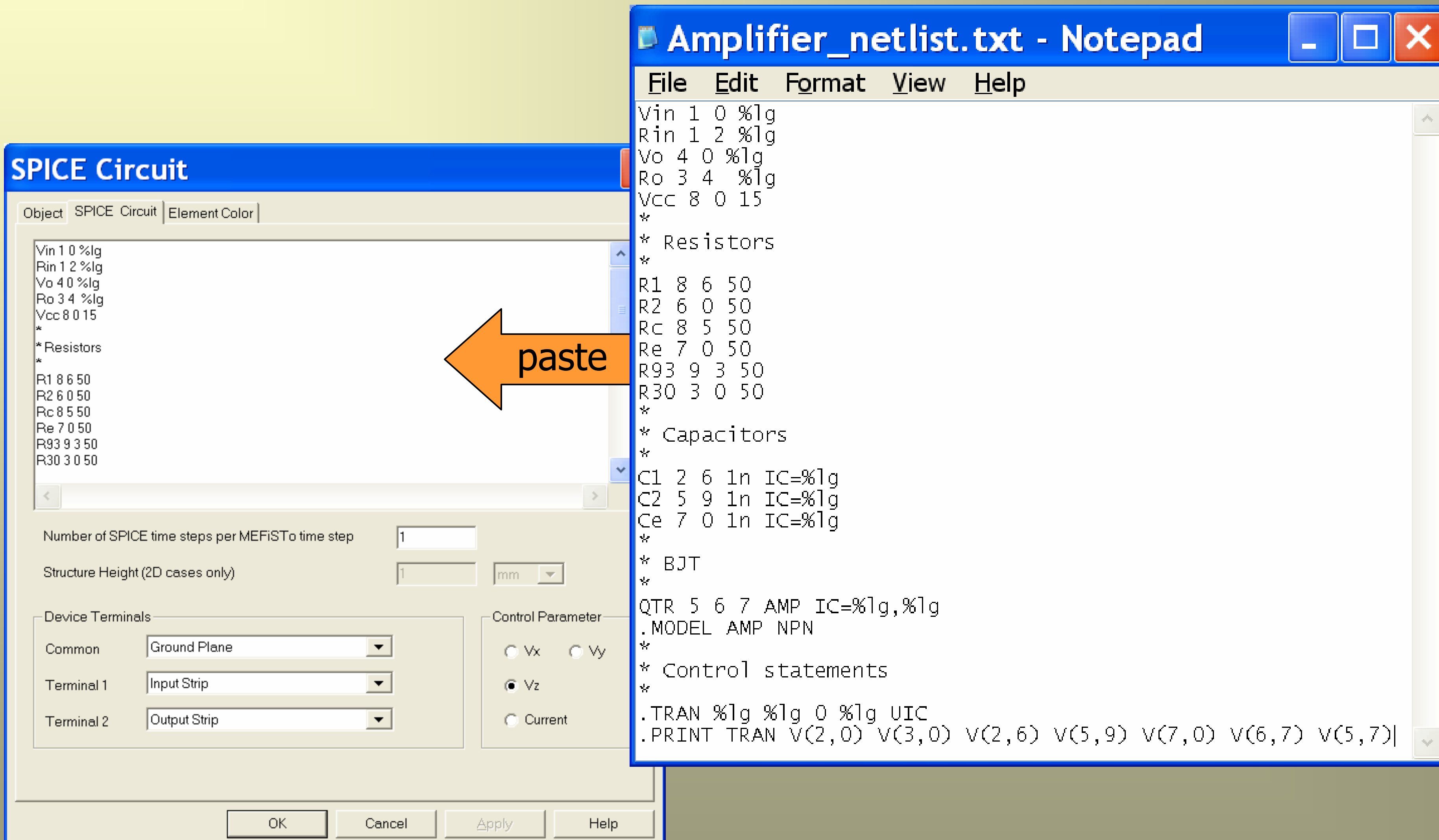
TLM - SPICE Connection



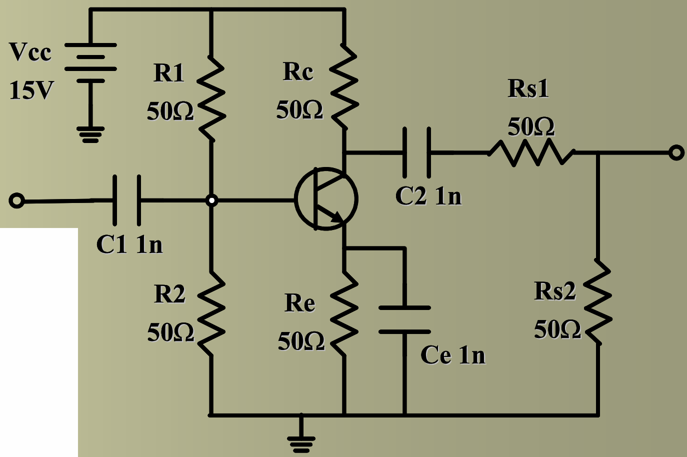
The SPICE circuit may contain sources

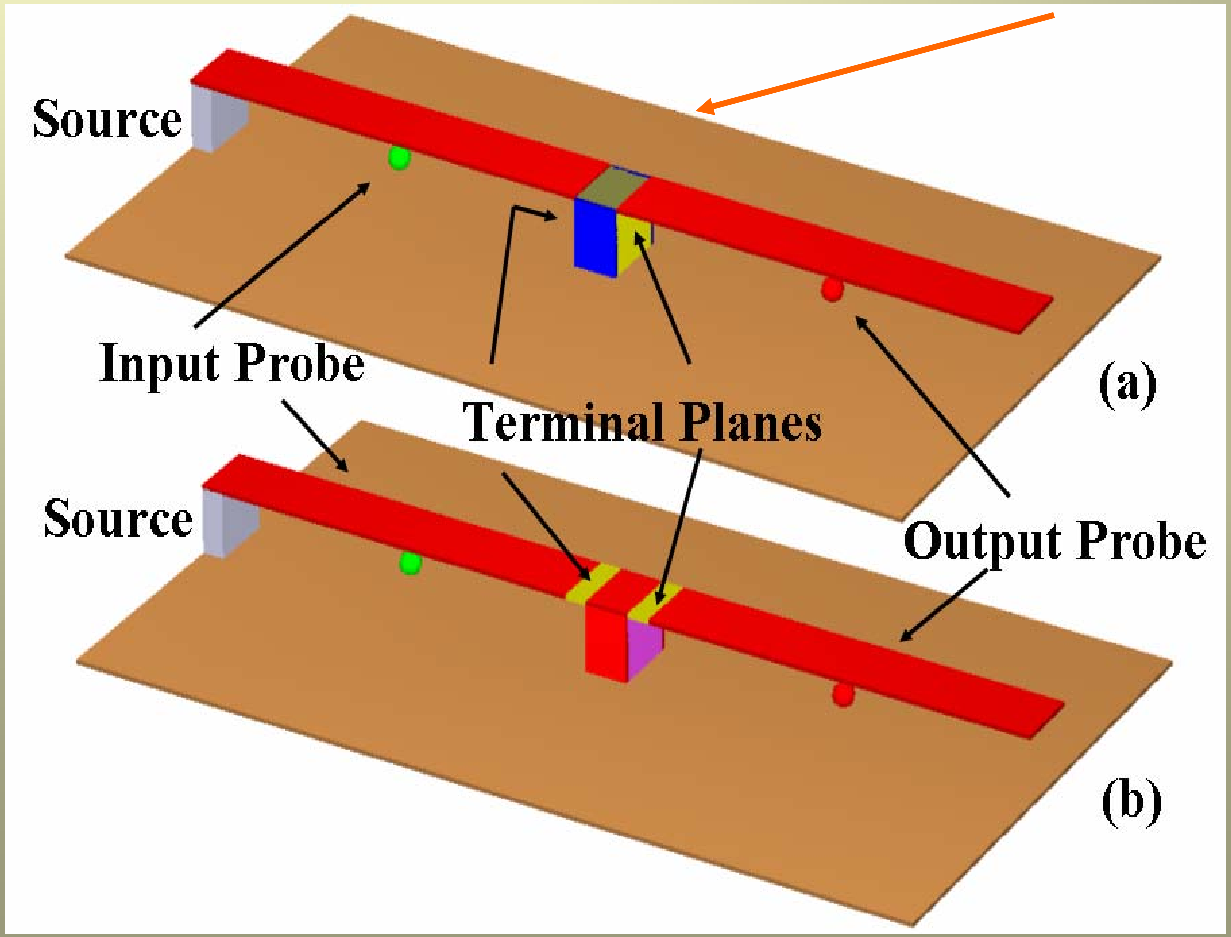
The TLM impulses incident at the *kth* time step upon the SPICE port are represented by an equivalent voltage ${}_kV_{TLM}=2{}_kV^i$ connected to the SPICE circuit at time $k\Delta t$ through an equivalent real reference impedance Z_{TLM} which depends on the port topology.

Spice Circuit Dialog Box



Transient Amplifier Response

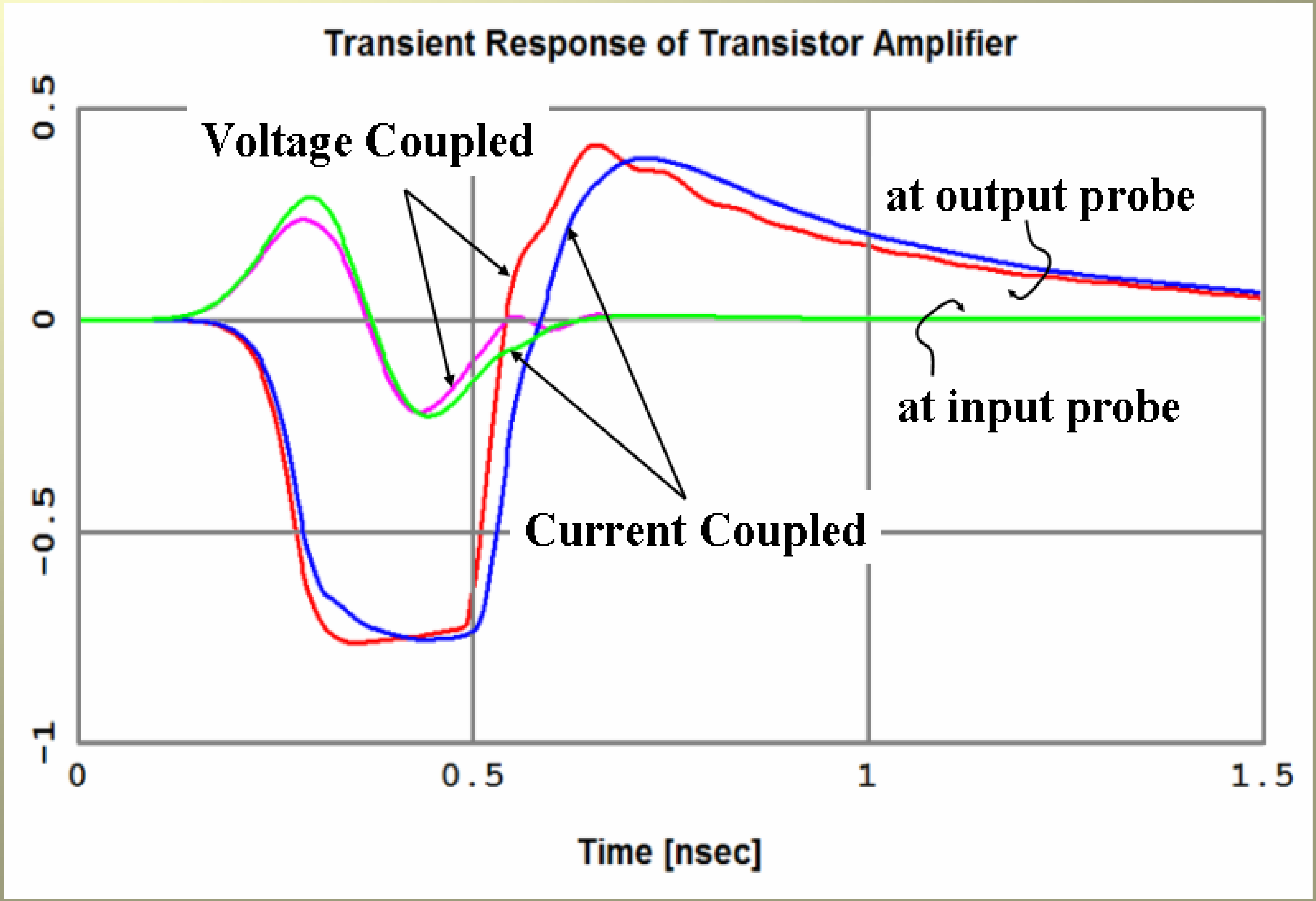




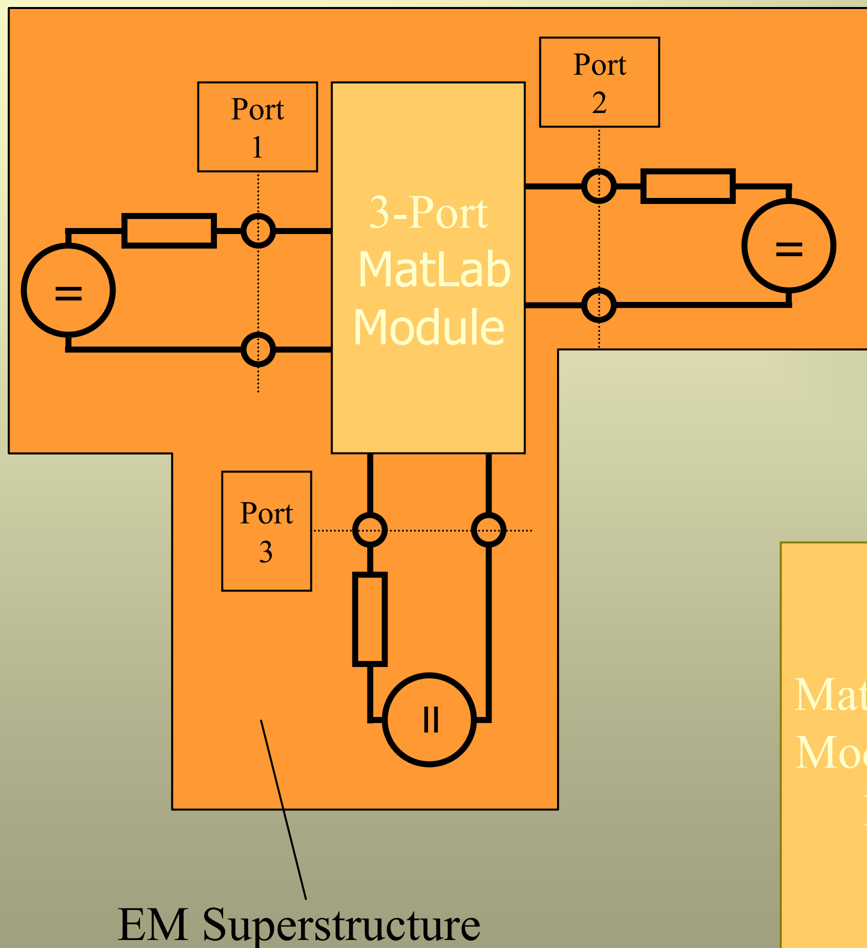
voltage-coupled

current-coupled

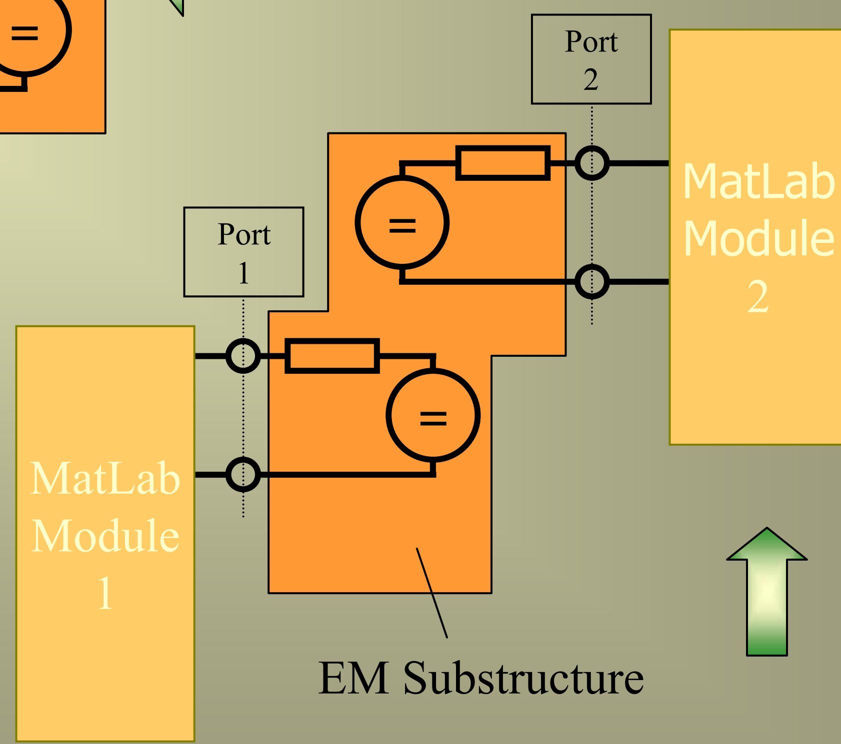
Transient Amplifier Responses



Interoperability with MatLab

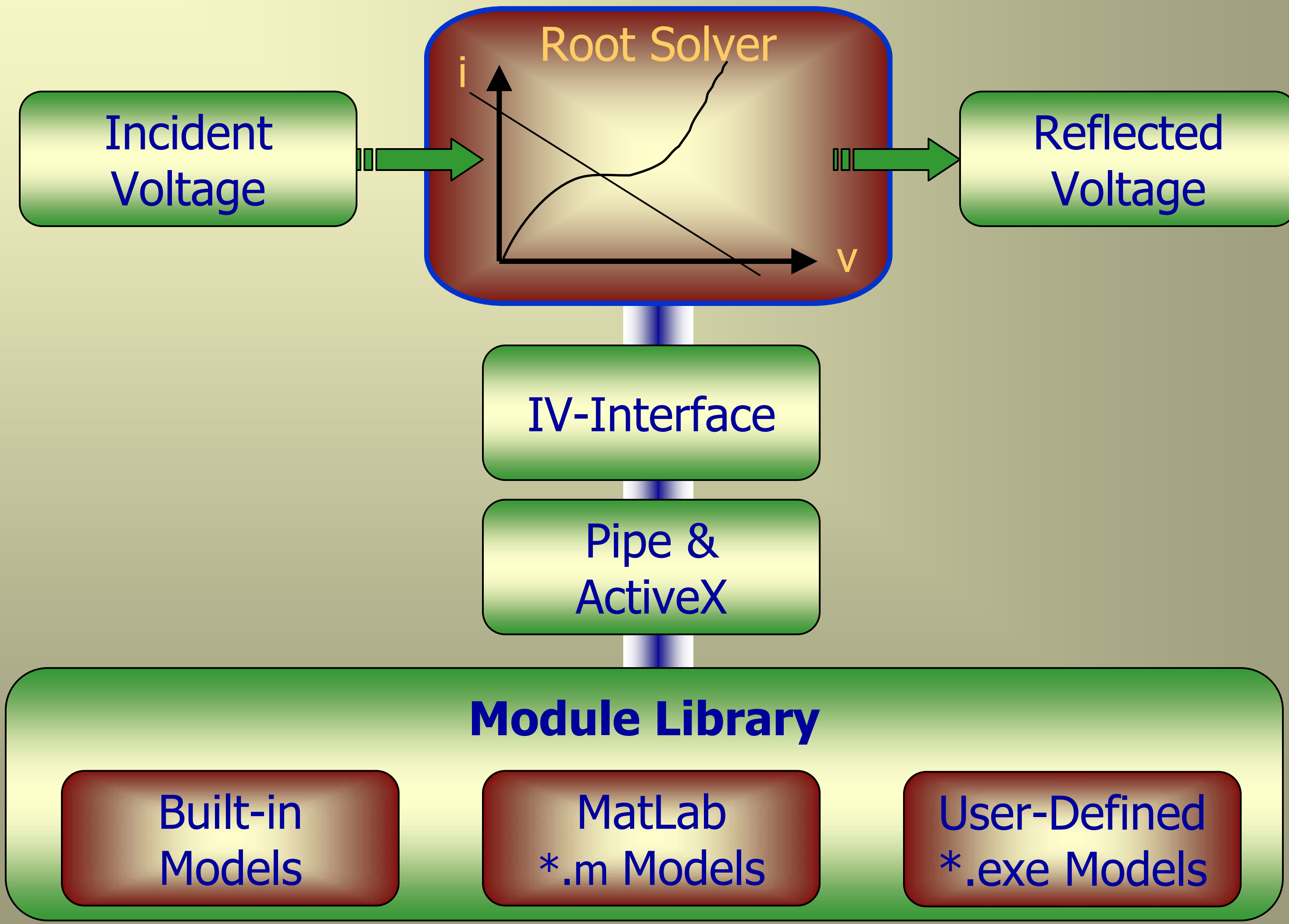


Three-Port MatLab module embedded in a EM Superstructure



EM Field Subdomain embedded between two external MatLab modules.

MEFiSTo's IV Module

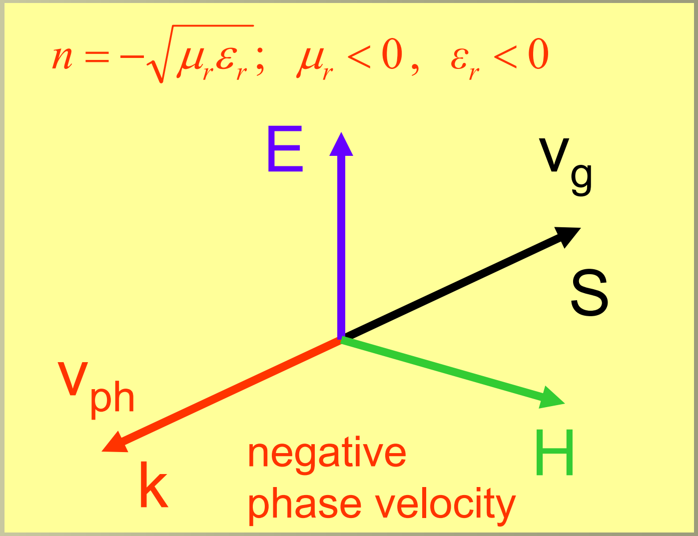


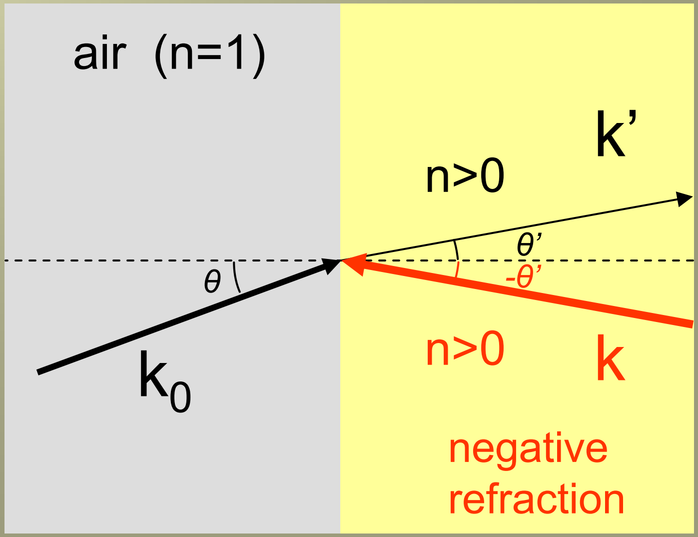
Metamaterials

Metamaterials with negative refractive index, (left-handed materials) have two unusual but related electromagnetic properties (Veselago, 1967):

1) The *phase velocity* is *opposite* to the *group velocity* and the flow of energy,

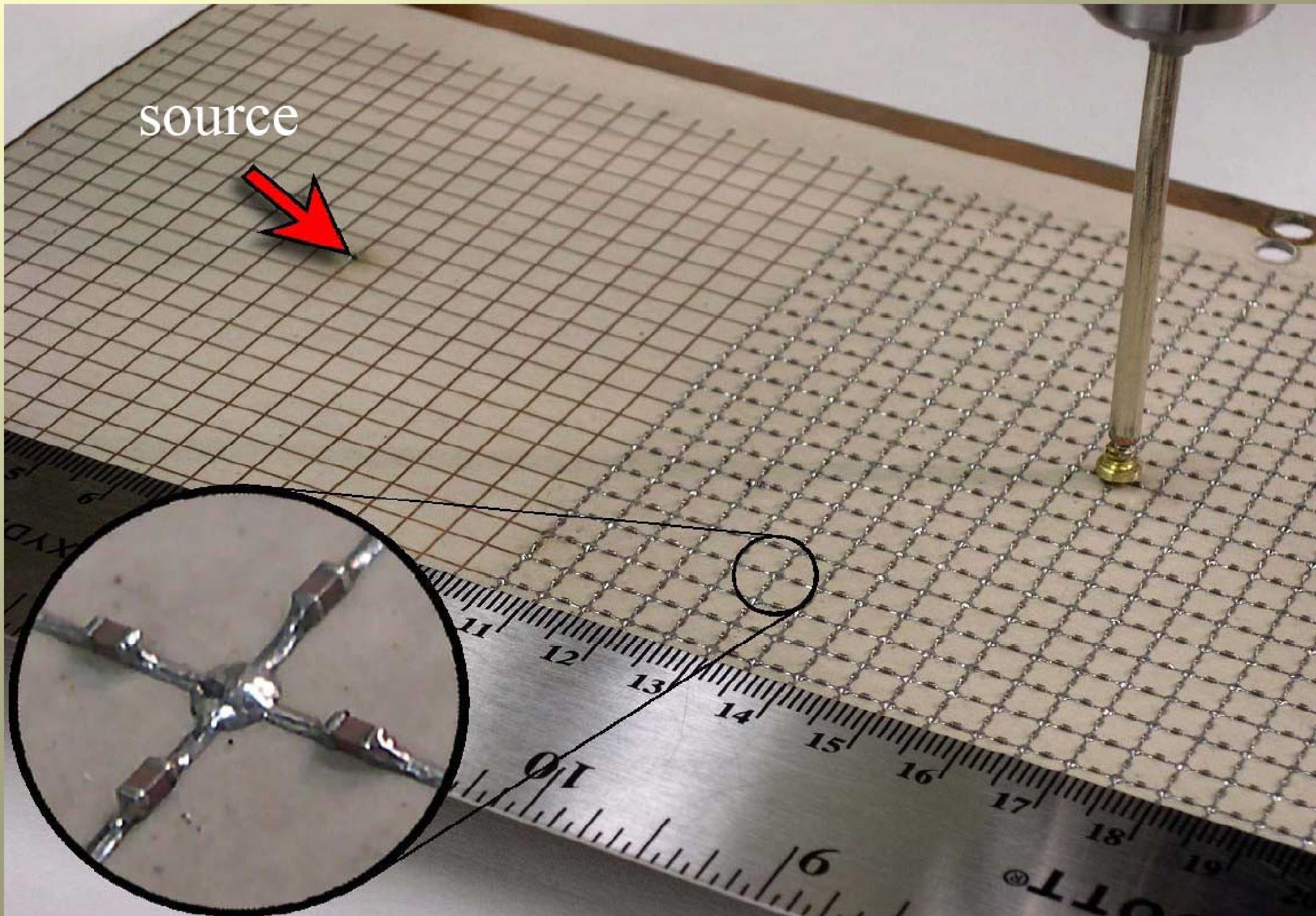
2) Waves are refracted at a *negative* angle (Focusing).



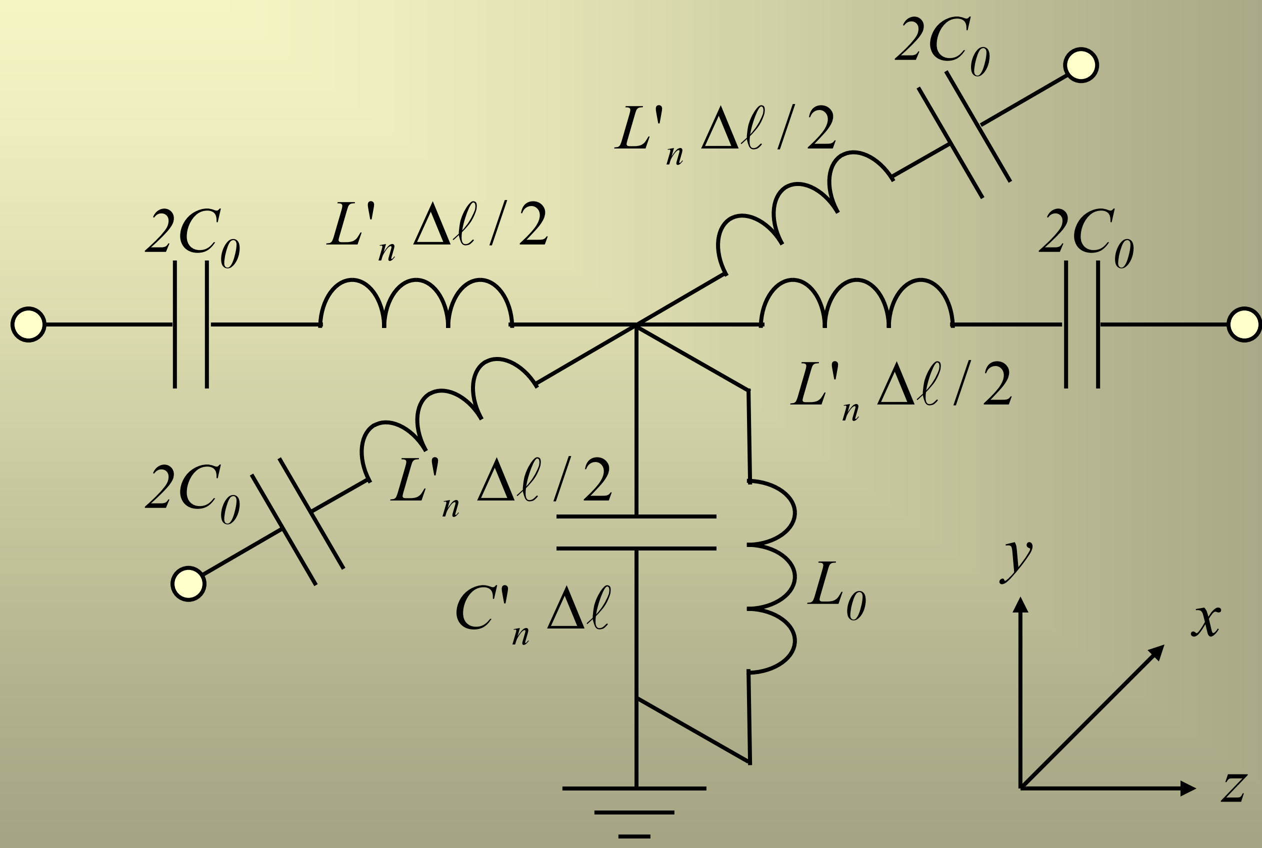


Loaded Line Model

Courtesy of A. K. Iyer and G.V. Eleftheriades, UoT

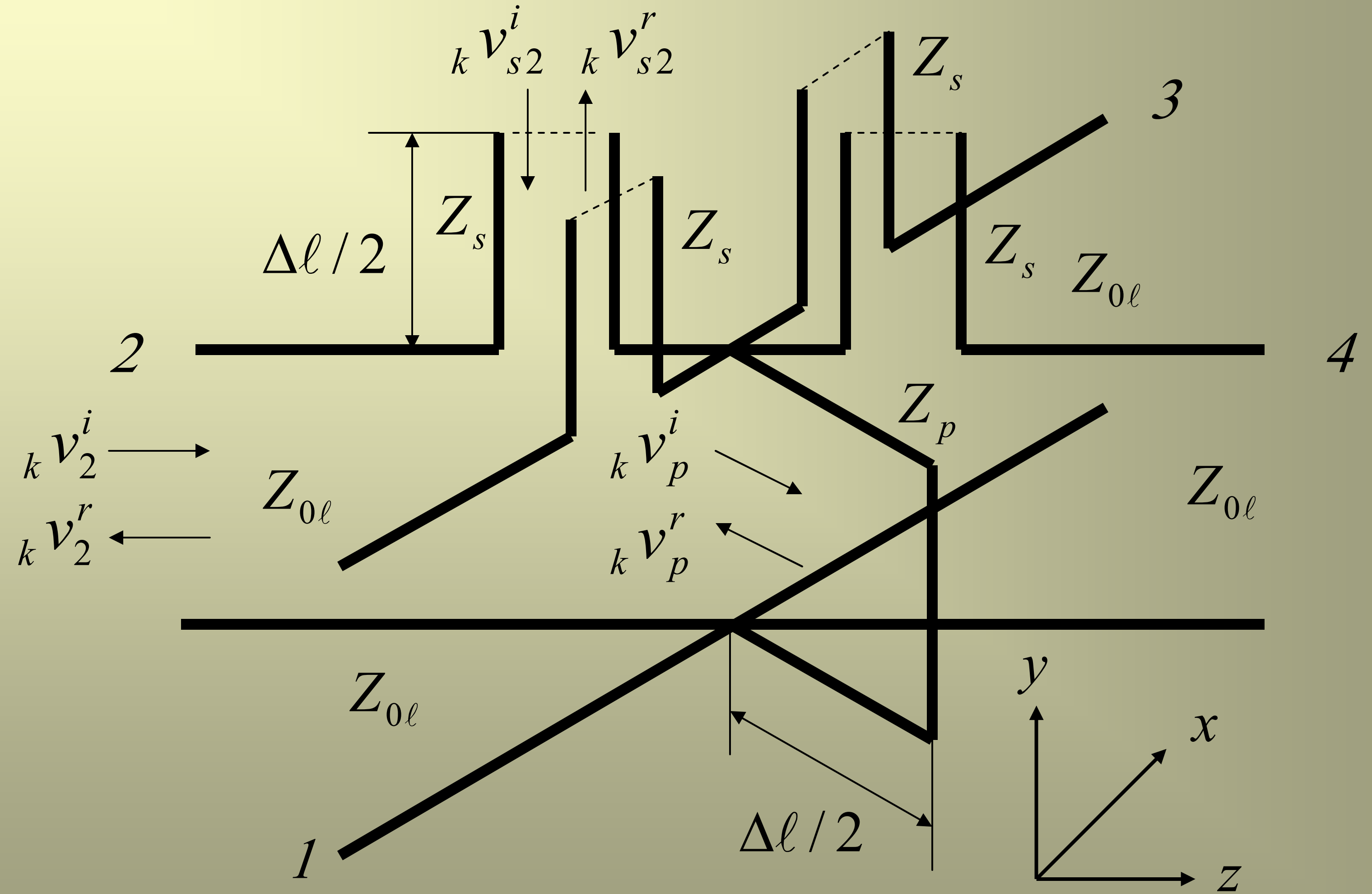


Modeling of Metamaterials



Unit Cell of a 2D Metamaterial Model (Eleftheriades et al.)

Modeling of Metamaterials



movie

n=2

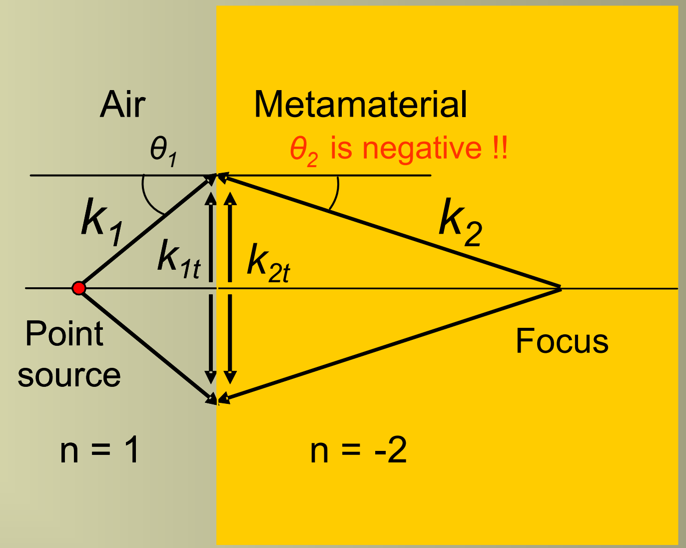
n=-2

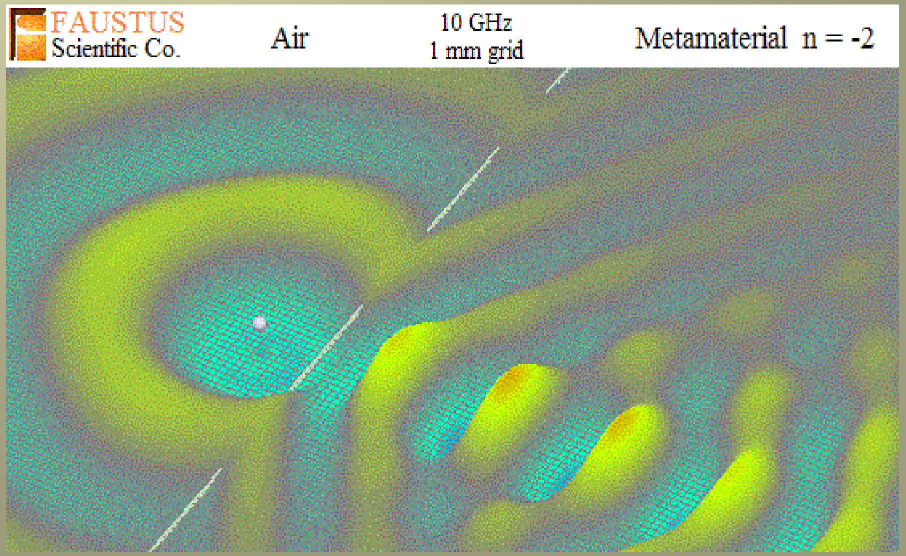
TLM Shunt Node Implementation of the Eleftheriades model

Negative Refraction

A wave emitted by a point source is focused in the metamaterial-filled half-space due to the negative angle of refraction.

The refraction angle is negative since the tangential component of the phase velocity must be continuous at the interface, as shown in the diagram above. The focusing effect and the negative phase velocity are confirmed by the MEFiSTo simulation.

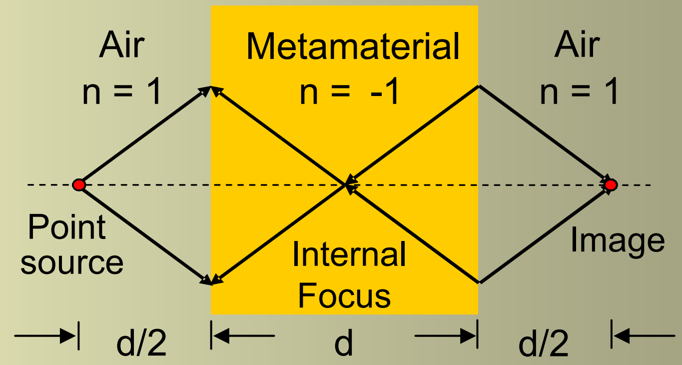


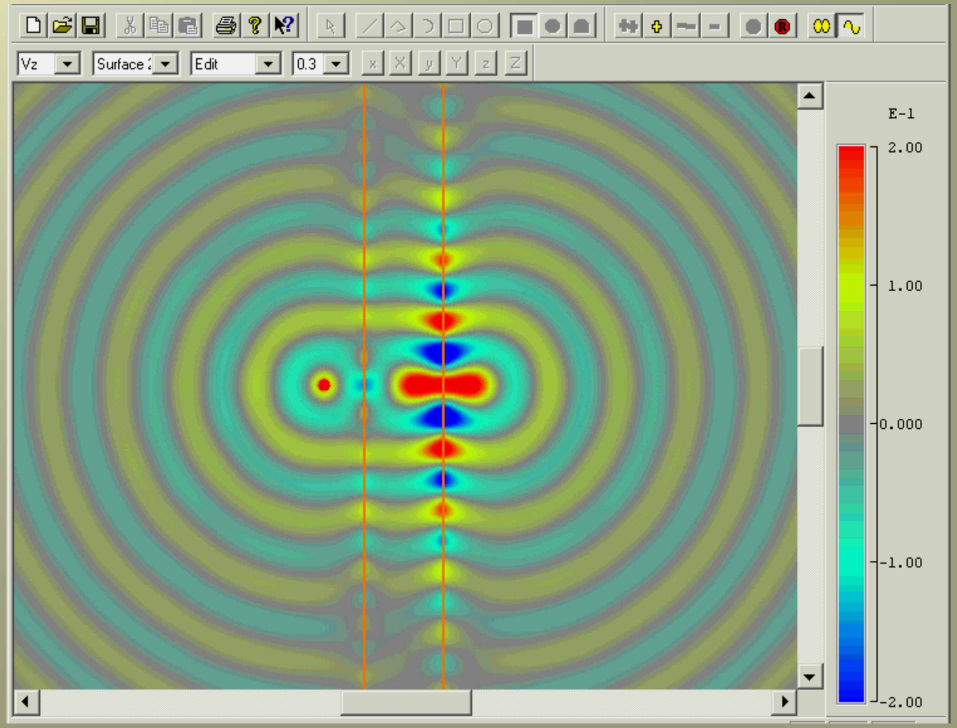


Pendry's Super Lens

John Pendry showed in 2000 that double negative refraction can be harnessed to create a perfect image of a point source. Pendry's lens outperforms classical lenses since it reconstitutes the near-field as well as the far-field of the source with sub-wavelength resolution.

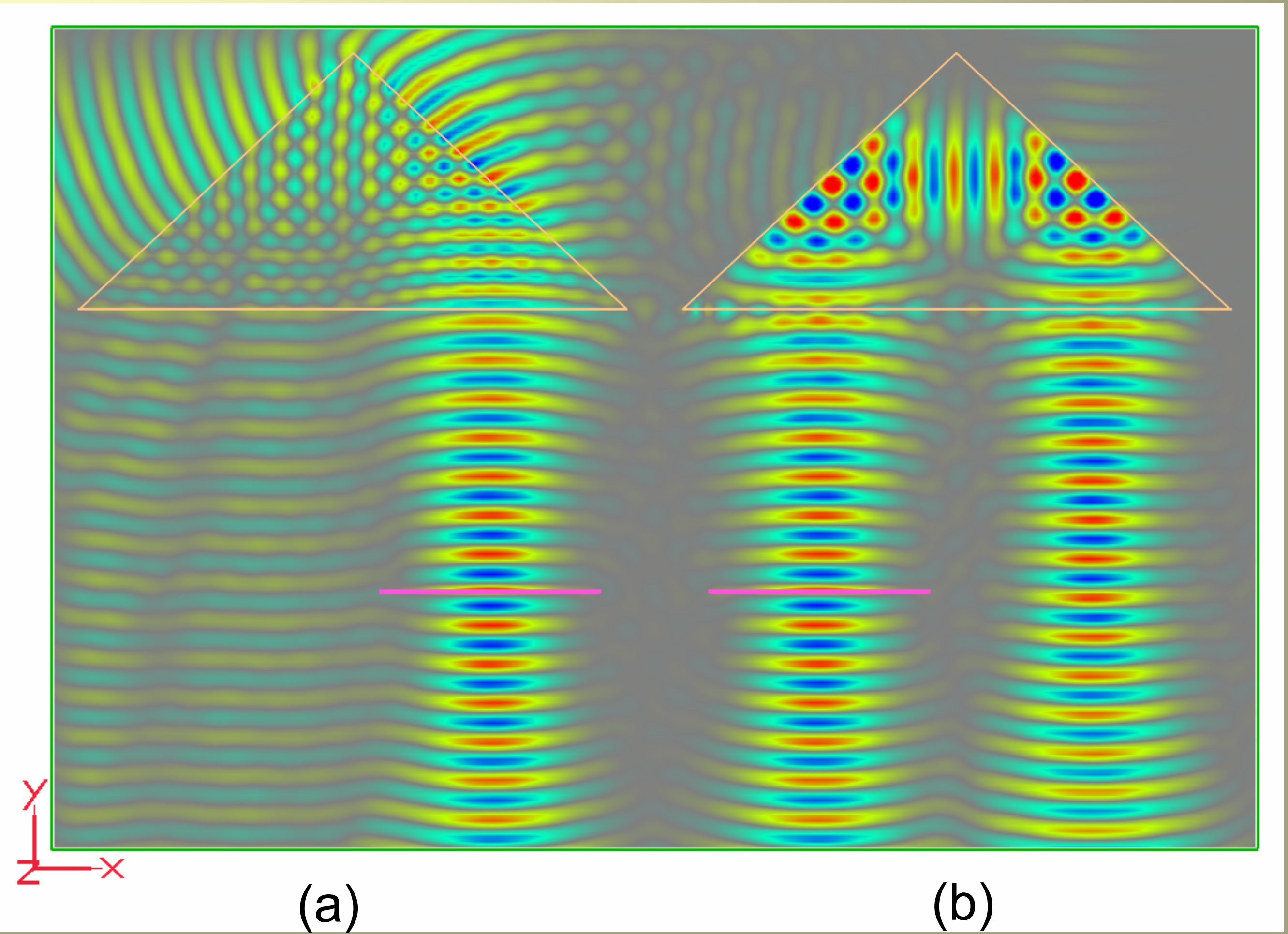
MEFiSTo visualizes this focusing action in all its complexity, confirming Pendry's theory as well as recent measurements made by Eleftheriades *et al*.





Metamaterial Prism

Refractive Index n=1.414



Refractive Index n = -1

Refraction of a Gaussian beam in a regular prism (a) and a metamaterial prism (b) computed with MEFiSTo-3D Pro

Conclusions

MEFiSTo Electromagnetic Simulators

- Extend traditional theory and laboratory work,
- Involve both the intellect and the intuition,
- Invite and facilitate experimentation,
- Are suitable for design, research, and education
- Emulate major instrumentation, such as:

- TDR	- Network Analyzer
- Oscilloscope	- Spectrum Analyzer
- Signal Processor	- Video System

Conclusion and Outlook

- MEFiSTo Time Domain Simulators are among the most general and versatile tools for electromagnetic modeling;
- They are easy to use by practitioners because they operate like a virtual electromagnetics laboratory;
- They are suitable for design, research, and education;
- They can be easily interfaced with other powerful tools;
- Research is continuing on many fronts:
  - Sensitivity Analysis based on Adjoint Modeling;
  - Direct electromagnetic synthesis;
  - Design of artificial materials with exotic properties;
  - Distributed and parallel computing;
  - Multi-level modeling and device – field interactions;
  - Time domain neural network models.