Introduction of Hybrid Multiscale Simulation Technologies

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Wave Computation Technologies, Inc.
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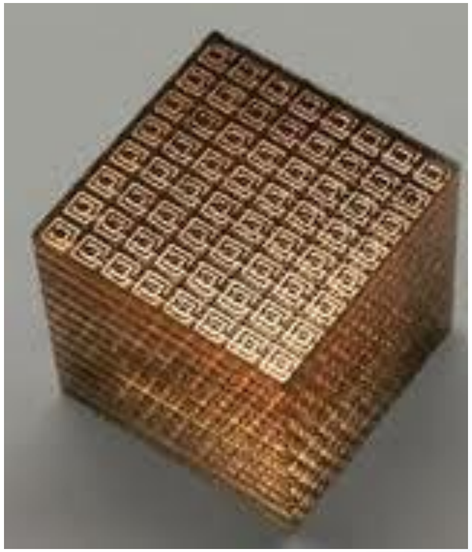
Contents

- Motivation and Vision
- Field-Circuit Co-Simulation
- Multiscale Simulation
- About the Company

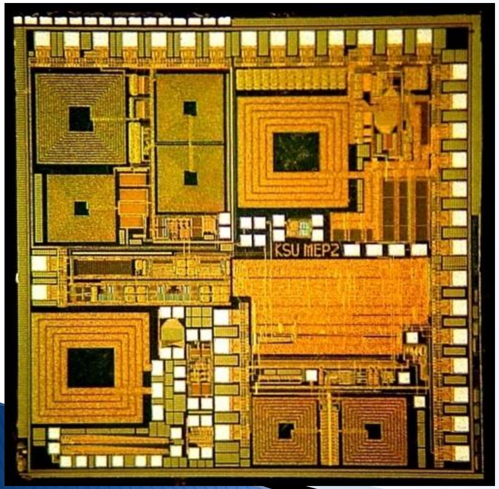
Why Hybrid & Multiscale?

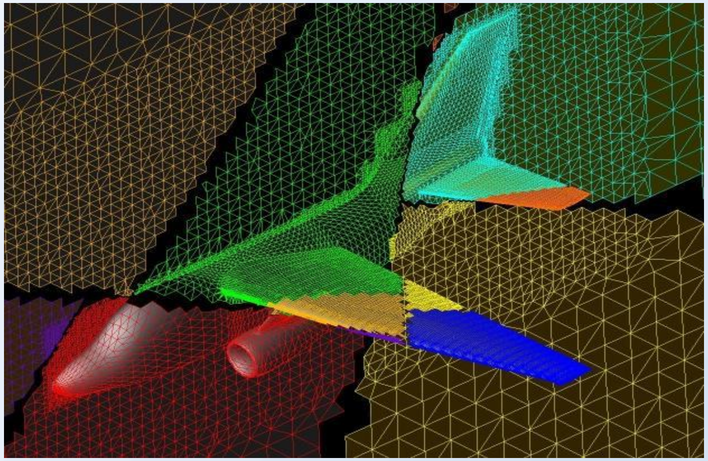
- Need
  Challenge
  Nature
  Vision

CAD Tools are Targeting More Practical Applications



Engineering Simulation





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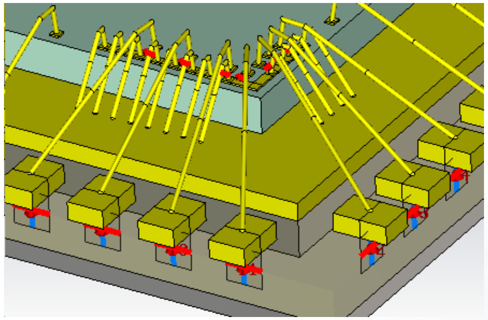
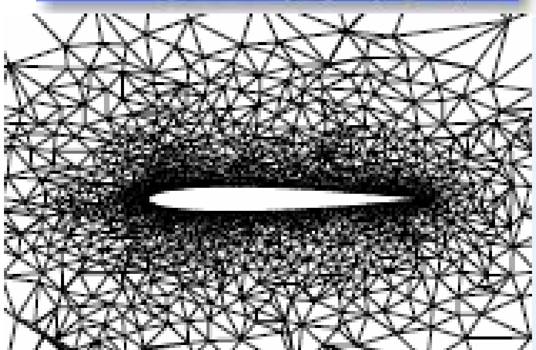
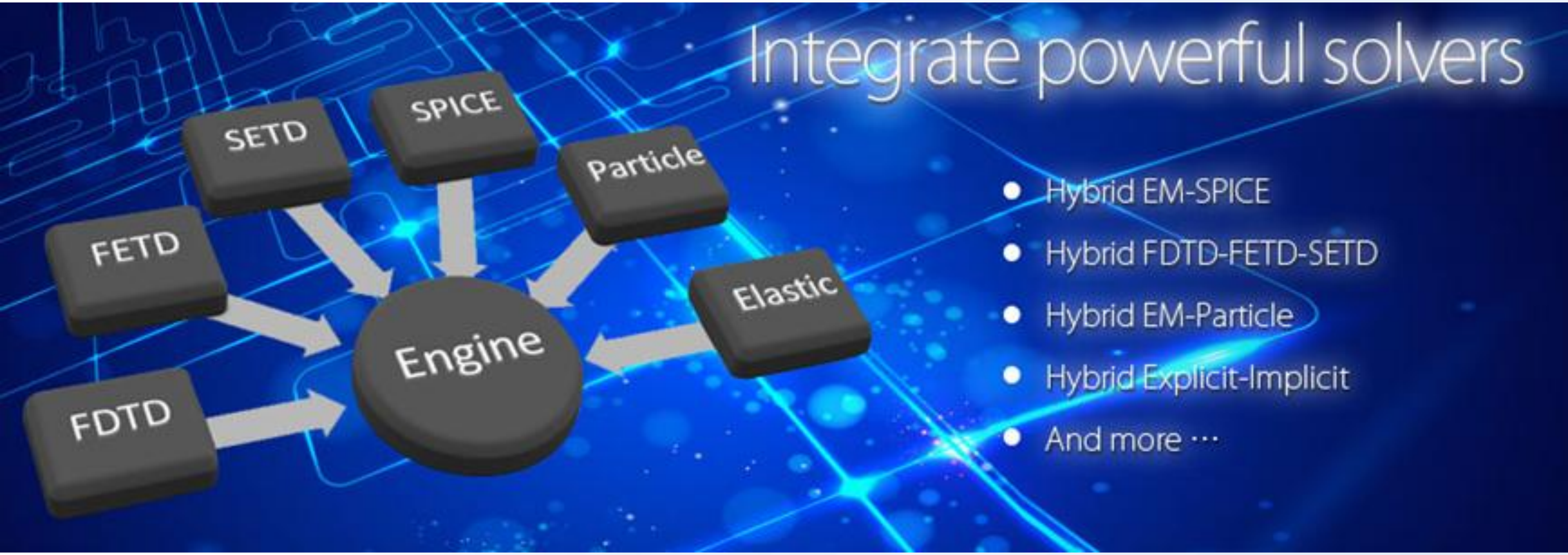
Understand the Real Challenge





- **Small features**
  - Sharp corners
  - Thin wires and surfaces
- **Multiscale**
  - From meters to millimeters
  - Thousands of small (mm level) units
  - Large (m level) platforms
  - L-band to U-band (1-60GHz)
- **Multiphysics**
  - Liquid or gas (CFD)
  - Heat transfer (Thermal)
  - RF-Circuit system (MNA)
  - THz antennas (Diffusion)
- **Solution**
  - Breathe the emerging technologies
  - Hybrid multiscale simulation engine

A Brief Review of Popular Transient Techniques



- FDTD – Finite Difference
- FETD – Finite Element
- SETD – Spectral Element
- DGTD – Discontinuous Galerkin
- SPICE – Simulation Program with Integrated Circuit Emphasis

NextGen Simulator

The thing is:

For multi-scale, multi-application problems, is hybrid technique simply putting things together?

- **Single Algorithm, Multi Physics**
  - FEM solvers
    - Mechanics, CFD, CEM
- **Single Physics, Multi Algorithms**
  - Multiscale EM problems
    - Hybrid time-domain solvers
    - Hybrid freq-domain solvers
- **Multi Algorithms, Multi Physics**
  - Hybrid FD, FE, FV
  - Hybrid DE, IE
  - Hybrid TD, FD
- **Multi Process**
  - Hardware computing (FPGA/CPLD)
  - Parallel computing (MPI/GPU/Multithreading)

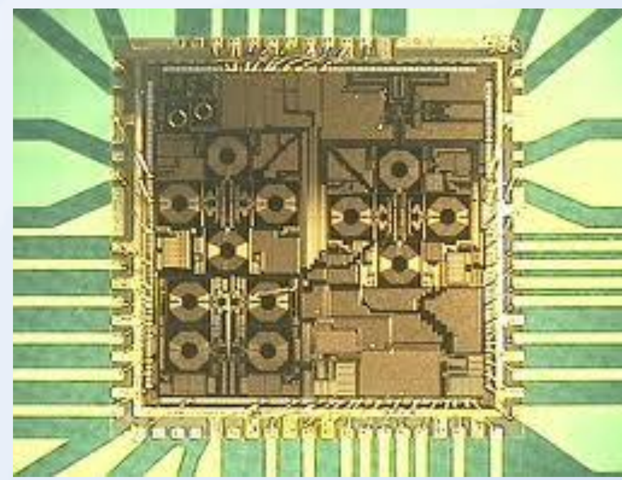
Field-Circuit Co-Simulation

- Key Techniques
- Applications

Background

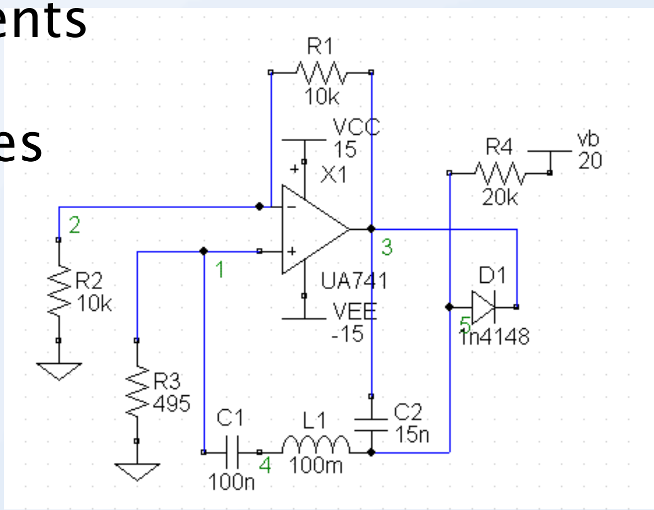
- **Modern Circuit Systems**
  - Multifunctional
  - High operating frequency
  - Large integration scale

- **Challenges**
  - Complex material and device
    - Equivalent circuit modeling is limited
  - High frequency
    - EM effects
  - Small distance
    - Interference



Circuit Solver – SPICE

- Modified Nodal Analysis (MNA)
  - General analysis method used to compute nodal voltages and branch currents of a lumped electronic circuit network
  - Graph Theory
    - Circuit is represented via a graph
    - Branches of the graph are circuit elements
    - Every branch is bound by two nodes
    - Nodes form the connectivity of branches
      - 1 reference node (typically ground)
    - Every node assigned a voltage
    - Every branch assigned a current



MNA

- DOFs
  - Node voltages
  - Branch currents of:
    - Voltage sources and inductors
- Linear system of equations
  - Kirchoff's current law (KCL) at every non reference node:
  - KVL about all branches supporting a voltage source

$$\sum_{i=1}^{N_a} I_i = 0 \qquad \sum_{i=1}^{N_b} V_i = 0$$

- MNA for general circuit
  - Reactive elements (L & C)
  - Non-linear elements

$$\begin{pmatrix} \mathbf{X} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \dot{\mathbf{x}}_{sp} \\ \dot{\mathbf{i}}_v \end{pmatrix} + \begin{pmatrix} \mathbf{Y} & \mathbf{B}^T \\ \mathbf{B} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{x}_{sp} \\ \mathbf{i}_v \end{pmatrix} + \begin{pmatrix} \mathbf{i}(\mathbf{x}_{sp}) \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} -\mathbf{i}_s \\ \mathbf{v}_s \end{pmatrix}$$

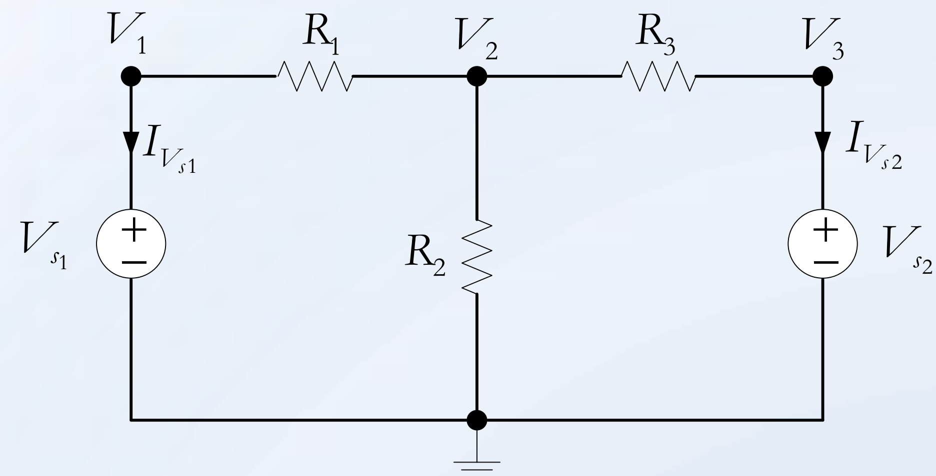
Example

- **MNA**

$$\frac{V_1 - V_2}{R_1} + I_{v_{s1}} = 0 \qquad V_1 = V_{s_1}$$

$$\frac{V_2 - V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_2 - V_3}{R_3} = 0 \qquad V_3 = V_{s_2}$$

$$\frac{V_3 - V_2}{R_3} + I_{v_{s2}} = 0$$



- **Linear System**

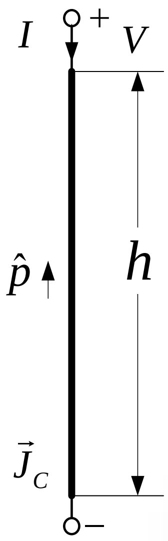
$$\begin{pmatrix} \frac{1}{R_1} & -\frac{1}{R_1} & 0 & 1 & 0 \\ -\frac{1}{R_1} & \frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3} & -\frac{1}{R_3} & 0 & 0 \\ 0 & -\frac{1}{R_3} & \frac{1}{R_3} & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ I_{v_{s1}} \\ I_{v_{s2}} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ V_{s_1} \\ V_{s_2} \end{pmatrix} \Rightarrow \begin{pmatrix} \mathbf{Y} & \mathbf{B}^T \\ \mathbf{B} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{v}_{sp} \\ \mathbf{i}_v \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ \mathbf{v}_s \end{pmatrix}$$

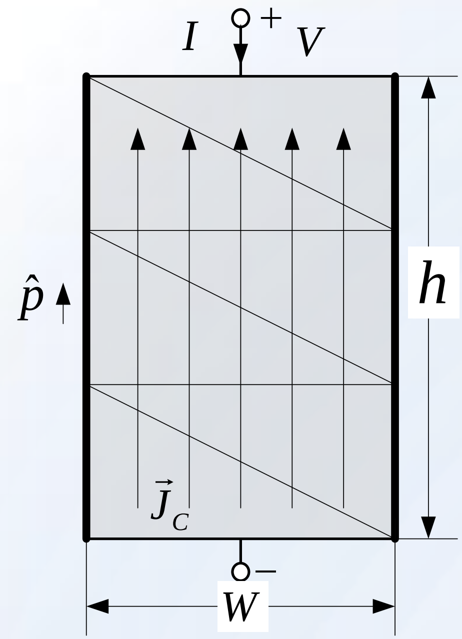
Field-Circuit Port (Cont'd)

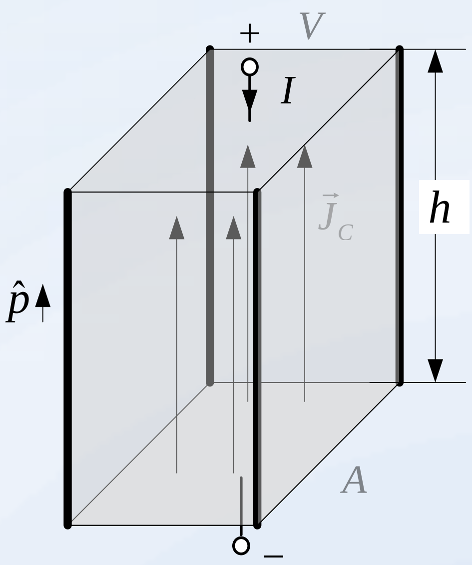
- **Port Definition**
  - An interface that handles the data exchanging between two solvers
- **Circuit Port**
  - Convert the local E-field into a circuit voltage and couple the circuit current back into EM solver as a equivalent "J" current source.
- **Quasi-Static Approximations**
  - E-field is conservative within the port region
  - Line integration of the field is assumed to be independent of the path
  - The feed-back current is evenly distributed through the port region

Bo Zhao, Young, J.C, Gedney, S.D "SPICE Lumped Circuit Subcell Model for the Discontinuous Galerkin Finite-Element Time-Domain Method," *Microwave Theory and Techniques, IEEE Transactions on* , vol.60, no.9, pp.2684-2692, Sept. 2012

Field–Circuit Port







$$V \approx -\int_{L_C} \vec{E} \cdot \hat{p} dl$$

$$V \approx -\frac{1}{W} \int_{S_C} \vec{E} \cdot \hat{p} ds$$

$$V \approx -\frac{1}{A} \int_{V_C} \vec{E} \cdot \hat{p} dv$$

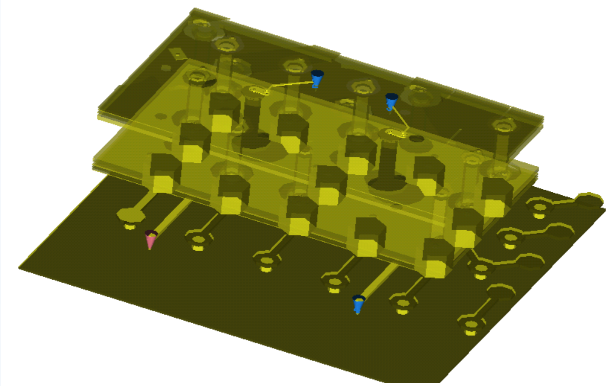
$$\vec{J}_C = \hat{p} I$$

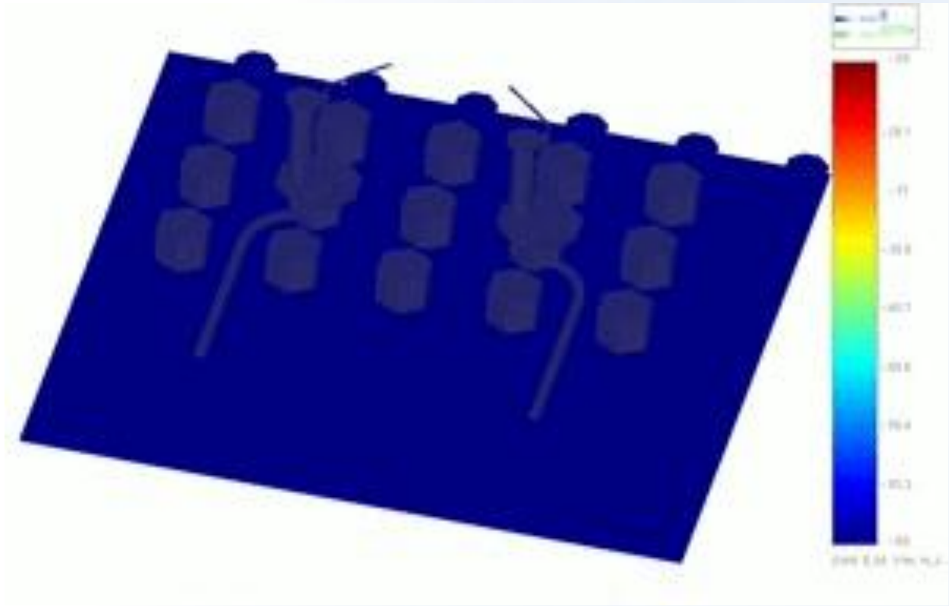
$$\vec{J}_C = \hat{p} \frac{I}{W}$$

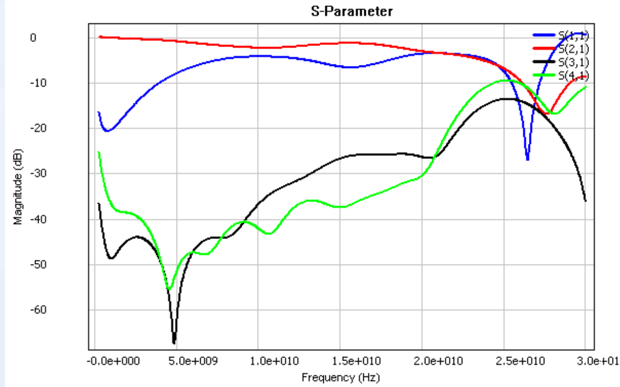
$$\vec{J}_C = \hat{p} \frac{I}{A}$$

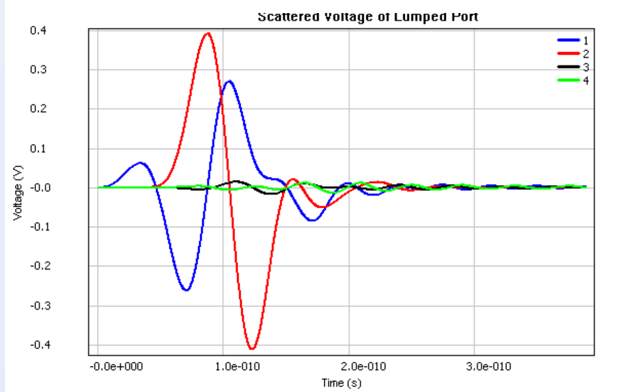
Crosstalk Analysis of an IC Package

- IC package
- Simulated by Wavenology EM using a quad-core PC. Takes around 10 hours and uses 4GB memory
- The sink in S11 indicates a resonance, and it is revealed in the surface current snapshot

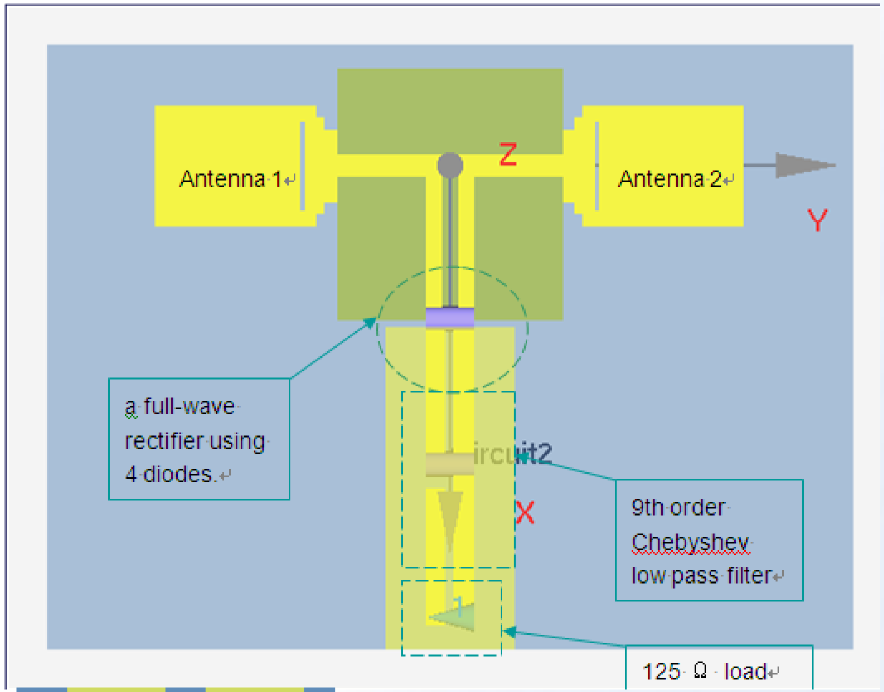


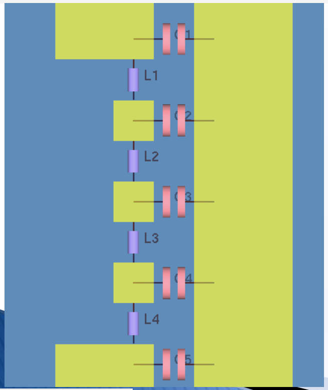


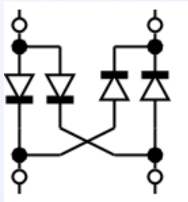


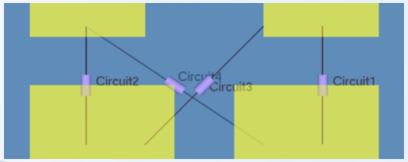


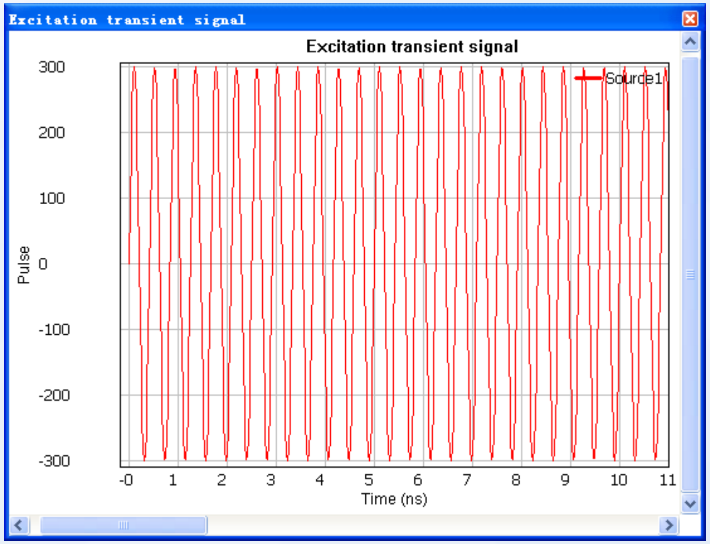
Ambient Power Collector

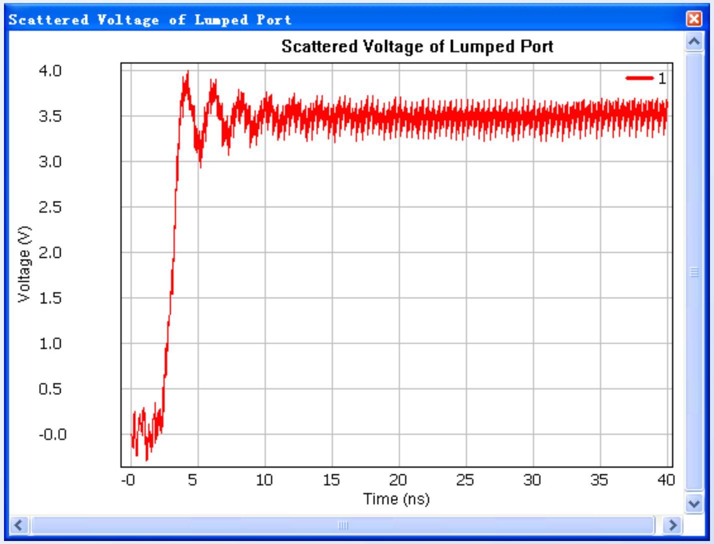






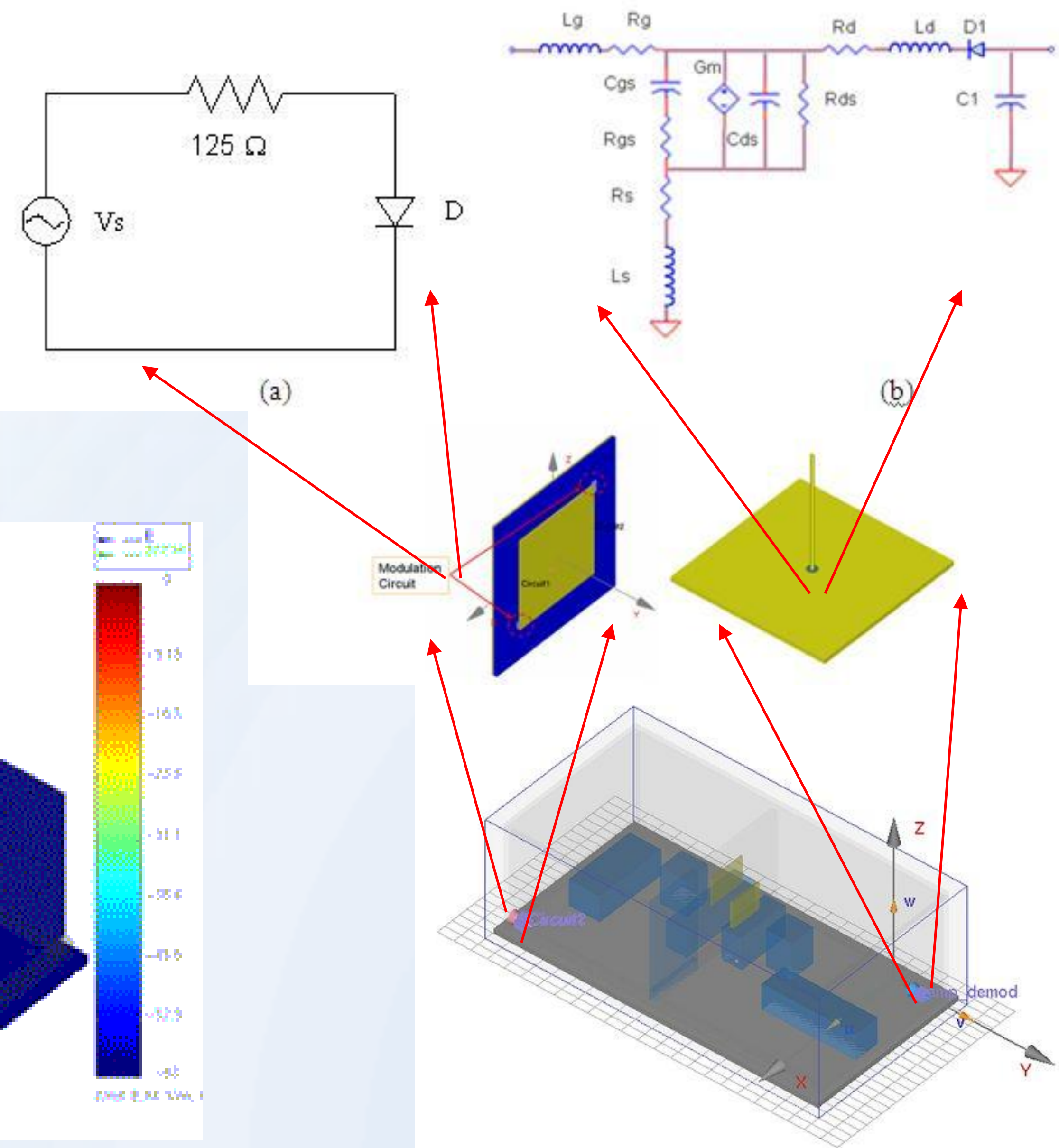


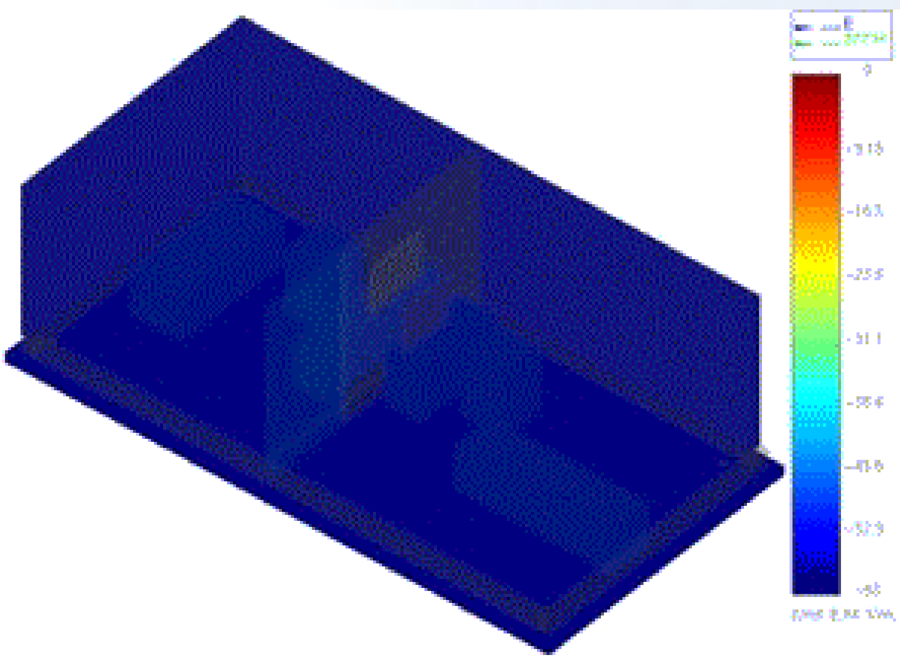




End-to-End Simulation of Antenna Systems

- Modulating Circuit applied on patch antenna
- Demodulating and amplification circuits applied on monopole antenna
- Two devices put in two corners of a two-bedroom model with walls, frames and furniture considered.





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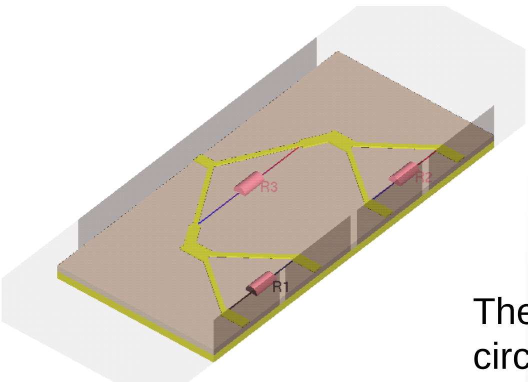
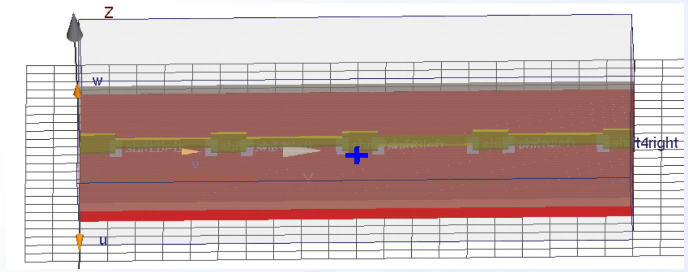
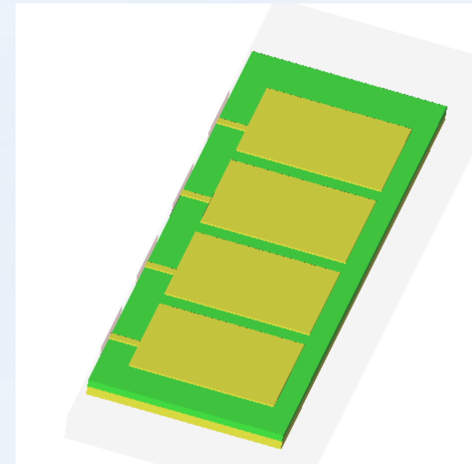
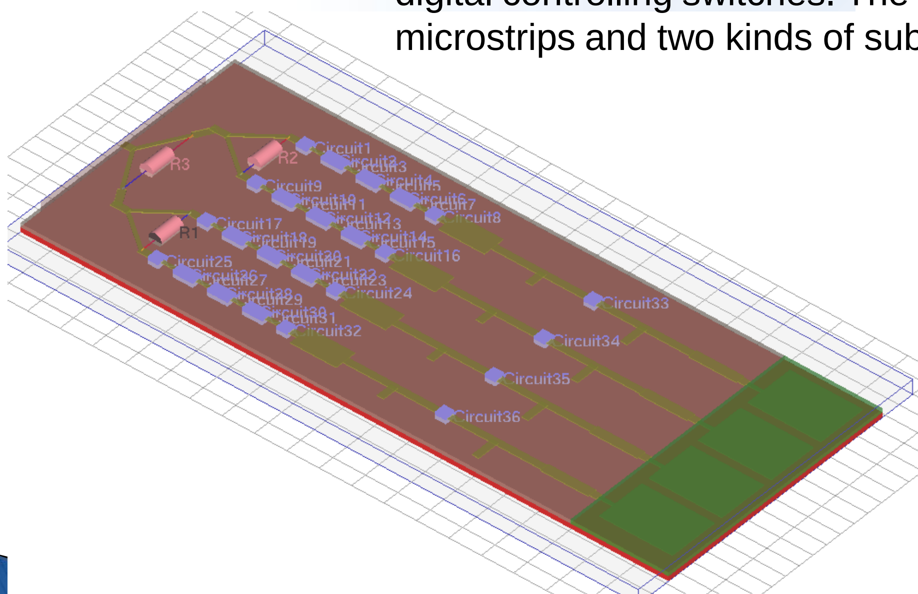
Solution for Phased Array Design

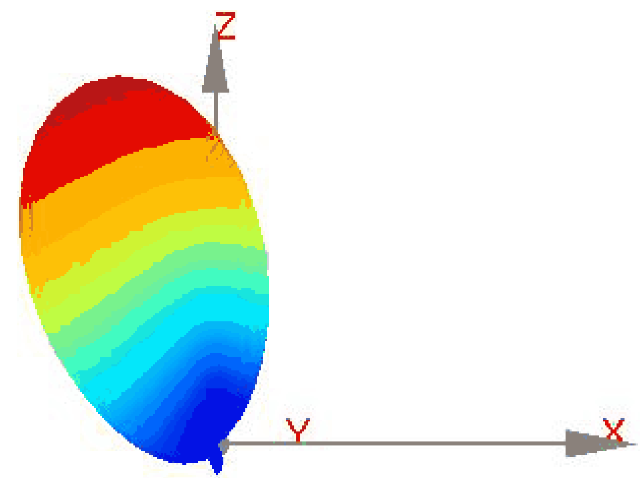






The system contains 32 independent circuits. Each circuit contains 4 capacitors, 2 resistors and two digital controlling switches. The system contains 53 microstrips and two kinds of subtrates

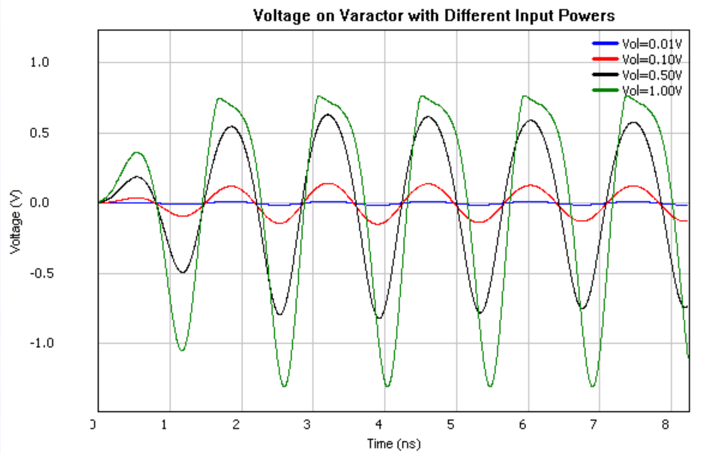


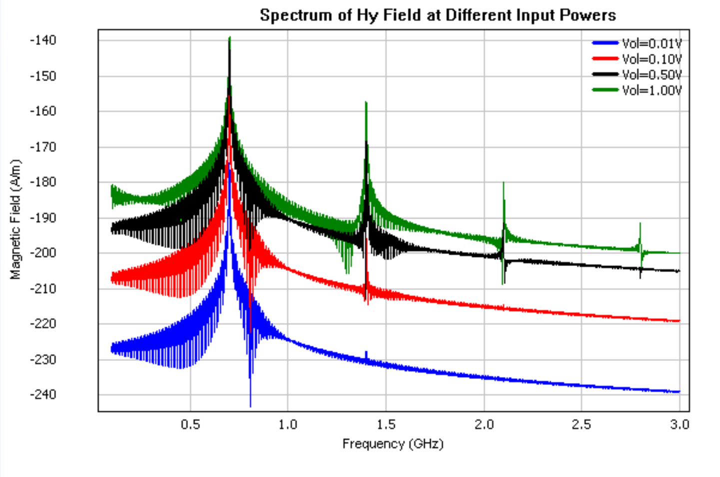


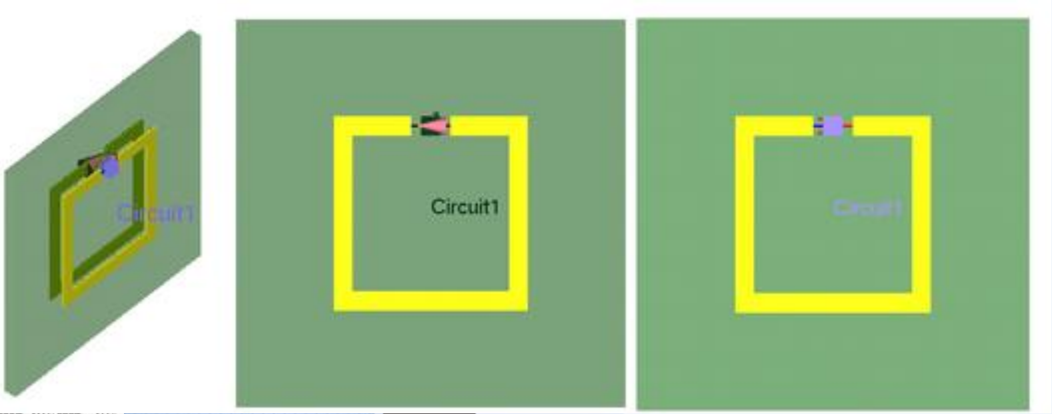
IEEE EMC SOCIETY

Full-Wave Non-Linear Analysis

- **Parametric Upconverter**
  - 50 Ohm lumped port
  - Varactor diode SMV1231
  - 0.7GHz sinusoid source signal
  - Power sweeping
    - 0.01, 0.1, 0.5 and 1V.
  - Cut-off effect in transient signal
  - Harmonics in spectrum

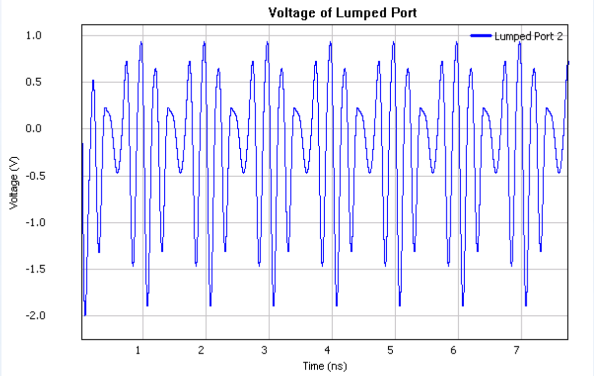


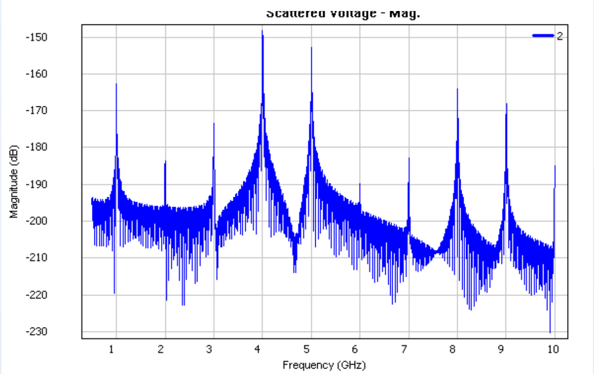


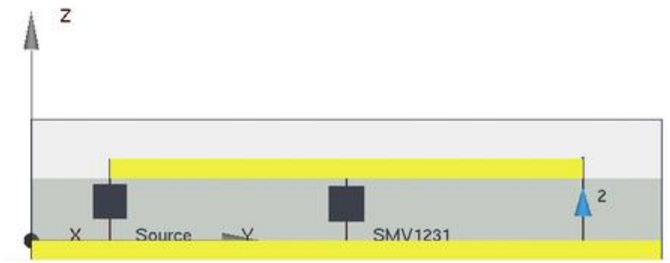


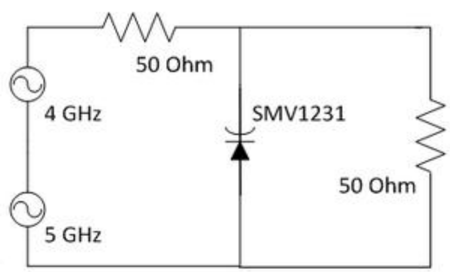
Beyond X-Parameters

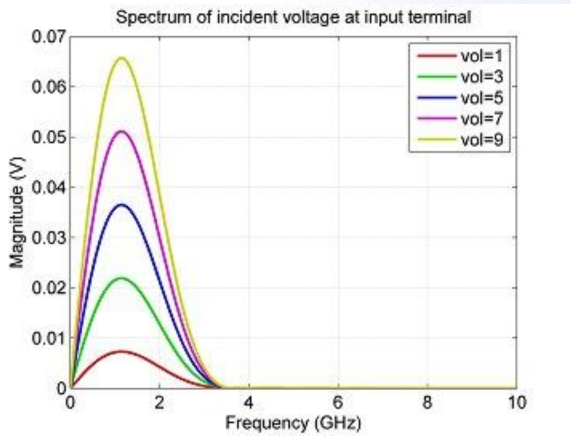
- **Parametric Amplifier**
  - 4GHz, 5GHz sinusoid signals are mixed.
  - f_down=1GHz, f_up = 9GHz
  - Wideband BHW signal also applied. Non-linear effects completely expanded the spectrum outside the input spectrum.

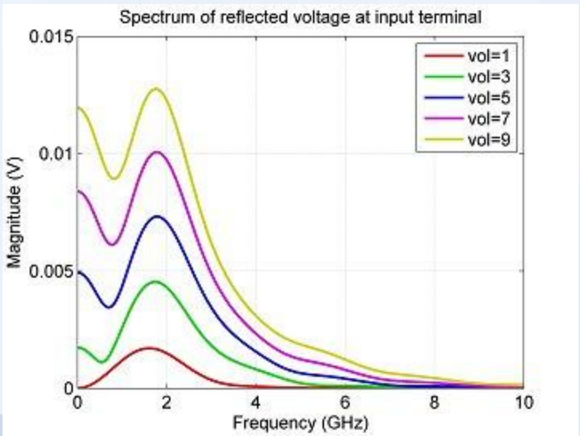


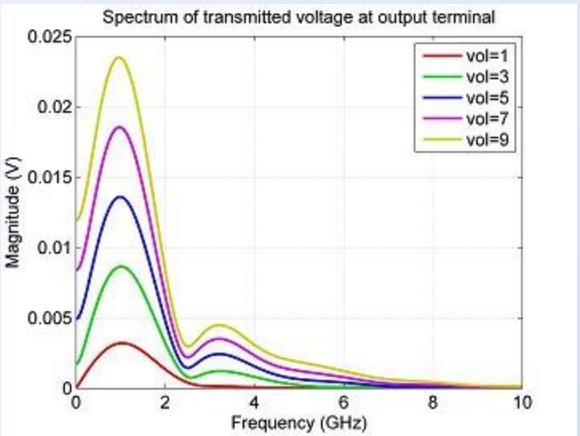




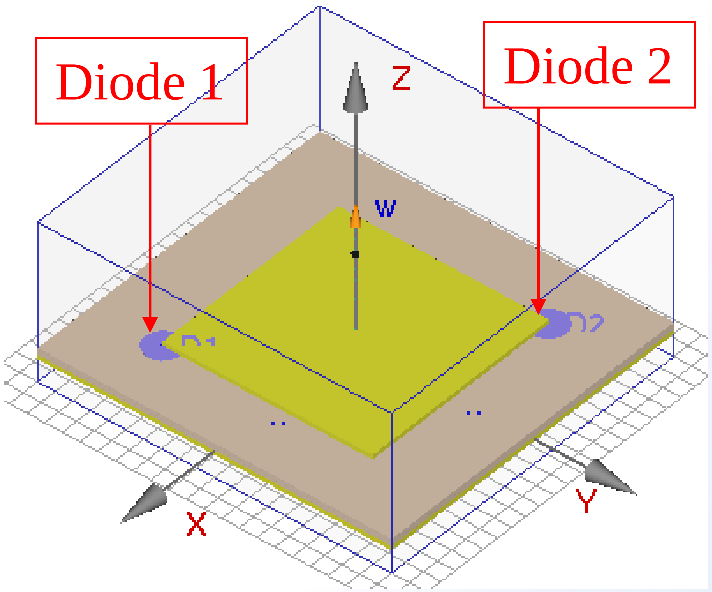




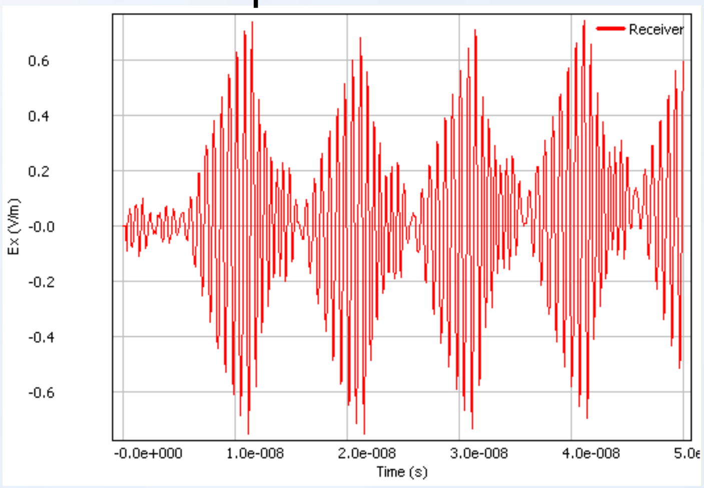




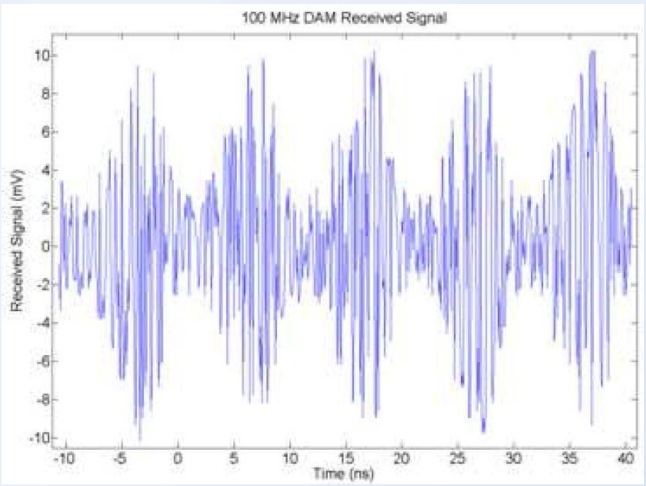
Antenna Direct Modulation



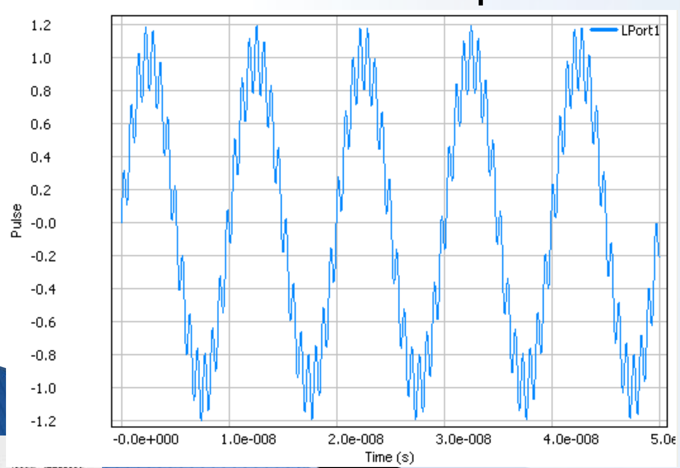
Output at receiver



Measured

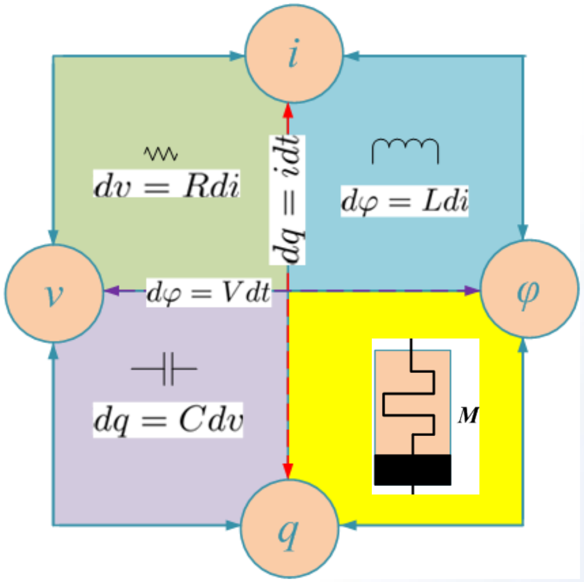


Modulated input



Steven David Keller, "DESIGN AND DEVELOPMENT OF DIRECTLY-MODULATED ANTENNAS USING HIGH-SPEED SWITCHING DEVICES," Thesis, Dept. of ECE, Duke Univ.

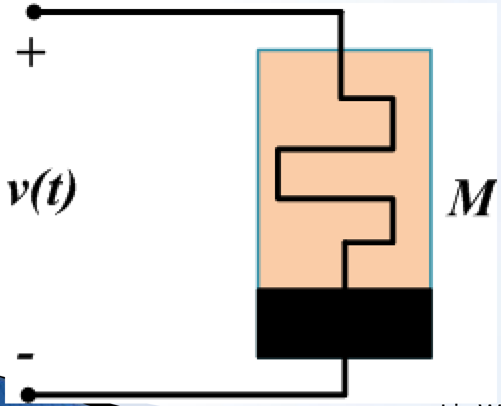
Memristor (M) – Memory Resistor: The Missing Fourth Passive Circuit Element

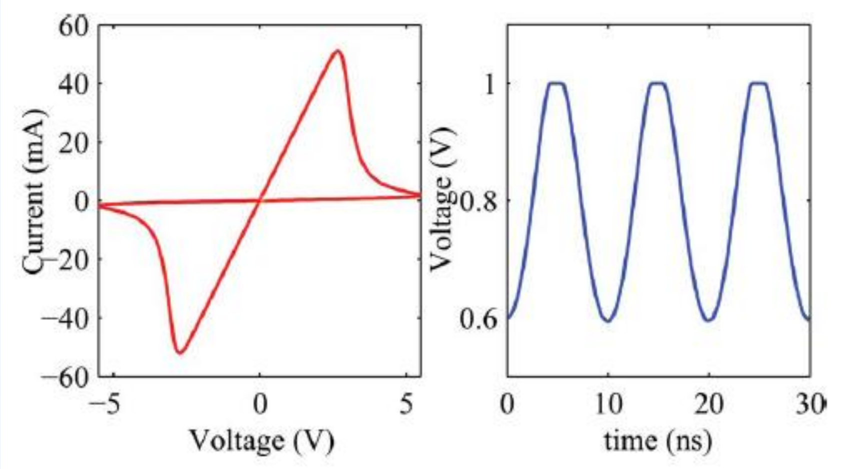


- 4 basic variables: v, i, q, φ
- 3 electrical circuit elements: R, L, C
- 2 time relationship: v - φ and q – I1

$$M(q(t)) = \frac{d\phi}{dq} = \frac{d\phi/dt}{dq/dt} = \frac{V(t)}{I(t)}$$

Invented by Leon Chua (1971). Produced by HP (2008)



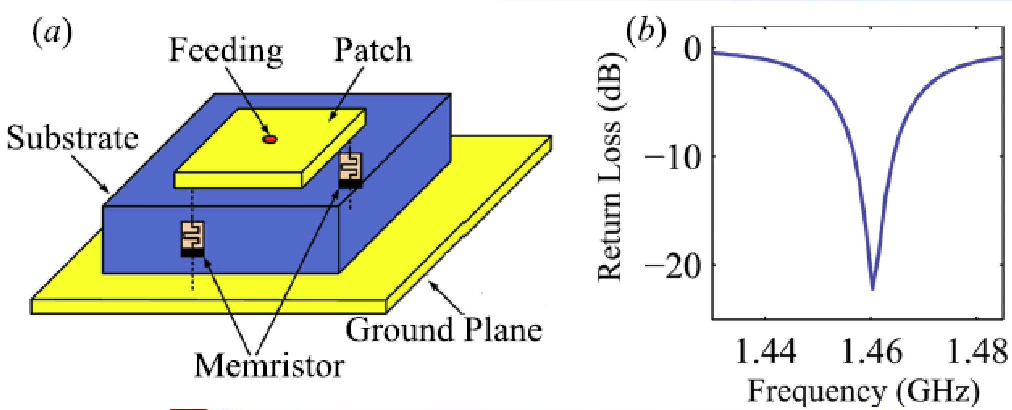


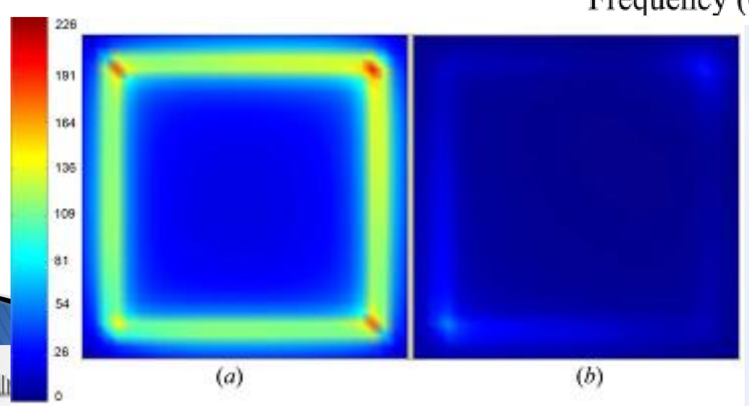
I-V hysteresis

Lin Wang; Mengqing Yuan; Tian Xiao; Joines, W.T.; Liu, Q.H.; , "Broadband Electromagnetic Radiation Modulated by Dual Memristors," *Antennas and Wireless Propagation Letters, IEEE* , vol.10, no., pp.623-626, 2011

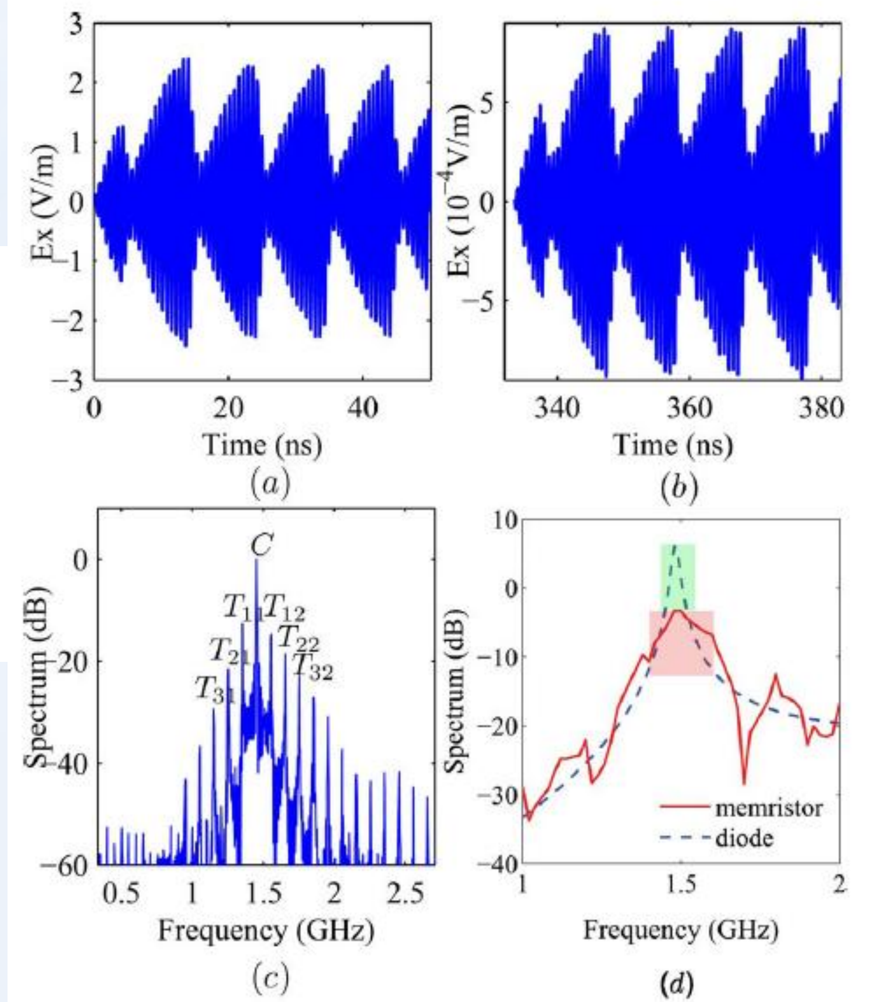
Antenna Direct Modulation with Memristors

- **Excitation source:**
  - 200 MHz – 4895 MHz,
  - Char. frequency: 1460 MHz

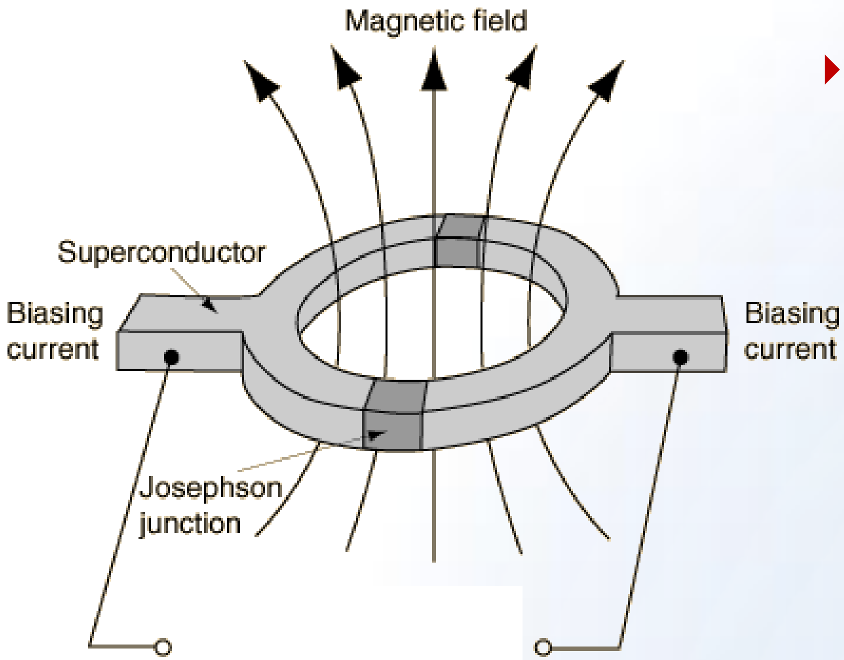


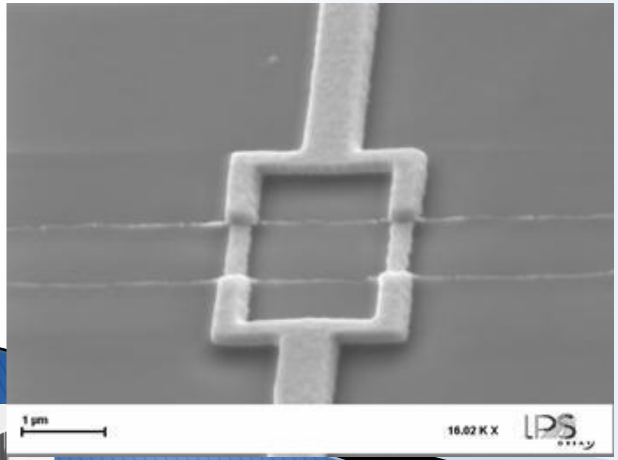


Near Field
Far Field



Superconducting Devices

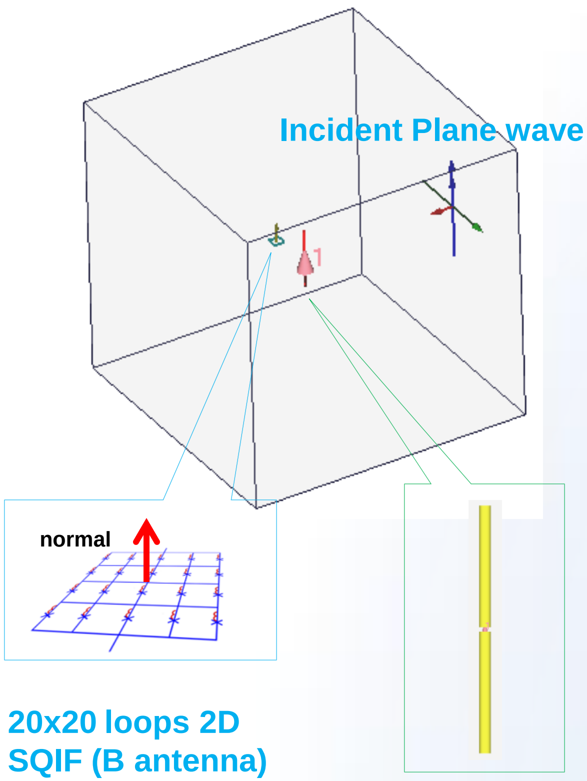




- **Superconducting Quantum Interference Devices (SQUIDs)**
  - Josephson Junctions (50-100GHz)
  - Extremely sensitive magnetic field sensors.
    - Low Noise SQUID Array Amplifiers
    - Ultra-High Resolution SQUID Magnetometers
    - SQUID Sensors for Low Frequency Imaging Applications
    - SQUID Particle and X-ray Detectors
    - SQUID Cryogenic Detector Arrays
    - SQUID Digital Processors
    - B-Field Receiving Antennas

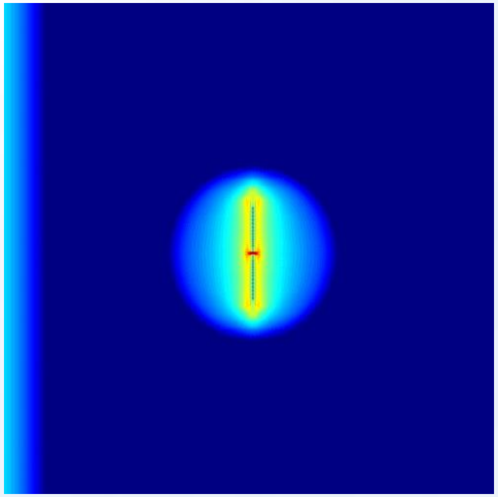
Field-SQUID Co-Simulation

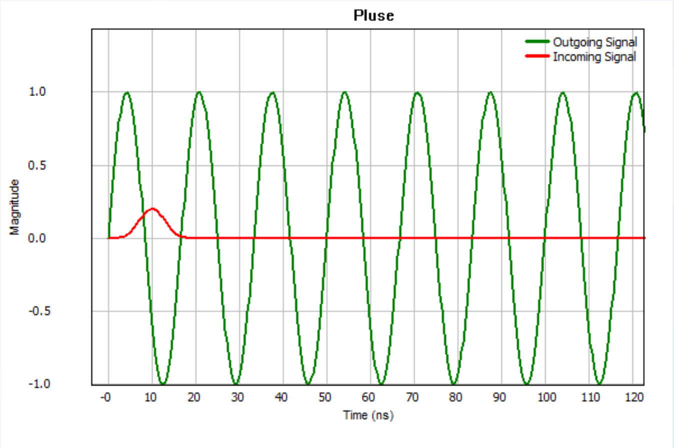
E-Transmitter: Dipole antenna
B-Receiver: SQIF array positioned near the dipole antenna
Transmitting signal: Sinusoid
Receiving signal: Gaussian



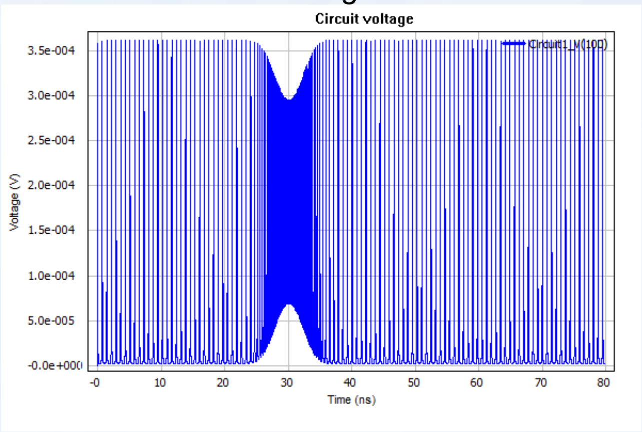
20x20 loops 2D SQIF (B antenna)

λ/2 dipole E antenna

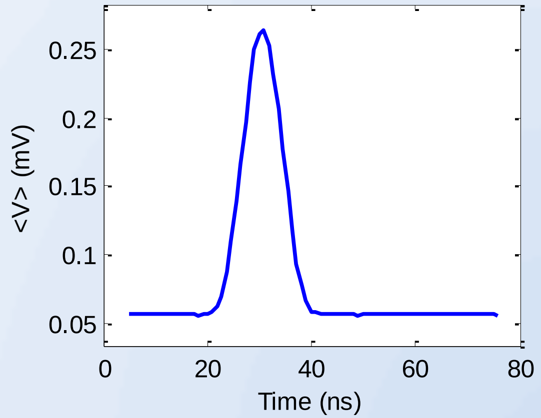




Transient voltage on B antenna



Averaged Voltage Output on SQIF



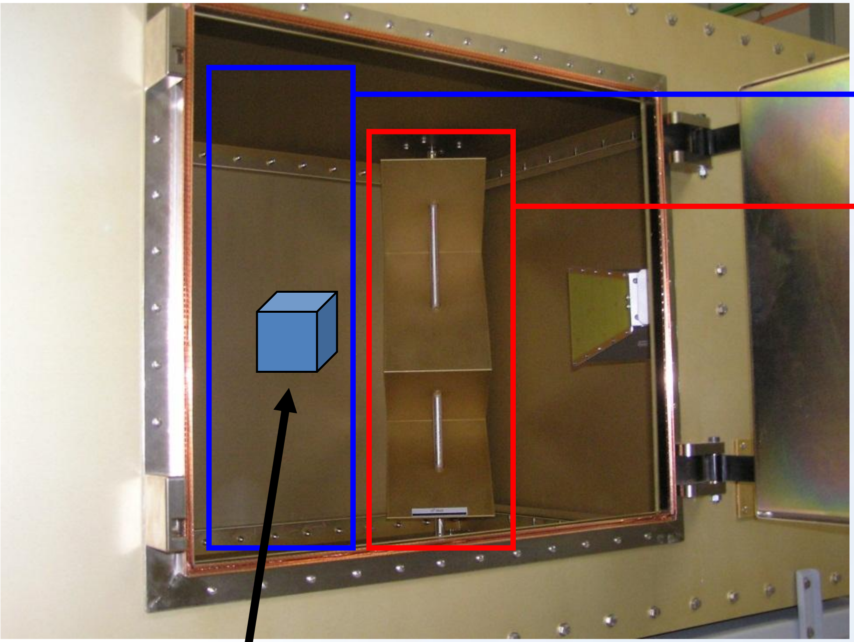
Summary

- **Field-Circuit Co-Simulation**
  - Internal Simple Circuit Elements
  - Full-Wave SPICE Analysis
    - Equivalent circuit modeling is still powerful
      - Semiconductor-based devices
      - Superconductor-based devices
      - Other novel devices
    - Non-linear effects considered in full-wave analysis
    - Coupling with EM fields is more critical as frequency goes higher and higher

Multiscale Simulation Techniques

- **Multiscale Concept**
- Review of Challenges and Solutions
- Applications

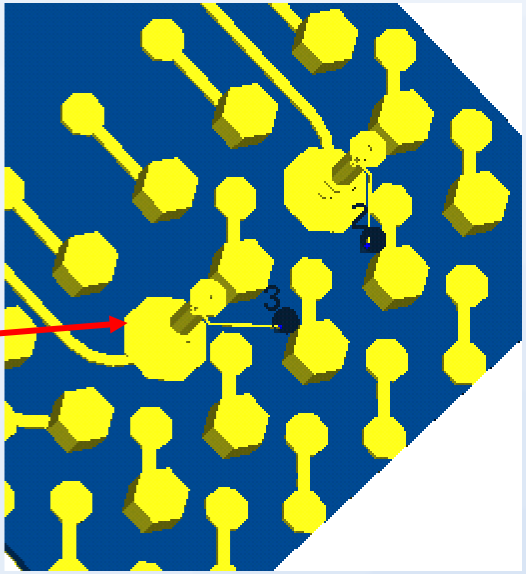
Challenge in System-Level RF Design: EMI Reverberation Chamber at 30 GHz (λ=1 cm)



- Electrically coarse structure

Chamber 1.6 m X 1.2 m X 0.8 m

- **Electrically fine structure**



Interconnect feature < 0.1 mm

No solvers can simulate such a problem on a workstation

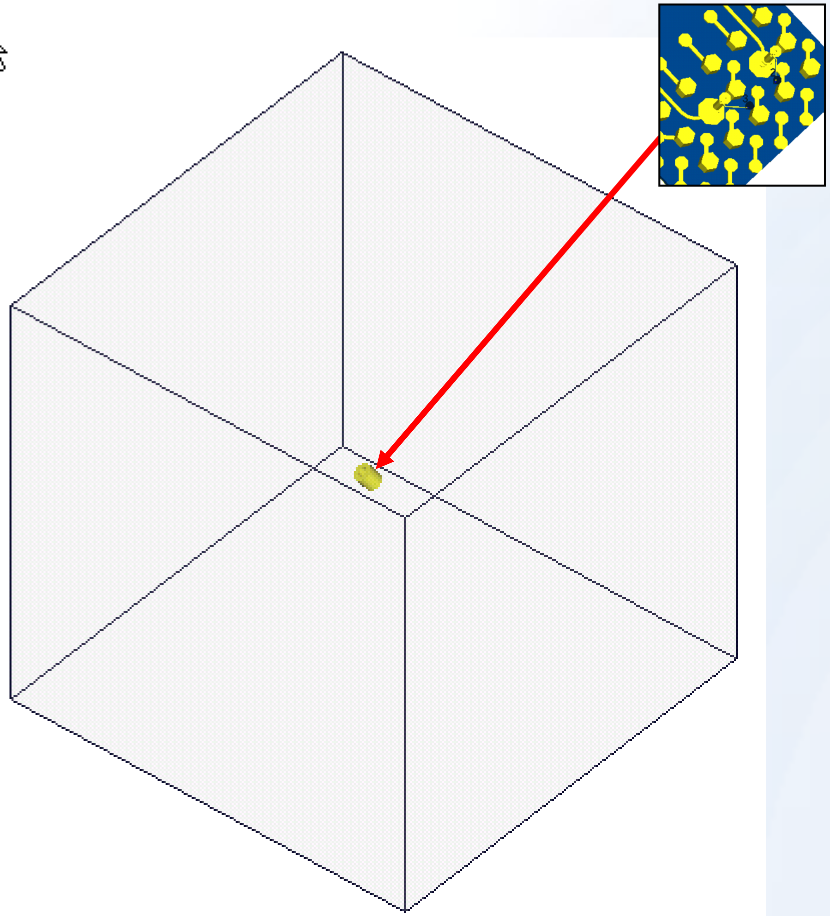
Uniform FDTD would require 40000 X 30000 X 20000 = 24 trillion cells

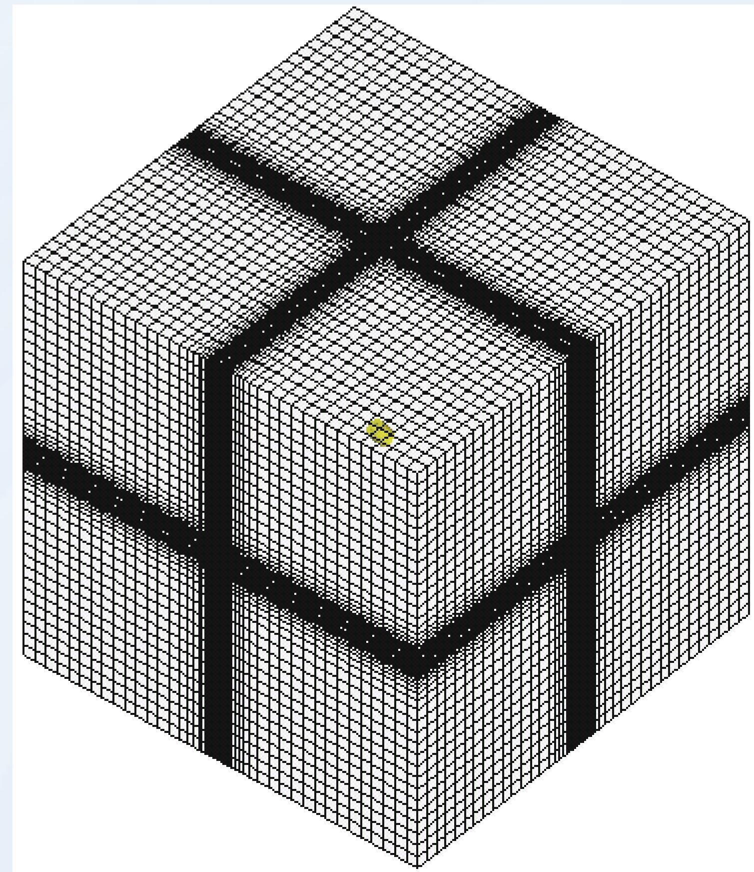
Multiscale factor: $\frac{\Delta}{\delta} = \frac{1.6}{0.0001} = 16000$

FDTD cell: $\Delta x = 0.04$ mm

Best and Worst Scenarios for FDTD

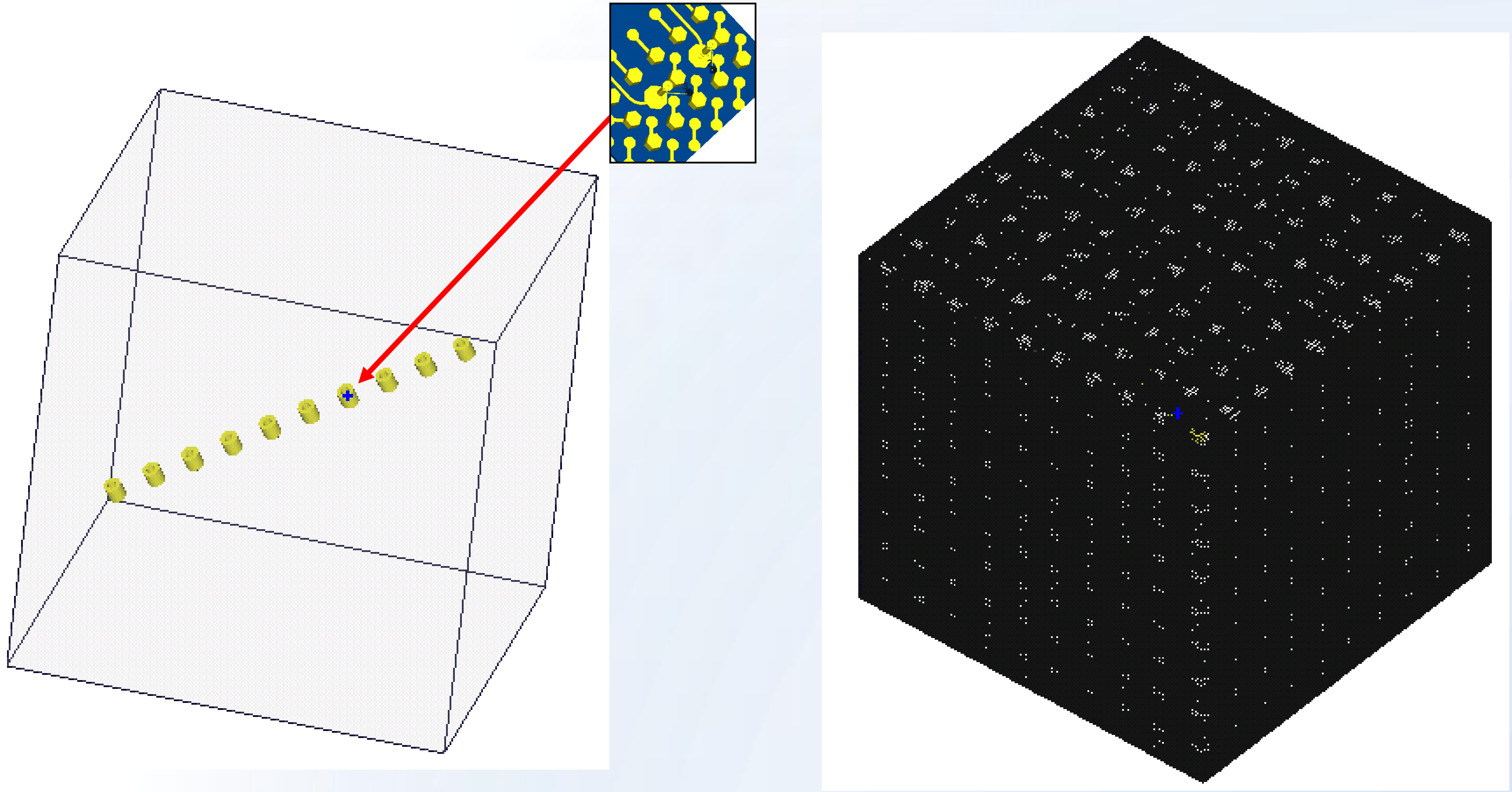
- Best scenario: Clustered fine details





Fine cells are localized

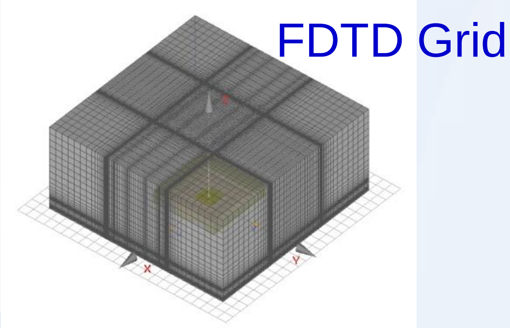
- Worst scenario: Spread-out fine details

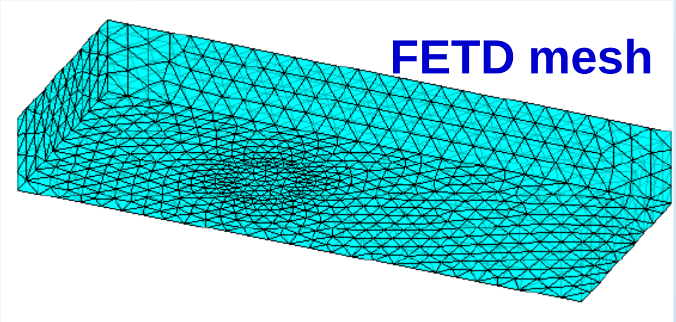


Fine cells are global

Challenges for Conventional Methods

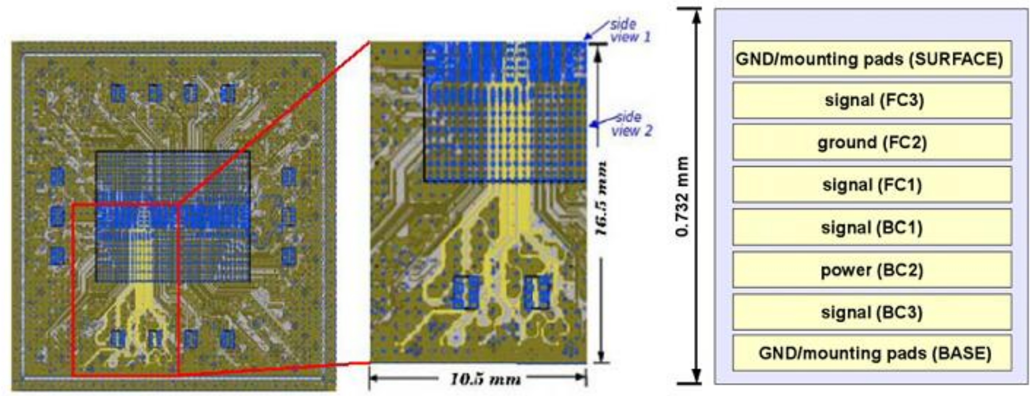
- **Spatial discretization**
  - FDTD: too many unknowns due to structured grid
  - FETD: inversion or factorization of large mass matrices
- **Time integration**
  - Explicit scheme: e.g. Leap-Frog, Ex Ruge Kutta
    - very small **Δt** due to CFL stability condition – too many time steps
  - Implicit scheme: e.g. Crank-Nicolson, Im Ruge Kutta
    - inversion or factorization of large matrices – large memory and CPU time



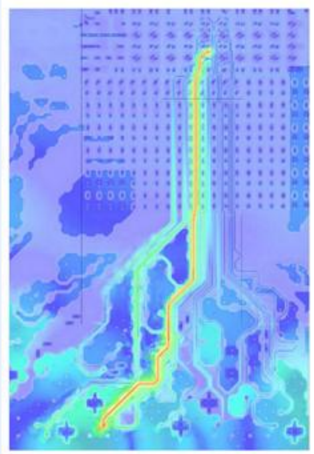


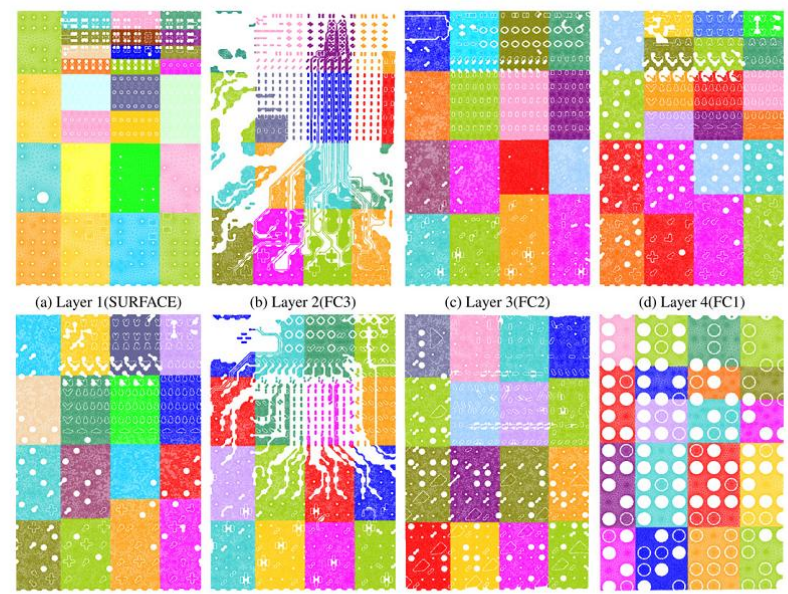
Transient DDM within Finite Element Method

- **Flux Operation**
  - Central Flux
  - Upwind Flux
- **Domain Interface**
  - Conformal
  - Non-Conformal
- **Parallel Computing**
  - MPI/GPU/Multithreading
  - Load Balancing



(a) IBM model (b) Layer Structure




(a) Layer 1(SURFACE) (b) Layer 2(FC3) (c) Layer 3(FC2) (d) Layer 4(FC1)
(e) Layer 5(BC1) (f) Layer 6(BC2) (g) Layer 7(BC3) (h) Layer 8(BASE)

Stylianos Dosopoulos, Bo Zhao, Jin-Fa Lee, Non-conformal and parallel discontinuous Galerkin time domain method for Maxwell's equations: EM analysis of IC packages, Journal of Computational Physics, Volume 238, 1 April 2013, Pages 48-70

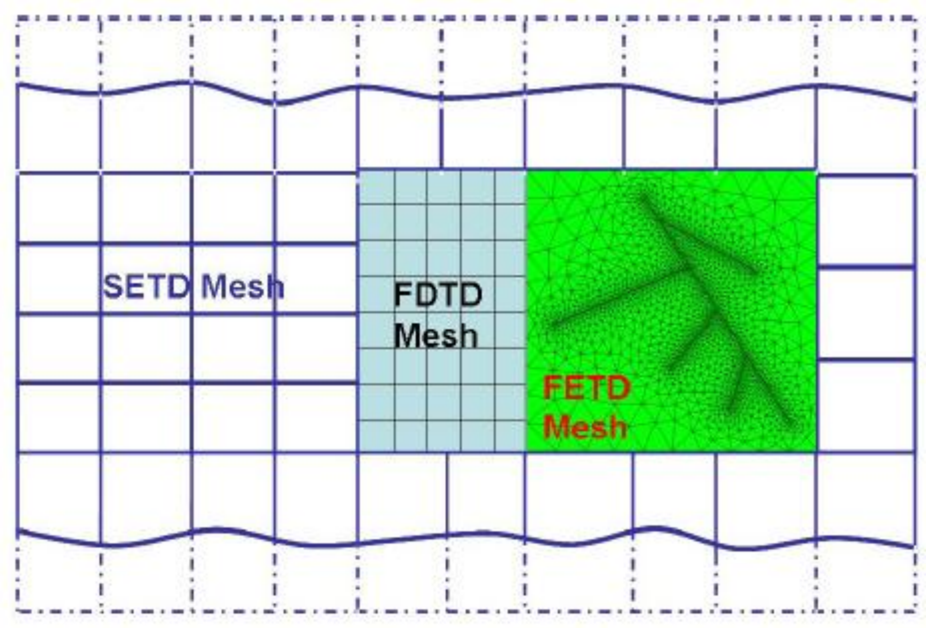
Multiscale Hybrid SETD/FDTD/FETD Method

- Electrically fine structures: lower order tetrahedral FETD
- Electrically coarse structures: higher order hexahedral SETD
- Intermediate structures: boundary conformal FDTD
- Interface between different subdomains: Riemann solver

Riemann Solver for interface

$$\left(Y^{(i)}+Y^{(j)}\right)(\mathbf{n}\times\mathbf{E})=\mathbf{n}\times\left(Y^{(i)}\mathbf{E}^{(i)}+Y^{(j)}\mathbf{E}^{(j)}\right) -\mathbf{n}\times\mathbf{n}\times\left(\mathbf{H}^{(i)}-\mathbf{H}^{(j)}\right)$$

$$\left(Z^{(i)}+Z^{(j)}\right)(\mathbf{n}\times\mathbf{H})=\mathbf{n}\times\left(Z^{(i)}\mathbf{H}^{(i)}+Z^{(j)}\mathbf{H}^{(j)}\right) +\mathbf{n}\times\mathbf{n}\times\left(\mathbf{E}^{(i)}-\mathbf{E}^{(j)}\right)$$

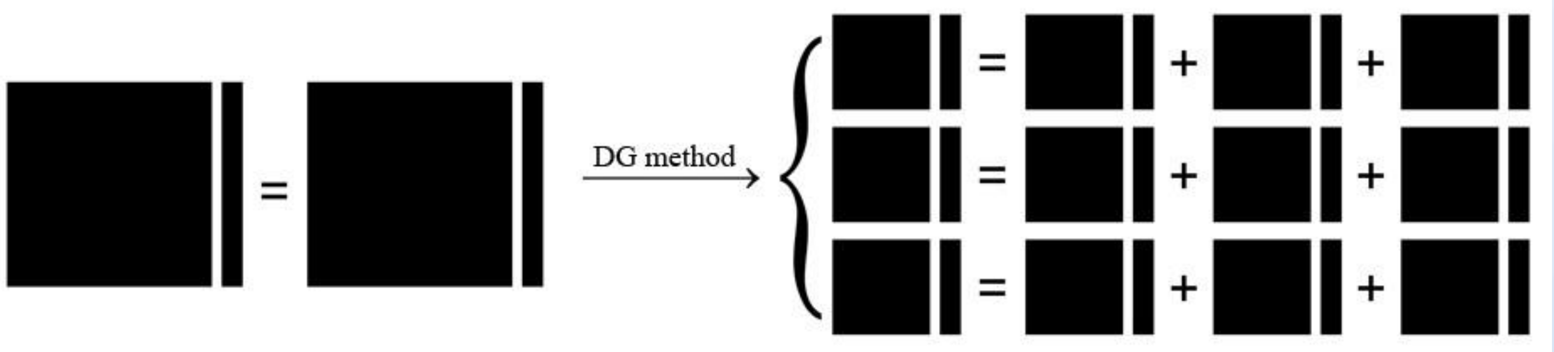


Local adaptive time integration scheme:

Implicit-explicit Runge-Kutta (IMEX-RK)

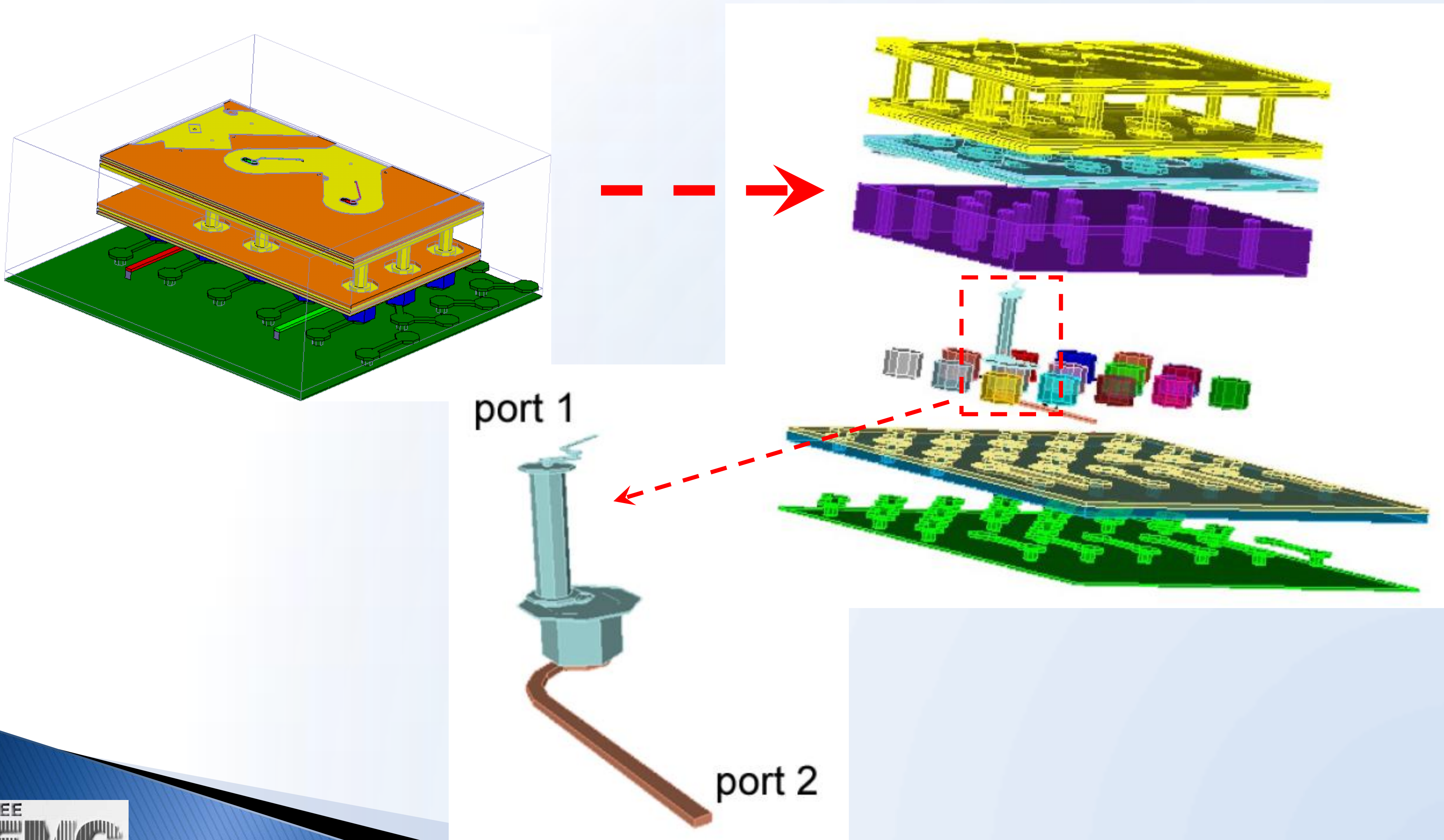
- Electrically coarse subdomains: explicit Runge-Kutta scheme
- Electrically fine subdomains: implicit Runge-Kutta scheme
- Adjacent explicit and implicit subdomains: IMEX-RK scheme

$$\mathbf{v}^{(i)}(t_{n+1}) = \mathbf{v}^{(i)}(t_n) + \Delta t \sum_{k=1}^{s} \sum_{j=1}^{N_{\text{ex}}} b_k^{\text{ex}} \mathbf{T}_{\text{ex}}^{(ij)} \mathbf{u}_{\text{ex}}^{(j)}(k)$$
$$+ \Delta t \sum_{k=1}^{s} \sum_{j=1}^{N_{\text{im}}} b_k^{\text{im}} \mathbf{T}_{\text{im}}^{(ij)} \mathbf{u}_{\text{im}}^{(j)}(k)$$



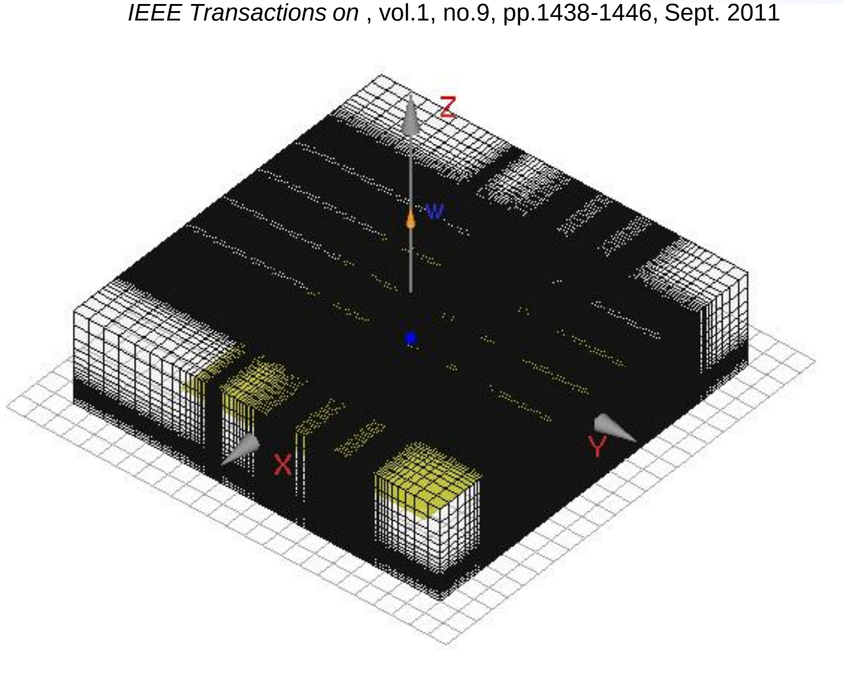
Large system matrices are divided into several middle sized matrices by the hybrid method

Interconnect package

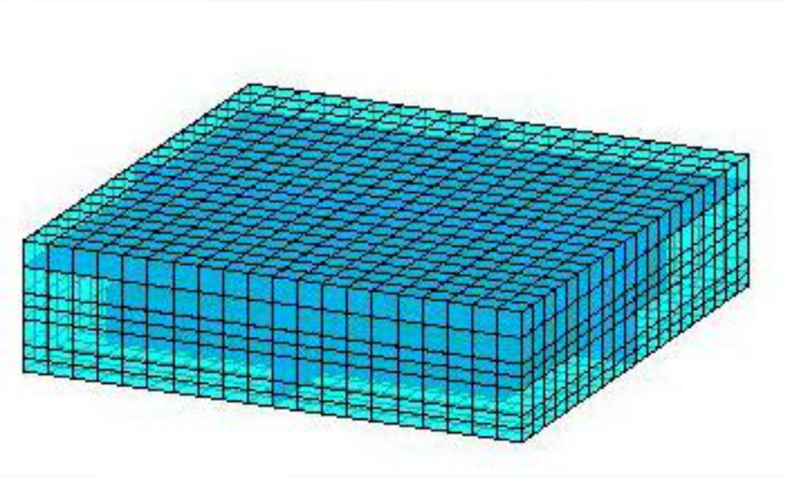


FDTD grid and SETD/FETD mesh

Jiefu Chen; Tobon, L.E.; Mei Chai; Mix, J.A.; Qing Huo Liu; , "Efficient Implicit–Explicit Time Stepping Scheme With Domain Decomposition for Multiscale Modeling of Layered Structures," *Components, Packaging and Manufacturing Technology, IEEE Transactions on* , vol.1, no.9, pp.1438-1446, Sept. 2011

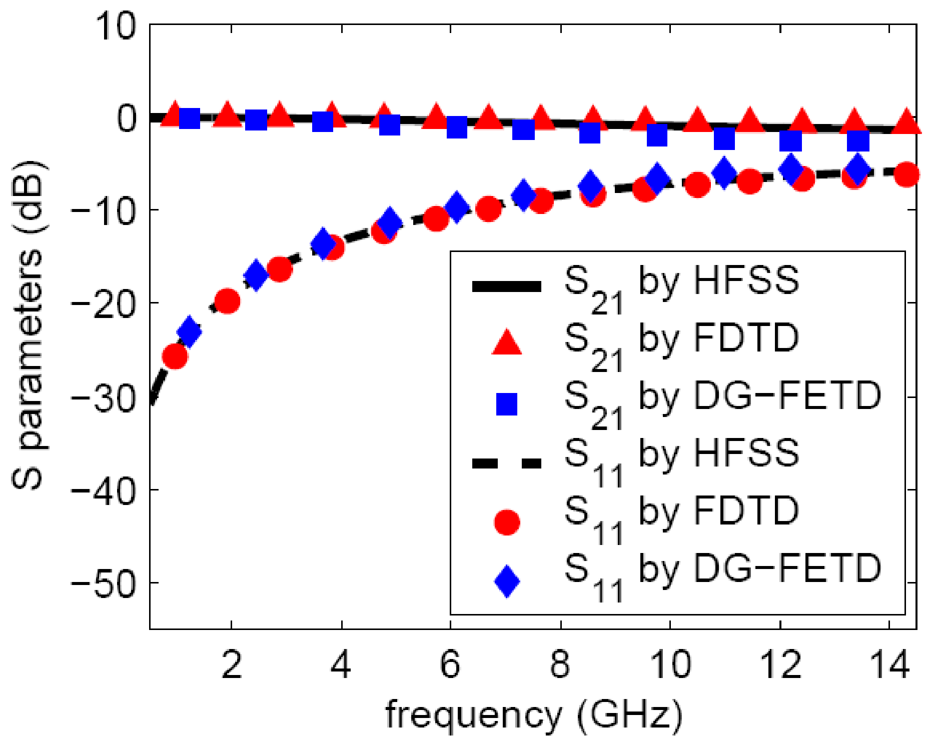


FDTD grid
PPW=40
cells: 511 X 323 X 60
total DoF: > 50 million
⊿t = 3.98 fs
nt = 125,628



SETD / FETD mesh
PPW=40
44 subdomains
total DoF: 152,356
⊿t = 500 fs
nt = 1,000

Numerical results by three methods

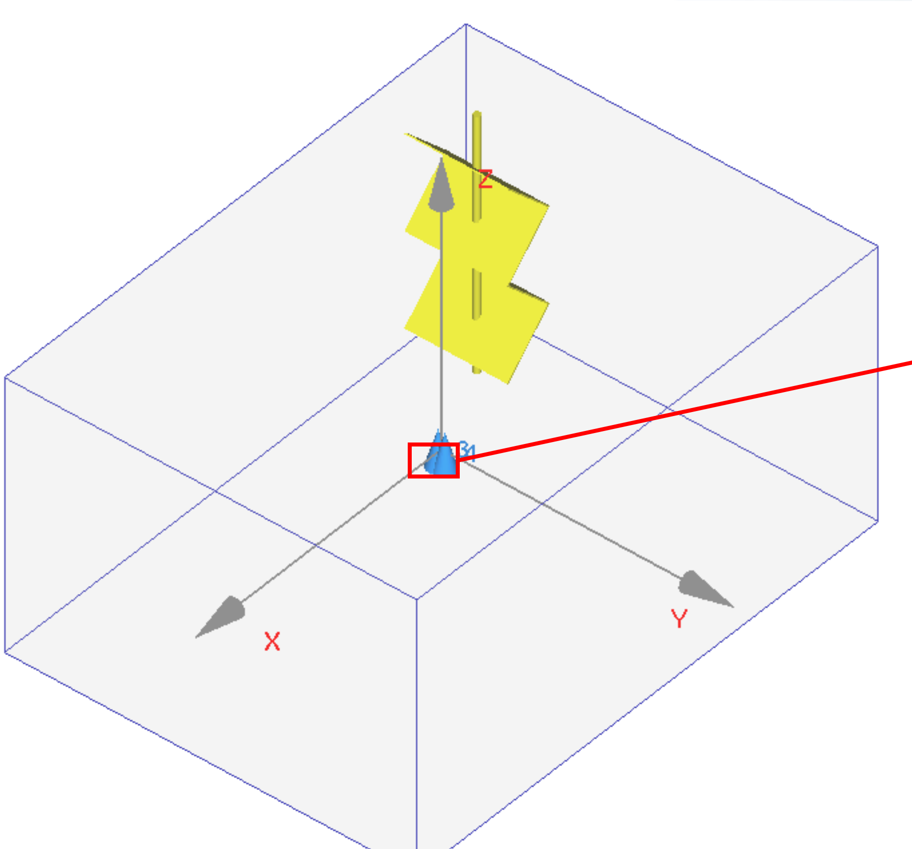


	hybrid SETD/FETD	FDTD	HFSS
memory (MB)	371	1,627	1,433
CPU time (minutes)	13.1	522	319

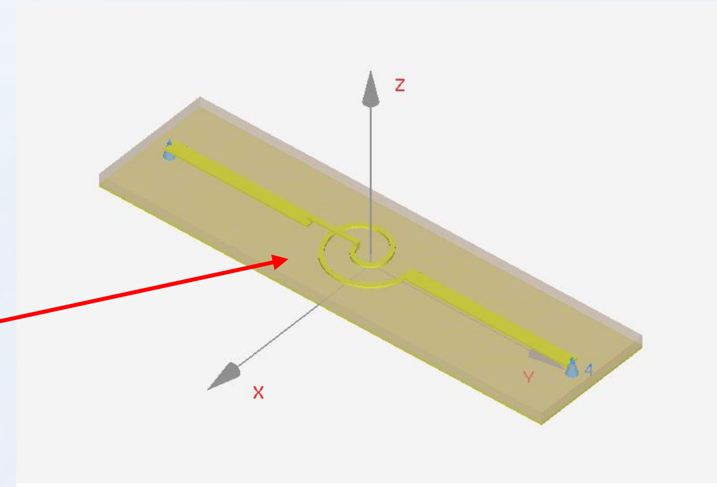
(efficiency ratio) hybrid : FDTD = 39

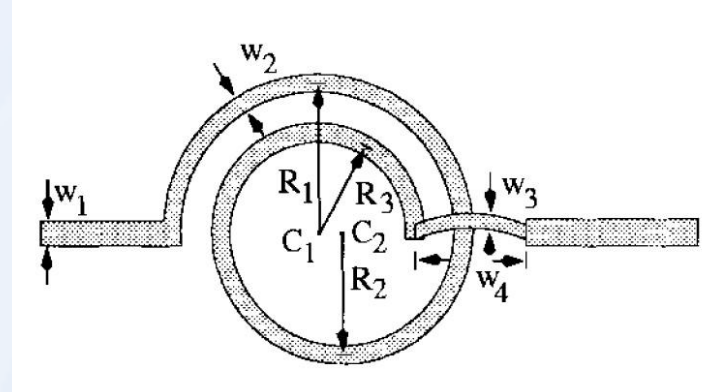
(efficiency ratio) hybrid : HFSS = 24

Spiral Inductor in a Reverberation Chamber (3 GHz)



chamber size: 1.6 m X 1.2 m X 0.8 m

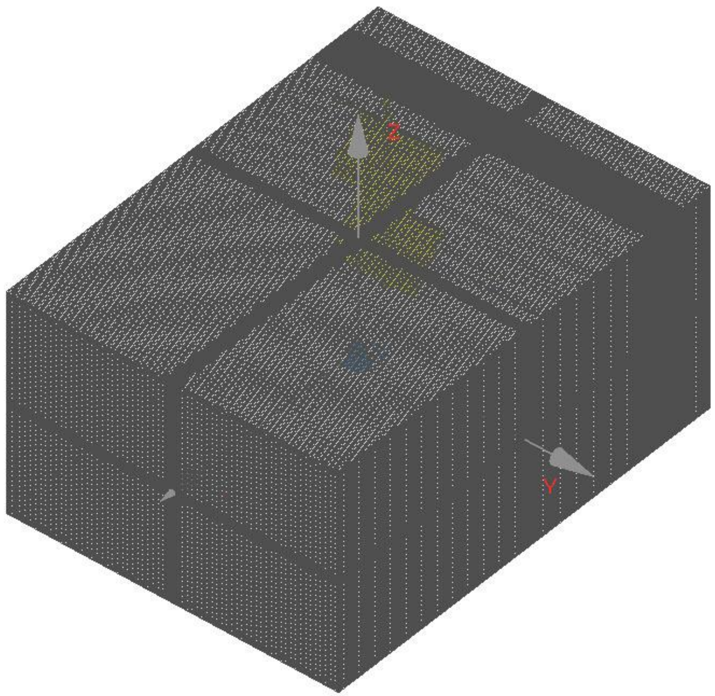


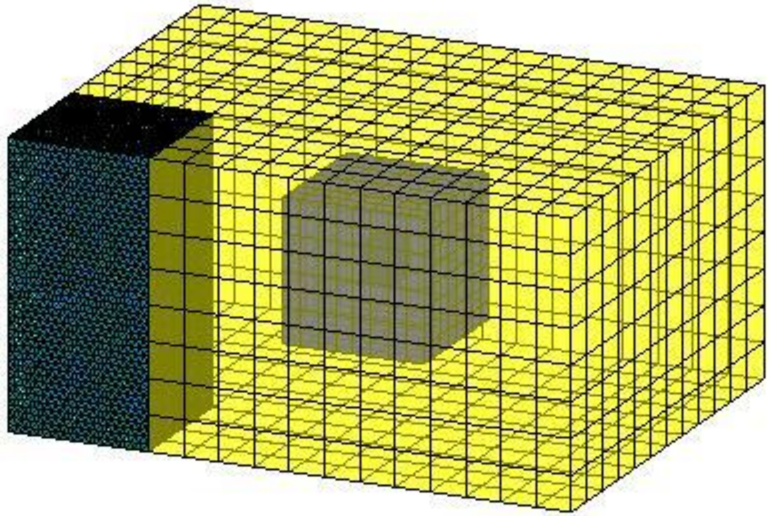


$w_1 = 0.635$ mm, $w_2 = w_3 = 0.2$ mm, $w_4 = 2.4$

$R_1 = 1.9$ mm, $R_2 = 1.3$ mm, $R_3 = 0.7$ mm

FDTD Grid Versus SETD/FETD Mesh

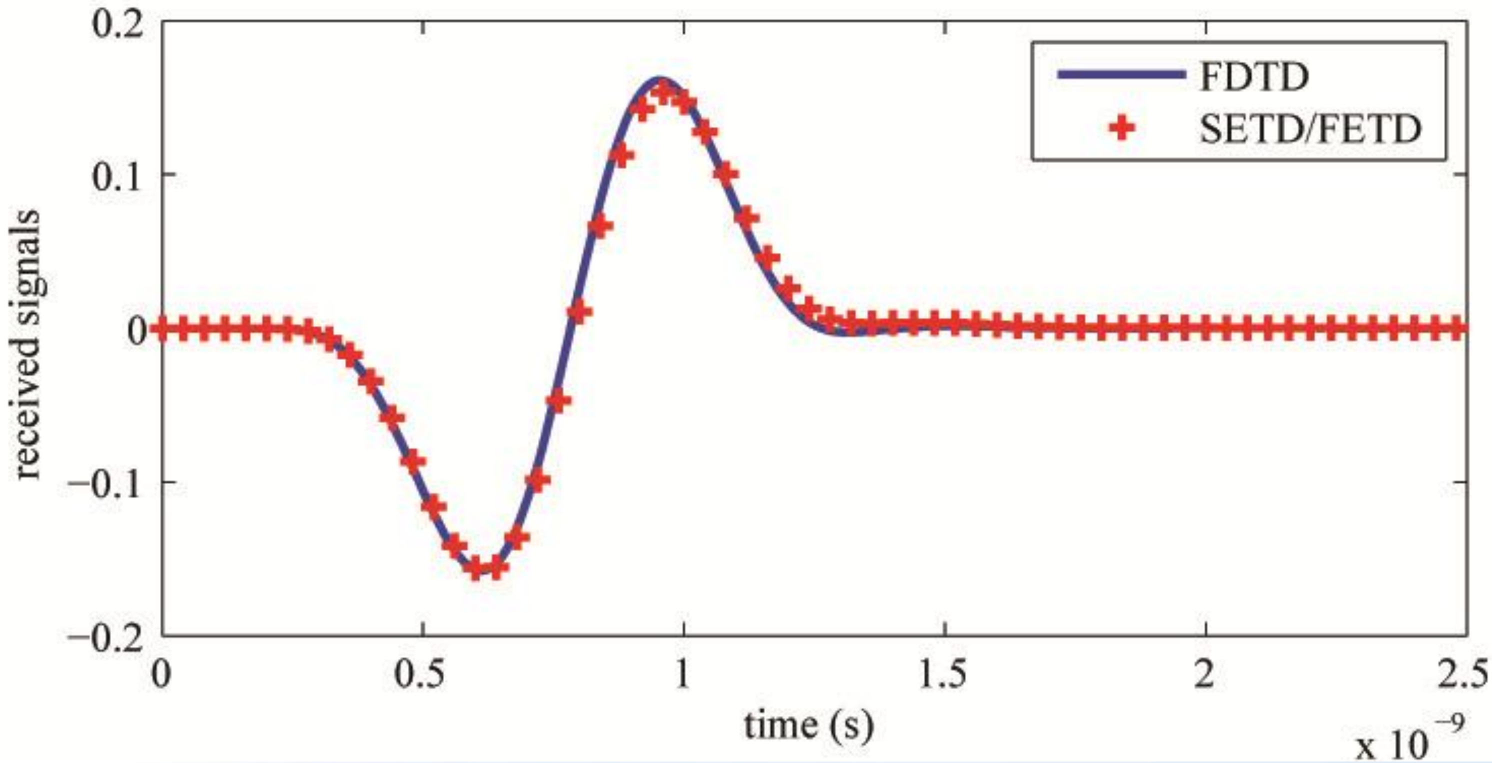




(PPW=16 with local refinement)
FDTD grid: 473 X 420 X 167
DoF: 199.1 million
memory cost: 3.3 GB
maximum Δt = 0.137 ps

(similar discretization as FDTD for fine structures and stirrer)
DoF: 1,654,475
Memory cost: 840 MB
Δt for IMEXRK = 10 ps

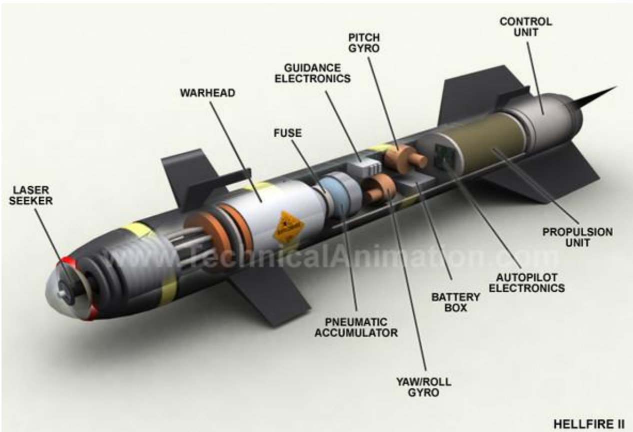
relative difference between FDTD and SETD/FETD = 8.5 %

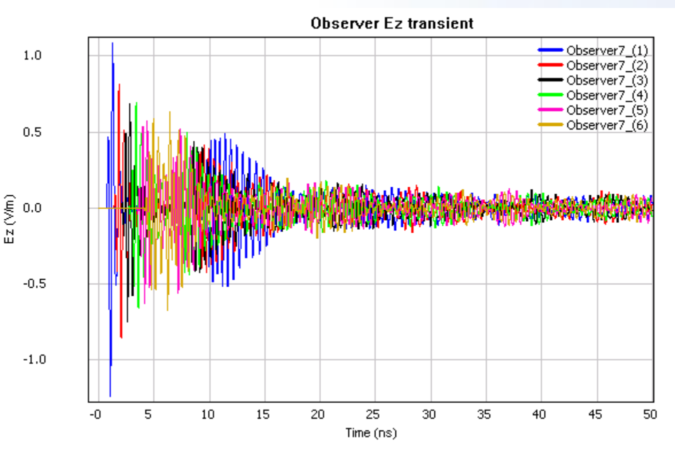


Tab. 1: comparison of computational costs

	FDTD	SETD/FETD	gain by SETD/FETD
memory (MB)	3379	840	4.0
CPU time (h)	19	7.2	2.6

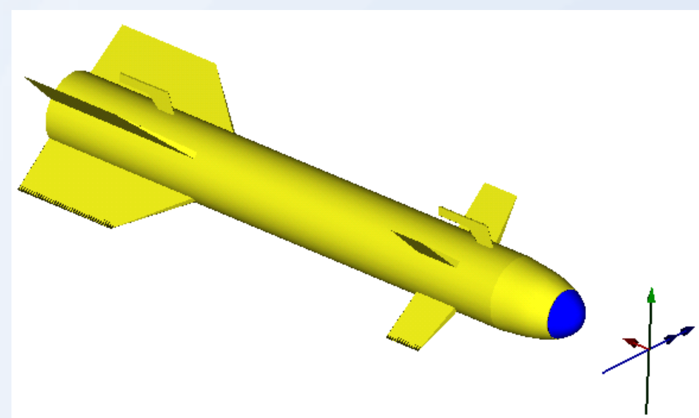
EMP/EMI of Unmanned Aerial Devices/Vehicles



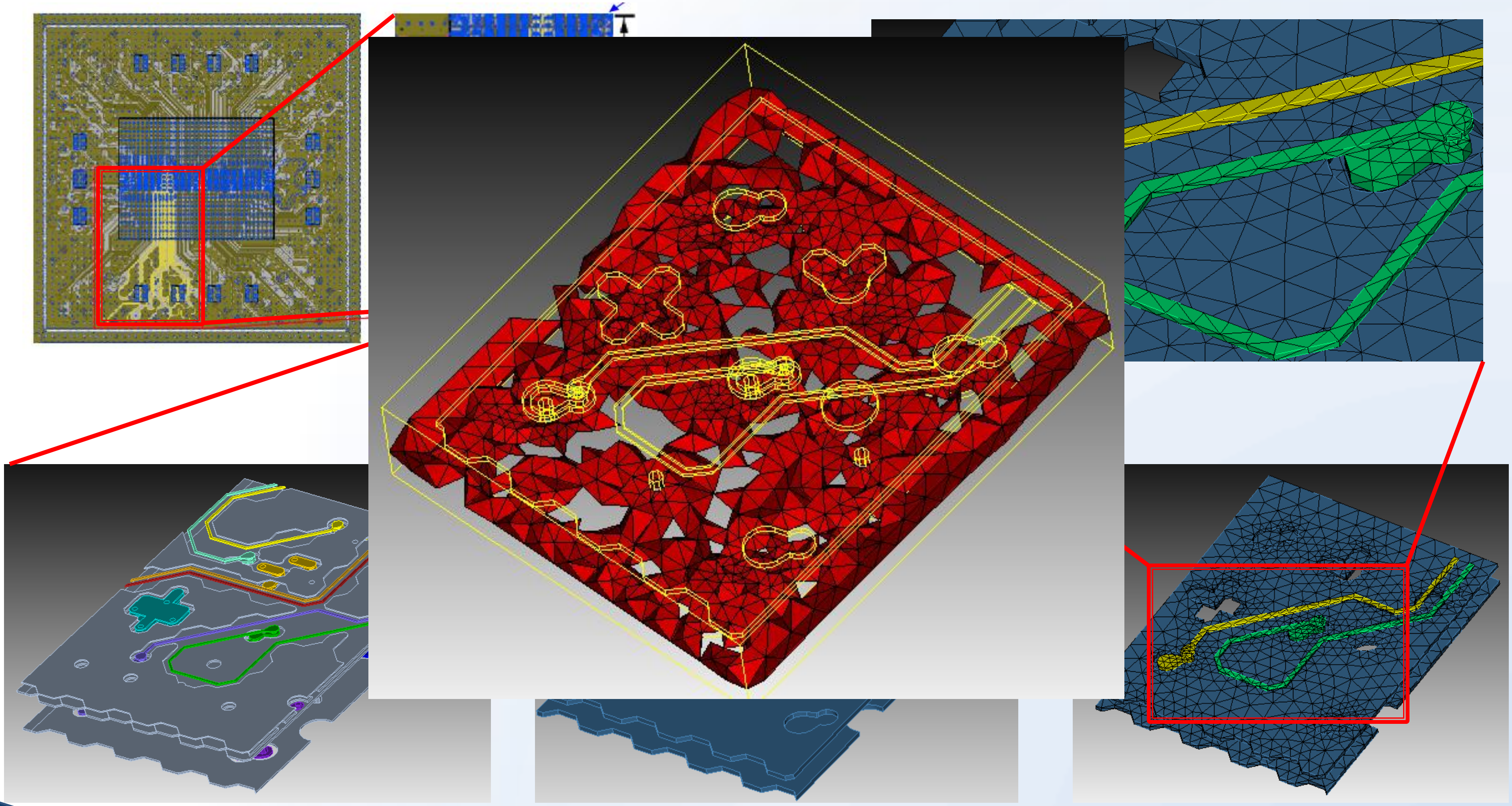


E field snapshot

H field snapshot

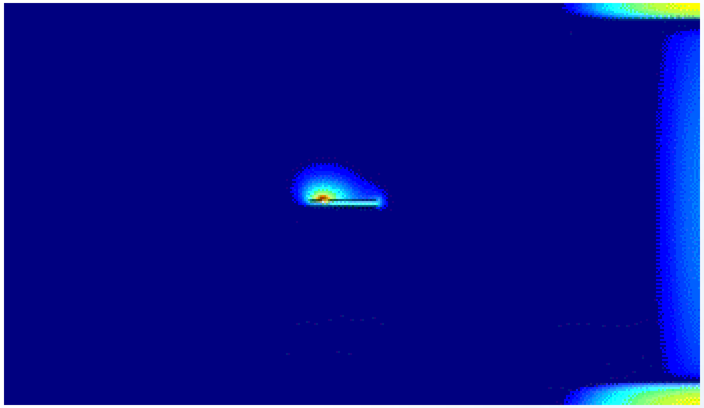


Capturing the Details

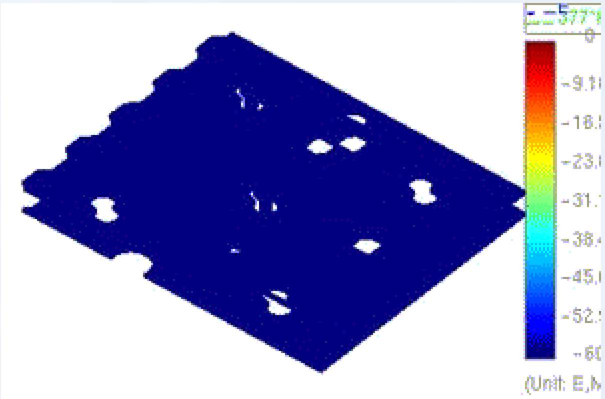


Reveal the EM Interference

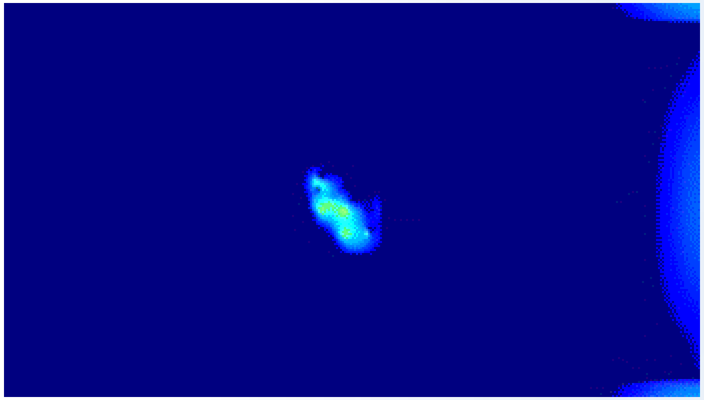
E field



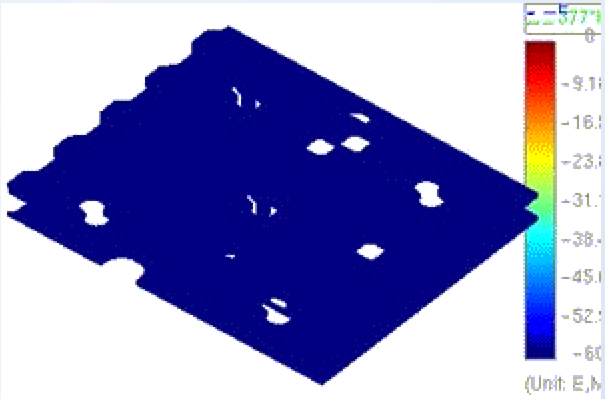
Current generated from source signal



H field



Current generated from interference signal

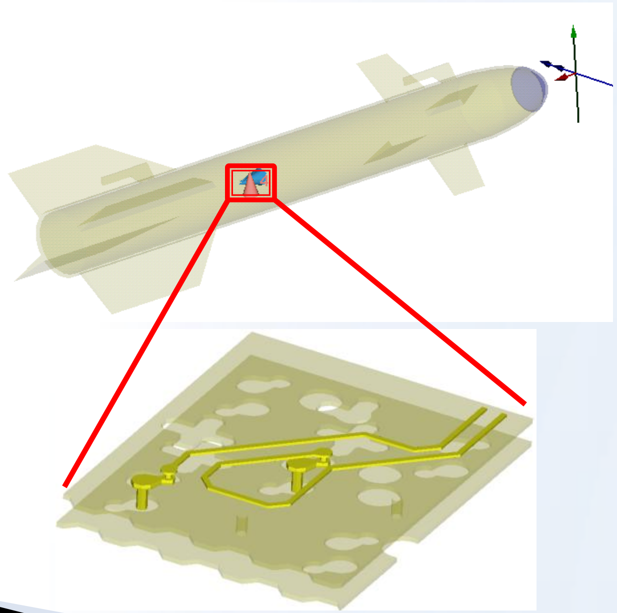


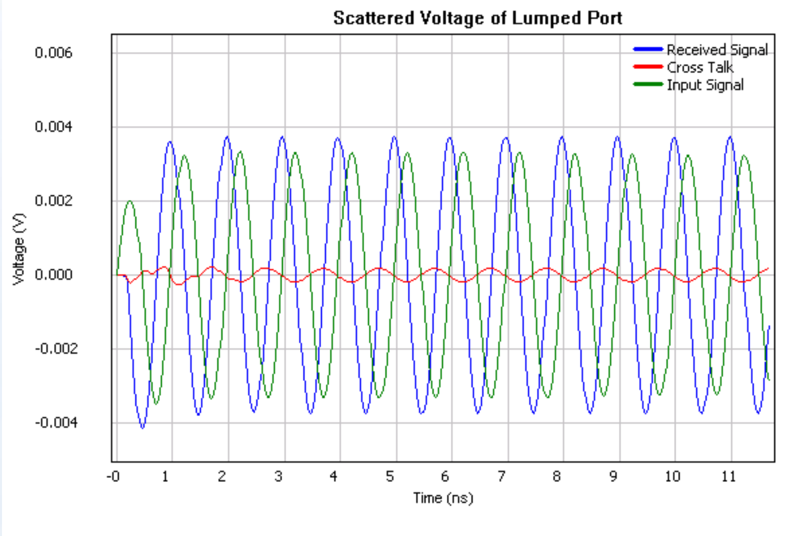
Resonating EM field interacting with the circuit board

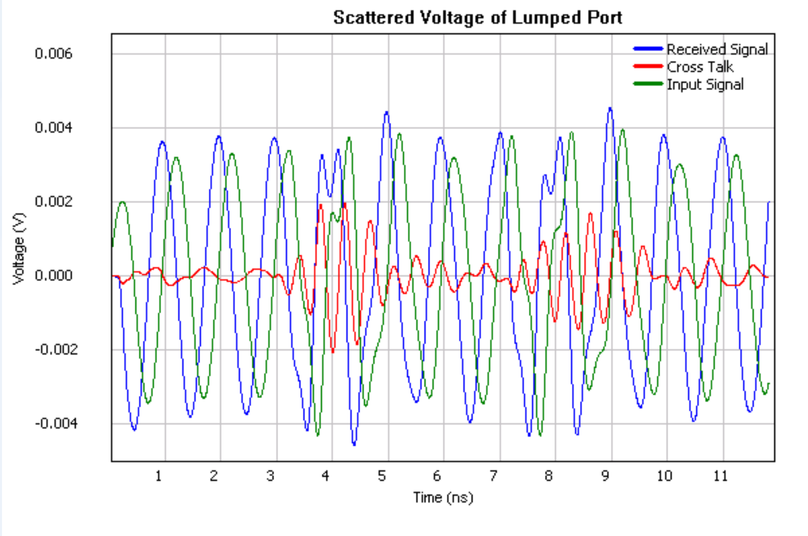
Surface current on the circuit board

Reveal the EM Interference (Cont'd)

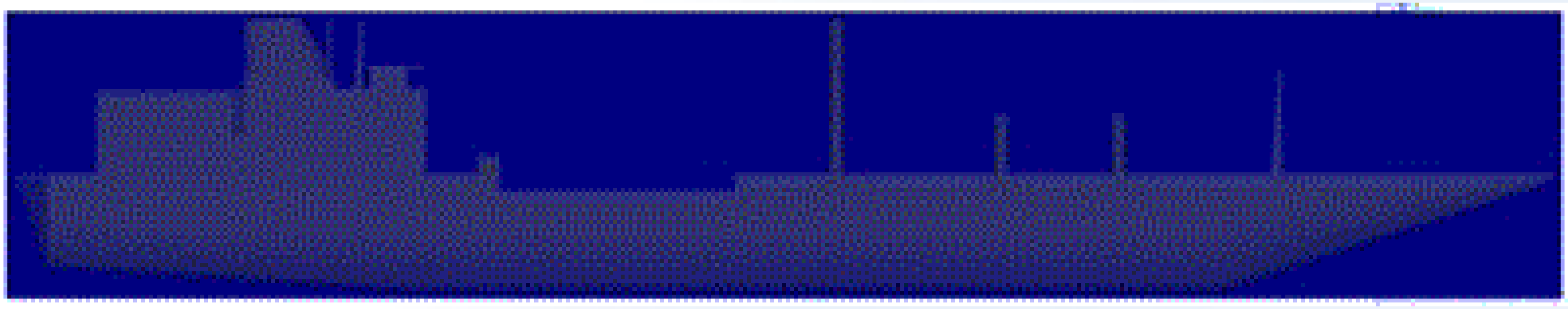
- Circuit board inside missile cavity
- Clean signal vs. interfered signal

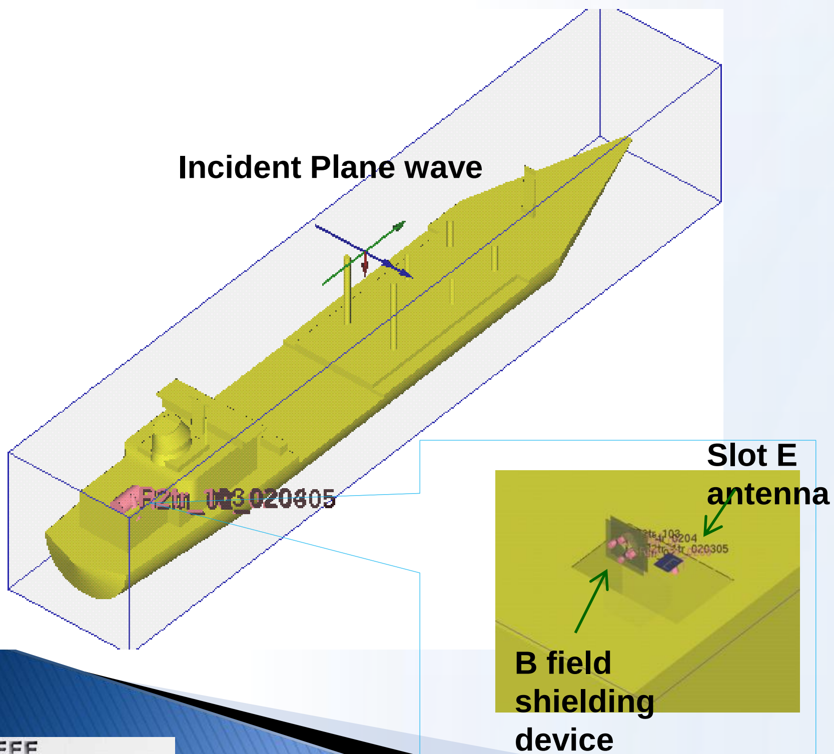


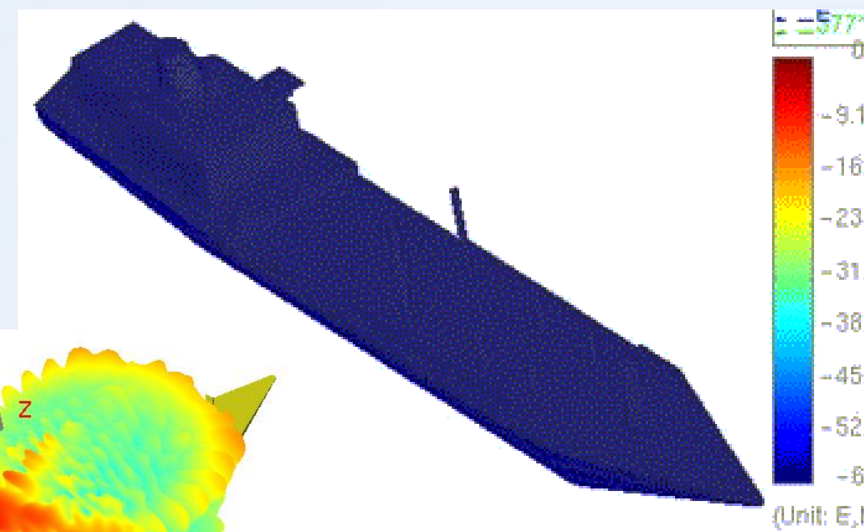


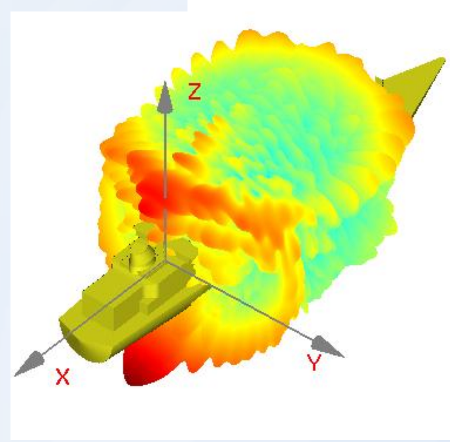


Other Novel Applications using Hybrid Multiscale Simulator









Ship size: 65.4 mx10 mx11.65 m
E/B Antennas system size:
20 cmx73 cmx40 cm

Summary

- Multiscale EM field solver

	FD	FE	SE
Efficiency	5	1	3
Accuracy	1	5	3

- DG is the key
  - Domain decomposition
    - Geometry decomposition
    - Flux operation
- Adaptive Time Stepping
  - LTS
  - IM-EX

About the Company

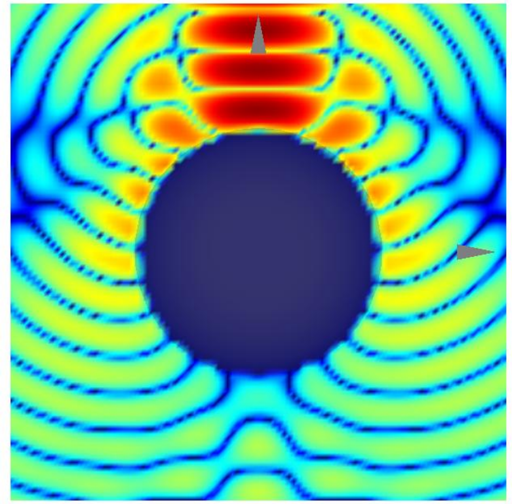
- Profile
- Products

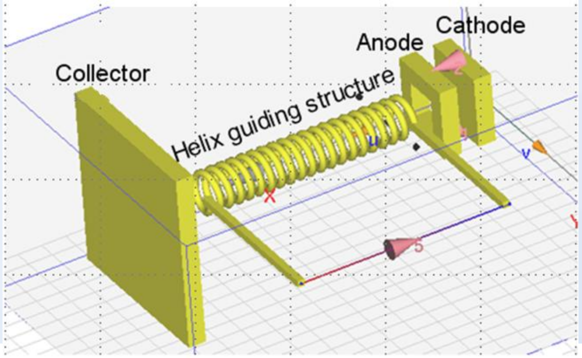
Company Profile

- **Overview**
  - Type of business: Research and development
  - Products: Engineering simulation software
  - Company Sites: Research Triangle Area, NC
  - Number of personnel: 5
- **History**
  - Founded in 2005
  - 5 Phase-I and 3 Phase-II SBIR Projects
    - Air Force (2), Navy (3), Army (2), NIH (1)
  - In Process on 3 projects
    - Navy (Phase-II.5), Department of Energy (pending), NASA (pending)
  - Reference: http://www.sbir.gov/sbirsearch/detail/349368

Commercialized Products

- **Wavenology EM (electromagnetics)**
  - General purpose transient EM field simulator. CAD tool for design of smart antenna, RF/microwave circuit system and novel devices.
- **Wavenology PIC (particle in cell)**
  - Designs of EM railguns, accelerators and other particle devices
- **Wavenology EL (elastrodynamics).**
  - An advanced elastic wave simulator. It focuses on oil exploration with ultrasonic, sonic and seismic waves, with major oil services companies as our clients.





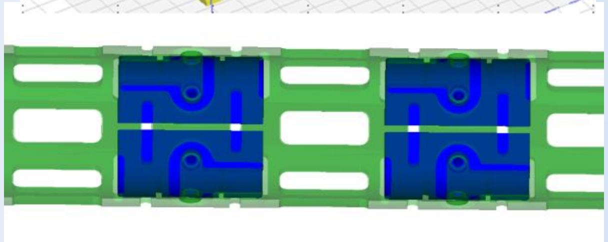


Image Citations

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Questions ?