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International Travelling Summer School on
Microwaves and Lightwaves

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International Travelling Summer Schools
on Microwaves and Lightwaves

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EM Simulators

This lecture has been based on the lecture prepared by the autor as a Distinguished Microwave Lecturer, IEEE MTT Society (2003-2005): ”Design of microwave passive structures without hardware prototyping-how close it comes with state-of-art electromagnetic simulation”

Summary:

1. *Introduction*
2. *Review of the methods of em modeling*
3. *Comparison of applicability of different methods to different enginering problems*
4. *Ten advices to em software users – illustrated by practical examples*
5. *Conclusions*

Basic question of a microwave engineer of the nineties: *Will electromagnetic modeling software really help me in my work?*
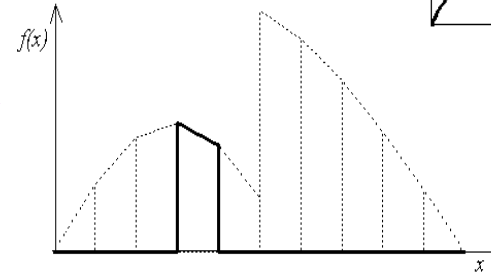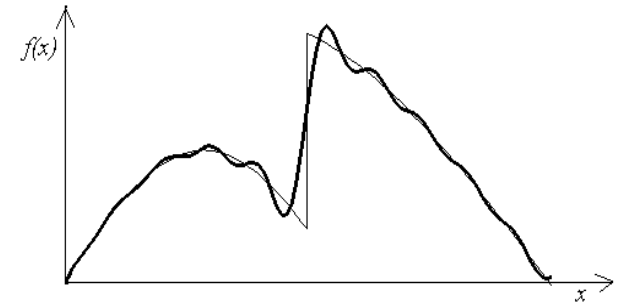
Basic question of a microwave engineer today: *Can I really trust electromagnetic modeling software so much as to skip the hardware prototyping?*

Options when choosing the simulation method

1) **Entire domain expansion**
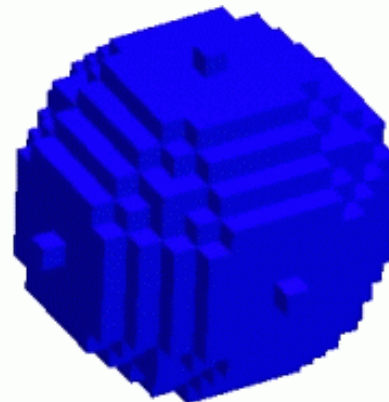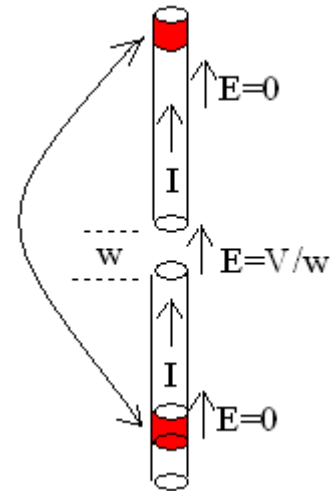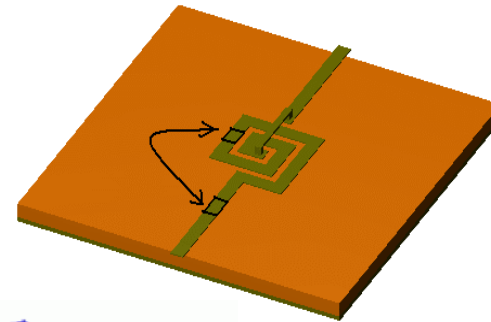
   versus

   Space discrete methods

2) **Boundary**

   discretization (BEM)

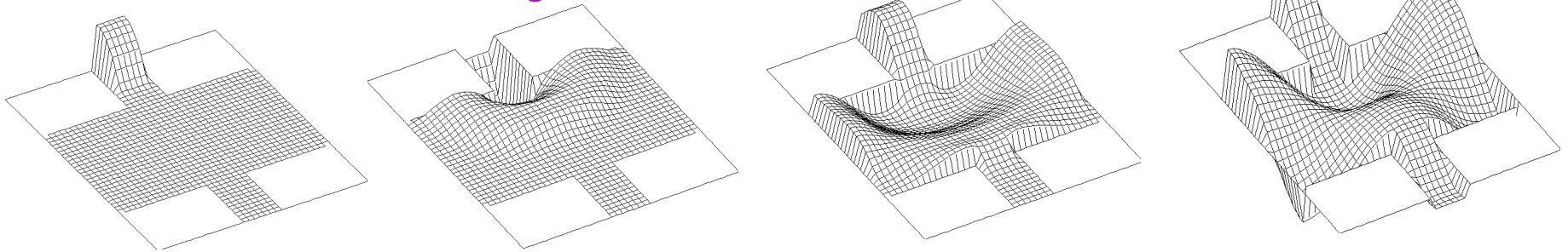   *versus*

   Volume discretization

Options when choosing the simulation method

3) Frequency domain analysis

versus

Time domain analysis

Note: *Direct discretization of time gives simple explicit algebraic relations between fields in consecutive instants. In frequency domain more sophisticated methods (e.g. Method of Moments, Perturbation Method, or Spectral Domain Method) are needed to formulate linear implicit algebraic problem (requiring inversion of a large matrix).*

Time or frequency domain?

Time domain analysis:

→ **explicit algebraic relations between fields in consecutive instants.**

Frequency domain analysis:

$$\begin{bmatrix} \beta_0^2 h^2 - 4 & 1 & & & 1 & & & & & & & \\ 1 & \beta_0^2 h^2 - 4 & 1 & & & 1 & & & & & & \\ & 1 & \beta_0^2 h^2 - 4 & 1 & & & 1 & & & & & \\ & & 1 & \beta_0^2 h^2 - 4 & 0 & & & 1 & & & & \\ 1 & & & 0 & \beta_0^2 h^2 - 4 & 1 & & & 1 & & & \\ & 1 & & & 1 & \beta_0^2 h^2 - 4 & 1 & & & 1 & & \\ & & 1 & & & 1 & \beta_0^2 h^2 - 4 & 1 & & & 1 & \\ & & & 1 & & & 1 & \beta_0^2 h^2 - 4 & 0 & & & 1 \\ & & & & 1 & & & 0 & \beta_0^2 h^2 - 4 & 1 & & \\ & & & & & 1 & & & 1 & \beta_0^2 h^2 - 4 & 1 & \\ & & & & & & 1 & & & 1 & \beta_0^2 h^2 - 4 & 1 \\ & & & & & & & 1 & & & 1 & \beta_0^2 h^2 - 4 \end{bmatrix} \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \\ \psi_5 \\ \psi_6 \\ \psi_7 \\ \psi_8 \\ \psi_9 \\ \psi_{10} \\ \psi_{11} \\ \psi_{12} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ g \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^T$$

→ **implicit algebraic relations between complex amplitudes of fields.**

Why space-discrete ?

- *It is universal in handling complicated geometries and complicated inhomogeneous and arbitrarily shaped materials (limits to minimum user involvement)*

- *It allows to differentiate easily dissipated power and physical parameters in various spots of the structure*

Conclusion: practically all commercial software packages available now use discrete methods, e.g. FEM, FDTD,TLM or BEM (with MoM formulation)

Speed of FDTD versus FEM and BEM

Basic operation count

$A=N\,a$

$A=N\,a$

$A=N\,a$
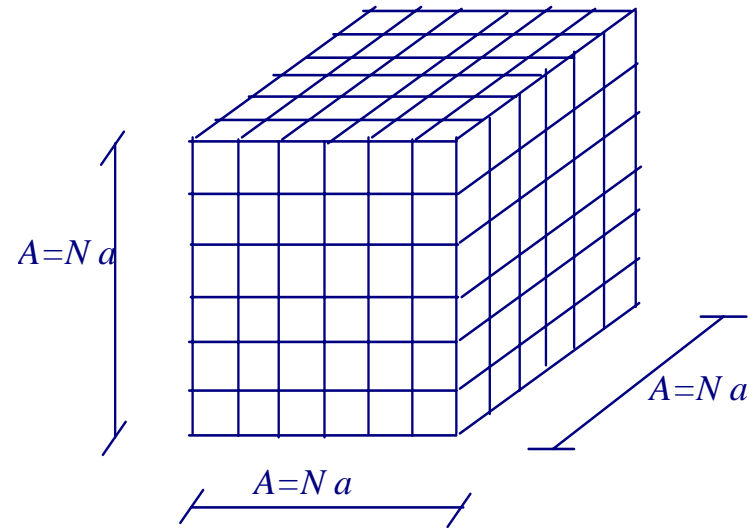
	FDTD	FEM direct	FEM iterative	BEM
No of variables	$6\,N^3$	$6\,N^3$	$6\,N^3$	$24\,N^2$
memory storage	$C_1\,N^3$	$C_2\,N^5$	$C_3\,N^3$	$C_4\,N^4$
floating point operations	$C_5\,N^4$	$C_6\,N^7$	$C_7\,N^{4..6}$	$C_8\,N^6$

BEM (with MoM formulation) versus FEM or FDTD

- **To apply BEM we need to know the Green's function (known for example for free space and for unbounded layered medium)**

- **BEM is effective only when the considered boundary has small surface e.g. wire antennas, planar structures (2.5 D problems) but becomes highly ineffective for such structures close to vertical boundaries**
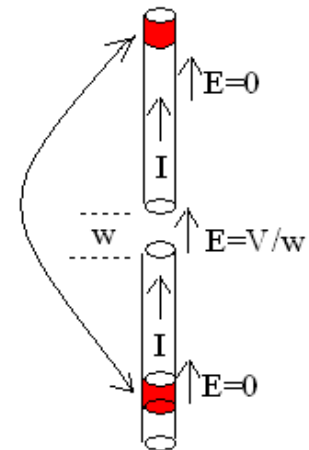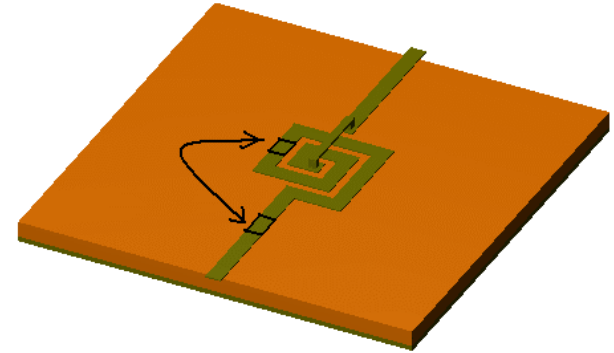
Why Finite Element Method ?

- *Time variable eliminated from equations (at the expense of restrictions to single frequency calculation and complex arithmetics)*

- *Implicit formulations for field relations allow flexibility of conformal meshing*

a   b   c
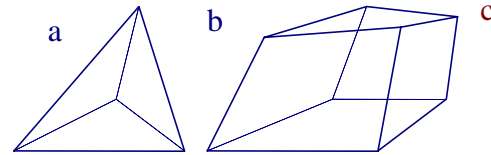
- *Easy implementation of frequency-dependent media*

Disadvantages of FEM and how they are fought

- **One simulation produces single frequency result -**

  remedy: fast frequency sweep techniques (e.g. Ansoft)

- **Computer time and memory rises fast with complication of the structure**

  remedy: various techniques of adaptive meshing are applied.

  Mesh can be adapted in size of the elements (h-adaptive) or order of elements (p-adaptive). The most advanced algorithms use both (hp-adaptive).

  The latter are not used so far in commercial software but very good research results are reported (see for ex. A.Zdunek et al. IEEE Trans. AP, 2002,pp.100-110 and recent works of prof.Demkowicz, Univ.of Texas, Austin)

Why time domain methods ?

- *Computationally more effective for electrically large structures (converging even faster for lossy structures)*

- *Simulation time can be a priori predicted*

- *For linear circuits & pulse excitation provide wide-band circuit parameters after one simulation*

- *Clear physical interpretations (good insight into device operation and especially transients!)*

- *Directly applicable to nonlinear and time-varying circuits*

- *Algorithms not sensitive to computer round-off errors*

- *Practically no problems with parasitic solutions*

Focus on FDTD method (1) – 1-D case
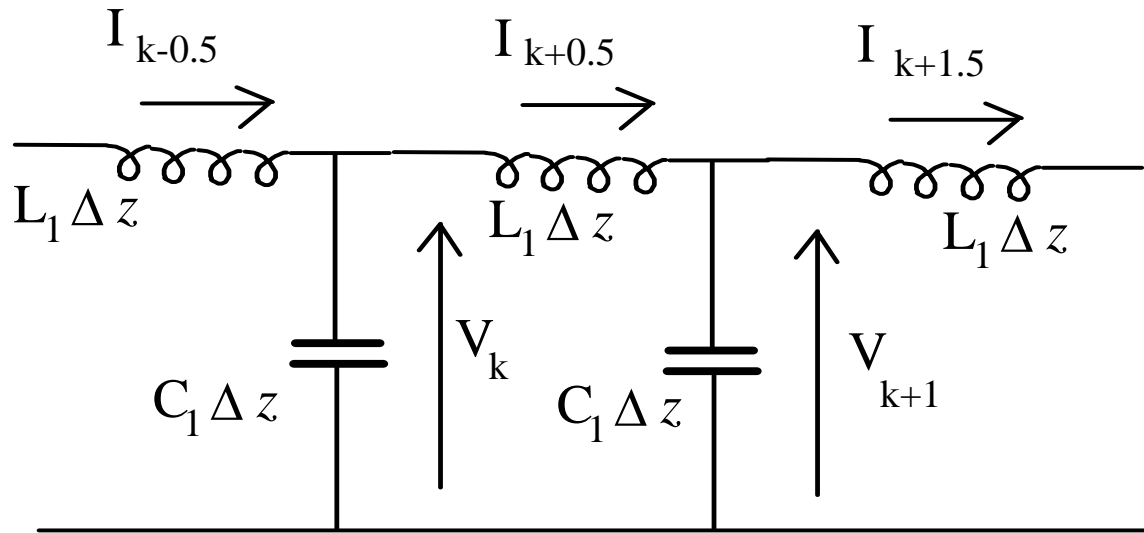
$$V_k^n = V_k^{n-1} - (I_{k+0,5}^{n-0.5} - I_{k-0,5}^{n-0.5})\frac{\Delta t}{C_1 \Delta z} \qquad I_{k+0.5}^{n+0.5} = I_{k+0.5}^{n-0.5} - (V_{k+1}^{n.} - V_k^n)\frac{\Delta t}{L_1 \Delta t}$$

1D case of a transmission line

approximated by lumped equivalent circuit

2D FDTD method
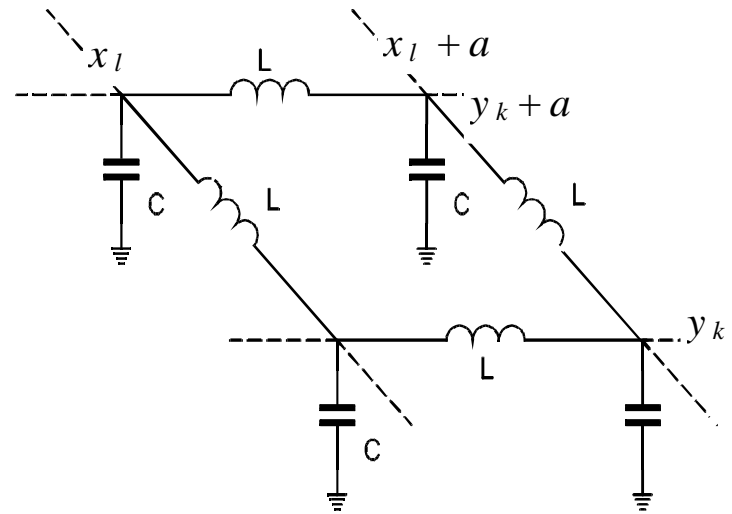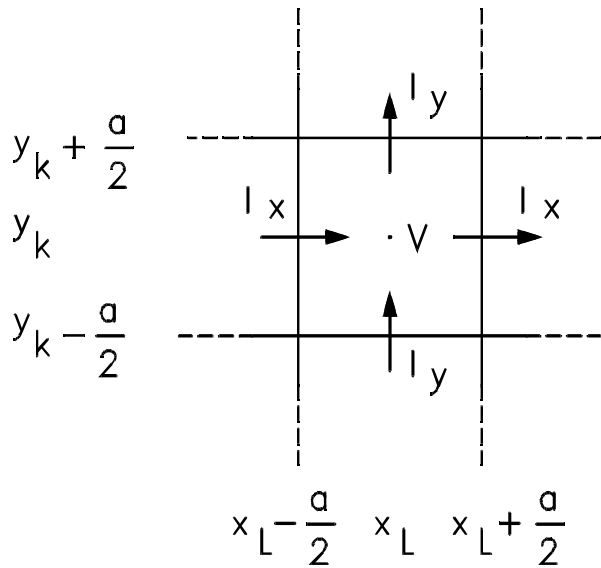
$$V(x_l, y_k, t_0 + \Delta t) = V(x_l, y_k, t_0) - [J_x(x_l + \frac{a}{2}, y_k, t_0 + \frac{\Delta t}{2}) + J_y(x_l, y_k + \frac{a}{2}, t_0 + \frac{\Delta t}{2})$$

$$-J_x(x_l - \frac{a}{2}, y_k, t_0 + \frac{\Delta t}{2}) - J_y(x_l, y_k - \frac{a}{2}, t_0 + \frac{\Delta t}{2})] \frac{\Delta t}{C_s a}$$

$$J_x(x_l + \frac{a}{2}, y_k, t_0 + \Delta t) = J_x(x_l + \frac{a}{2}, y_k, t_0) \quad -[V(x_l + a, y_k, t_0) - V(x_l, y_k, t_0)] \frac{\Delta t}{L_s a}$$

Focus on FDTD (3) – 3-D case (Yee mesh)

Discretizing the Mawell curl equations :

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Notation:

$$_{k,l,m+0.5}E_z^n = E_z(x_k, y_l, z_m + 0.5\Delta z, t_0 + n\Delta t)$$

$$_{k,l,m+0.5} E_z^{n+1} = {}_{k,l,m+0.5} E_z^n + \{[_{k+0.5,l,m+0.5} H_y^{n+0.5} - {}_{k-0.5,l,m+0.5} H_y^{n+0.5}]\,(\Delta t/\Delta x)$$

$$+ [_{k,l-0.5,m+0.5} H_x^{n+0.5} - {}_{k,l+0.5,m+0.5} H_x^{n+0.5}](\Delta t/\Delta y)\} /(_{k,l,m+0.5}\varepsilon_z \varepsilon_0)$$

$$_{k,l,m+0.5} u_z^{n+1} = {}_{k,l,m+0.5} u_z^n + \{ {}_{k+0.5,l,m+0.5} i_y^{n+0.5} - {}_{k-0.5,l,m+0.5} i_y^{n+0.5}$$

$$+ {}_{k,l-0.5,m+0.5} i_x^{n+0.5} - {}_{k,l+0.5,m+0.5} i_x^{n+0.5} \} / {}_{k,l,m+0.5} c_z$$

$$u_z = E_z \Delta z / \sqrt{Z_0}, \ \ i_x = H_x \Delta x \sqrt{Z_0}, \ \ i_y = H_y \Delta y \sqrt{Z_0} \ ; \ \ c_z = \varepsilon_z (\Delta x \, \Delta y) / (\Delta z \, \Delta t \, c);$$

Z_0 - free space impedance; c – speed of light
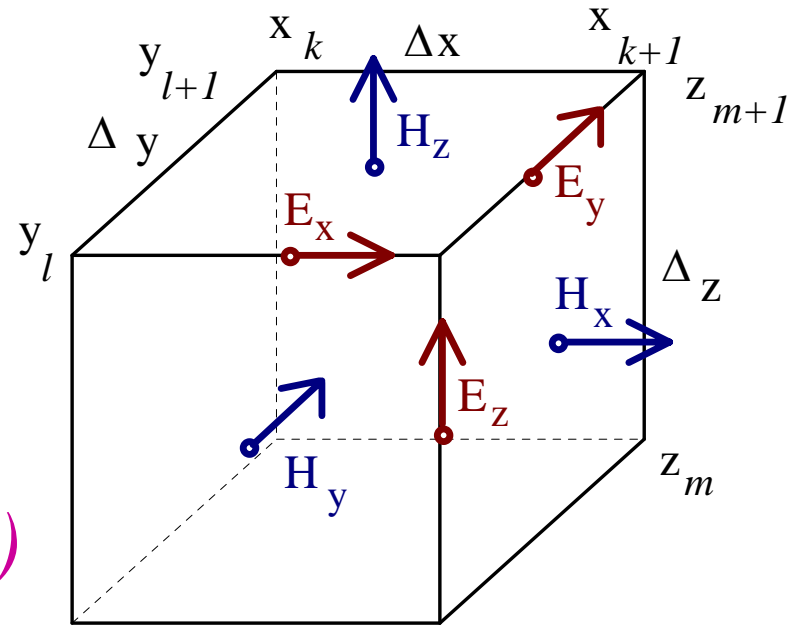
Bridging the concepts of field and circuit theory
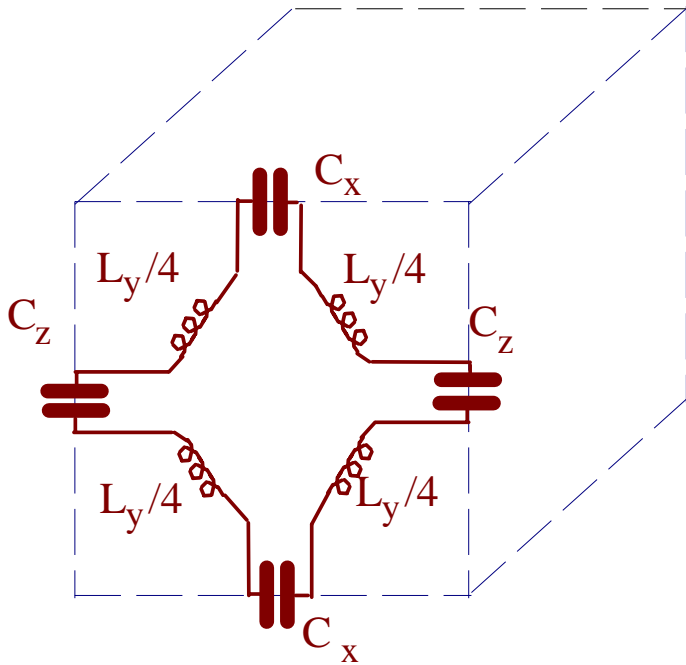
Notation:

$$U_x = E_x \Delta x; \quad U_y = E_y \Delta y; \quad U_z = E_z \Delta z;$$

$$I_x = H_x \Delta x; \quad I_y = H_y \Delta y; \quad I_z = H_z \Delta z;$$

$$C_z = \frac{\varepsilon \Delta x \Delta y}{\Delta z}; \quad L_z = \frac{\mu \Delta x \Delta y}{\Delta z};$$

Discretizing the Maxwell curl equations :

$$_{k,l,m+0.5} U^n_z = _{k,l,m+0.5} U^{n-1}_z + (_{k+0.5,l,m+0.5} I^{n-0.5}_y - _{k-0.5,l,m+0.5} I^{n-0.5}_y +$$

$$_{k,l-0.5,m+0.5} I^{n-0.5}_x - _{k,l+0.5,m+0.5} I^{n-0.5}_x) \frac{\Delta t}{C_z}$$

$$_{k+0.5,l+0.5,m} I^{n+0.5}_z = _{k+0.5,l+0.5,m} I^{n-0.5}_z - (_{k+0.5,l,m} U^n_x - _{k+0.5,l+1,m} U^n_x +$$

$$_{k+1,l+0.5,m} U^n_y - _{k,l+0.5,m} U^n_y) \frac{\Delta t}{L_z}$$

Difficulties in FDTD and how they are fought

- *Explicit algorithm makes it less flexible in meshing*

  remedy: conformal meshing &/or subgridding.

- *Difficult to apply with dispersive media*

  remedy: use special dispersive media models

- *Slowly converging with high-Q structures*

  remedy: use special signal processing techniques (e.g. Prony method)

Relationships between FDTD and TLM
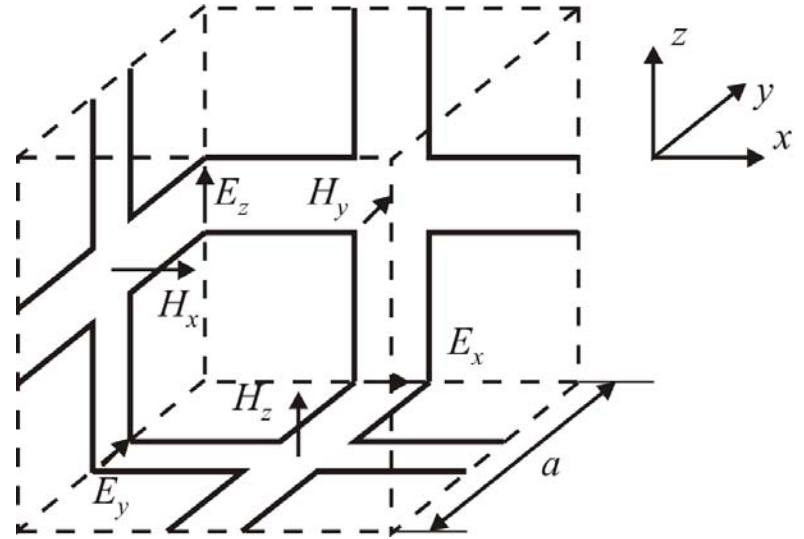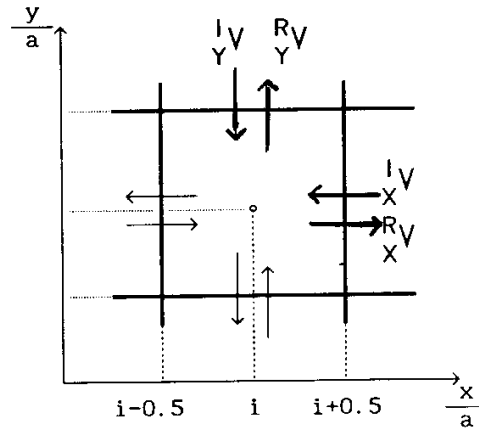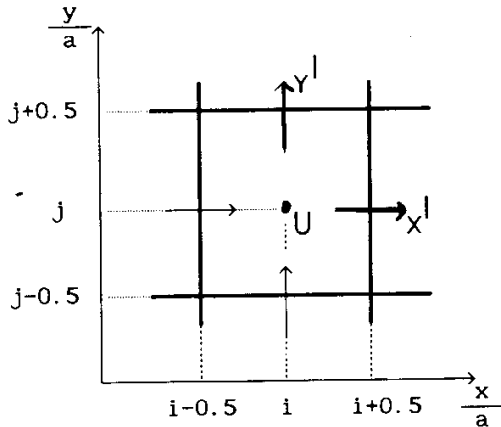
3 variables per cell of 2D FDTD:
$$i_x \big|_{i+0.5,j}^{t+0.5}; \quad i_y \big|_{i,j+0.5}^{t+0.5}; \quad u \big|_{i,j}^{t};$$

versus 4 variables per cell in 2D TLM
$$V_{ix} \big|_{i+0.5,j}^{t+0.5}; V_{rx} \big|_{i+0.5,j}^{t+0.5}; V_{iy} \big|_{i,j+0.5}^{t+0.5}; V_{ry} \big|_{i,j+0.5}^{t+0.5};$$

with
$$i_x \big|_{i+0.5,j}^{t+0.5} = 0.5 \left(V_{ix} \big|_{i+0.5,j}^{t+0.5} - V_{rx} \big|_{i+0.5,j}^{t+0.5} \right);$$
$$u \big|_{i+0.5,j}^{t+0.5} = 0.5 \left(V_{ix} \big|_{i+0.5,j}^{t+0.5} + V_{rx} \big|_{i+0.5,j}^{t+0.5} \right);$$

W.Gwarek, P.B.Johns: Comments on "On the relationship between TLM and finite-difference methods for Maxwell's equations".IEEE Trans MTT, vol.35, September 1987.

Formal equivalence between FDTD and TLM
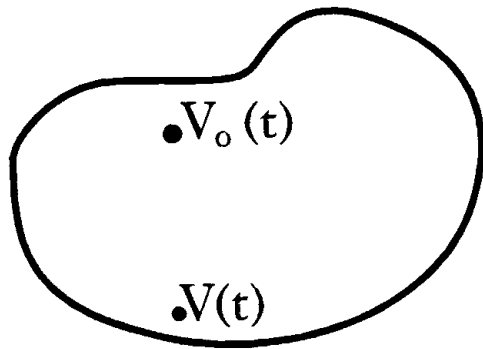
case 1
TLM analysis
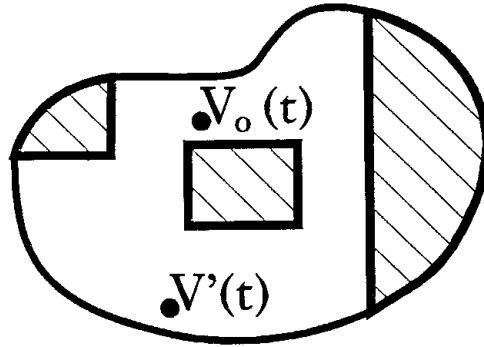
case 2 ▨ FD-TD region

We calculate signals excited by $V_0(t)$ and received as $V(t)$ or $V'(t)$ in two different cases of circuits

FDTD and TLM methods are equivalent in the sense that:

1. Signals $V(t)$ and $V'(t)$ are different only by computer round-off errors (negligible in virtually all practical cases) and thus the additinal information available in TLM is irrelevant

2. Any property of TLM algorithm relevant from the point of view of electromagnetic analysis can be reproduced in FDTD and vice versa

3. Methods differ by required computer resources and FDTD is clearly more effective in this regard

M.Celuch, W.K.Gwarek, "Formal equivalence and efficiency comparison of the FD-TD, TLM and SN methods in application to microwave CAD programs",Proc. of the XXI European Microwave Conference, Stuttgart, September 1991, pp.199-204.

''Additional information'' in TLM

- is a spurious mode of the wavelength equal to two TLM cells!

Example of the parasitic mode:

Its contour (right) and field values in two consecutive time steps (down)
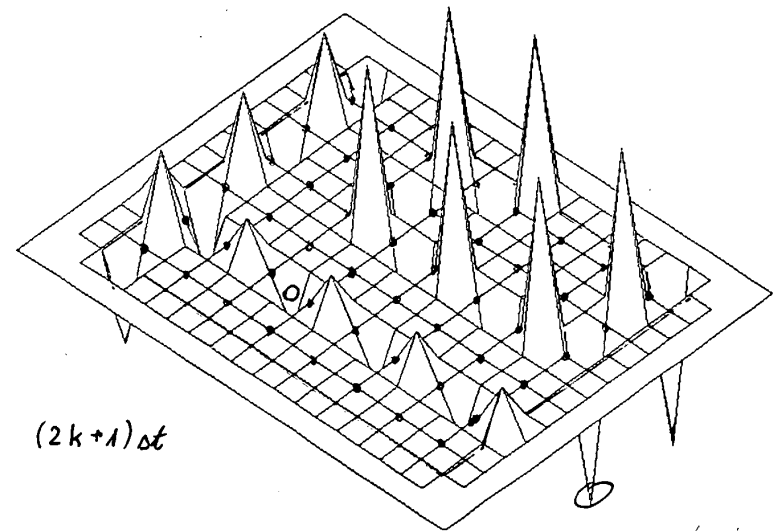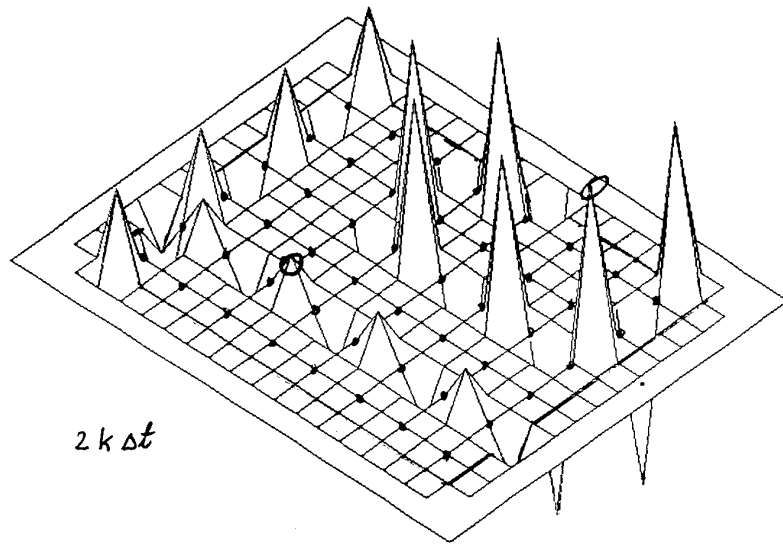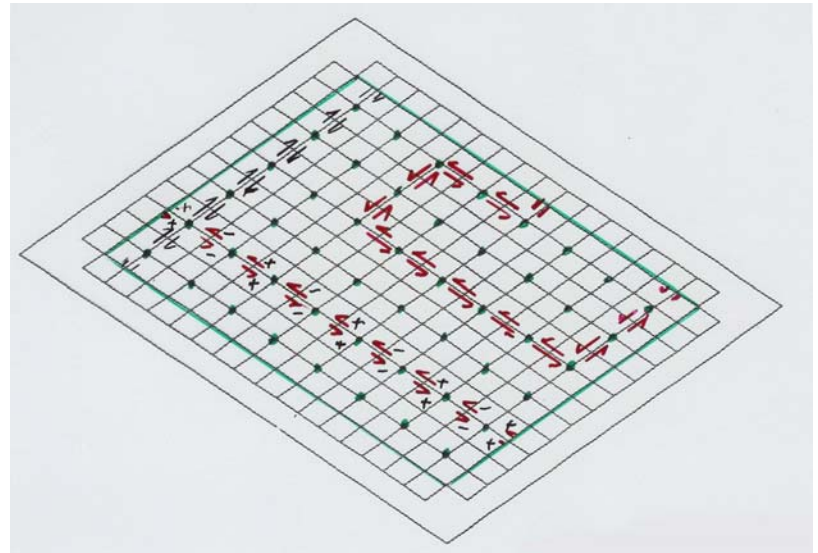
$2k\,\Delta t$

$(2k+1)\Delta t$

Classification of numerical methods for electromagnetic modeling

Space → Time ↓	Continuous: expansion into "modes"	Discrete: expansion into "cells"
Continuous – monochromatic – frequency domain (FD)	**MoM with mode expansion**	**BEM with MoM** **FEM** FDFD
Discrete – probed pulses – time domain (TD)	MoMTD	**FDTD** **TLM** FETD

Commercial software on the market*:

2.5 D for (mainly) planar structures

LINMIC by AC Microwave (Spectral Domain)

Ensemble by Ansoft (BEM/MoM)

Momentum (in ADS) by Agilent EEsoft EDA (BEM/MoM)

EMSight (in Microwave Office) by AWR (BEM/MoM)

Sonnet Software by Sonnet (BEM/MoM)

Zeland Software by Zeland (BEM/MoM)

Commercial software on the market*:

3 D arbitrary geometry solvers

HFSS by Ansoft *(FEM)*

HFSS by Agilent EEsoft EEsoft EDA *(FEM)*

Microwave Studio by CST *(FDTD)*

Micro-Stripes by Flomerics *(TLM)*

QuickWave 3D by QWED & CONCERTO by Vector Fields *(FDTD)*

MEFiSTo-3D by Faustus Scientific *(TLM)*

* After Swanson & Hoefer, *Microwave Circuit Modeling Using Electromagnetic Field Simulation*

And also: **Ansys Multiphysics by Ansys** *(FEM);*

Empire by IMST *(FDTD);* **XFDTD by Remcom** *(FDTD);*

Fidelity by Zeland *(FDTD);*

Suggestions to electromagnetic software users

1 - Try to synchronize your actual needs (or what you can get from the measurements) with what you can get from the software. Referring to idealistic notions may be as difficult for the software as for the measurements.

Examples:

- *infinitely small dipole*
- *driving point impedance*

Example of a problem: Imagine that we have a segment of a 70Ω coax line and want to calculate its S-parameters with respect to 50 Ω

reference plane

extension by a segment of the 70Ω line
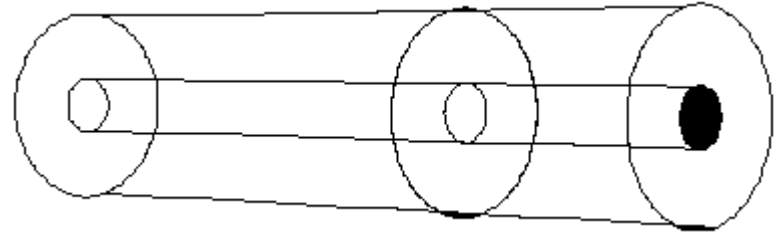
extension by a wire- we need to consider inductance of the wires
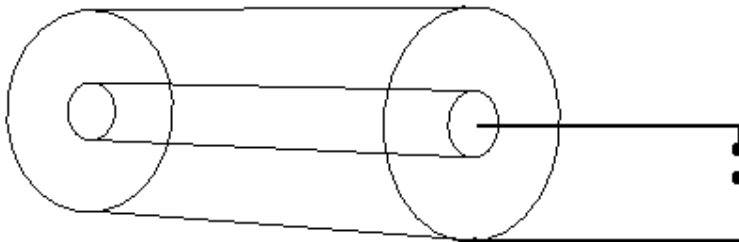
nodes of measurement system

extension by a segment of the 50Ω line- parasit we need to consider parasitics of the step
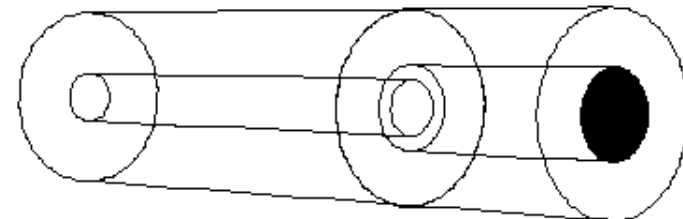
TEM lines versus quasi-TEM lines

shielded microstrip on air substrate
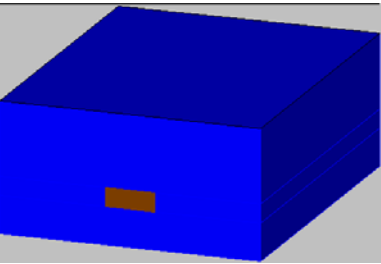
- *E*-field integration over CE1 and CE2 gives the same result *V*,
- *H*-field integration over CH1 gives *I*
- Impedance $Z_{c=}V/I$ is well defined and frequency independent
- Integration over CE3 and CH1 gives zero
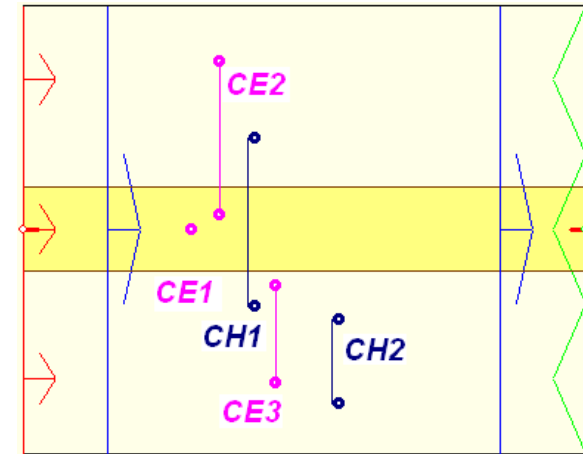
shielded microstrip on a 20 mils FR4 substrate (with 70 mils uper air layer)
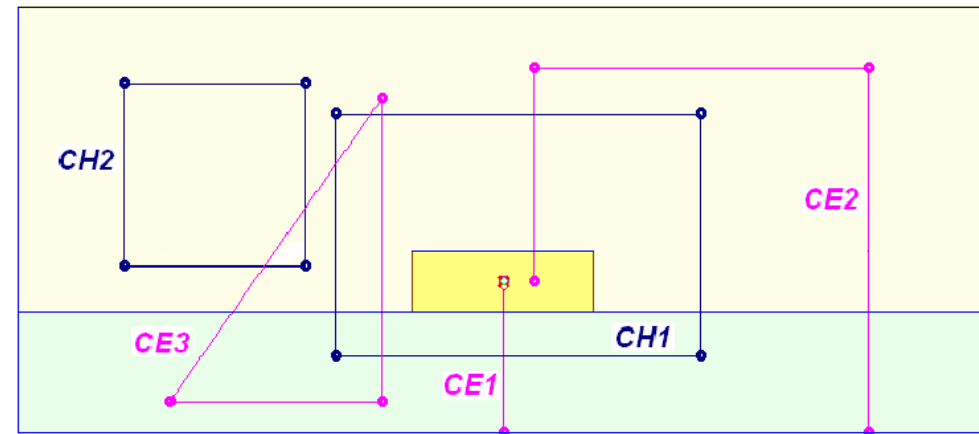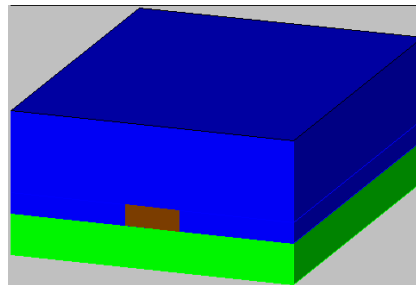
In inhomogeneous line, for higher frequencies:
- *E*-field integration over CE1 and CE2 gives somewhat different results
- *E*-field is not irrotational (integration over CE3 does not give zero)
- *H*-field integration is also not irrotational (integration over CH2 does not give zero)
- *V, I* and Z_c not well defined and frequency dependent
- Propagation constant frequency dependent

TEM lines versus quasi-TEM lines
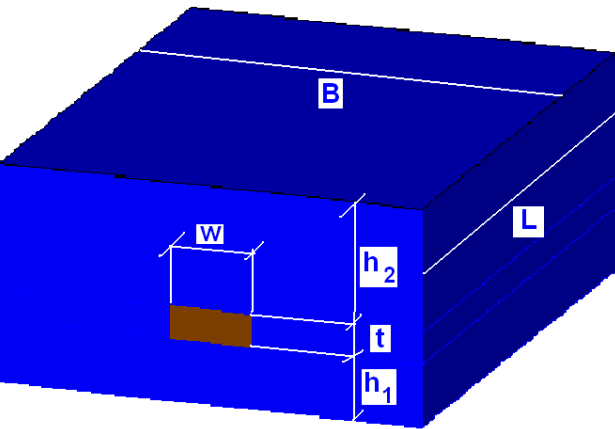
Consider air filled line with L=1", B=0.8", h_1=5.6 mils, h_2=40 mils, t=0

and the same line on a substrate of ε_r=2.6
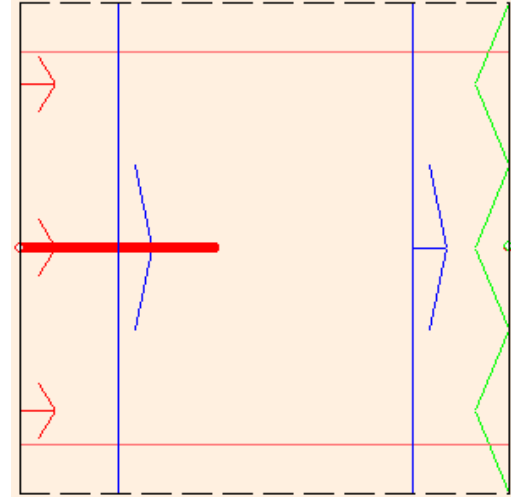
Line becomes leaky with inhomogeneous filling (red S_{21} curve on the right)

Leaky waves can be observed on the E-field picture displayed within 60 dB scale below with sinusoidal excitation at 20 GHz.

View Results total 12 including 6 from tasker

Symbol	Name	Domain	Value
	|S21|	F=13.9500 [GHz]	-24.305710
	|S21| F:/Projects/Go...	F=13.9500 [GHz]	-82.887688
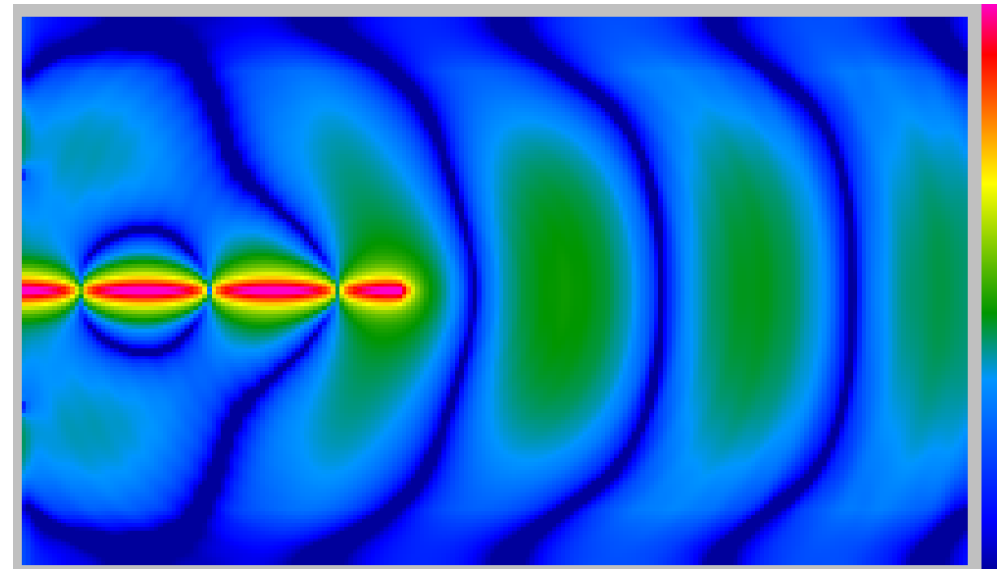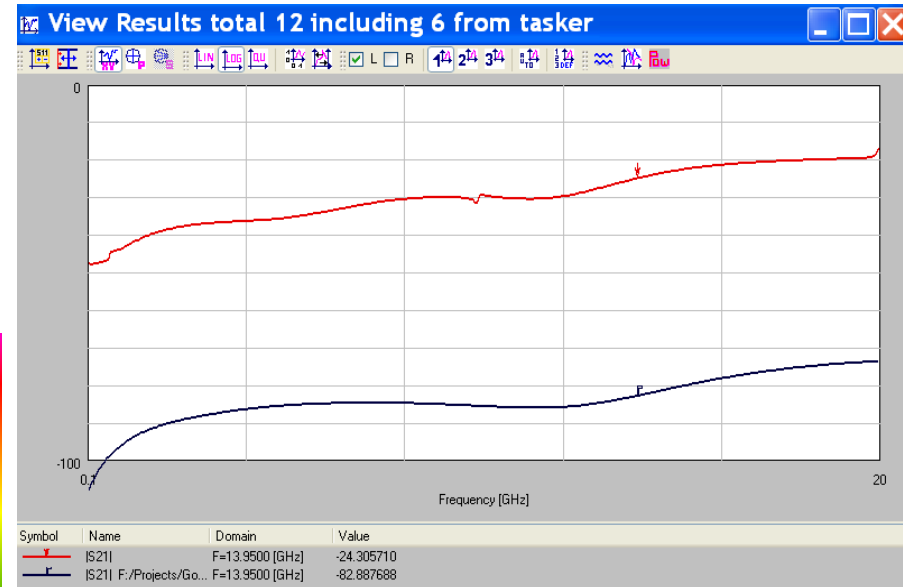
Suggestions to electromagnetic software users

2 – In the initial stage try to estimate the computer resources needed to solve the problem.

Example: how to estimate resources for a 3D FDTD software:

- Usually 10 to 20 cells per λ are needed (depending on the accuracy required and quality of conformal meshing). Thus we need 1000 – 8000 cels per $λ^3$

- about 70 to 140 bytes of memory are needed for one FDTD cell (software dependent) which makes 70 to 1120 kB per $λ^3$

Example - cont

- thus with one 1 GB of RAM we can discretize the volume of 14 300 – 893 $λ^3$ which means a cube of the size of 24.2 – 9.6 λ.

- we assume: the maximum size of the structure of 20λ, biggest-to-smallest cell size ratio 5 and that steady state is reached in 3 wave passages through the structure (60 periods). This makes the total of 100 -200 FDTD iterations per period or a total of 6000 - 12000 iterations.

- a modern 3GHz PC should need about 1-3 s to calculate 1 FDTD iteration with 14 mln cells and thus the above example should be calculated in 100 – 600 min.

Note: 32 bit systems address up to 2GB memory. 64 bit system is needed for bigger tasks.

Example - cont
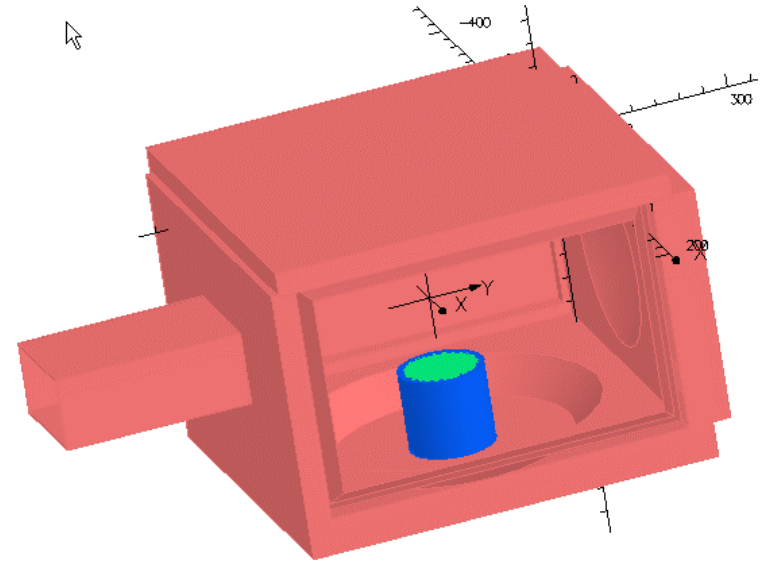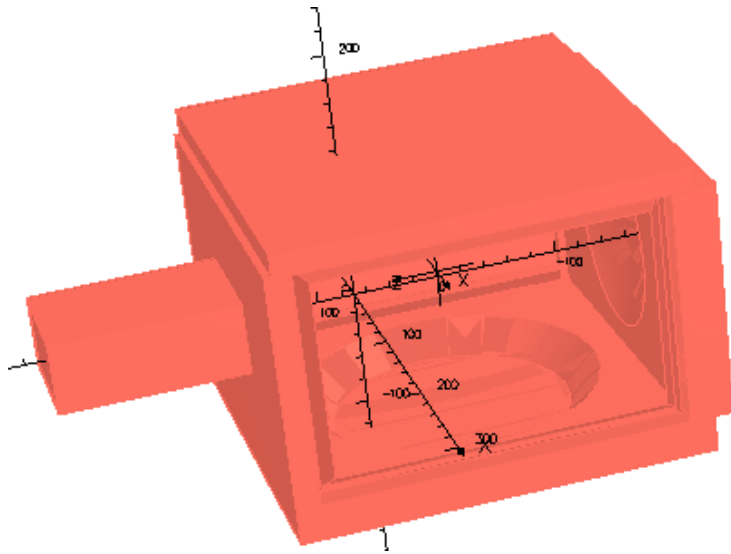
Empty microwave oven can be theoretically calculated at 2.45 GHz with about 10 mm cell thus with about 40x30x30 = 36 000 cells.

In practice presence of:

- high permittivity loads (up to ε_r=80 in water)

- parts of complicated shapes

- sharp edges causing field singularities

cause that a typical case can be (depending on the software) a 0.5 to 3 mln cell problem (requiring 40- 420 MB of memory)

Hardware accelleration of FDTD codes

The speed of FDTD codes is often compared by indicating number of cells (in millions) multiplied by the number of iterations per second.

In the comparison:

- 2CPU or 4CPU refers to number of processors of the PC

- Open MPI is one of new compiler optiona for multiprocessor PC's

- AxFDTD refers to hadware accelleration cards (www.acceleware.com)

QuickWave3D accelerated versions comparison

Version	Mcells/s
sequential	20
mt3 @ 2CPU	32
OpenMPI @ 2CPU	40
mt3 @ 4CPU	45
OpenMPI @ 4CPU	70
QW3D & AxFDTD	200
QW3D & AxFDTD (future)	400

Mcells/s
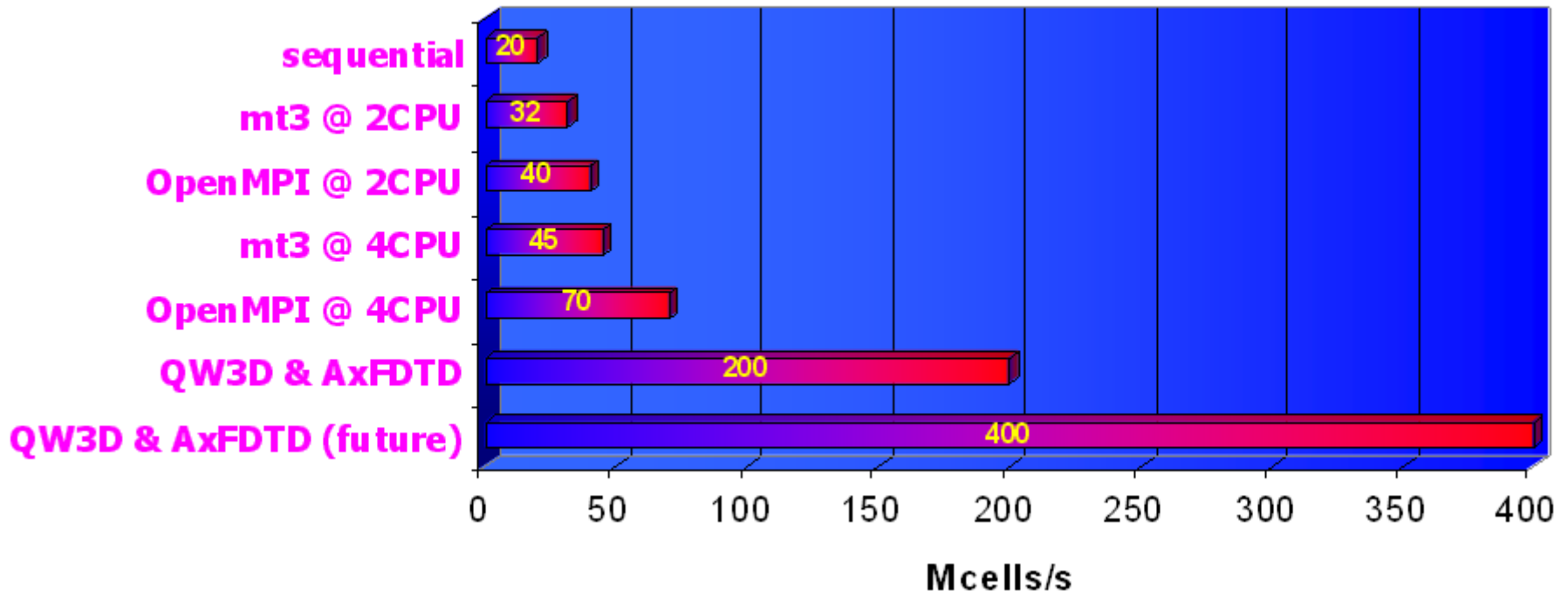
Suggestions to electromagnetic software users

3 – Be aware of the basic properties of the method used (e.g. dispersion, convergence, boundary approximation). Look closer into your structure singularities. Try to find out how they will be treated by the software. In case of doubts perform a test of accuracy on a simple singularity

Conformal versus stair-case mesh
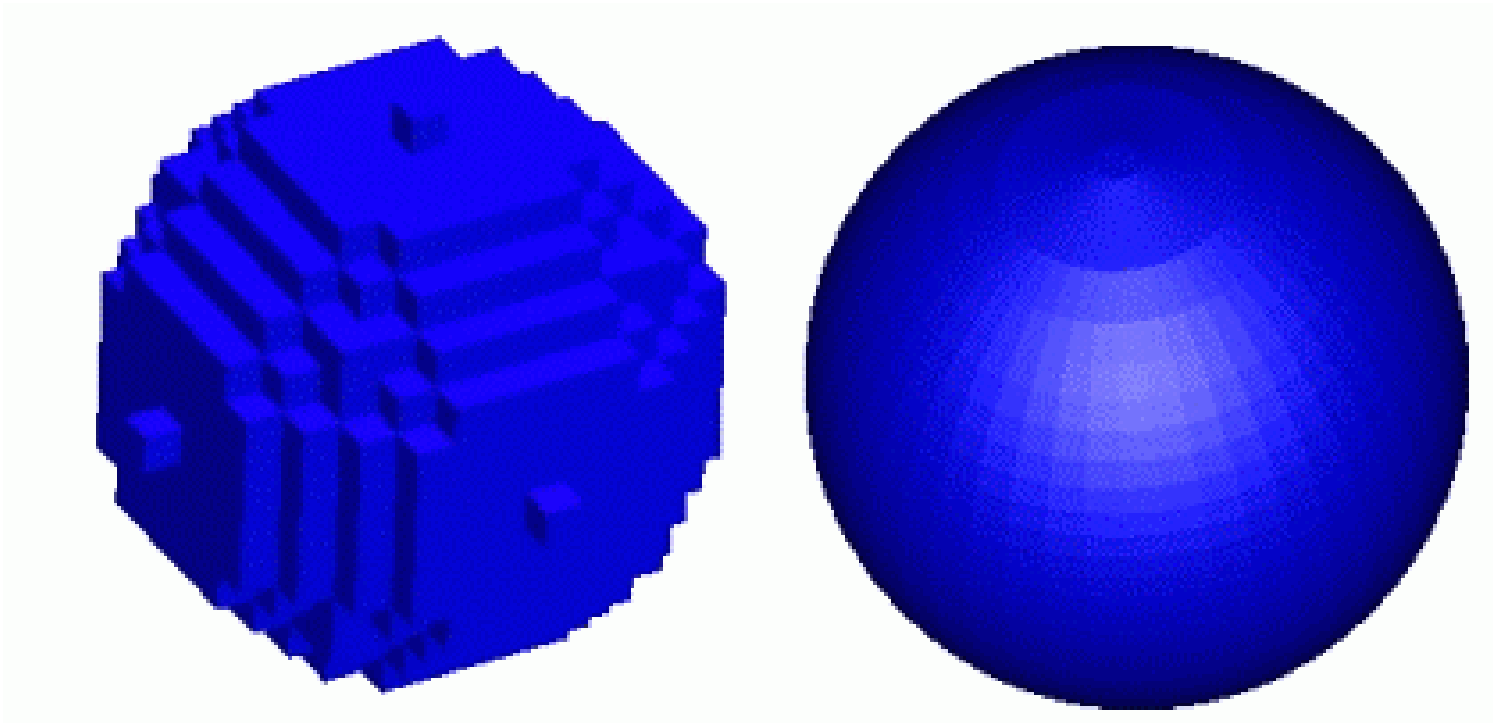
FDTD meshes & boundary approximation
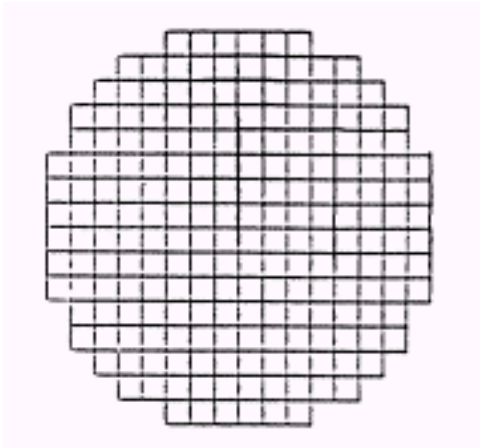
Stair-case
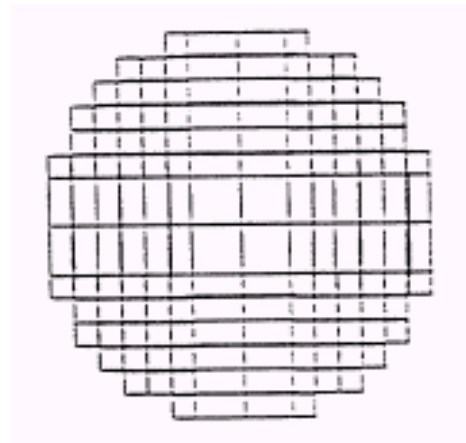
Variable mesh
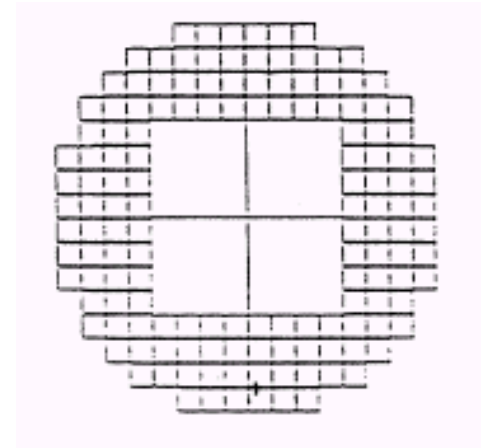
Subgridding
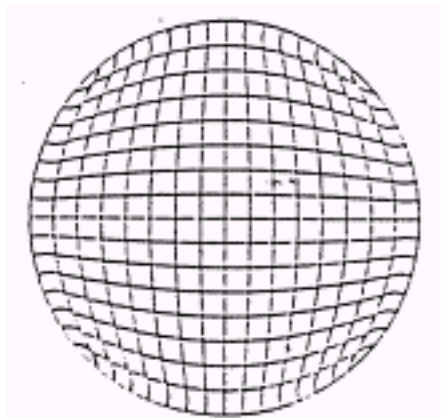
Nonorthogonal
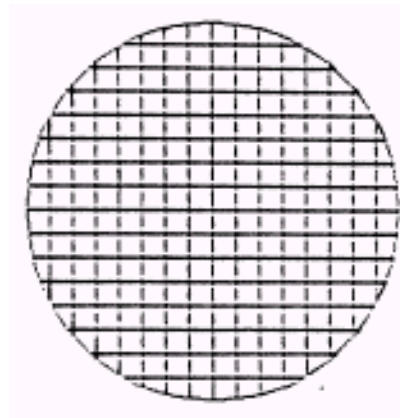
Conformal

Basic errors of FDTD method

1. Errors of modelling wave propagation over large, homogeneous subregions:

- dispersion errors on uniform meshes,

- numerical reflection from mesh non-uniformity.

2. Errors of shape approximation:

- dielectric interfaces,

- metal boundaries.

3. Errors of finite computing time
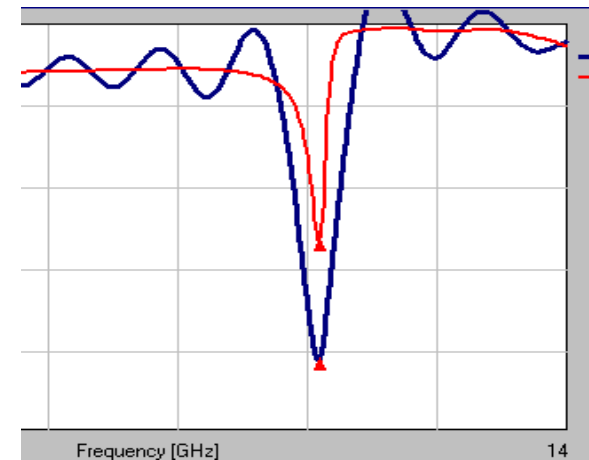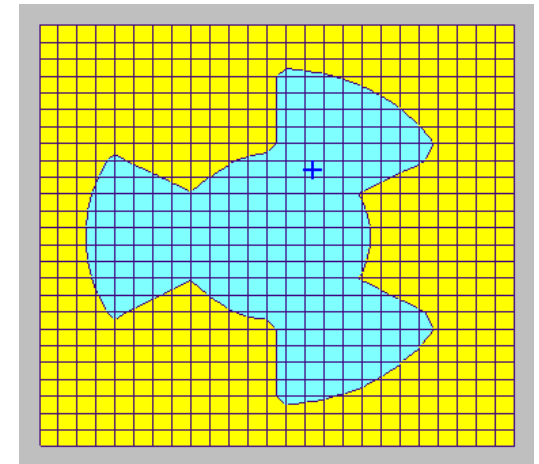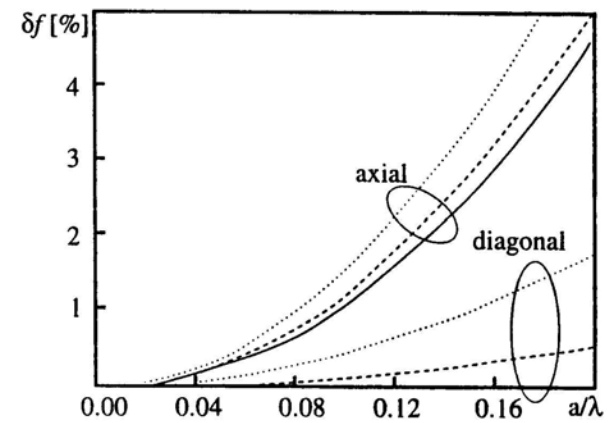
Examples of singular fields
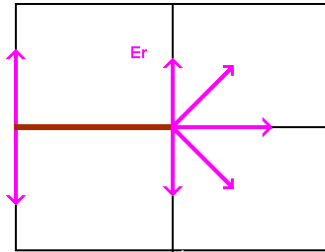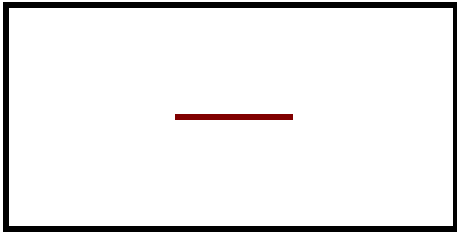
$$E_r \sim r^{-0.5}$$

$$H_\phi \sim r^{-0.5}$$
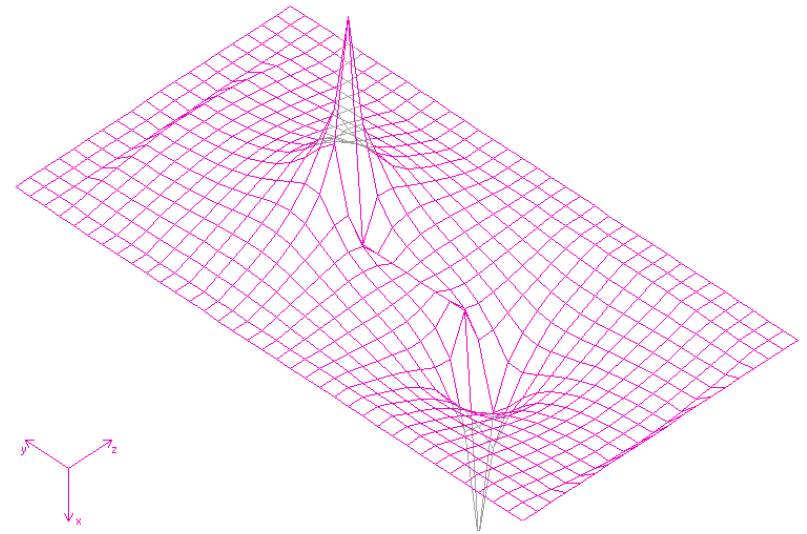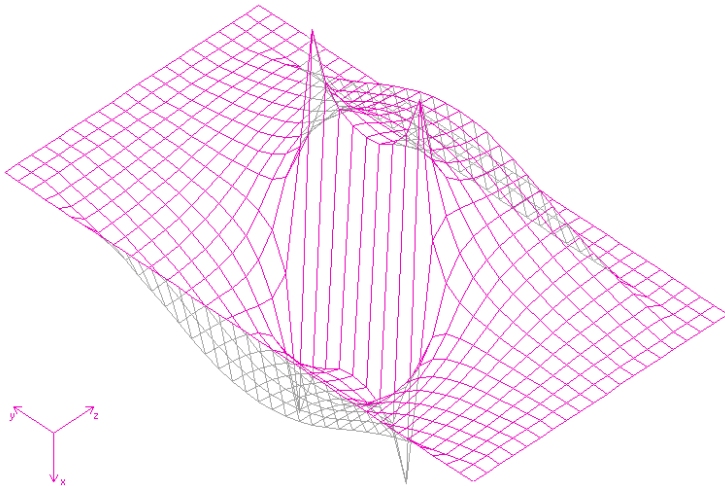
[29] M.Celuch-Marcysiak, „Local stereoscopic field singularity models for FDTD analysis of guided wave problems", 2003 IEEE IMS Symp., Philadelphia, June 2003, pp.1137-1140.

Examples of structures prone to field singularities

TEM transmission lines
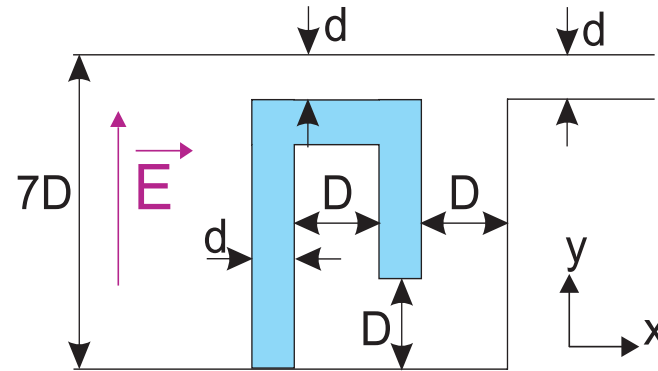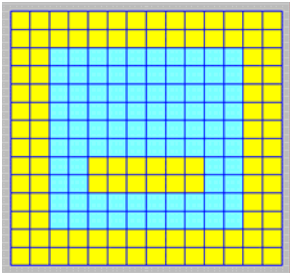
resonators
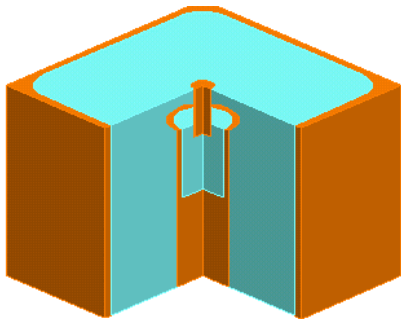
filters
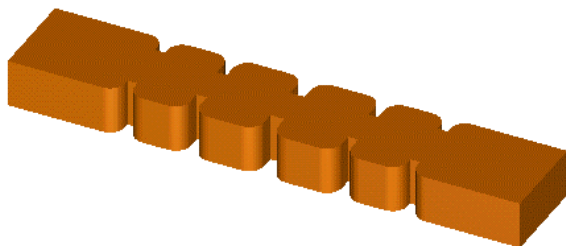
Choke of a microwave oven in raw FDTD gives frequency error about 40 times bigger than dispersion error. Good correction can make singularity error comparable with dispersion error
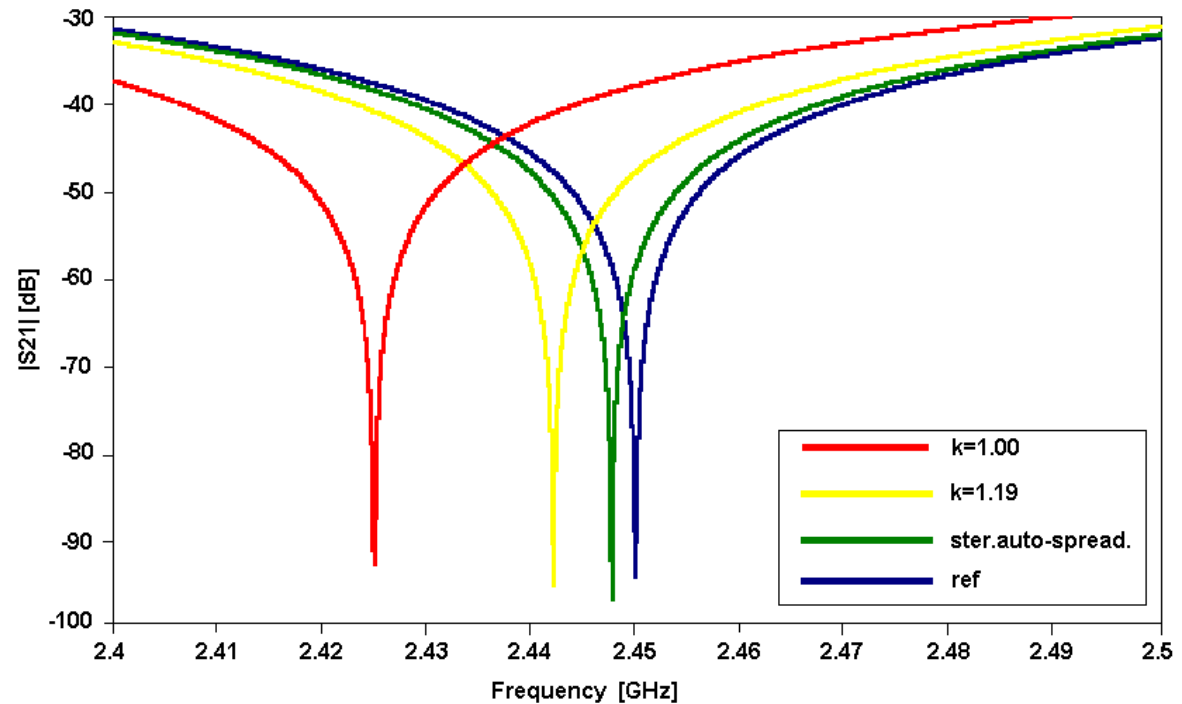
Singularity issues in FD & FDTD

	errors by raw FD / FDTD	action by singularity models
E -field	$\varepsilon \uparrow$	$\varepsilon \downarrow$
H -field	$\mu \downarrow$	$\mu \uparrow$
Z_0	$\downarrow$	$\uparrow$
f	depends on mode	consider stability

In TEM transmission lines singularity errors of both field types boost the impedance error.

Singularity corrections become indispensable for analysis of transmission lines with reasonable discretization
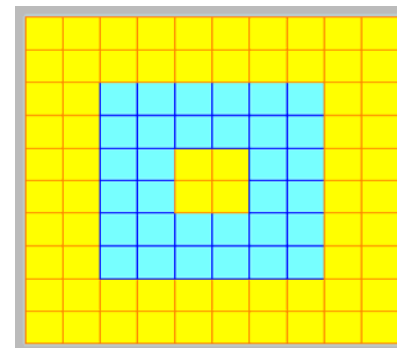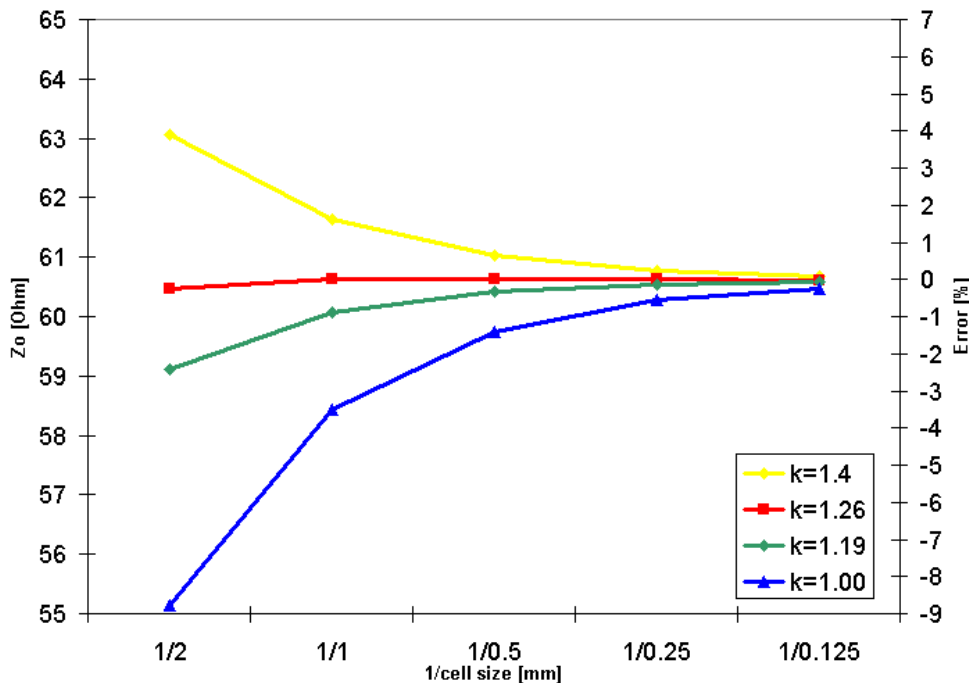
Example of a 3-D problem – septum polarizer
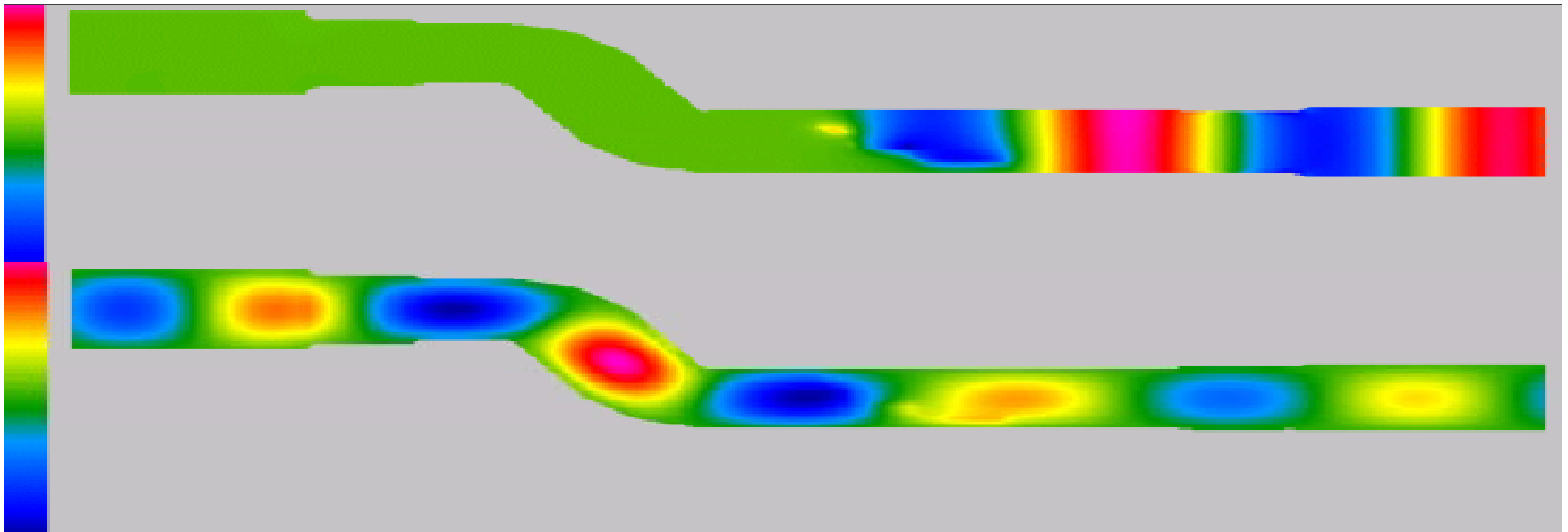
Above pictures illustrate propagation of two polarisations at center frequency
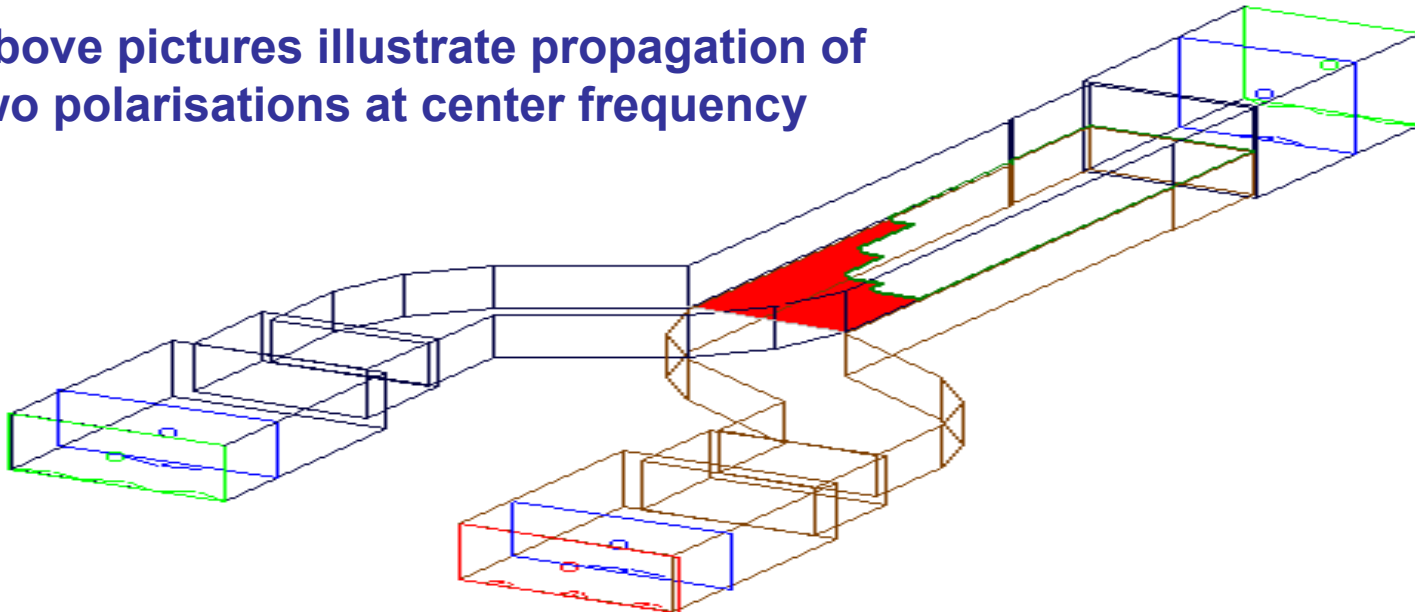
Example of a 3-D problem – septum polarizer

Comparison of measurements by Saab Ericsson Space and simulations by QWED of the phase difference between polarizations
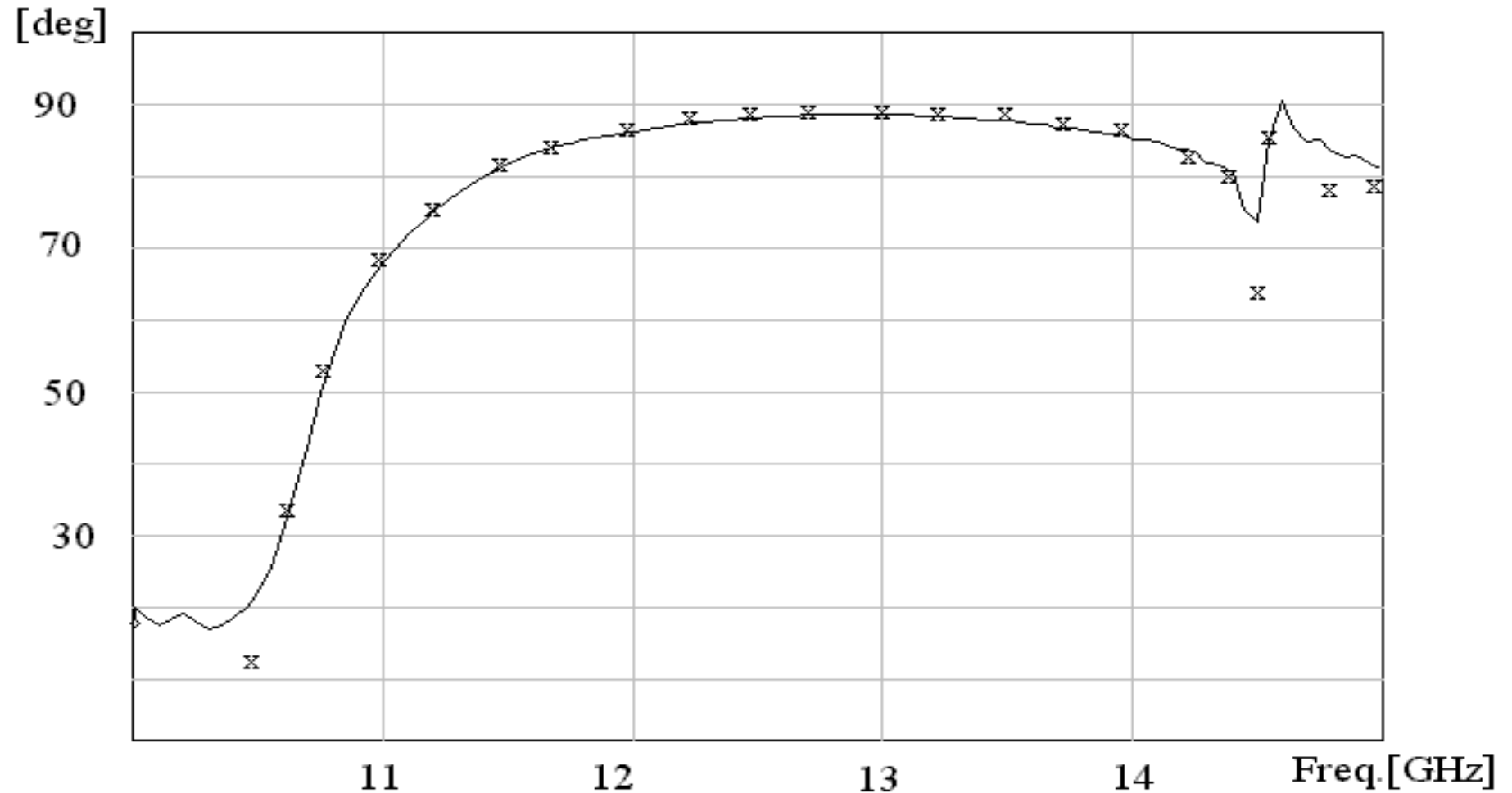
Example of a 3-D problem – septum polarizer

If the singularities are not fully accounted for in the software they can be sometimes accounted for as systematic errors

Results of calculation of the phase difference between horizontal and vertical polarization produced by the septum polarizer.
1. thin blue curve - initial dimensions of the polarizer, FDTD cell size 0.5
2. medium green curve - initial dimensions of the polarizer, FDTD cell size 0.15
3. thick magenta curve - optimized polarizer, FDTD cell size 0.5
4. v.thick red curve - optimized polarizer, FDTD cell size 0.15
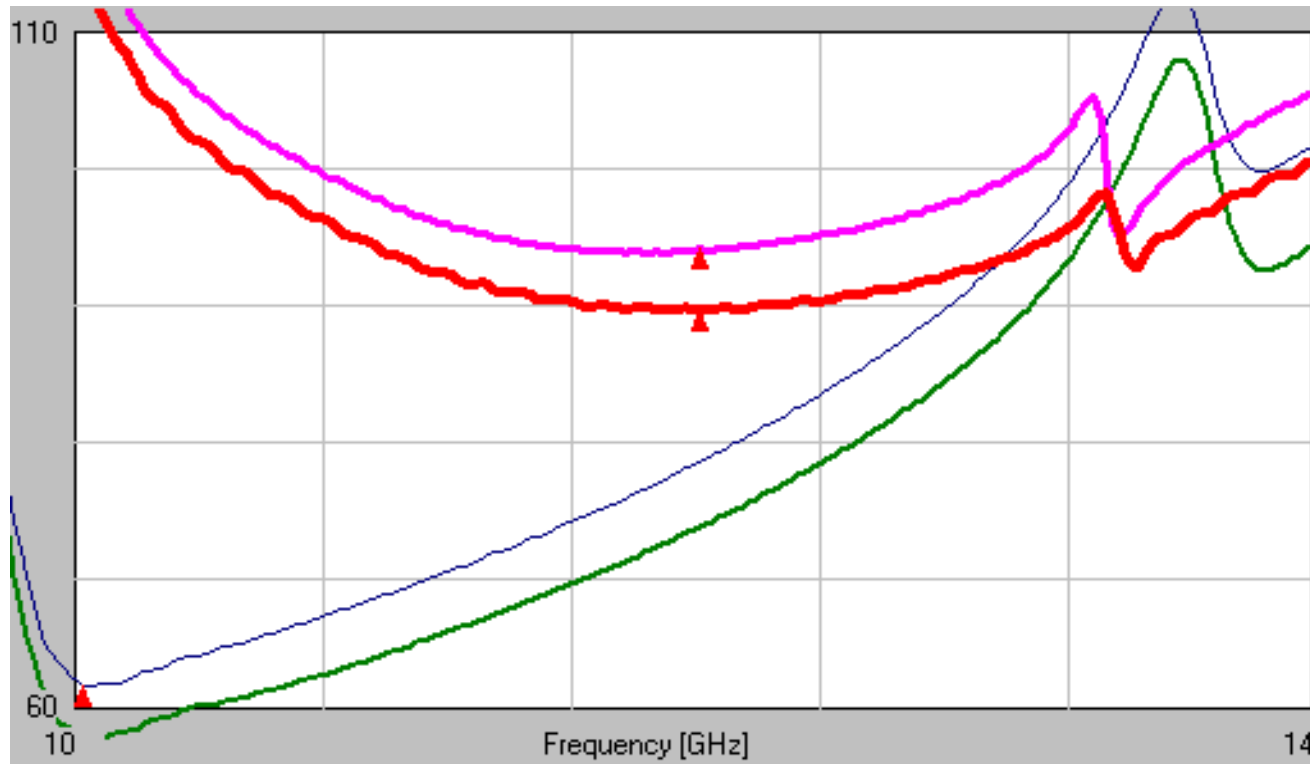
Trapped modes in waveguide structures
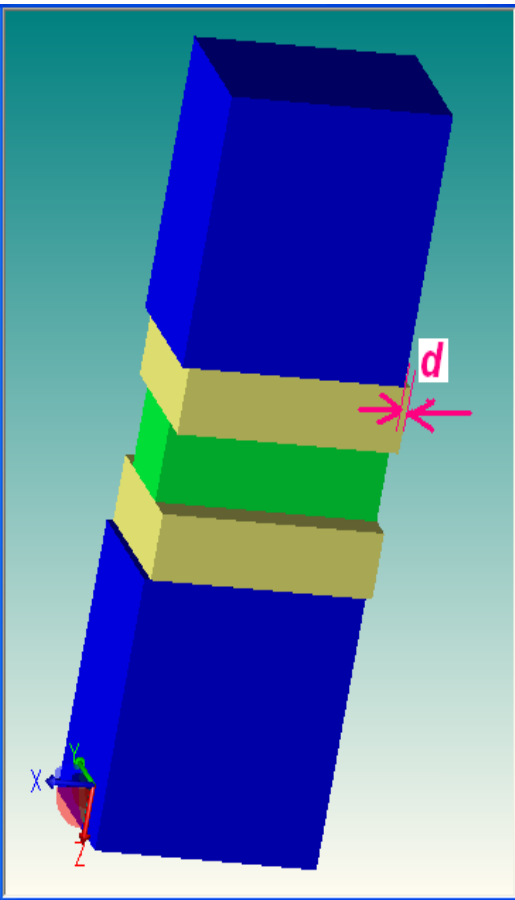
We consider a waveguide window made of teflon (yellow) and SiO$_2$ (green) in air-filled waveguide. It has been found that even very small assymetry of the window placement (d>0) produces devastating spurious resonances introduced by trapped modes at 70.6 GHz and 103.1 GHz.

Trapped modes in waveguide structures
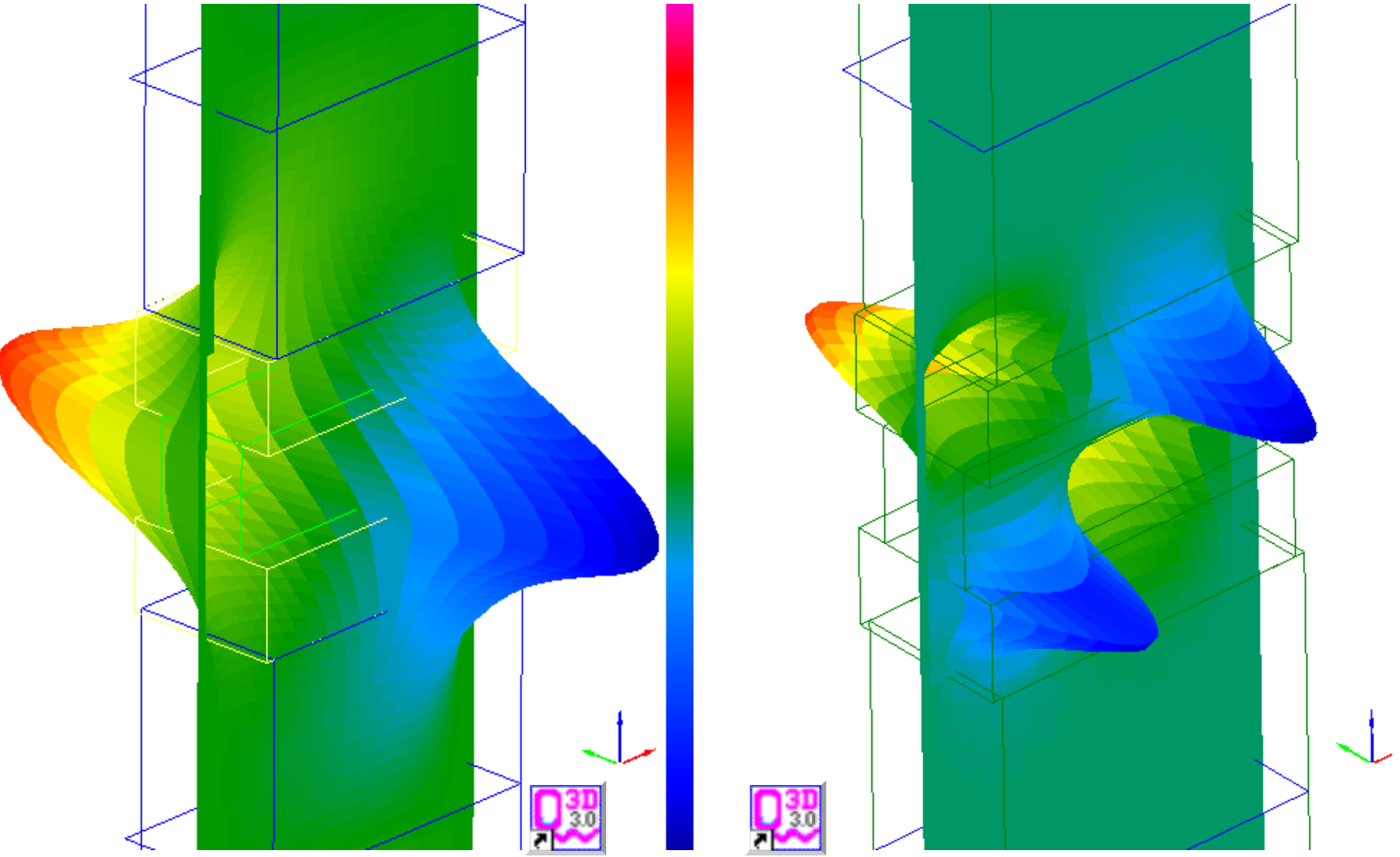
QW-3D pictures of the modes trapped in the window region ar 70.6 GHz (left) and at 103.1 GHz (right)

Suggestions to electromagnetic software users

4 – review if you have sufficient knowledge about materials used and about technological details of your structure

Characterization of dielectric materials: monocristals, ceramics, plastics, laminated

A. Monocristals

- have material properties very well defined and known
- they are often anizotropic

B. Ceramics – with alumina as most frequently used

- isotropic and relatively homegeneous
- contain impurities decisively changing loss factor
- porous material and the air content decides on permittivity (for example alumina can have permittivity from 10.0 down to 9.0)

C. Plastics

- pure electron polarisation matrials (teflon, polystyrene, polyetylene) have well known properties
- many mixed materials have properties highly depending on content of basic components and impurities

D. Laminated materials eg PCB material FR4 ($\varepsilon_0 \approx 3.8$)

- are by principle inhomogeneous
- are signifficantly anizotropic

Characterization of dielectric materials

Special hints:

1. **Most materials are temperature dependent**

- Temperature coeffcient for permittivity changes of most material is in the range of 20-100 $*10^{-6}/^oK$ (mostly positive, in teflon negative)

2. **Most materials expand with temperature, some of them signifficantly (e.g. teflon)**

3. **Many materials are hygroscopic**

- water content (with $\varepsilon=80$) modifies low-ε materials (eg.FR4)

- water content increases losses

Characterization of dielectric materials

Most manufacturers provide ε with accuracy 2-3% and losses with accuracy of 30-70%

To know them better we must measure them.

For example special measurement resonators can provide ε with accuracy 0.5% and losses with accuracy of 2-3% for tanδ above 10^{-3} and slowly rising with lowering of tanδ

Dissasembled 3.2 GHz split post
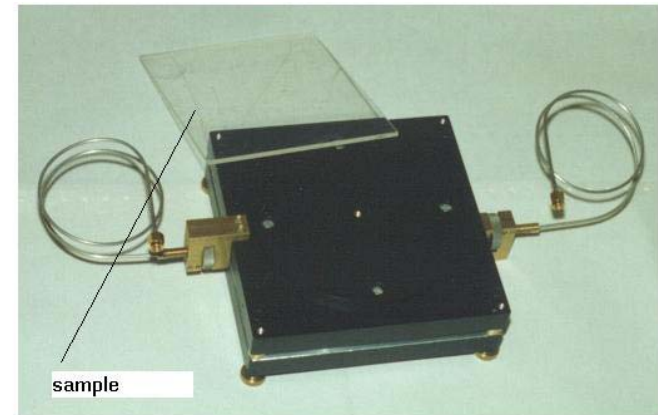
1.4 GHz split post

Importance of slots between metal or high-permittivity dielectric parts
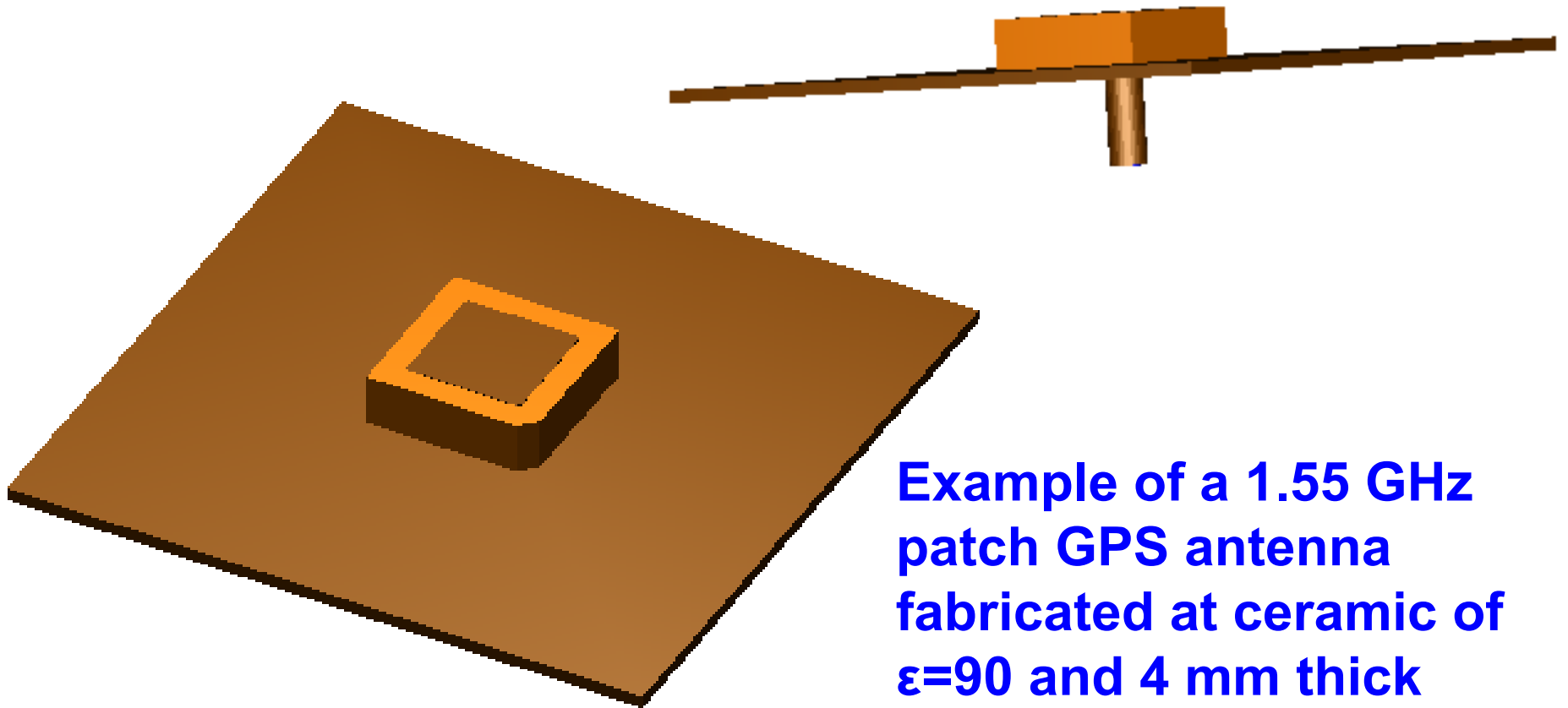
Example of a 1.55 GHz patch GPS antenna fabricated at ceramic of ε=90 and 4 mm thick

Example of GPS antenna - cont
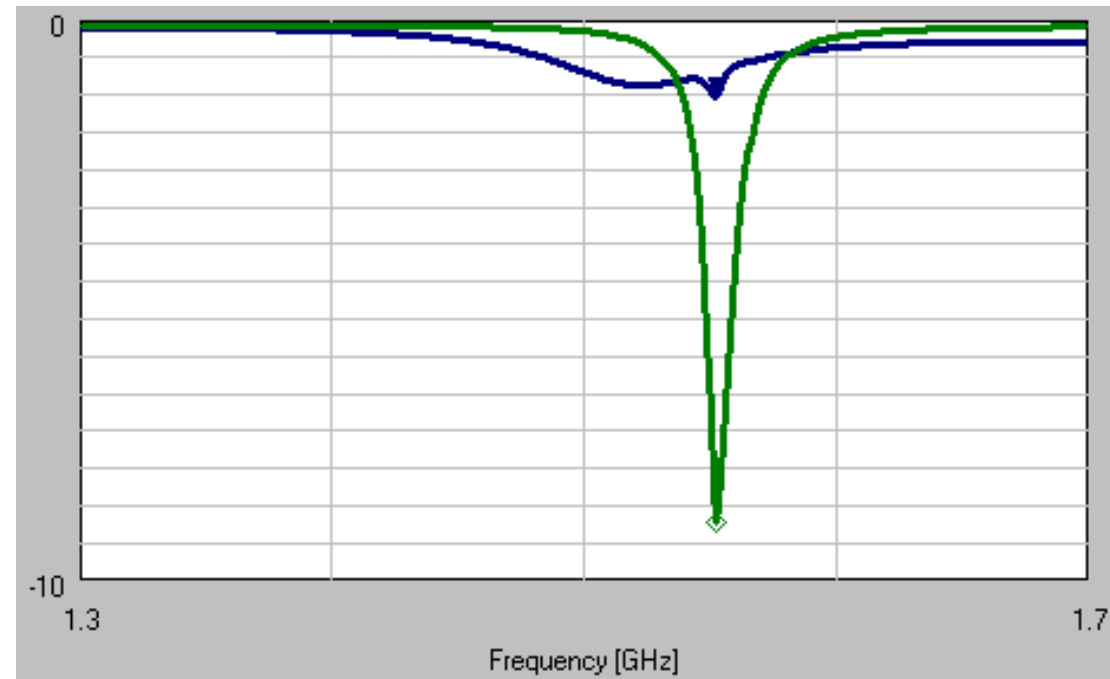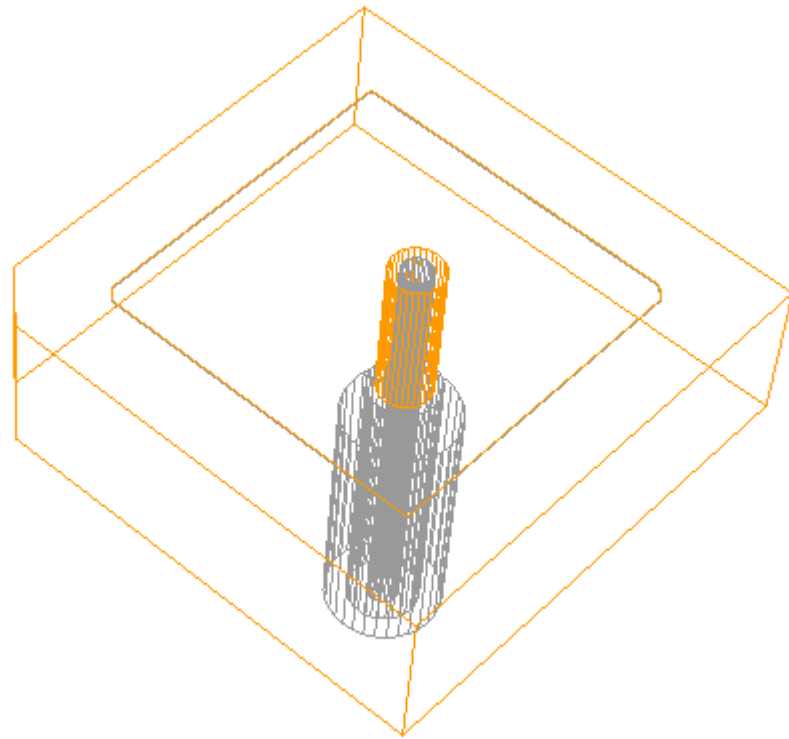
0.7 mm wire is connected to the patch through the ceramic 4 mm.

S_{11} versus frequency in two cases were considered:

- no slot between wire and ceramic (blue curve)

- 0.3 mm slot between wire and ceramic (green curve)

The simulation results in the latter case match the measurements.

Illustration of boundary conditions

1. **Distribution of electric and magnetic field in a line of L-shaped inner conductor**

2. **Electric field in a parallel-plate line with a teflon insert**

3. **Illustration of E field amplification in a dilectric slot in a ceramic material (ε_r=10)**

Note: Assume a ceramic capacitor 1 mm thick filled with a ceramic of (ε_r=100). Air slot of thickness 0.01 mm causes a drop in capacitance by ≈50%.

Disadvantages of FDTD and how they are fought

• **Natural formulation for frequency-independent ε, μ, σ**
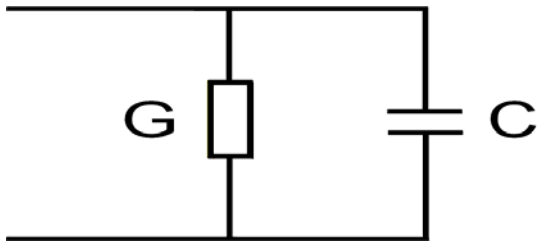
remedy: dispersive media models, e.g. Lorentz (simplifies to Debye, Drude)
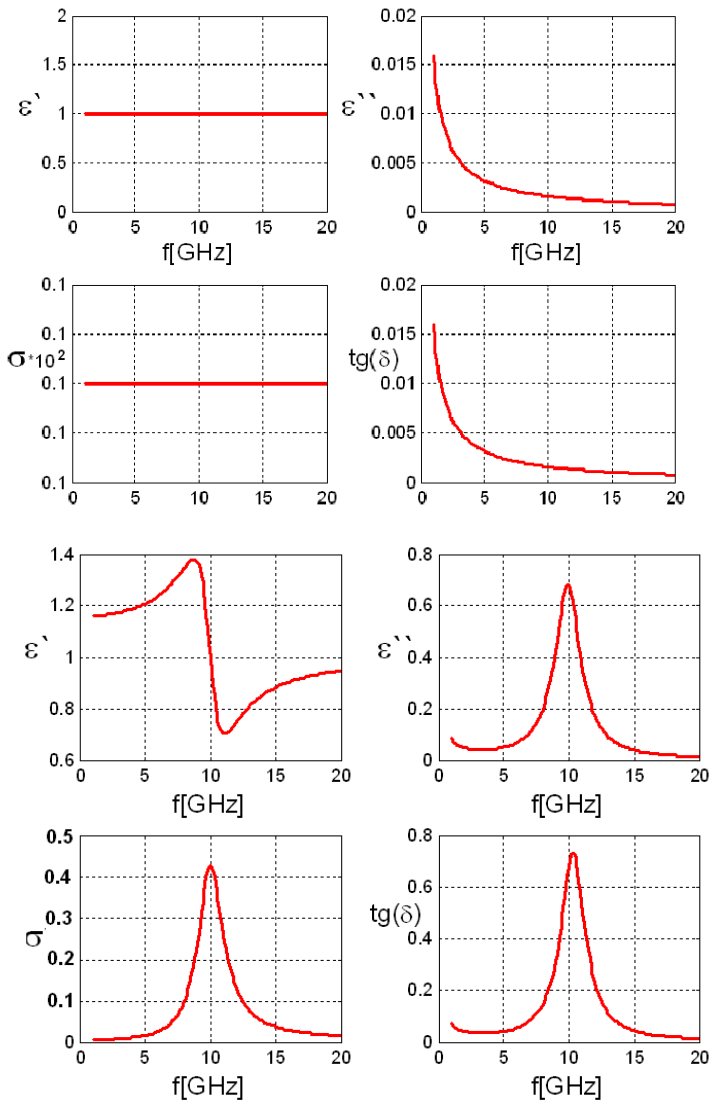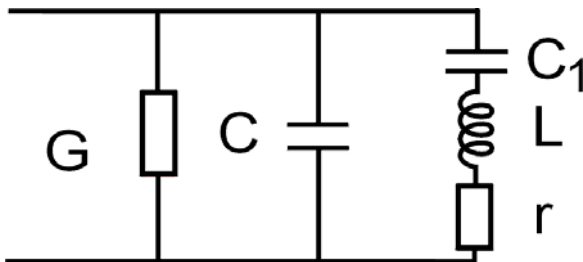
Analysis of magnetized ferrites

Polder vector description

$$\mu = \mu_0 \begin{bmatrix} \mu_1 & -j\kappa & 0 \\ j\kappa & \mu_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\kappa = \frac{\omega\,\omega_m}{\omega_0^2 - \omega^2} \qquad \mu_1 = 1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}$$

a)
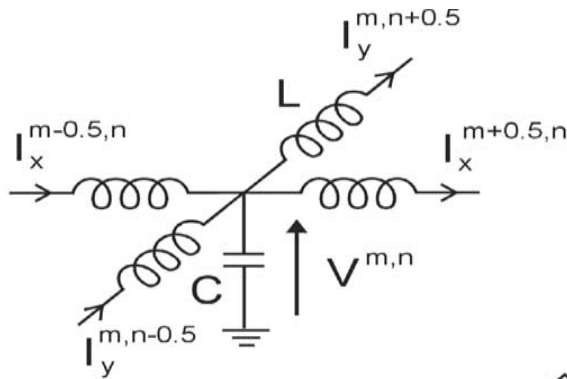
$\omega_0 = H_i\,\gamma$; $\omega_m = M_s\,\gamma$ **where:** γ **is a gyromagnetic ratio,** M_s **,** H_i **denote saturation magnetization and static biasing magnetic field assumed to be z-directed.**

b)
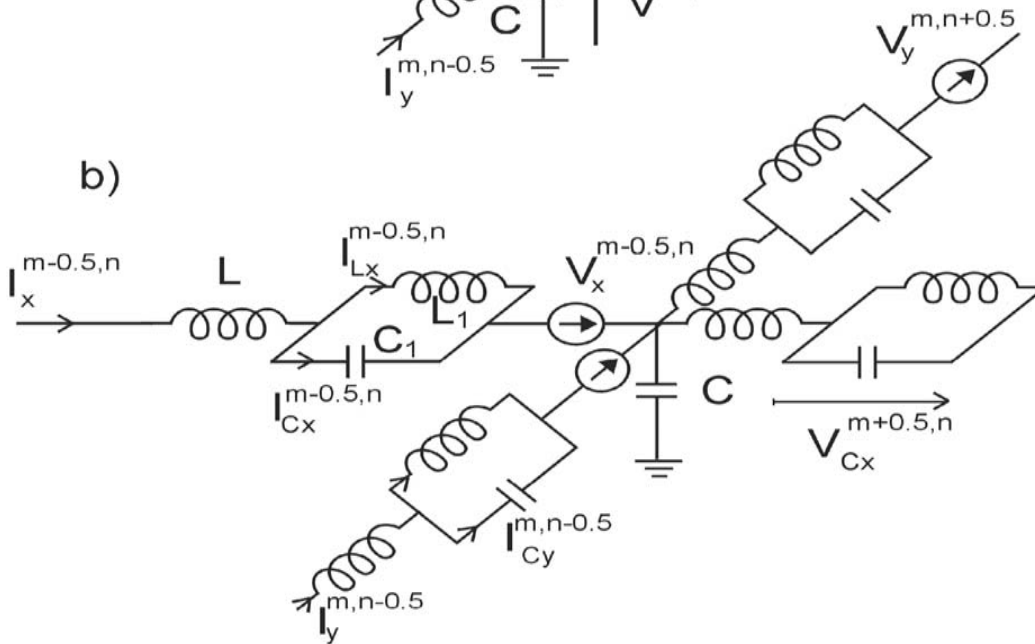
$$V_x^{m-0.5,n} = 0.25/(\omega_0 C_1)(I_{Cy}^{m,n-0.5} + I_{Cy}^{m,n+0.5} + I_{Cy}^{m-1,n-0.5} + I_{Cy}^{m-1,n+0.5})$$

Media parameters may change with temperature (dissipated power) especially when freezing
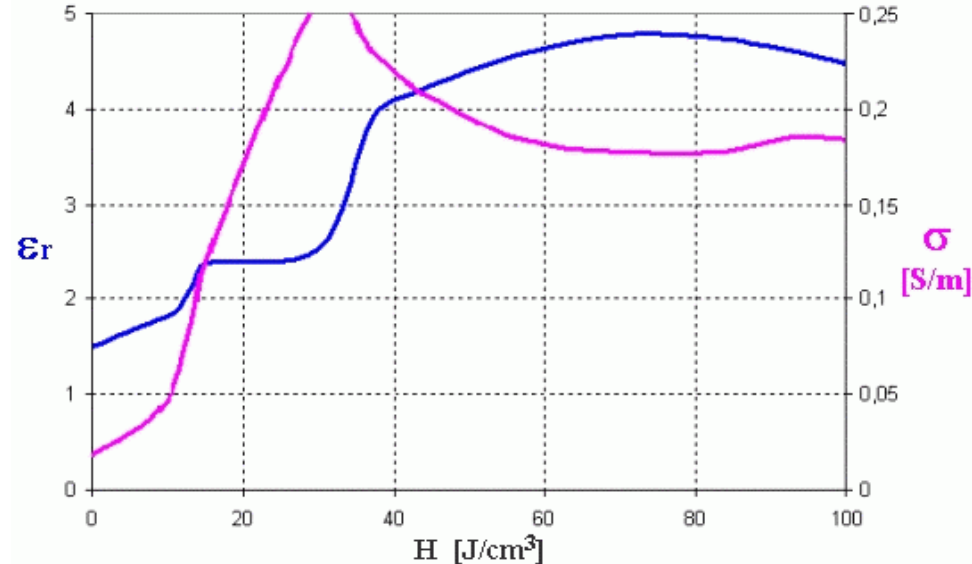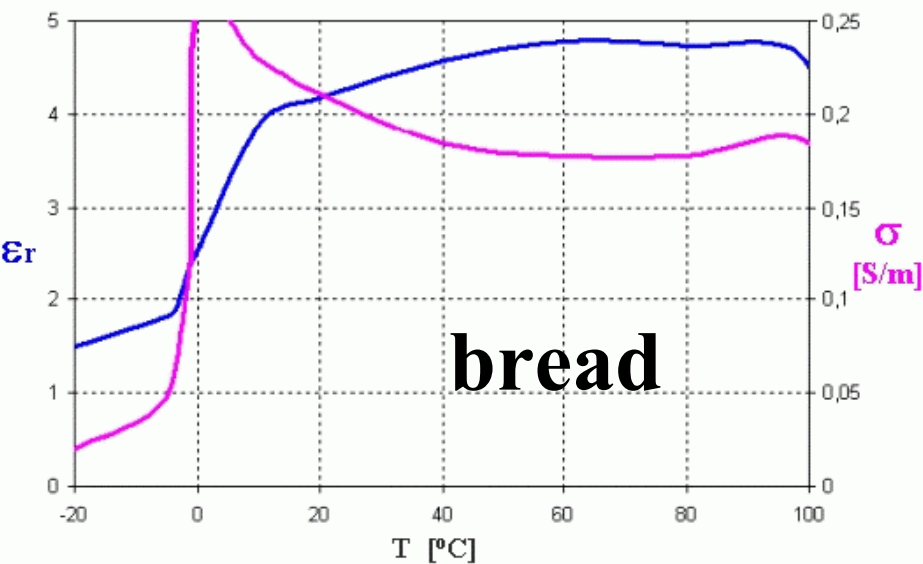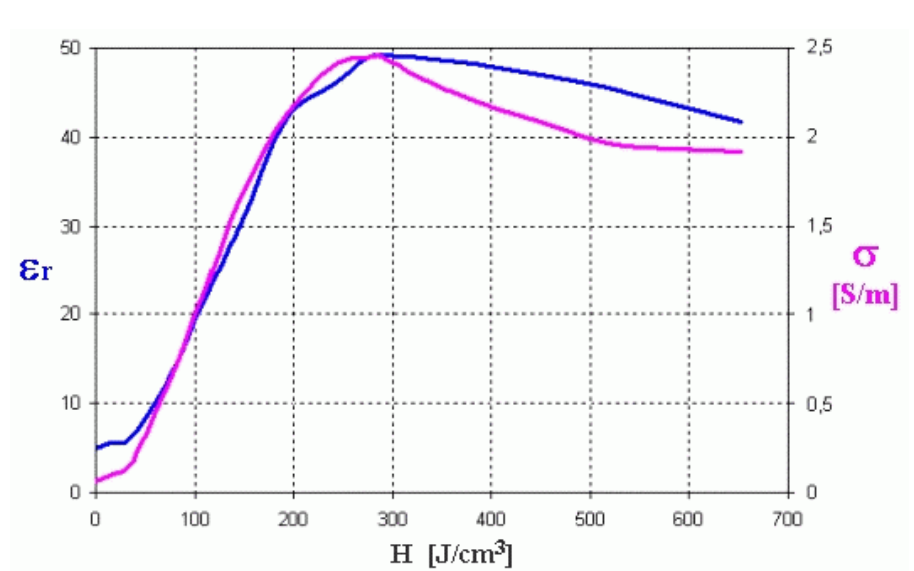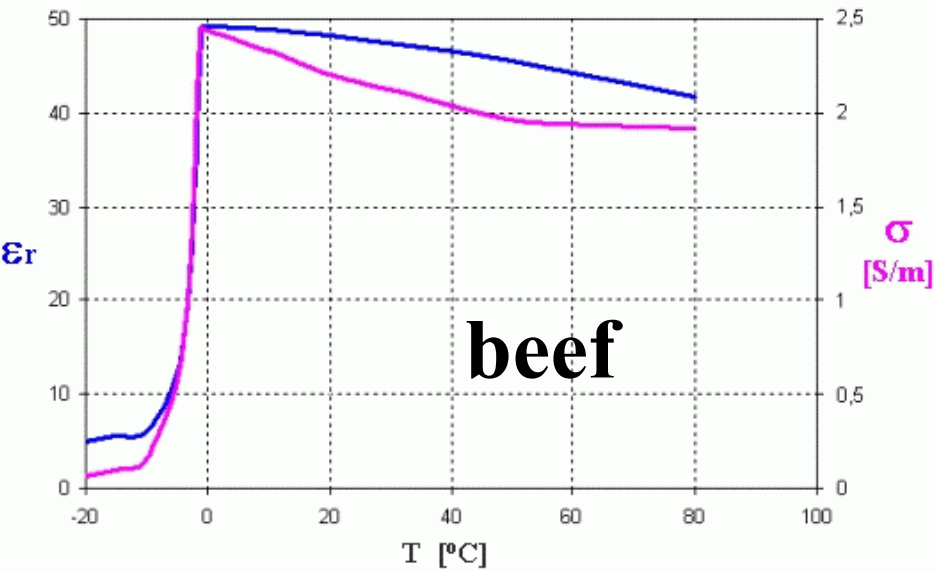
Example: modeling of thawing & heating bread with updating meterial parameter changes in BHM module
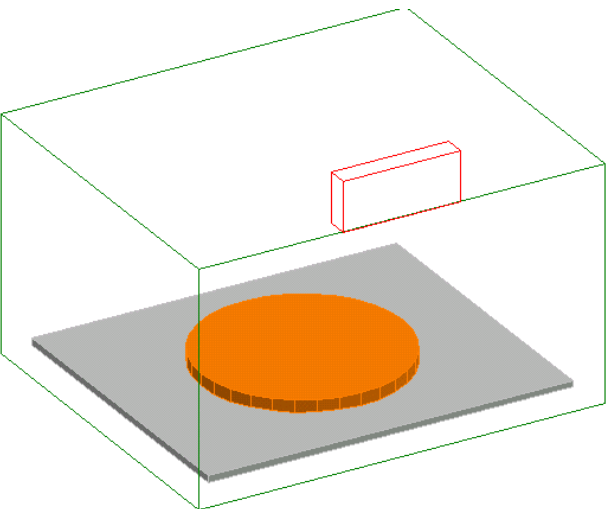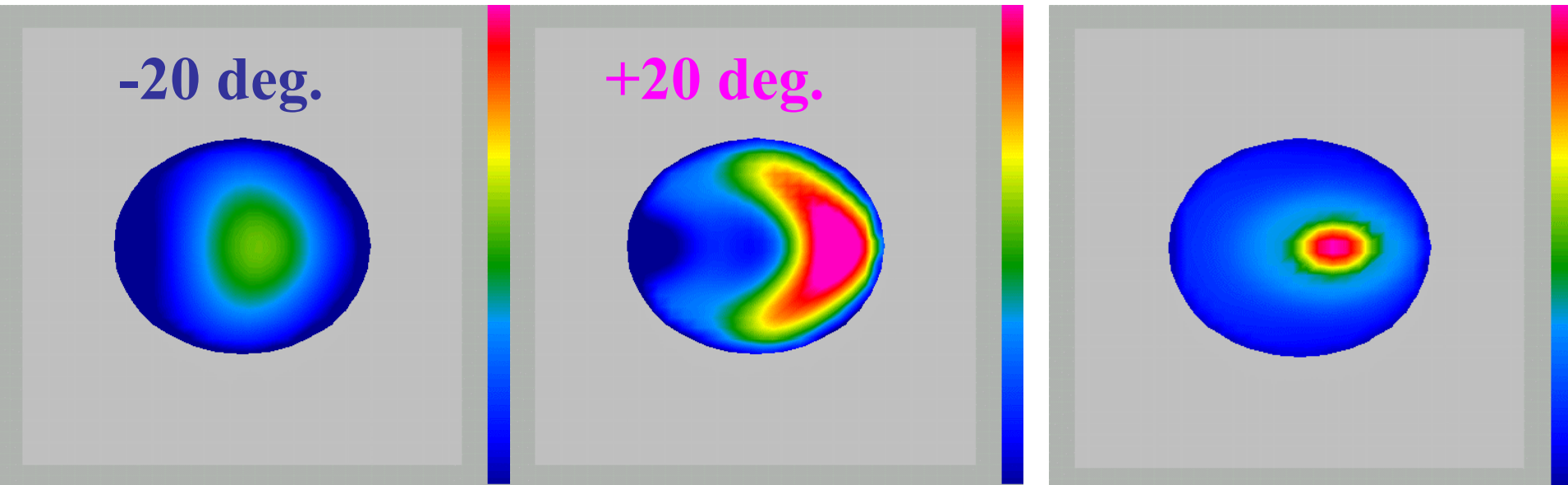
-20 deg.

+20 deg.

cavity 204x204x228mm,
plate 180x216x6mm
at z=12mm, ε'=6
feed 12x70mm,
source 2.45GHz, 625W,
bread r=60mm, h=6mm

FDTD-BHM result

**7 thermal iter., each 2 sec.
frozen edge -10 deg.
hot spot +33 deg.**

Return loss at +20 deg.
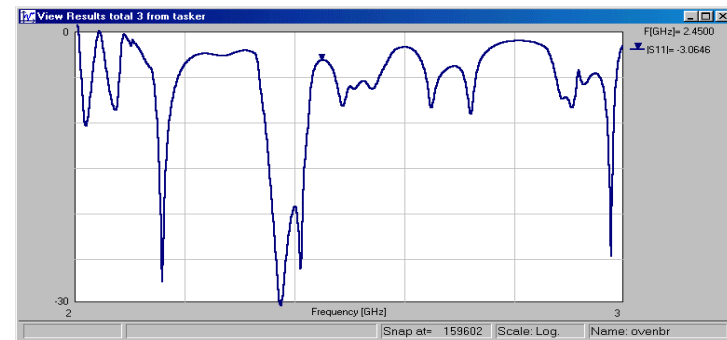
Suggestions to electromagnetic software users

5 – *Choose the proper method for a proper problem. Try to use as much as possible symmetries and reduction of dimensionality (eg 2D or 2DV approximation of axially symmetrical structures). If possible analyze separately parts of the structure.*
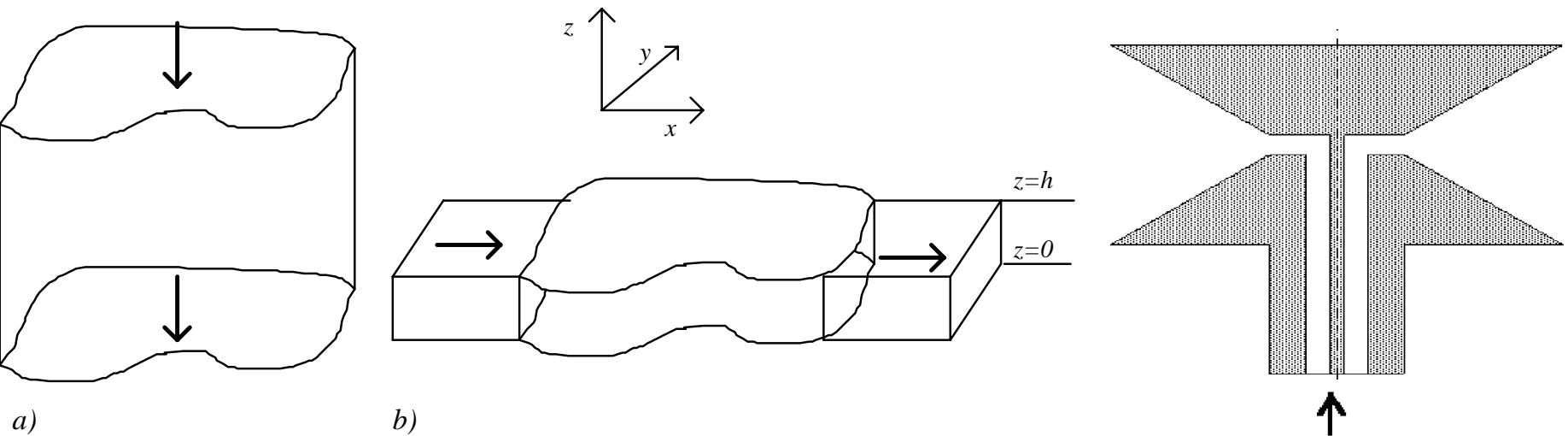
Examples of vector 2-D (V2D) problems

(geometry is 2-dimesional, all 6 fields components are present, structure is described by vector wave equation with 2 Hertz potential components)
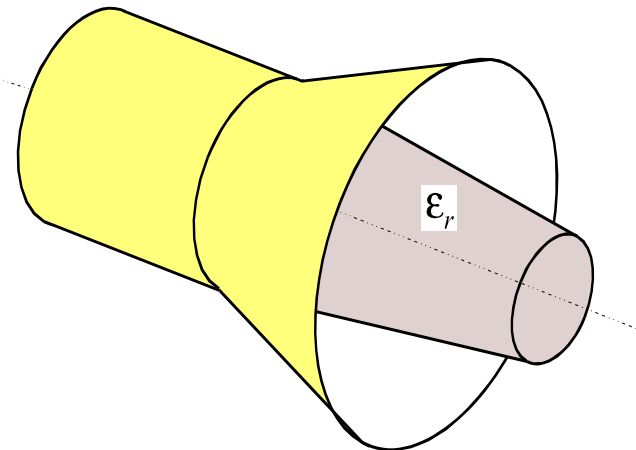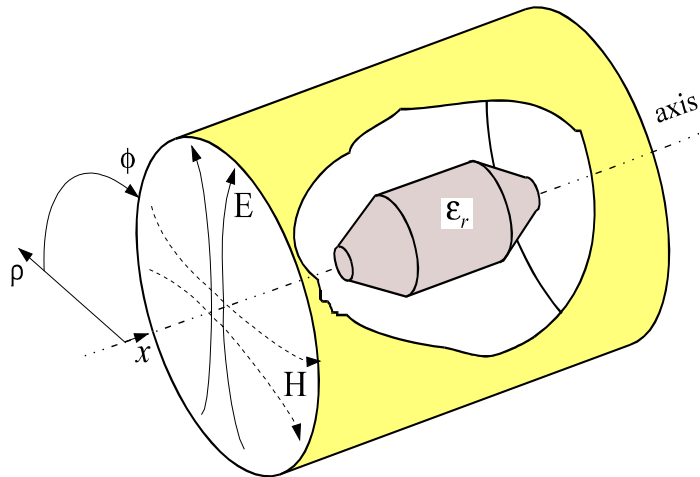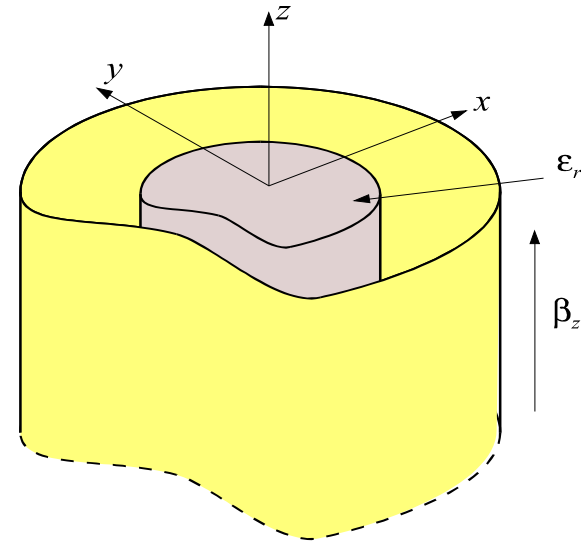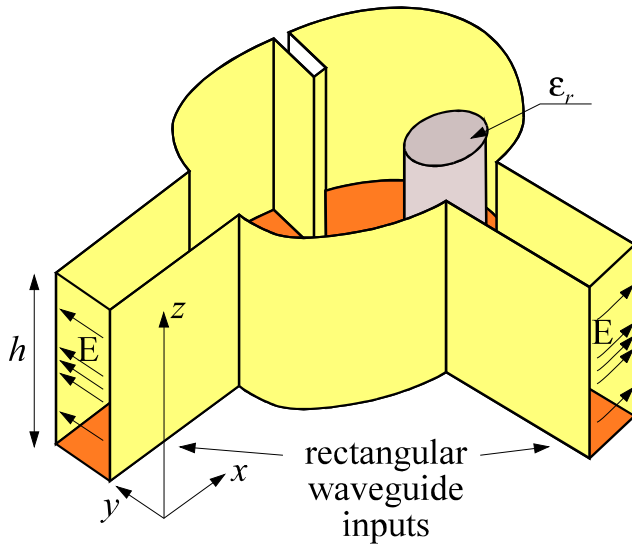
Examples of scalar 2-D problems

(geometry is 2-dimesional, 3 to 5 fields components are present, structure is described by a scalar wave equation with 1 Hertz potential component)

a)

b)

a) Detecting modes in homogeneous transmission line (eigenvalue problem)

b) Waveguide inhomogeneity (deterministic problem)

c) Biconical antenna (body of revolution (BOR) deterministic problem)

Transformation used in axisymmetrical 2D software

3-D Maxwell equations in cylindrical co-ordinates (x, r, φ) with known dependence versus φ of a type cos(n φ) are transformed into 2D equations with respect to x and r.
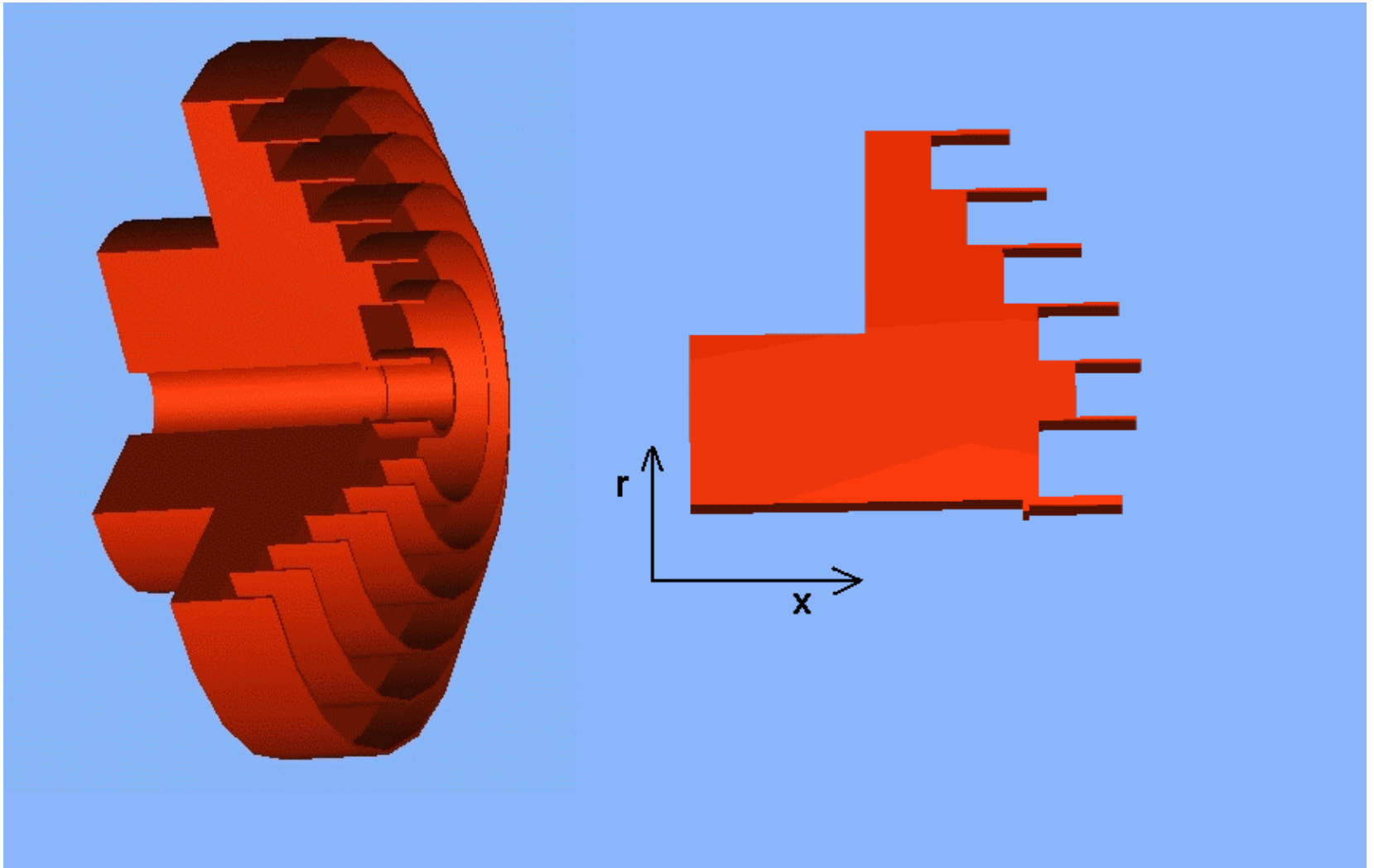
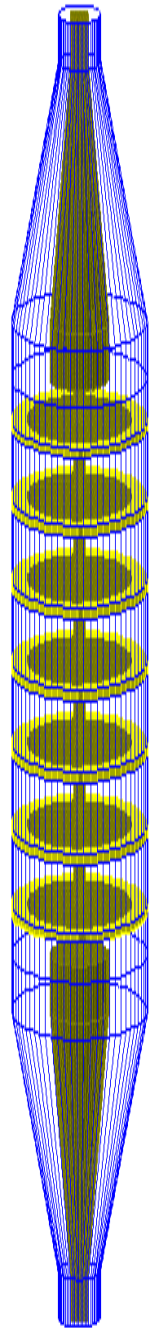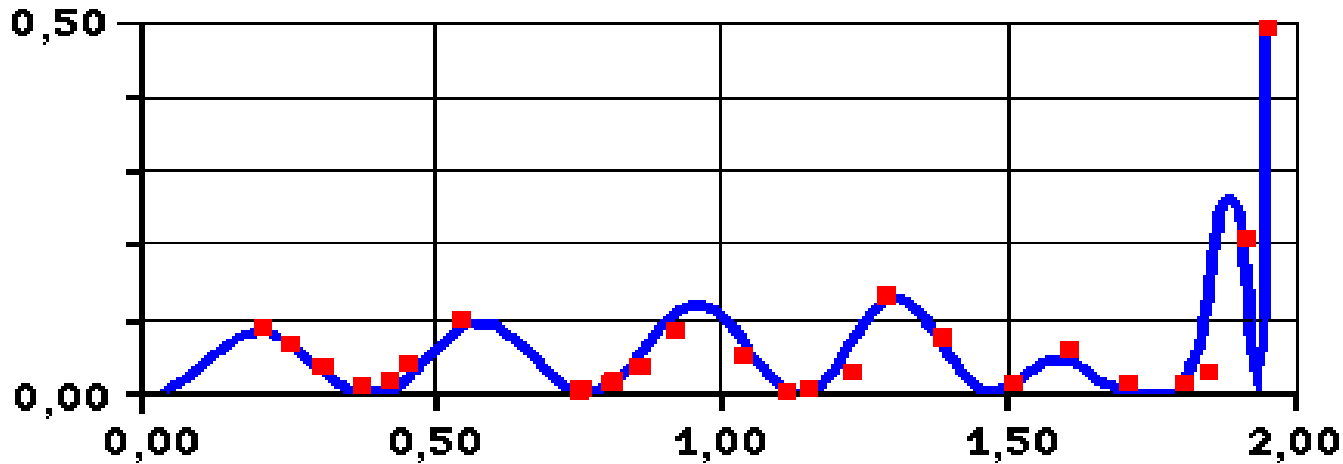# *Example of 2-D analysis- coaxial filter*

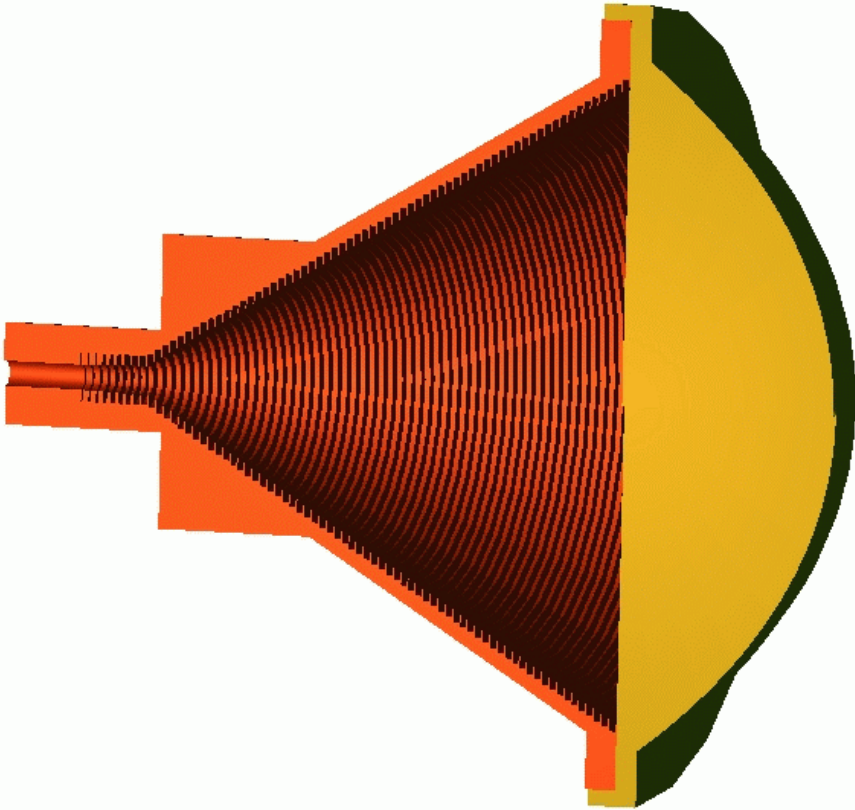## A classical coaxial low-pass filter

blue – air inside outer conductor,

green - inner conductor, yellow – bead supports

Design & measurements (●): G.Matthaei et al., *'Microwave filters...'*, Artech House 1980, p.365.
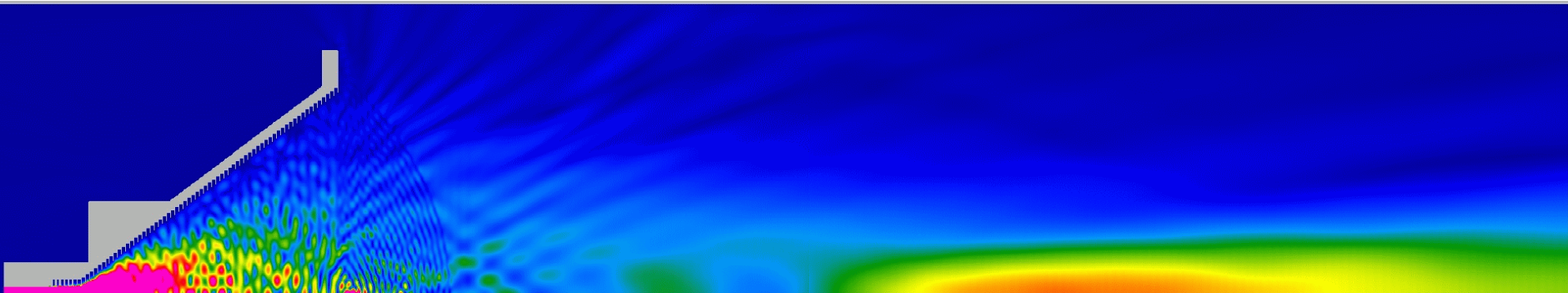
blue line **-QWCX** simulation

Example of 2-D analysis

Setup composed of corrugated horn and lens designed for quasi-optical measurements

(after Ph.D. Thesis of Marc Le Goff – Universite de Bretagne Occidentale, France, 1999)

Measurements of horn radiation patterns, input reflections and the shape of the waist by M. Le Goff confirm the simulation results with QW-V2D
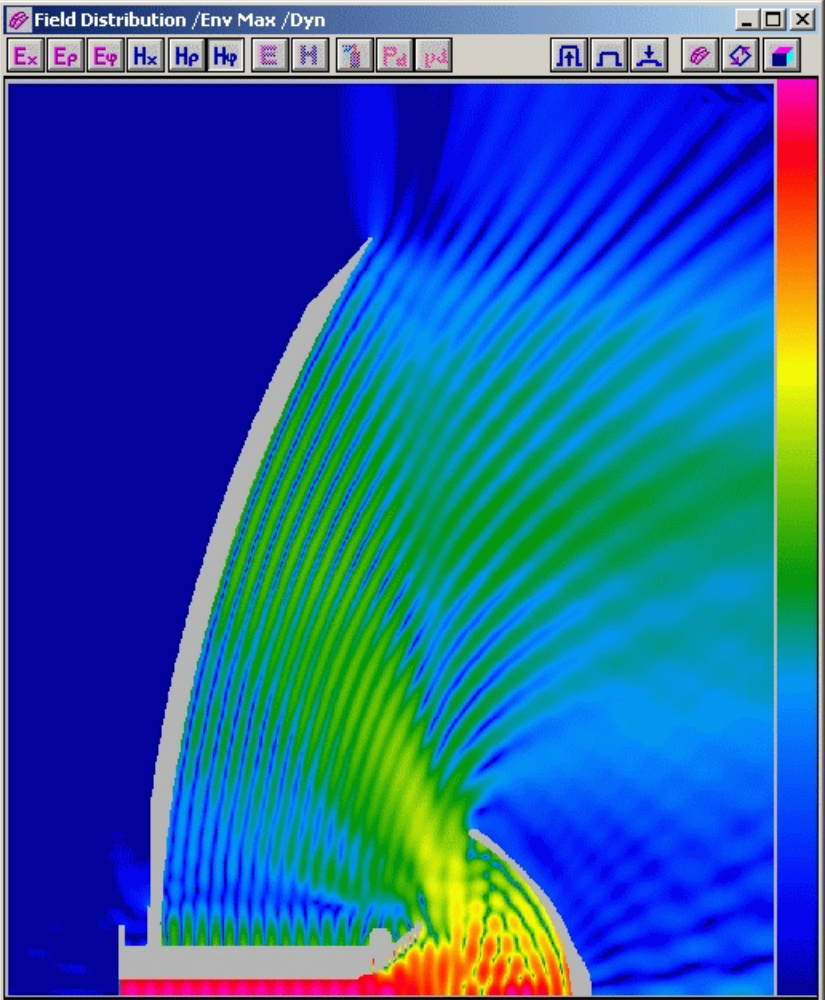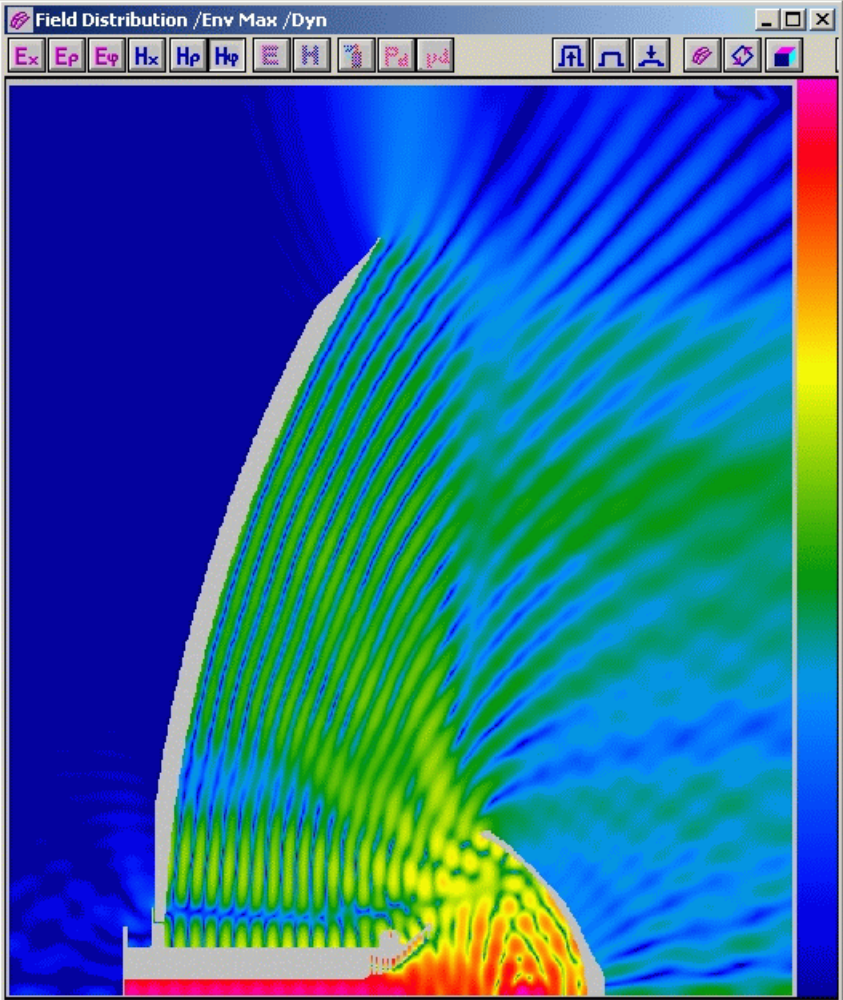
Application of V2D BoR approach to antennas

Illustration of spillover from a bi-reflector antenna: Hφ amplitude in logarithmic scale from maximum (purple) down to -60 dB (blue) at two frequencies different by 3 %

Suggestions to electromagnetic software users

6 - Remember that S-matrix can be defined only on a straight segment of a transmission line with defined mode(s) or on a lumped impedance. Use the S-matrix definition adequate to the situation (e.g. multi-port matrix in multimode case, proper treatment of evanescent modes -if any). Be cautious about the impedance definition. Impedance becomes ambiguous for any other modes than TEM.
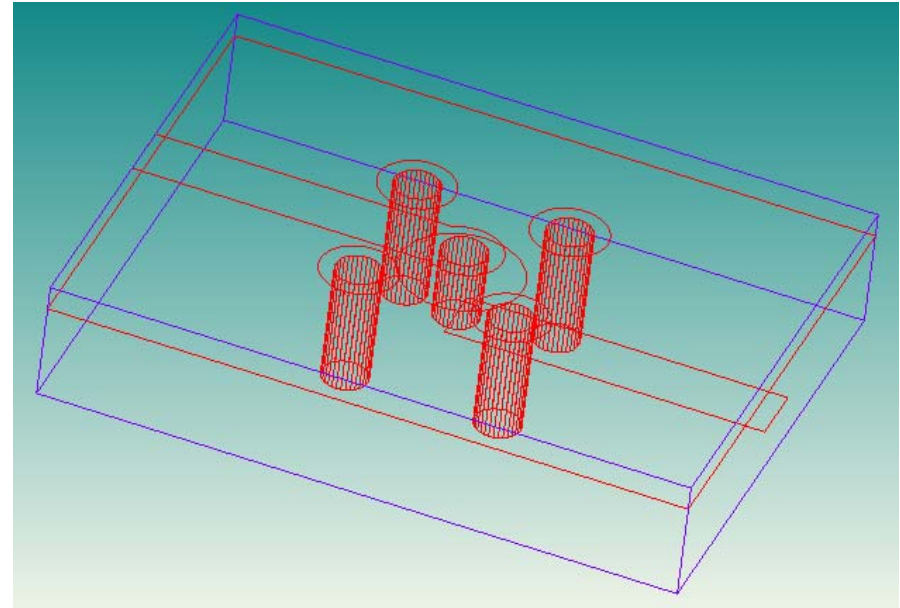
A signal integrity problem

Consider a transition from a microstrip (upper layer to a strip line (lower layer) through a via. 4 ther vias assure the ground contact.
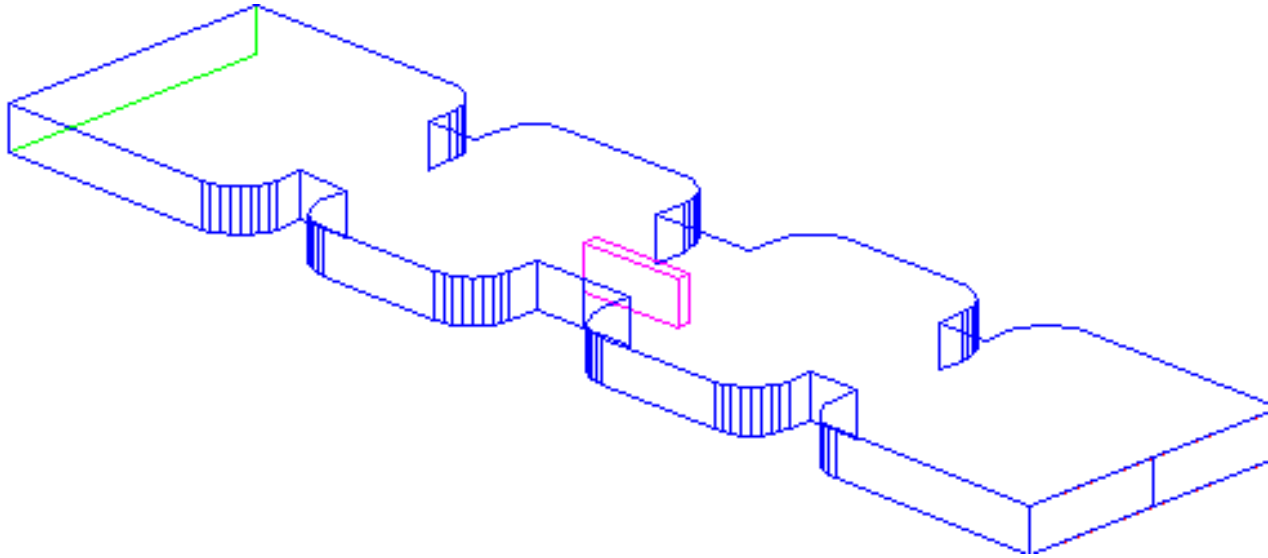

Simulations of S-matrix versus time show reflections rising with frequency and a clear signal intergrity problem at 31.4

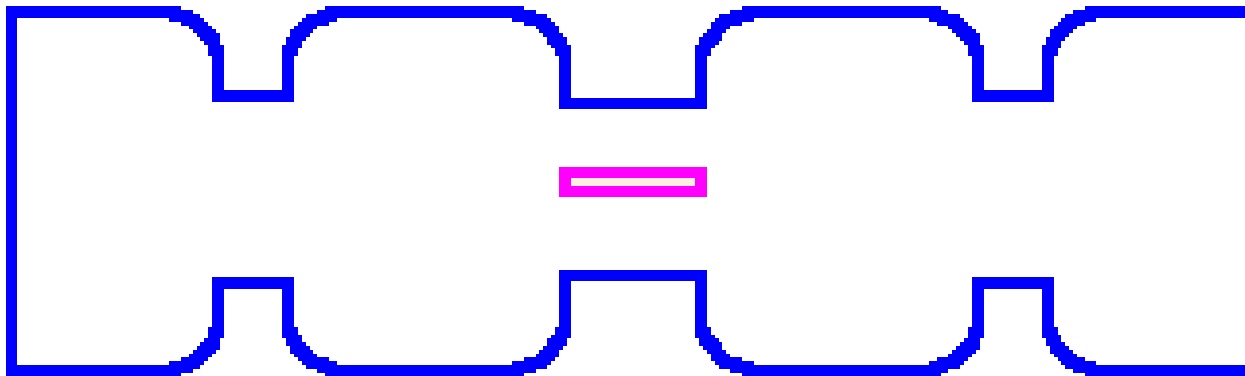Sinusoidal simulations at 20 GHz and 31.4 GHz show the physics of the problems.

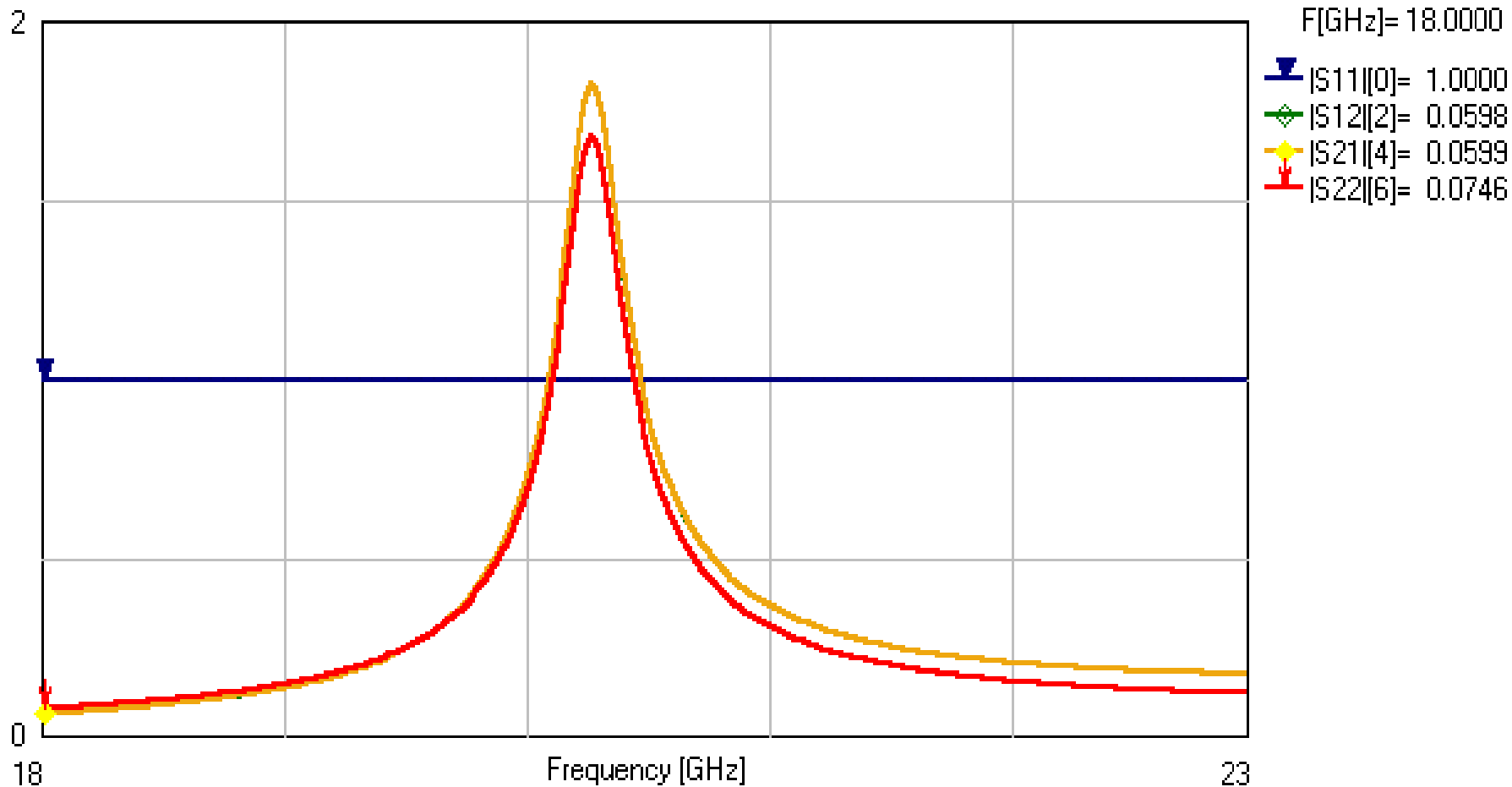# Example of circuit segmentation on evanescent mode: a 2-resonator waveguide filter

reference planes

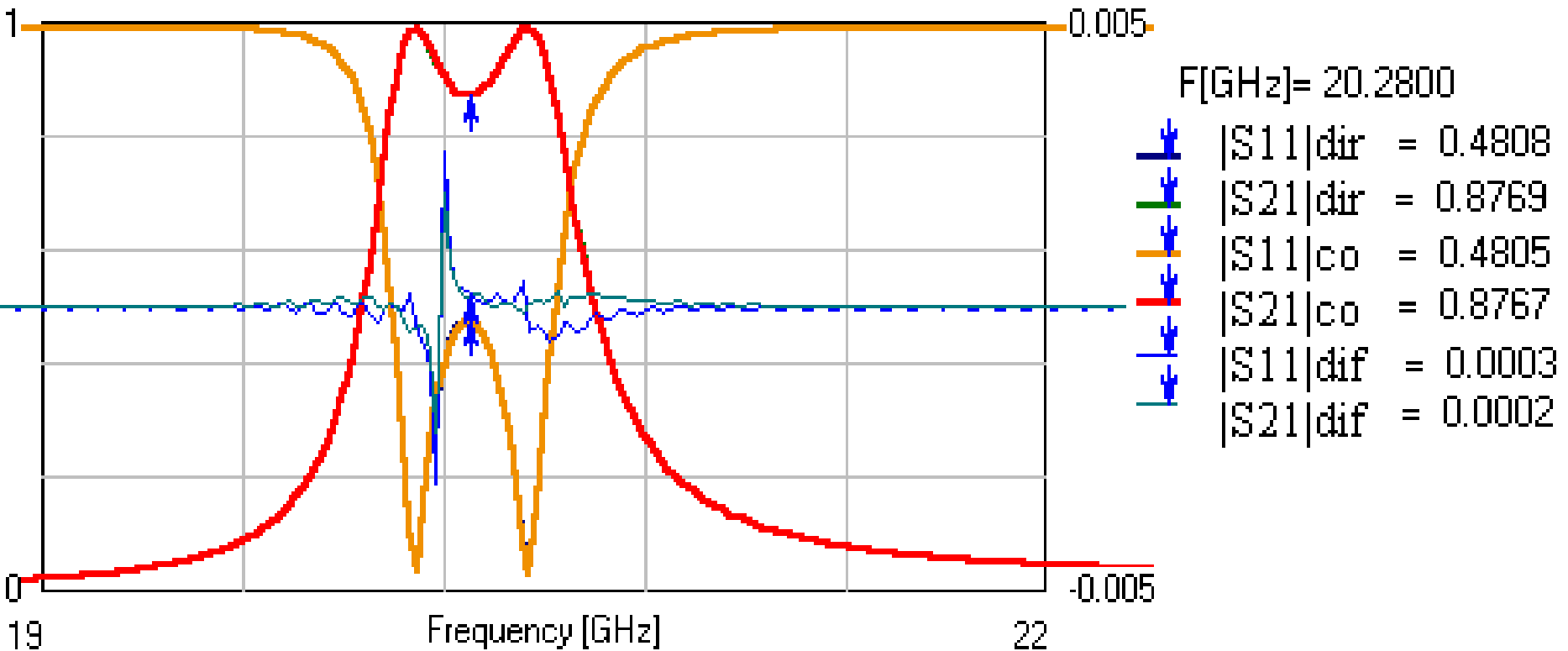|1 |2 |3 |4 |5 |6 |7 |8   9|

Example cont.: Characteristics of one half of the filter

W.Gwarek, M.Celuch, "Wide-band S-parameter extraction from FD-TD simulations for propagating and evanescent modes in inhomogeneous guides", *IEEE Trans. MTT,* No.8, Aug.2003, pp.1920-1928.

Example cont.: Characteristics of the entire filter calculated directly and by S-matrix operations on two halves

(**Presented differences between two results amplified 100 times**)

F[GHz]= 20.2800

|S11|dir = 0.4808
|S21|dir = 0.8769
|S11|co = 0.4805
|S21|co = 0.8767
|S11|dif = 0.0003
|S21|dif = 0.0002

Suggestions to electromagnetic software users

7 – *Avoid direct application to the electromagnetic software files prepared for mechanical design without special preprocessing. They may include irrelevant details or unphysical slots confusing the em software. Treat with suspicion nice and smooth 3-D pictures of the em software input. Try to find out what the actual meshing is and how the meshing is turned into the field approximation.*

Application of industrial CAD files
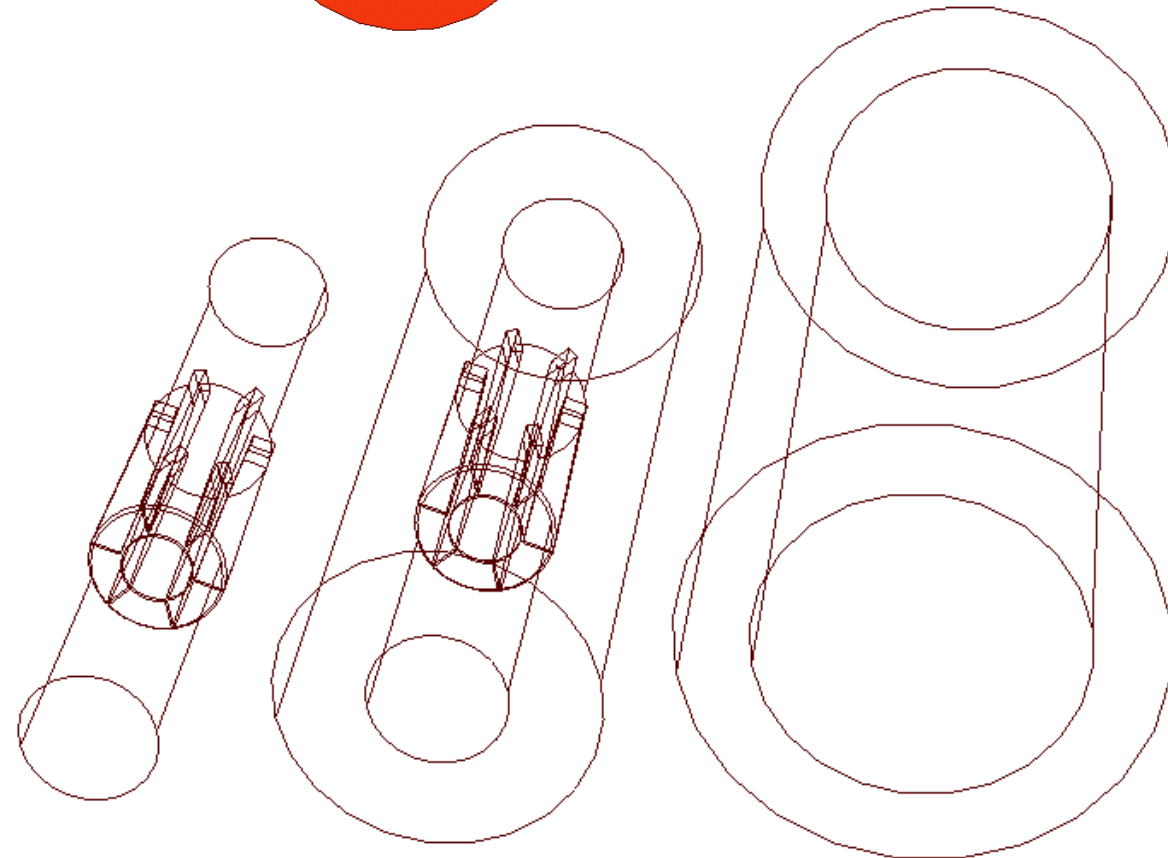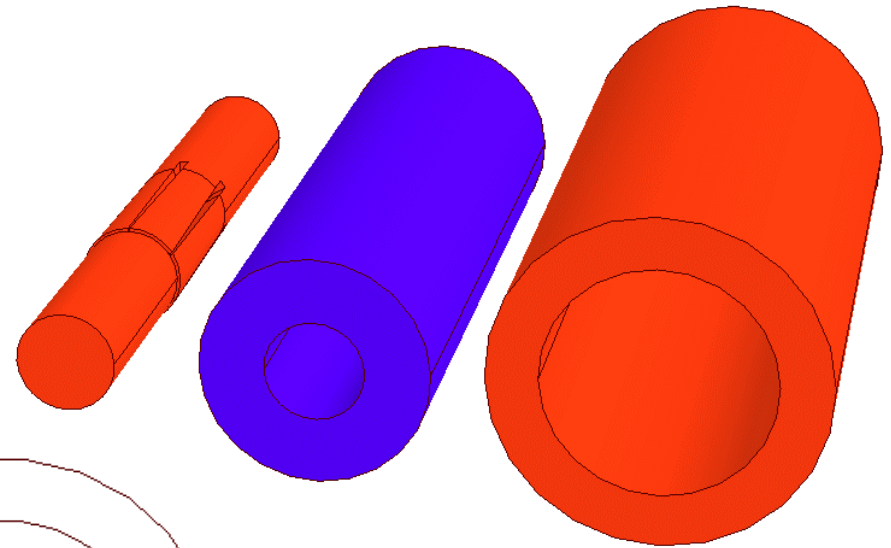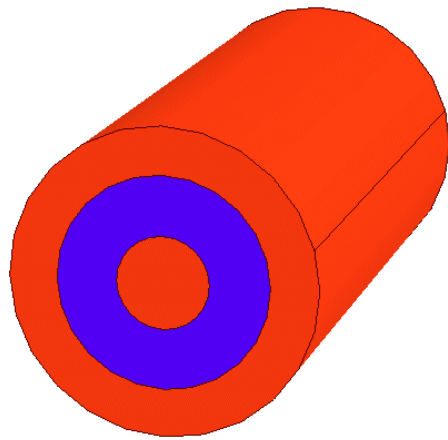
A coaxial connector modelled in PROengineer software and exported in SAT format

Example curtesy of M.Neaves,

W.L. Gore & Assoc

Suggestions to electromagnetic software users

8 – When extracting the absolute amplitude or power values make sure that the software fully controls the level of excitation. Find out how the displayed quantities are averaged in space and time.

Differences in heating patterns and time averaging procedures between linear (up) and circular (down) polarisations are visible at an example of heating a sample in a circular waveguide
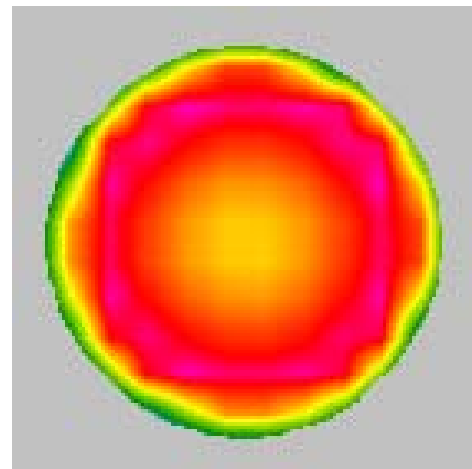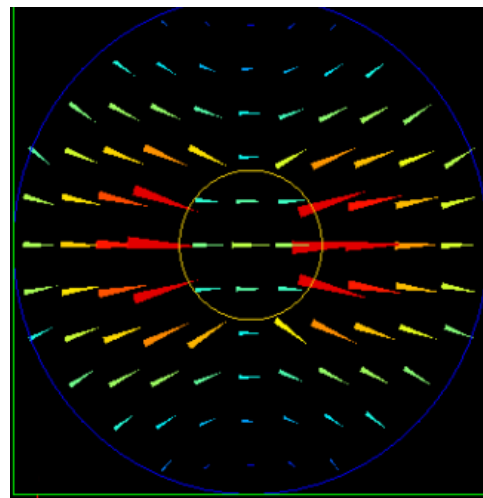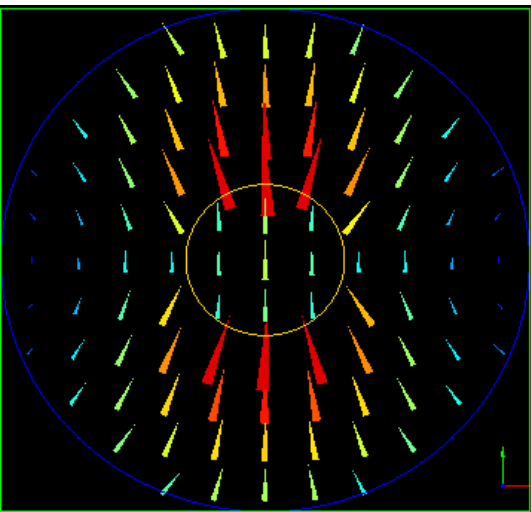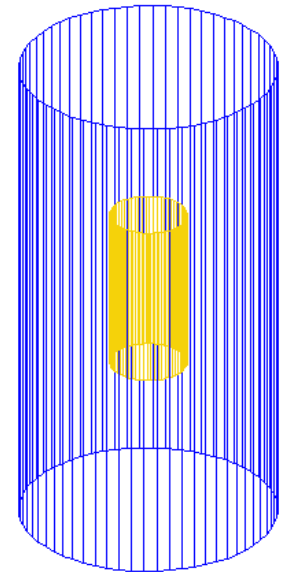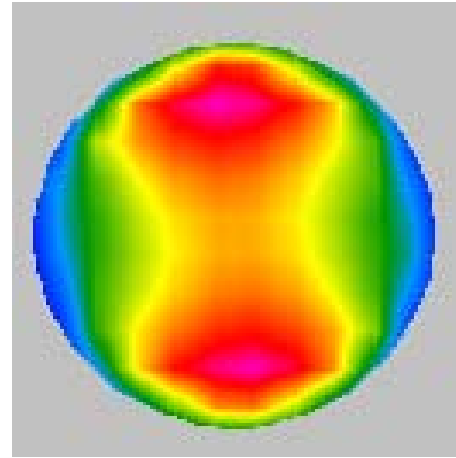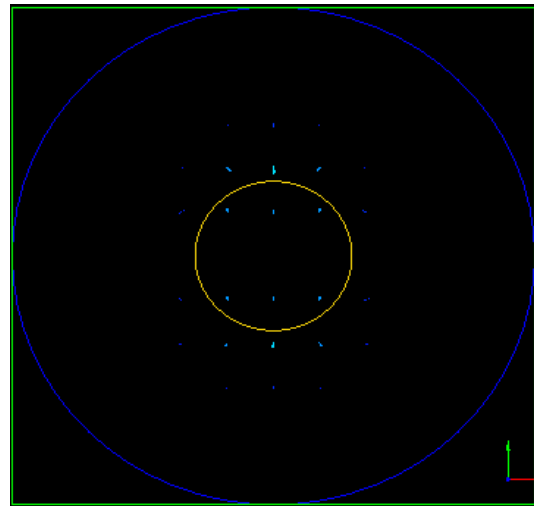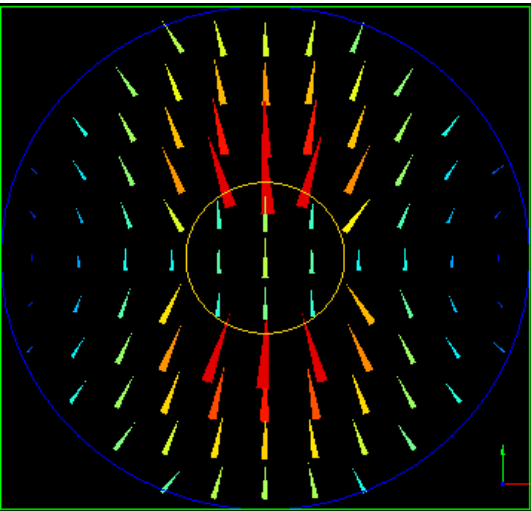
Suggestions to electromagnetic software users

9 – Remember that the open space boundary conditions are approximated in the software by absorbing boundary conditions (ABC). Even if they are excellent they react differently with near fields than the open space.

Comparison of absorbing boundaries
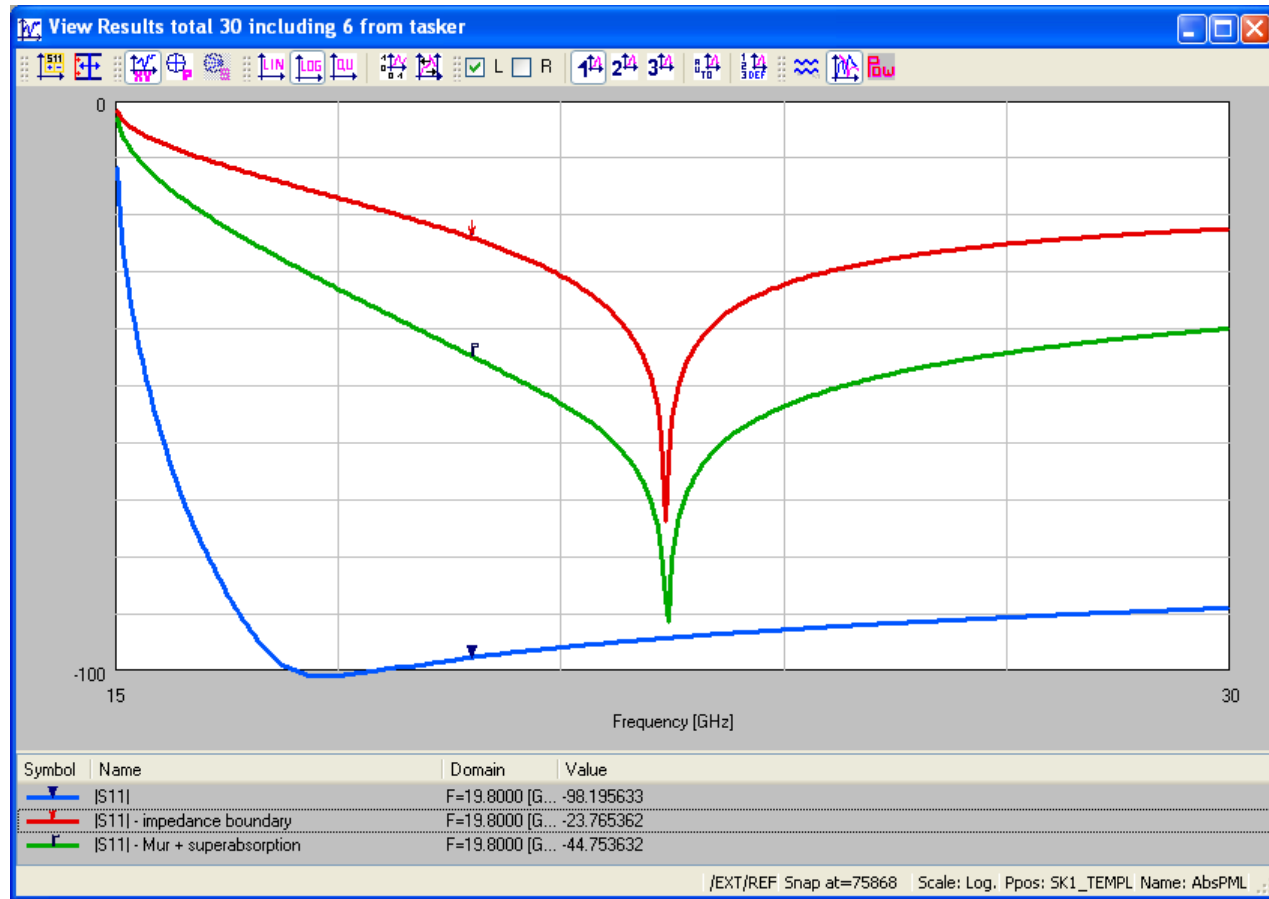
Comparison of reflection (in dB) from different ABCs in a 10 mm wide rectangular waveguide analysed with 0.5 mm FDTD mesh.

blue – 16 layers PML of parabolic profile; green - Mur's boundary with superabsorption; red – impedance boundary condition;

Suggestions to electromagnetic software users

10 – After obtaining the simulation results check them by running simulation with different meshing. If possible try to verify at least some of the obtained results by other package (preferably by other method). Different methods are prone to different errors (imposed by the method itself, the software or the user).
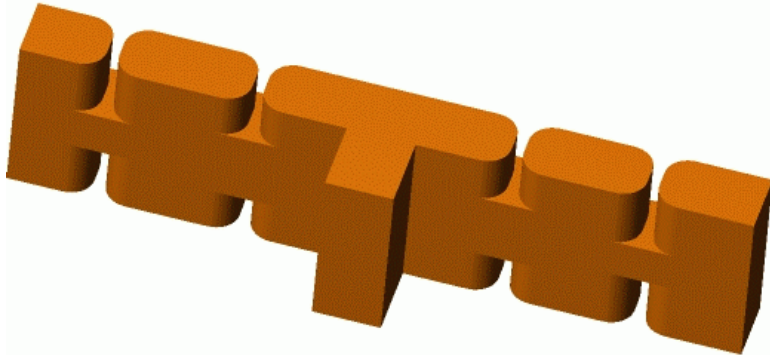
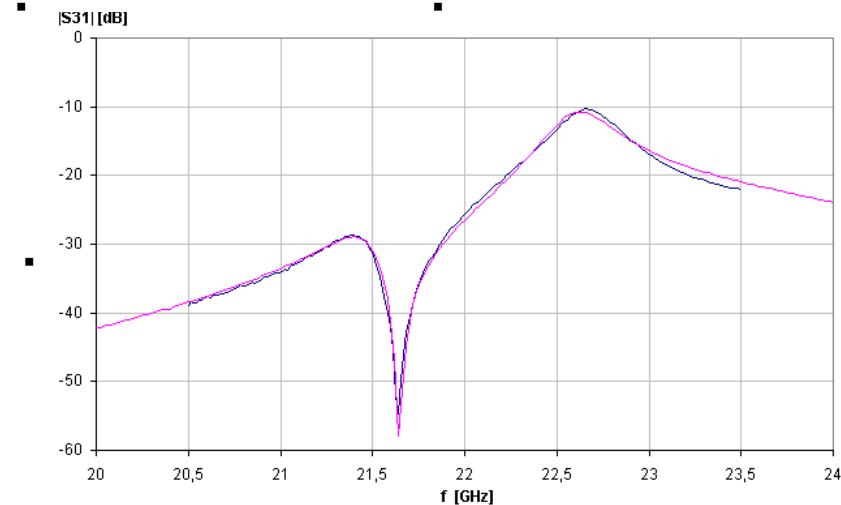# *Example of a waveguide 3-D problem - cont*
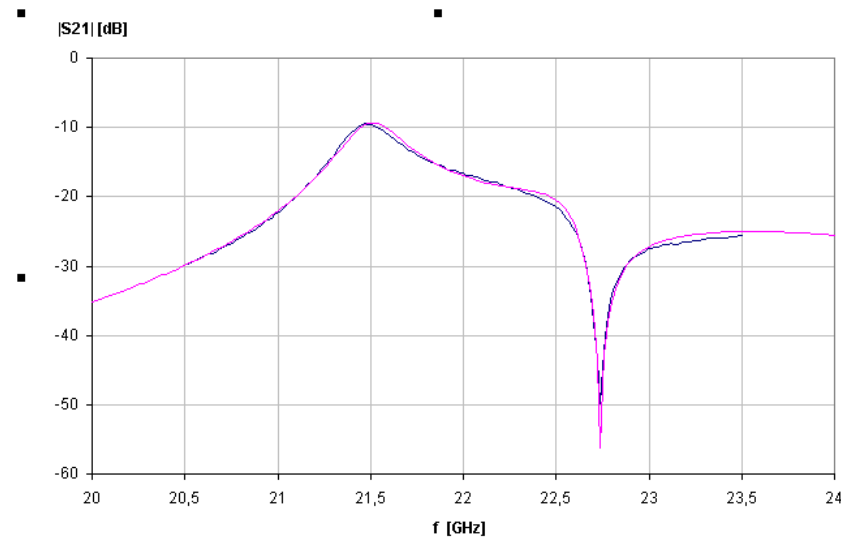
E-plane waveguide diplexer

Transmission into higher-frequency (upper) and lower-frequency (lower) channels:

measurements

simulations

Design, measurements and QW-3D simulations:
T.Schnabel, Zomatch, CA

Conclusions

1. *Can the user trust modern em software packages? - Yes, but they must be used consciously.*

2. *Is it possible to skip the hardware prototyping stage? – Yes in many cases, when the accuracy is under control (as explained in the "suggestions to electromagnetic software users") but there are many other practical case where it would not be prudent.*

3. *Can we expect that the progress in hardware will solve once and for all the problem of long em simulation runs? – No, the times for presently calculated problems will be shorter, but the demand for more complicated tasks will grow at least as fast as the speed of computers.*