New approaches to increase the efficiency of the electromagnetic modeling of planar RF and microwave circuits

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Agilent Technologies

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Outline

- Introduction: some challenges for planar solvers
- High-speed and RF circuits
  - quasi-static approximation
  - polygonal mesh
  - star-loop transformation
  - examples
- Multidimensional Adaptive Parameter Sampling
  - full-wave versus circuit analysis
  - adaptive model building based on reflective exploration
  - examples
- Conclusion

Some challenges for planar solvers

- very large structures e.g. antenna arrays
- finite ground plane effects
- optimisation as a function of frequency and geometrical parameters e.g. in filter or antenna design
- thick conductors e.g. in on-chip interconnect
- geometrically complex structures with many ports
- real 3D features e. g. bonding wires or non-planar stratified substrates
- ....

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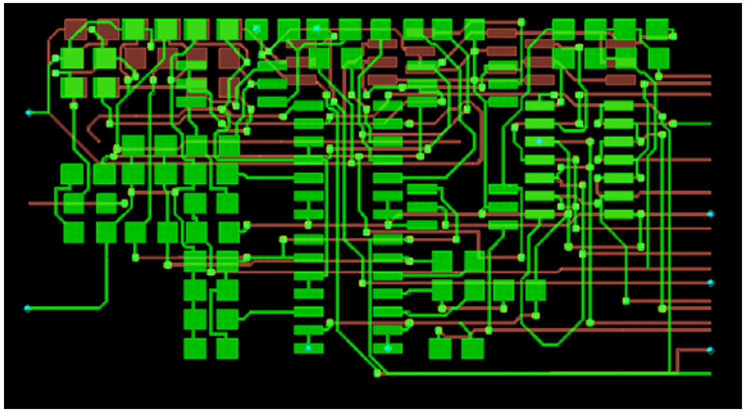
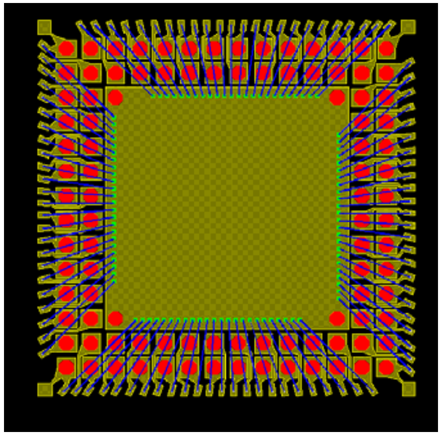
- ***optimisation as a function of frequency and geometrical parameters e.g. in filter or antenna design***
- **thick conductors e.g. in on-chip interconnect**
- ***geometrically complex structures with many ports***
- **real 3D features e. g. bonding wires or non-planar stratified substrates**
- **............**

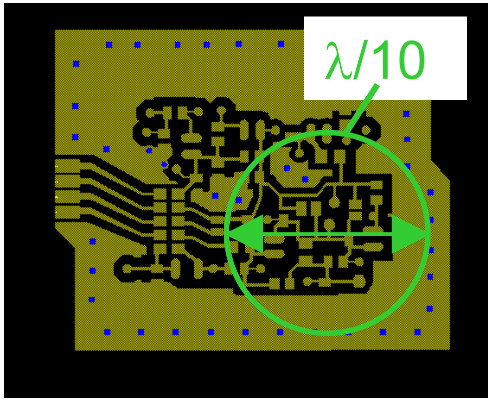
First challenge: high-speed and RF circuits



Challenging circuits

- high-speed digital RF board
- IC package (e.g. BGA)
- RF module (MCM, LTCC)
- RFIC (silicon)





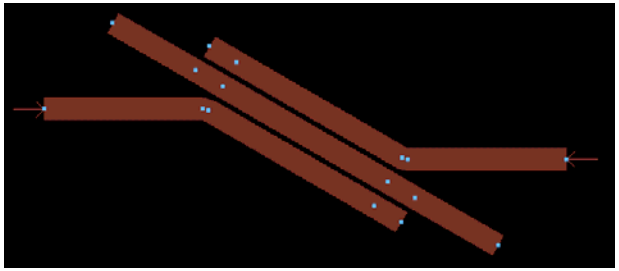
Distinguishing features

- electrically small
- geometrically complex
- many ports
- from DC to RF

“Classical” circuits

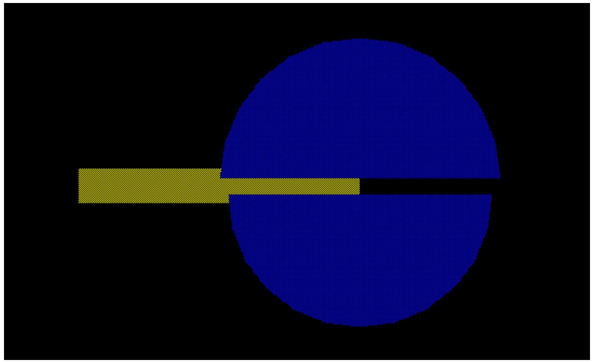
Classical circuits

- microwave hybrid (Alumina)
- microwave MMIC (GaAs)
- planar antennas and arrays



Typical features

- order of wavelength dimensions
- geometrically simple
- few ports
- microwave and millimeter waves
- mixed strip-slot circuits



Electromagnetic basics for a planar solver

Mixed Potential Integral Equation

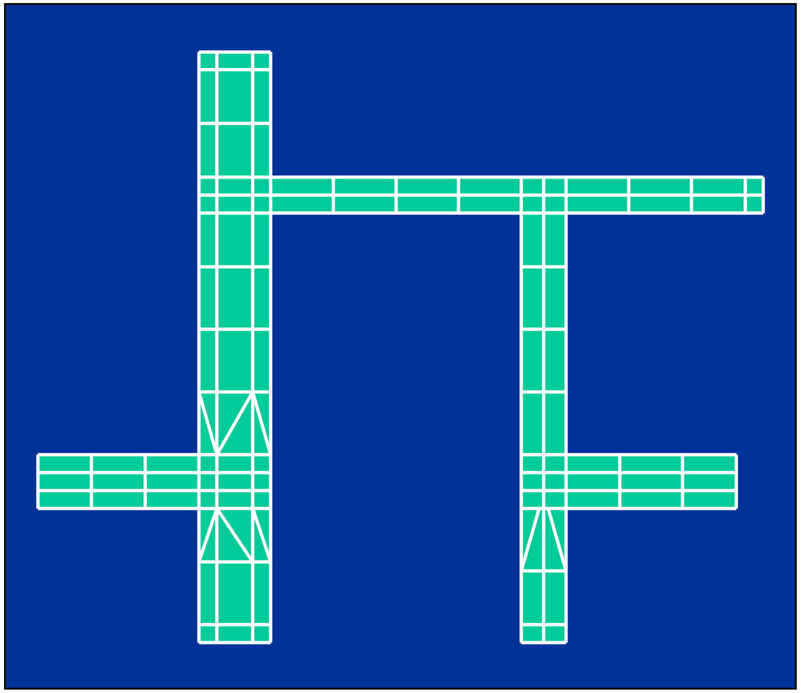
$$\mathbf{E}(\mathbf{J}_S) = -j\omega\mathbf{A}(\mathbf{r}) - \frac{1}{j\omega}\nabla\Phi(\mathbf{r})$$

$$\mathbf{A}(\mathbf{r}) = \iint_S \overline{\overline{G}}^A(\mathbf{r}\,|\,\mathbf{r}')\cdot\mathbf{J}_S(\mathbf{r}')dS'$$

$$\Phi(\mathbf{r}) = \iint_S G^\Phi(\mathbf{r}\,|\,\mathbf{r}')(\nabla_t'\cdot\mathbf{J}_S(\mathbf{r}'))dS'$$

Method of Moments solution

- mixed triangle - rectangle mesh
- introduction of rooftop basis functions to represent unknown surface currents



EM basics for a planar solver - cont.

Method of Moments

Maxwell's equations

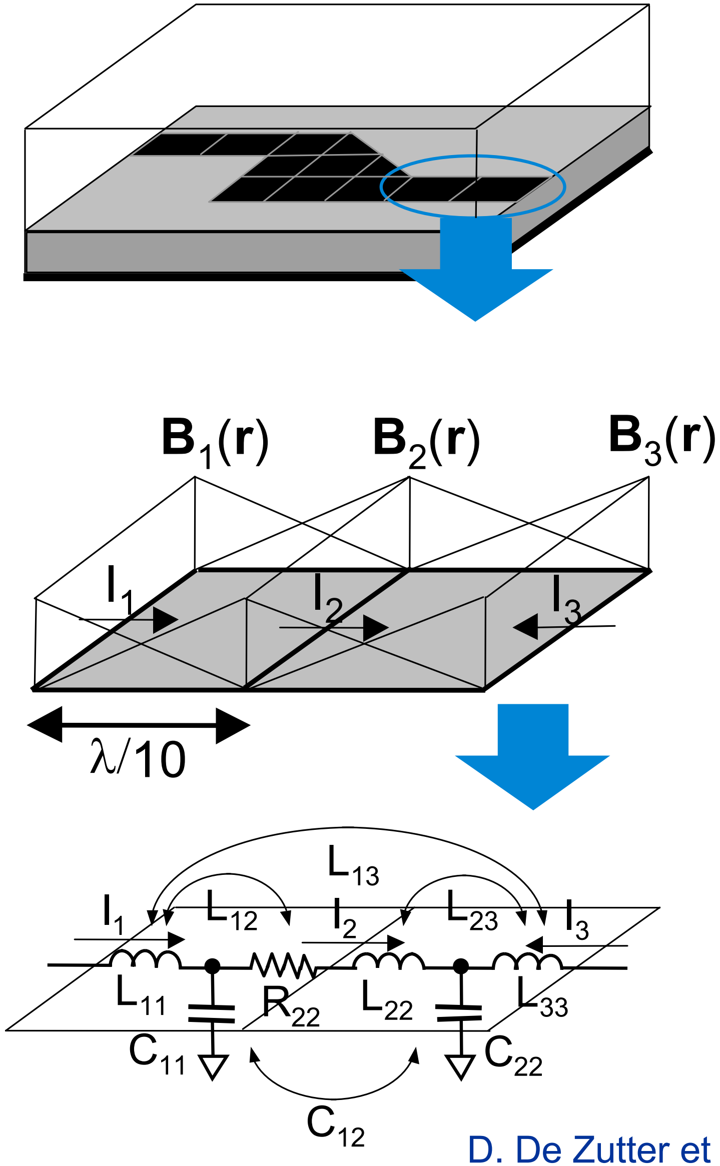
matrix equation

$[Z(\omega)].[I]=[V]$

equivalent circuit

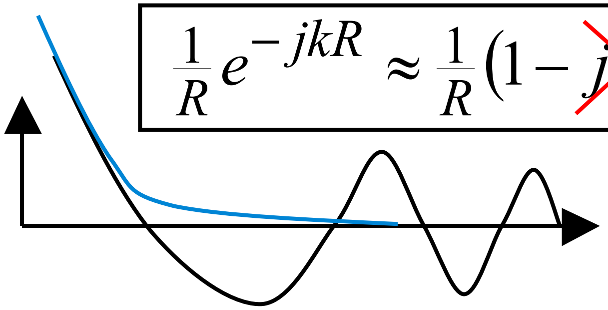
$[Z] = [R] + j\omega[L] + 1/j\omega\ [C]^{-1}$

frequency dependent !



Full-wave versus quasi-static

$$\boxed{\frac{1}{R}e^{-jkR} \approx \frac{1}{R}\left(1 - \cancel{jkR} + \ldots\right)}$$



Distinguishing features

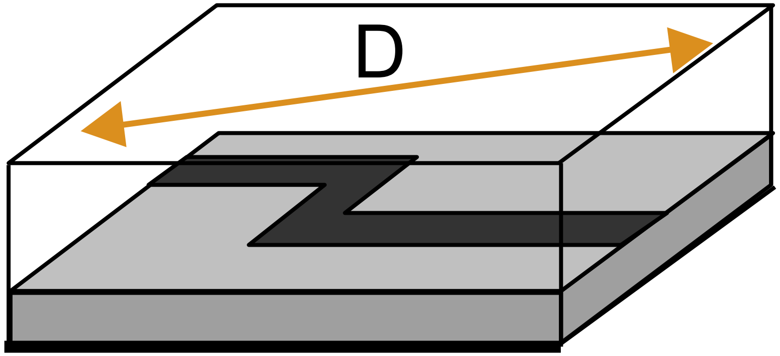
- electrically small
- geometrically complex
- many ports
- from DC to RF

- near-field / low frequency approximation

$$L(\omega) = L_0 + \cancel{\omega L_1} + \cancel{\omega^2 L_2} + \ldots.$$

$$C(\omega) = C_0 + \cancel{\omega C_1} + \cancel{\omega^2 C_2} + \ldots.$$

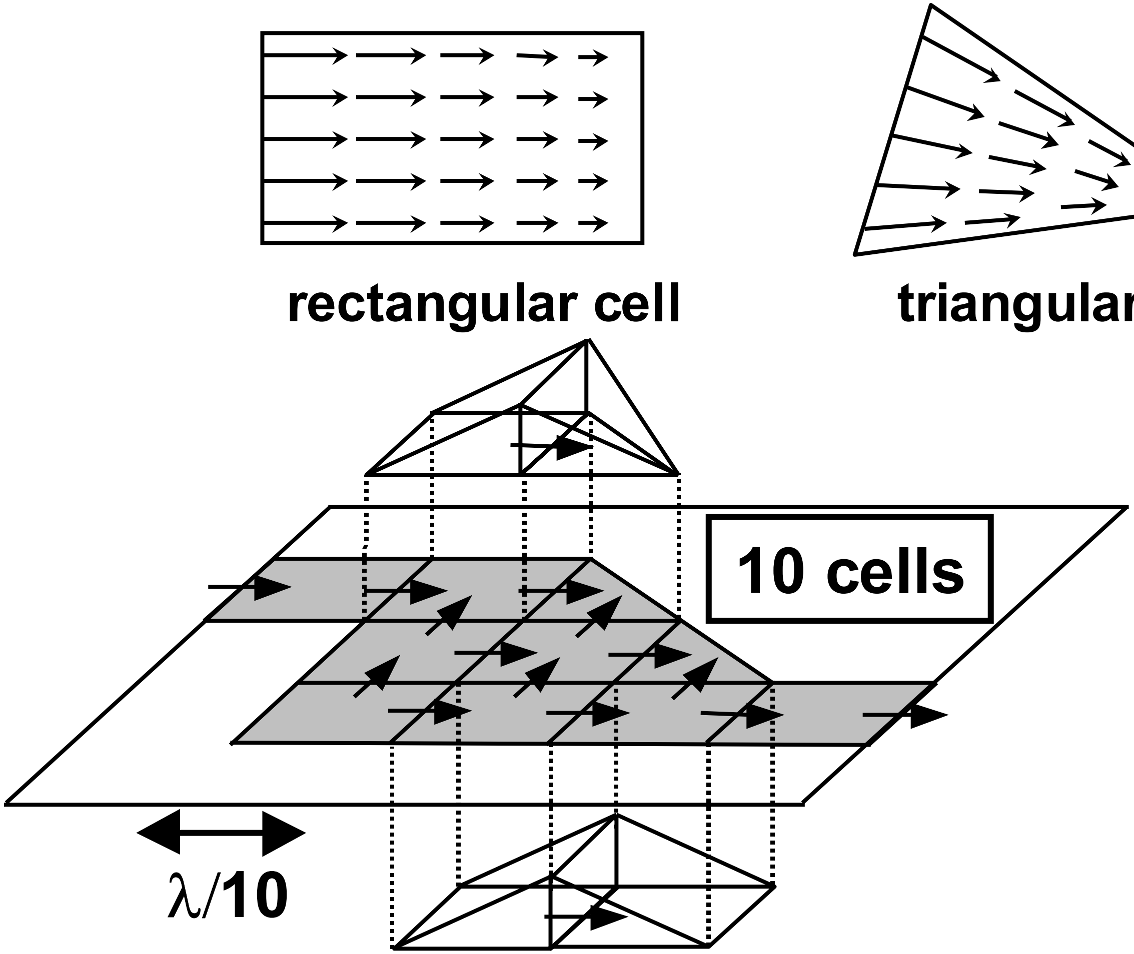
- L_0 and C_0 are frequency independent
- far-field radiation terms are neglected



$$\text{freq [GHz]} < \frac{150}{D\,[\text{mm}]}$$

Traditional meshing

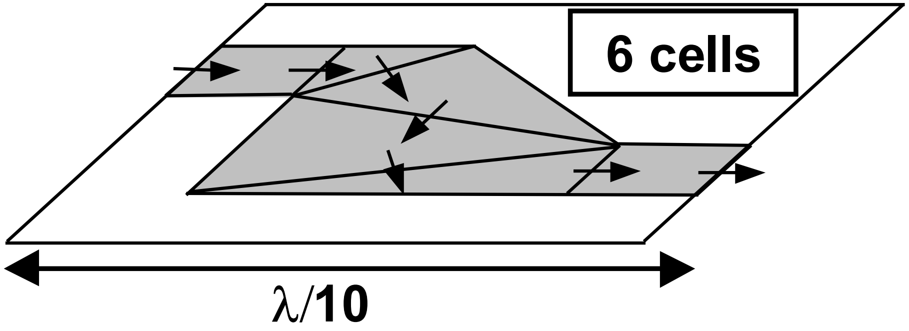
Rectangular - triangular mesh at microwave frequencies



the mesh is governed by a wavelength criterion i.e. typically 10 divisions per wavelength

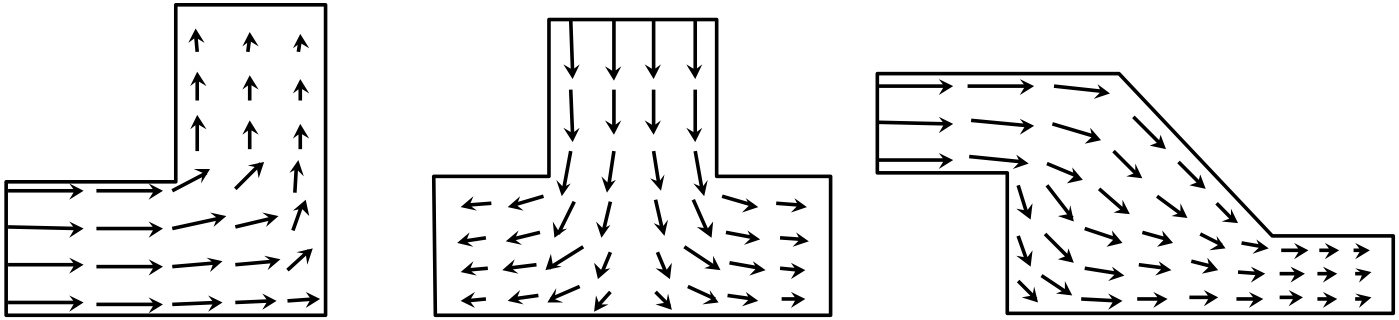
Polygonal meshing

Rectangular - triangular mesh at RF frequencies



now the mesh is governed by the geometrical complexity

Introduction of arbitrary polygonal cells and corresponding current basis functions



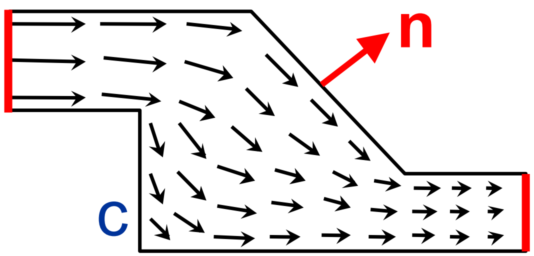
L-shaped cell T-shaped cell polygonal cell

Generalised basis functions

- **generalisation** of well-known **rooftops** on triangles and rectangles
- current is curl free
- the divergence is constant i.e. **constant surface charge**

$$\frac{\partial}{\partial x} J_x + \frac{\partial}{\partial y} J_y = A$$

$$\frac{\partial}{\partial y} J_x - \frac{\partial}{\partial x} J_y = 0$$



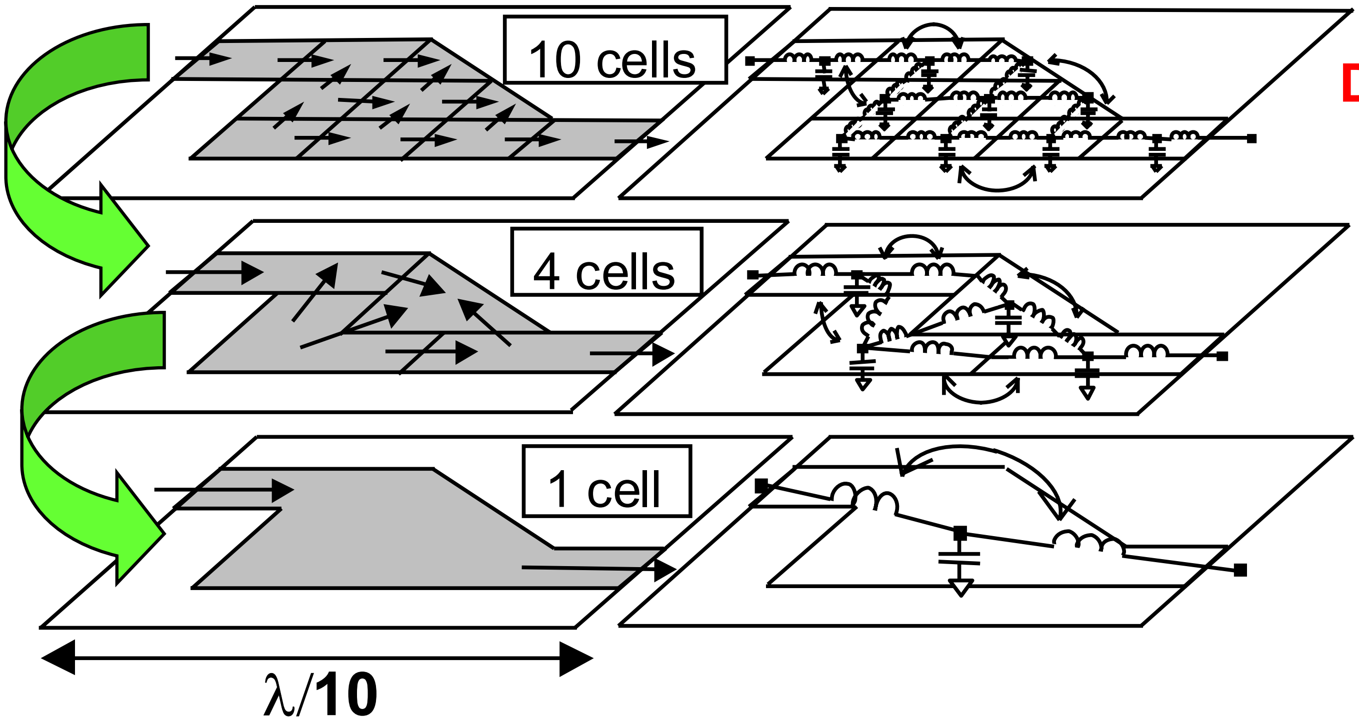
$\mathbf{J} \cdot \mathbf{n} = 0$ on boundary c, except on **red** parts, where the value is either 0 or 1

Solution: solve an integral equation for a function K

$\mathbf{J}(\mathbf{r}) = \frac{A}{2}\mathbf{r} + \nabla K$ (*K* is a harmonic function)

$$\frac{\partial}{\partial n} K = \left\{ \begin{matrix} 0 \\ 1 \end{matrix} \right. - \frac{A}{2} \mathbf{r} \cdot \mathbf{n}$$

Optimised polygonal mesh



Distinguishing features

- **electrically small**
- **geometrically complex**
- **many ports**
- **from DC to RF**

- minimizes number of cells, respecting $\lambda/10$ criterion
- handles geometrical complexity
- extends well-known concepts for triangles and rectangles

The low-frequency breakdown

Method of Moments

$$[Z].[I]=[V]$$

$$[Z] = j\omega[L] + 1/j\omega\ [C]^{-1}$$

$\downarrow$ $\downarrow$

for low frequences: zero infinity

Distinguishing features

- **electrically small**
- **geometrically complex**
- **many ports**
- **from DC to RF**

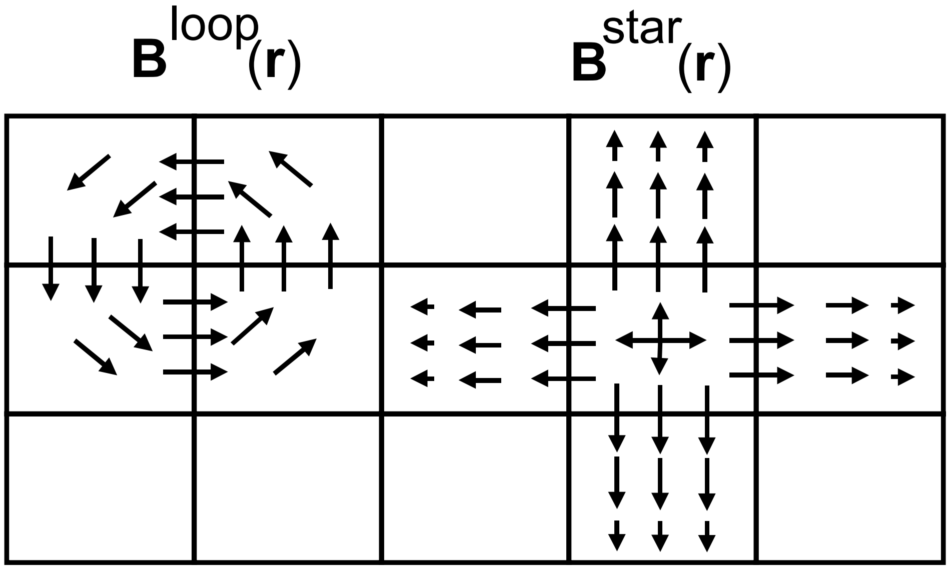
[Z] is ill-conditioned for low frequencies

⇨ numerical solution breaks down

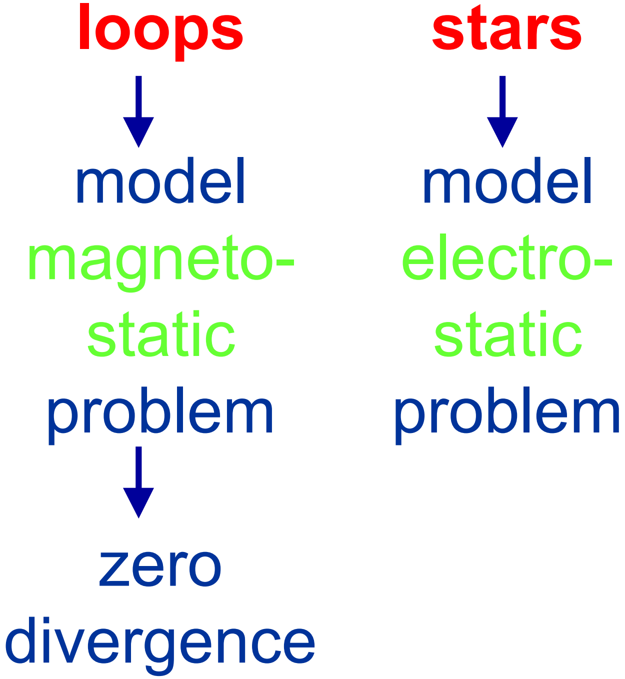
solution: the star-loop transformation

The star-loop transformation

- original basis functions: rooftops
- these basis functions are now transformed into a new set of basis functions: the loop functions and the star functions
- this transform is linear



loop function **star function**



loops

↓

model magneto-static problem

↓

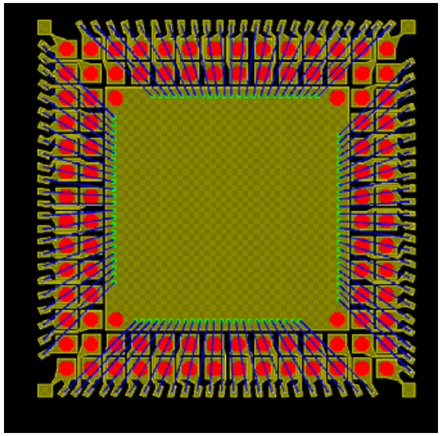
zero divergence

stars

↓

model electro-static problem

First challenge: high-speed and RF circuits - summary



High Speed Digital and Analog RF Applications

- speed
- capacity
- accuracy

⇨ **advanced planar solution technique**

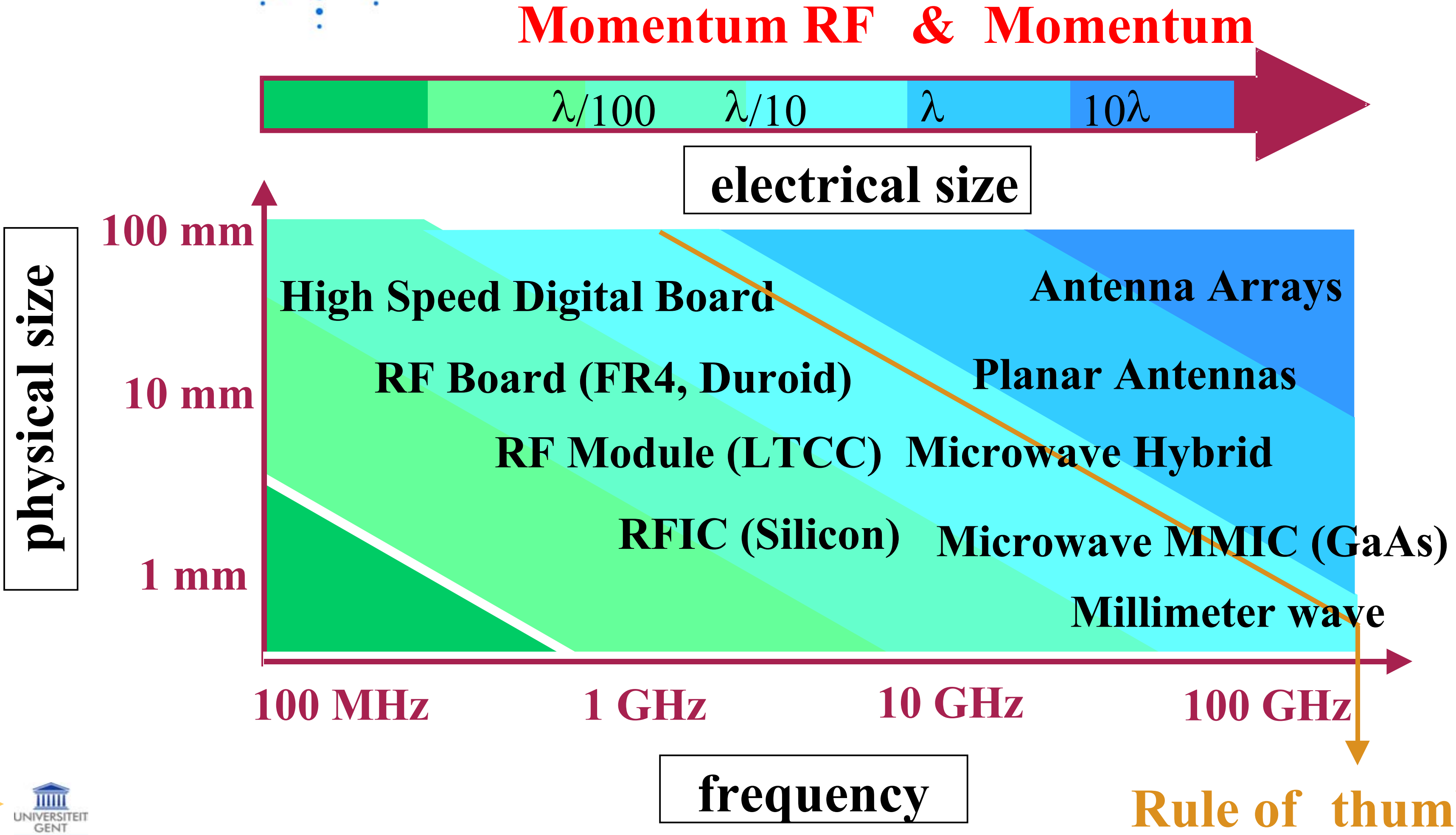
Electrically small ⇨ **Quasi-static model**

Geometrically complex ⇨ **Polygonal mesh**

DC to RF frequencies ⇨ **Star-loop transform**

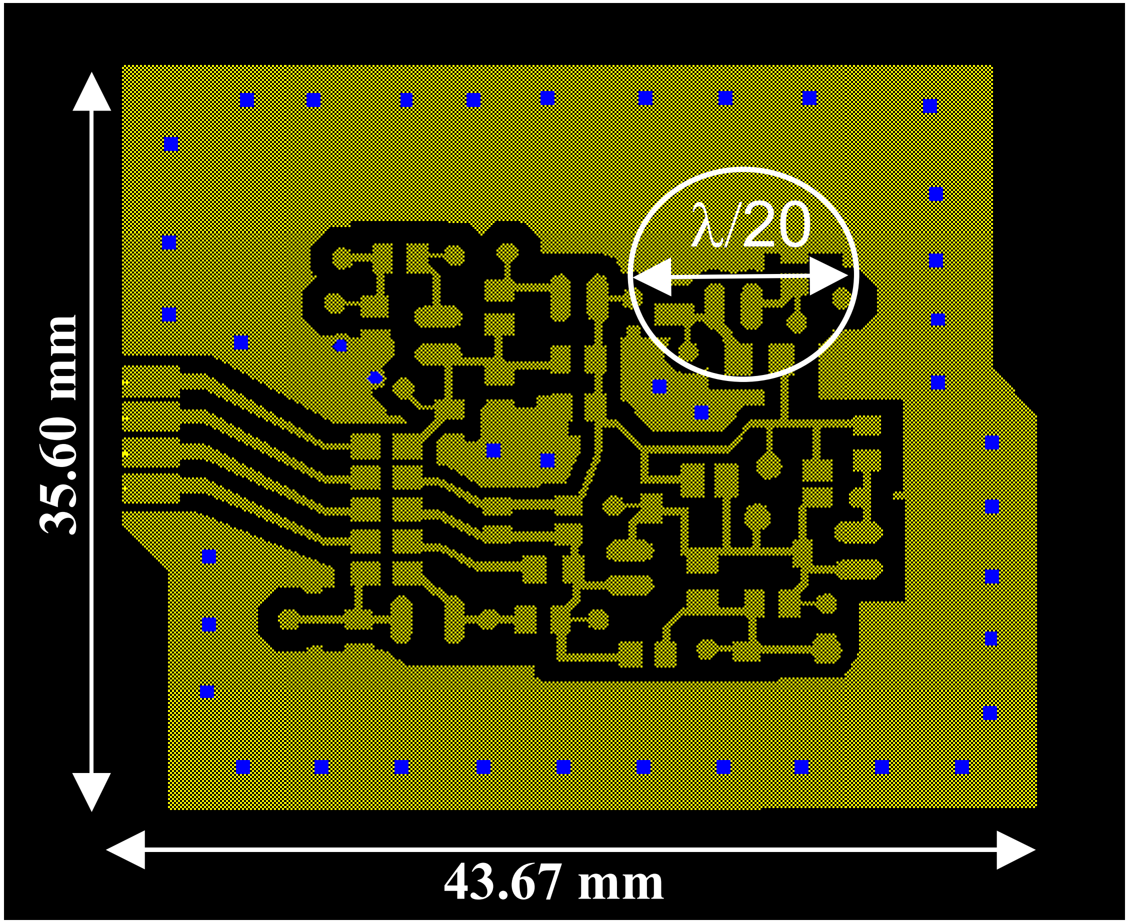
Some sample applications

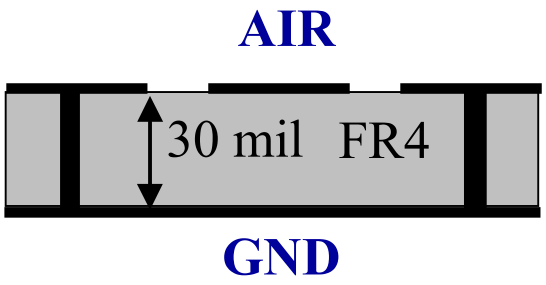
Agilent Technologies



Rule of thumb line

Example 1: RF board interconnect





Purpose:
compare classical approach with new techniques

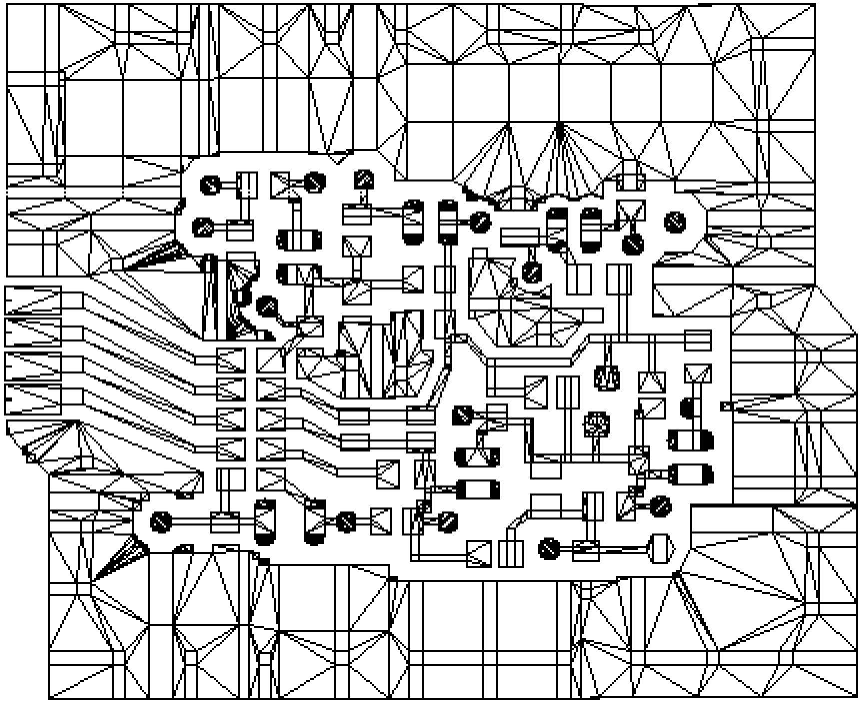
Rule of thumb: frequency < 2.66 GHz

Example 1: RF board interconnect - cont.

classical (Momentum)

mesh: 20 cells/λ at 1 GHz

Matrix size	:	3428
Process size	:	152.48 MB
User time	:	3h 14m 51s



rectangular and triangular mesh

Example 1: RF board interconnect - cont.

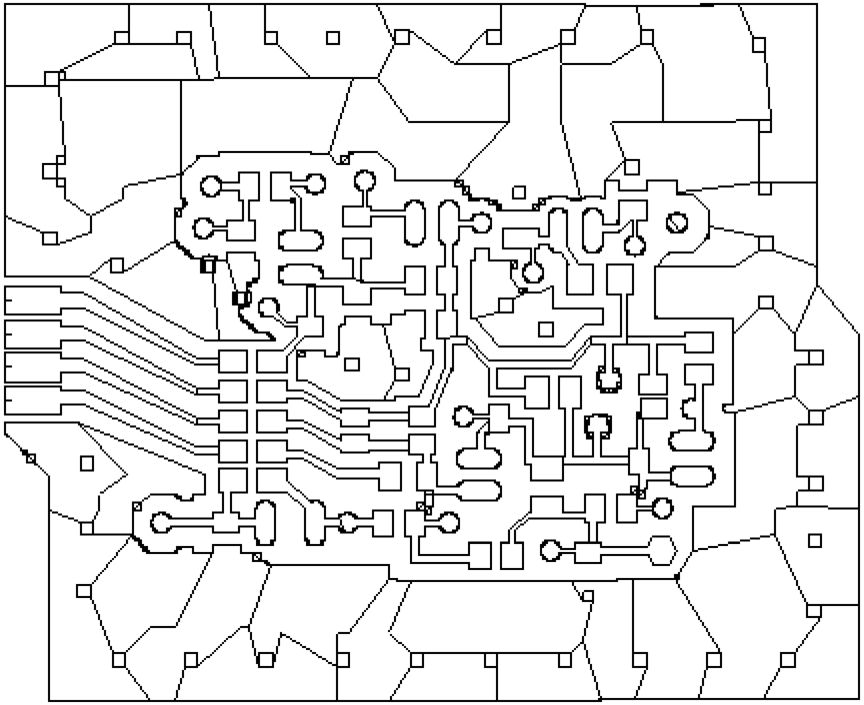
new (Momentum RF)

mesh: 20 cells/λ at 1 GHz

Matrix size : 733

Process size : 59.35 MB

User time : 14m 24s

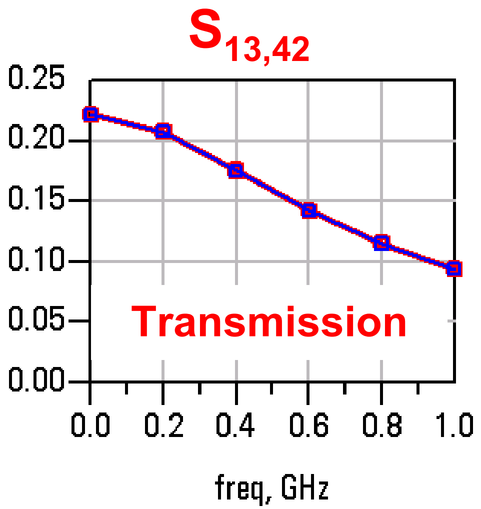


polygonal mesh

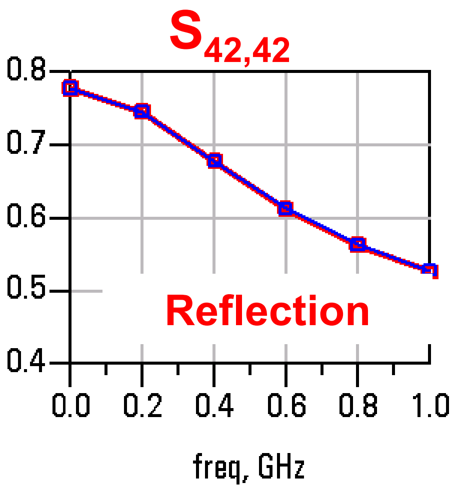
memory saving: factor 3

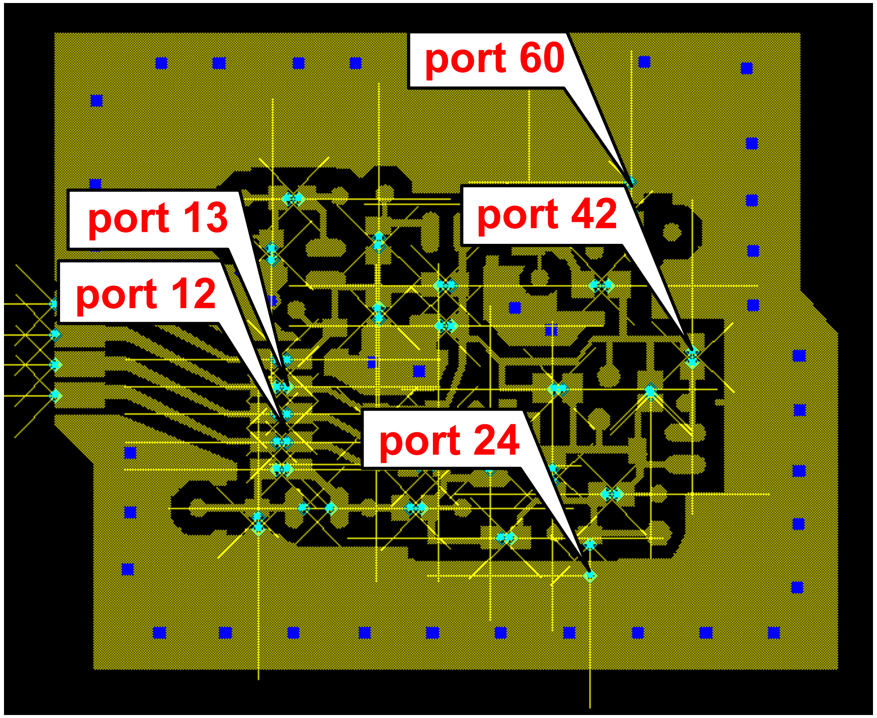
CPU-time saving: factor 14

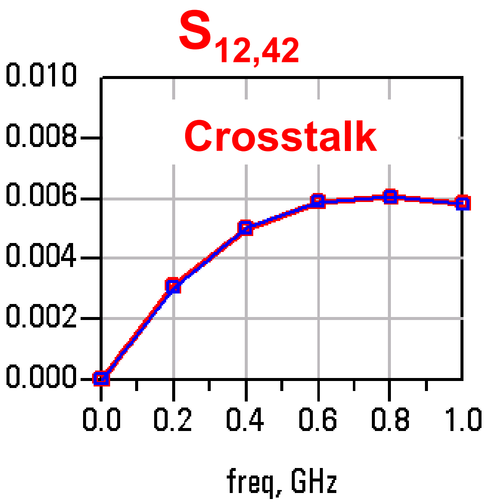
Example 1: RF board interconnect - cont.

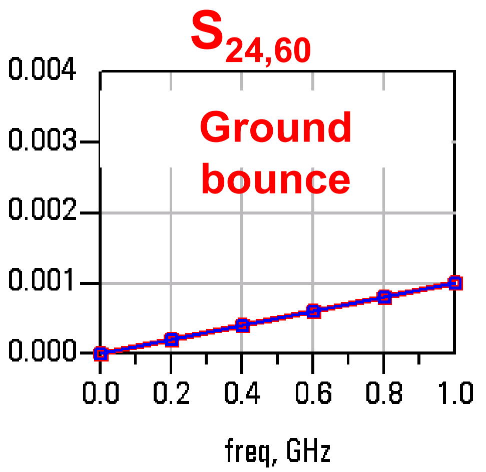

$S_{13,42}$

- Momentum
- Momentum RF

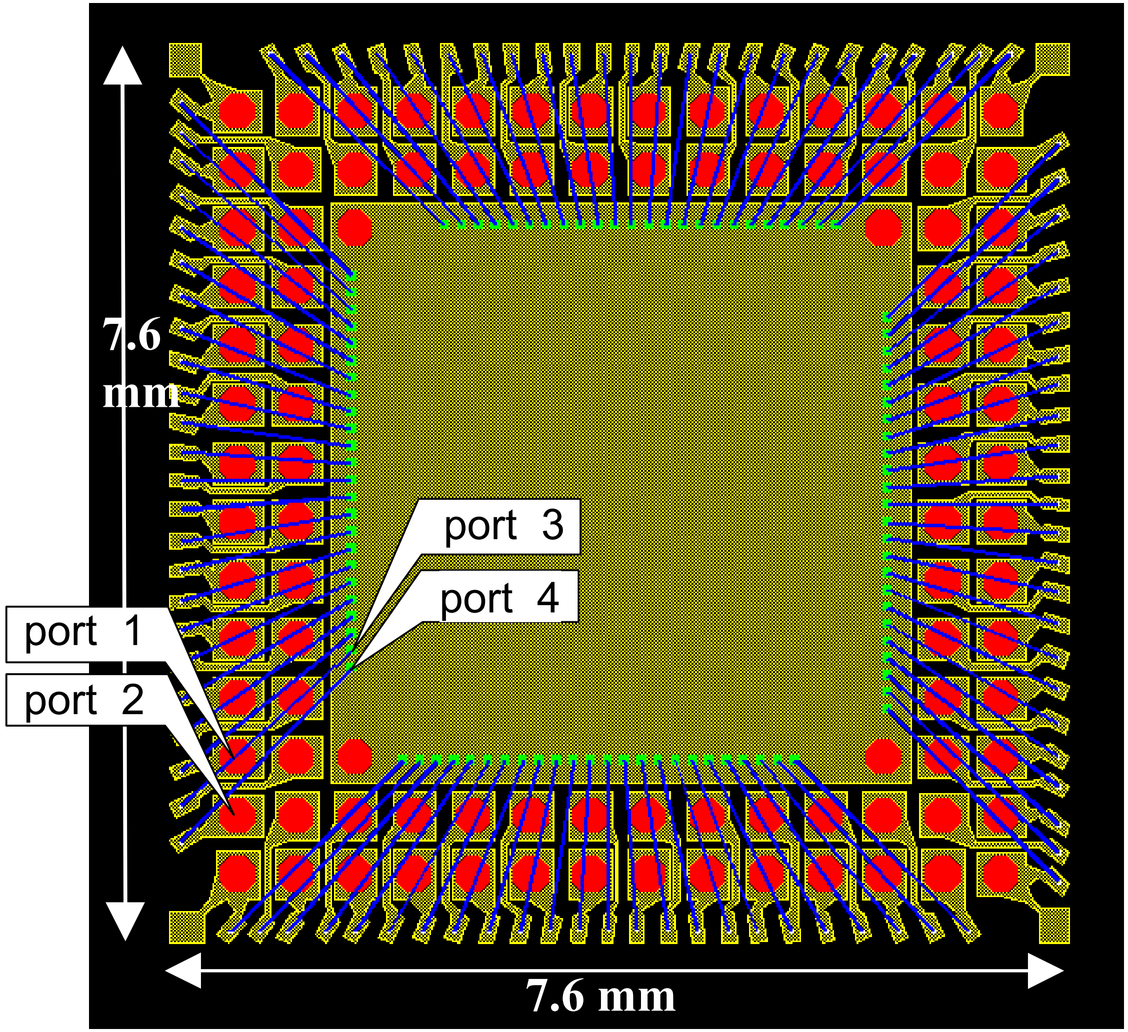

$S_{42,42}$




$S_{12,42}$


$S_{24,60}$

Example 2: ball grid array package



Rule of thumb:
frequency < 2.66 GHz

Purpose:
time-domain analysis for a 100ps rise time signal and 50Ω loads

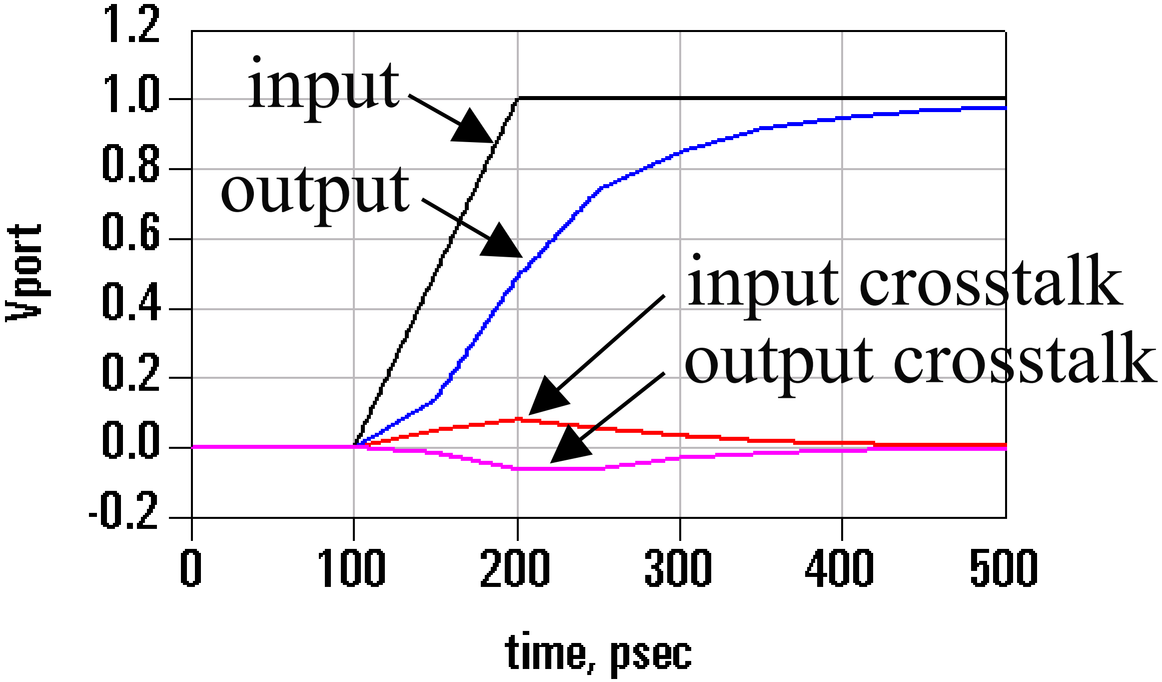
Example 2: ball grid array package - cont.

classical (Momentum)

Matrix size : 8244
Process size : > 1 GB
User time : > 1 day

new (Momentum RF)

Matrix size : 1354
Process size : 106.6 MB
User time : 1h 47m 53s



memory saving: factor 10
CPU-time saving: factor 20

Some challenges for planar solvers - cont.

- **very large structures e.g. antenna arrays**
- **finite ground plane effects**
- **optimisation as a function of frequency and geometrical parameters e.g. in filter or antenna design**
- **thick conductors e.g. in on-chip interconnect**
- ***geometrically complex structures with many ports***
- **real 3D features e. g. bonding wires or non-planar stratified substrates**
- **............**

Field analysis versus circuit analysis

Field Analysis

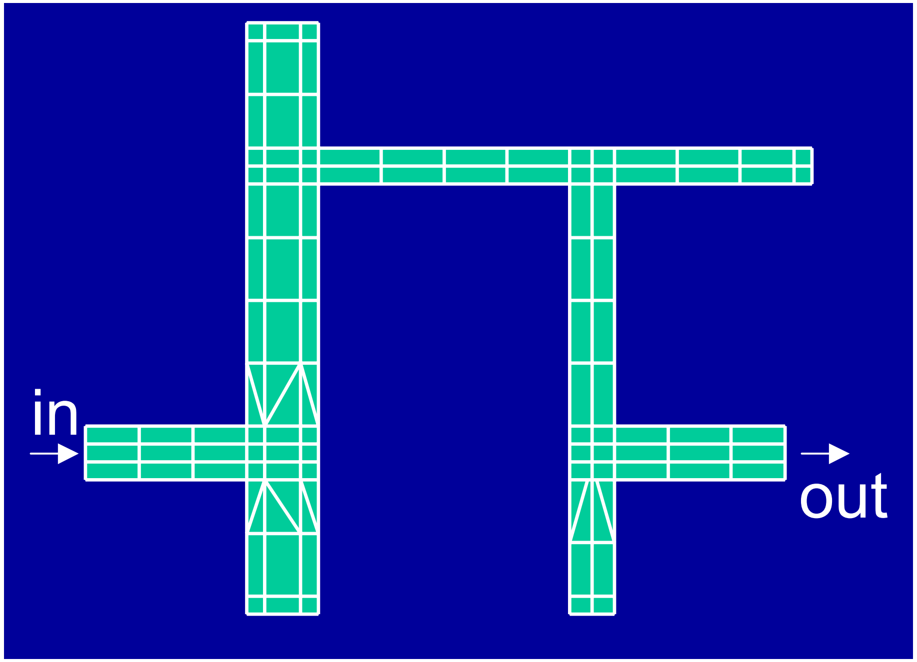
- numerical solution of Maxwell's equations (finite elements; finite differences in time domain; method of moment solution of an integral equation)
- no partitioning - complete circuit as a whole
- **all high frequency couplings and radiation effects are included**
- **very accurate**
- **"slow": very CPU-time and memory demanding**
- **less suited for design, optimisation and tolerance analysis**

Field analysis versus circuit analysis - cont.

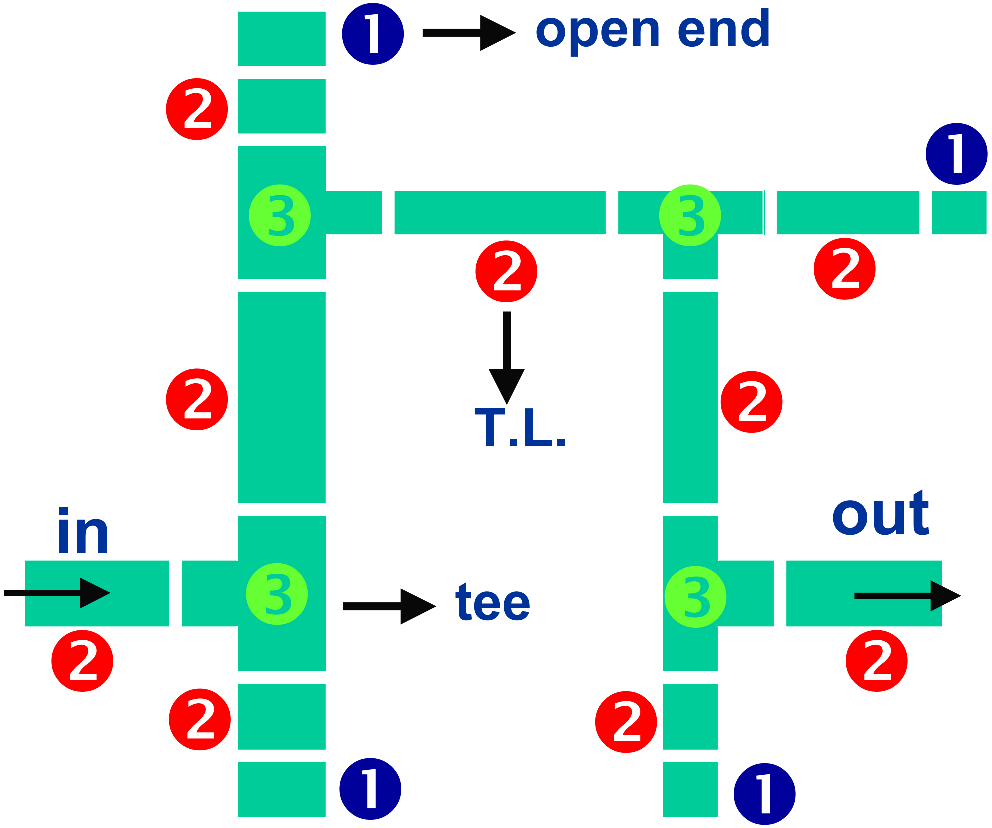
Circuit Analysis

- based on Kirchoff laws
- structure is first partitioned into subcircuits
- **parameterised models of (a class of) substructures are available**
- **fast and suited for design and optimisation**
- **many models of substructures are not very accurate**
- **the set of available models is limited (e.g. a tee, a step-in-width, an open end, ...)**
- coupling between substructures and radiation is neglected

Field analysis versus circuit analysis - cont.

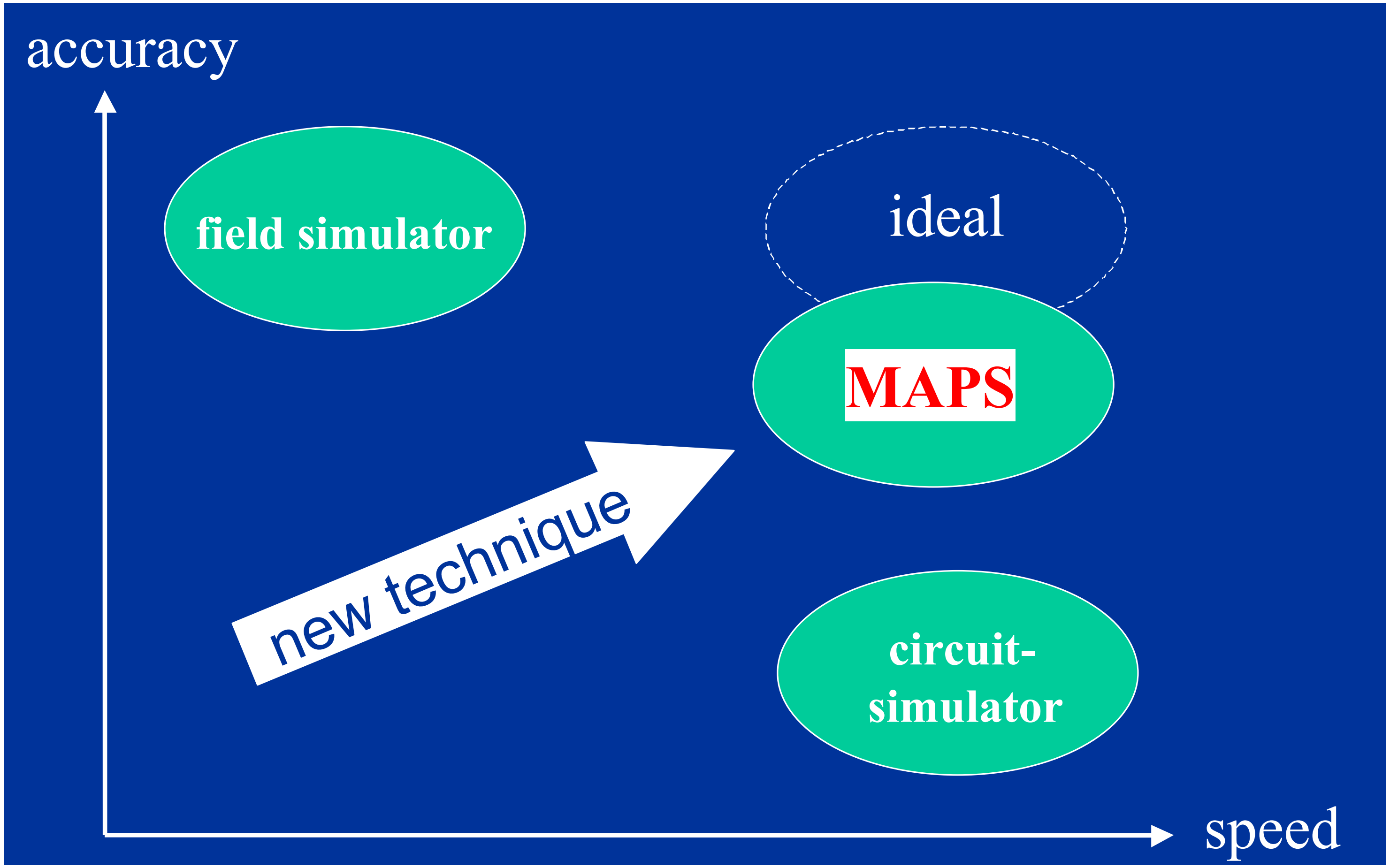


Method of Moment meshing
of a low pass filter



subcircuit partitioning
via S-parameters

Multidimensional Adaptive Parameter Sampling



MAPS: “best of both worlds” ⇨ field accuracy

circuit speed and optimisation

Existing approaches and techniques

- hand-made analytical models
- discrete model library
- look-up tables combined with local curve fitting
- artificial neural networks
- ....

Common drawbacks

- oversampling / undersampling
- inability to automatically control the accuracy

What are we looking for?

- fully automated algorithm
- no a-priori knowledge required
- minimum number of samples
- guaranteed and predefined accuracy
- highly adaptive
  - adaptive model building
  - adaptive sample selection in both frequency and parameter space
- samples: full wave MoM simulations
- obtained model: S-parameter or RLGC circuit model

Data representation

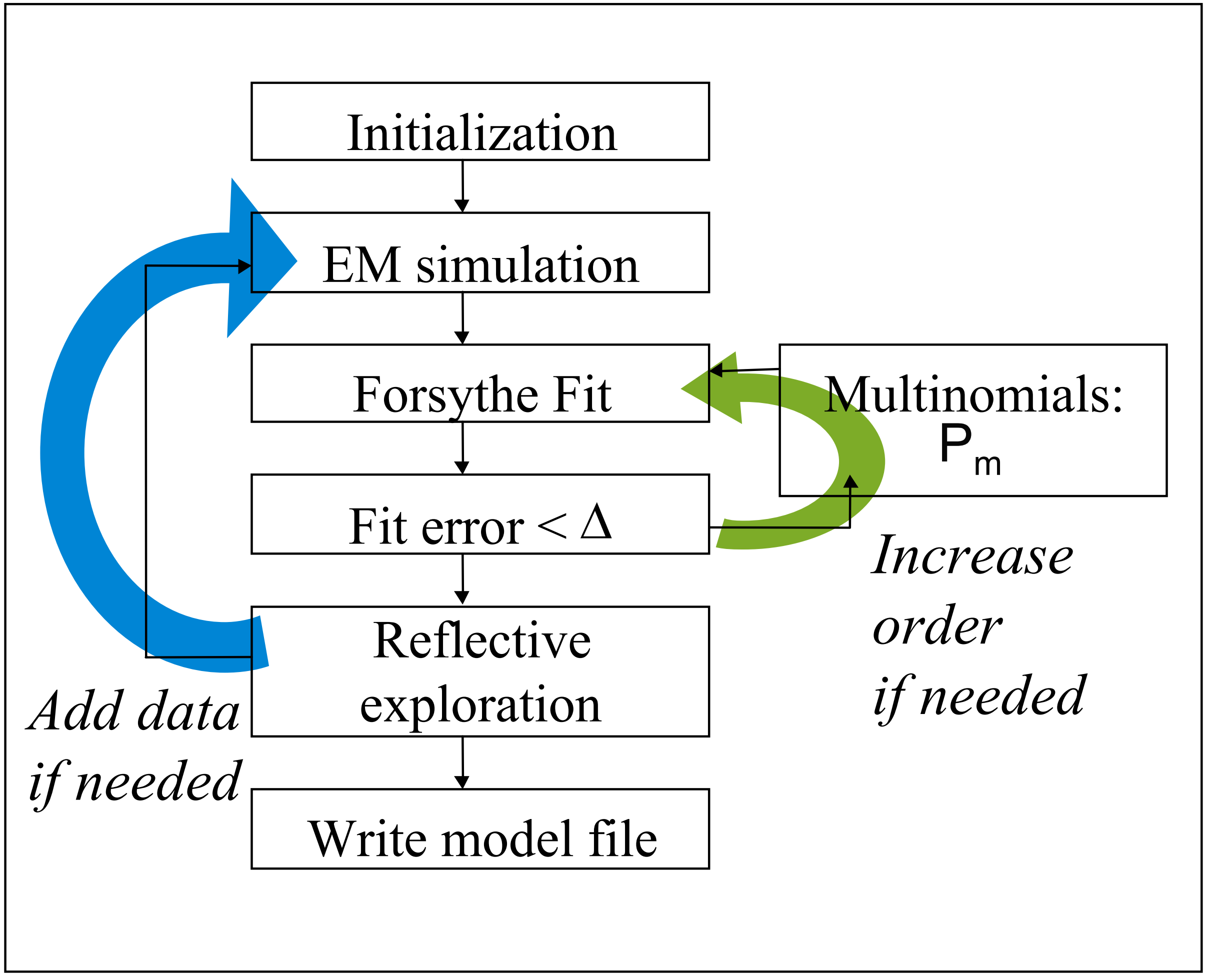
$$\text{data}(f, \boldsymbol{p}) = \sum_{m} \{C_m(f)\ P_m(\boldsymbol{p})\}$$

- data: **S-parameters** or transmission line parameters **(RLGC)**
- f: **frequency**
- **p**: **coordinates in parameter space**
- P_m: orthonormal multidimensional polynomials (generalized Forsythe multinomials) *(stored in database)*
- C_m: frequency dependent fitting coefficients *(stored in database)*

Adaptive sampling and model building

Flow chart of up-front calculation

adaptive sample selection loop



adaptive model selection loop

Adaptive sampling and model building - cont.

Data selection for very costly data

Reflective exploration at multiple frequencies

↓

start with initial set of data points

↓

new data points are selected based on reflective functions, e.g.

difference between models of different order:

check: | model1 - model2 | < accuracy level

extrema:

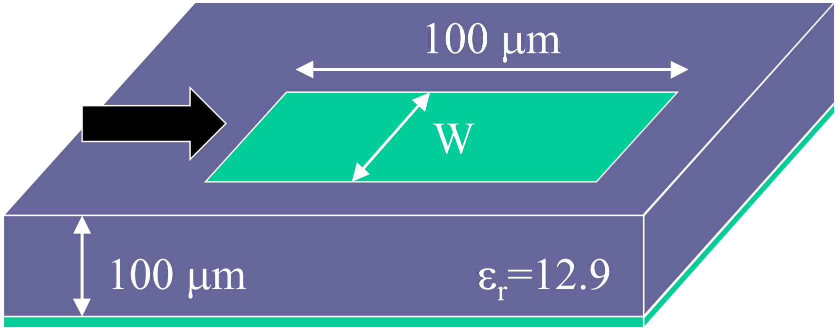
add samples near local minimum/maximum

physical conditions:

no gain allowed, check radiation

……….

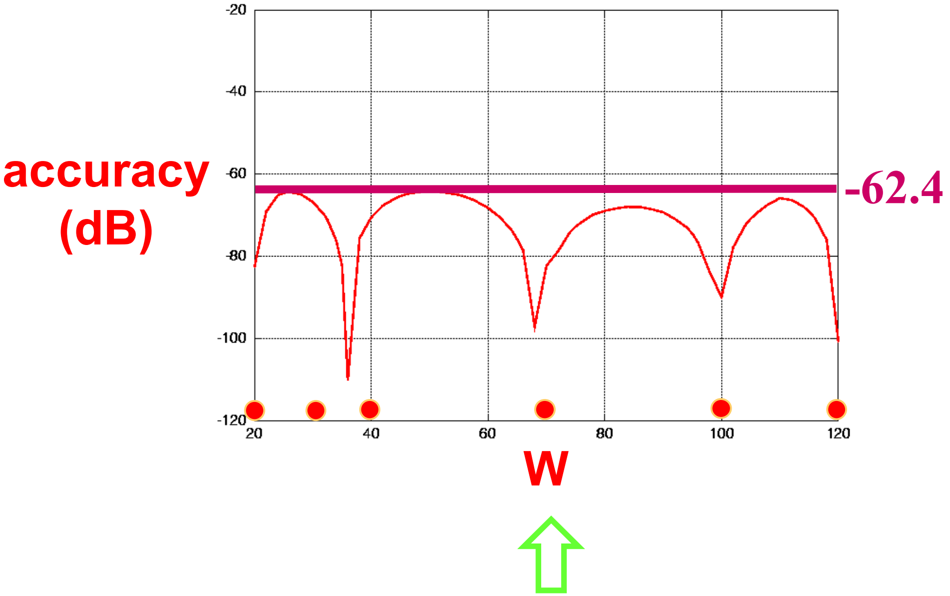
Example 1: open end

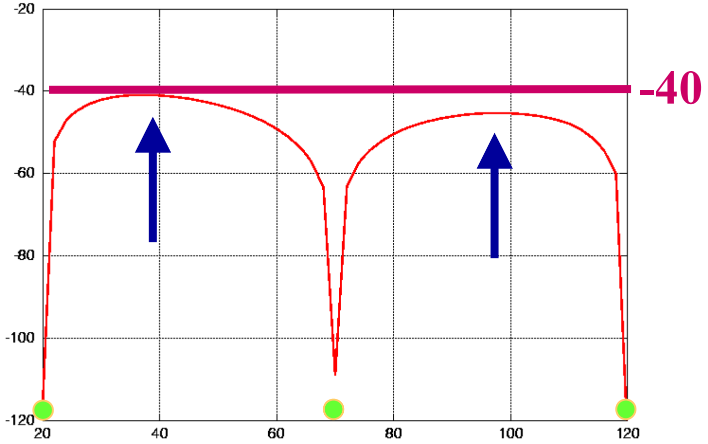


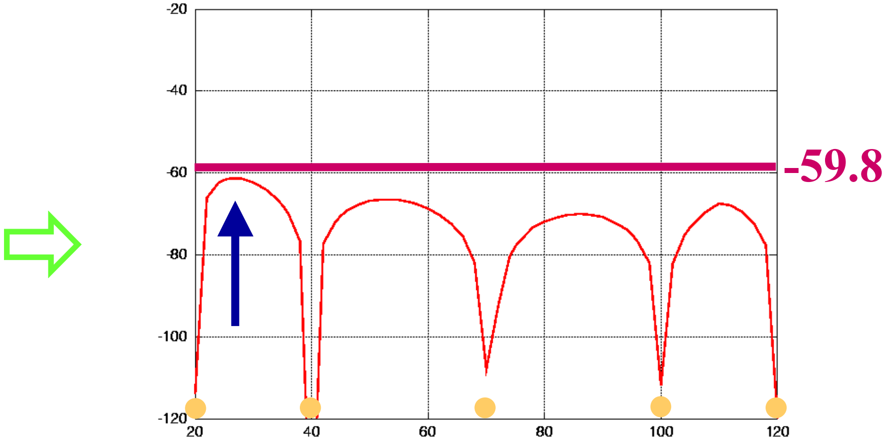
W: 20 μm → 120 μm

freq.: 0 → 60 GHz

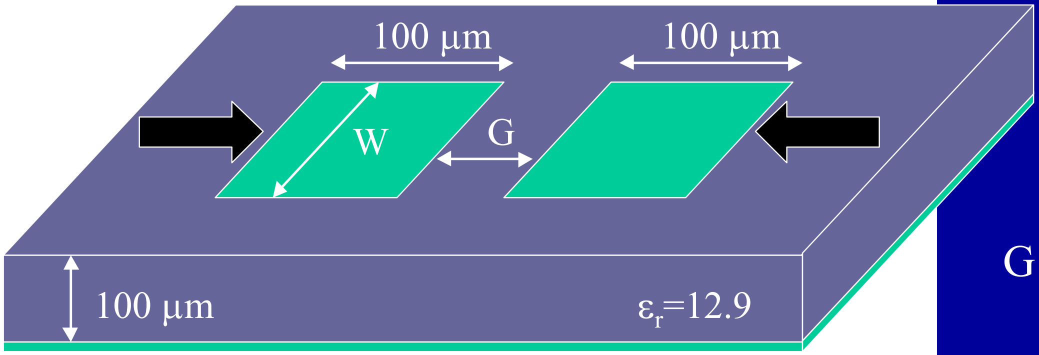
accuracy: -60 dB

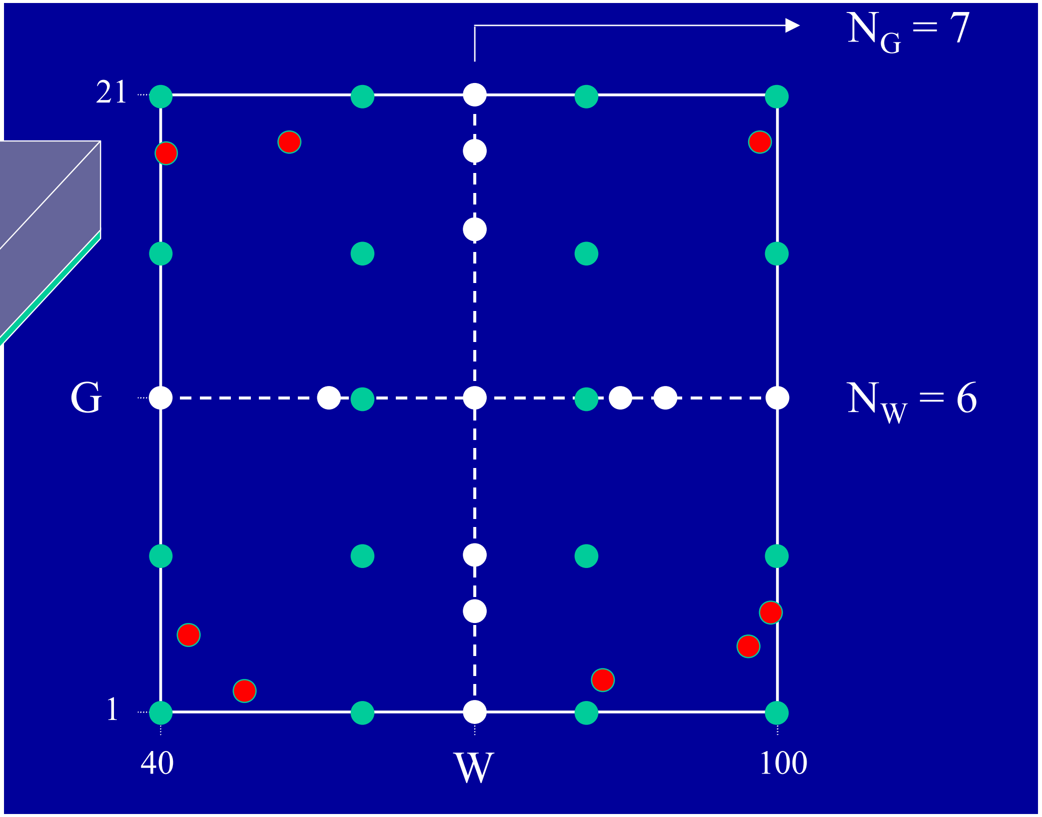






Example 2: gap coupling





W: 40 μm → 100 μm

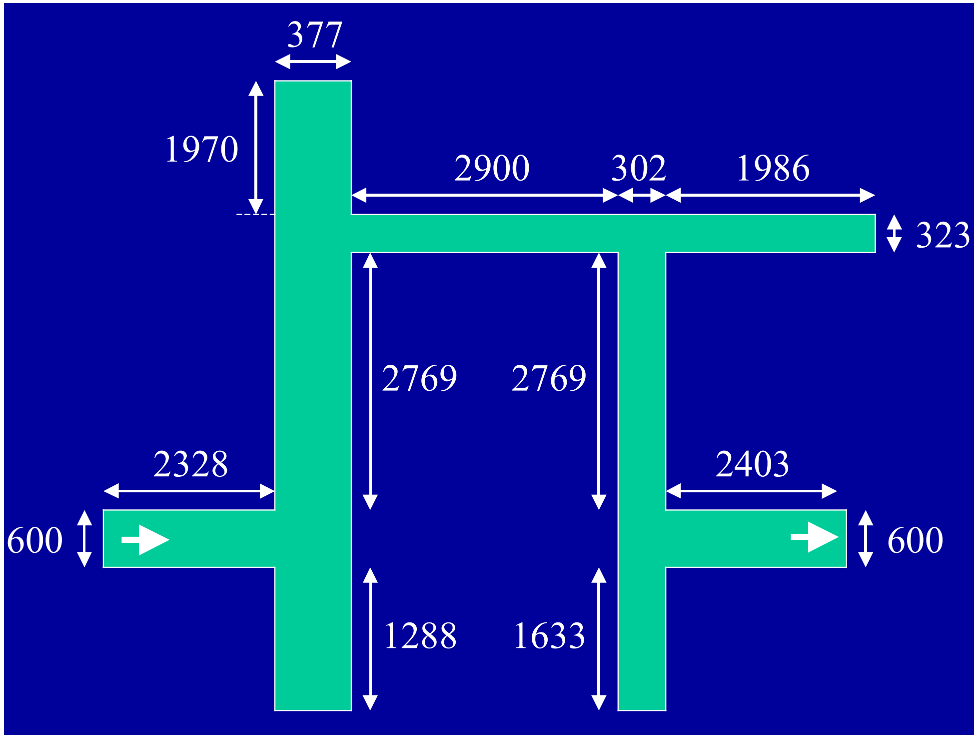
G: 1 μm → 21 μm

freq.: 0 → 60 GHz

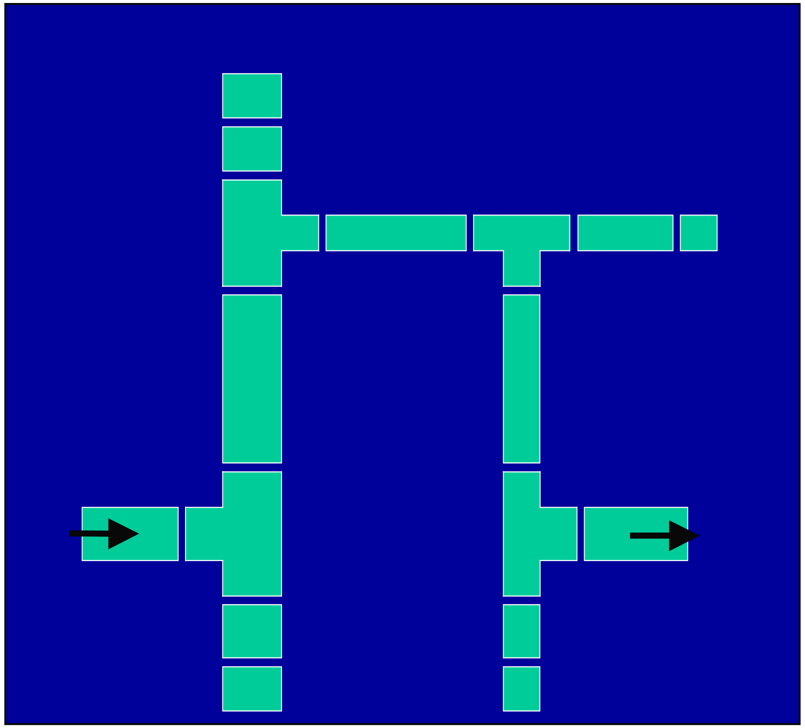
accuracy: -60 dB

$$S(W,G,f) = C_o(f) + C_1(f)\,W + C_2(f)\,G + C_3(f)\,WG + \ldots\, C_{26}(f)\,W^4G$$

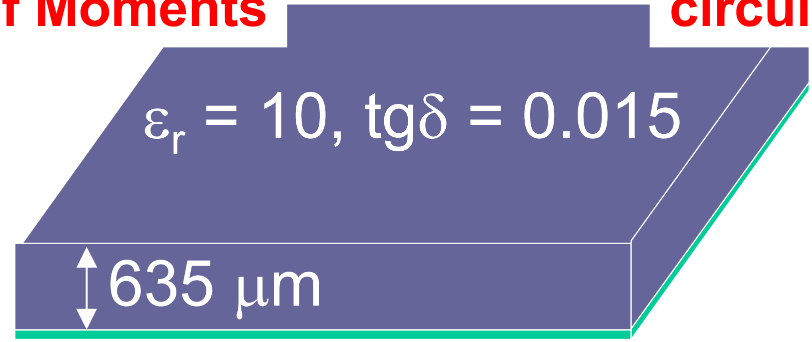
Example 3: low pass filter



Method of Moments



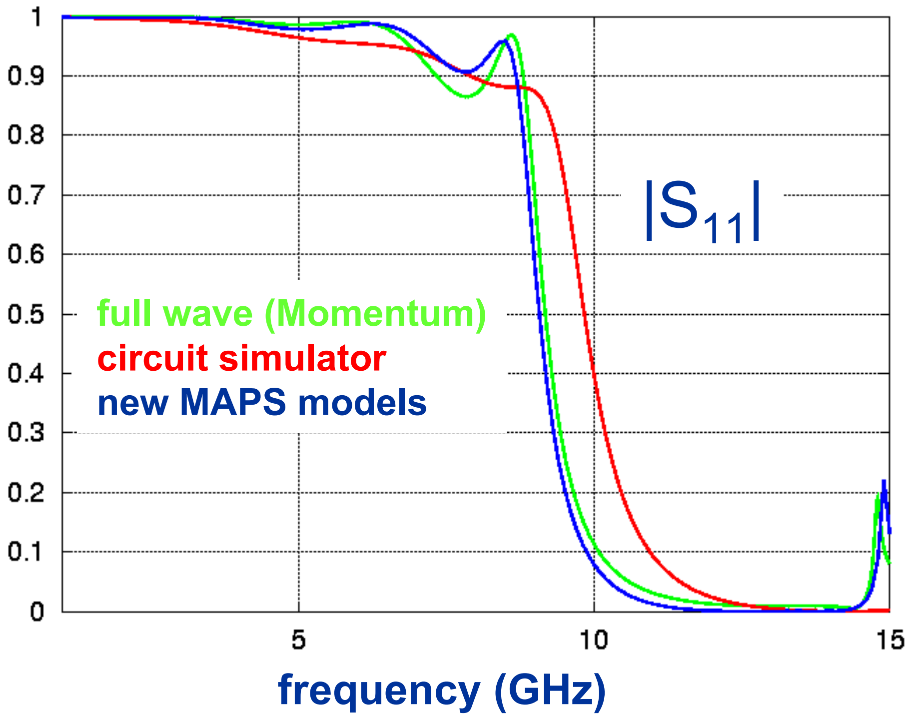
circuit partitioning + MAPS

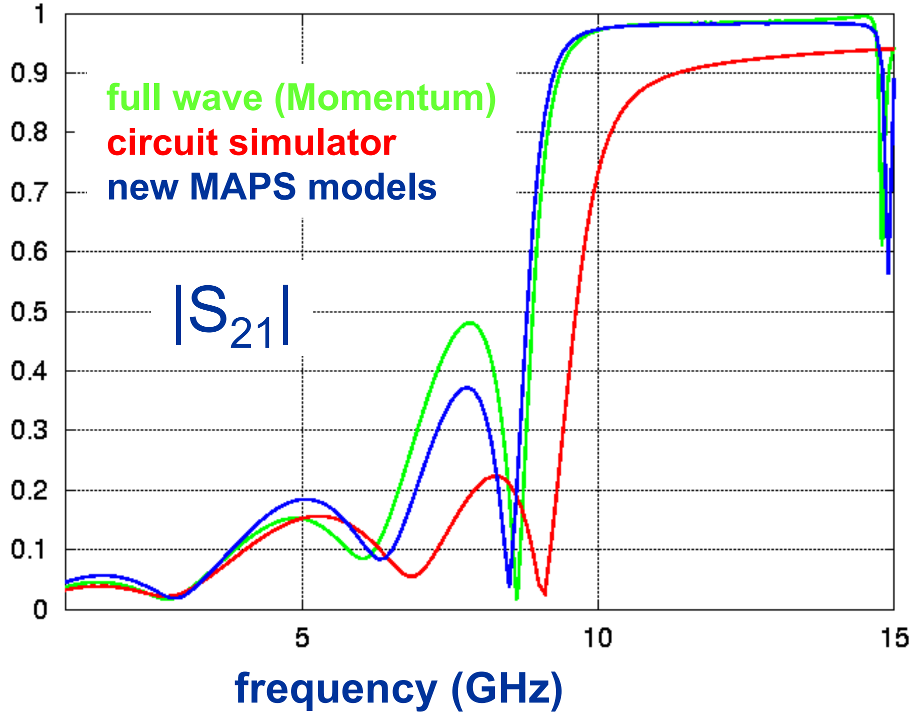


$\varepsilon_r = 10$, $\mathrm{tg}\delta = 0.015$

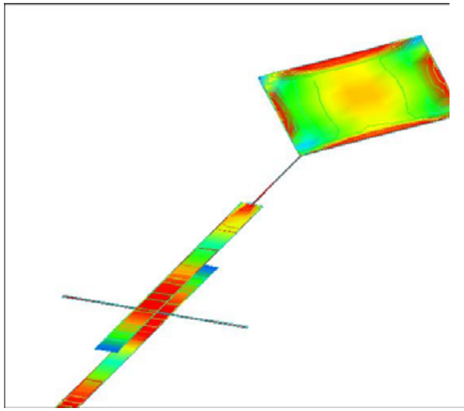
635 µm

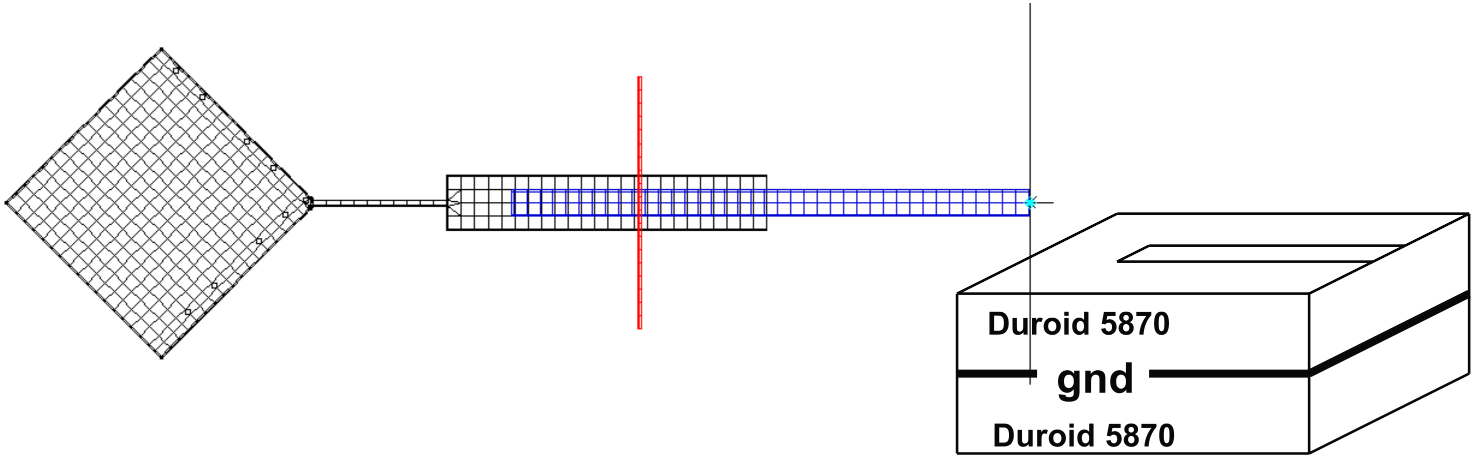
Example 3: low pass filter - cont.



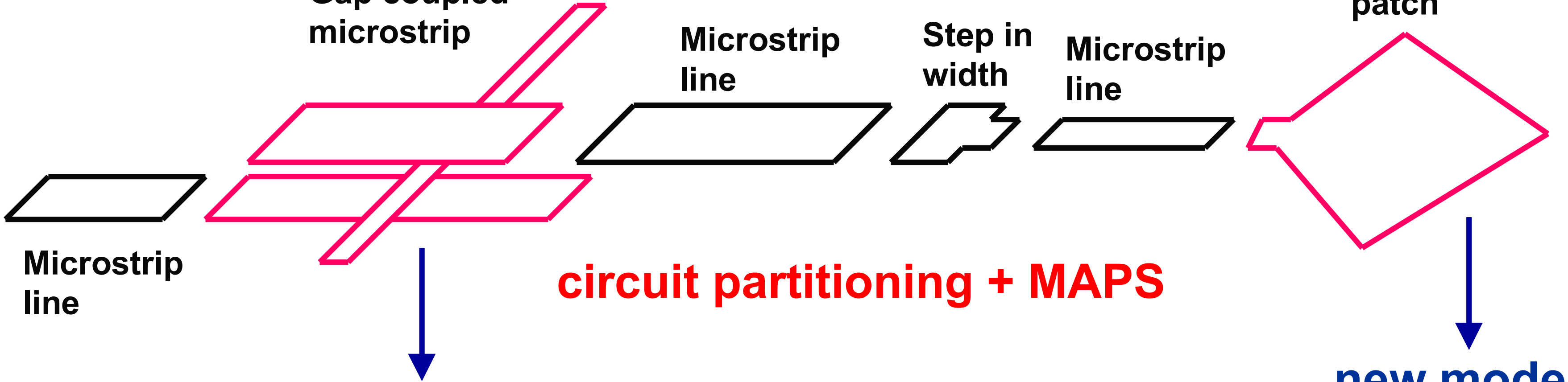


Example 4: microstrip-fed patch antenna @ 10GHz





2 layer substrate



Gap coupled microstrip

Microstrip line

Step in width

Microstrip line

antenna patch

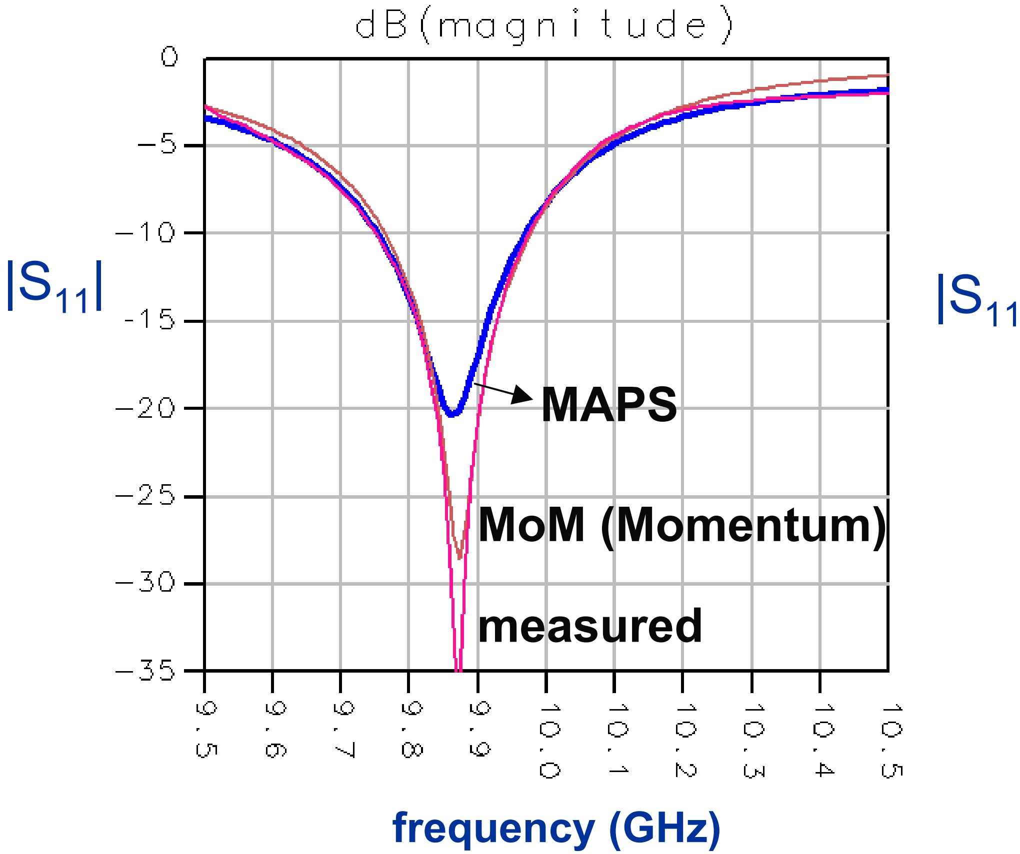
Microstrip line

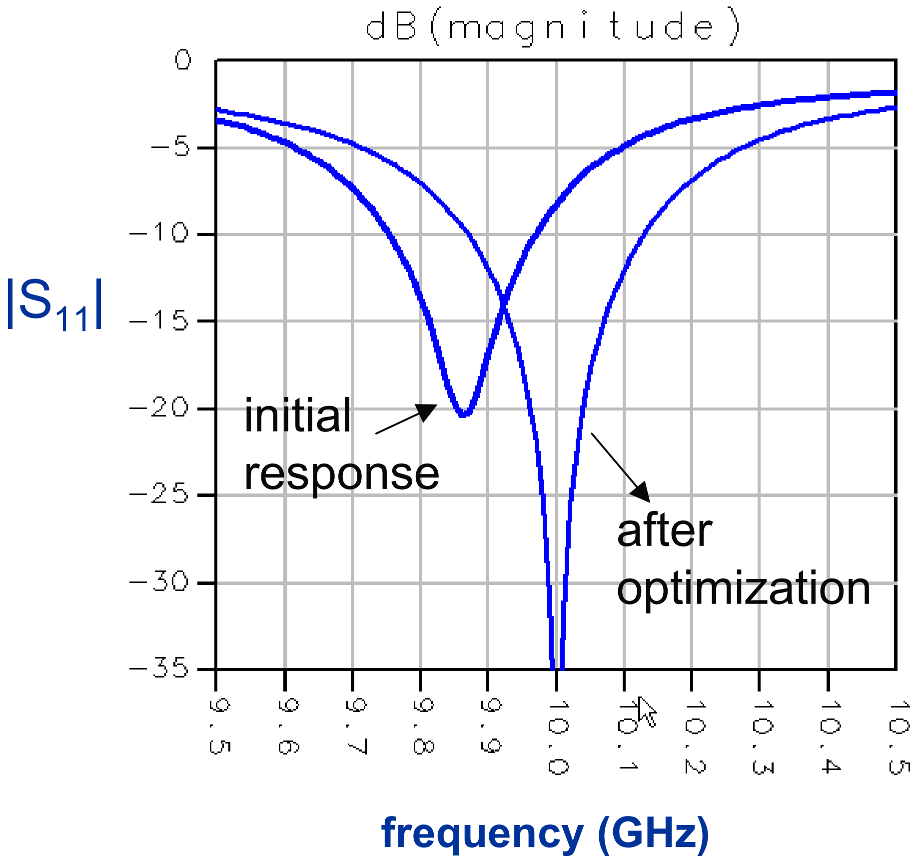
circuit partitioning + MAPS

new model

new model

Microstrip-fed patch antenna @ 10GHz - cont.



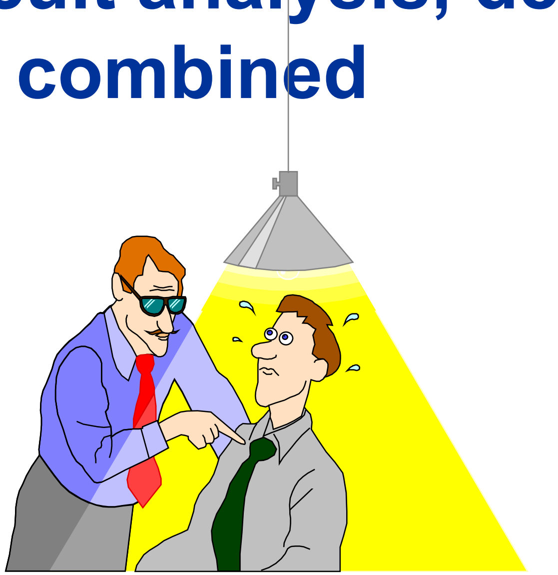


- some couplings are neglected
- differences between model parameters and actual material and geometry data

- optimised for 10 GHz center frequency
- takes only a few minutes of CPU-time!

Conclusions

- ☺ planar solution techniques can now handle complex high-speed and RF circuits with many ports
- ☺ full-wave analysis accuracy and flexibility and fast circuit analysis, design and optimisation can now be combined



Questions?