Efficient MoM techniques for complex digital high-speed and RF-circuits and for parametrized model building

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Outline

- Planar MoM solvers: the challenges
- High-speed and RF circuits
  - the MoM for planar circuits
  - quasi-static approximation
  - polygonal mesh
  - star-loop transformation
  - examples
- Parameterized Model Building
  - full-wave versus circuit analysis
  - adaptive model building and reflective exploration
  - examples
- Conclusion and references

Planar MoM solvers: the challenges

- 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
- ....

Planar MoM solvers: the challenges - part 1

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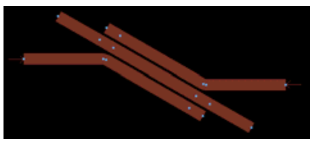
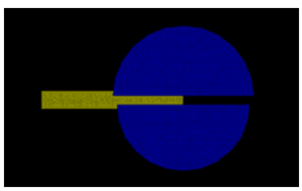
“Classical” circuits





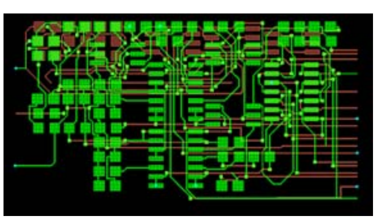
Classical circuits

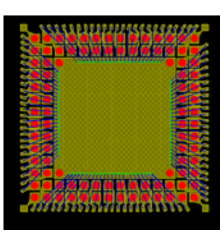
- microwave hybrid (Alumina)
- microwave MMIC (GaAs)
- planar antennas and arrays

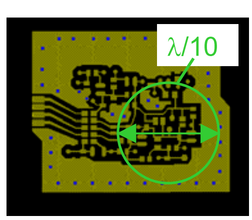
Typical features

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

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

Electromagnetic basics for a planar solver

Mixed Potential Integral Equation

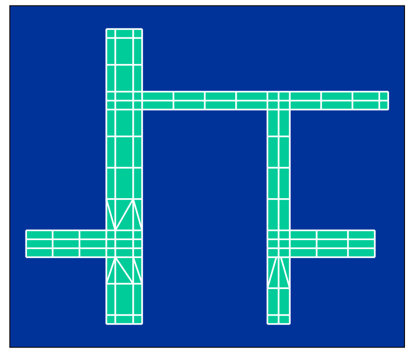
$$\mathbf{E}(\mathbf{J}_S) = -j\omega \mathbf{A}(\mathbf{r}) - \frac{1}{j\omega}\nabla\Phi(\mathbf{r})$$

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

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

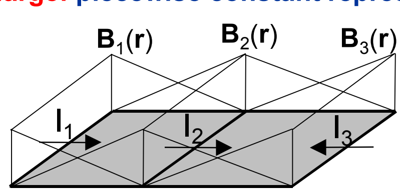
Method of Moments solution

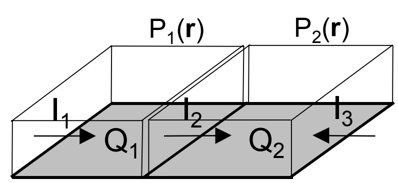
- mixed triangle - rectangle mesh
- introduction of rooftop basis functions to represent unknown surface currents



EM basics for a planar solver - cont.

- **current:** represented by rooftops i.e. piecewise linear approximation in the flow direction and piecewise constant appr. perpendicular to the flow
- **charge:** piecewise constant representation





$$\mathbf{J}(\mathbf{r}) = I_1\mathbf{B}_1(\mathbf{r}) + I_2\mathbf{B}_2(\mathbf{r}) + I_3\mathbf{B}_3(\mathbf{r}) \quad\Rightarrow\quad q(\mathbf{r}) = -\frac{1}{j\omega}\nabla\cdot \mathbf{J}(\mathbf{r}) = Q_1P_1(\mathbf{r}) + Q_2P_2(\mathbf{r})$$

$$\nabla\cdot \mathbf{B}_1(\mathbf{r}) = -P_1(\mathbf{r})$$
$$\nabla\cdot \mathbf{B}_2(\mathbf{r}) = P_1(\mathbf{r}) - P_2(\mathbf{r})$$
$$\nabla\cdot \mathbf{B}_3(\mathbf{r}) = -P_2(\mathbf{r})$$

$$Q_1 = \frac{1}{j\omega}(I_1 - I_2)$$
$$Q_2 = \frac{1}{j\omega}(I_2 + I_3)$$

conservation of charge is respected!

EM basics for a planar solver - cont.

Method of Moments

Maxwell's equations

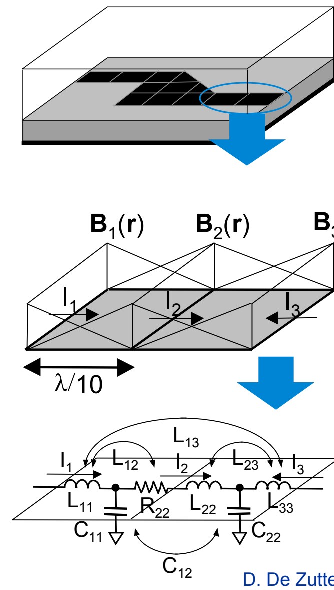
matrix equation

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

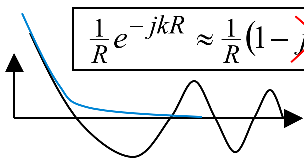
equivalent circuit

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

frequency dependent !



Full-wave versus quasi-static



$$\frac{1}{R}e^{-jkR} \approx \frac{1}{R}(1 - jkR + ...)$$

Distinguishing features

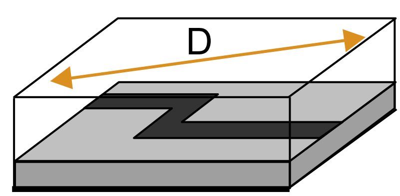
- **electrically small**
- **geometrically complex**
- **many ports**
- **from DC to RF**

- **near-field / low frequency approximation**

  $L(\omega) = L_0 + \omega L_1 + \omega^2 L_2 + ...$

  $C(\omega) = C_0 + \omega C_1 + \omega^2 C_2 + ...$

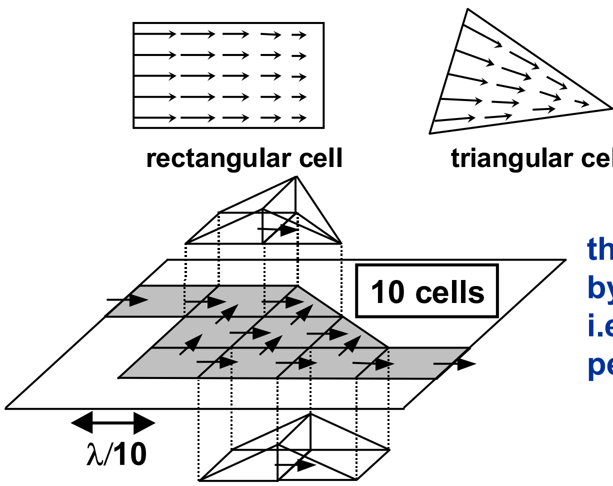
- **L_0 and C_0 are frequency independent**
- **far-field radiation terms are neglected**



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

Traditional meshing

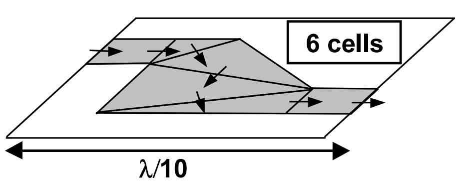
Rectangular - triangular mesh at microwave frequencies



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

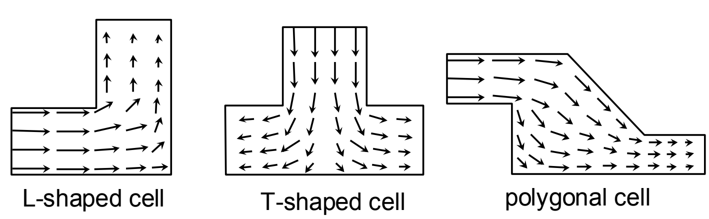
Polygonal meshing

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

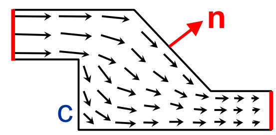


Generalised basis functions

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

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

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



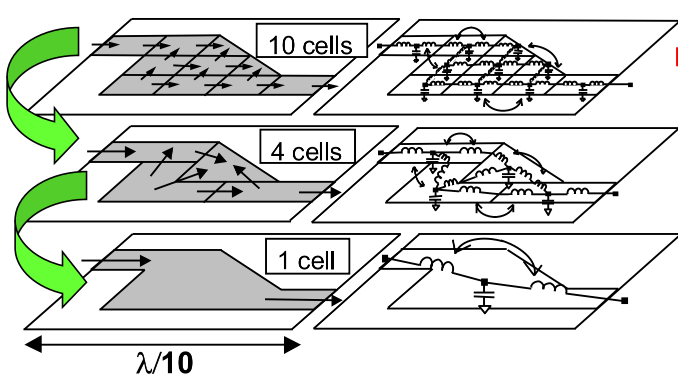
$\mathbf{J}\cdot\mathbf{n} = 0$ on boundary c, except on **red** parts, where the value is either 0 or 1

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)

$$\frac{\partial}{\partial n}K = \begin{cases}0\\1\end{cases} - \frac{A}{2}\mathbf{r}\cdot\mathbf{n}$$

Optimised polygonal mesh



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

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

The low-frequency breakdown

Method of Moments

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

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

for low frequences: **zero** **infinity**

[Z] is ill-conditioned for low frequencies

⇨ numerical solution breaks down

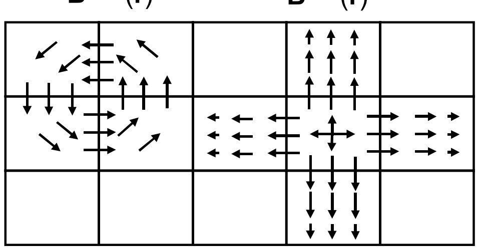
solution: the star-loop transformation

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

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

$\mathbf{B}^{loop}(\mathbf{r})$ $\mathbf{B}^{star}(\mathbf{r})$



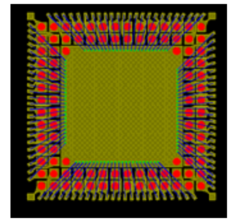
loop function **star function**

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



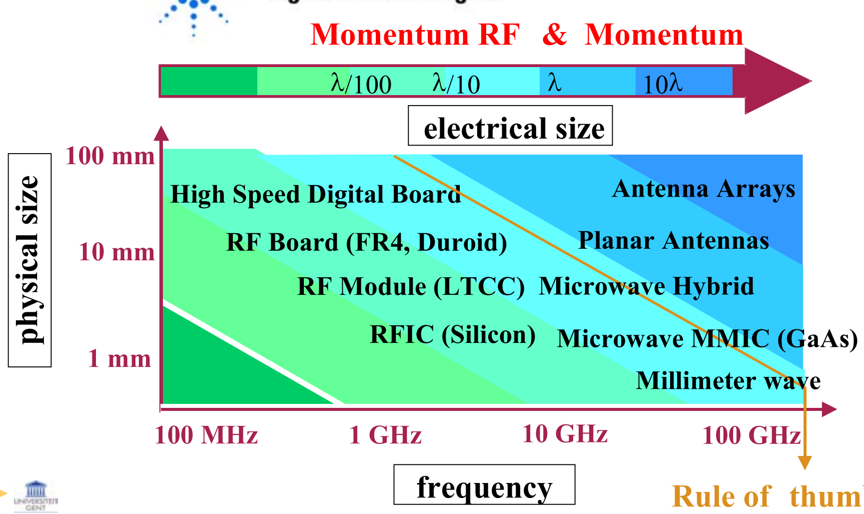
- speed
- capacity
- accuracy

⇨ **advanced planar solution technique**

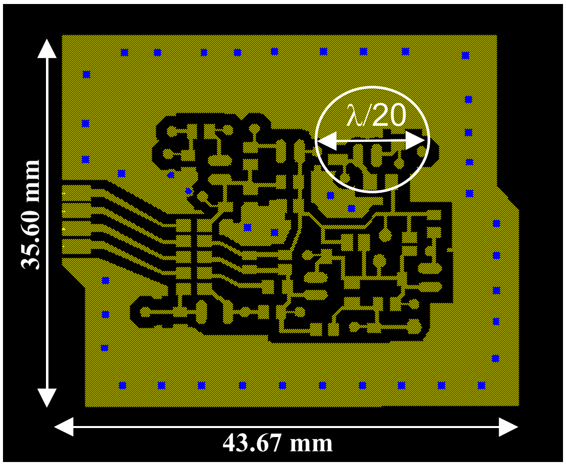
Electrically small	⇨	Quasi-static model
Geometrically complex	⇨	Polygonal mesh
DC to RF frequencies	⇨	Star-loop transform

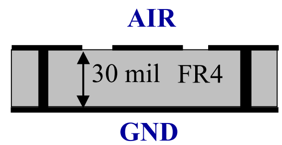
Some sample applications

Agilent Technologies



Example 1: RF board interconnect





Purpose:
compare classical approach with new techniques

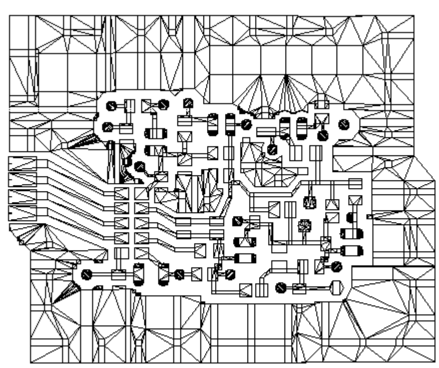
Rule of thumb: frequency < 2.66 GHz

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



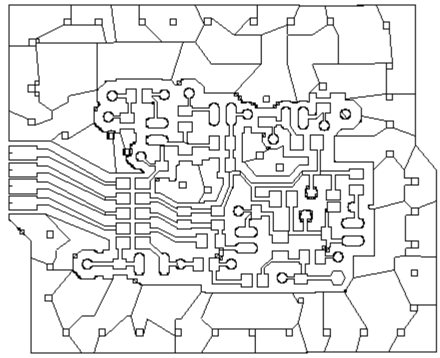
rectangular and triangular mesh

Example 1: RF board interconnect - cont.

new (Momentum RF)

mesh: 20 cells/λ at 1 GHz

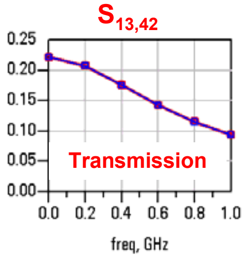
Matrix size	:	733
Process size	:	59.35 MB
User time	:	14m 24s

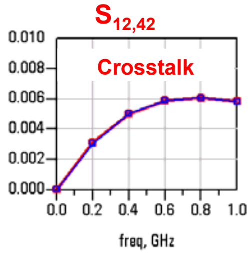


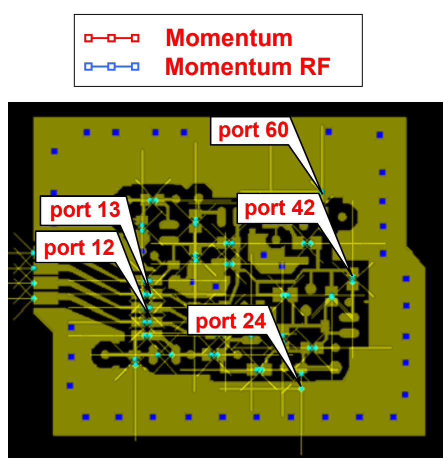
polygonal mesh

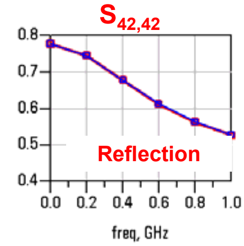
memory saving: factor 3
CPU-time saving: factor 14

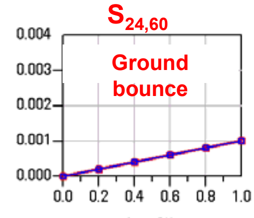
Example 1: RF board interconnect - cont.



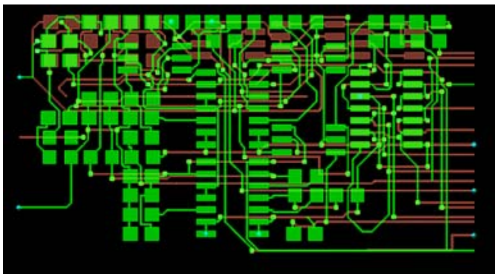








Example 2: digital board interconnect



new (Momentum RF)

mesh: 10 cells/λ at 3 GHz

Matrix size : 722

Process size : 151 MB

User time : 1h 37m

classical (Momentum RF)

mesh: 10 cells/λ at 3 GHz

Matrix size : 8124

Process size : > 1 GB

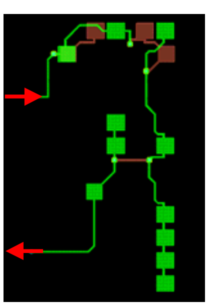
User time : > 1 day

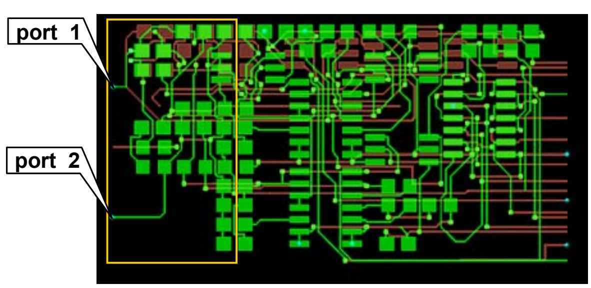
memory saving: factor 10

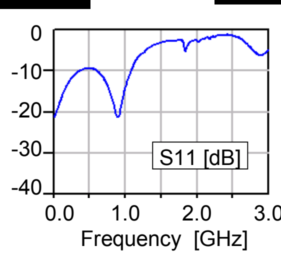
CPU-time saving: factor 20

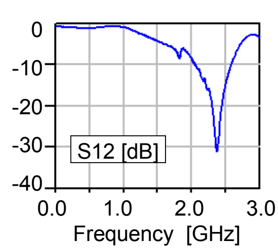
Example 2: digital board interconnect

Reflection & transmission of single trace

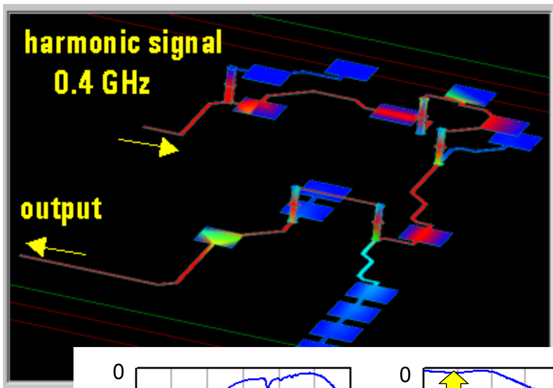


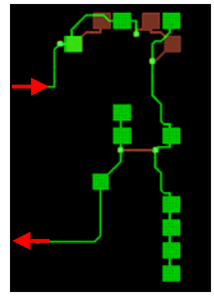


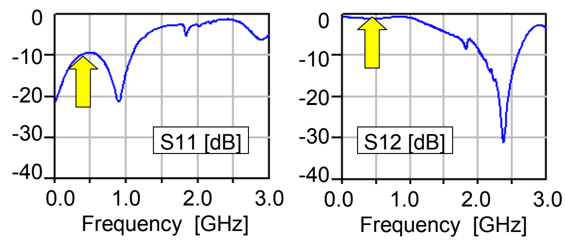




Example 2: digital board interconnect - cont.







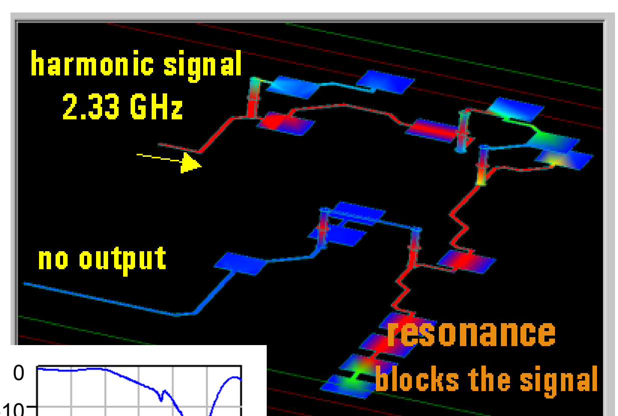
current flow at 400 MHz

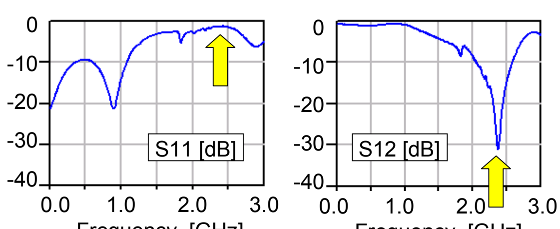
- high-current
- low-current

Example 2: digital board interconnect - cont.

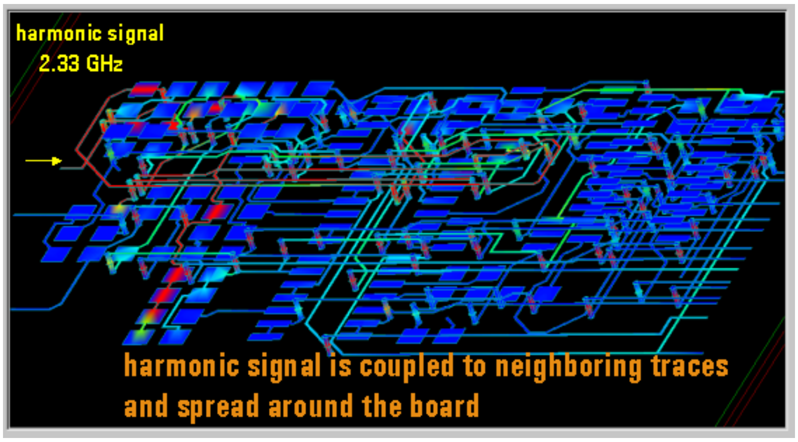
current flow at 2.33 GHz

- high-current
- low-current



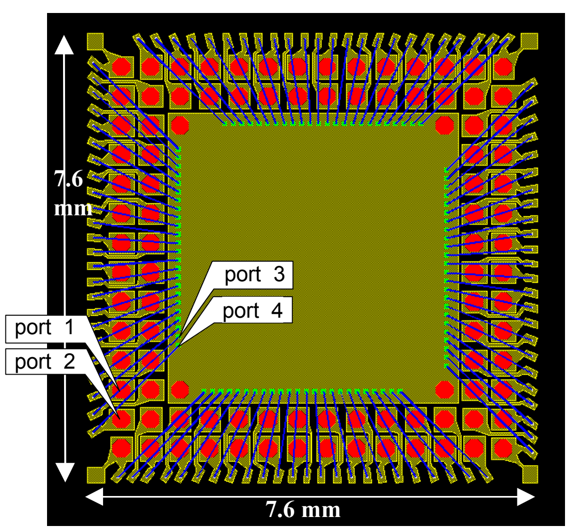


Example 2: digital board interconnect - cont.



signal integrity is compromised over the whole board!

Example 3: ball grid array package



Rule of thumb:
frequency < 2.66 GHz

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

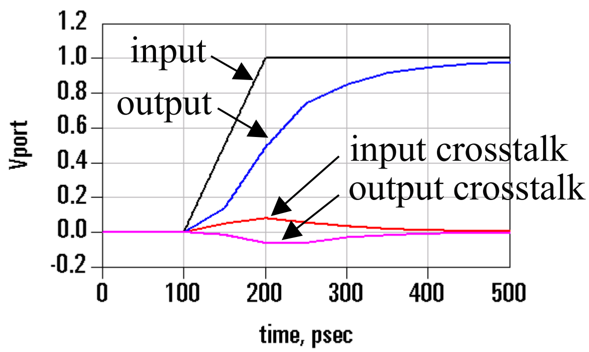
Example 3: ball grid array package - cont.

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

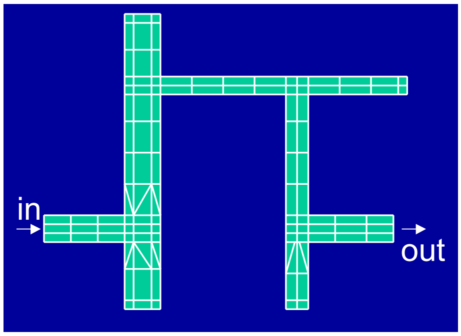


memory saving: factor 10
CPU-time saving: factor 20

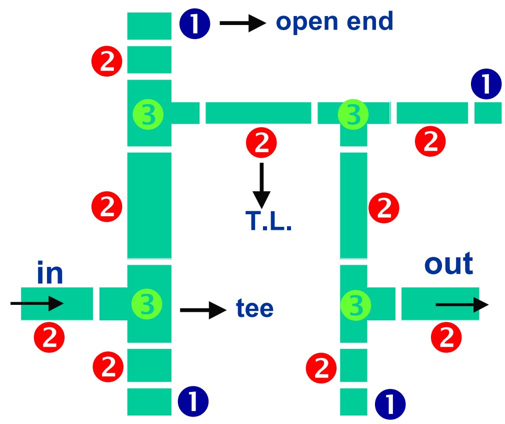
Planar MoM solvers: the challenges - part 2

- 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

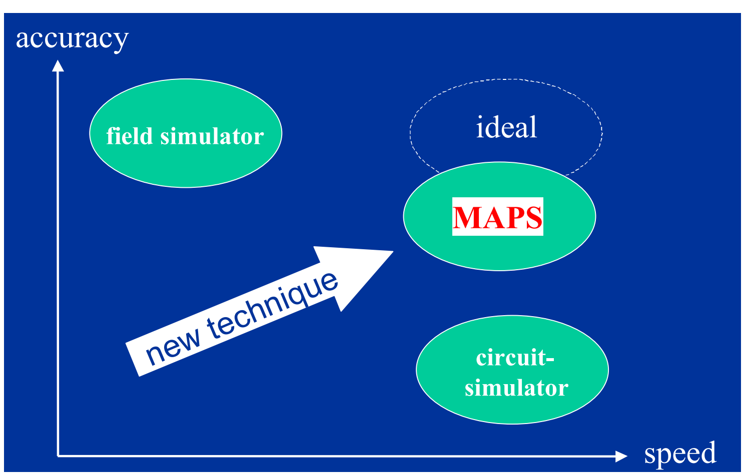


Method of Moment meshing
of a low pass filter



subcircuit partitioning
via S-parameters

Multidimensional Adaptive Parameter Sampling



MAPS: "best of both worlds" ⇨ field accuracy
circuit speed and optimisation

What are we looking for?

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

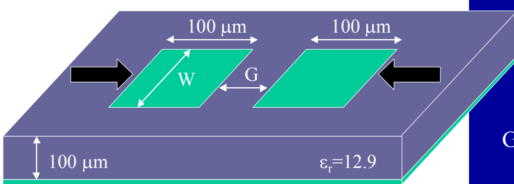
Data representation and reflective exploration

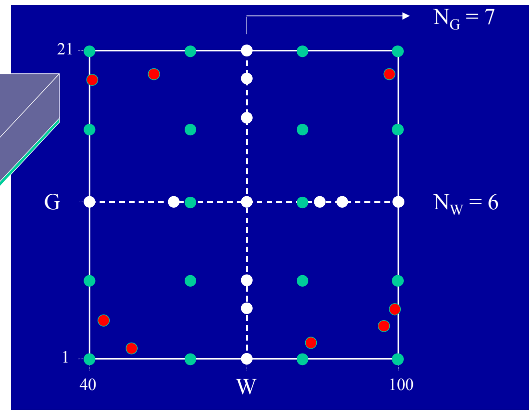
$$\text{data}(f, \boldsymbol{p}) = \sum_{m} \{C_m(f)\ P_m(\boldsymbol{p})\}$$

- 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)*

Reflective exploration at multiple frequencies to determine M = max m, p and C_m

Example 1: gap coupling





W: 40 µm → 100 µm

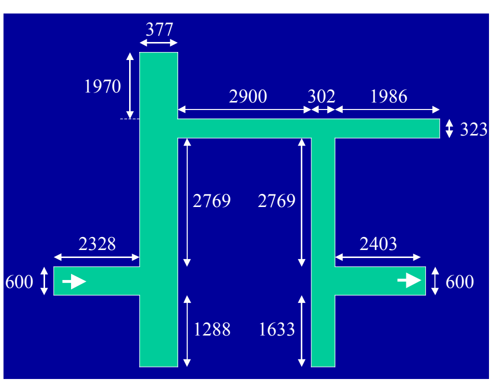
G: 1 µm → 21 µm

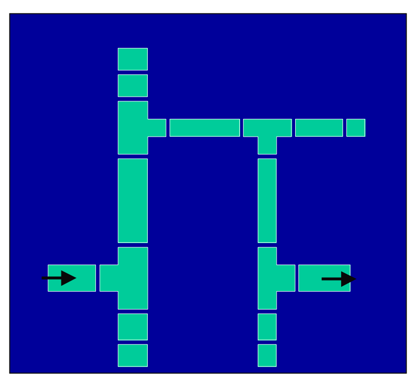
freq.: 0 → 60 GHz

accuracy: -60 dB

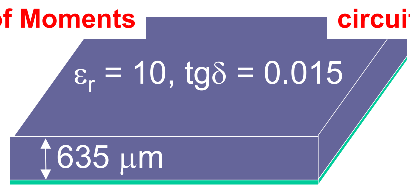
$$S(W,G,f) = C_o(f) + C_1(f)\,W + C_2(f)\,G + C_3(f)\,WG + \ldots\, C_{26}(f)\,W^4G$$

Example 2: low pass filter

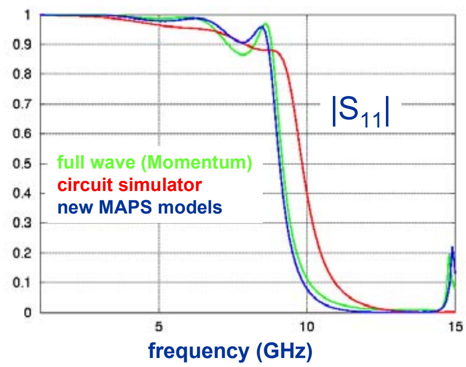


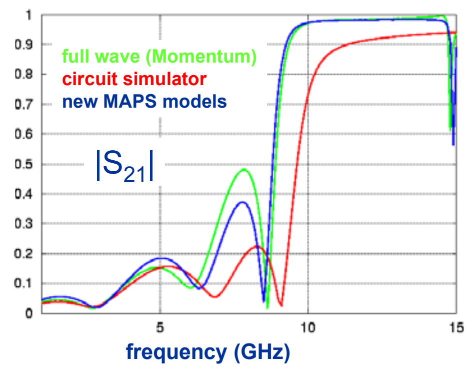


Method of Moments **circuit partitioning + MAPS**

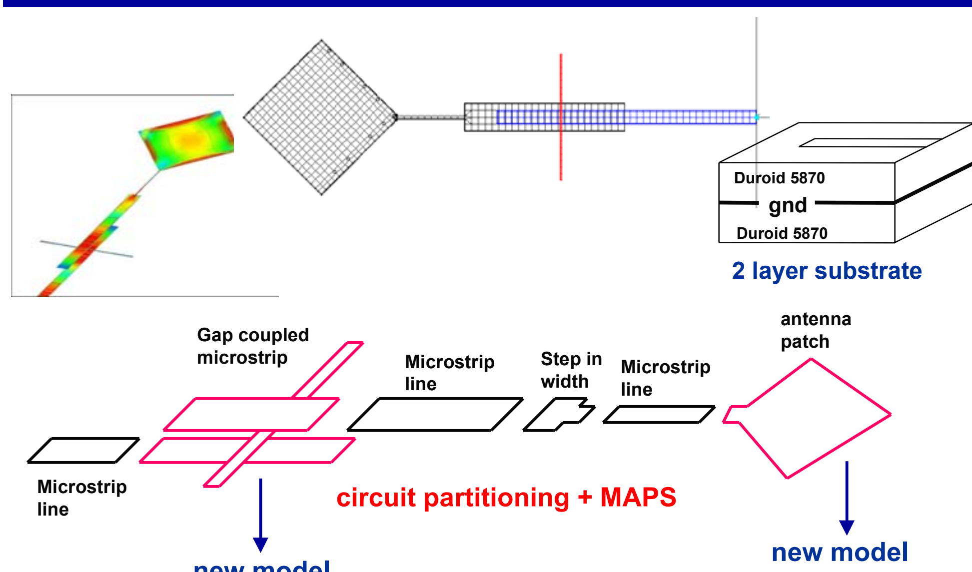


Example 2: low pass filter - cont.

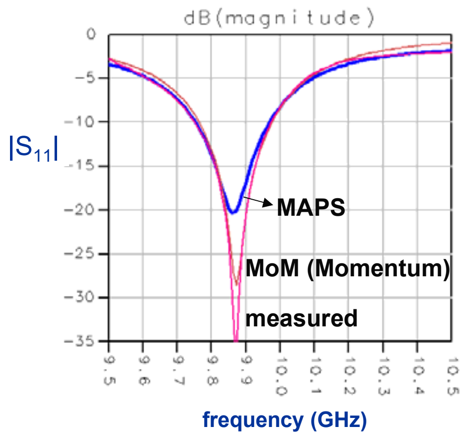


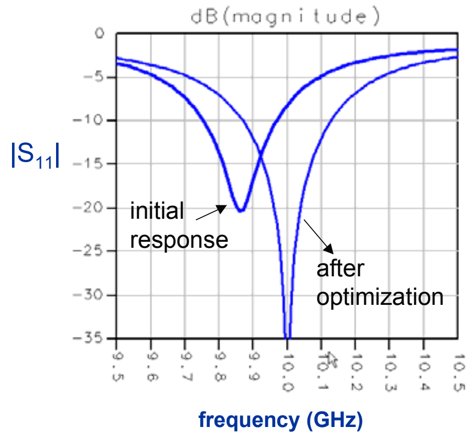


Example 3: microstrip-fed patch antenna @ 10GHz



Microstrip-fed patch antenna @ 10GHz - cont.



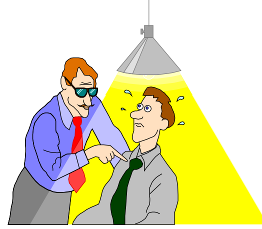


- some couplings are neglected
- differences between model parameters and actual material and geometry data

- 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?