Optimization Strategies for Planar Microwave Circuits

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Outline

- The field-circuit optimization challenge: overview
- The model database approach
  - general block diagram of the optimization process
  - the generalized layout component (GLC)
  - the Electromagnetic Model Database (EMDB)
- Two ways to build the EMDB
  - on-the-fly ⇨ minimal-order multidimensional linear interpolation
  - upfront ⇨ multidimensional adaptive parameter sampling (MAPS)
  - examples
- Conclusion and references

Circuit Analysis

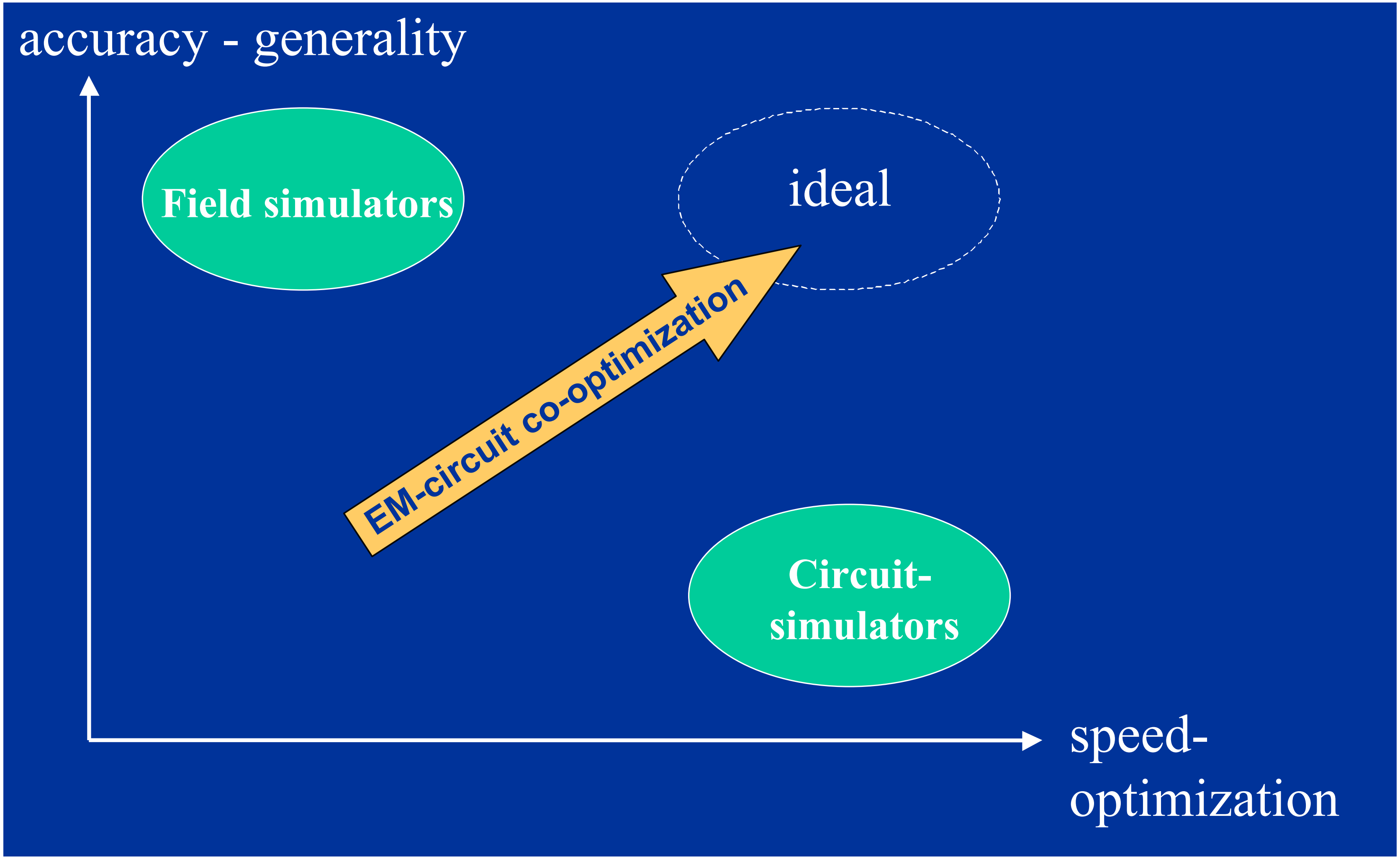
- based on Kirchoff's laws (Y, Z, S-parameters, lumped, T.L.)
- partitioning into subcircuits ⇨ divide and conquer
- use (semi-) analytical models for subcircuits or dedicated CAD-tools for these subcircuits
- **appeals directly to the designer**
- **fast and suited for design and optimization**
- physical effects of actual circuit lay-out are neglected
- coupling between substructures and radiation is neglected

Field analysis versus circuit analysis - cont.

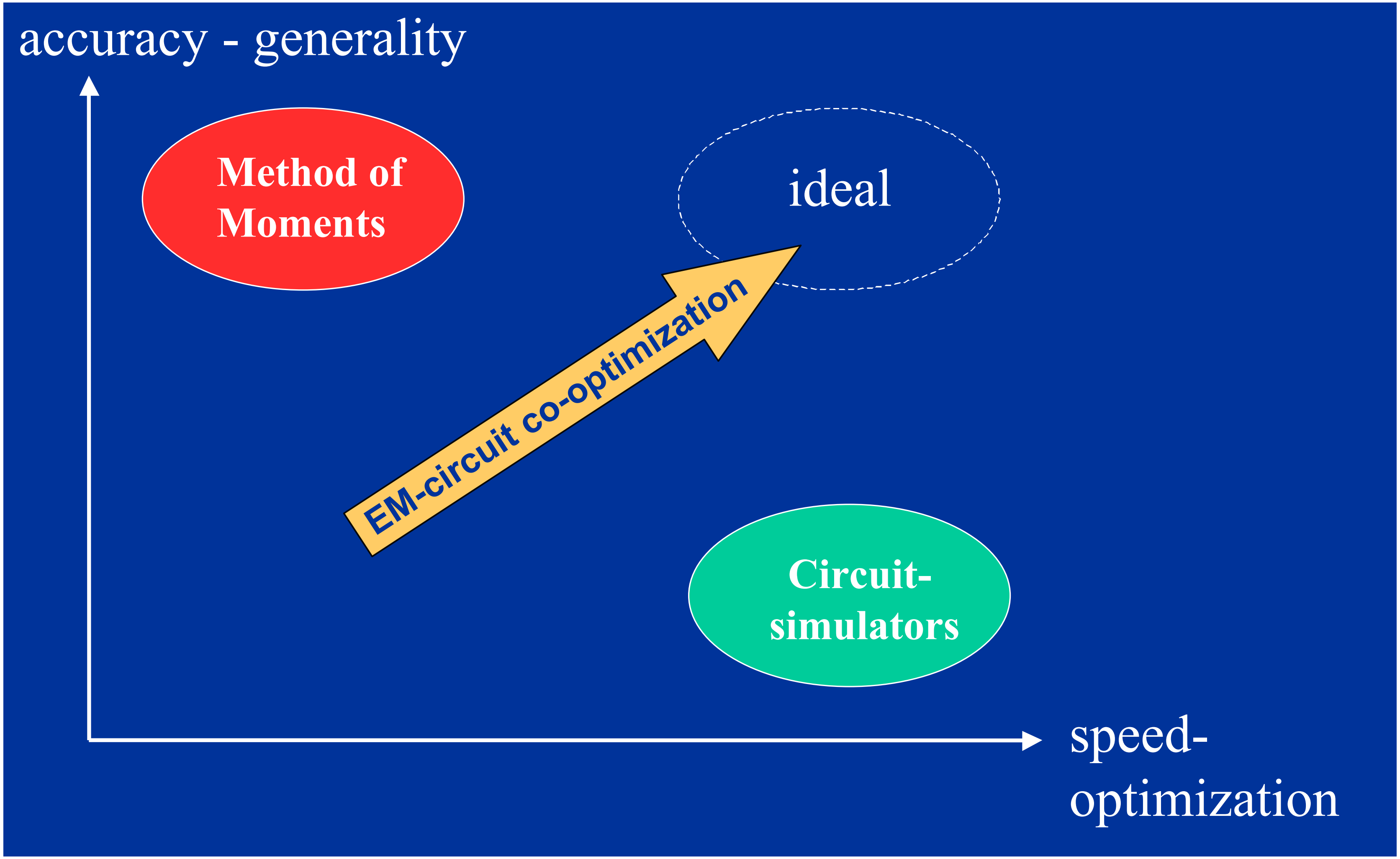
Field Analysis

- numerical solution of Maxwell’s equations (finite elements; finite differences in time domain; method of moment solution of an integral equation; mode matching, .,..)
- 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 and less “intuitive”**
- **difficult to include active non-linear components**

Field-circuit co-optimization



Field-circuit co-optimization for planar circuits



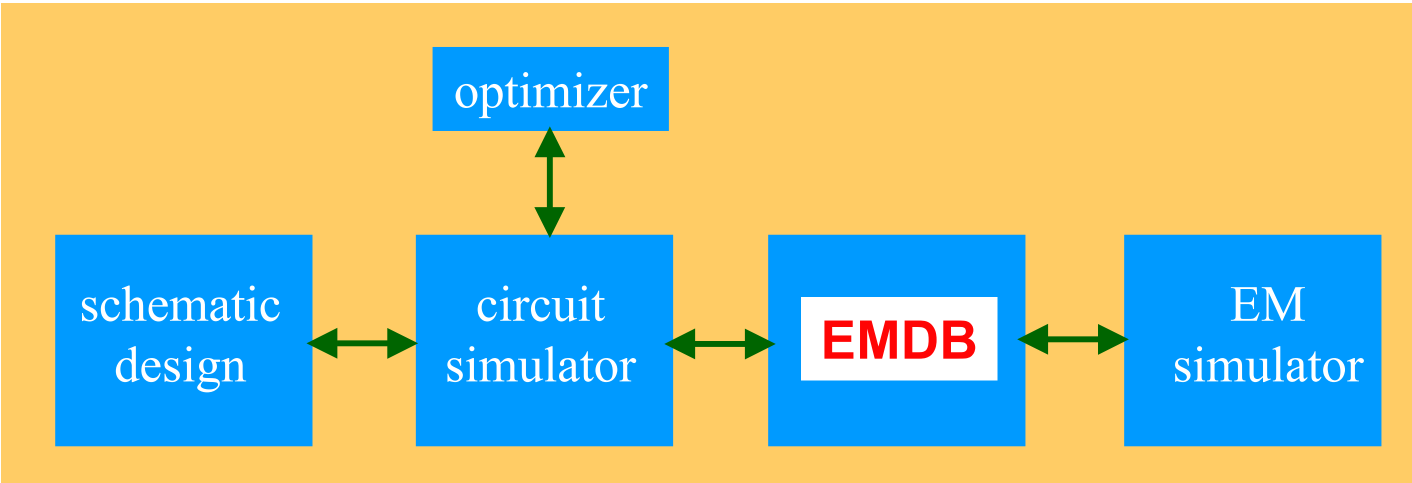
What are the challenges?

- we focuss on **planar circuits** (RF & digital boards, filters, antennas, ...)
- **direct** optimization versus **indirect** optimization
  - direct: classical optimization loop driving an EM-solver

    ⇨ very CPU-time intensive
  - indirect: measures are taken to minimize the number of EM simulations
- optimization space (**OS**) versus electromagnetic space (**EMS**)
  - OS: empirical model, circuit model, coarse grid space, ...
  - a mapping between OS and EMS
  - fast optimization in OS

    Bandler et al. : (Aggressive) Space Mapping technique
- **gradient** information:
  - possibly compromised by finite difference errors
  - possibly compromised by meshing noise

EM-circuit co-optimization environment



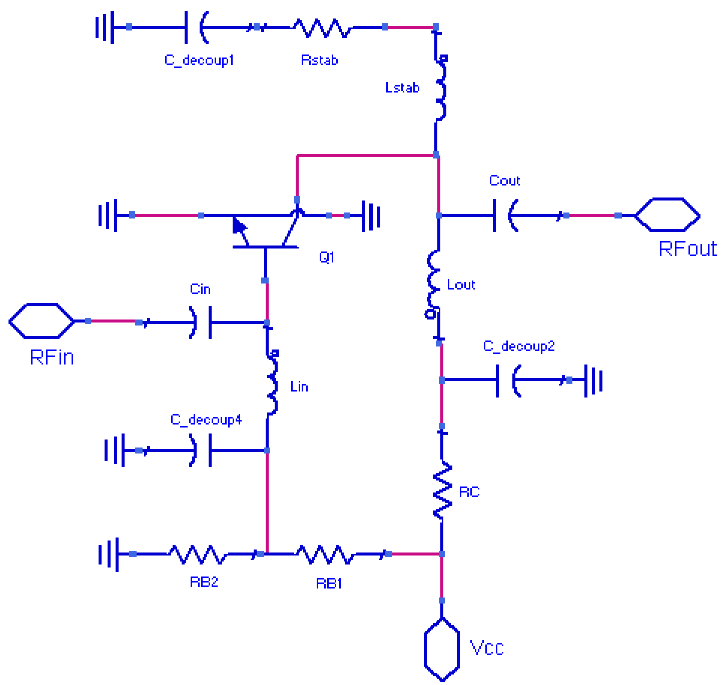
EMDB =
Electromagnetic
Model
Data**B**ase

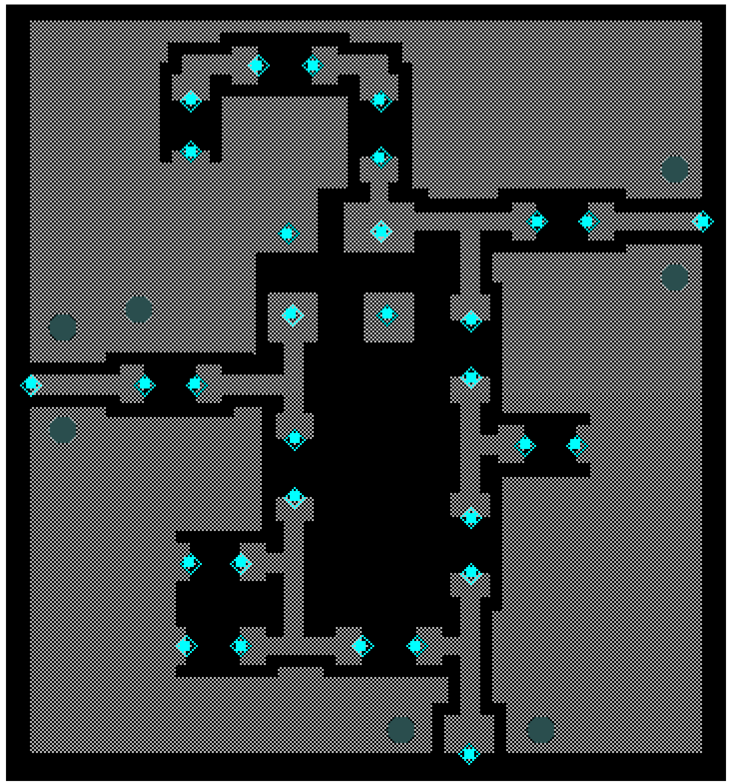
circuit simulator ⇨ transient, frequency domain,
DC, AC, Harmonic Balance, Envelope Analysis, ...

EMDB ⇨

- the EMDB holds the data for a **GLC**
- **GLC**: **G**eneralized **L**ayout **C**omponent
- data: S-parameter data

Low noise amplifier example

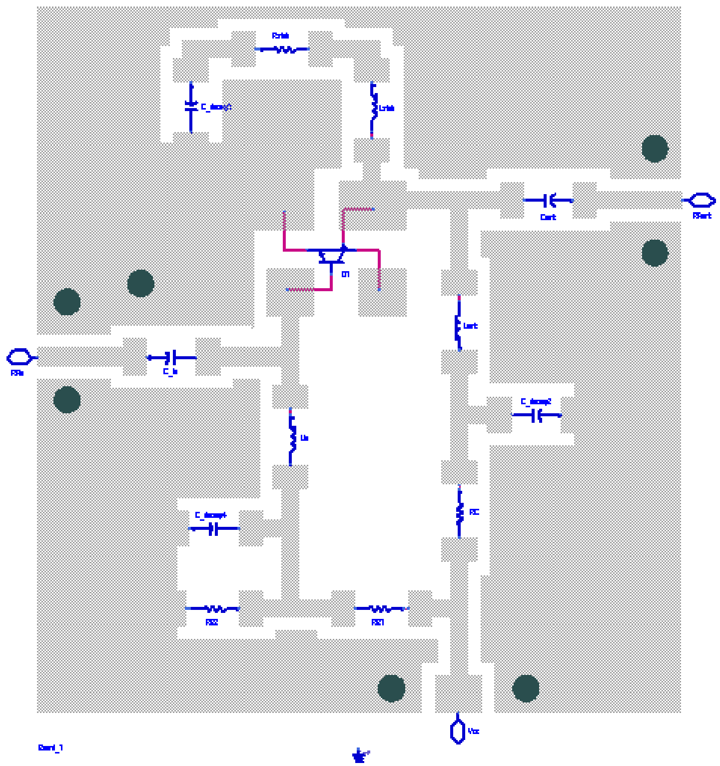




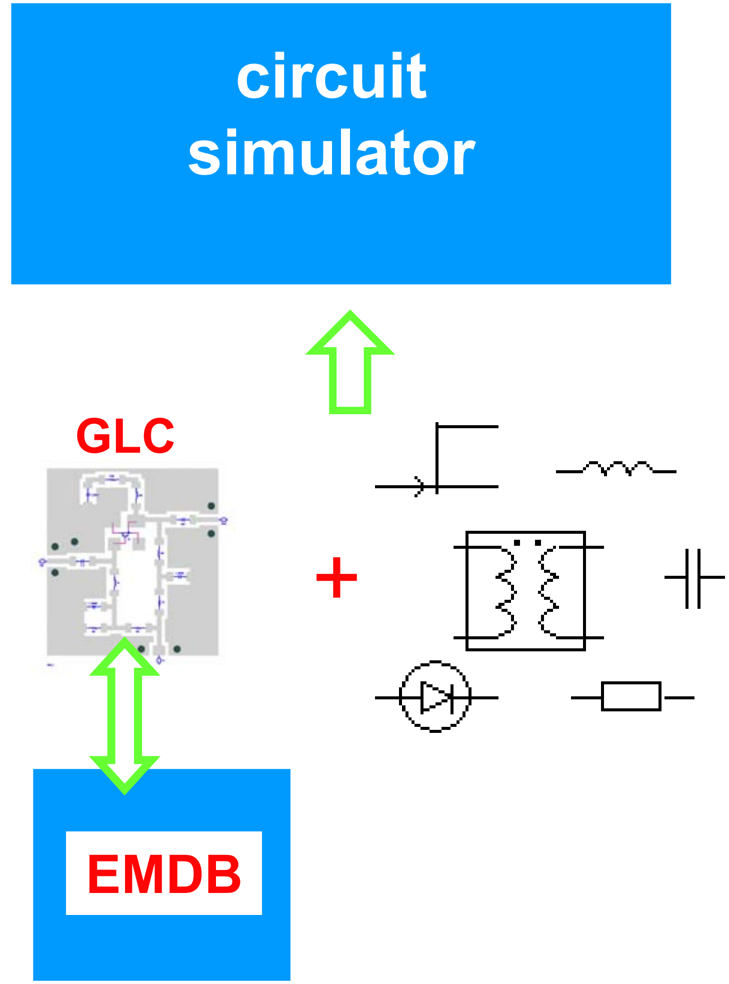
Low noise amplifier schematics

RF board foorprint

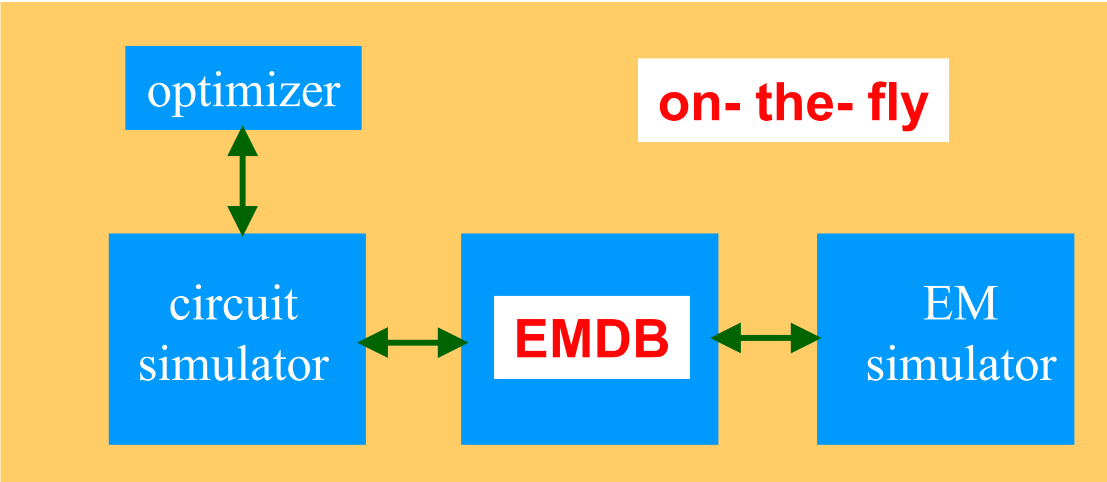
Generalized Layout Component

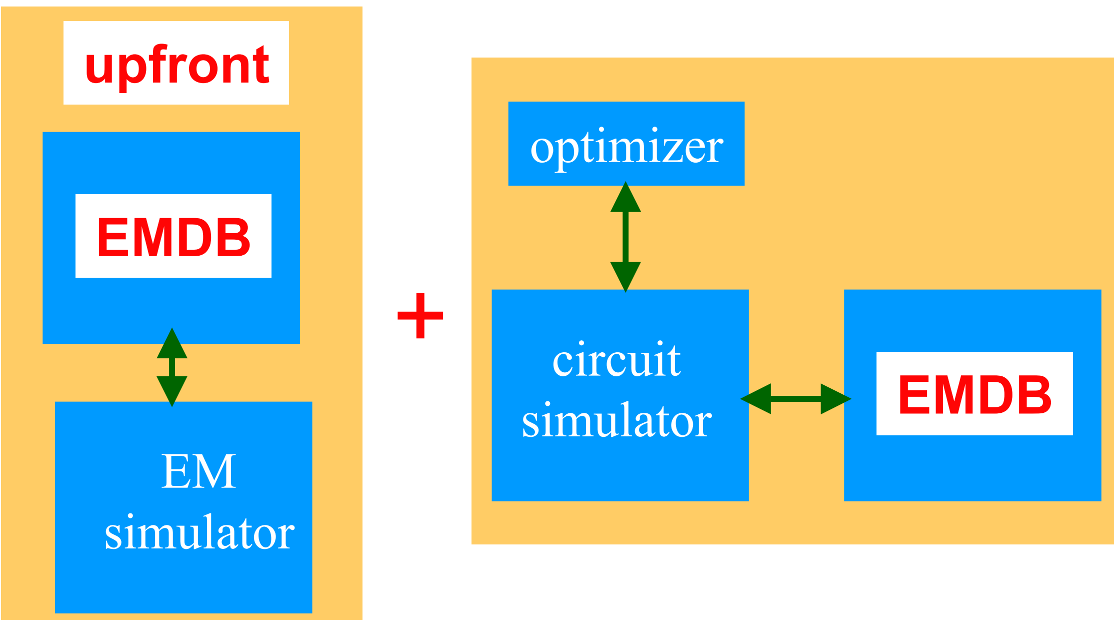


Schematic of the low noise amplifier including the GLC for the RF board footprint



Collecting data for the EMDB





EMDB

- supports multidimensional parameter space
- supports broad frequency range
- not based on equivalent circuit models
- not based on pole-zero models
- each of the two approaches is based on a dedicated interpolation & model building approach
- the two approaches will further be integrated

On-the-fly technique to collect data

- uses a minimal-order multidimensional interpolation
- N-layout parameters: $p_1, p_2, \ldots\ldots, p_N$
- data point = $\mathbf{P}^i (p_1, p_2, \ldots\ldots, p_N)$ i.e. a vector in N-dimensional parameter space
- suppose a set of M independent data points already exists $\{\mathbf{P}^i, \mathbf{P}^i, \ldots, \mathbf{P}^M\}$
- each new data point can be represented as $\mathbf{P} = \sum_{j=0}^{M} r_j \, \mathbf{P}^j$ through the coordinates r_j
- S-parameters are obtained by interpolation: $S(\mathbf{P}) = \sum_{j=0}^{M} r_j \, S(\mathbf{P}^j)$

On-the-fly technique to collect data - cont.

Optimizer requires new data point

1. interpolation possible?
2. how many existing data points $\{\mathbf{P}^i,\mathbf{P}^i,\ldots,\mathbf{P}^M\}$ to be used?
   i.e. M? (try linear interpolation first,
   interpolation over a triangle next, ...)
3. is interpolation warranted?
   - dangerous extrapolation has to be avoided $0 \leq r_j \leq 1$
   - the new data point must be sufficiently close to the original set

$$L_1(\mathbf{P},\mathbf{P}^j) = \sum_{k=1}^{N} \left| \frac{p_k - p_k^j}{\Delta p_k} \right|$$

4. gradient information is trustworthy !

new EM simulations

On-the-fly technique to collect data - cont.

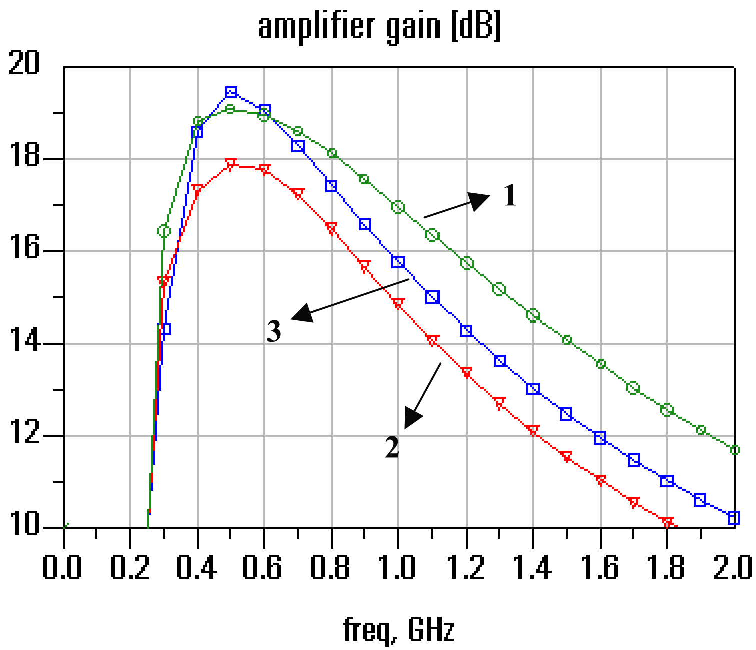
Optimizer requires new data point

interpolation

1. interpolation turns out to be impossible
2. search set of existing data points for data point $\mathbf{P}^k$ sharing the largest number of layout parameters with the new data point **P**
3. Q parameters are different
4. Q EM-simulations are performed in a suitable neighborhood of $\mathbf{P}^k$

Low noise amplifier example - cont.

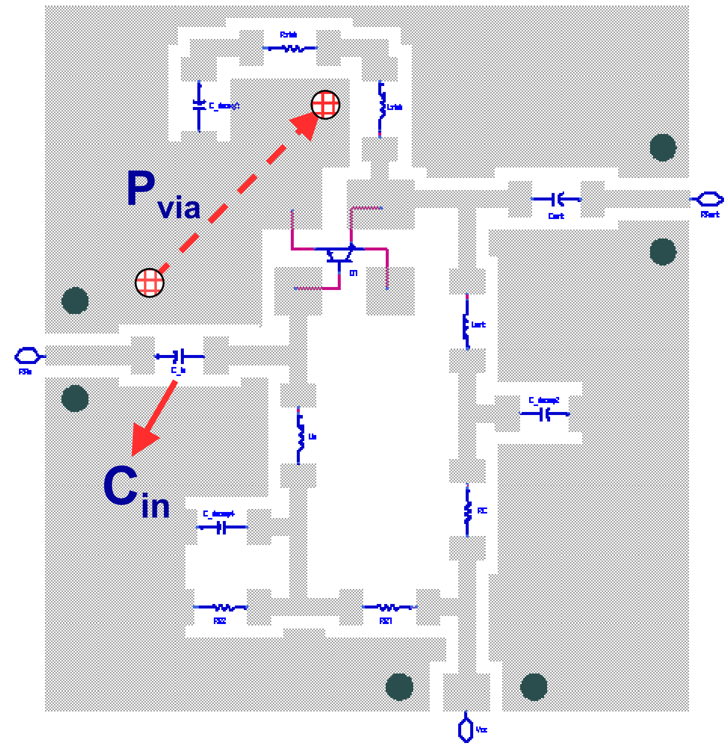
Amplifier gain as a function of frequency



result of original schematic without effect of RF board

result of original schematic including effect of RF board

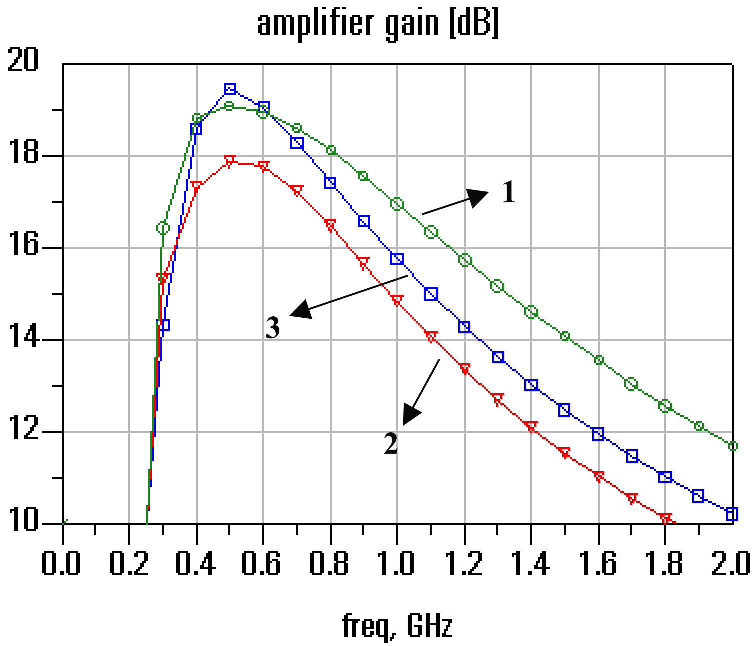
Optimization of the amplifier gain



parameter p_1: input capacitance value C_{in}
parameter p_2: position of grounding via of emitter contact P_{via}

Low noise amplifier example - cont.

Amplifier gain as a function of frequency



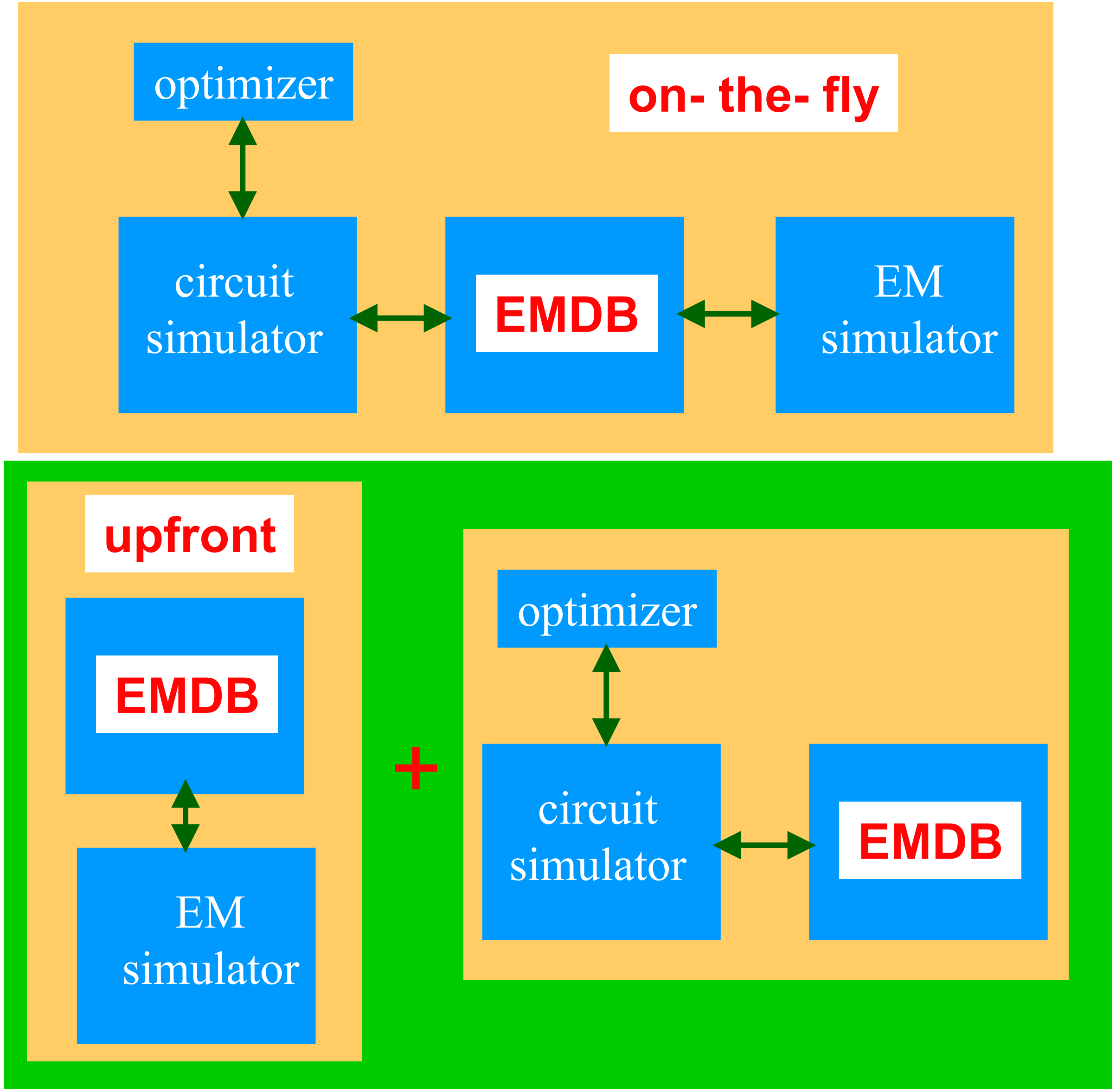
result of optimized gain including effect of RF board

$C_{in,opt}$ = 120 pF
$P_{via,opt}$ = 89.73 mil
extra gain of 2dB

Optimization of amplifier gain - results

- initial values: p_1 = C_{in} = 12 pF,
- p_2 = P_{via} = 20 mil (see curve 2)
- 0 < P_{via} < 120 mil
- goal: optimize gain between 0.4
- and 0.6 GHz
- number of iterations: 13
- number of EM simulations: 11
- CPU-time: 2.5 minutes per EM
- simulation (Pentium II, 330MHz)

Collecting data for the EMDB



Upfront technique to collect data (MAPS)

- uses a **M**ultidimensional **A**daptive **P**arameter **S**ampling technique
- N-layout parameters: $p_1, p_2, \ldots\ldots, p_N$
- a range is specified for each parameter: $p_{k,min} \leq p_k \leq p_{k,max}$
- a frequency range is specified: $f_{min} \leq f \leq f_{max}$
- **how to obtain an S-parameter model with a predefined accuracy over the specified parameter space and frequency range, with a minimum number of EM simulations?**
- if successful gradient information will again be very trustworthy!

Data representation for MAPS

$$S(f,\mathbf{P}) = \sum_{m} C_m(f)\, F_m(\mathbf{P})$$

- **P**: data point in parameter space (as in the on-the-fly technique)
- F_m: orthonormal multidimensional polynomials
  (generalized Forsythe multinomials) *(stored in database)*
- C_m: frequency dependent fitting coefficients *(stored in database)*
- calculation of the weights by fitting Q data points $\mathbf{P}^s$ (s = 1,2,..Q)

$$\sum_{s=1}^{Q} F_k(\mathbf{P}^s)\, F_l(\mathbf{P}^s) = \delta_{kl}$$

(orthogonality of the polynomials)

$$C_m(f) = \sum_{s=1}^{Q} S(f,\mathbf{P}^s)\, F_m(\mathbf{P}^s)$$

Data representation for MAPS

- for 1 parameter p_1: sum of terms of the form $(p_1)^t$ with $t \leq Q-1$

  for 3 parameters: sum of terms of the form $(p_1)^i\,(p_2)^j\,(p_3)^k$

$$S(f,\mathbf{P}) = \sum_m C_m(f)\,F_m(\mathbf{P})$$

$$\sum_{s=1}^{Q} F_k(\mathbf{P}^s)\,F_l(\mathbf{P}^s) = \delta_{kl}$$

$$C_m(f) = \sum_{s=1}^{Q} S(f,\mathbf{P}^s)\,F_m(\mathbf{P}^s)$$

1. How to select the data points $\mathbf{P}^s$ such that a minimum number is needed and hence a minimum number of EM simulations?
2. How to select the F_m's to be used and which powers of the parameters?
3. How to model the frequency dependence (which is still continuous up to now)?

MAPS data point selection

1. How to select the data points **P**^{s} such that
   a minimum number is needed and hence
   a minimum number of EM simulations?

⇨ non-statistical
reflective
data exploration

$$R(\mathrm{f},\mathbf{P}) = \left| \sum_{m=1}^{M_{new}} C_m(\mathrm{f}) F_m(\mathbf{P}) - \sum_{m=1}^{M_{old}} C_m(\mathrm{f}) F_m(\mathbf{P}) \right| = \left| \sum_{m=1+M_{old}}^{M_{new}} C_m(\mathrm{f}) F_m(\mathbf{P}) \right|$$

Selection of new data points:

- until *R*(f,**P**) drops below a prescribed accuracy (e.g. -60db)
- at points where passivity is violated (the most)
- at or near local maxima/minima of the scattering parameters
- for resonance frequencies: near local maxima of the power loss
- ....

MAPS multinomials and frequency dependence

INTEC

2. How to select the F_m's and which powers of the parameters?

- step 1: one-dimensional analysis for p_i with all p_j's kept constant at their midpoint values
- step 2: maximum order from step 1 is used to assign a relative importance to that parameter in the reflective exploration analysis

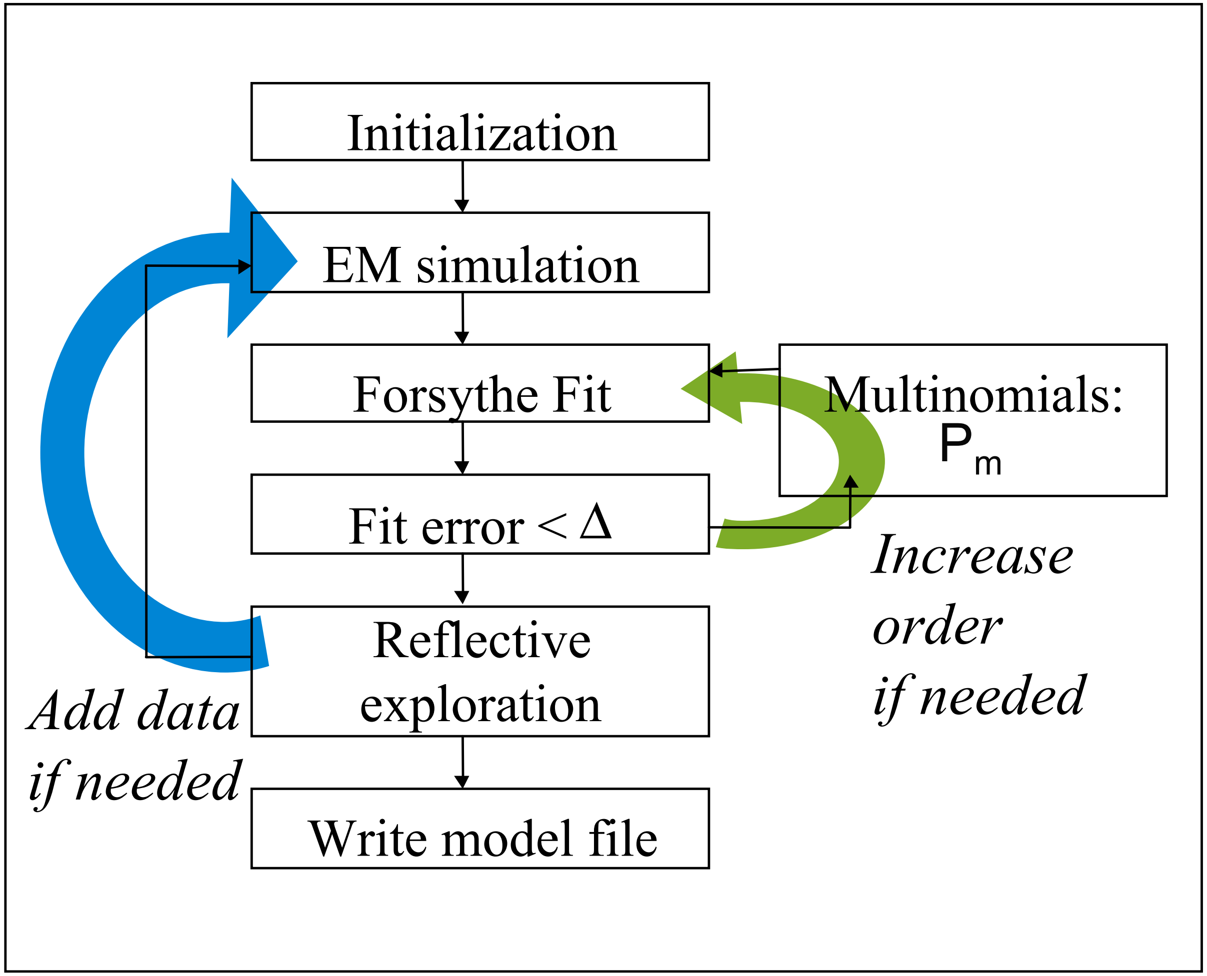
2. How to model the frequency dependence?

- step 1: select a number N_f of discrete frequencies e.g. using an adaptive frequency sampling algorithm
- step 2: apply the reflective procedure at each frequency
- step 3: build on overall model based on the different number of F_m's at each frequency

Adaptive sampling and model building

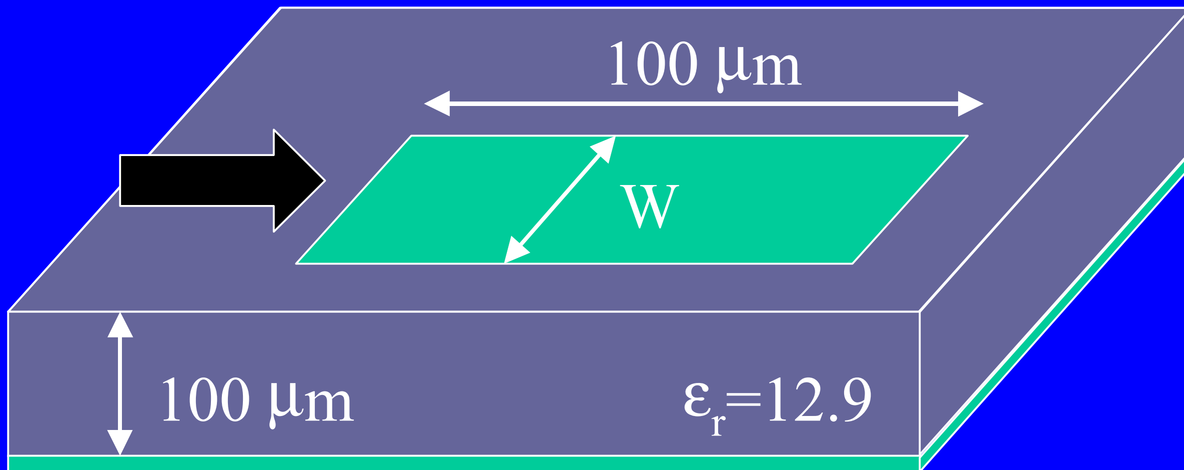
Flow chart of up-front calculation

adaptive sample selection loop



adaptive model selection loop

Example 1: Microstrip open stub on GaAs

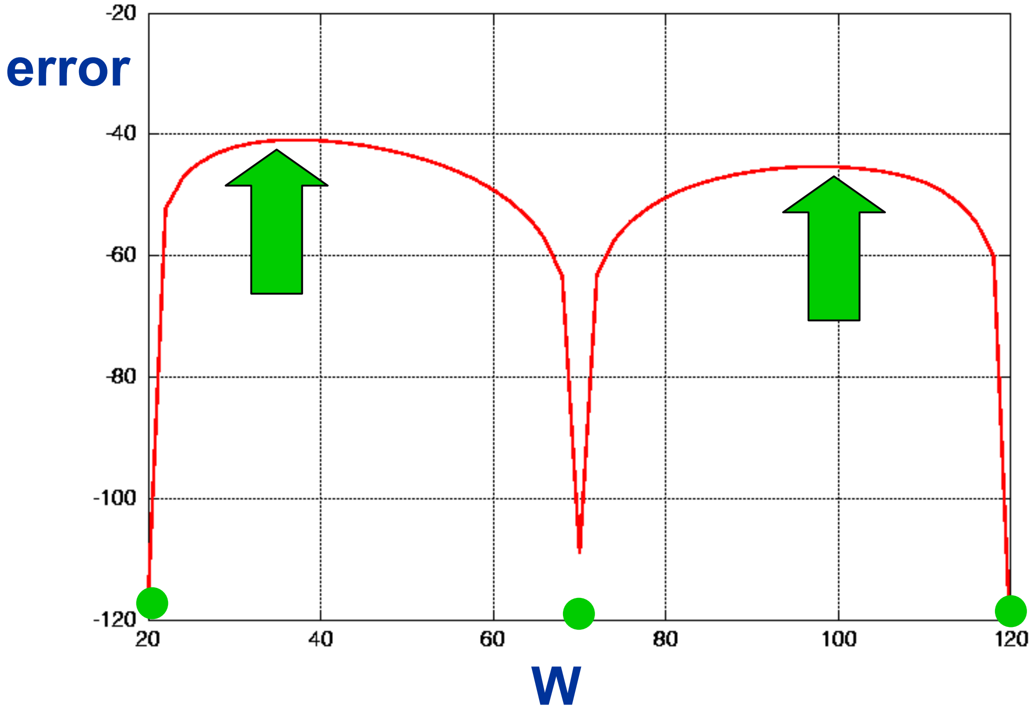


W: 20 µm ↔ 120 µm

f : 0 GHz ↔ 60 GHz

accuracy: -60dB

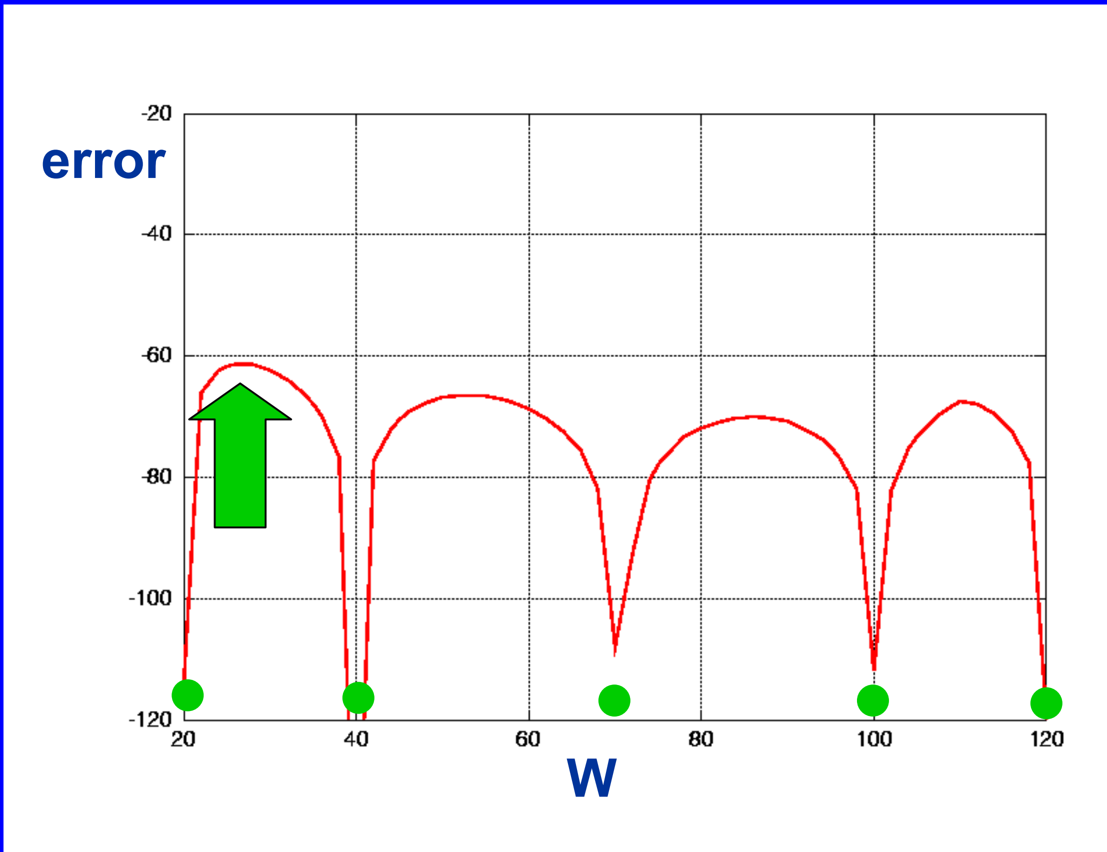
Example 1: Microstrip open stub on GaAs



$W_1 = 20\mu m$
$W_2 = 70\mu m$
$W_3 = 120\mu m$

$S(W,f) =$
$C_0(f) + C_1(f)\, W$
$+ C_2(f)\, W^2$

Example 1: Microstrip open stub - cont.



$W_1 = 20\mu m$

$W_2 = 70\mu m$

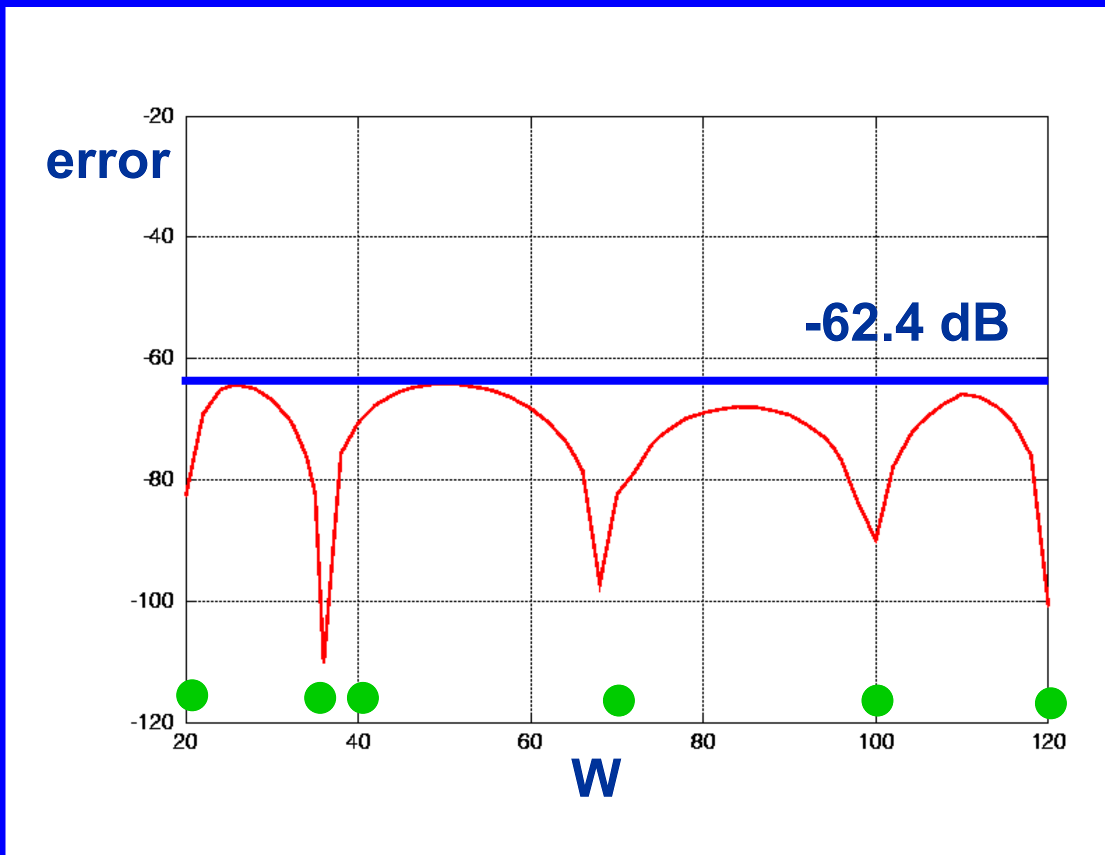
$W_3 = 120\mu m$

$W_4 = 40\mu m$

$W_5 = 100\mu m$

$$S(W,f) = C_0(f) + C_1(f)\,W + C_2(f)\,W^2 + C_3(f)W^3 + C_4(f)\,W^4$$

Example 1: Microstrip open stub - cont.



$W_1 = 20\mu m$

$W_2 = 70\mu m$

$W_3 = 120\mu m$

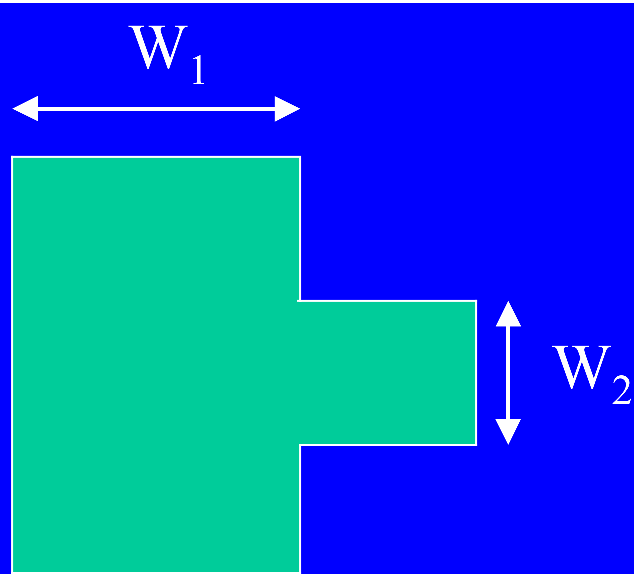
$W_4 = 40\mu m$

$W_5 = 100\mu m$

$W_6 = 32\mu m$

$$S(W,f) = C_0(f) + C_1(f)\,W + C_2(f)\,W^2 + C_3(f)W^3 + C_4(f)\,W^4$$

Example 2: T-junction

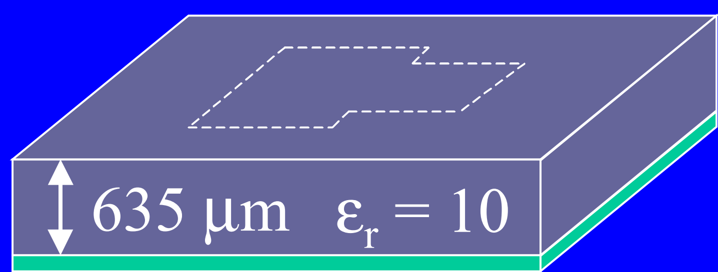


W_1: 100 µm ↔ 1000 µm

W_2: 300 µm ↔ 600 µm

f : 1 GHz ↔ 20 GHz

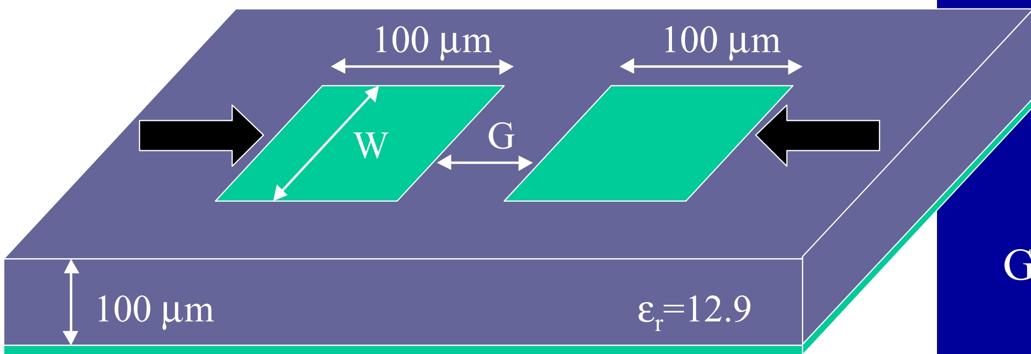
accuracy: -55 dB

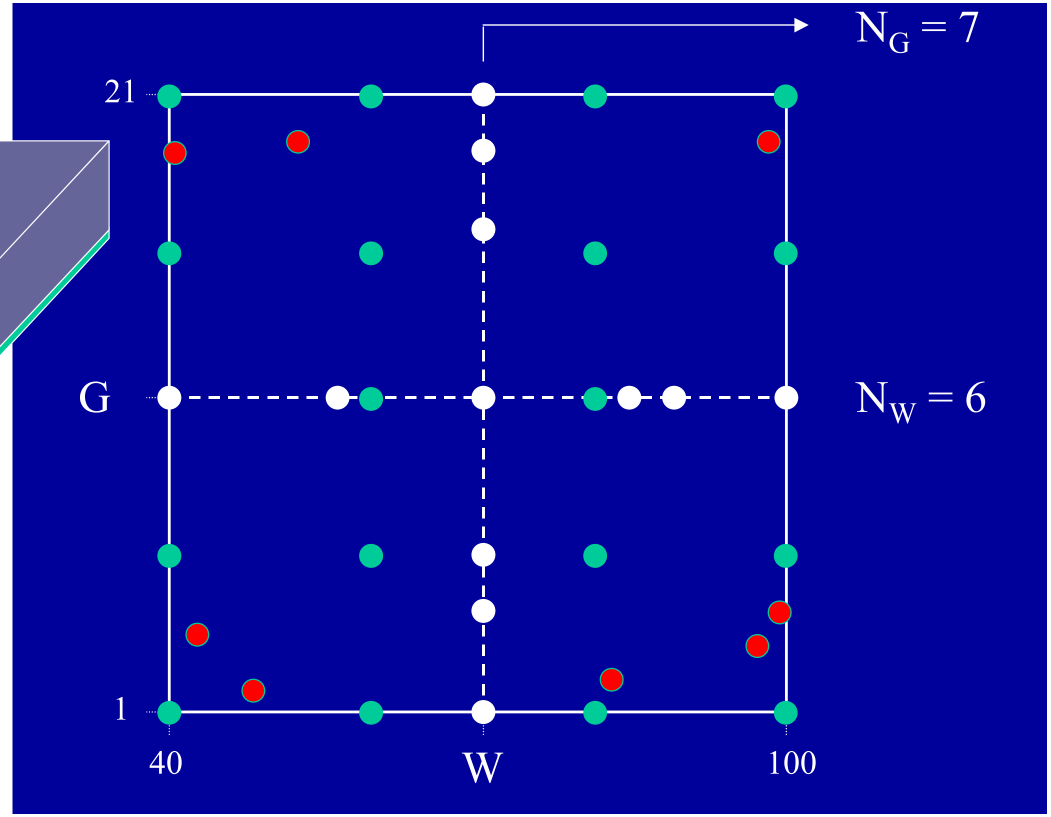


31 data points

accuracy = -55.3 dB

Example 3: gap coupling





W: 40 μm → 100 μm

G: 1 μm → 21 μm

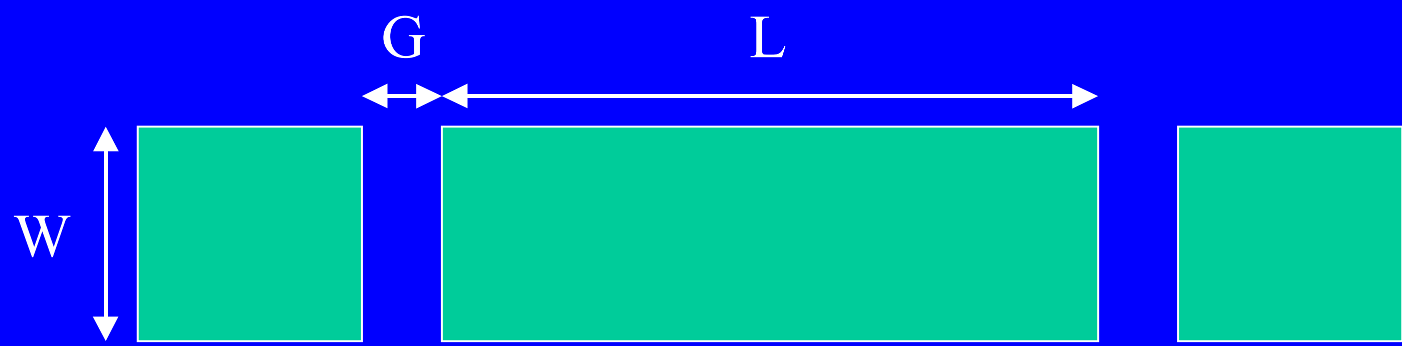
freq.: 0 → 60 GHz

accuracy: -60 dB

$$S(f,W,G) = \sum_{i=0}^{5}\sum_{j=0}^{3} C_{ij}(f)\, G^i\, W^j + C_{04}(f)\, W^4 + C_{14}(f)\, G\, W^4 + C_{60}(f)\, G^6$$

Example 4: Bandpass filter

Filter specifications (100µm GaAs substrate)

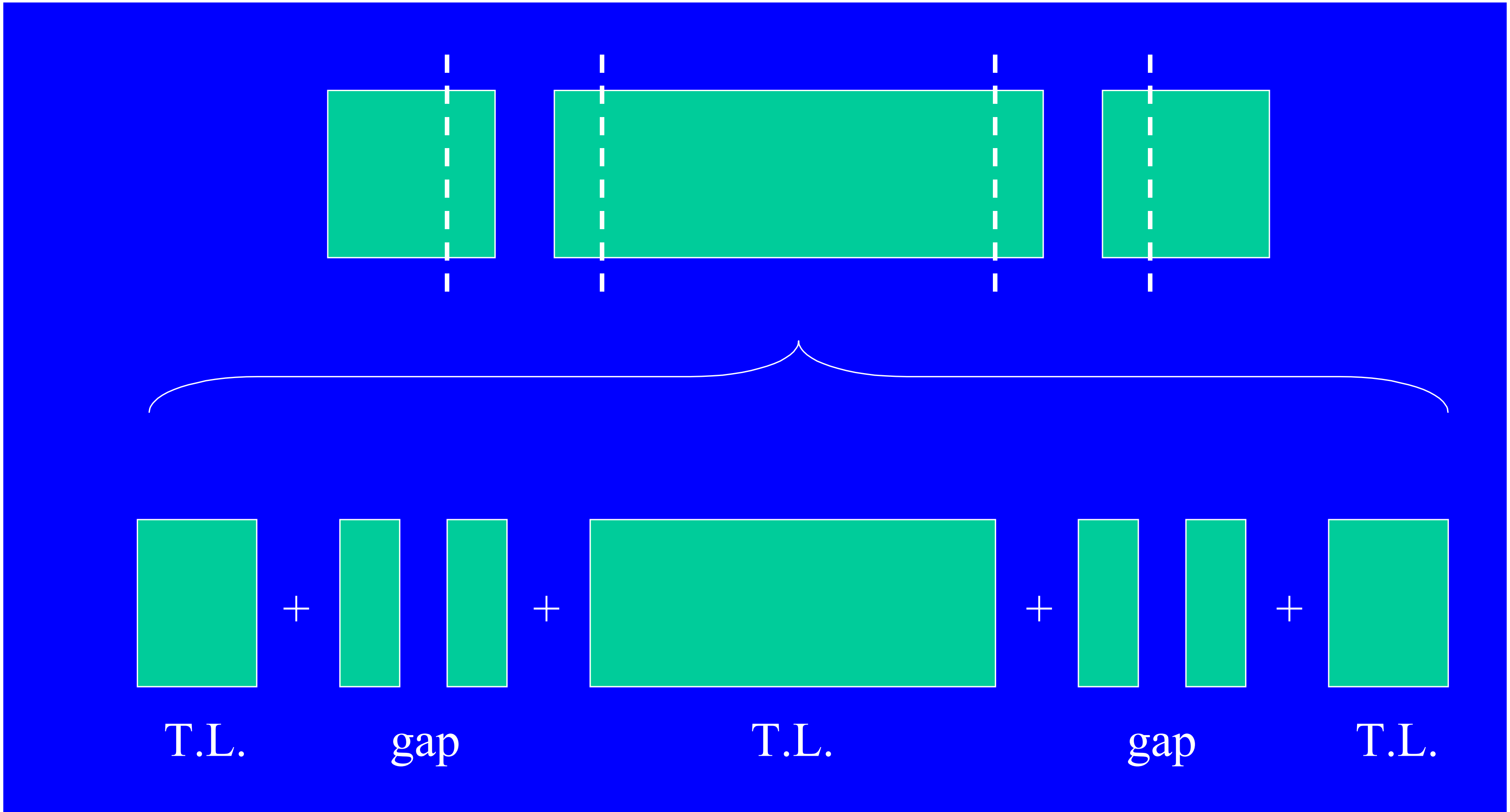


Choose W, G and L to obtain a resonance frequency at f = 48 GHz

$$\begin{cases} dB(S_{12}(f)) < -20 & \text{for} \quad 40.00 \le f \le 46.00 \text{ GHz} \\ dB(S_{12}(f)) > -1 & \text{for} \quad 47.95 \le f \le 48.05 \text{ GHz} \\ dB(S_{12}(f)) < -20 & \text{for} \quad 50.00 \le f \le 60.00 \text{ GHz} \end{cases}$$

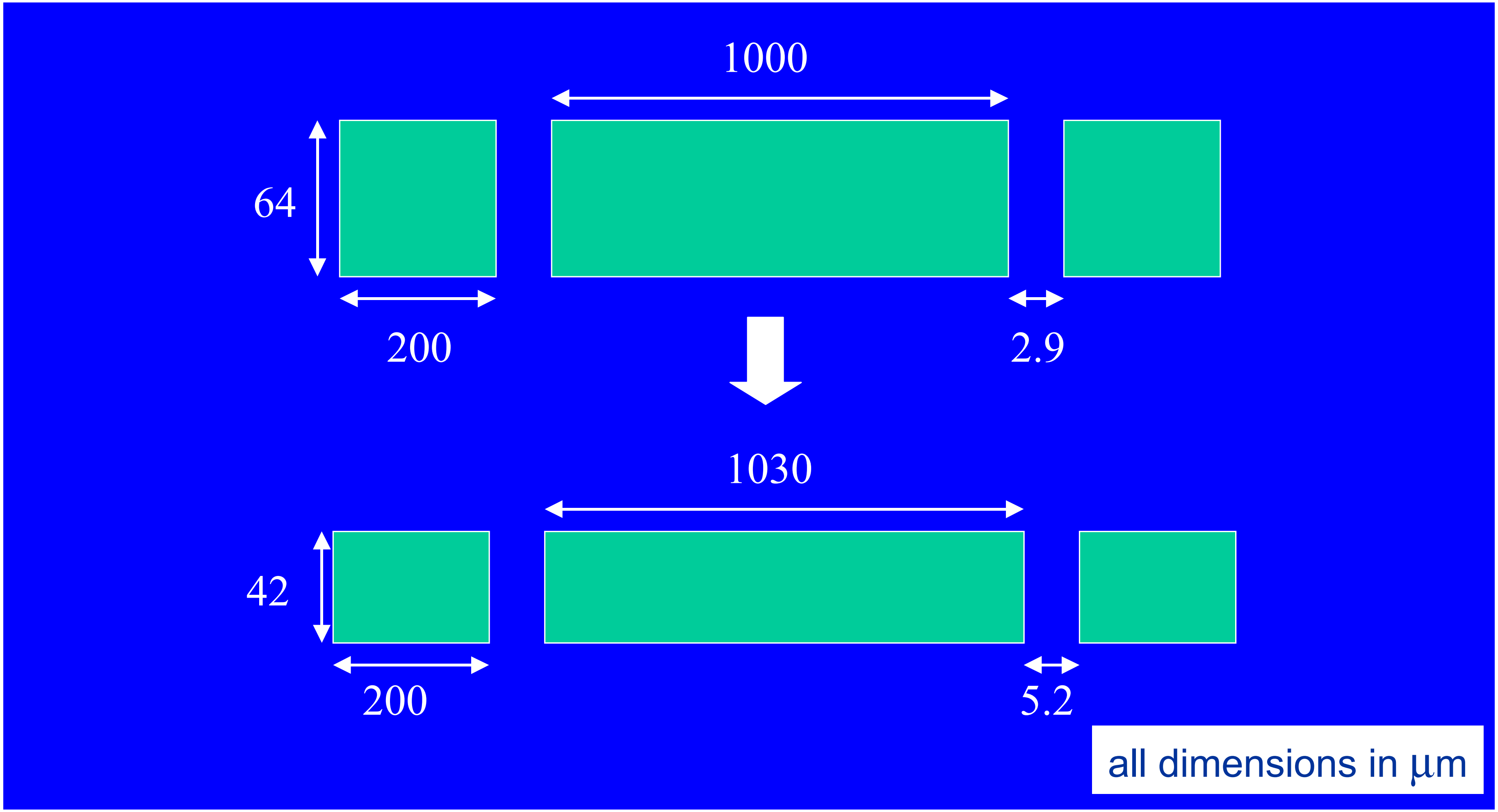
Example 4: Bandpass filter - cont.

Filter partitioning



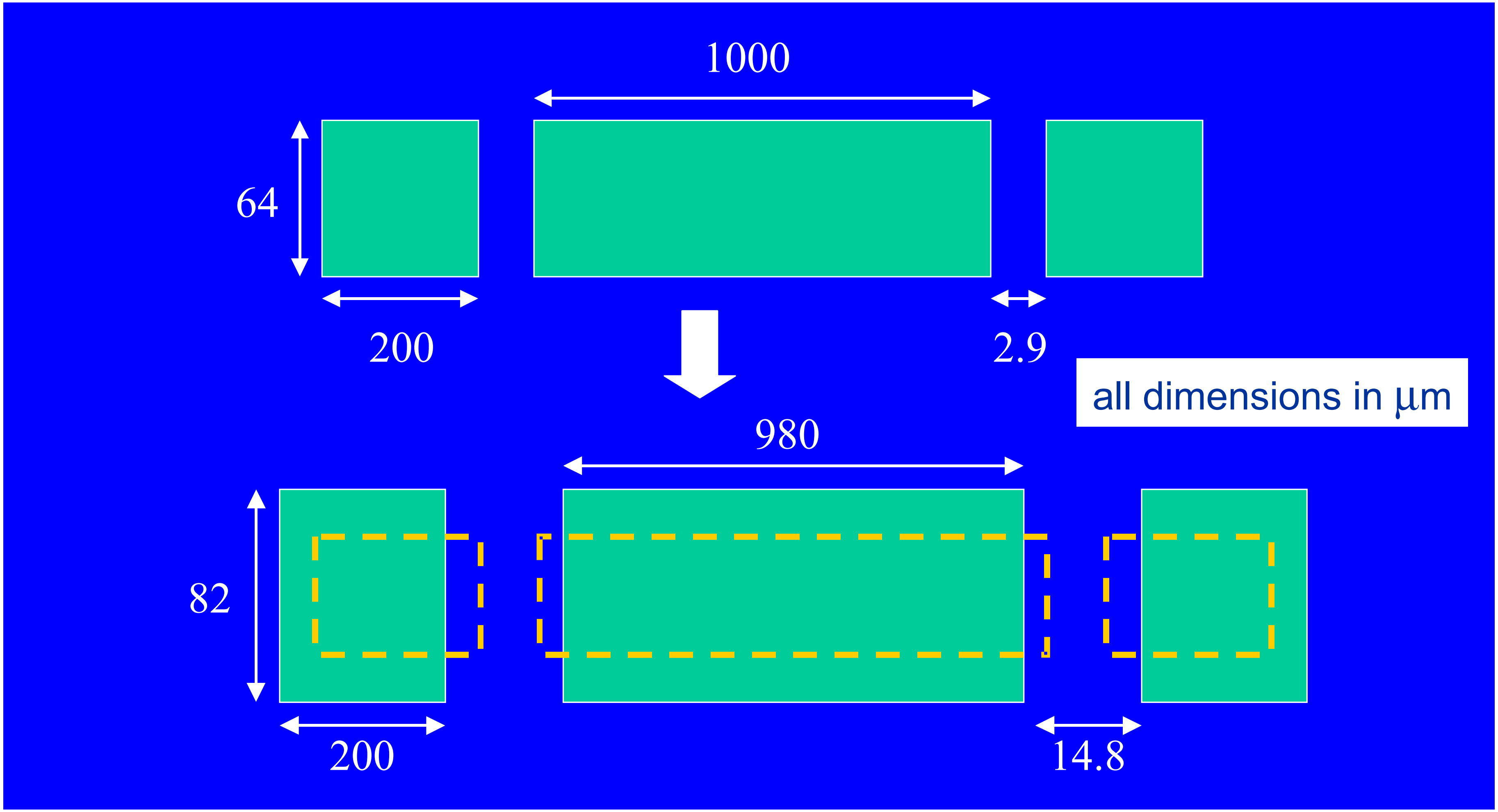
Example 4: Bandpass filter - cont.

Filter optimization using circuit models



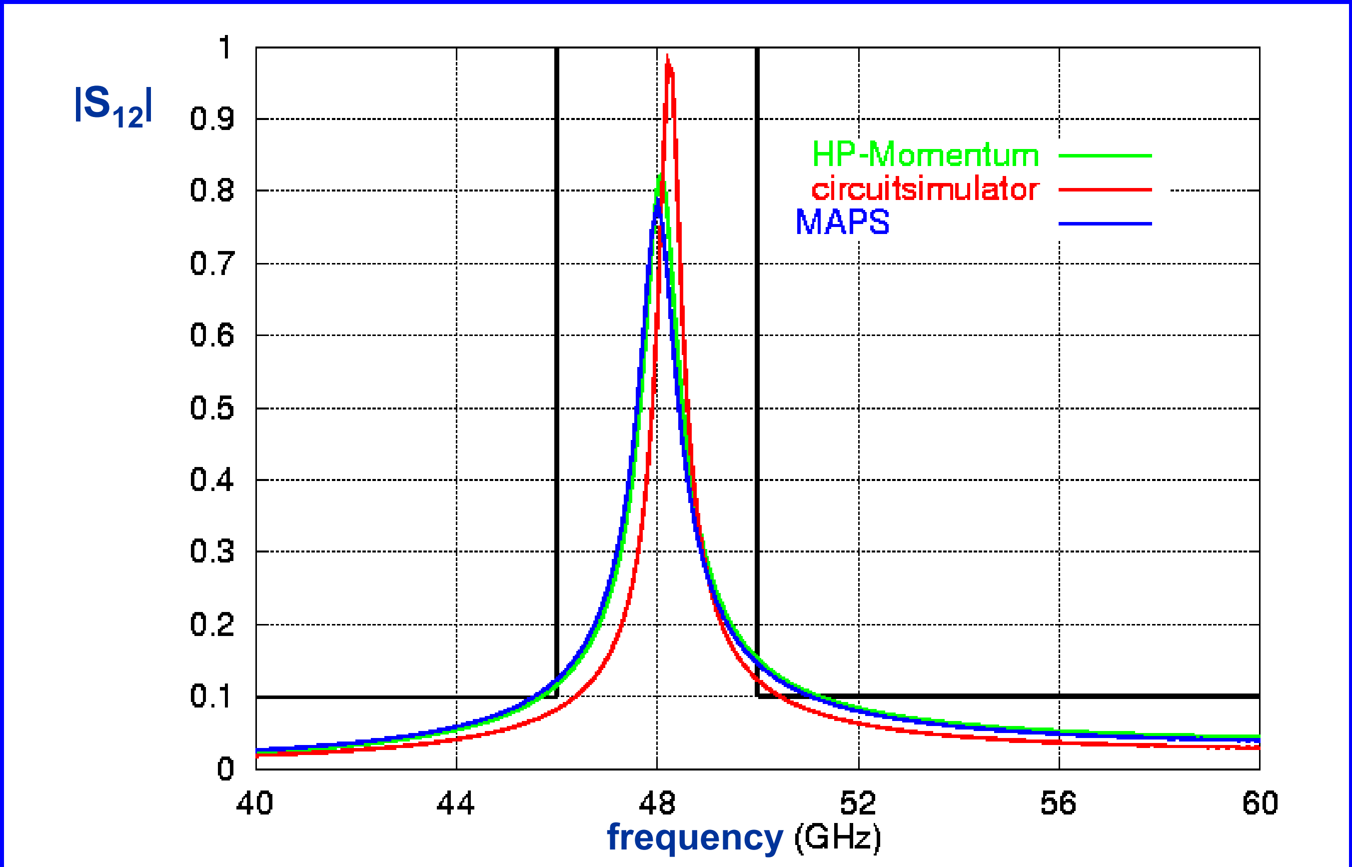
Example 4: Bandpass filter - cont.

Filter optimization using MAPS models



Example 4: Bandpass filter - cont.

Filter optimization - simulation results



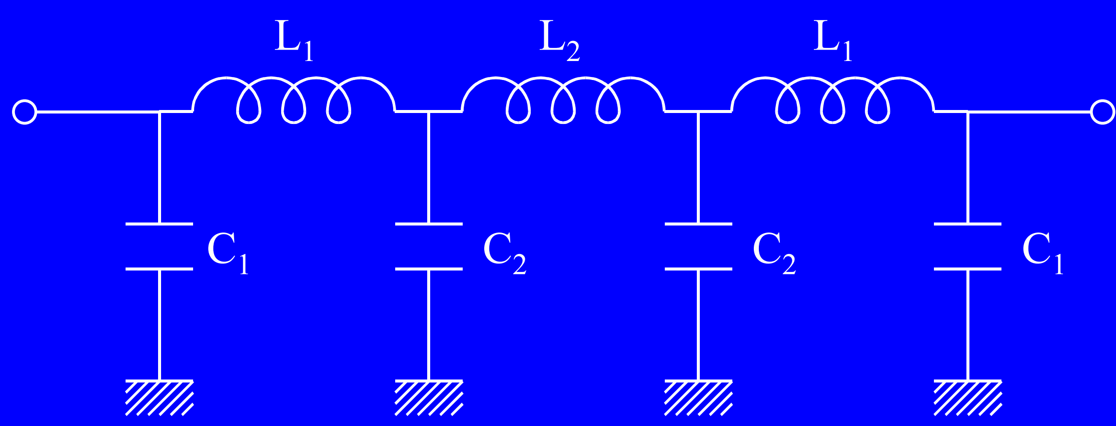
Example 5: Chebyshev filter design

Specifications

- lowpass filter
- passband:
  - between 0 and 3.2 GHz
  - maximum of 1 dB attenuation
- stopband:
  - from 3.9 GHz up to 7 GHz
  - minimum attenuation must be 25 dB
- to be realized in a microstrip version
  - microstrip height: 59 mil
  - relative dielectric permittivity: 4.3

Example 5: Chebyshev filter design - cont.

Initial circuit design



$C_1 = 1.7227$ pF

$C_2 = 2.6141$ pF

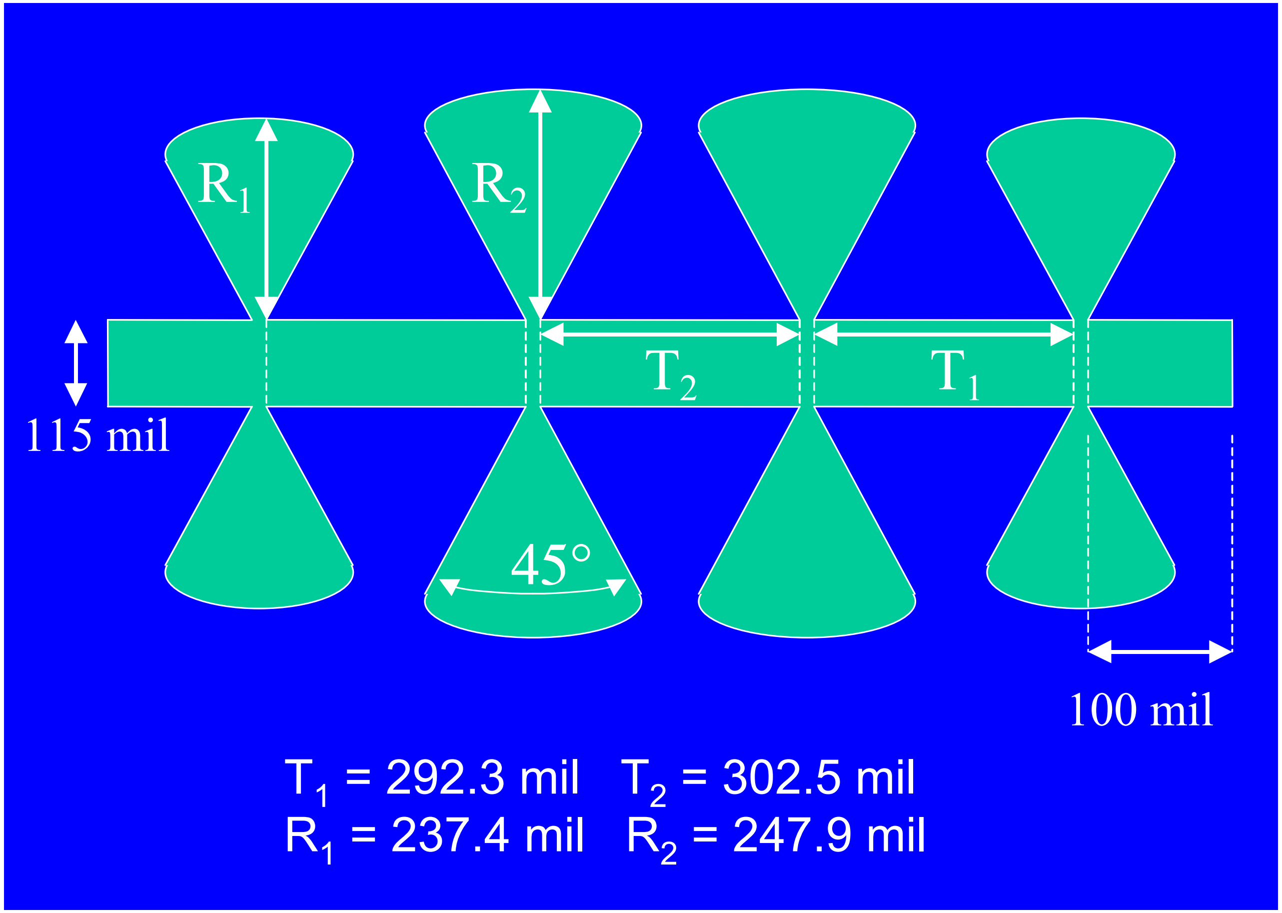
$L_1 = 3.1965$ nH

$L_2 = 3.4136$ nH

- 7th-order Chebyshev
- passband:
  - between 0 and 3.2 GHz
  - ripple of 0.5 dB
- stopband:
  - minimum attenuation slightly less than 25 dB
- more compact than 9th-order alternative

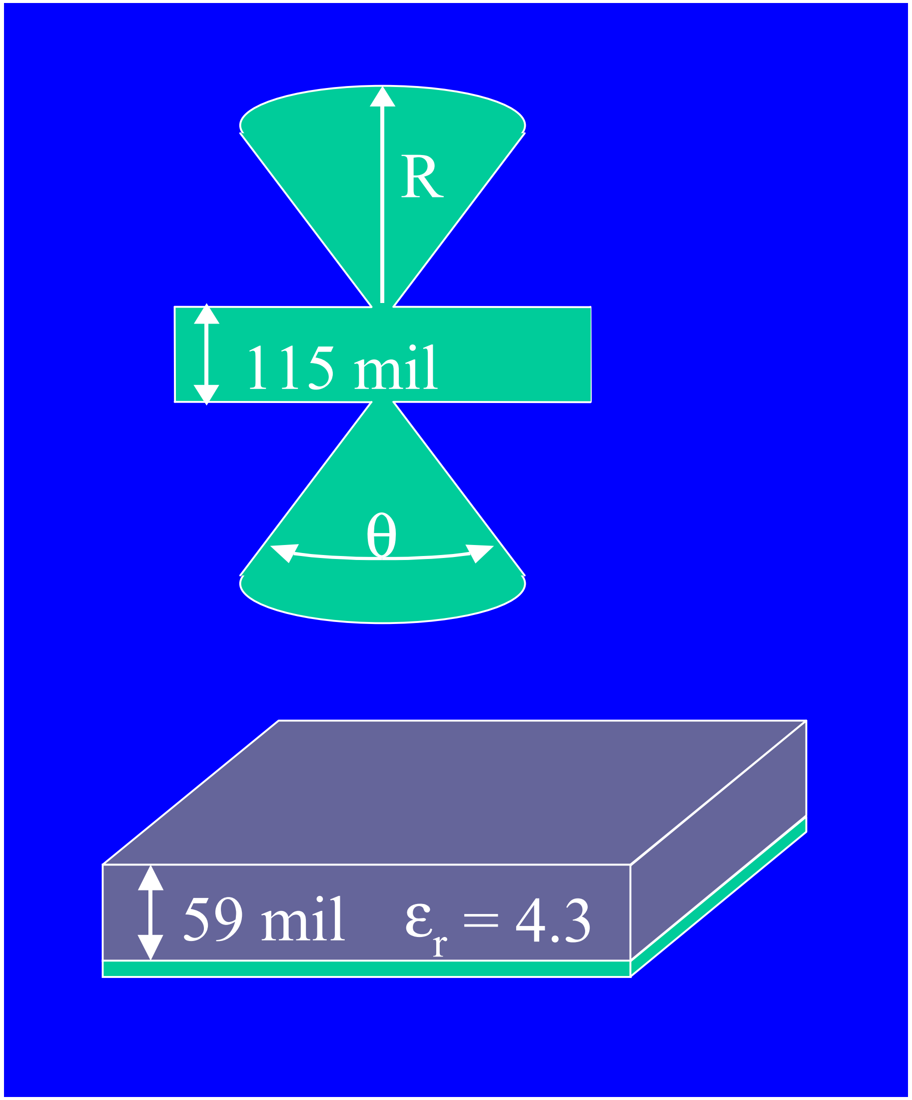
Example 5: Chebyshev filter design - cont.

Initial layout



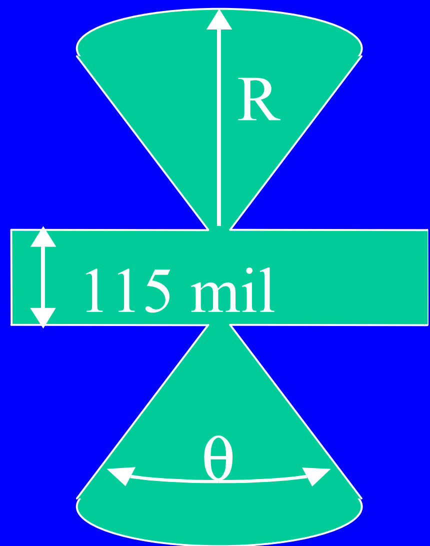
- realization of lumped model at 3.2 GHz
- inductors:
  - 50Ω transmission lines
  - line width: 115 mil
- capacitors:
  - butterfly capacitors
  - opening angle 45º
- 100 mil port lines

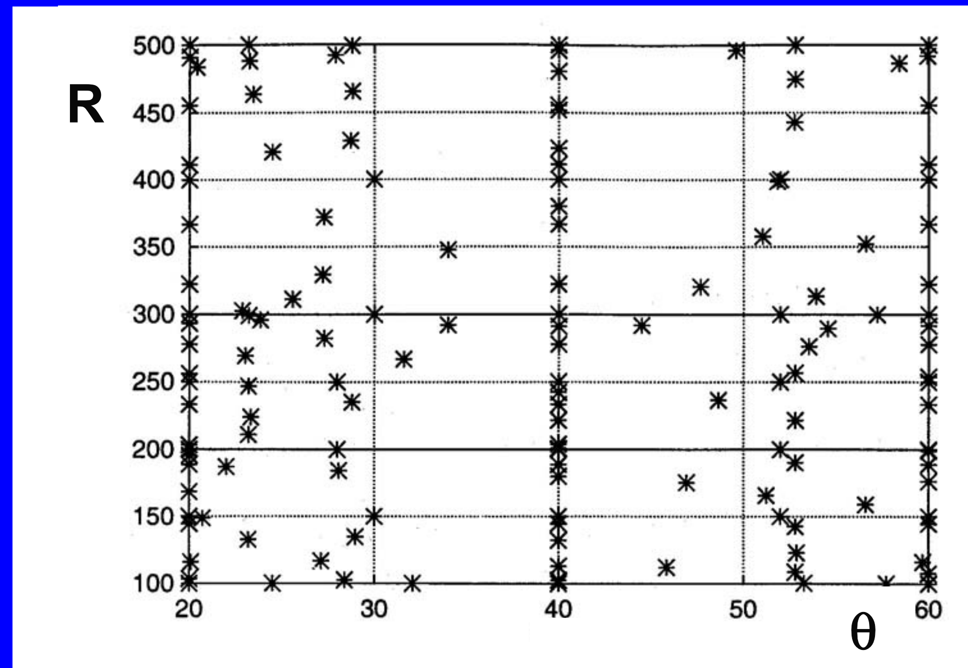
MAPS model for the butterfly capacitor

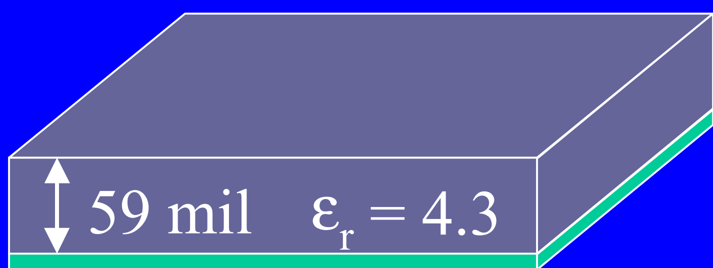


- $S_{11} = S_{22}$ and $S_{12} = S_{21}$
- layout parameters:
  - opening angle θ : $20° < \theta < 60°$
  - stub radius R: 100mil < R < 500mil
- frequency range: from 0.5 to 7 GHz
- prescribed accuracy: -45 dB

MAPS model for the butterfly capacitor - cont.



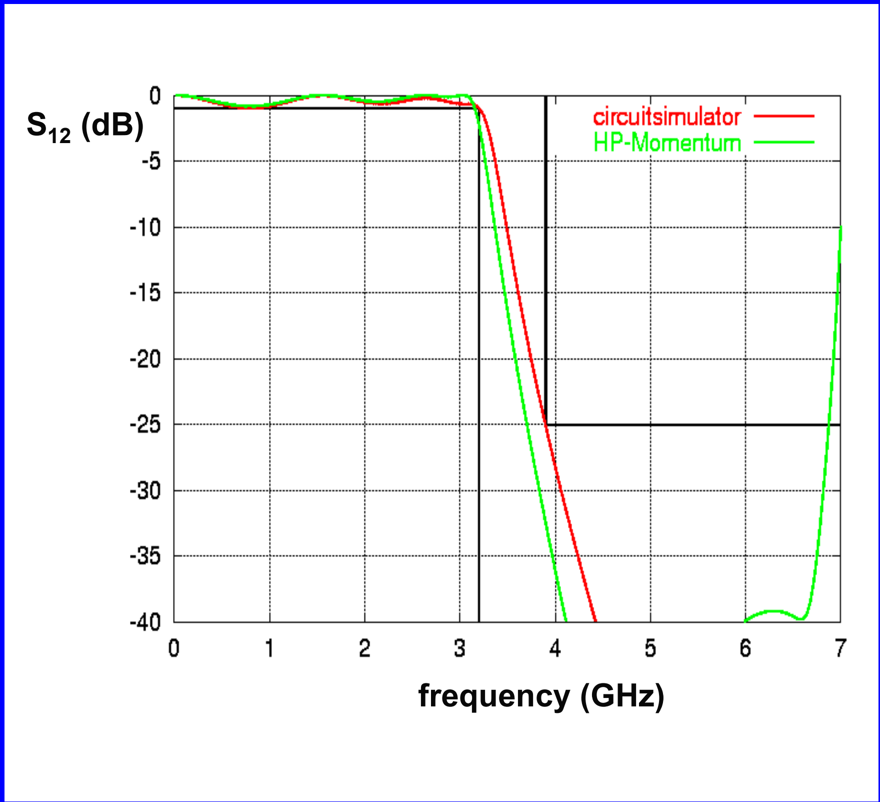


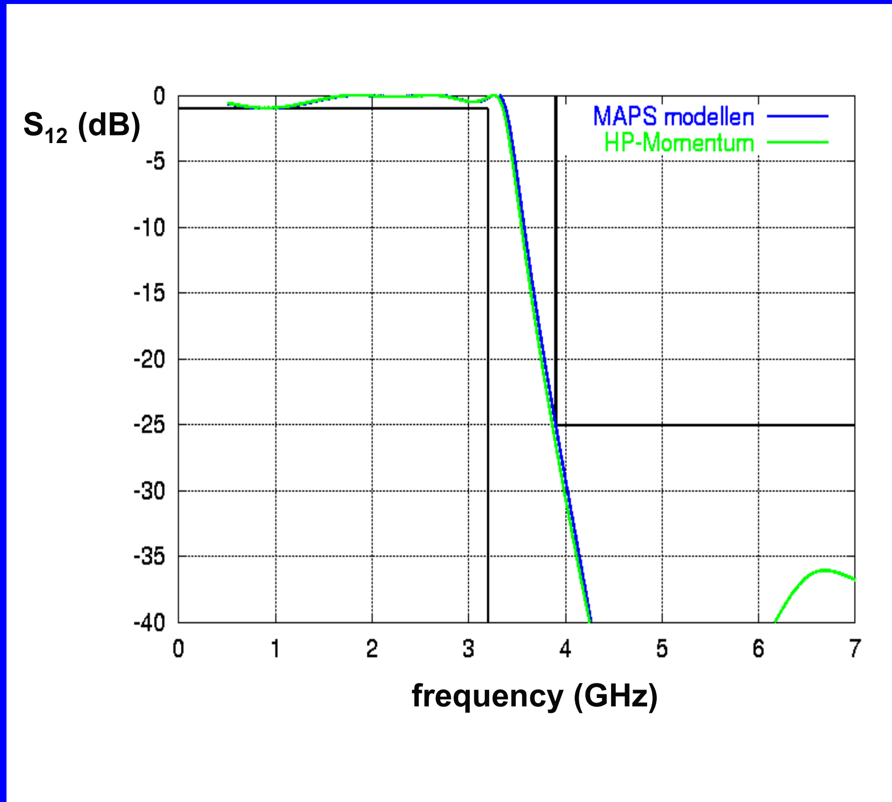


- 144 data points needed
- validated in 416 random points in 25 discrete frequencies
- - 45dB in 99.1% of the test points

Example 5: Chebyshev filter design - cont.

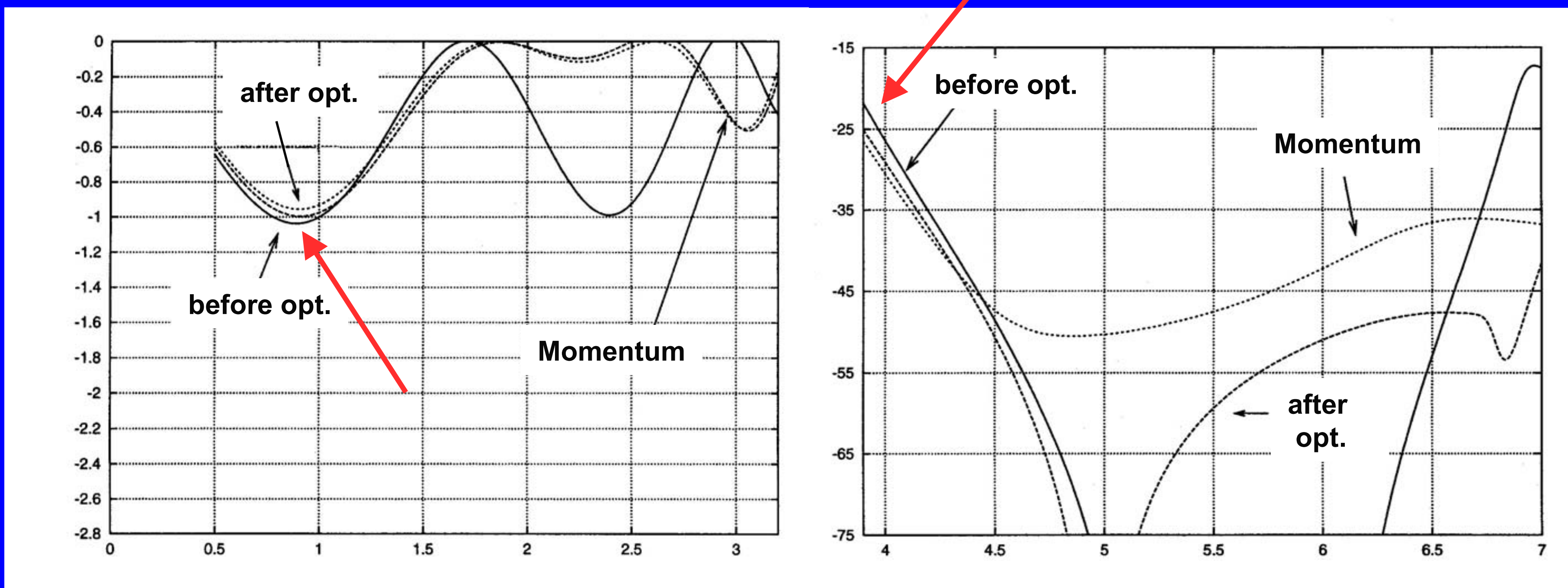
Simulation results





Example 5: Chebyshev filter design - cont.

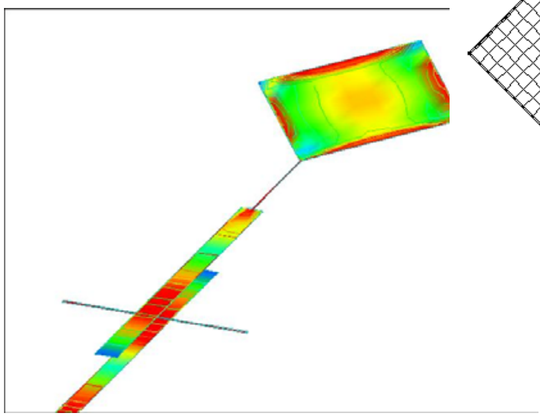
Simulation results - cont.

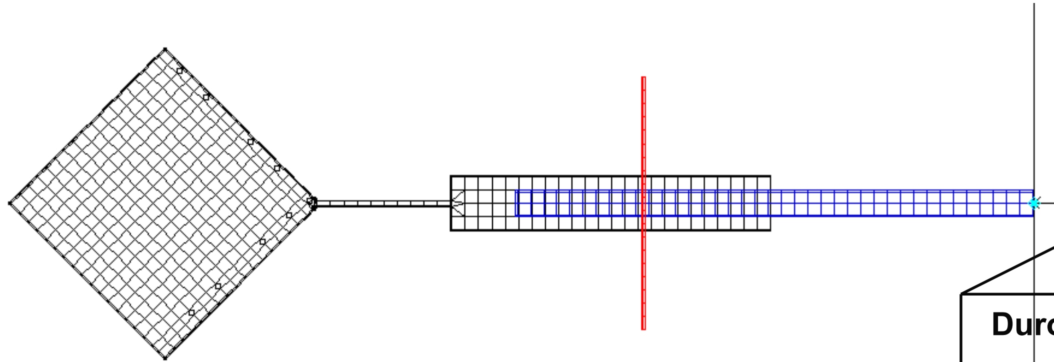


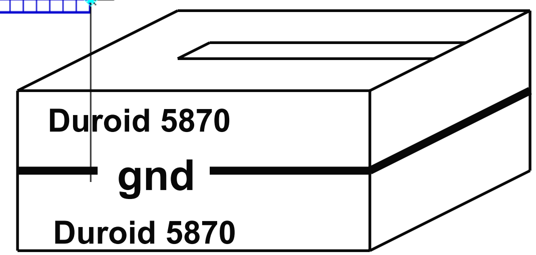
	start	optimum				start	optimum	
T_1	292.3	355.4	mil		R_1	237.4	216.1	mil
T_2	302.5	271.7	mil		R_2	247.9	283.3	mil

$\theta = 45°$

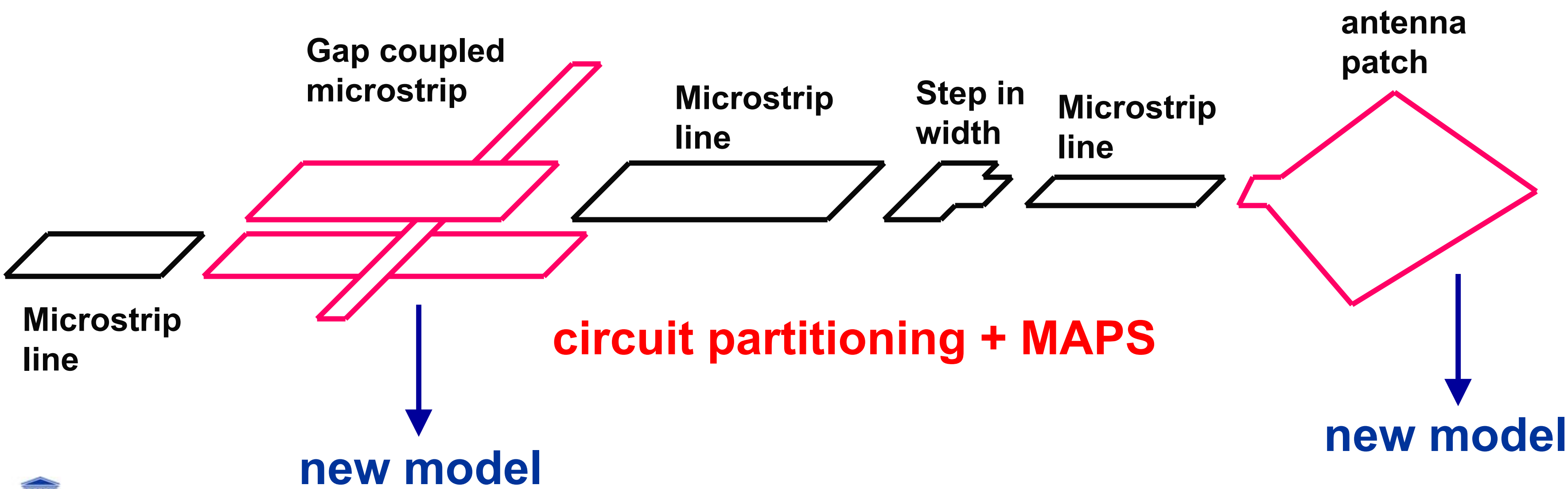
Example 6: microstrip-fed patch antenna @ 10GHz



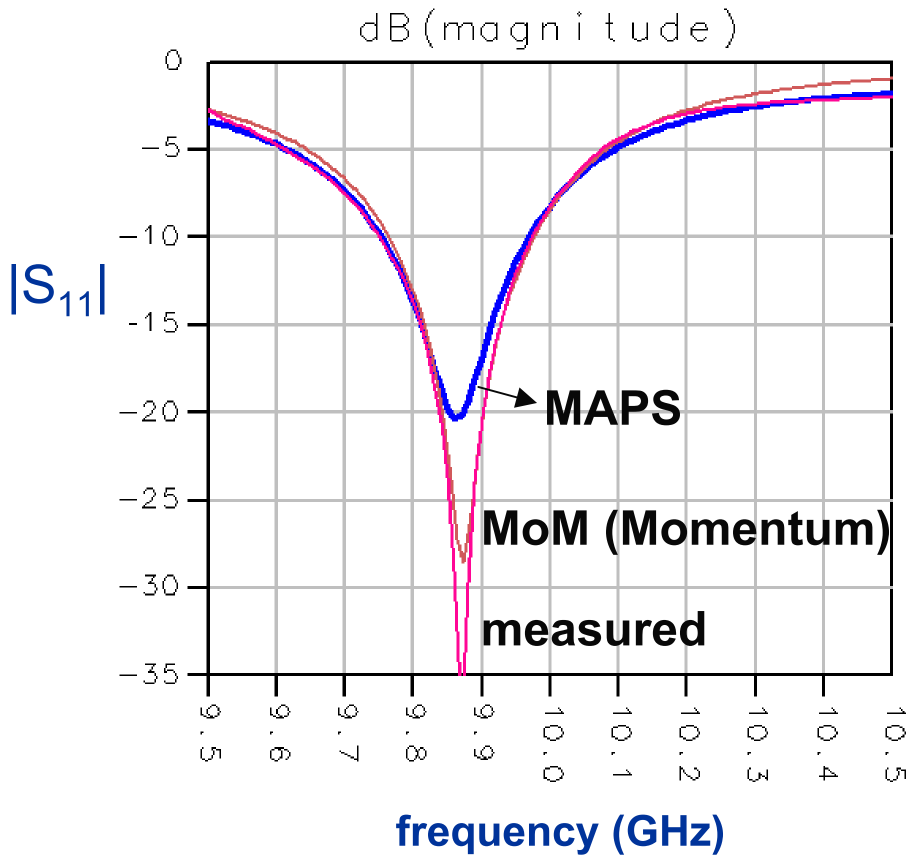


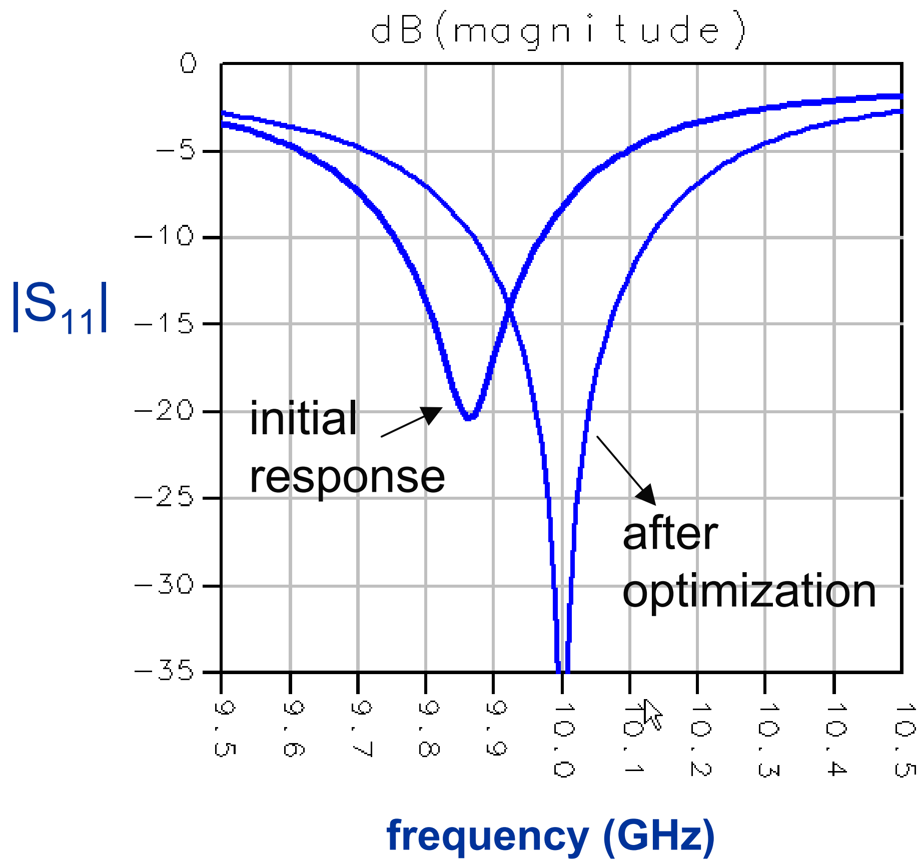


2 layer substrate



Microstrip-fed patch antenna @ 10GHz - cont.



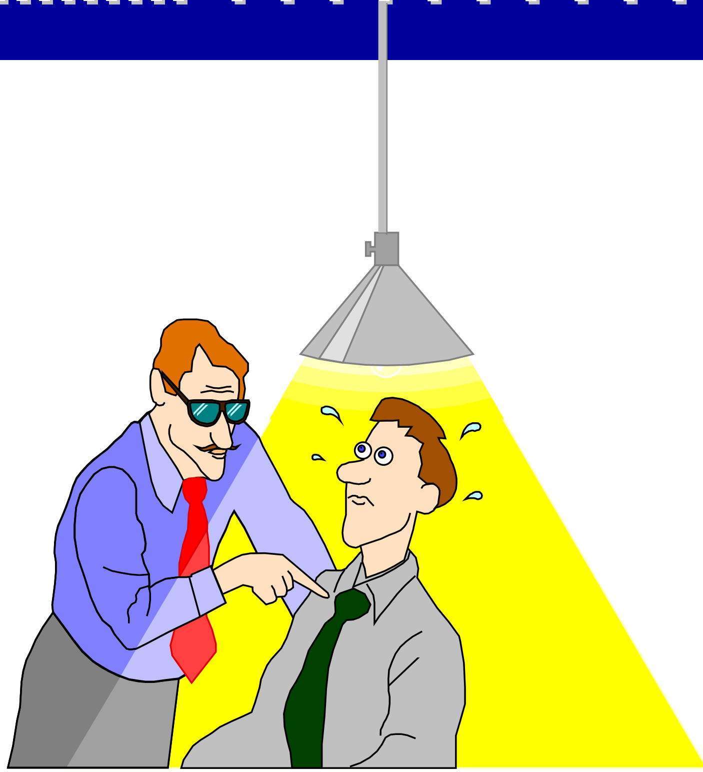


- some couplings are neglected
- differences between model parameters and actual material and geometry data

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

Conclusions

- **indirect optimization using an intermediate electromagnetic database for S-parameter data offers a very powerful solution to the EM-circuit co-optimization challenge**
- **we have demonstrated that this database can either be constructed during the optimization process (on-the-fly) or upfront (MAPS) and with a minimal cost in EM-simulations**
- **to complete the picture, it must be emphasized that direct EM optimization is also available to the user**



Questions?

More information ....

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INTEC

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