Coupled Resonator Filter Realization by 3D-EM Analysis and Space Mapping

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Abstract

The realization of narrowband coupled resonator filter structures involves relatively complex resonator topologies to be designed in such a way that a given coupling matrix [1] is realized by physical couplings, such as apertures between resonators. 3D EM analysis of filter structures and manual response optimization is elaborate, time consuming and demands accurate resonator tuning. Coarse mesh model (fast model) 3D EM simulation [S]-matrix data - while limited in its absolute accuracy - contains valid information on the couplings between resonators. Minor resonator tuning offsets have no bearing on the coupling matrix of a given structure. A space mapping technique [2] linking a subset of the physical model parameter space to the coupling matrix of an equivalent LC network is used in a fast-converging iterative process for properly adjusting the physical parameters.

Purpose

- To minimize the number of EM analysis cycles during physical filter design
- To exploit coarse mesh 3D EM analysis data (fast model)
- To ensure rapid convergence of an iterative design process

Outline

- Description of design problem
- Circuit model and coarse mesh 3D EM model
- Application of space mapping technique
- Example
- Outlook

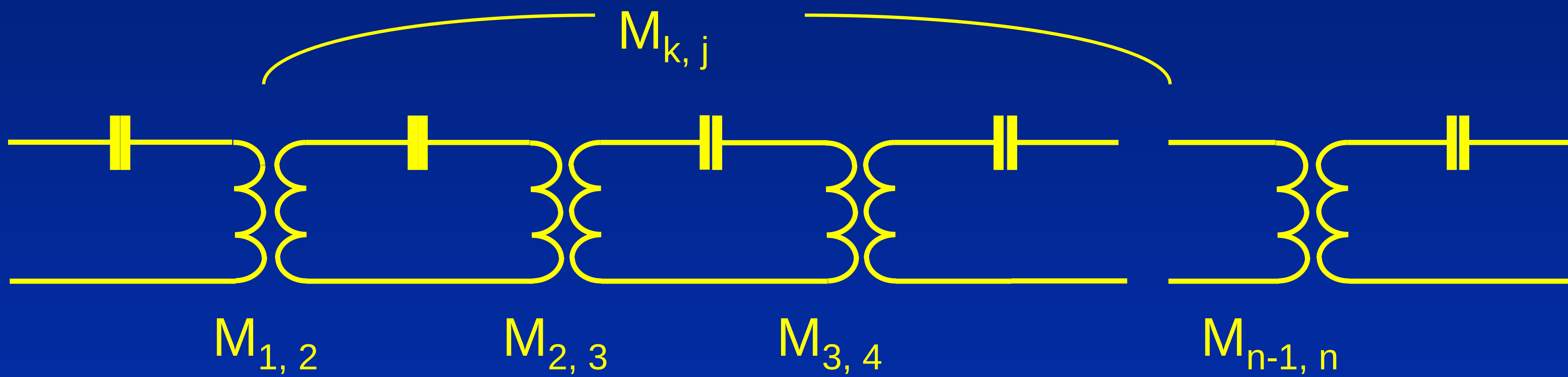
Design Problem

- A given physical coupled resonator bandpass filter structure has to correspond to a particular equivalent LC - network coupling matrix
- The physical dimensions of apertures between resonators need to be determined

Design Problem Scenario

- Coupling aperture dimensions for a chosen physical filter structure cannot be calculated directly
- Strong interaction between physical couplings can exist
- Natural frequencies of the structure are sensitive to 3D mesh resolution
- Fine mesh 3D EM analysis is time consuming

Circuit Model of Coupled Resonator Bandpass Filter



Coupling matrix

$$[M]_n = \begin{bmatrix} 0 & M_{12} & 0 & M_{14} & 0 \\ M_{12} & 0 & M_{23} & 0 & \ldots \\ 0 & M_{23} & 0 & \ldots & 0 \\ M_{14} & 0 & \ldots & 0 & M_{n-1,n} \\ 0 & \ldots & 0 & M_{n-1,n} & 0 \end{bmatrix}$$

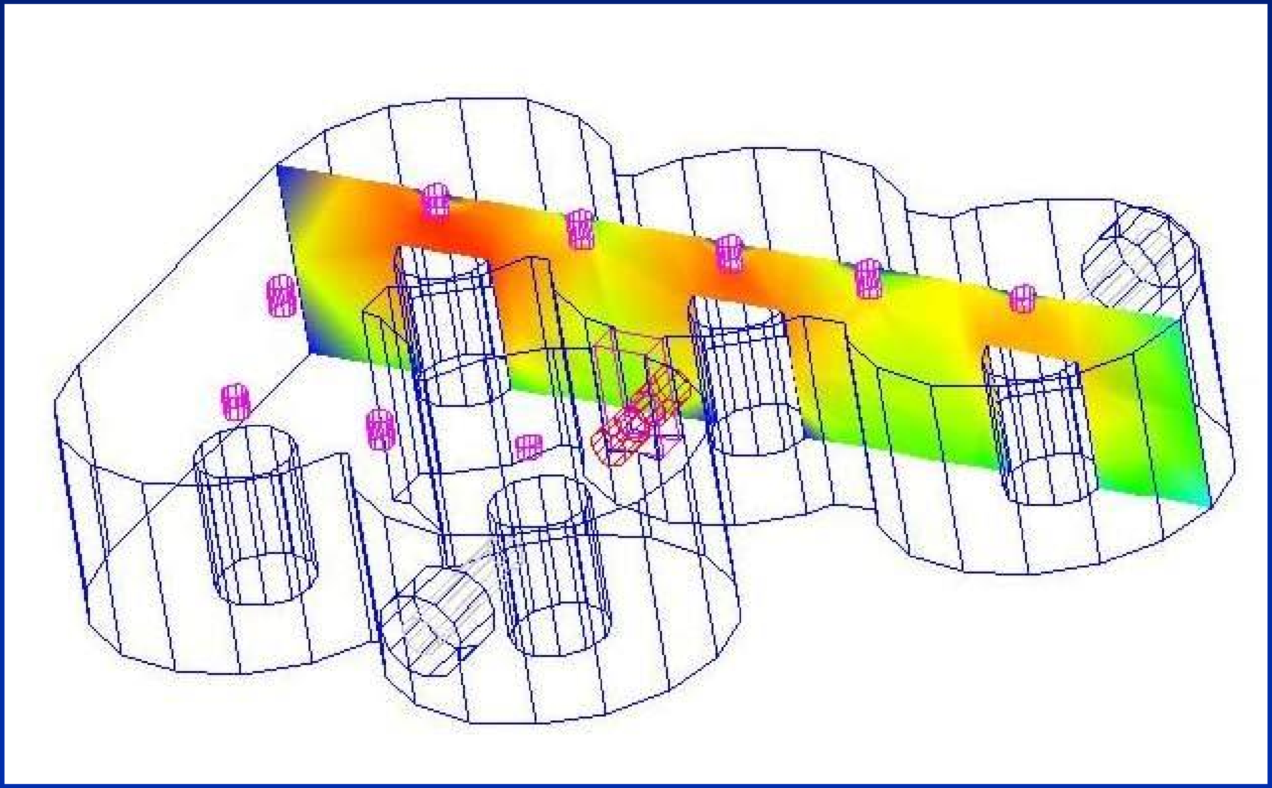
$$[k] = \frac{[M]}{L_{Loop}}$$

Loop Current Analysis of LC Circuit Model

$$[I(f)] = [Z(f)]^{-1} * [V]$$

$$[Z(f)] = j * [[M] + [X] + [I] * \lambda(f)] + [R]$$

3D EM Model (HFSS)



3D EM Model (HFSS)

- minimum number of geometry faces
- coarse line approximation of circular shapes
- avoid structure details in areas of low field variation
- fast frequency sweep (rational function fitting) can be used

Application of Space Mapping

- Nominal coupling matrix of equivalent LC - network is known (synthesis)
- Space mapping relates 3D EM model dimension data subset to coupling matrix
- Coupling matrix of 3D EM model is adjusted iteratively by modification of dimension data subset

Variable Subsets

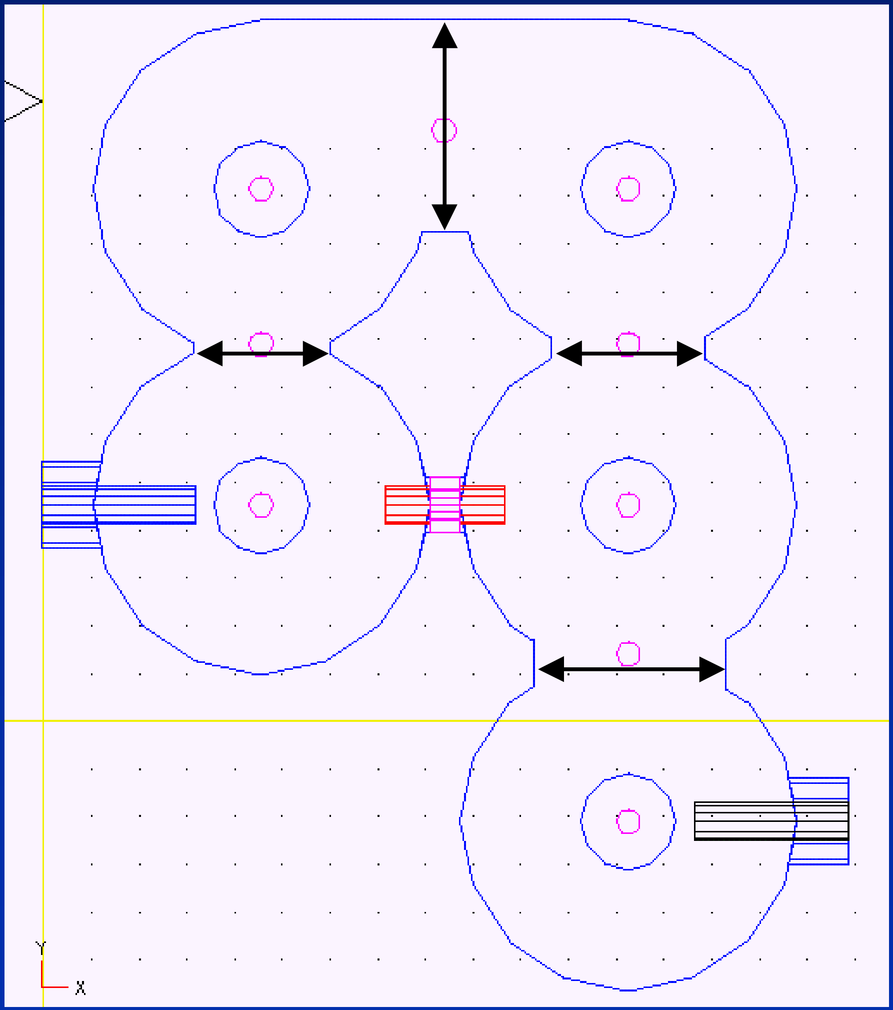
3D EM model variable subset

$$x_{CMM} = [w_{12}, w_{23}, \ldots . w_{k,\ k+1}, w_{k,\ k+j}, \ldots .\ w_{n-1,\ n}]^T$$

Circuit network model variable subset

$$x_{CNM} = [M_{12}, M_{23}, \ldots . M_{k,\ k+1}, M_{k,\ k+j}, \ldots .\ M_{n-1,\ n}]^T$$

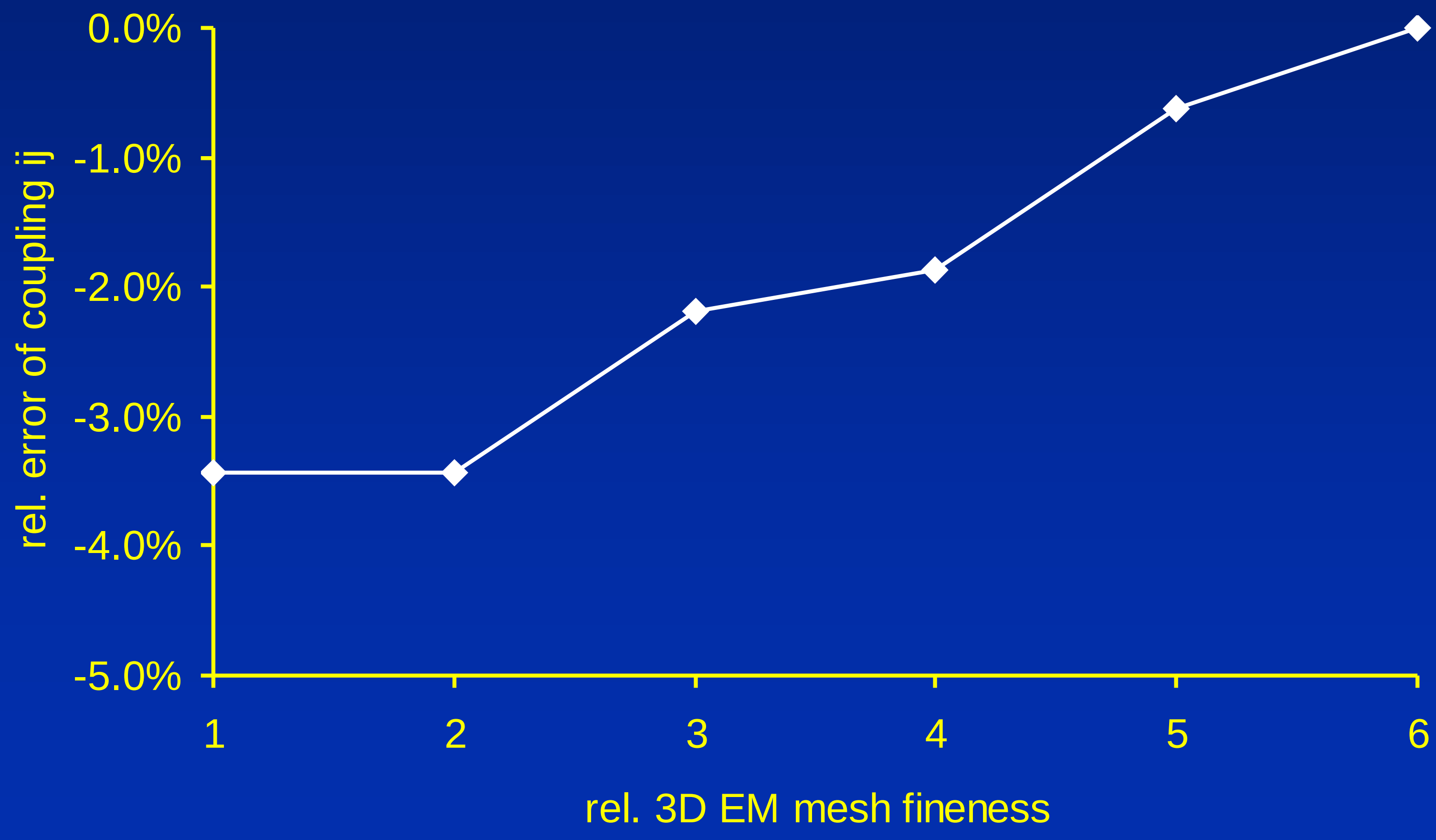
Example of 3D EM Model Parameter Subset



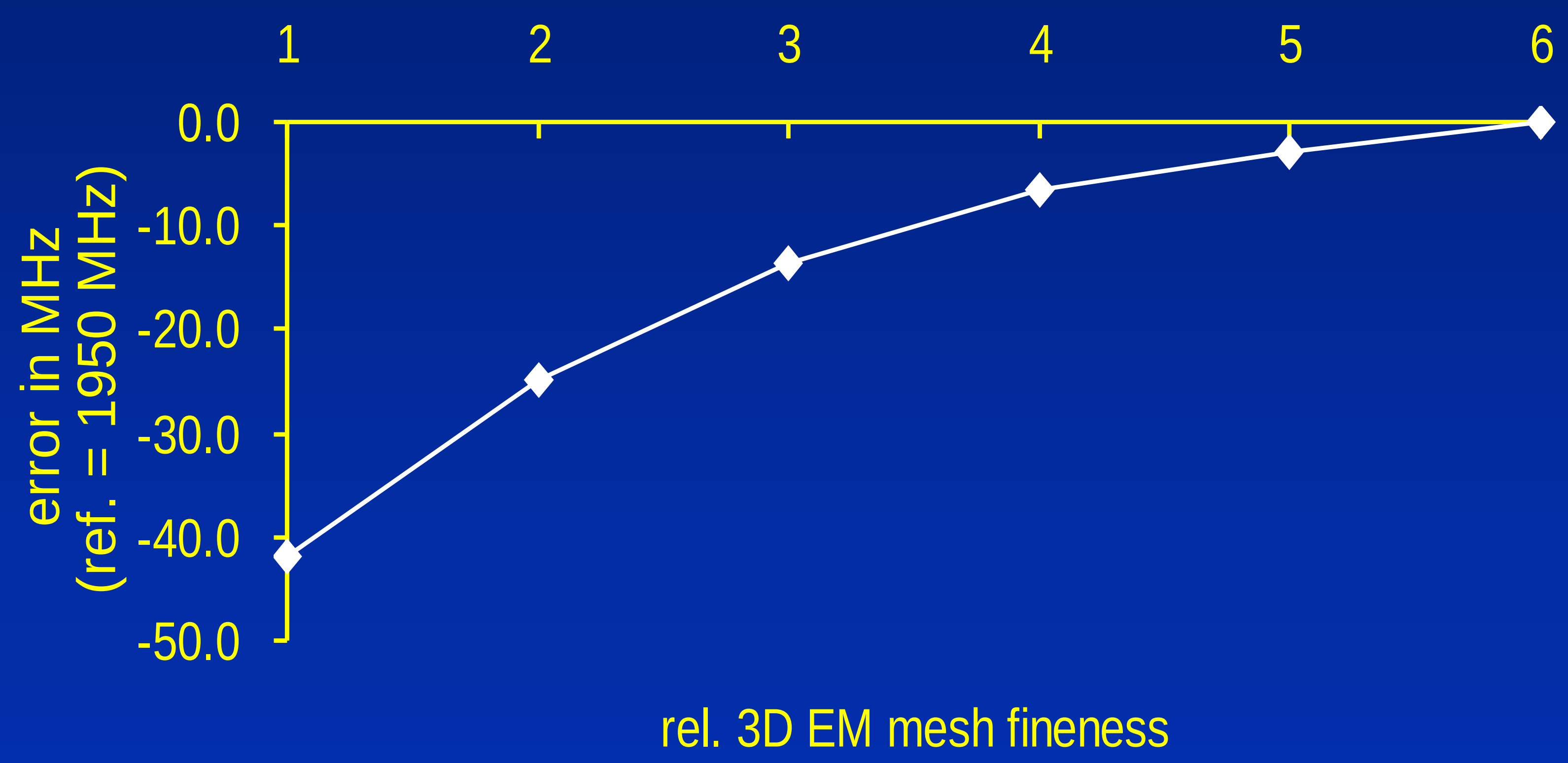
Exploiting the Coarse Mesh Model

- Coarse mesh 3D EM analysis is sufficiently accurate with respect to the couplings between resonators
- A very coarse mesh can be used for the initial iterations
- The coarse mesh simulation response is offset in frequency

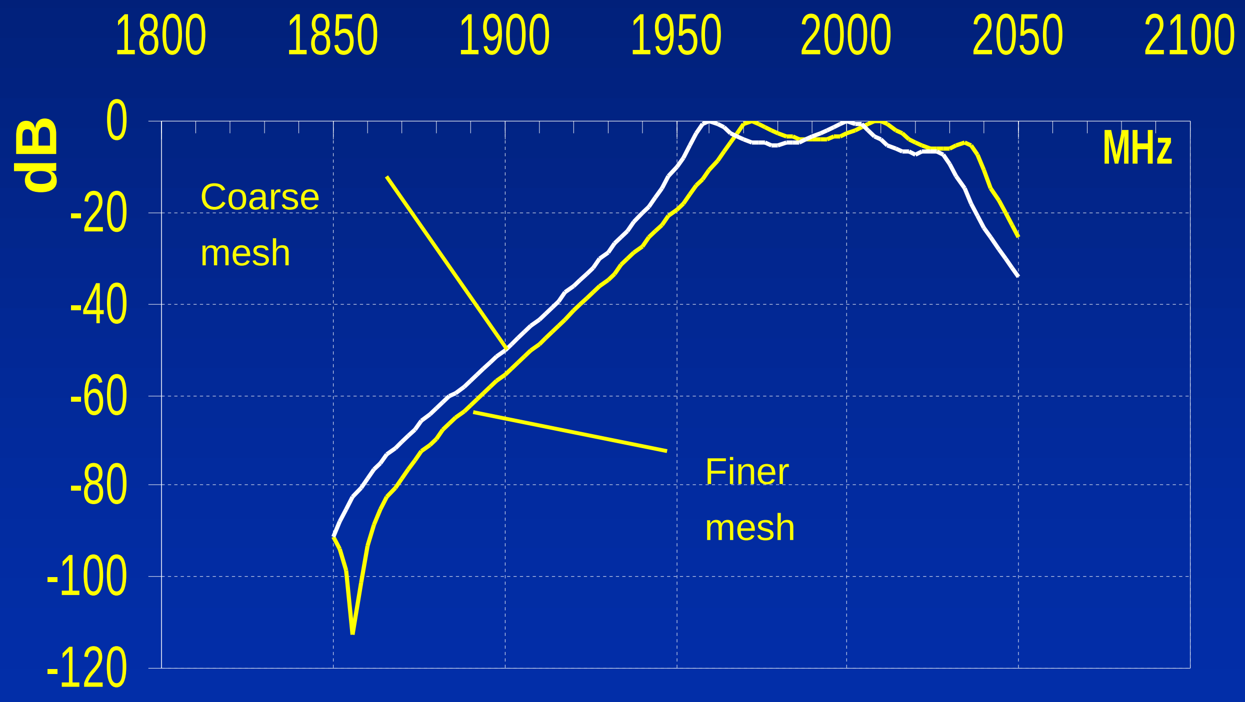
Coupling error and 3D EM mesh fineness



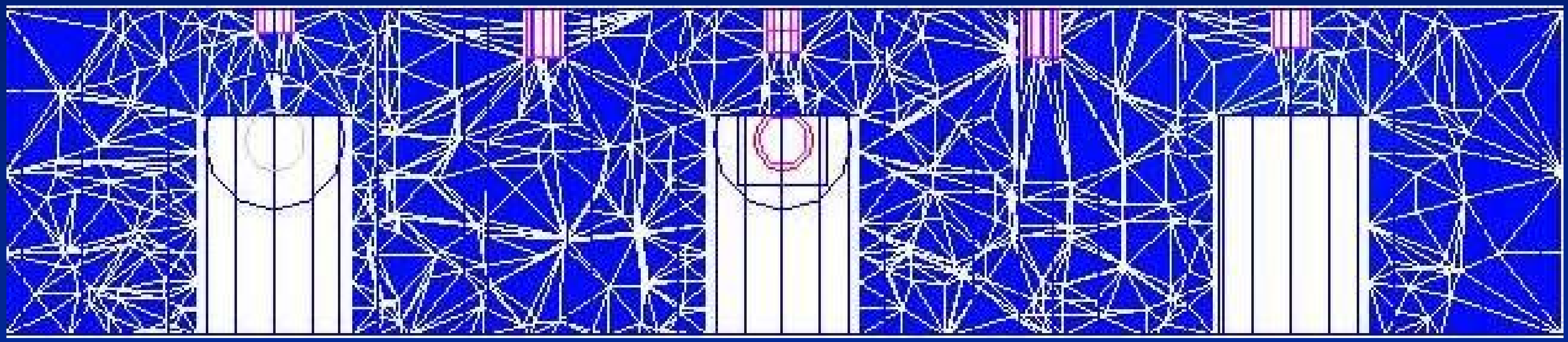
Extracted natural resonance of i-th resonator vs mesh fineness

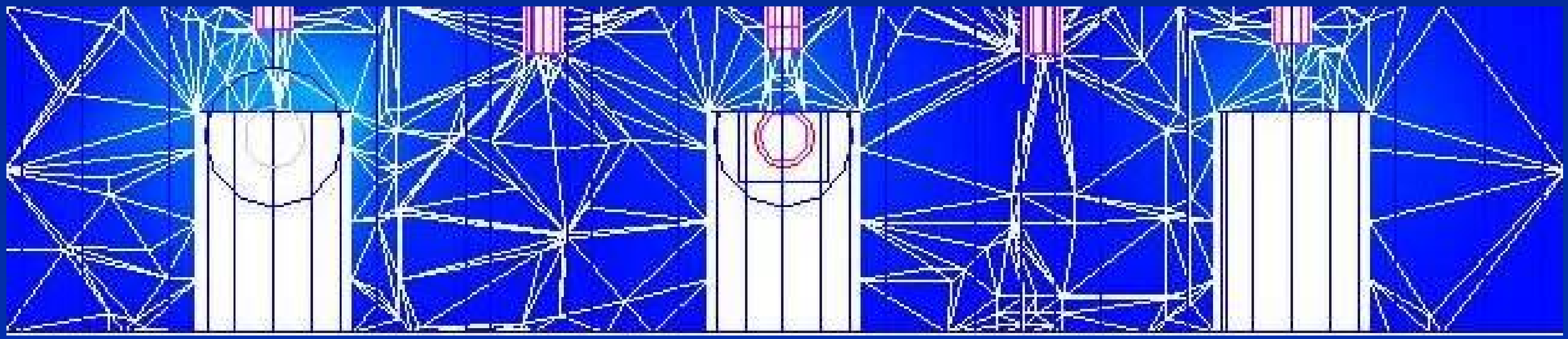


Frequency response offset after mesh refinement

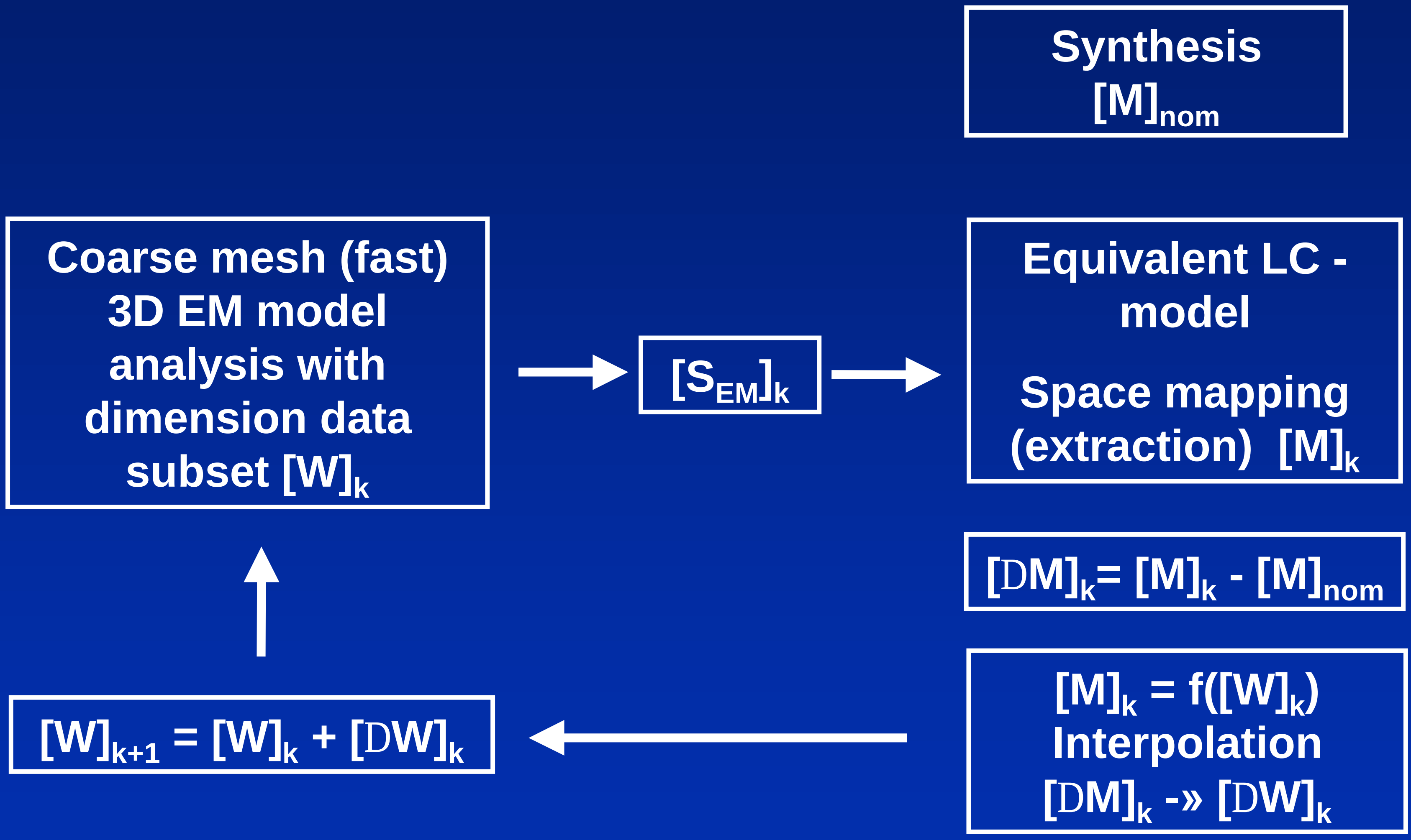


Fine and coarse 3D EM simulation mesh
(HFSS)





Block Diagram of the Process



From physical model variable space to electrical model variable space

$$x_{CNM}^{(i)} = \arg \min_{x_{CNM}} \left\| \left[S(f, x_{CMM}^{(i)}) \right] - \left[S(f, x_{CNM}^{(i)}) \right] \right\|$$

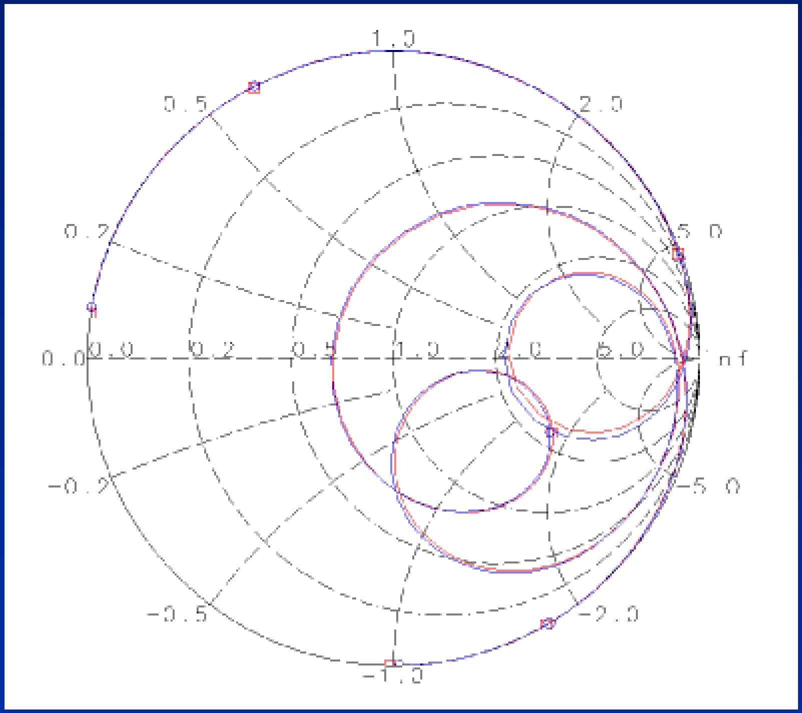
Extraction of Circuit Model Parameters from EM Simulation Data

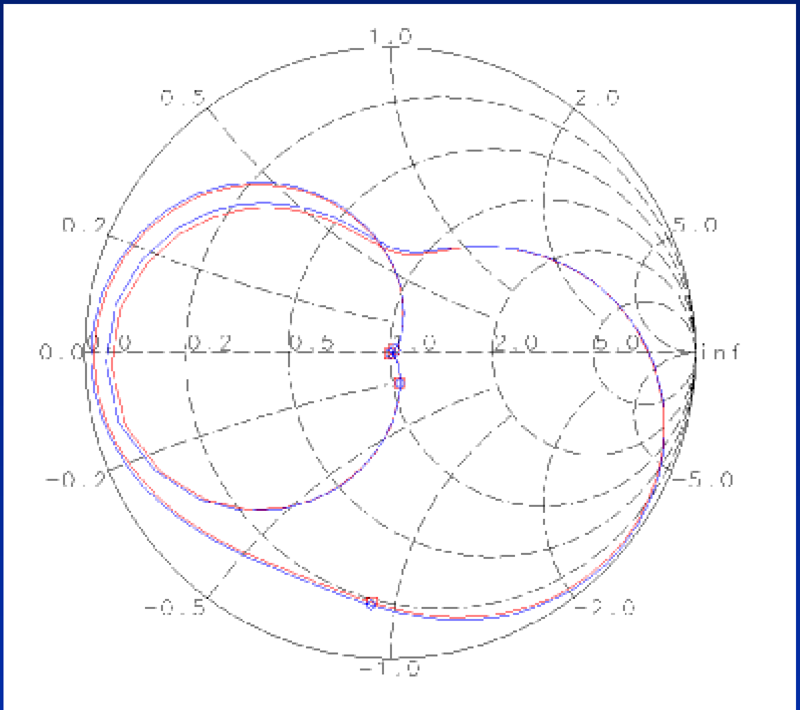
$[S]_{EM}^{k}$ → LC network model → $[M]_{k}$

Circuit model

- Real-world effects must be represented adequately
- “electrically long” coupling structures require suitable circuit model representation
- insufficient circuit detail can lead to wrong accommodation of real-world effects

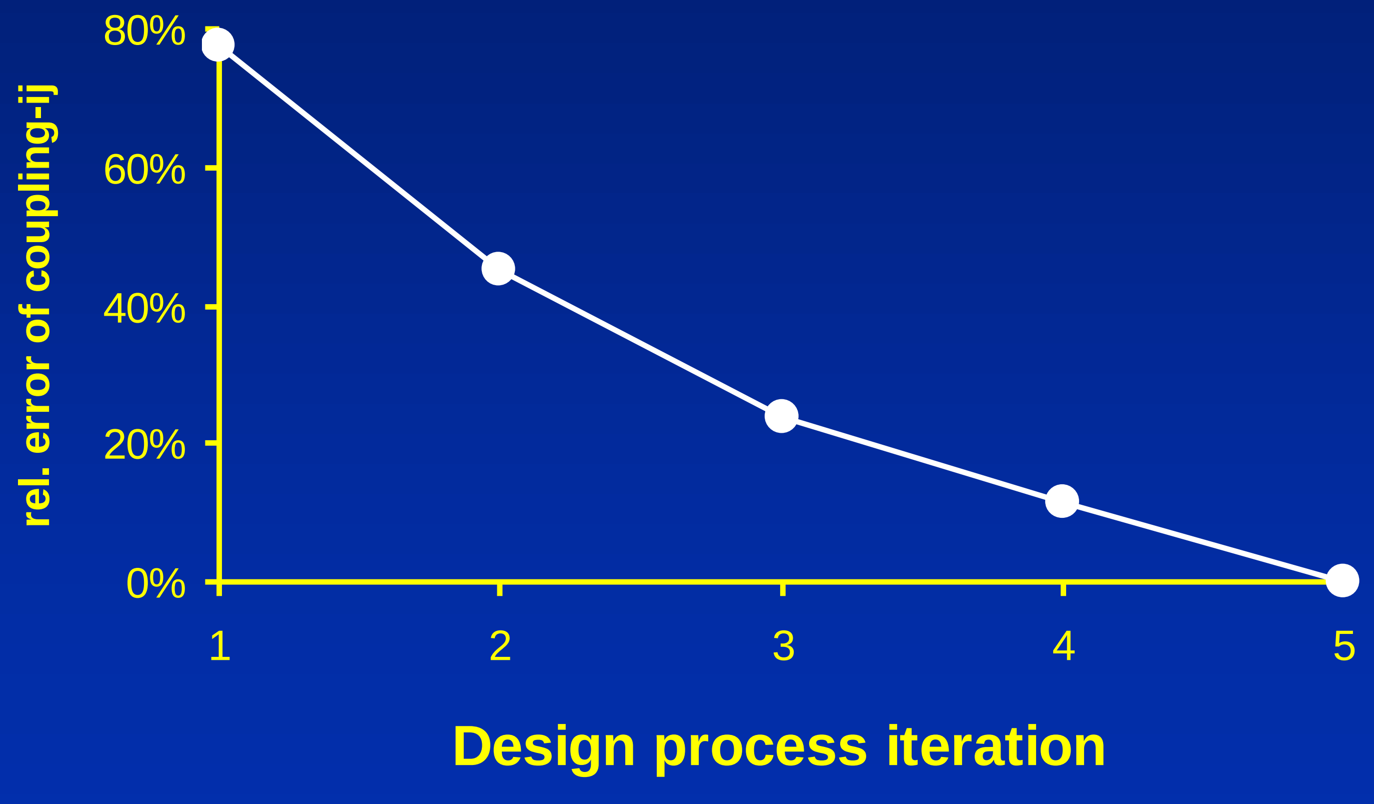
LC Model Extraction accuracy



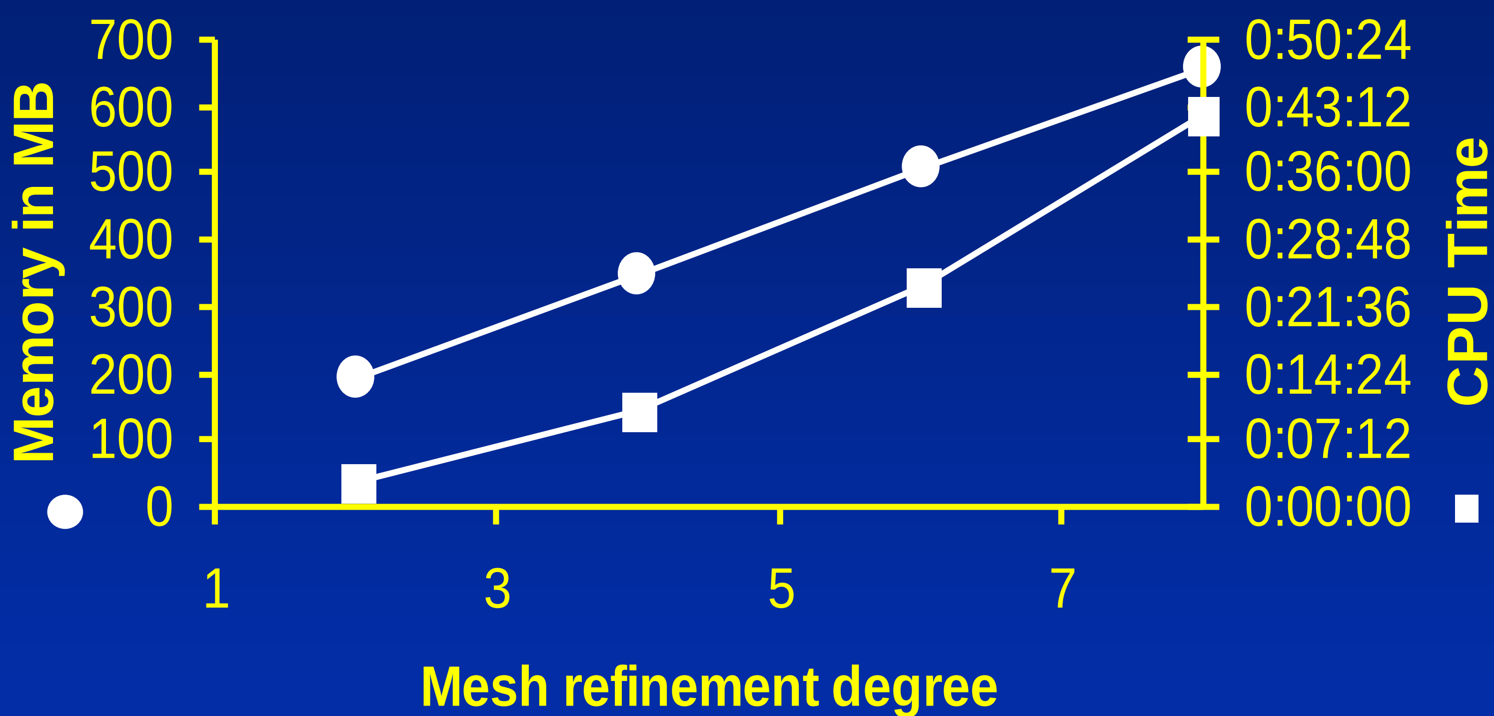


S_{11} S_{21}

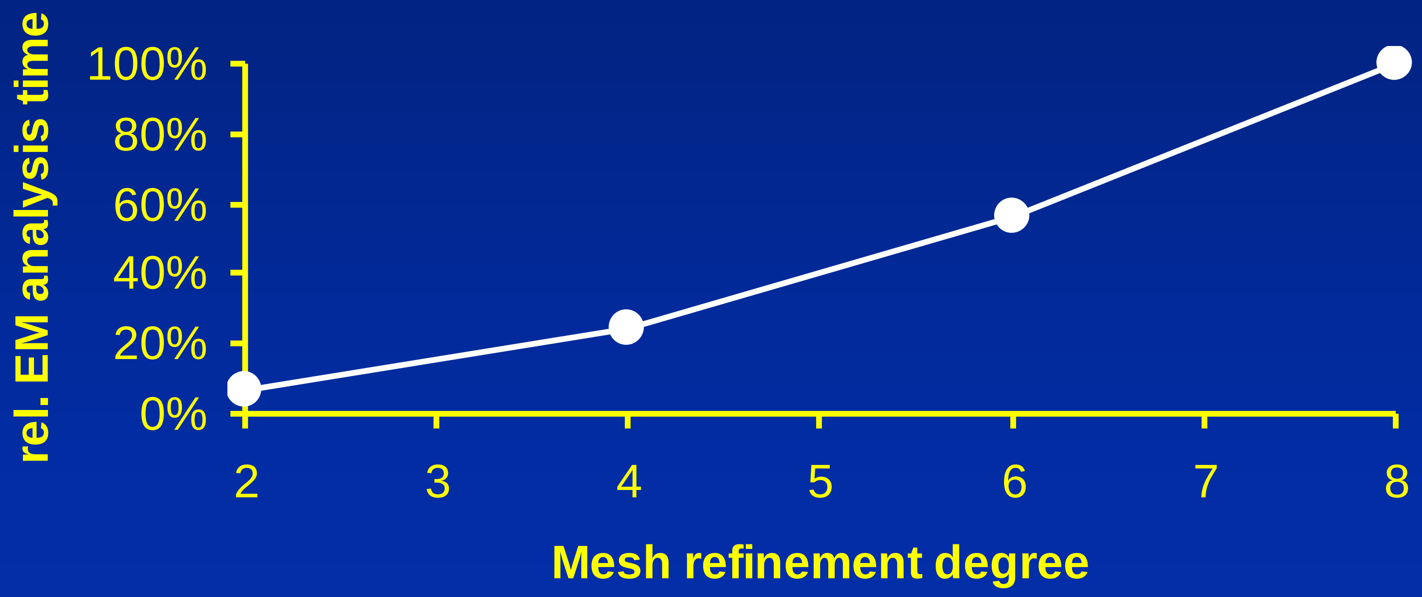
Convergence of Design Process



Computational effort



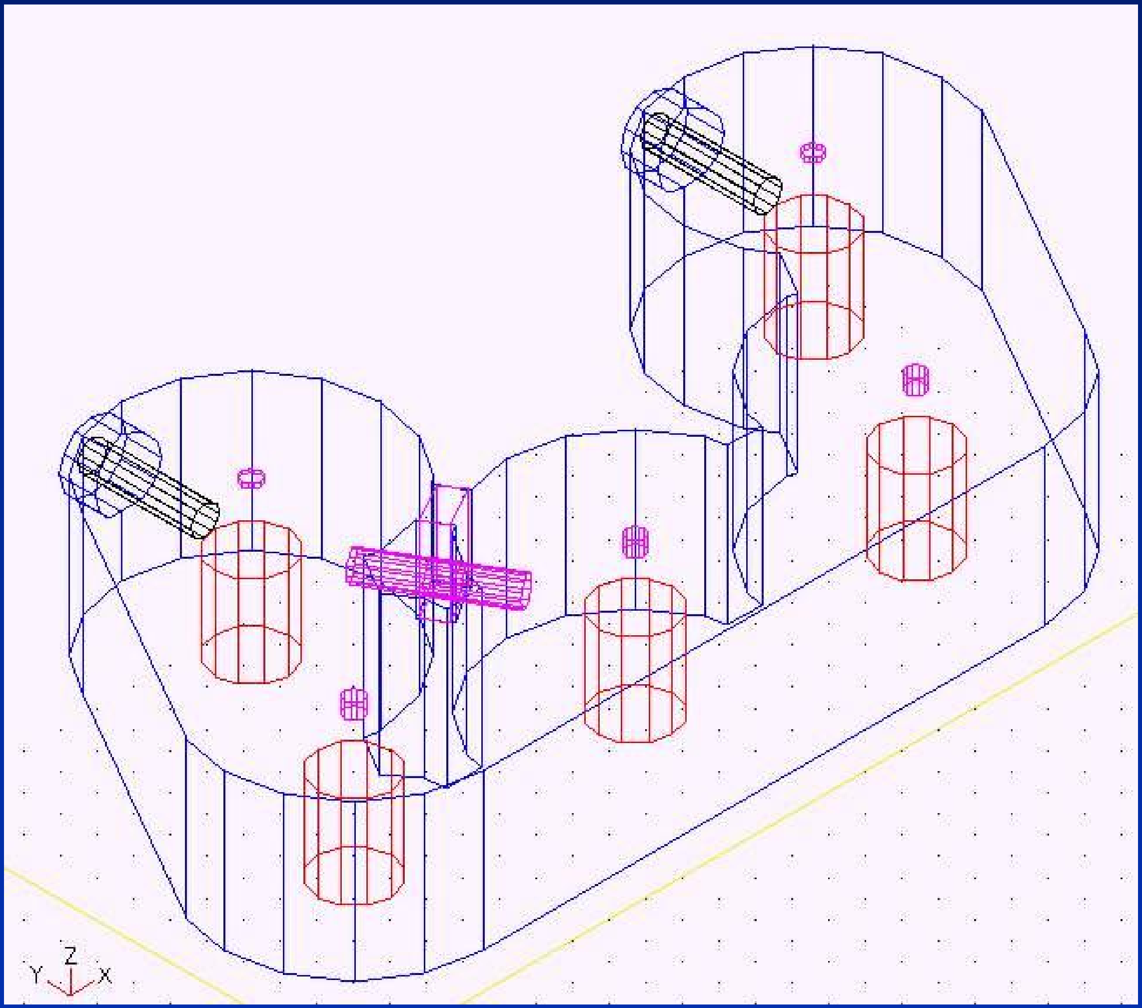
EM Analysis Time



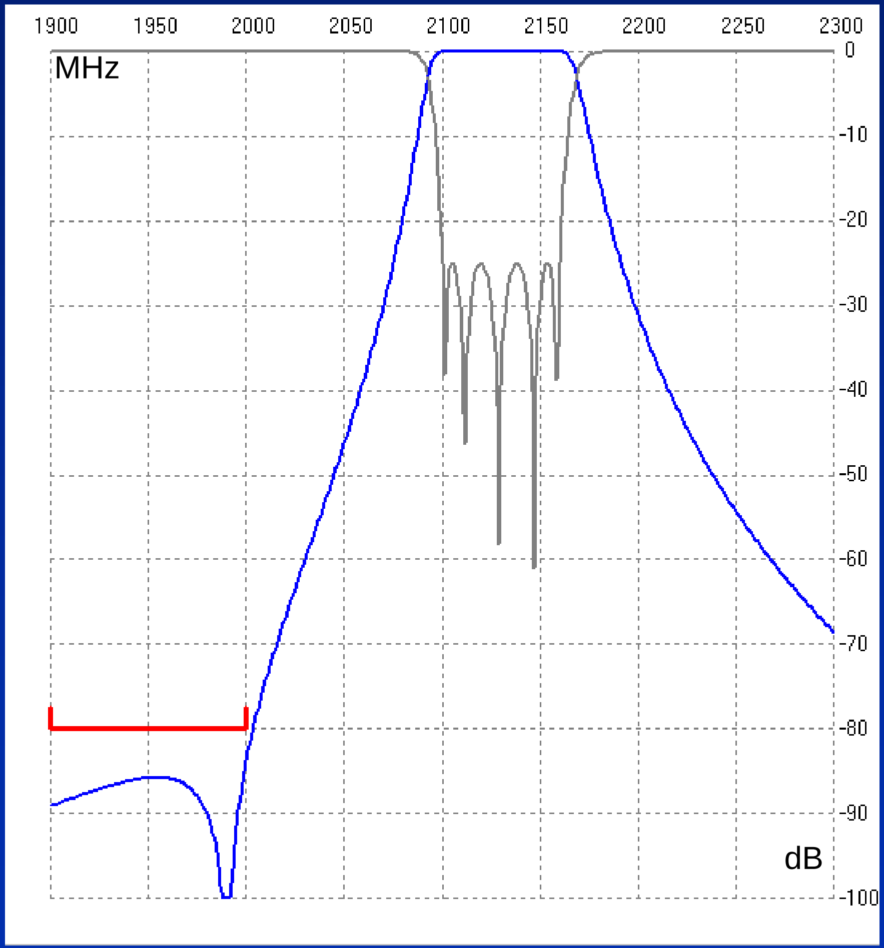
Example: 5-pole filter

		Nominal		Iteration 1	Iteration 2	Iteration 3	Iteration 4
		values					
	k_{12}	0.0274		0.0116	0.0164	0.0272	0.0273
	k_{23}	0.0195		0.0329	0.0302	0.0225	0.0196
	k_{34}	0.0199		0.0303	0.0244	0.0224	0.0190
	k_{45}	0.0290		0.0112	0.0162	0.0291	0.0291
	w_{12}			30.0	33.0	38.9	39.0
	w_{23}			42.0	40.0	36.2	34.7
	w_{34}			41.0	38.0	36.6	34.8
	w_{45}			30.0	33.0	40.3	40.2
w_{ij} in mm				k_{ij} error			
				-57.7%	-40.1%	-0.7%	-0.4%
				68.7%	54.9%	15.4%	0.5%
				52.3%	22.6%	12.6%	-4.5%
				-61.4%	-44.1%	0.3%	0.3%

Example: 5-pole filter



Example: 5-pole filter



Outlook

MHz

- Classical space mapping can be applied to further increase the accuracy of coarse mesh simulation derived coupling matrix data
- 3D EM simulation and linear circuit simulation could be combined

References

[1] Ali E. Atia, “Multiple Coupled Resonator Filter Synthesis by Optimization”, IEEE MTT-S 2000, WSC workshop notes

[2] J.W. Bandler, et. al., “Space Mapping Technique for Electromagnetic Optimization”, IEEE MTT Vol. 42, No. 12, Dec. 1994

[3] M.H. Bakr, J.W. Bandler, K. Madsen, J. Sondergaard, “Review of the Space Mapping Approach to Engineering Optimization and Modeling”, Optimization and Engineering, vol.1 2000, pp. 241 - 276 (available at www.bandler.com)

[4] D. Pelz, “Fast Design of Cross-Coupled Filter Sub-Structures”, The Microwave Journal, Vol. 44, No. 9, Sept. 2001, p. 204