Tuning and Optimization of Bandpass Filters

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Agenda

- Introduction
- Optimizers
- Tuning Methods
- Application of Local optimization strategies
- Solver selections, accuracy
- Guidelines and Summary

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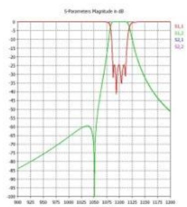
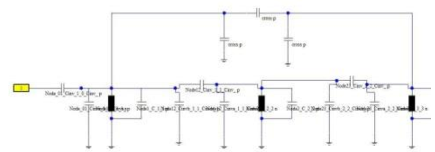
Introduction

Typical Flow Chart of the Filter design and Tuning process

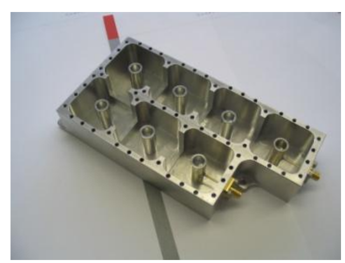
Specifications



Circuit Design
Analytical models



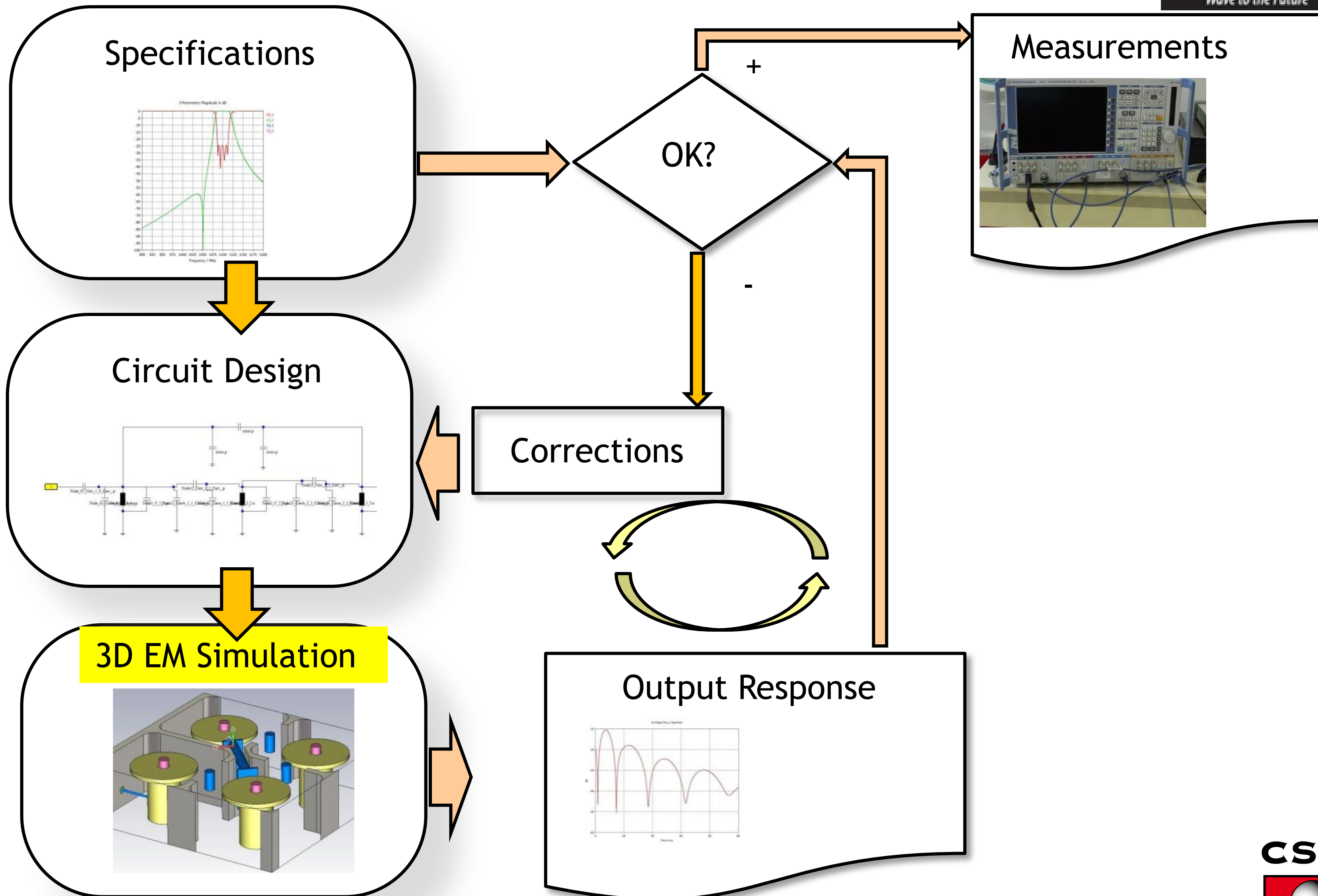
Empirical adjustments
on the structure



Measurements

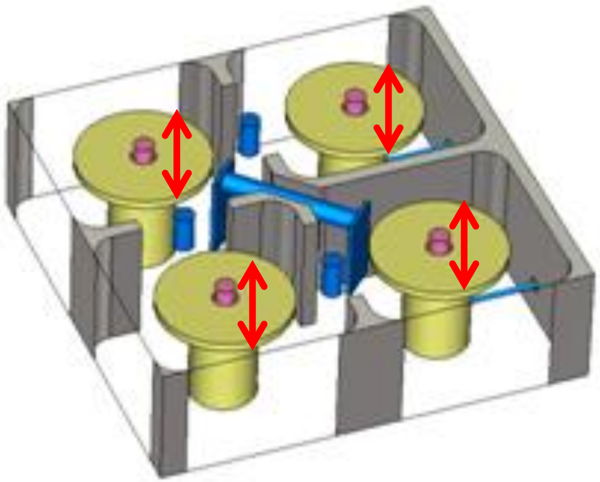
Introduction:

Improved Flow Chart of the filter design and tuning process



Introduction: General Optimizer Setup

Parameterization



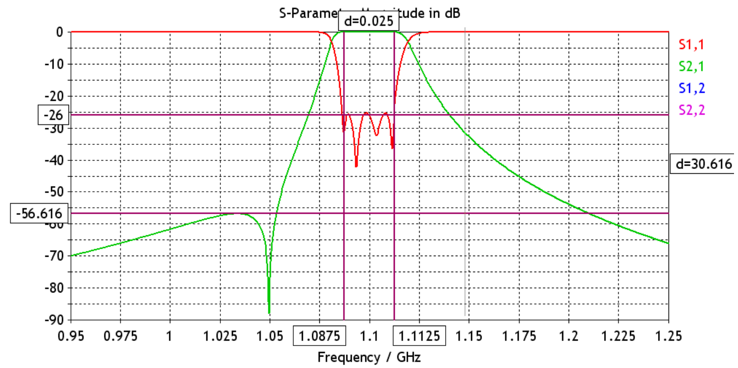
1. Define structure parameters

Name	Value	Description
res_tuner_lengt	5.9168	
res_tuner_lengt	5.2251	
res_tuner_lengt	5.0041	
res_tuner_lengt	5.9817	

2. Define parameter ranges

Parameter	Min	Max
res_tuner_lengt	5.9168	6.1584
res_tuner_lengt	5.2251	5.4383
res_tuner_lengt	5.0041	5.2084
res_tuner_lengt	5.9817	6.2259

Definition of Goal function



Parameters | Goals | Info | Specials

Add new goal ... | Edit... | Remove All | Remove

Type	Operator	Target	Range	Weight
|S1,1|	min	0.0	1.0875...1.1125	1.0

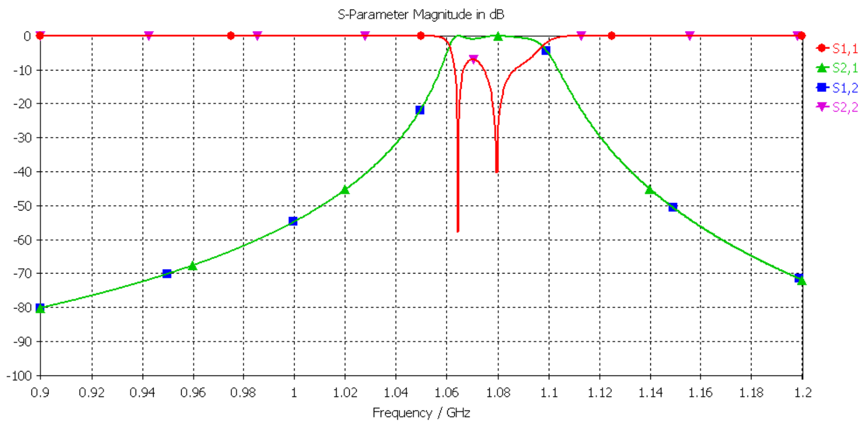
Optimizer Choice

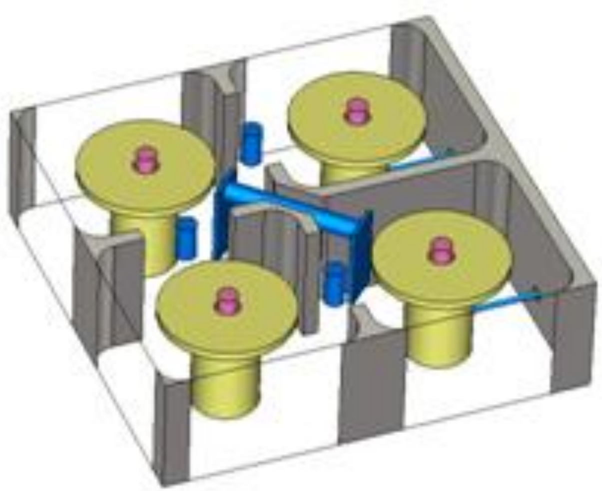
Trust Region Framework

- Genetic Algorithm
- Particle Swarm Optimization
- Nelder Mead Simplex Algorithm
- Interpolated Quasi Newton
- Trust Region Framework
- Classic Powell

Introduction: Optimizer Results

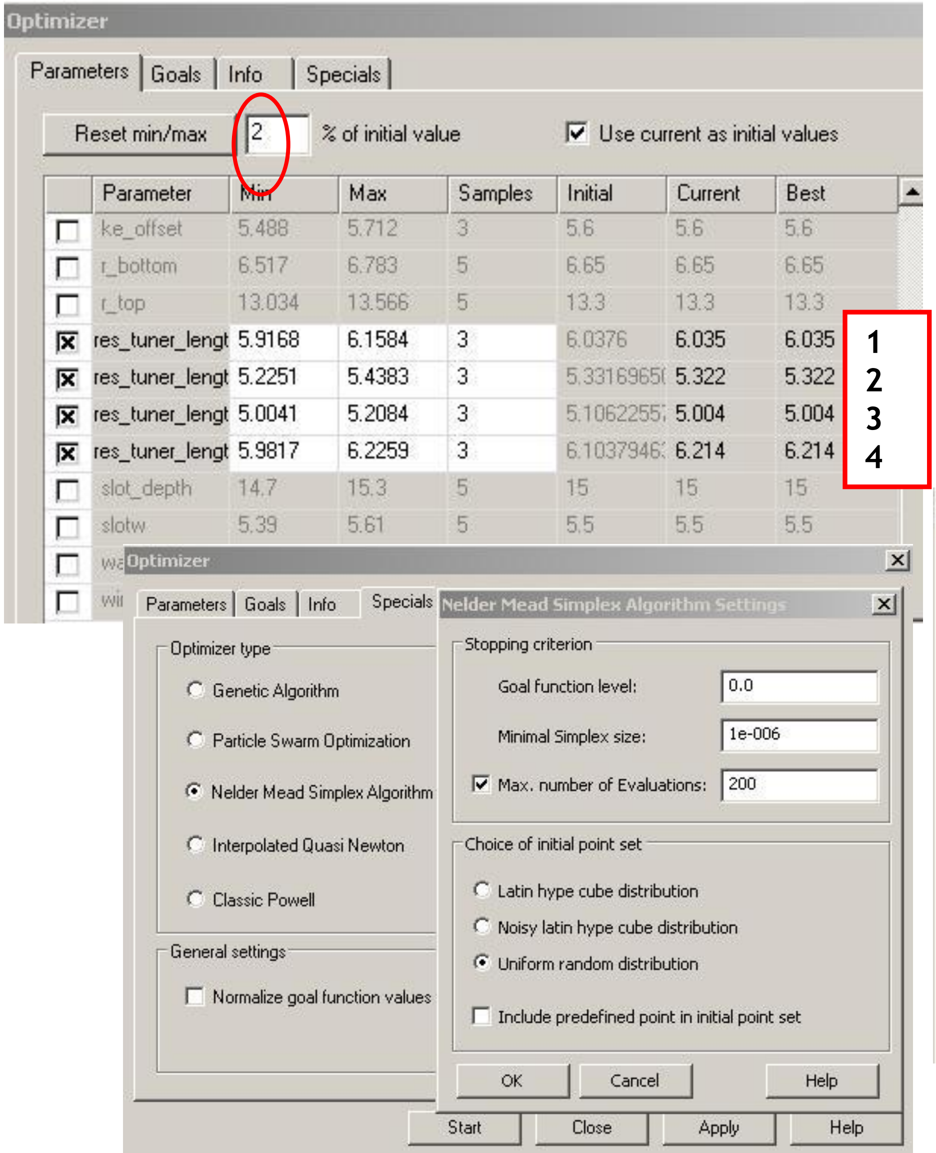
Only a few parameter considered yet, in general there are a lot more parameters to consider



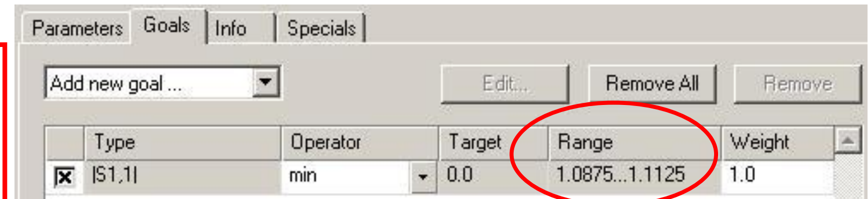


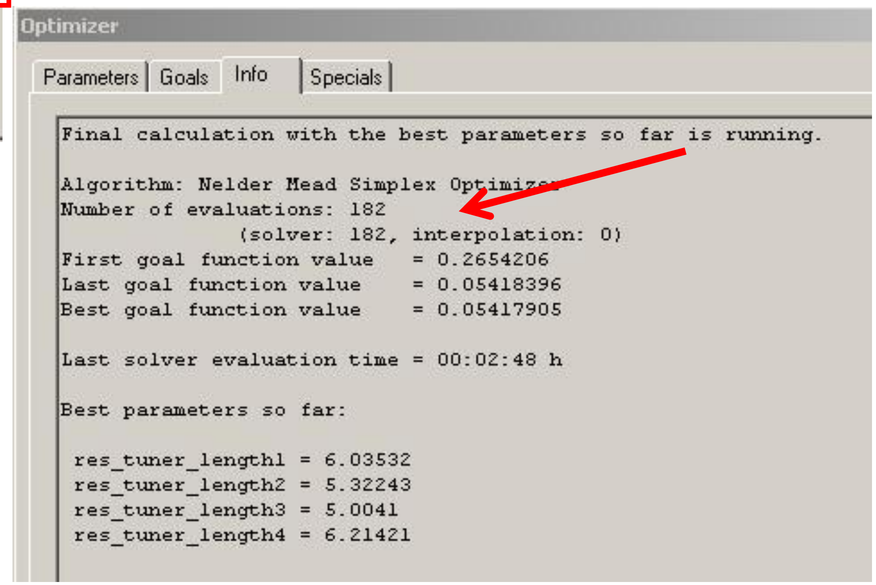
Name	Value	Description
a	40	side-length
b	a	
blend	5	blend radius
c	25	casting hight
coupl_tuner_12	7.5	length of coupling screw 1-2
coupl_tuner_23	7.5	
epsr	1.3	teflon
h_bottom	20.4	20.7
h_top	1.7	1.8
hole_radius	2.5	
k12	22	
k23	18.5	
ke_offset	5.6585468083622	offset from center face 5.66
r_bottom	6.65	6.5
r_top	13.3	15.4
res_tuner_length1	6.35	6.35
res_tuner_length2	5.73	
res_tuner_length3	res_tuner_length2	
res_tuner_length4	res_tuner_length1	
wall_thickness	3	
wire_r	.5	feed wire radius

Introduction: General Optimizer Setup



Optimizing the structure using Nelder Mead Simplex Optimizer **only** for resonator's lenghts





Introduction

To summarize

- In general many parameters to consider
- Wide parameter ranges necessary in order not to miss an optimum

-> global optimizer strategies required

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Local vs. Global Optimizers

Classic Powell

Interpolated Quasi Newton

Trust Region Framework

Nelder-Mead Simplex Algorithm

Particle Swarm Optimization

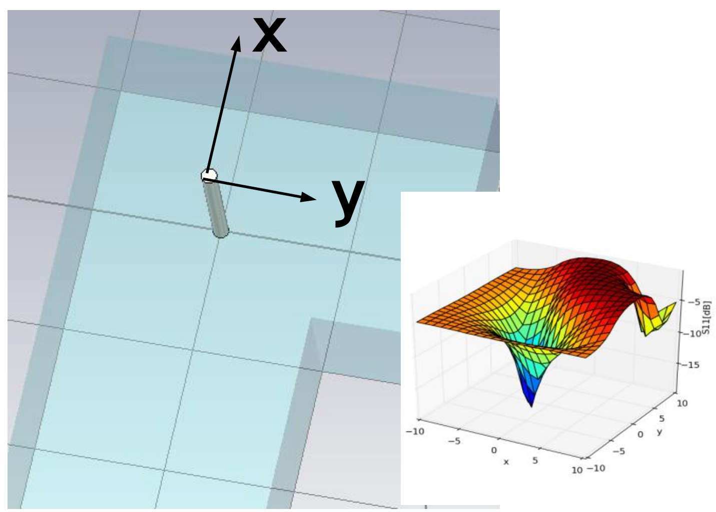
Genetic Algorithm

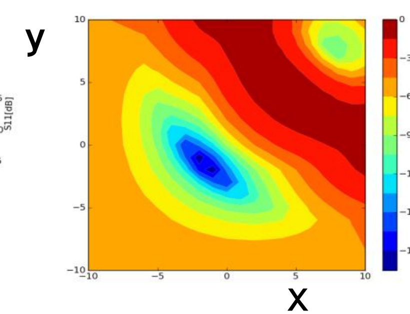
local ⟷ global

Initial parameters already give a good estimate of the optimum, parameter ranges are small

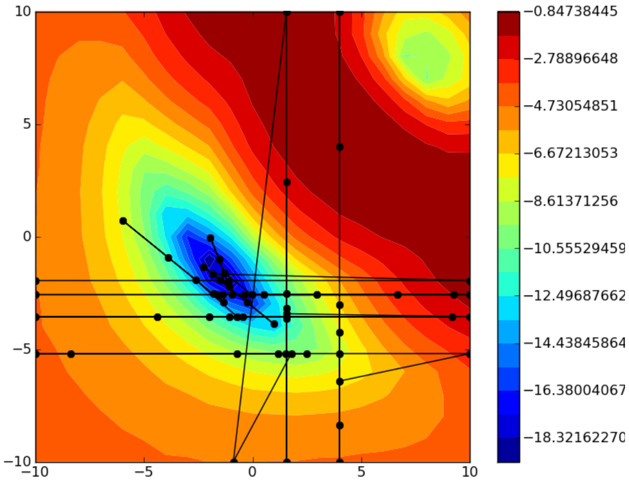
Initial parameters give a poor estimate of the optimum, parameter ranges are large

Beispiel:
Waveguide Corner Goal:
Minimize S_{11}



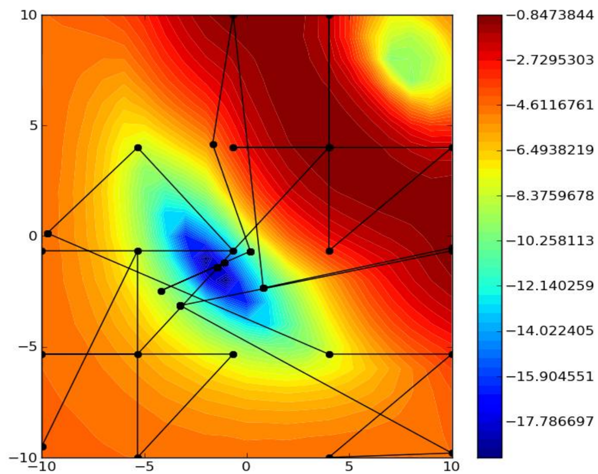


WG Corner: Landscape Visualization (1)



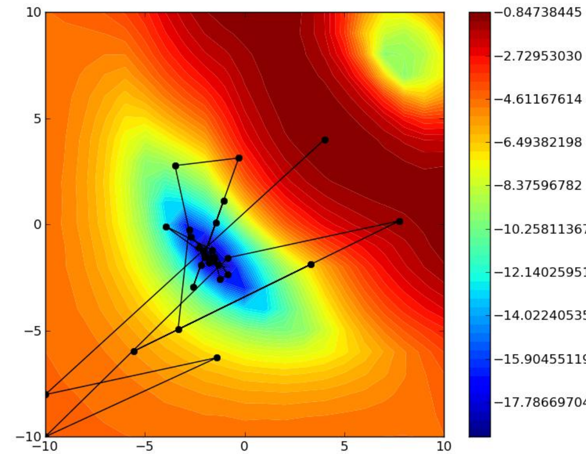
Classic Powell:

A local optimizer that robustly finds an optimum within the given parameter bounds. Sometimes, many iterations are necessary when closing in on the optimum.



Quasi Newton:

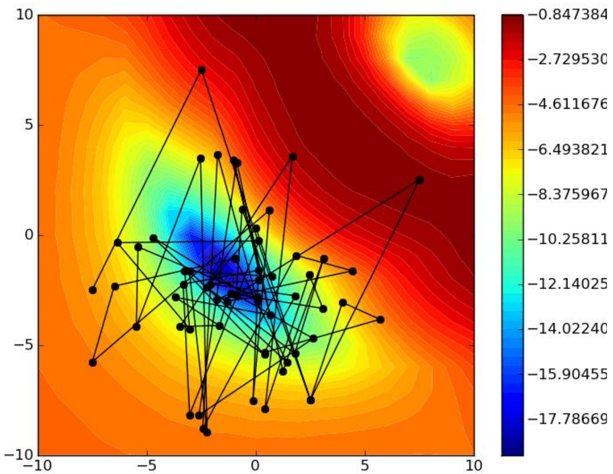
A Search algorithm for expensive problems: The parameter space is sampled in each variable direction. EM simulations are only performed for these discrete parameter space points. A model is created from these evaluations and used for optimization. During the search, the model is updated regularly by real evaluations.

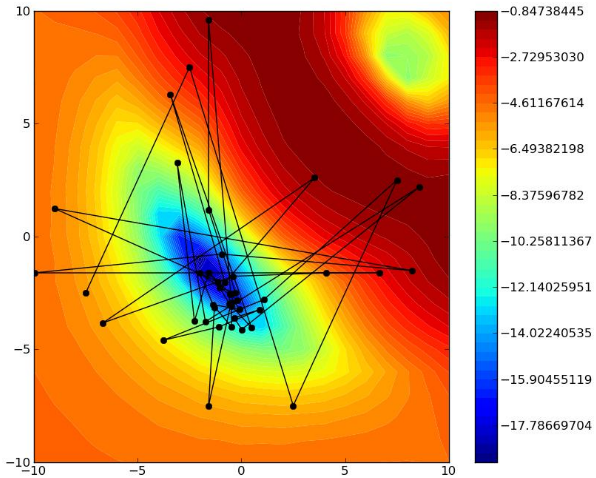


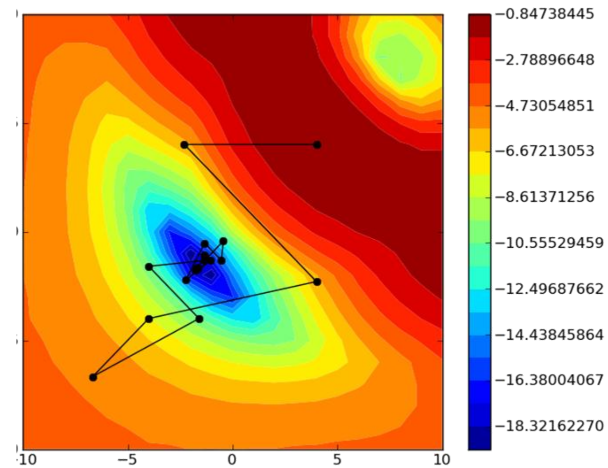
Nelder Mead

An optimizer for more complex problem domains with good convergence behavior: Uses relatively few evaluations if the problem has a low number of parameters (i.e., less than 5). In geometry, a simplex or *n*-simplex is an *n*-dimensional analogue of a triangle.

WG Corner: Landscape Visualization (2)







Particle Swarm

A global optimizer that uses a higher number of evaluations to explore the search space, also suited for larger numbers of parameters (hint: use distributed computing).

Genetic Algorithm

A global optimizer that uses a high number of evaluations to explore the search space, suited for large numbers of parameters or very complex problem domains (hint: use distributed computing).

Trust Region Framework (TRF)

A fast and accurate optimizer that converges robustly and finds an optimum within the given parameter bounds using a low number of evaluations.

Introduction

A possible solution to speed up the tuning effort is „pretuning“:

Advantage:
local optimizers can be used in addition

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Groupdelay

Coupling Bandwidth, Group delay

Coupling-Coefficients and Td-Values computations are available via Macro

GroupDelay-Macros and 1D ResultsTemplates available for CST-MWS and CST-DS

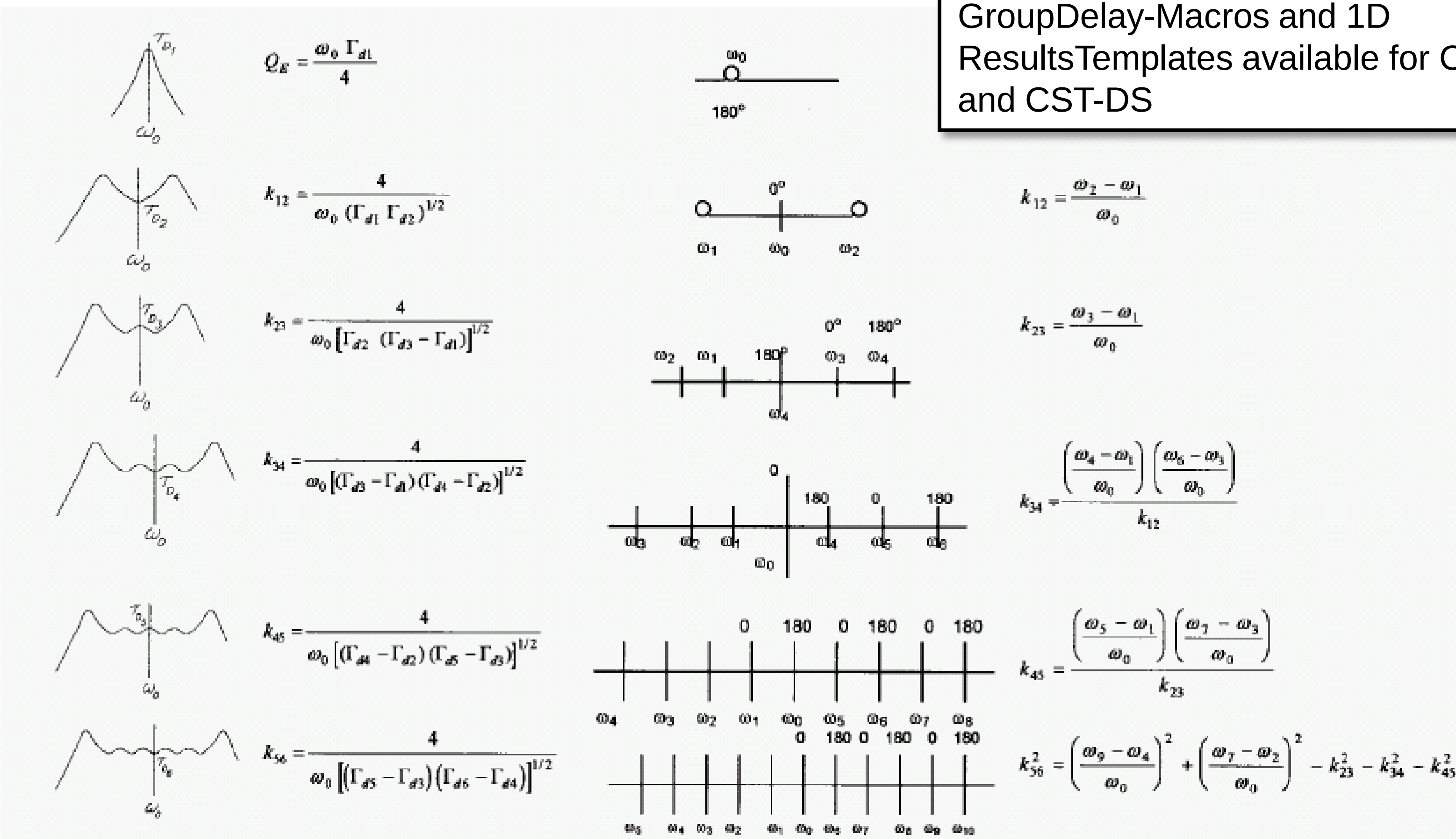
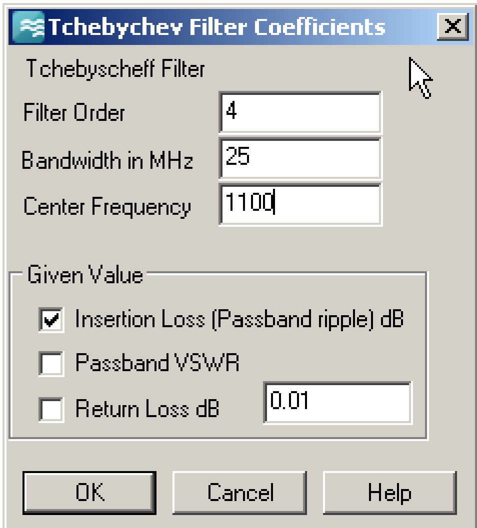
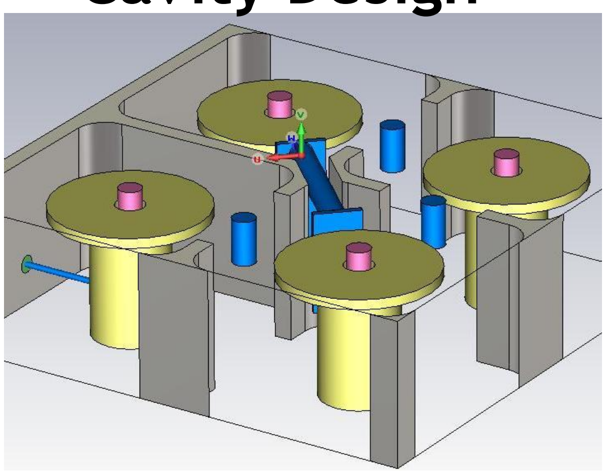


Fig. 3. Coupling values in terms of group-delay and frequency-crossing parameters.

Defining the Specifications

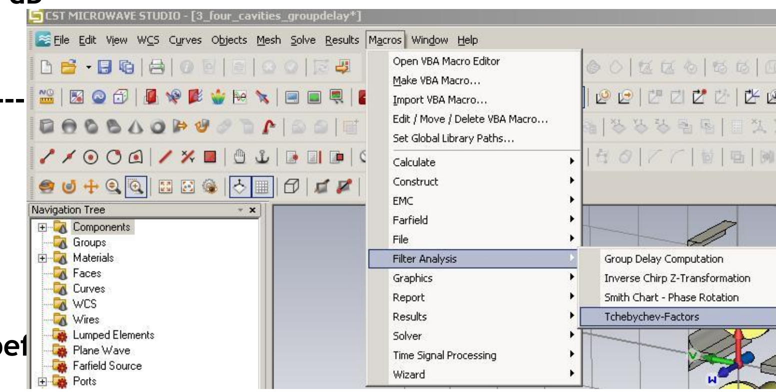


Cavity Design



Tchebychev Filter
===================

Order = 4
Bandwidth = 25 MHz (rel. BW=2.3%)
Center Frequency = 1100 MHz
Passband ripple = 0,01 dB (1,100747 VSWR)
Return loss = -26,3828 dB



Normed g values:
----

g1 = 0,7129
g2 = 1,2004
g3 = 1,3213
g4 = 0,6476
g5 = 1,1008

Corresponding coupling coef
(rel):
----

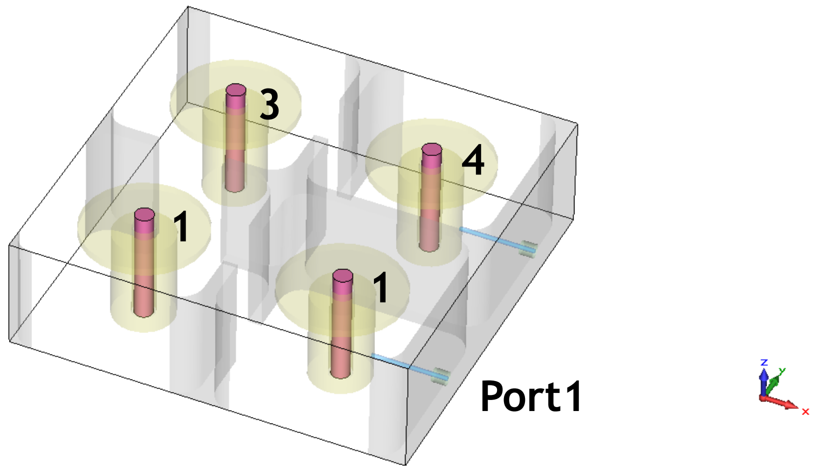
k_E = 35,07 (0,0318809)
k1_2 = 27,03 (0,0245688)
k2_3 = 19,85 (0,0180464)
k3_4 = 27,03 (0,0245688)
k_out = 35,07 (0,0318809)

Group Delay Time
----

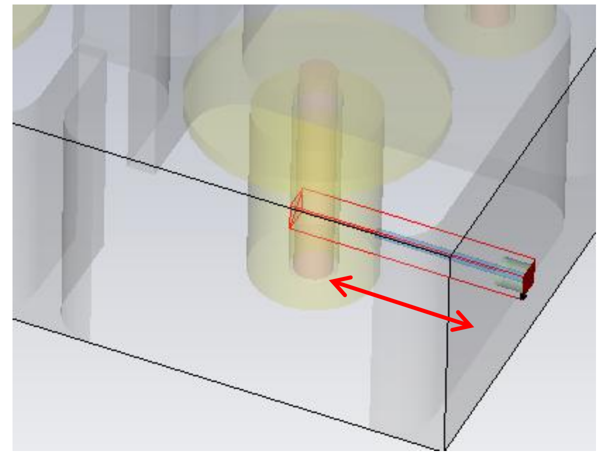
t_d1 = 18,153 ns
t_d2 = 30,566 ns
t_d3 = 51,798 ns
t_d4 = 47,057 ns
t_d5 = 71,78 ns

Groupdelay: Determine FlatPhase

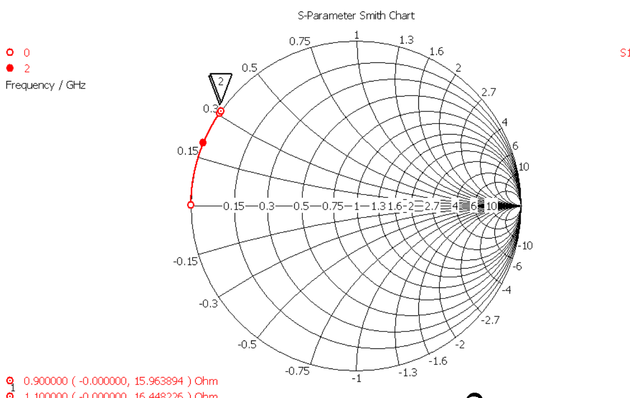
1. Short all resonators



2. Move deemebdding distance

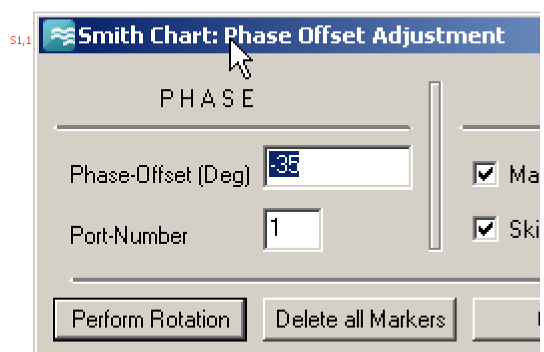


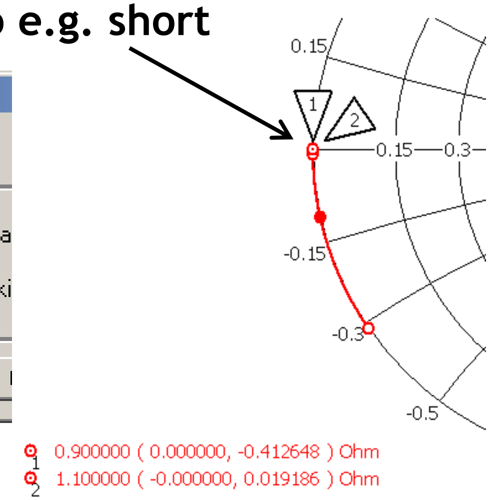
3. Untill flat phase is found



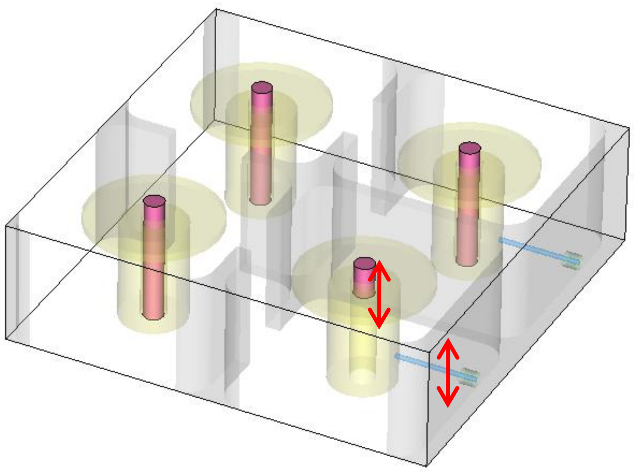
$$g\_delay = -\frac{\partial \varphi}{\partial \omega} = 0!$$

4. Rotate focal point to e.g. short

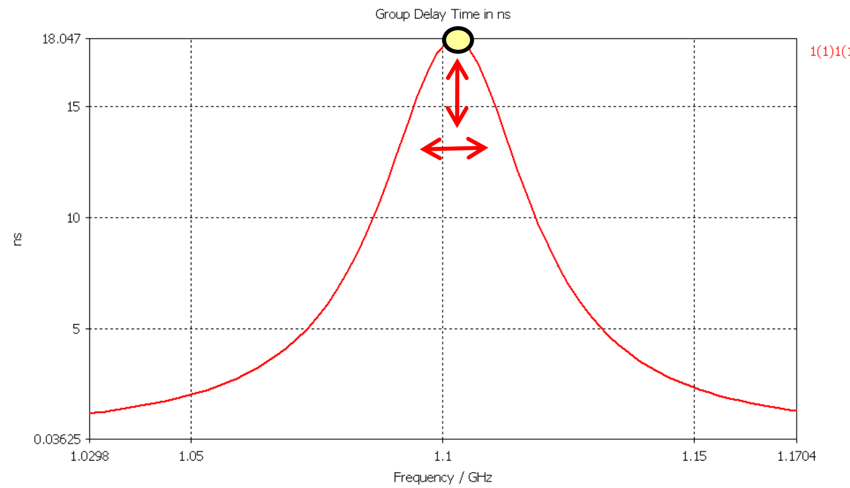




Groupdelay: Tuning of 1st Resonator



Only two variables at a time!!



1D Template

Template Based Postprocessing

1D Results | 0D Results

Add new postprocessing step...

	Result name	Template name
1	Group Delay 1(1)1(1)	Group Delay Time
2	S21dB	S-Parameter

0D Template

Template Based Postprocessing

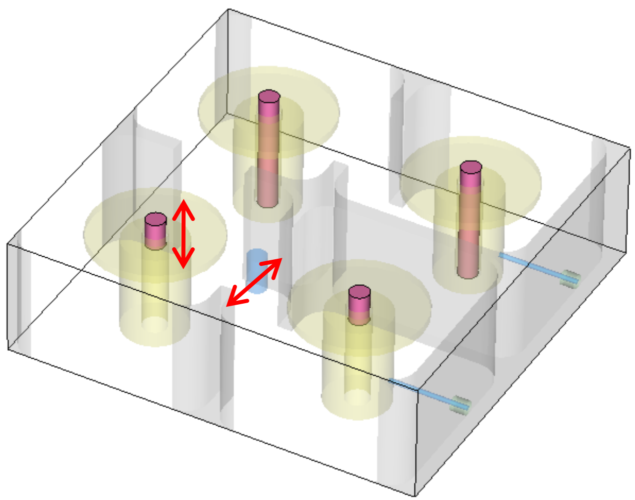
1D Results | 0D Results

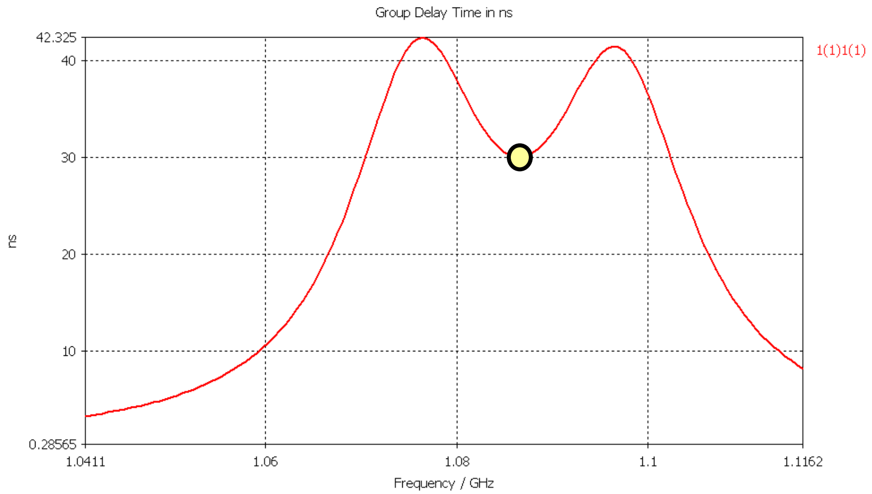
Add new postprocessing step...

	Result name	Template name	Value
1	Group Delay 1(1)1(1)_frequency	+ 0D Value from 1D Result	1.06305
2	Group Delay 1(1)1(1)_max	+ 0D Value from 1D Result	52.3785

Groupdelay: Tuning of 2nd Resonator

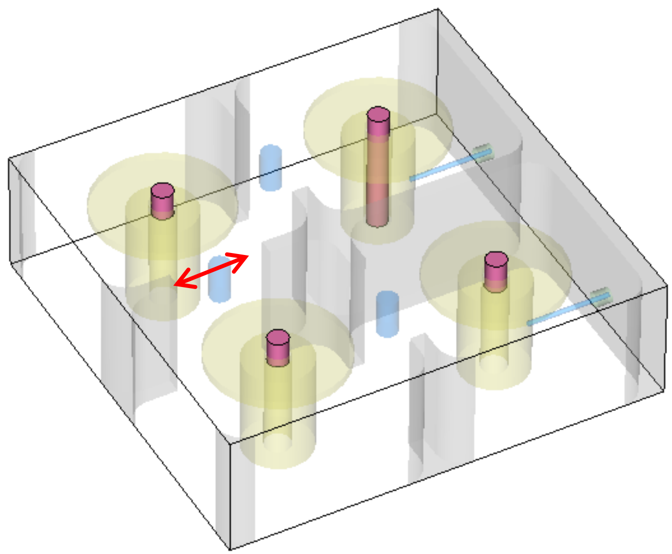
Only two variables at a time!!

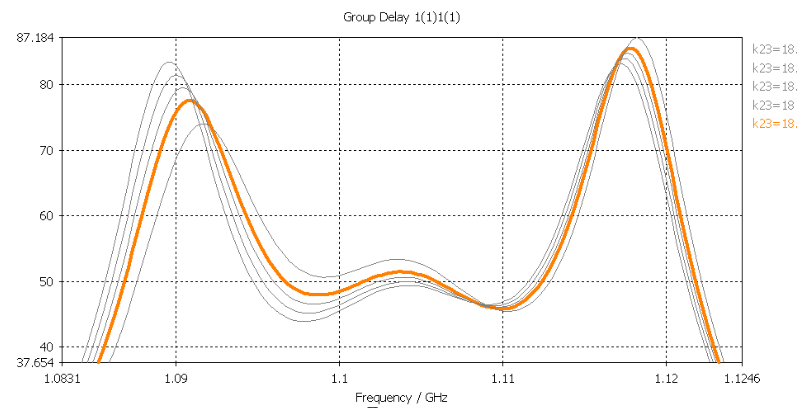


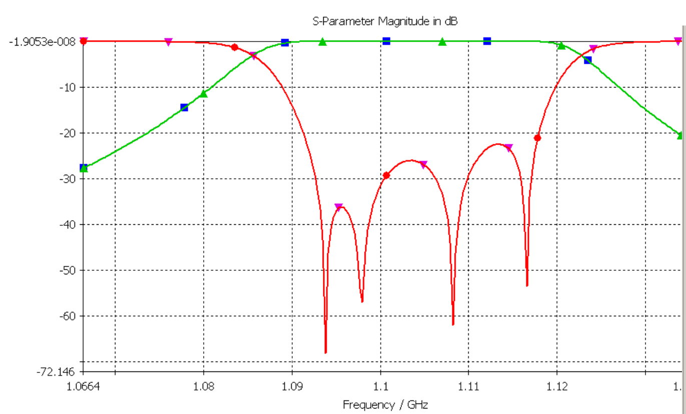


CST

Groupdelay: Tuning of coupling between 2nd and 3rd Resonator

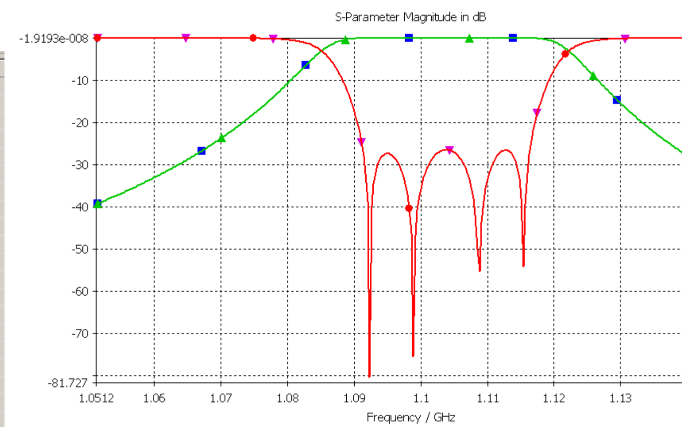






Name	Value
a	40
b	a
blend	5
c	25
coupl_tuner_12	7.5
coupl_tuner_23	7.5
epsr	1.3
h_bottom	20.4
h_top	1.7
hole_radius	2.5
k12	21.7
k23	18.2
ke_offset	5.679897142732
r_bottom	6.65
r_top	13.3
res_tuner_length1	6.1072215294614
res_tuner_length2	5.15
res_tuner_length3	res_tuner_length2
res_tuner_length4	res_tuner_length1
wall_thickness	3
wire_r	.5

Nearly perfect



Name	Value
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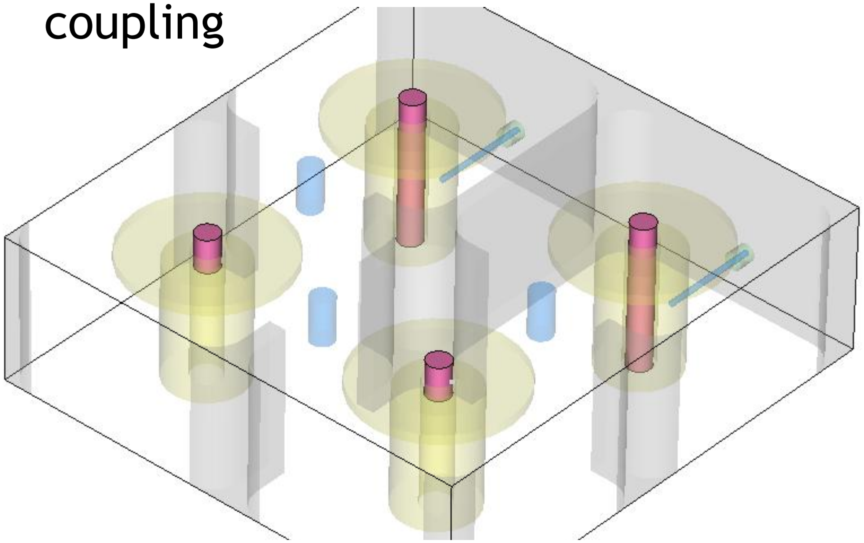
b	a
blend	5
c	25
coupl_tuner_12	7.5
coupl_tuner_23	7.5
epsr	1.3
h_bottom	20.4
h_top	1.7
hole_radius	2.5
k12	21.7
k23	18.2
ke_offset	5.679897142732
r_bottom	6.65
r_top	13.3
res_tuner_length1	6.1072215294614
res_tuner_length2	5.165
res_tuner_length3	res_tuner_length2
res_tuner_length4	res_tuner_length1
wall_thickness	3
wire_r	.5

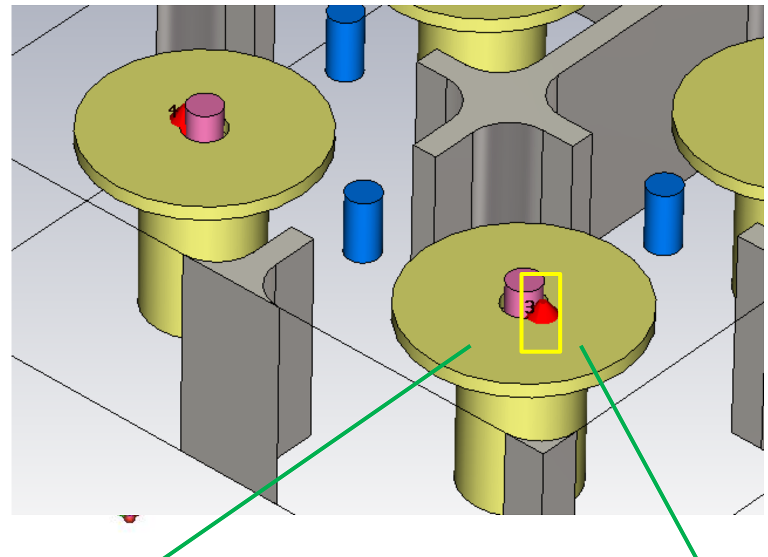
Perfect, dL(tuner2)= 15 mue-m!

Pin-Probes: Tuning of the 3rd Resonator

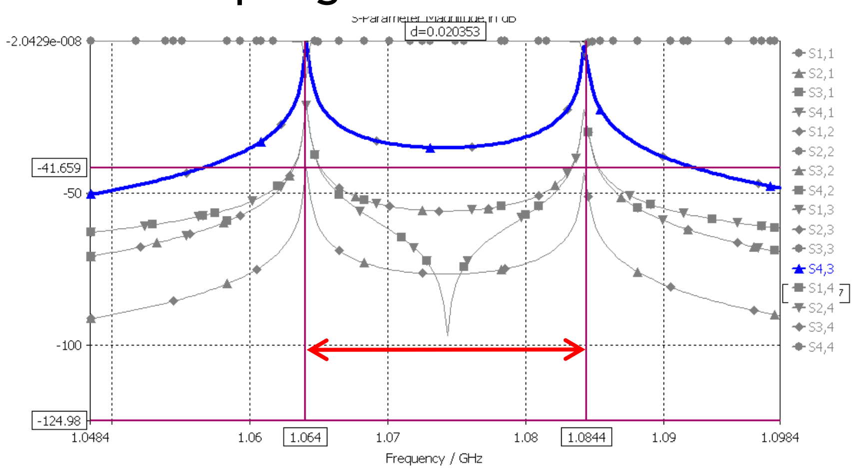
1. Short out all resonators except the pair considered for coupling

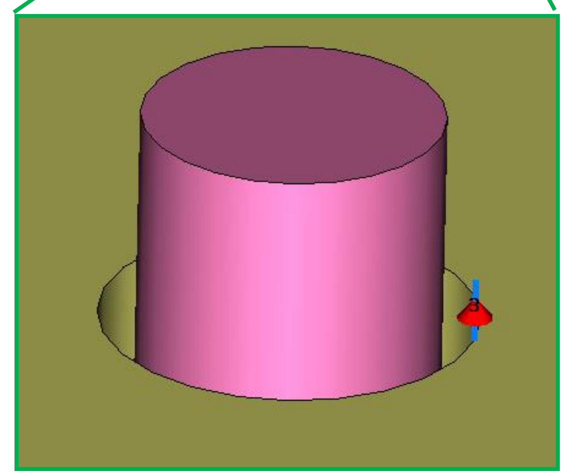


2. Add two small discrete ports to excite the modes

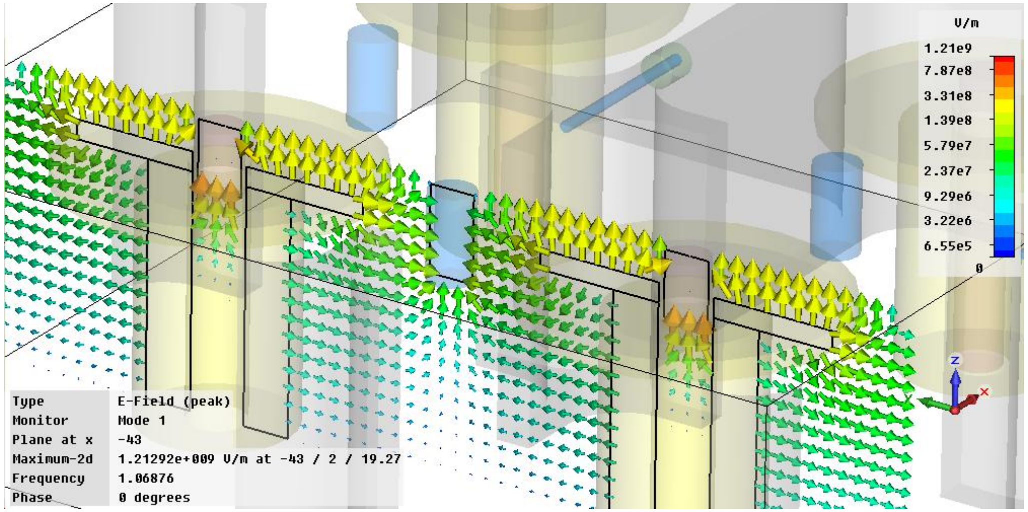


3. Coupling bandwidth

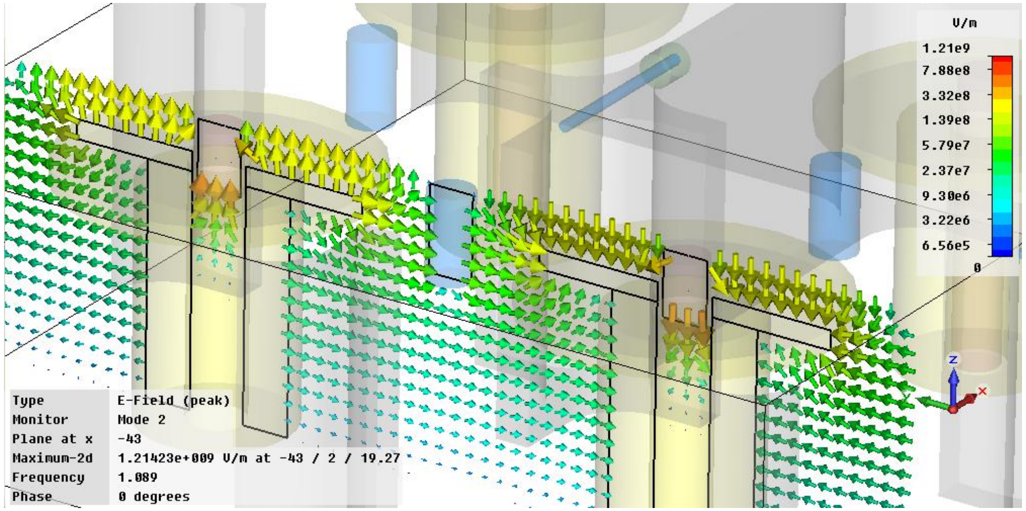




Even/Odd Eigenmodes:



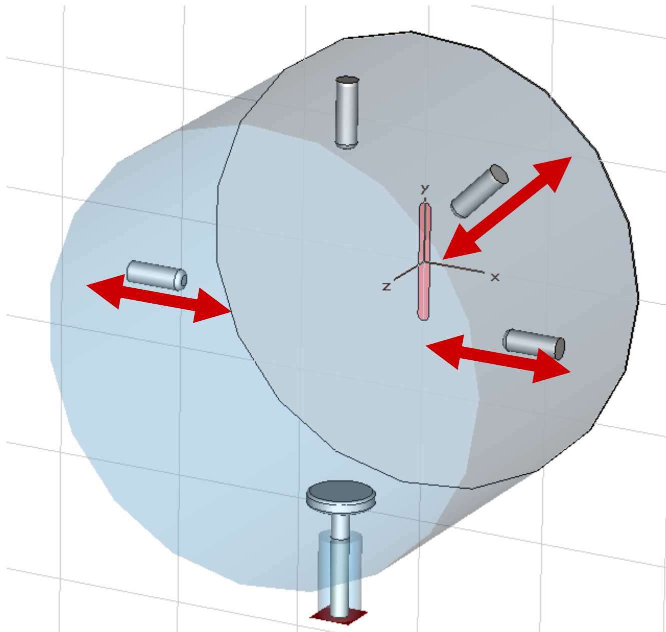
Even-Mode

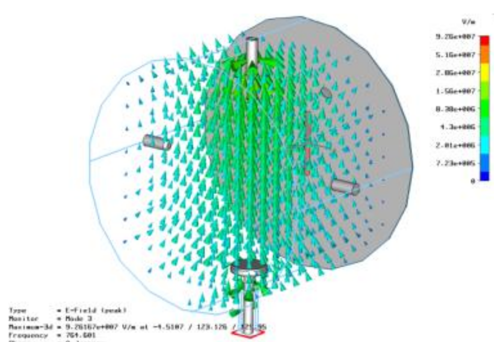


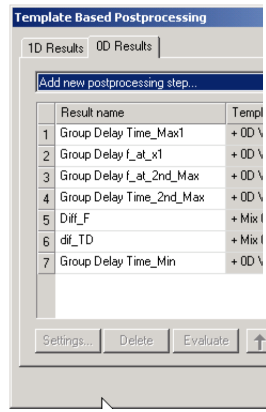
Odd-Mode

Filter Tuning via Groupdelay: Examples

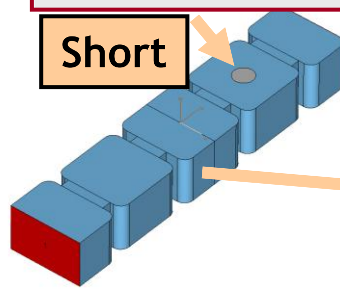
Tuning of a Dual Mode Filter

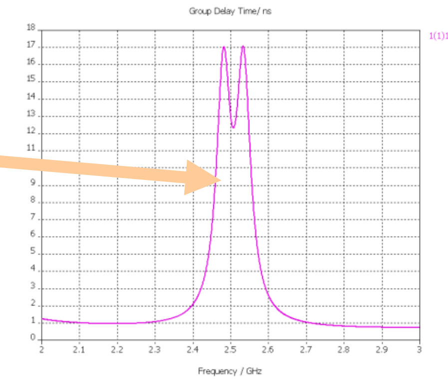




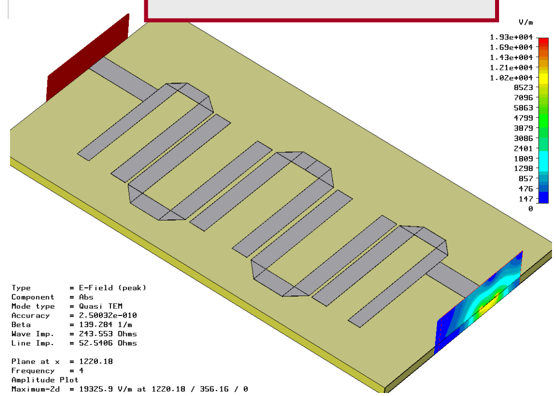


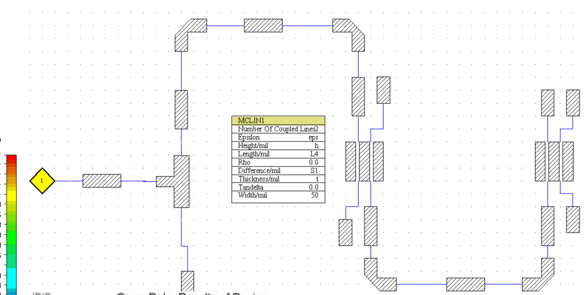
Iris Coupled Cavity Filter

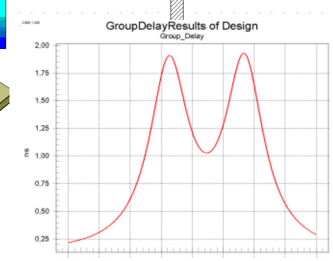




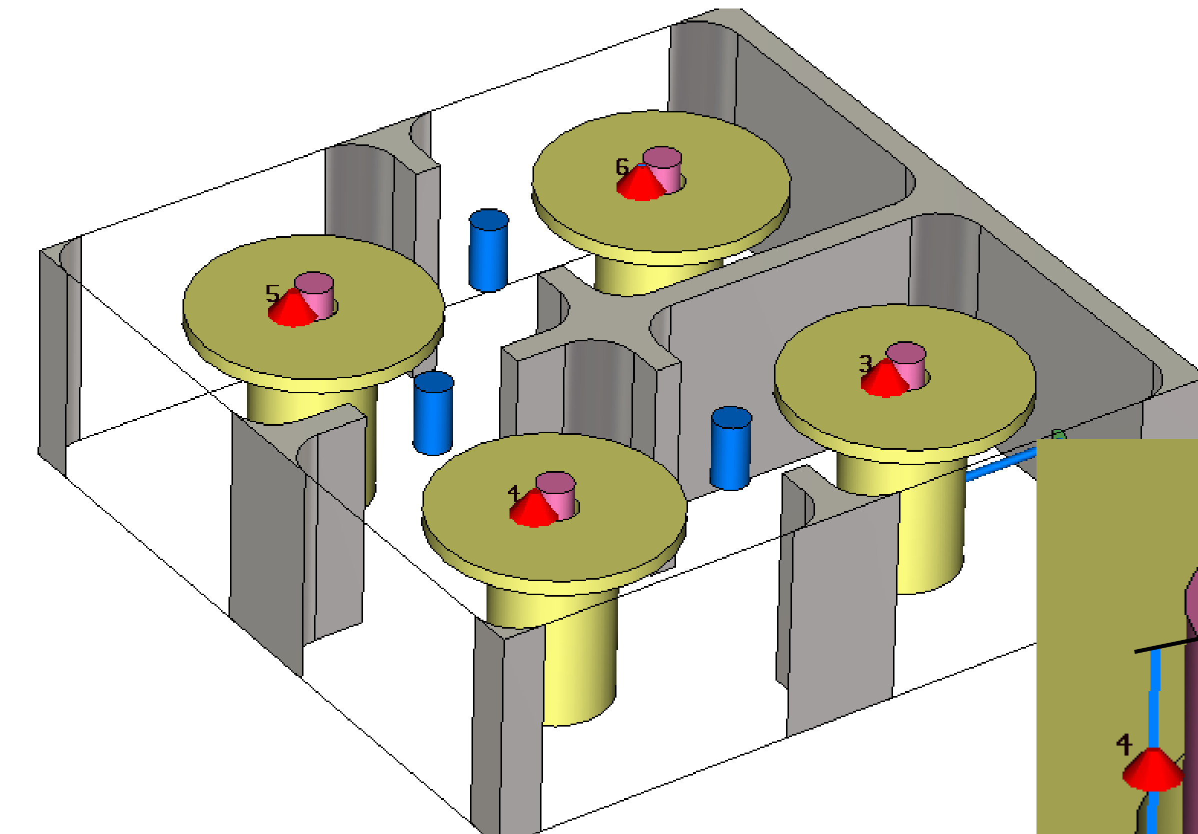
Hairpin Filter

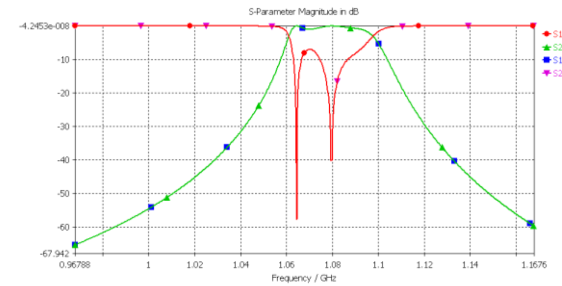




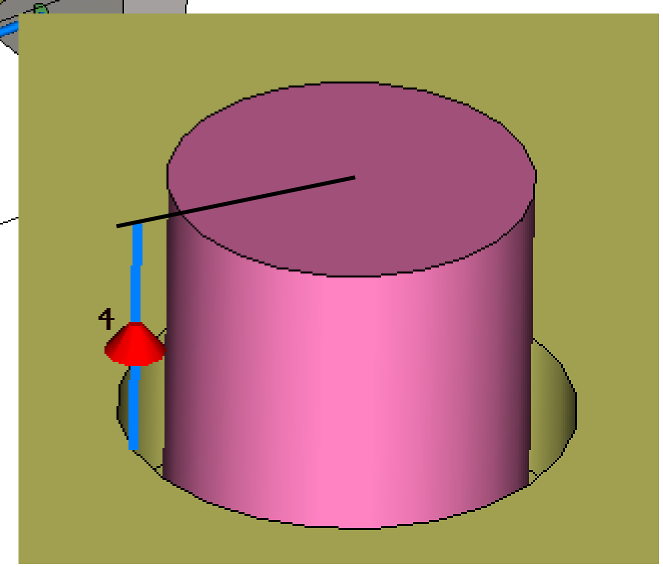


Method of Porttuning



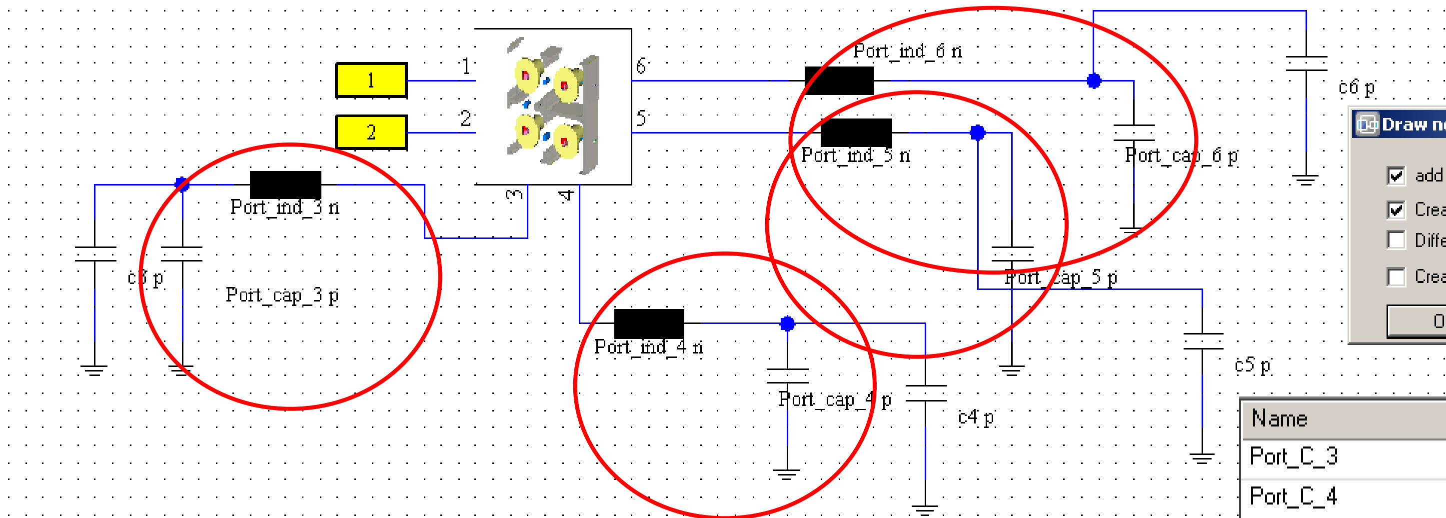


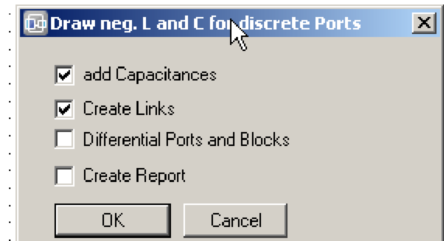
Discrete Ports are assigned at the Resonators



Method of Porttuning

1. Deembedding of Selfinductance and Selfcapacitance of discrete Ports via macro

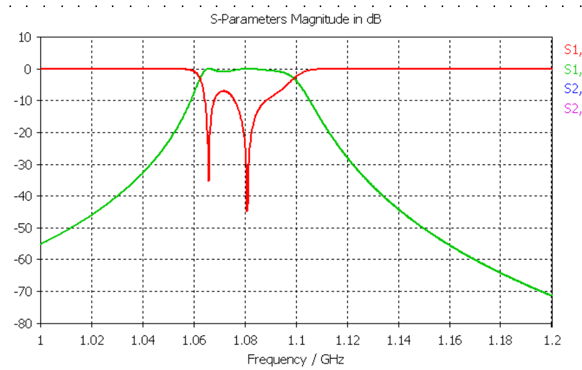




Name	Value
Port_C_3	-34.9641914
Port_C_4	-34.9641914
Port_C_5	-34.9641914
Port_C_6	-34.9641914
Port_L_3	-1.8097085
Port_L_4	-1.8097085
Port_L_5	-1.8097085
Port_L_6	-1.8097085
Port_cap_3	-0.0349642
Port_cap_4	-0.0349642
Port_cap_5	-0.0349642
Port_cap_6	-0.0349642
Port_ind_3	-1.8097085
Port_ind_4	-1.8097085
Port_ind_5	-1.8097085
Port_ind_6	-1.8097085

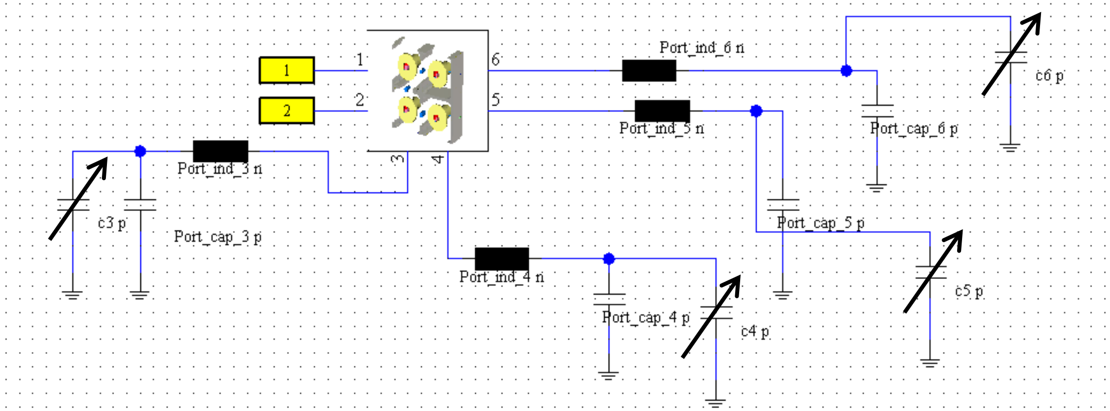
2. C3..c6 set initially to 0 F and then tuned via optimisation (GA: simplex)

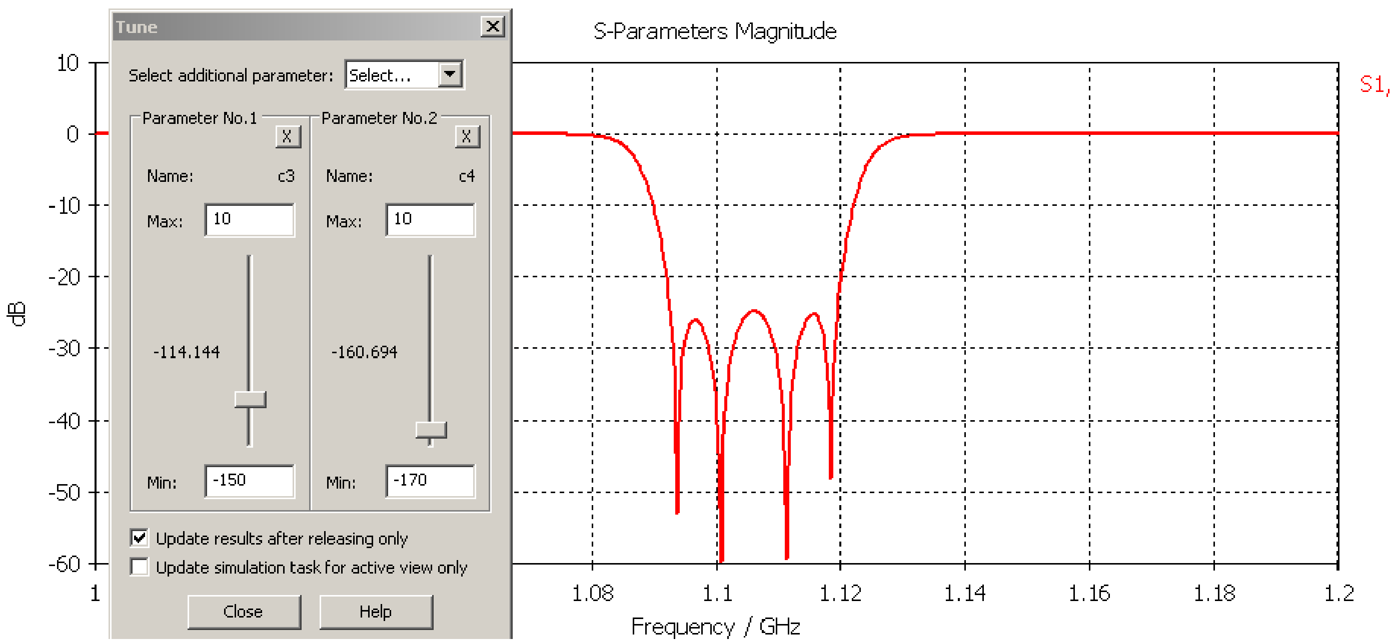
c16	0
~~c23~~	~~c16~~
c3	0
c34	0
c4	0
~~c45~~	~~0~~
c5	c4
~~c56~~	~~c34~~
c6	c3



Method of Porttuning

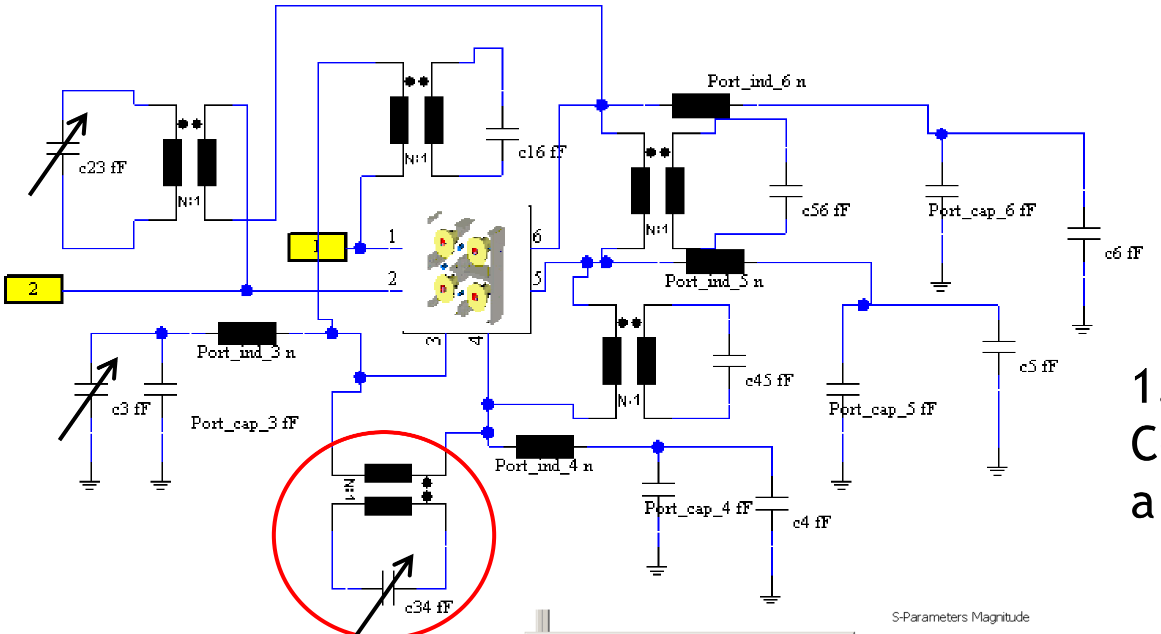
3. Use Tuner for C3 and C4 to manually adjust a good filter response





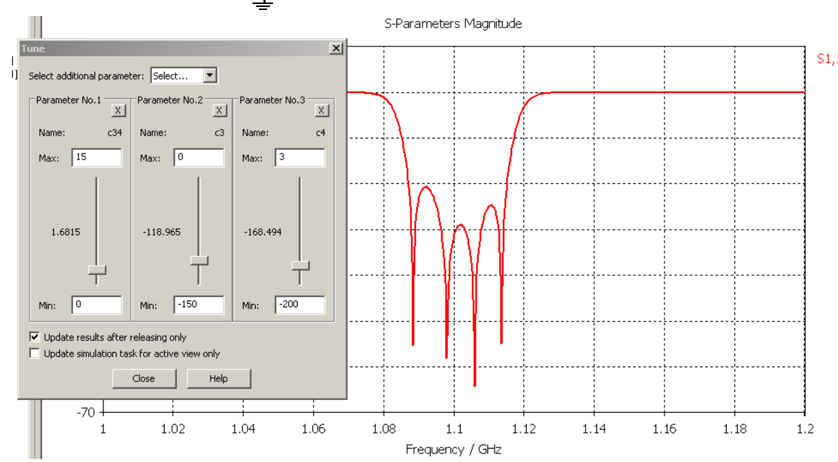
Method of Porttuning

Coupling between resonators are designed as negative Cs (act as TLs 90 deg)



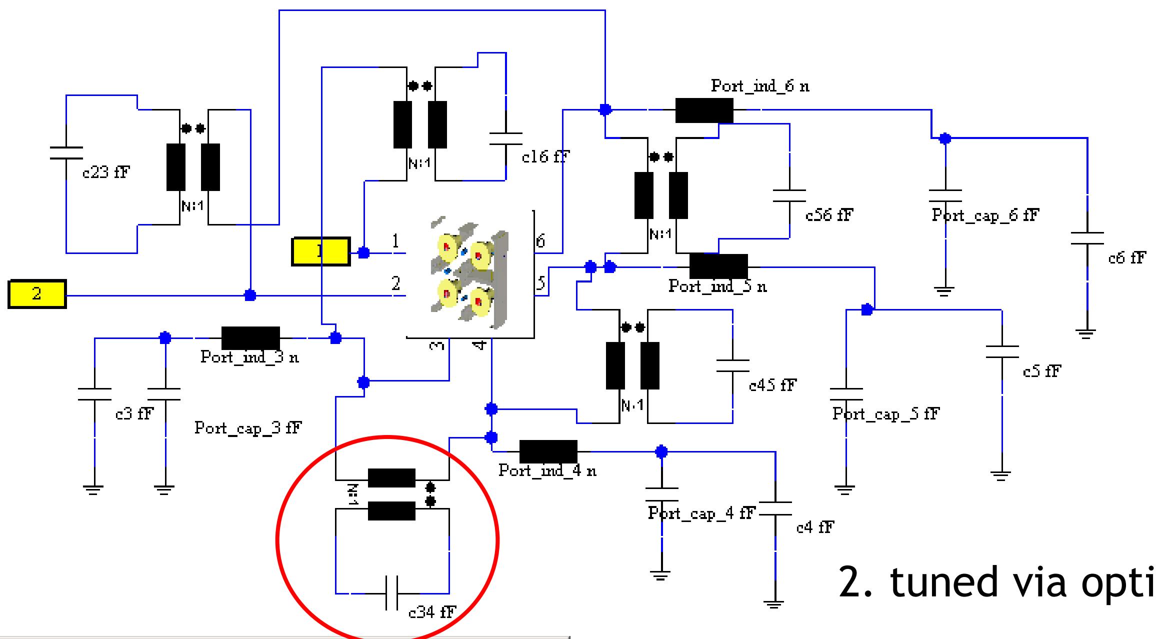
1. Use Tuner for C3 to C6 to manually adjust a good filter response

c16	0
c23	c16
c3	0
c34	0
c4	0
c45	0
c5	c4
c56	c34
c6	c3

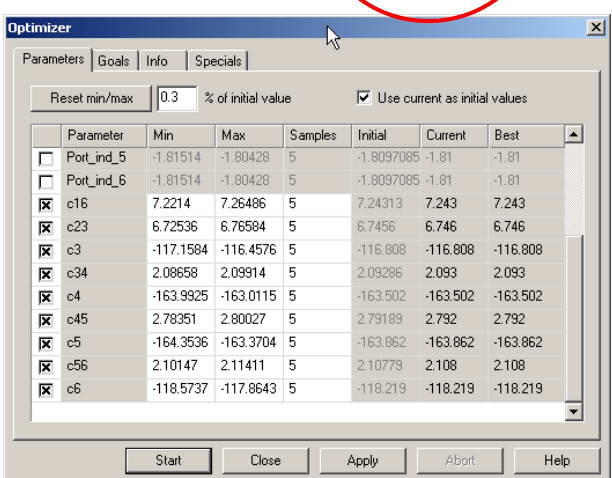


Method of Porttuning

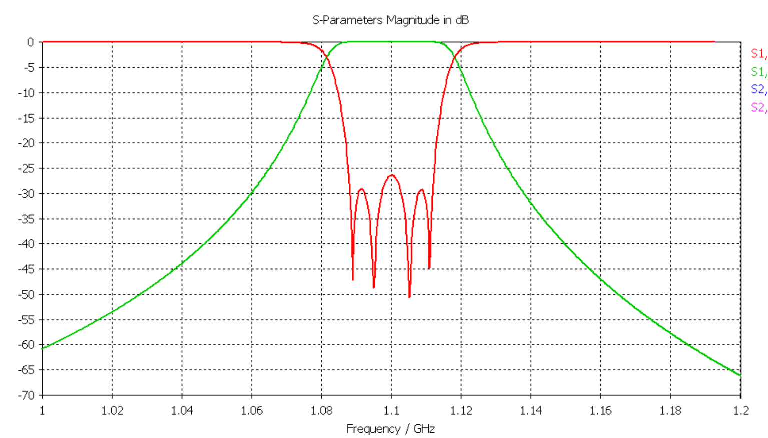
Coupling between resonators are designed as negative Cs (act as TLs 90 deg)



2. tuned via optimisation (GA: simplex)

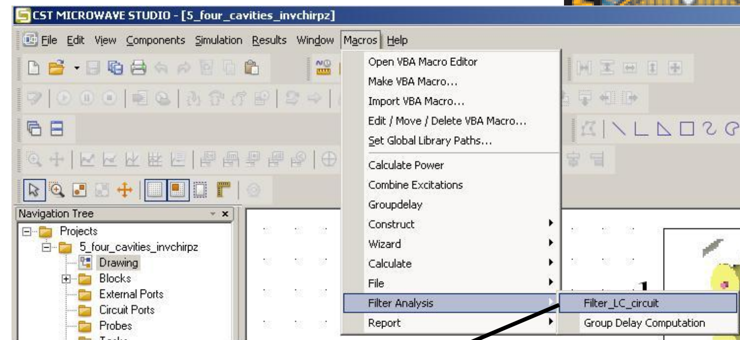


	Parameter	Min	Max	Samples	Initial	Current	Best
☐	Port_ind_5	-1.81514	-1.80428	5	-1.8097085	-1.81	-1.81
☐	Port_ind_6	-1.81514	-1.80428	5	-1.8097085	-1.81	-1.81
☒	c16	7.2214	7.26486	5	7.24313	7.243	7.243
☒	c23	6.72536	6.76584	5	6.7456	6.746	6.746
☒	c3	-117.1584	-116.4576	5	-116.808	-116.808	-116.808
☒	c34	2.08658	2.09914	5	2.09286	2.093	2.093
☒	c4	-163.9925	-163.0115	5	-163.502	-163.502	-163.502
☒	c45	2.78351	2.80027	5	2.79189	2.792	2.792
☒	c5	-164.3536	-163.3704	5	-163.862	-163.862	-163.862
☒	c56	2.10147	2.11411	5	2.10779	2.108	2.108
☒	c6	-118.5737	-117.8643	5	-118.219	-118.219	-118.219

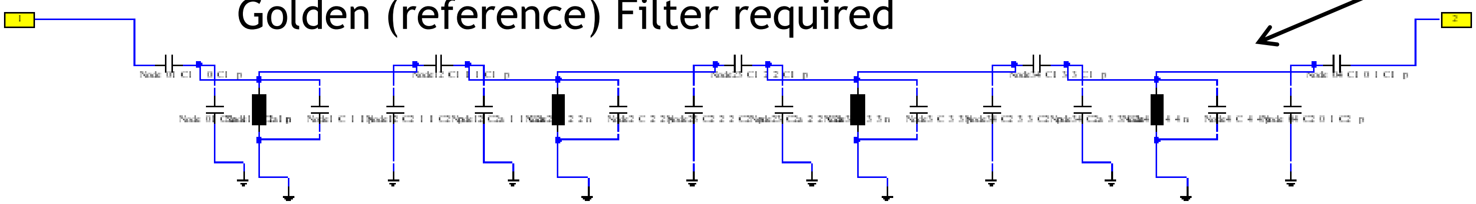


Inverse Chirp-Z Transformation

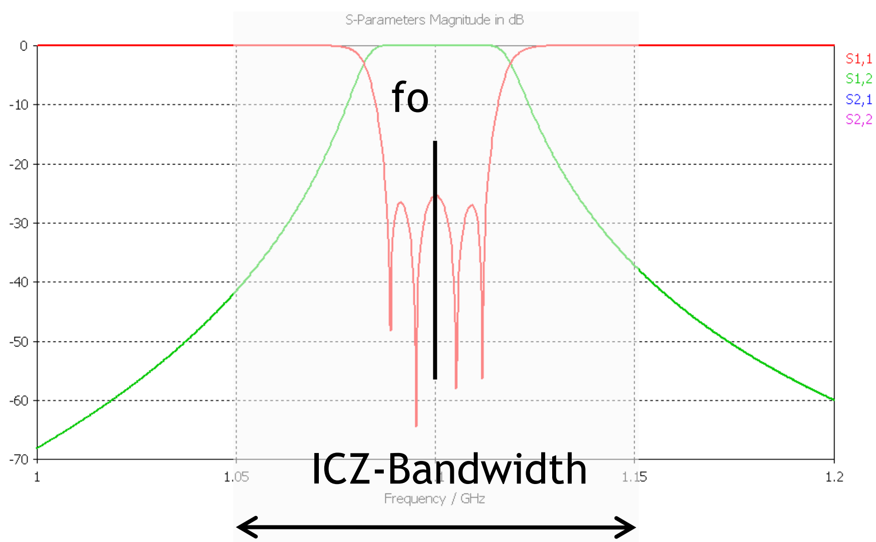
The chirp Z-Transformation can be used as a more flexible means to calculate discrete Fourier transforms. In particular, the unit circle version (known as chirp-transform) can be used to create a high-quality zoom function.



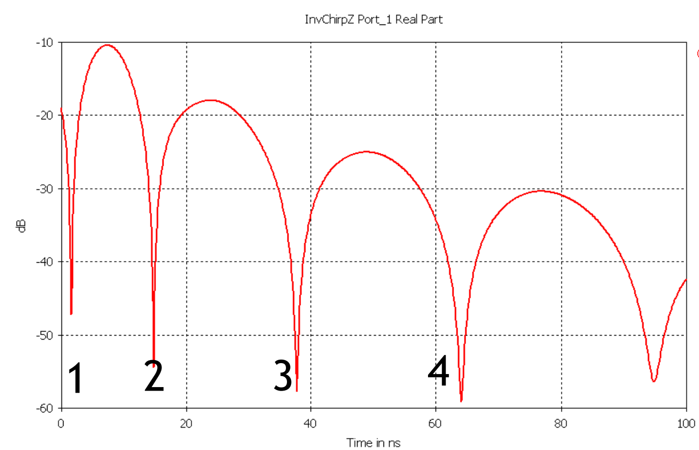
Golden (reference) Filter required



S-Parameter

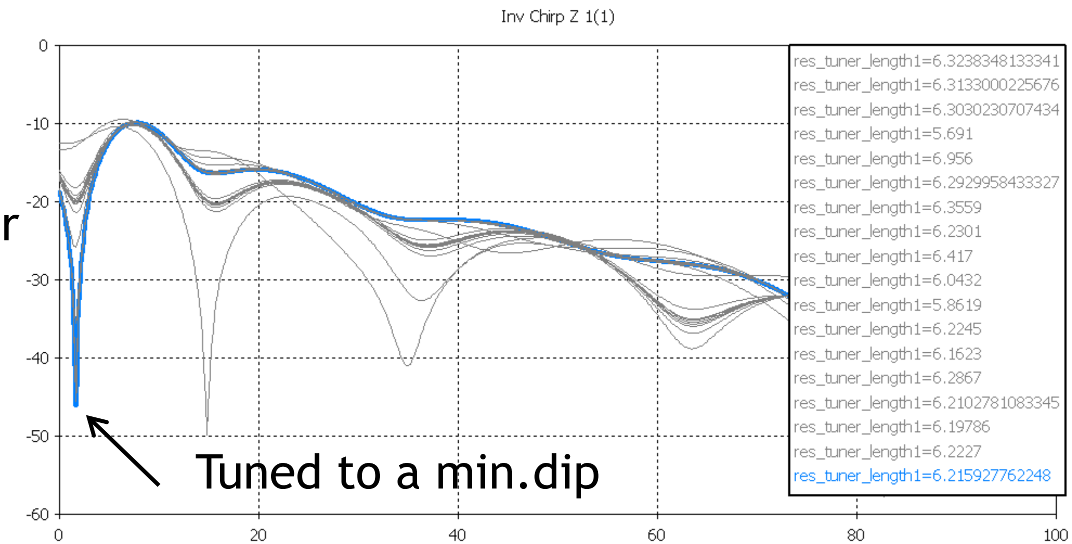


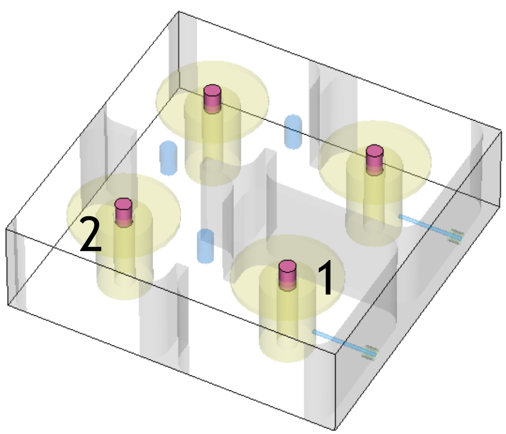
Inverse Chirp-Z response



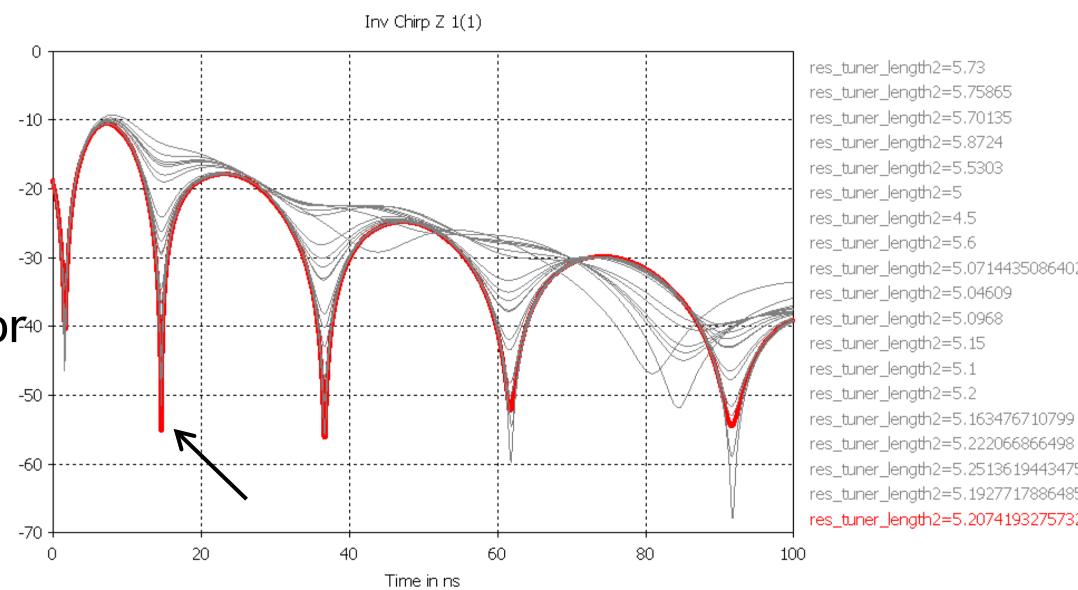
Inverse Chirp-Z Transformation

Tuning of 1st resonator

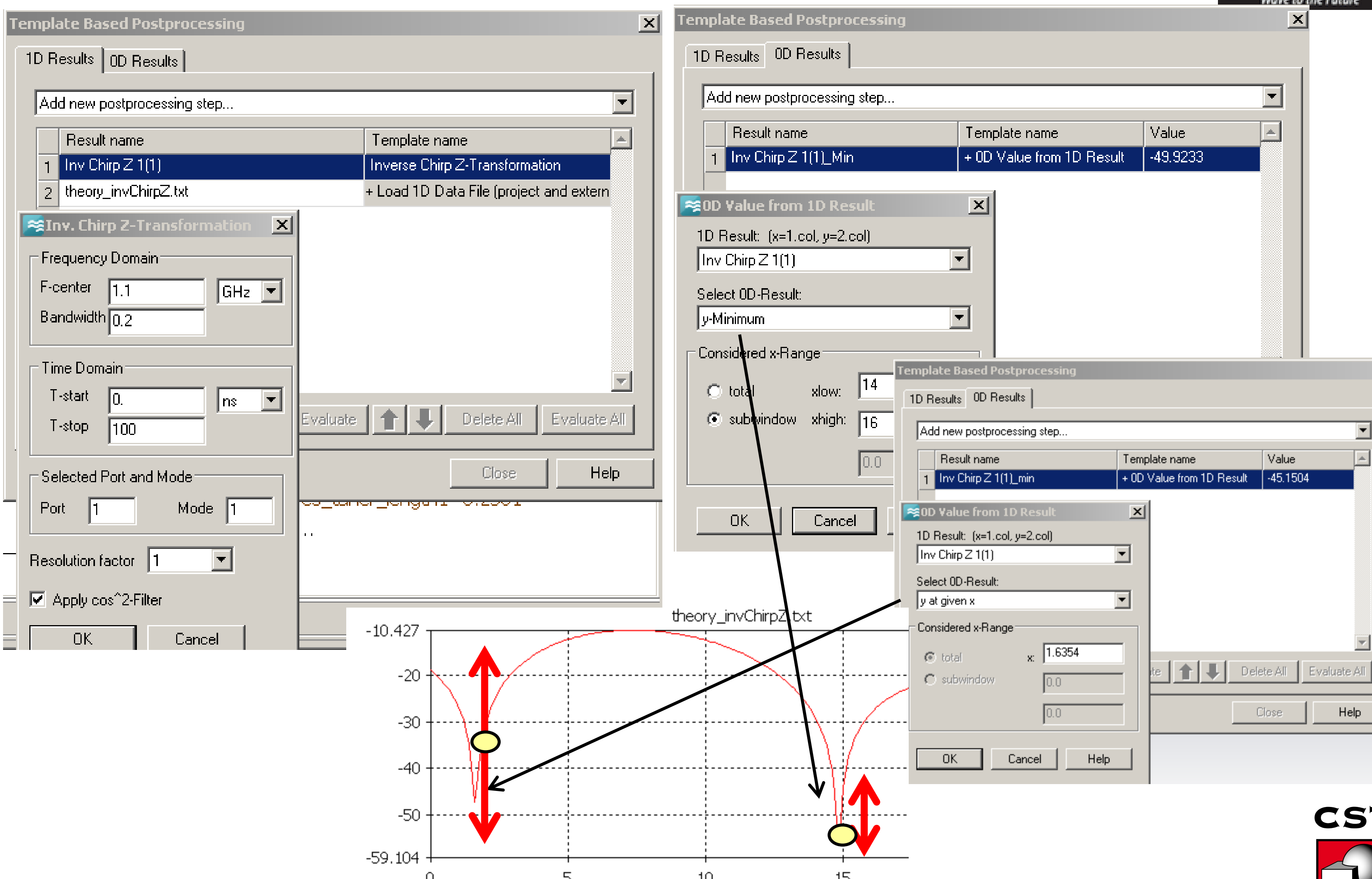




Tuning of 2nd resonator

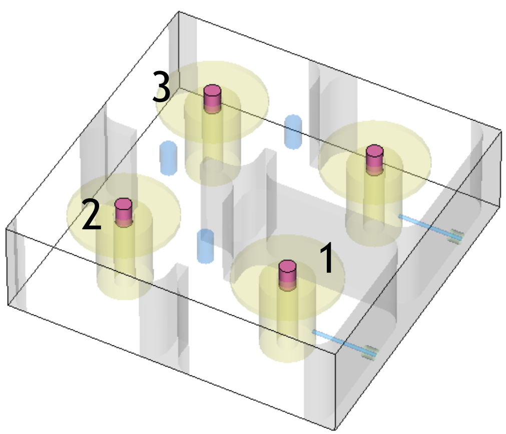


1D Template / 0D Template

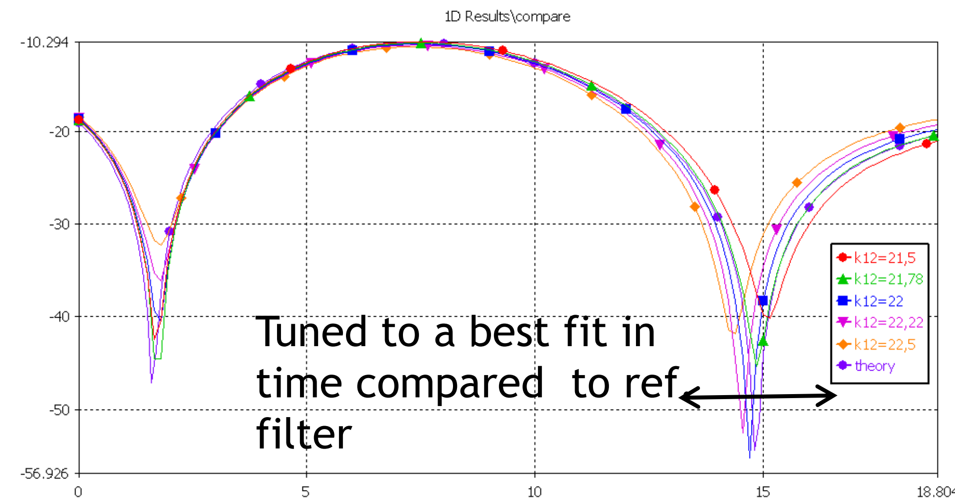


Inverse Chirp-Z Transformation

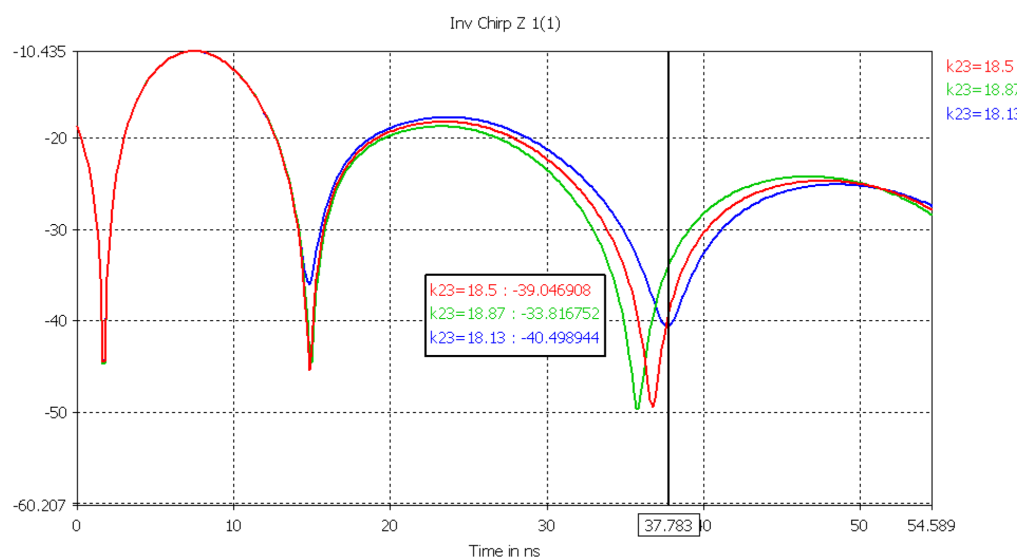
Tuning of coupling between 1st and 2nd resonator



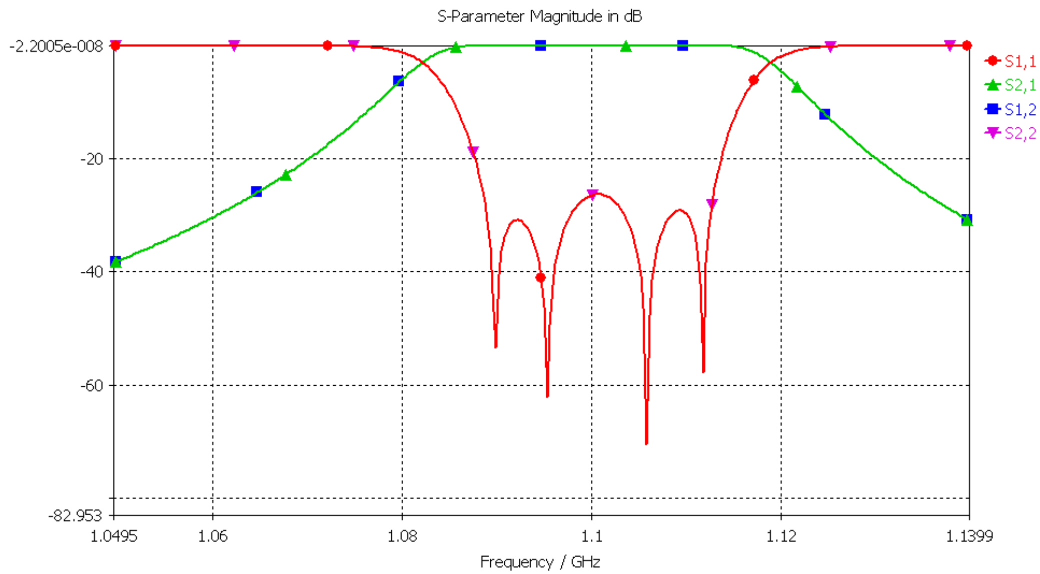
Tuning of coupling between 2nd and 3rd resonator

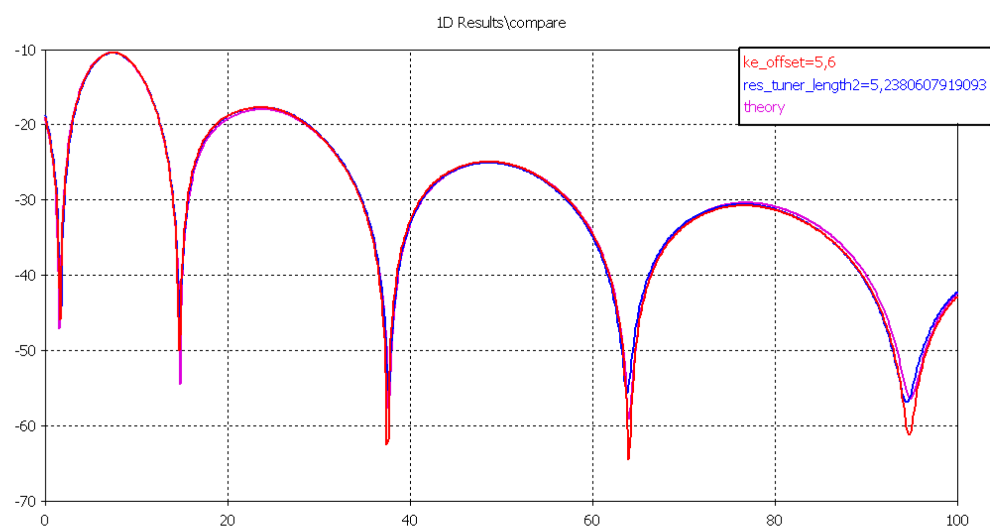


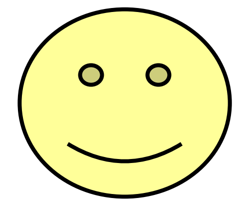
Tuned to a best fit in time compared to ref filter



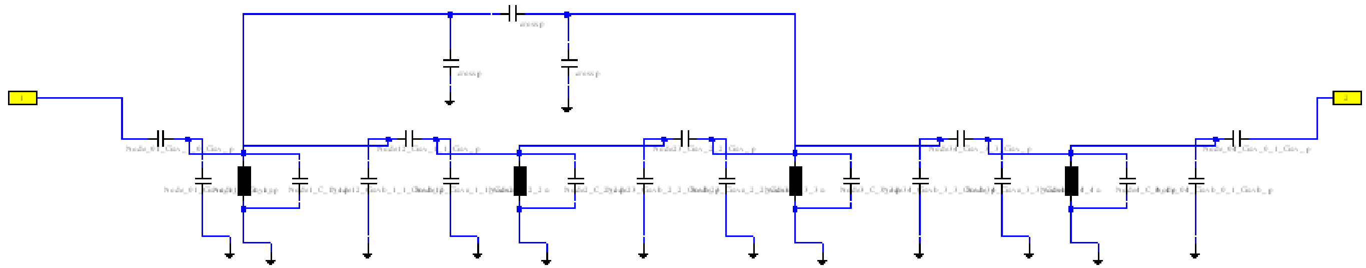
Inverse Chirp-Z Transformation

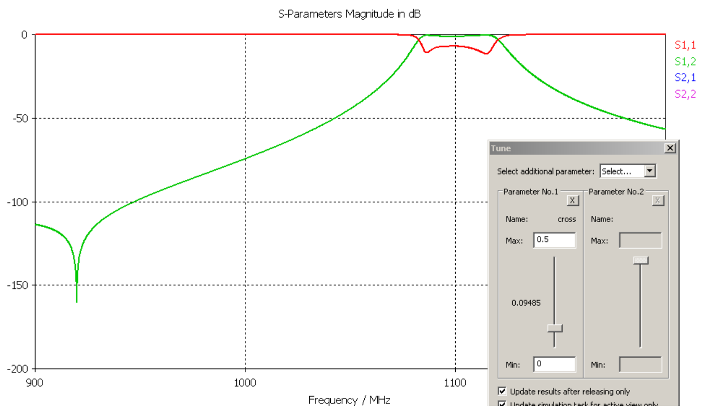


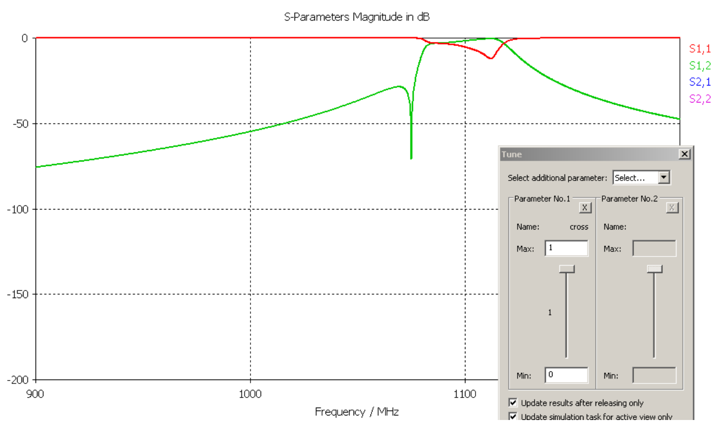




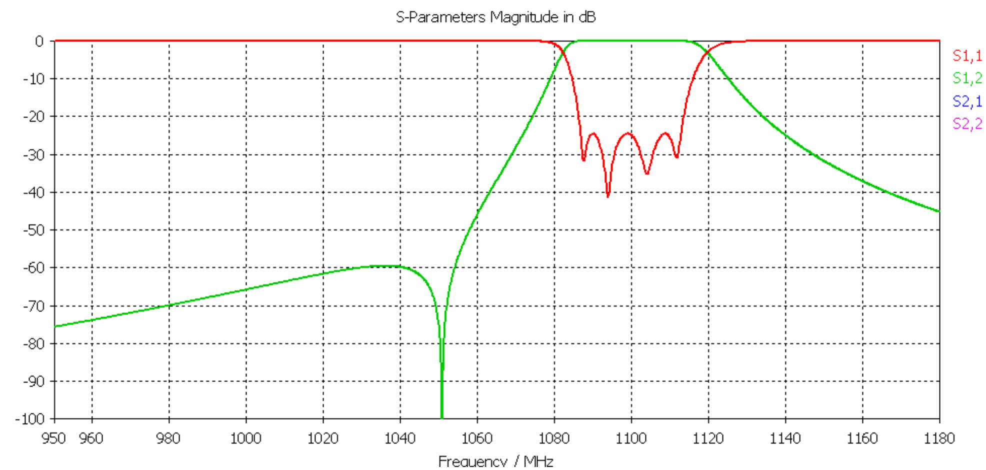
Introduction of a single Crosscoupling





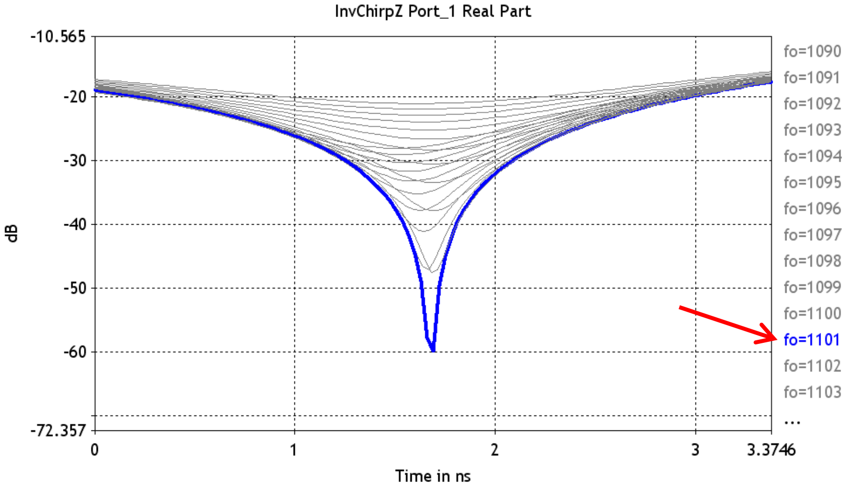


Tuned using the Simplex Optimizer

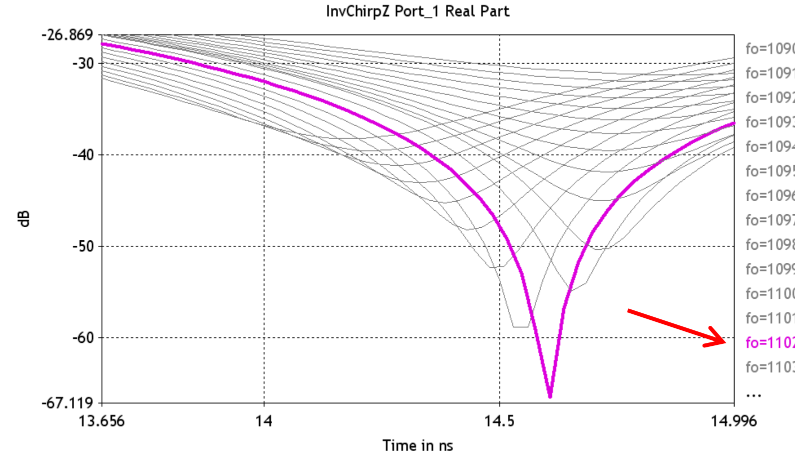


Introduction of a single Crosscoupling

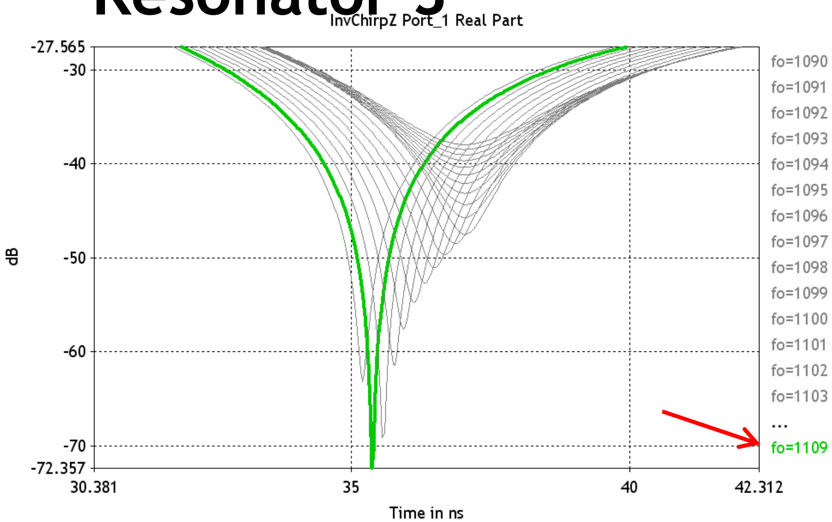
Resonator 1



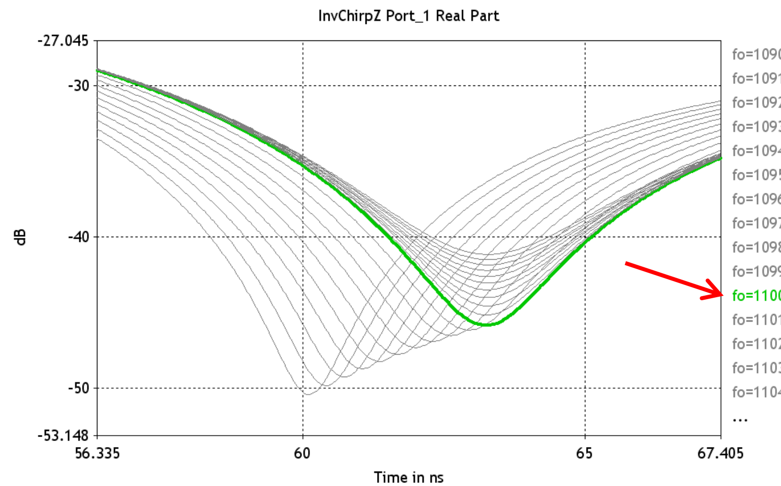
Resonator 2



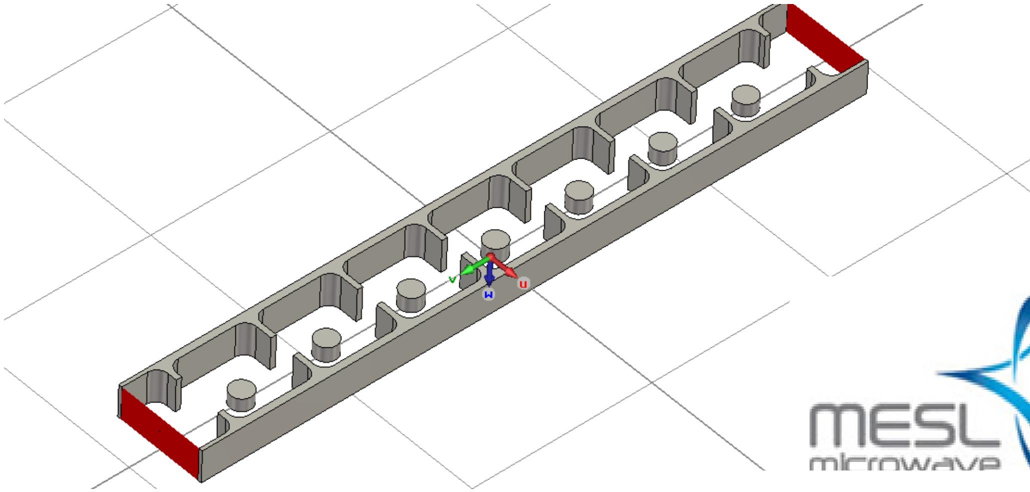
Resonator 3



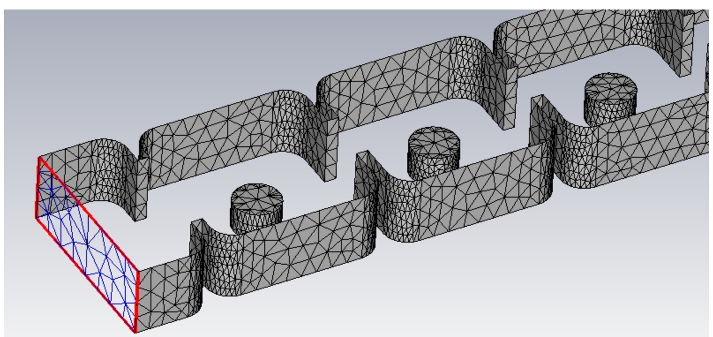
Resonator 4

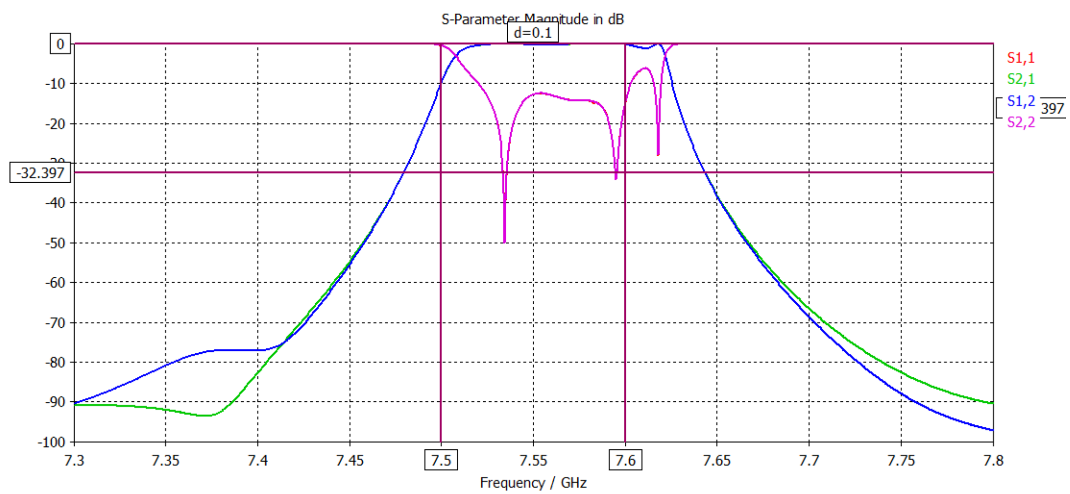


Real World Example: 7-Post Filter *)



Center frequency: 7.55 GHz
Bandwidth: 100 MHz
Rel Bandwidth: 1.3 %
Insertion Loss: -0.01 dB
Return Loss: – 26 dB



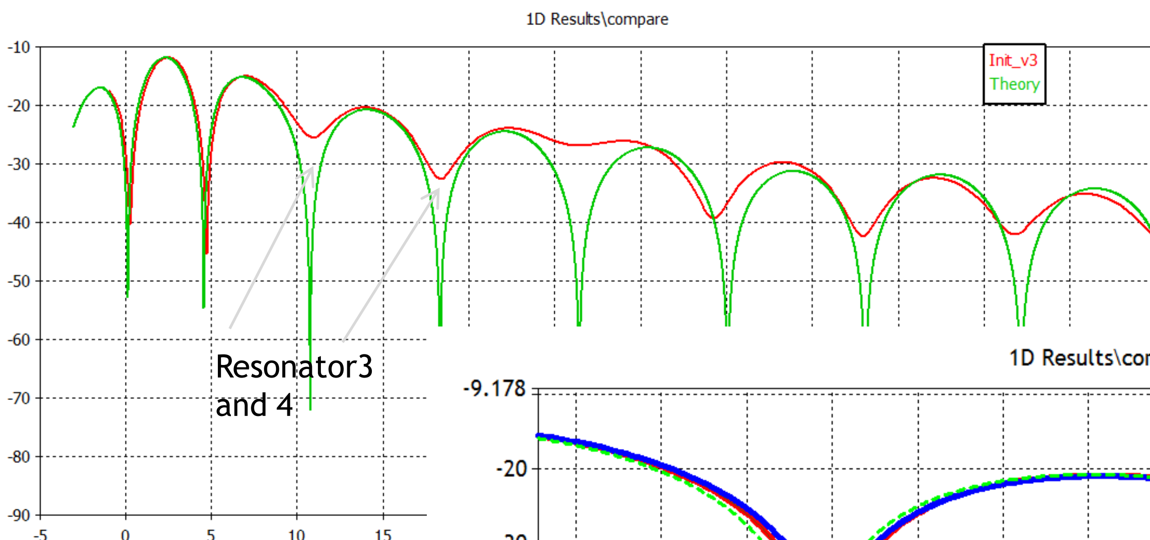


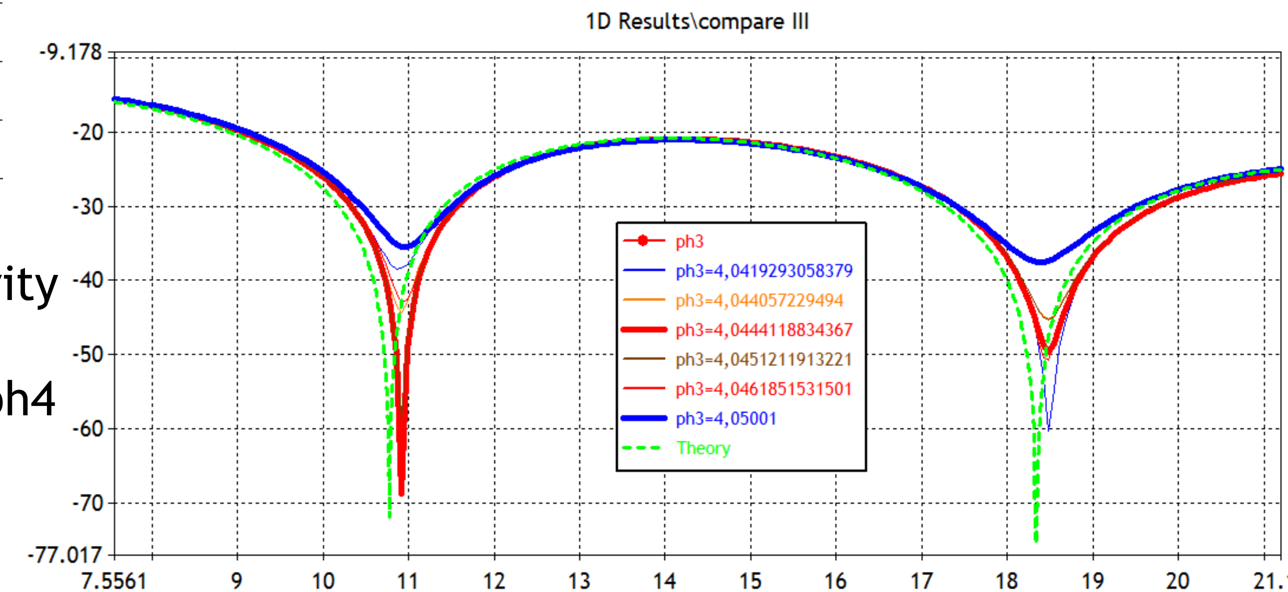
Best results obtained by Group delay Tuning

*) By courtesy of MESL Microwave Limited, Edinburgh

7Post Filter: Method of InvChirpZ

Comparison of the InvChirpZ-resonse between groupdelayed tuned filter and Theory

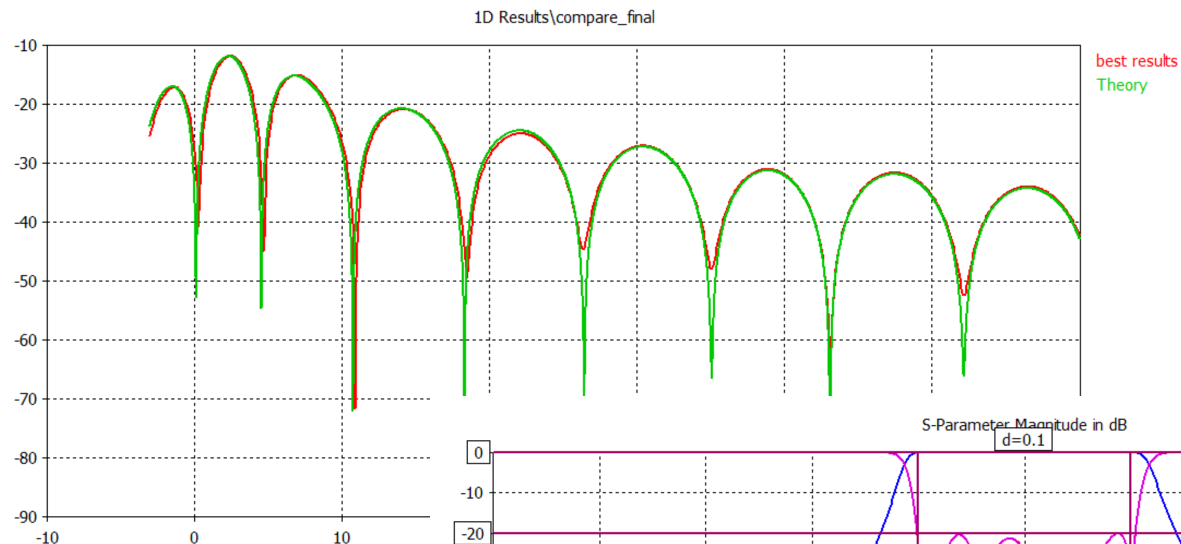


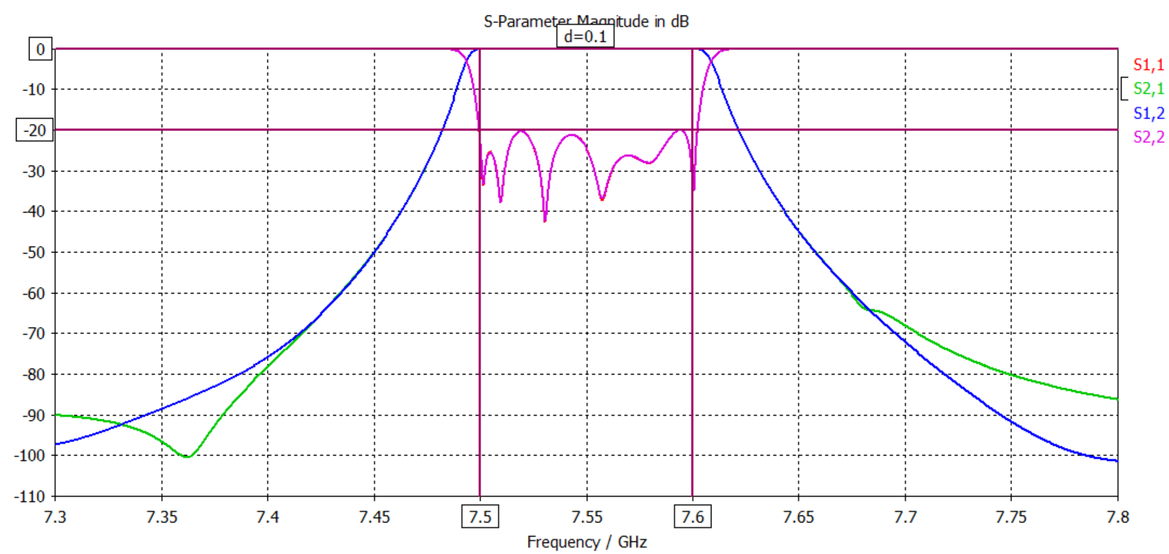


Note the high sensitivity at resonator 3 and 4 (parameter ph3 and ph4 respectively)

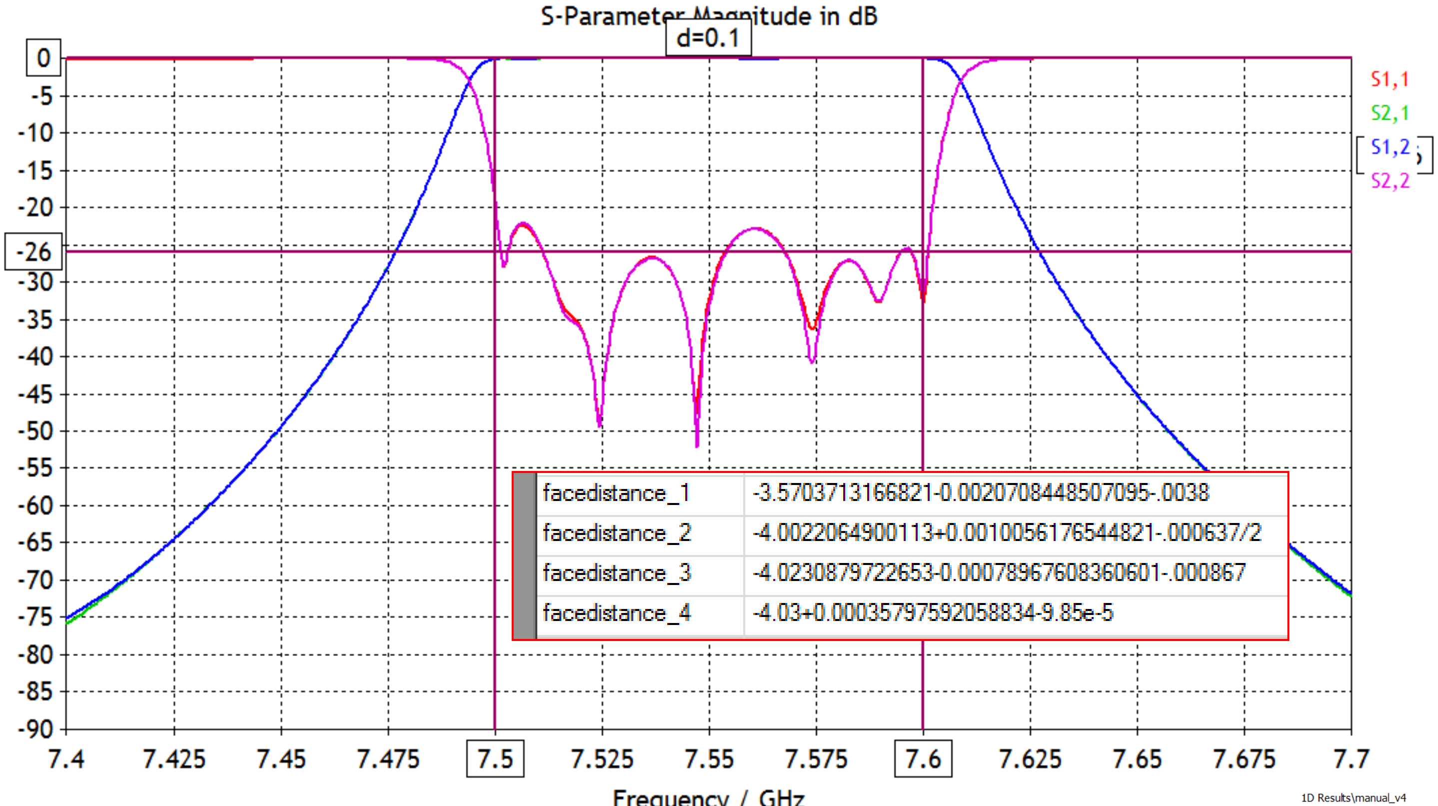
7Post Filter: Method of InvChirpZ ´

Final results by individually tuned posts



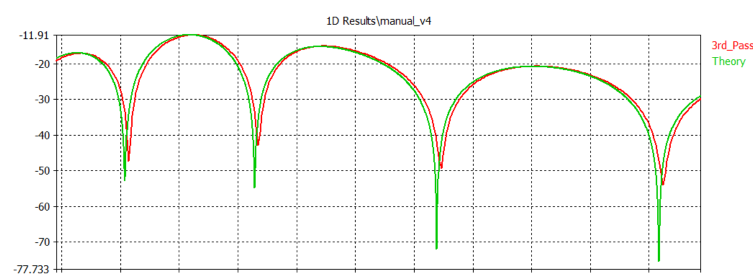


7PostFilter: Method of InvChirpZ ´



facedistance_1	-3.5703713166821-0.0020708448507095-.0038
facedistance_2	-4.0022064900113+0.0010056176544821-.000637/2
facedistance_3	-4.0230879722653-0.00078967608360601-.000867
facedistance_4	-4.03+0.00035797592058834-9.85e-5

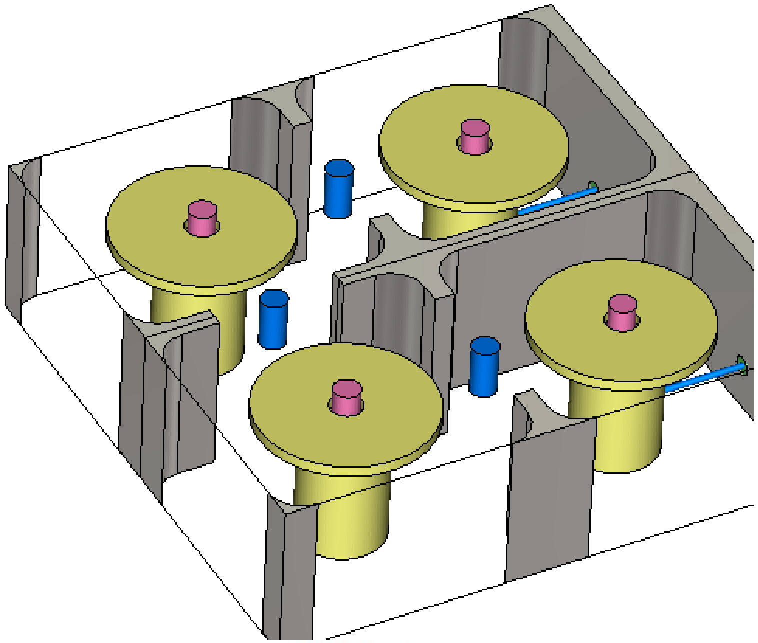
Result of the new 3D simulation

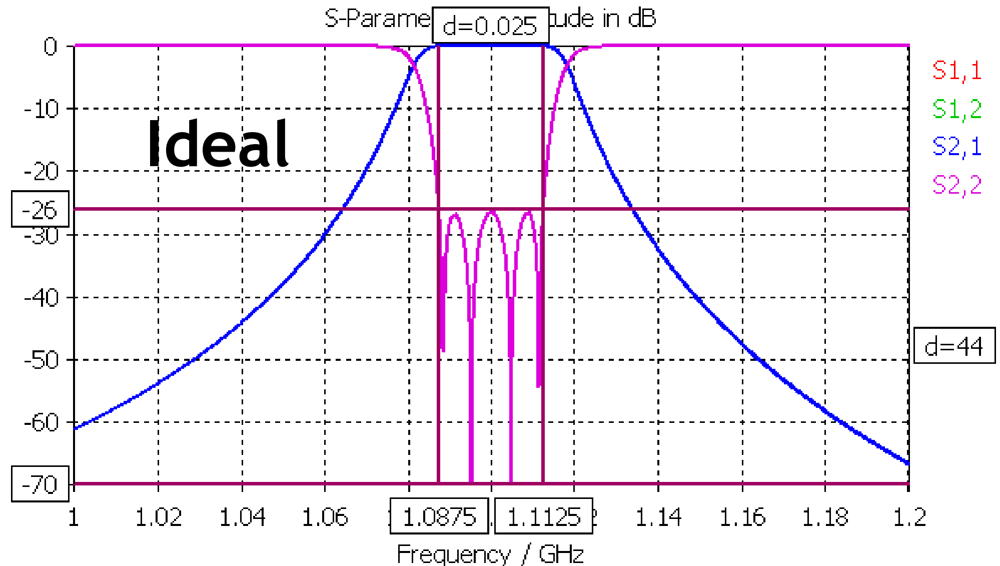


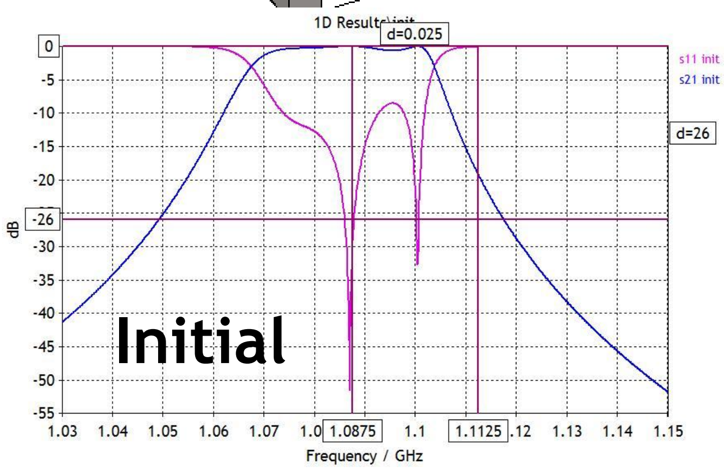
Agenda

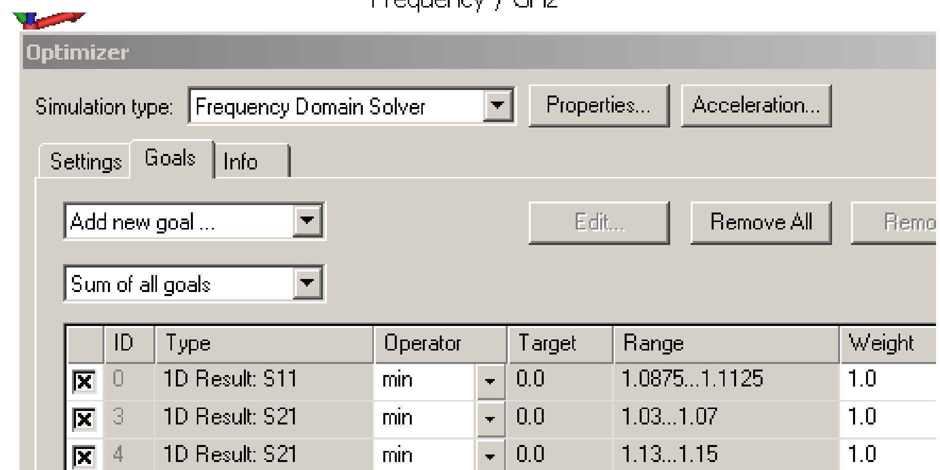
- Introduction
- Optimizers
- Tuning Methods
- **Application of Local optimization strategies**
- Solver selections, accuracy
- Guidelines and Summary

4-Pole Bandpass Filter (2.3% fractional Bandwidth)

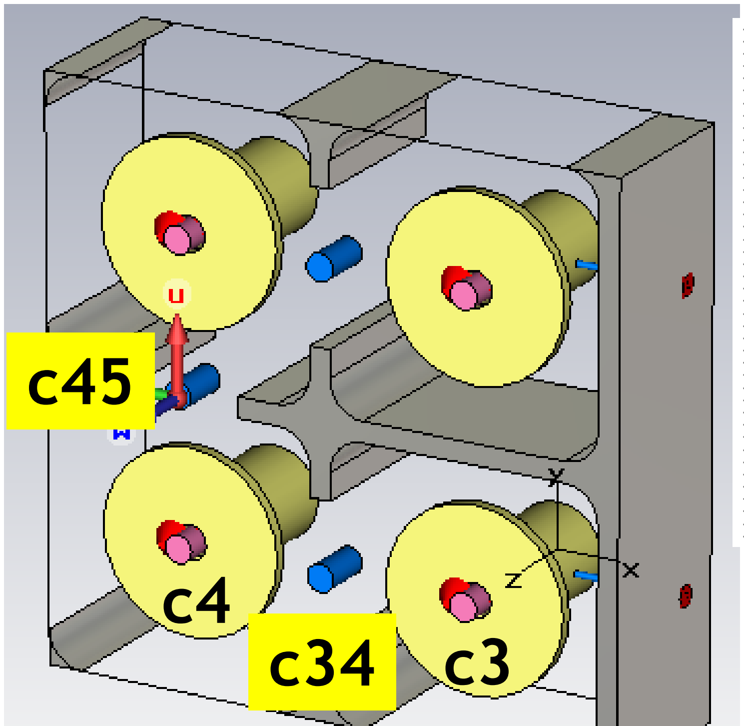


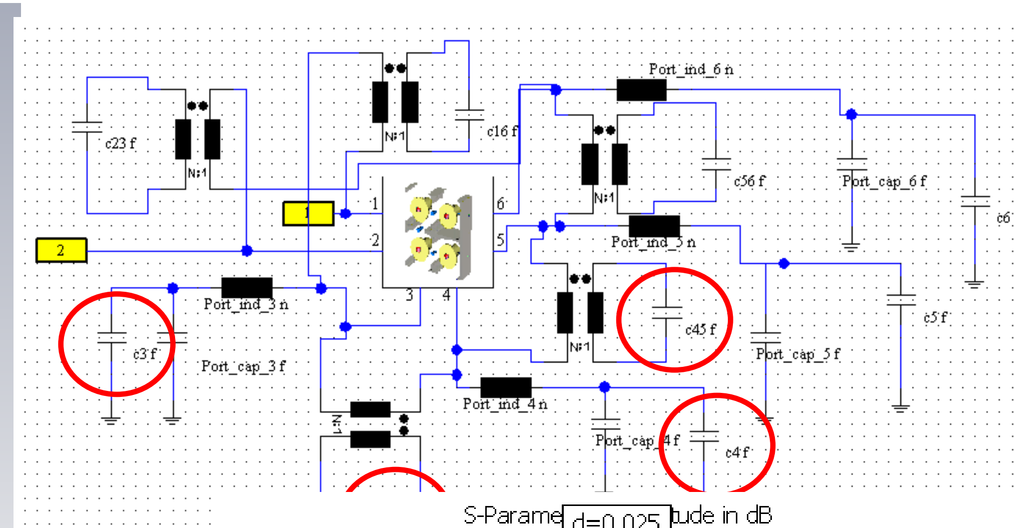




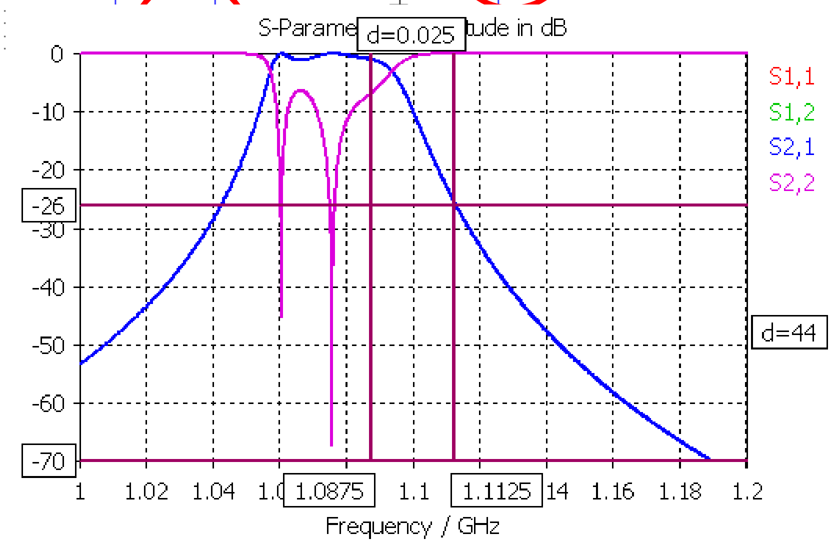


4PostFilter: Parameters:





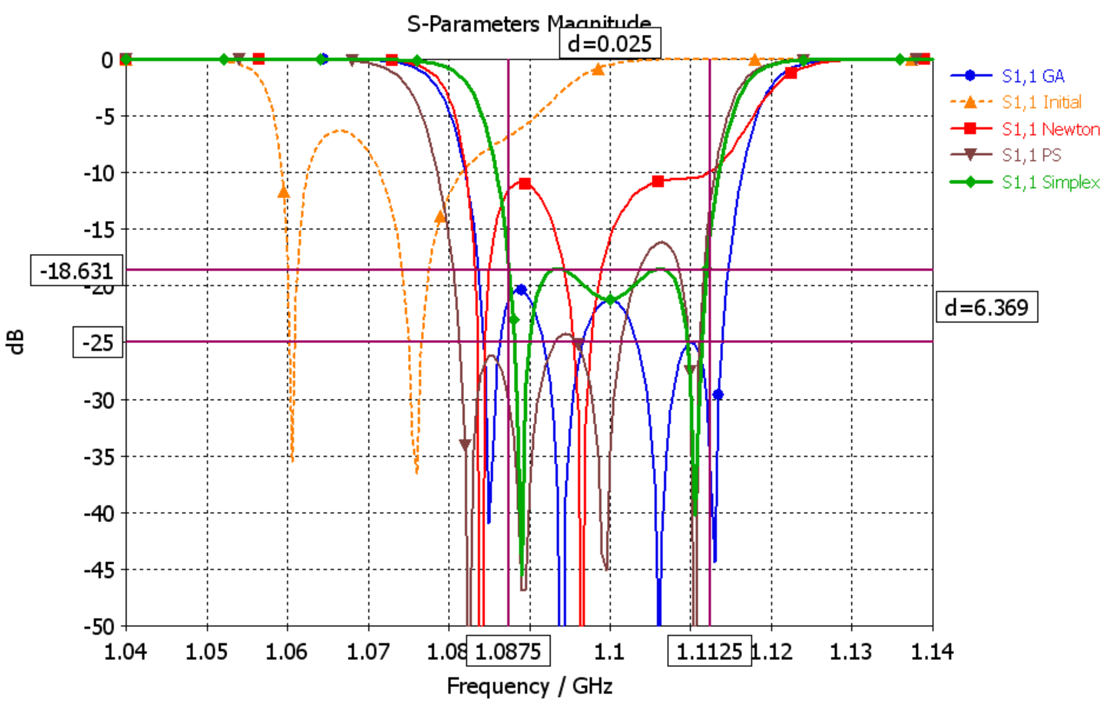
port1



Parameter	Min	Max
c3	-300	300
c34	-30	30
c4	-300	300
c45	-30	30

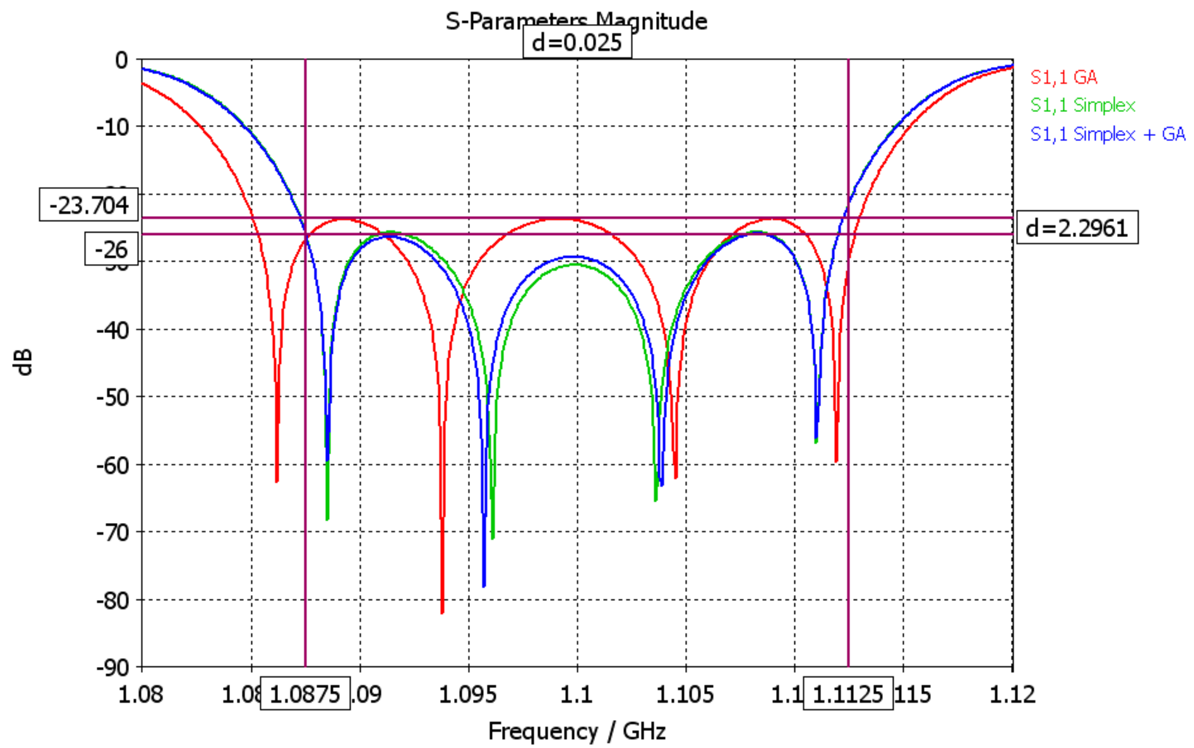
4PostFilter: Result Comparison

Optimization Algorithm	Goal value	Number of Iterations	C3	C34	C4	C45
Nelder - Mead Simplex	6.5304	284	-116.703	10.8331	-173.935	6.06555
Genetic Algorithm	4.6469	497	-101.677	-3.12807	-147.783	-3.7497
Particle Swarm	9.4008	451	-71.691	-2.31349	-125.868	-4.65223
Quasi-Newton	15.7412	66	-133.449	-5.62373	-147.671	-0.730258

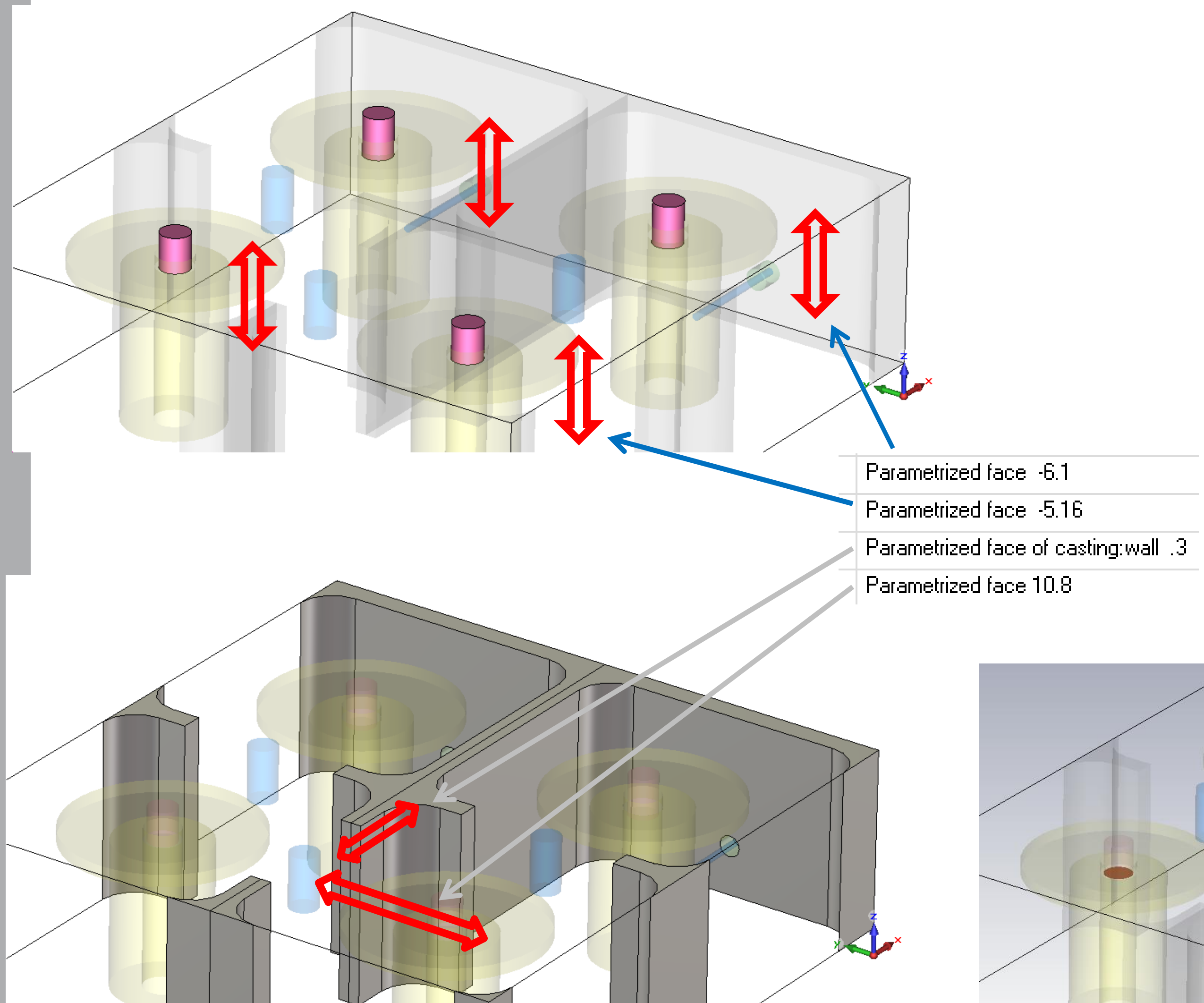


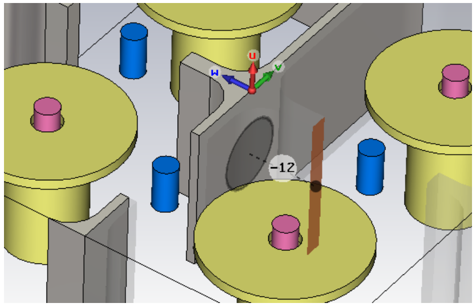
4PostFilter: 2nd Step - Fine Optimization

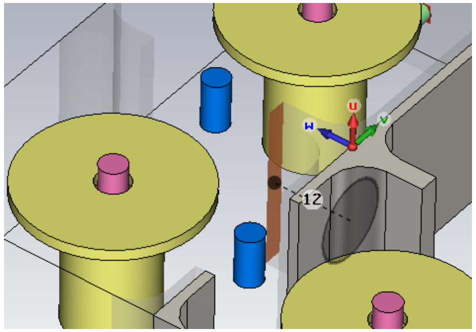
Optimization Algorithm	Goal value	Number of Iterations	C3	C34	C4	C45
Nelder - Mead Simplex	0.0517	352	-109.806	4.32482	-164.966	3.500
Genetic Algorithm	0.0653	1953	-100.589	-0.23677	-151.744	-0.920112
Simplex + GA	0.0508	1953	-109.279	4.09072	-164.547	3.43842

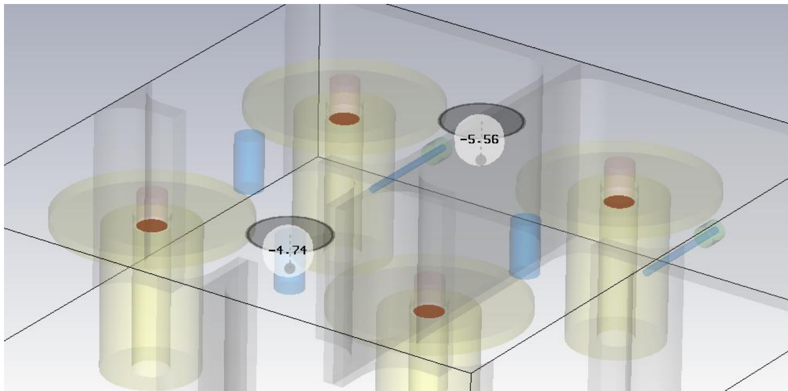


4PostFilter: Tuning Parameters/FaceConstraints -> TRF Optimizer



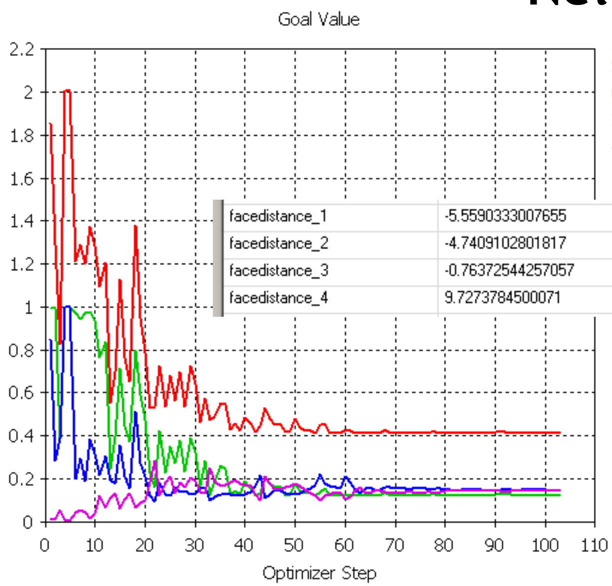




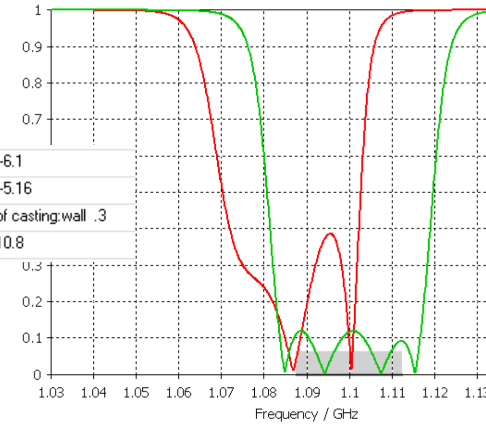


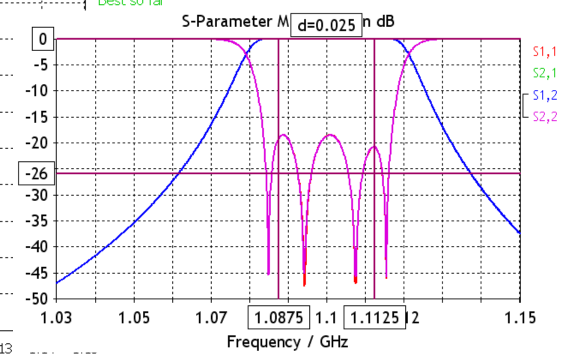
4PostFilter: Results

Nelder Mead: 70 Iterations

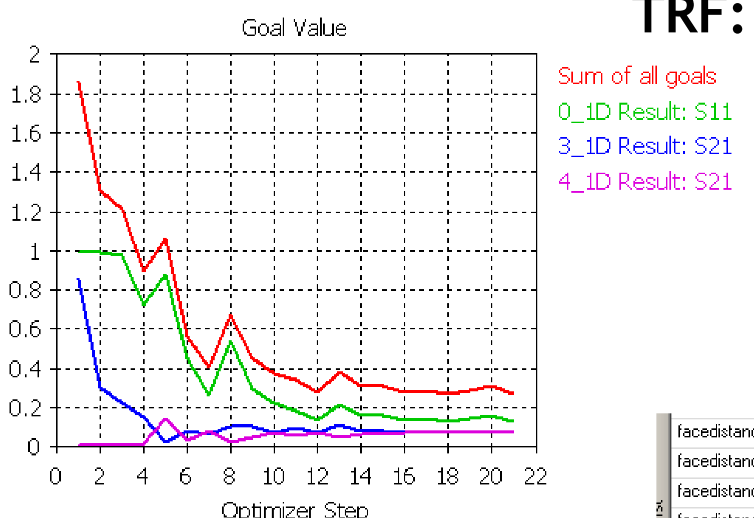


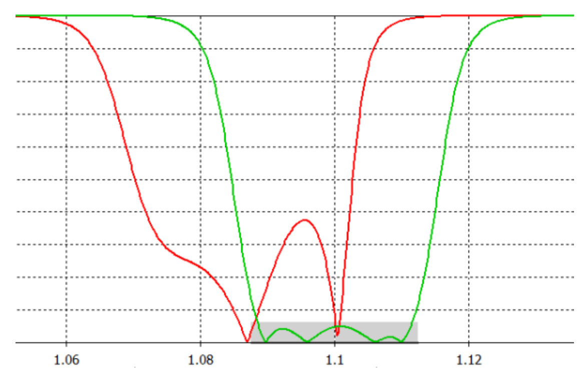
facedistance_1	-5.5590333007655	Parametrized face -6.1
facedistance_2	-4.7409102801817	Parametrized face -5.16
facedistance_3	-0.76372544257057	Parametrized face of casting:wall .3
facedistance_4	9.7273784500071	Parametrized face 10.8

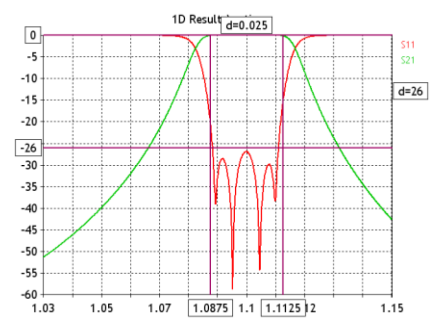




TRF: 15 Iterations



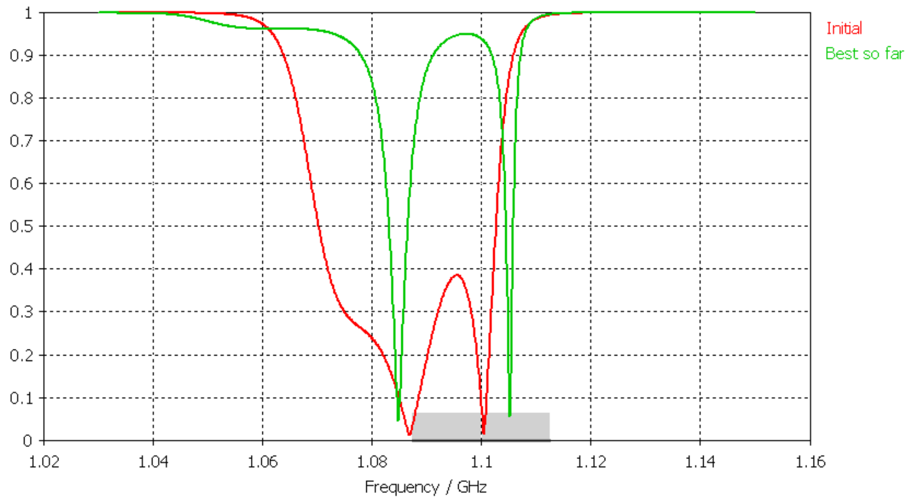




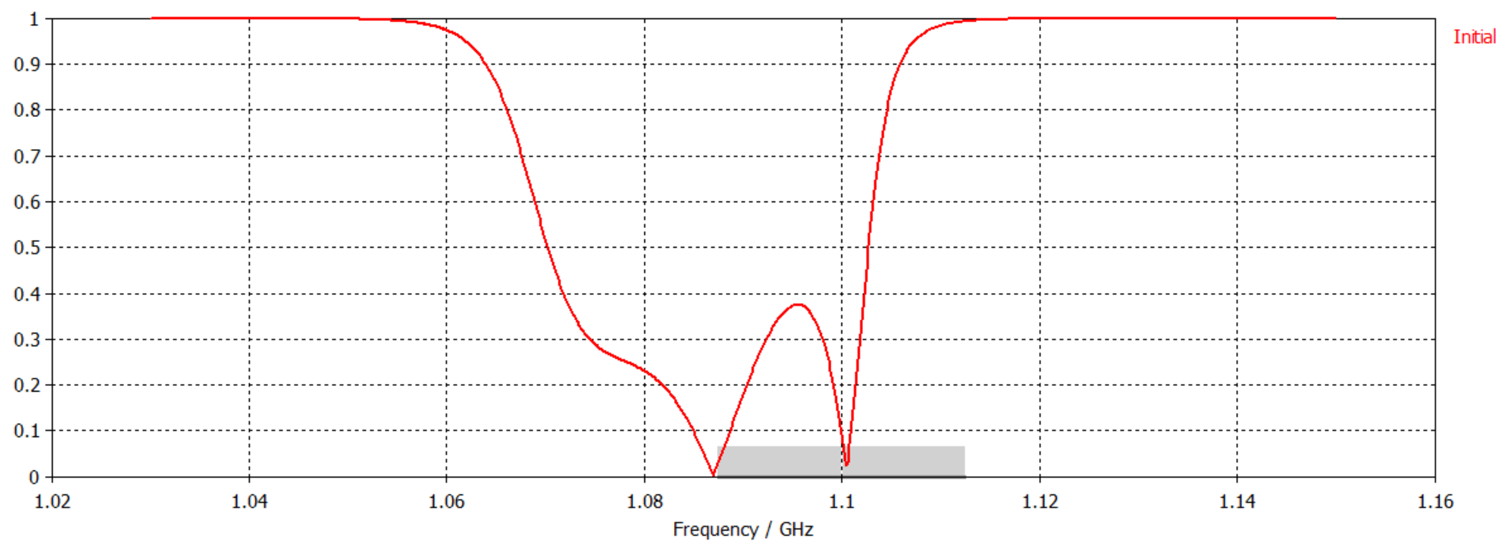
facedistance_1	-5.6140452203368	Parametrized face -6.1
facedistance_2	-4.8580310433415	Parametrized face -5.16
facedistance_3	0.89864122848554	Parametrized face of casting:wall .3
facedistance_4	11.323478857037	Parametrized face 10.8

Convergence Speed (animated)

NelderMead



TRF

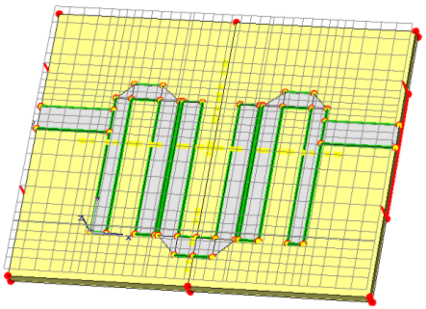


Agenda

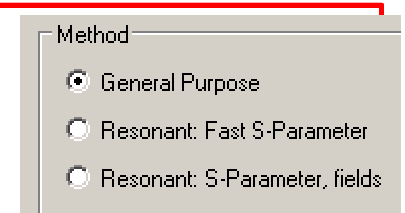
- Introduction
- Optimizers
- Tuning Methods
- Application of Local optimization strategies
- **Solver selections, accuracy**
- Guidelines and Summary

Solver Selection

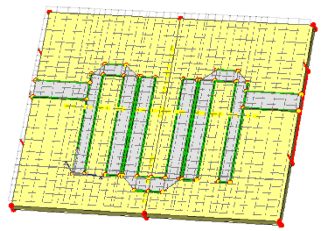
Time Domain (TD)

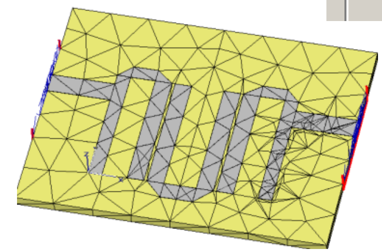


Frequency Domain (FD)

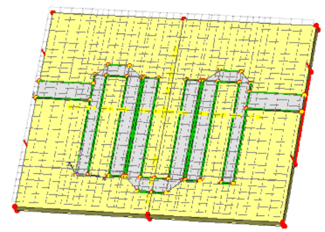


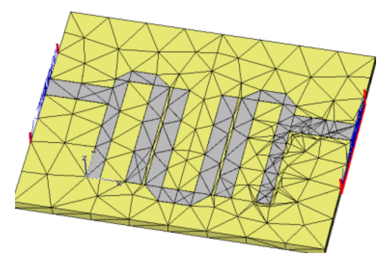
General Purpose



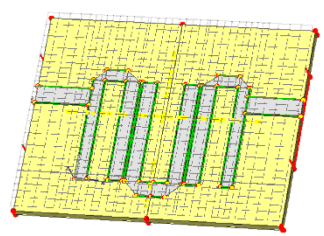


Resonant: Fast S-parameter (MOR)



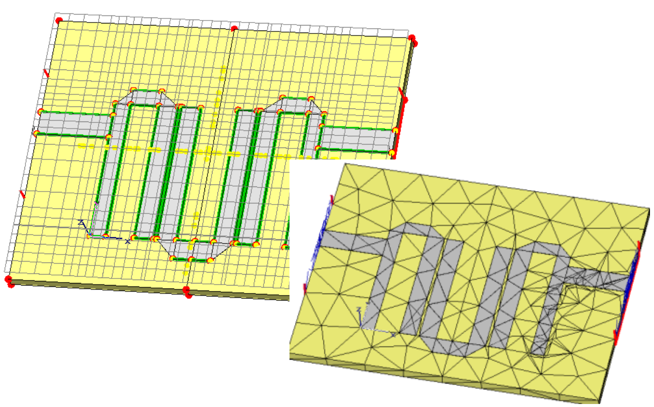


Resonant: S-Parameter, Fields (Modal Analysis)

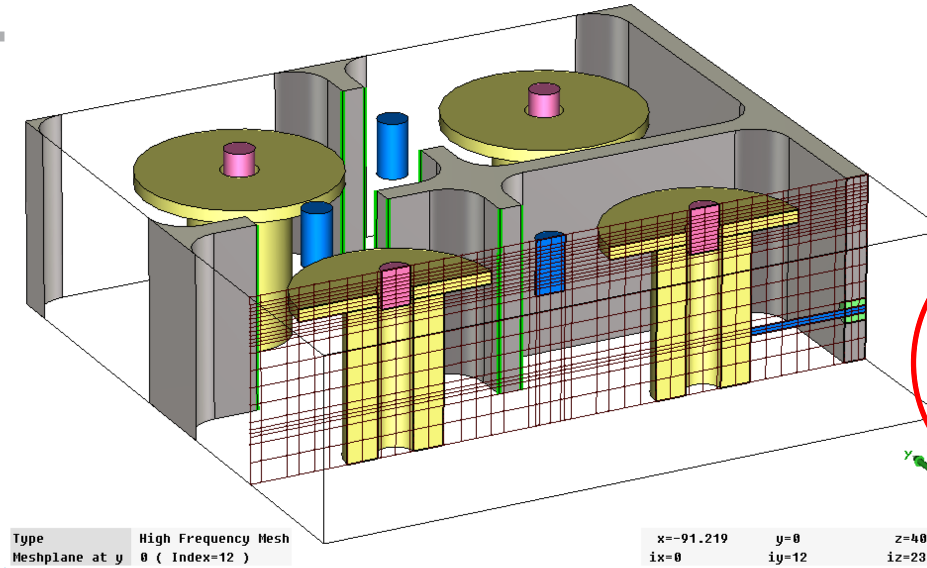


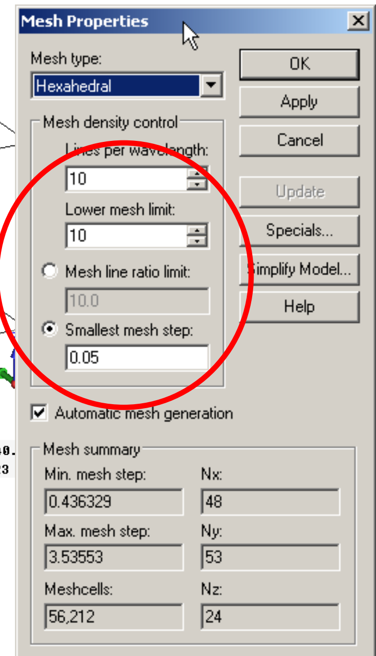
Eigenmode (E)

Modal (Resonant Fields)
Lossy/Lossless

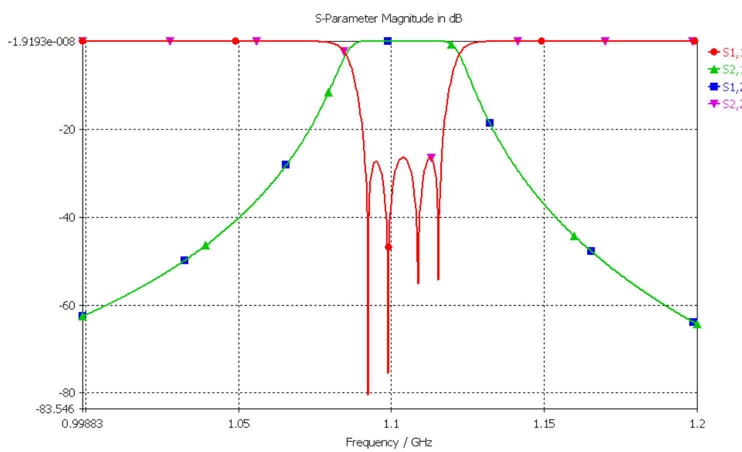


Accuracy vs. Meshdensity I

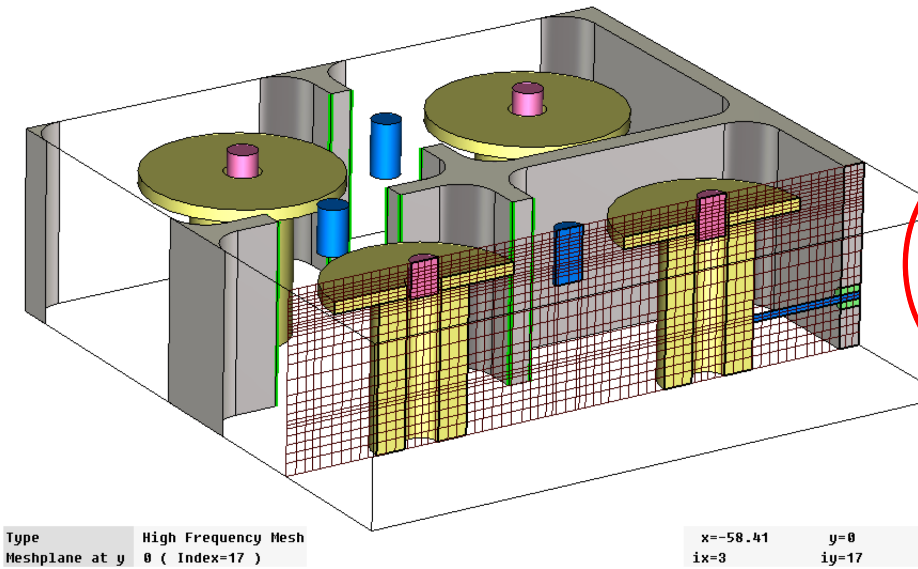


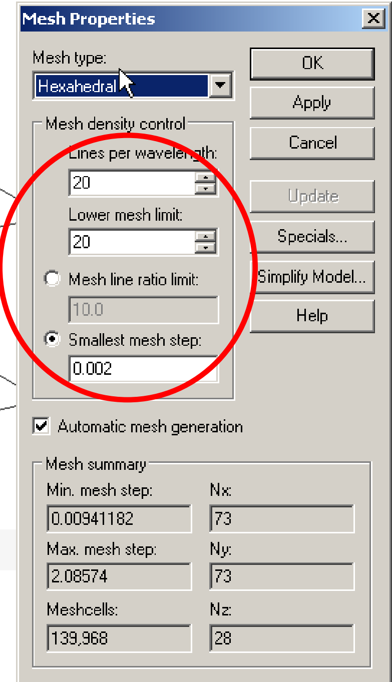


Name	Value
a	40
b	a
blend	5
c	25
coupl_tuner_12	7.5
coupl_tuner_23	7.5
epsr	1.3
h_bottom	20.4
h_top	1.7
hole_radius	2.5
k12	21.7
k23	18.2
ke_offset	5.679897142732
r_bottom	6.65
r_top	13.3
res_tuner_length1	6.1072215294614
res_tuner_length2	5.165
res_tuner_length3	res_tuner_length2
res_tuner_length4	res_tuner_length1
wall_thickness	3
wire_r	.5

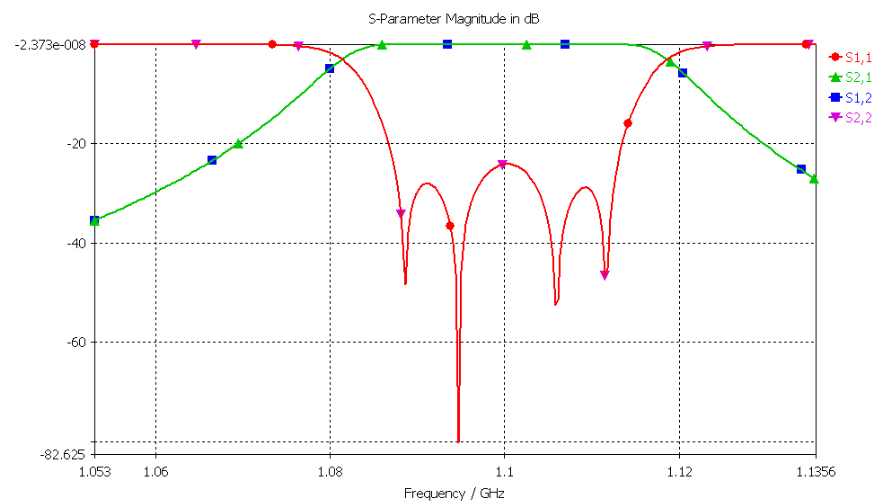


Accuracy vs. Meshdensity II

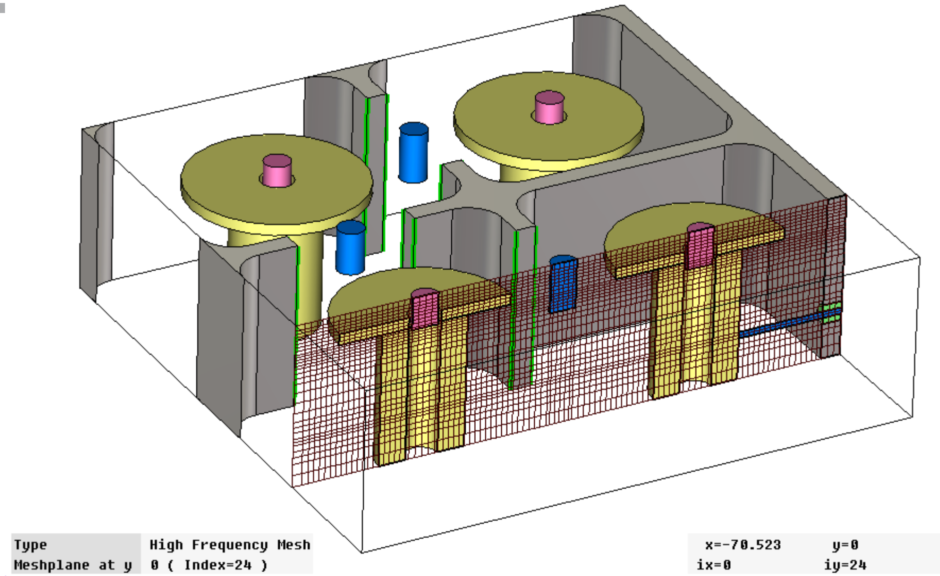


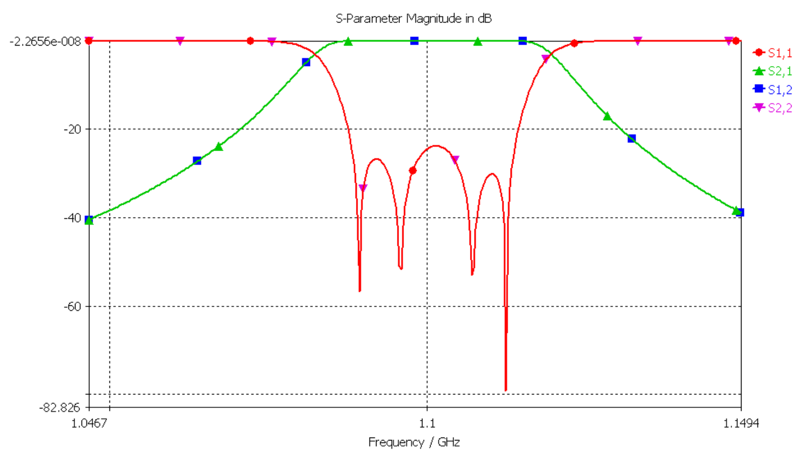


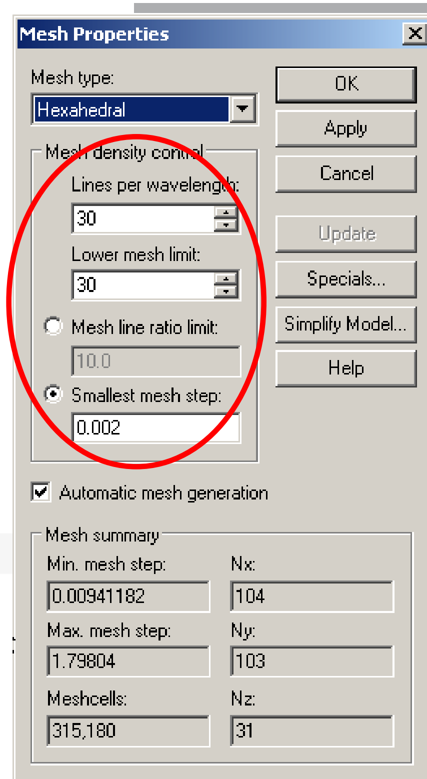
Name	Value
a	40
b	a
blend	5
c	25
coupl_tuner_12	7.5
coupl_tuner_23	6.35
epsr	1.3
h_bottom	20.4
h_top	1.7
hole_radius	2.5
k12	21.7
k23	18.2
ke_offset	5.6
r_bottom	6.65
r_top	13.3
res_tuner_length1	5.8
res_tuner_length2	4.94
res_tuner_length3	res_tuner_length2
res_tuner_length4	res_tuner_length1
wall_thickness	3
wire_r	.5



Accuracy vs. Meshdensity III



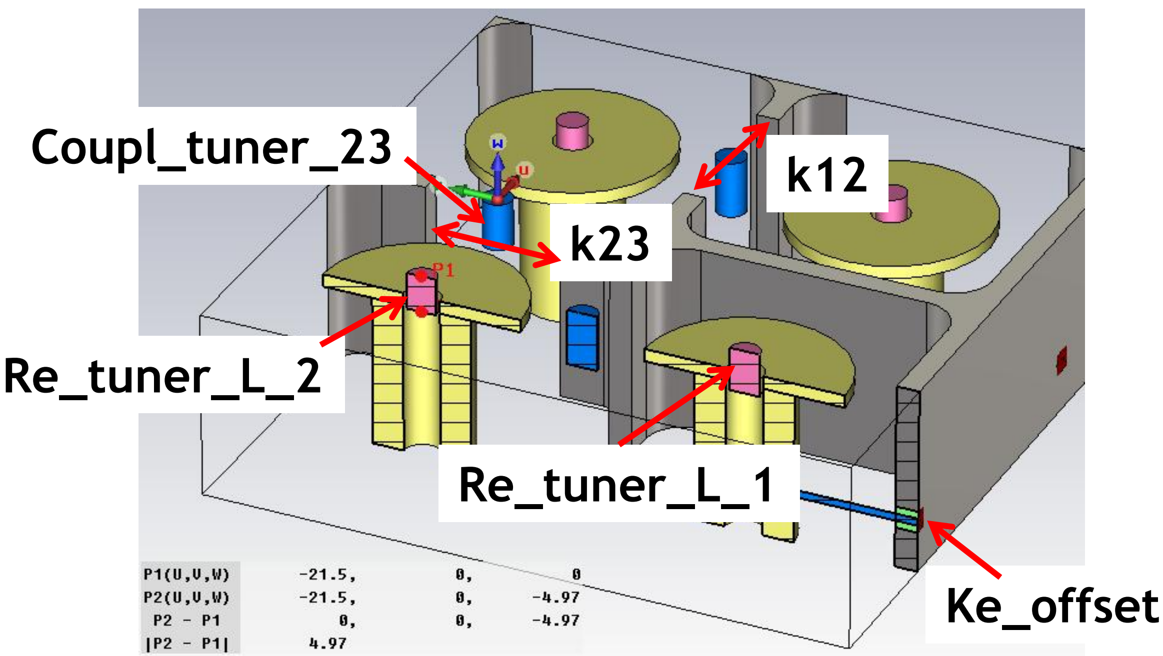




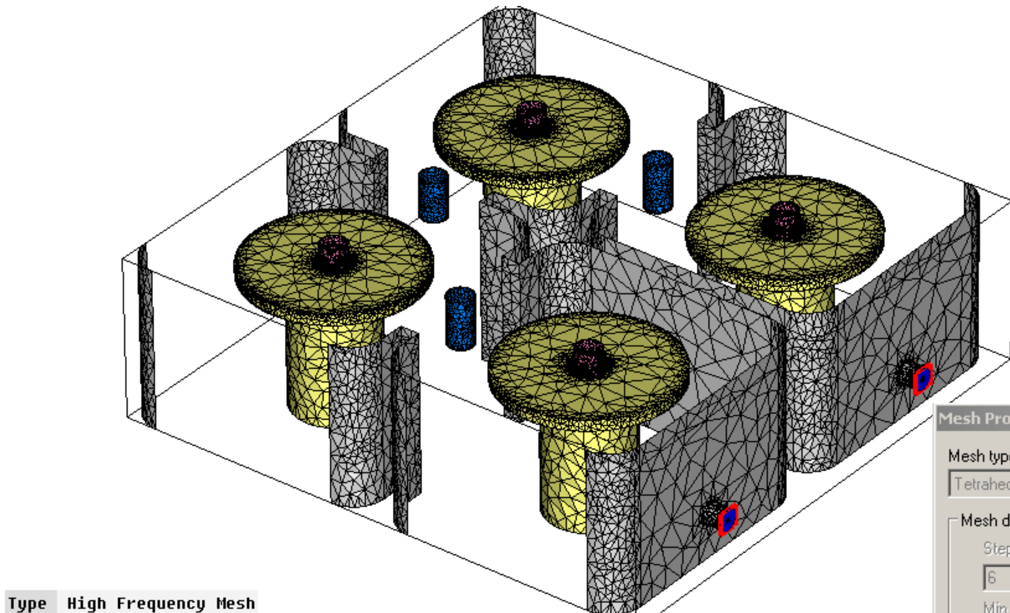
Name	Value
a	40
b	a
blend	5
c	25
coupl_tuner_12	7.5
coupl_tuner_23	6.35
epsr	1.3
h_bottom	20.4
h_top	1.7
hole_radius	2.5
k12	21.7
k23	18.2
ke_offset	5.6
r_bottom	6.65
r_top	13.3
res_tuner_length1	5.85
res_tuner_length2	4.97
res_tuner_length3	res_tuner_length2
res_tuner_length4	res_tuner_length1
wall_thickness	3
wire_r	.5

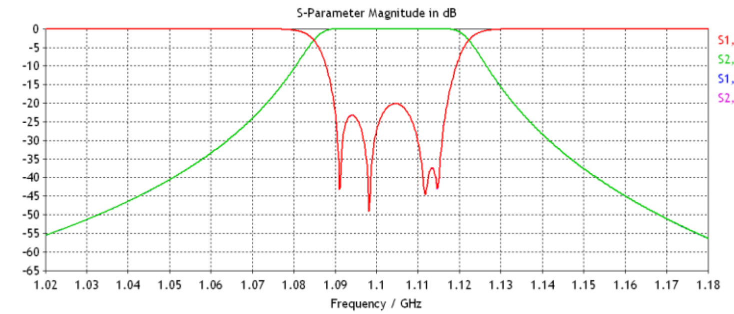
Accuracy vs. Meshdensity

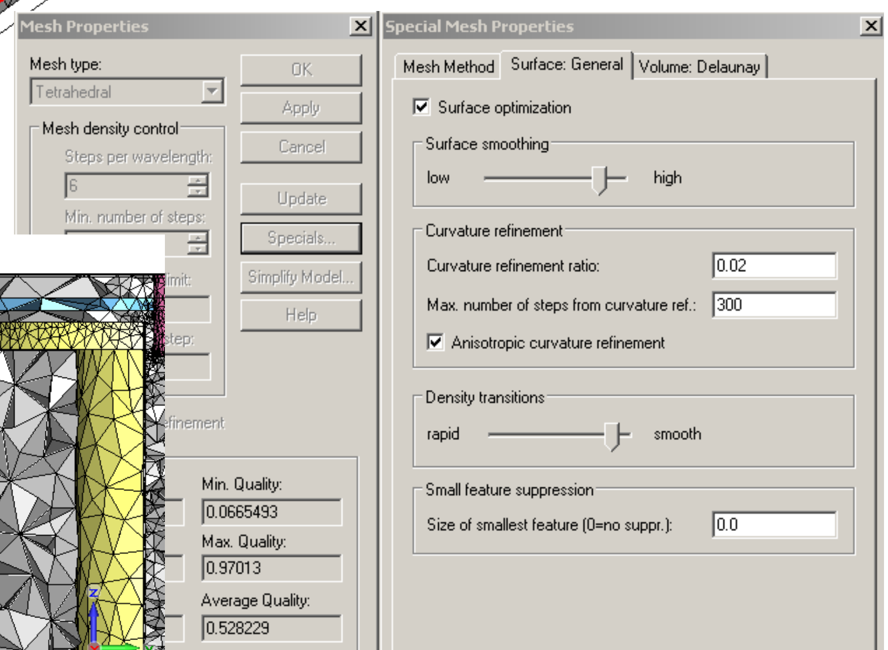
Variable / Mesh	Coarse 10/10	Medium 20/20	Fine 30/30	40/40	60/60
Coupl_tuner_23	7.5 mm	6.35	6.35	6.35	6.35
Ke_offset	5.68	5.6	5.6	5.45	5.45
Re_tuner_L_1	6.107	5.8	5.85	5.722	5.731
Re_tuner_L_2	5.165	4.94	4.97	4.924	4.942
k23	18.2	18.2	18.2	18.22	18.22
CPU Time (HEX MOR)	26s	129s	485s	18m	60m

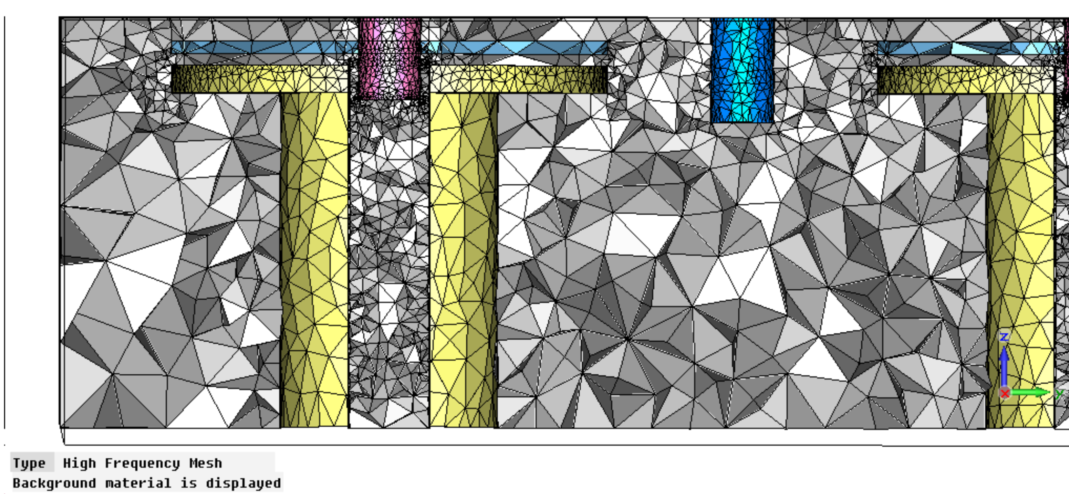


FD General Purpose Tet-Mesh (6 steps/lambda)









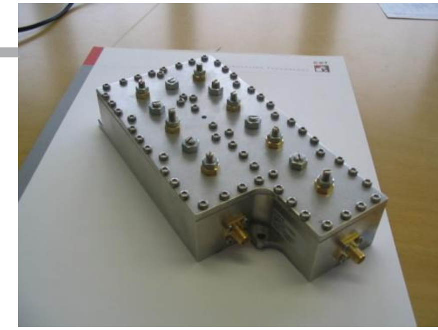
Some Guidelines

- **Start out with a rather coarse mesh models**
  - Don‘t use meshadaptation
- **Pretuning is helpful to apply local optimizer strategies**
- **Select the appropriate solver**
- **Refine the mesh and retune again**

  (Parameter ranges are a lot smaller)

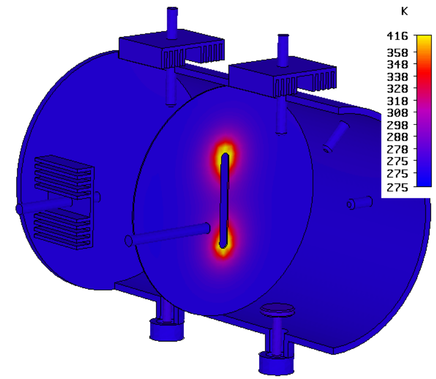
  until parameter changes are smaller than a given manufactoring tolerance

Summary



- CAD Modeler easy to use with respect to parameterization

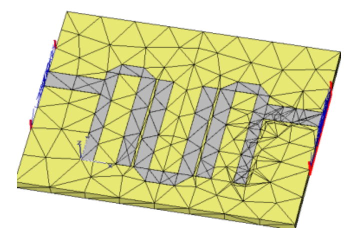
- CST Complete Technology™: TD, FD, E, Th



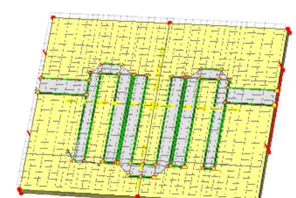
- Various optimizer strategies

- Optimization and parameterization control via complex post processing templates

- Various meshing techniques available



- Flexible link to circuit simulator CST- DESIGN STUDIO including CST- MICROWAVE STUDIO –submodels



- Various tuning procedures available for a successful tuning