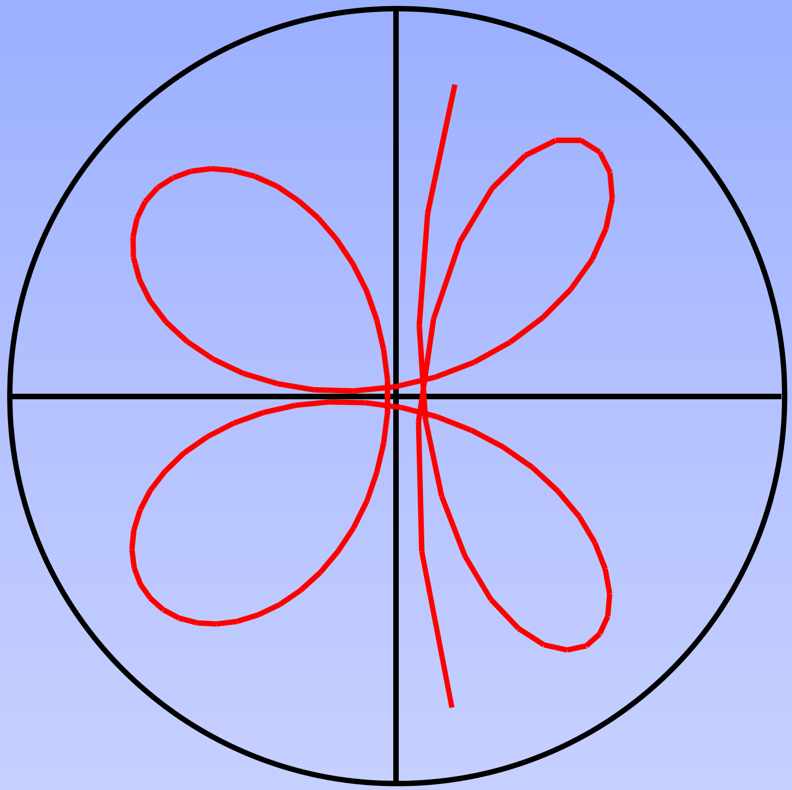

Narrowband Combline Filter Design with ANSYS HFSS

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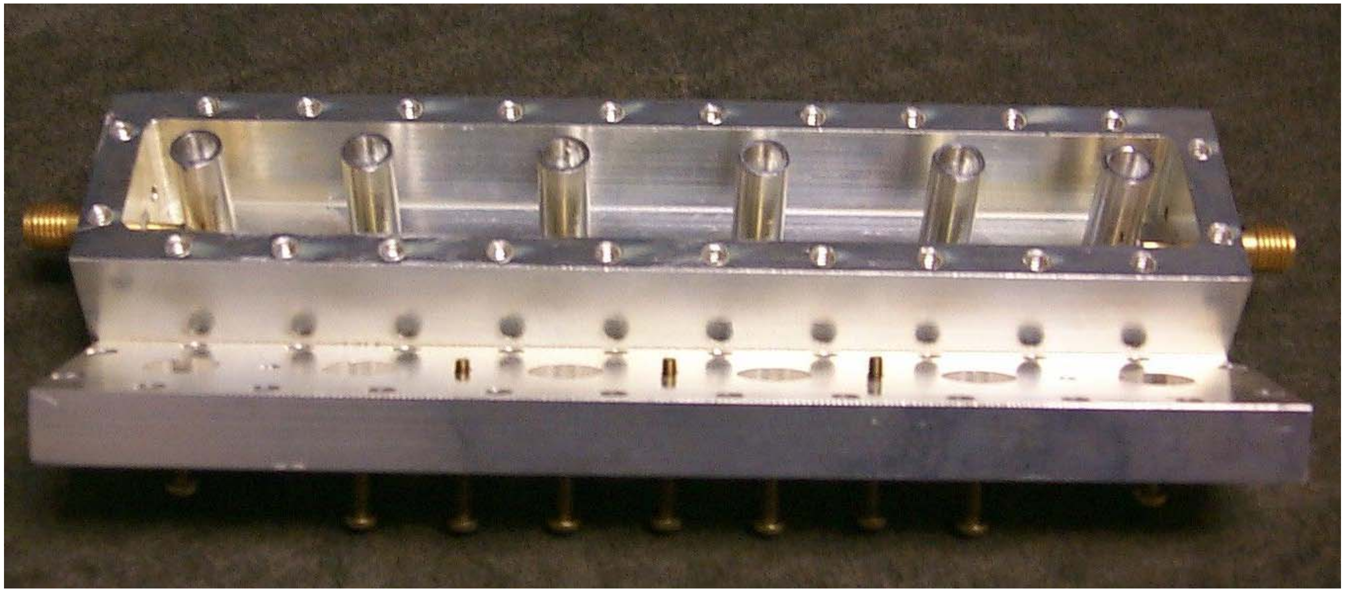
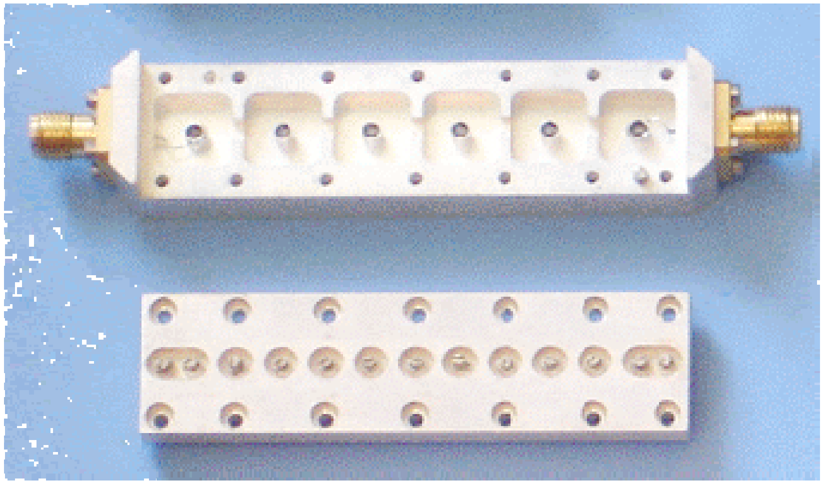
Introduction

N = 6 Inline, Cover Loaded, Combline Filter

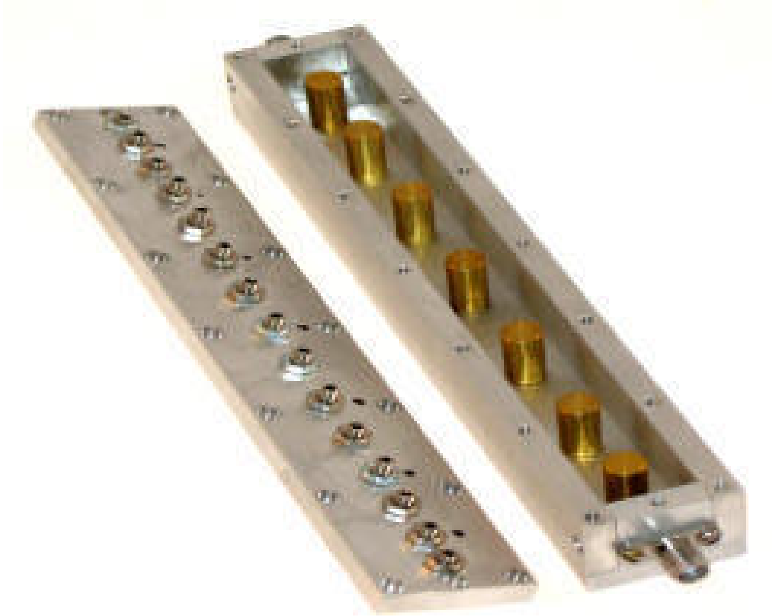


- Single combline filters and combline multiplexers can be found in many wireless systems.
- Today we will introduce a simple design flow for narrowband combline filters using ANSYS HFSS.
- This material is suitable for the non-specialist who wants a better understanding of narrowband filter design.

Combline Filter Examples



www.orionmicrowave.com

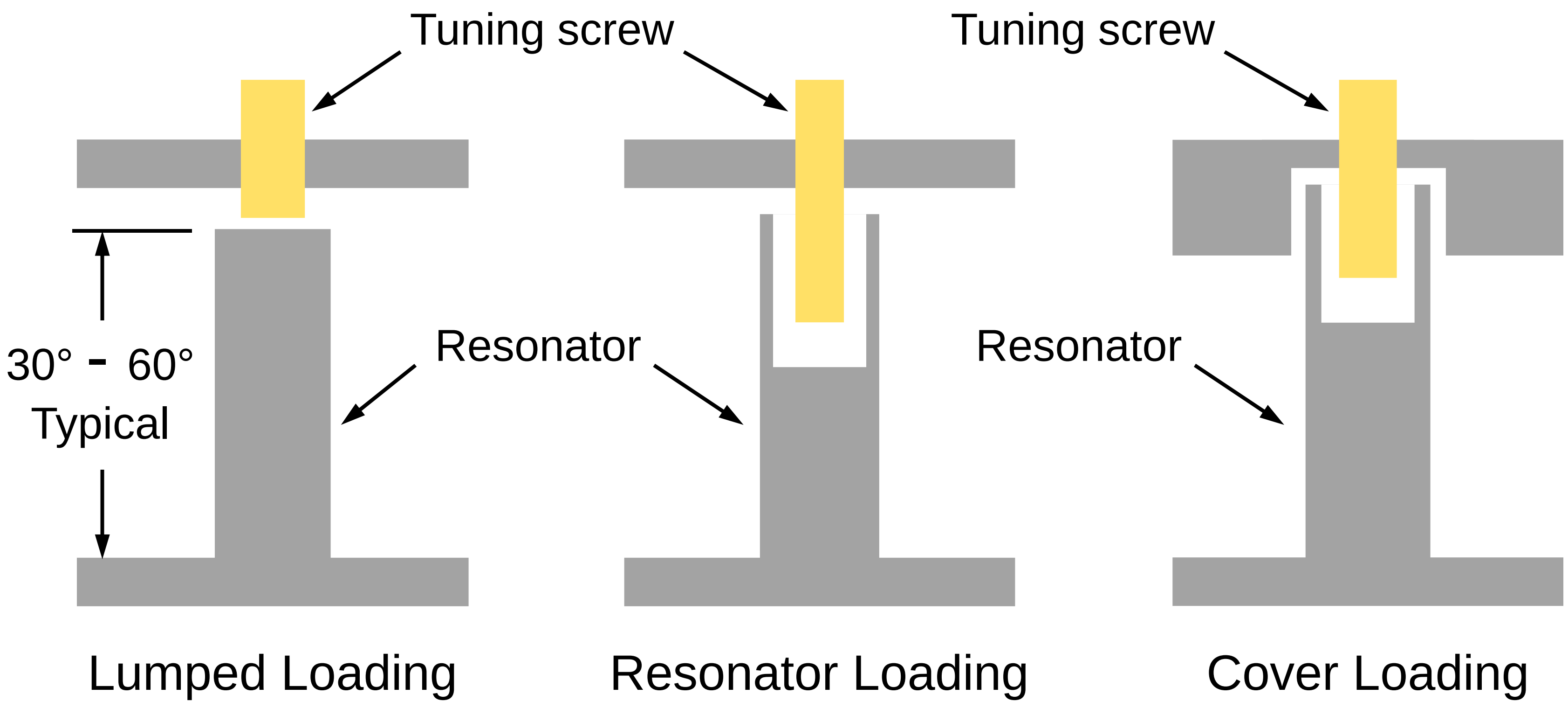


www.allenavionics.com

Combline Triplexer

www.swfilterdesign.com

Combline Resonator Loading



- We have resonators that are less than 90° long that we resonate with capacitance off the end.
- Resonator loading is perhaps the most flexible.
- Lumped loading is used at higher frequencies.
- Cover loading is typically used at lower frequencies.

Input / Output Coupling Options

Tapped Resonator Inductive Loop Capacitive Probe

- Tapping into the resonator works over a broad range of bandwidths and is quite common.
- Coupling with an inductive loop near the base of the resonator is another option.
- Using a capacitive probe is a third option.

Combline Filter Design Flow

- Estimate order of filter and stopband rejection
- Build a model of the proposed resonator:
  - Compute available unloaded Q
  - Estimate insertion loss
- Build Kij design curve
- Build Qex design curve
- Build a model of complete filter and apply port tuning
- Use port tuning corrections to refine filter dimensions
- Do final simulation of filter with loss:
  - Verify insertion loss in passband
  - Verify rejection in stopbands

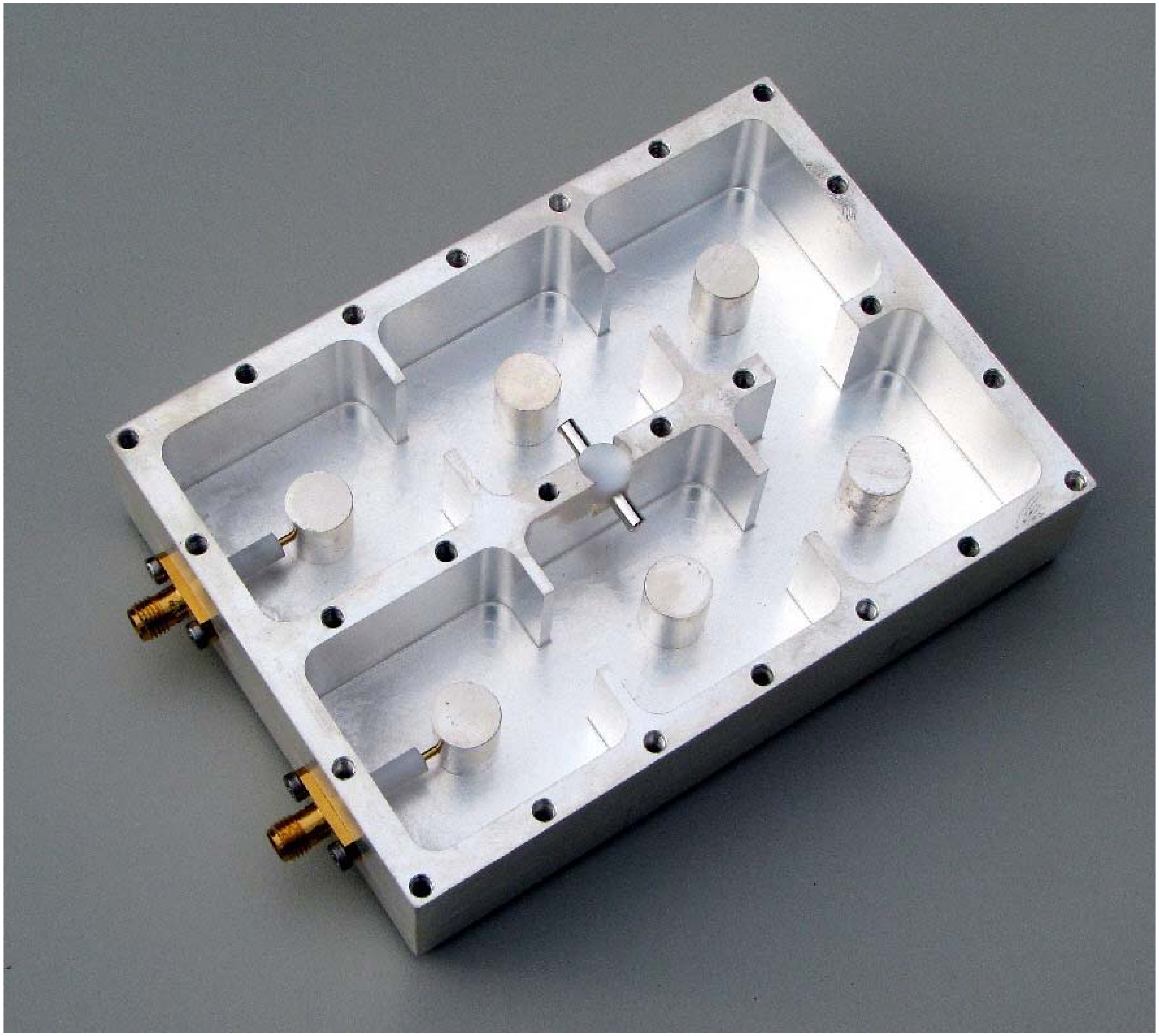
Wimax Filter Example

Center Frequency:	f_0 = 3440 MHz
Equal Ripple BW:	BW = 70 MHz (add 10 MHz for temp)
Rejection:	>30 dB @ f_0 +/- 80 MHz
Insertion Loss:	<1 dB at band edges
Return Loss:	RL > 20 dB (should add margin)
Temperature Range:	-30 to +70 deg C
Power Handling:	< 20 dBm

Morten Hagensen, “Narrowband Microwave Bandpass Filter Design by Coupling Matrix Synthesis,” Guided Wave Technology, April 26, 2009.

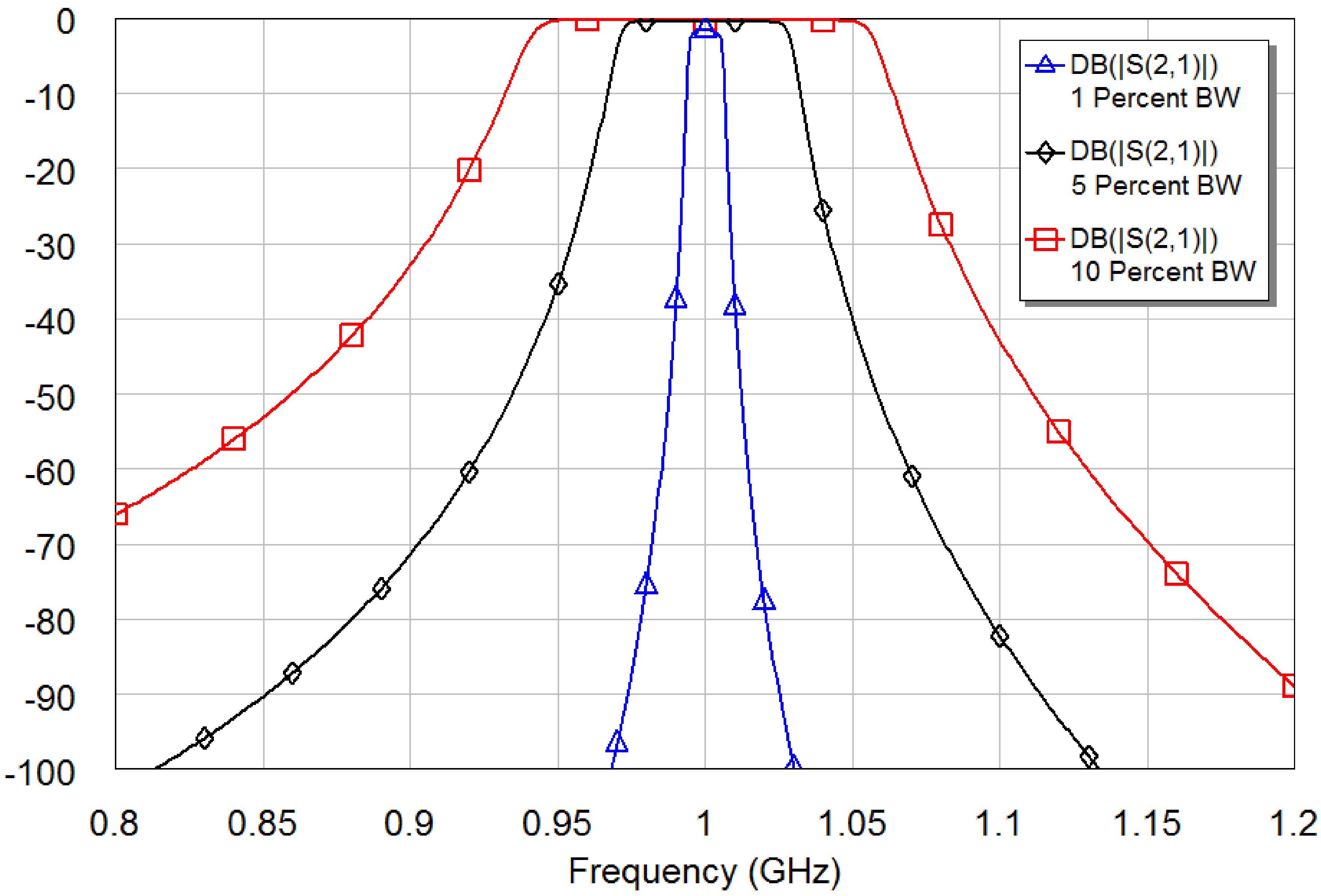
www.gwtsoft.com/Misc/Hagensen3.pdf

Wimax Filter Example



www.gwtsoft.com/Misc/Hagensen3.pdf

Combline Filter Asymmetry or “Skewing”



Estimating Filter Order

$$N > \frac{Rejection\,(\mathrm{dB}) + RtnLoss\,(\mathrm{dB}) + 6}{20\log_{10}(S + \sqrt{S^2 - 1})}$$

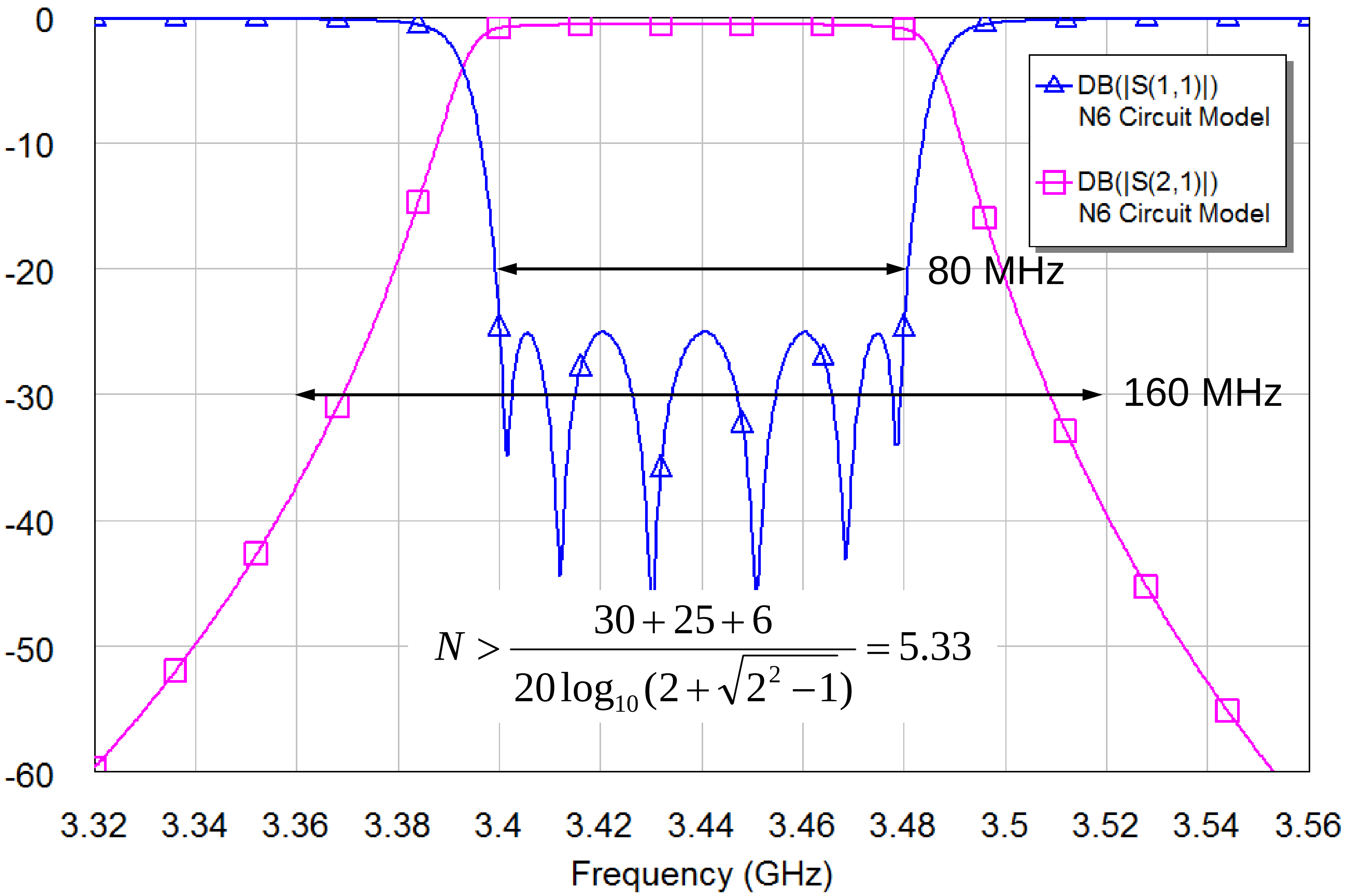
$$Rejection = \text{Stopband Insertion Loss}$$

$$RtnLoss = \text{Passband Return Loss}$$

$$S = \frac{\text{Reject Bandwidth}}{\text{Filter Bandwidth}}$$

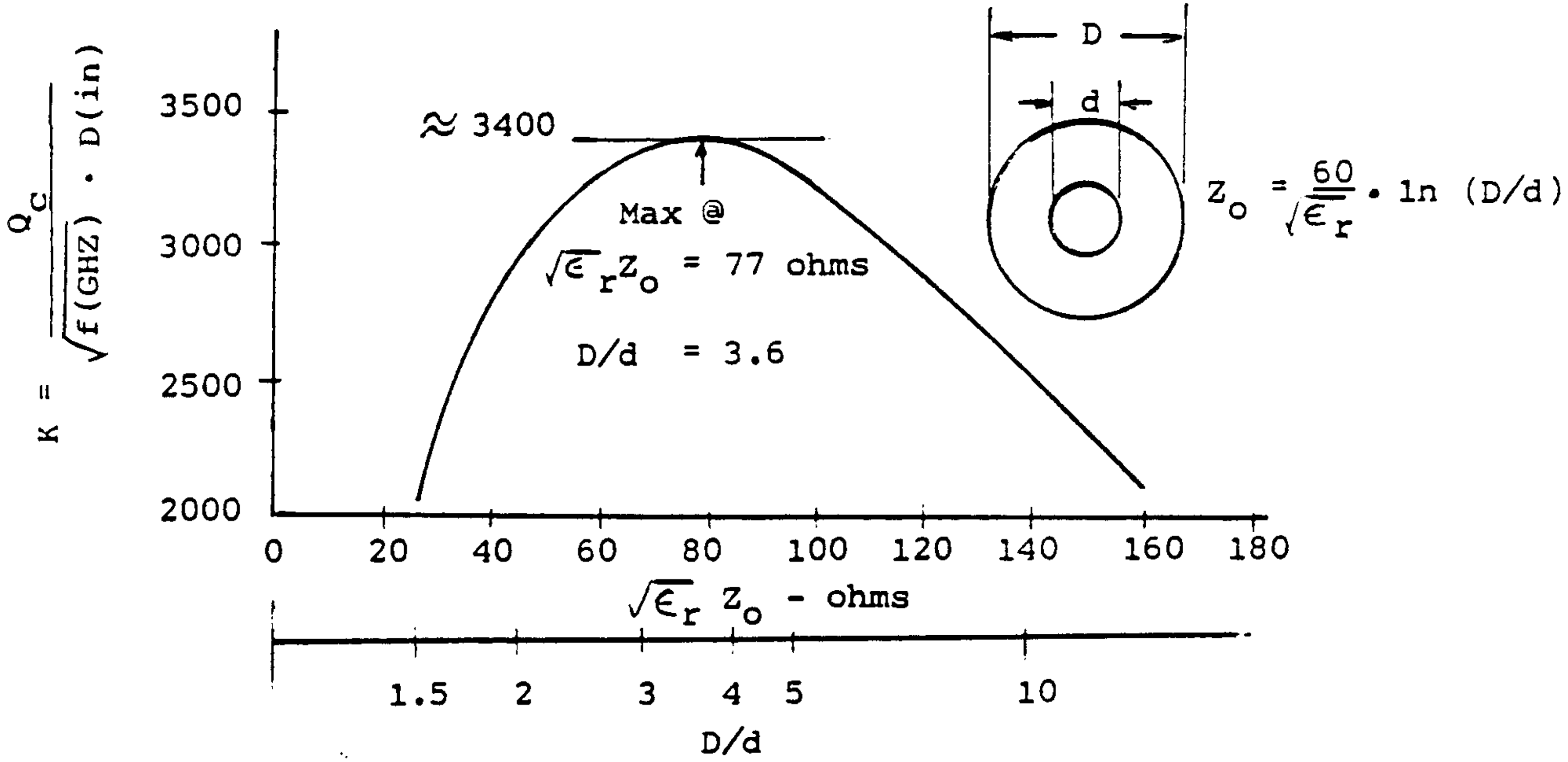
- Any simple formula that estimates filter order, N assumes the filter is symmetrical.
- Our 2% bandwidth filter is almost symmetrical and this estimate is probably good enough.
- For broader band combline filters, we may want to generate a circuit theory model to get a better estimate of stopband performance.

Estimating Filter Order



$$N > \frac{30+25+6}{20\log_{10}(2+\sqrt{2^2-1})} = 5.33$$

Qc of Infinitely Long Coaxial Line

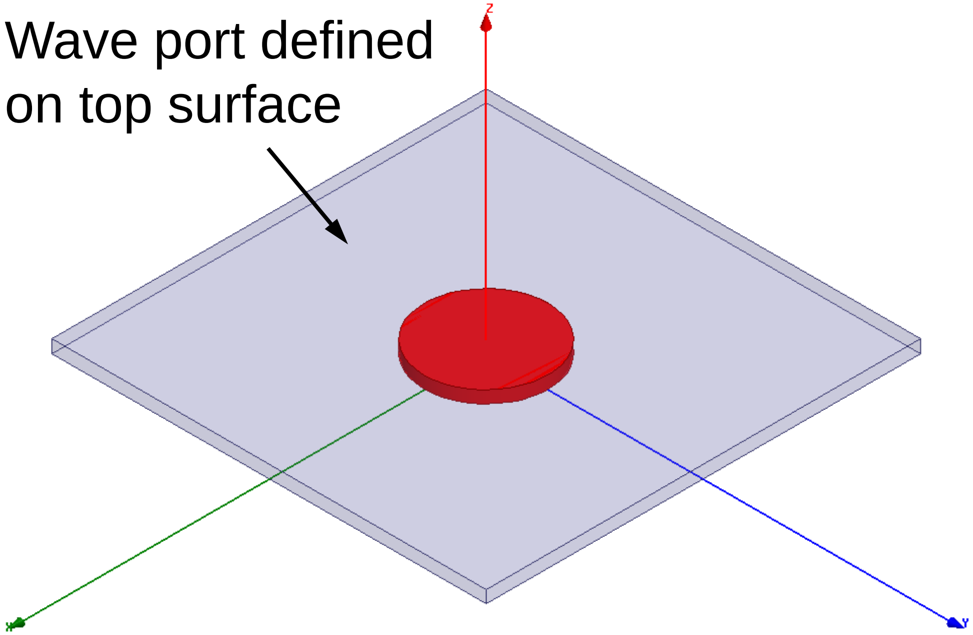


For a given dominant dimension D, maximum K and hence maximum realizable Q_c is achieved when $D/d = 3.6$, or $\sqrt{\varepsilon_r} Z_0$ is about 77 ohms.

$Q = K\sqrt{f}D$ Collect K data from measured filters [1]

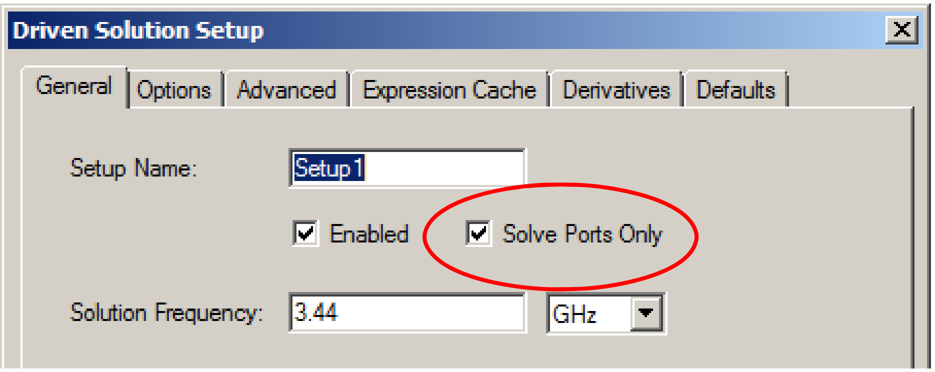
Resonator Design: Zo

Wave port defined on top surface



Outer: 35 x 35 mm
Inner: 10 mm dia
Height: Don’t care

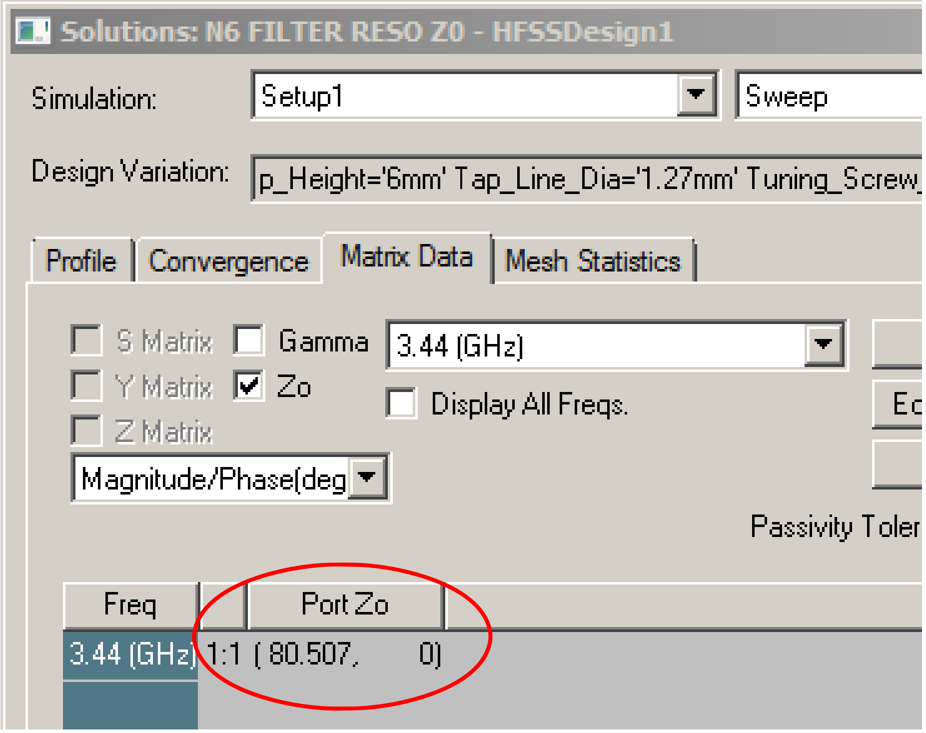
- Use HFSS as a 2D cross-section solver
- 80.5 ohms is close enough to ideal Zo.


Driven Solution Setup

Setup Name: Setup1

☑ Enabled ☑ Solve Ports Only

Solution Frequency: 3.44 GHz


Solutions: N6 FILTER RESO Z0 - HFSSDesign1

Simulation: Setup1 Sweep

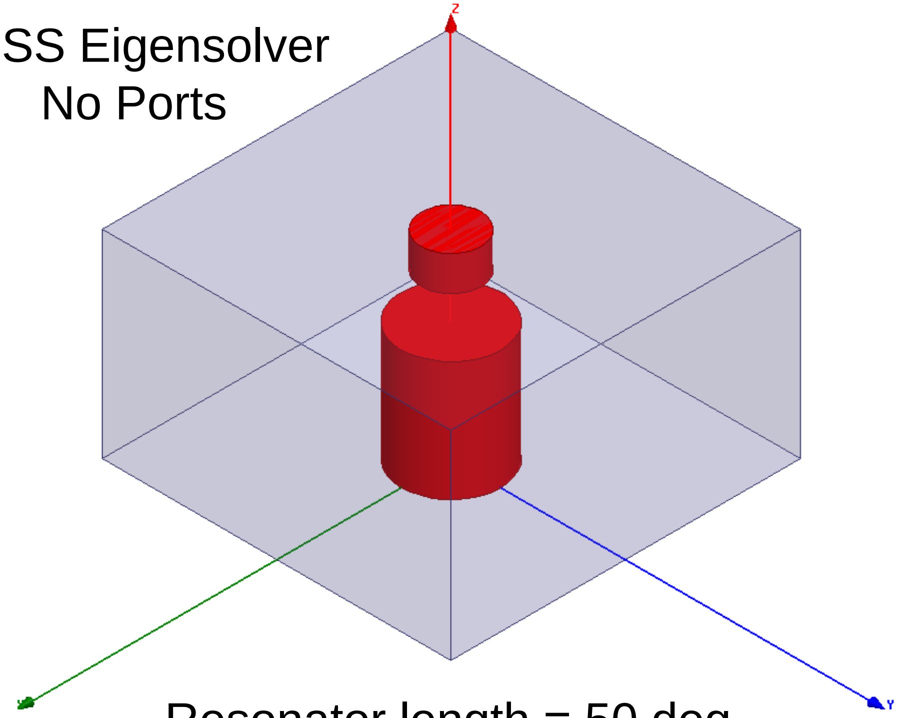
Design Variation: p_Height='6mm' Tap_Line_Dia='1.27mm' Tuning_Screw_

☐ S Matrix ☐ Gamma 3.44 (GHz)
☐ Y Matrix ☑ Zo ☐ Display All Freqs.
☐ Z Matrix
Magnitude/Phase(deg

Freq	Port Zo
3.44 (GHz)	1:1 (80.507, 0)

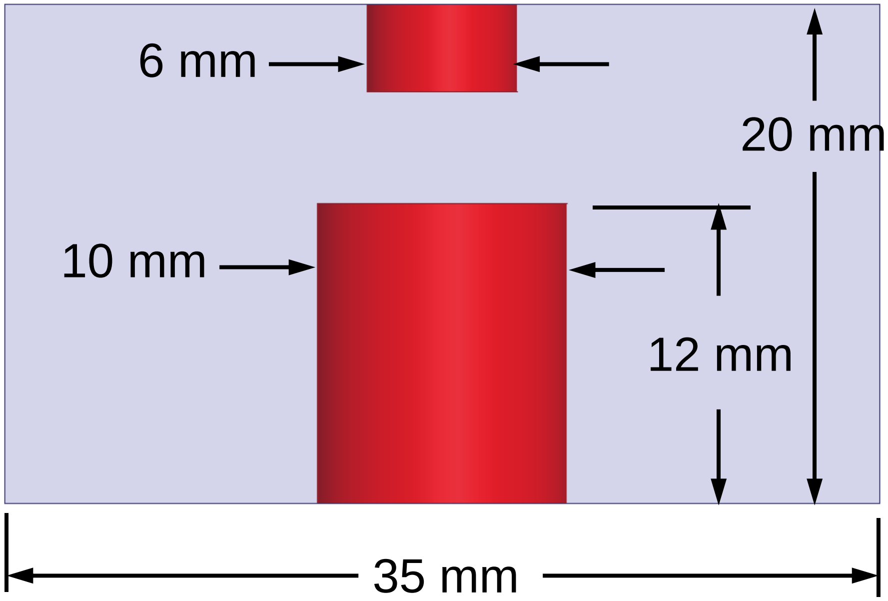
Resonator Design: Freq and Qu

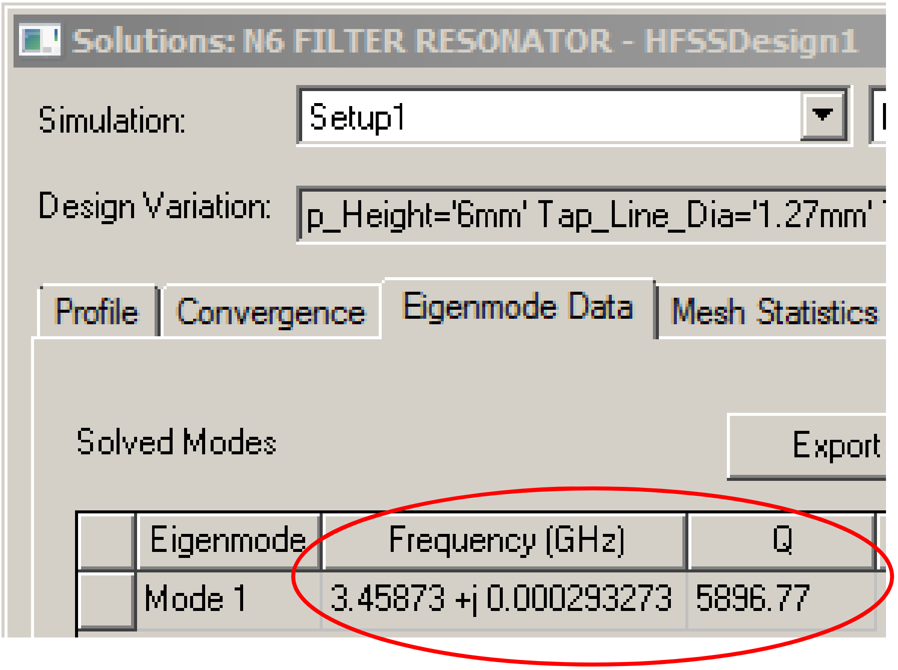
HFSS Eigensolver
No Ports



Resonator length = 50 deg

- Surface of box, resonator and screw assumed to be silver plated.
- Use 80% of ideal conductivity as a starting point.
- Use measured data from filters to adjust conductivity in the future.





Solutions: N6 FILTER RESONATOR - HFSSDesign1

Simulation: Setup1

Design Variation: p_Height='6mm' Tap_Line_Dia='1.27mm'

Solved Modes

	Eigenmode	Frequency (GHz)	Q
	Mode 1	3.45873 +j 0.000293273	5896.77

Chebyshev Lowpass Prototype

Chebyshev Lowpass Prototype: 0.044 dB ripple, 20 dB return loss, 1.22 VSWR

N	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	$\Sigma\, g_1 - g_N$
2	1.0000	0.6682	0.5462	1.2222								1.2144
3	1.0000	0.8534	1.1039	0.8534	1.0000							2.8144
4	1.0000	0.9332	1.2923	1.5795	0.7636	1.2222						4.5727
5	1.0000	0.9732	1.3723	1.8032	1.3723	0.9732	1.0000					6.4989
6	1.0000	0.9958	1.4131	1.8950	1.5505	1.7272	0.8147	1.2222				8.4011
7	1.0000	1.0097	1.4368	1.9414	1.6216	1.9414	1.4368	1.0097	1.0000			10.4028
8	1.0000	1.0189	1.4518	1.9682	1.6570	2.0252	1.6104	1.7744	0.8336	1.2222		12.3447
9	1.0000	1.0252	1.4618	1.9852	1.6772	2.0662	1.6772	1.9852	1.4618	1.0252	1.0000	14.3710

- N is the lowpass or bandpass filter order.
- The g_i’s are frequency and impedance scaled values for a lowpass filter with a cutoff frequency of $\omega = 1$ radian and a return loss of 20 dB.
- Any given passband ripple / return loss level requires a unique table.
- Other tables are available in the literature or the g_i’s can be computed.

Midband Insertion Loss

Chebyshev Lowpass Prototype: 0.044 dB ripple, 20 dB return loss, 1.22 VSWR

N	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	$\Sigma\, g_1$ - g_N
2	1.0000	0.6682	0.5462	1.2222								1.2144
3	1.0000	0.8534	1.1039	0.8534	1.0000							2.8144
4	1.0000	0.9332	1.2923	1.5795	0.7636	1.2222						4.5727
5	1.0000	0.9732	1.3723	1.8032	1.3723	0.9732	1.0000					6.4989
6	1.0000	0.9958	1.4131	1.8950	1.5505	1.7272	0.8147	1.2222				8.4011
7	1.0000	1.0097	1.4368	1.9414	1.6216	1.9414	1.4368	1.0097	1.0000			10.4028
8	1.0000	1.0189	1.4518	1.9682	1.6570	2.0252	1.6104	1.7744	0.8336	1.2222		12.3447
9	1.0000	1.0252	1.4618	1.9852	1.6772	2.0662	1.6772	1.9852	1.4618	1.0252	1.0000	14.3710

$$Loss(f_0) = \frac{4.343 \cdot \sum_{i=1}^{N} g_i \cdot f_0}{\Delta f \cdot Q_u} = \frac{4.343 \cdot 8.4011 \cdot 3.44}{0.08 \cdot 5900} = 0.27\,\mathrm{dB}$$

- Q_u is a little optimistic, at the high end of what is possible.
- Loss will be higher at the band edges.

Dishal’s Method

- As early as 1951, Milton Dishal [2] recognized that any narrow band, lumped element or distributed bandpass filter could be described by three fundamental variables:
  - the synchronous tuning frequency, f_0
  - the couplings between adjacent resonators, $K_{r,r+1}$
  - the singly loaded or external Q, Q_{ex}
- The K_{ij} set the bandwidth of the filter and the Q_{ex} sets the return loss level.
- For any narrowband filter (<10% bandwidth) we can compute the required K_{ij} and Q_{ex} from the Chebyshev lowpass prototype.
- The K and Q concept is universal and can be applied to any lumped element or distributed filter topology or technology [4,5].

Definition of Kij and Qex

$$Q_{ex} = \frac{f_0 \cdot g_0 \cdot g_1}{f_2 - f_1} = \frac{g_0 \cdot g_1}{BW}$$

$$K_{ij} = \frac{(f_2 - f_1)}{f_0\sqrt{g_i \cdot g_j}} = \frac{BW}{\sqrt{g_i \cdot g_j}}$$

$$f_0 = \frac{f_1 + f_2}{2} \qquad BW = \frac{f_2 - f_1}{f_0}$$

f_1 = bandpass filter lower equal ripple frequency

f_2 = bandpass filter upper equal ripple frequency

f_0 = bandpass filter center frequency

BW = percentage bandwidth

g_i = prototype element value for element i

Note: Equations assume Qu is infinite.

Our Filter: N = 6, BW = 2.3%

Chebyshev Lowpass Prototype: 0.044 dB ripple, 20 dB return loss, 1.22 VSWR

N	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	$\Sigma\, g_1$ - g_N
2	1.0000	0.6682	0.5462	1.2222								1.2144
3	1.0000	0.8534	1.1039	0.8534	1.0000							2.8144
4	1.0000	0.9332	1.2923	1.5795	0.7636	1.2222						4.5727
5	1.0000	0.9732	1.3723	1.8032	1.3723	0.9732	1.0000					6.4989
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9	1.0000	1.0252	1.4618	1.9852	1.6772	2.0662	1.6772	1.9852	1.4618	1.0252	1.0000	14.3710

$$K_{1,2} = \frac{BW}{\sqrt{g_1 \cdot g_2}} = \frac{0.023}{\sqrt{0.9958 \cdot 1.4131}} = 0.0194$$

$$K_{2,3} = \frac{BW}{\sqrt{g_2 \cdot g_3}} = \frac{0.023}{\sqrt{1.4131 \cdot 1.8950}} = 0.0141$$

$$K_{3,4} = \frac{BW}{\sqrt{g_3 \cdot g_4}} = \frac{0.023}{\sqrt{1.8950 \cdot 1.5505}} = 0.0134$$

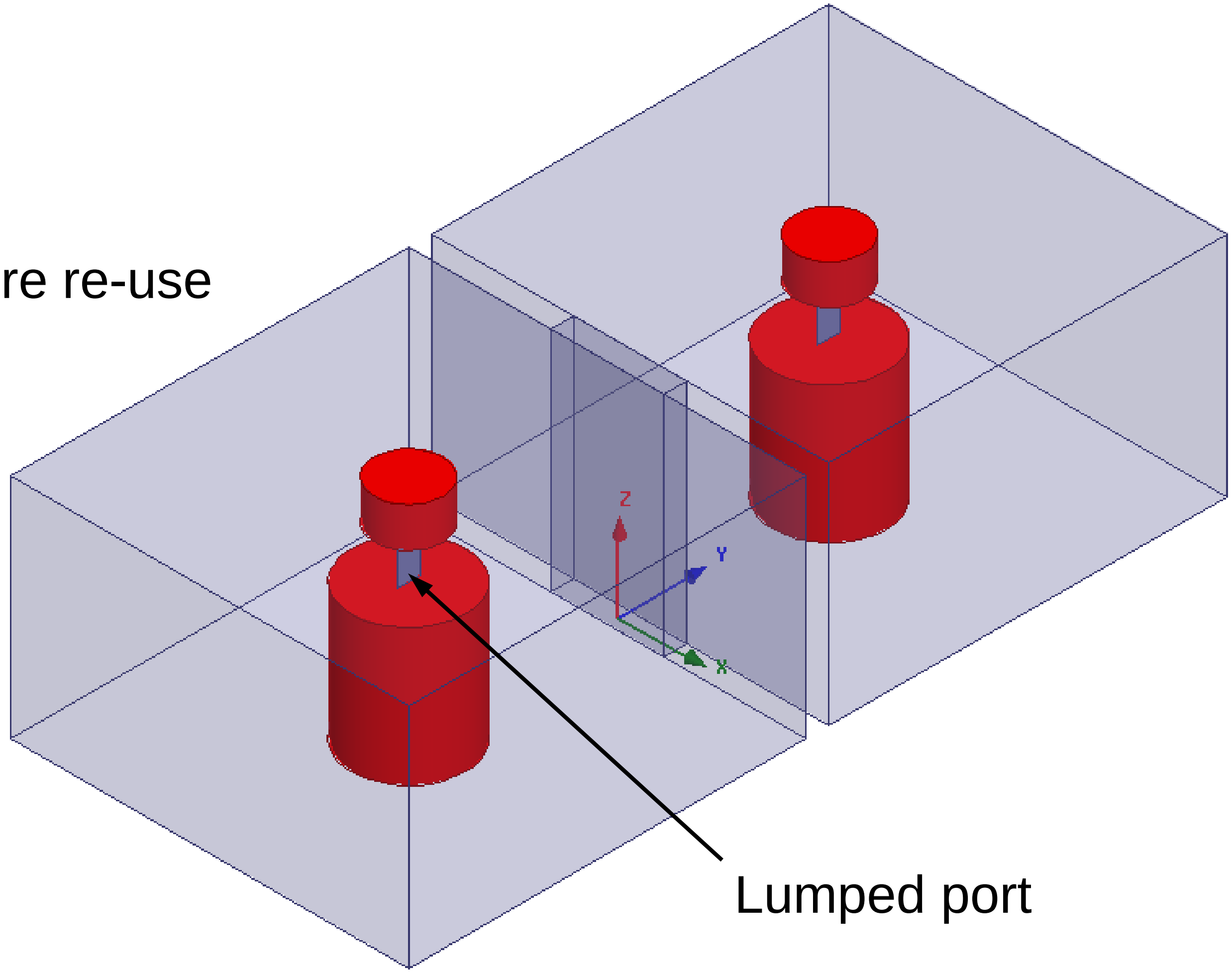
$$Q_{ex} = \frac{g_0 \cdot g_1}{BW} = \frac{1.0 \cdot 0.9958}{0.023} = 43.3$$

Computing Iris Widths and Tap Height

- Our resonator geometry is now fixed.
- We have enough Qu to meet the insertion loss goal.
- We have goals for the Kij’s and Qex
- Now we need to compute the iris widths and the tap height.

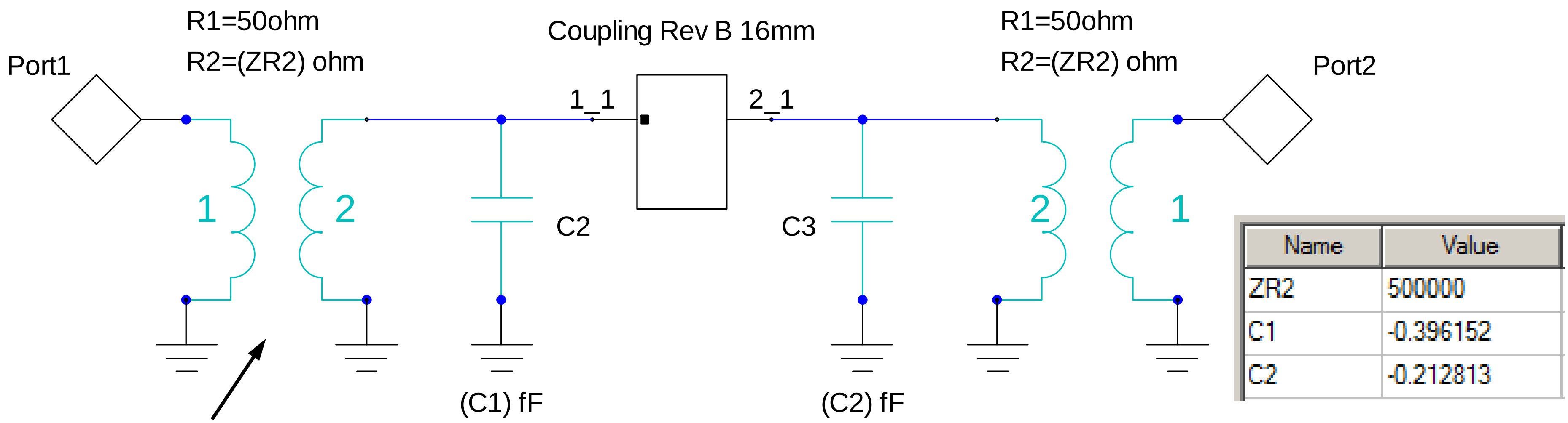
Basic Two Resonator HFSS Project

- Distance between resonators is fixed
  - Iris width controls coupling
  - Some details ignored, like corner radii
- Lossless model
  - Faster
  - No corrections to Kij
- Make it parametric for future re-use
- Lumped ports for tuning in our circuit simulator
  - FEM mesh is not perfectly symmetrical
  - Faster than making geometry changes in the EM model



Lumped port

Extracting Coupling Coefficents



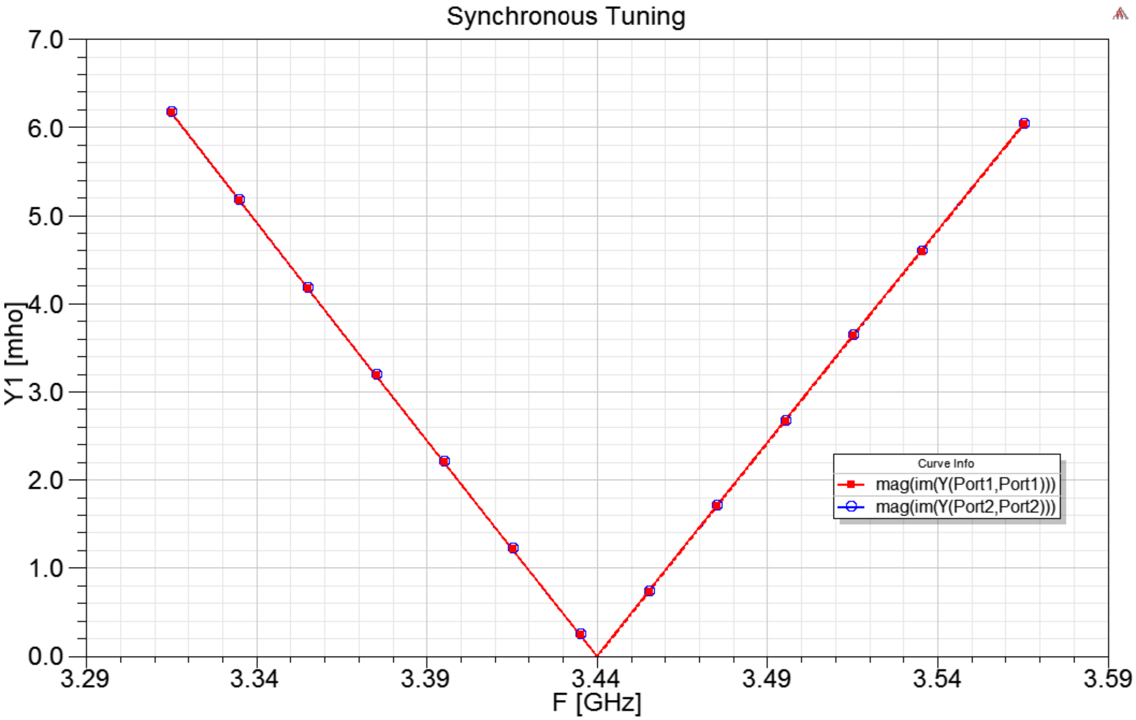
Name	Value
ZR2	500000
C1	-0.396152
C2	-0.212813

Loosely couple
with transformers.

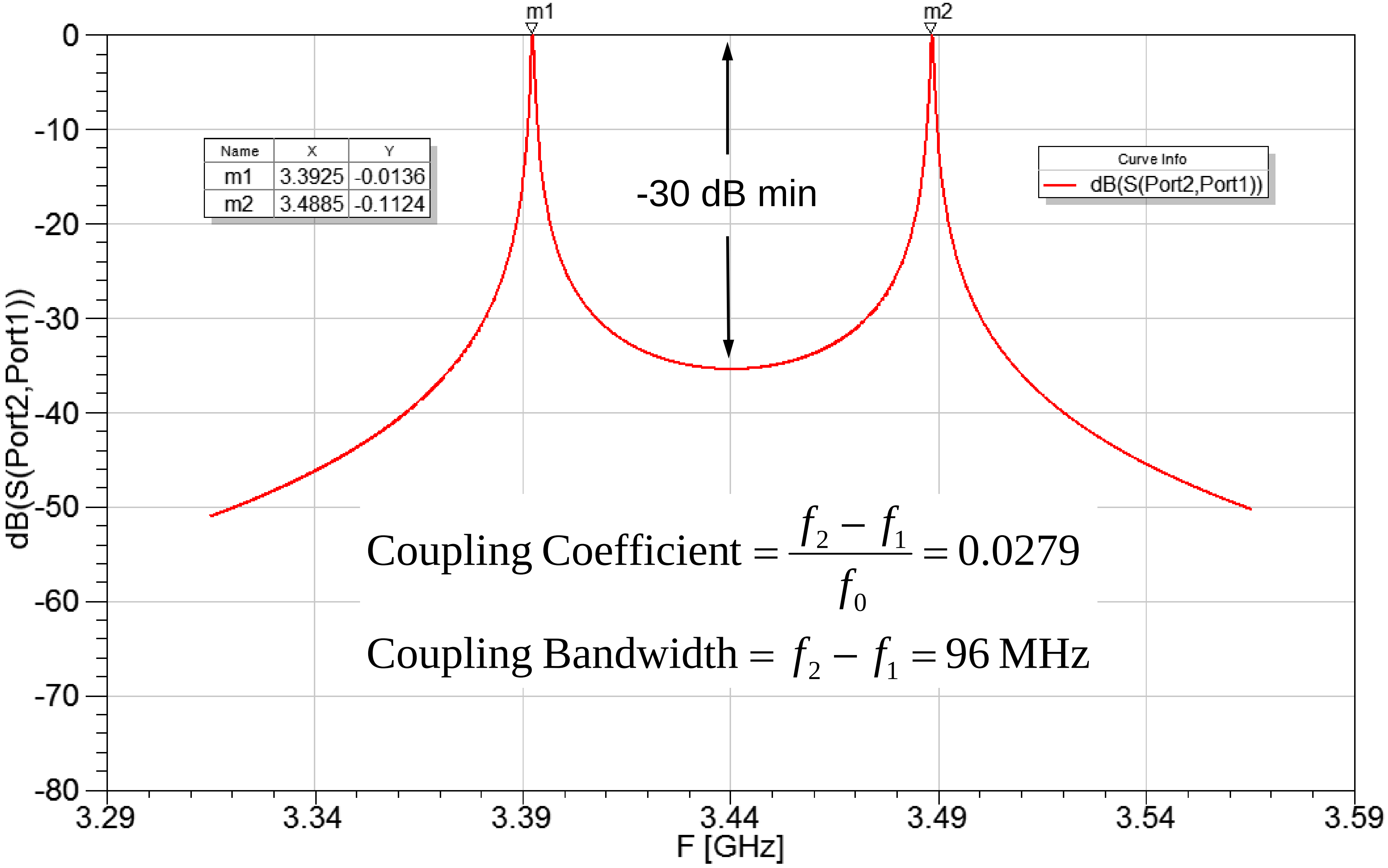
We want to force
synchronous tuning.
At resonance:

$$mag(im(Y(1,1))) = 0$$

$$mag(im(Y(2,2))) = 0$$



Extracting Coupling Coefficients



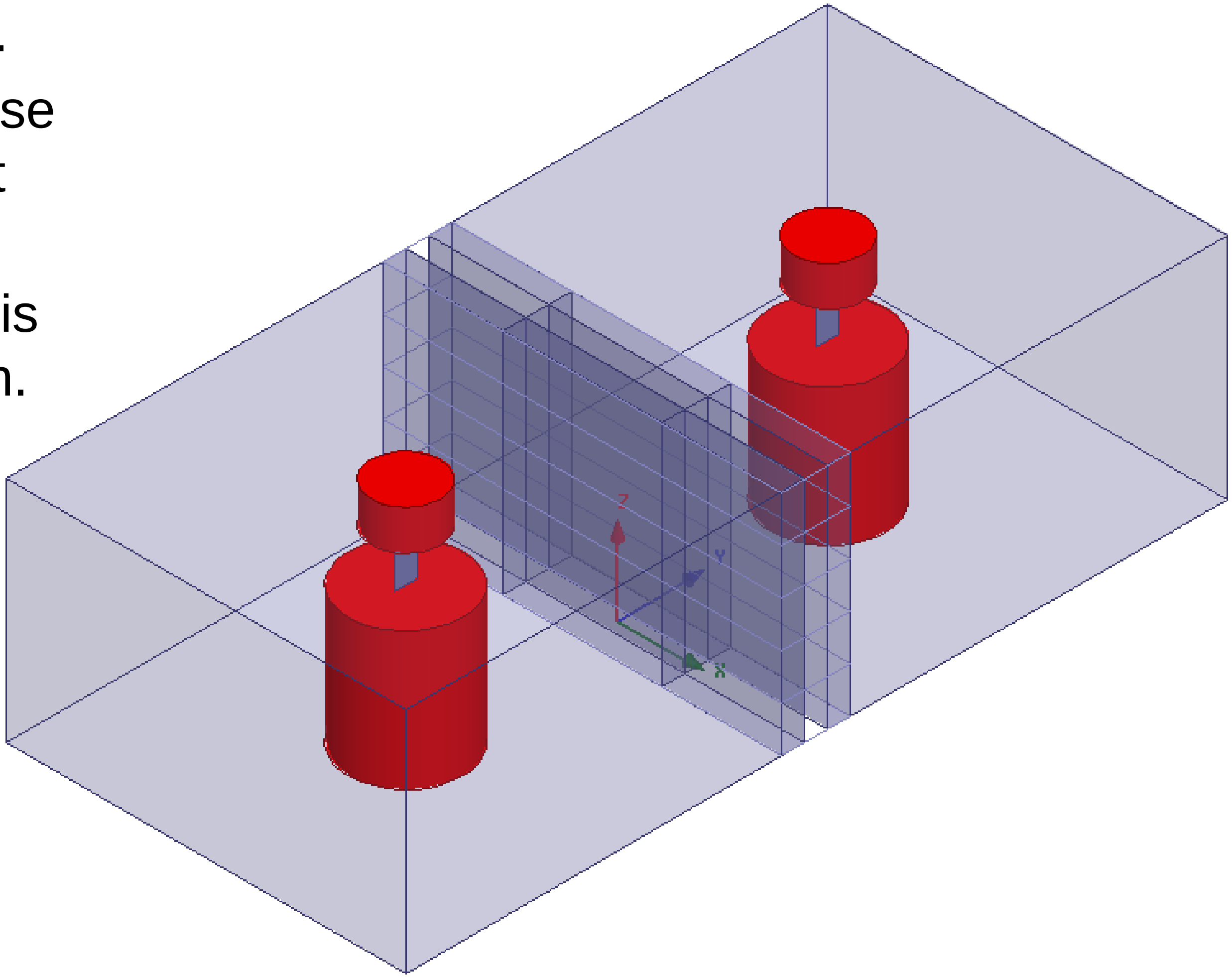
Name	X	Y
m1	3.3925	-0.0136
m2	3.4885	-0.1124

$$\text{Coupling Coefficient} = \frac{f_2 - f_1}{f_0} = 0.0279$$

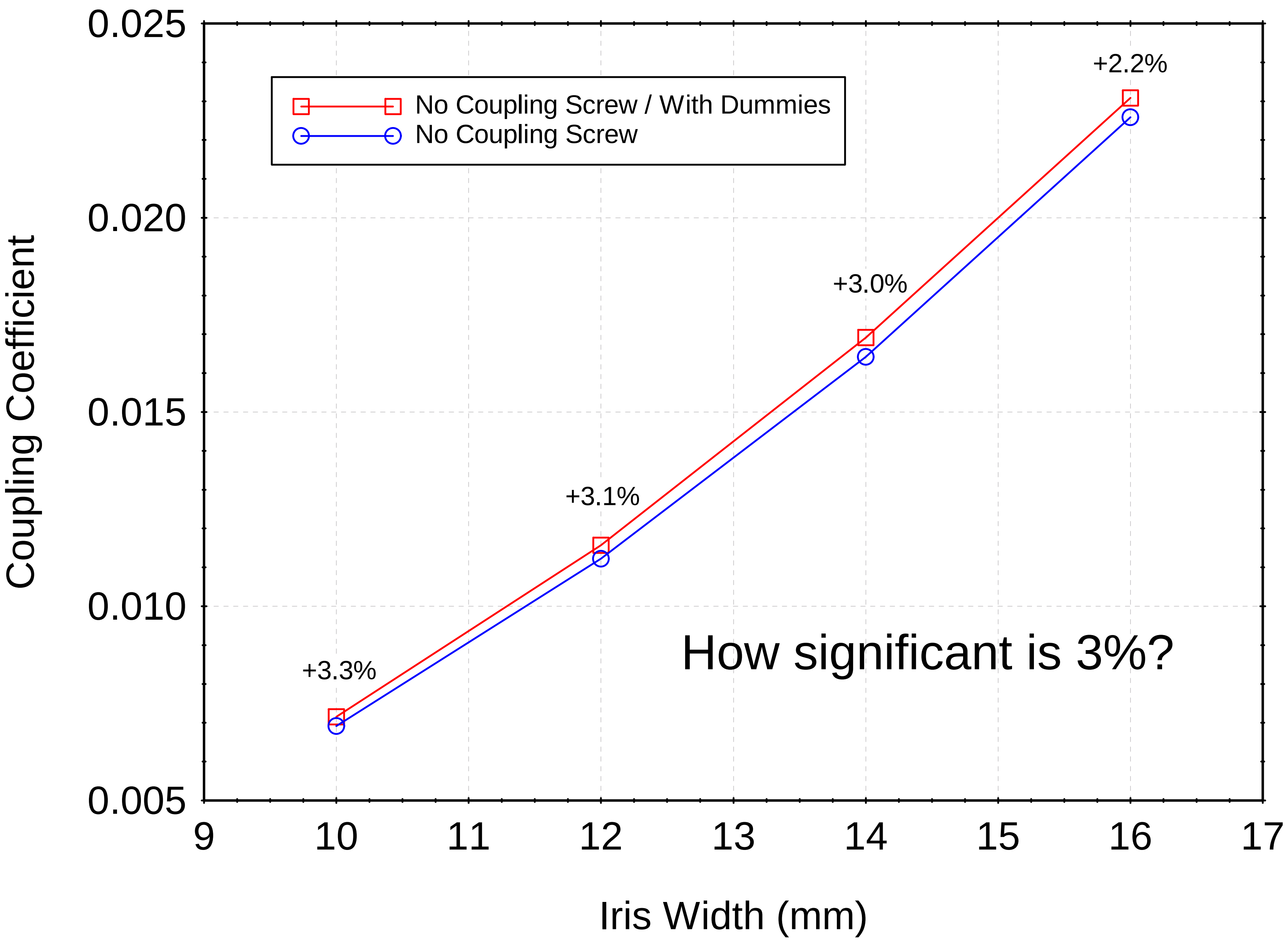
$$\text{Coupling Bandwidth} = f_2 - f_1 = 96\,\text{MHz}$$

Dummy Elements Around The Iris

- There are many evanescent modes in the iris region.
- The FEM mesher uses energy balance to refine the mesh.
- The mesh may be too coarse in the iris region for highest accuracy.
- Add physical detail in the iris region to force a finer mesh.
- Only important if you are comparing this simulation to measured hardware.

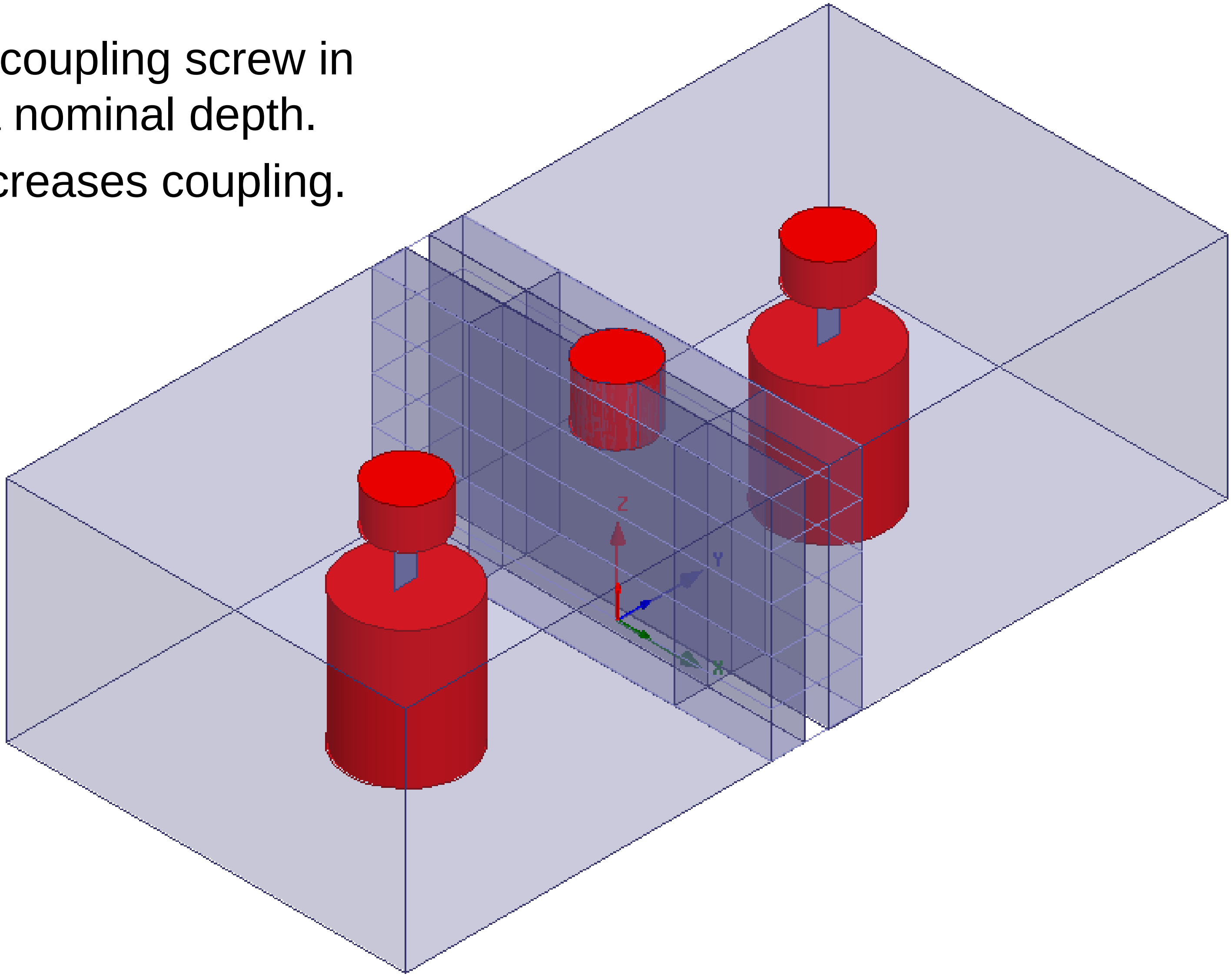


Coupling With and Without Dummies

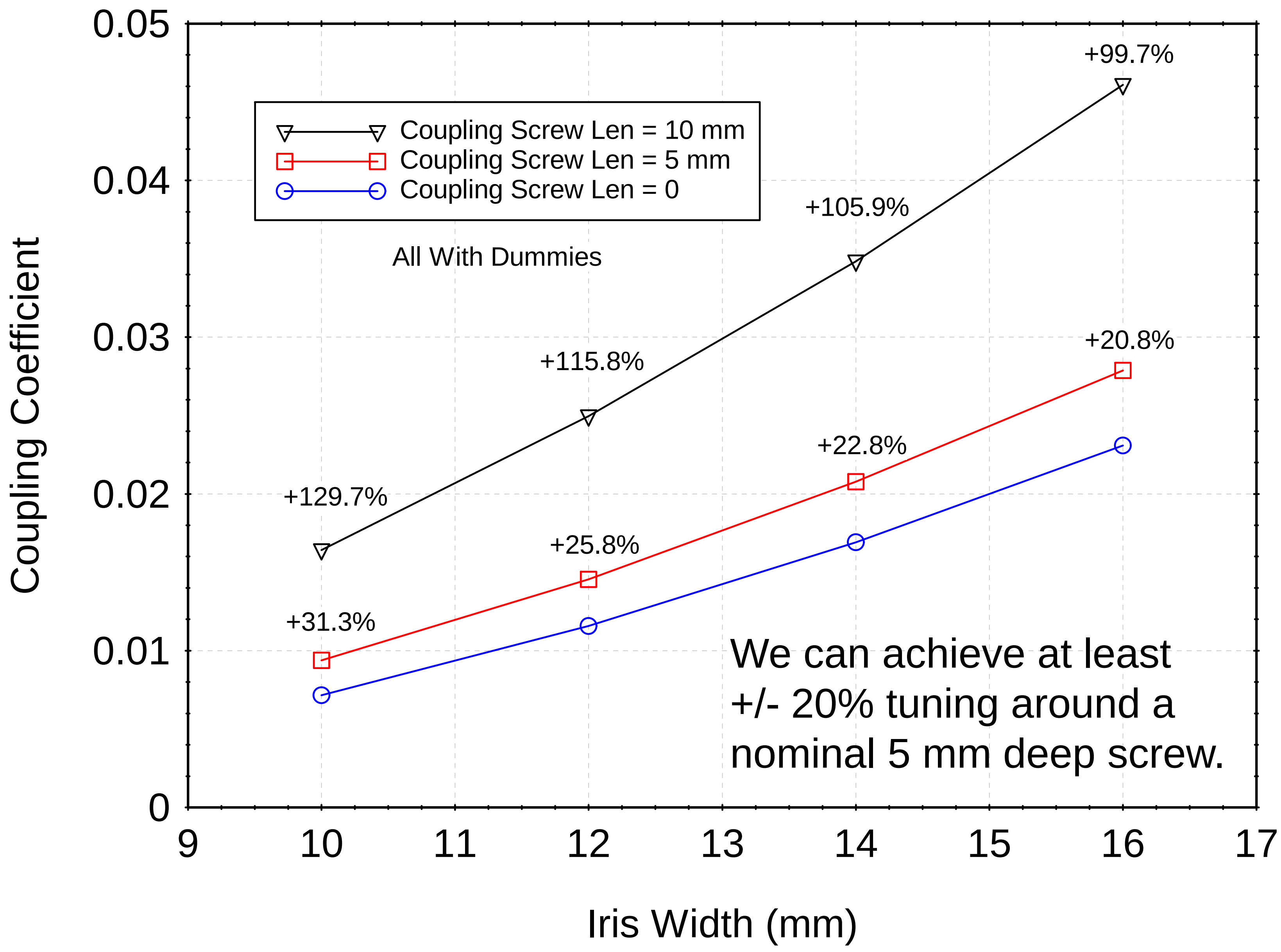


Add Coupling Screw

- We can include a coupling screw in our model set to a nominal depth.
- A longer screw increases coupling.

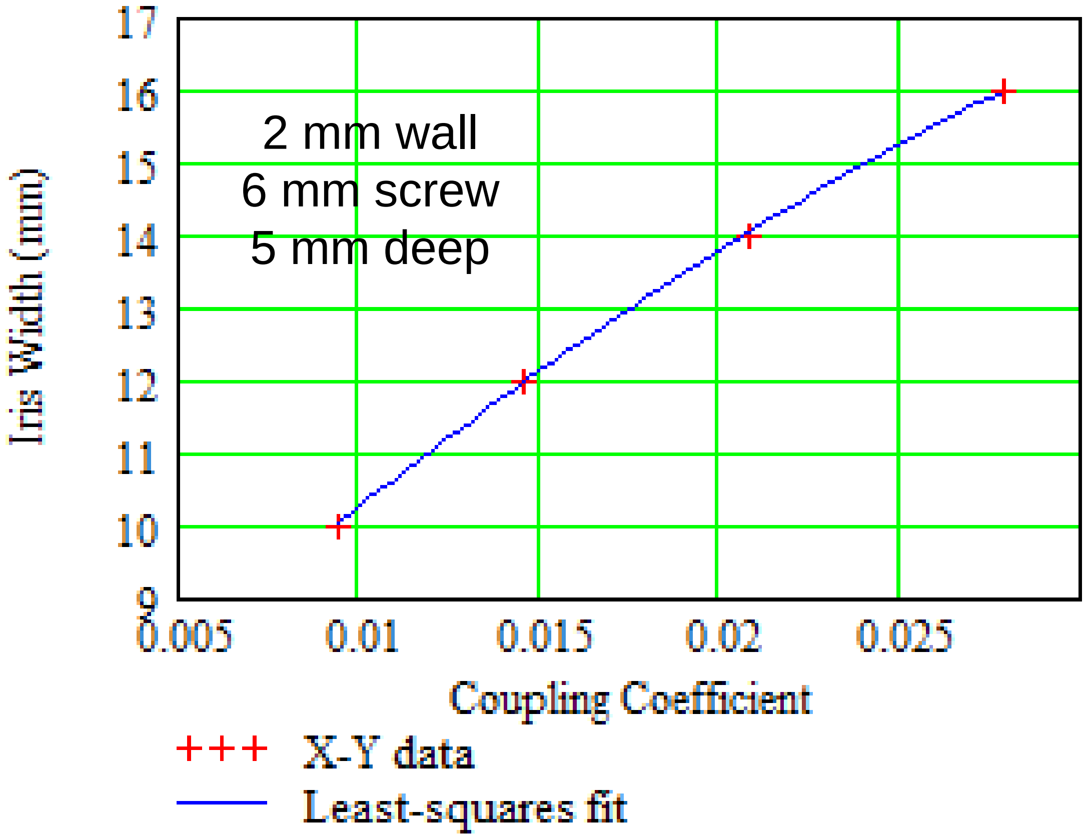


Coupling vs Screw Length & Iris Width



We can achieve at least +/- 20% tuning around a nominal 5 mm deep screw.

Coupling Curve For 2 mm Thick Wall



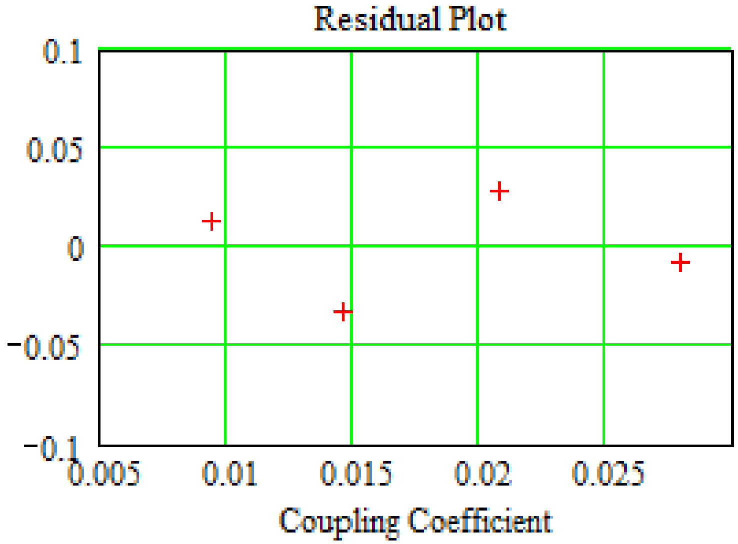
$$S = \begin{pmatrix} 5.902 \\ 476.295 \\ -4.103 \times 10^{3} \end{pmatrix}$$

2nd order polynomial coefficients

$K := .01493$

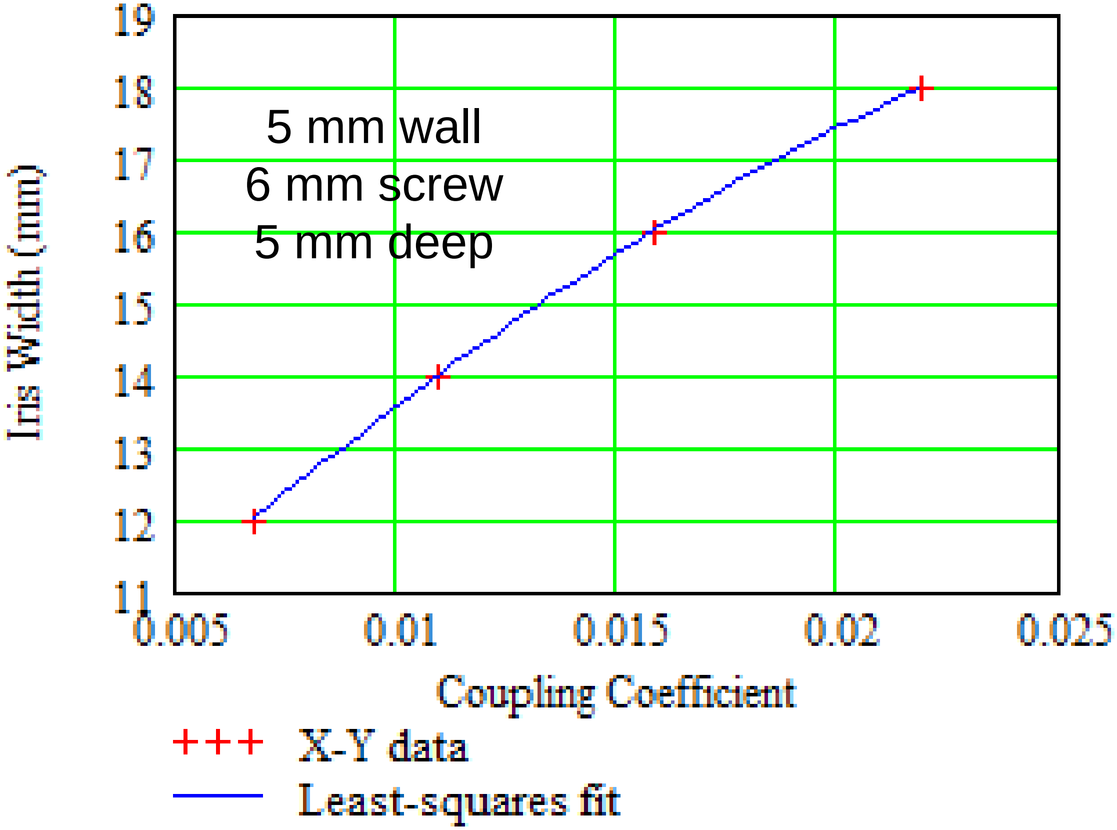
$\text{Iris\_Width}(x) := F(x) \cdot S$

$\text{Iris\_Width}(K) = 12.099$



$$Iris\,Width = 5.9 + 476.3 \cdot K - 4103 \cdot K^{2}$$

Coupling Curve For 5 mm Thick Wall



5 mm wall
6 mm screw
5 mm deep

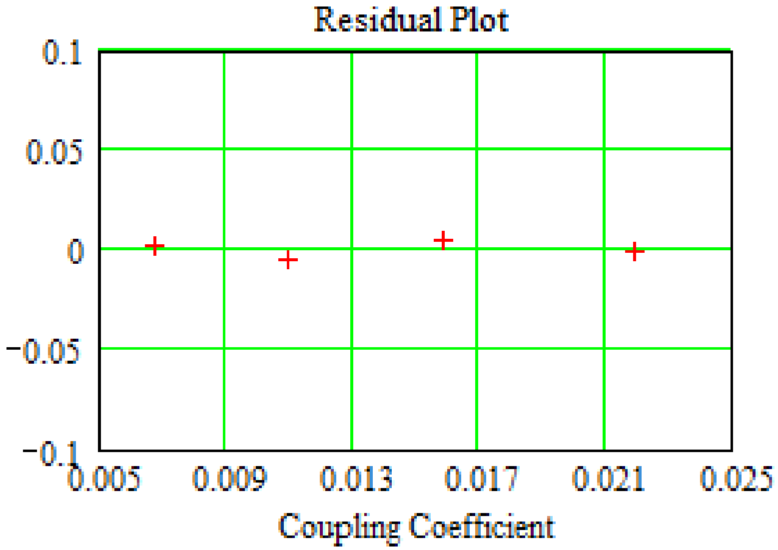
$$S = \begin{pmatrix} 8.261 \\ 604.054 \\ -7.273 \times 10^{3} \end{pmatrix}$$

2nd order polynomial coefficients

$K := .01493$

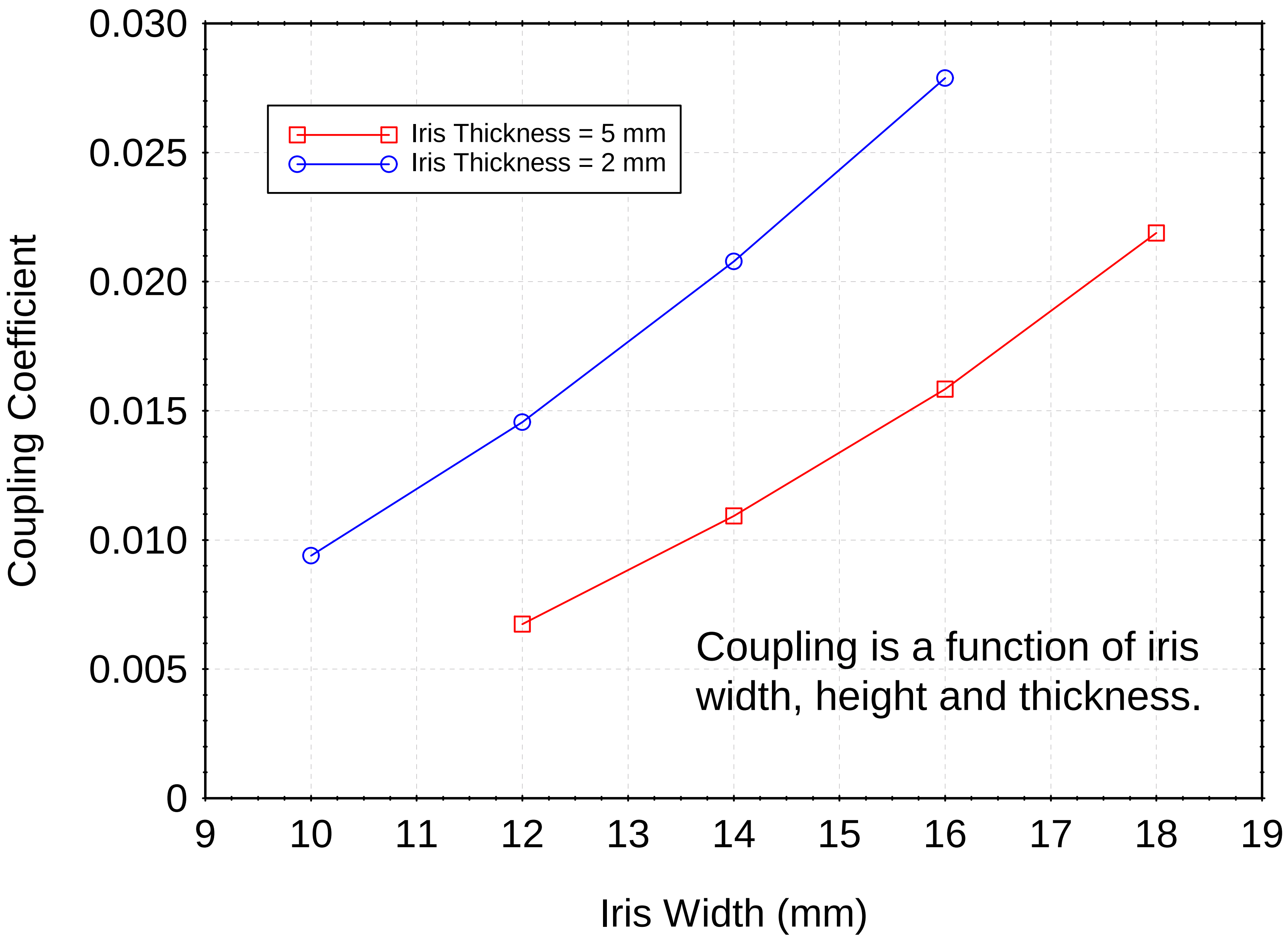
$\mathrm{Iris\_Width}(x) := F(x) \cdot S$

$\mathrm{Iris\_Width}(K) = 15.658$



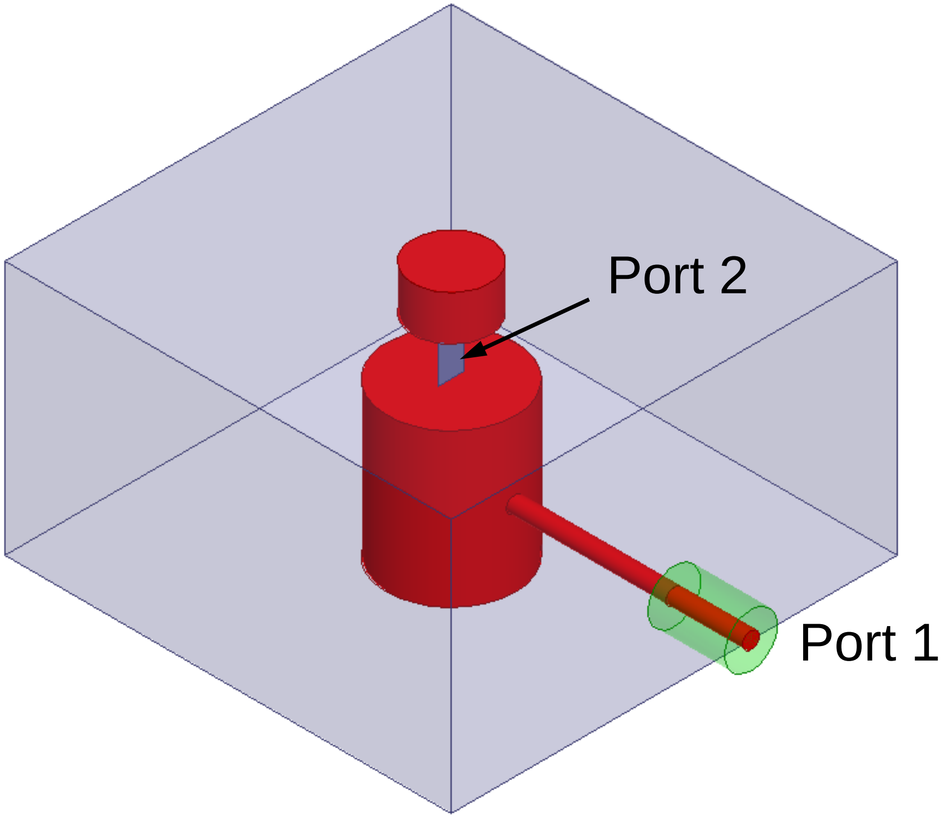
$$Iris\,Width = 8.3 + 604.1 \cdot K - 7273 \cdot K^{2}$$

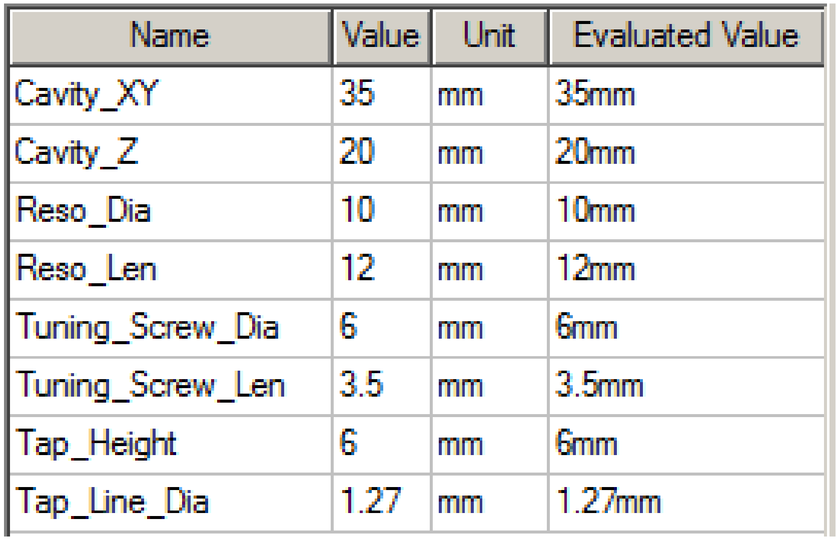
Coupling Coefficients vs Iris Thickness



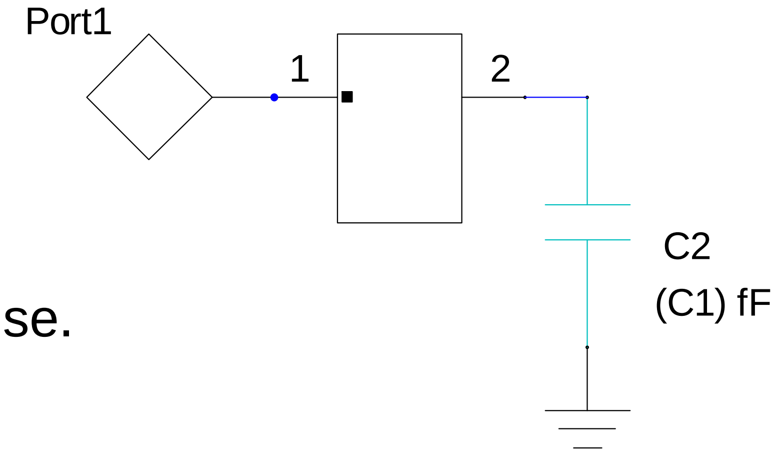
Coupling is a function of iris width, height and thickness.

HFSS Project for Qex



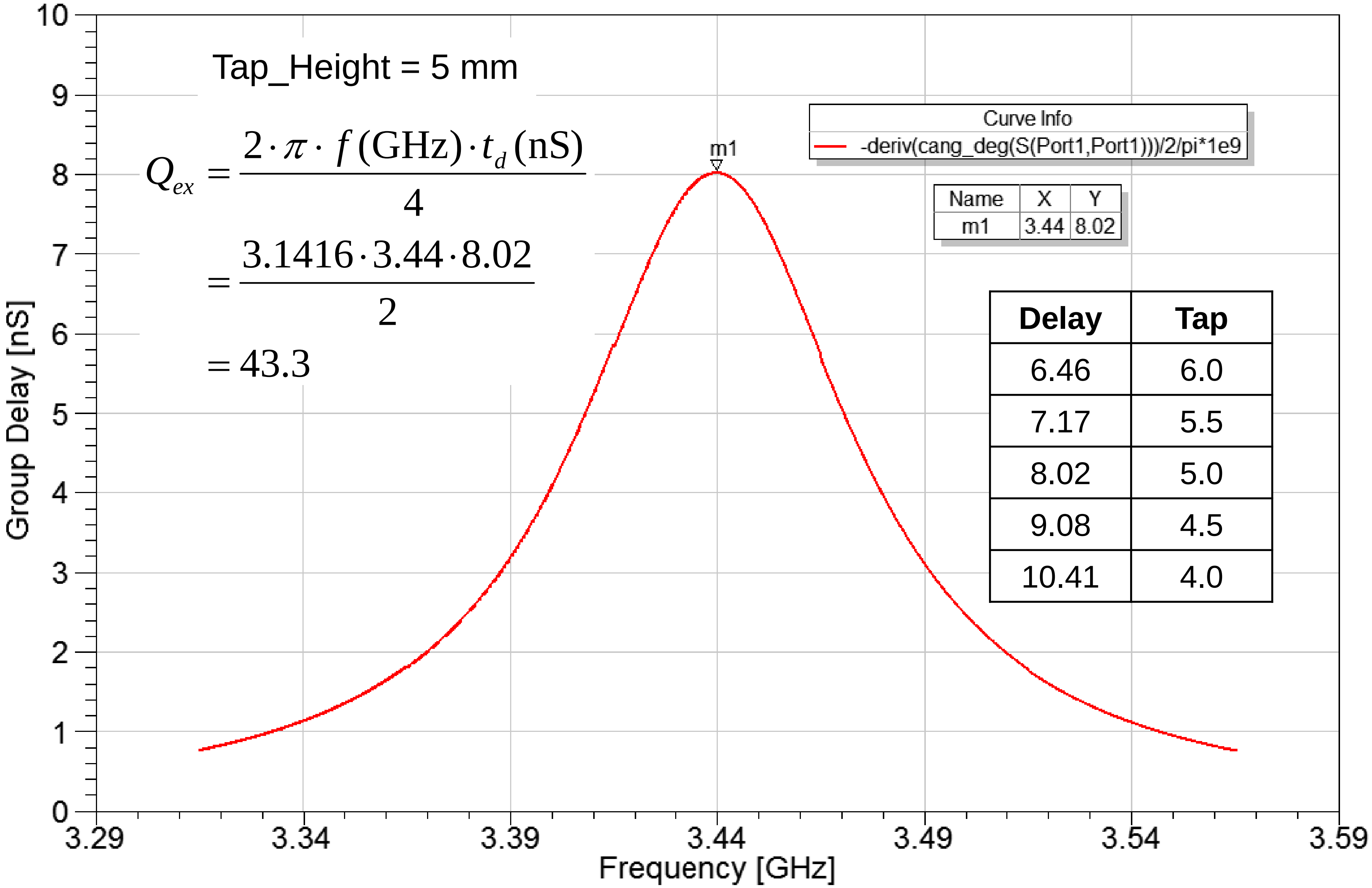


Name	Value	Unit	Evaluated Value
Cavity_XY	35	mm	35mm
Cavity_Z	20	mm	20mm
Reso_Dia	10	mm	10mm
Reso_Len	12	mm	12mm
Tuning_Screw_Dia	6	mm	6mm
Tuning_Screw_Len	3.5	mm	3.5mm
Tap_Height	6	mm	6mm
Tap_Line_Dia	1.27	mm	1.27mm



- Make the model parametric for future re-use.
- Tune to center frequency at Port 2.
- Measure reflected group delay at Port 1.
- Tap height sets the return loss level of our filter.

Port Tuned Reflected Delay



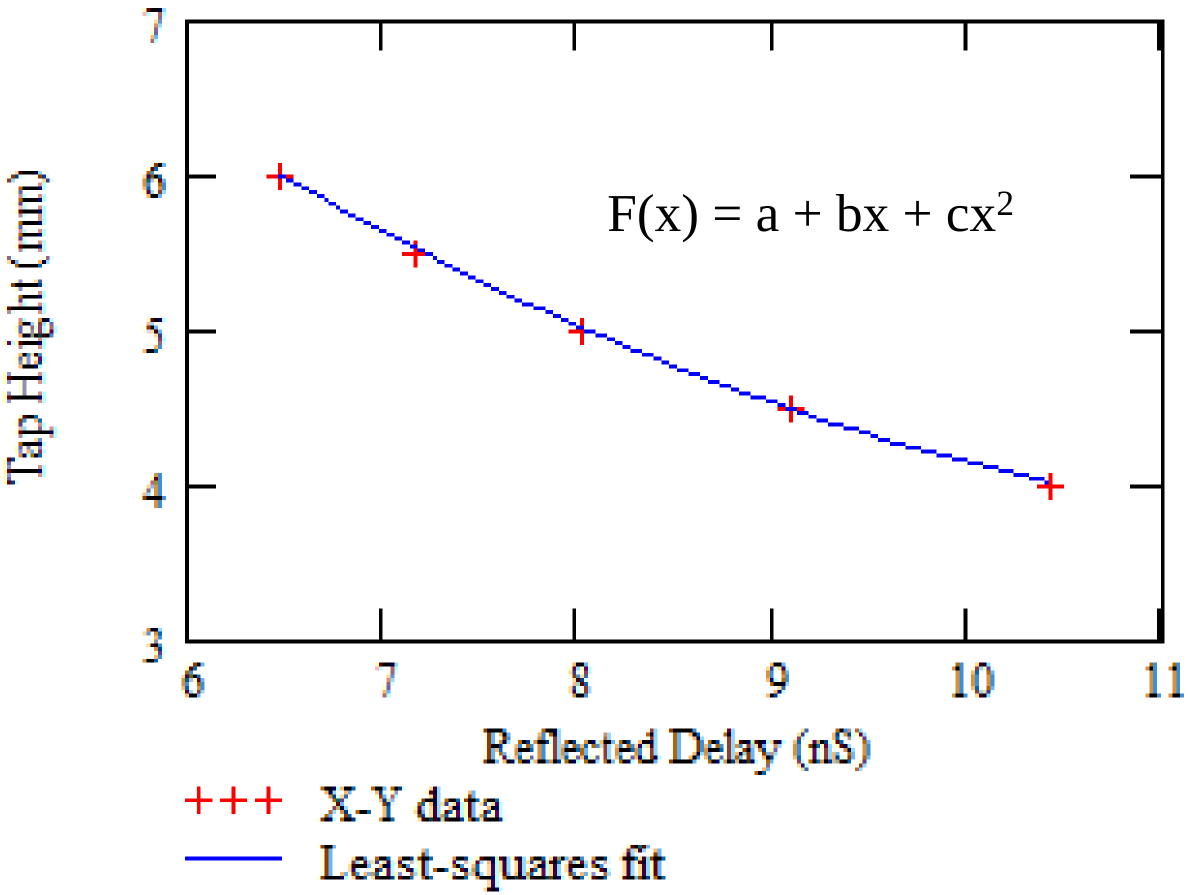
Name	X	Y
m1	3.44	8.02

Tap_Height = 5 mm

$$Q_{ex} = \frac{2 \cdot \pi \cdot f\,(\text{GHz}) \cdot t_d\,(\text{nS})}{4} = \frac{3.1416 \cdot 3.44 \cdot 8.02}{2} = 43.3$$

Delay	Tap
6.46	6.0
7.17	5.5
8.02	5.0
9.08	4.5
10.41	4.0

Qex Data Curve Fit in MathCAD

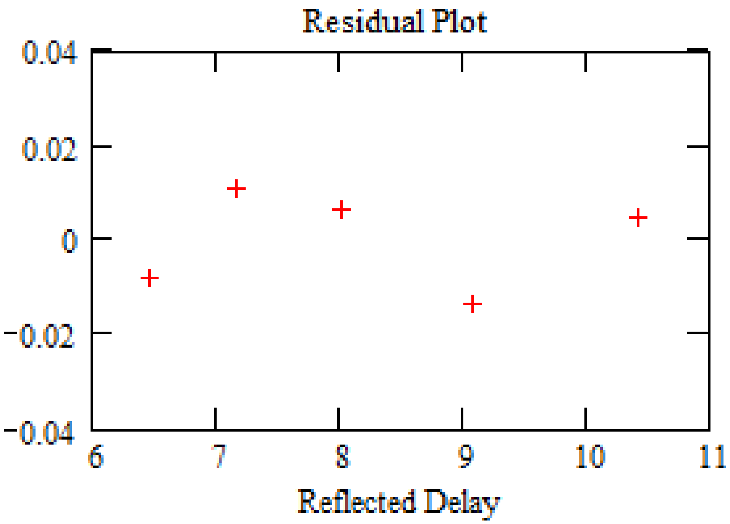


$$S = \begin{pmatrix} 12.865 \\ -1.412 \\ 0.054 \end{pmatrix}$$

$$td := 7.96$$

$$Tap\_Height(x) := F(x) \cdot S$$

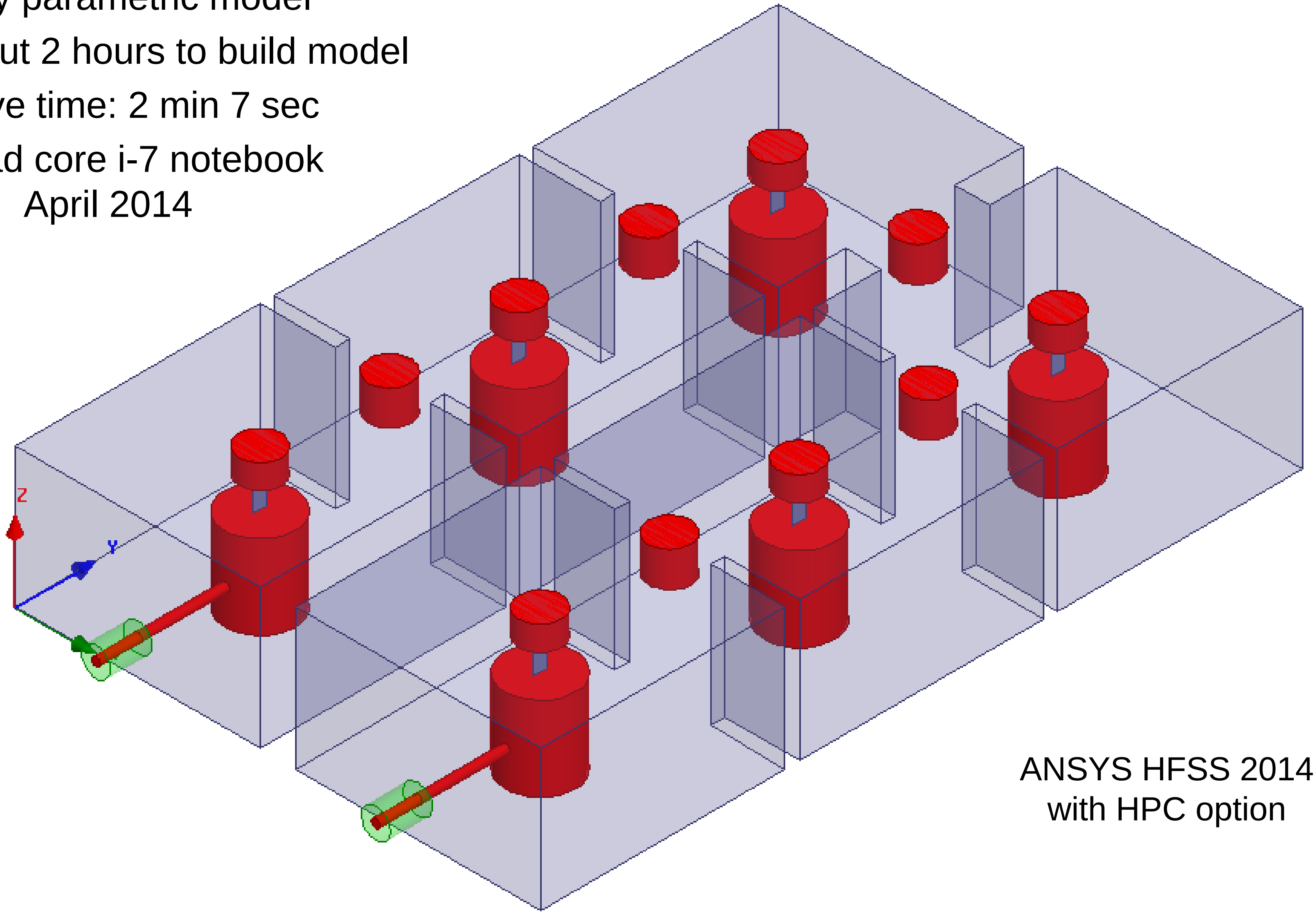
$$Tap\_Height(td) = 5.039$$



$$Tap\ Height = 12.865 - 1.412 \cdot Delay + 0.054 \cdot Delay^2$$

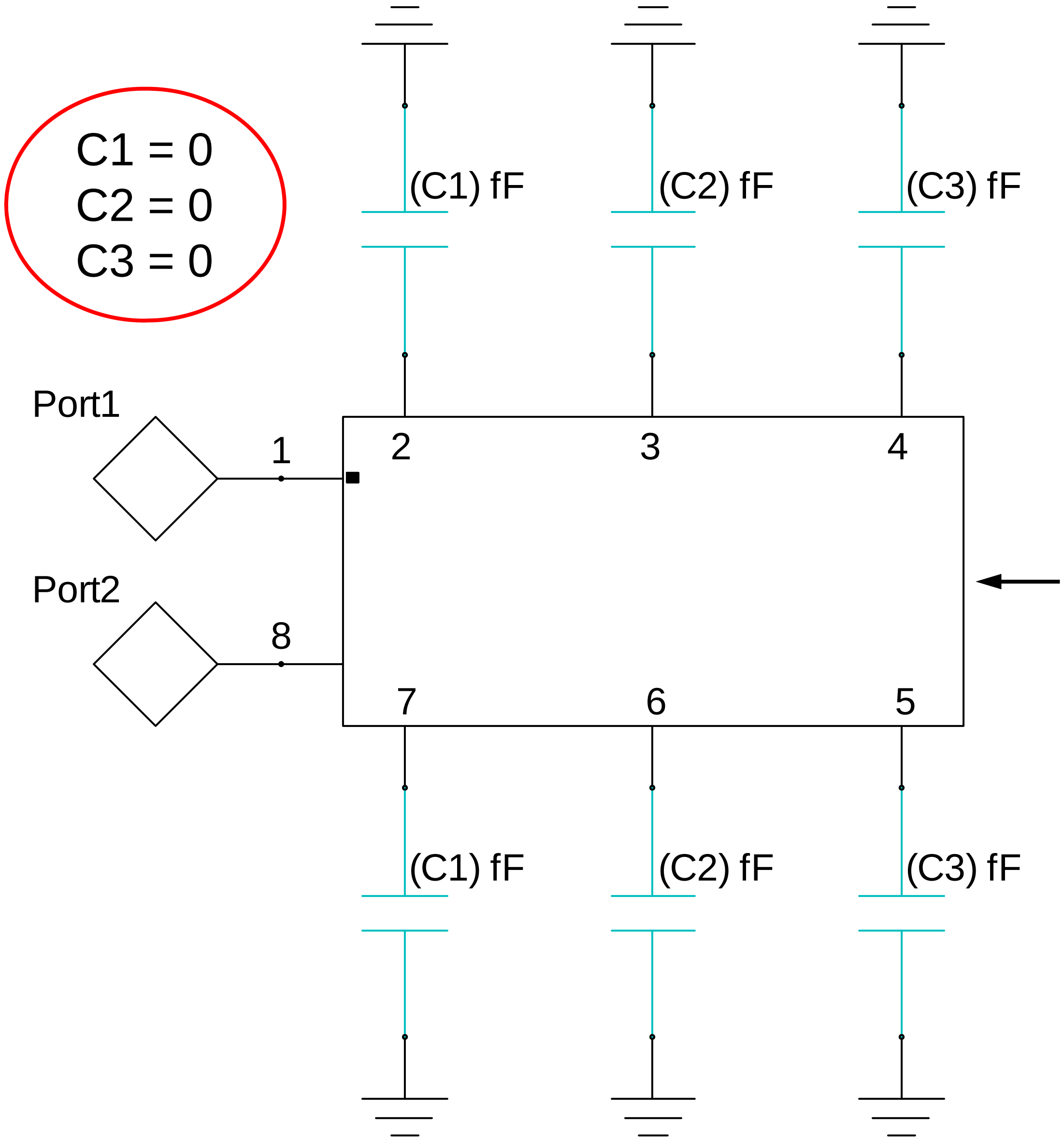
HFSS Model of Complete Filter

- Fully parametric model
- About 2 hours to build model
- Solve time: 2 min 7 sec
- Quad core i-7 notebook
  April 2014



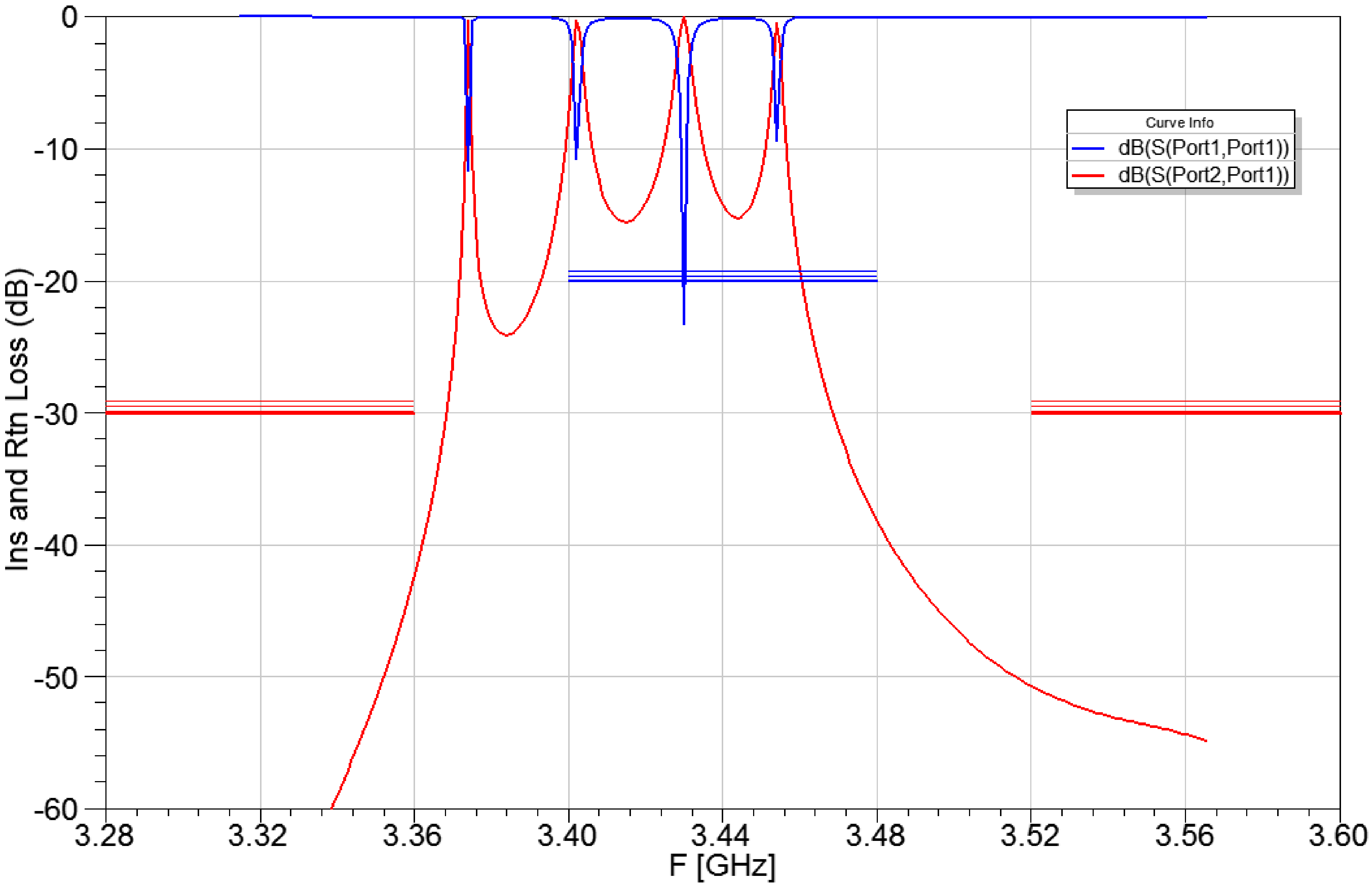
ANSYS HFSS 2014
with HPC option

Initial Simulation – No Tuning

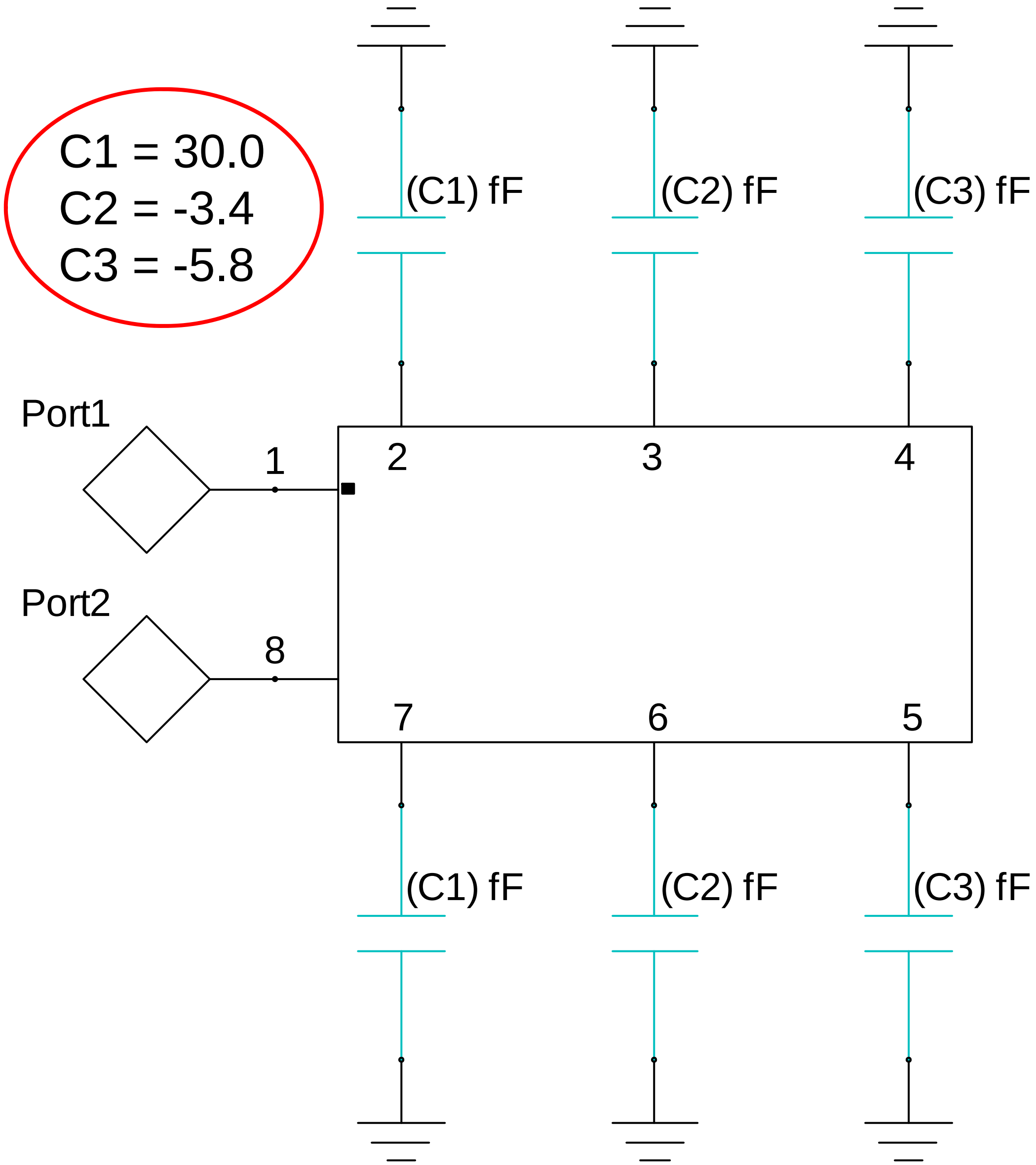


User defined symbol for S-parameter data

Initial Simulation – No Tuning



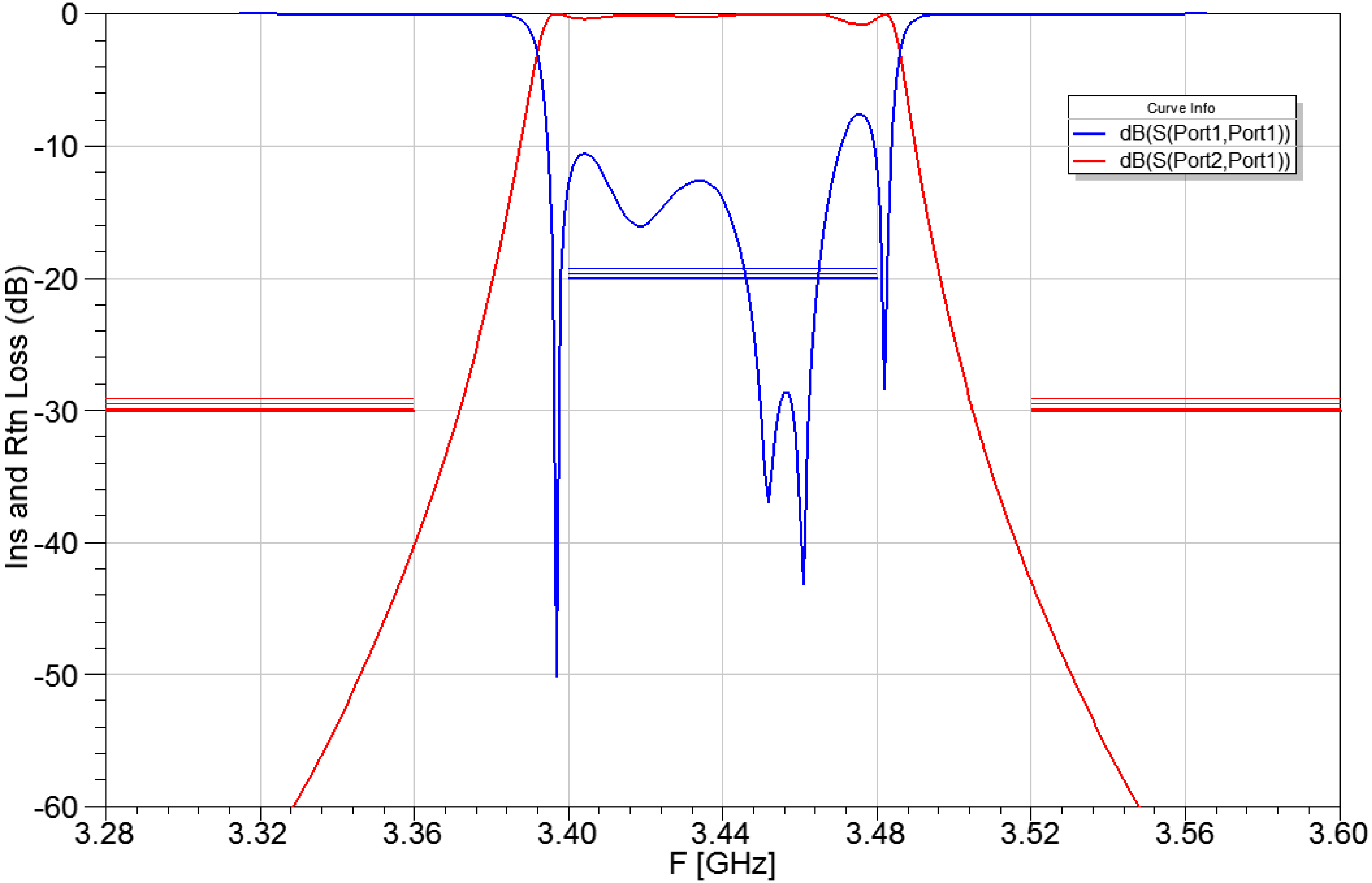
Symmetrical Tune of Resonators



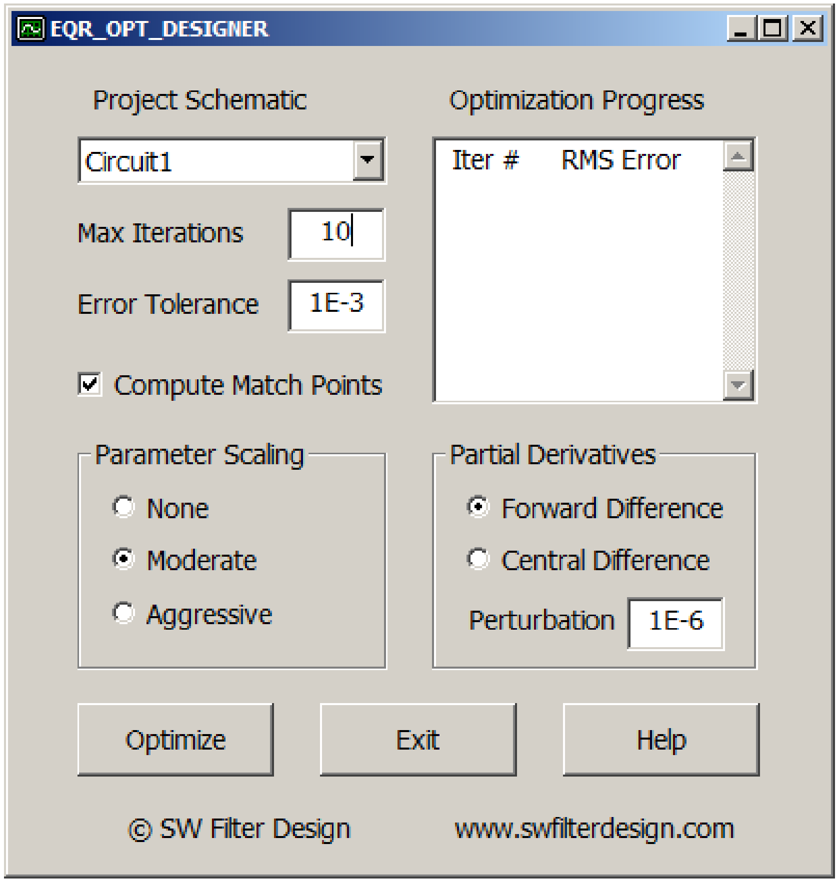
C1 = 30.0
C2 = -3.4
C3 = -5.8

- Only tune the resonators, not the couplings.
- Use symmetry to reduce the number of variables.
- We can tune this manually, don’t need an optimizer.

Symmetrical Tune of Resonators



Full Port Tune with EQR_OPT



Project Schematic: Circuit1

Max Iterations: 10

Error Tolerance: 1E-3

☑ Compute Match Points

Optimization Progress

Iter # RMS Error

Parameter Scaling
- ○ None
- ● Moderate
- ○ Aggressive

Partial Derivatives
- ● Forward Difference
- ○ Central Difference

Perturbation: 1E-6

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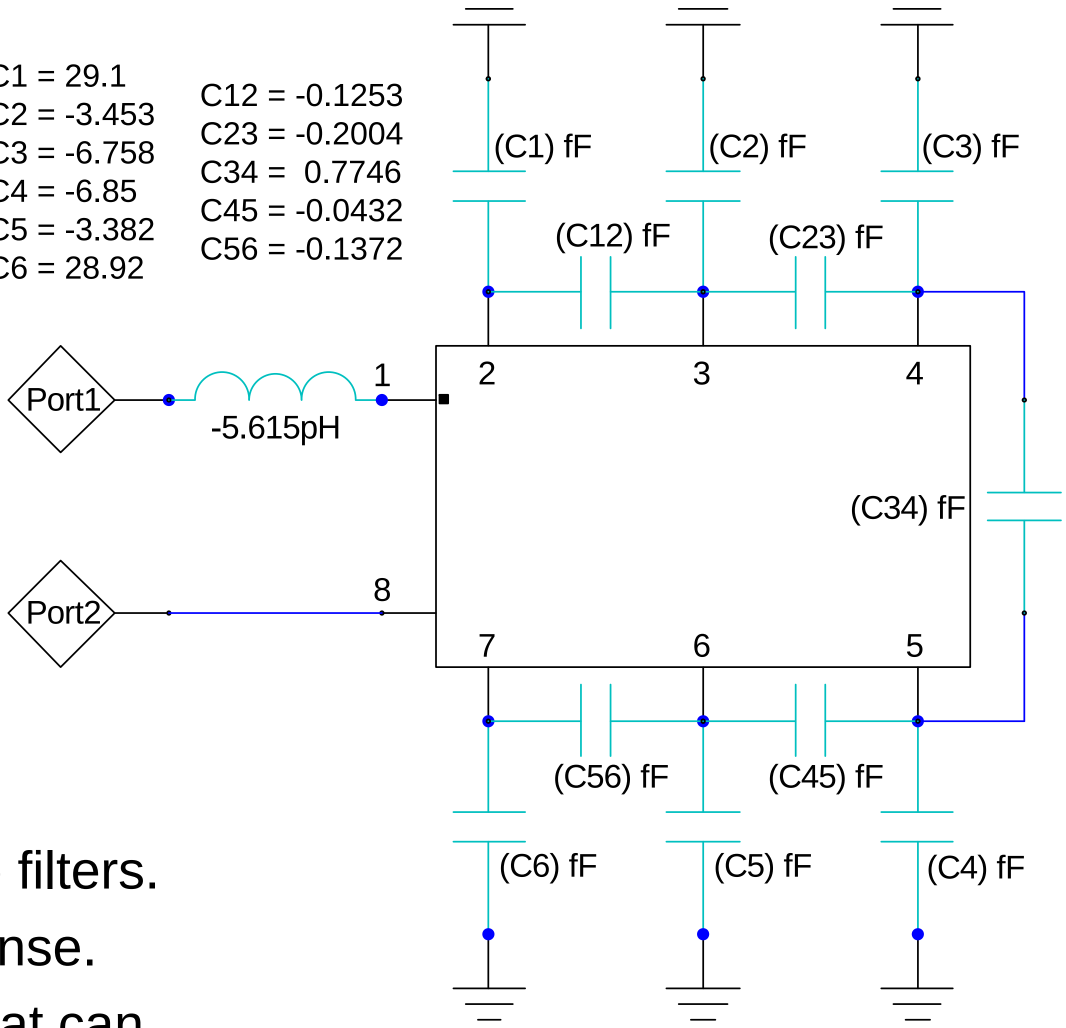
Note: Units are fF and pH

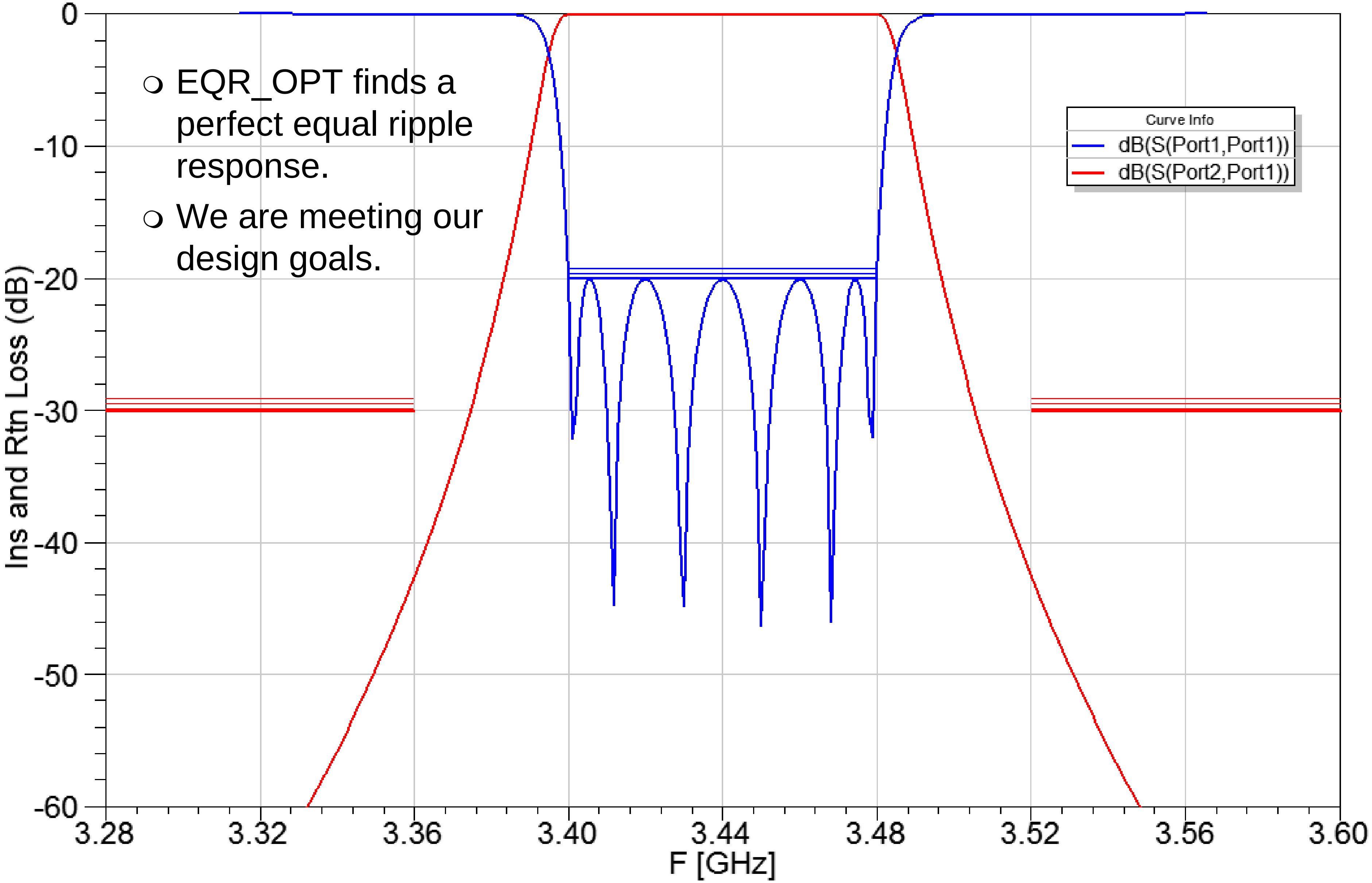
C1 = 29.1
C2 = -3.453
C3 = -6.758
C4 = -6.85
C5 = -3.382
C6 = 28.92

C12 = -0.1253
C23 = -0.2004
C34 = 0.7746
C45 = -0.0432
C56 = -0.1372



- Dedicated optimizer for microwave filters.
- It finds an exact equal ripple response.
- It works on any Chebyshev filter that can be defined in your circuit simulator.

Full Port Tune of HFSS Model

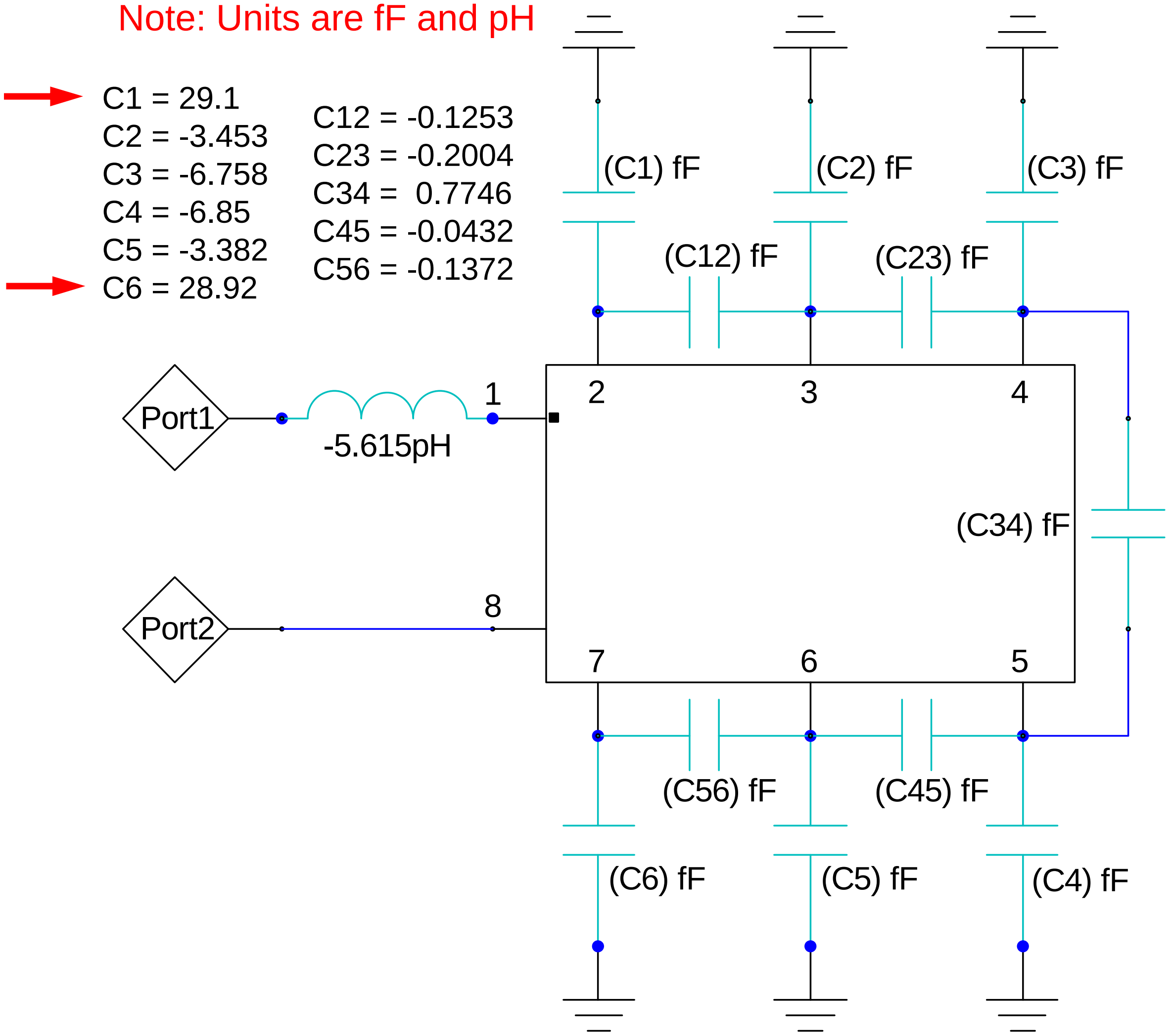


- ❍ EQR_OPT finds a perfect equal ripple response.
- ❍ We are meeting our design goals.

Moving The Tuning Screws

- The largest errors are the first and last resonator tunings.
- This is a well known characteristic of tapped resonators.
- We can move the tuning screws in the HFSS model to get a feel for the amount of correction needed.

Note: Units are fF and pH



C1 = 29.1
C2 = -3.453
C3 = -6.758
C4 = -6.85
C5 = -3.382
C6 = 28.92

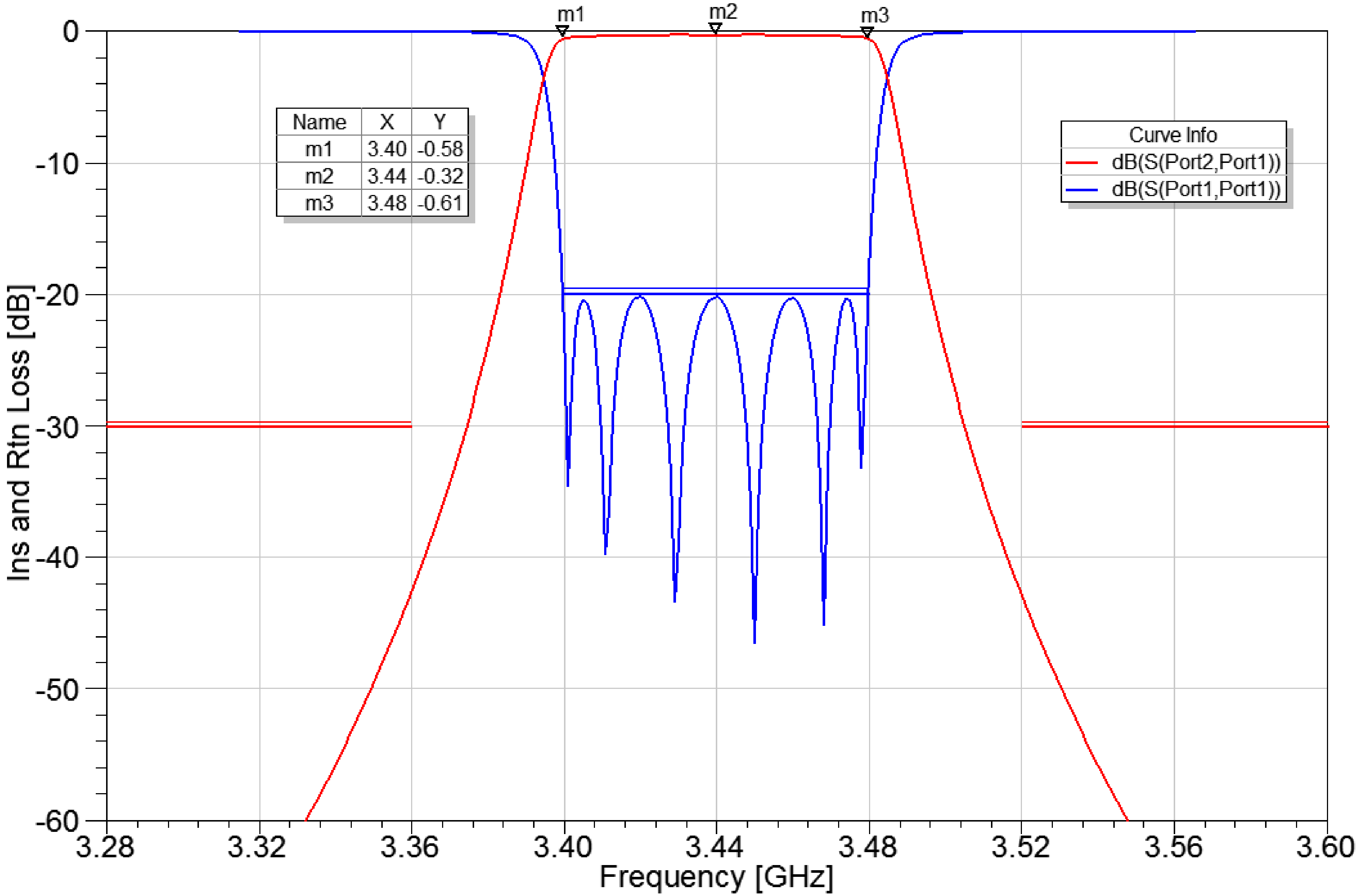
C12 = -0.1253
C23 = -0.2004
C34 = 0.7746
C45 = -0.0432
C56 = -0.1372

Tuning Results

Variable	Initial Screw Depths (mm)	Initial Tunings (fF)	Final Screw Depths (mm)	Final Tunings (fF)
C1	3.5	29.100	4.33	1.168
C2	3.5	-3.453	3.35	0.224
C3	3.5	-6.850	3.27	0.148
C4	3.5	-6.850	3.27	-0.132
C5	3.5	-3.382	3.35	0.223
C6	3.5	28.920	4.33	0.659
C12	5.0	-0.125	5.2	0.031
C23	5.0	-0.020	5.0	-0.028
C34	5.0	0.775	2.8	0.043
C45	5.0	-0.043	5.0	-0.036
C56	5.0	-0.137	5.2	0.019

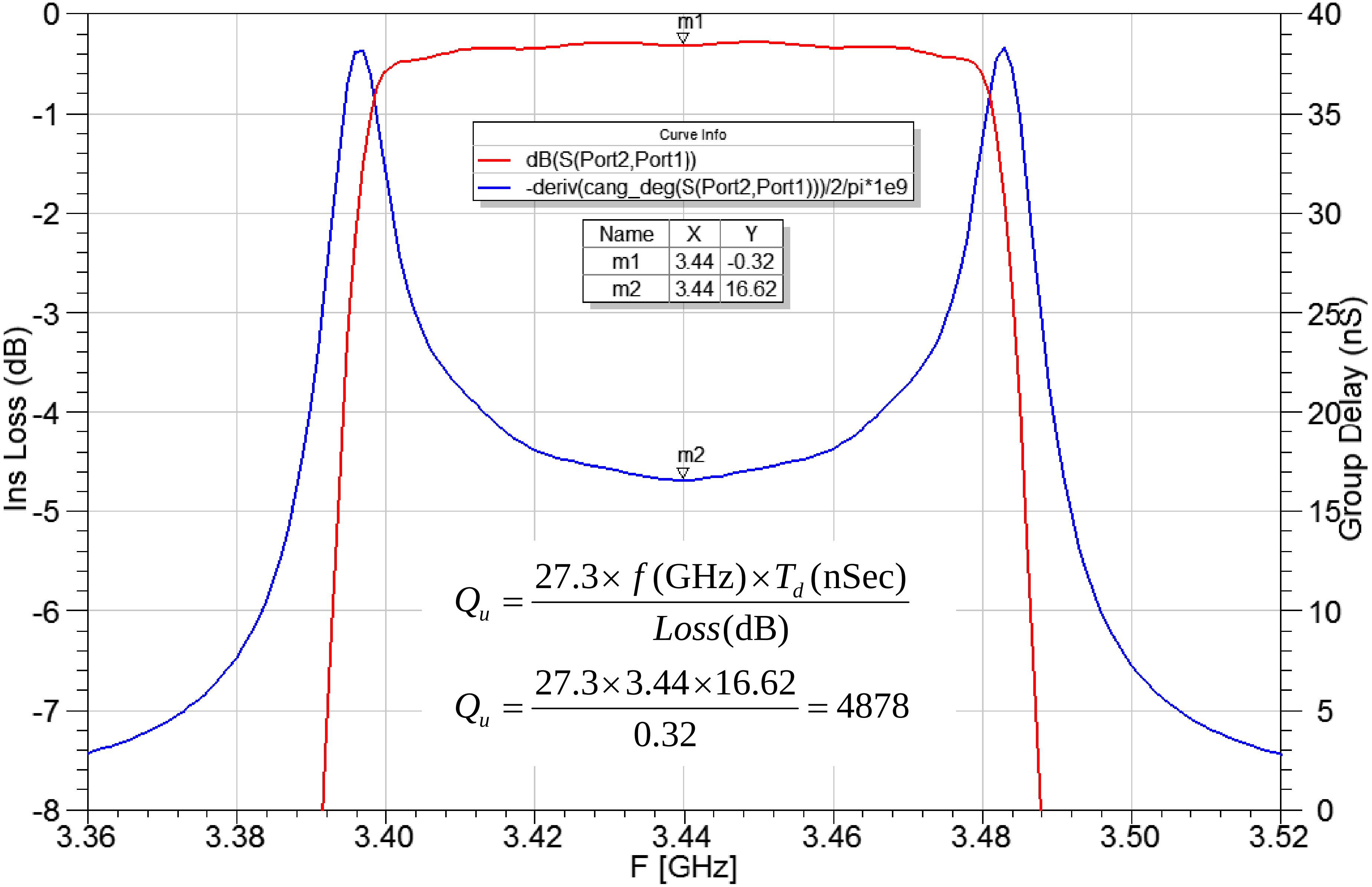
- We see strong symmetry in the initial tunings.
- We see some numerical noise in the final tunings.

HFSS Simulation With Loss



Name	X	Y
m1	3.40	-0.58
m2	3.44	-0.32
m3	3.48	-0.61

Computing Average Qu



Name	X	Y
m1	3.44	-0.32
m2	3.44	16.62

$$Q_u = \frac{27.3 \times f\,(\mathrm{GHz}) \times T_d\,(\mathrm{nSec})}{Loss(\mathrm{dB})}$$

$$Q_u = \frac{27.3 \times 3.44 \times 16.62}{0.32} = 4878$$

Summary

- Dishal’s K and Q method leads us to a simple design flow for narrowband filters.
- We can modernize the method by using HFSS to build the Kij and Qex design curves that we need.
- We can then build a complete model of our filter in HFSS, port tune it and get a very good prediction of performance.
- These virtual prototypes in HFSS avoid the time and expense of multiple hardware prototypes.
- Experience has shown that we can rely on the HFSS filter model.

References

[1] R. Levy, R. Snyder and G. Matthaei, “Design of Microwave Filters,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-50, pp. 783-793, March 2002.

[2] M. Dishal, “Alignment and adjustment of synchronously tuned multiple resonate circuit filters,” *Proc IRE*, vol. 30, pp. 1448-1455, Nov. 1951.

[3] M. Dishal, “A simple design procedure for small percentage bandwidth round-rod interdigital filters, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 696-698, Sept. 1965.

[4] J. Wong, “Microstrip tapped-line filter design,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 44-50, Jan. 1979.

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[6] D. G. Swanson, Jr., “Corrections to “Narrow-Band Microwave Filter Design, “ *IEEE Microwave Magazine*, vol. 9, no. 1, p. 116, Feb. 2008.