Designing Microstrip Bandpass Filters

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Introduction

- This talk describes a technique for designing coupled resonator RF filters.
- The design technique involves an producing an approximate initial design using filter K and Q tables and model measurements using a simple resonator.
- The resulting initial filter designs is then optimised to provide the final design for the filter.

Introduction

- Lowpass and Highpass filters
  - Most often LC filters. Low Q requirements.
  - Can use Transmisison Lines for Inductors and Stubs for Capacitors if > 1 GHz.
- Bandpass Coupled Resonator filters.
  - LC coupled resonator < 300 MHz
  - Microstrip filters **low cost** > 300 MHz
  - Stripline filters now becoming realisable (Multi-layer RF PCB and LTCC substrates)

Introduction

Most RF filters are narrowband (<10% BW)

– Parallel Coupled Line filter, Interdigital filter narrowband only.

– Direct Coupled Resonator filter, wideband and narrowband

Wideband filters are difficult to design.

Technique applied to a 500 MHz BW filter with a 1GHz Centre frequency.

Microstripline Filter Q

- Microstripline filters are simple to make but:
  - Resistive, Radiation and Dielectric losses.
  - For RT Duroid (E_r = 2.3) max Q = 217
  - For 0.635 mm substrate:
    - Resistive losses Q = 192
    - Radiation losses Q = 3873
    - Dielectric losses Q = 1219
  - For low radiation loss need thin substrate
  - For low resistive loss need thick substrate

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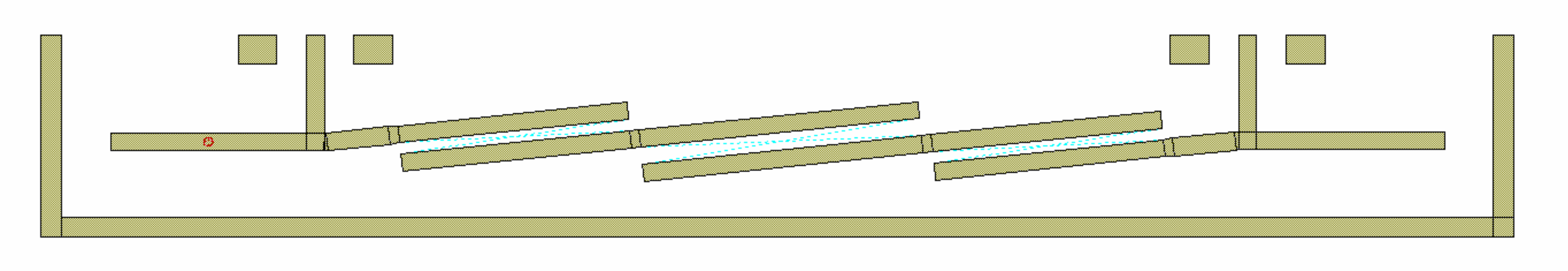
Introduction

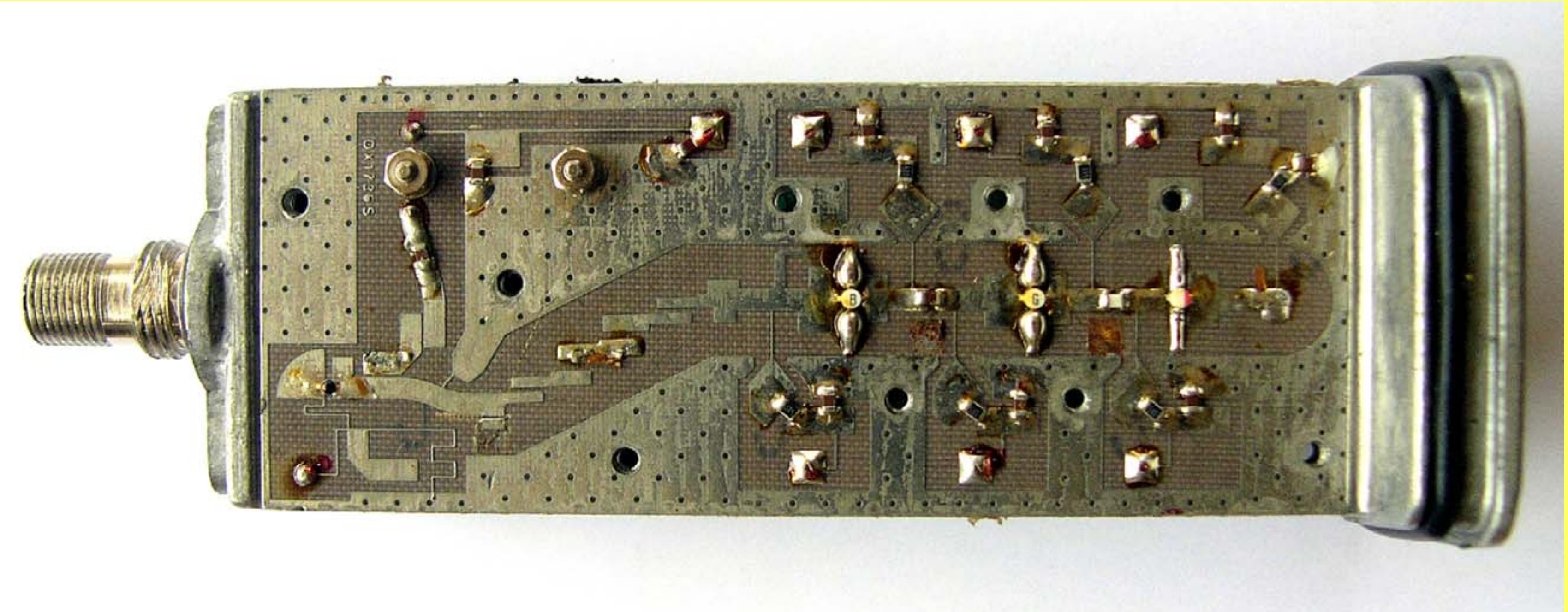
- For Microstrip Circuits the following filters are commonly used:
  - Parallel Coupled Line and Hairpin filter
  - Interdigital filter
- We will also consider:
  - Direct Coupled Resonator filter.
- The design technique described here is applicable to all these filters.

Parallel Coupled line Filter

- Resonator half wavelength long.
- Narrower bandwidth, increases gaps.
- Gap (>0.1 mm) limits Bandwidth.
- Good design accuracy.
- Good symmetry of filter response.
- Large Third Harmonic response.

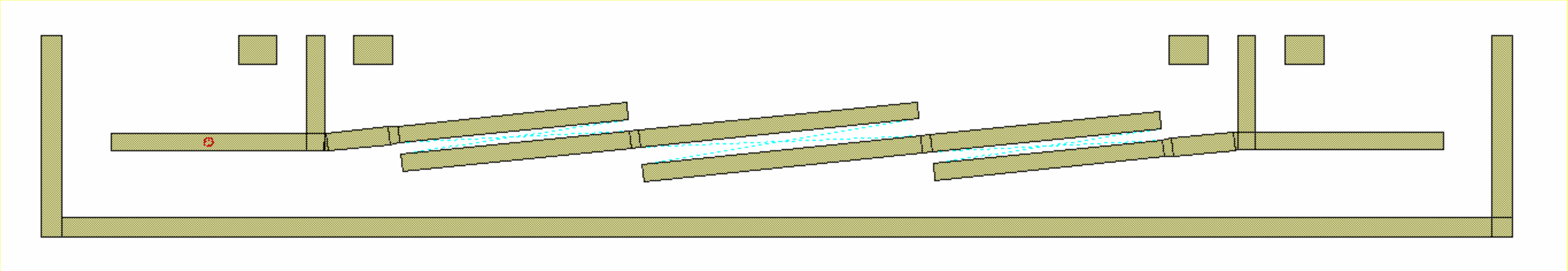


Parallel Coupled line Filter



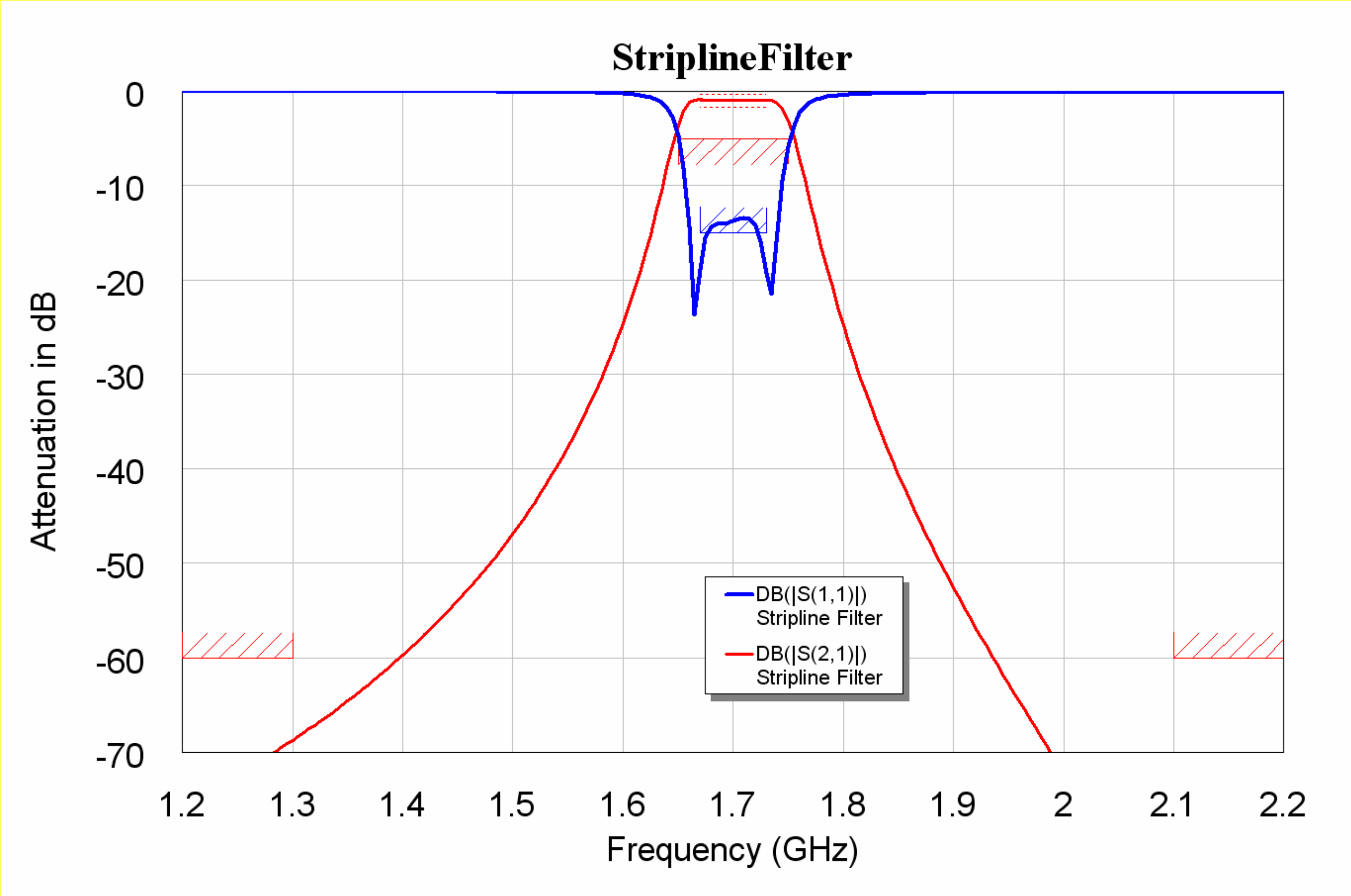
- Typical LNB from NORSAT. Note how filter is tuned.

Parallel Coupled Line Filter



- Tap coupling avoids the requirement for very narrow gaps (0.1mm) in PCB layout.
- This type of layout is hard to mount as an individual filter, long and skinny.

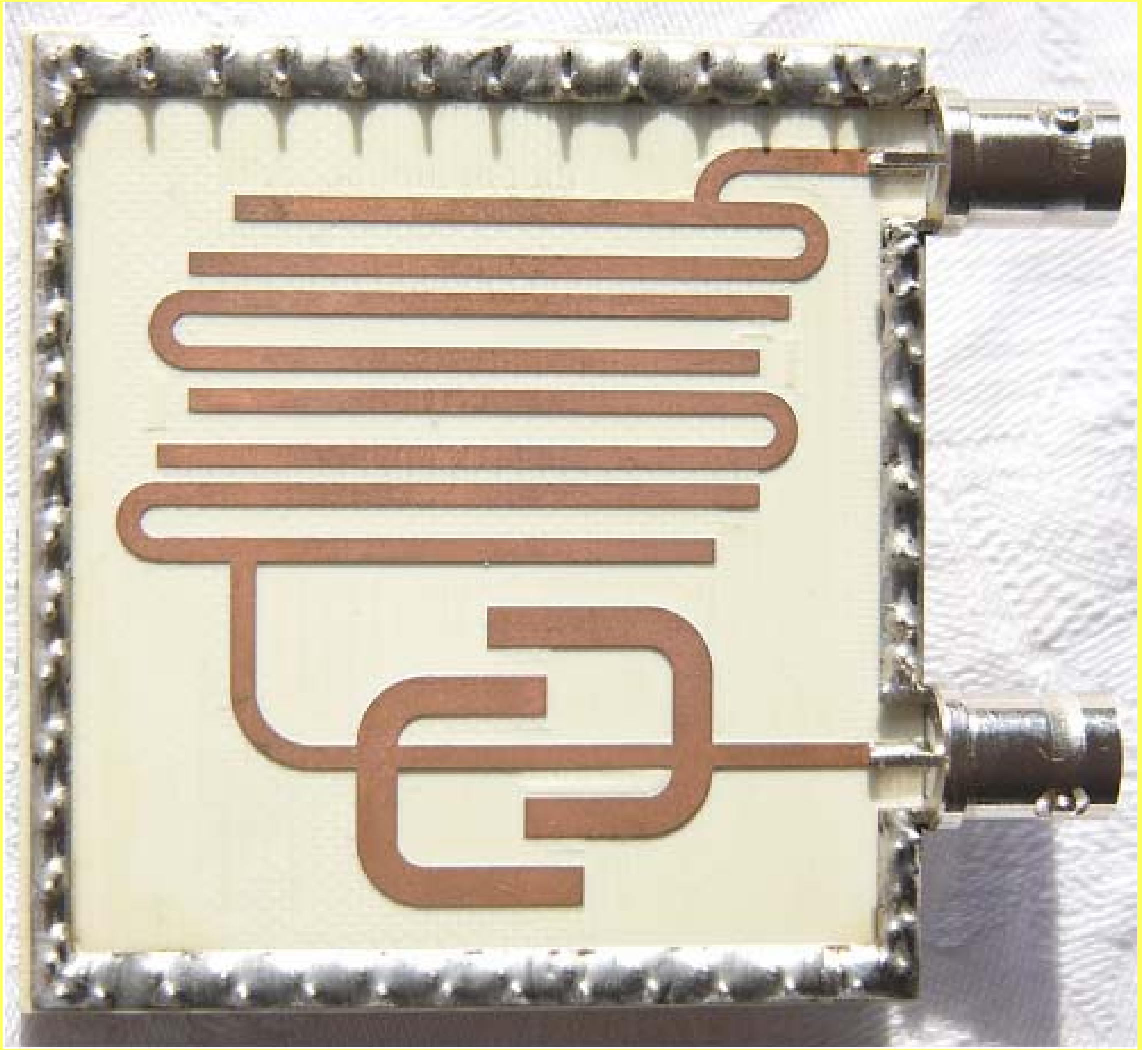
Parallel Coupled Line Filter



Hairpin Filter

- Bend the resonator to form a hairpin like structure.
- Occupies similar area, but close to square shape.
- Harmonic response can be removed using second and third harmonic stubs.
- Typical centre frequency accuracy 2%.

Hairpin Filter



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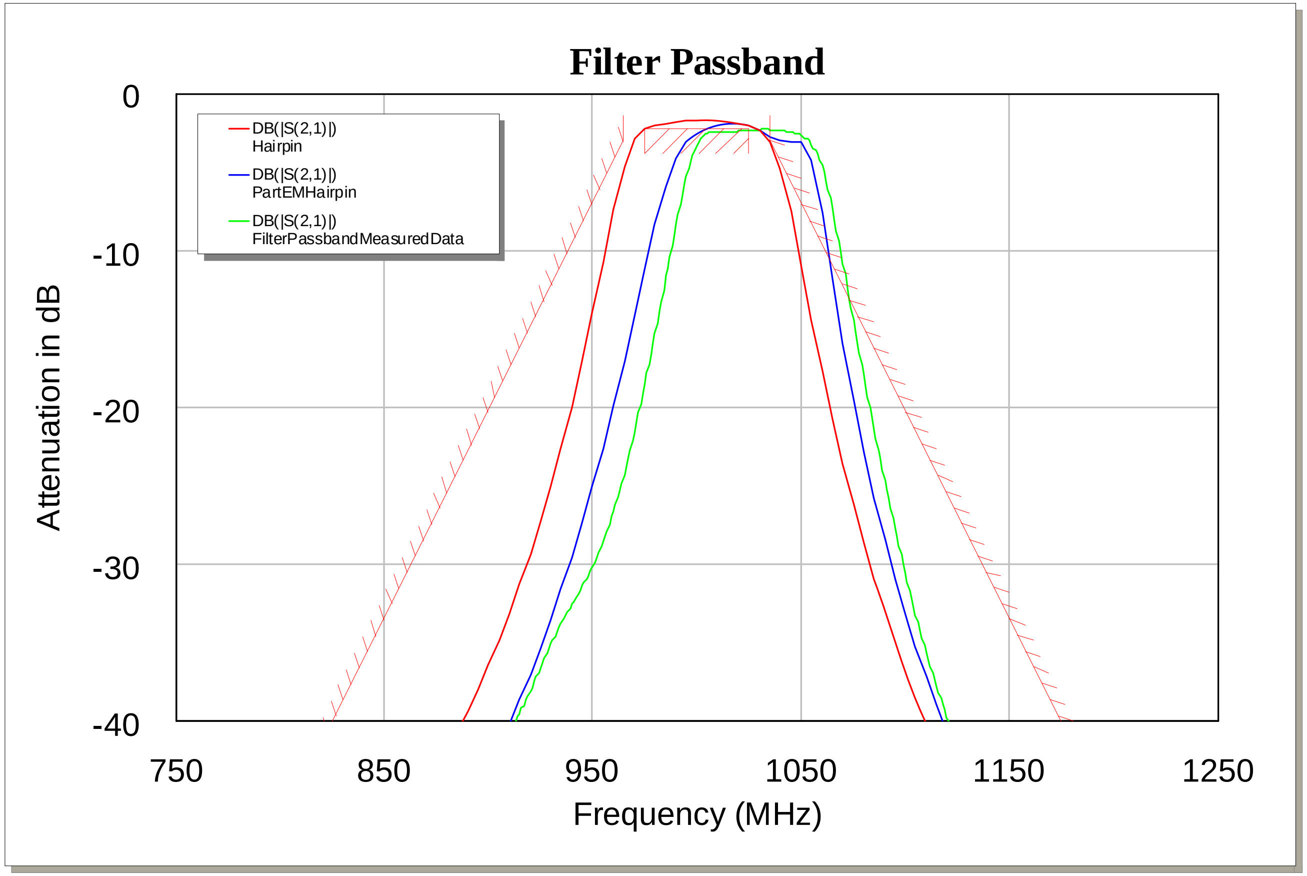
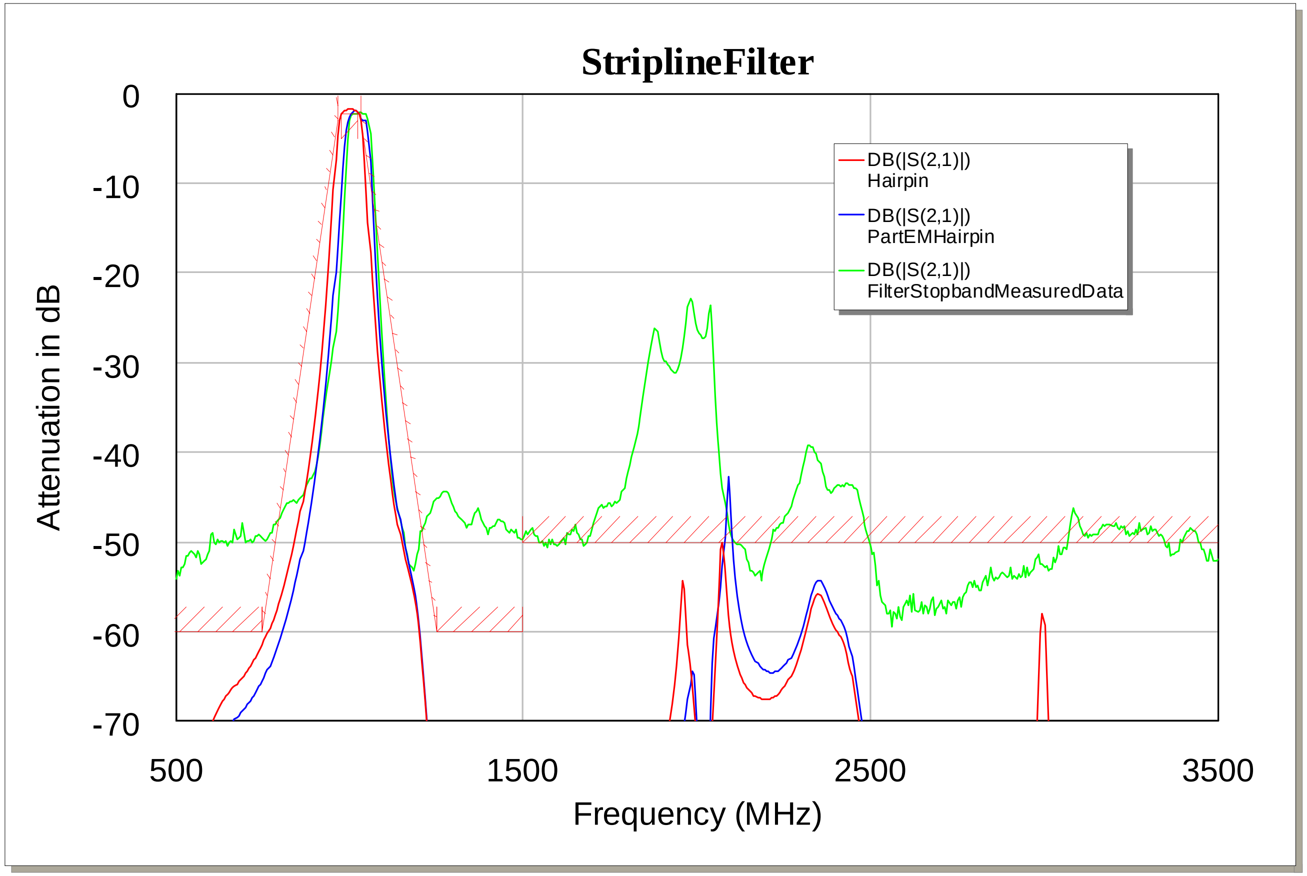
Hairpin Filter



Hairpin Filter



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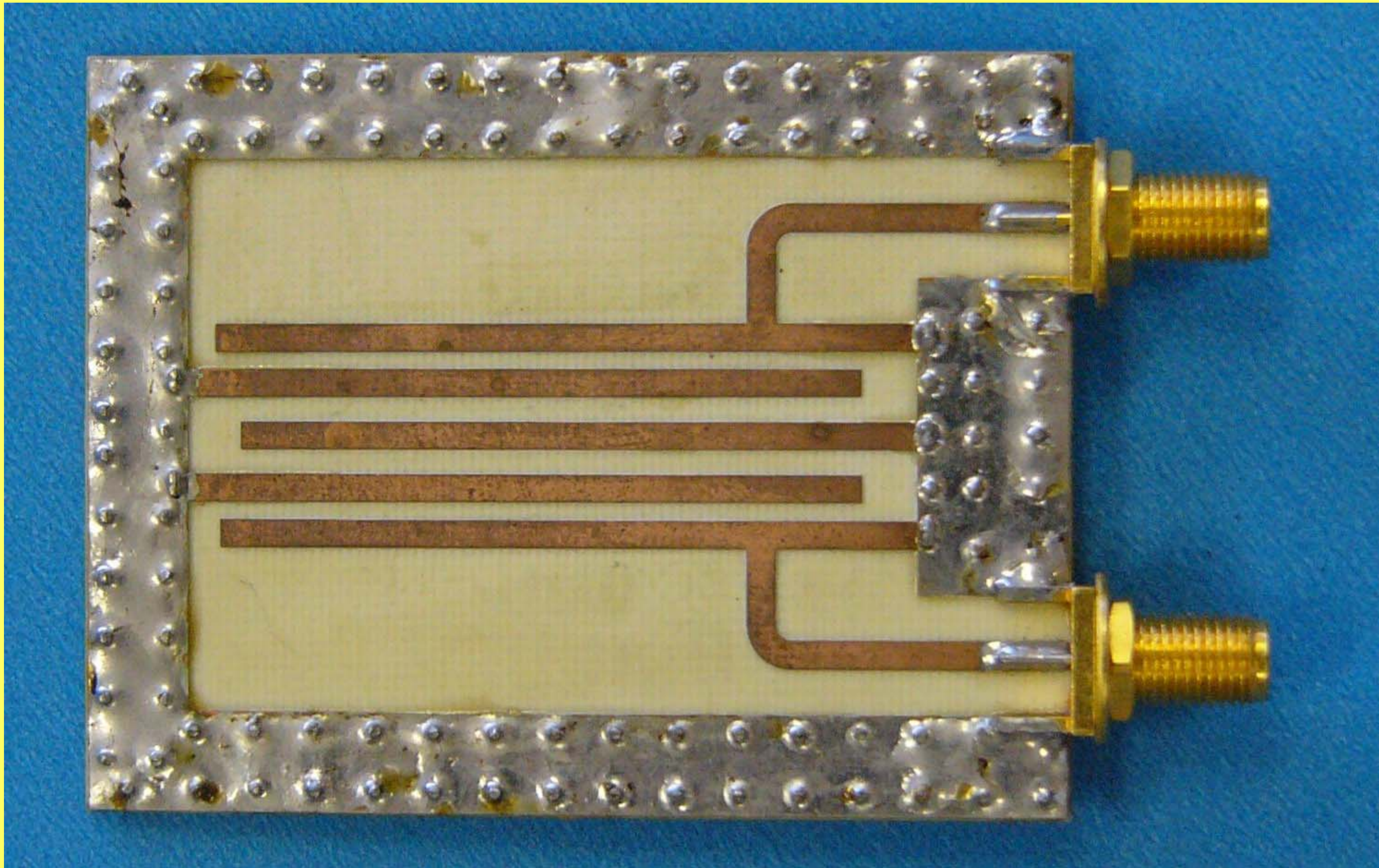
Interdigital Filter

- Very Common.
- Narrow bandwidth.
- Small area, smaller than other filters.
- Slightly asymmetrical response.
- Typical centre frequency accuracy 3%.

Interdigital Filter



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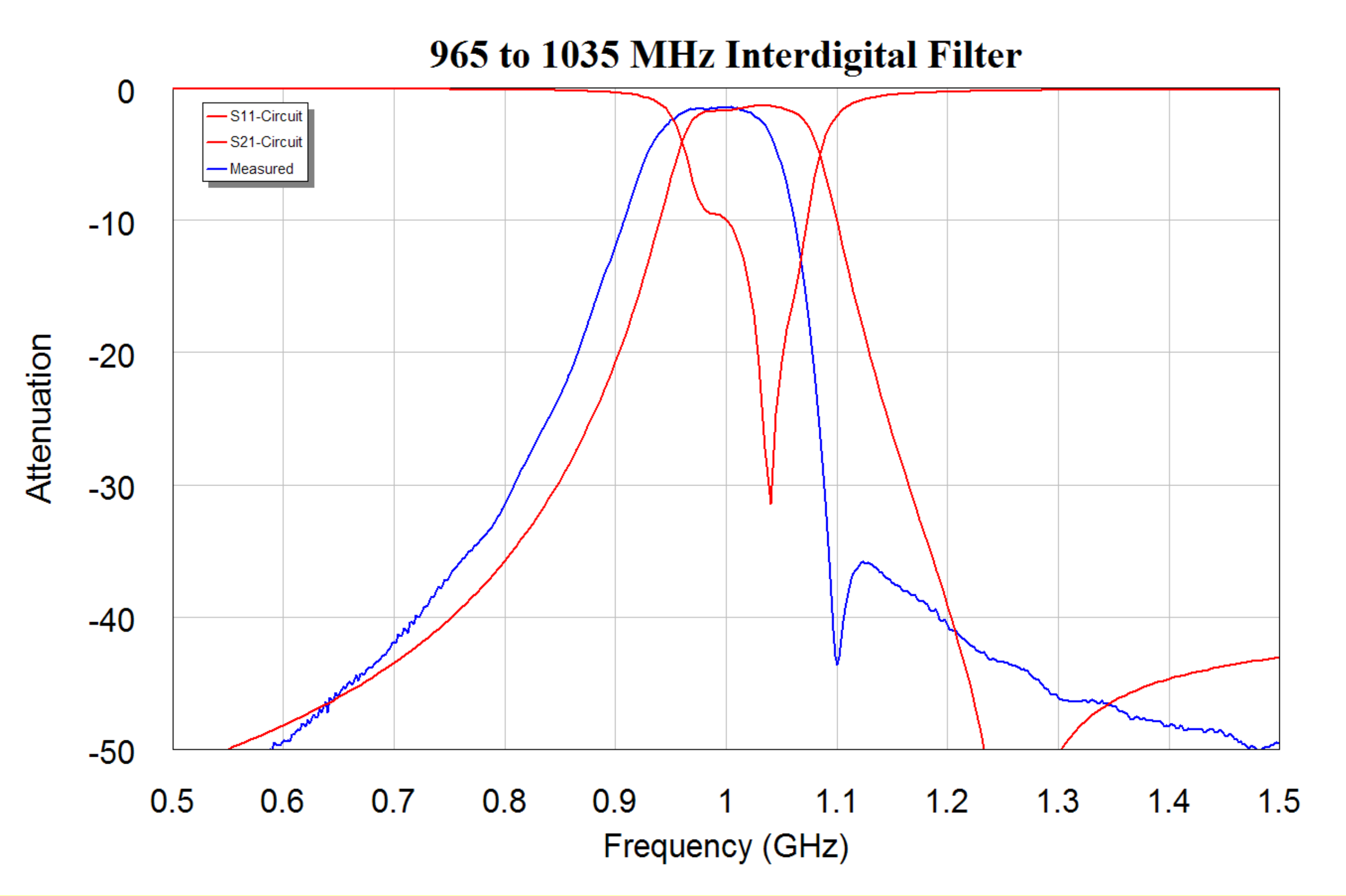
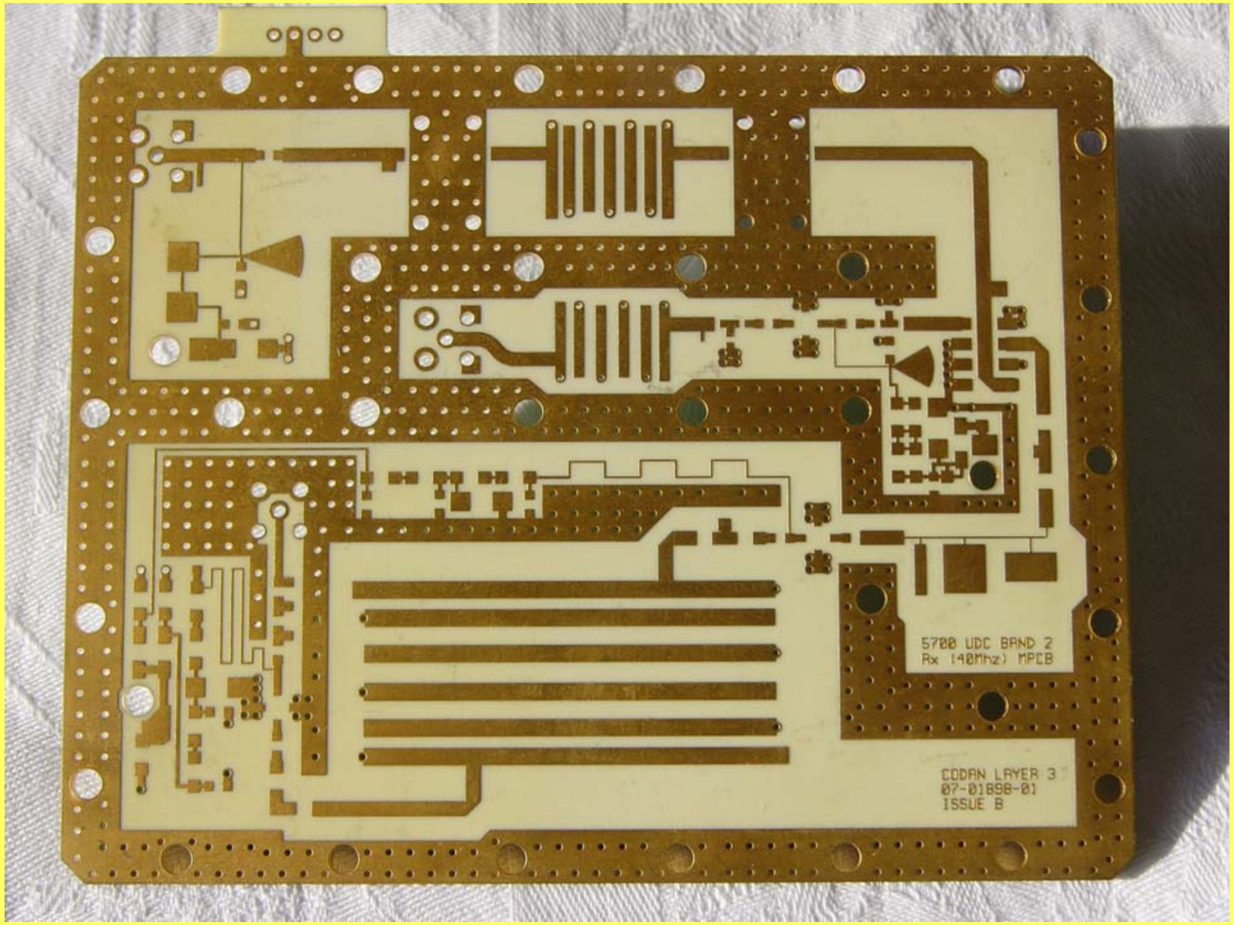
Interdigital Filter



Interdigital Filter

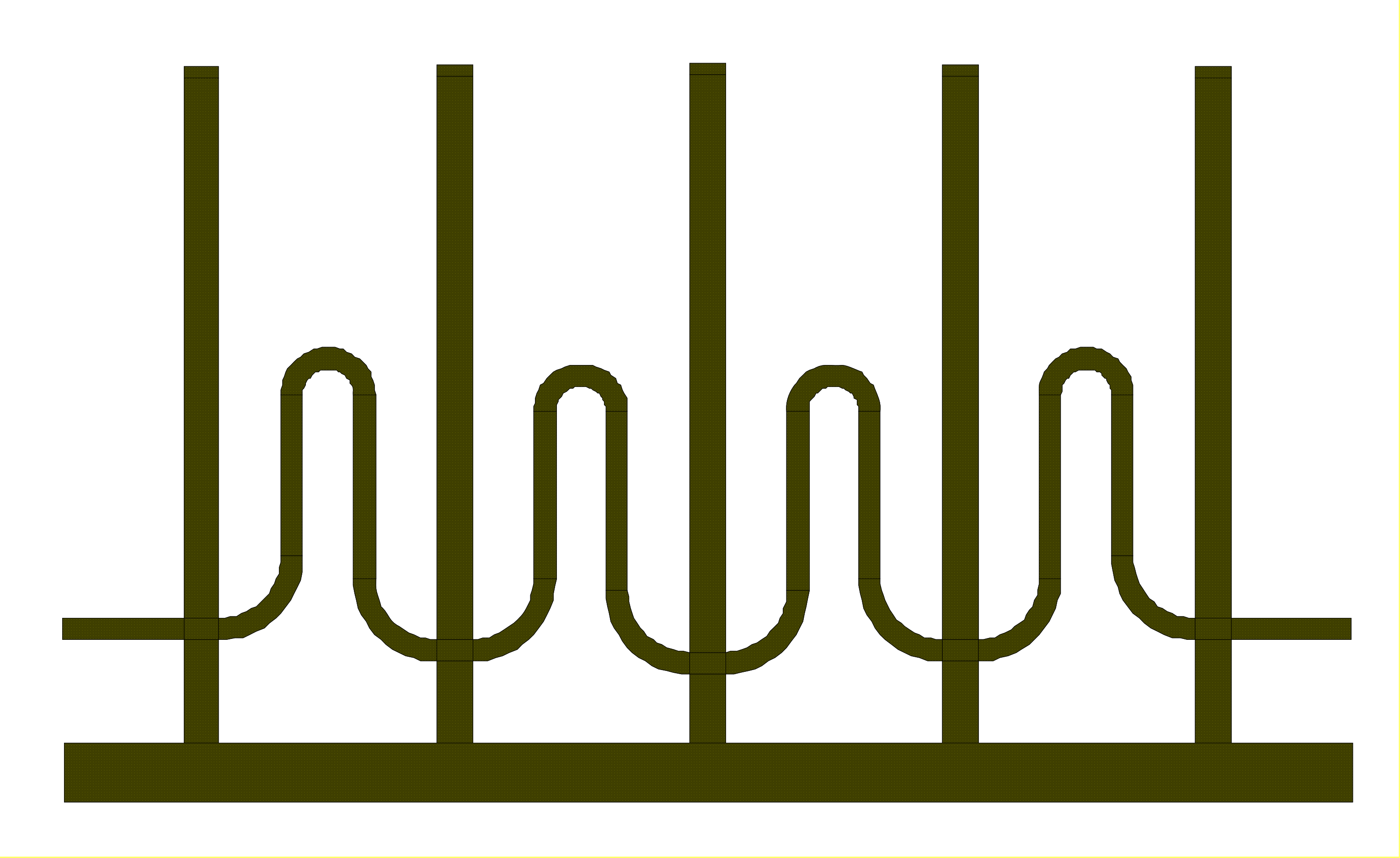


Commercial design by Codan

Direct Coupled Resonator Filter

- Good for wideband filters.
- The quarter wavelength resonators are coupled using quarter wavelength transmission lines.
- Very good agreement between simulated and measured results since no EM modelling is required.
- Low insertion loss.

Direct Coupled Resonator Filter



Design Procedure

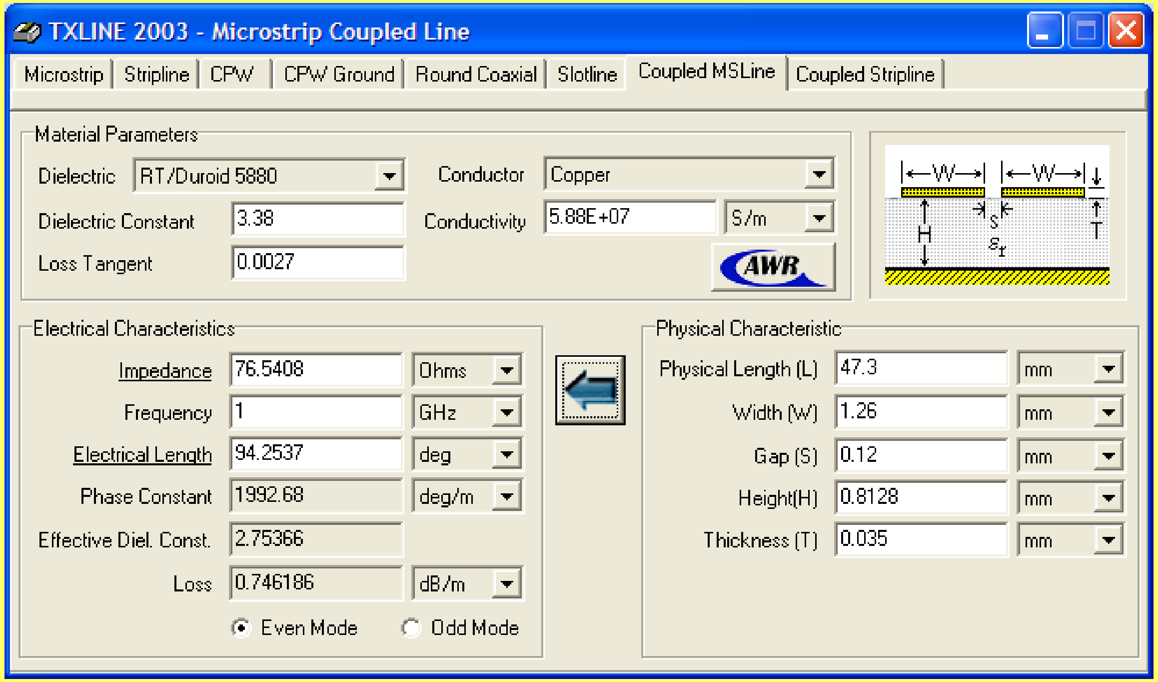
For Parallel Coupled line filters a design procedure exists:

$$a(0) = \sqrt{\frac{\pi BW}{2 q_1 F_c}} \qquad a(i) = \frac{\pi BW}{2F_c} k_{i,i+1}$$

$$Z_{oo} = Z_{in}(1 - a(i) + a(i)^2)$$

$$Z_{oe} = Z_{in}(1 + a(i) + a(i)^2)$$

Design Procedure



- Use coupled microstrip line design program TxLine
- Adjust W and S for required Zoo and Zoe
- Layout the resulting filter

Design Procedure

- Design procedure for Parallel Coupled Line filter.
- Not for other filter types.
- Modern computer simulation tools like Microwave Office or ADS enable designs to be optimised, to meet design specifications.
- Typical accuracy 2% on centre frequency.

Design Procedure

- Using Filter tables (Zverev) or equations give Loaded Q and the coupling factors (K) required for the required filter.
- Need to determine the coupling factors for the layout for the filter type to be used.
- Computer simulation of a single and coupled resonator can be used to match coupling factors to the layout.

Butterworth Filter k and q

$$k_{ij} = \frac{1}{2\sqrt{Sin\frac{(2i-1)\pi}{2n}Sin\frac{(2i+1)\pi}{2n}}}$$

$$q_0 = q_n = 2Sin\frac{(2-1)\pi}{2n} = 2Sin\frac{\pi}{2n}$$

Use a spreadsheet to calculate these values.

Determining Loaded Q

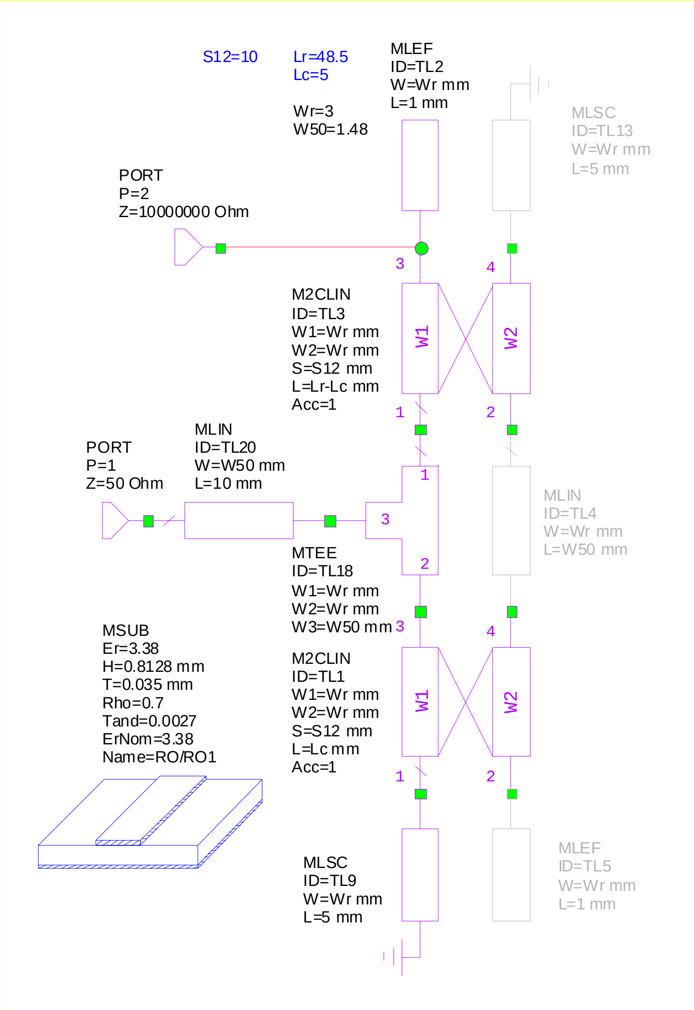
$$\text{Resonator1}\,\Delta_{3dB} = \frac{Filter\ BW_{3dB}}{q_1}$$

Couple the input into the first resonator, using tap, gap or loop coupling.

Measure frequency response of voltage at top of resonator.

Adjust coupling to obtain the resonator BW above using required Q.

Determining Loaded Q

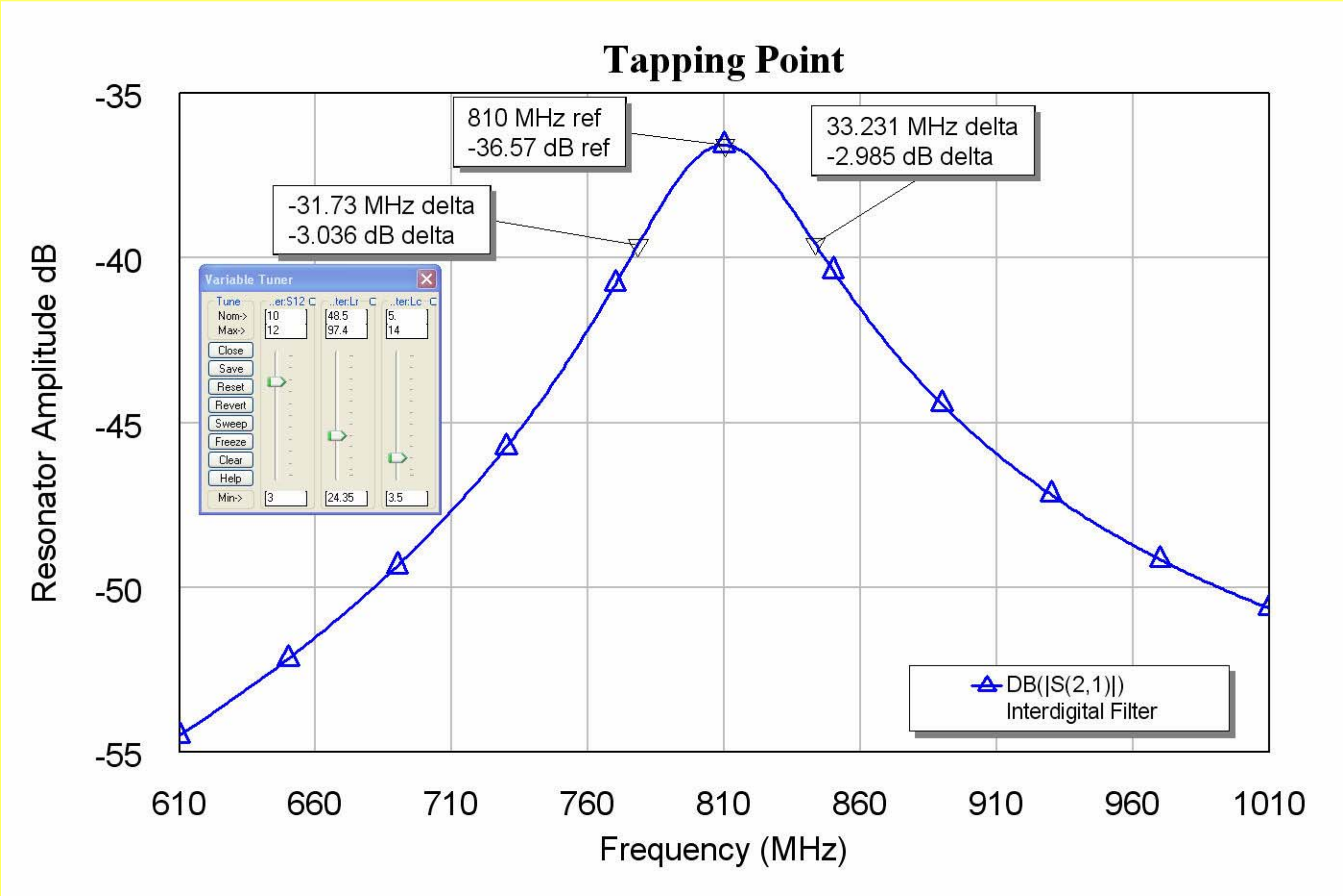


Couple the input into the first resonator.

Detune the second resonator.

Adjust tapping point until correct Bandwidth is obtained.

Determining Loaded Q



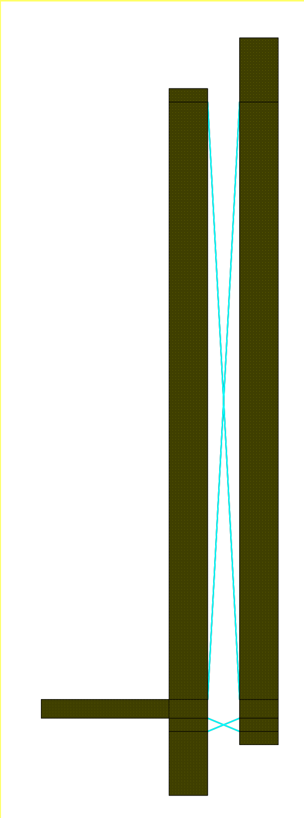
Tapping point for Interdigital Filter.

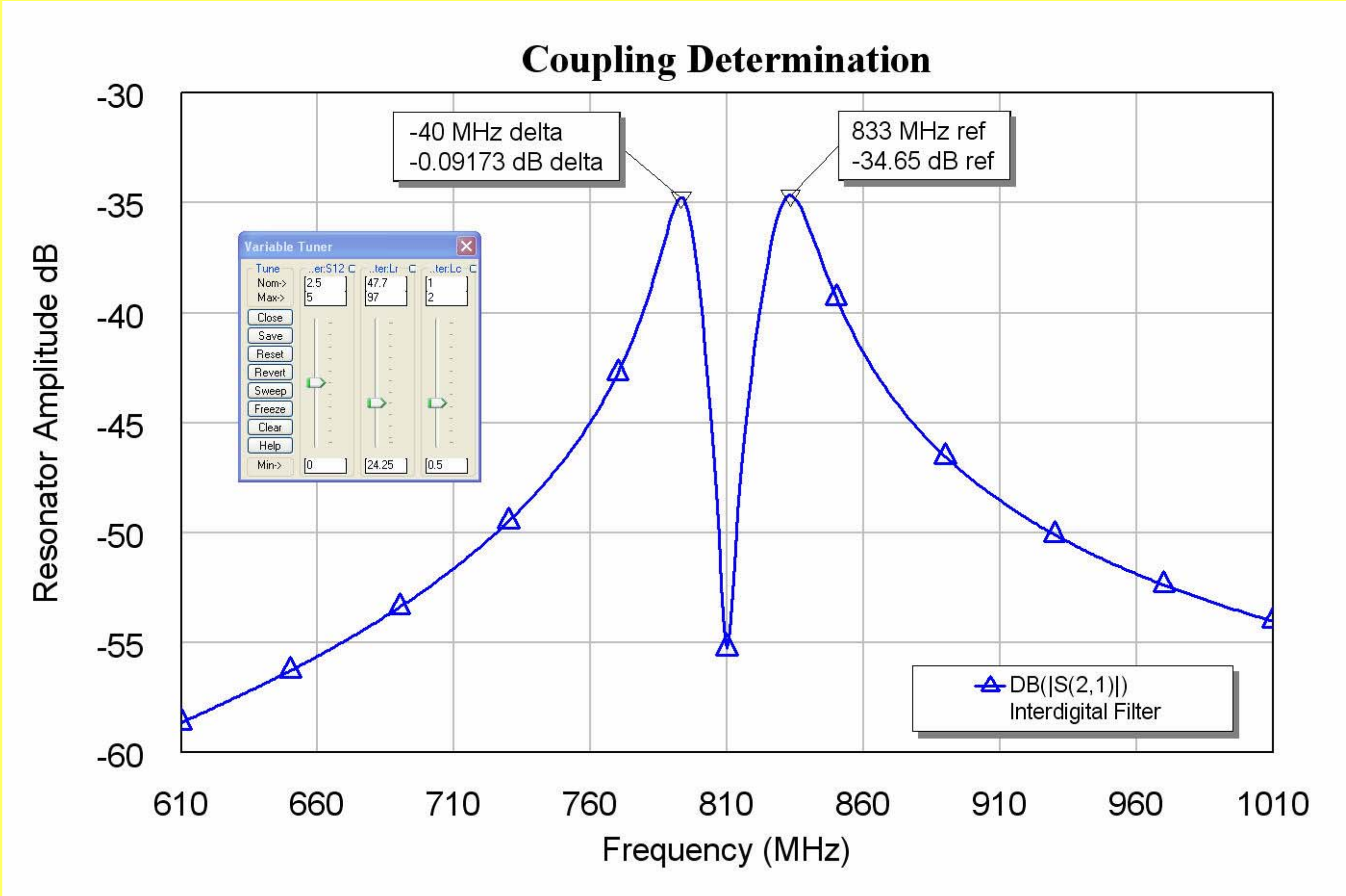
Determining K

$$\Delta_{fp} = k_{12} BW_{3dB}$$

- Use an unloaded two resonator structure
- Use a low unloaded Q for input coupling
- Adjust the coupling to obtain the required frequency spacing between peaks.

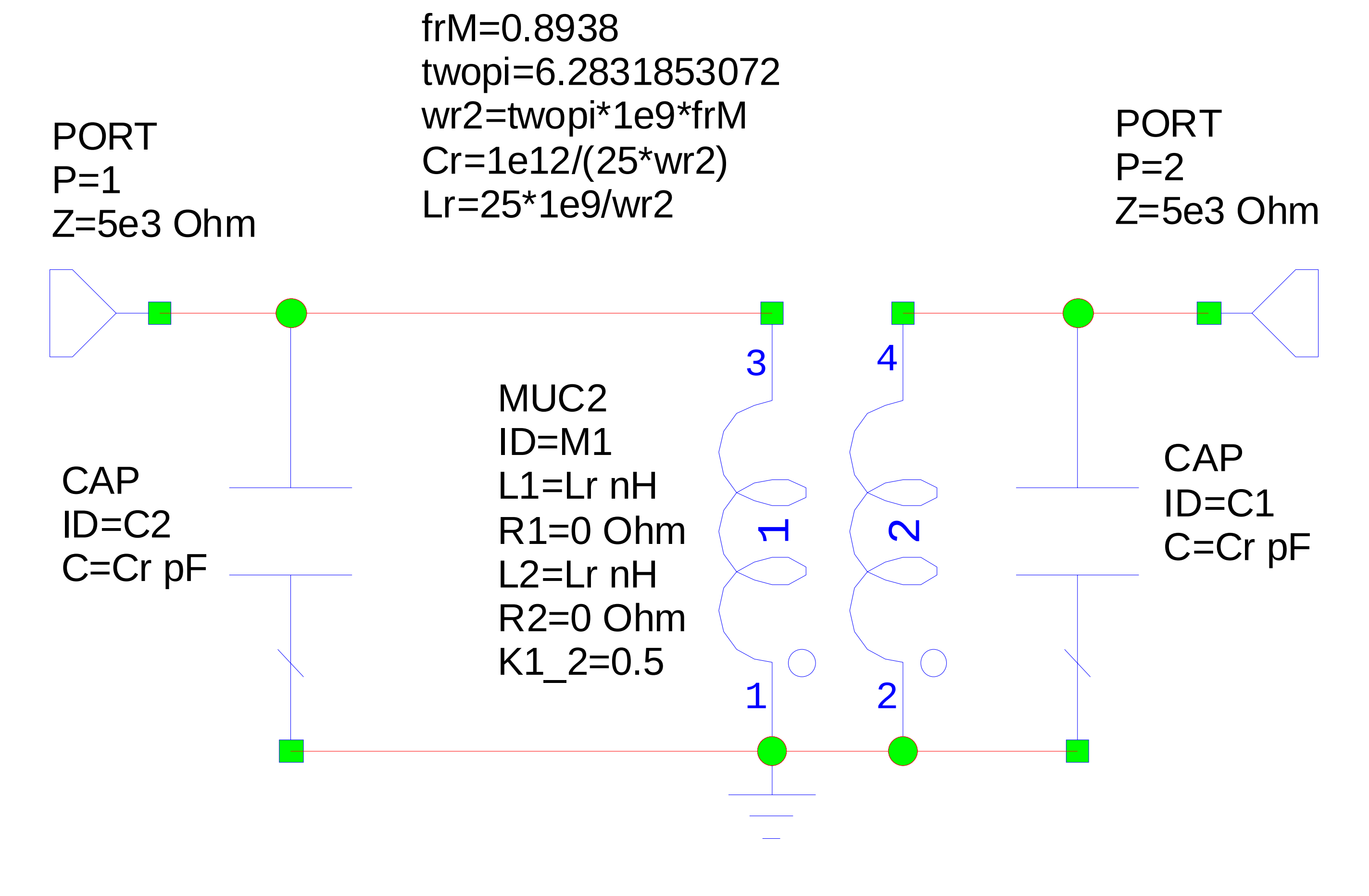
Determining K



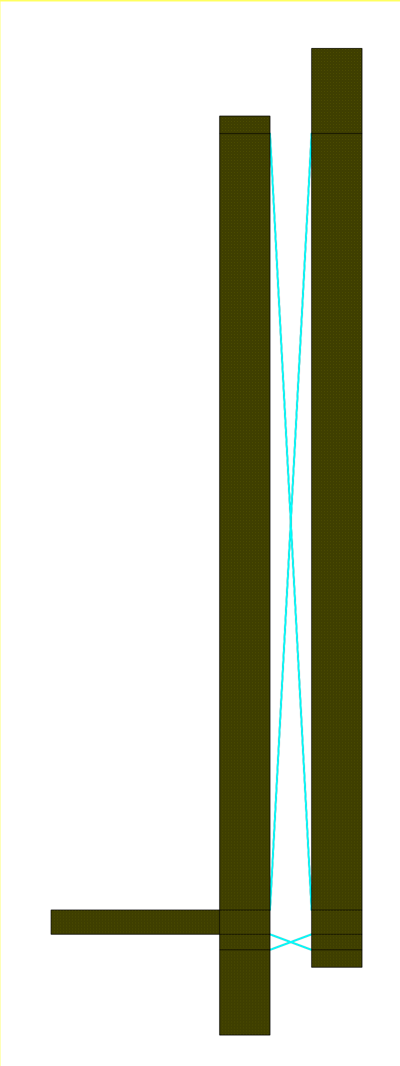


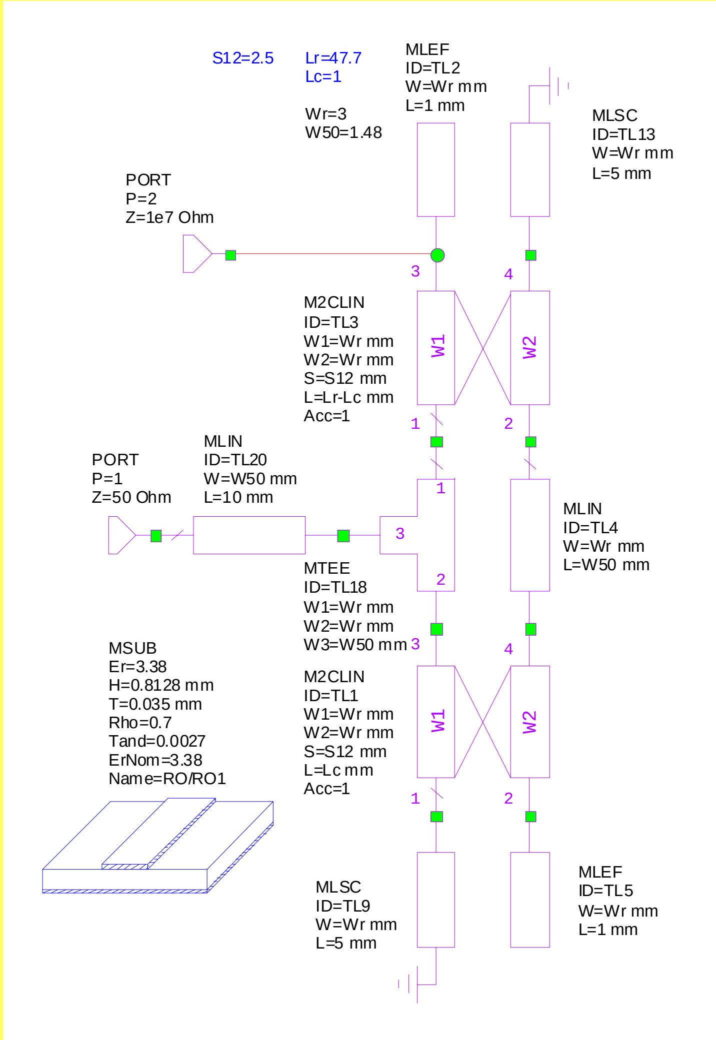
Interdigital filter coupling

Coupled Transformer

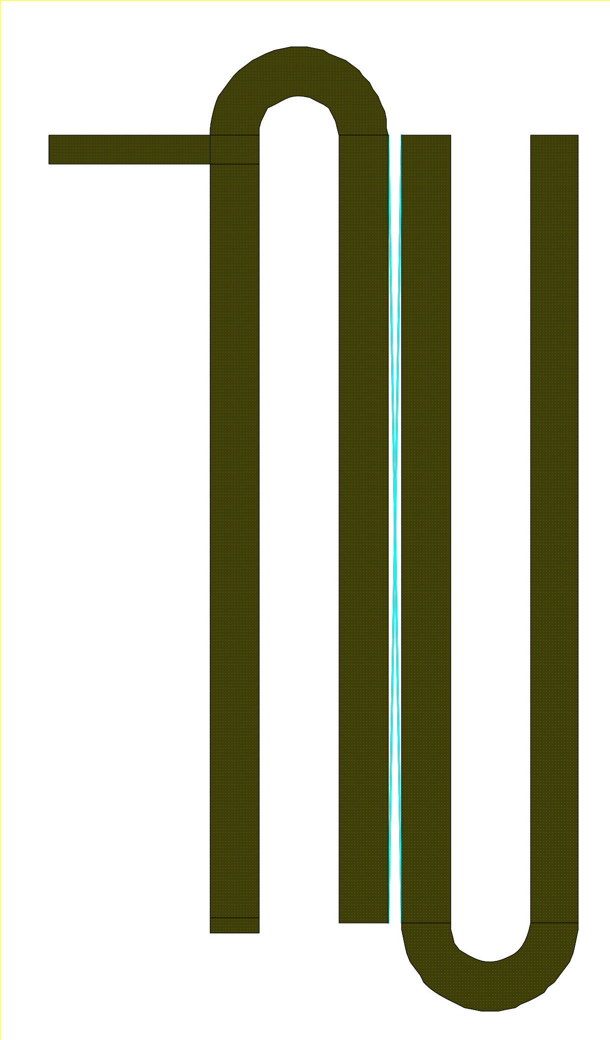


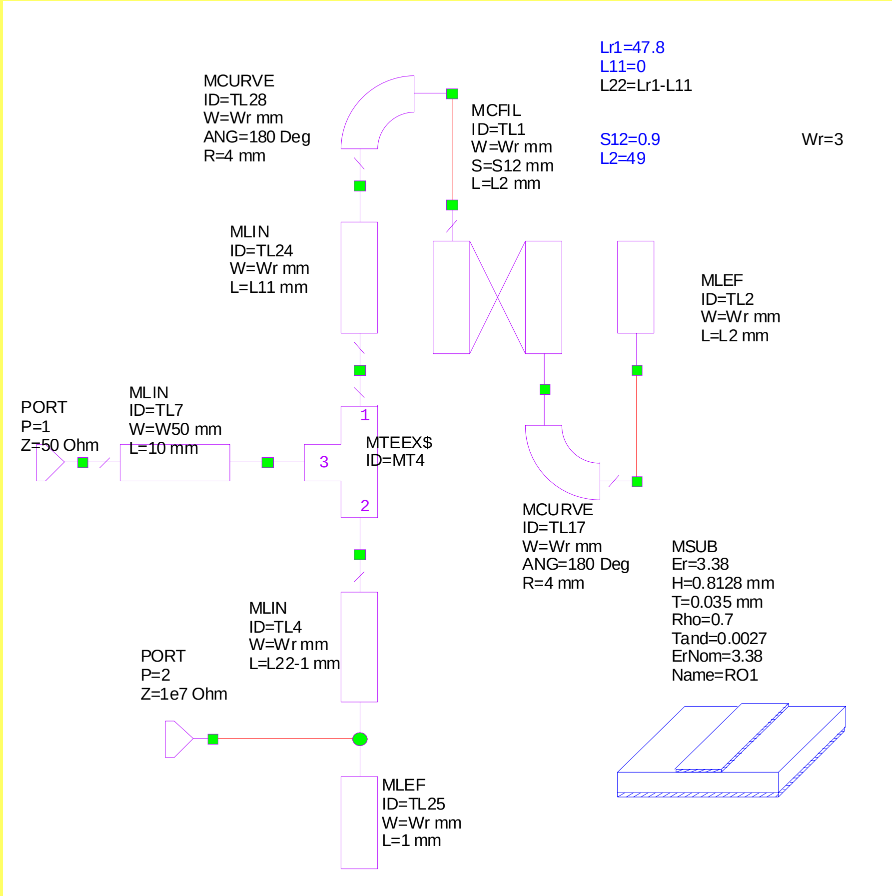
Interdigital Resonators



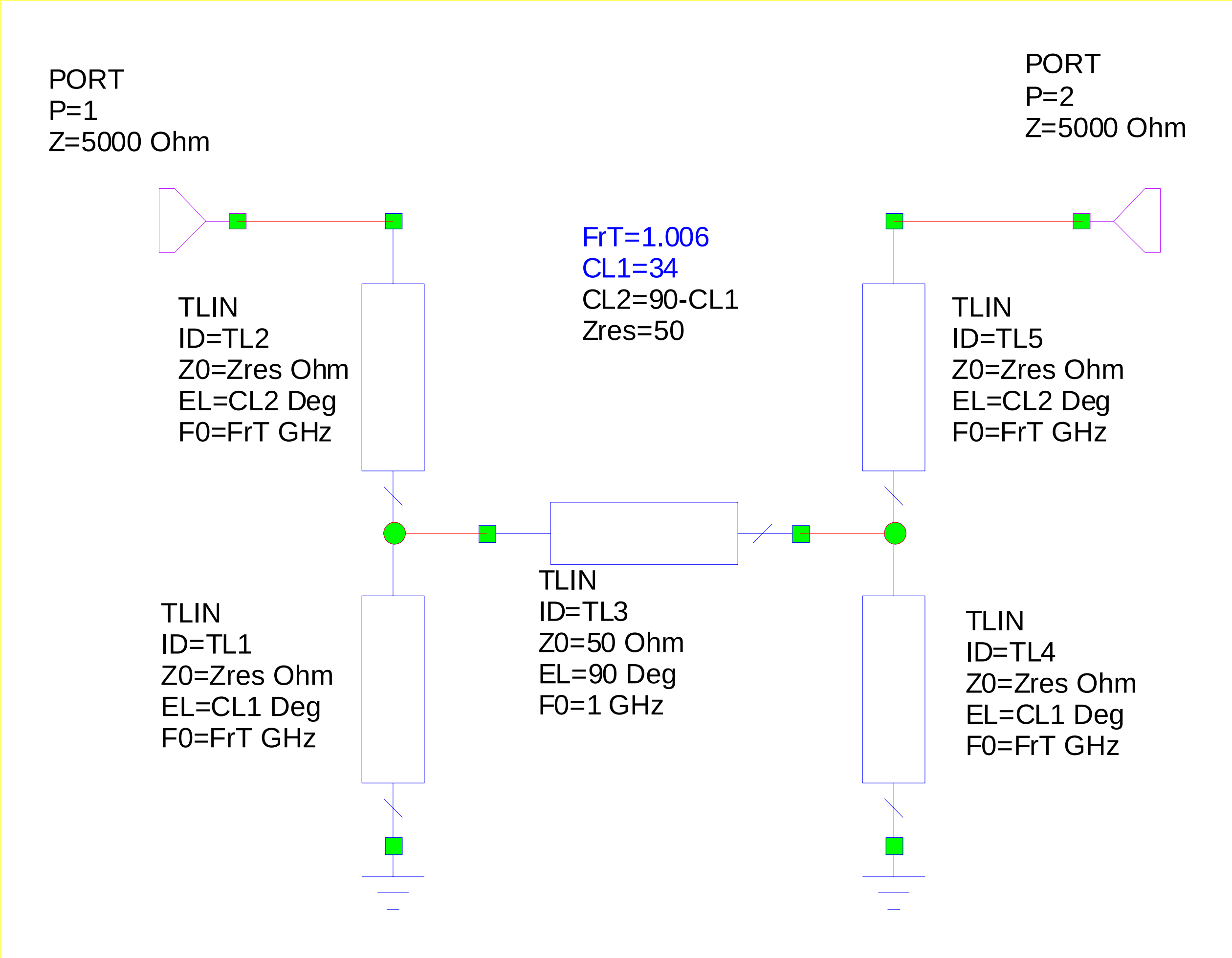


Hairpin Resonator

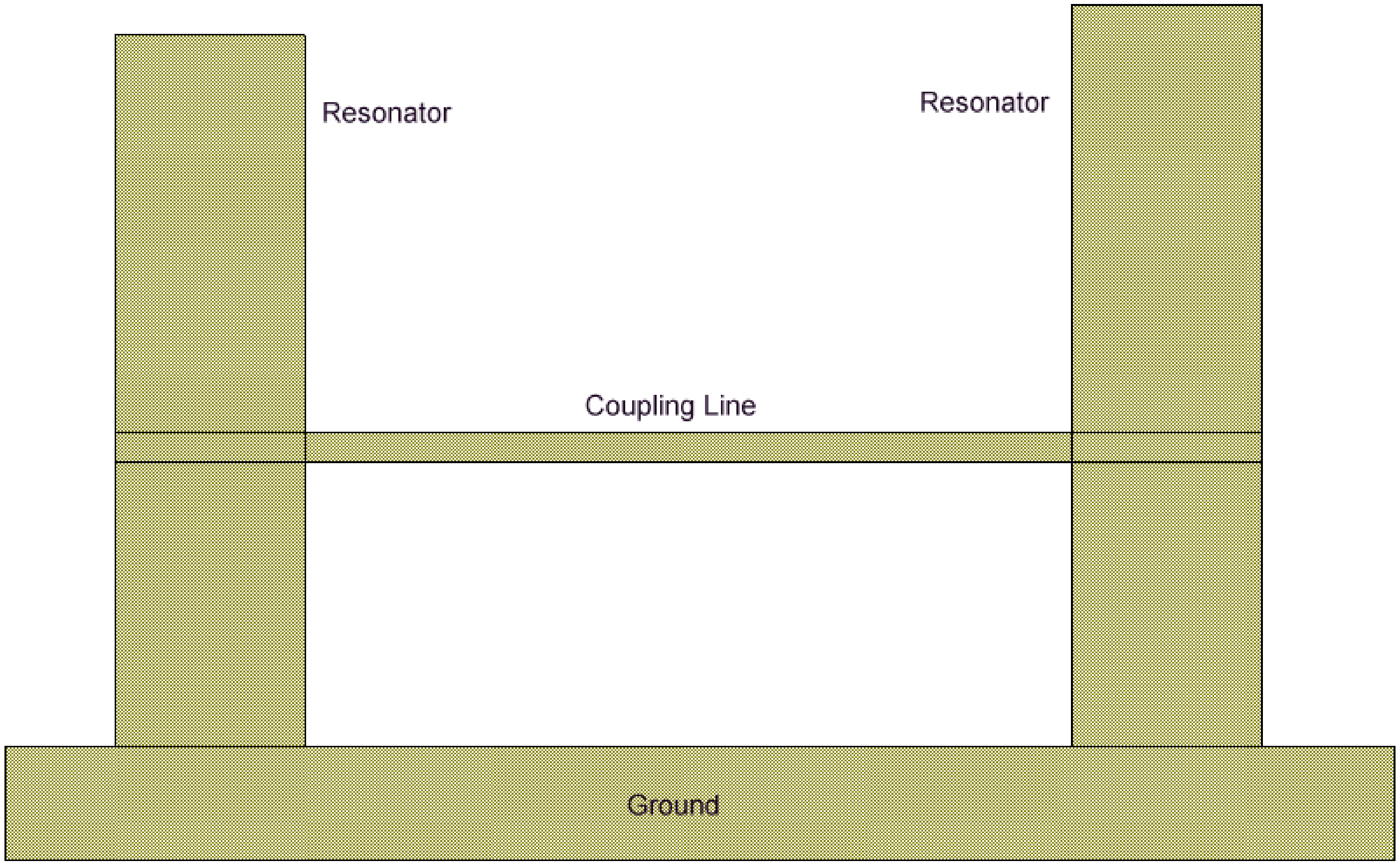




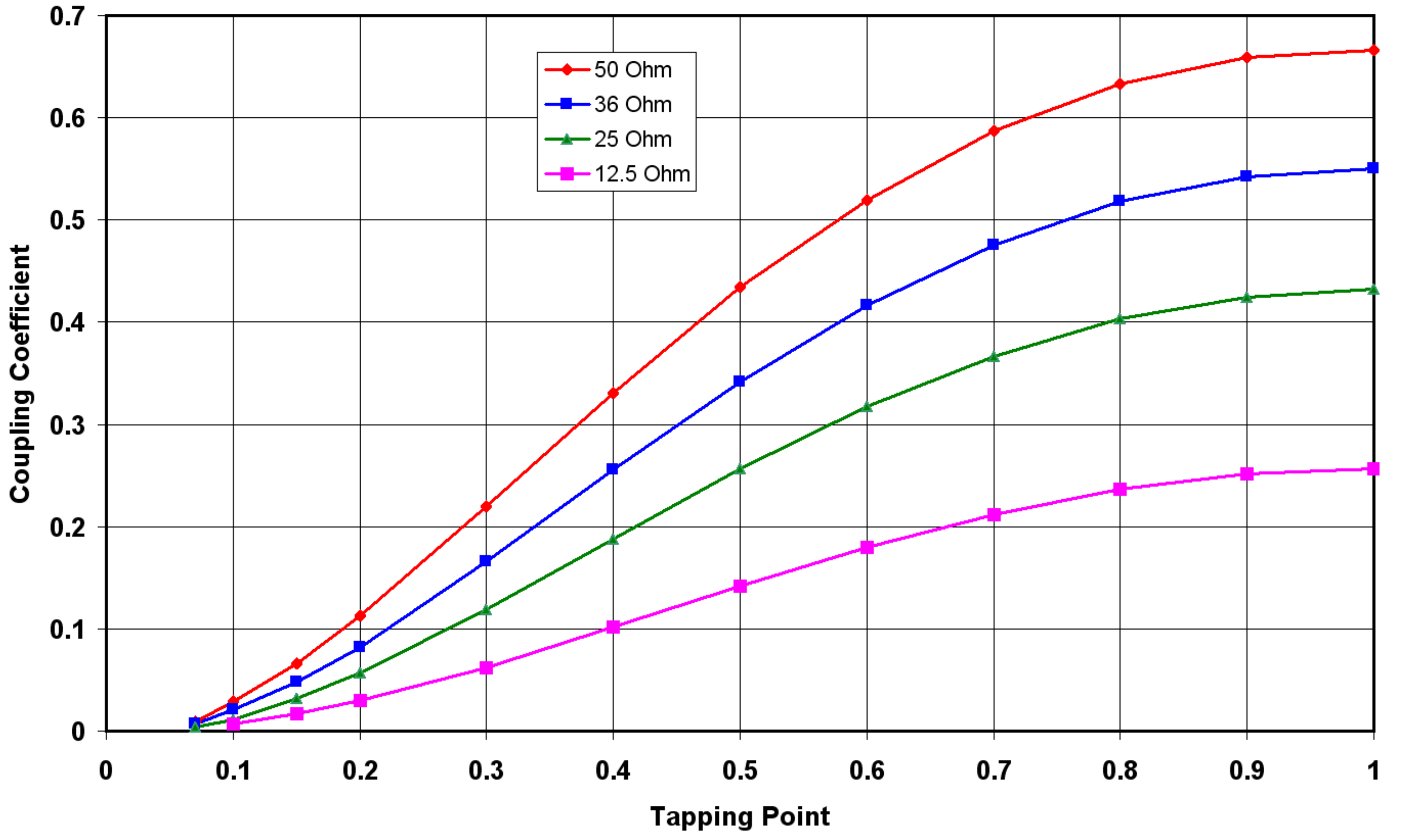
Direct Coupled Resonators



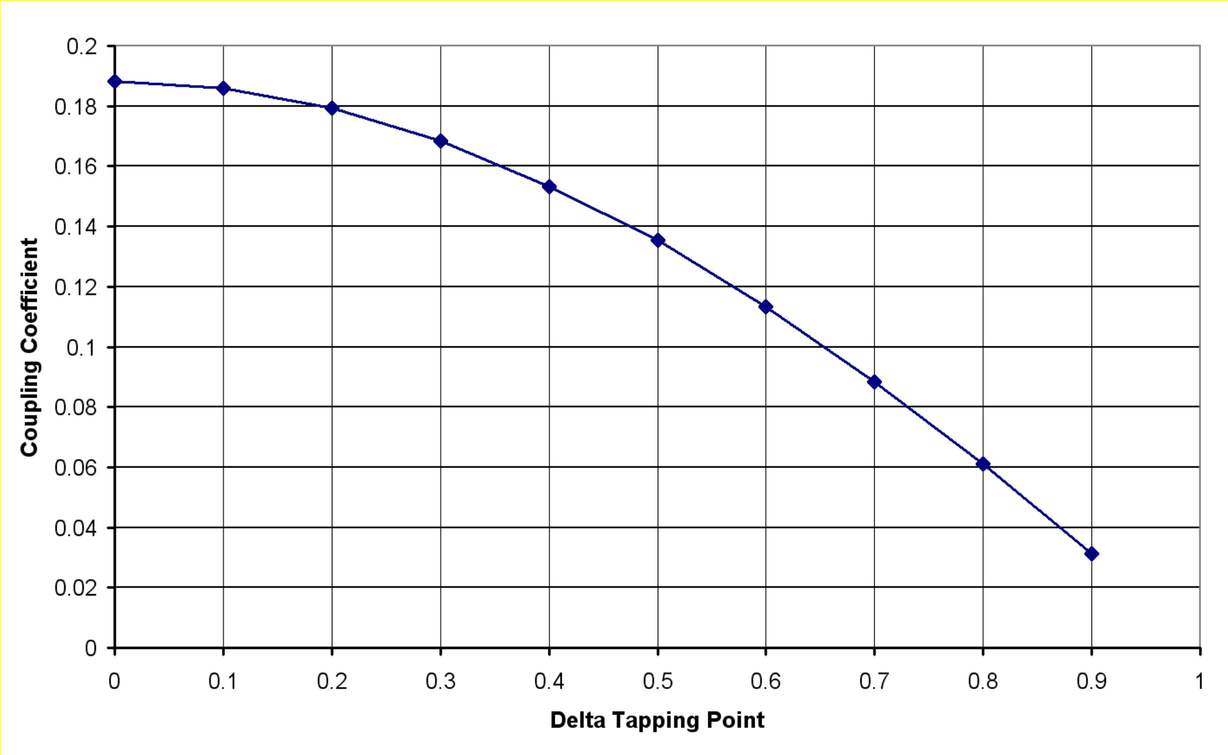
Microstrip Coupled Resonator

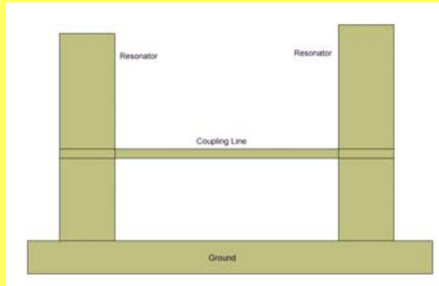


Coupling Coefficients



Unequal Tapping Points





$$Tap_{\mathrm{Required}} = Tap_{Average} + 0.2(\Delta Tap)^2$$

Filter Design Example 1

For comparison, the design technique is applied to 5 resonator filters with 40 MHz bandwidth at 810 MHz. The filter types are:

- Interdigital Filter
- Hairpin Filter
- Direct Coupled Resonator

Use a spreadsheet to calculate the initial values of gaps and tapping points.

PCB Material

- Rogers RP4003, Ceramic loaded, dielectric constant 3.38, 0.813 mm thick, 1 oz copper.
- 3mm wide resonator for each filter type.

Butterworth Filter k and q

$$q_0 = q_n = 2Sin\frac{(2-1)\pi}{2n} = 2Sin\frac{\pi}{2n}$$

For n=5 q_0= 0.6180 BW = 64.7 MHz

$$k_{ij} = \frac{1}{2\sqrt{Sin\frac{(2i-1)\pi}{2n}\,Sin\frac{(2i+1)\pi}{2n}}}$$

For n=5 k_{12}= k_{45} = 1.0 BW = 40.0 MHz

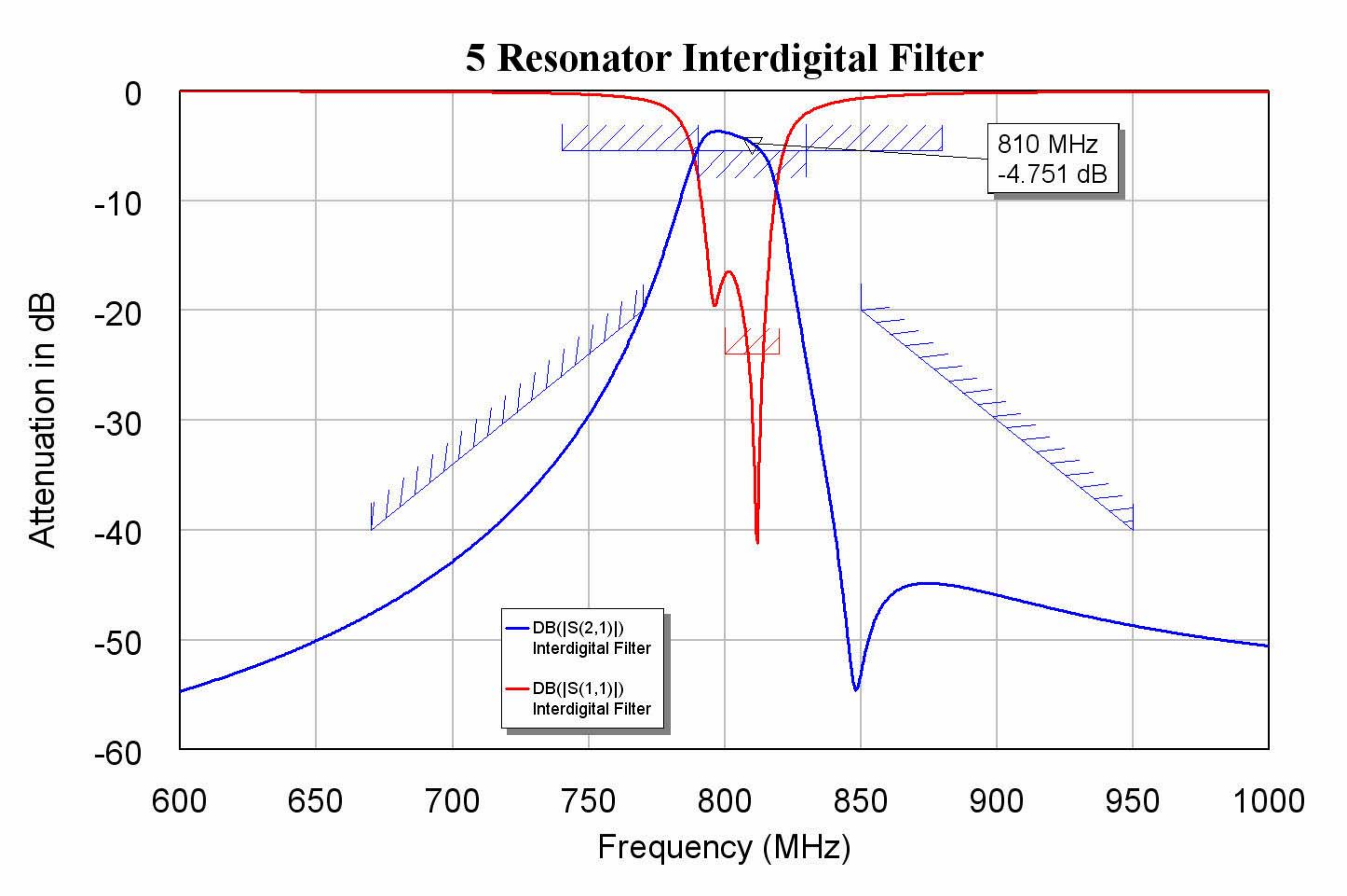
k_{23} = k_{45} = 0.5559 BW = 22.2 MHz

Interdigital Filter

Initial Design from Spreadsheet:

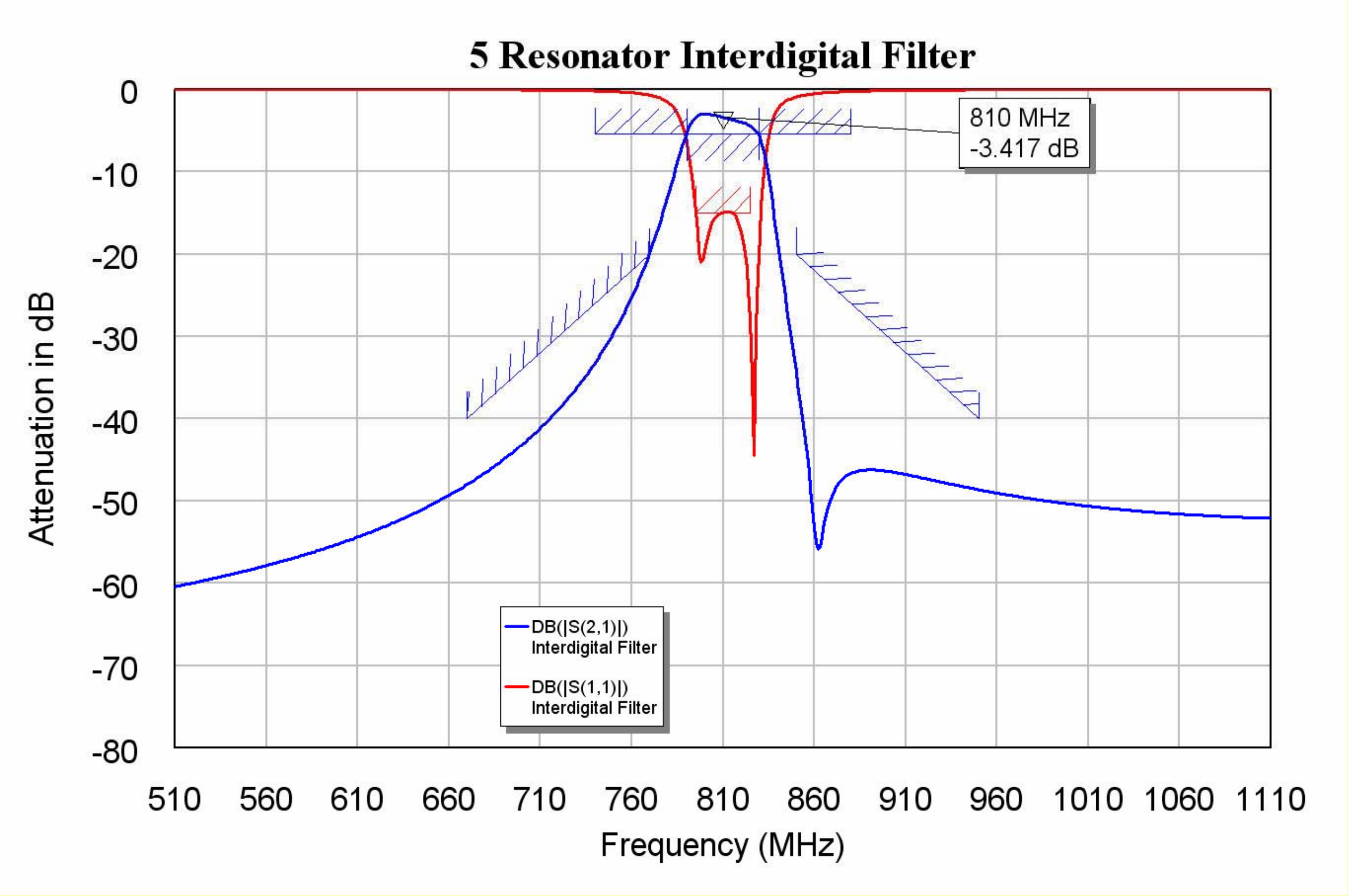
- Resonator 48.5 mm (plus 7.44 mm)
- Tapping Point 5 mm for Res 1, 4 (+5mm)
- Gap 1-2 and 4-5: 2.5 mm
- Gap 2-3 and 3-4: 4.5 mm

Interdigital Filter



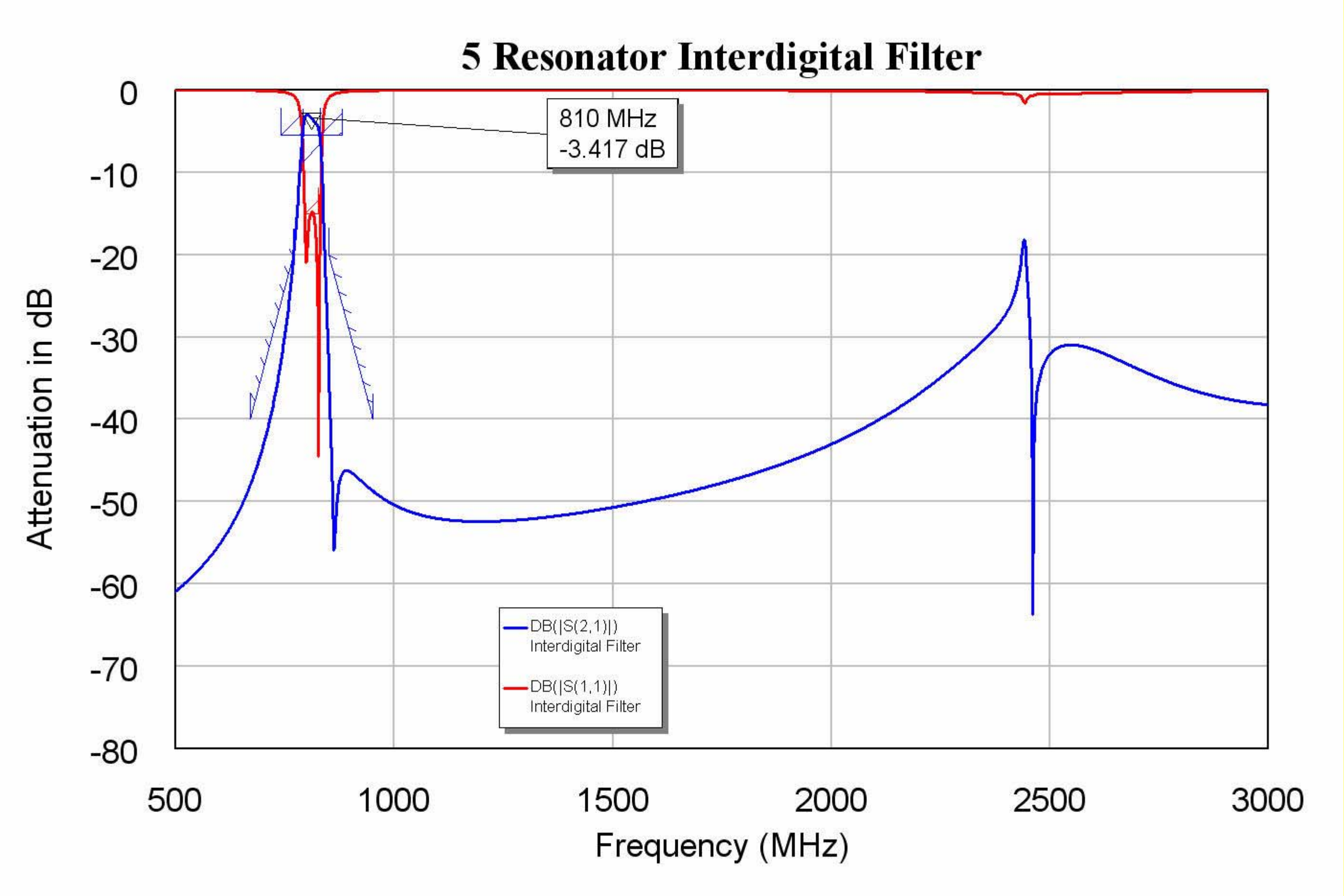
Initial values from spreadsheet

Interdigital Filter



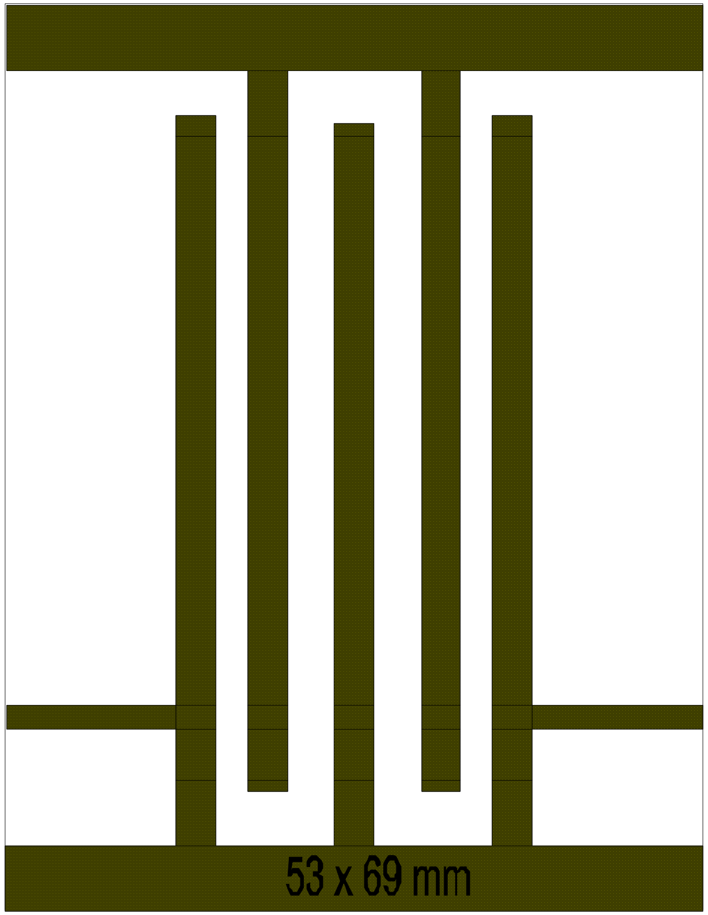
After optimisation. Note not flat response

Interdigital Filter



Stopband response. Response at third harmonic.

Interdigital Filter



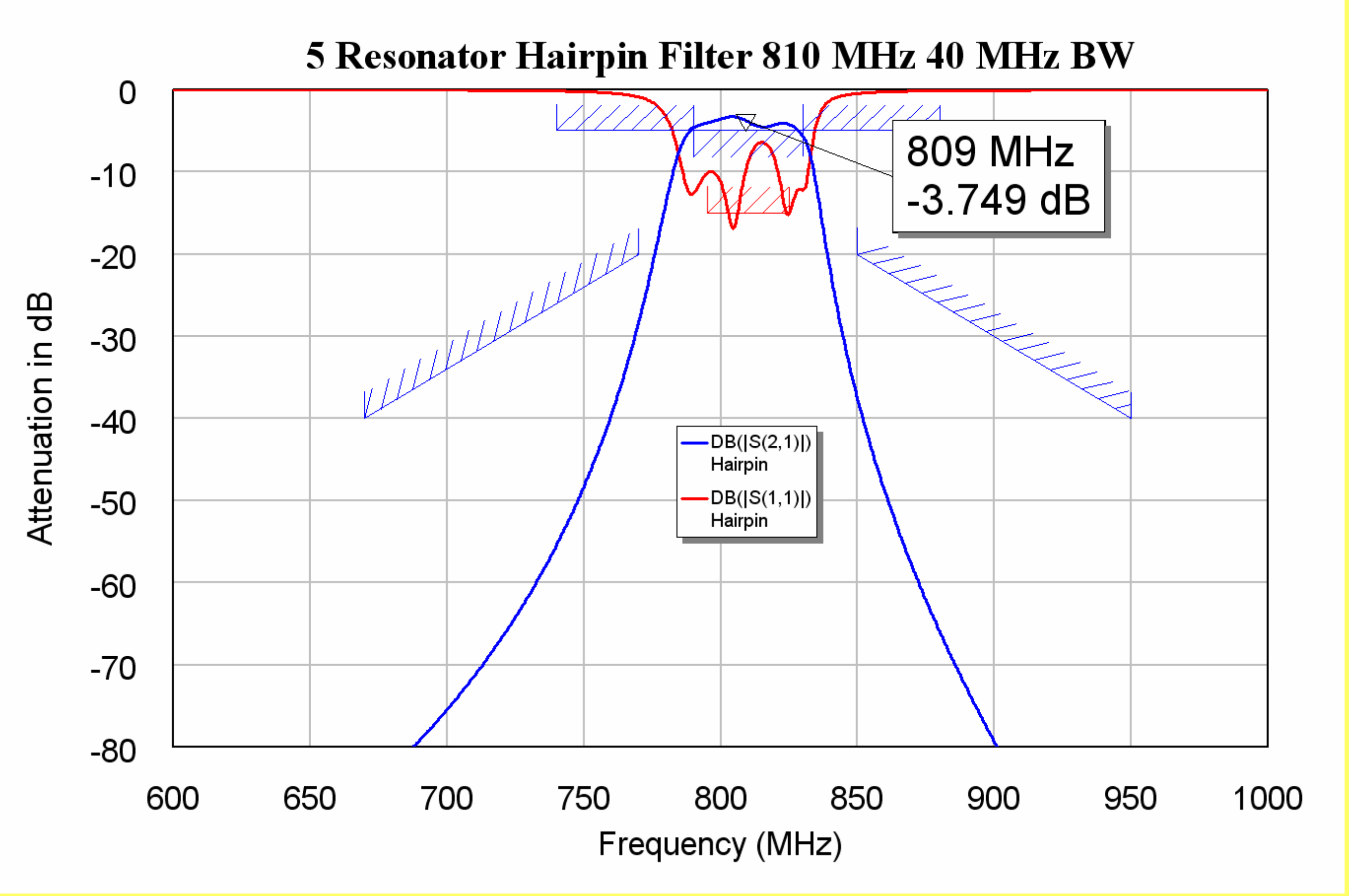
Interdigital Filter Layout.

Hairpin Filter

Initial Design from Spreadsheet:

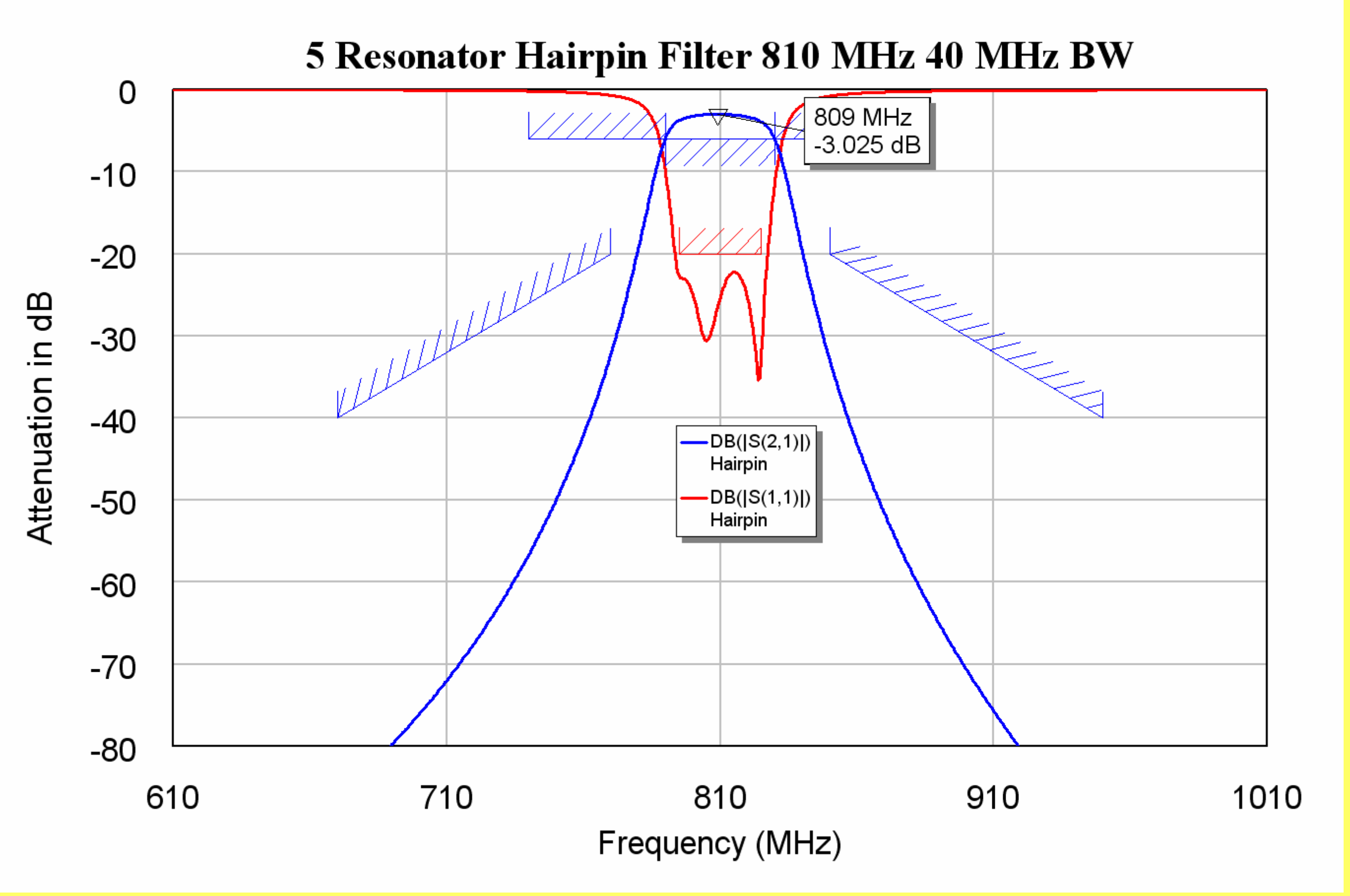
- Resonator 47.75 mm (plus bend)
- Tapping Point 5 mm for Res 1, 4
- Gap 1-2 and 4-5: 0.9 mm
- Gap 2-3 and 3-4: 1.7 mm
- Gaps much smaller than for Interdigital filter

Hairpin Filter



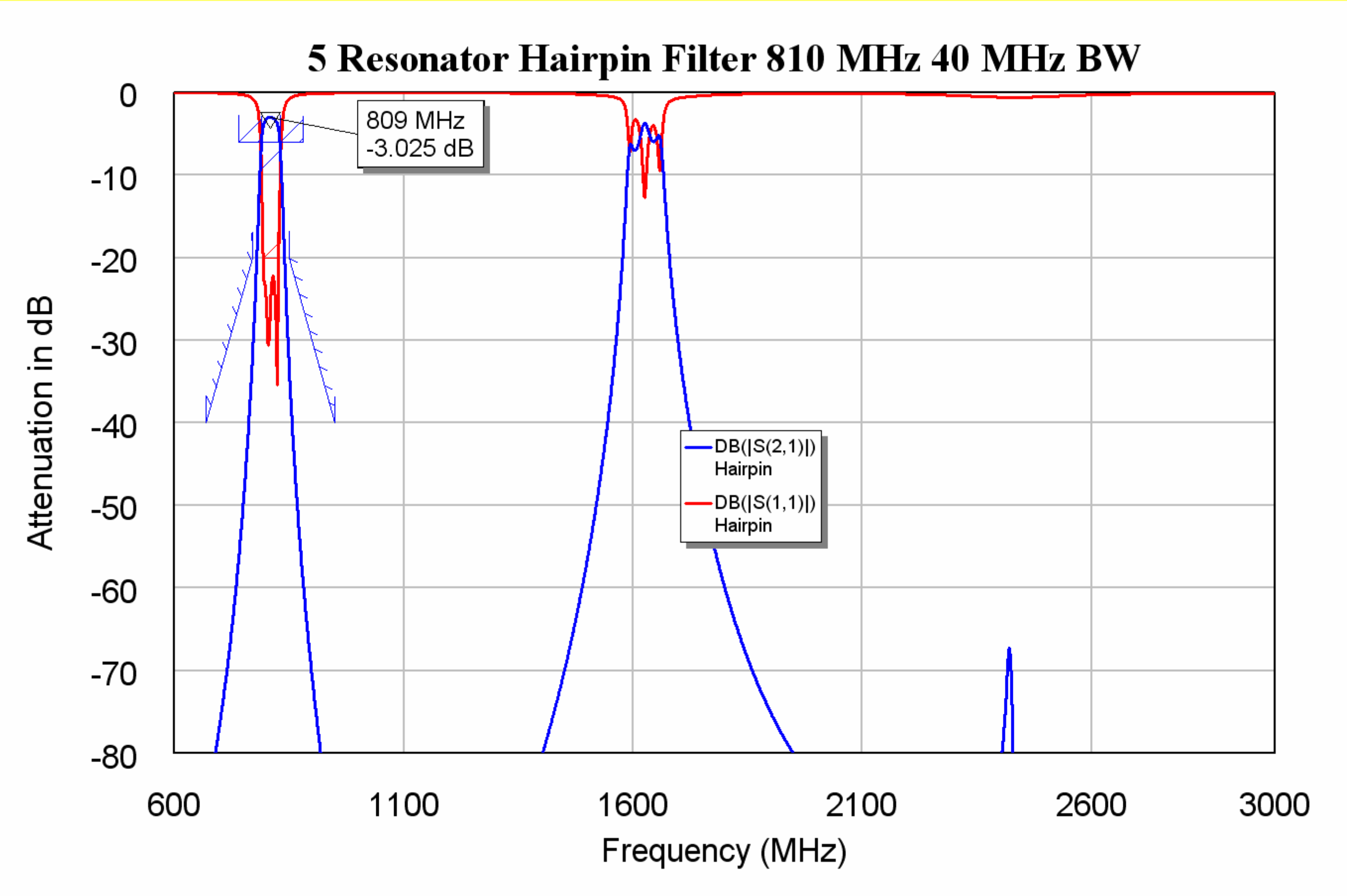
Values as per spreadsheet. Note close to specifications

Hairpin Filter



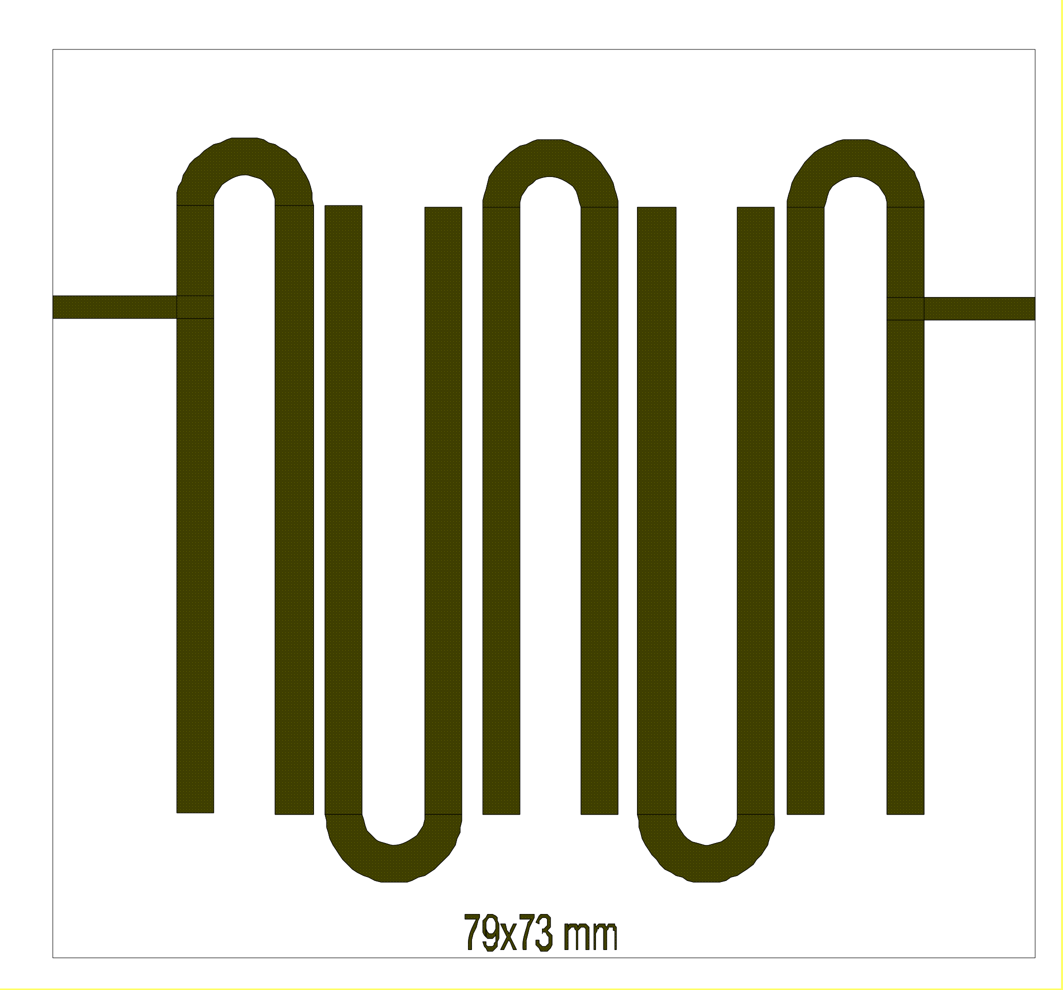
After optimisation. Good Symmetry. Note close to specification.

Hairpin Filter



Stopband response. Response at second harmonic.

Hairpin Filter



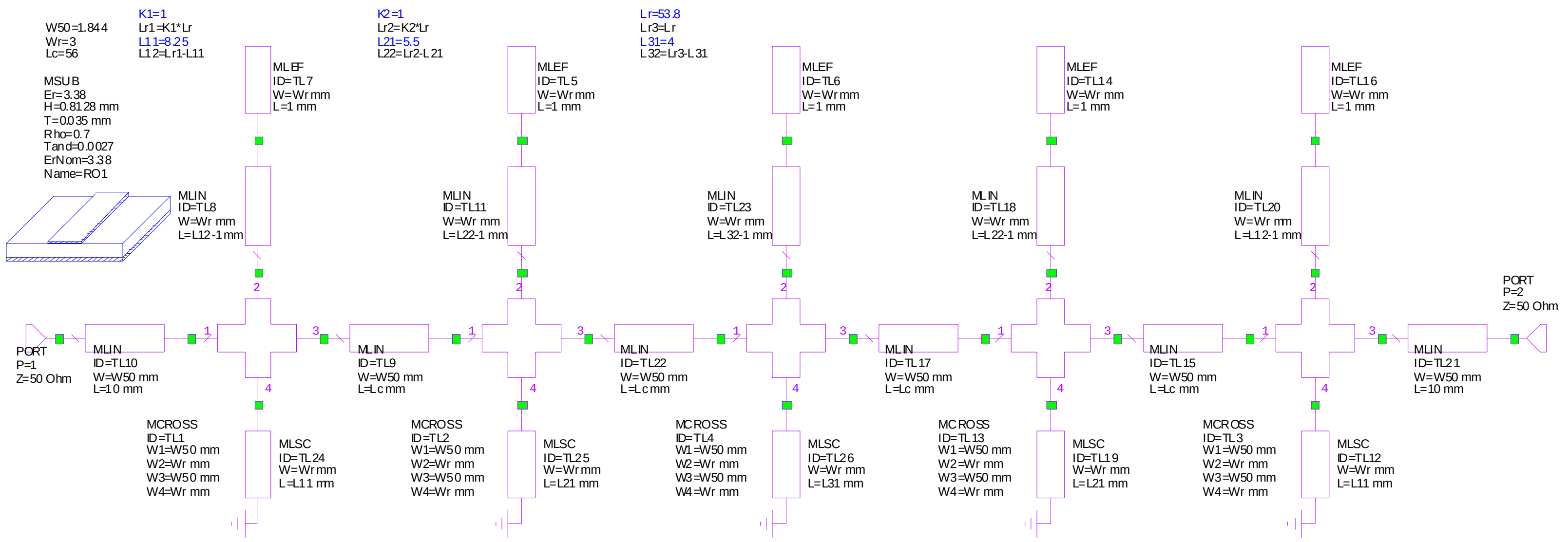
Hairpin filter layout.

Direct Coupled Resonator Filter

Initial Design from Spreadsheet:

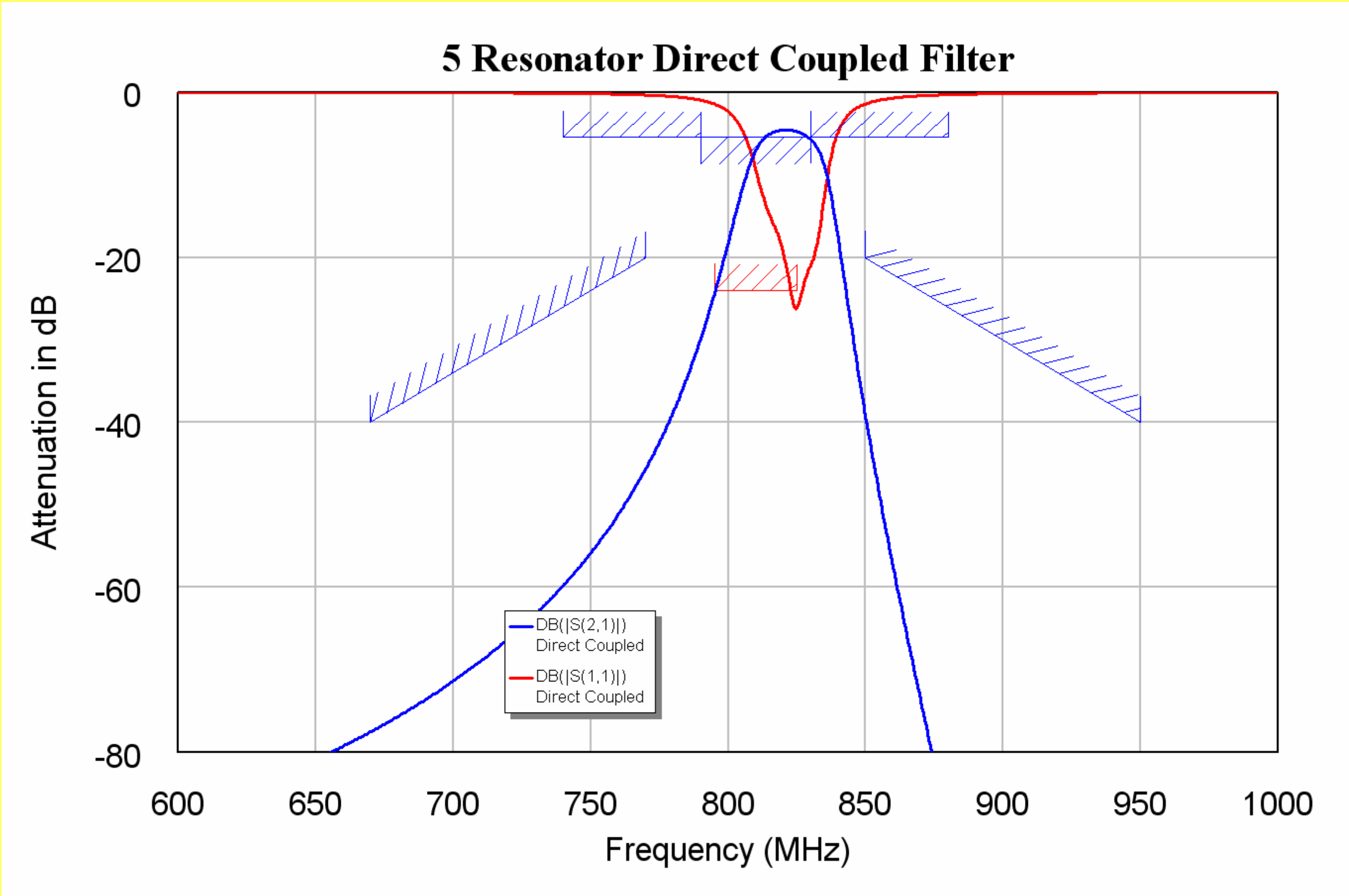
- Resonator 53.8 mm
- Tapping point 9.5 mm for Res 1, 4
- Tapping point 1-2 and 4-5: 7 mm
- Tapping point 2-3 and 3-4: 4 mm
- In realisation tapping points on same resonator are made the same.

Direct Coupled Resonator Filter



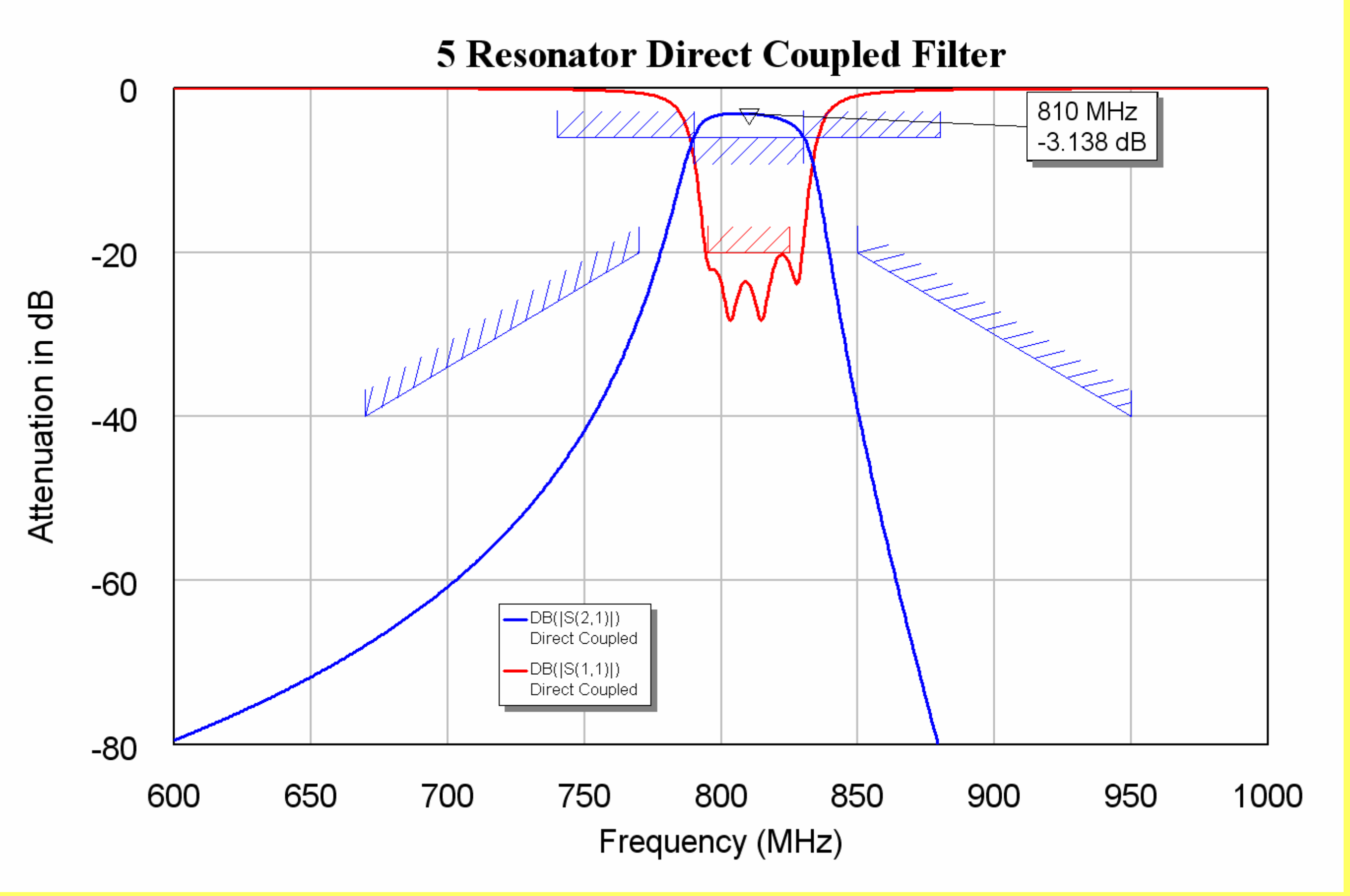
Initial tapping: R1, R5 - 8.25mm, R2, R4 – 5.5 mm, R3 – 4mm

Direct Coupled Resonator Filter



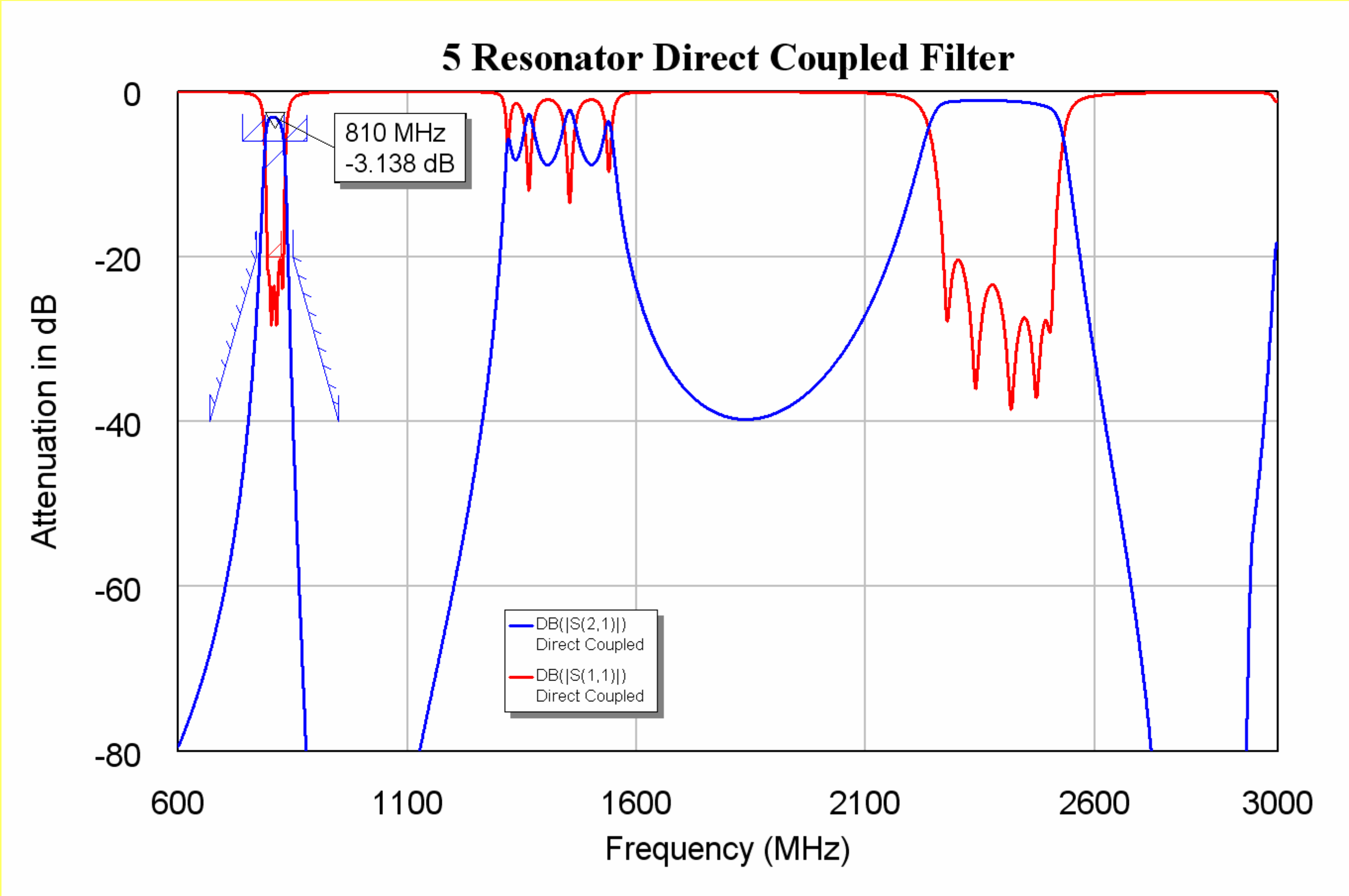
Response with initial tapping points, averaged per resonator

Direct Coupled Resonator Filter



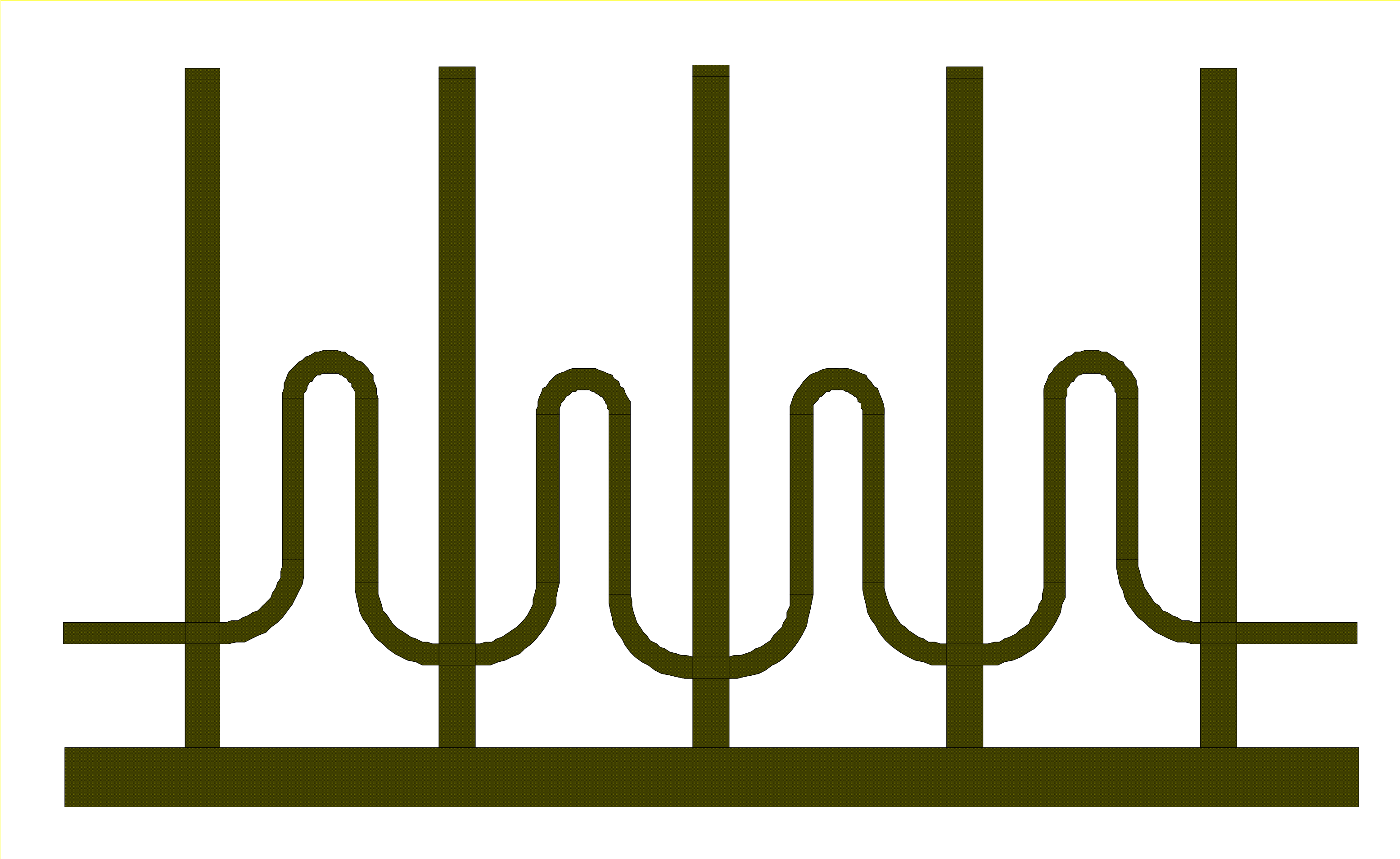
Response after optimisation.

Direct Coupled Resonator Filter



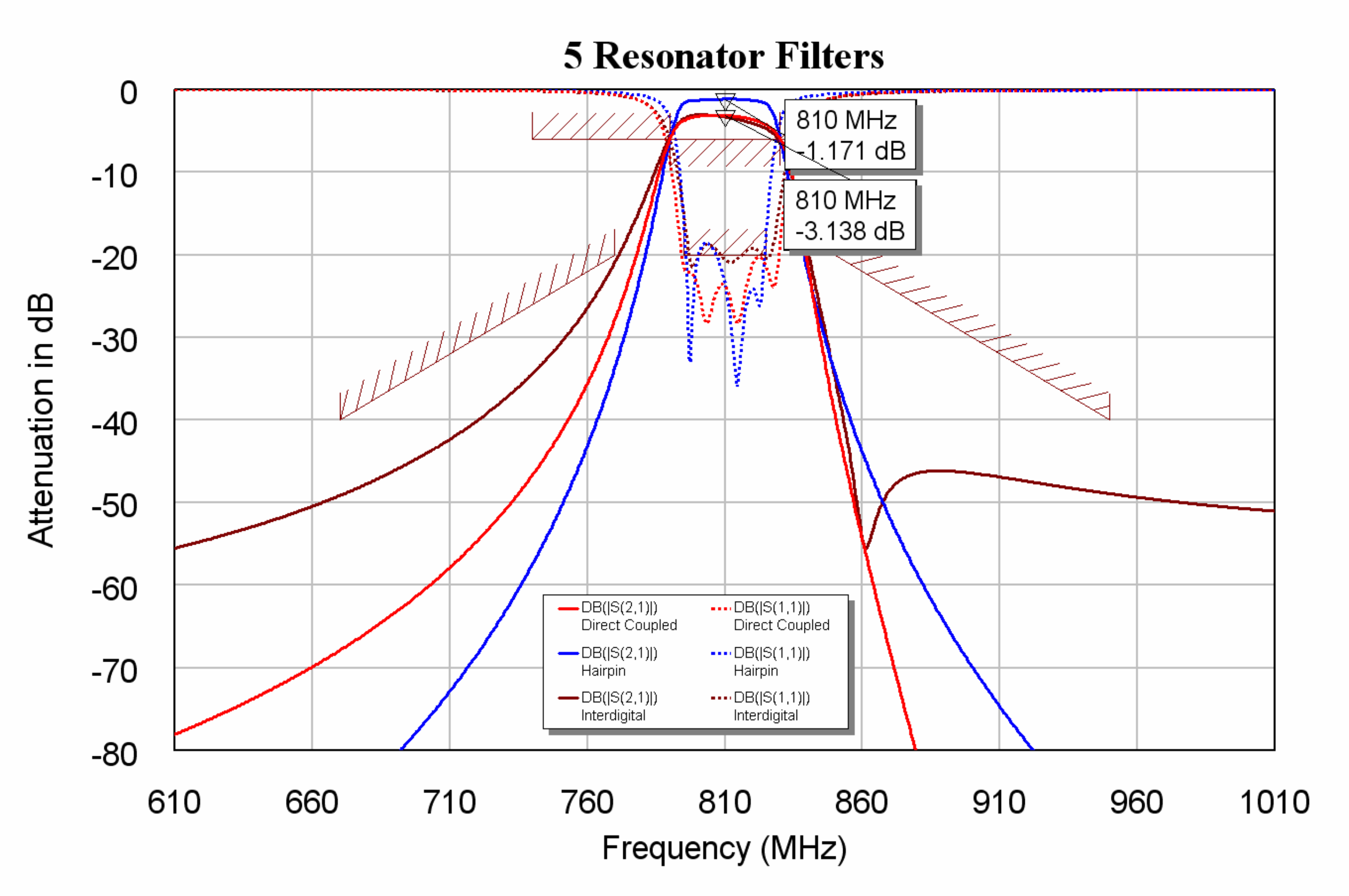
Large harmonic response. Need stubs to remove them.

Direct Coupled Resonator Filter

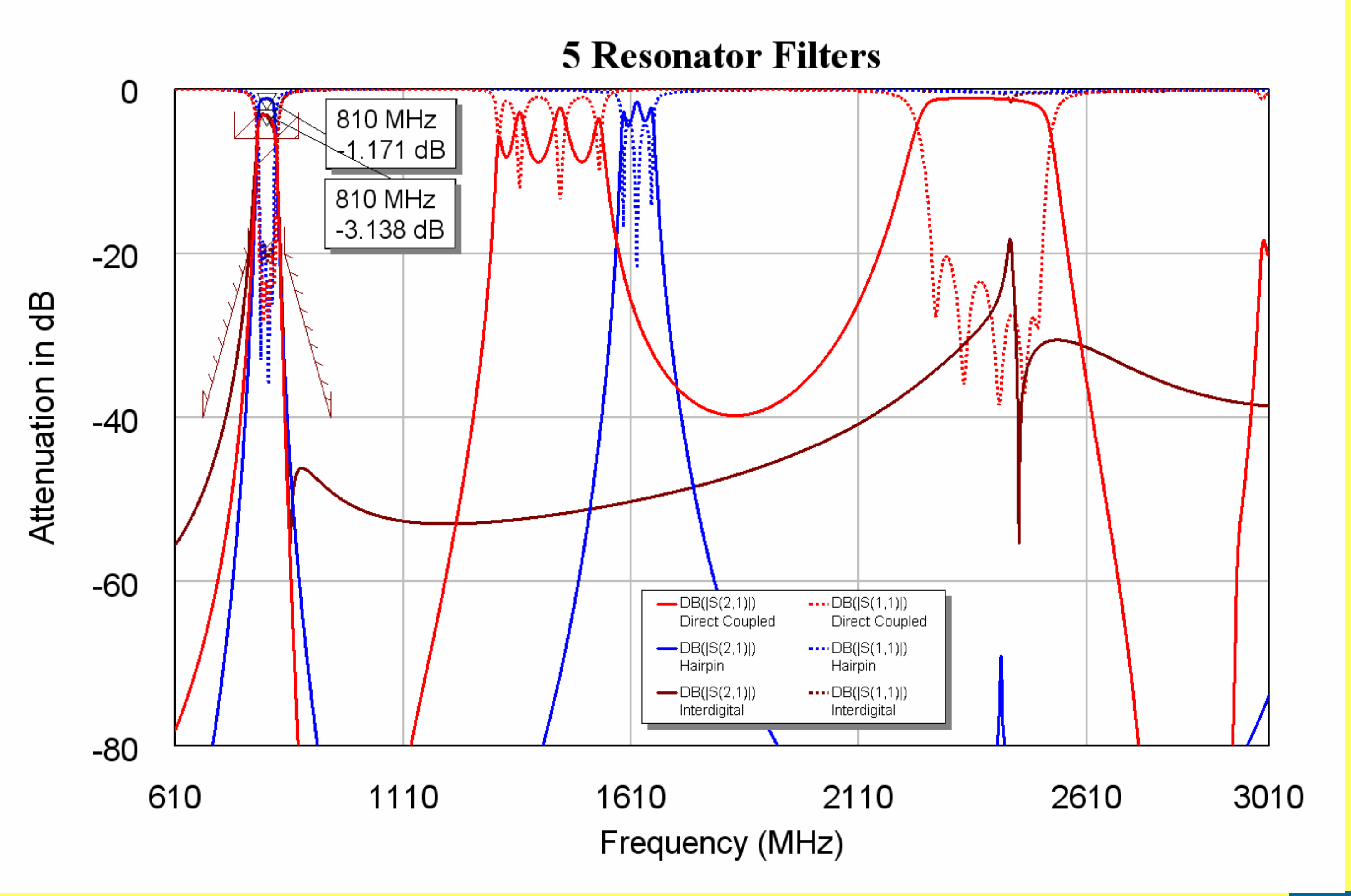


Large harmonic response. Need stubs to remove them.

Filter Comparison



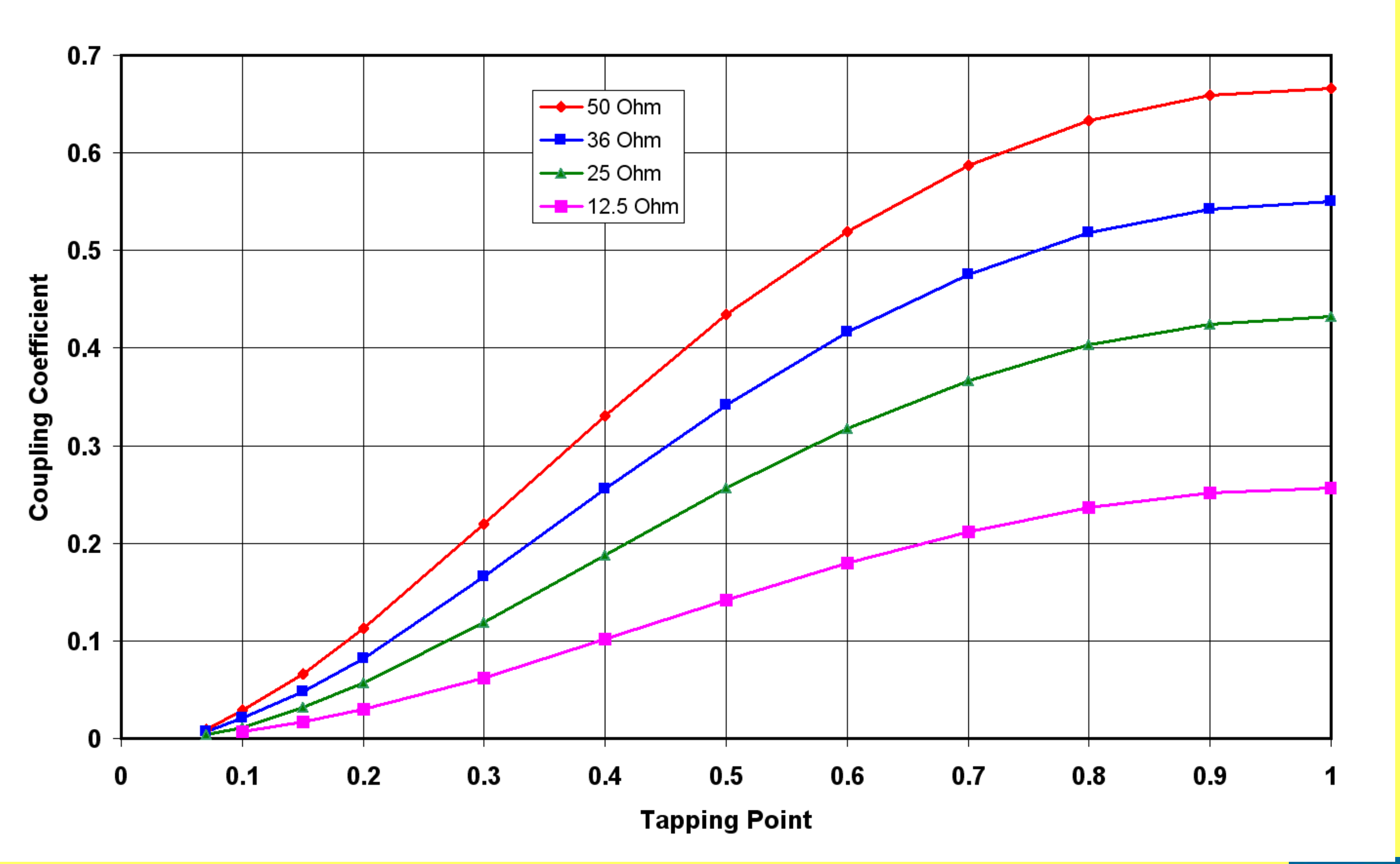
Filter Comparison



Design Example 2

- Centre Frequency 1 GHz
- Bandwidth 500 MHz
- 5 Resonators
- q1= qn =0.618 Q1= Qn =0.309
- k12 = k45 = 1 K12 = K45 = 0.5
- k23 = k34 = 0.556 K23 = K34 = 0.278

Design Example



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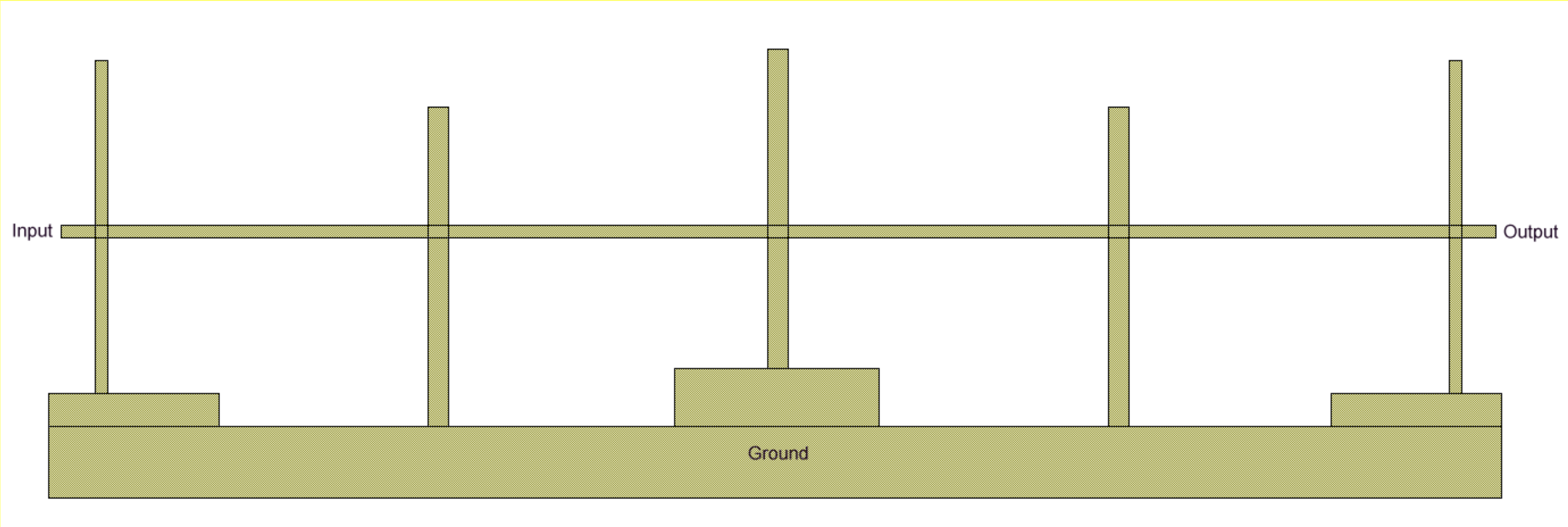
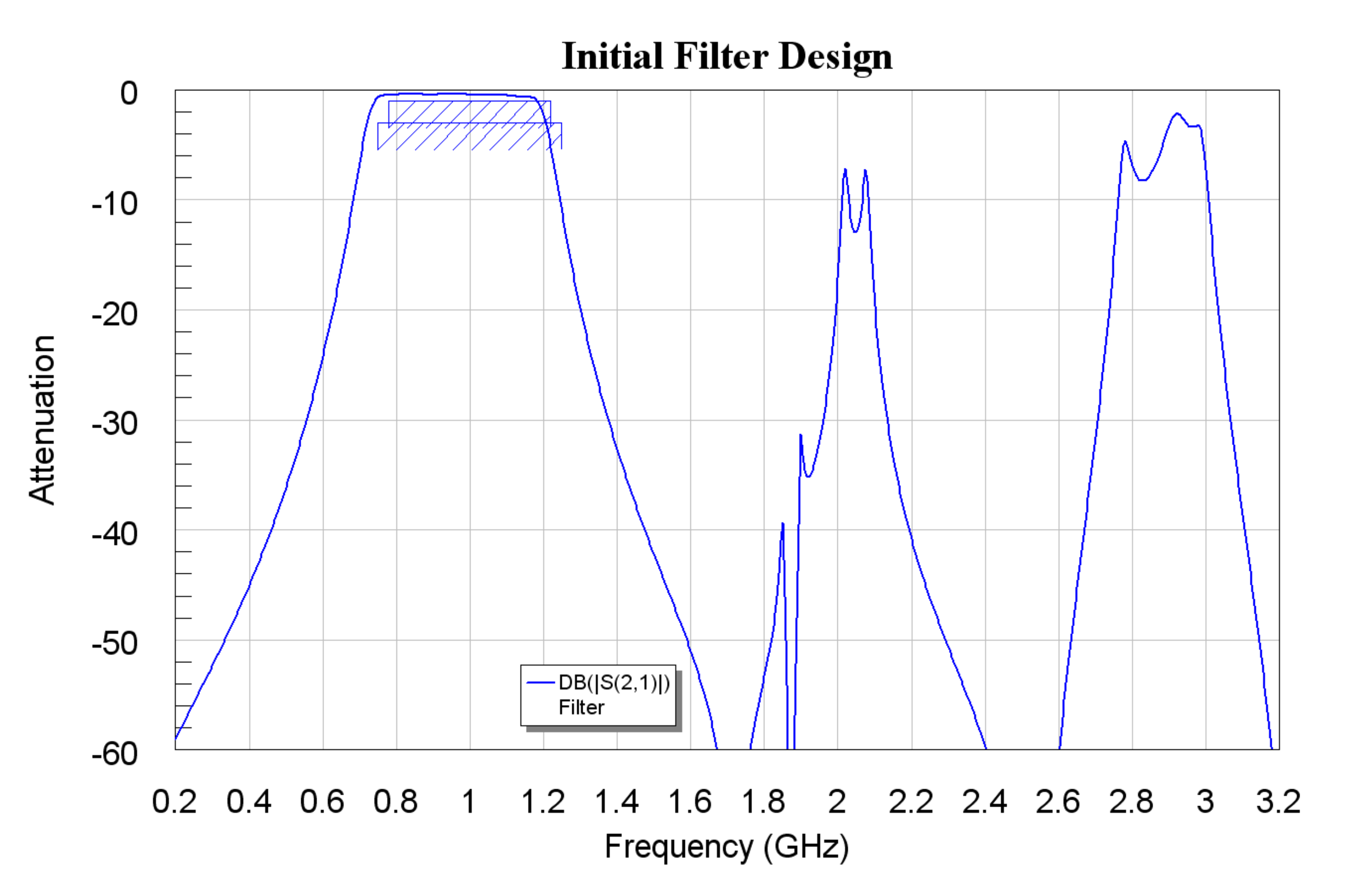
Design Example

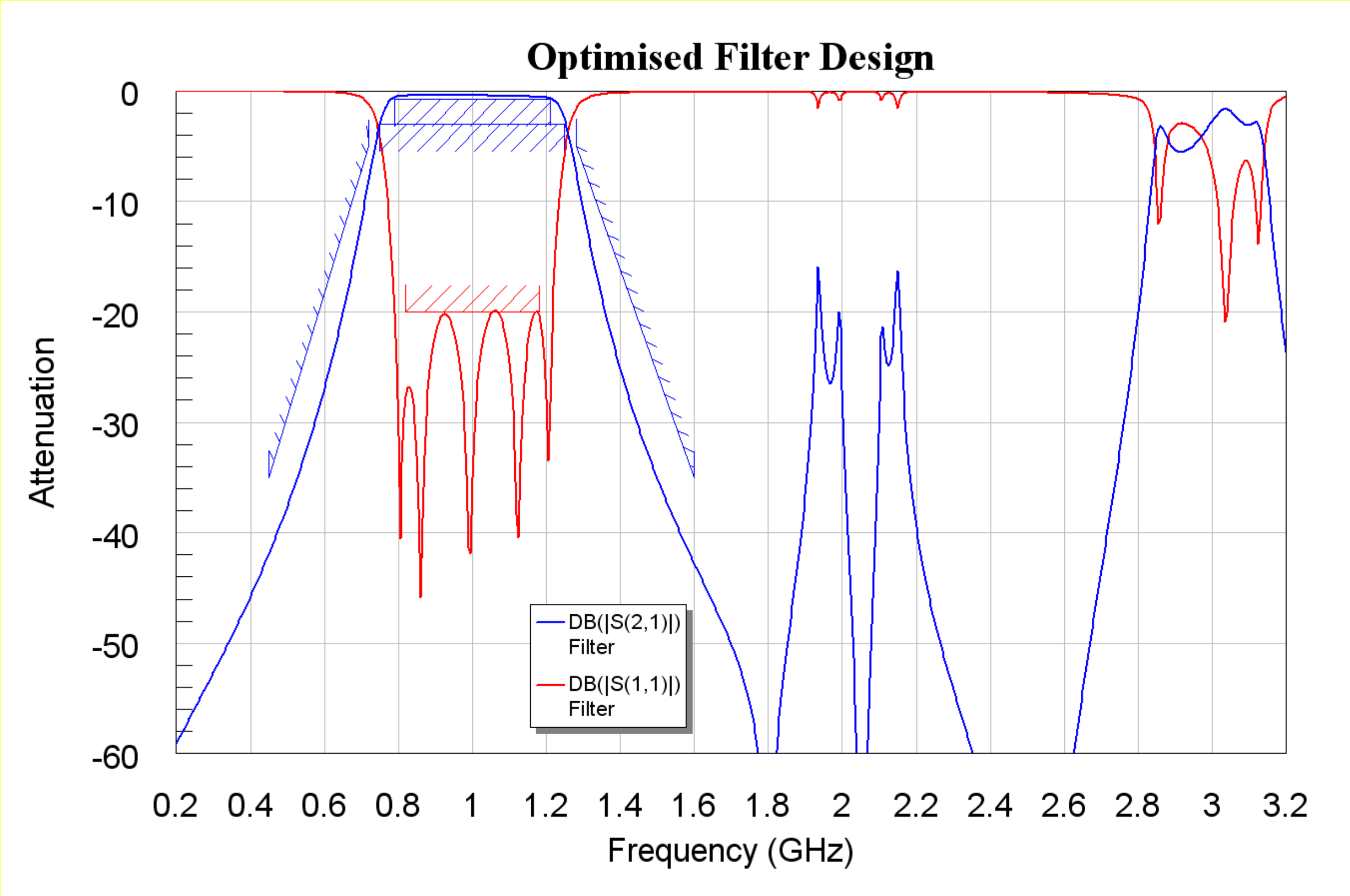


Res 1	50Ω	Tap = 0.487	Res 2	36Ω	Tap = 0.614
Res 3	36Ω	Tap = 0.426	Res 4	36Ω	Tap = 0.614
Res 5	50Ω	Tap = 0.487			

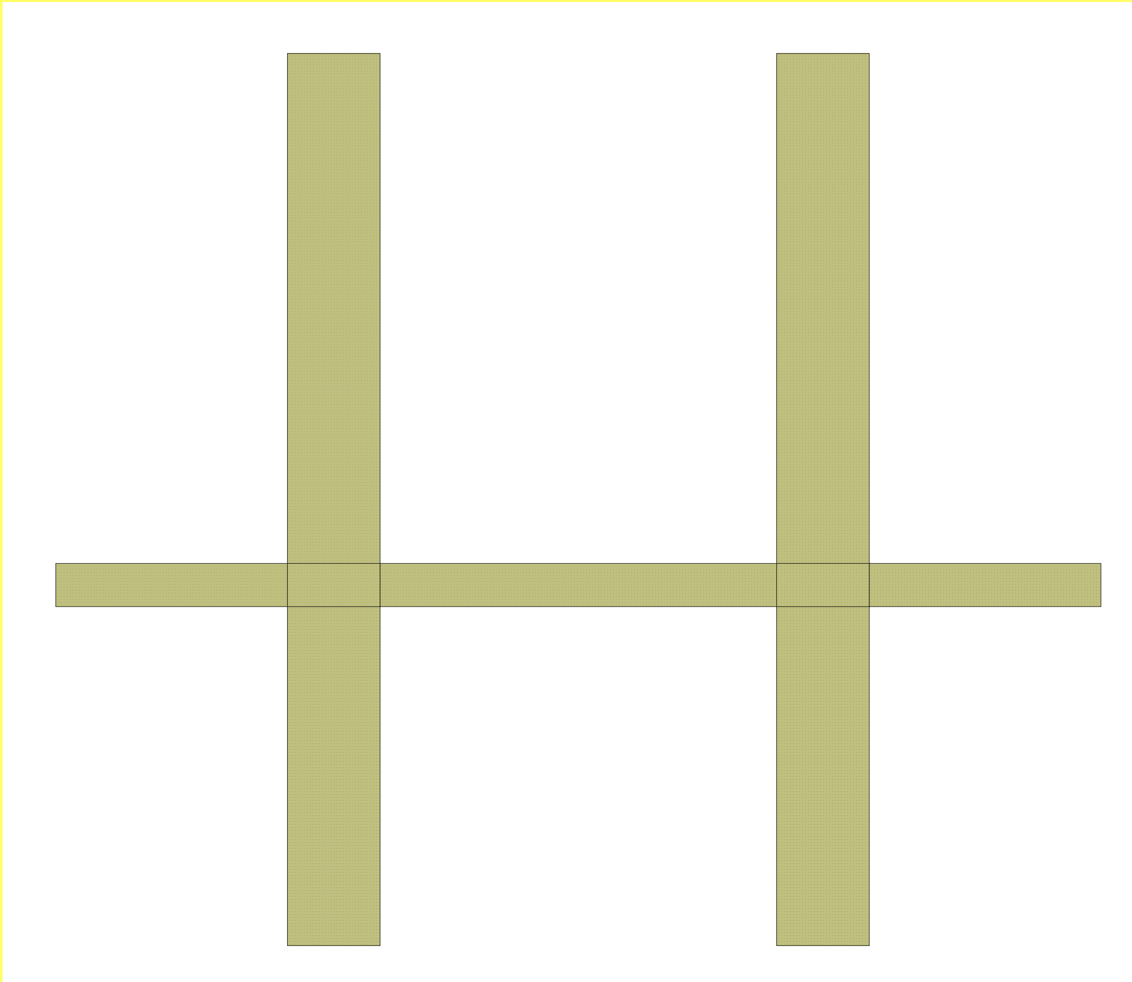
Design Example



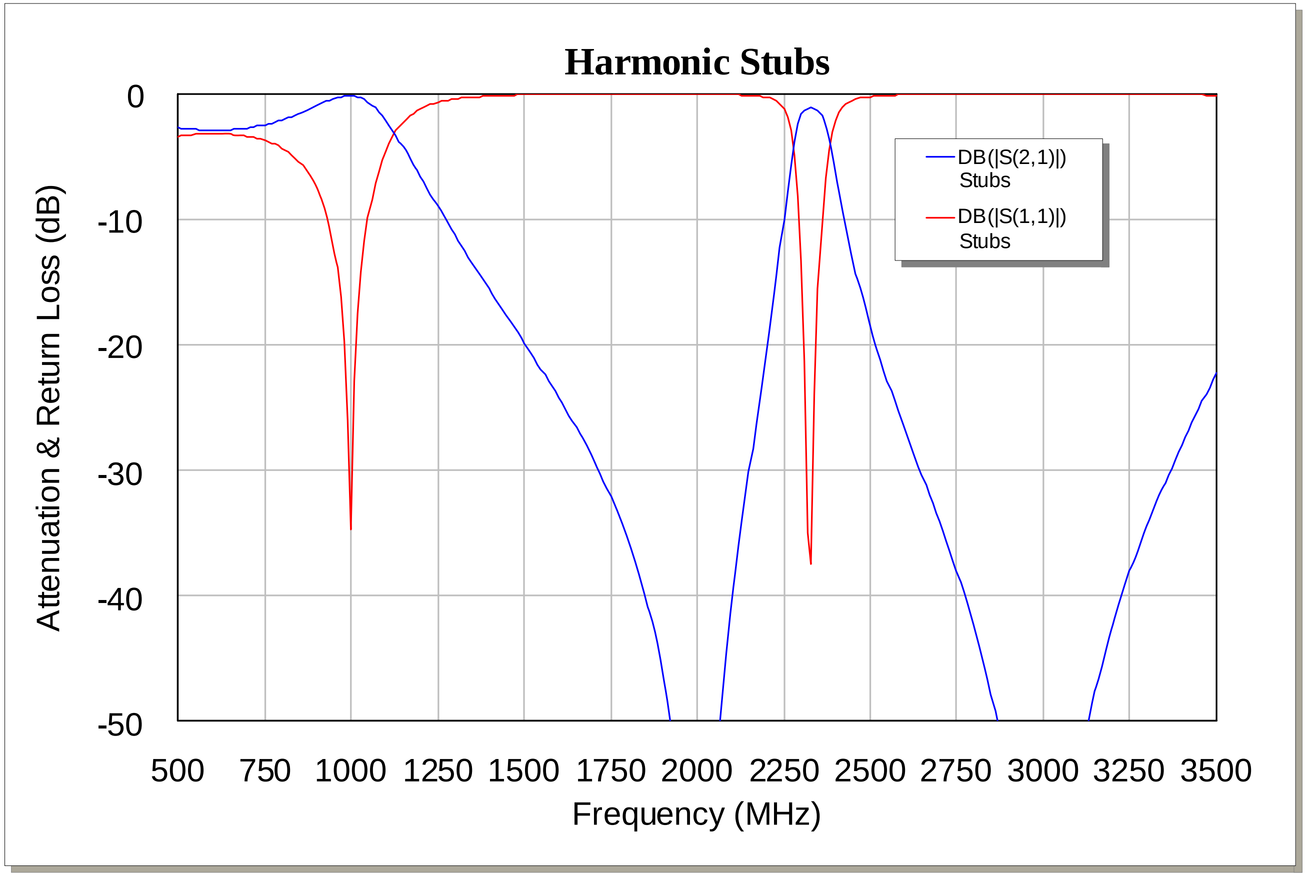
Design Example



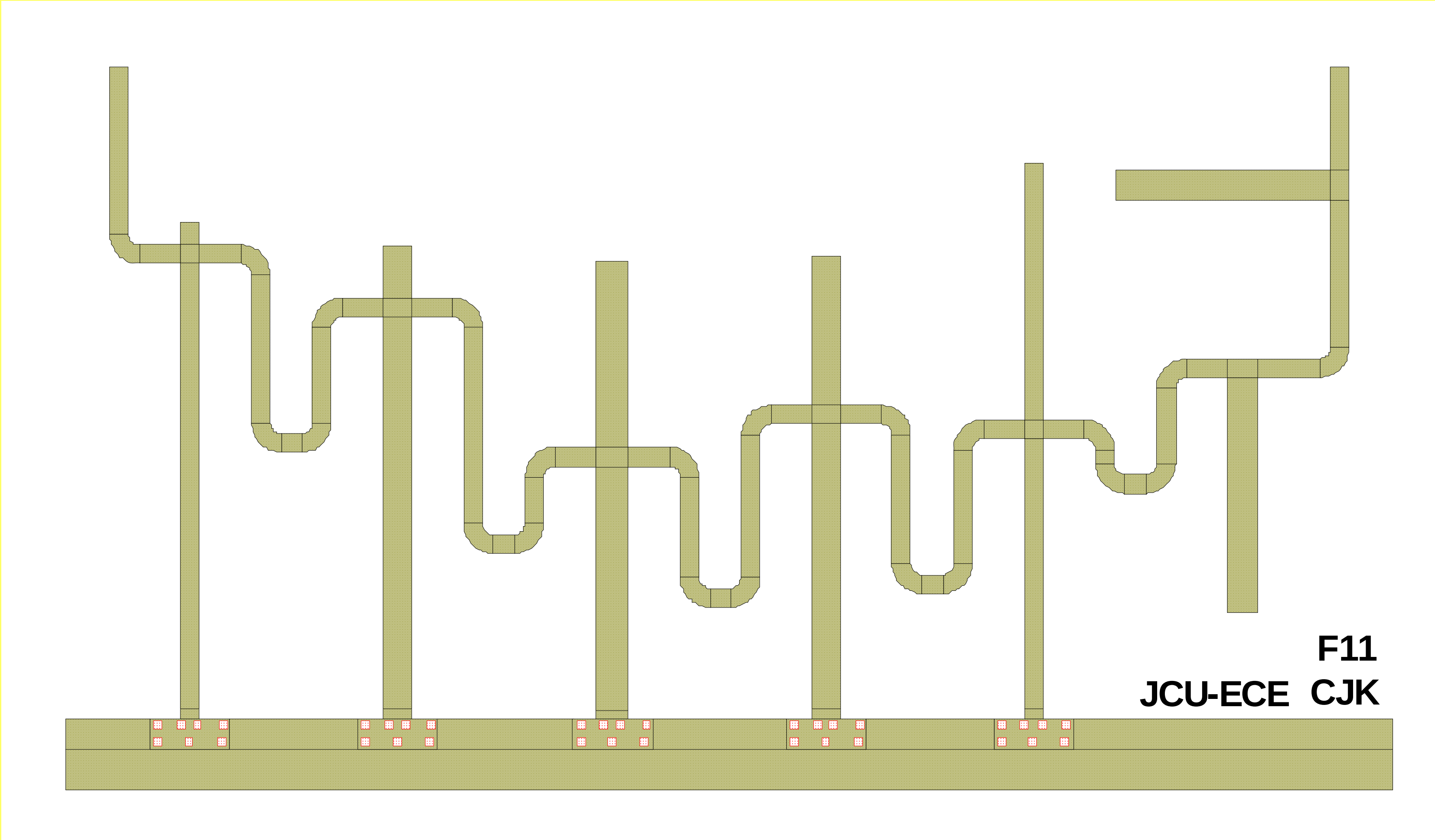
Harmonic Stubs



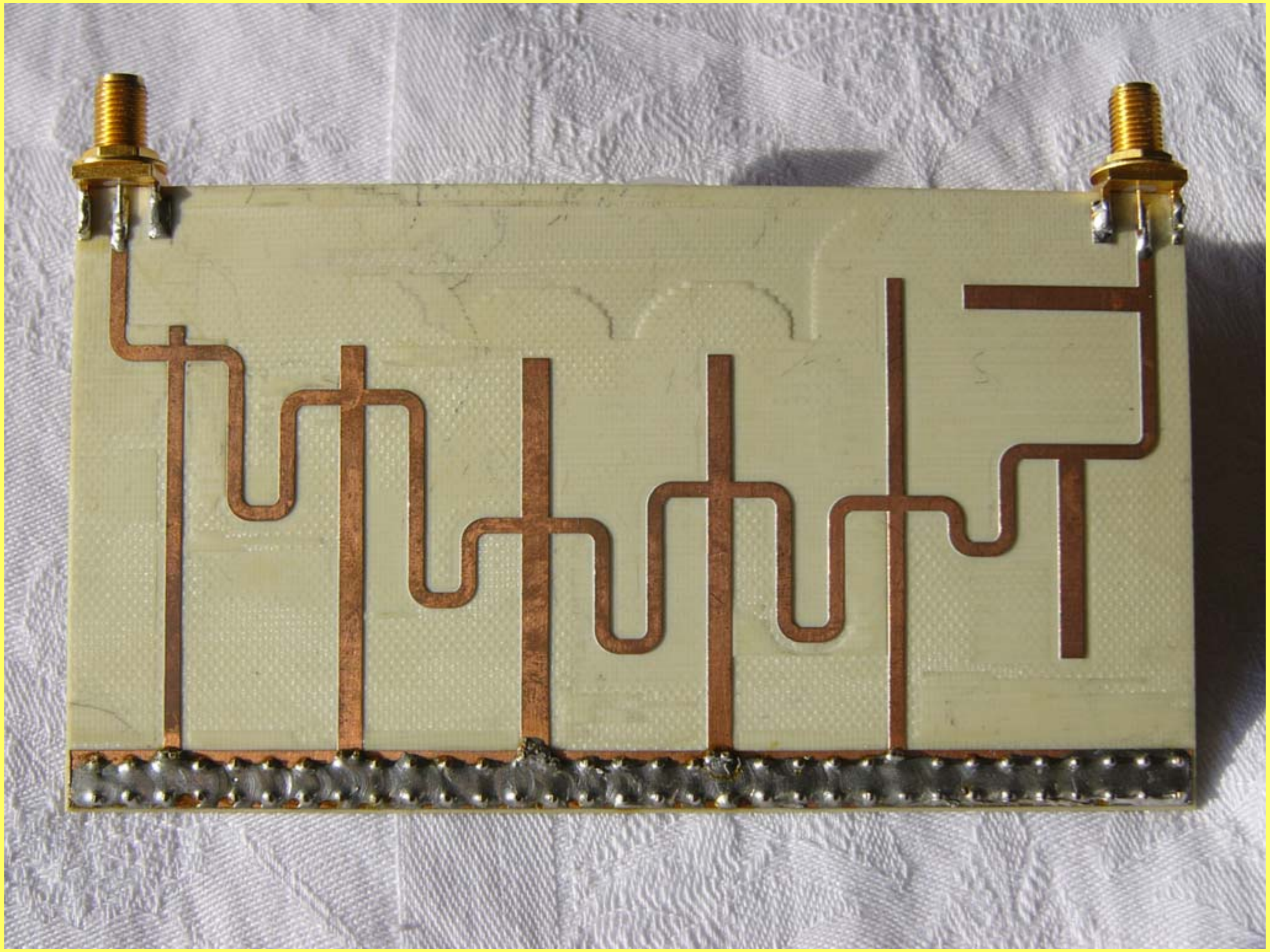
Harmonic Stubs



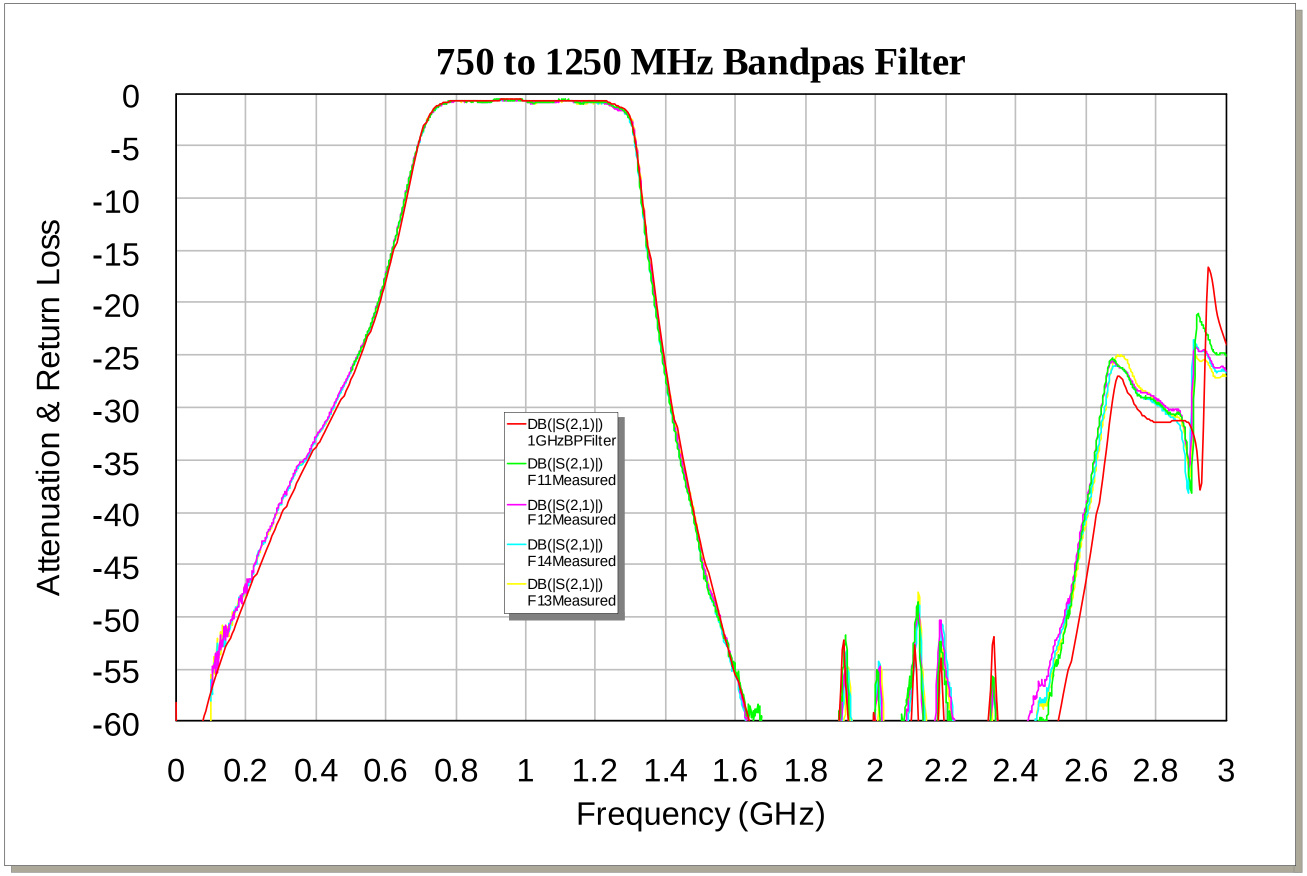
Layout Design Example



Hardware Design Example



Comparison Calculated-Measured



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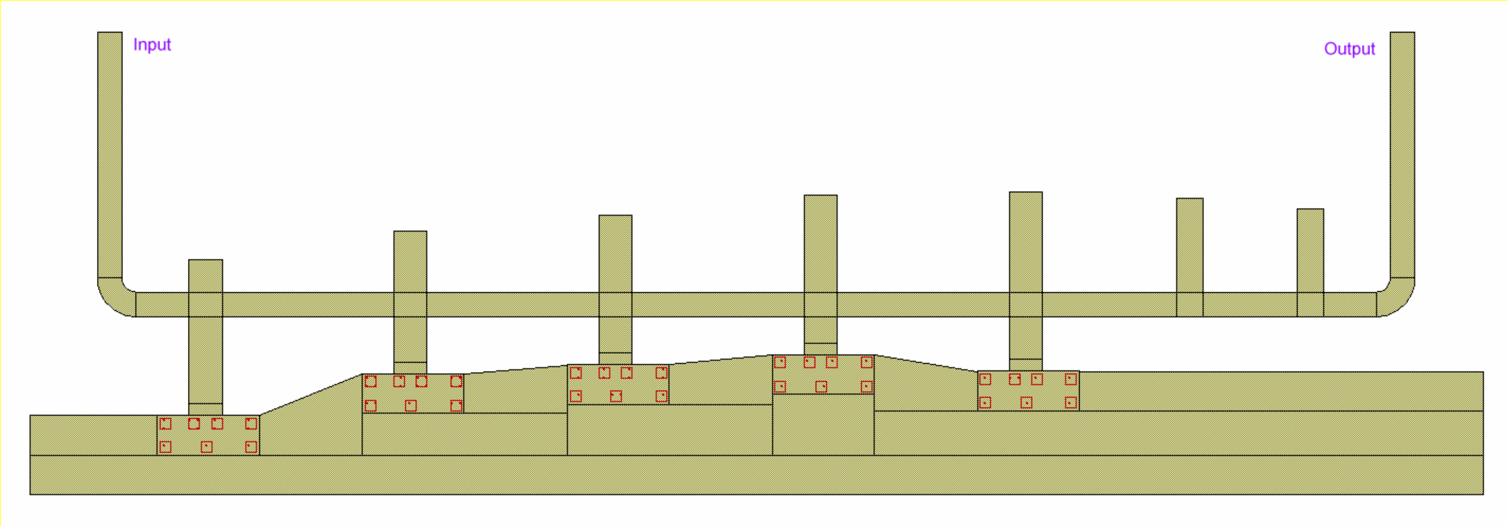
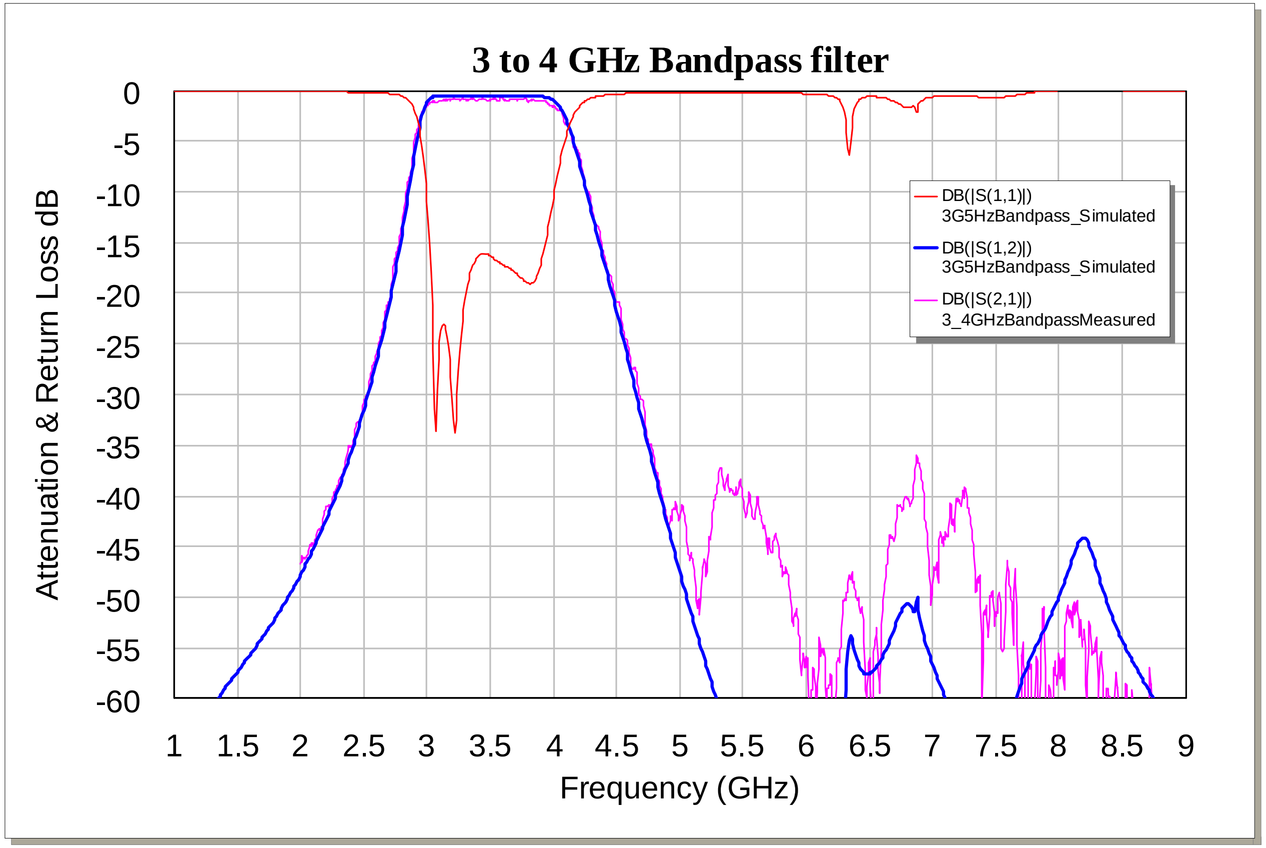
Higher Frequency Filters



3.5 GHz Centre Frequency, 1 GHz BW
Filter size 110x35 mm

Higher Frequency Filters



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Conclusion

- The design technique developed, resulted in filters that:
- Can have wide bandwidth (50% example)
- Are easy to design by following procedure outlined.
- Give very good agreement between design and hardware.
- Are bigger than interdigital filters.

Any Questions?