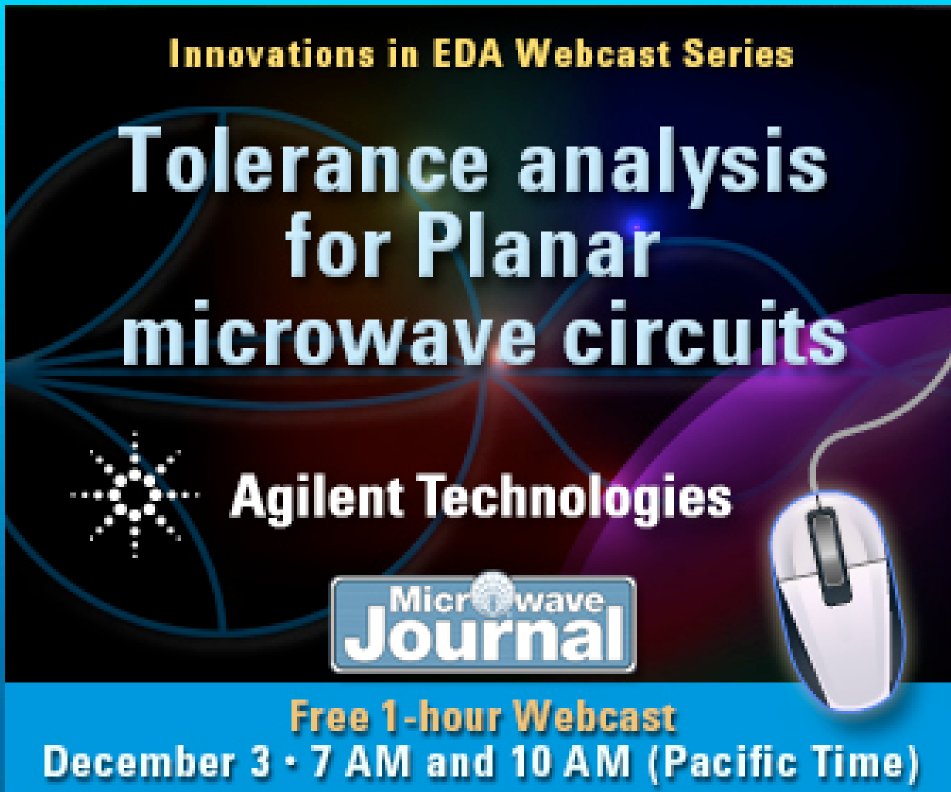
Welcome



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Tolerance analysis for Planar microwave circuits

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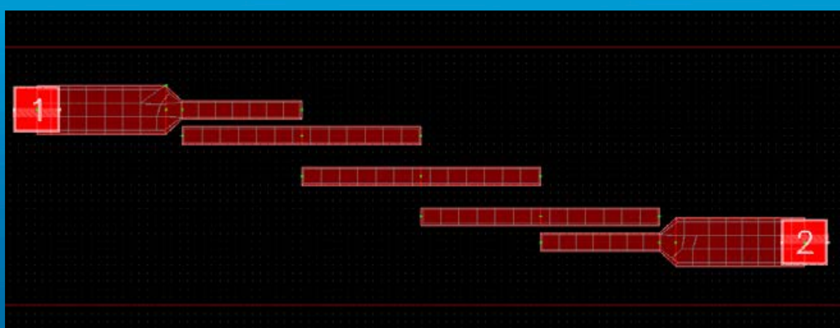


Planar microwave circuit tolerance analysis
Overview

- Microstrip bandpass filters can make or break a highly integrated design, making them a perfect example for discussing tolerance analysis.
- Having a method for performing a tolerance analysis on these structures can save iterations, time, money and unnecessary stress.
- The analysis is useful for vetting designs, determining feasibility, and failure analysis of existing designs.
- Consider this as a bit of a checklist at a design review; something to prevent repeating mistakes or overlooking the impact of tolerance.

Planar microwave circuit tolerance analysis
Motivation

"Lessons learned the hard way" is one motivation for better tolerance analysis early in the design cycle.

I would prefer to discuss the financial incentive of rolling your own filter designs ***where appropriate***:

- Consider a typical XPIC or MIMO radio at microwave frequencies could require 6-12 bandpass filters.
  - Custom or even off the shelf SMT microwave filters cost in the neighborhood of $1-$15 in medium to high volume(personal experience).
  - How much does the board area cost? What is the lead time?
  - *Tolerance issues (without post-manufacture tuning) will preclude Microstrip filters for* ***some*** *applications.*

Planar microwave circuit tolerance analysis
Introductory discussion

- Designing a filter to perform across variation (picking appropriate initial targets for the design) is nearly as challenging and time consuming as designing a filter itself.
- My success was unreliable until I adopted the basic framework presented here for evaluating designs.
- No one size fits all approach
    - The application requirements for band pass filters vary considerably – from image noise rejection in receivers to transmitter spurious content

Planar microwave circuit tolerance analysis

List of some of the analyses that we'll setup in Genesys

Using a 29 GHz bandpass filter as our test subject we will perform the following analyses

- The easiest:
  - Dielectric constant variation
  - Substrate height variation
- More challenging:
  - Using a simple and practical model (modification to our circuit) for analyzing etching tolerances
  - Some work on advanced post processing to analyze the relative variation of different process steps
- Peripheral analysis
  - Impact of shielding/cover height
  - Impact of the circuit being off-center in the shielded environment

Planar microwave circuit tolerance analysis

Some specifics about the choice of a 29 GHz edge-coupled bandpass filter

- Classic edge coupled band pass filter and the variations derived from them are fairly easy to synthesize.
- Compact and efficient to analyze
- Center frequency of 29 GHz was chosen because the dimensional tolerances significantly impact both the coupling between resonators and the center frequencies.
- Tolerance analysis reviews non obvious insights to caution against making snap decisions on the frequency response of prototype samples of filters.
  - Author discovered this while doing some similar design work at these scales (center frequency, substrate dimensions)

Planar microwave circuit tolerance analysis

Some specifics about the choice of a 29 GHz edge-coupled bandpass filter

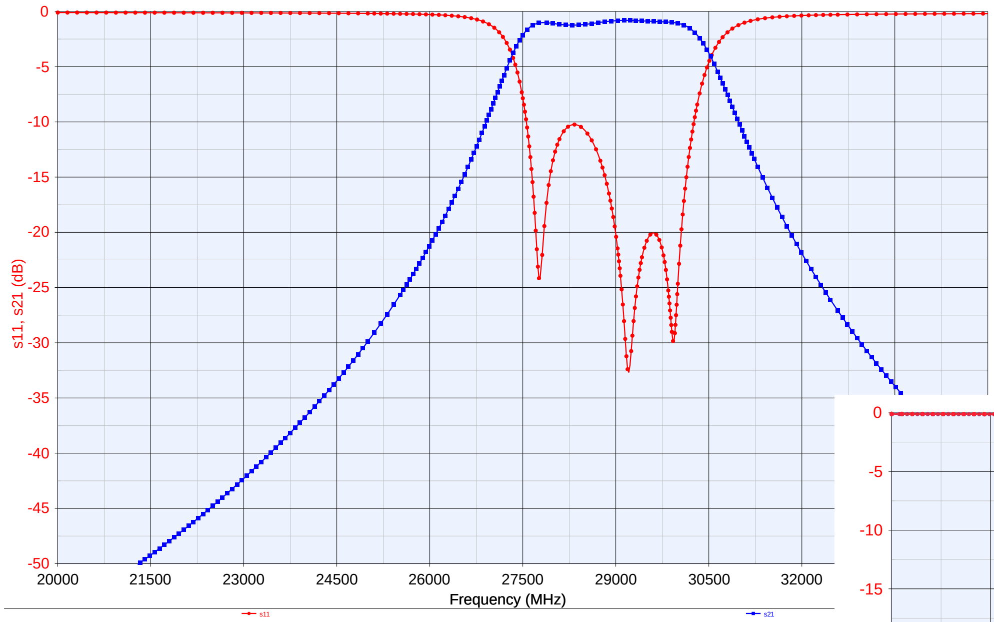
- Simplicity of this filter makes it practical to rely heavily on linear models. Many popular variations differ from this case considerably (bent, folded, compact versions).

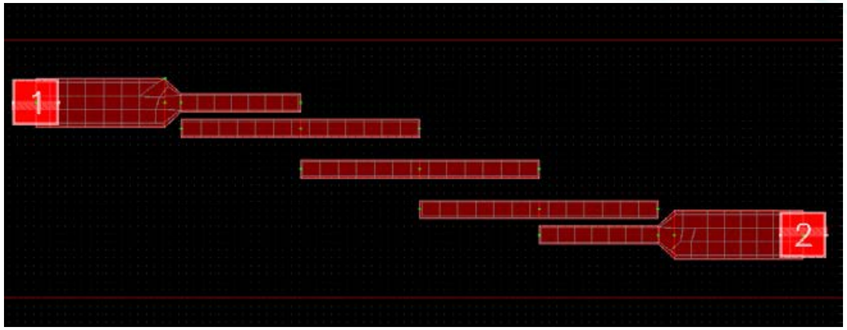
- Use Momentum electromagnetic simulation exclusively since it handles arbitrarily constructed filters as quickly and efficiently as those represented by perfectly parallel coupled lines.

- The bottom line is that going straight to Momentum makes for a more robust and general solution to the analysis challenge.

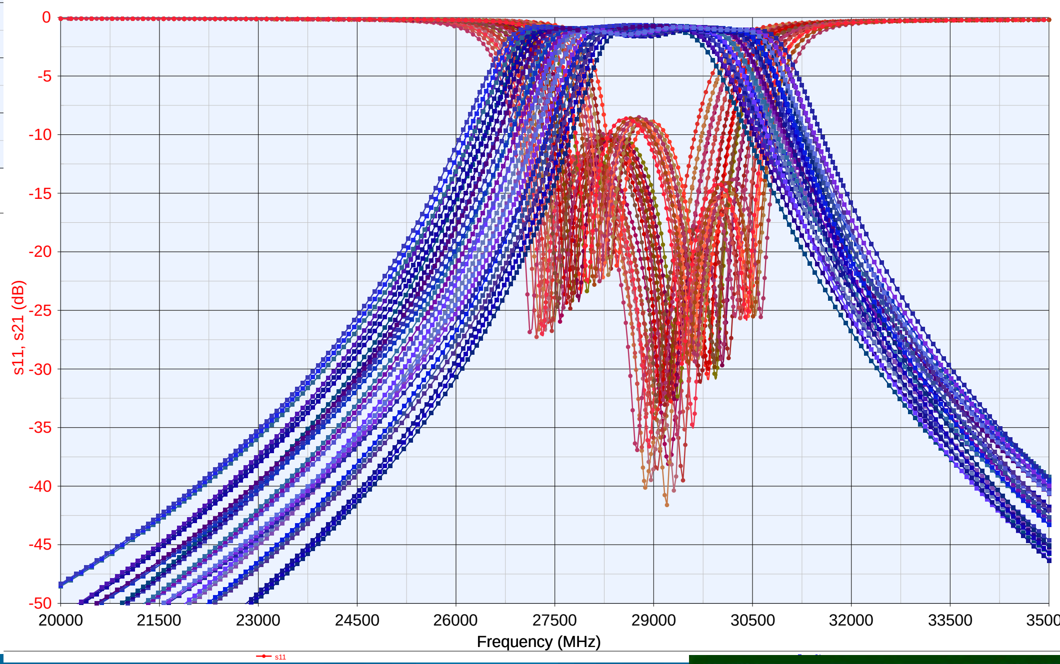
Planar microwave circuit tolerance analysis

The filter meets the process





- Baseline design (above)
- Process variations applied (right)



Planar microwave circuit tolerance analysis

How this filter was designed

Design process

- Synthesized initial design with M/Filter
- Simplified the number of unique dimensions
  - rounded resonator width and spacing to even numbers
  - kept all resonators the same widths
  - removed linear disco models since we will be using Momentum
  - added taper to keep 50 ohm line from shorting the resonators
  - empirically adjusted spacing values to achieve a reasonable response with Momentum as the baseline design
  - added additional features to handle the variation analysis (more later)

Planar microwave circuit tolerance analysis
29 GHz Filter assumptions

Material choice

- premium substrate: Rogers RO5880
  - Thickness chosen: 0.254mm (10 mil)
    - Thickness tolerance (substrate height): +/- 18um (0.7 mil)
  - Dielectric constant: 2.2 +/- 0.02
  - Dissipation factor /Loss Tangent: assuming 0.0009
  - 50 ohm lines ~ 0.75mm wide

Fabrication tolerance:

- For this work, assume etching tolerance = +/- 25 um (1 mil)
  - A simplistic model for analyzing this will be described later

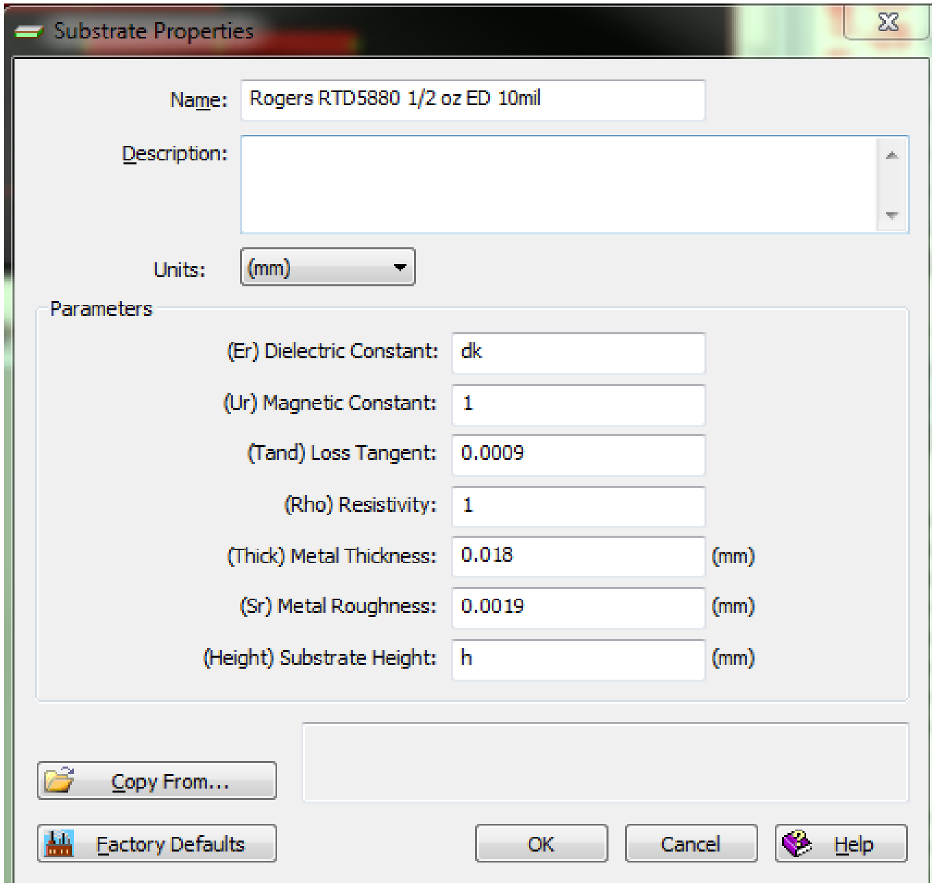
Planar microwave circuit tolerance analysis

Parameters are the key to reuse of designs and analyses

- While no aspect of what is presented today is particularly complex, there is no need to go through the setup tasks for each design.
- Simply get into the habit of parameterizing substrates, frequencies, and common dimensional parameters.
- You can then develop your circuit in another workspace and easily copy it into a tolerance test bed template like the one presented today.

Planar microwave circuit tolerance analysis

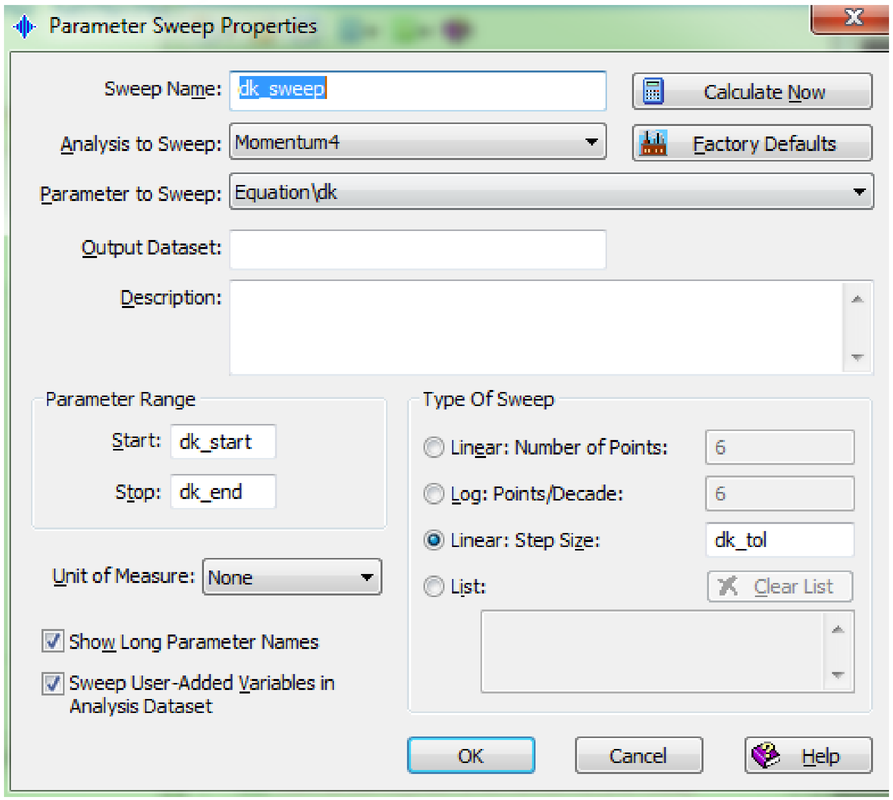
Setup the easiest analyses in Genesys



- Populate the dielectric constant and height positions with variables (dk, h)

Planar microwave circuit tolerance analysis

Example of a sweep of the dielectric constant

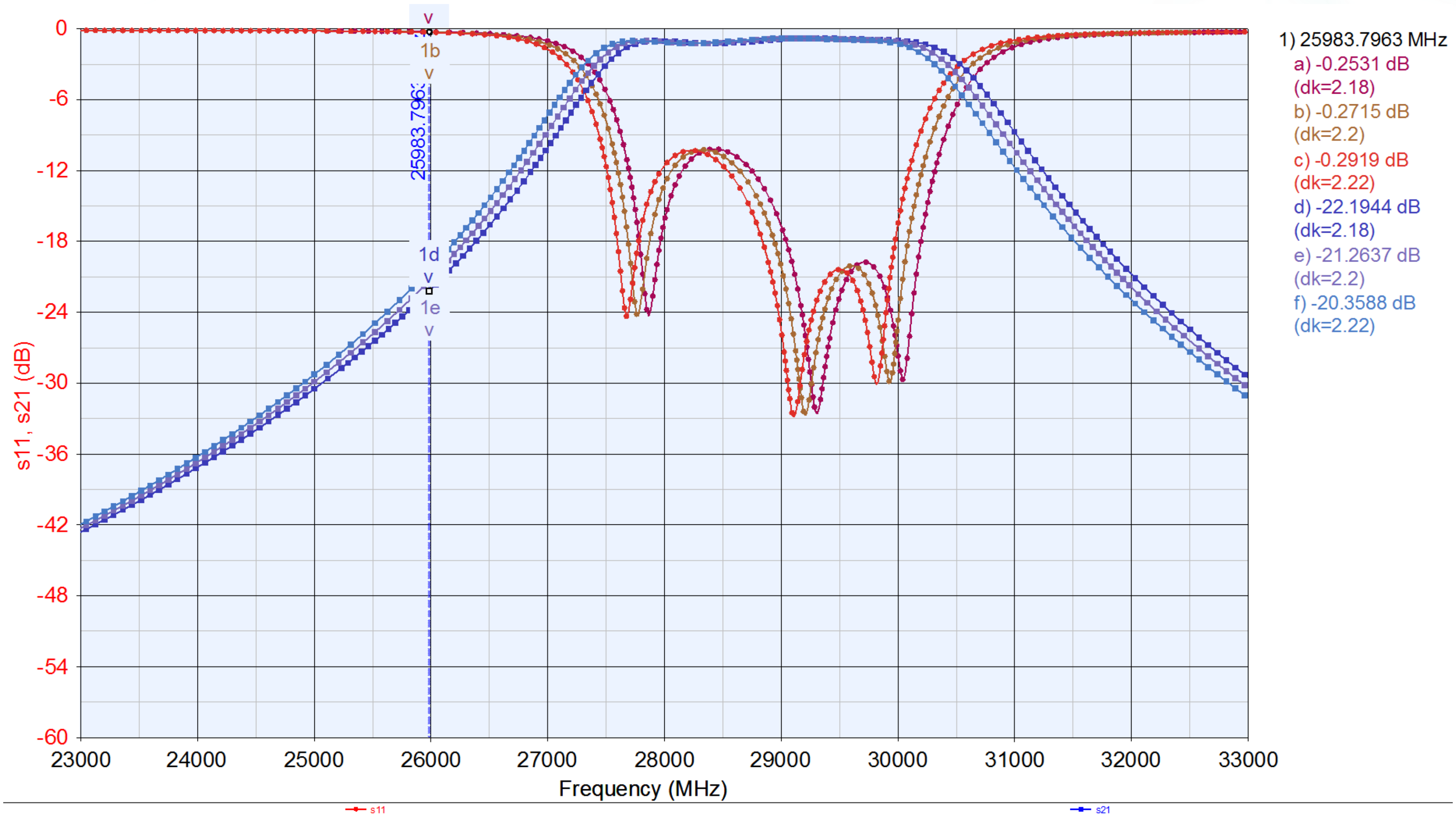


- Setup the parameter sweep.
- When run, this sweep runs the analysis Momentum4 for three discrete values of the "dk" variable
  - (**dk_start**,
  - **dk_start+dk_tol**,
  - **dk_end** (= **dk_start** +2 * **dk_tol**))
  - And collects the data in a single dataset named **dk_sweep_Data (**name inherited from the name of the sweep, shown as blank here)

Planar microwave circuit tolerance analysis

Example of a sweep of the dielectric constant

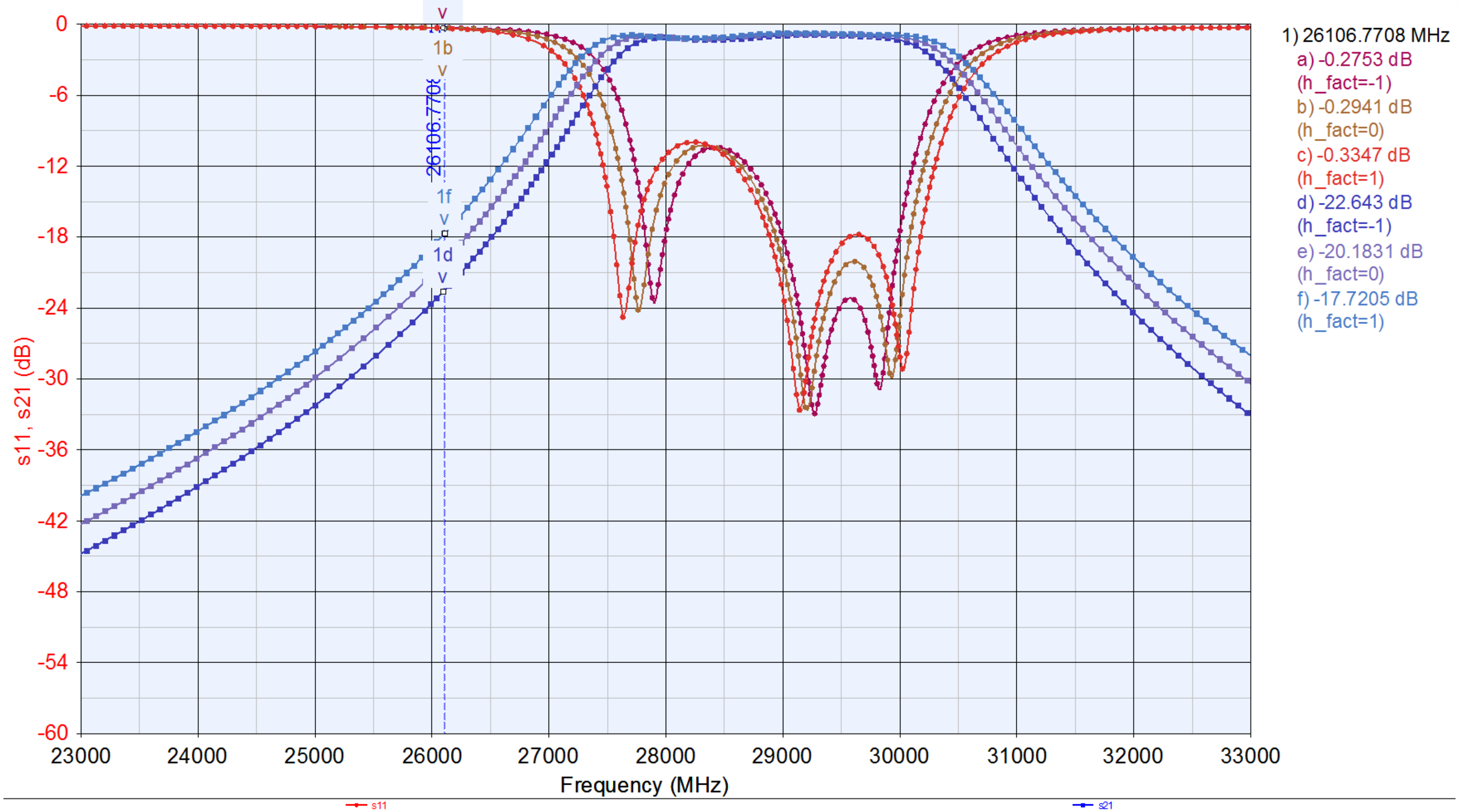
- Due to the tight tolerance of the dielectric constant, the change in response is small.



Planar microwave circuit tolerance analysis

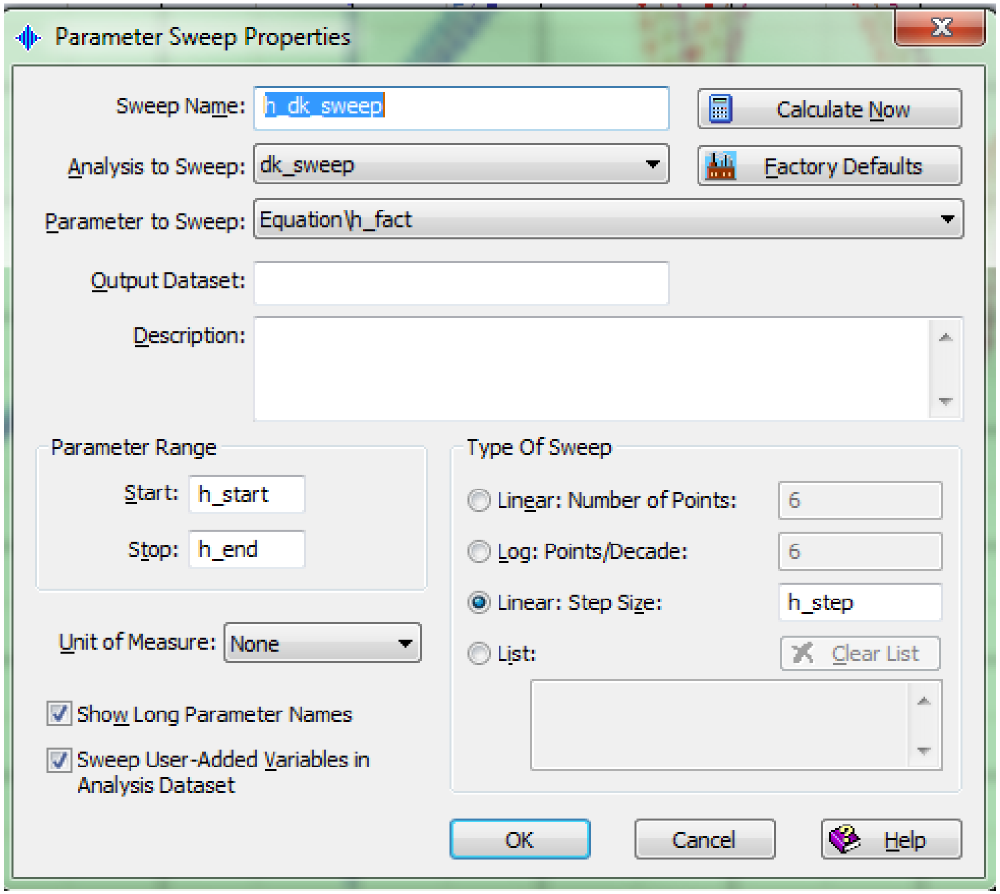
Example of a sweep of the height

- Parameter sweep for height in the same way we did for the dielectric constant
- Greater spread in response



Planar microwave circuit tolerance analysis

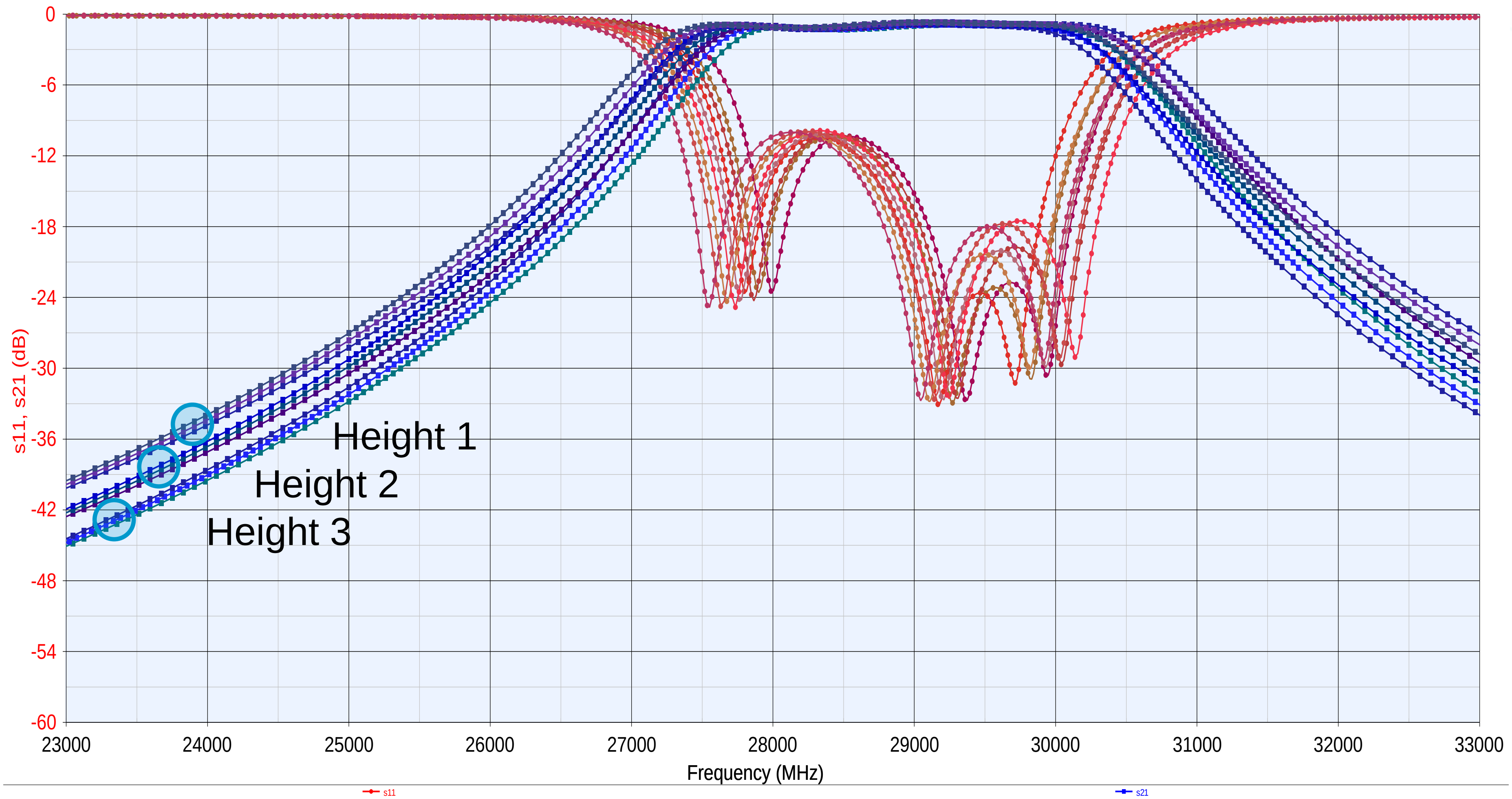
Next let us stack these tolerances together to look at all variation that is in the hands of the substrate manufacturer.



- **I've heard the claim that Genesys can't sweep multiple variables; that's simply not true. Here's how we do it:**
- Simply copy the parameter sweep that we created to vary height only and have it "run" the dielectric constant sweep.
- This is nothing more than nesting of loops – for each value of height variation, each value of dielectric constant will also be simulated. The combine dataset will reside in **h_dk_sweep_Data (the outermost "loop")**
- The dataset name is not shown here, rather it is inherited from the name of the sweep.

Planar microwave circuit tolerance analysis

All variations of Dielectric Constant and height



Planar microwave circuit tolerance analysis

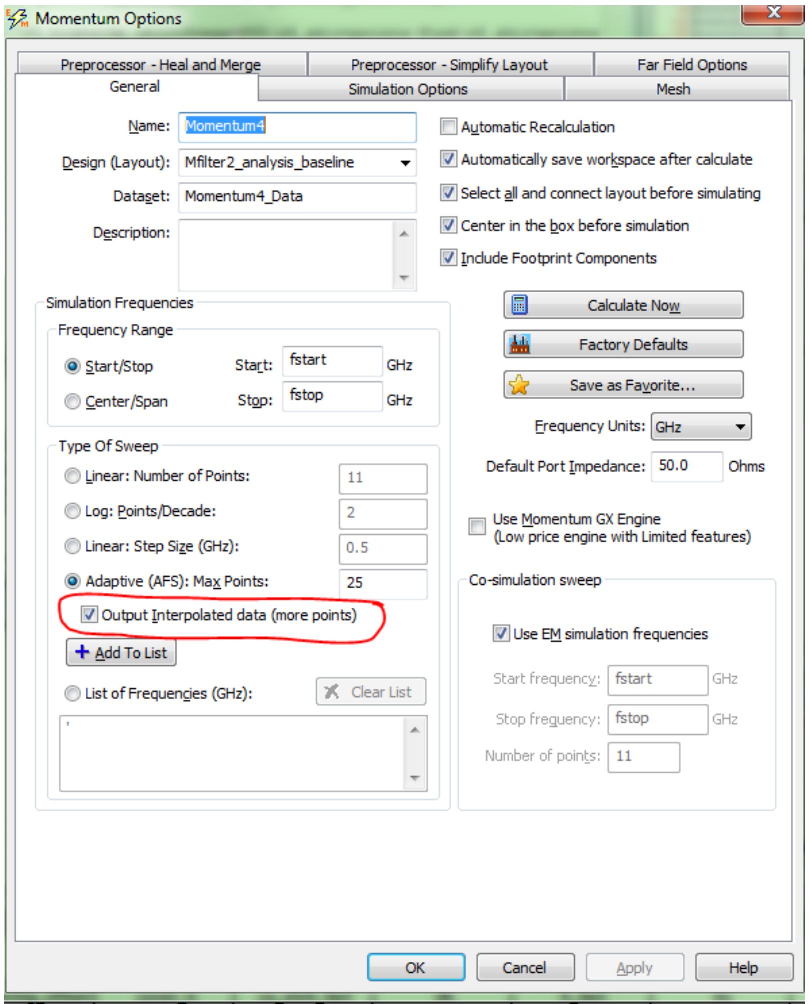
More analysis of the variation with post processing

Post processing can be used to crunch the swept data and quantify variation

- Quantitative:
  - Easer to realize actual design improvements and make fair comparisons.
- But, automatically crunching the data presents some challenges:
  - Look for relative or absolute parameters (such as attenuation)?
  - False positives?
  - Precise value or window?
  - Momentum with AFS (automatic frequency sweep) will not necessarily provide data at the same frequency each sweep

Planar microwave circuit tolerance analysis

More analysis of the variation with post processing



- In order to have enough points to successfully post-process, “output interpolated data” (more points) should be enabled.

Planar microwave circuit tolerance analysis

More analysis of the variation with post processing

For this series of examples, I decided to derive the following from the sweeps:

- Frequency for the **maximum passband response** (reference point for skirt attenuation, not much value otherwise)
- Frequencies for **upper and lower relative attenuation skirt value**
- I arbitrarily used -20 dB as the relative attenuation to track the filter skirts. To avoid the complications of finding data points at exactly –20 dB, I searched for all points within a tolerance of +/- 1.5 dB (-18.5 to -21.5 dB). This skirt value and tolerance can be changed easily but realize that if the tolerance is too tight the analysis may fail since there might not be a resulting point that falls in the window when the search is performed.

The post processing for each sweep goes like this:

1. Find frequency (and swept point index) of maximum response.
2. Find all points below the point of **maximum response** (lower index value) that have a relative amplitude of the **skirt value** +/- the tolerance
3. Repeat for the points on the upper end of the **skirt value**.
4. The upper and lower attenuation skirt frequencies were calculated as the average of all the points that fell into the window.

This method is not ideal but the tolerance, windowing, and averaging yields more consistent results than manually viewing data at markers.

Planar microwave circuit tolerance analysis

More analysis of the variation with post processing

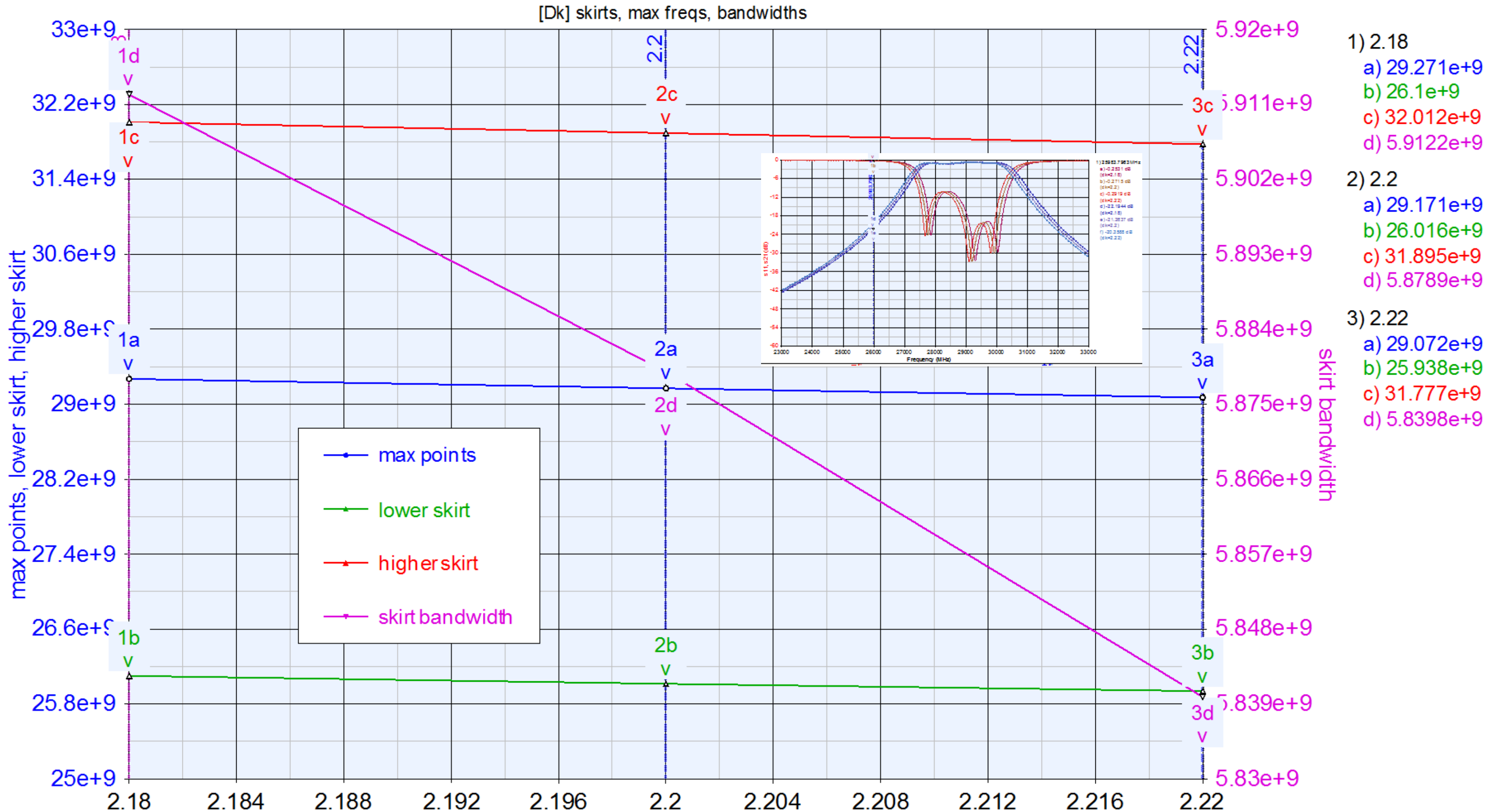
The post processing blocks are too lengthy to include here, but they are available in the companion workspace. Admittedly this can take some time to get the hang of but once done the work can be reused easily.

The post processing setups did the following steps:

1. Collect arrays of the indices in the data for each value of the parameter
2. Collect arrays of frequencies represented by these response points
3. Collect arrays of the response values (s21 in this case)
4. Process to collect the maximum value for each response curve and record the frequency this occurred at
5. Search the response arrays each for the target skirt value (-20dB relative to the maximum response) within the +/- 1.5 dB window.
6. Average the frequency values for those points that fell within the window (once each for the lower and upper skirt points).
7. Calculate the “skirt bandwidths”

Planar microwave circuit tolerance analysis

Results after post-processing (Dielectric constant)



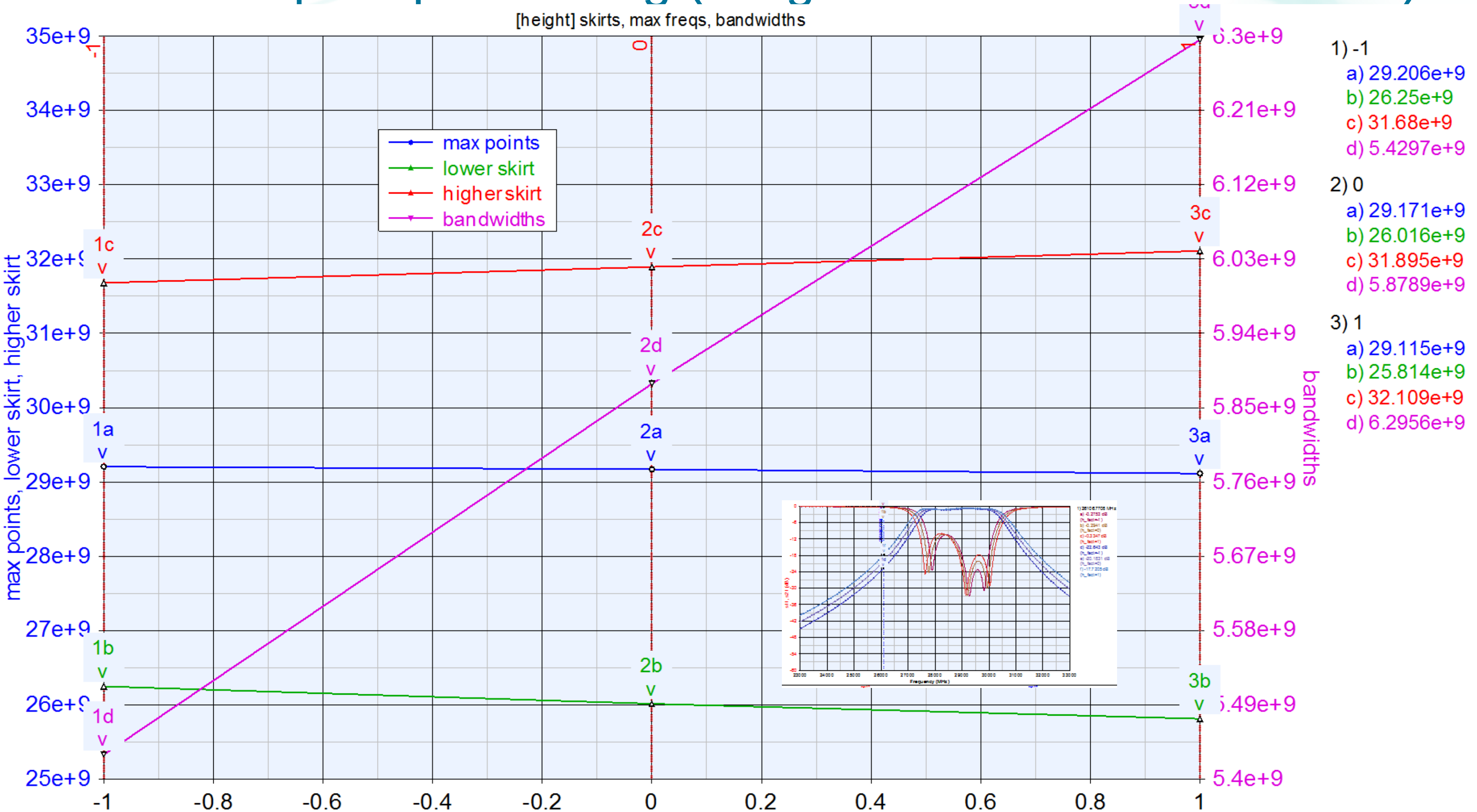
max points = peak of response

Skirts = -20 dB edges ------- ------- **all units GHz**

Bandwidth = -20 dB bandwidth (right axis)

Planar microwave circuit tolerance analysis

Results after post-processing (Height 0.254mm +/-0.018mm)



max points = peak of response

Skirts = -20 dB edges ------- ------- **all units GHz**

Bandwidth = -20 dB bandwidth (right axis)

Planar microwave circuit tolerance analysis
Discussion of substrate only parameters

The results from the variation in dielectric constant and substrate height are expected.

- Both an increase in dielectric constant and a decrease in height would reduce the resonator coupling and thus reduce the filter bandwidth.
- Because of the relative scales (1% in dielectric constant but 7% in substrate thickness), the impact of the height dominates.

Planar microwave circuit tolerance analysis

Build tolerances: Etching

You may find it nearly impossible to get a PWB manufacturer to firmly commit to holding a dimensional tolerance for etching. Industry standards exist but do not seem to be cited regularly – an example is: IPC-6018A is titled "Microwave End Product Board Inspection and Test" (http://www.ipc.org/toc/ipc-6018a.pdf)

For the purposes of this analysis, I suggest a simplistic model where all copper grows or shrinks by a copper "etching factor". The basis for this intuitive model is the exposure time, quality (freshness), and circulation of the etchant.

For the analysis we will test three states that can result from the copper etching process:

- "under etched" (could be caused by rushing the process, using saturated etchant, etc.)
- "dimensionally accurate" (no imperfections due to the etching process)
- "over etched" (exposure too lengthy, etc.).

Planar microwave circuit tolerance analysis

Build tolerances: Etching

Description of the basic modeling assumptions for etching tolerance in this presentation and the analyses presented:

- **Under-etched**: All copper shapes grow by a fixed amount which lengthens lines and shrinks spacing.
- **Over-etched**: All copper shapes shrink by a fixed amount which shortens and narrows lines and increases spacing.

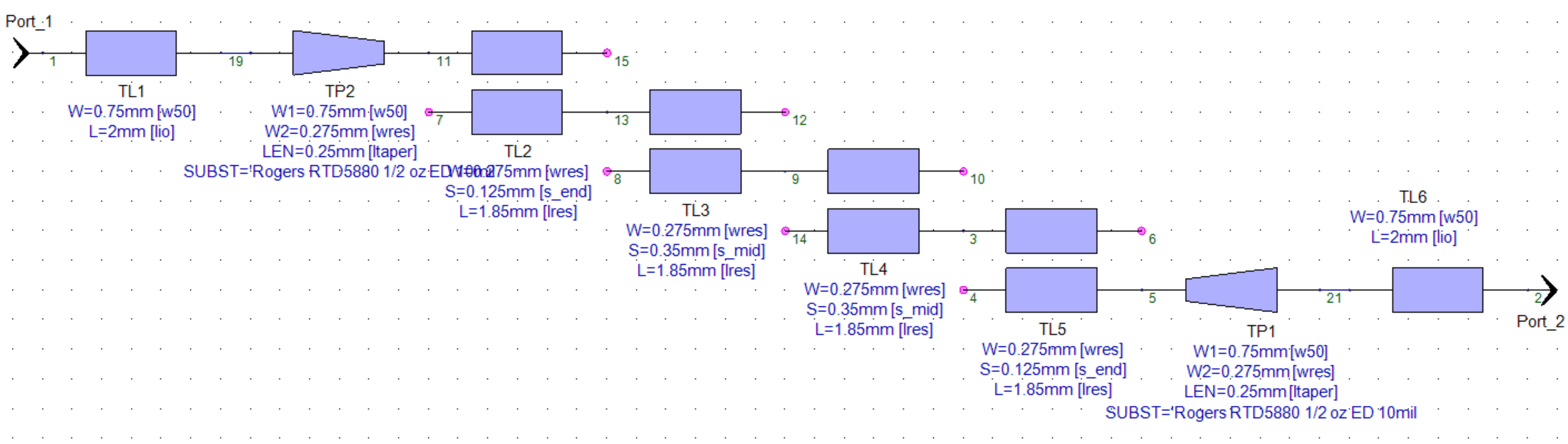
This model is only a suggestion that can be used for very efficient analysis. We can anticipate some cases where this might diverge from reality or where more detail should be added for the best results:

- Structures where the aspect ratios vary dramatically across the circuit or the board
- When plating processes are marginally applied.

Planar microwave circuit tolerance analysis

Build tolerances: Etching

- Typical conductor width/spacing tolerances are usually +/- 25 um, but I have seen extremes that hit twice that.
- So how do we make this tolerance analysis work?
- Equations and parameter sweeps of course.



Planar microwave circuit tolerance analysis

Build tolerances: Etching tolerance analysis mechanics

```
cu_etch = 0.025e-3;  % 25 micron

cu_etch_fact=?2;

w50_base=?0.75e-3

wres_base=?0.000275

lres_base=?1.85e-3

s_end_base=?0.000125

s_mid_base=?0.00035

%copper dimensions /spacing below

w50=w50_base - (cu_etch_fact * cu_etch)

wres= wres_base - (cu_etch_fact * cu_etch)

lres= lres_base - (cu_etch_fact * cu_etch)

s_end= s_end_base + (cu_etch_fact * cu_etch)

s_mid= s_mid_base + (cu_etch_fact * cu_etch)
```

The equations (Mathlang, MKS units) to the left are a subset of the main equation block in the downloadable workspace used for this presentation.

These two variables:

- **cu_etch** sets the incremental etching increment,
- **cu_etch_fact** is the multiplier (often swept between -1 and 1 in steps of one).

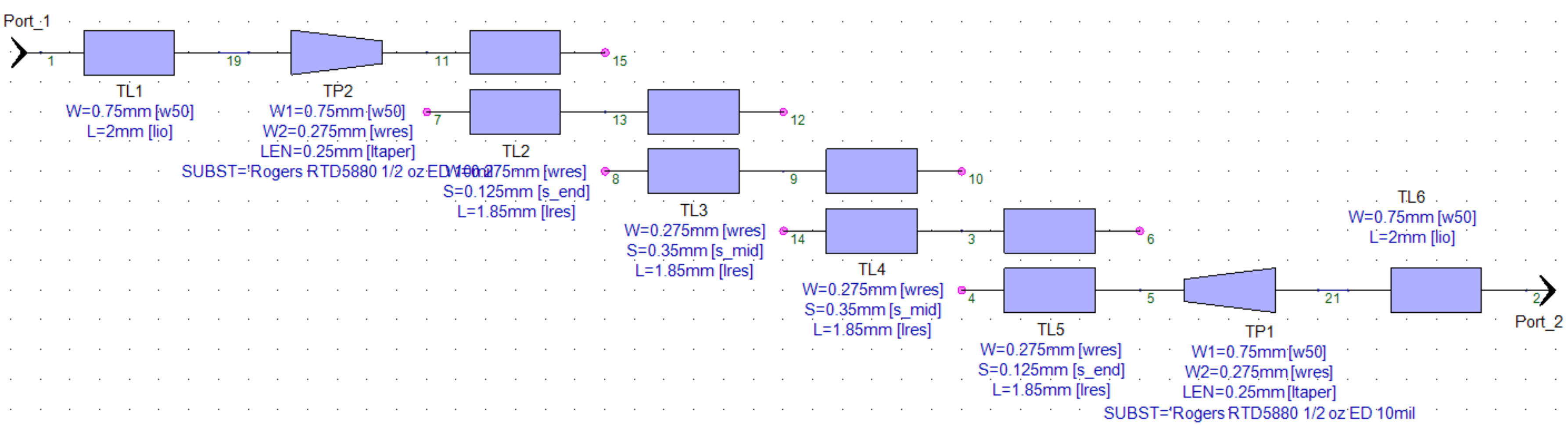
are used to modify all copper dimensions and spacing's listed here:

- **wres** = resonator width
- **lres** = resonator length
- **s_end**= input/output coupling spacing
- **s_mid**= inter-resonator coupling spacing

Planar microwave circuit tolerance analysis

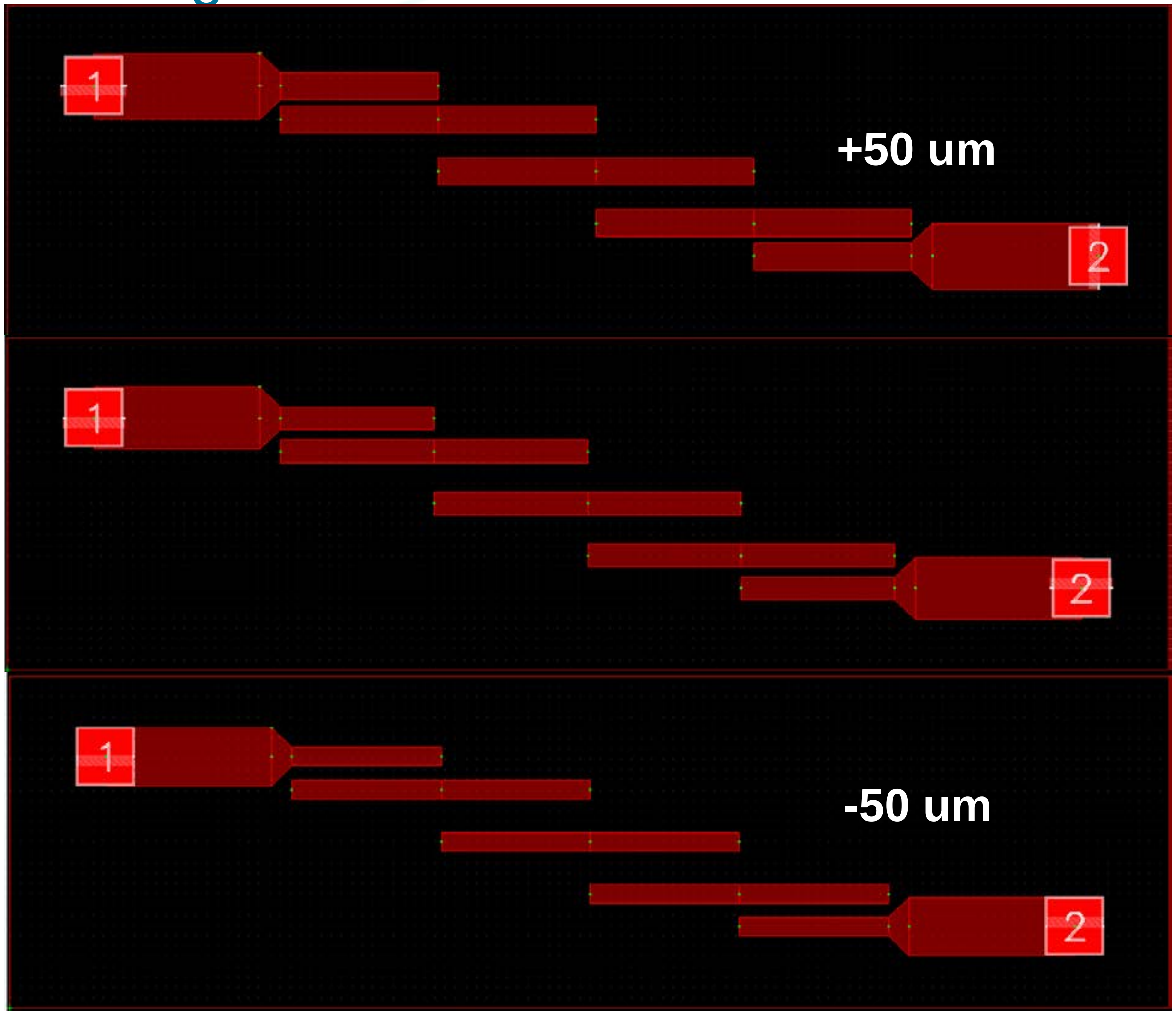
Build tolerances: Etching tolerance analysis mechanics

- Below the schematic is shown for the filter with the variables used as parameters to the Microstrip elements.
- We're using the schematic to create the copper for Momentum to analyze, no linear analysis will be performed.



Planar microwave circuit tolerance analysis

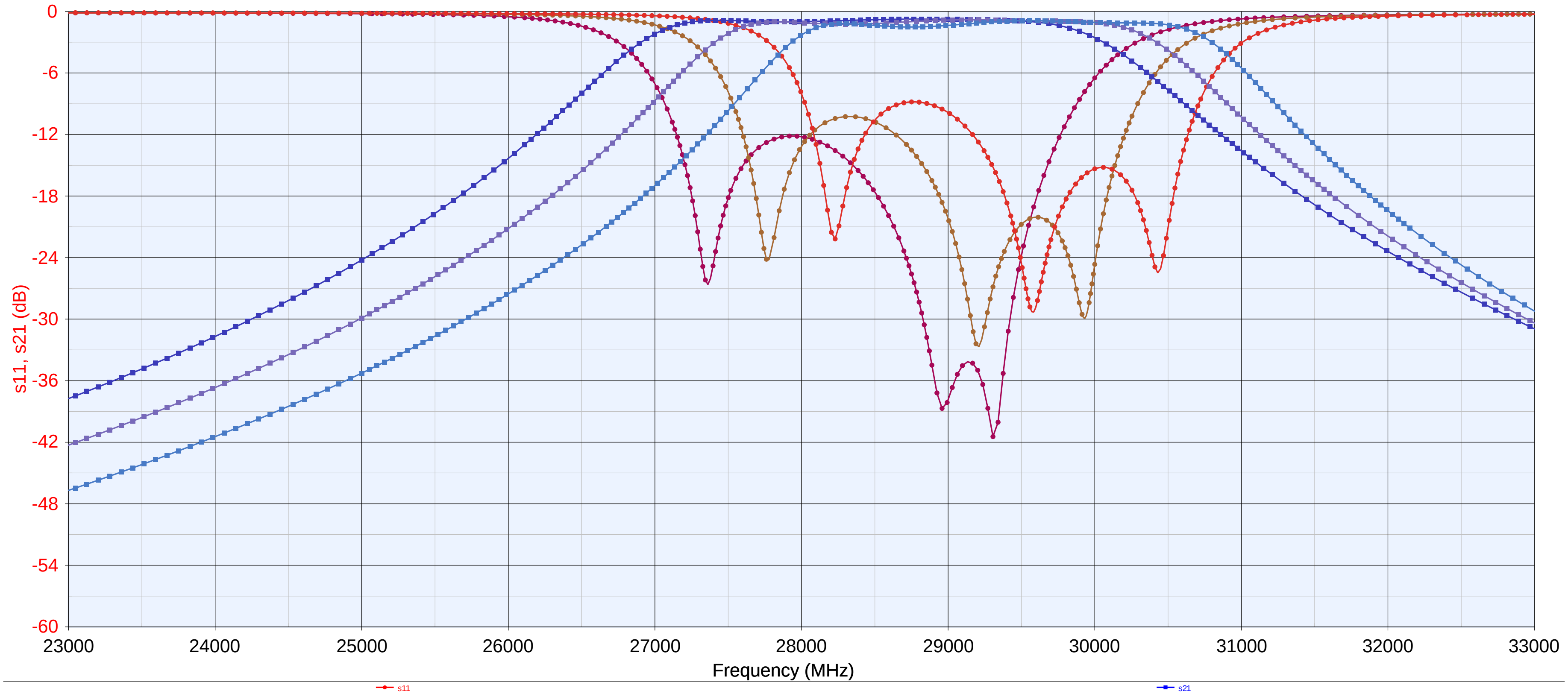
Etching tolerances



- In order to make it clearly visible, the etching tolerances were exaggerated to +/- 50um for the pictures to the left.
- Top shows under-etching by 50 um,
- Middle shows nominal dimensions,
- Bottom shows over-etched by 50 um.

Planar microwave circuit tolerance analysis

Etching: This is the result of the filter with +/- 25 um of etching variation.



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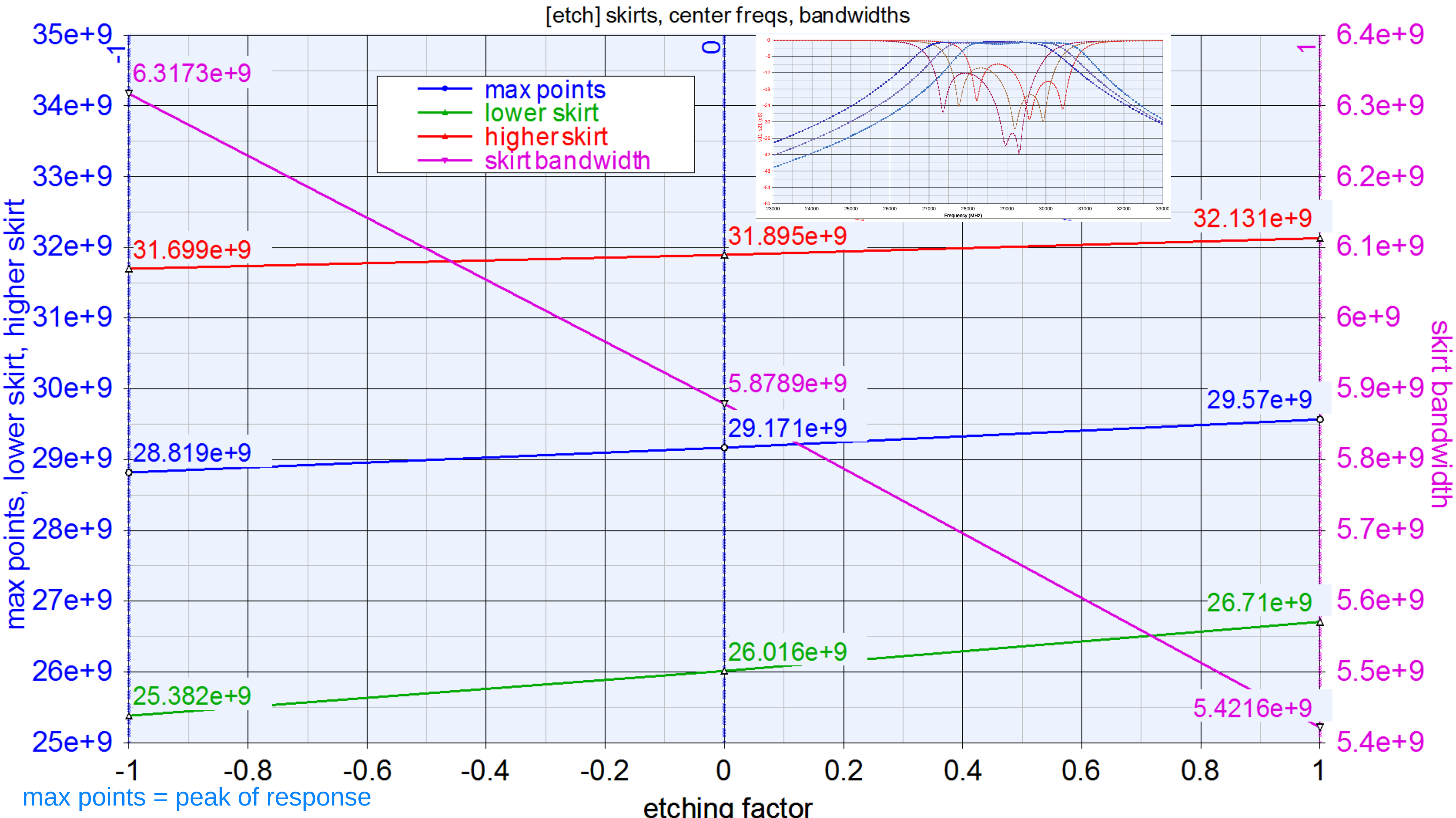
Planar microwave circuit tolerance analysis

Etching: results



max points = peak of response

Skirts = -20 dB edges ------- ------- **all units GHz**

Bandwidth = -20 dB bandwidth (right axis)

Planar microwave circuit tolerance analysis

Results after post-processing the etching case

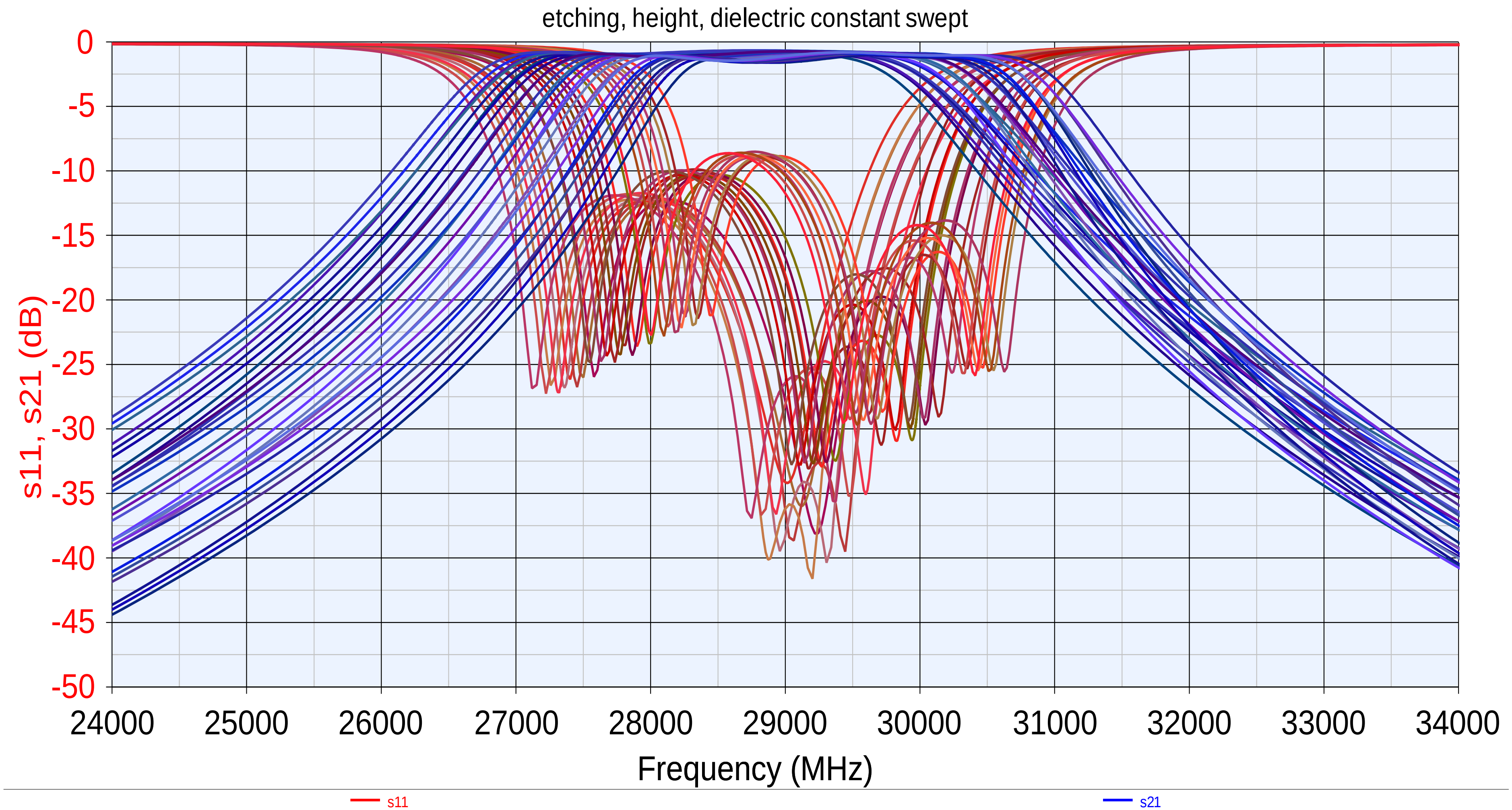
The case of etching tolerance results in the most interesting transformation of this filter.

From the under-etched case (etch factor -1) to the over-etched case (etch factor +1), the bandwidth drops about 15%. The shift in bandwidth is quite asymmetrical as the lower skirt frequency moves up almost three times as fast as the upper skirt frequency. Why?

- Under-etching means longer resonators (lower frequency) and tighter coupling (wider bandwidth).
- Over-etching will shorten the resonators shifting the frequency up, but the coupling will also be reduced reflecting in the narrower bandwidth.

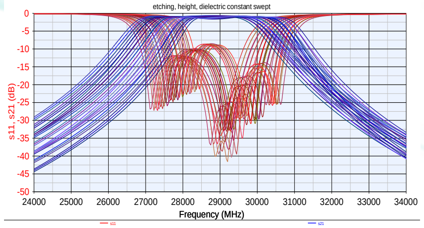
Planar microwave circuit tolerance analysis

Design centering: all variations together



Planar microwave circuit tolerance analysis

Design centering



Conclusions:

- When it comes to individual parameters, it is best to review the family of curves with variation applied more like an eye diagram plot where the responses should be centered around the desired bands of interest. The best compromise will impact upper and lower bounds of the regions equally.
- Any single measurement can be very misleading.
- Expect variation and don't adjust the design until you're sure you won't make things worse over all variation! (i.e. don't chase samples of the process, center in the whole process)

Planar microwave circuit tolerance analysis

Design centering and degrees of freedom

The analysis presented can be kicked off with one click of the mouse once it is setup.   Why is this significant?

This means that variations on the design can be explored for tolerance sensitivity without much effort.

Iterate:

- Change material, resonator impedance, spacing, etc.
- Optimize or manually “re-center” the design roughly
- Run tolerance analysis to see if more robust to process
- Repeat

This is fast and **very** thorough.

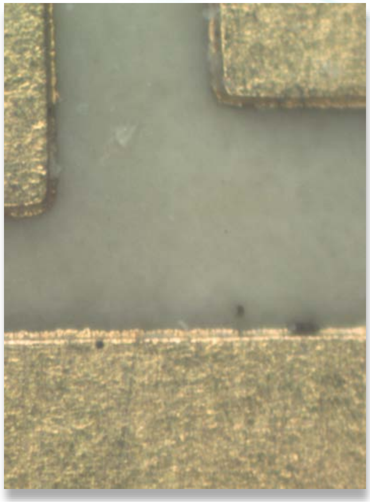
Planar microwave circuit tolerance analysis

Closing the loop: Verifying parameters through measurement

- There are well known test structures that can be built onto boards for parameter monitoring, but due to the size and equipment required it is often impractical to make this a production test procedure.
- Thickness and dielectric constant for premium substrates should be within the specified limits.
- Etching and finishing are parameters that can be measured, at least roughly on production samples without exotic equipment.

Planar microwave circuit tolerance analysis

Closing the loop: Verifying parameters through measurement



- The low cost method that I have used to examine production board copper patterns can be implemented for $500-$1000 depending on what equipment is on hand already.
- I use a 10MP digital camera (~$425USD / 2012) that bolts onto my low cost bench microscope (~$500USD). The ability to do absolute measurements come from the use of a reference/calibration slide with a known scale. Measurements are made in pixels and converted to absolute numbers.
- With this, I have achieved ~ 1850 pixels /mm, thus each pixel is around 0.5 um. Since most board tolerances are around 1 mil / 25 um, this provides plenty of pixels to record that level of variation.

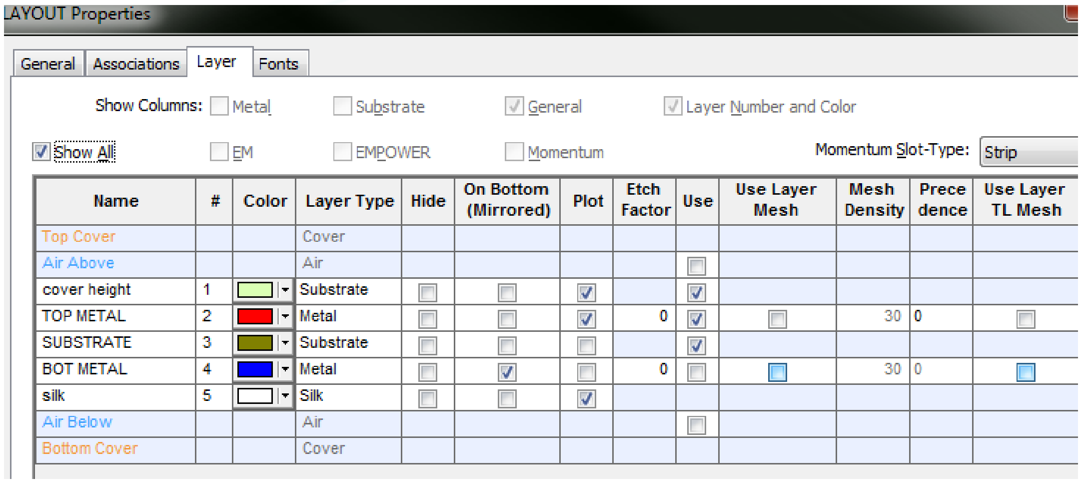
Planar microwave circuit tolerance analysis

Other parameters: Cover height

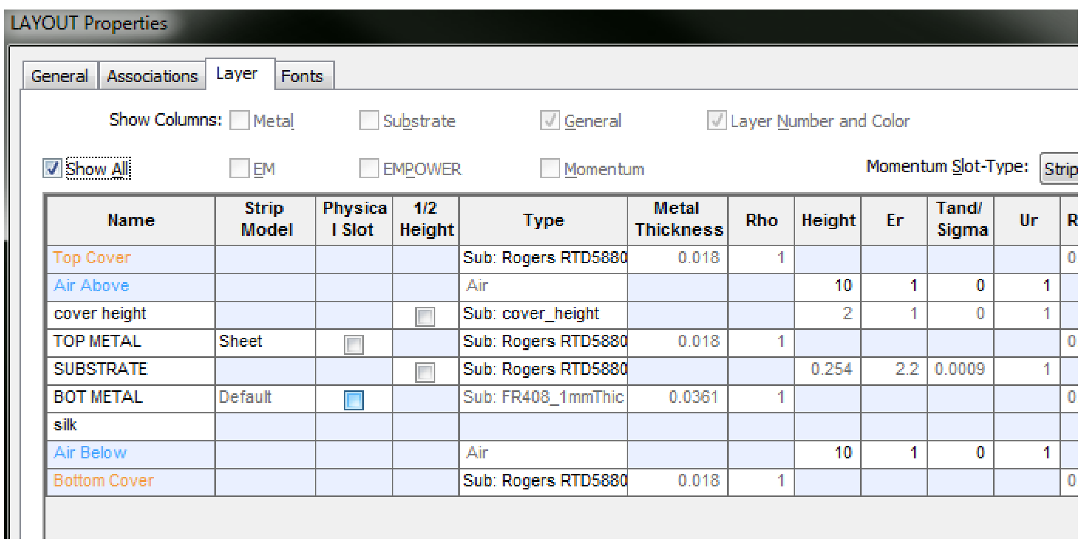
- The majority of Microstrip circuits reside in shielded boxes so it makes sense to look at the impact of the cover height on the circuit performance. In most cases this will not be a tolerance issue, but since the analysis is easy we have included it here.
- In all cases (whether analyzing variation or not), I strongly recommend including the shielded box in the simulation environment early in the design.
- **The trick that allows us to automate this through a parameter sweep is to represent the air above the circuit with a substrate rather than the fixed value of "air above"**. This way we can sweep the height parameter of the cover height substrate just like any other.

Planar microwave circuit tolerance analysis

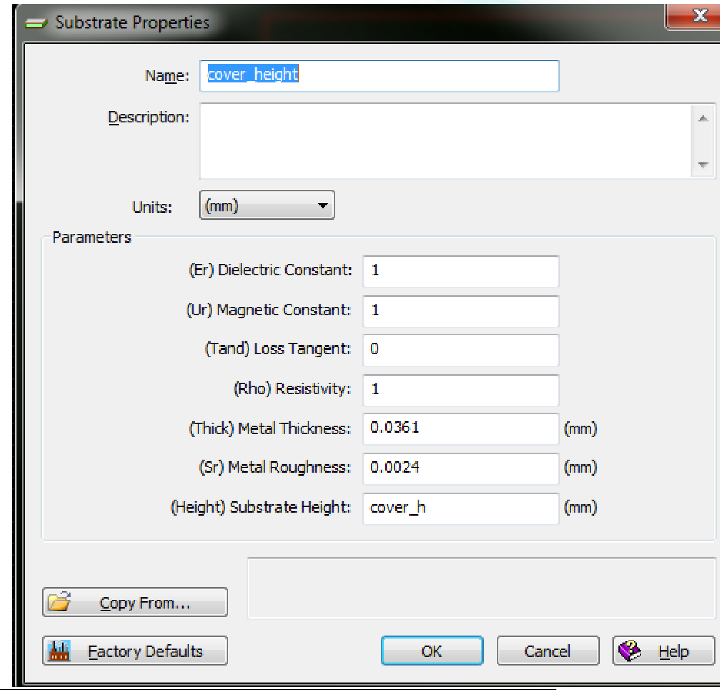
Other parameters: Cover height

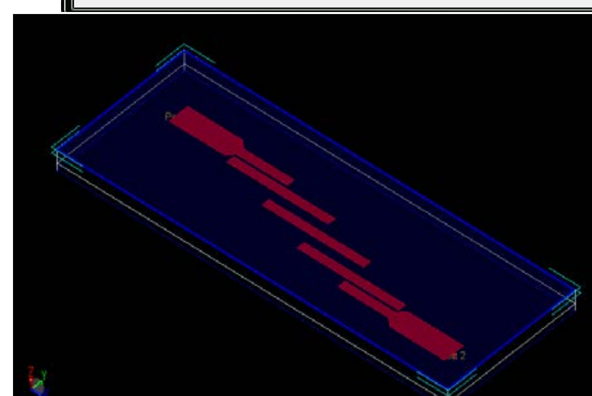


Name	#	Color	Layer Type	Hide	On Bottom (Mirrored)	Plot	Etch Factor	Use	Use Layer Mesh	Mesh Density	Precedence	Use Layer TL Mesh
Top Cover			Cover									
Air Above			Air					☐				
cover height	1		Substrate	☐	☐	☑		☑				
TOP METAL	2		Metal	☐	☐	☑	0	☑	☐	30	0	☐
SUBSTRATE	3		Substrate	☐	☐	☐		☑				
BOT METAL	4		Metal	☐	☑	☐	0	☐	☐	30	0	☐
silk	5		Silk	☐	☐	☑						
Air Below			Air					☐				
Bottom Cover			Cover									



Name	Strip Model	Physical Slot	1/2 Height	Type	Metal Thickness	Rho	Height	Er	Tand/Sigma	Ur	R
Top Cover				Sub: Rogers RTD5880	0.018	1					0
Air Above				Air			10	1	0	1	
cover height			☐	Sub: cover_height			2	1	0	1	
TOP METAL	Sheet	☐		Sub: Rogers RTD5880	0.018	1					0
SUBSTRATE			☐	Sub: Rogers RTD5880			0.254	2.2	0.0009	1	
BOT METAL	Default	☐		Sub: FR408_1mmThic	0.0361	1					0
silk											
Air Below				Air			10	1	0	1	
Bottom Cover				Sub: Rogers RTD5880	0.018	1					0

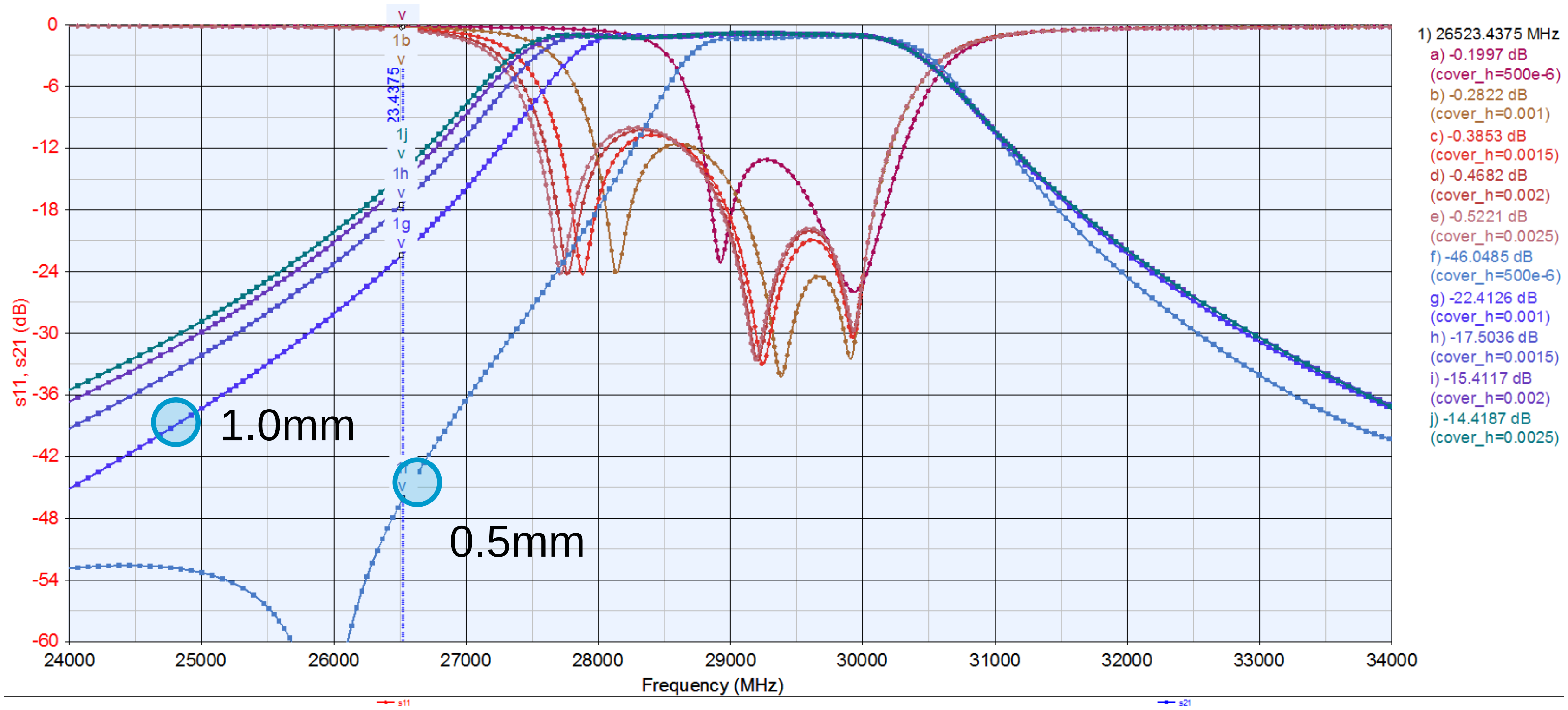




Planar microwave circuit tolerance analysis

Other parameters: Cover height

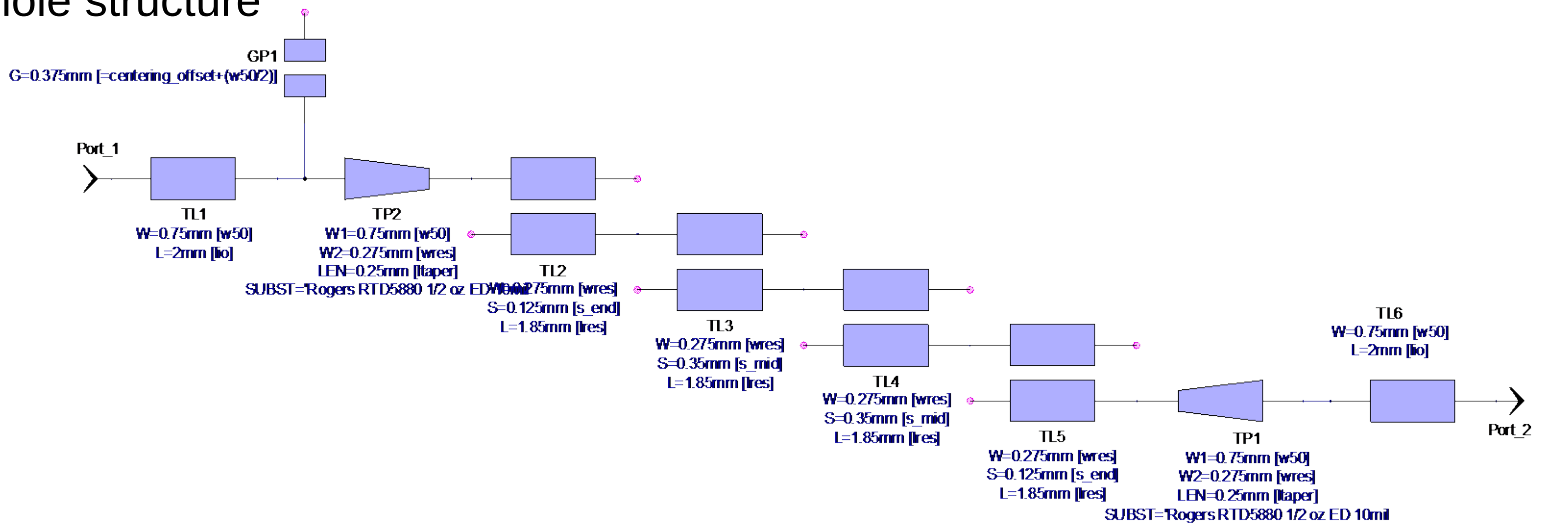
- Results from sweeping the cover height from 0.5mm to 2.5mm above the filter.
- Above1.5mm, impact is low
- Impact is more significant at lower cover height (0.5mm and 1.0mm).

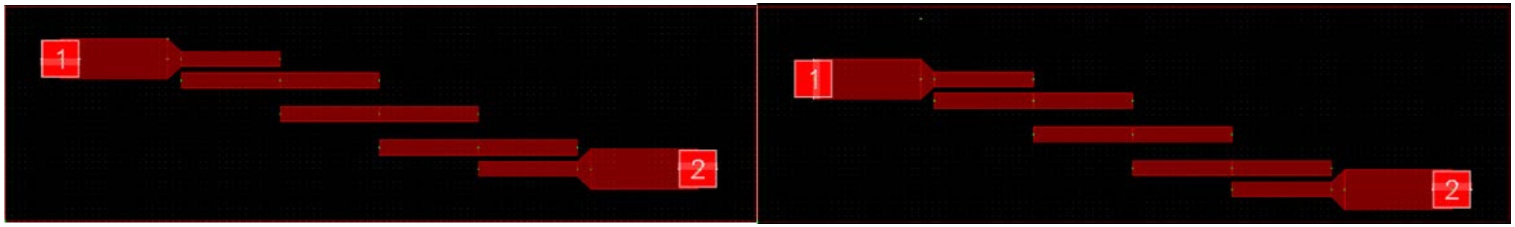


Planar microwave circuit tolerance analysis

Other parameters: centering in the enclosure

- To automate sweeps of the position we exploit the automatic centering feature of the Genesys Layout and Momentum.
- We put a gap element in the circuit (GP1 below) which is programmed to add a tiny piece of copper at a prescribed offset from one vertical extent of the circuit.
- The centering algorithm will use that piece as the new vertical maximum and center the whole structure



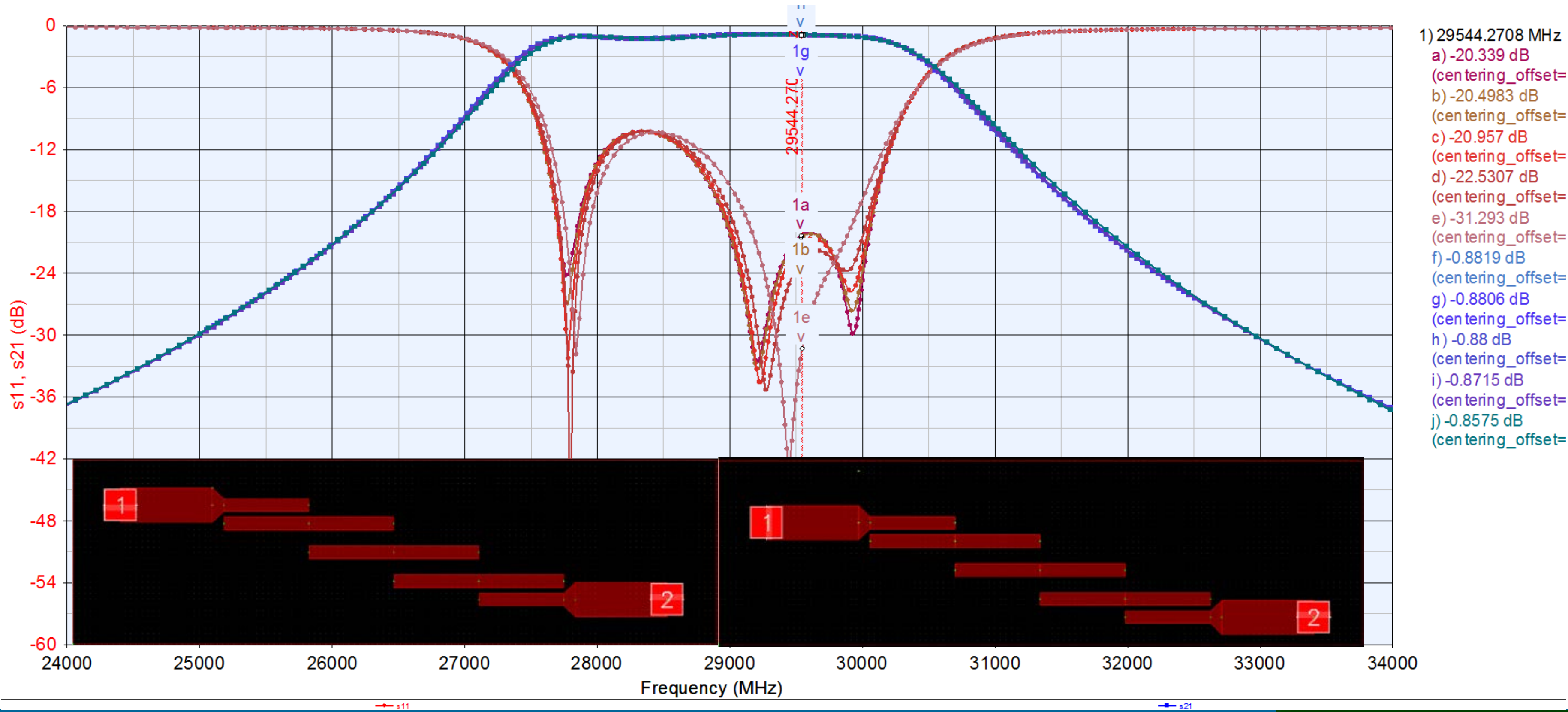


Centered (left), 0.75mm offset (Right)

Planar microwave circuit tolerance analysis

Other parameters: centering in the enclosure

- Results of the centering was not significant. This is not the general case
- The analysis was easy to sweep the offset between zero and 1 mm.



Planar microwave circuit tolerance analysis

Summary and conclusion

- Today we've presented a straightforward and powerful framework for analyzing the common sources of variation in Microstrip circuits.
- Properly used, this can greatly speed up the "make versus buy" evaluation for filters and provide an efficient comparison of materials and filter design variations.
- Perhaps the most important outcome of this analysis is the ability to provide a credible expectation of how these circuits will vary in mass production.
- Thank you for your time!
- The Genesys workspace and slides will be available on the www.agilent.com/find/eesof-innovations-in-eda and www.rfdude.com/webcast

Thank you for attending!

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