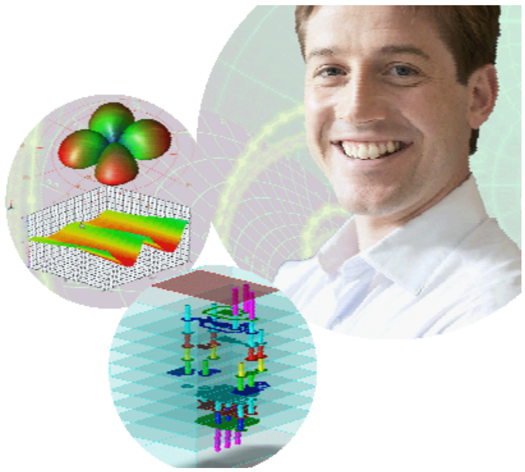
Filter Design For LTE

2nd of 6 “How-To-Design” GENESYS seminar series

Sep 2009 to July 2010



Using Agilent GENESYS software to speed RF and Microwave board designs for circuits and subsystems

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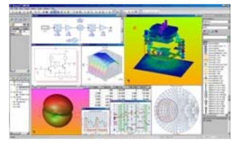
Welcome to this presentation which helps to highlight the capability of Genesys in the design and optimization of RF/Microwave filters for LTE receiver applications.

Agenda



- Discuss Filter Design for LTE systems
  - Uses
  - Types & selection
- Use PASSIVE filter synthesis with EM verification & refinement
- Evaluate effects of real part tolerance on manufacturing yield
- Diplexer design technique
- Use MFILTER filter synthesis and EM refinement for distributed filter layout
- Evaluate effects of layout manufacturing tolerances on yield
- Designing novel filter structures with DGS (defected ground structure) topologies

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We will use circuit and electromagnetic simulation and statistical tools available in the Genesys to design our filters with Passive and Mfilter syntheses.

Filter Function

Filters Elements Are Required In All Communications Equipment

- They Limit The Signals That Are Received And Transmitted
- They Help To Select The Information That Will Be Processed And Signals That Are Developed (IF & PLL)
- Direct Frequency Dependant Energy (Diplexer)

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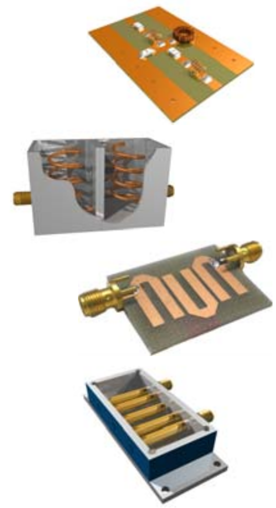
Filters are basic to all RF networks limiting the signal and or noise bandwidth.

Types Of Filters

Separated According To Frequency

- Passive
  - Discrete inductors, capacitors useable to ~1GHz
  - Crystal Lattice useable to ~250 MHz
  - SAW (surface acoustic wave) ~1GHz
- Hybrid
  - Helical useable to ~2-3GHz
- Distributed
  - Transmission Line useable 1GHz –100GHz
  - Dielectric Resonators 1GHz-100GHz
  - Waveguide 100MHz- near light
- Active
  - Operation Amplifier 50MHz
- Digital
  - FIR & IIR Upper Frequency Is Changing ~100MHz



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Filters have a common function however based upon the frequency that they are required to operate different physical realization are used base upon the ‘operating’ frequencies. Passive filters made up of inductors and capacitors make up the bulk of filters from very low 60 Hz to 1-2GHz. They are well understood and direct synthesis methods are available to design them. The hybrid filter offers superior Q characteristics in the VHF-UHF range useable to 3GHz. Above 1GHz distributed filters make up the bulk of applications to near light frequencies. Active filters are supported by amplifiers which are limited to lower frequencies however they provide very compact solutions at the low end of the spectrum. Finally, digital filtering techniques are widely used at baseband frequencies up to 20 MHz. They provide nearly perfect brick wall filtering in a very compact size and can be integrated into the basic signal processing chips that are used for decoding digital data.

Filter Selection

Considerations

- Frequency Band
- Performance: Insertion Loss, Rejection, etc.
- Power: us to Mega-Watts
- Size
- Cost To Manufacture

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Each of the physical types discussed in the previous slide offer tradeoffs between the considerations listed above. For example for high power transmitter applications; distributed, hybrid, or at low frequencies passive filters are producible for thousands of watts. At the same time the cost increases due to the size and materials that are needed.

GENESYS Synthesis Tools

1. Passive Filter
2. Microwave Filter
3. S-Filter
4. Active Filter
5. Equalize
6. Impedance Match
7. Oscillator Synthesis
8. Advanced Transmission line
9. PLL
10. Signal Control
11. Mixer Synthesis

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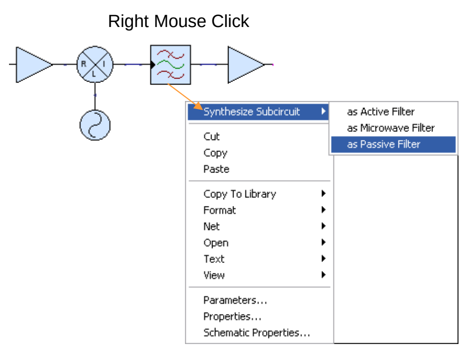
Of the eleven Genesys synthesis tools available we will be discussing the benefits and uses of the first 2 filter synthesis tools in the design of LTE components

Passive Filter Synthesis

Starting The Synthesis Tools

- Top Level Synthesis From Spectrasys
  - Filter Information Is Transferred To Passive Filter



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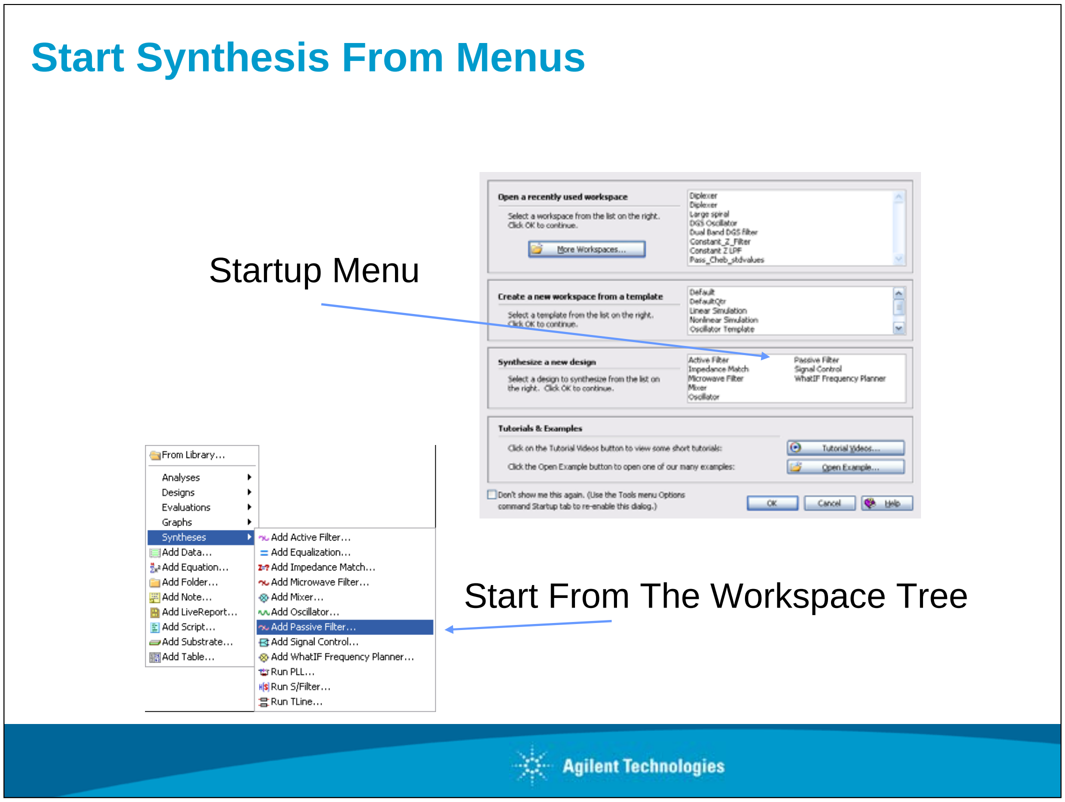
The Passive Filter Synthesis tool. There are several ways to start the synthesis tool set. If using Spectrasys system design then a mouse click on the block diagram launches the synthesis toolset from a menu pick.

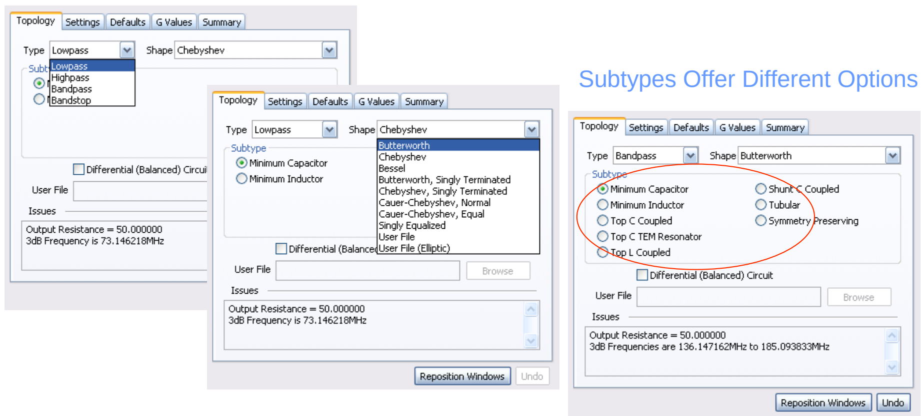


Alternately the synthesis tool set may be launched from a new workspace start up menu or from the workspace tree as shown above

Synthesis Dialog

Select Type And Shape

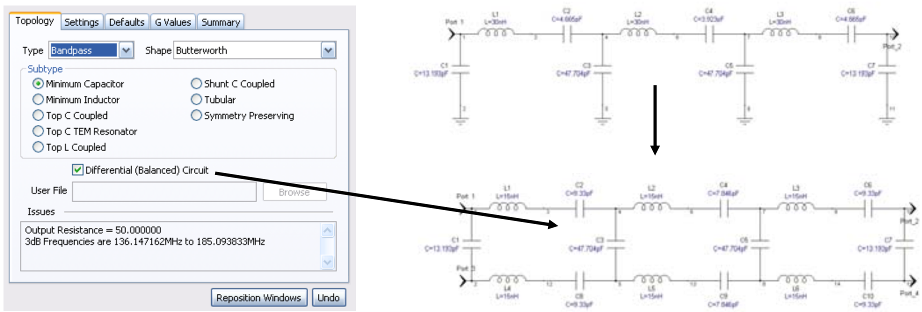
Subtypes Offer Different Options



From the Synthesis dialog we first select the type of filter i.e. lowpass, bandpass etc. The filter shape is next. This describes and sets roll off characteristics as well as phase linearity and whether or not the filter is singly terminated. Finally, the physical realization is selected. Some topologies are better suited for larger bandwidth than others or are optimized for using a single valued inductor or capacitor. Observation of the effect in changing these subtypes is immediate within Genesys providing rapid schematic regeneration and graphs.

Differential Filters

Simple Click Provides Balanced Network



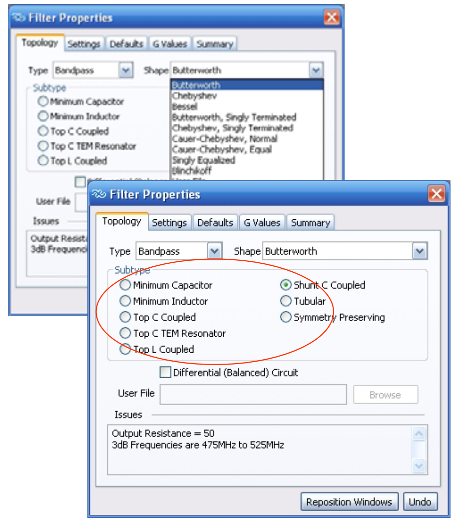
If the filter required is part of a balanced chain as in some MMIC mixers or receivers then a simple check on the differential box provides an immediate balance network equivalent.

Filter Synthesis Procedure

IF filter design example:

Passive Filter dialog

- Select the type
  - Band-pass, low-pass etc.
- Select shape
  - Butterworth etc.
- Select subtype
  - Filter implementation



Here is a step by step process to design a bandpass filter. We select a bandpass Butterworth filter using a common capacitor shunt-C design.

Filter Example

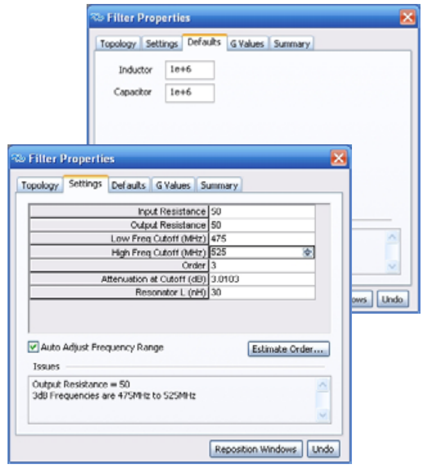
Settings Tab

- Set input/output impedances
- Set corner frequencies
- Number of sections or order
- Attenuation at cutoff
- Common filter inductor/capacitor*

Defaults Tab

- Finite Q elements specified

**Common inductors or capacitors for specific filter types*



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Under the settings tab we select the input and output impedance, note that some configurations allow the user to select different impedances for terminations which can aide in designs where the corresponding circuits have broadly different impedances. An example might include matching from 50 ohms to the higher input of a FET or MOSFET device. We also specify the frequencies for band edges and filter order, that is the number of sections. Under the defaults tab, Q's for inductors and capacitors can be specified to improve accurate response.

Replacing Ideal Values

Synthesized Band-pass:

- Substitute continuous values for standard ones

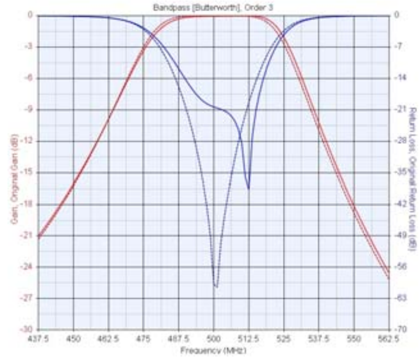
Synthesized values

Variable	Value
Standard	5%
C1.C	13.193
C2.C	4.665
C3.C	47.704
C4.C	3.923
C5.C	47.704
C6.C	4.665
C7.C	13.193

Standard 5% values

Tune Window

Variable	Value
Standard	5%
C1.C	13
C2.C	4.7
C3.C	47
C4.C	3.9
C5.C	47
C6.C	4.7
C7.C	13



The final synthesized element values are often fractional sizes which are not readily available, therefore we use ‘standard’ 5% values. If we were to choose 1% or 10% standard values then the incremental values for these components would change accordingly. Note that there is a slight shift in center frequency, and return loss. Optimization might improve the response however the resolution of component values is dependent upon the tolerance used. 1% components would offer finer step sizes however they are much more costly.

Parasitic Effects

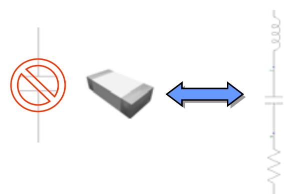
Substitute For The Ideal Components

Use Measured S-Data For Components Or…
Expand Model Definition In Parameter Dialog i.e. Q, Rx etc.

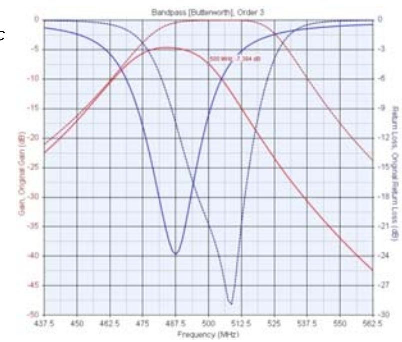
Effective inductance and capacitance values are shifted X_L-X_C

Parasitic resistance affects insertion loss

SRF effects response



WHY THIS SHIFT?



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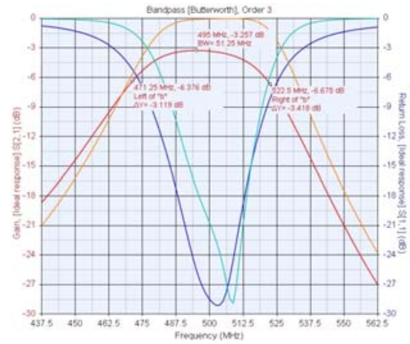
Substituting measured S-data or using the built in model parameters; Q , loss, and reactance is affected. The shift is caused by an increase in loss, decreased Q and decrease in reactance (i.e. Xl-Xc) results in a lower capacitance reactance which indicates a larger value of capacitance. Image illustrates that capacitor is not ideal. Note the shift in frequency, increased insertion loss, and narrowing of the filter's bandwidth.

Retuning Circuit

Substitute With Standard Valued Measured Components

- Evaluate s-data for effective capacitance or inductance
- If bandwidth or center frequency cannot be established filter redesign of center frequency and bandwidth may be necessary



We still need to evaluate the effect of our layout on the filter's performance

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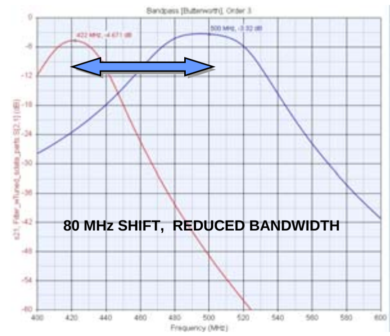
We now tune the filter using standard valued parts which have s-parameter data associated with them which accounts for loss, and reactance over frequency. If after tuning with the modeled parts, an unacceptable response if found then re-design or re-synthesis will need to be performed with modified bandwidth or center frequency such that the final goal, given real valued components, can be used.

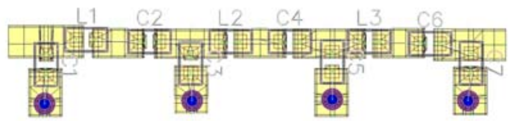
Pad Effects On Filter Performance

Adding A Layout

- The effect of the layout pads on our filter's response
  - Pads add capacitance at each node
  - Coupling between pads

This subtlety is lost without the aid of **Momentum GX** and co-simulation





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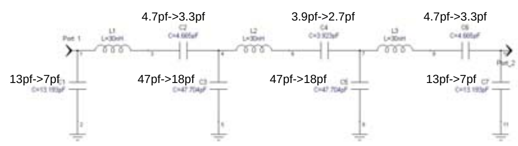
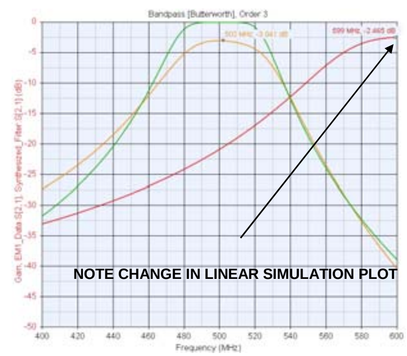
Once a layout of our filter is performed, pads added for connecting our components add problems of their own. Depending on the component values a few tenths of a picofarad may or may not influence the filter's response. At 500 MHz as shown above the parasitic capacitance and coupling from pads shift the filter's center frequency and bandwidth. The ability to view this effect is not possible without an accurate EM engine. Momentum provides insight into the actual filter response including cover height and coupling between pads as well as inherent parasitics.

Layout Parasitics

Effect of component parasitics and layout pads shifted the capacitance….



Note the shift from starting values



Knowledge of these effects is not available without Momentum GX

Co-simulation aides choosing the optimum values

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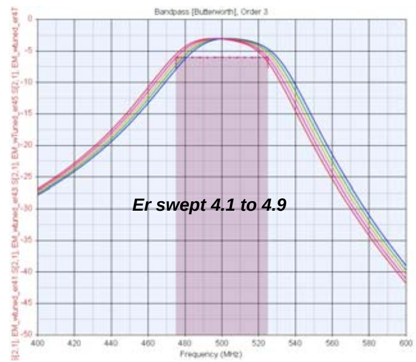
The ability to co-simulate our design with actual component s-parameter values and EM the structure provides us a truly accurate simulation that removes any doubt that our filter will behave as predicted. Note the change in values of our components from the original synthesized values to the final ones. (13pf to 7pf), (47pf to 18pf).

Design For Manufacturability

What else is needed to ensure manufacturability?

- Accounting for device and board variations
- Monte Carlo analysis of component tolerances
- Sweeping the expected ε_r variation for our substrate
- Specify the require tolerances for substrate material and component tolerances



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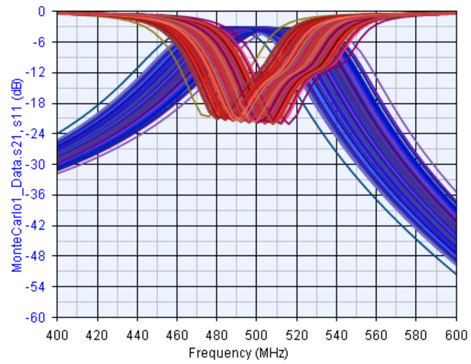
Before we commit our design to manufacturing we need to verify that a large percentage of the filters will pass test. To validate the design for manufacturing variables and tolerances we employ statistical analysis provided by the Genesys environment.

Monte Carlo Analysis

Monte Carlo Helps Us To Determine

- Yield
- Required Component Tolerance
- Final Cost



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A Monte Carlo simulation of component variations lead to determining yield, and required component tolerances. Depending on requirements the filter shown may not meet standards for manufacture.

Lessons Learned

PASSIVE FILTER Provides A Fast Seamless Method For Synthesizing Lumped Element Filters

Using standard value <u>ideal parts is not practical</u>

- Limited component Q's introduce losses in the passband
- Reactive parasitics with the components change their effective value
- Resonant frequencies due to parasitics limit the useful range of many lumped elements
- Layout pad size and placement dramatically alter the response of our filters

Statistical and swept analysis is required to ensure manufacturability

Momentum GX is an indispensable tool necessary to ensure first pass success

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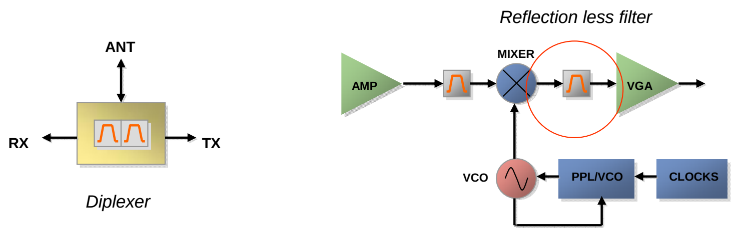
Diplexer Design In GENESYS

Diplexers Used To Provide A Common Path For Different Frequencies

- Common Antenna Path To Receive-Transmit
- Provide A Reflection-less Filter For Mixers

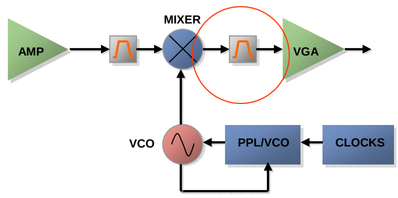


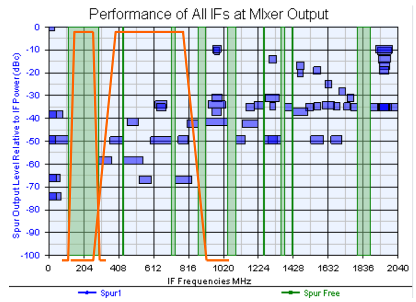
Diplexers are special filter implementations. They can be used to separate the transmit and receive bands in a transceiver or can be used as reflection less terminations following a mixer which improves spurious products.

WHAT IF

WHAT IF Determines IF Frequencies

- Use To Define The Diplex Filter





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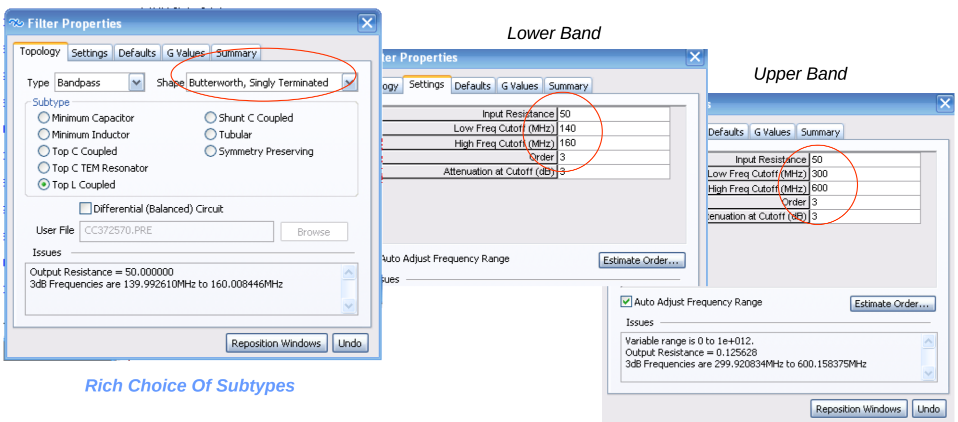
WhatIF is a Genesys synthesis tool that allows us to determine a spurious free range of frequencies that may be used for the IF frequencies. As shown above the first passband has a spurious free range of 100 dB while between 300 MHz and 800 MHz mixer products that are not absorbed will reflect back into the mixer for re-mix and perhaps inject an undesirable signal into our IF band. We can now glean the band of frequencies we wish to attenuate or absorb that will mitigate the re-mix.

Design Procedure

Select “Singly Terminated” Shape

- Two Filters Will Be Synthesized

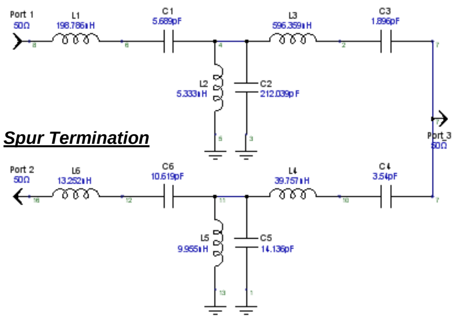


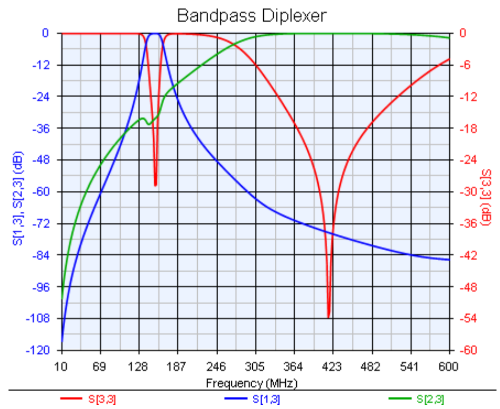
The procedure consists of choosing two bandpass filters which are ‘singly terminated’. This implies either and open or closed circuit load as opposed to a common 50 ohm load. Note that the IF band that we wish to pass is 140 MHz to 160 MHz. The upper bandpass is the group of frequencies we wish to absorb.

Absorption Of Mixer Products

Flexible Control Over Adjacent Band

- Contiguous or Non- Contiguous





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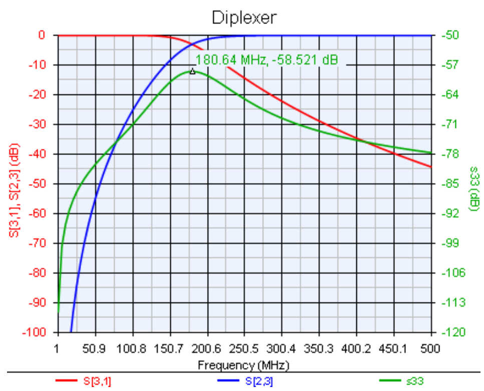
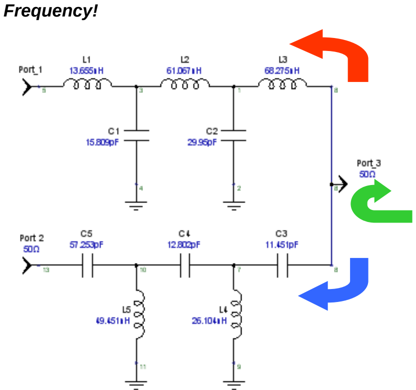
The passive filter synthesis tool provides great flexibility over the two bands. In this case they are not contiguous. Note that S[1,3] maps the IF bandpass while S[2,3] passes the secondary or upper spur filled band. Note that the filter's input S[3,3] provides and excellent match to both bands. The un-desired spurs are terminated at port 2.

Zero Reflection Filter

Using Singly Terminated Low-pass Hi-pass

Note Reflection Over Frequency!

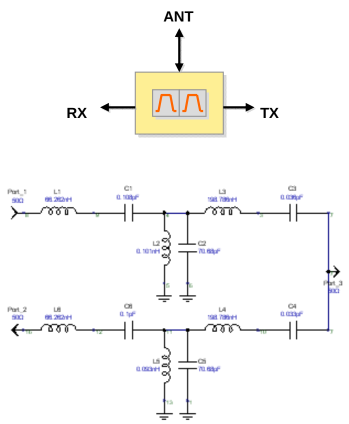


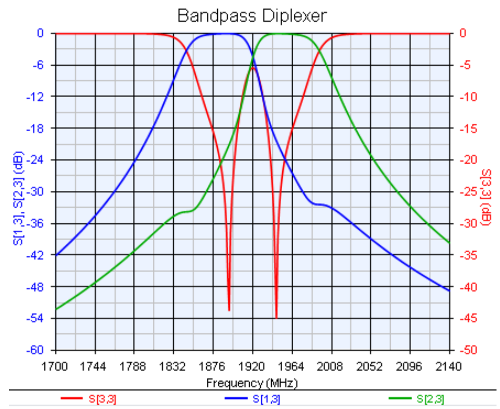


When using a simpler hi-pass/ low-pass design we separate whole bands of frequencies. This technique can be used for terminating a mixer for a zero reflection filter. Note S[3,3] common port has a return loss of -58dB worst case.

LTE Band Separation

Transmit And Receive Channels Divided





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Here is an example of a diplexer arrangement for the LTE band. Because in this example the bandpass' are contiguous (overlap), worst case match at the common port is -6dB.

Lessons Learned

GENESYS Passive Filter Tools

- Provide Extended Usage For Multiplexers And Diplexers
- The Design And Implementation Is Fast And Straight Forward
- Multiple Network Realizations Are Available

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Recap.

GENESYS Synthesis Tools

1. Passive Filter
2. Microwave Filter
3. S-Filter
4. Active Filter
5. Equalize
6. Impedance Match
7. Oscillator Synthesis
8. Advanced Transmission line
9. PLL
10. Signal Control
11. Mixer Synthesis

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We now view the microwave filter synthesis tool.

Microwave Filters

MFILTER: Microwave Filter Synthesis Tool

- Review the process from filter selection to layout

Verifying the design with MOMENTUM GX

Extending filter design capability with MOMENTUM GX

- Explore Non-Analytical or Non-Closed form Filter Design Methods
  - Defective Ground Structures (DGS)

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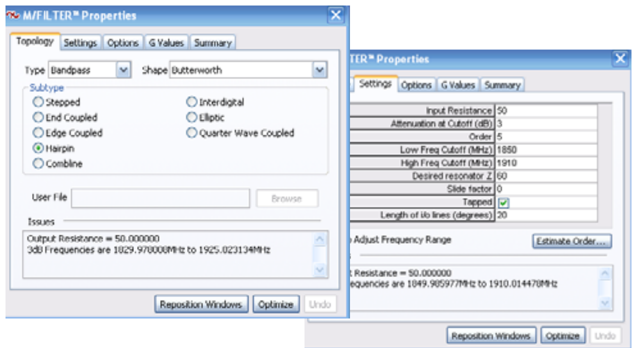
In this section we will view the process for designing a microwave filter using MFILTER. We will show the effect of losses and parasitics. Finally we verify the design using Momentum GX field simulation. In the last section we investigate new topologies in Microwave filter design which is only possible with Momentum since these new concepts do not have a closed form solution.

MFILTER

Microwave Filter Synthesis Tool

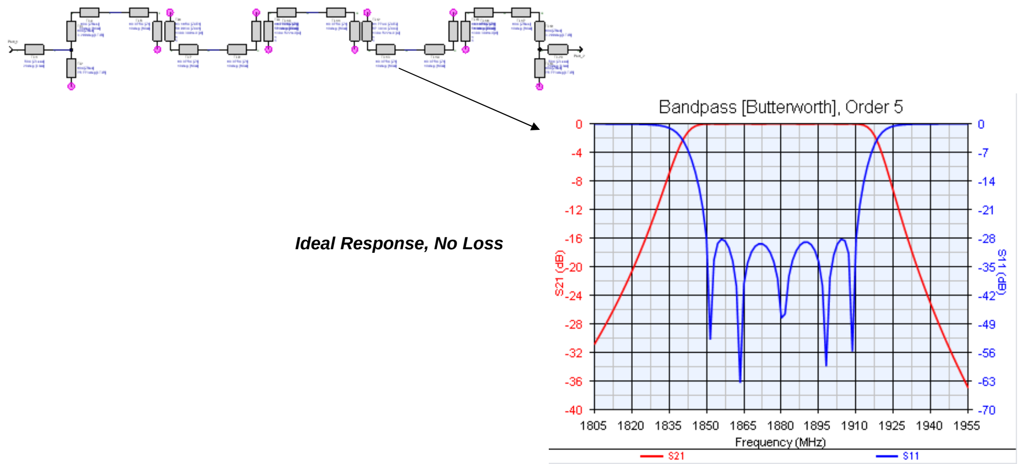
Initiate Via SPECTRASYS, Workspace Toolbar Or Start Menu



As with each of the synthesis tools launching is performed from the workspace tree or directly from a system level component in Spectrasys or from the start up menu. We have selected MFILTER which provides a familiar properties screen for choosing the type, shape and subtype of filter. The settings tab is where we select the filter's pertinent parameters including IO lines for the filter type.

Generate Filter Topology

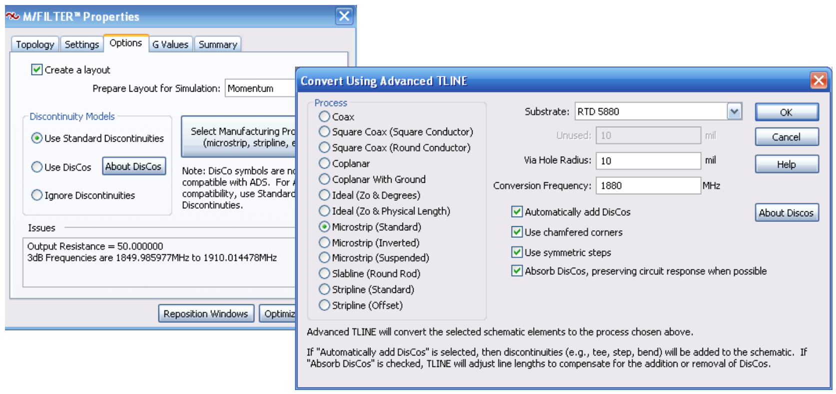
Instant Generation Of Network And Graph



Having selected a ‘hairpin’ filter a schematic and graph representing the filter’s response is plotted. Since this is an ideal implementation there is no loss or parasitic effects.

Select Physical Layout

Create A Layout, Convert To Microstrip



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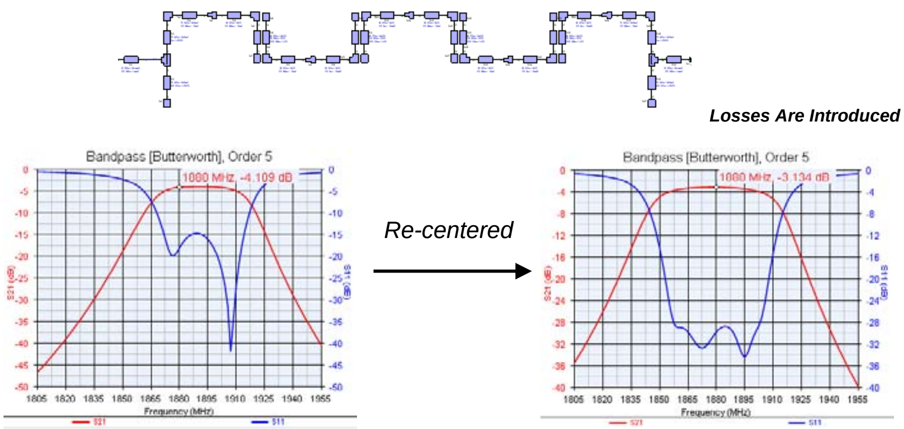
Following the design flow in MFILTER we next select a manufacturing process as well as create a layout. Note that we chose Duroid RTD5880 as a substrate material because of it' lower loss properties and set the conversion frequency to near band center for our filter.

Optimized Microstrip Filter

Using Built In Optimization Function



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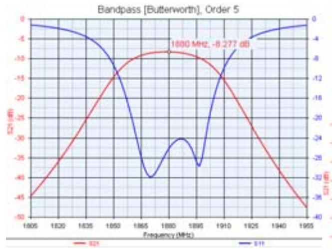
The resulting graph now models microstrip loss as well as coupling and parasitic effects. Using the pre-loaded optimization filter variables we optimize the filter’s dimensions to re-center the filter for our desired response.

Substrate Influences

Substrate Selection Affects Size, Loss And Response

Taconics



1160x600mils

E_r=10

Duroid

2225x1200mils

E_r=2.2

Why The Increase In Loss?

Duroid
Stripline

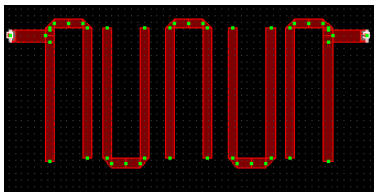
880x490mils

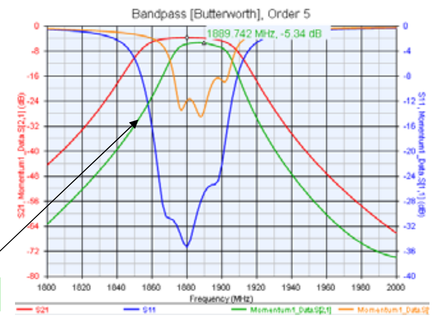
Relative permittivity affects more than the size of a filter. Smaller trace widths for the same impedance line results in higher loss. For the Duroid example, the stripline width is less than half of the microstrip. The loss is almost double per unit length. Trade offs between size, loss, and cost are all part of determining the best solution.

MOMENTUM Verification

EM Evaluation Shows Shift, Narrowing And Increased Loss

What are the causes?



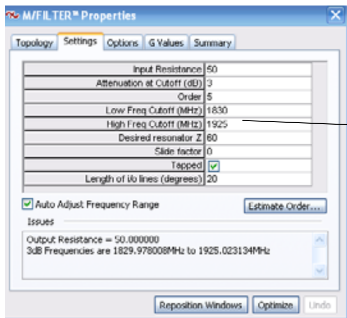


MOMENTUM Evaluation

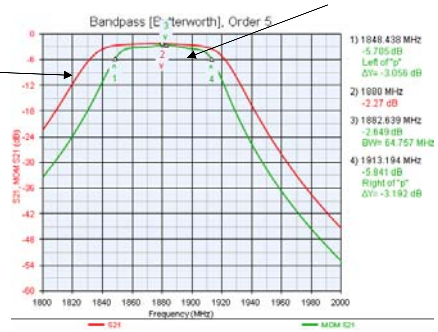
Slight Under coupling, line end effects, cover influences. Analytical models are inferior. Note that some will ask why the shift is up in frequency and not down. It depends on the filter and phasing of the coupled lines as well as type. Interdigital filters will shift lower etc.

Modify Filter

Shift Center Frequency And Bandwidth



Layout New Filter And Simulate With MOMENTUM



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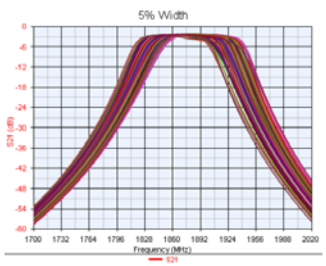
In practice this procedure may take several iterations, however Momentum GX helps us to optimize the correct response. Final filter response is in green. Accurate filter results are therefore a combined effort between the synthesis tools and Momentum.

Check For Manufacturability

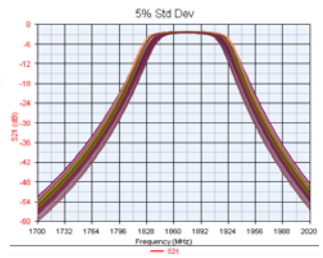
Run Monte Carlo Simulations On Variables

Which Filter Parameter Is Most Critical?



Variations of Width

Variations of Er



Variations of Spacing

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Statistical analysis helps us to improve yield by identifying the greater influences. In this example being mindful of over or under etching of the line width is justified. Selecting a board vendor in not ‘in-house’ becomes a critical choice.

Lessons Learned

GENESYS MFILTER

- Provides The Base For A Multitude Of Microwave Filter Implementations
- Seamless Layout And Physical Implementation
- Manufacture Verification With Monte Carlo And Yield Analysis
- MOMENTUM Provides Physical Verification And Aides In Optimization

Agilent Technologies

MFILTER and Momentum provide an indispensable toolset for design and development of a large class of microwave filters.

Allow Your Imagination To Go Free

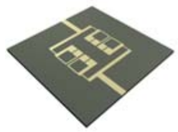
GENESYS And MOMENTUM GX Provide The Tools For You To Try New Forms Of Filters, Components, And Antenna Concepts Without The Need For Closed Form Analytical Expressions

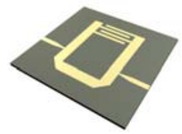
Agilent Technologies

Synthesis tools are rooted in closed form analytical solutions of known topologies. In years past new structures required an equivalent of a PHD dissertation to provide a usable model or method for filter types. The advancements in EM technologies has made it possible to explore new ideas regarding filter technology without the necessity of being an expert in EM theory. Let your imagination go free.

New Filter Components

Recent Technical Journals Have Brought Us Many New Classes Of Microwave Components (ref)





Today's Discussion Will Focus On *Defective Ground Structures* (DGS) As They Relate To Microwave Applications

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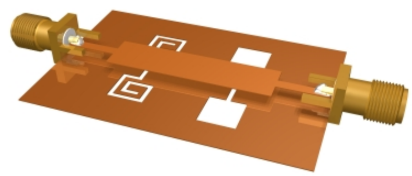
With the advent of new EM solvers such as Momentum accurate determination of unique metal patterns have added compact designs with special frequency characteristics and responses. One such method is the removal of sections of the common ground structure around surface conductors. The results are many and varied. We attempt to show some of these filters which have been written about recently.

What Is A DGS?

A Strategic Break In The Ground Plane To Enhance A Desired Response

- Basically A Break Or Pattern In The Ground Plane



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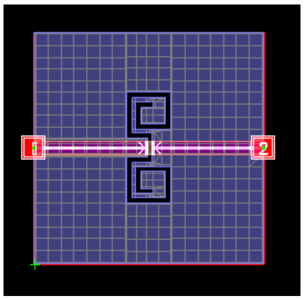
Note on the transparent board that the ground plane has an opening or “defect”. This disrupts the ground currents in such a way that enhances our ability to generate new filter forms.

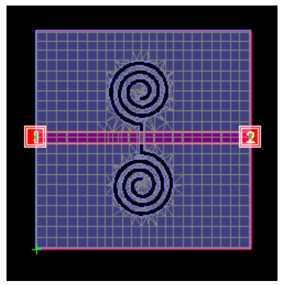
Ground Plane Openings

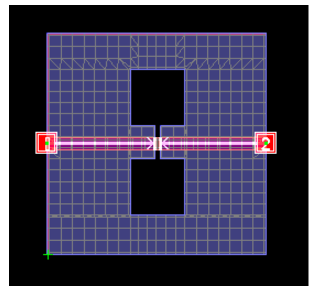
Common DGS Filter Patterns



Square Spiral

Round Spiral



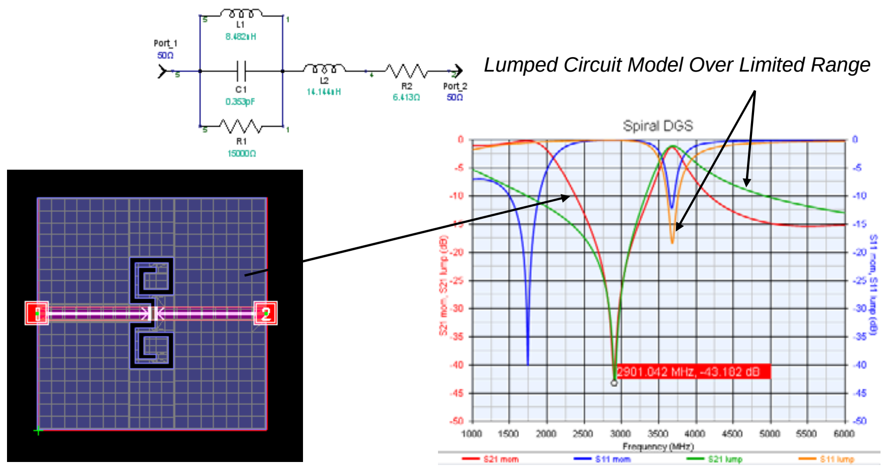


Dumbbell

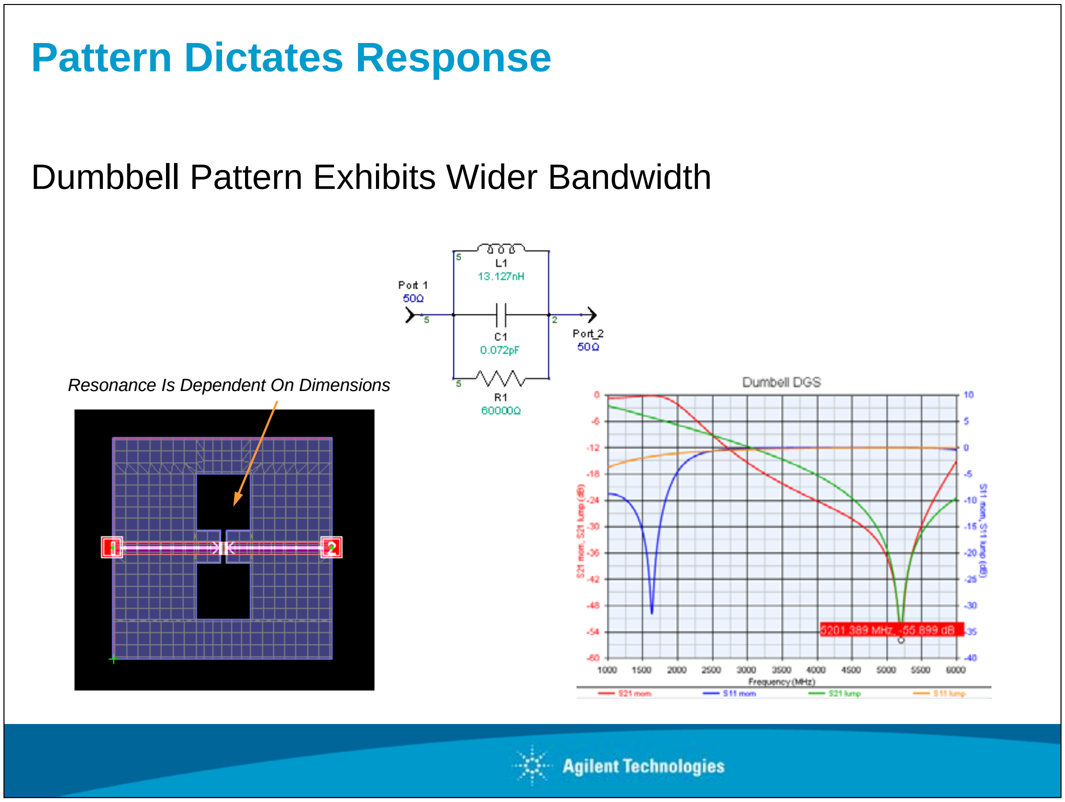
There are many DGS patterns, each lends it’s own features regarding resonant frequency and return loss shape vs. frequency.

Circuit Equivalences

Square Spiral Produces A Resonant Notch



Shown above is the result of placing a spiral DGS under a straight transmission line. Note that the frequency response mimics that of a series parallel resonant lumped element circuit over a range of frequencies. The red and blue traces track the Momentum generated data while the green and orange represent the lumped equivalent network.

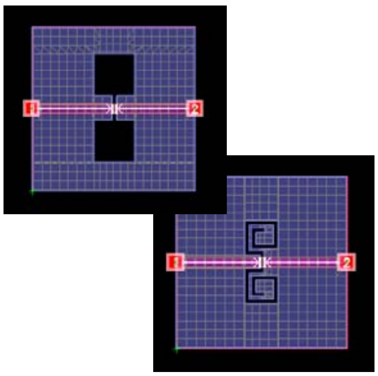


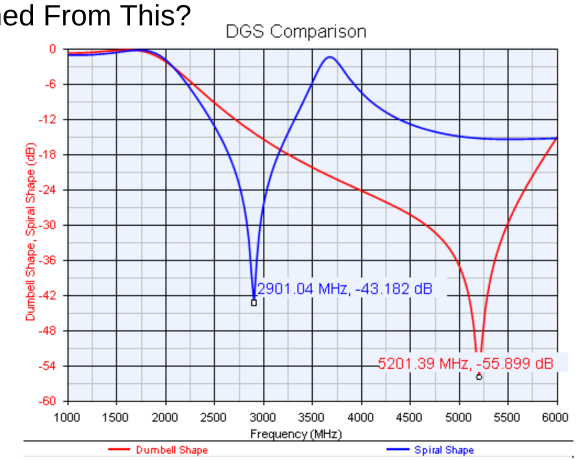
A square pair of notches below the through line have a similar equivalent lumped circuit response of a parallel resonant structure.

Combined Response

Note How The Overlapped Responses Have Similar Band edges With Two Separate Poles

- Can Some Advantage Be Gained From This?





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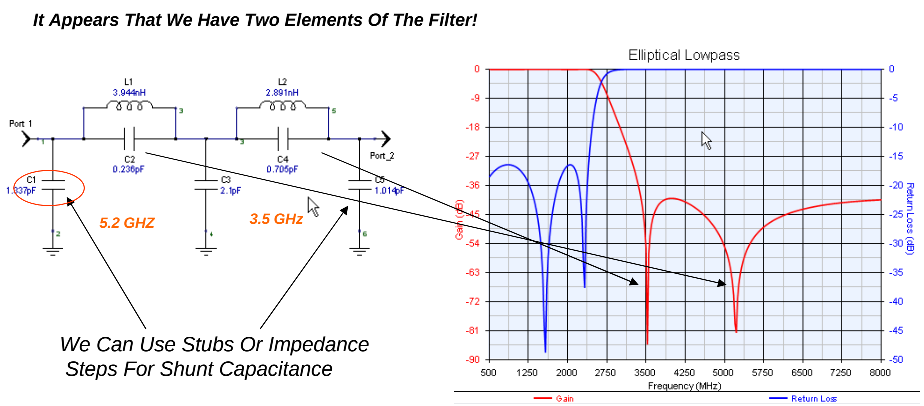
If we view the response for the two DGS networks overlaid on each other we see two resonances or poles of attenuation. If we combined these structure then perhaps an enhanced filter response may be had.

Elliptical Prototype

Passive Synthesized Lumped Filter



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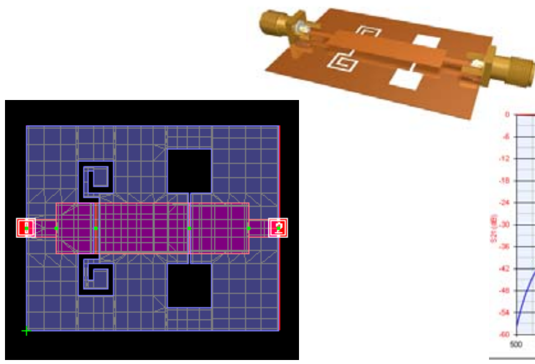
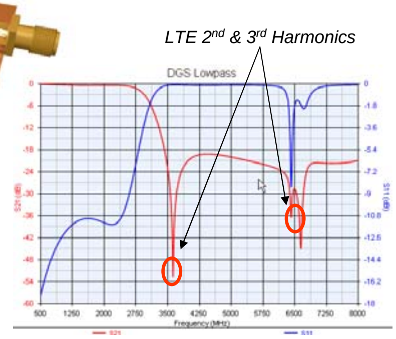
If we were to view a lumped element elliptical filter response we would note that the series traps correspond to the transmission zeros of the filter's response. If we choose our DGS carefully we can mimic the series network in distributed form and use distributed equivalence for the parallel capacitors.

DGS Benefits

- Smaller Size For Comparable Distributed Filter
- Ease Of Manufacture
- For Low pass, Rejection Band Is Wider, Faster Roll Off
- Poles Can Be Set Independently For Harmonic Suppression



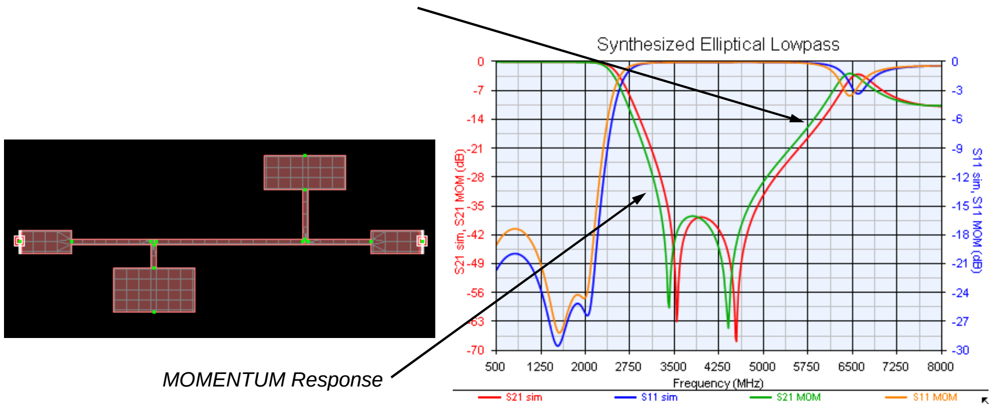


By combining the two structures shown in previous slides and using a stepped impedance through line, an equivalent multi-pole elliptical filter is produced. Note that the resonant poles can be selected to provide a wider stop band than is usual for distributed filters and that that they correspond to the 2nd and 3rd harmonic of the LTE transmit band.

Synthesized Comparison

Elliptical Low Pass Compared

- Larger Size In Layout
- Recurring Response At 6.5 GHz

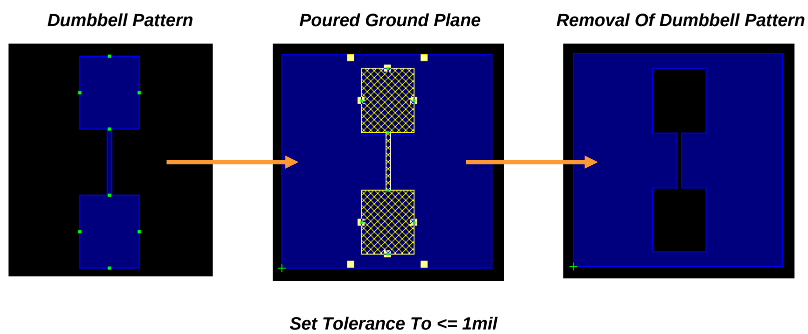


For comparison we synthesized a distributed elliptical filter from MFILTER and plotted both the modeled and Momentum simulation results. Note the recurring pass band at 6.5 GHz. The size is also larger than our DGS example.

Creating A DGS

Start With A Pattern In GENESYS Layout

- Creating an open ground area is easy and straight forward



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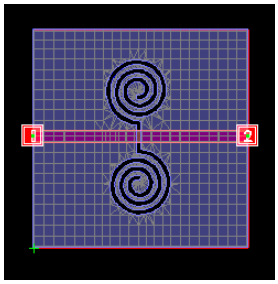
Procedure is extremely easy using the ‘Pour’ function in layout. The tolerance governs how close to the dumbbell that the pour will come (the keep away). Once poured, delete the dumbbell pattern

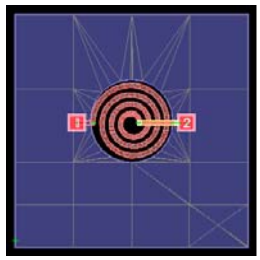
MOMENTUM Meshing

Complicated Patterns Are Easily Meshed In Momentum GX

- Ground removal improves component performance

Not limited to square grid!





Inductance Increases

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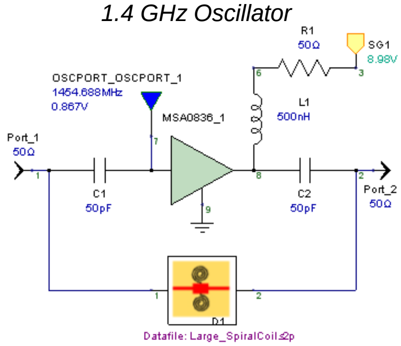
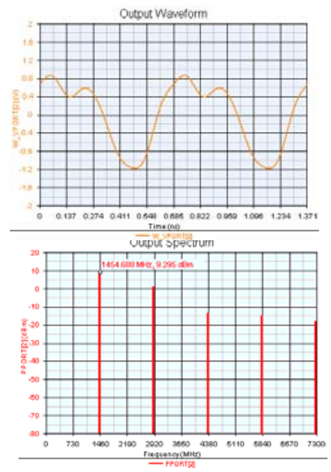
Another example where a ground removal may improve component performance is with printed inductor patterns. Removing the ground selectively increases inductance and shifts the resonant characteristics.

Additional Applications

What Other Applications Can Use A DGS?

1.4 GHz Oscillator





Since DGS exhibit a high Q or narrow resonance they can be incorporated into other circuitry that benefits from resonant structures such as oscillators. Show above is the result of placing a spiral DGS under a stepped impedance line which behaves as a parallel resonant circuit. At all but the trap frequency negative feedback reduces the amplifier's gain. Resonant frequency of the trap provides positive gain at only that frequency. The resulting harmonic balance analysis is shown in the graphs. The layout diagram has been made into a jpeg file which is used as a symbol for our schematic.

Lessons Learned

The Combination Of GENESYS And MOMENTUM GX Expands The Capability And Range To Investigating New Component Technologies

MOMENTUM GX Is A Flexible and Accurate Electromagnetic Problem Solver

Conclusions

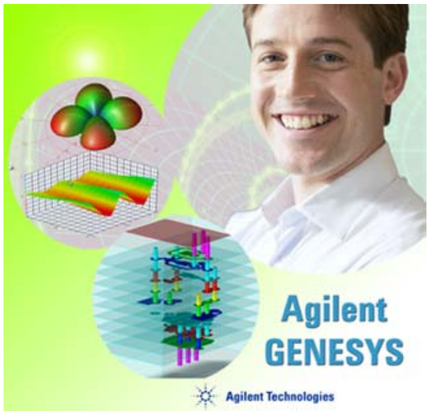
We have shown that Genesys provides affordable RF tools and the means to accomplish more in less time

No longer is special knowledge required to design and produce sophisticated filters and signal routing networks for new RF and Microwave technologies

Networks which include layout effects and non-ideal components aide in producing first pass success rates which are necessary in “fast-turn” product development

Thank You

Additional Information-
Just Google search “Agilent Genesys”



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