Design Chebychev bandpass filters efficiently

Get optimum results in days by teaming a 3D full-wave field solver with a circuit simulator.

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Designing filters is not an easy talk, despite the fact that the technology involved is mature and understood. Modern software tools are available that provide the circuits in terms of lumped electrical components, but designing the actual 3D microwave structure can take weeks. This article shows how a circuit simulator and a 3D field solver can work together to reduce the design time from weeks to days.

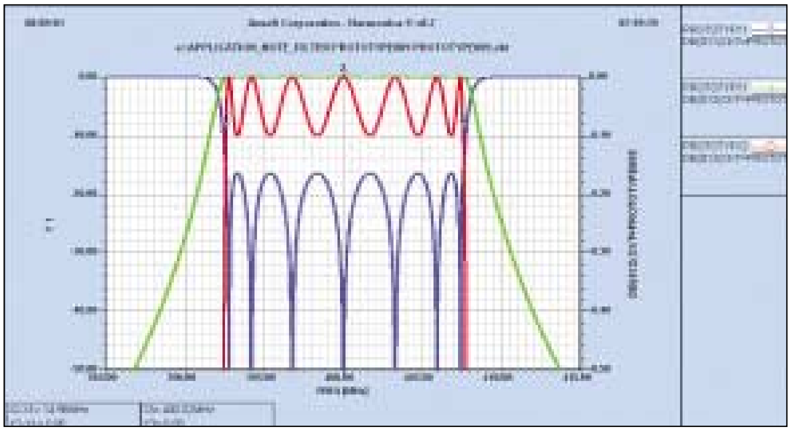

Figure 1. Desired filter characteristics.

While others have explored the basic idea[1], they used different circuits. This method, through an example, will design a Chebychev band pass filter with the following specifications:

Center frequency : 400 MHz
Ripple bandwidth: 15 MHz
Ripple: 0.1 dB
Out-of-band rejection: 24 dB at 390 MHz and 410 MHz

To achieve out-of-band rejection, seven poles will be required. The desired filter characteristic is shown in Figure 1.

As the basic geometry for this filter, a cavity was chosen with seven coaxial resonators (see Figure 2). In the figure, the “buckets” have been drawn as wire frames for clarity to show that the cylinders, which form the inner conductors of the individual coaxial resonators, don’t extend all the way to the bottom.

This geometry is symmetrical with respect to the central cylinder. In this kind of filter, the walls of the cavity, the long cylinders, the buckets under the cylinders and the disk-shaped objects near the first and last cylinder are all made of metal. Cylinders and buckets don’t touch. This way, each cylinder-bucket combination is a resonating structure. The disk-shaped objects near the first and last resonator are connected to the input and output transmission lines and provide the necessary coupling to the source and the load. For the purpose of clarity, the objects will be referred to as antennas in this document. They are near the first and last cylinders, but never touch them.

At this stage, without design restrictions, the option to choose many dimensions of the filter is available. For this case, the following choices were made:

Cavity dimensions: 280 x 30 x 120 mm
Resonator diameter: 10 mm
Buckets’ inner diameter: 12 mm
Buckets’ outer diameter: 16 mm
Buckets’ height: 15 mm
Antennas’ diameter: 26 mm
Antennas’ thickness: 4 mm

Once the above has been determined, six dimensions remain. They will be crucial in obtaining the desired filter characteristic. They are:

- *The length of the first and last resonating cylinder (both have equal length)*
- *The length of the five interior cylinders (all five have equal length)*
- *The distance between an antenna and its nearest cylinder*
- *Three distances between neighboring cylinders (remember the filter is symmetric)*

Steps in the design process

With traditional filter design methods, obtaining the correct dimensions is a time-consuming task that commonly takes several weeks. Filter design with a circuit simulator, on the other hand, is relatively straightforward. Filter theory provides the values for the lumped inductors and capacitors that are needed to obtain the desired filter characteristic.

First, it will be shown how to design a circuit that not only has the desired filter characteristic, but also lends itself to implementation with microwave components. In such a circuit, we use series *L* and *C* for each resonator, i.e. the cylinder-and-bucket combinations, and impedance inverters to represent the distances between adjacent resonators.

Second, relationships between components in the

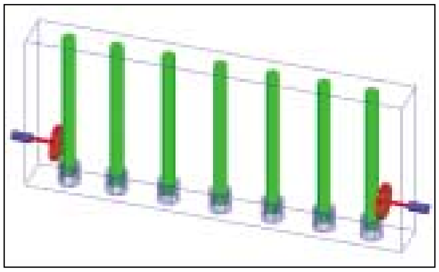

Figure 2. Basic filter geometry.

circuit and dimensions in the physical filter will be determined.

Third, an iterative procedure between the electromagnetic field solver and the circuit simulator to optimize the design will be presented. The procedure converges quickly.

Circuit representation of the filter

To design an order-seven band-pass filter around 400 MHz with a 0.1 dB ripple, filter theory[2] tells us to start with an order-seven low-pass filter, normalized to 1 radian/s. The normalized filter is to have a 0.1 dB ripple like the desired band-pass filter. The source and load impedances of the normalized low-pass filter are normalized to 1Ω (see Figure 3).

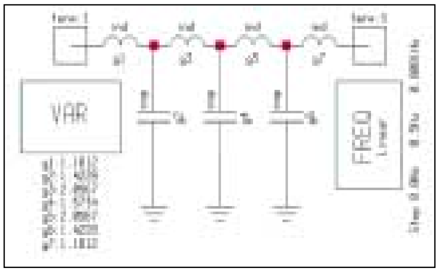

Figure 3. Normalized low-pass filter circuit, starting point for design procedure.

Filter theory provides us with the values for the inductors and the capacitors, denoted by g_1 through g_7 in the figure. These values in this case are:

$g_1 = g_7 = 1.1812$ H
$g_3 = g_5 = 2.0967$ H
$g_2 = g_6 = 1.4228$ F
$g_4 = 1.5734$ F.

An important step is the replacement of shunt capacitors by series inductors and impedance inverters.

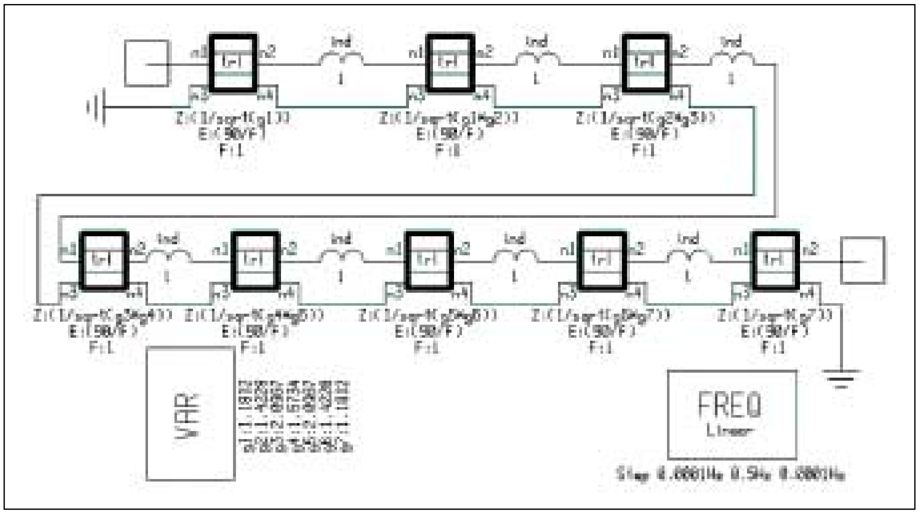

Figure 4. Normalized low-pass filter without shunt capacitors.

Basically, an impedance inverter transforms impedances in the same way as a λ/4 transmission line, but independent of frequency. The resulting circuit is shown in Figure. 4. This is still a normalized low-pass filter with the same characteristic as the circuit in Figure 3. Taking advantage of impedance inverters, it is possible to transform shunt capacitors into series inductors. In the physical filter these impedance inverters will be realized by couplings between the coaxial resonators.

Following a standard procedure[2], the following steps are taken to derive the desired band-pass filter model:

- *De-normalize the low-pass cut-off angular frequency from 1 rad/s to bw rad/s.*
- *Transform the low-pass filter to a band-pass filter with a relative bandwidth of bw and a center angular frequency of 1 rad/s by inserting a 1 F capacitor in series with every 1 H inductor.*
- *De-normalize the center frequency to* 400 *MHz by choosing L* = 1/(2π4^8) H and C = 1/(2π4x10^8) F.
- *De-normalize the port impedances from* 1Ω *to the usual* 50Ω *by introducing impedance inverters at the input and output with coupling coefficients of* √50.
- *Introduce finite quality factors to the individual resonators by adding a series resistor to each resonator.*
- *Introduce individual resonant frequencies to the first and last resonators to be able to take the frequency shift due to the coupling antennas into account.*
- *Add a homogeneous transmission line of length* ZUL *between filter input/output and port* 1*/port* 2 *to be able to adjust the phase due to the connectors.*

The result is the filter shown in Figure 5.

In this circuit, every *LC* pair res-

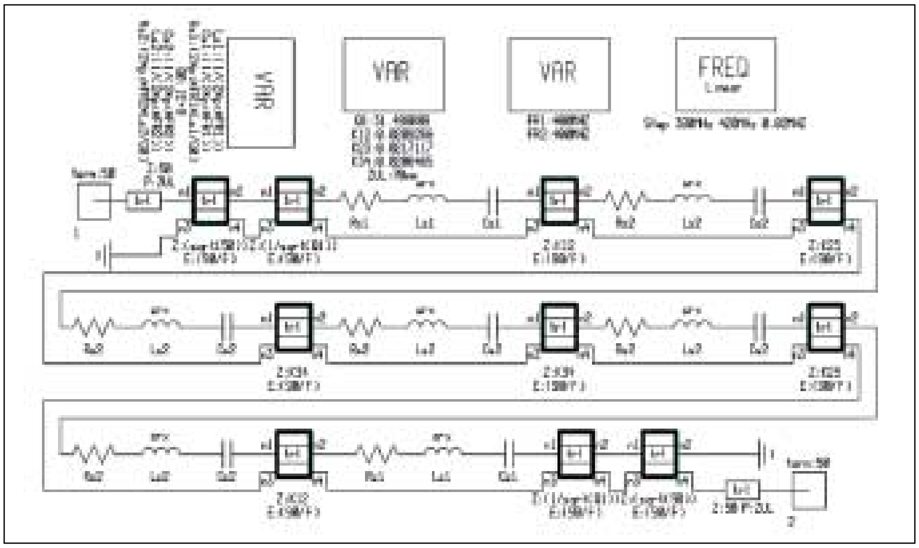

Figure 5. Final filter circuit, representing the desired band-pass filter.

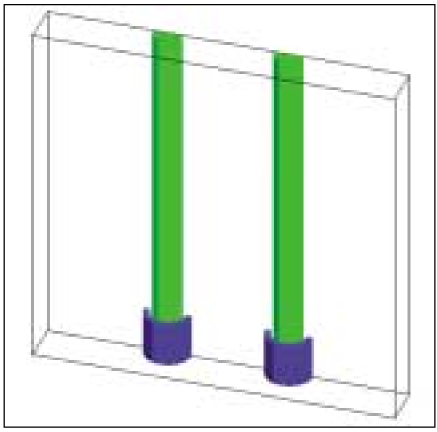

Figure 6. Model used to determine the coupling coefficient K.

onates at 400 MHz. Further K_{12}, K_{23}, K_{34} and Q_L have been defined as:

$$K_{ij} = \frac{bw}{\sqrt{g_i g_j}} \qquad (1)$$

and:

$$Q = \frac{g_1}{bw} \qquad (2)$$

where *bw* is the relative bandwidth and g_i is the ith *g* value from filter theory.

Notice that, because the *g* values are known from filter theory, the values of all the components in the circuit are still known, even though the components have changed considerably in the process.

Filter theory[3] tells us that $K_{i,\,i+1}$ and Q_L have important physical meanings. $K_{i,\,i+1}$ is known as the coupling constant between adjacent resonators. If there are only two resonators in the cavity with a very light, ideally zero, coupling to the source and the load, then the relation between coupling constant K_{12} and resonant frequencies f_1 and f_2 is given by:

$$K_{12} = \frac{2(f_2 - f_1)}{f_2 + f_1} \qquad (3)$$

Q_L is known as the loaded *Q* of the circuit. If there is just one resonator in the cavity, coupled to source and load, the relation between Q_L, resonant frequency f_R and 3 dB band width BW_{3dB} is given by:

$$Q_L = \frac{f_R}{BW_{3dB}} \qquad (4)$$

In the next section, the components of this circuit will be linked to the dimensions in the physical geometry of the filter.

Making the links

The software model that was used to determine the coupling coefficient *K* as a function of resonator spacing is shown in Figure. 6. Two resonators have been placed in a closed metal cavity. As can be seen in the figure, symmetry has been exploited. Further, because we want to determine resonances in the ideal case of zero coupling to source and load, there are no transmission lines nor ports for signal input and output. The resonances of this structure are to be determined through an eigenmode simulation.

By embedding the project in an optimizer, its dimensions can be easily varied.

First, the length of the cylinders was adjusted such that the resonances are centered at 400 MHz. Then, the distance between the resonators was varied and, for each distance, the eigenmode solver computed the two eigen frequencies and obtained *K*. The relation between the resonator spacing and *K* is shown graphically in Figure 7.

With this graph, for any coupling coefficient required by filter theory, the spacing to be applied between resonators in the physical model can be readily determined.

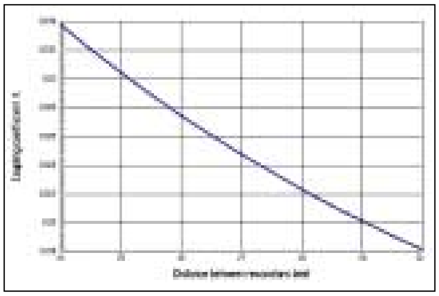

Figure 7. Relation between resonator spacing and coupling coefficient K.

Antenna distance and loaded Q

The model that was used to determine the loaded *Q* as a function of antenna spacing is shown in Figure 8. An antenna-resonator combination has been placed in a closed metal cavity. The 50Ω transmission line is present. However, we have chosen to determine *Q* through an eigenmode analysis rather than through a frequency sweep. Therefore, the transmission line has been terminated by a perfectly matched layer (PML) of absorbing material. The power dissipation in the PML takes the place of power dissipation in a 50Ω load.

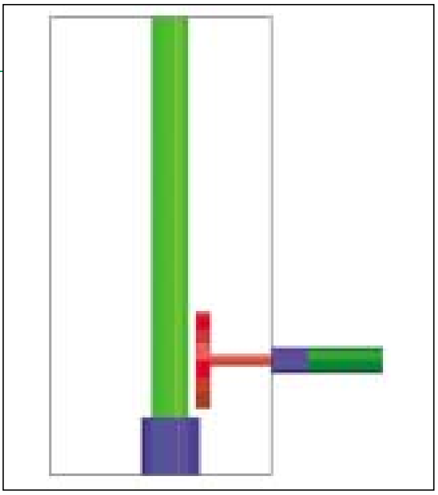

Figure 8. Model used to determine the loaded Q.

Because this project has been embedded in an optimizer, the antenna distance and the cylinder length were varied simultaneously and independently (since both influence the resonant frequency and the loaded *Q*). As an example of the results, the relation between antenna spacing and loaded *Q* is shown graphically in Figure 9 for a constant cylinder length of 113.4 mm.

With results like these, for any loaded *Q* and resonant frequency required by filter theory, the antenna spacing and cylinder length to be applied in the physical model can be readily determined.

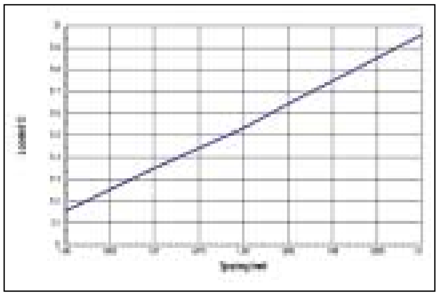

Figure 9. Relation between antenna spacing and loaded Q at a resonator length of 113.4 mm.

Initial filter design

Now that the circuit is defined and the relations between circuit components and physical dimensions are known, it is possible to construct the filter in the field solver. Filter theory tells us we need to achieve the following parameters:

Resonant frequency of the outermost resonators: fR1 = 400 MHz.

Resonant frequency of the inner resonators: f_{R2} = 400 MHz.

Loaded Q: Q_L = 31.498.

Coupling coefficients: K_{12} = 0.02893, K_{23} = 0.02171, K_{34} = 0.02065.

The calibration projects above indi-

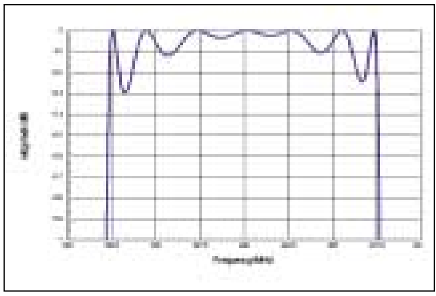

Figure 10. S_{21} results for the initial design.

cate that the dimensions of the filter, as shown in Figure 2, are to be:

Length of the two outermost resonators: 113.399 mm.

Length of the five inner resonators: 114.69 mm

Antenna distance: 1.879 mm.

Distances between resonators: 25.513 mm , 28.291 mm and 28.767 mm.

The resulting filter characteristic is shown in Figure 10. Notice that the center frequency and the ripple bandwidth are almost perfect. While the correct number of ripples is shown, the actual value is 0.3 dB rather than 0.1 dB.

Curve Fitting

The simulator results shown in the previous section have been exported to the circuit simulator, in which we can determine, through curve fitting, what the actual parameters of this initial design are.

Figure 11 shows the curve-fitting results. Notice that there are still a few hundredths of a dB difference between the simulator results and the best fit in the circuit simulator. This indicates that this design method is accurate to a few hundredths of a dB.

The curve fitting procedure indicates that a filter has been constructed with a resonant frequency of the outermost resonators f_{R1} = 400.058 MHz; a resonant frequency of the inner resonators of f_{R2} = 399.926 MHz, a loaded *Q of* Q_L = 30.368, and coupling coefficients of, K_{12} = 0.02825, K_{23} = 0.02173 and K_{34} = 0.02068.

The calibration projects will indicate how much correction is needed to achieve the desired characteristic. For example, noticing that Q_L is 1.132 lower than the desired value of 31.5, the next iteration will aim for a Q_L that is 1.132 higher. This procedure produces a filter with the dimensions of : *length of the two outermost resonators*: 113.44 mm; *length of the five inner resonators*: 114.684 mm; *antenna distance*: 1.928 mm; *distances between resonators*: 25.286 mm, 28.3 mm and 28.78 mm.

Hence, the dimensions that undergo the largest changes are the antenna distance and the distance between the first and second resonator.

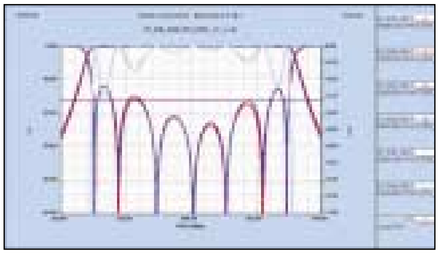

Figure 11. Result of curve fitting, magnitude.

Corrected filter design

The corrected filter was again modeled and simulated. The resulting characteristic is shown in Figure 12. Note that the ripple, which was 0.3 dB in the initial design, is better than 0.13 dB now. The target is 0.1 dB.

In most practical cases, this corrected design can be considered good enough to serve as the final design. Notice that it took only one iterative step to get here from the initial design. In case more improvement is desired, the results in Figure 12 can be exported to the circuit simulator for another iterative step.

Once the final design is known, the field solver easily produces additional information: the effects of internal losses, the maximum power handling capability and the effects of mechanical tolerances.

Conclusion

An efficient method to design microwave filters with modern simulation software, using standard techniques as resonating *LC* combinations separated by impedance inverters has been presented. Then, through a series of calibration projects with the software, relationships are established between components in the circuit simulator and in the circuit solver.

Next, an iterative procedure involving simulation in the solver and curve fitting in the circuit simulator yields the optimum dimensions for the microwave filter. The iterative procedure converges in one step. This entire process can be carried out in a matter of days, as opposed to weeks for more traditional filter design methods.

References

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[3] Randall W. Rhea, "HF Filter Design and Computer Simulation," McGraw-Hill, Inc., 1995, ISBN 0-07-052055-0.

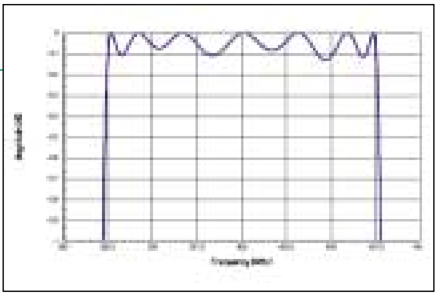

Figure 12. S_{21} results in HFSS for the corrected design.

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