New Filter Synthesis Software Designs Space Efficient Interdigital Filters

By Dale D. Henkes, ACS

Some of the advantages cited for planar interdigital microwave filters are that they can be designed for narrow bandwidths as well as bandwidths as large as 70% or more, they make efficient use of the available layout area, and they exhibit arithmetical symmetry resulting in better phase and delay responses [1, 2]. This article will compare the interdigital filter to another common microwave filter, the parallel edge-coupled microstrip filter.

One of the difficulties in designing bandpass filters with coupled lines is that the required coupling increases with bandwidth until the adjacent lines get too close to maintain manufacturing tolerances. **Figure 1** shows how the separation between lines decreases with increased fractional bandwidth for both edge-coupled parallel line filters and interdigital filters. **Figures 2** and **3** show the spacing (S1 through S4) between each pair of mutually coupled lines for both kinds of filters. The tightest coupling, and therefore smallest spacing, occurs for the coupled lines closest to the filter's source and load ports. The separation spacing for these tightly coupled lines is labeled S1 and S4 in Figures 2 and 3. Generally, the coupling at the ports are equal and S1=S4. S1 was taken as the source for the line spacing data plotted as a function of bandwidth in **Figure 1**.

The data plotted in Figure 1 was based on 5th order Chebyshev bandpass designs, each with a center frequency of 5 GHz. The circuit board material was 1/2 oz. copper on 50 mil substrate with a relative dielectric constant of Er=6.15. The important thing to note about **Figure 1** is that it indicates that the maximum bandwidth for the parallel coupled-line (CPL) filter is about 15% (FBW = 0.15), since at that point the smallest line-to-line edge spacing is only about 5 mils. For this, and most other common circuit board material, 4 or 5 mils is near the limit for the smallest gap that can be etched to reliably hold the required tolerance on this dimension.
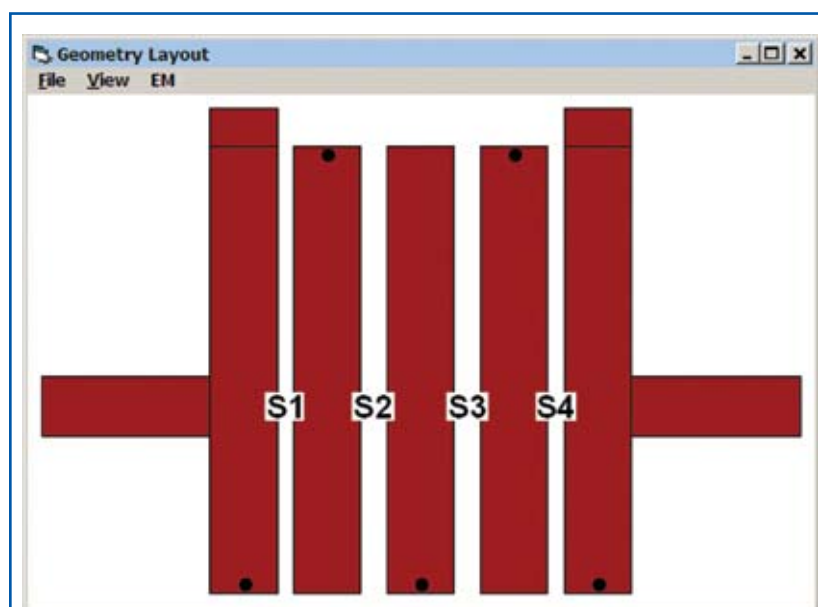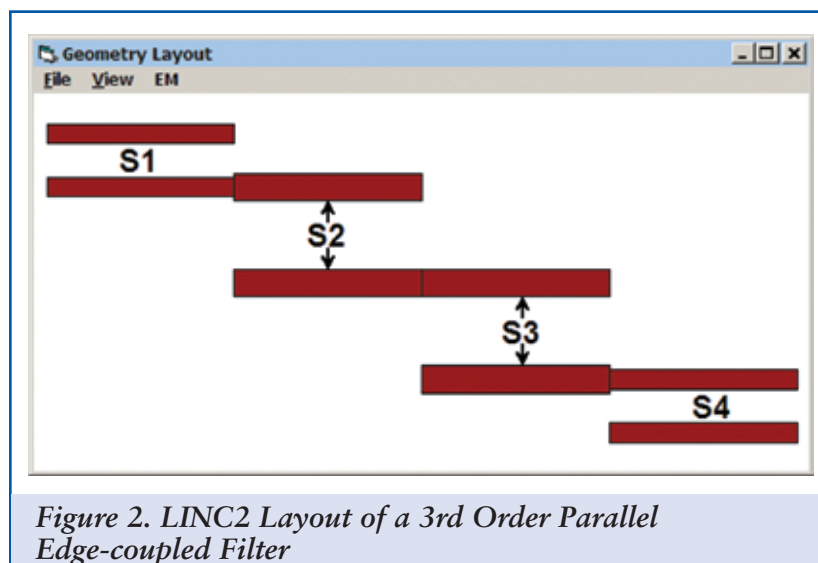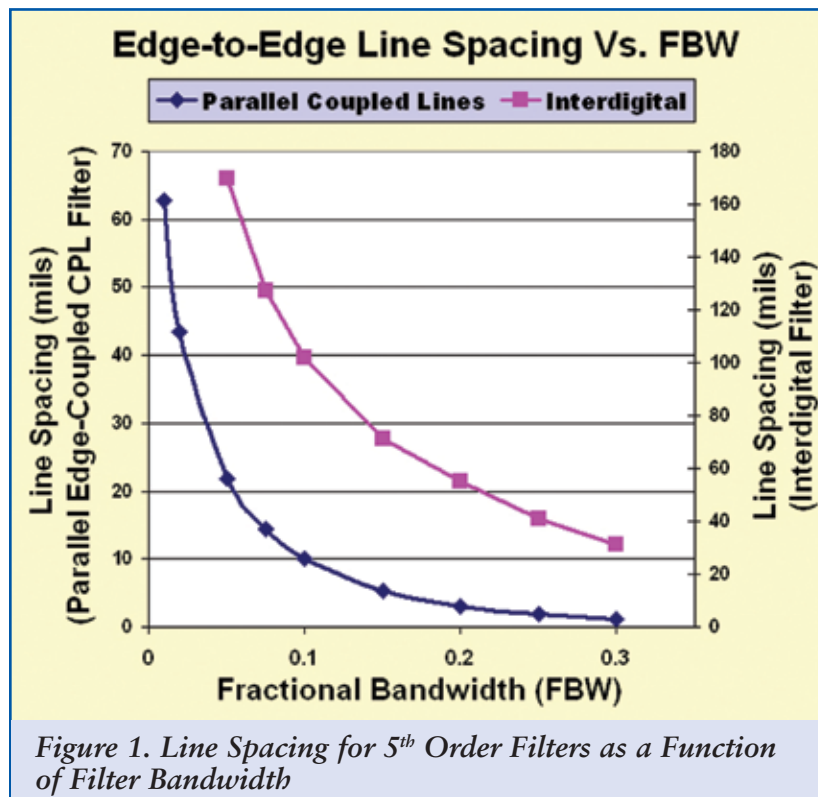

Figure 1. Line Spacing for 5th Order Filters as a Function of Filter Bandwidth

Figure 2. LINC2 Layout of a 3rd Order Parallel Edge-coupled Filter

Figure 3. LINC2 Layout of the 5th Order Interdigital Filter

At 30% bandwidth the smallest line-to-line spacing drops to an unmanageable 1 mil spacing for the parallel coupled-line filter. However, **Figure 1** indicates that at this (30%) bandwidth the interdigital filter still has more than 31 mils of minimum line-to-line spacing. Indeed, analysis shows that the bandwidth for the interdigital filter extends to 70% before its minimum line-to-line spacing equals the 1 mil spacing that occurred at only 30% bandwidth for the coupled line filter. Other factors, such as circuit board material and substrate thickness will have an influence on the maximum bandwidth achievable, but this example is illustrative of what can be expected for these two kinds of filters.

Another point of interest in comparing these two kinds of filters is the amount of circuit board layout area that each requires for various bandwidths around a given center frequency (f0). **Figure 4** shows that both types of filters require less layout area as the bandwidth increases. This is because the spacing between coupled lines decreases with bandwidth, resulting in the filter becoming more compact. However, for the range of bandwidth considered in **Figure 4**, the parallel coupled-line filter consistently requires about 6 or 7 times as much layout area as the interdigital filter. Each filter employs resonator sections that are electrically 90 degrees in length. However, the parallel edge-coupled filter places these 90 degree resonator sections end-to-end while the interdigital filter uses 90 degree resonator strips that are placed side-by-side. Additionally, the edge-coupled filter has an extra 90 degree section for a total electrical length of (N+1)*90 degrees (where N is the filter order).

To summarize, at 15% bandwidth centered at 5 GHz, the dimensions for the parallel coupled-line filter are 1.67" L x 0.785" W = 1.311 Sq. inches of area. Whereas, the interdigital filter with the same 15% bandwidth centered at 5 GHz has dimensions of 0.695" L x 0.281" W = 0.1956 Sq. inches of

area. Thus, for theses 5th order filters constructed on the given circuit board material, the interdigital filter is approximately 6.7 times more efficient in its use of the available layout area.

LINC2 Filter Pro Software and Sonnet® EM Interface

The LINC2 Filter Pro software from ACS (Applied Computational Sciences, Escondido, CA) has the ability to synthesize the parallel edge-coupled and interdigital filters discussed here as well as many other lumped and distributed filter types. In addition to all types of traditional single-ended filters, the LINC2 filter software can design and automatically synthesize differential (balanced) filters as well. Integrated circuits (ICs) with differential ports are increasingly being used in RF and microwave systems. Therefore, filter design software that can synthesize differential filters with balanced ports that interface directly to these ICs without the need for BALUN transformers is very useful. The LINC2 software saves design time and effort and produces designs that use less compo-

nents, resulting in improved performance and reliability.

Performance verification is an important part of the design process, especially when automatic circuit synthesis software is used to create circuits (including filter circuits) for operation at high frequencies. The LINC2 Filter Pro software provides two distinctly different and fundamentally independent methods for circuit design verification (circuit theory simulation and electromagnetic simulation). The LINC2 software offers built-in circuit simulation based on schematic capture and a general purpose (arbitrary circuit topology) electrical circuit theory simulator. This method works best for analyzing lumped element filters.

Distributed filters can also be analyzed with the built-in LINC2 circuit simulator. Additionally, the LINC2 program can automatically convert all the electrical transmission line models on the synthesized schematic to physical microstrip or stripline models (including dimensions of length, width, substrate height and metal thickness, etc.). Discontinuity models, such as an abrupt step

in line width, can be obtained from the LINC2 Parts menu and added to the schematic for improved accuracy at high frequencies. However, at higher frequencies or for large discontinuities, there will be a point at which EM (electromagnetic) simulation will provide the best analysis. For this purpose, LINC2 is equipped with an interface to Sonnet Software's EM simulation software (see "Using LINC2 with Sonnet EM Software Enhances Simulation Accuracy" in the April 2007 issue of MPD) [3]. LINC2 microstrip and stripline filter designs can be automatically exported to Sonnet EM with a single menu click. LINC2 automatically starts the Sonnet EM program, exports the layout geometry into the Sonnet geometry editor (xgeom), and sets up default values for the EM simulation environment.

Automatic setup of the EM

simulation environment is convenient and saves a lot of time because it includes placing the ports, de-embedding the ports, defining the metal and dielectric layers, specifying the metal and dielectric material properties, creating the EM simulation box dimensions, setting up the simulation frequencies and number of EM simulation cells for EM meshing. Fortunately, this is all done automatically in LINC2 (before exporting the design) using reasonable default values so that in many cases all that needs to be done in Sonnet to get EM simulation results is to simply click **Analyze** in the Project menu. In the Sonnet xgeom editor, the user can select **Circuit | Box...** to review the default cell size and estimate the required memory.

Sonnet Lite is included free with LINC2 Pro and LINC2 Filter Pro (or it can be downloaded from Sonnet Software's
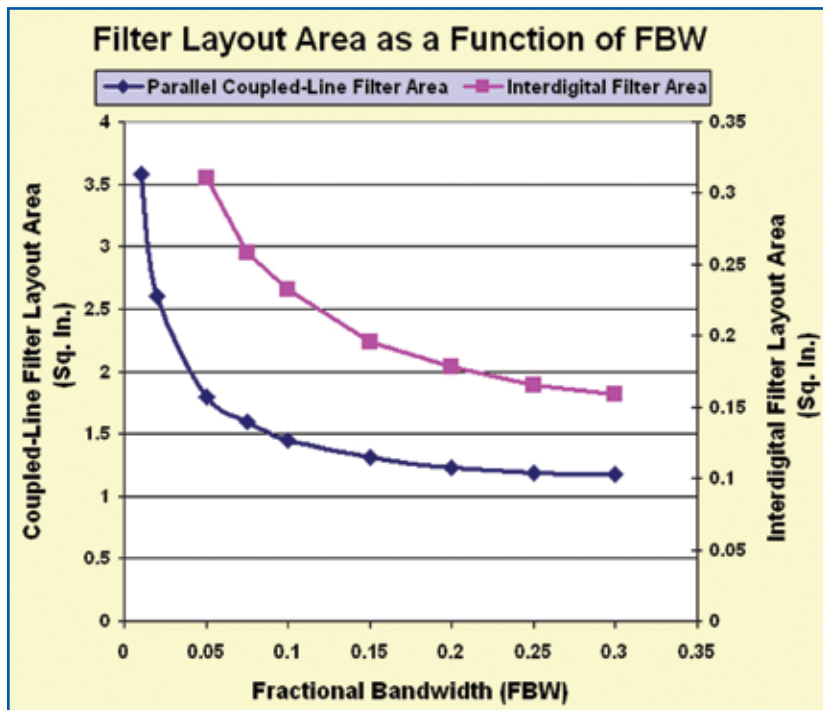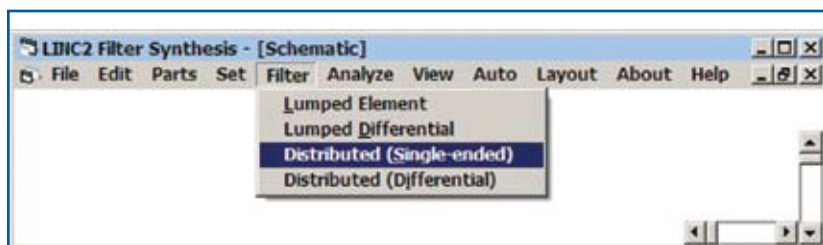
Figure 4. Required Filter Layout Area
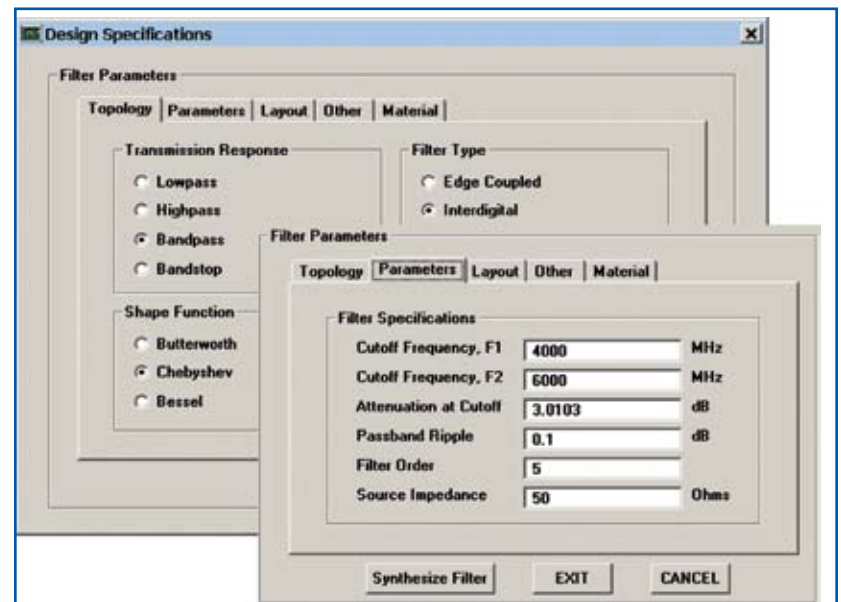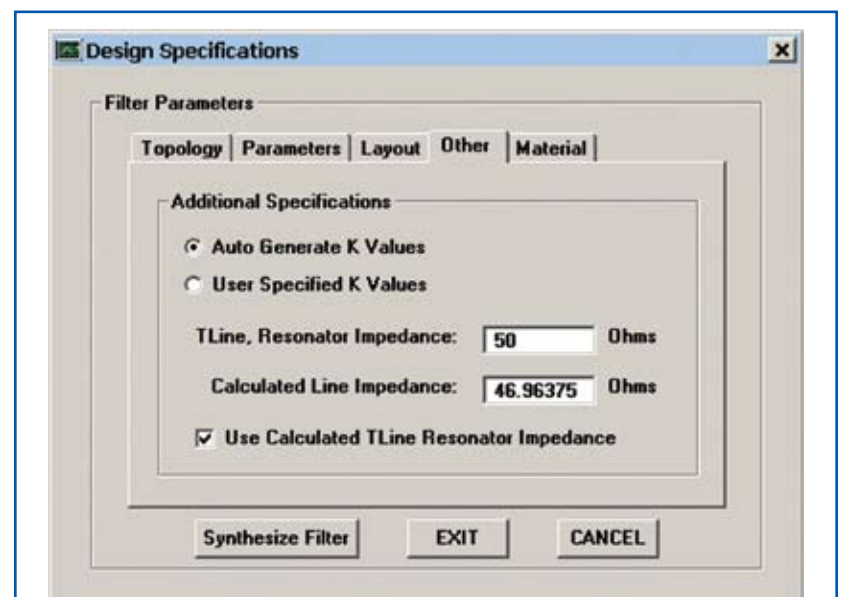
Figure 5. The LINC2 Filter Menu

Figure 6. Filter Design Specifications Form

Figure 7. Other Filter Parameter Selections

web site at www.sonnetsoftware.com/lite). The amount of available EM simulation memory can be increased by registering the product with Sonnet (free of charge) or by upgrading to a higher level version of Sonnet. With increased simulation memory, larger projects can be analyzed with greater accuracy.

Interdigital Bandpass Filter Design Example

In the following example, a 5th order tapped-line interdigital bandpass filter is designed using the LINC2 filter synthesis software. An EM simulation will then be performed on the initial synthesized circuit to determine the effects of the discontinuities at the tapped-line microstrip junctions and other non-ideal effects [3]. The results will be compared to the design goals for determining the proper steps for improving or optimizing the design.

For this example, the design specifications will include the following:

Filter implementation: 5 GHz band-pass tapped-line interdigital microstrip filter.
Filter type: 5th order Chebyshev.
Material: Rogers RT/duroid® 6006.
Lower 3 dB cutoff frequency: 4000 MHz (+/- 2%).
Upper 3 dB cutoff frequency: 6000 MHz (+/- 2%).
Stop-band attenuation at 7500 MHz: > 45 dB.
Operating pass-band: 4250 - 5750 MHz.
Operating pass-band return loss: > 10 dB.
Pass-band ripple: 0.1 dB.
Port impedance: 50 ohms.

Table 1: Design Goals Versus Simulation Results

Fifth Oder Tapped-Line Interdigital Microstrip Filter		
Specification	Goal	EM Simulation
Operating passband	4250 MHz - 5750 MHz	
Lower 3dB cutoff frequency	4000 MHz +/- 2%	3991 MHz (-0.225 %)
Upper 3 dB cutoff frequency	6000 MHz +/- 2%	5942 MHz (-0.97 %)
Attenuation at 7500 MHz	> 45 dB	45.25 dB
Operating passband return loss	> 10 dB	> 16.65 dB
Passband ripple	0.10	0.1

The LINC2 filter synthesis program is started by selecting **Filter Design** from the LINC2 **Tools** menu. This action opens the LINC2 Filter Synthesis Schematic Window shown in **Figure 5**. LINC2 can design lumped and distributed filters in both single-ended as well as differential configurations for operation between balanced ports. For this example, **Distributed (Single-ended)** is selected from the **Filter** menu.

The Design Specifications Form pops up as shown in **Figure 6** where the specifications for the 5th order interdigital bandpass filter are entered.

For Filter Topology, Bandpass, Chebyshev and Interdigital are selected. For the Filter Parameters tab, the upper and lower cutoff frequencies, attenuation at cutoff, passband ripple, filter order and filter impedance are entered with the numerical values shown in **Figure 6**. In the Other tab **(Figure 7)**, the program is directed to calculate the best resonator imped-

ance value for matching the tapped port line to the filter's port impedance. Auto Generate K Values is also selected under Additional Specifications in **Figure 7**. This selection allows the program to automatically generate the required coupling (K value) between resonators. (Manually entering these values and the resonator impedance gives the user more control over the width of the resonator strips and the spacing between them).

Finally, the filter's construction materials are specified as shown in **Figure 8**. For this example, microstrip material specifications for Rogers Duroid 6006 are entered. This completes the design specifications for the filter in this example. Clicking **Synthesize Filter** automatically generates the 5th order interdigital bandpass filter shown in **Figure 3**.

LINC2 filter synthesis generates and displays the physical layout details in the Geometry Layout window **(Figure 3)**. There are several methods available for generating output. New in version 1.13 is the ability to export the filter geometry to a DXF file. The DXF export feature provides the capabil-

ity to send the physical geometry (with exact dimensions) to other programs. For example, there are third party software programs available that can import the LINC2 DXF file for circuit analysis, electromagnetic (EM) analysis or for incorporating the LINC2 filter designs into other (new or existing) circuit or system designs and project schematics.

Exporting a LINC2 filter layout to one of the many layout programs available for fabricating printed circuit boards is another example of layout file transfer via the DXF file format. Also, a free program is available for translating LINC2 DXF layout files directly to the Gerber file format for PCB fabrication. Filter layouts can also be printed as bitmap images on graphics printers, plotted as vector graphics or written to a file in vector graphics or plotter file formats. The default output scale size is 1:1, but the printer and plotter scale can be set to any other value by selecting **File | Preferences... | Plot Scale Factor**.

The next section will detail another important method of exporting LINC2 filter layout designs. This next section
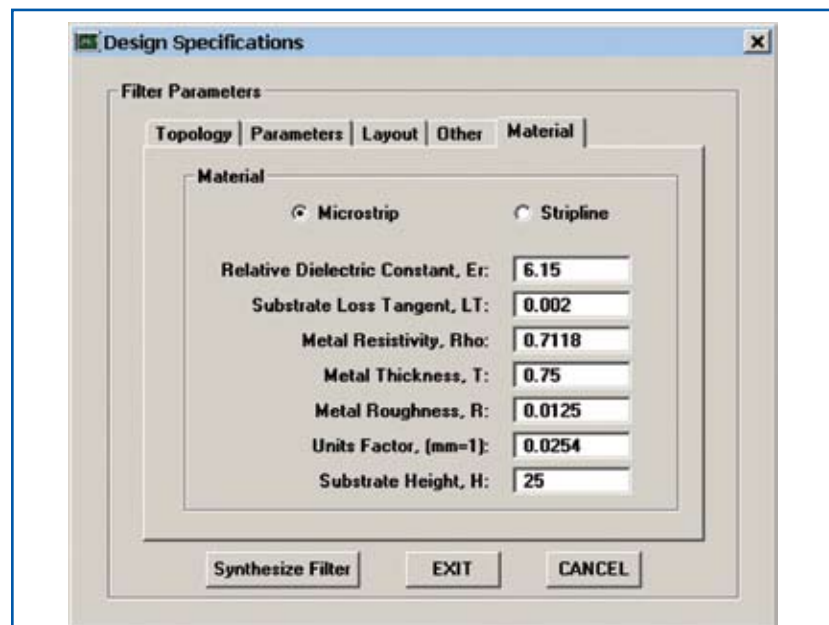

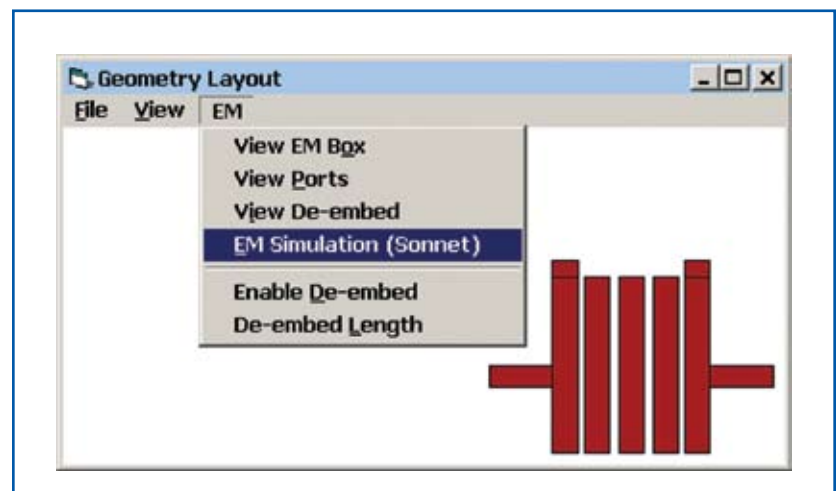*Figure 8. The Filter Material Specifications*

Figure 9. LINC2 EM Simulation Menu

demonstrates how the LINC2 Sonnet interface provides accurate EM simulation of LINC2 filter designs by invoking Sonnet EM from the Geometry Layout window.

Analyzing Filter Performance Using Sonnet EM Simulation
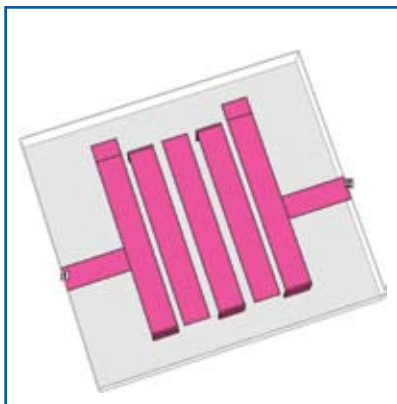When LINC2 synthesizes a dis-

Figure 10. Sonnet 3-D View of the LINC2 Interdigital Filter

tributed filter, such as the 5th order interdigital bandpass filter in this example, the physical (geometric) details are rendered in the LINC2 Geometry Window. Transferring the design to Sonnet for EM simulation is easy. Simply clicking **EM Simulation** (**Sonnet**) from the LINC2 Geometry Window's **EM** menu, as shown in **Figure 9**, automatically starts Sonnet and exports the filter geometry into the Sonnet geometry editor (xgeom). A Sonnet top side view of the 3-D rendering of this filter is shown in **Figure 10**.

If the version of Sonnet used provides enough memory space to analyze the entire filter structure, then all that needs to be done is to click **Project | Analyze** to get the EM simulation results.

(However, in this example, a combination of editing the analysis setup for coarse edge

meshing and adjustments to the cell size was made to reduce the memory requirements enough to run this simulation in Sonnet Lite-Plus). When the EM simulation completes, clicking **Project | View Response | New Graph** displays the results shown in **Figure 11**.

The light grey curves show the simulation results for the initial filter as first synthesized from the specifications entered in **Figures 6, 7,** and **8**. While the first cut results produced an excellent filter response that is quite close to the desired goals for the filter, the bandpass center frequency is shifted down by nearly 7%.

EM simulation can do a better job (than a circuit theory simulator) of capturing the effects of discontinuities such as the tapped-line microstrip junction and the open end (fringing) effect at the ungrounded (open) end of the resonators. The light grey plots in **Figure 11** suggest that these effects can be addressed by adjusting the frequency specification upward. After re-specifying the lower and upper cutoff frequencies (as 4300 MHz and 6300 MHz respectively) and adjusting the tap point slightly, EM simulation results were obtained that met the original goals as indicated by the heavy red and blue curves in **Figure 11**. The simulation results shown in **Figures 11** and **12** now meet all the design goals listed in **Table 1**.

Summary and Conclusions
This article demonstrated how the LINC2 filter design software can be used to design space efficient interdigital filters quickly and accurately. The frequency response for the 5th order interdigital filter design example was determined and the design was verified using Sonnet EM simulation software. A well designed and matched filter of this kind should have, distributed throughout the passband, a number of reflection zeros equal to the filter's order. For the 5th order filter design presented here, 5 reflection zeros can be clearly seen as distinct dips in the S11 plots shown in **Figures 11** and **12** (indicating that return loss peaks at these points). This does not mean that the filter is not usable if two or more of the zeros overlap, but it is an indication that the filter is well matched (through proper adjustment of

the tap point) and that the individual resonators have the correct size and spacing.

The interdigital filter in this example had a bandwidth of 40% which resulted in a minimum edge-to-edge resonator strip spacing of about 10 mils. The resonator strips were approximately 40 mils wide by 265 mils long (except for the end strips that are slightly longer). It should be possible to increase the minimum gap spacing between resonators by changing the resonator impedance, but the tolerances for these dimensions should not be too difficult to hold for manufacture.

It would be virtually impossible to construct a 5th order parallel edge-coupled filter with the same bandwidth on the given PCB material due to the tight (less than 1 mil) coupled line spacing. However, in spite of the difficulty this would pose for construction, it is still interesting to compare the relative sizes between these two kinds of filters. The parallel edge-coupled filter would be more than 1.7 inches long versus the less than 0.246 inches required for the length of the interdigital filter. Thus, the port-to-port length of the coupled-line filter would be nearly 7 times longer than the interdigital filter and require nearly 8 times as much circuit board layout area.

LINC2 Filter Pro is one of several circuit synthesis products that are part of the LINC2 suite of circuit design and synthesis tools from ACS. LINC2 offers exact circuit synthesis, schematic capture, circuit simulation, circuit optimization and yield analysis in a single affordable design environment. More information about LINC2 can be found on the ACS web site at www.appliedmicrowave.com.

References
1. Kinayman, Noyan and Aksun, M. I., "Modern Microwave Circuits", Artech House: Norwood, MA, 2005.
2. Rhea, Randall W., "HF Filter Design and Computer Simulation", Noble Publishing: Atlanta, GA, 1994.
3. Henkes, Dale D., "Using LINC2 with Sonnet EM Software Enhances Simulation Accuracy", Microwave Product Digest magazine, April 2007.
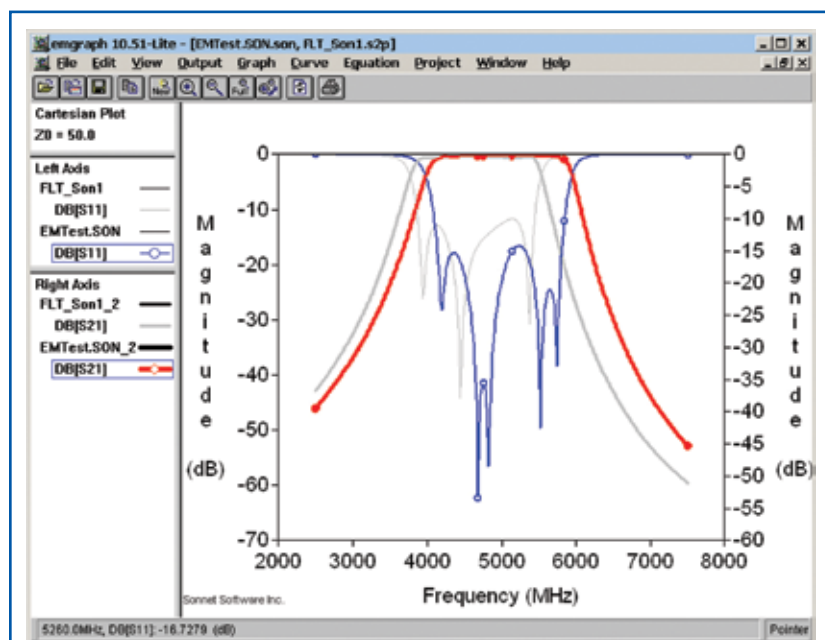
ACS

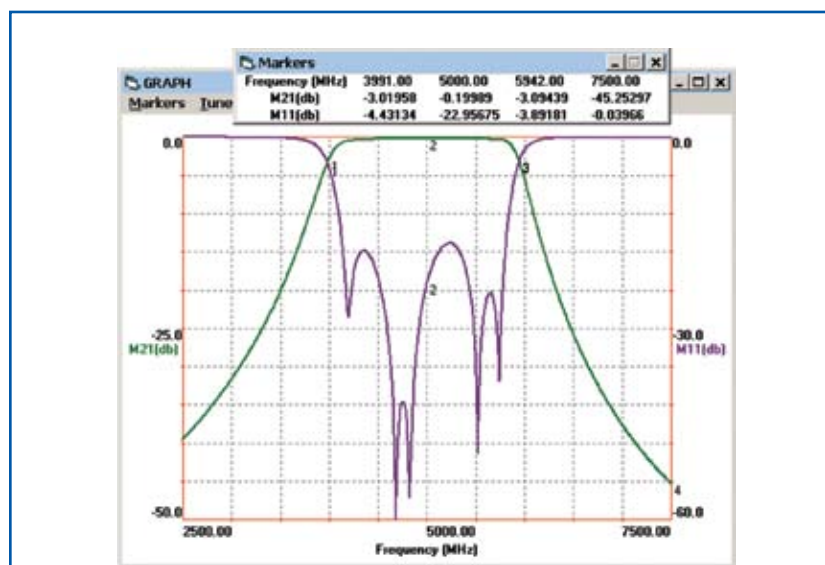*Figure 11. EM Simulation Results*

Figure 12. LINC2 Display of Simulation Results for the Interdigital Bandpass Filter