Application Example

Using Accurate Component Models to Achieve First-Pass Success in Filter Design

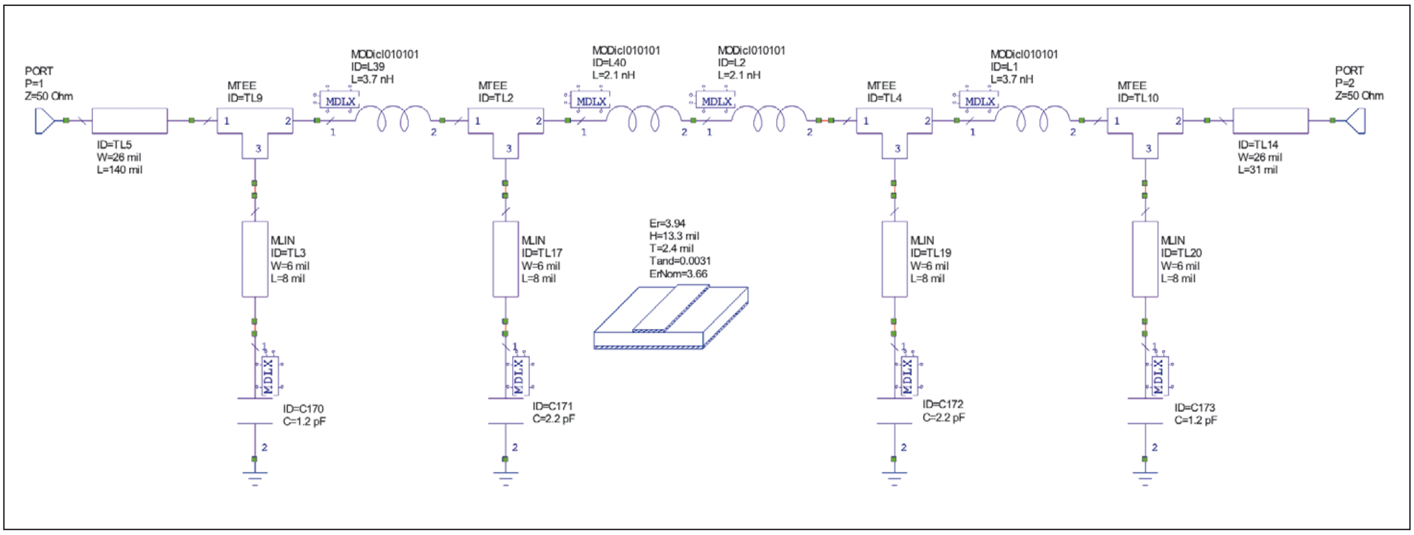

Figure 1: Ideal harmonic filter schematic, including transmission line interconnects

Utilizing models that include component and printed circuit board (PCB) parasitics in place of ideal lumped elements in microwave circuit design software produces filter simulation results that are accurate enough to achieve first-pass success and in this application note will be demonstrated for a harmonic filter design for a transmitter application.

This note presents a case study in simulation-based RF/microwave design in the context of a filter design for a transmitter using advanced linear component models and simulation methods. More precisely, the example is of a low-pass harmonic filter that was successfully designed in a single pass using NI AWR Design Environment software, and Modelithics' models.

Circuit Simulations Using Component Models

RF/microwave design computer-aided-engineering (CAE) tools have existed for many years and are used extensively by engineers to design linear and nonlinear RF/microwave circuits. These design efforts have been supported by linear S-parame-

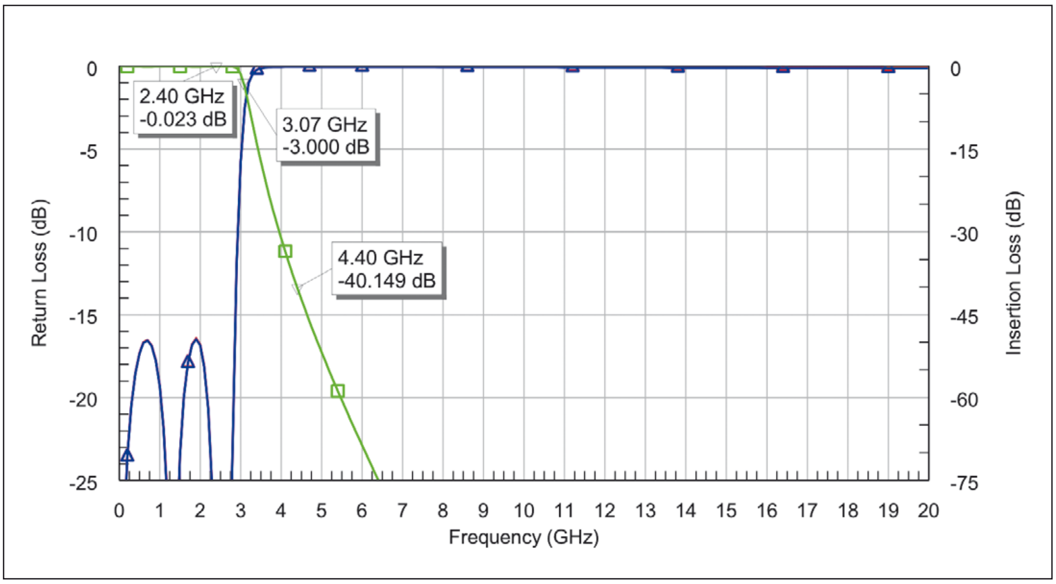

Figure 2: Simulation of 2.4 GHz harmonic filter including transmission line interconnects

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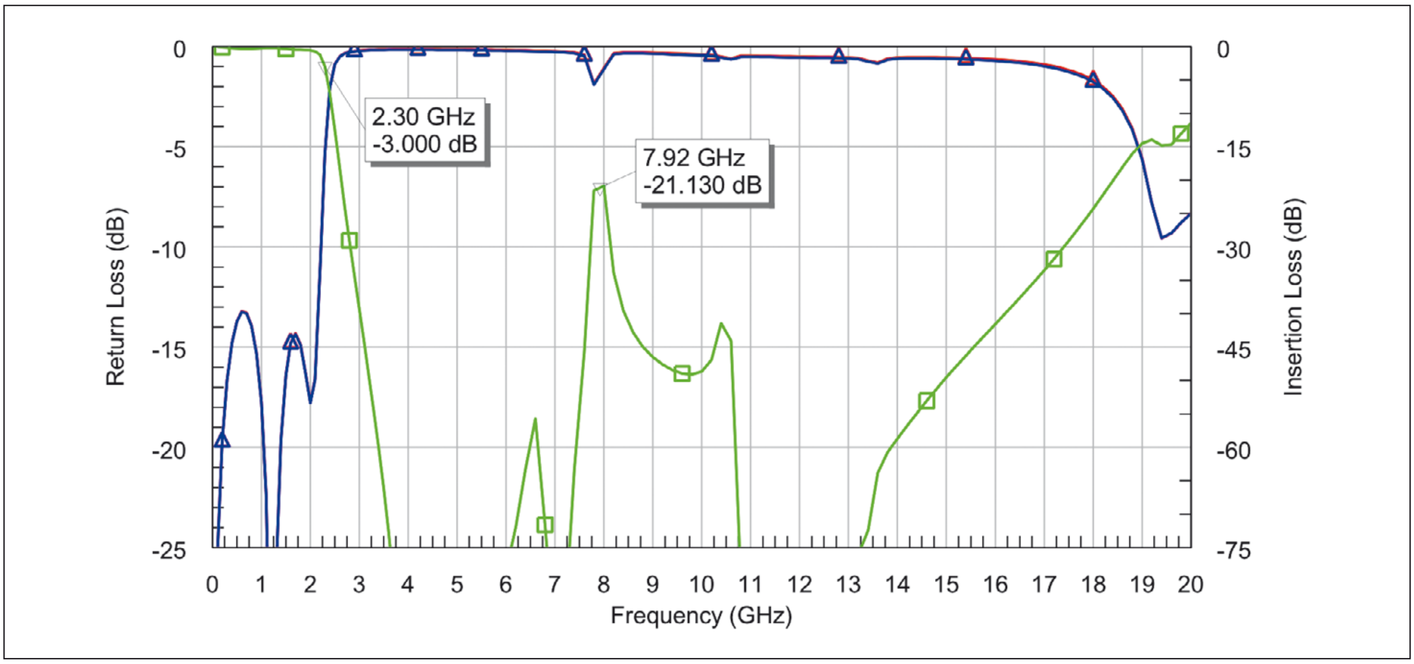


Figure 3: Simulation of 2.4 GHz harmonic filter, including device L-C parasitics

ters or models for passives and compact nonlinear models and load-pull power device data for active devices, as provided by many component manufacturers.

More recently X-parameter models are also provided by some manufacturers and model providers. At application frequencies above 1 GHz, the component parasitics such as series inductance in capacitors and shunt capacitance in inductors, as well as substrate-dependent component parasitics, significantly impact the actual circuit performance.

If these component parasitics are not included in the simulation, the accuracy of the simulation results will be significantly degraded.

Circuit simulations with accurate component models that include the component parasitics can produce very accurate results. For example, an accurate low-pass filter simulation might show steeper rolloff due to the parasitic series inductance in the shunt capacitors and will certainly show the “flybacks” (frequencies where the filter has degraded rejection in the stop band) where the series inductors are resonant.

Many circuit designers recognize the importance of including component parasitics in their simulations and create their own models

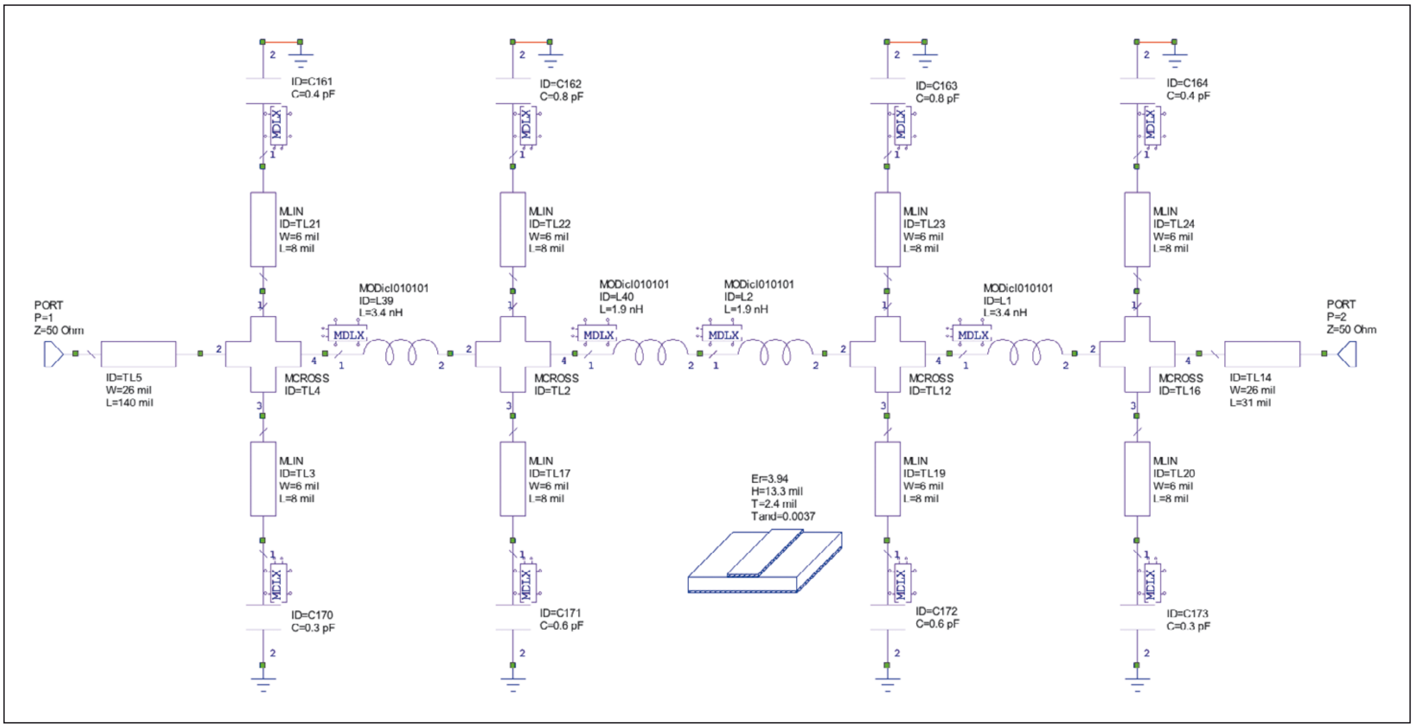
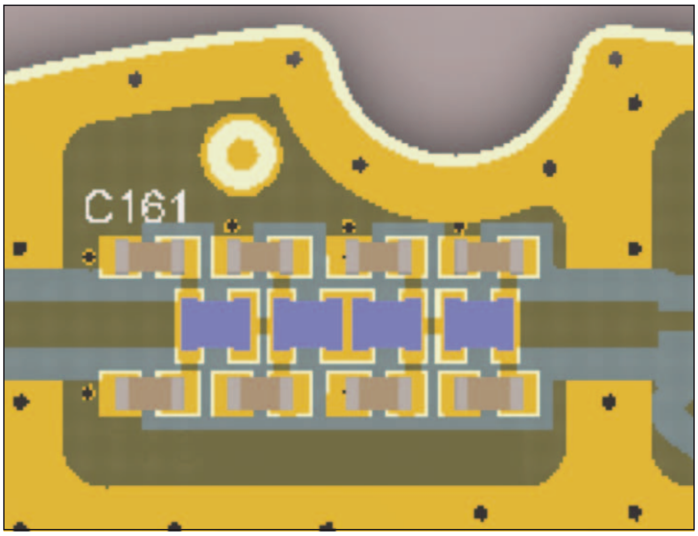


Figure 4: Redesigned 2.4 GHz harmonic filter schematic



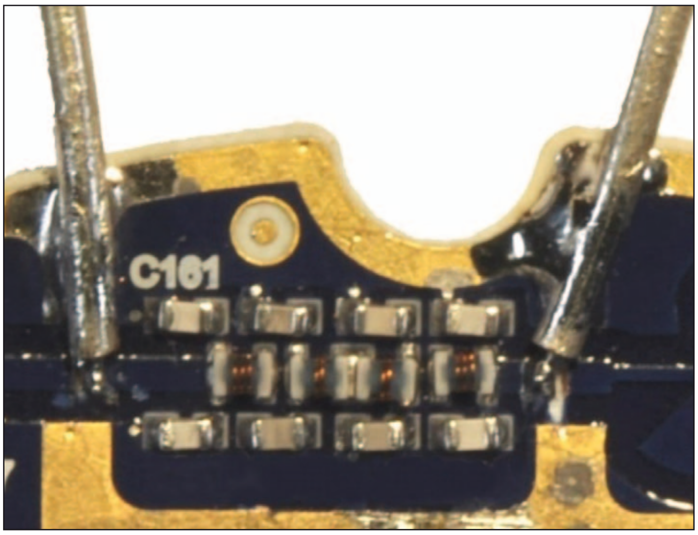


Figure 5: Complete harmonic filter PCB with pigtails; layout (left) and fabricated circuit (right)

for the desired components by measuring S-parameters using a network analyzer and then de-embedding the results. Models created using this approach are typically accurate only for a specific pad size, PCB thickness, and dielectric constant and this effort is time consuming and requires specialized test fixtures and measurement expertise.

These models provide for pad scaling that account for substrate/ground-plane effects and are measurement validated on numerous substrates over a wide frequency range. Obviously, there is a cost required to develop component models, even if it is done in-house.

Harmonic Filter Design Example

In this design of a harmonic filter for a transmitter application, the cutoff frequency and level and frequency of the flybacks was crucial to ensure that the level of the transmit harmonics would be below the required limit. Using NI AWR Design Environment, the design of a low-pass harmonic filter appeared to be a straightforward effort.

For this 1-W transmitter application, a filter was required to reduce the level of the second and third harmonics at the output (below -20 dBm), as well as the level of the higher order harmonics (below -80 dBc).

Starting with ideal lumped-element capacitors and inductors and including the interconnecting microstrip lines, the 2.2-2.4 GHz harmonic filter shown in Figure 1 was designed for low S11 in the passband and high rejection at the second harmonic and above.

The schematic shows the circuit using Modelithics model symbols but the parasitics were set to "ideal," so are not included in the simulation results.

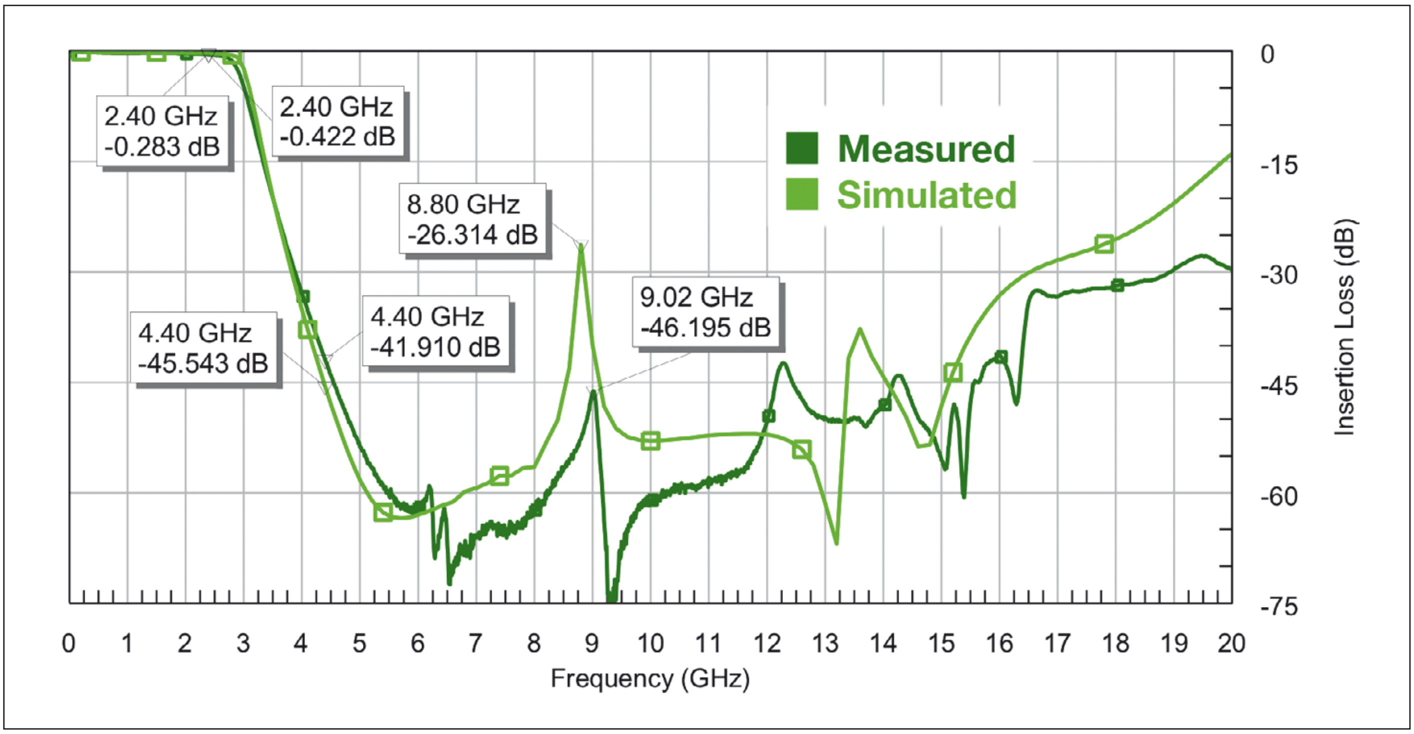


Figure 6: Microwave Office with Modelithics results for the 2.4 GHz discrete harmonic filter (simulation vs. measured data)

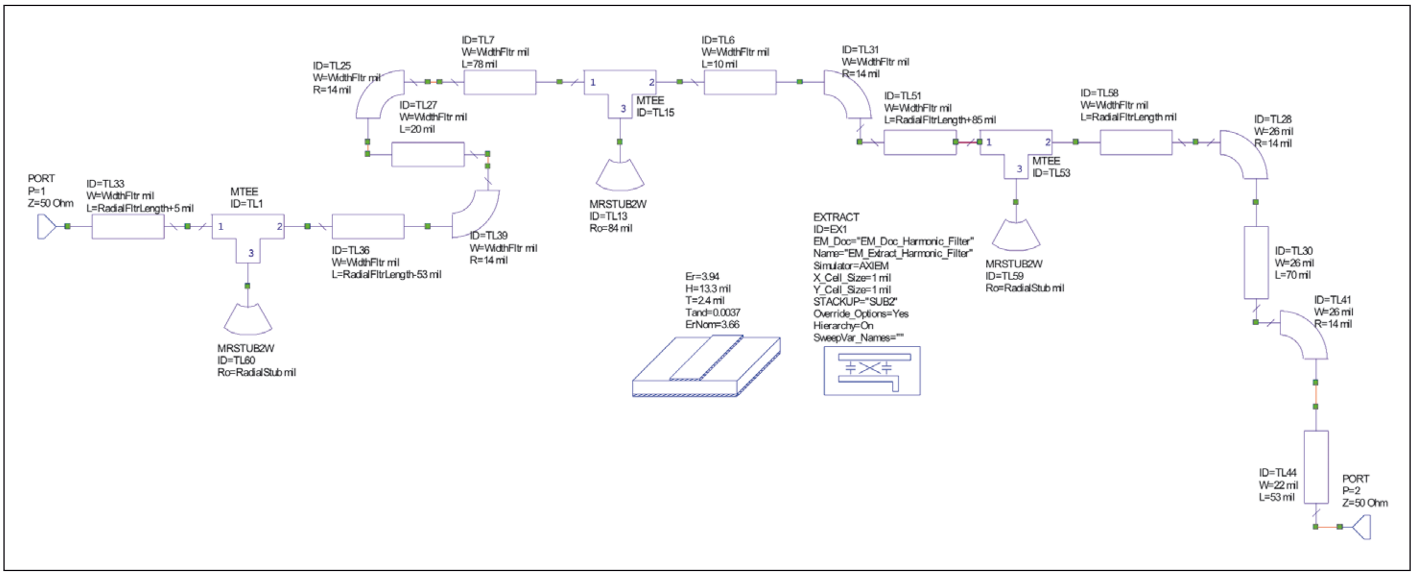


Figure 7: Microwave Office schematic of the radial stub filter

The simulated response (Figure 2) shows insertion loss less than 0.05 dB, 2nd harmonic rejection of 49 dB, and minimum 47 dB rejection up to 20 GHz. The experienced engineer would recognize that this response is unrealistic and assume the simulation software is somehow incorrect. However, this was because the lumped element components utilized in this harmonic filter differed from their ideal models at microwave frequencies.

In addition to the component parasitics, including resistance, series inductance, and shunt capacitance, the response was further changed when the shunt capacitance between the component PCB pads and the substrate ground was included in the model. Taking all these parasitics into account, the simulated results look like the simulation in Figure 3, in which the parasitics and shunt pad capacitance were enabled in the Modelithics component models (simmode=0 model setting).

It was apparent, when comparing Figures 2 and 3, that the filter response was significantly different when the parasitics L-C models were included in the simulation. The 3-dB cutoff frequency response was shifted lower by 20 percent. Even worse, the level of the fourth and higher harmonics, leaking through the filter, would be significantly higher due to the filter flybacks and degraded rejection. Improving the rejection after fabrication to meet the requirements would require time-consuming re-design and an expensive second and probably third spin of the PCB.

The harmonic filter shown in Figure 4 was designed using Modelithics models for ATC capacitors and Coilcraft inductor families. Because there was not yet a Modelithics model for the Coilcraft 0403HQ inductors used in this transmitter at the time of this design, the model for the larger 0604HQ inductors was simulated instead. In comparison to the previous circuit, additional shunt capacitors were added to decrease the parasitic shunt inductance in the capacitors to reduce the level of the flybacks. The completed PCB is shown in Figure 5.

Figure 6 shows a comparison between the simulated and measured S21 responses. The analysis (using EM for microstrip lines and solder pads and circuit models for components) displays a -36 dB flyback at 8.4 GHz and only about 15 dB rejection above 13 GHz due to coupling from the microstrip lines at the input to the output around the filter. The measured response was as built with no shielding and compares favorably to the simulated measurement except for a lower resonance peak at 8.8 GHz.

The level of this resonance in the simulation results was very sensitive to the layout and was expected to be substantially lower in the measured performance after the shield was installed. The measured insertion loss is 0.14 dB higher and the second harmonic rejection was 3.6 dB less than simulated. The reason for the differences in the passband is likely due to the smaller, lower Q 0403HQ inductors used in the actual board, compared to the 0604HQ inductors used in the simulation.

Compared to the simulation using ideal components (Figure 2), the simulation plots in Figure 6 indicate the need for additional

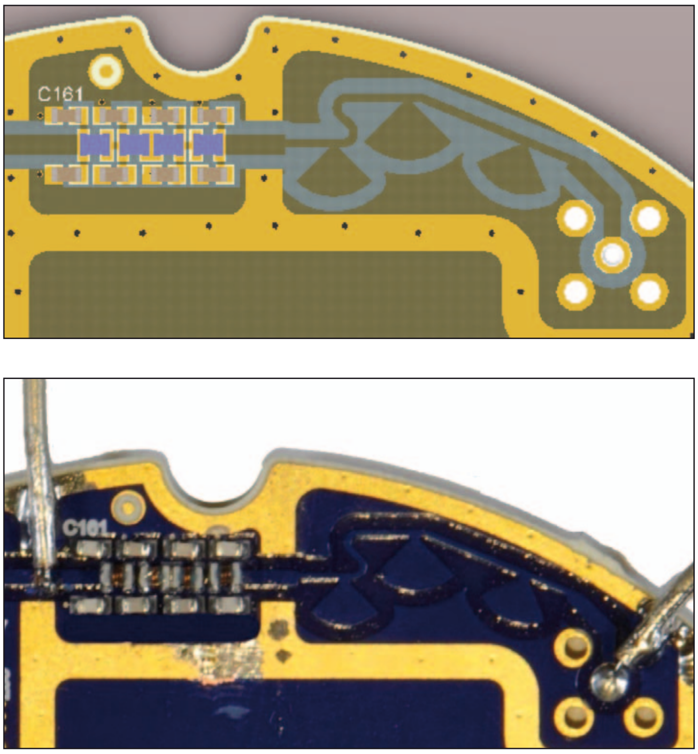


Figure 8: Discrete LC plus radial stub harmonic filter

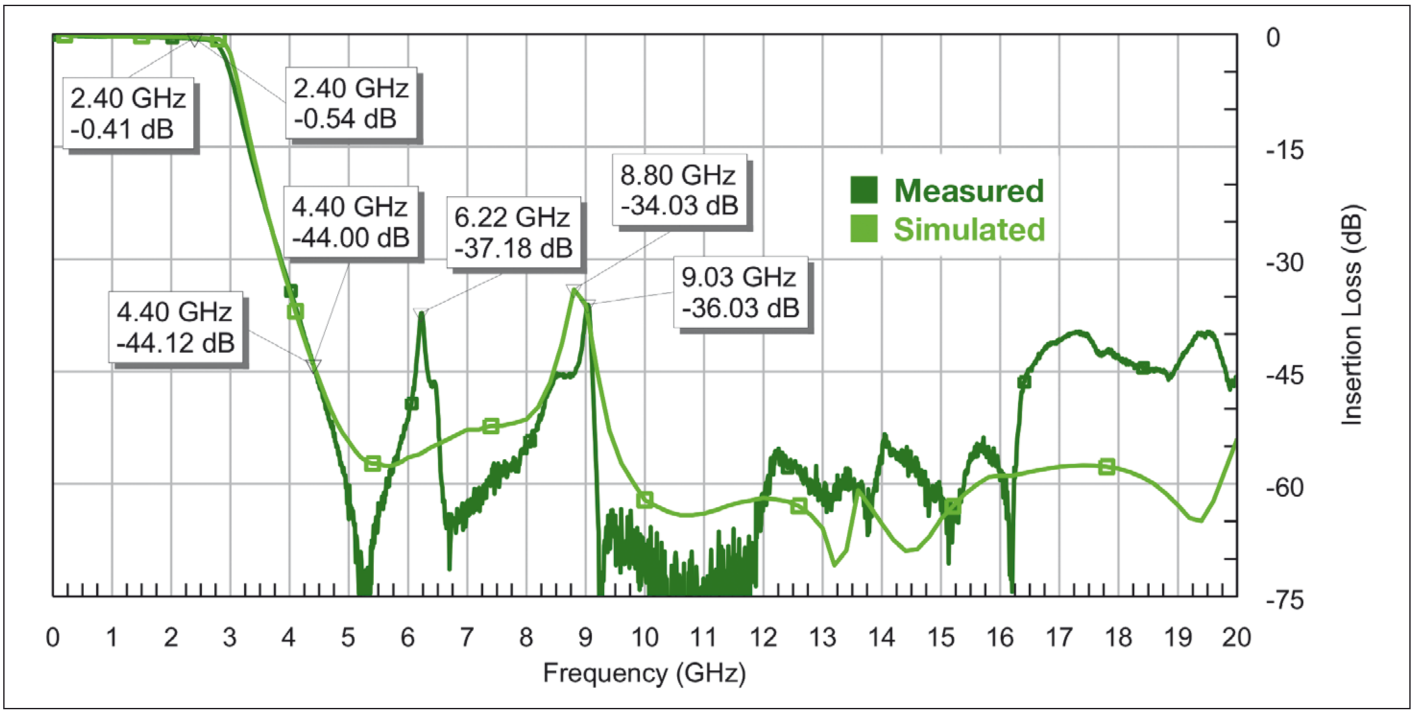


Figure 9: Microwave Office and Modelithics results for the 2.4 GHz harmonic filter (simulation vs. measured data)

filtering to improve the rejection above 8 GHz. For that reason, a radial stub microstrip filter (Figure 7) was appended to the output of discrete filter.

The completed PCB layout for the combined discrete plus distributed low-pass harmonic filter is shown in Figure 8. The gold outline shows where shielding will be added to reduce flybacks. A comparison of the simulated and measured performance of the filter in Figure 8 shows good agreement, as presented in Figure 9.

The passband insertion loss and stopband rejection were accurately simulated, especially given the difference in the inductor model versus the actual inductor body size, as noted previously. The degraded rejection above 16 GHz was due to coupling around the filter and would improve once the filter is placed in a shielded housing.

The source of the measured 6.2 GHz flyback was traced to coupling between the discrete inductors and radial stub filter added at the output. Unfortunately, this radiated coupling from the inductors was not included in component models nor S-parameter data on individual components.

Development Effort and Cost

RF circuit development is typically accomplished by prototyping the individual circuit components and individually characterizing and optimizing them via tuning on the bench, resulting in multiple iterations of the design before acceptable performance is achieved. Modern RF/microwave CAE tools such as NI AWR Design Environment provide the capability to accurately simulate microwave circuits. If designers first accurately measure the optimized component performance on their particular substrate, the resulting component model can be inserted into the Microwave Office simulator. Instead of relying on multiple prototypes, the simulator can be utilized to optimize the combined circuitry for optimal performance. This approach can eliminate one or two PCB spins and shorten the circuit development cycle by one to two months.

Additionally, accurately characterizing a component and de-embedding the results for inclusion into the Microwave Office simulator requires substantial RF expertise. The alternative approach explored in this application note utilizes component models developed by a third party (in this case Modelithics). This approach eliminates the time-consuming component characterization and enables the engineer to proceed directly with circuit development, thereby saving several weeks of effort.

Conclusion

At frequencies above 1 GHz, simulating with ideal components produces ideal results that can deviate from the actual performance by 20 percent and omit critical responses such as flybacks. Simulating circuit performance and using component models that include parasitics produces results that are typically accurate enough to realize design goals on a first-pass PCB fabrication. This example has demonstrated very good agreement in the passband and second harmonic cutoff, as well as reasonable agreement through the stopband. The coupling between the closely-spaced inductors resulted in undesirable flybacks, which were not included in the component model and not predicted by the simulation. The development time and cost savings of simulating with accurate component models is believed to easily justify the cost of using accurate models as part of this filter design flow.

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