

## CONSIDERATIONS IN CAPACITOR-PAIRING TO OBTAIN NONSTANDARD PART VALUES

Series- and parallel-combining of surface-mount capacitors is a standard approach to realize semi-arbitrary capacitance when designing a printed circuit board layout. This pairing of components is often necessary as surface-mount parts are available in only a limited number of fixed values, such as 0.5, 1.0, 2.0 pF. This article addresses some potential pitfalls that may arise in the form of unexpected resonance effects, brought about by the interaction of the paired parts and the complexity of their frequency behavior. The use of accurate computer-aided engineering (CAE) models to predict these effects is demonstrated.

Fig. 1 Simple LC circuit model for a capacitor. ▼



**TABLE I**  
CAPACITORS USED IN THIS STUDY  
(0402 BODY STYLE)

Capacitance (pF)	1st Series Resonance (GHz)	$L_{eff}$ (nH)
0.5	14.5	0.24
0.7	11.2	0.29
1.2	8.7	0.27
1.5	8.0	0.26
3.3	5.1	0.30
6.8	3.2	0.36

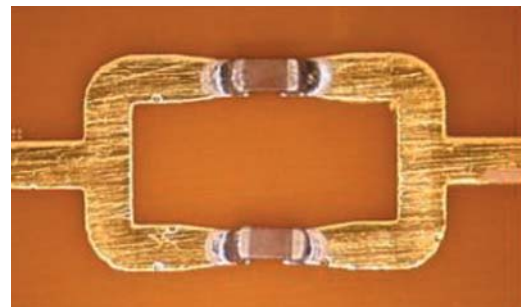
For the purposes of this analysis, a simplified series L-C equivalent circuit model (Figure 1) was used to extract an effective series inductance for each part, based on the measured first resonance:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (1)$$

The characteristics of the capacitors used in the study are listed in Table 1, as mea-

sured on 14 mil-thick FR4 using series, two-port, microstrip, test fixtures. None of the capacitors exhibited secondary, higher order resonances below 15 GHz. The series L-C model is often used to represent capacitor performance, but it will become evident in the examples presented that models with greater physical representation are required for accurate performance prediction, even in simple, two-capacitor arrangements.

The three multiple-capacitor configurations considered here are the series-parallel (Figure 2), shunt-parallel



▲ Fig. 2 Series-parallel capacitor configuration.

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(Figure 3) and shunt-series arrangements (Figure 4). Measured results for these configurations are analyzed below. In each case, comparisons are made with accurate, substrate-scaleable capacitor models.<sup>1</sup> The schematics used to generate the simulated results included a complete representation of the interconnect discontinuities.

## SERIES-PARALLEL RESULTS

A comparison of the  $S_{11}$  magnitude and phase for a series-parallel combination of a 3.3 and 6.8 pF capacitor is shown in Figures 5 and 6, respectively. In these graphs, the measured data is compared against the simulated results obtained using accurate, substrate-scaleable equivalent circuit models, and those from the simple L-C models. It is apparent that when paired together the series resonance of neither individual capacitor — which would manifest as a low  $S_{11}$  — is observed (5.1 and 3.2 GHz for the 3.3 and 6.8 pF capacitors, respectively, as listed in the table). Furthermore, if one applies the simple L-C circuit model for each capacitor and combines the two in parallel, an effective capacitance of

10.1 pF is obtained with a net inductance of 0.17 nH. From these values, a parallel resonance (minimum return loss or large  $S_{11}$ ) at 3.84 GHz is predicted, which is not evident in the data. On the contrary, a sharp series-parallel resonant frequency pair appears near 1.8 GHz, along with a strong series resonance at 11.8 GHz.

As noted above, the circuit schematics for the substrate-scaleable and simple L-C models both accounted for all discontinuity effects in the layout. The low frequency correlation between the simulated and the measurement data argues the importance of proper interconnect modeling, as the resonant effects that would be expected from even the simple L-C model analysis are not observed via simulation. The high frequency behavior points out the limitations of the simple L-C model, however, even when embedded within proper interconnect elements.

## SHUNT-PARALLEL RESULTS

Measured data and simulation results of  $S_{21}$  for a shunt-parallel combination of a 0.5 and 1.5 pF capacitor are given in Figures 7 and 8. In the shunt configuration, the fundamental (series) resonance of the capacitors results in low impedance to ground

and thus high insertion loss. The measured data show such effects at approximately 5.8 and 9.8 GHz, as do the simulated results using the substrate-scaleable model.

As an approximate analysis of this layout, each capacitor can be considered independently. Assuming the nominal capacitance value for each part, and attributing the low and high resonances individually to the 1.5 and 0.5 pF capacitor, respectively, an effective inductance of approximately 0.5 nH is extracted. Using the data in the table, it may be determined that each ground-via contributes an additional 0.25 nH inductance to the circuit. Thus, there is some consistency in treating the capacitors separately, since the analysis on each resonance yields approximately the same via inductance.

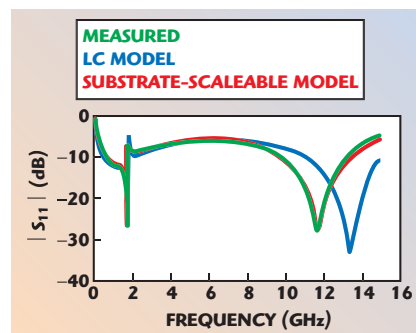
From a different perspective, one might consider first each capacitor in isolation (with its nominal capacitance and an overall inductance of 0.5 nH, after accounting for the via) and then evaluate the parallel combination of the two. This calculation leads to a net capacitance of 2.0 pF and an effective series inductance of 0.25 nH. The corresponding resonant frequency is approximately 7.1 GHz, an effect that would lead to high insertion loss and one not noticeably present in the



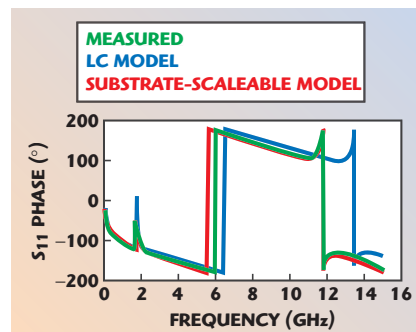
▲ Fig. 3 Shunt-parallel capacitor configuration.



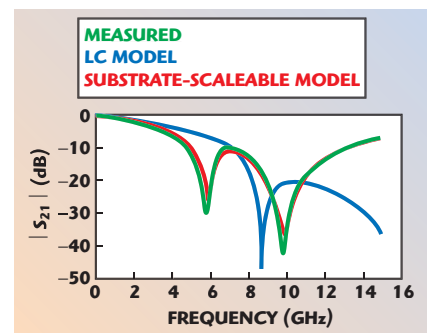
▲ Fig. 4 Shunt-series capacitor configuration.



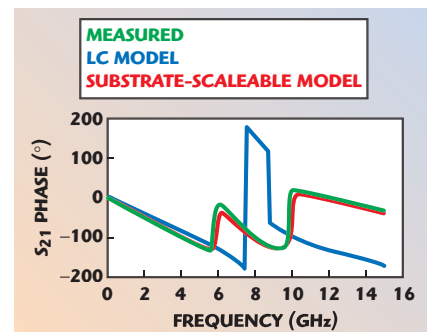
▲ Fig. 5  $S_{11}$  magnitude for a 3.3 and 6.8 pF capacitor in the series-parallel configuration.



▲ Fig. 6  $S_{11}$  phase for a 3.3 and 6.8 pF capacitor in the series-parallel configuration.

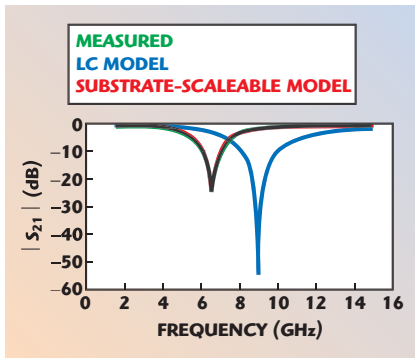


▲ Fig. 7  $S_{21}$  magnitude for a 0.5 and 1.5 pF capacitor in the shunt-parallel configuration.

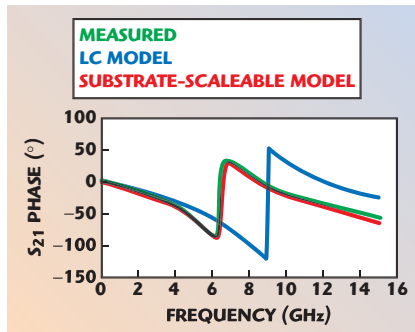


▲ Fig. 8  $S_{21}$  phase for a 0.5 and 1.5 pF capacitor in the shunt-parallel configuration.

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▲ Fig. 9  $S_{21}$  magnitude for a 0.7 and 1.2 pF capacitor in the shunt-series configuration.



▲ Fig. 10  $S_{21}$  phase for a 0.7 and 1.2 pF capacitor in the shunt-series configuration.

graphs. The simple L-C representation does, however, falsely predict a single resonance behavior (near 8.8 GHz).

## SHUNT-SERIES RESULTS

Finally, consider the shunt-series combination of a 0.7 and a 1.2 pF capacitor. Measured data and simulation results of  $S_{21}$  for this case are shown in **Figures 9 and 10**. As before, a preliminary analysis based on the simple series L-C model is used for each capacitor.

From the data in the table, along with the 0.25 nH via inductance determined above, the total inductance of the combined circuit is found to be 0.81 nH. The effective capacitance of the series combination is 0.44 pF. This analysis leads to the prediction of a resonance at 8.4 GHz, whereas the measured results show it to occur at 6.5 GHz. It might be argued that the interconnect-line between the two capacitors introduces an additional inductance, tending to lower the resonant frequency. While this is true to some extent, the overall inductance would have to be greater

than 1.3 nH in order for the frequency to drop to 6.5 GHz (assuming the net capacitance remained at 0.44 pF). It is unreasonable to assume that the short interconnect-line, which is less than 1 mm in length, adds more than 0.5 nH to the circuit.

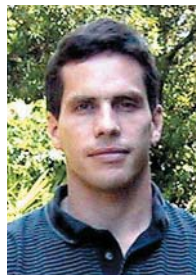
As was found with the shunt-parallel circuit, simulated results using the simple L-C model, along with complete interconnect models, incorrectly predict the frequency response. The L-C model simulation indicates the resonance to occur very near to the frequency arrived at from the preliminary analysis (8.9 versus 8.4 GHz). Such a result may provide misplaced confidence in CAE simulation results.

## CONCLUSION

A well-argued analysis, based on inadequate capacitor models, thus fails in varying degrees for the three examples described. In each case the distributed effects of the interconnect-lines play a role in determining the frequency response. However, the most significant factor required in accurately predicting the circuit behavior is the capacitor model. The substrate-scaleable models provide nearly exact comparisons to the test results. Simplified L-C models, which might closely emulate measurement data from a series two-port test fixture, often prove to be inaccurate when used in common circuit configurations. ■

## References

1. "Advanced Microwave Chip Capacitor Models," *Microwave Journal*, Vol. 45, No. 1, January 2002, pp. 190-192.



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