



Precision Measurements and Models You Trust

White Paper

UNDERSTANDING S-PARAMETER VS EQUIVALENT CIRCUIT-BASED MODELS FOR RLC COMPONENT SIMULATIONS WITH NI/AWR MICROWAVE OFFICE

Abstract

For many years, S-parameter data files have been the default industry standard for representing passive surface mount devices in the microwave industry. In many cases, however, S-parameters fall short in terms of equipping designers with the simulation capability that is needed for circuit design success. In contrast, a properly extracted equivalent circuit model can avoid many inherent limitations of data file representations and provide for scaling, extrapolation, and statistical yield analyses not easily accomplished with S-parameters alone. This article discusses “best-practice” surface-mount component modeling from a number of points of view. Several examples are presented to illustrate common problems with S-parameter models and solutions that can be accomplished using a combination of modern tools. These tools include on-board RF probing, electromagnetic analysis and complex equivalent circuit modeling. The equivalent circuit models enable simulations that can very accurately represent microwave as well as mm-wave passive surface mount devices in ways that enable reliably successful circuit design flows from synthesis, through optimization and yield analysis to measured results that correlate well with simulation predictions using National Instruments (formerly AWR) Microwave Office.

Introduction

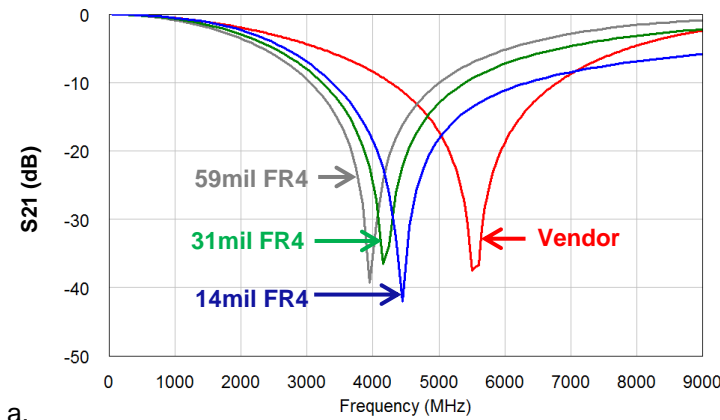
The S-parameters provided commonly in the industry for passive RLC components are typically obtained using a split-block fixture and loose devices. However, practical circuits do not use components in this environment; instead they are soldered onto custom pads on a specific substrate. Pad geometry, substrate characteristics and other standard assembly features have significant effects on the performance of a surface mount component, especially at increasing frequencies. A more representative test fixture for obtaining S-parameters of a surface-mount component is to solder mount it on a substrate along with microstrip interconnects. Figure 1 shows the variation of S-parameters for a SMT inductor as measured on different substrates along with S-parameters downloaded from the vendor’s website. Note that all data are in agreement below 500 MHz, but at higher frequencies significant differences emerge. The frequency at which such substrate-dependent variations emerge will vary with component type, size, value and mounting configuration. Also shown in Figure 1 is how one might approach construction of a simple equivalent circuit model for such an inductor (Fig. 1b). Two different fixturing approaches are also suggested with the solder mounted approach (Fig. 1d) being preferred over the commonly used split block approach (Fig. 1c) for development of scalable models in-line with PCB design applications.

S-parameter models are most commonly based on a standard file format known as “.s2p” or “Touchstone” file format. The data in these files represents the 2-port (or N-port) S-parameter data for a discrete set of frequencies from some practical start frequency and stop frequency. Common S-parameter start frequencies are 10 MHz or 50 MHz (sometimes lower, sometimes higher) to some upper frequency typically set by instrument or fixture limitations. Common upper frequencies for vendor S-parameters for surface mount devices are 3, 6 or sometimes 18 GHz, occasionally higher. S-parameter files and S-parameter-based models are sometimes provided by Modelithics. Our standard approach is to measure the device in a manufacturer’s suggested surface mount configuration using RF probing and custom calibration standards. Detailed information about the fixture and reference plane locations are provided,

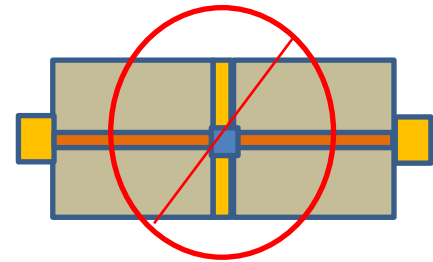


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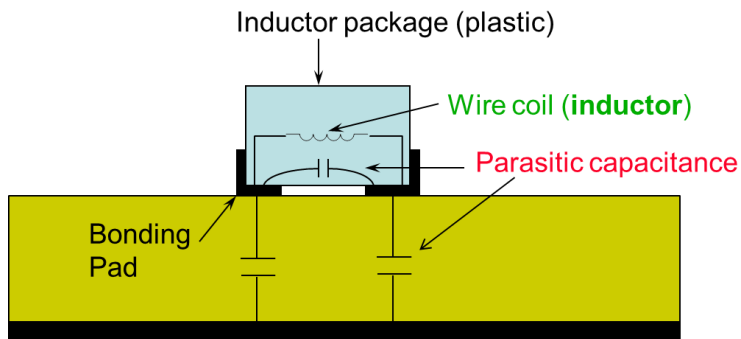
so that the test conditions are known and repeatable. In some cases convenient pull-down menus facilitate part value selection. A preferred solution available from Modelithics that has many advantages over S-parameter models for surface mount devices is that of using accurate and scalable "Global" equivalent circuit models. This note will explore the benefits of such models for accelerating design success using electronic design automation (EDA) tools, such as AWR's Microwave Office.



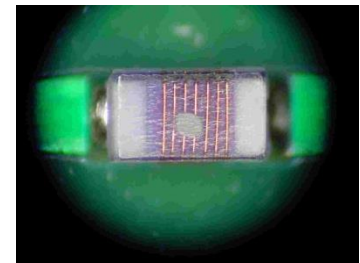
a.



c.



b.



d.

Figure 1. Measurement and modeling of a surface mount inductor. a. Measured S_{21} data of a 0805 inductor as mounted between microstrip interconnects on multiple FR4 substrate thicknesses. The S_{21} response from vendor-provided S-parameter data is also shown in grey. b. Physical motivation for some of the elements of a complex equivalent circuit for such an inductor. c. Split-block fixture approach used for many commonly available S-parameter libraries. d. Solder mount fixturing approach used for Modelithics Global models (device shown is a surface mount inductor.)



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Scalable Equivalent Circuit Models

Modelithics Global Models™ are equivalent circuit models that are based on actual device measurements usually tested on various substrate types to allow for substrate scalability [1]. Substrate scalability of a model is important in achieving accurate simulation results, considering the variation in response seen for a component measured on different substrates, as in Figure 1. Figure 2 shows an example S-parameter simulation setup for a Modelithics Global model for a surface mount capacitor. The model itself is a complex equivalent circuit, which allows for accurate analyses that predict self-resonance as well as higher order resonant behavior in a way that scales with model and simulation input parameters. This scalability enables efficient design optimization for circuits such as filters and matching networks [2]. Model inputs for the model shown include a required substrate specification, a simulation mode switch (0/1/2 → full parasitic/ideal/pads removed), pad dimensions and a physical orientation switch (0/1 → horizontal/vertical).

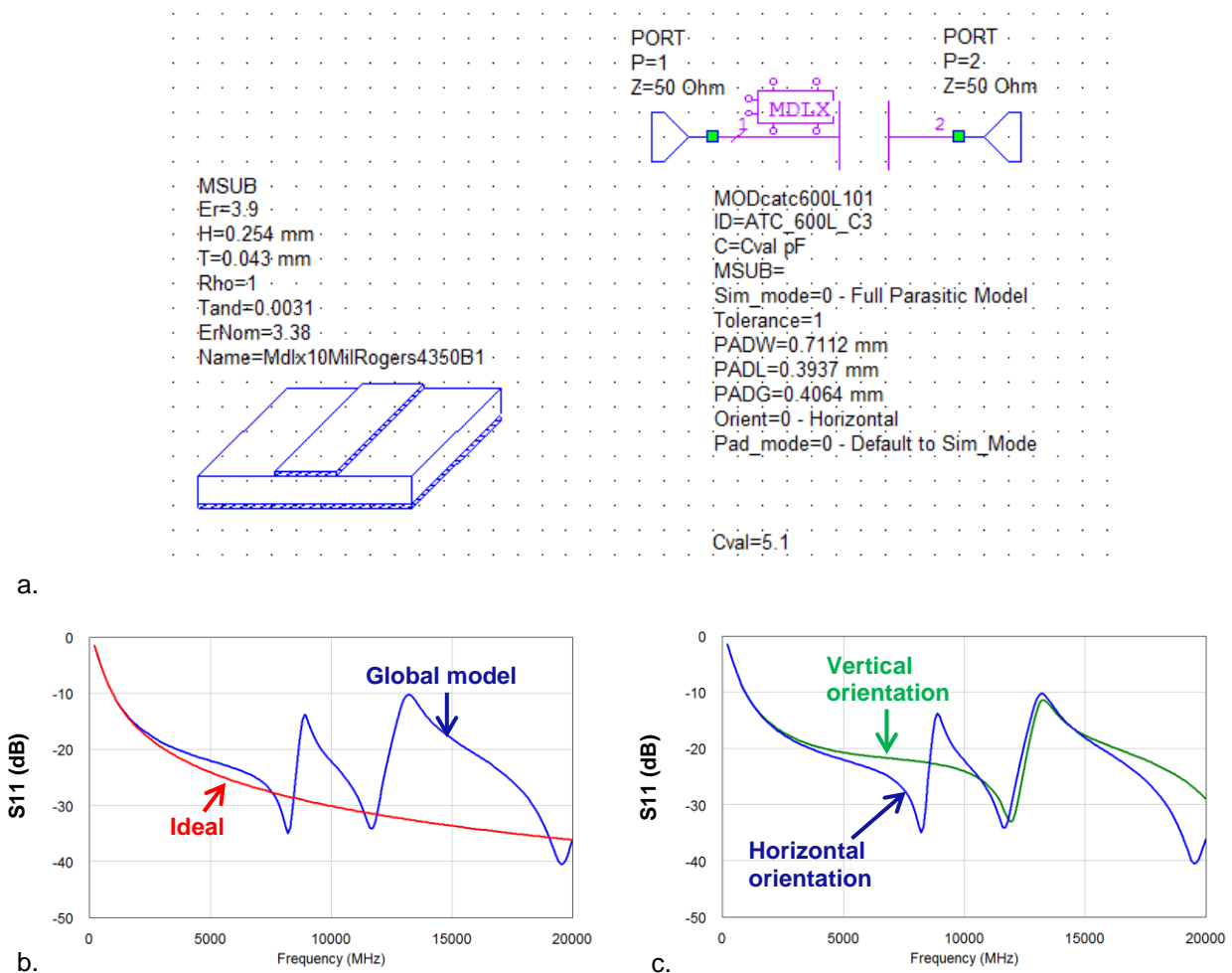


Figure 2. a. Example simulation setup in AWR Microwave Office for a Modelithics Global model whose scalability and input parameters include nominal part value, substrate, pad geometries, simulation mode and orientation switches. b. Simulated S₁₁ comparison of an ideal 5 pF capacitor (red) compared to Global Model (blue). c. Simulated S₁₁ comparison for Global Model for 5 pF capacitor in horizontal (blue) and vertical orientations (green).



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As mentioned above, surface mount components exhibit substrate-dependent performance. The substrate's effects increase as frequency increases. For capacitors and inductors, the primary resonant frequency can vary as much as 7 times between a 5-mil and a 59-mil thick FR4 PCB depending on the component value. Figure 3 shows S_{11} simulations from Global Models for typical capacitor, inductor and resistor families, simulated at 2 GHz for a wide range of part values. Shown is the ideal performance along with performance on various substrates for each component family.

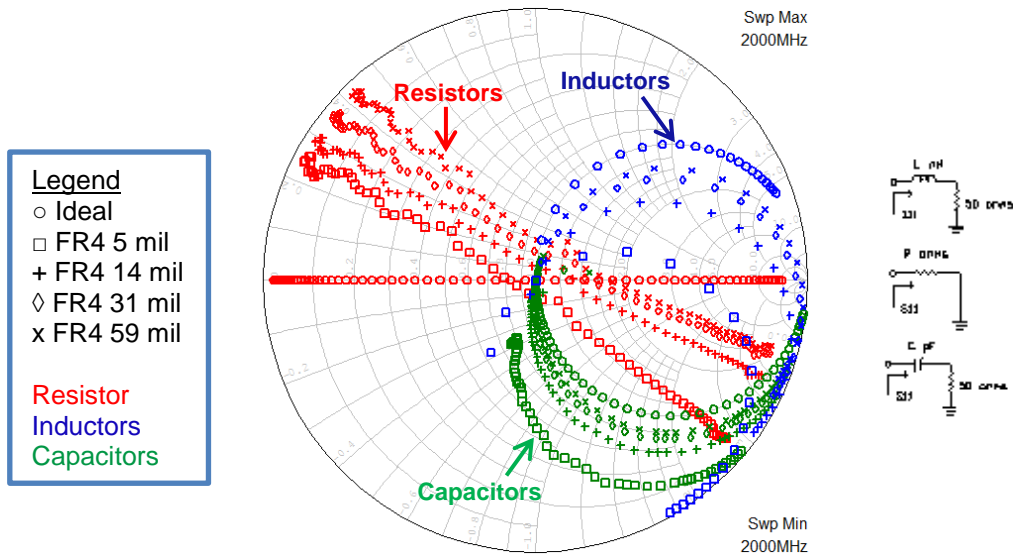


Figure 3. Substrate dependent S_{11} behavior for surface mount resistors (red), inductors (blue), and capacitors (green) at 2 GHz.

In Figure 4, measured and modeled results are displayed for a broad-band DC blocking capacitor [3]. Measurement data is included for performance on various substrates up to the maximum valid frequency, which varies with substrate. Simulations are shown to 65 GHz and show smooth well-behaved model extrapolations beyond where measurement data may be available. In addition, good measured to simulation data agreement is demonstrated for the 5-mil alumina substrate where measurement data out to 65GHz is available.

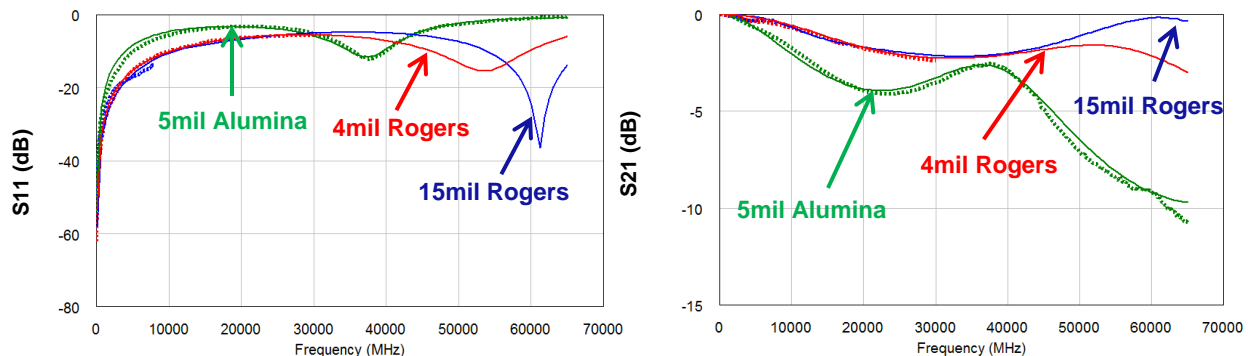


Figure 4. Substrate dependent S_{11} (left) and S_{21} (right) behavior for a broad-band DC Blocking capacitor measured and modeled through 65 GHz. Legend (Lines – Model simulations, Symbols - Measured data) : □ 4mil Rogers 4350B, + 15mil Rogers TMM10, ◇ 5mil Alumina, Measured data stops at highest valid frequency for each substrate (4 mil - 30 GHz, 60 mil - 8 GHz, 5mil Alumina - 65GHz).



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Extrapolation Performance of Equivalent Circuit Models

Devices modeled with a sufficiently complex, physically motivated, equivalent circuit can predict high order resonance performance, and will never produce non-physical results during frequency extrapolation. In contrast, both high and low frequency extrapolation of S-parameter data can produce errors and non-physical results leading to design simulation problems [4]. At high frequencies, S-parameter data can show positive values if simulated outside the frequency range of the measurements. As seen in Figure 5, it is clear that the frequency limit of the S-parameter data is around 9.4 GHz, as the S_{21} response of the vendor data must be extrapolated past this point. Depending on the extrapolation settings in the circuit simulator, this can result in non-physical results (e.g. $>0\text{dB } S_{11}$ for a passive device). Modelithics Global equivalent circuit model performance trends very well with the measured data (e.g. please refer to the model information data sheet available for all Modelithics models [5]).

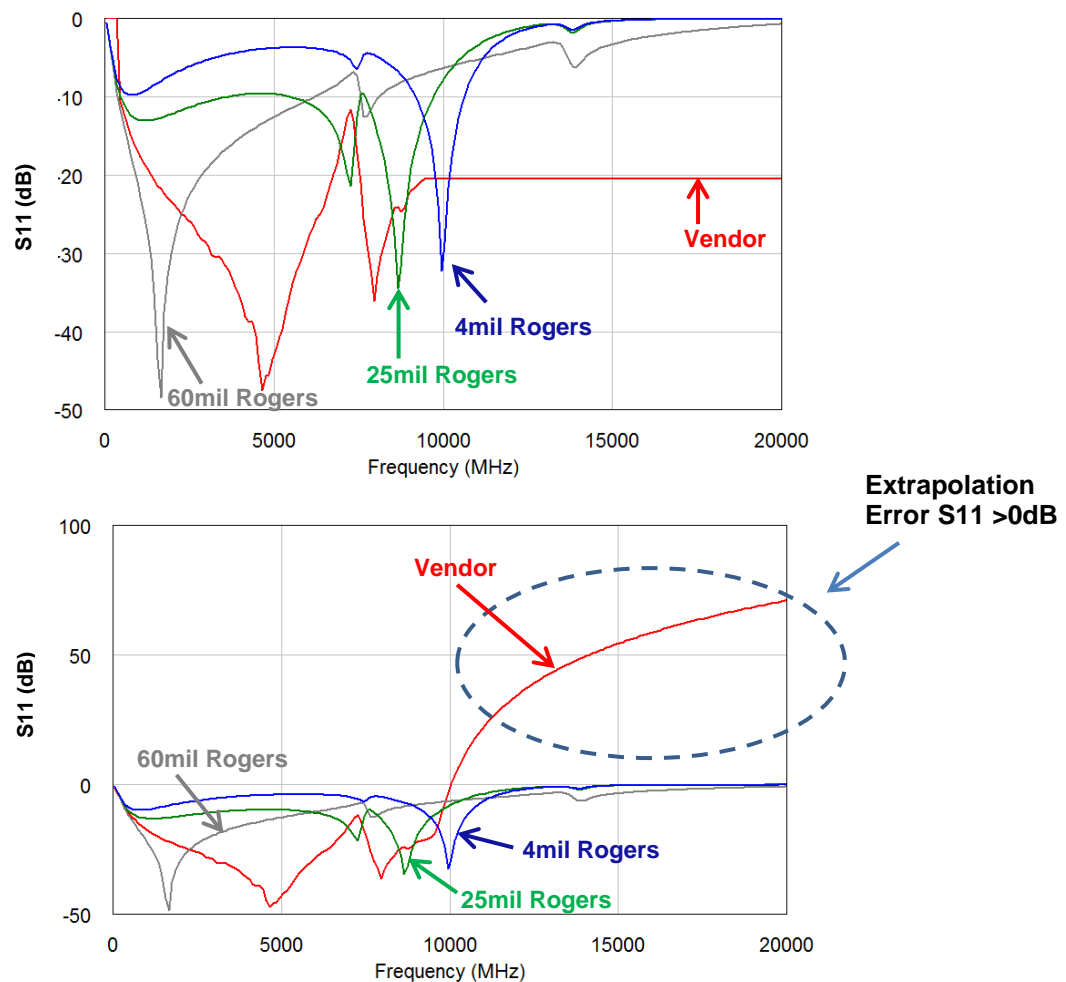


Figure 5. Simulated S_{11} results for a 12pF 1111 size SMT capacitor. Equivalent circuit model results for three different substrates. Red - vendor S-parameter data, Blue - 4 mil Rogers 4350B, Green - 25 mil Rogers 6010LM, Grey - 60 mil Rogers 4003C. (which is only provided in this case to 9.4 GHz), showing erroneous high-frequency extrapolation after 9.4GHz using “floor” interpolation (upper) and “cubic” interpolation (lower) methods. The interpolation method can be set in AWR by double clicking the S-parameter block and selecting “Show Secondary” on the *Parameters* tab.



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Extrapolation errors can also occur at low frequency when using S-Parameter files. The equivalent circuit model is designed to trend towards ideal device behavior at DC, but the S-Parameter measurement extrapolation is incorrect below the lower frequency limit of the data (Figure 6).

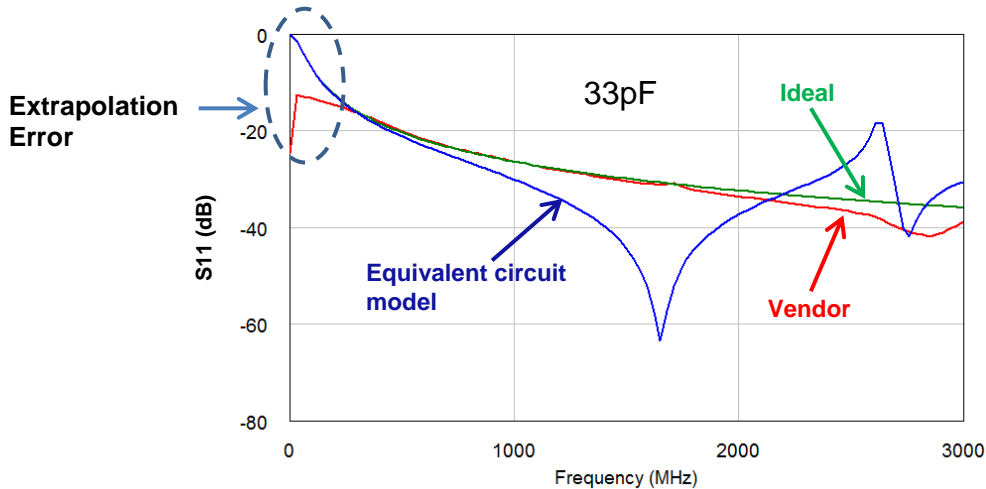


Figure 6. Illustration of low-frequency extrapolation errors of modeling with S-Parameter files. The blue equivalent circuit model simulation lines up with an ideal capacitor characteristic (green) near DC. The red S-Parameter data does not extrapolate correctly below the starting frequency of the data.

ESR Representation in Equivalent Circuit Models

S-Parameters, referenced to 50 ohms, are often not sensitive enough to accurately capture the effective series resistance (ESR) of high Q components. For modeling, Modelithics takes the loss factor information from either a resonant (Boonton) line technique or an impedance analyzer measurement. Figure 7a provides an example capacitor model ESR response versus capacitance frequency compared to measured data. Although ESR is independent of the substrate, Q-factor can vary due to changes in the reactance introduced by the substrate the element is mounted on. Figure 7b demonstrates this phenomenon.

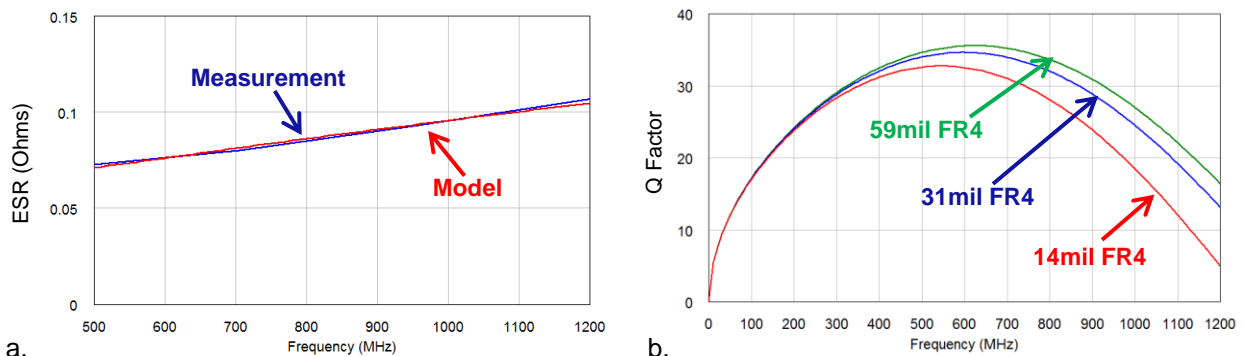


Figure 7. a. ESR (Ω) with respect to frequency for a 3.3 pF capacitor. Red line: model performance. Blue line: average measurement data. b. Simulated Q-factor for a 22 nH SMD inductor on varying substrates.



Statistical Simulations

Another advantage of the equivalent circuit model approach is in representing manufacturing tolerance. Results from a Yield Analysis simulation of a 2.2GHz low pass filter [2] using Gaussian distributions about the nominal part values are shown in Figure 8. In the simulator, the standard deviations for the inductors and capacitors were specified at +/- 1.66% and +/- 5%, respectively. Over 30 simulation trials, the extreme capacitance values obtained were 86% and 114% of the nominal value, or about three standard deviations. This is a typical result, and is the reason why the specified standard deviation in a simulator should be ~33% of the vendor-specified tolerance if the part value spread is assumed to be Gaussian [6]. In light of this, Figure 9 shows the results of a Yield analysis using a bi-modal (Normal - Tol) Gaussian distribution for the capacitors.

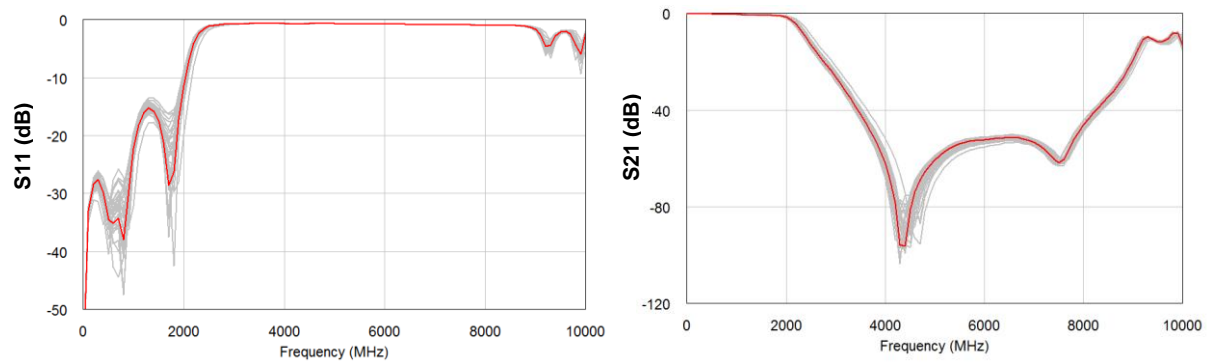


Figure 8. Yield simulation (grey) results using Gaussian distributions for the inductors and Gaussian distributions for the capacitors around the nominal value. The red curve is the filter simulation using Modelithics Global models and microstrip line interconnects and the grey represents the statistical simulation.

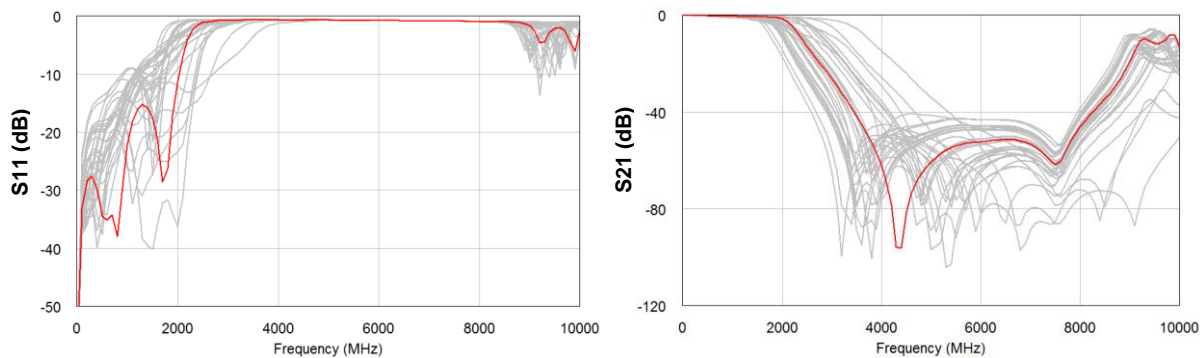


Figure 9. Yield simulation (grey) results using Gaussian distributions for the inductors and bi-modal Gaussian distributions for the capacitors around the nominal value. The red curve is the filter simulation using Modelithics Global models and microstrip line interconnects and the grey represents the statistical simulation.



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Pad Effect Treatment

Surface mounted components experience a pad effect based on the dimensions of the footprint used. Information regarding the pad dimensions, if used, for S-Parameter files is not usually provided by the vendor. This can add another degree of uncertainty in the design process. Modelithics provides a solution to this uncertainty [7,8]. Many Modelithics Global models offer pad scaling through measurement and validation over a range of footprint dimensions. In addition, Global models offer several options for pad effect treatment during simulation. Model setting “Sim Mode = 0” includes the measured pad effect and can be adjusted over the range of pad dimensions validated for the model. In this mode, the reference planes are at the outer edges of the pads (see model datasheets); “Sim Mode = 1” will simulate the device as an ideal component; And “Sim Mode = 2” will de-embed the pad models and pad effect, and moves the reference planes to the edges of the part so the designer can add custom pads to the design.

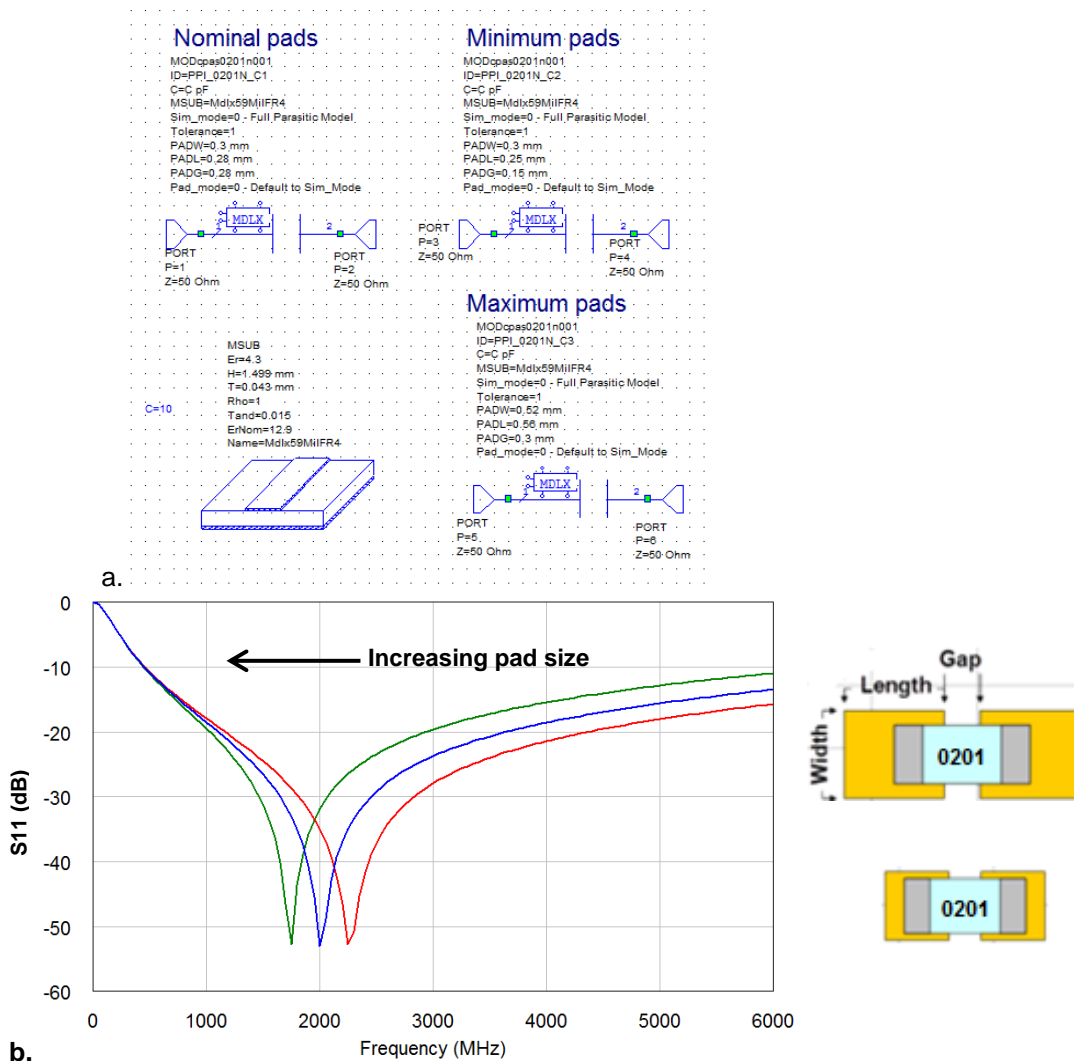


Figure 10. a. Example of pad geometry and pad geometry scaling effects as simulated with a Modelithics Global Capacitor Model in AWR Microwave Office. b. From right to left (red to green): Increasing pad dimensions. Above shows the model schematics and substrate definition used to generate the graphical results.



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EM Co-Simulation with Equivalent Circuit Models

Some designers may want to use EM analysis for pad treatment. Reasons may include: use of a pad size different from the one included with the model (or outside the range of pad dimensions if using a pad-scalable model), adding the step effect when the feed line is different from the pad width (this step can also be included using an analytical model in a circuit simulation), adding the effects of coupling between the pads and another part of the circuit, and having the desire to simulate the pads along with other printed circuit patterns as a standard practice. Equivalent circuit models offer flexibility for designers working with EM simulation, provided due attention is paid to port-treatment [9].

One approach for EM co-simulation of pad effects when using Modelithics models is to use the pad de-embedding feature of the model (“Sim Mode = 2”), and model the pad geometry with EM analysis [10]. Figure 12 provides an example of a layout in the EM simulator and Figure 11 provides an example of a model utilizing the “Sim Mode 2” feature. Example EM co-simulation results for a series mount inductor are shown in Figure 12 (based on the setup of Figure 11).

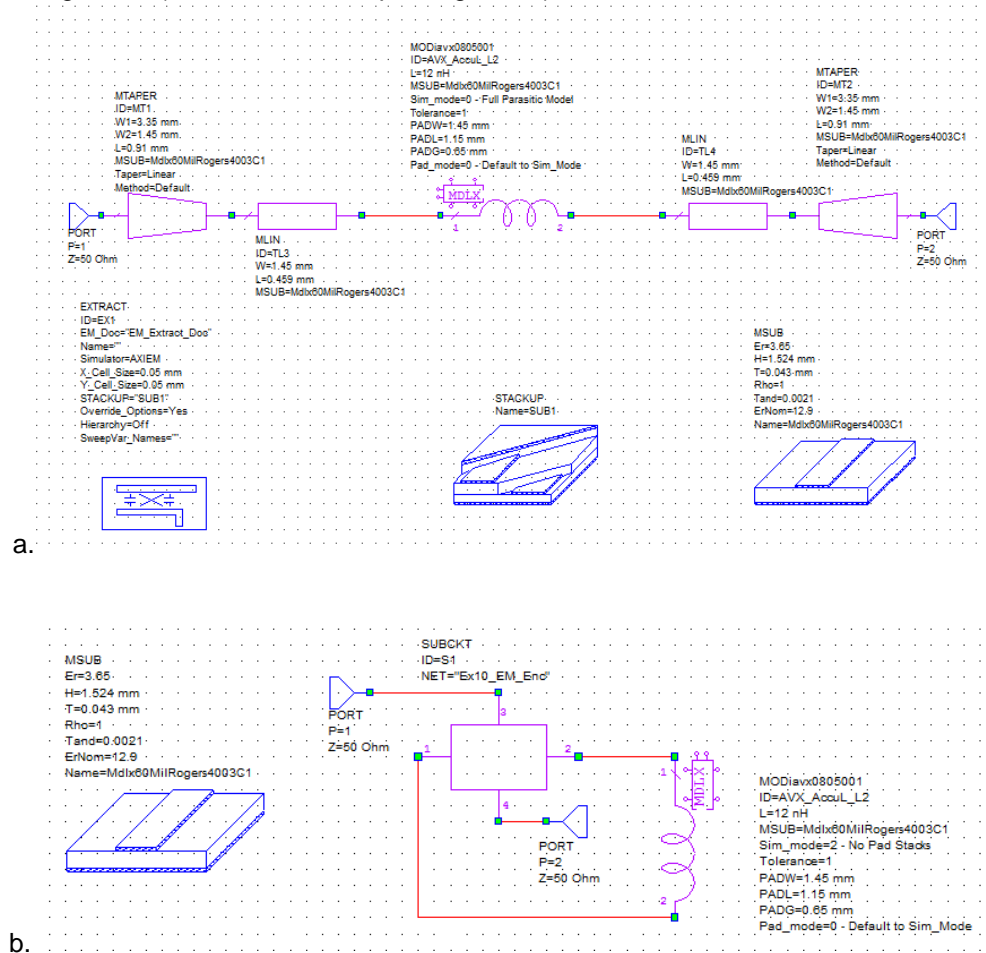


Figure 11. Example of a co-simulation using a Modelithics Global model utilizing the “Sim Mode 2” feature. a. Schematic to setup EM Extraction in Axiem. Pads and internal edge ports will have to manually drawn into EM structure. b. Schematic for co-simulation.

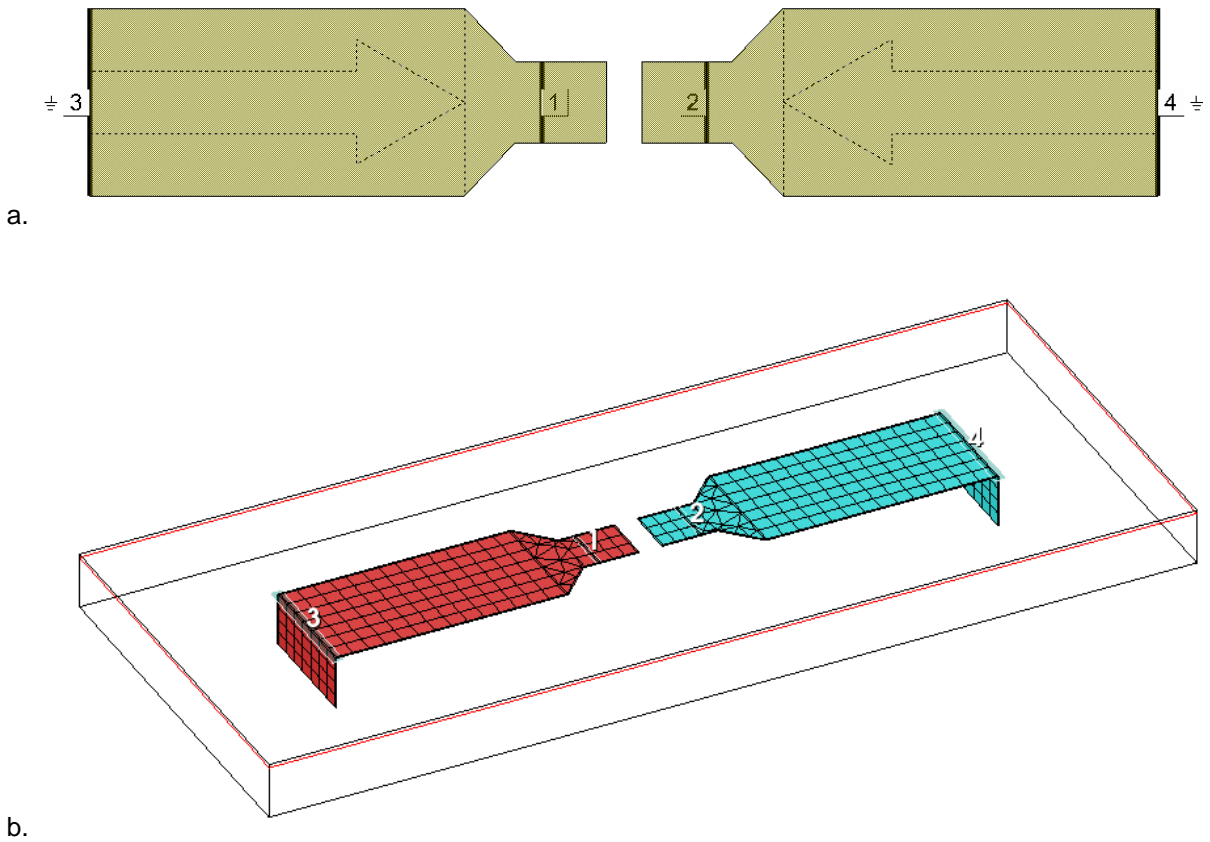


Figure 12. Example of a series component mount layout in the Axiem EM simulator. a. EM Structure. b. meshed structure.

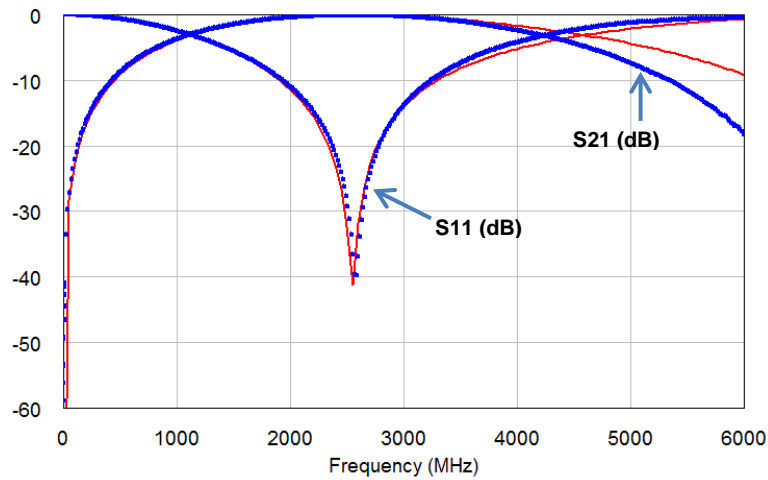


Figure 13. Example EM co-simulation results (red line) compared to measured data (blue circles) for a surface mount inductor.



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Conclusions

S-parameter models are helpful and sufficient for many needs; however scalable equivalent circuit models, such as those exemplified in this note, are significantly superior in terms of the accuracy, the flexibility, and the convenience they offer. Designers are able to simulate using their specific application environment, including substrate influences and mounting pad effects. With such scalable equivalent circuit models in their EDA tool kit, designers can more reliably and efficiently perform part optimization, statistical analysis, and EM co-simulation on designs. Equivalent circuit models will also prevent potentially large frequency extrapolation errors and will accurately represent ESR, even for high-Q components.

Modelithics Global equivalent circuit models are developed to equip designers with the tools necessary for first pass design success and increased confidence that what they see in the simulation environment is a more reliable representation of what they will get on the test bench.

References and Additional Reading:

(some web resources listed require one-time web registration at www.modelithics.com to down-load)

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2. "Lumped Element Filter Design and Optimization," Modelithics AN 017. <http://www.modelithics.com/literature.asp>
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Note: please contact Modelithics at info@modelithics.com if you have any difficulty locating or downloading any of the above references.

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