



Electromagnetic Simulation Software

Antenna Analysis using FDTD and Equivalent Circuits

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The Objective and Approach

- Antennas with real-world RF devices:
 - For example, an antenna with a matching circuit using real inductors and capacitors; an antenna with a bandpass filter.
 - For these RF devices, only measured S-parameters or other parameters are available at a limited frequency band.
- To simulate these antennas with real-world RF devices in a time domain method:
 - Rational models can be created from the measured parameters of the RF devices by extracting the pole-residue pairs.
 - The rational models are then used to generate equivalent circuits.
 - The equivalent circuits are finally simulated in the time domain by using FDTD and circuit co-simulation method.

Rational Models

The frequency domain admittance can be fitted by the rational functions and be expressed by the pole-residue pairs:

$$Y(s) = \sum_{i=1}^m \frac{r_i}{s - p_i} + k_0 + sh$$

where m is the number of the poles, r_i and p_i are the residues and poles, k_0 and h are the constant and linear terms, respectively, and s is related to the angular frequency $j\omega$.

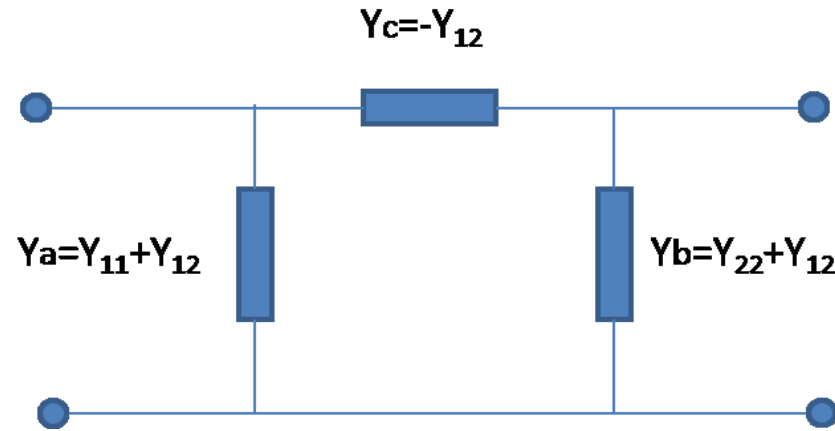
The inverse eigenvalue passivity enhancement method is applied for the extraction of pole-residue pairs because it guarantees causality and passivity.

Generation of Equivalent Circuits from Rational Models

- The constant term is equivalent to a resistor.
- The linear term is equivalent to a capacitor
- The real poles are equivalent to a series RL circuit.
- The complex pole-residue pair is equivalent to
 - ✓ a series RL and a R||C circuit.
 - ✓ a series RLC with a voltage controlled current source (VCCS).
- For multiple poles / pole-residue pairs, these equivalent circuits are parallel with each other.

Two Port RF Devices

A Pi equivalent circuit may be created from the Y-parameter matrices of the 2-port RF device. Only Y_{12} is used due to the reciprocity of the passive networks.



This concept is valid for general n -port reciprocal network.

$$Y_i = \sum_{j=1}^n Y_{ij}, i = 1, \dots, n,$$
$$-Y_{ij} \quad i = 1, \dots, n - 1; j = i + 1, \dots, n$$



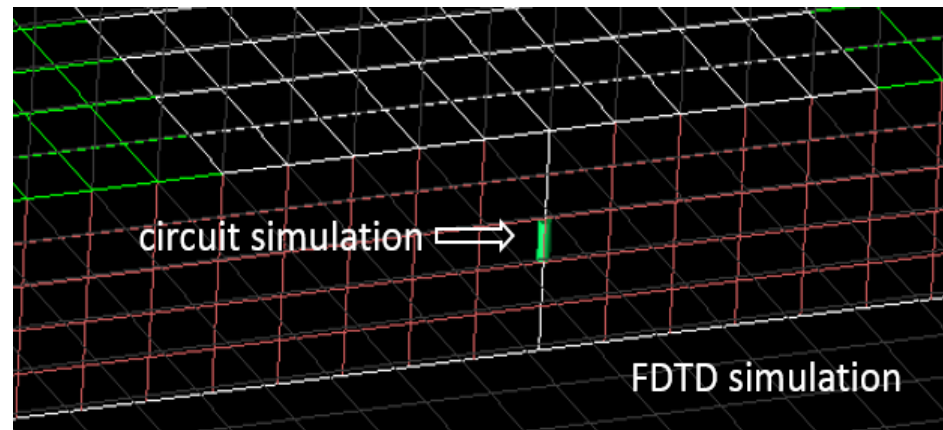
FDTD and Circuit Co-Simulation Method

- The FDTD method is popularly used for the EM simulation of complex geometries and materials.
- However, the full wave EM method has limitations in simulating complex circuits.
- It will make the FDTD solver more powerful if it can be combined with a time domain circuit solver.
- In the FDTD circuit co-simulation, each circuit takes one Yee cell edge in the FDTD meshes.
- For a 2-port circuit, such as the Tee or Pi network, the circuit can be integrated with the discrete source in the FDTD simulation.

N. M. Kriplani, J. Fletcher, S. Langdon, C. W. Penney, S. A. Fast and M. B. Steer, "Integration of FDTD EM analysis and transient circuit simulation of RF systems," IEEE International Microwave Symposium, Boston, 2009.

Communications between Two Solvers

- The FDTD solver and the time domain circuit solver can communicate with each other by using the current and voltage at the Yee cell edge at each time step.
 - The current at the Yee cell edge calculated from the FDTD solver is passed to the circuit solver.
 - The voltage at the Yee cell edge calculated from the circuit solver is passed to the FDTD solver.

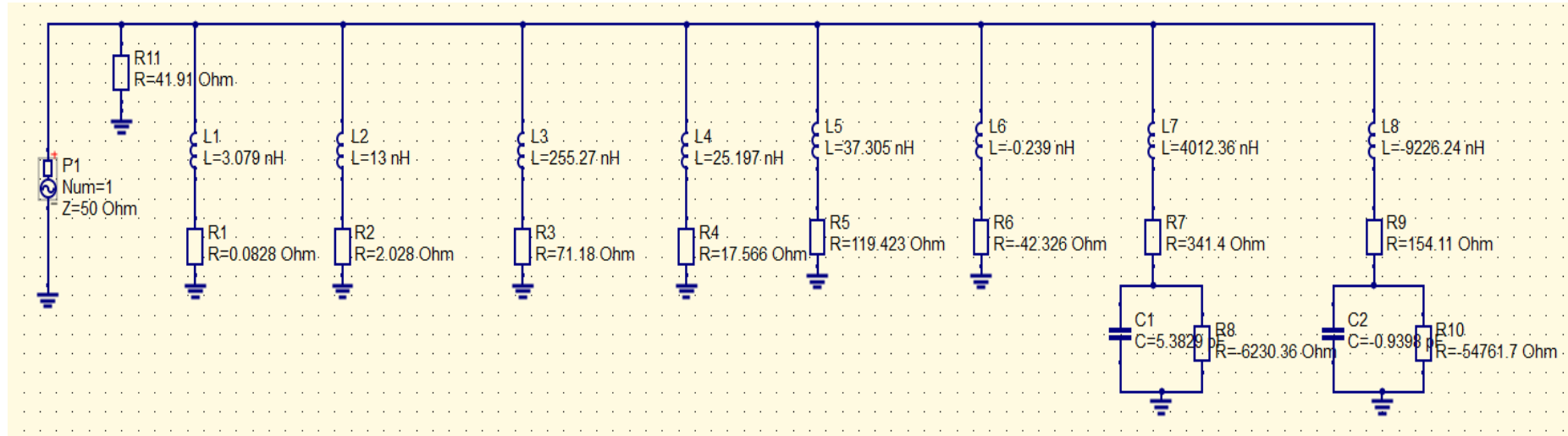




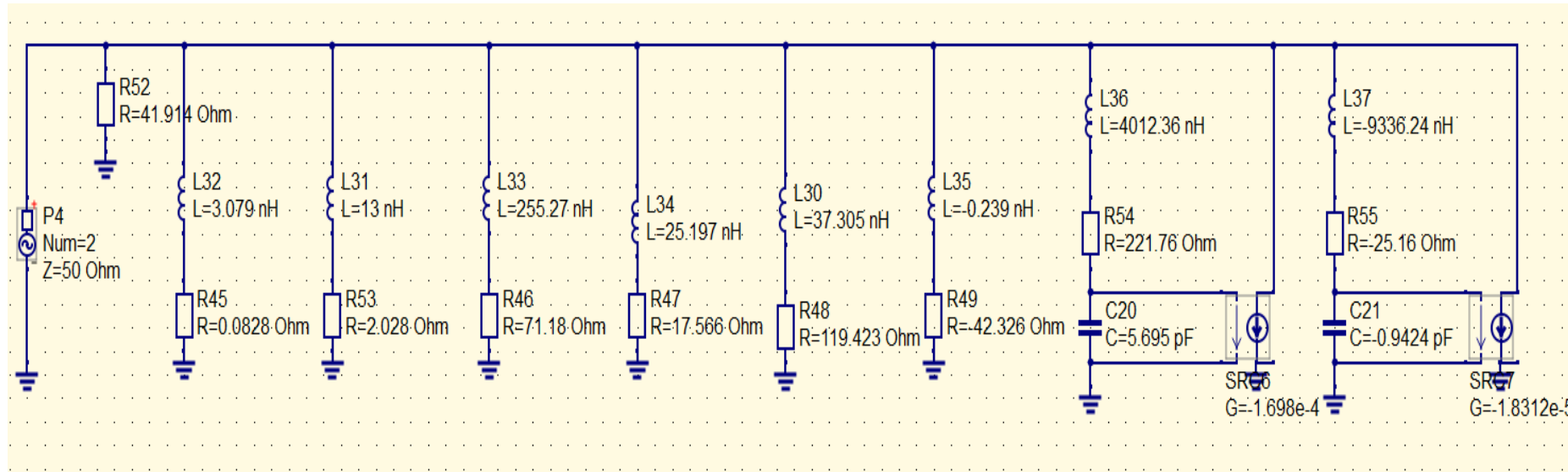
Chip Inductor LQP03PN2N2C02 from Murata

- The measured spectrum of inductance L and quality factor Q are available from the manufacturer.
- The L and Q are used to create the admittance Y -parameters.
- A constant term, six real poles and two complex poles are extracted for this inductor.
- The equivalent SPICE networks are then generated from the poles and residues using RLC circuits and RLC circuits with VCCSs, respectively.

Equivalent Circuits of the Inductor

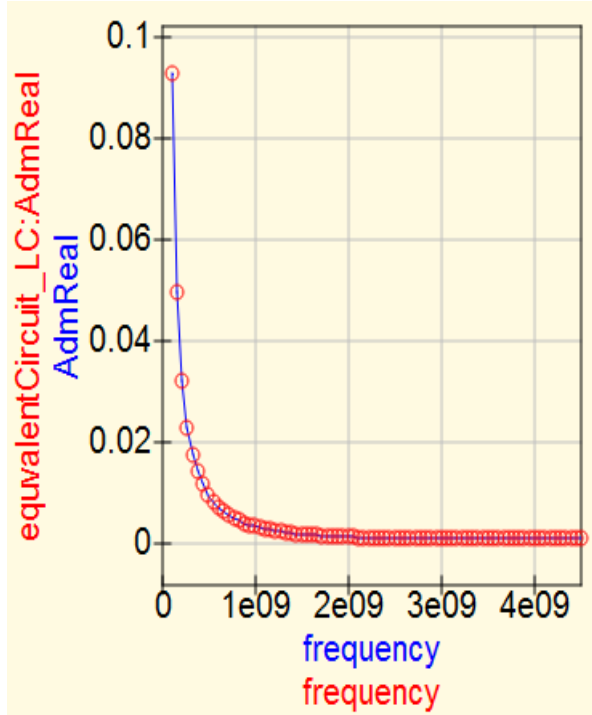


RLC circuits

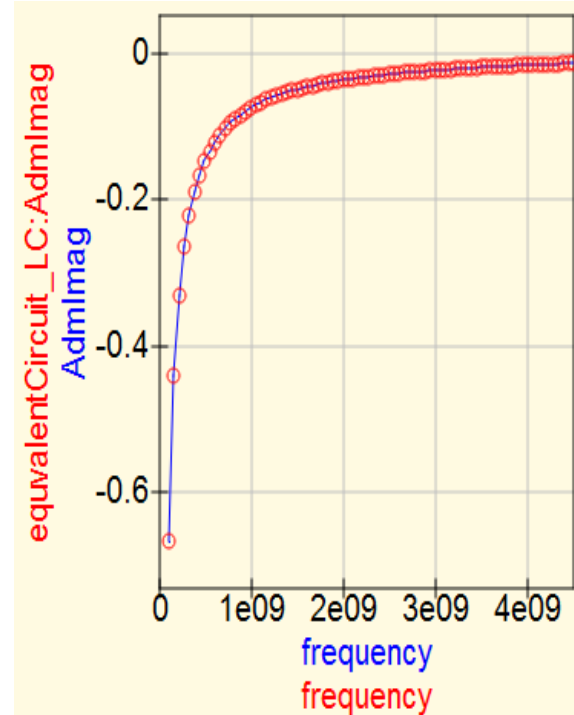


RLC circuits with VCCSs

Comparison of Admittance of the Inductor

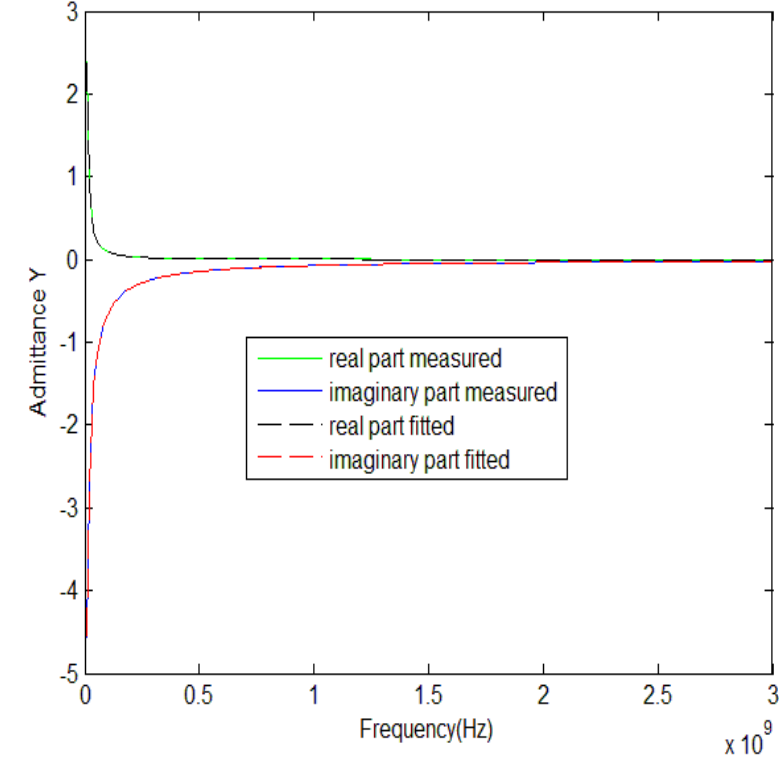


real part



imaginary part

simulated using the equivalent circuits with and without the VCCSs



curve-fitted using rational model and originally measured



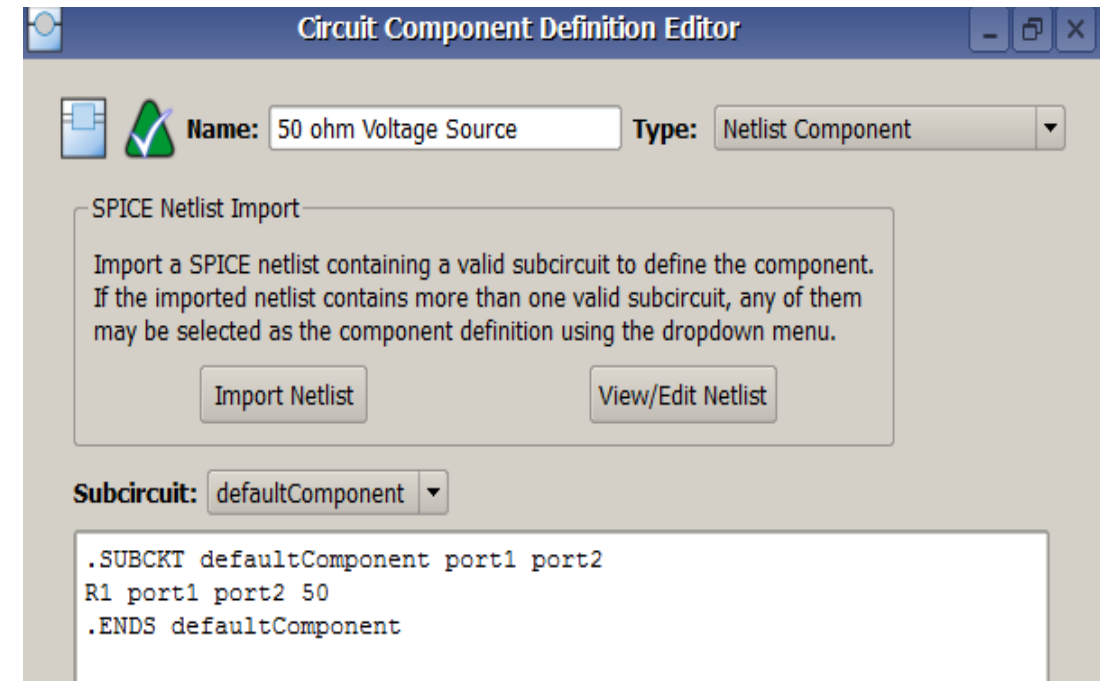
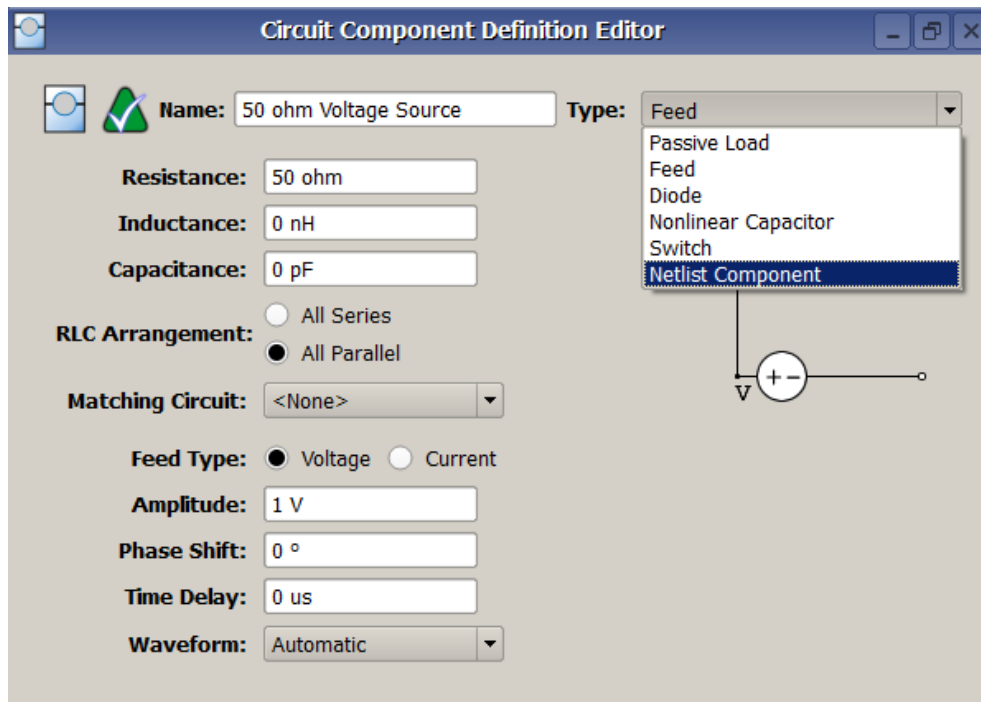
Y. Wang and S. Langdon, "FDTD simulation of real lumped components and RF devices," European Conference on Antenna and Propagation (EuCAP), Davos, Switzerland, April 2016.

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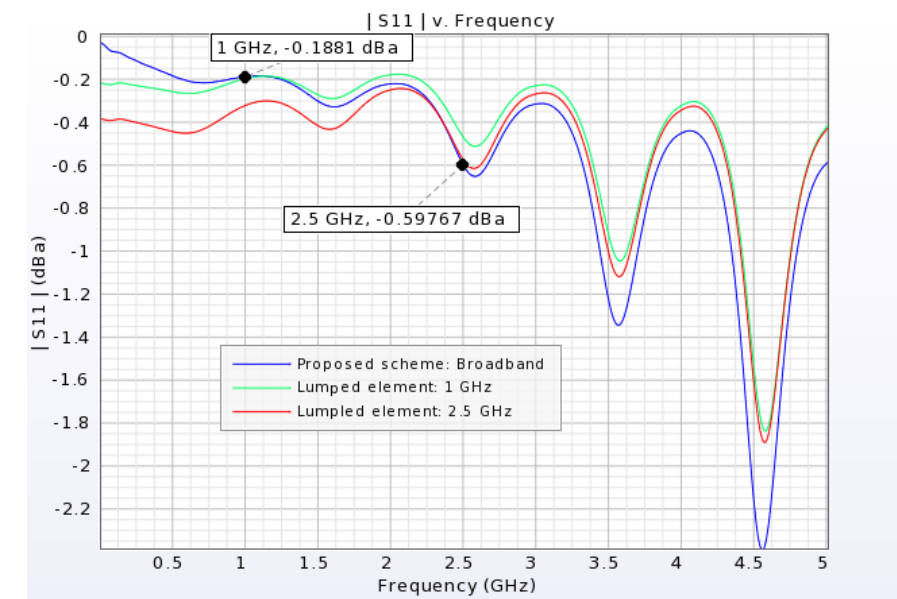
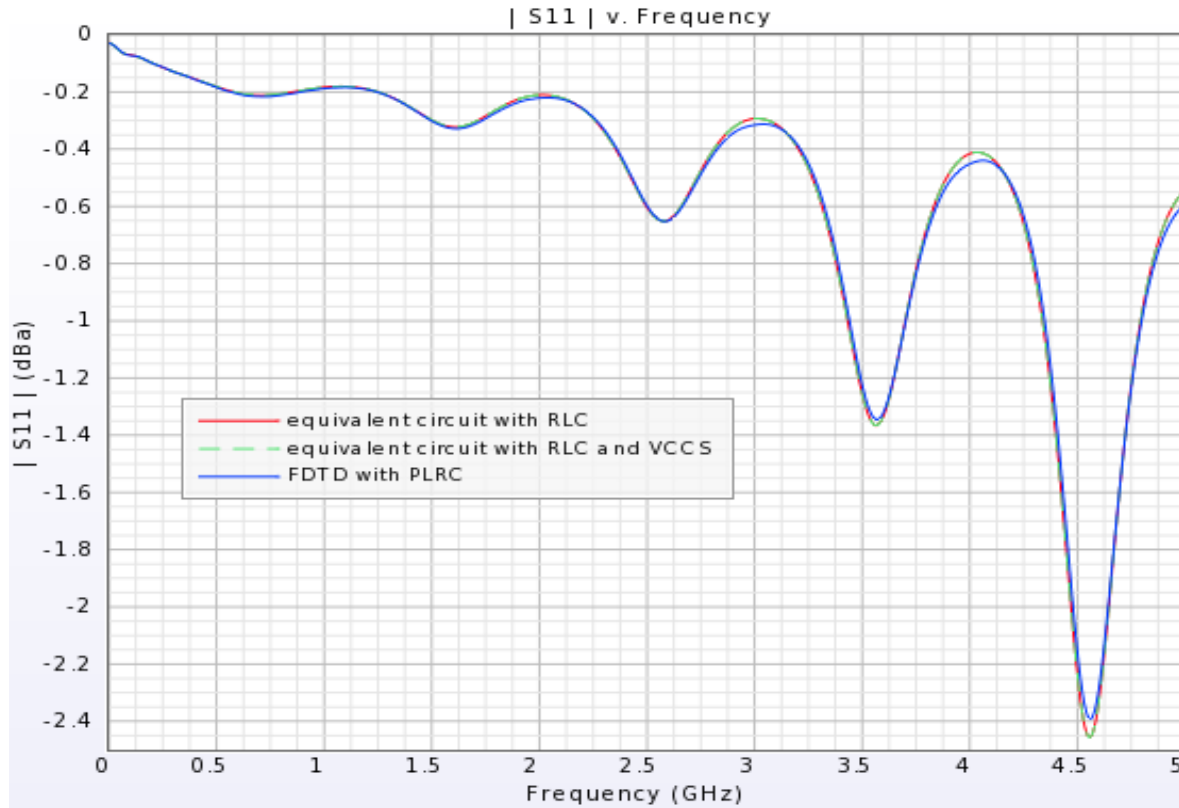
FDTD and Circuit Co-Simulation



XFDTD offers some support for SPICE3 netlists to be used as a circuit component definition. This allows for complex circuits that are part of a device to be simulated without having to actually create the circuit layout.



Co-Simulation Results of the Inductor



- The inductor is connected as a passive load to a microstrip line.
- The netlist component of the equivalent circuit is used for the inductor.
- The FDTD and circuit co-simulation is stable although there are negative values for the lumped elements.



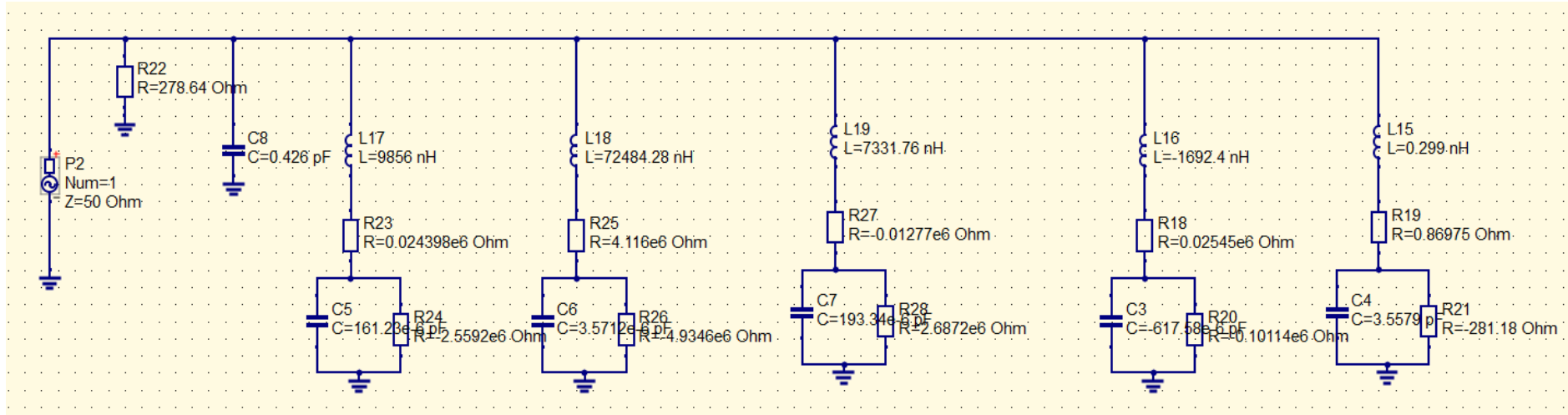
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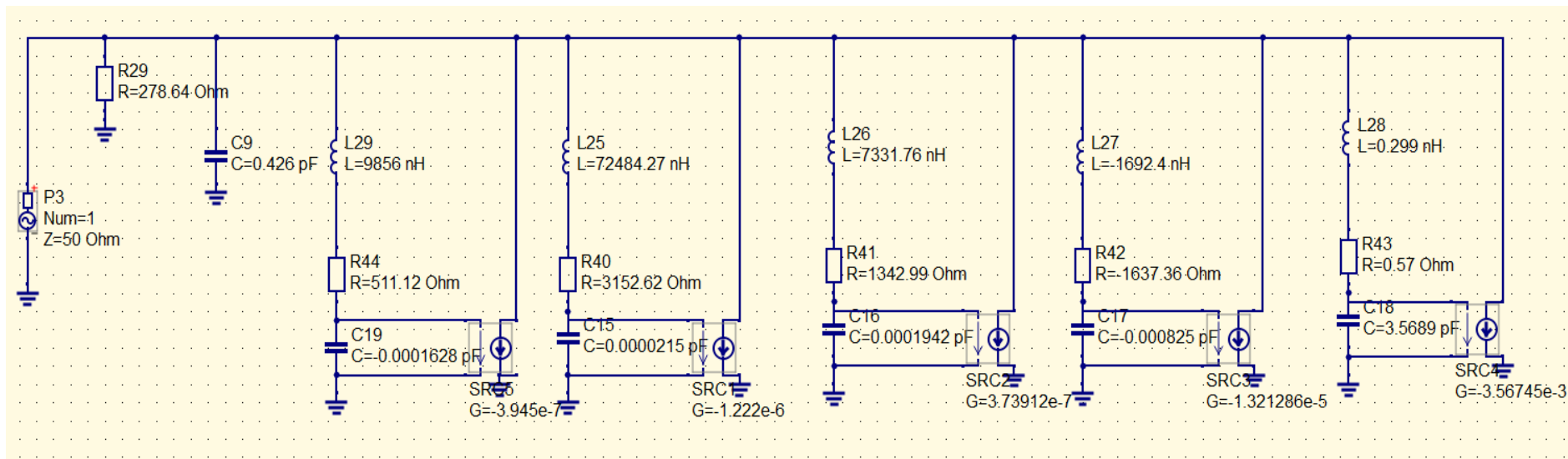
Ceramic Capacitor GRM0332C2A4R0BA01

- The measured spectrum of capacitance C and quality factor Q are available from the manufacturer.
- The C and Q are used to create the admittance Y -parameters.
- One linear term, one constant term and five complex poles are extracted.
- The equivalent SPICE networks are then generated from the poles and residues using RLC circuits with and without VCCSs, respectively.

Equivalent Circuits of the Capacitor

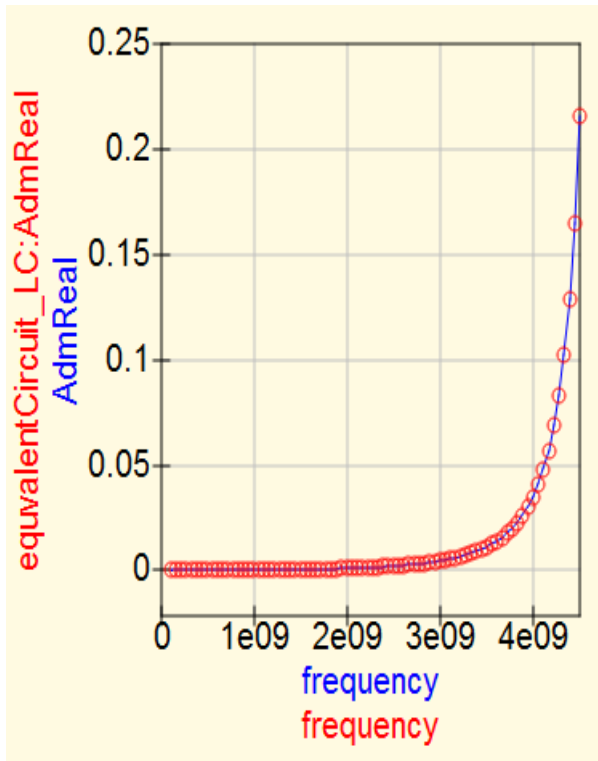


RLC circuits

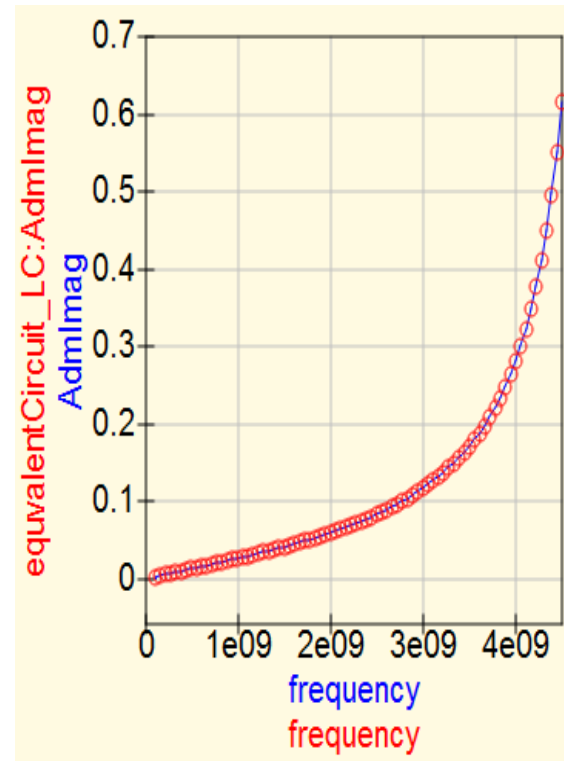


RLC circuits with VCCSs

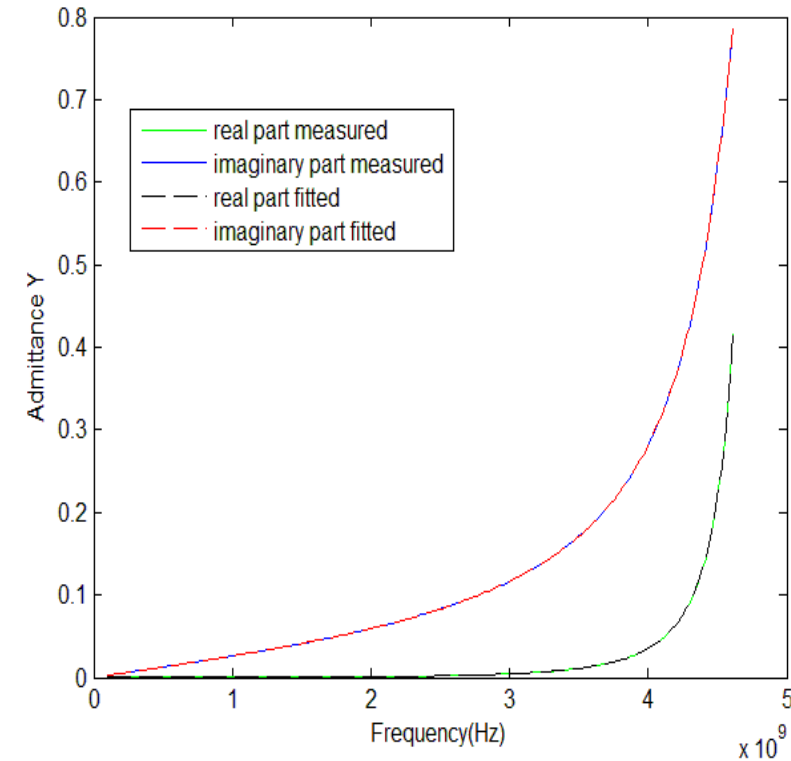
Comparison of Admittance of the Capacitor



real part



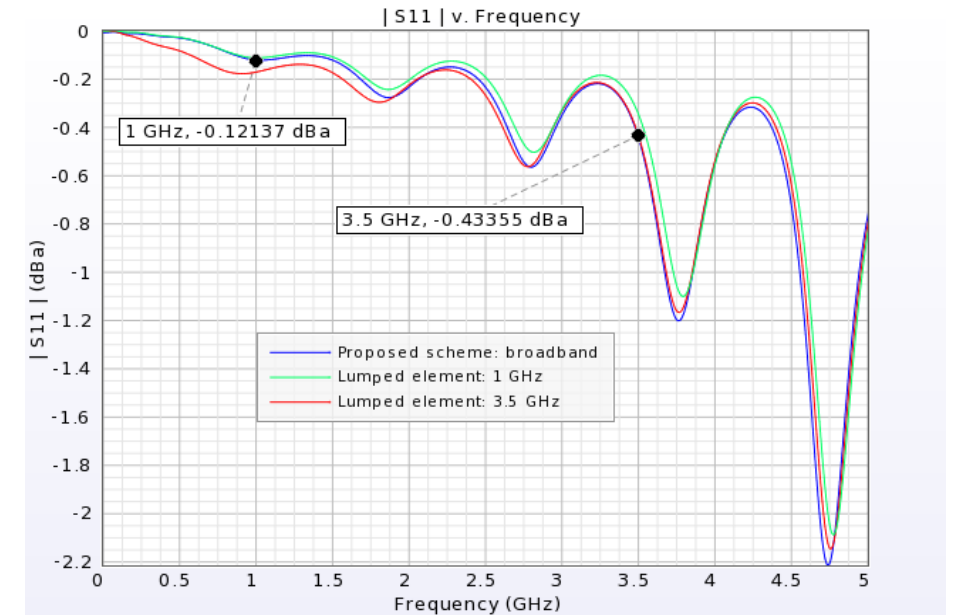
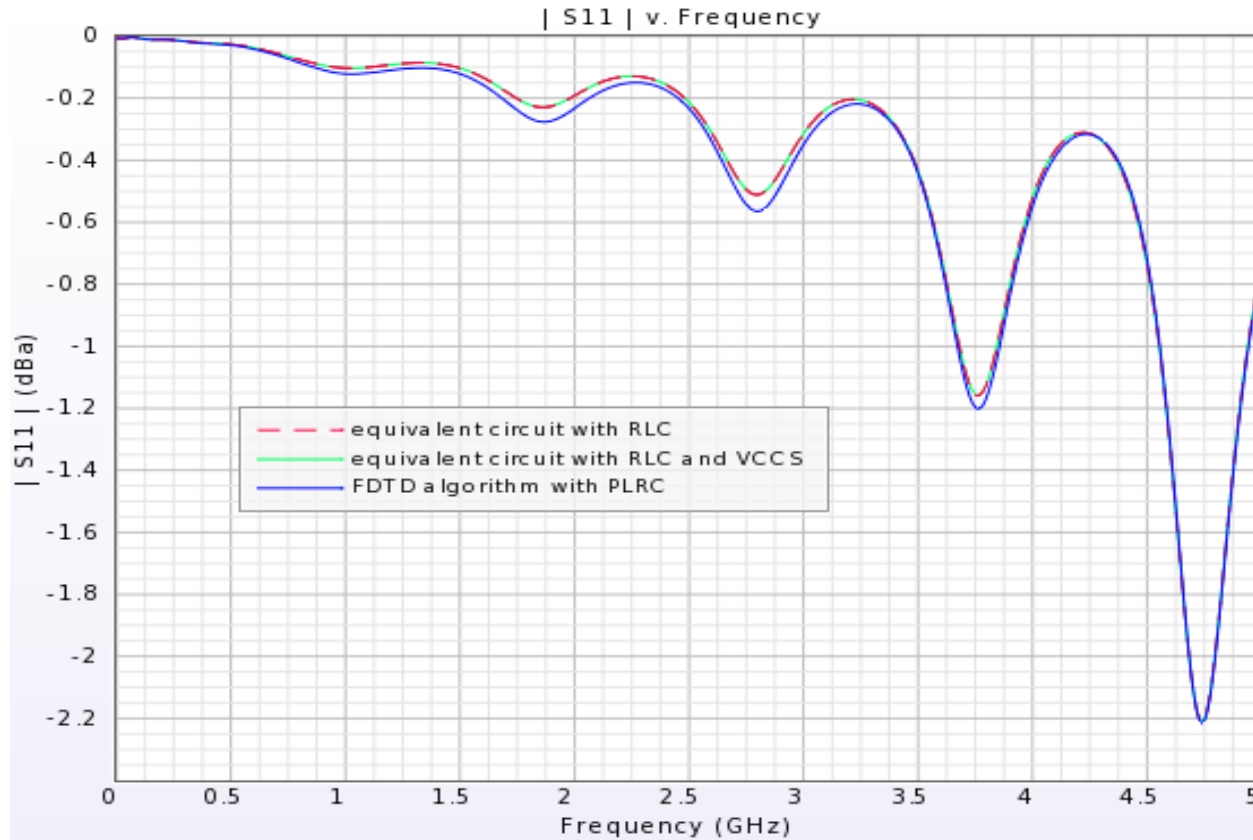
imaginary part



curve-fitted using rational model and originally measured

simulated from the equivalent circuits with and without the VCCSs

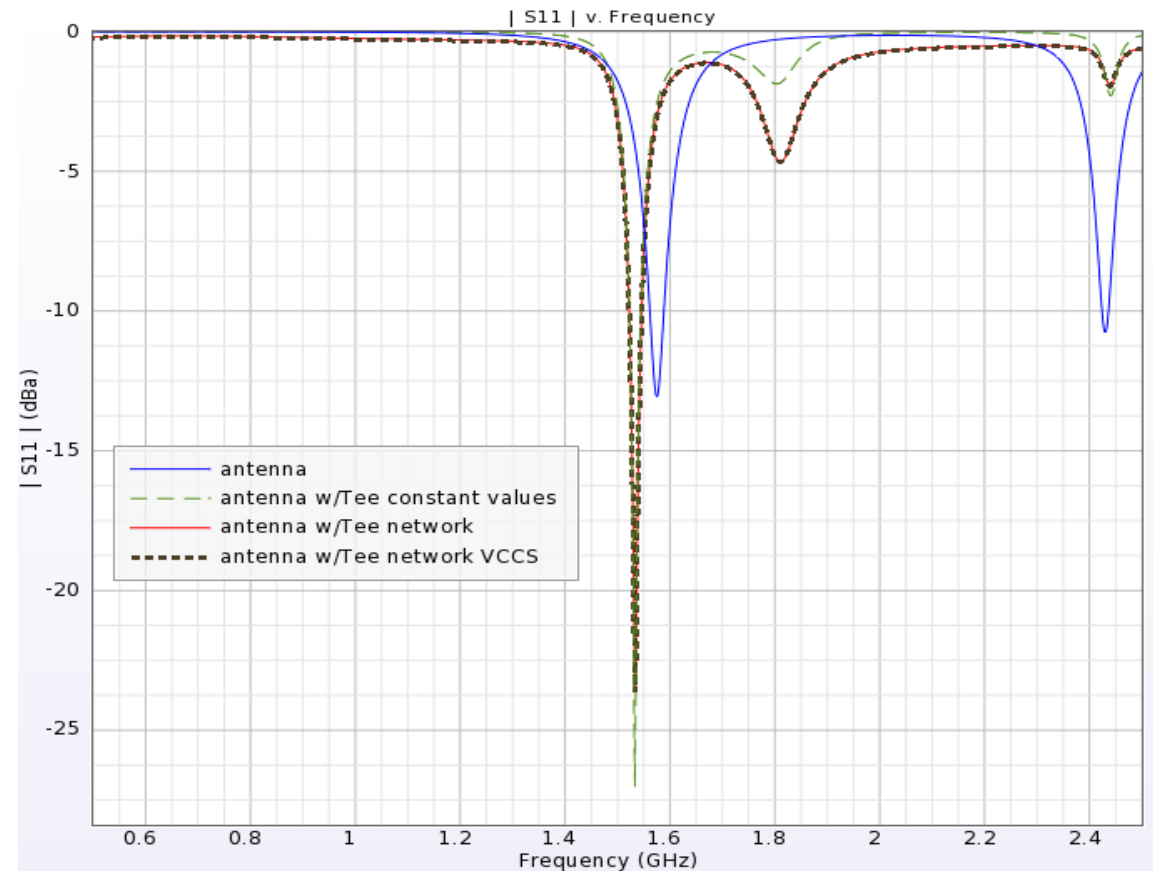
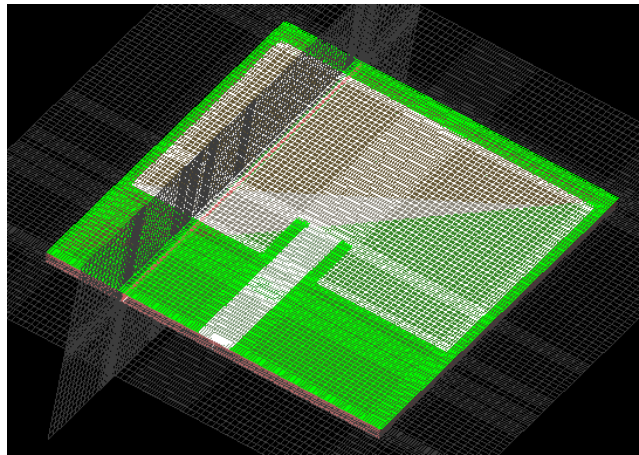
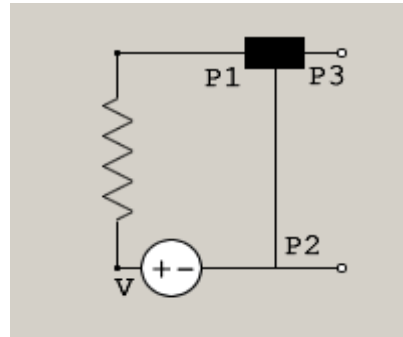
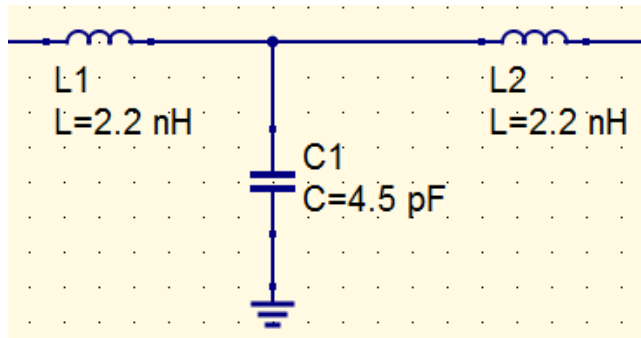
Co-Simulation Results of the Capacitor



- The capacitor is connected as a passive load to a microstrip line.
- The netlist component of the equivalent circuit are used as the capacitor.
- The FDTD and circuit co-simulation is stable.

Simulation of an Antenna with a Matching Circuit

The inductor and capacitor are used to create a Tee matching circuit for a patch antenna.

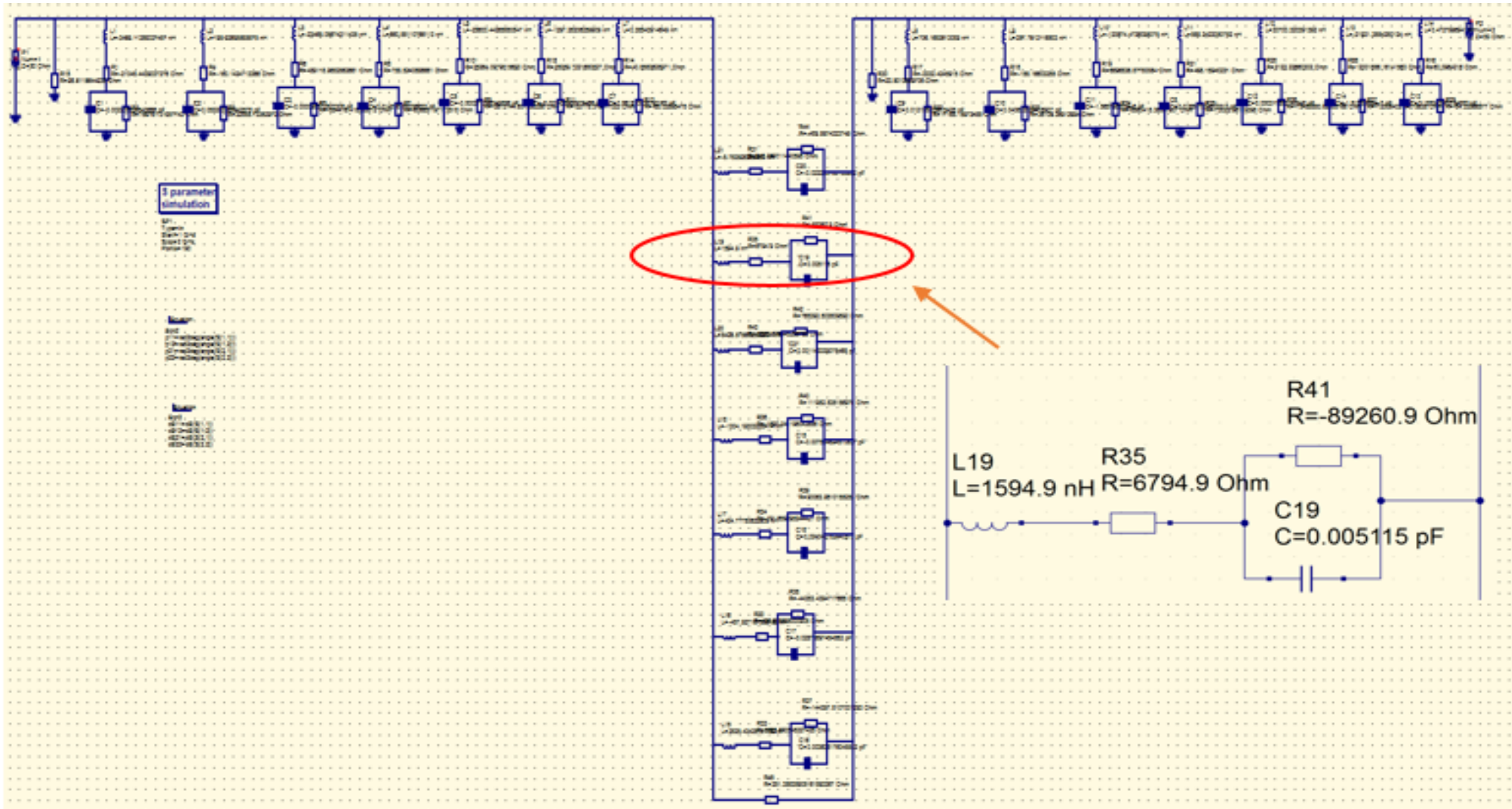




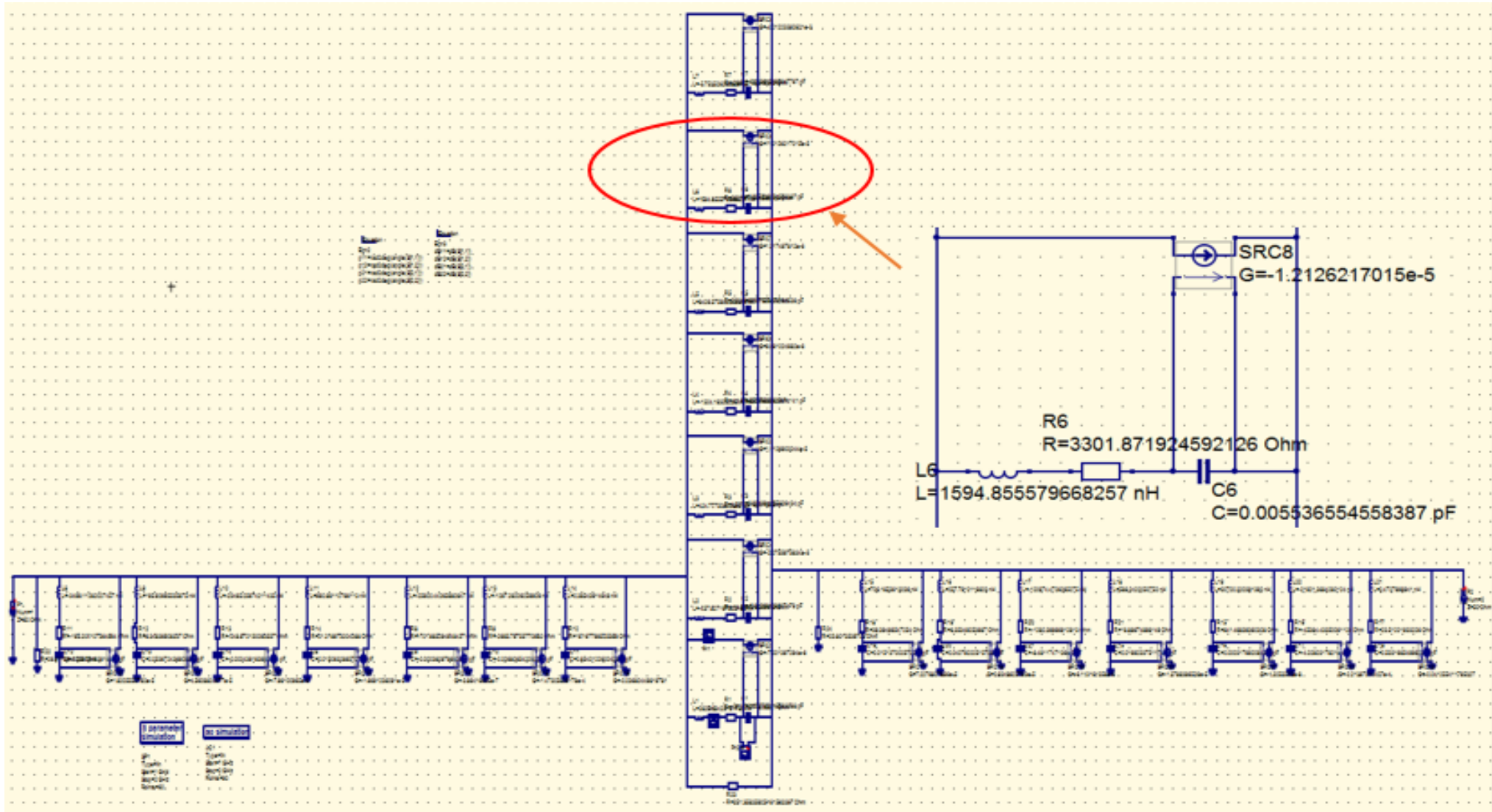
GPS SAW Bandpass Filter 856561 from TriQuint

- This is a two-port RF device.
- The measured 2×2 S-parameters matrices are available from the manufacturer.
- A constant term and fourteen complex poles and residues are extracted.
- The Pi networks with and without VCCSs are then generated.

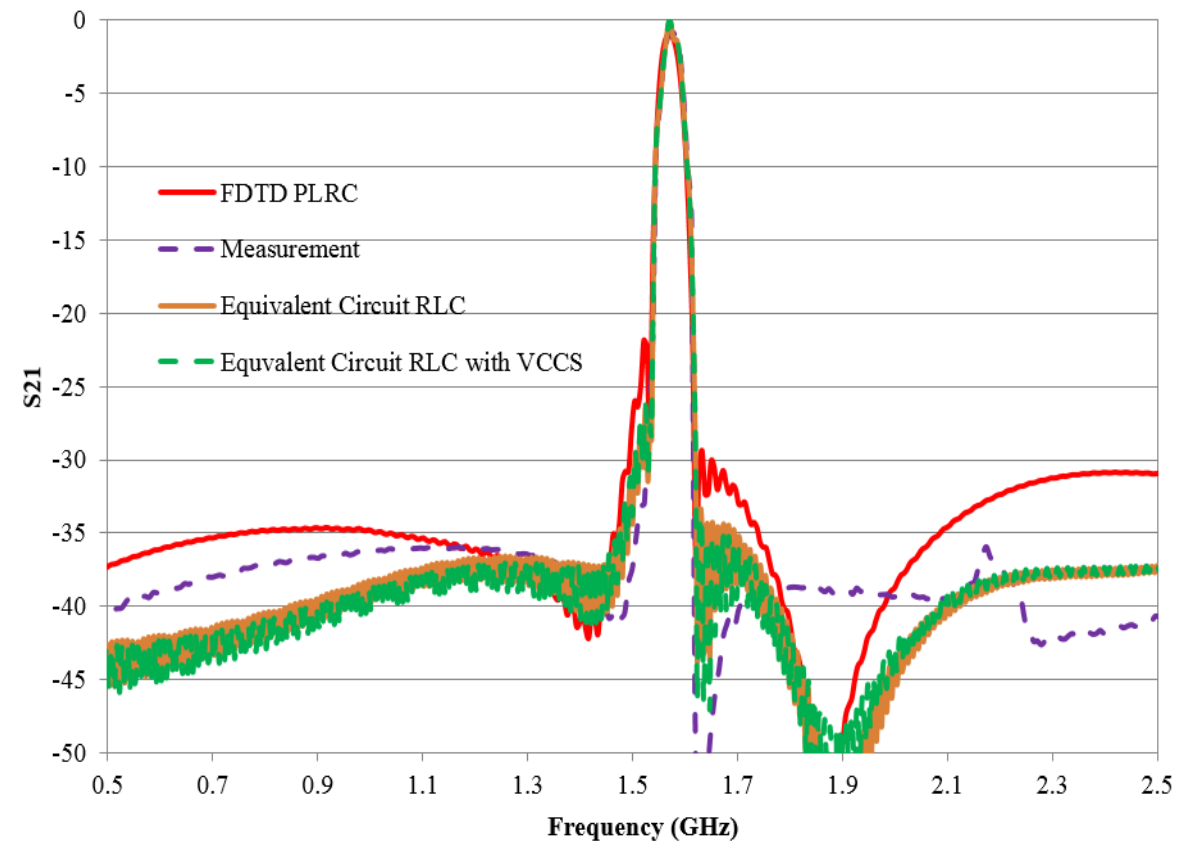
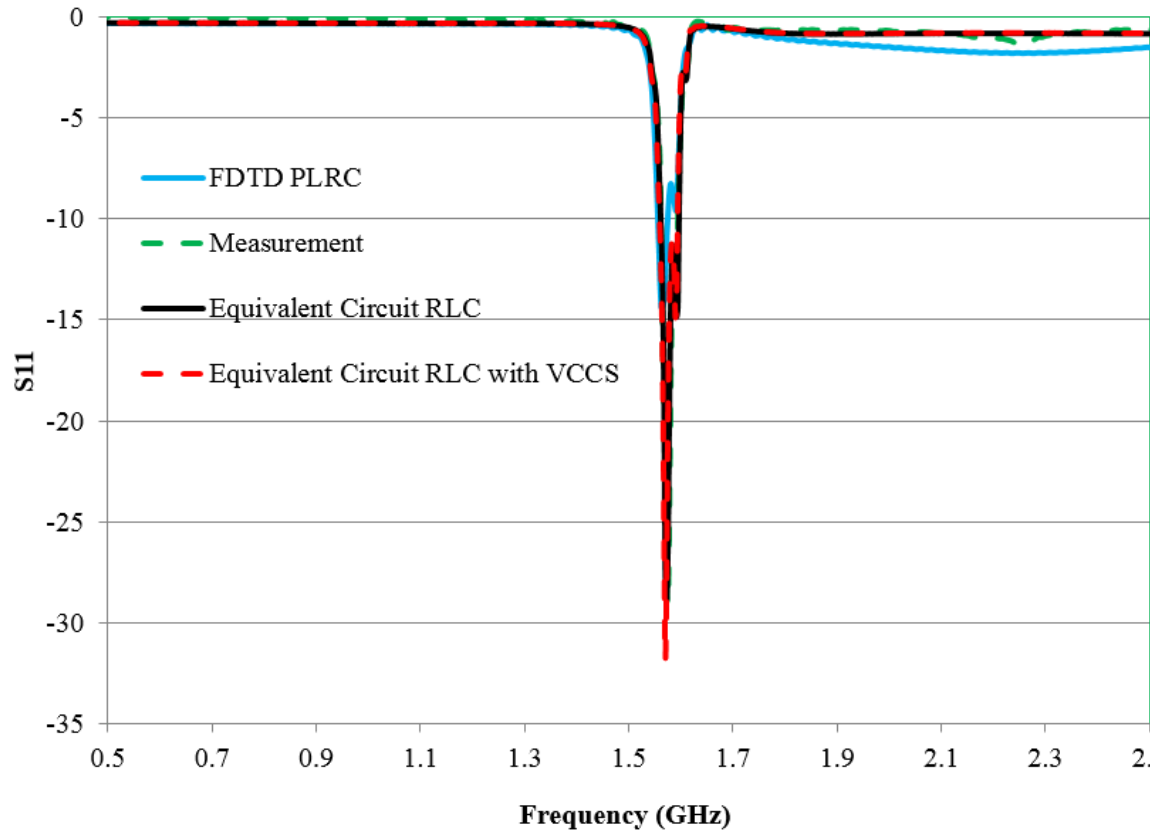
Equivalent Circuit of the GPS Filter



Equivalent Circuit of the GPS Filter with VCCSs



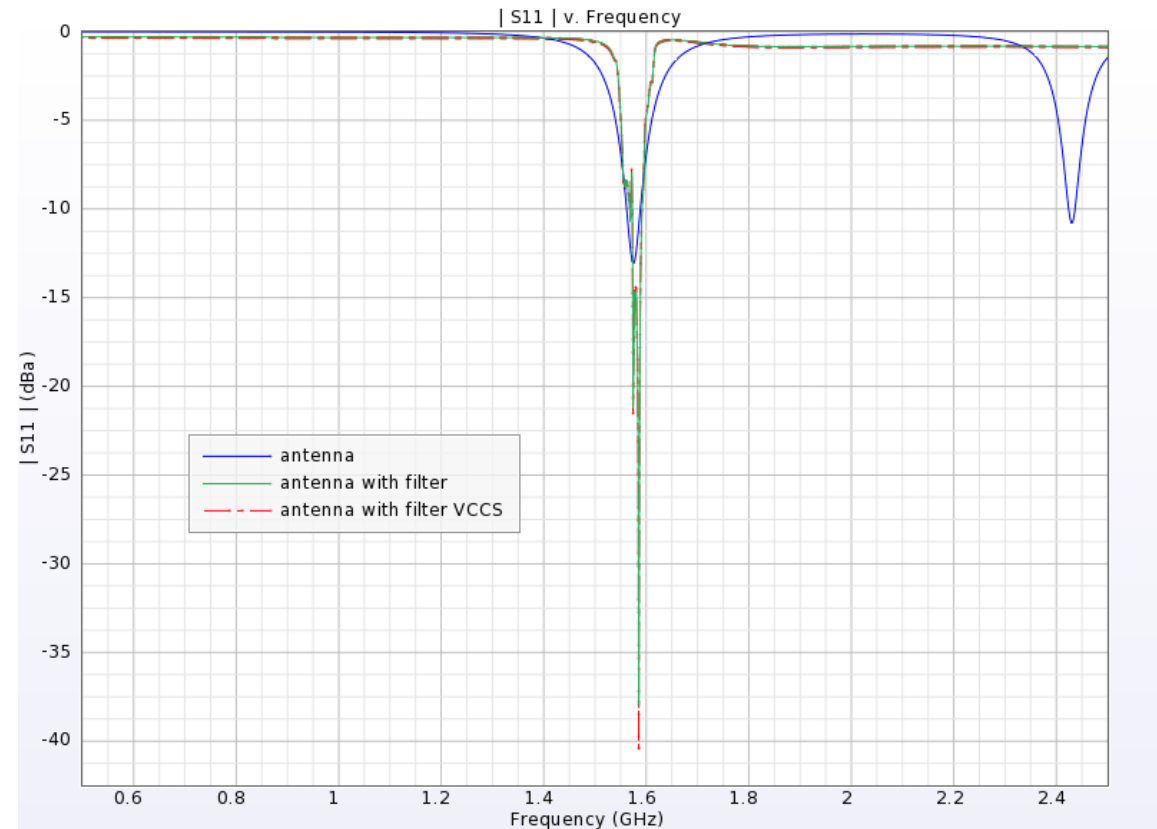
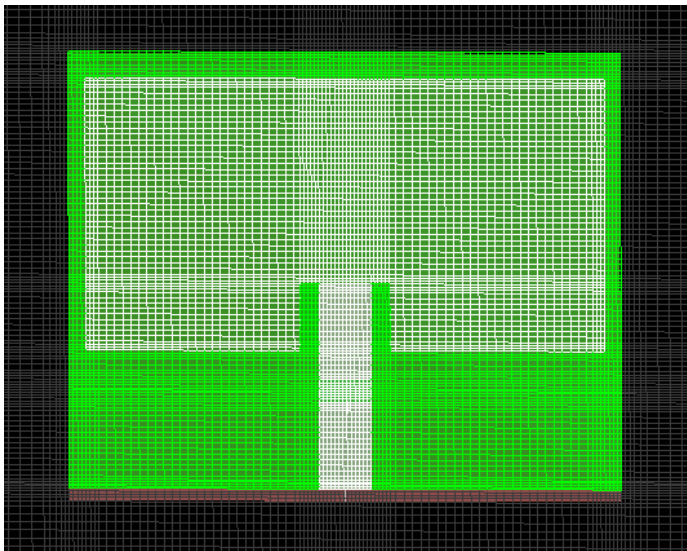
Co-Simulation Results of the GPS Filter



The netlist components of the equivalent circuits are embedded within a feed in XFDTD. The S-parameters simulated using the equivalent circuits are compared with the FDTD method with Piece-wise Linear Recursive Convolution and originally measured data.

A Patch Antenna with the GPS Filter

A patch antenna is connected with the GPS filter and is simulated in the FDTD circuit co-simulation environment.





Summary

- RF devices characterized by measured S-parameters or other parameters can be represented by equivalent circuits.
- The RF devices can then be simulated by the FDTD and circuit co-simulation method.
- The FDTD circuit co-simulation is stable and accurate if the rational model is causal.
- This equivalent circuit method is useful for simulating antennas with real-world RF devices.