Accuracy and Robustness of FDTD Simulation of Devices Characterized by Measured S-Parameters

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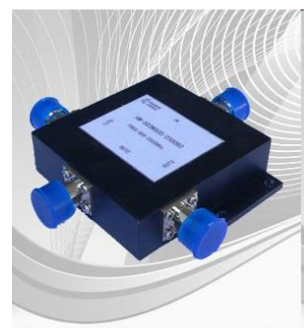
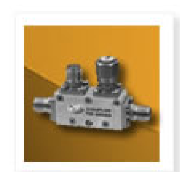
Motivation of This Work

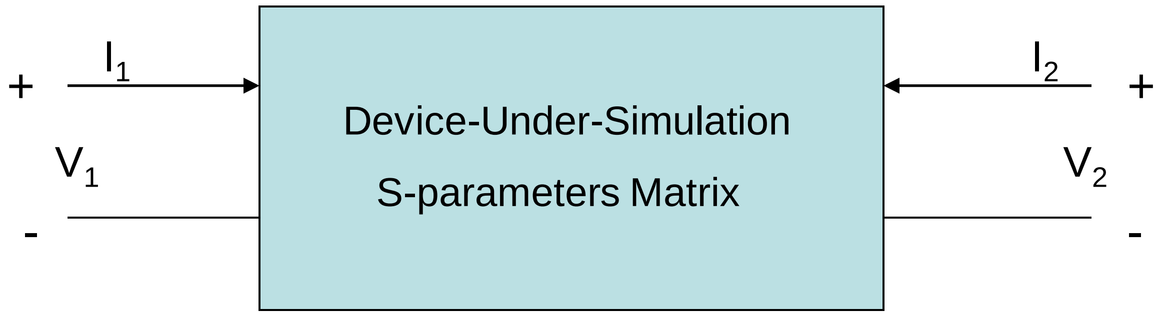
Simulate passive and active circuits characterized by simulated and measured S-parameters together with other geometries in FDTD.

- Filters
- Power Dividers
- Amplifiers
- Circulators
- RF Systems
- Inductors
- Capacitors





Convolution Method



$$\begin{bmatrix} S_{11}(s) & S_{21}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix} \Rightarrow \begin{bmatrix} Y_{11}(s) & Y_{21}(s) \\ Y_{12}(s) & Y_{22}(s) \end{bmatrix} \Rightarrow \begin{bmatrix} Y_{11}(t) & Y_{21}(t) \\ Y_{12}(t) & Y_{22}(t) \end{bmatrix}$$

$$\begin{bmatrix} I_1(s) \\ I_2(s) \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & Y_{12}(s) \\ Y_{21}(s) & Y_{22}(s) \end{bmatrix} \begin{bmatrix} V_1(s) \\ V_2(s) \end{bmatrix} \Longrightarrow \begin{bmatrix} I_1(t) \\ I_2(t) \end{bmatrix} = \begin{bmatrix} Y_{11}(t) \otimes V_1(t) + Y_{12}(t) \otimes V_2(t) \\ Y_{21}(t) \otimes V_1(t) + Y_{22}(t) \otimes V_2(t) \end{bmatrix}$$

Ye and Drewniak, *IEEE Trans. Electromagnetic Compatibility*, vol.44, no.1, pp. 175–181, 2002.

Luo and Chen, *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 3, pp. 969–976, Mar. 2005.

Inverse Laplace Transform

$$Y(s) \approx \sum_{i=1}^{M} \frac{r_i}{s - p_i} + \alpha \quad \Longrightarrow \quad y(t) \approx \alpha\delta(t) + u(t)\sum_{i=1}^{M} r_i e^{p_i t}$$

$$i(t)_{t=k\Delta t} = \left[y(t) \otimes v(t) \right]$$

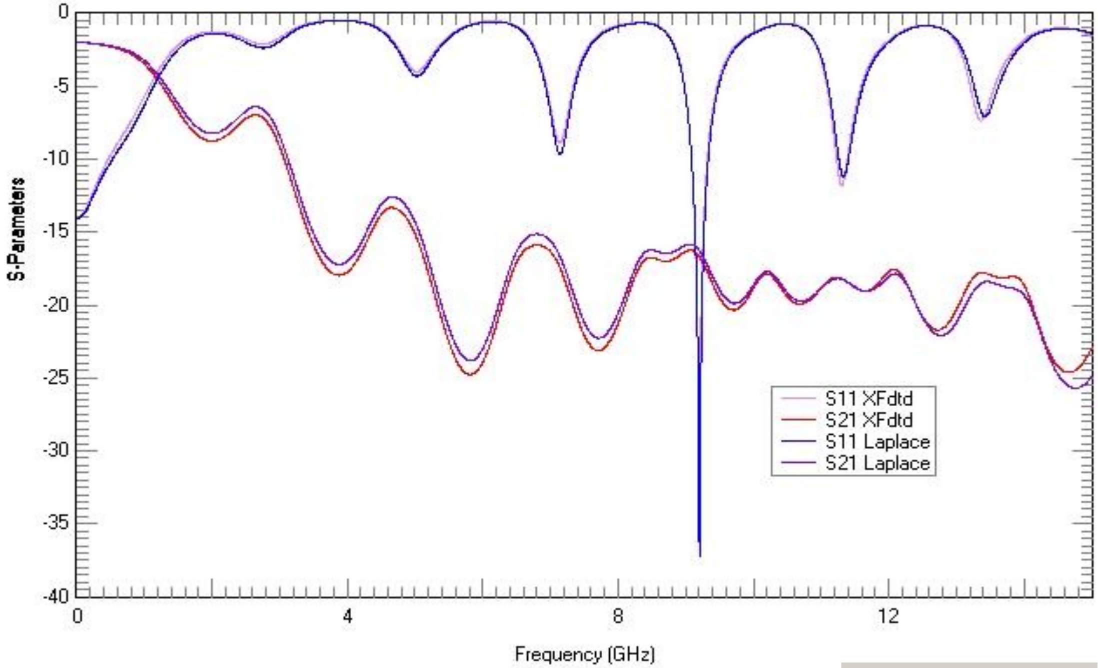
$$\Downarrow$$

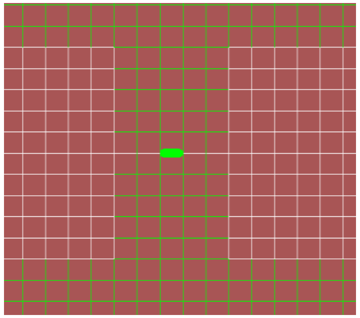
$$i(t)_{t=k\Delta t} = \alpha v(t)_{t=\Delta t} + \sum_{i=1}^{M} r_i \psi_i(t)_{t=k\Delta t}$$

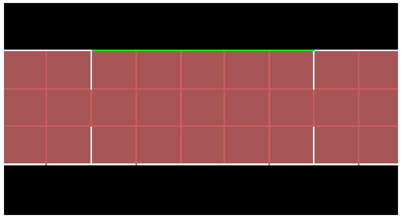
$$\psi_i(t)_{t=k\Delta t} = e^{p_i \Delta t} \psi_i(t)_{t=(k-1)\Delta t} + \Delta t / 2 \left[e^{p_i \Delta t} v(t)_{t=(k-1)\Delta t} + v(t)_{t=k\Delta t} \right]$$

Luo and Chen, *IEEE Transactions on Circuits and Systems—I: regular papers*, vol.52, no.6, pp.1205-1210, 2005.

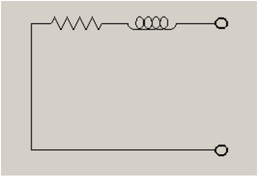
FDTD vs. Inverse Laplace Transform







$$Y(s) = \frac{1/L}{s-(-R/L)}$$



A series RL circuit (R=25 Ohm, L=10 nH) simulated by Remcom's XFdtd® and the inverse Laplace transform.

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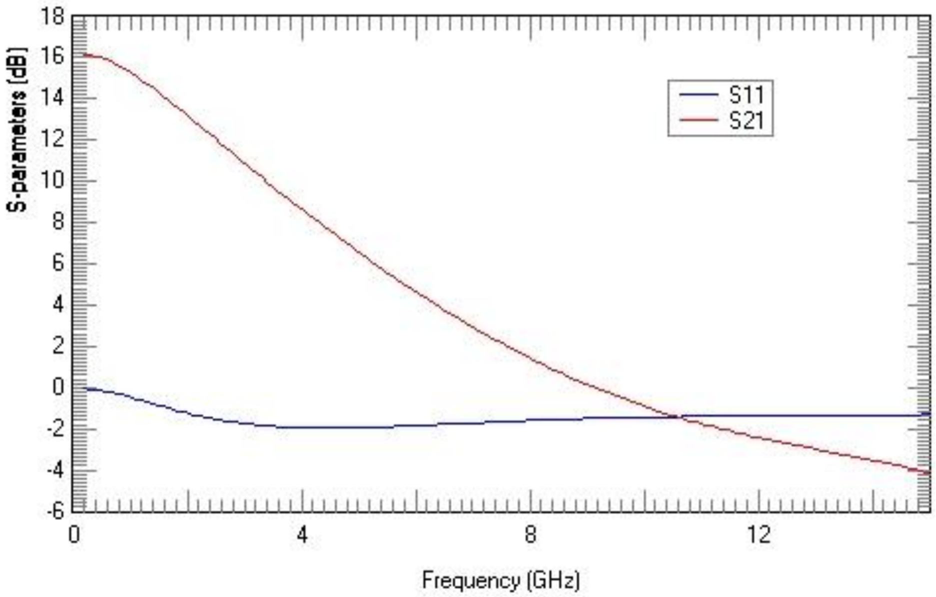
Bilinear-Transform

$$Y_{pq}(s) = \frac{\sum_{m=0}^{M_{pq}} a_m^{(p,q)} s^m}{\sum_{n=0}^{N_{p,q}} b_n^{(p,q)} s^n} \quad + \quad s = \frac{2}{\Delta t}\frac{1-z^{-1}}{1+z^{-1}} \quad \Longrightarrow \quad Y_{pq}(z) = \frac{\sum_{m=0}^{M_{pq}} c_m^{(p,q)} z^{-m}}{1+\sum_{n=0}^{N_{p,q}} d_n^{(p,q)} z^{-n}}$$



González et al, *IEEE Microwave and Wireless Components Lett.*, vol.17, no.7, pp.477-479, 2007.

Simulated S-parameters of a MESFET characterized by analytical Y-parameters.

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Passivity Enhancement Method

- Transient circuit simulators: admittance representations in form of rational transfer functions.
- Measured or calculated frequency domain responses are band limited, error contaminated and not in the appropriate rational form.
- A reduced order rational model has to be causal, stable, passive and accurate.
- The passivity enhancement method was proposed using an inverse eigenvalue method.

Saunders and Steer, *IEEE Trans. Microwave Theory Tech.*, vol.60, no.1, pp.8-20, 2012.

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Poles/Residues of a Bandpass Filter

A SAW filter for GPS applications: 14 complex poles and residues

Y_{11} Residues

(34070.584551123633,-53119.371112613575)
(1460094.778391400800,-109000.419673486210)
(1155778.530517811400,-14927.811108331025)
(373186.902657350180,38834.913235098669)
(39805.171980597923,-4659.906070365948)
(-71913.182212009619,845344.246937821270)
(1210318408.436479100000,1919087340.209662200000)

Y_{12} Residues

(-176963.948006825550,-35337.290654441298)
(1091876.690182048400,-109139.966116357430)
(-1177086.810548629100,54361.396008882140)
(383378.830882090490,46021.439147500911)
(-59336.084264568235,6589.844513568966)
(-313508.010614982460,-95471.447472298940)
(86903227.091137365000,-100182463.143305690000)

Y_{21} Residues

(-176963.948006825550,-35337.290654441298)
(1091876.690182048400,-109139.966116357430)
(-1177086.810548629100,54361.396008882140)
(383378.830882090490,46021.439147500911)
(-59336.084264568235,6589.844513568966)
(-313508.010614982460,-95471.447472298940)
(86903227.091137365000,-100182463.143305690000)

Y_{22} Residues

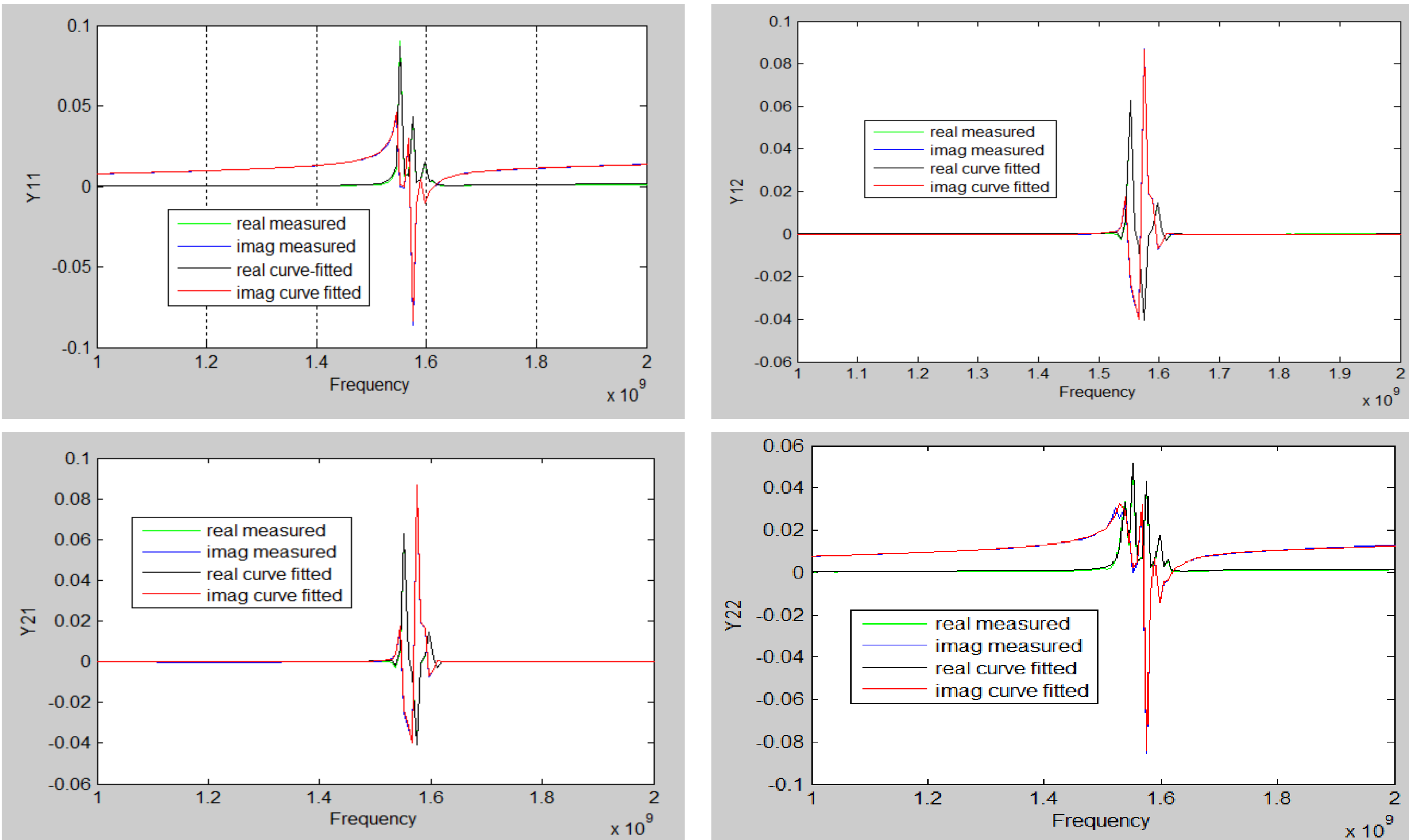
(885013.404124003020,-312160.416136991350)
(847677.403772644820,-16113.604622687069)
(1172943.432175491700,-24150.176920717440)
(466611.182901630700,24437.542630346048)
(75622.559246770485,-6500.701101628966)
(290699.236360470760,1276739.963624418500)
(970627068.057553170000,1968655525.232881300000)

Poles

(-27893371.461747594000,9672195057.513483000000)
(-16202050.648703106000,9751617287.788698200000)
(-5305167.867902691500,9884716723.278949700000)
(-16053548.027104480000,10022541470.749012000000)
(-13704553.940730477000,10125697554.577724000000)
(-1035163298.384340900000,10591442623.479601000000)
(-24864884250.049561000000,57867968741.893501000000)

	α
Y_{11}	0.041275638722673
Y_{12}	-0.003978383705929
Y_{21}	-0.003978307748375
Y_{22}	0.045992716542651

Curve Fitting Results of Y-Parameters



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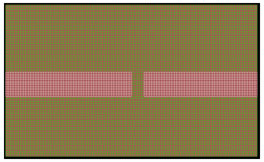
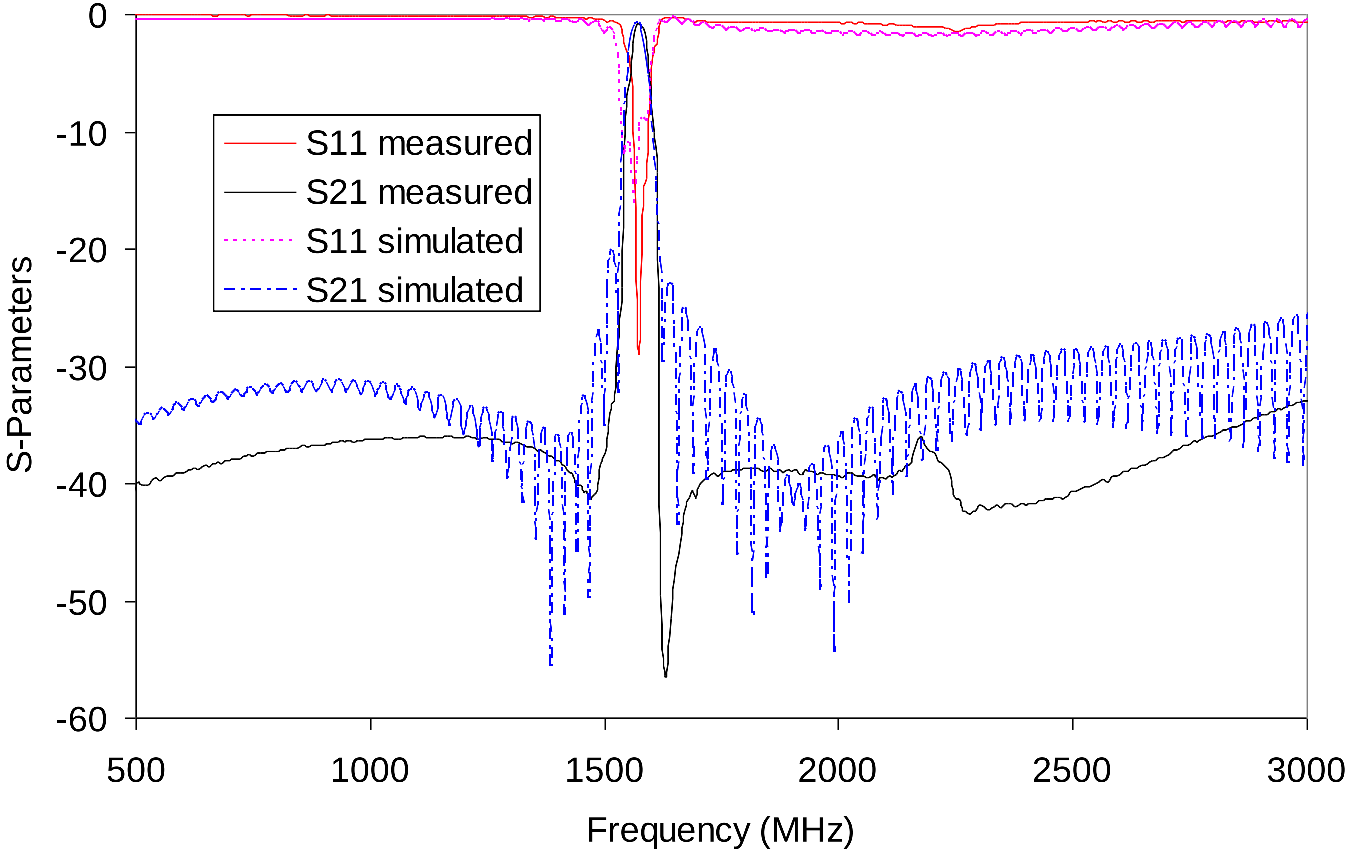
FDTD Results of the Bandpass Filter





FDTD simulated results with inverse Laplace transform vs. measured results.

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Poles and Residues of a Lowpass Filter with XFdtd Simulated S-Parameters

Y_{11} Residues

31812050.288548764000
-67720.378185156267
(37529822.648174129000,-40026.932531441707)
(-175537.295868410210,100652.444307371570)
(32392712.101842962000,-14512.622772633333)
(6270545.547076162000,-207580.103401408180)
(49156211.928048506000,2050072.390816211700)
(129731961.875055690000,460418.940590875340)

Y_{12} Residues

-31813592.799060587000
78301.228427462629
(39457266.054141641000,-45556.762022539915)
(211703.907292048940,-24848.565070452780)
(-26311467.861838698000,-17154.272250205446)
(21400107.453707609000,-202104.424720217970)
(-25041759.577760383000,416622.199634957070)
(12059010.913733162000,-2200955.706581799300)

Y_{21} Residues

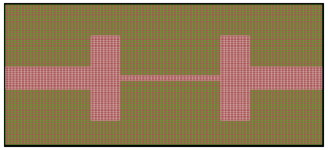
-31812468.753139541000
75753.944933024948
(39457704.640739337000,-39201.331262409738)
(217020.159751129800,-38824.076965930770)
(-26321027.264643978000,-9834.522905352111)
(21515279.215645216000,-80330.984723144895)
(-25415085.211731233000,338694.722983689340)
(12642396.875211176000,-2714517.396533716900)

Y_{22} Residues

31812588.873190239000
-82279.456605251486
(41485349.264375225000,-43913.246282403590)
(-119752.664515433000,84499.041433761216)
(21376426.643237699000,31852.822150754459)
(55805643.720411658000,-396771.982839323350)
(17001996.008426346000,1789434.263083778800)
(106321194.371849310000,1608058.822462805100)

Poles

-975499.326105132930
-182376301.994609360000
(-768821.177385819610,5213972461.037248600000)
(-1998672141.173676500000,6844683932.097068800000)
(-19353320.144730210000,7689094515.626965500000)
(-17228320.405101445000,19450970805.905277000000)
(-16142328.993978474000,21311629765.987656000000)
(-11653615720.134962000000,32355121510.571266000000)



α

Y_{11}	-0.000006146043415
Y_{12}	-0.000041757518324
Y_{21}	-0.000064686896071
Y_{22}	0.000247556357697

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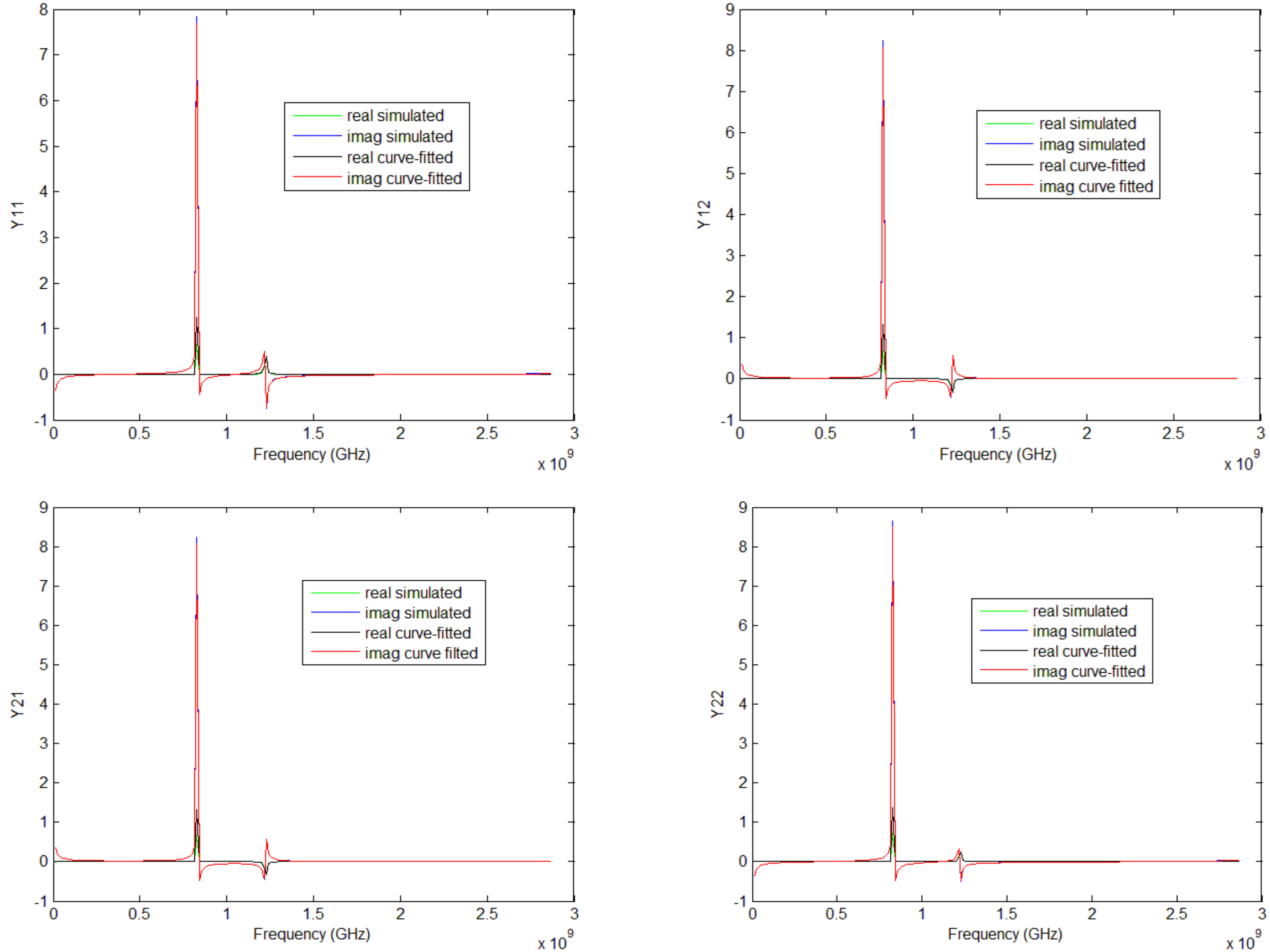
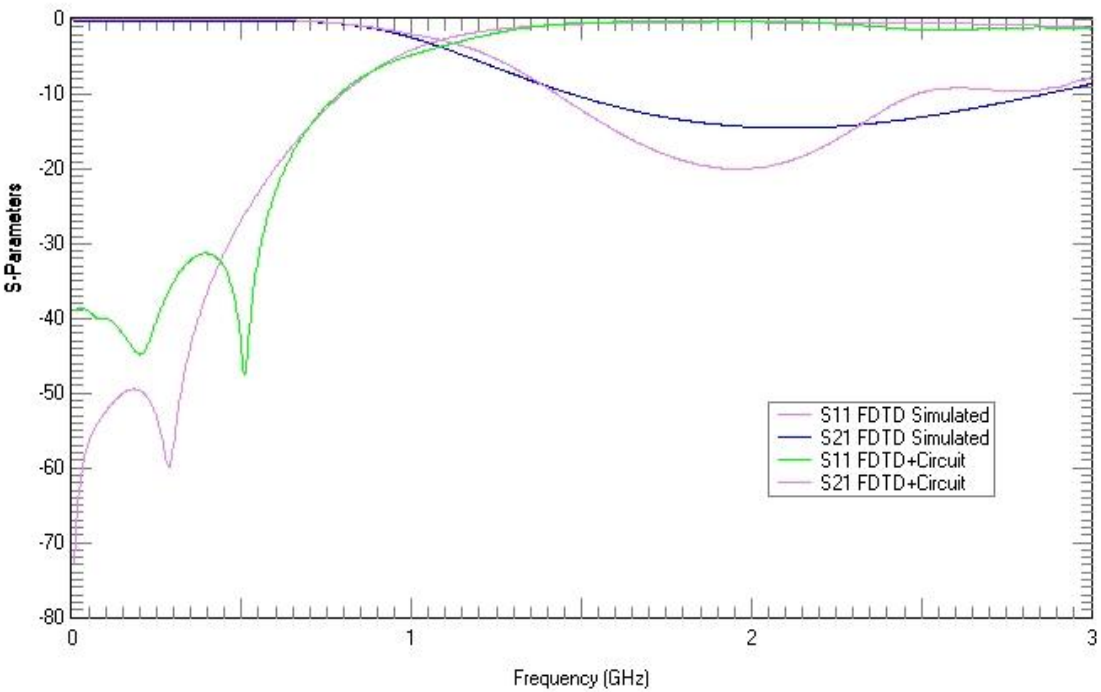
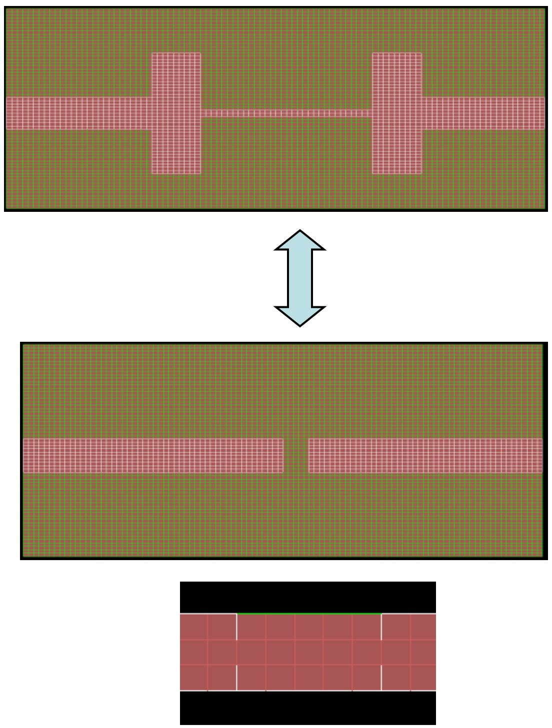
Curve Fitting Results of Y-Parameters



Simulated S-Parameters of the Lowpass Filter





FDTD simulated results using a circuit network vs. the LPF geometry.

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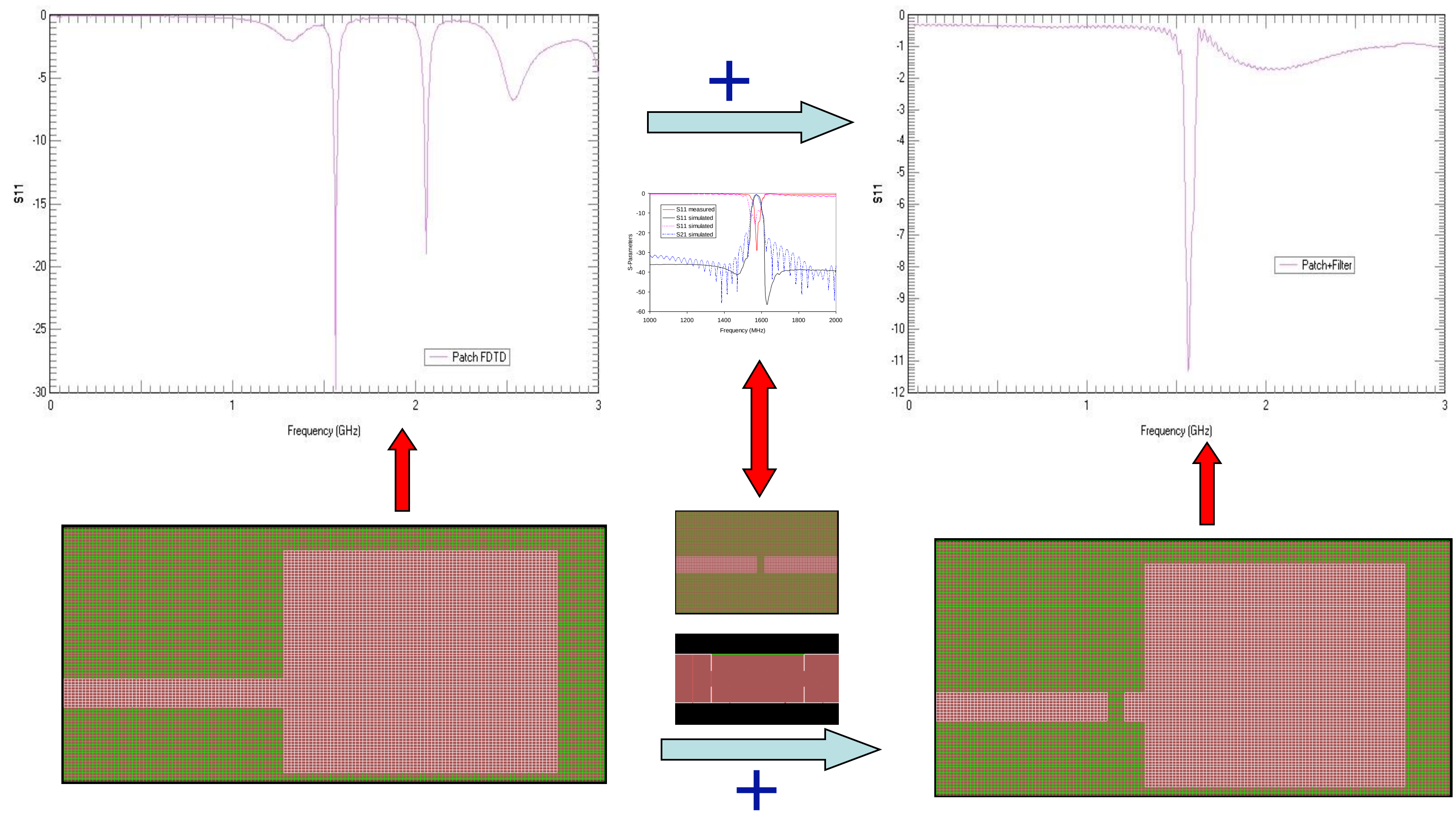
Patch Antenna + Bandpass Filter



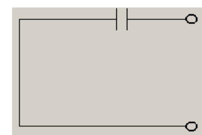
Discussion (1): Admittance

- Additional term for admittance Y

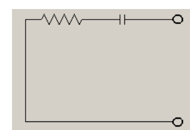
$$Y(s) \approx \sum_{i=1}^{M} \frac{r_i}{s - p_i} + \alpha + sh$$

Chen and Chu, *Progress In Electromagnetics Research*, PIER vol.73, pp.327–341, 2007 (piecewise linear recursive convolution).

  - Pure C or Shunt C: Y=sC



  - Series RC: Y=sC/(1+sRC)



- From poles/residues to rational functions

$$Y(s) \approx \sum_{i=1}^{M} \frac{r_i}{s - p_i} + \alpha \quad \Longrightarrow \quad Y_{pq}(s) = \frac{\sum_{m=0}^{M_{pq}} a_m^{(p,q)} s^m}{\sum_{n=0}^{N_{p,q}} b_n^{(p,q)} s^n}$$

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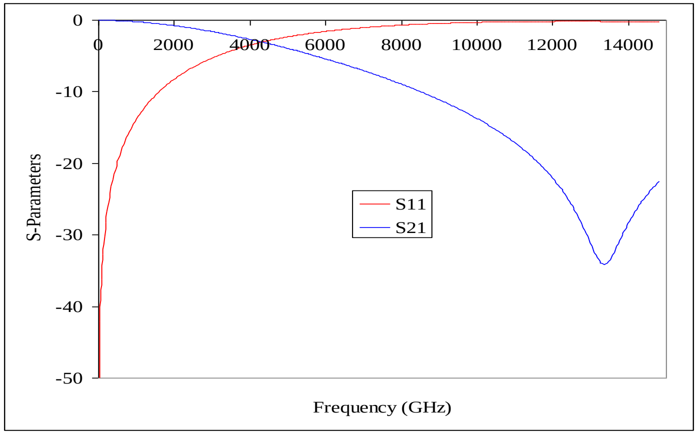
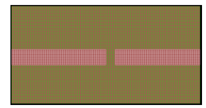
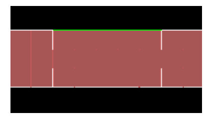
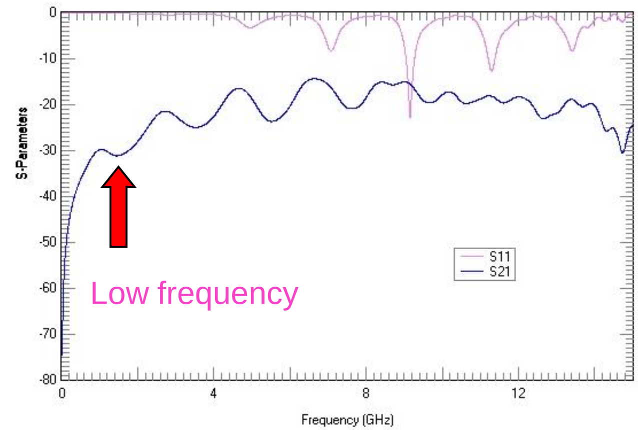
Discussion (2): Chip Inductor



Measured S-parameters of a chip inductor (~3nH)







S-parameters of a microstrip gap

Extracted two Poles and residues from Y_{11} of the chip inductor

Poles

-338390130769.249150000000

-4574092.101910794200

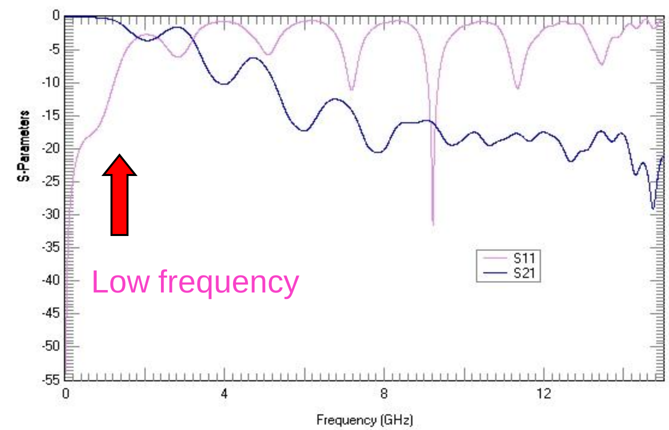
Residues

-4934782755.190588000000

302889269.765195730000

α

0.014614553416800



Simulated S-parameters of a chip inductor (2 poles)

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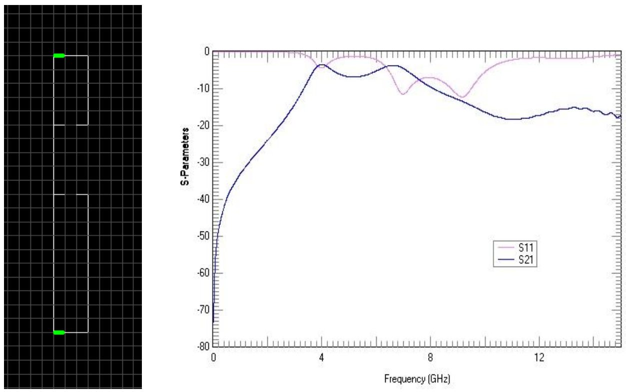
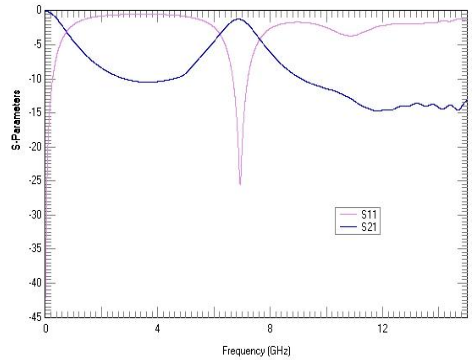
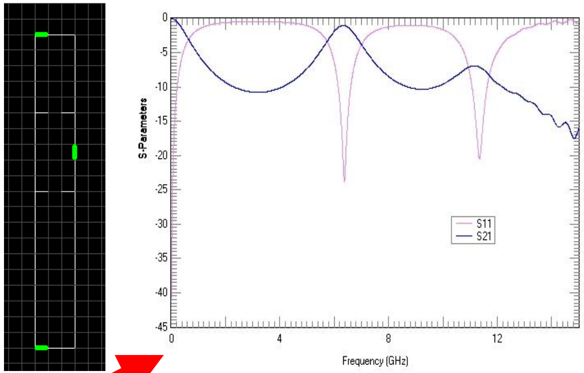
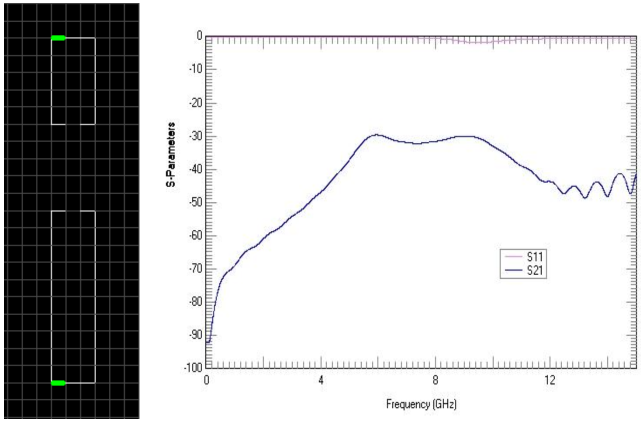
Effect of microstrip transmission line on S-parameters

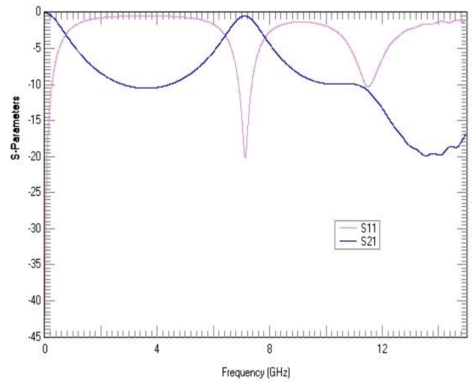
Discussion (3): Wire Connector

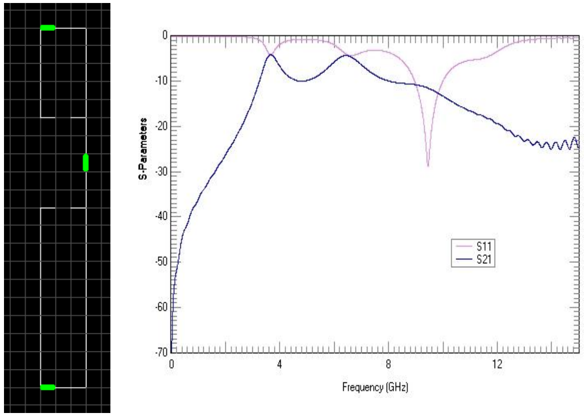












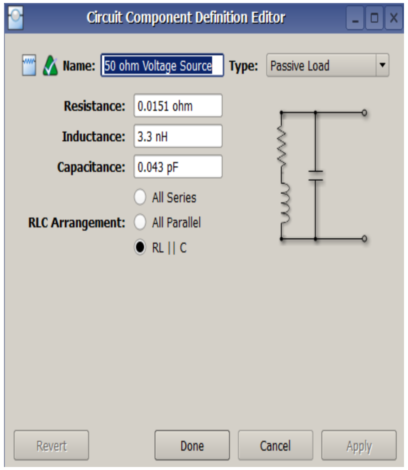
S-parameters for connected or broken ground wires

S-parameters for a chip inductor with connected or broken ground wires

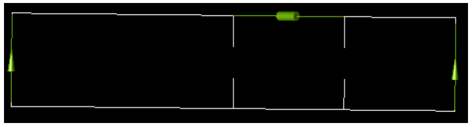
S-parameters for a 3 nH inductor as a lumped element

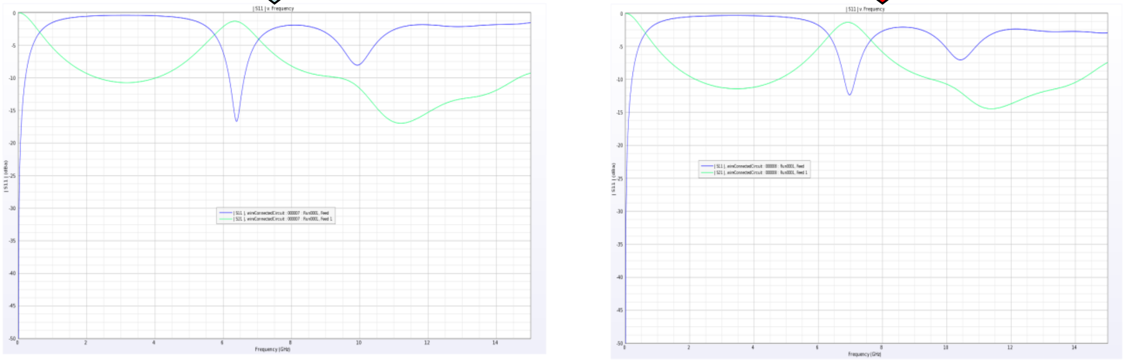
Effect of ground wires on S-parameters

Discussion (4): Equivalent Circuit

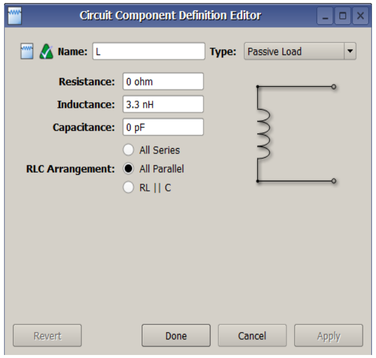


Equivalent circuit of a chip inductor
(Circuit parameters are obtained by PSO)

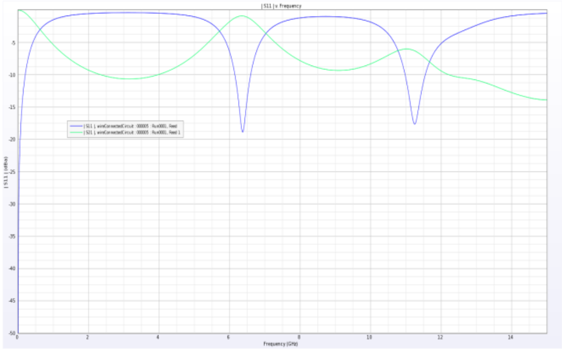


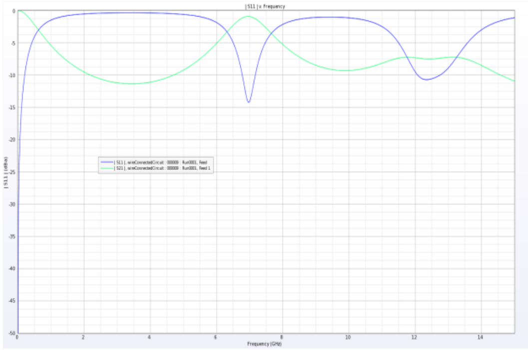


S-parameters of the equivalent circuit of chip inductor



Pure inductor





S-parameters of 3.3 nH pure inductor

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Effect of connecting wires on S-parameters

Conclusion

- Electronic devices characterized by simulated and measured S-parameters can be simulated in FDTD using the inverse Laplace transform combined with the passivity enforcement method.
- The simulation is quite accurate and robust once the admittance is well represented by poles and residues.
- The effects of microstrip and wires connecting the circuit network cannot be ignored.
- This combined FDTD and circuit method can be applied to simulate geometries together with these devices characterized by simulated and measured S-parameters.

Acknowledgement

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- Prof. Jose Pereda of Universidad de Cantabria for discussion of Bilinear-transform.
- Prof. James Drewniak of University of Missouri for discussion of convolution method.

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