Ansoft HFSS Engineering Note

Lumped RLC Elements in HFSS Version 8

In Ansoft's High Frequency Structure Simulator (HFSS), a specified impedance boundary condition has always referred to field values because HFSS is a full-wave field simulator. You may wish to model a physical lumped resistance (R), inductance (L), or capacitance (C) element that is connected to the field or distributed model.

HFSS Version 8 enables you to specify any combination of parallel-connected lumped RLC elements on surfaces in terms of circuit definition by using lumped RLC boundaries. A typical application is the simulation of a Monolit Microwave Integrated Circuit (MMIC), in which the lumped elements are represented by thin sheets.

HFSS Version 8's fast and interpolating frequency sweep options support the frequency dependence of an impedance, which consists of either a lumped inductance or a lumped capacitance, with the use of lumped RLC elements. HFSS's 3D Boundary Manager supports any combination of parallel-connected RLC elements on a surface. To model serial-connected lumped elements, define two serial-connected surfaces for the serial elements.

This engineering note explains the difference between field and lumped impedances and presents applications for both cases.

Field and Lumped Impedances

Figure 1 shows a thin, rectangular sheet on which a lumped impedance boundary condition will be defined.

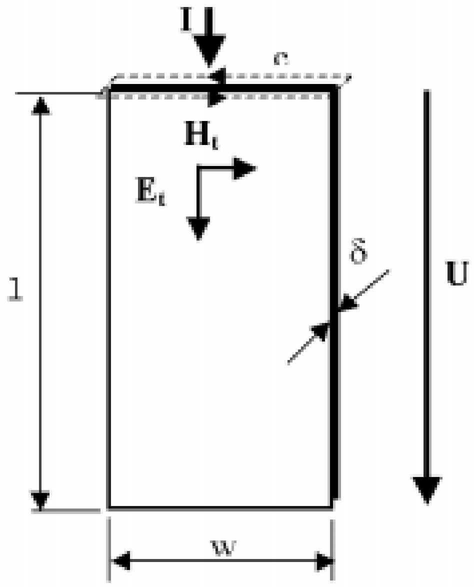

Figure 1: Thin rectangular sheet

where:

- *l* is the length of the sheet
- *w* is the width of the sheet
- E_t is the tangential component of the electric field on the impedance boundary surface
- H_t is the tangential component of the magnetic field on the impedance boundary surface
- *I* is the current flowing on the sheet
- *c* is a closed curve surrounding the sheet
- *U* is the voltage drop
- δ is the thickness of the sheet

The definitions for the lumped and field impedances are:

$$Z_{lumped} = \frac{U}{I} \qquad Z_{field} = \frac{E_t}{H_t}$$

The circuit quantities *U* and *I* can be expressed by the field quantities as:

$$U = \int_l E_t dl = E_t l \qquad \oint_c H_t dc = H_t w = I$$

Substituting the field quantities into the impedance definition yields:

$$Z_{lumped} = \frac{U}{I} = \frac{E_t l}{H_t w} = Z_{field}\frac{l}{w}$$

$$Z_{field} = Z_{lumped}\frac{w}{l}$$

Z_{field} is measured in ohms / square. It is also denoted by Zφ.

The shape of a lumped impedance surface is not always rectangular. An arbitrarily shaped surface is transformed into a rectangular-shaped surface by defining the length of the main current flow, as shown in the following figure:

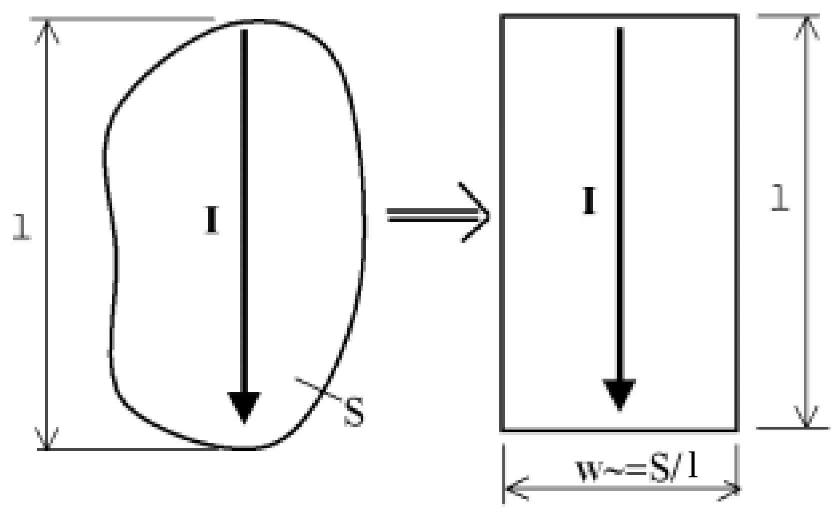

Figure 2: Transformation of an arbitrarily shaped surface to an equivalent rectangular-shaped surface

The width of the equivalent rectangular surface is:

$$w \cong \frac{S}{l}$$

where S is the area of the sheet.

The relationship between the lumped and field impedances is:

$$Z_{lumped} = Z_{field}\frac{l^2}{S} \qquad Z_{field} = Z_{lumped}\frac{S}{l^2}$$

Define the length of the current flow in the 3D Boundary Manager. The area of the surface is calculated automatically.

The parallel-connected RLC lumped elements are assigned to the selected surface (see Figure 3) using the user-defined current path:

$$R_{field} = R\frac{S}{l^2} \qquad L_{field} = L\frac{S}{l^2} \qquad C_{field} = C\frac{l^2}{S}$$

The frequency dependence is taken into account as:

$$\frac{1}{Z_{field}} = \frac{1}{R_{field}} + j\left(\omega C_{field} - \frac{1}{\omega L_{field}}\right)$$

where:

- j is the imaginary unit, $\sqrt{-1}$
- ω is the angular frequency, $2\pi f$

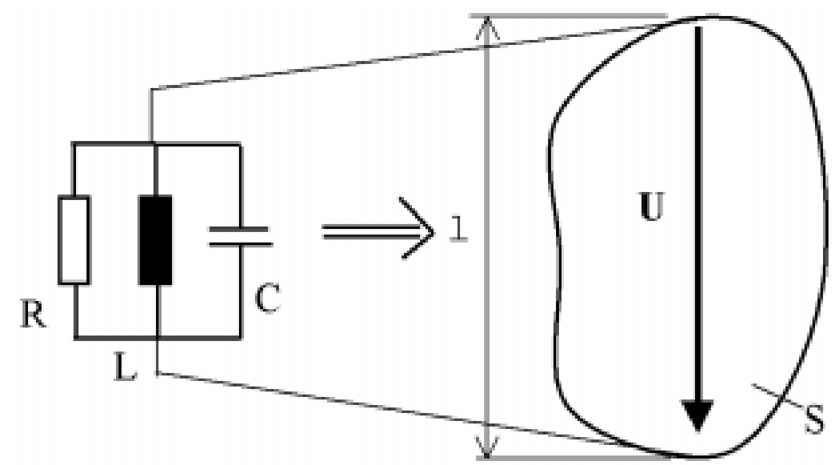

Figure 3: Parallel-connected lumped RLC elements assigned to a boundary surface

Parallel Plate Waveguide Terminated with a Parallel Lumped RLC Circuit

In the following example, a parallel plate waveguide is terminated by a parallel-connected RLC circuit, as shown in Figure 4.

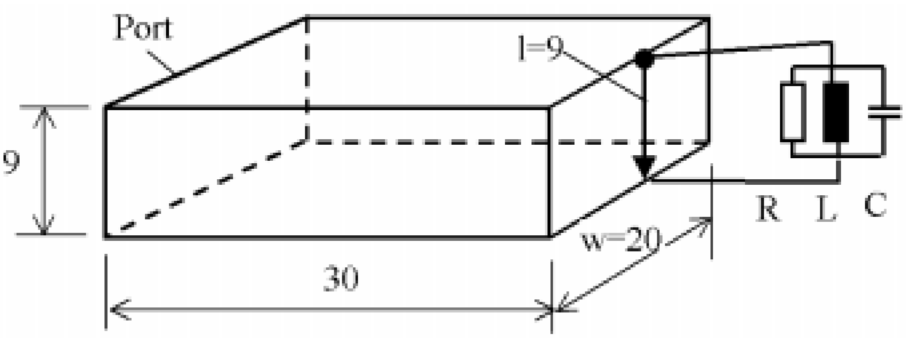

Figure 4: Parallel plate waveguide terminated by parallel lumped RLC elements
R = 33.75 Ohms, L = 0.1 nH, C = 2.533 pF

The magnitude of S_{11} was calculated using HFSS's new lumped element boundary feature. The problem has an analytical solution. The magnitude of parameter S_{11} can be calculated as:

$$|S_{11}| = \left|\frac{Z_2 - Z_w}{Z_2 + Z_w}\right|$$

where:

$$\frac{1}{Z_2} = \frac{1}{R_{field}} + j\left(\omega C_{field} - \frac{1}{\omega L_{field}}\right) \text{ and } Z_w = 377 \text{ Ohms}$$

The field values are given by:

$$R_{field} = R\frac{w}{l} \qquad L_{field} = L\frac{w}{l} \qquad C_{field} = C\frac{l}{w}$$

Figure 5 shows good agreement between the results calculated by the analytical method and the HFSS results. HFSS results were calculated using the interpolating sweep method, a frequency sweep in which solved frequency points are chosen so that the entire solution lies within a specified error tolerance. Approximately 2000 tetrahedra were used and the solution time was approximately 7 1/2 minutes on a Pentium/266MHz PC.

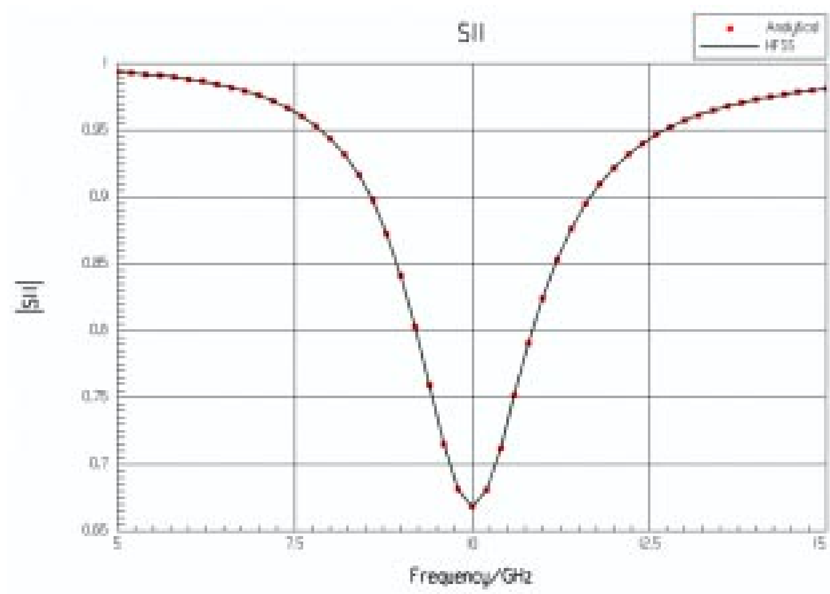

Figure 5: The magnitude of S_{11} compared to the analytical solution

Parallel Plate Waveguide Terminated with a Serial Lumped RLC Circuit

A parallel plate waveguide is terminated by a serial-connected RLC circuit, as shown in Figure 6. This connection type can not be specified directly in HFSS using the new lumped RLC boundary interface; the surface can be subdivided into three serial-connected subsurfaces as an approximation, assigning a single R, a single L and a single C value to them. Using this method for this example will not provide a reasonable approximation because the spatial distribution of the RLC elements plays an important role. (The next application shows an example where this technique is applicable.)

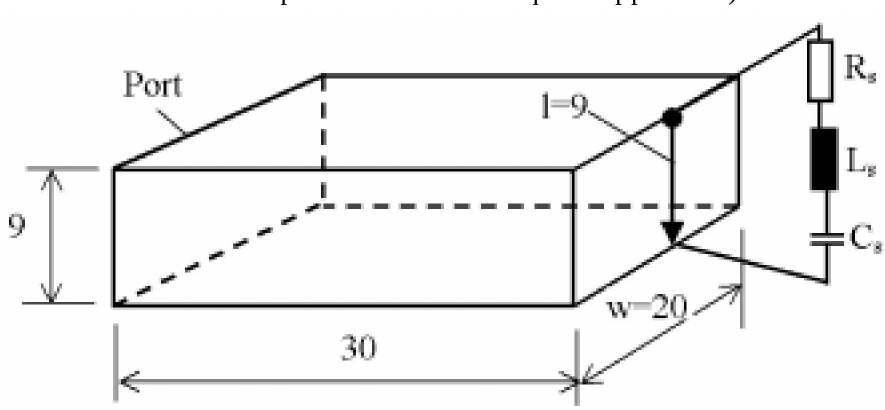

Figure 6: Parallel plate waveguide terminated by serial RLC elements.
The field values are: R_s = 75 Ohms, L_s = 100 nH, C_s = 2.533fF

where:

- R_s, L_s, and C_s are the serial connections
- fF represents 10^{-15}

This example can be solved using Ansoft Optimetrics in combination with HFSS. The impedance boundary condition is used to define the serial load as a function of the frequency:

$$Z_{load} = R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)$$

Because the HFSS 3D Boundary Manager's lumped element interface was not used, the field values, or ohms / square values, of the loads must be used. Three new parameters must be introduced in the 3D Boundary Manager, namely, Z_{re}, Z_{im} and f, where:

$$Z_{re} = R_s \qquad Z_{im} = \left(\omega L_s - \frac{1}{\omega C_s}\right)$$

After setting up the nominal HFSS project using the discrete frequency sweep option, Optimetrics must define the parameter frequency as f. Figure 7 shows good agreement between the HFSS results and the analytical solution.

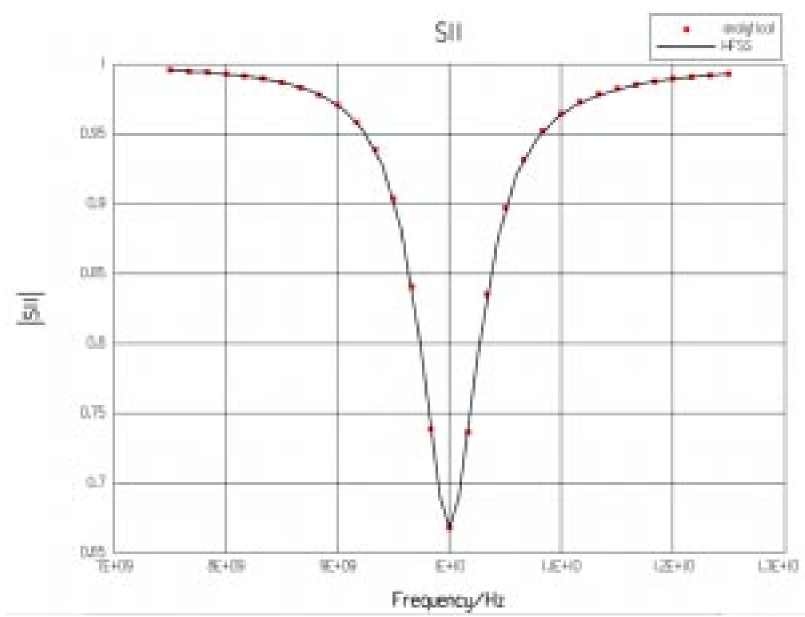

Figure 7: Magnitude of S_{11} compared to the analytical solution

Microstrip Line with a Serial-Connected Lumped Resistor

The lumped RLC boundary feature is useful for simulating the following example of a microstrip line. The microstrip line, which has a 100-ohm lumped resistor connected throughout a gap of the strip, is shown below:

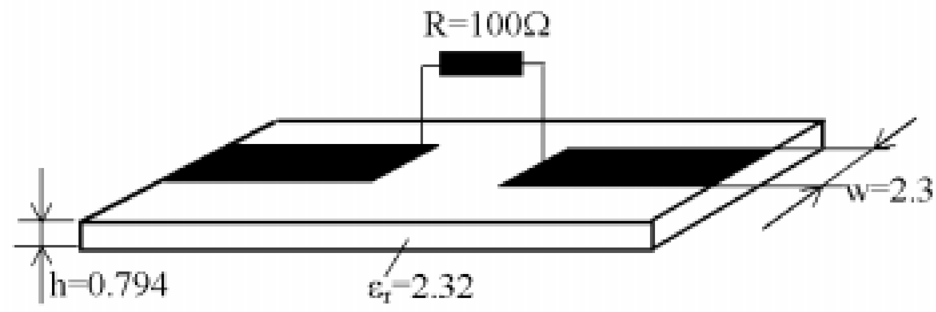

Figure 8: Microstrip line with a lumped resistor throughout a gap

The HFSS model is shown below:

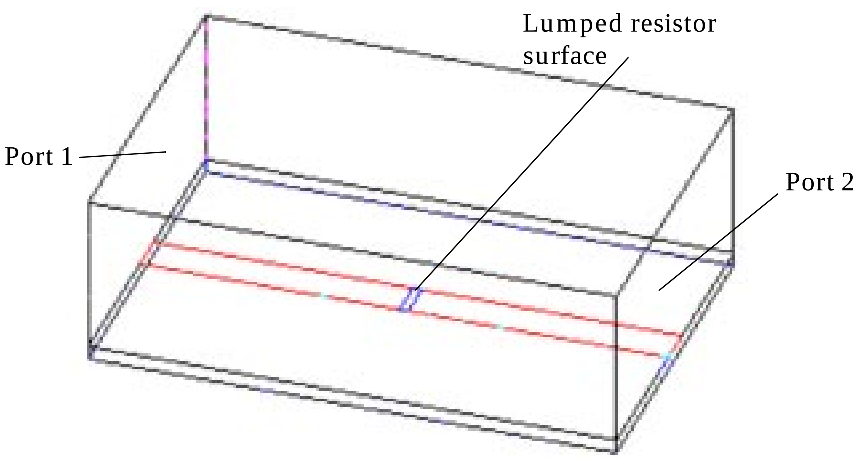

Figure 9: HFSS model of a microstrip line with a lumped resistor throughout a gap

The surface for the lumped resistor is defined to be as wide as the strip. If the width of the lumped resistor surface was defined as very thin, an additional inductance would be introduced to the system. (The length of the surface does not play an important role.) Figure 10 shows the frequency response of the magnitude of S_{11}. The HFSS results agree well with the analytical results obtained using Ansoft's Serenade design environment.

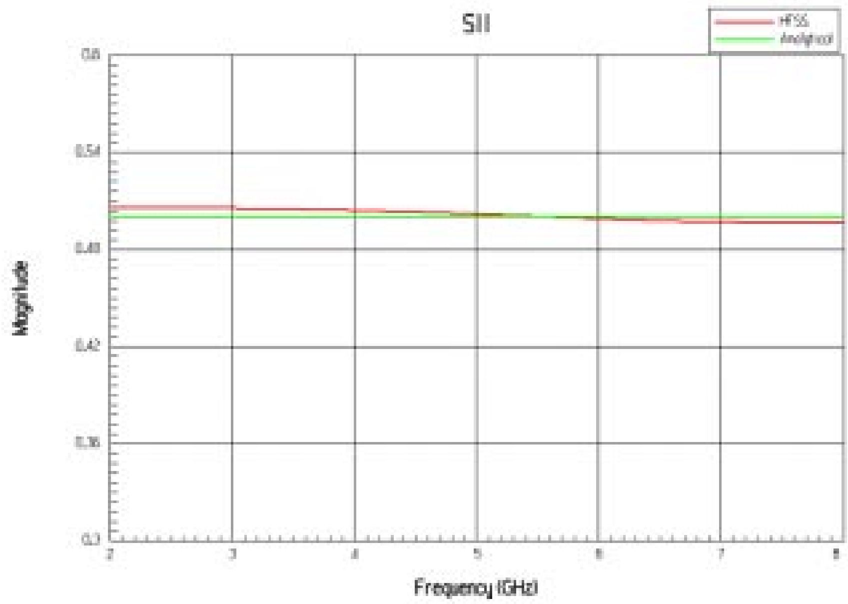

Figure 10: Magnitude of S_{11} of a microstrip line with a lumped resistor throughout a gap

Microstrip Line with a Serial-Connected Lumped LC Resonant Circuit

The following example is a microstrip line with a lumped, serial-connected resonant circuit connected throughout a gap of the strip. It is shown below:

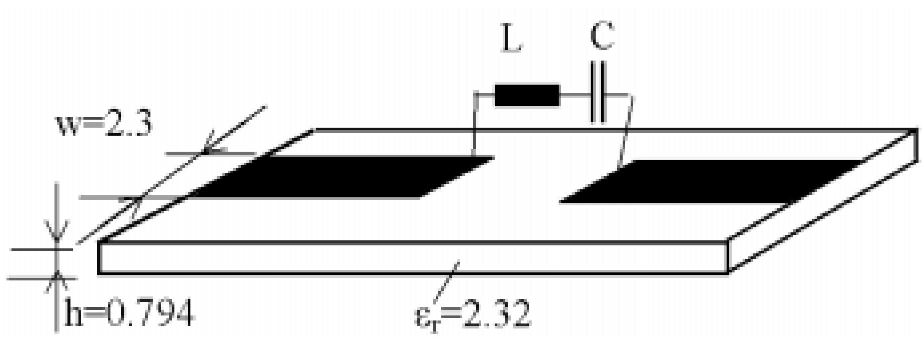

Figure 11: Microstrip line with a a lumped LC circuit throughout a gap
L = 10 nH, C = 3.96 pF

The HFSS model is shown below:

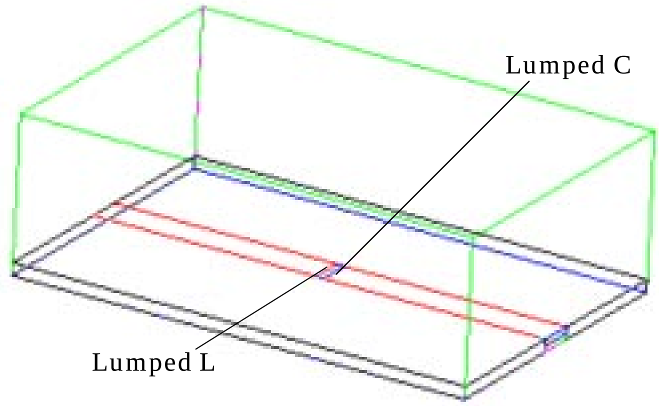

Figure 12: HFSS model of a microstrip line with a lumped LC circuit throughout a gap

The lumped elements' surfaces are defined to be equal to the strip's width. Because the length of the surface does not play an important role, the serial-connected LC circuit can be modeled with two serial-connected surfaces, as shown in Figure 12. The inductance is assigned to one surface and the capacitance is assigned to the other surface. Figure 13 shows the frequency response of the magnitude of S_{11}. The HFSS results agree well with the analytical results obtained using Ansoft's Serenade design environment.

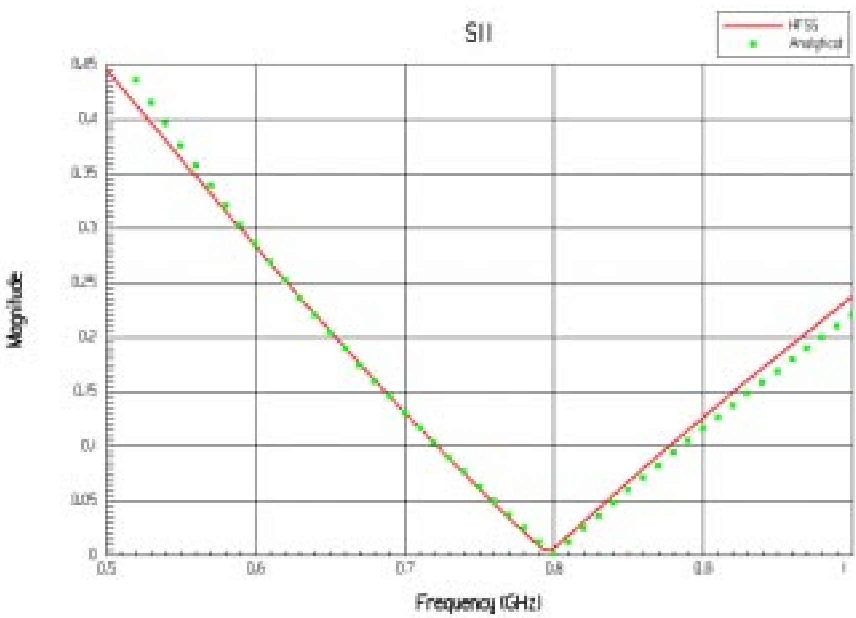

Figure 13: The magnitude of S_{11} of a microstrip line with a lumped LC circuit throughout a gap

Thick-film Chip Resistor Inserted in a Microstrip Line

The next example is a thick-film chip resistor inserted in a microstrip (see Figure 14). The equivalent circuit of the chip resistor is measured in the absence of the microstrip line.

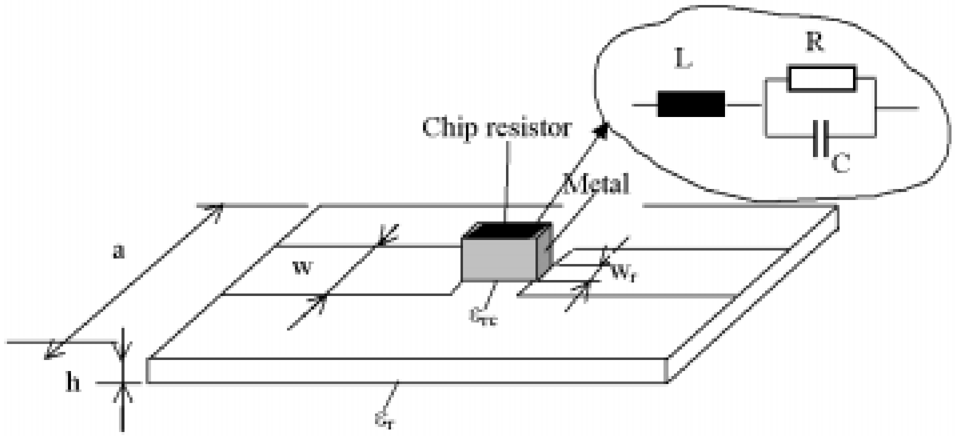

Figure 14: Thick-film resistor inserted in a microstrip line
a = 6.578 mm, h = 0.508 mm, w = 1.518 mm, w_r = 1.214 mm, ε_r=2.2, ε_{rc}=9.6

The chip resistor is replaced by its equivalent circuit distributed on the serial-connected surfaces, as shown in Figure 15. Note that the serial connection of surfaces possessing lumped element definition is an approximation.

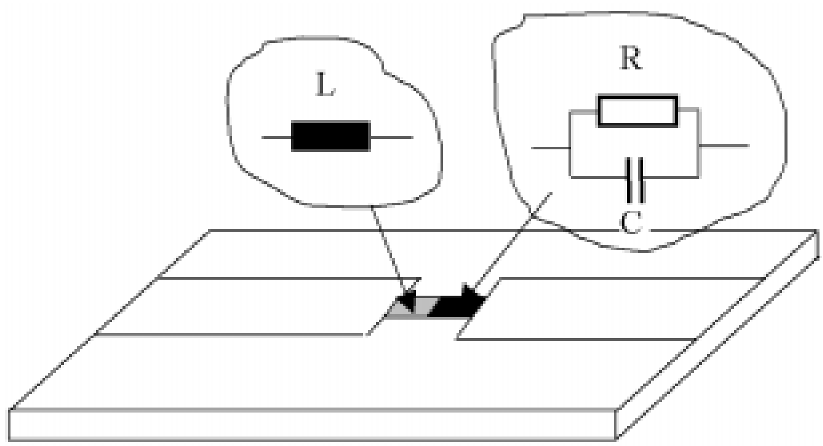

Figure 15: Thick-film chip resistor replaced by lumped circuit elements
and inserted back in a microstrip line
R = 10,820 Ω, L = 0.55 nH, C=24 fF

Figure 16 shows the magnitude of S_{11} for different R values and compares them to measured values. The HFSS results agree with the measured curves. The results were calculated by performing an interpolating sweep. About 9446 tetrahedra were used and the solution time was approximately 13 minutes on a Pentium / 266MHz PC.

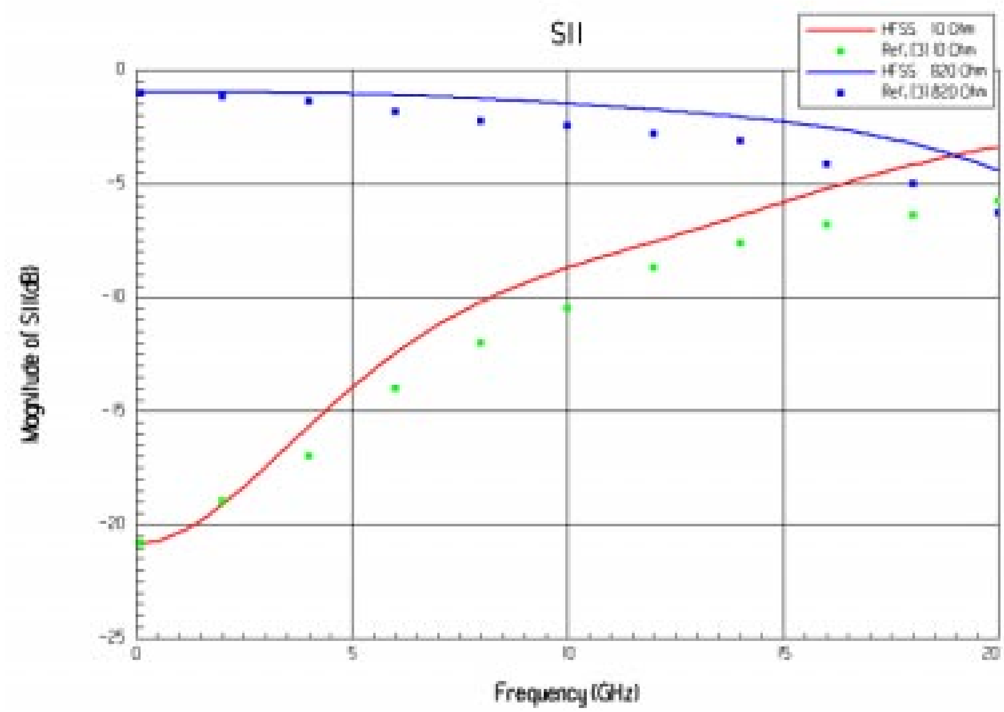

Figure 16: Magnitude of S_{11} of the microstrip line

Figure 16 illustrates that the discrepancy between the field simulation results and the measurements increase with frequency. This is a result of the presence of parasitic capacitances and inductances introduced by the small air gap and impedance surfaces.

The agreement is excellent in the lower frequency range, as shown in the following figure:

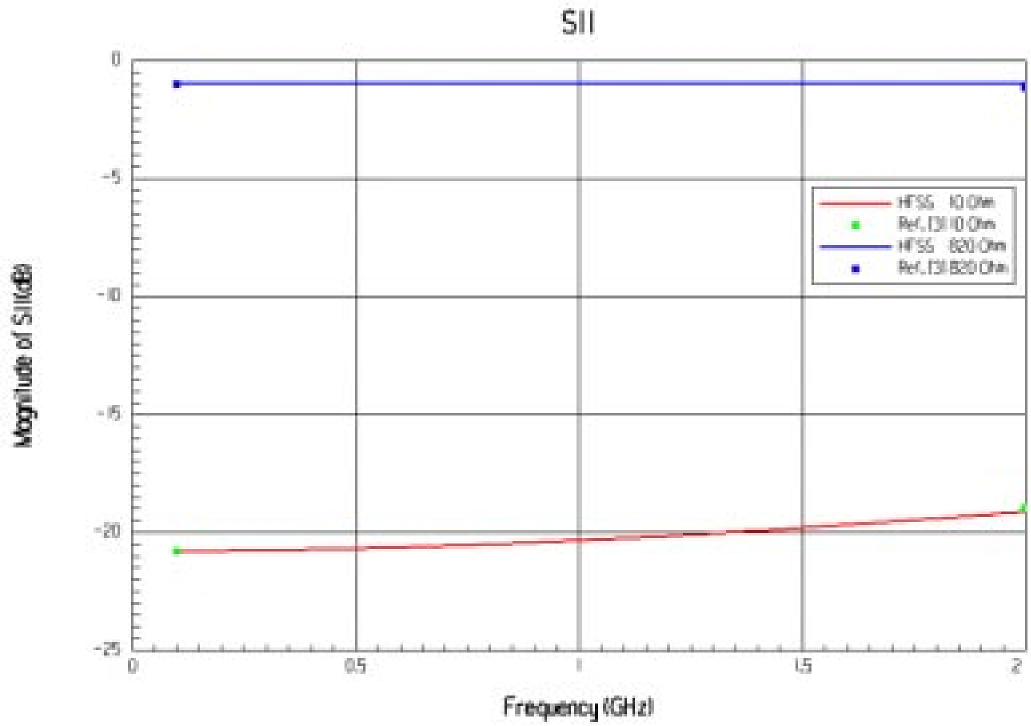

Figure 17: Magnitude of S_{11} of the microstrip line

Conclusions

HFSS Lumped RLC elements are useful for inserting lumped circuits into the field model, especially in the case of MMIC structures. The usage of lumped elements reduces the problem size by replacing complex sub-structures with an equivalent circuit model. Both the fast frequency sweep and the interpolative frequency sweep support lumped RLC elements.

References

[1] HFSS Version 8 Online Documentation. Ansoft Corporation, 2001.

[2] K. Guillouard, M. Wong, V.F. Hanna and J. Citerne, "A New Global Finite Element Analysis of Microwave Circuits Including Lumped Elements," IEEE Trans. MTT, Vol. 44, No. 12, December 1996, pp. 2587-2594.

[3] R. Gillard, S. Daugnet and J. Citerne, "Correction Procedures for the Numerical Parasitic Elements Associated with Lumped Elements in Global Electromagnetic Simulators," IEEE Trans. MTT, Vol. 46, No. 9, September 1998, pp. 1298-1306.

[4] J.A. Pedra, F. Alimenti, P. Mezzanotte, L. Roselli and R. Sorrentino, "A New Algorithm for the Incorporation of Arbitrary Linear Lumped Networks into FDTD Simulators," IEEE Trans. MTT, Vol. 47, No. 6, June 1999, pp. 943-949.

[5] L. Zhu and K.Wu, "Accurate Circuit Model of Interdigital Capacitor and Its Application to Design of New Quasi-Lumped Miniaturized Filters with Suppression of Harmonic Resonance," IEEE Trans. MTT, Vol. 48, No. 3, March 2000, pp. 347-356.

[6] K. Hettak, N. Dib, A.F. Sheta and S. Toutain, "A Class of Novel Uniplanar Series Resonators and Their Implementation in Original Applications," IEEE Trans. MTT, Vol. 46, No. 9, September 1998, pp. 1270-1276.