FDTD Simulation of a coaxial reactive calibration standard

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Abstract:

This paper presents a procedure to simulate an open-circuit coaxial reactive calibration standard having whole axial symmetry.

The simulation is carried out on a planar microstrip equivalent circuit representing the coaxial standard.

Abstract (cont.) :

A two-dimensional (2-D) finite-difference time-domain (FDTD) method is used to reach this purpose.

The lumped equivalent circuit inductance and capacitance of an undetermined planar circuit are used to define the characteristic impedance of the microstrip circuit.

The open-circuit termination is first approximated by a middle-large impedance to obtain an initial uncompensated response, which will subsequently be compensated by means of a factor attained from a transmission line circuit analysis.

Abstract (cont.) :

Then, a second open-circuit approximation is reached when a zero current density and a source potential are stated at the microstrip output cells giving a more realistic straight response.

Both, the direct and the compensated responses are compared to a measured response showing a good agreement among them.

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1. Introduction :

Calibration standards are core components of any high-frequency measurement system.

The choice of a suitable electromagnetic simulation method depends on the type of the line.

The optimal choice is the use of a 3D technique but in some cases, e.g., for coaxial standards having a complete axial symmetry, performing a simple 2-D simulation could gives good results.

Introduction (cont.) :

The 2-D FDTD method used to the simulation of an open-circuit coaxial standard is the proposed by Gwarek.

This method can be easily implemented for simulating coaxial type standards, because, it needs only a pair of simple closed-form equations.

This equations must be evaluated in order to define a characteristic impedance proper of a planar circuit (as microstrip, stripline, coplanar, etc.).

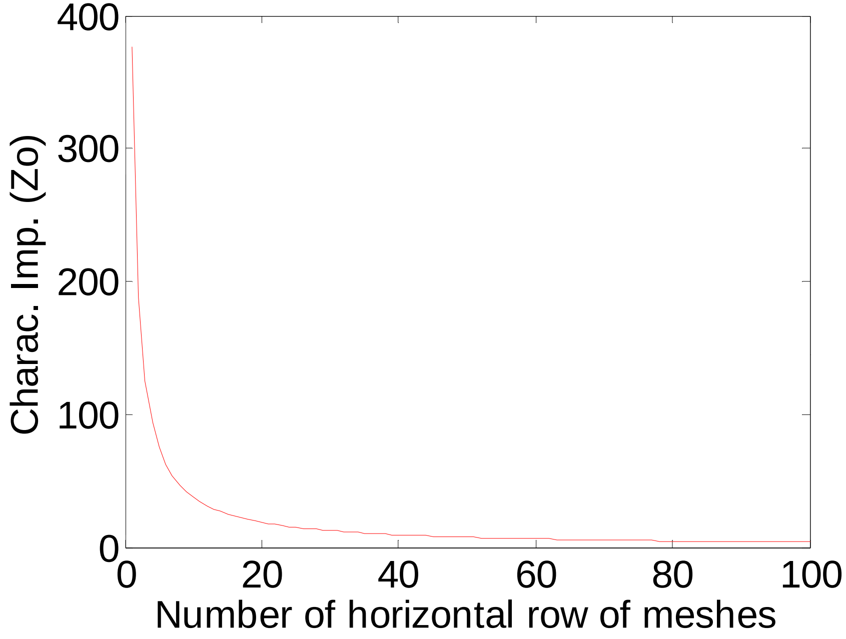
Introduction (cont.) :

The characteristic impedance is stated by choosing a number of discretizing meshes or segmentation cells on an impedance graph generated by the two closed-form (inductance and capacitance) equations.

The number of horizontal row of meshes corresponds to the number of vertical cells segmenting the planar geometry.

Introduction (cont.) :

The impedance goes from 377 Ω for 1 cell to a value tending to zero for bulky segmentations.



Introduction (cont.) :

Once the characteristic impedance is defined, a 2-D FDTD simulation can be carried out by the following procedures presented by [2].

First, an open-circuit termination is roughly defined as 6.5 times the microstrip characteristic impedance in order to avoid numerical dispersion.

Afterwards, a transmission-line analytical study is developed tending to compensate this poor approximation of the open-circuit termination.

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Introduction (cont.) :

Next, a code amend implementing a zero current flux at the microstrip output is performed aiming to simulate a better open-circuited load.

Finally, the measurement of an actual standard and the comparison of the different responses are presented.

2. The coaxial reactive calibration standard :

Most of the commercial microwave or high-frequency measurement instruments (as network analyzers, spectrum analyzers or signal generators) use type N, APC7 or APC3.5 – SMA connectors and adapters for interconnecting or converting among them and for the input and output ports at the reference planes.

A proposal of an open-circuited coaxial line was presented in [3] as a standard intended for APC7 connectors.

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The coaxial reactive calibration standard (cont.) :

The coaxial-line standard is terminated on a circular waveguide created by the abrupt truncation of the line´s inner conductor.

The discontinuity at the transition between the coaxial line and the circular waveguide is modeled by a frequency-dependent lumped capacitance approximated by means of an equation obtained from a fitting procedure. The approximation expression is given by

$$C(w) = \frac{C(0)}{\sqrt{1 - \left(\frac{f\,(MHz)}{34450}\right)^2}} \qquad (1)$$

Where $C(0)$ is the capacitance limiting value (zero frequency) of the APC7 open standard. By permitting a prolongation instead of a truncation on the line´s inner conductor, a capacitively loaded coaxial line can also be used like an open-circuit standard as shown in Fig. 1. In this geometry (APC3.5), the radiation effect at the open-end termination might give rise to non-negligible losses which must be reduced in some extent.

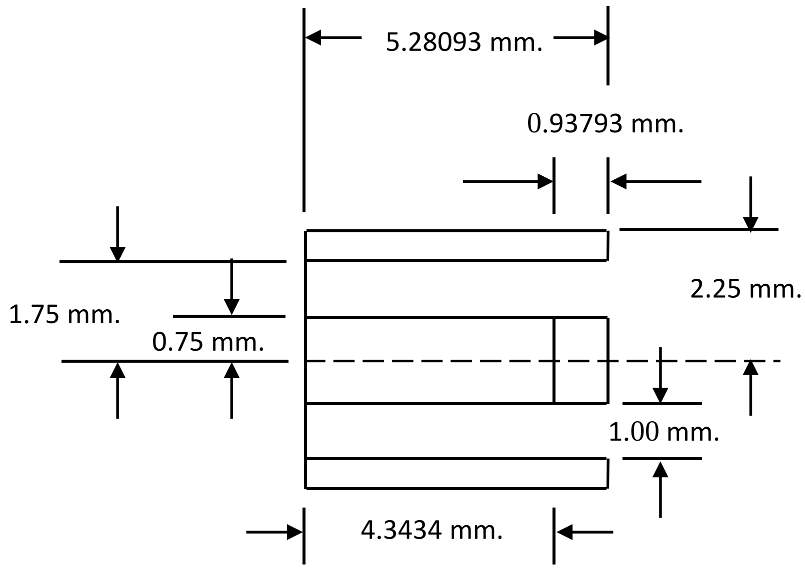

Fig. 1 A capacitively loaded coaxial line.

The coaxial reactive calibration standard (cont.) :

In order to make some comparisons, the 8048B1 open-circuit standard of Maury Microwave® was measured and analyzed. The Maury´s data sheet for this standard gives the following capacitive coefficients:

Coefficients
C (0) = C0 = 62.54 x 10 $^{-15}$
C1 = - 1284.00 x 10 $^{-27}$
C2 = 107.60 x 10 $^{-36}$
C3 = - 1.886 x 10 $^{-45}$

Table 1 The capacitive coefficients of the 8048B1 open-circuit standard.

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The frequency-dependent lumped capacitance for the 8048B1 standard is approximated by a power series using the four capacitive coefficients of Table 1 as a follows

$$C(w) = C(0) - C1 \cdot f + C2 \cdot f^{2} - C3 \cdot f^{3} \qquad (2)$$

where f is given in GHz.

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As can be seen from Fig. 2 for all the frequency range, the blue trace corresponding to (1), is underestimated as compared to the red trace, corresponding to the measurement. Likewise, for frequencies larger than 2 GHz, the black trace corresponding to (2) diverges from the red trace.

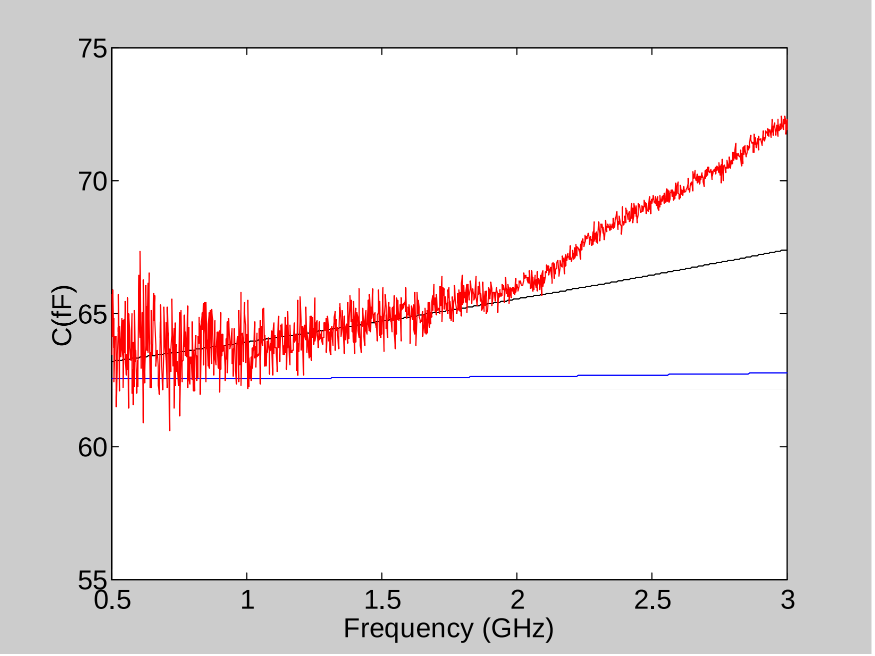

Fig. 2 The frequency-dependent capacitance of geometry of Fig. 1.

3. Lumped equivalent circuit inductance and capacitance :

The characteristic impedance of the microstrip equivalent circuit is defined by means of the following undetermined lumped inductance and capacitance [1]

$$L_s'(r_k) = \frac{\varepsilon \mathrm{a}}{\ln\left(\dfrac{r_k + \mathrm{a}/2}{r_k - \mathrm{a}/2}\right)}, \tag{3}$$

$$C_s'(r_k) = \frac{\mu}{\mathrm{a}} \ln\left(\frac{r_k + \mathrm{a}/2}{r_k - \mathrm{a}/2}\right) \tag{4}$$

Lumped equivalent circuit inductance and capacitance (cont.) :

where r is the radial coordinate, k is the number of horizontal row of meshes, s refers to an arbitrary square for the inductance and a unitary square for the capacitance, ε and μ are the permittivity and permeability of the dielectric medium, and a is the size of the square meshes.

Thus, for a k varying from 1 to 100, the characteristic impedance given by

$$Z_0 = \sqrt{L_s' / C_s'} \tag{5}$$

generates the curve of Fig. 3. Choosing k as 4, a Z_0 of $94.188\,\Omega$ will be the characteristic impedance of the microstrip equivalent circuit.

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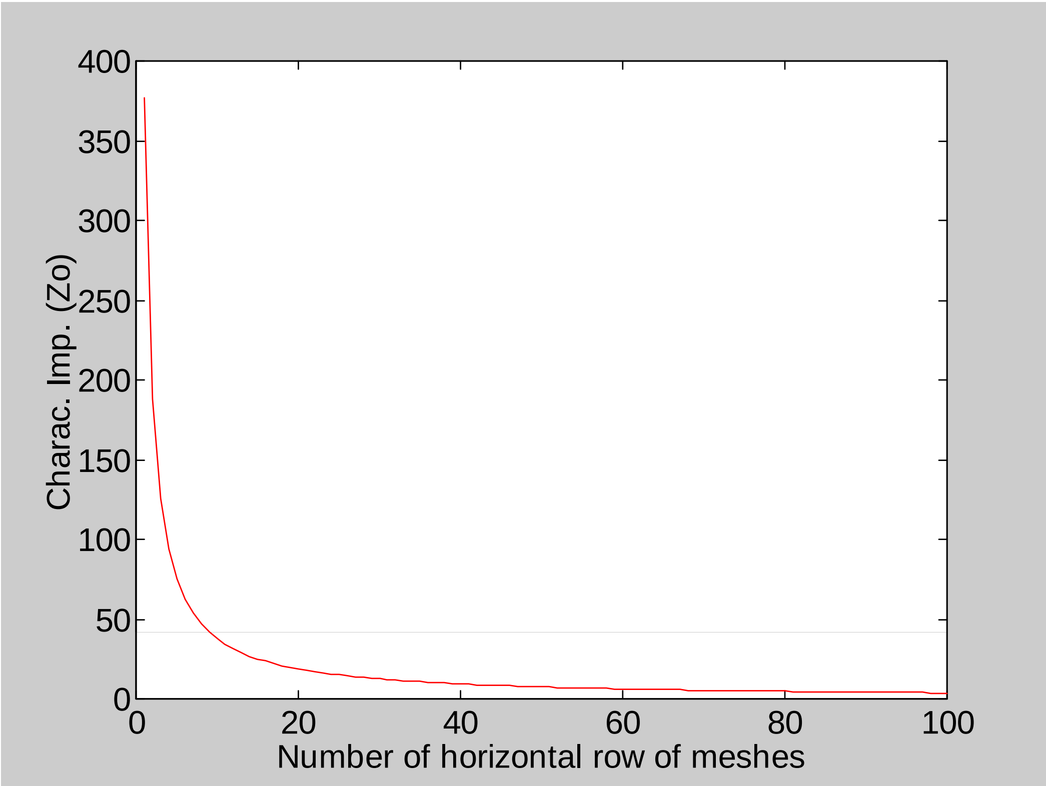

Fig. 3 The characteristic impedance of the microstrip equivalent circuit.

4. FDTD Simulation :

Both, the responses of the compensated simulation (green trace) and the direct simulation (blue trace) are presented in Fig. 4. Only 2800 timesteps are necessary to reach the steady state but a run of 3500 timesteps is allowed with the aim of confirm the permanence of an invariable response.

The compensation factor for the entire bandwidth (0 to 3 GHz), was found as a constant value of 0.178 via the transmission line circuit analysis. This value is directly added to reflection coefficient magnitude of the uncompensated response.

5. Microstrip circuit analysis :

In order to enhance the comparison process but also to validate the simulation responses, a circuit analysis of the microstrip equivalent circuit is carried out by following the procedure described in section 3.5 of [2] for a non-connectorized microstrip transmission line. Thus, the input impedance is simply obtained by using the following equation:

$$Z_{in} = Z_{0m} \frac{Z_L + jZ_{0m} \tan\left(\beta_m l_m\right)}{Z_{0m} + jZ_L \tan\left(\beta_m l_m\right)} \tag{6}$$

where Z_{0m} is the characteristic impedance of the microstrip, Z_L is the load impedance and $\beta_m l_m = \theta_m$ is the electric length of the microstrip.

The response obtained from this expression is drawn with the black trace on the polar graph of Fig. 4.

6. Measurement :

The measurement was performed on one Agilent 8714ES automatic network analyzer calibrated using an open-short-load (OSL) technique with a user one-port calibration for 1600 points. The four responses, i.e., the compensated and direct simulations, the circuit analysis and the measurement (red trace), are all presented in Fig. 4.

As can be seen from the polar graph, the analytical (microstrip) and measured responses are almost identical except for a small difference on the phase. Likewise, the compensated and direct simulated responses closely follow the traces of the first two until the ending part of the bandwidth. In this part, a notable divergence is appreciated because it starts the typical response of a spiral loop closing clockwise over itself, mainly on the direct response.

Measurement (cont.) :

This behavior is of course generated by the losses there will be in an actual microstrip circuit and because in any case neither the middle-large impedance nor the load zero current alone are a perfect representation of an open circuit.

Despite the aforesaid, the traces are so similar that they covalidate themselves and thereby the simulation method.

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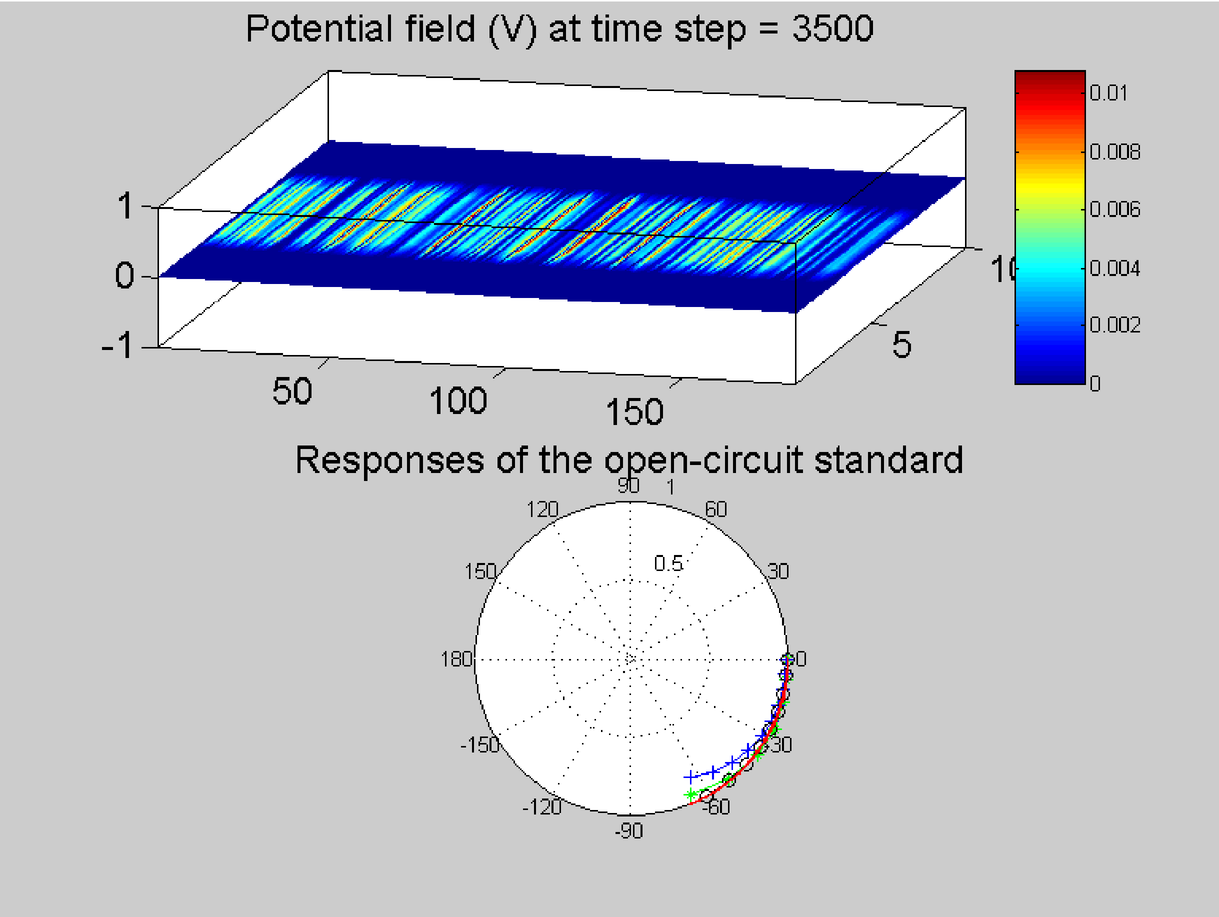

Fig. 4 Reflection coefficient responses of the proposed open-circuit standard.

7. Conclusion :

The simulation, analysis and measurement of an open-circuit standard were performed in order to facilitate the cumbersome cut-and-try design process for fabricating this kind of microwave fixtures. The intercomparison of the frequency-dependent capacitances generated by the reactive termination of APC3.5 open-circuit standards, demonstrated the necessity of an enhanced curve fitting to obtain better modeling closed-form equations. Likewise, it was proven that a 2-D FDTD electromagnetic simulation is good enough to simulate a simple planar circuit as the microstrip equivalent representing the open-circuited coaxial line standard. In addition a simple microstrip circuit analysis in conjunction with a physical measurement confirmed well the simulation results.

REFERENCES

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[2] A. Dueñas Jiménez, *2-D Electromagnetic Simulation of Passive Microstrip Circuits*. Boca Raton, FL: CRC Press a Taylor and Francis Company, 2008, 274 pp.

[3] B. Bianco, A. Corana, L. Gogioso, and S. Ridella, “Open-circuited coaxial lines as standards for microwave measurements,” *Electron. Lett.*, vol. 16, no. 10, pp. 373-374, May. 1980.