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Proposal of a slotted circular waveguide as an open-circuited standard for calibration of L-band network analyzers

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Abstract: This paper presents a slotted circular waveguide as an open-circuited standard structure. This device as well as its previous stages are simulated with a 3D FDTD program. The dimensions are based on estimations of the MM8048B1® open-circuited standard. The results obtained through a variational method and a static MoM simulation, when compared with those obtained by means of 3D FDTD simulation, are found to be in good agreement, especially in the L-band.

Keywords: calibration standard, circular waveguide, FDTD simulation, network analyzer, open-circuited, slots

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Open-circuited standards are used in several network analyzer calibration techniques. One such technique is the popular SOLT, which employs Short, Open, Load, and Thru standards. It is widely applied to calibrate Agilent® Vector Network Analyzers (VNAs). Open-circuited standards are easy to manufacture, but their analysis and simulation are more complicated, due to the impossibility of achieving a perfect infinite load and even a sufficiently good approximation.

Some papers have examined this kind of standards using variational methods [1, 2, 3] or implementing a 2D-FDTD method for structures that have complete axial symmetry [4]. All these studies have considered the discontinuity of open termination as an equivalent shunt capacitance. Based on the previous works as well as those that carried out the analysis on slots, such as [5, 6], this paper presents a new open-circuited standard. A 3D FDTD and a static MoM programs have been used for the simulation of the standard. The former was originally created by [7] and was modified for working with small circular geometries, while the latter was created by [8].

2 Simulation of the previous stages

For the simulation of the novel standard, it is convenient to evaluate two standards whose structures are their previous stages.

The 3D FDTD program uses cylindrical coordinates: the step size is 0.125 mm in z (longitudinal) and r (radial) axes, and 30° in ang (angular) axis for the first two standards, and 10° for the last one. This small cell size (i.e., 0.125 mm) is the best option for obtaining a better simulation result without increasing the computing time too much. The signal excitation is a typical Gaussian pulse, and the absorbing boundary condition (ABC) region is a fifteen-cell size perfectly matched layer (PML).

The first structure is a simple 3.5-mm air coaxial line, designed to emulate the response of the Maury Microwave MM8048B1® (open standard) for a bandwidth of 0–3 GHz. Based on the MM8048B1® data sheet, this standard

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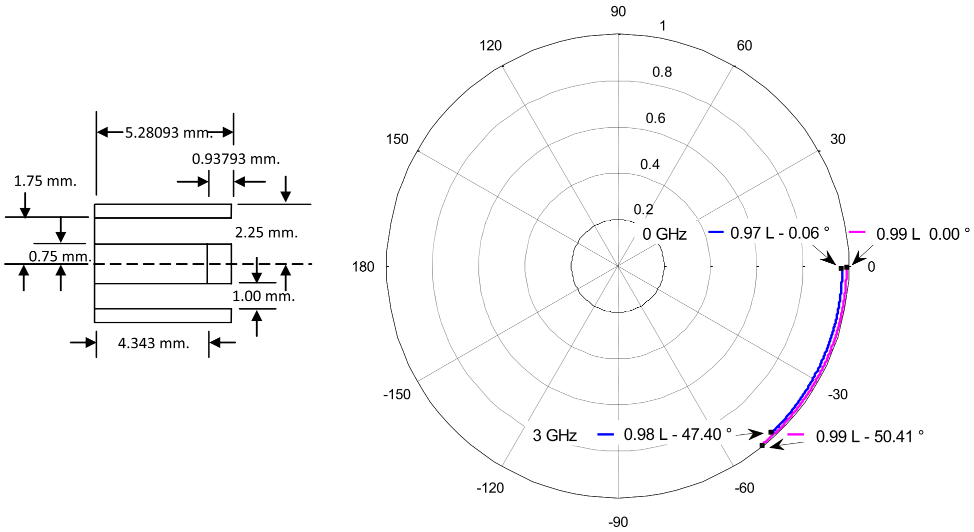
could be considered as two sections. One is a 4.343-mm long coaxial line, and the other is a shunt, frequency-dependent, equivalence capacitance. The capacitance can be replaced by a second line with a length that corresponds to the calculated capacitance. In this case, the last section is a 3.5-mm air coaxial line of 0.93793-mm length open-load terminated (see Fig. 1 a).

The analysis and the 2D FDTD simulation of the line, using the technique originally introduced by [9], and the comparisons with the measurement of the MM8048B1® standard, are detailed in [4] with regard to the S_{11} parameters for 0–3 GHz. Here, the 3D FDTD simulation, using 300 time steps, was carried out and contrasted with their analytical response, as shown in Fig. 1 b.



a) b)

Fig. 1. The 3.5-mm coaxial line open-terminated, which emulates the MM8048B1® open standard behavior. a) Its dimensions and b) its analytical results (magenta line), and 3D FDTD simulation (blue line).

The second structure is the HP8542A® open standard. This was formed from a 7-mm air coaxial, terminated in a 33.4-mm long circular waveguide, as shown in Fig. 2 a. The length of the coaxial was considered to be 5 mm. This dimension was estimated based on the usual distance in some of the commercial standards, as there was no specific information about it.

The standard was found to have different dimensions when compared with the earlier and the subsequent structures. It was selected for two reasons: one, its geometry is the next step in obtaining the final structure of the new standard and two, it has a precise closed-form formula. This standard was measured and evaluated in [3], employing a variational method developed by [1]. Bianco achieved a simple yet highly accurate equation, Eq. (1), which could provide the value of the equivalent capacitance of the circular waveguide

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as a function of the frequency

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

where C is the capacitance and $C(0)$ is the limiting capacitance value (at 0 Hz).

Based on Eq. (1) that corresponds to the shunt equivalent capacitance and considering its effect at the beginning of the standard, the S_{11} parameters can be calculated. These S_{11} parameters and those that give the 3D FDTD simulation, using 200 time steps, are presented in Fig. 2 b,

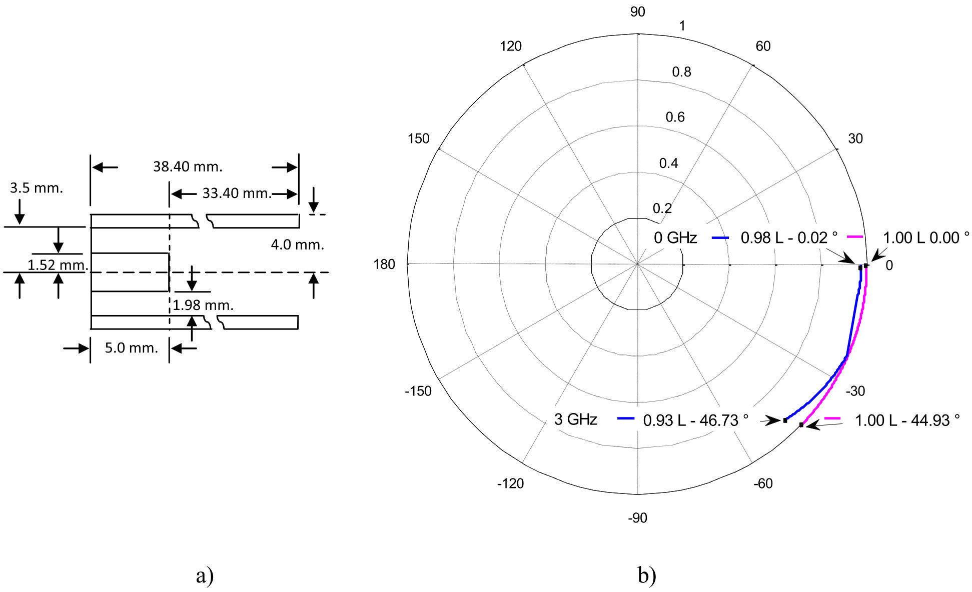

Fig. 2. The 7-mm coaxial line terminated in a circular waveguide, HP8542A® open standard. a) Its dimensions and b) its analytical results (magenta line), and 3D FDTD simulation (blue line).

3 The new standard simulation

The novel structure was selected using a slotted circular waveguide because the slots decrease the equivalent shunt capacitance [6], thereby reducing the deviation angle of the S_{11} parameter for a given frequency. The dimensions of the proposed standard were taken from the MM8048B1®, but by changing the equivalent capacitance section to a circular waveguide with slots. The 5.25-mm-long device has two parts, one is a 3.5-mm coaxial line that maintains the same length of the first standard, 4.343 mm, but in both cases, to match with the simulation cell size, it was rounded to 4.375 mm, the other part, is a circular waveguide of 0.9126 mm, rounded to 0.875 mm, with two slots. As the depth of the slots is of the same value as the waveguide length, this becomes a pair of semicircular plates. The slot angle is 20° wide and 180° opposite to each other, as shown in Fig. 3 a.

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Two ways of comparing the values obtained by the 3D FDTD, using 300 time steps, were employed. One was the analytical way, via a variational method, and the other was via a static MoM simulation [9].

To analyze the structure by the variational method, it is necessary to separate it into two sections. The first is the coaxial line and the second is the slotted circular waveguide that transforms into two semicircular plates because the waveguide is cut totally along its length by the slots. The equivalence capacitance due to the plates can be calculated via the variational method. This method, originally proposed by [5] for calculating the characteristic impedance for the slotted coaxial lines, was modified for semicircular plates by [6], from which it was possible to obtain their equivalence capacitance, and considering the coaxial section, to calculate the S_{11} parameters.

The alternate method of checking the 3D FDTD outcomes is the static MoM. This simulation is used for evaluating the second-order TEM modes, mentioned in [5], due to the fact that the transverse fields of a TEM wave are the same as the static fields [10]. There is a second TEM mode because the central inner conductor of the slotted circular coaxial is reduced to an infinitesimally small radius, but not totally eliminated for numerical reasons. The static MoM simulation is carried out and the capacitance [8] is obtained from

$$C = \frac{|Q_l|}{Vd}, \tag{2}$$

where C is the capacitance in F/m, Q_l is the charge per unit length, and Vd is the potential difference on the strips, i.e., the semicircular plates. The capacitance value of the two semicircular plates is calculated by

$$Cap = C \cdot dist, \tag{3}$$

where $dist$ is the length of the plates, in this case, 0.875 mm. The frequency shift is made out of the MoM loop from 0 to 3 GHz. Capacitance reactance is computed from

$$X_c = \frac{1}{2\pi f C}. \tag{4}$$

If loss in the plates is not considered, then X_c becomes $Z_L = -jX_c$, the load impedance, and from this, the input impedance, Z_{in}, is estimated by

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)}, \tag{5}$$

where Z_0 is the characteristic impedance of the 3.5-mm air coaxial line, γ is its propagation constant, and l is its 4.375 mm length. The S_{11} parameters can be obtained from

$$S_{11} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}. \tag{6}$$

Finally, the 3D FDTD simulation is performed. These outcomes are shown with those of the other two methods, for the same frequency bandwidth (0–3 GHz), in Fig. 3 b.

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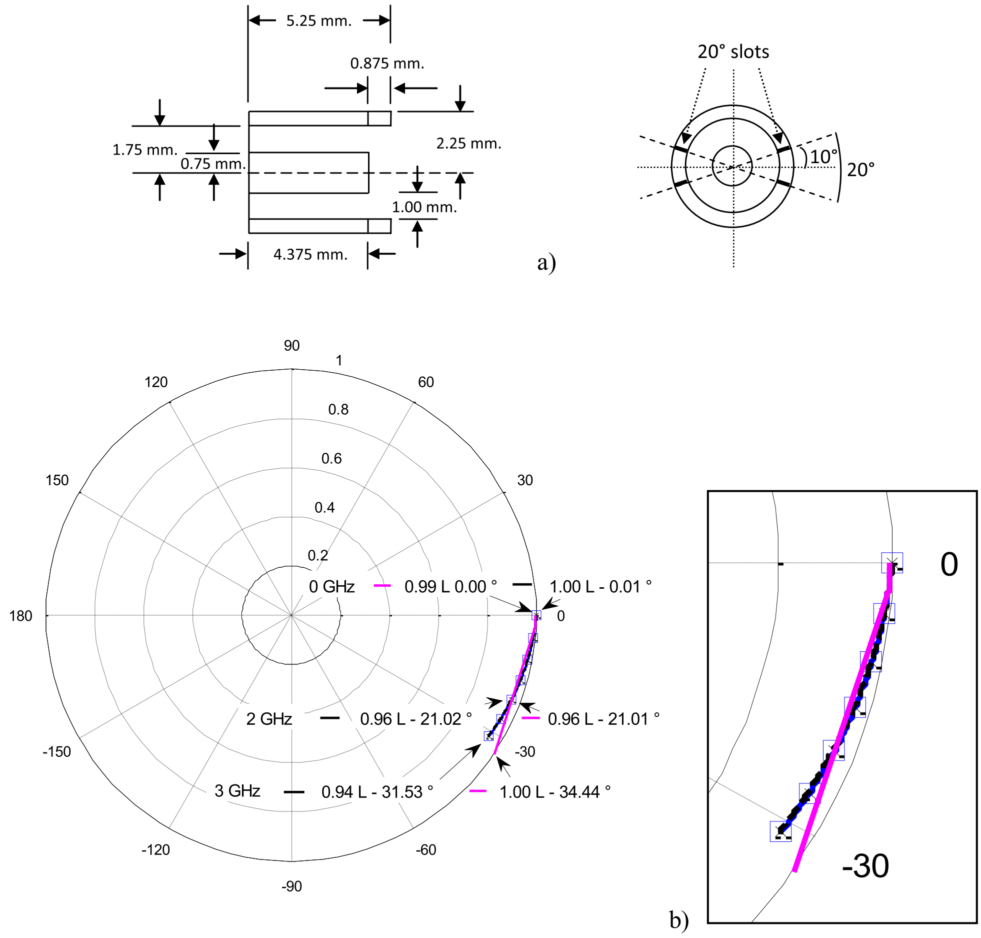

Fig. 3. The 3.5-mm coaxial line terminated in a slotted circular waveguide, open standard. a) Its dimensions and b) its variational results (squares and continuous line in blue), MoM simulation (cross and dashed line in black), and 3D FDTD simulation (magenta line).

4 Conclusion

As seen from Fig. 3 b, there is a very good agreement between the 3D FDTD simulation (the magenta line) and the other two methods, namely, the variational proposed by [6], represented by the cross and dashed black line, and the static MoM [9], corresponding to the squares and blue one. The values from 0 to 2.0 GHz, the L-band, match very well, but from 2.0 to 3.0 GHz, they diverge and this effect could be due to the numerical dispersion. However, it should be noted that for the same frequency bandwidth, from 0 to 3 GHz, the phase deviation for the new standard is less than that in the two previous structures. This is good because it indicates that for the same frequency, this standard behavior is closer to an open-circuit load (0°). As mentioned earlier, this novel standard is a good start from which posterior improvements could be made, as in the design of the FDTD code.

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