FINITE ELEMENT ANALYSIS OF OPEN-ENDED COAXIAL LINES

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Abstract

The open-ended coaxial line is used as a probe for sensing complex permittivity since the reflection coefficient varies as a function of both frequency and permittivity. Results from a finite element analysis of the open-ended coaxial line compare well with published results. One aspect of measurement accuracy is derived from how well a model relating the reflection coefficient to complex permittivity matches the actual structure. Finite element analysis can be used as a tool to examine the effects on model accuracy of finite ground planes as well as profiles within the ground plane.

Comparison with Previously Reported Results

The finite element simulations described in this paper were computed by the High Frequency Structure Simulator (HFSS) from Hewlett Packard. HFSS creates an initial mesh that fills the geometric structure and defines the points that contribute to the solution. For each adaptive pass the mesh is refined providing greater detail in the regions where EM field intensities are greatest. The complexity of a simulation can be greatly reduced if planes of symmetry are used to reduce the size of the structure that is analyzed. The circular symmetry of the coaxial line allows a thin pie shaped wedge to be used as the structure analyzed by HFSS.

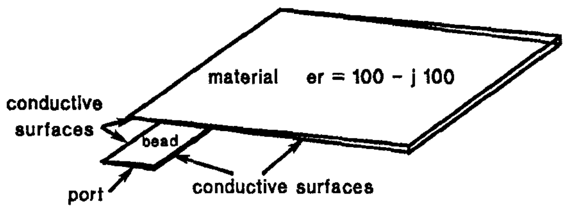

Figure 1

Figure 1 shows a three degree wedge of an open-ended coaxial with a center conductor and outer conductor radii equal to 2.333 mm and 7.549 mm respectively. (In the figure the center conductor and outer conductor are determined by specifying the appropriate surfaces of the bead to be perfect conductors.) The dielectric constant between the center conductor and outer conductor is 2.15. The HFSS simulation was computed at a frequency of 1 GHz for a contacting material having $\varepsilon_r^* = 100 - j100$. This yields a complex reflection coefficient with magnitude 0.6722 and phase -165.55°. This result compares favorably with a magnitude of 0.6716 and phase of -165.5° reported by Jenkins *et al.*[1]

Examination of a Coaxial Probe

There have been several models developed for the coaxial probe [2,3,4,5], these models generally assume a flat infinite ground plane in contact with a homogenous material of semi-infinite extent. Verification that a particular probe geometry matches the theoretical model is an important aspect of any uncertainty analysis. Figure 2 shows the open-ended coaxial probe used for the subsequent measurements and simulations presented in this paper. The coaxial probe has the following characteristics:

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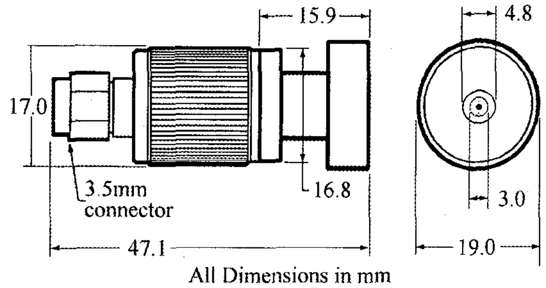

Figure 2

1. Inner conductor diameter = 0.66 mm
2. Outer conductor inner diameter = 3.0 mm
3. Glass bead with permittivity equal to 3.3
4. Ground plane diameter = 19.0 mm
5. Ground plane pedestal diameter = 4.8 mm
6. Ground plane pedestal height = 0.25 mm

(NOTE: The ground plane pedestal helps insure intimate contact between the probe and the contacting material.)

HFSS can be used to examine the difference between a probe having a finite diameter ground plane with ground plane pedestal and an idealized probe with semi infinite, flat ground plane. Figure 3 shows the structure analyzed by HFSS; changing the material properties of the different regions allows the same structure can be used for both cases.

It is easy to simulate a semi-infinite sample when the contacting material has loss (figure 1). From a practical point of view the assumption of a semi-infinite material is equivalent to the conditions that the exterior boundaries of the material are not sensed at the probe aperture. To simulate a semi-infinite sample for a lossless case requires the addition of a matching boundary to the exterior region of the contacting material. In figure 3 the outer shells (B, C, D, E) are used to provide an absorptive exterior boundary to the material. The loss tangent increases for each shell ($\tan\delta = 0.1$ for B, $\tan\delta = 0.5$ for C, $\tan\delta = 1.0$ for D and $\tan\delta = 2.0$ for E).

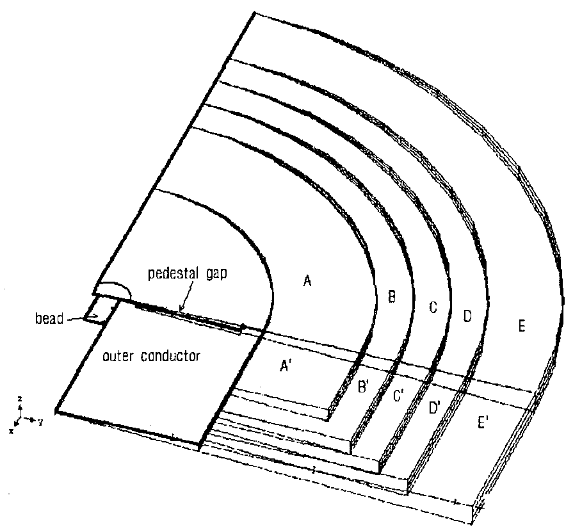

Figure 3

An HFSS simulation was run for the case of the coaxial probe contacting a material with $\varepsilon_r^*=1\text{-}j0$. Initially the pedestal gap, regions A', B', C', D', and E' (see figure 3) were all defined with $\varepsilon_r^*=1\text{-}j0$. Several passes were made for a frequency of 10 GHz until S11 converged. The magnitude of the difference between the last two passes was 4.888e-06. The pedestal gap, the A', B', C', D', and E' regions were then redefined to be metal and the new problem was computed using the same mesh. Redefining the areas to be metal simulated a much larger, flat ground plane that more closely matches an infinite ground plane. The following table summarizes the results

Freq (GHz)	Finite Ground Plane with Pedestal dia=19.0 mm		Infinite Ground Plane dia=64.0 mm		$\lvert\Delta S_{11}\rvert$
	S_{11} mag	S_{11} phase (deg)	S_{11} mag	S_{11} phase (deg)	
0.100	1	-0.08	1	-0.08	0.000000
3.417	1	-2.63	1	-2.64	0.000175
6.733	1	-5.22	0.9999	-5.22	0.000100
10.005	0.9995	-7.9	0.9994	-7.88	0.000363
13.370	0.997	-10.62	0.9981	-10.6	0.001154
16.680	0.991	-14.39	0.994	-14.53	0.003858
20.000	0.9907	-16.02	0.9903	-16.23	0.003652

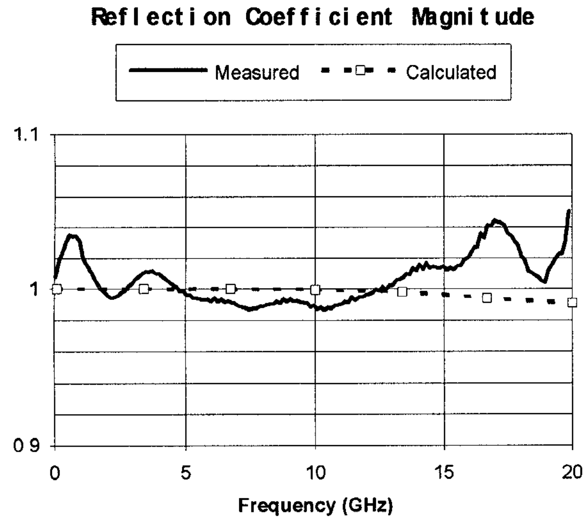

Figure 4

Measurements were then made using an HP8510B over the frequency range of 45 MHz to 20 GHz. A TRL calibration was performed using an HP85052C calibration kit. The coaxial probe (Figure 2) was connected to the test port of the HP8510B.

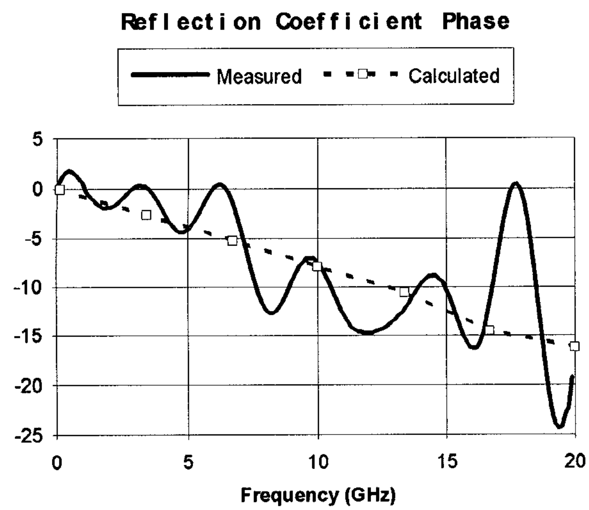

Figure 5

A short was placed at the end of the coaxial probe and a measurement was made and stored into the HP8510B memory. The short was removed from the probe and a phase offset of 180° was added. The measurement without the short was normalized to the short measurement. Figures 4 and 5 shows the comparison of the measured results to the results calculated by HFSS. The ripples apparent in the measured data are due to the internal mismatches within the coaxial probe. The effect of internal mismatch makes it difficult to draw any conclusions from the measured magnitude data but the trend of the measured phase data agrees quite well with the results computed by HFSS.

Conclusions

The finite element simulations are useful in analyzing how well the simplifying assumptions made with a theoretical analysis match an actual structure. In this case, the agreement between an idealized probe having an infinite ground plane and a probe with a finite ground plane was quite good. The difference was less than 0.004 for air; for lossy materials (such as water), the difference would be smaller.

When the coaxial probe is used to measure the permittivity of a material a calibration is required. It is possible to use three known standards such as an open, short and water to establish the measurement reference plane at the end of the coaxial probe and to characterize the systematic errors. The model relating the complex permittivity to the measured reflection coefficient is used during the calibration as well as subsequent measurements[6]. Nyshadahm *et al.* have analyzed the effect of uncertainty in the known standards on the final measurement[7]. The differences in the model due to simplifying assumptions such as an infinite ground plane can be treated in a similar manner.

References

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