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Coaxial Line-Reflect-Match Calibration

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Abstract **- We describe a coaxial line-reflect-match calibration that corrects for imperfections in the load used as a match standard. The method provides a practical means of obtaining accurate, wideband calibrations with compact coaxial standard sets. When our load model is valid, the load may be characterized using an additional line of moderate length.**

INTRODUCTION

In this paper, we adapt the line-reflect-match (LRM) calibration method of Williams and Marks [1] to coaxial lines. That work, which applied to coplanar waveguide, showed that compensating for imperfections in the standards provides a significantly more accurate calibration than conventional implementations of LRM.

The most accurate calibration for coaxial circuits is the multiline TRL calibration [2], which offers high bandwidth and accuracy through the use of multiple lines. The calibration also measures the propagation constant of the line standard so that the reference impedance and the reference plane can be set accurately [3]. However, a set of coaxial airlines, some long, is required to obtain a wideband measurement. Coaxial airlines also require considerable care, especially with smaller connectors, to ensure a good connection without damaging the standard. Furthermore, a set of lines can be costly.

The LRM calibration, which requires only a thru connection, a coaxial load, and a reflection, overcomes these limitations. However, the reference impedance of the LRM calibration is set to that of the load used as a match standard. Recently, Stumper, *et al.* [4,5] developed coaxial loads with nearly ideal impedance characteristics. The resistance and reactance of many conventional coaxial loads, however, are nonideal. This can result in significant error in LRM calibrations.

An earlier approach [6] to the problem of an imperfect load required its complete prior characterization in terms of its reflection coefficient. This in turn required one-time access to a full calibration set, normally a multiline TRL set. In the case of coplanar waveguide, [1] eliminated the requirement for a full characterization by instead postulating a simple model of the load and then applying a minimal calibration sufficient to determine the model coefficients. Here we apply that notion to coaxial lines, employing the measurement of the load after a single-line TRL calibration to fit the parameters of an equivalent-circuit model. This provides a practical means of obtaining an accurate wideband LRM calibration with a compact coaxial standard set consisting of a reflection, a match standard, and a line of moderate length. Although we do not use any reference plane translations here, we do show that our airlines are ideal enough that their measurement is unnecessary.

LOAD CHARACTERIZATION

We used a set of commercially available APC-7 artifacts for these experiments. The artifacts consisted of 2.25 cm, 10 cm, and 30 cm airlines, a short circuit, and a nominally 50 Ω coaxial load. We assumed that our sexless APC-7 connectors mated perfectly with our line, allowing a direct connection between the two ports to serve as a thru line.

First, two consecutive multiline TRL calibrations using identical standards were compared to assess the limitations on calibration repeatability due to contact error and instrument drift. The technique of [7] was used to determine an upper bound on this repeatability error. The comparison determines the upper bound for $|S_{ij}'-S_{ij}|$ for measurements of any passive device, where S_{ij} is its S-parameter measured with respect to the first calibration and S_{ij}' is its S-parameter measured with respect to the second. The bound is obtained from a linearization which assumes that the two calibrations are similar to first order. The result, plotted as a solid curve in Fig. 1, roughly indicates the minimum deviation between any pair of calibrations.

We assessed the accuracy of the LRM calibrations by comparing them to the 50 Ω multiline TRL calibration using

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all of the lines. We found the characteristic impedance from their capacitance and propagation constants, allowing the reference impedance of the TRL calibration to be accurately set to 50 Ω [3]. Figures 2-3 plot the real and imaginary parts of the characteristic impedance Z_o of the lines as a function of frequency. Figures 4-5 plot the real and imaginary parts of the effective relative permittivity $\epsilon_{r,eff}$. These justify the approximation $\epsilon_{r,eff} \approx 1$ for reference plane translations.

Figure 1 plots the maximum possible difference $|S_{ij}'-S_{ij}|$, where in this case S_{ij}' is the S-parameter measured with respect to the simple LRM calibration. Here, the difference is large at high frequencies since the reference impedance of the LRM calibration, which is equal to the impedance of the nonideal load, was not 50 Ω.

MODELING

In Figs. 6-7 we plot measurements of the real and imaginary parts of the load impedance. The impedance was determined by a TRL calibration using only the thru connection and the 2.25 cm line; this explains the inaccuracy at multiples of 6.67 GHz. The figures show that the load deviates significantly from 50 Ω.

In an attempt to account for these nonidealities, we modeled the load using the equivalent circuit of Fig. 8. The load was approximated by an impedance of $R + q\omega^2 + j\omega L$ preceded by a lossless line of characteristic impedance Z_o, length l, and effective relative permittivity $\epsilon_{r,eff}$. Table 1 lists the equivalent circuit values of the load. The value of R was chosen to be 50.7 Ω, the measured dc resistance of the load. The value of Z_o was chosen to be 50 Ω, as specified by the manufacturer, and $\epsilon_{r,eff}$ was assumed to be 1. L, q and l were determined by optimizing the model. The fitted value of l was close to the manufacturer's specifications. Figures 6-7 illustrate that the real and imaginary parts of the modeled load correspond closely to the measured values.

IMPROVED LRM CALIBRATION

Figure 1 illustrates an LRM calibration based on a model of the load. Here we used a single-line TRL calibration, as suggested in [1], to characterize and model the load, and then applied an impedance transformation to the calibration that would take the modeled impedance to 50 Ω. The measurement differences for this LRM calibration are better than 0.05 at most frequencies.

We also compared a single-line TRL calibration using only the thru connection and the 2.25 cm line. The result is plotted in Fig. 1. Since we used only one line standard, our calibration accuracy is poor near multiples of 6.67 GHz, where the difference in line lengths corresponds to a multiple of half a wavelength [2]. Otherwise, the single-line TRL calibration is marginally better than our LRM calibration at most frequencies.

CONCLUSIONS

We showed that LRM calibrations can be performed with imperfect coaxial loads with little loss of accuracy. Imperfections in the load must either be fully characterized or else modeled. If a valid model can be found, the second method is preferable in that it uses a simpler set of calibration standards. If an adequate model cannot be found, then the first method is more useful. With both these methods, once the load is characterized, the problem of handling airlines never again arises. With TRL, airlines must be used with every calibration.

This experiment was performed exclusively with sexless APC-7 connectors since LRM assumes the load is the same on both ports. This technique is applicable to sexed connectors if the male and female reflections and loads are almost identical, but further research will have to be done to determine if this can be achieved. If it can, it will be especially useful with smaller connector sizes, where handling airlines is even more of a problem.

ACKNOWLEDGEMENTS

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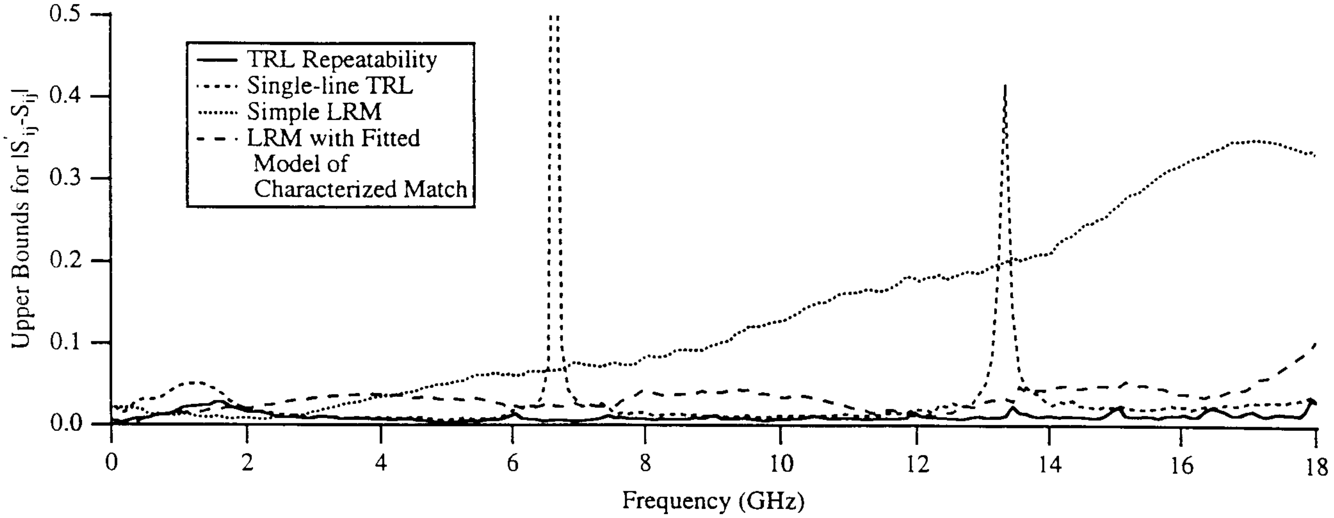

Figure 1. The maximum possible differences between measurements of passive devices from LRM and TRL calibrations and the multiline TRL calibration.

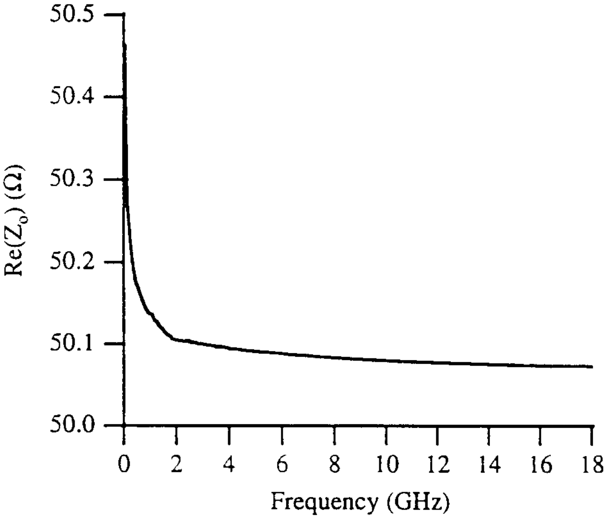

Figure 2. Real part of the characteristic impedance of the lines.

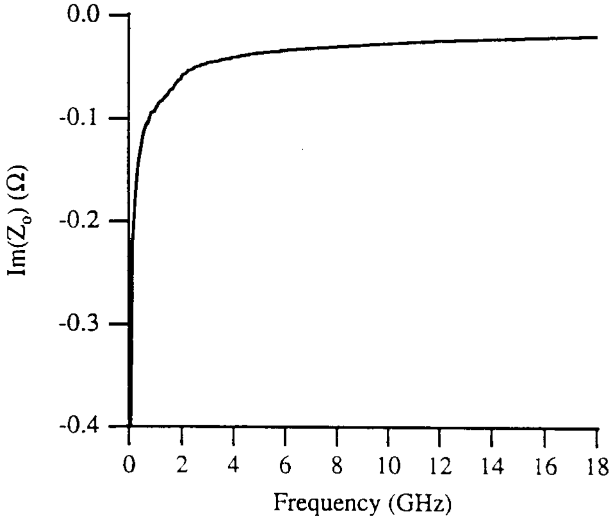

Figure 3. Imaginary part of the characteristic impedance of the lines.

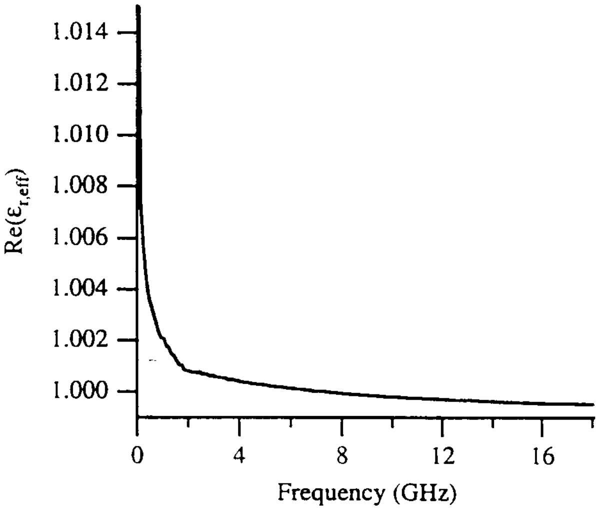

Figure 4. Real part of the effective relative permittivity of the lines.

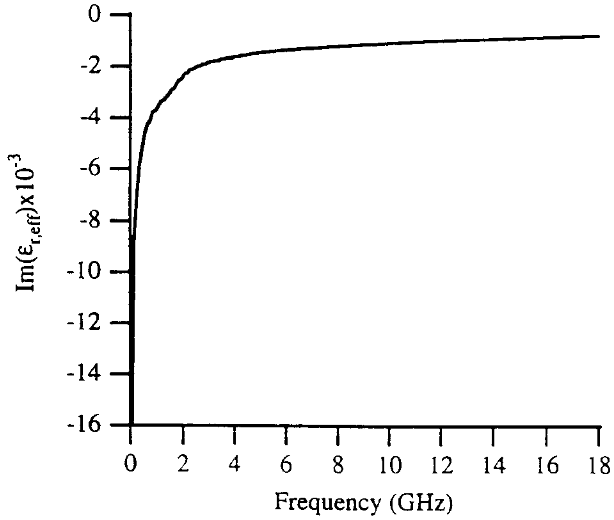

Figure 5. Imaginary part of the effective relative permittivity of the lines.

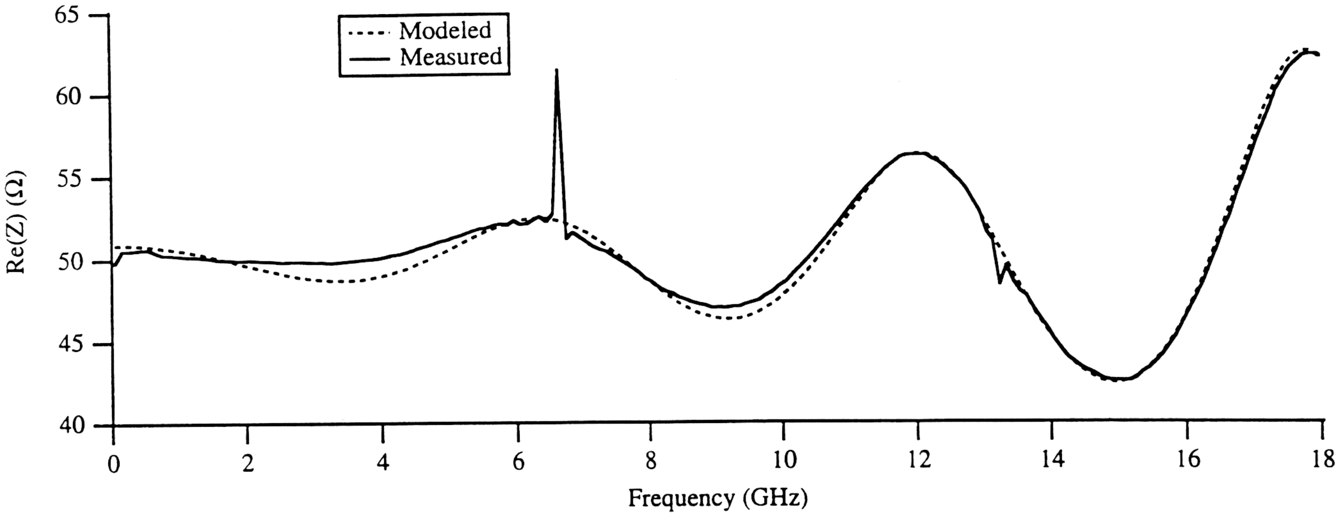

Figure 6. Real parts of the measured and modeled impedance of the load.

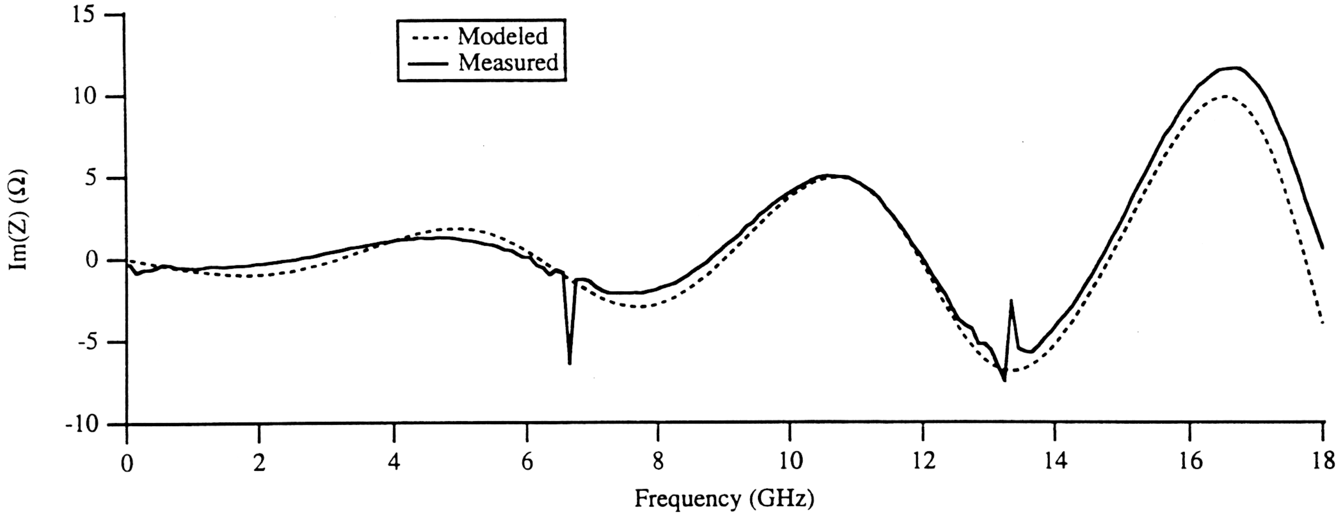

Figure 7. Imaginary parts of the measured and modeled impedance of the load.

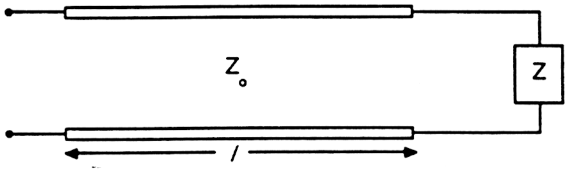

Figure 8. Equivalent circuit model of the load.

Parameter	Model Value
R	50.7 Ω
L	25 pH
q	0.95×10^{-21}
l	25.6 mm
$\epsilon_{r,eff}$	1.0
Z_o	50 Ω

Table 1. Equivalent circuit values of the load.