# LRM Probe-Tip Calibrations with Imperfect Resistors and Lossy Lines[1]

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## Abstract

The line-reflect-match calibration is extended, without significant loss of measurement accuracy, to accommodate imperfect match standards and lossy lines typical of monolithic microwave integrated circuits. We characterize the match and line standards using an additional line standard of moderate length. The new method provides a practical means of obtaining accurate, wideband calibrations with compact standard sets.

## Introduction

This paper shows how line-reflect-match (LRM) calibrations of microwave probe stations can be extended, with minimal loss of measurement accuracy, to cases in which the match and line standards are imperfect.

When Eul and Schiek [1] introduced LRM as an alternative to the thru-reflect-line (TRL) calibration [2], they noted that the LRM calibration set the reference impedance to the impedance of the match standard. This is further discussed in [3].

More recently, Barr and Pervere [4] studied the LRM calibration and noted that the line must be characterized in order to translate the reference plane. They did not suggest a means of performing this characterization, however. Davidson, *et al.* [5] applied the LRM technique to probe-tip calibrations, that is, probe-station calibrations with reference plane near the probe tips and reference impedance of 50 Ω. As a match standard, these authors used resistors trimmed to a dc resistance of 50 Ω. They attempted to determine the resistor's reactance and concluded that it was small. They achieved the reference plane translation by using a very short low-loss line standard, estimating its parameters from lossless approximations. This implementation of the LRM calibration is therefore limited to ideal match standards and to short low-loss line standards.

In [6], Davidson, *et al.* introduced a procedure which attempts to determine and account for the reactance of the planar resistors they used as match standards. They achieved this by introducing a lossless reflect into the calibration. This method is still limited to match standards with a frequency-independent resistance and with a reactance due only to a frequency-

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independent inductance, to short low-loss line standards, and to lossless reflects.

The most accurate calibration for monolithic microwave integrated circuits (MMICs) is the multiline TRL calibration [7]. Because it is based on the TRL algorithm, it measures the ratios of traveling waves in the transmission lines [3]. The bandwidth and accuracy of the calibration are increased over conventional TRL by the use of multiple lines. The calibration also measures the propagation constant of the line standards so that the calibration reference impedance and the reference plane can be set accurately [8,9]. The calibration is thus especially well suited to MMICs, in which wide bandwidth is needed and small geometries result in very lossy lines with complex frequency-dependent characteristic impedance.

The multiline TRL calibration suffers one important drawback, however. To obtain a wide measurement bandwidth, a set of lines, some quite long, is required; this uses expensive space on the wafer. While LRM overcomes this limitation, the imperfect standards typical of MMICs, which include match standards with frequency-dependent resistance and inductance, lossy line standards, and lossy reflects, are incompatible with the assumptions of conventional implementations of LRM.

In this paper we extend the LRM calibration to the imperfect match and line standards typical of MMICs. We show that a TRL calibration with a single line moderately longer than the thru line is accurate enough in practice to characterize the match and line standards. This suggests a practical means of obtaining accurate wideband calibrations with a compact standard set consisting of a thru line, a reflect, a match standard, and a second line standard of moderate length.

## Comparison of Probe-Tip Calibrations

For these experiments we constructed a set of coplanar waveguide (CPW) calibration artifacts, typical of those found on MMICs, on a gallium arsenide (GaAs) substrate. The artifacts consisted of a CPW thru line 550 $\mu$m long; four longer lines of length 2.685 mm, 3.75 mm, 7.115 mm, and 20.245 mm; and two shorts offset 0.225 mm from the beginning of the line. We also fabricated a match standard by terminating a 275 $\mu$m section of the CPW with a single 73 $\mu$m by 73 $\mu$m nickel-chromium thin-film resistor. These artifacts were fabricated with a 0.5 $\mu$m evaporated gold film adhered to the 500 $\mu$m GaAs substrate with an approximately 50 nm titanium adhesion layer. The lines had a center conductor of width 73 $\mu$m separated from two 250 $\mu$m ground planes by 49 $\mu$m gaps.

We assessed the accuracy of our LRM calibrations by comparing them to a multiline probe-tip TRL calibration [7] using all five lines. These calibrations had a reference impedance of 50 Ω and a reference plane 25 $\mu$m in front of the physical beginning of the CPW lines. The characteristic impedance of the lines was found from the capacitance and propagation constant of the lines, allowing the reference impedance of the TRL calibration to be accurately set to 50 Ω [8]. The capacitance $C$ of the lines was determined from the reflection coefficient and dc resistance of the lumped resistor [9].

We first compared two consecutive multiline TRL calibrations using identical standards in order to assess the limitations on calibration repeatability due to contact error and instrument drift. We used the technique of [10] 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 essentially assumes that the two calibrations are reasonably similar. The result, plotted as a dashed line in Fig. 1, roughly indicates the minimum deviation between any pair of calibrations.

In order to examine the effect of the imperfect match and line, we performed a simple LRM calibration in which we applied an impedance transformation which would take a reference impedance of $R_{dc}$ to 50 Ω and in which an effective dielectric constant of 6.95 was used to translate the reference plane to the probe tips. The curve marked with circles in the figure plots the result of the comparison of this LRM calibration to the multiline TRL calibration using the same thru and reflect measurements. This result shows that errors in measurements using the simple LRM calibration can be quite large.

We also compared a single-line TRL calibration, which used only the 550 μm thru line and the 2.685 mm line, to our multiline TRL calibration. The result is shown in the curve labeled with solid squares in the figure. Here the differences are generally small except at low frequencies and near the point where the 2.685 mm line is approximately a half wavelength longer than the thru line, as indicted by the arrow labeled "$\Delta\varphi \approx \pi$."

By contrast, the measurement differences for the LRM calibration based on the match and line standards characterized by the single-line TRL calibration (hollow squares) are not much greater than the calibration repeatability. Here we translated the reference plane using the effective dielectric constant determined from the single-line TRL calibration. We set the reference impedance of the calibration by applying an impedance transformation to the LRM calibration that would take a reference impedance of $R_{dc} + q\omega^2 + j\omega L$ to 50 Ω; $q$ and $L$ were determined by fitting to the match impedance measured by the single-line TRL calibration. In this case, the differences between the LRM and multiline TRL calibrations are reduced to nearly the repeatability. This indicates that any further improvements in translating the reference plane and setting the reference impedance of the LRM calibration would not add significantly to the overall accuracy of the calibration.

## Conclusions

LRM calibrations can be performed with imperfect CPW artifacts typical of MMICs with little loss of accuracy. Furthermore, while the imperfections in the match and line standards must be characterized and accounted for, a full multiline TRL calibration is not required for this purpose. In fact, only a line of moderate length need be added to the LRM calibration set. Therefore, accurate broadband LRM calibrations can be achieved using compact sets of calibration artifacts.

The experiments were conducted with well behaved resistors deeply embedded in the CPW line and required only moderate reference plane translations. Thus, the results may be inapplicable to poorly behaved resistors, such as some of those investigated in [11]; the suitability of resistors in microstrip remains to be established. The method may also be inapplicable to resistors placed directly under the probe tips or to calibrations with large reference plane translations.

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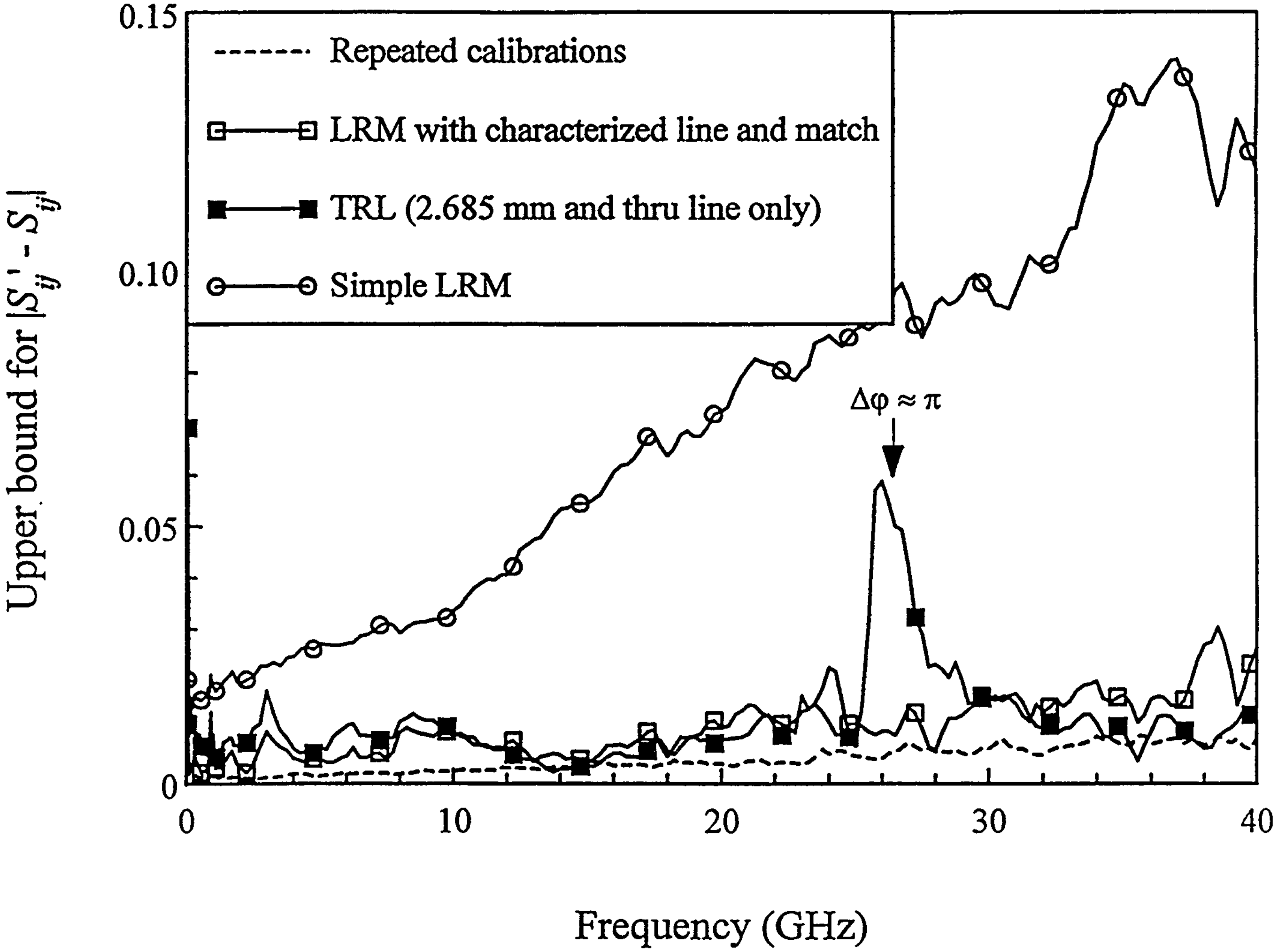

Figure 1. The maximum possible differences between measurements of passive devices from LRM and TRL calibrations and our multiline TRL calibration. The dashed curve corresponds to the calibration repeatability.