LRM Probe-Tip Calibrations using Nonideal Standards

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Abstract—The line-reflect-match calibration is enhanced 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. Without the enhancement, calibration errors due to imperfections in typical standards can be severe.

I. INTRODUCTION

This paper, which has been presented in conference [1], shows how line-reflect-match (LRM) calibrations of microwave probe stations can be extended to cases in which the match and line standards are imperfect. Eul and Schiek [2] introduced LRM as an alternative to the thru-reflect-line (TRL) calibration [3]. They noted that the LRM calibration sets the reference impedance to the impedance of the match standard, which is generally unknown except at dc. This is further discussed in [4].

More recently, Barr and Pevere [5] studied the LRM calibration and noted that a characterization of the lossy line is also necessary in order to translate the reference plane. They did not suggest a means of performing this characterization, however. Davidson, et al. [6] applied the LRM technique with the intent of obtaining a probe-tip calibration, that is, a probe-station calibration 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 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. These implementations of the LRM calibration are therefore limited to ideal match standards and to short low-loss line standards.

In [7], 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-independent inductance, to short low-loss line standards, and to lossless reflectors.

The multiline TRL calibration [8] does not suffer from these limitations. Because it is based on the TRL algorithm, it measures the ratios of traveling waves in the transmission lines [4]. 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 [9], [10]. The calibration is thus especially well suited to monolithic microwave integrated circuits (MMIC’s), in which wide bandwidth is needed and small geometries result in very lossy lines with a 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. When realized in MMIC form, LRM standards while far more compact than multiline TRL standards, are incompatible with conventional LRM assumptions. Typical imperfections include match standards with process-dependent dc resistance and frequency-dependent resistance and inductance [11]. Lossy line standards, and lossy reflectors, are incompatible with the assumptions of conventional implementations of LRM.

In this paper we show how to modify the LRM calibration to account for the imperfect match and line standards typical of MMIC’s. We first study coplanar waveguide (CPW) resistors and lines, evaluating separately their use as match and line standards in LRM probe-tip calibrations. We show that both the real and imaginary parts of the resistor impedance must be known if the LRM reference impedance, which is initially set to the impedance of the match, is to be reset to some standard value (e.g. 50 Ω). We also show that the line loss and characteristic impedance must be considered when setting the reference plane position. Finally, we examine a TRL calibration with a single line moderately longer than the thru line and show that it is accurate enough in practice to characterize the match and line standards. This results in 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.

II. REFERENCE IMPEDANCE

For these experiments we constructed a set of CPW calibration artifacts, typical of those found on MMIC’s, on a gallium arsenide substrate. The artifacts consisted of a CPW thru line 550 μm 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 μm section of the CPW with a single 73 μm by 73 μm nickel-chromium thin-film resistor; the resistor geometry is described in [11]. These artifacts were fabricated with a 0.5 μm evaporated gold film adhered to the 500 μm gallium arsenide substrate with an approximately 50 nm titanium adhesion layer. The lines had a center conductor of width 73 μm separated from two 250 μm ground planes by 49 μm gaps.
We assessed the accuracy of our LRM calibrations by comparing them to a multiline probe-tip TRL calibration [8] using all five 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 [9]. The capacitance $C$ of the lines was determined from the reflection coefficient and dc resistance of the lumped resistor [10].

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 [12] to determine an upper bound on this repeatability error. The comparison determines the upper bound for $[S_{21} - S_{11}]$ 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 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 on the LRM calibration, we compared a simple LRM calibration to the multiline TRL calibration, using the same thru and reflect measurements in both cases. We found that the maximum possible difference $[S_{21} - S_{11}]$, where in this case $S_{ij}$ is the S-parameter measured with respect to the LRM calibration, exceeded 0.8. This large difference is not surprising since the reference impedance of the LRM calibration was equal to the match impedance $Z_{\text{match}}$ (with dc resistance $R_{\text{th}} = 91.15$ Ω) while the reference impedance of the multiline TRL calibration had been adjusted to 50 Ω. While this difference could have been minimized by fabricating resistors with a dc resistance of 50 Ω, this would have required improved process control and, as will be discussed below, still would not guarantee an accurate calibration at high frequencies, where the resistor impedance may depart significantly from its dc resistance [11].

In a second experiment we applied an impedance transformation that would transform a reference impedance of $R_{\text{dc}}$ to one of 50 Ω. This would transform the LRM reference impedance $Z_{\text{match}}$ to 50 Ω if and only if $Z_{\text{match}} = R_{\text{dc}}$. This result is labeled with circles in the figure. A comparison to the dashed line in the figure shows that the maximum possible difference in measurements for this impedance-transformed LRM calibration remains significantly larger than the repeatability of the calibrations. As we will show below, the cause for these significant measurement differences is related to the fact that $Z_{\text{match}}$ is not equal to $R_{\text{dc}}$.

In Fig. 2 we plot the imaginary part of the resistor impedance measurements $Z$ and $Z_{\text{11}}$. The fitted reactances are plotted in solid lines.

In this case the differences in the LRM measurements are reduced to nearly the level to which we could repeat calibrations. This indicates that any further improvements in setting the reference impedance of the LRM calibration would not significantly improve the accuracy of the calibration.
III. REFERENCE PLANE TRANSLATION

The reference plane of a probe-tip calibration is located just beyond
the probe tips. In our case, we apply a translation of reference
plane from the center of the thru line 250 µm toward the probes
to bring the reference plane to a position 25 µm in front of the
physical beginning of the line. To investigate the effect of line
loss on this reference plane translation, we compared our multiline
TRL probe-tip calibration to another calibration, identical except
that the reference plane translation of the second calibration was
accomplished assuming a different effective dielectric constant ϵr.
Each case, we determined the line characteristic impedance from
ϵr and the capacitance C' of the lines, as described in [9]. C' was
assumed identical for all cases.

In the first experiment we set ϵr to 6.95, the approximate effective
dielectric constant obtained from the lossless, thin metal approxi-
mation. The maximum possible differences between the LRM
and TRL measurements are labeled with circles in Fig. 4 and exceed
the repeatability of the calibrations by a significant amount. In
the second experiment we set ϵr to ϵr0, the frequency-dependent
effective dielectric constant measured by the TRL calibration using
only the 500 µm thru line and the 2.685 mm line. The result,
transformed to a single line is smaller than the repeatability of
the calibrations. This indicates that the error introduced into the
 calibration by determining ϵr, from a single line is smaller than the
repeatability error and is thus of little practical significance.

IV. PROBE-TIP CALIBRATIONS

Probe-tip calibrations, which have a 50 Ω reference impedance
and a reference plane just in front of the physical beginning of
the line, are used to calibrate probes to the reference plane translation.
In Fig. 5 we compare several LRM and
TRL calibrations to our multiline calibration. The figure shows
that differences in measurements using the simple LRM calibration
(curves labeled with circles), in which we applied an impedance
transformation which would take an initial reference impedance of
R0 to 50 Ω and in which ϵr was assumed to be 6.95, can be
quite large. The maximum possible differences for the single-line
TRL calibration (curve labeled with solid squares) 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 indicated by the arrow labeled “Δλ ≈ π”. By contrast,
the measurement differences for the LRM calibration based on the match

V. CONCLUSIONS

LRM calibrations can be performed with imperfect CPW artifacts
typical of MMIC’s with good 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
depth-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 resistance placed directly under the
probe tips or to calibrations with large reference plane translations.
REFERENCES


