MILLIMETER-WAVE DEEMBEDDING USING THE EXTENDED TRL (ETRL) APPROACH*

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ABSTRACT

A new approach for deembedding is presented which utilizes known physical transmission line lengths instead of electrical characteristics for calibration standards. This allows one to perform millimeter-wave deembedding for waveguide based vector network analyzers. Theoretical formulation of ETRL and experimental characterization for V-band microstrip lines will be shown. Important design guidelines and selection of valid root choice of the formulation will be described.

INTRODUCTION

Millimeter-wave deembedding of MMICs is a new frontier in which established unterminating techniques appear questionable for two reasons. First and most important, is the requirement to accurately know the electrical length of a standard. At millimeter-wave frequencies, the knowledge of microstrip characteristics is a function of the analysis selected. Second, is that the physical waveguide ports of available millimeter-wave vector network analyzers are fixed (this is an area which is changing).

We have developed an unterminating procedure that overcomes the obstacles described above. Our approach does not assume that the fixtures (input and output ports embedding the device under test) are identical; it also does not assume that input reflections are negligible. Our sole assumption is that each fixture is a passive linear two-port in which reciprocity can be invoked. Our technique does not require the electrical knowledge of any of its standards nor does it need to know a propagation constant. Based on the evolutionary development of our approach, we have called it the Extended TRL (ETRL) method. The theoretical framework for the TRL approach is presented by Engen and Hoer (1) and will be the starting point for the work presented in this paper.

ETRL APPROACH

To properly characterize any RF circuit, especially a MMIC, the measurement reference should physically be located at the device port. Unfortunately, the test measurement reference plane is physically removed from the device plane (Figure 1). The procedure to characterize the two-port network that intervenes between the test reference and device planes is called unterminating. Once the embedding circuit is known, its effects on measured "raw" data can be removed using a simple procedure known as deembedding. For an excellent review of general deembedding approaches, one is referred to the article by Lane (2).

The TRL[†] approach by Engen and Hoer(1) is the starting point for this paper. The analytic formulation entails the solution of three root selections which will be addressed in the next section. The Extend TRL method utilizes the exact procedure as TRL; however, the key extension is the elimination of having to know the approximate electrical length of the reflection standard which is usually an open or short circuit.

From the thru and delay line measurements, we obtain a generic set of equations for the embedding fixtures [equations 26 to 29,1]:

$$t_{11}r_{11} + t_{12}r_{21} = r_{11}e^{-\gamma l} \quad (1)$$

$$t_{21}r_{11} + t_{22}r_{21} = r_{21}e^{-\gamma l} \quad (2)$$

$$t_{11}r_{12} + t_{12}r_{22} = r_{12}e^{\gamma l} \quad (3)$$

$$t_{21}r_{12} + t_{22}r_{22} = r_{22}e^{\gamma l} \quad (4)$$

from which a quadratic equation can be formed. Once the proper root choice is made, we can calculate the value of the exponential terms in equations (1) to (4). By utilizing a reflection standard which is either a short or open circuit with a length of

$$L_{Refl.} = \left[\frac{L_{Thru}}{2}\right] + L_{Delay} \quad (5)$$

where $L_{Refl.}$ is the reflection length and L_{Thru}, L_{Delay} are the thru and delay lengths, respectively, we eliminate the need to know the electrical characteristics of the reflection standard. The reflection coefficient can be analytically derived from equations (1) to (4) using hyperbolic tangent (cotangent) definitions for a short (open) circuit standard. Electrical knowledge of the thru and delay are not required as well. **Now the emphasis is in the knowledge of mechanical transmission line lengths which are controllable.**

*This work was supported by Hughes Internal Research and Development Funding.
†We are including LRL as a generalized version of TRL and will be implicitly included when TRL is referred to.

PROPER ROOT SELECTION

When solving for the embedding fixture parameters using the ETRL method, one encounters three root choices to make. In this section, we will concentrate on the quadratic solution which is a result of the thru and delay measurements and provide fixture guidelines when the ETRL analysis is valid.

Both Engen and Hoer (1) and Romanofsky and Shalkhauser (3) have addressed the root selection for the thru-delay quadratic equations [equations 30 to 31,1].

$$t_{21} \left[\frac{r_{11}}{r_{21}}\right]^2 + (t_{22} - t_{11}) \left[\frac{r_{11}}{r_{21}}\right] - t_{12} = 0 \qquad (6)$$

$$t_{21} \left[\frac{r_{12}}{r_{22}}\right]^2 + (t_{22} - t_{11}) \left[\frac{r_{12}}{r_{22}}\right] - t_{12} = 0 \qquad (7)$$

Both in our work and [3] we have determined that

$$\left|\frac{r_{11}}{r_{21}}\right| > \left|\frac{r_{12}}{r_{22}}\right| \qquad (8)$$

$$\left|\frac{r_{11}}{r_{12}}\right| > \left|\frac{r_{21}}{r_{22}}\right| \qquad (9)$$

where equation (8) is for embedding network A and equation (9) is for embedding network B (see Figure 1). To gain a physical feeling for this criteria, we converted equations (8) and (9) to S-parameters and performed a worst case analysis to yield the following fixture guideline when ETRL root selection will be valid when

$$\frac{|S_{21}\ S_{12}|}{|S_{11}|\ |S_{22}|} > 2. \qquad (10)$$

Equation (10) holds true for both embedding networks A and B of Figure 1 and is graphically shown in Figure 2. It is clear to see the regions of where the ETRL root choice is valid. As an example in Figure 2, we show that for a fixed S_{11} value of 0.4 and for instance a S_{22} which at best is 0.5, we have a permissible S_{12} range from 0.63 to 0.92 and still ensure that the root selection will be correct. The minimum insertion loss (0.92) is determined by the criteria of having a passive fixture. Now a user of the ETRL method will have a physical feeling of the formulation for root criteria and confidence of validity.

Due to the limitation of the paper length, we will present the final two root choice criteria at the conference. Unlike the preceding analysis, the remaining root choices are easily determined using experimental data and the analytically known reflection coefficient described in the prior section. As a final note, the only limitation of the ETRL/TRL methods is in the S_{12} (S_{21}) phase. The absolute phase is unknown for individual fixtures (a 180 degree ambiguity may exist); however, the ETRL solution provides a consistent solution for the configuration shown in Figure 1. Additional measurements and techniques are available to determine the individual phase information, but is is not required for most applications.

EXPERIMENTAL VERIFICATION

A matched transmission line provides an extremely sensitive tool to study the effects of experimental and numerical errors of the unterminating an deembedding process. For the present example, our frequency range is 57 to 62 GHz. Our unknown device is a straight 50-ohm microstrip line fabricated on a 5 mil alumina substrate and is 371 mils long. Figure 3 shows the experimental and deembedded results for the S_{21} phase. The experimental phase shift was 154°, while theory predicts 153°. This correlation was extremely pleasing. Figure 4 shows that the insertion loss of the line is negligible, as expected, and that the fixture contributed approximately 4 dB of loss.

Figure 5 shows the raw and deembedded data for S_{11} of the matched transmission line. Ideally, these values ought to be 0. Our data is still acceptable; however, there are frequency

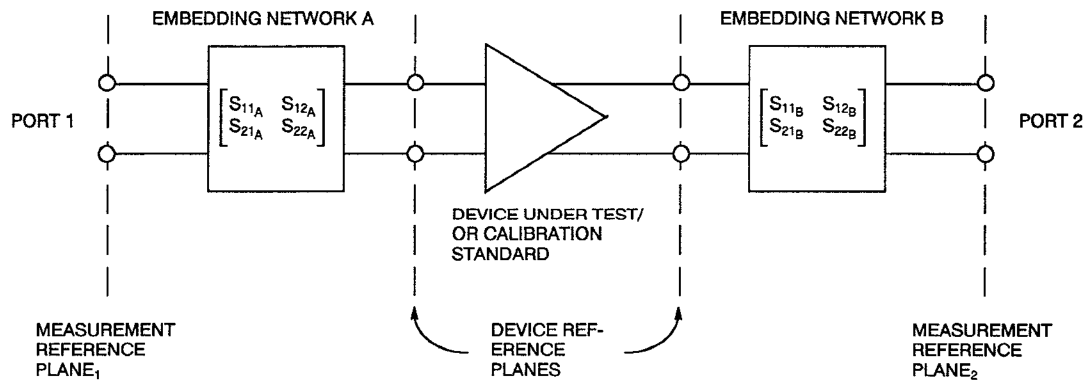

Figure 1 Experimental configuration. Ports 1 and 2 are usually connected to a vector network analyzer that is calibrated up to measurement reference plane. A typical example of millimeter-wave embedding networks A and B are waveguide to microstrip transitions.

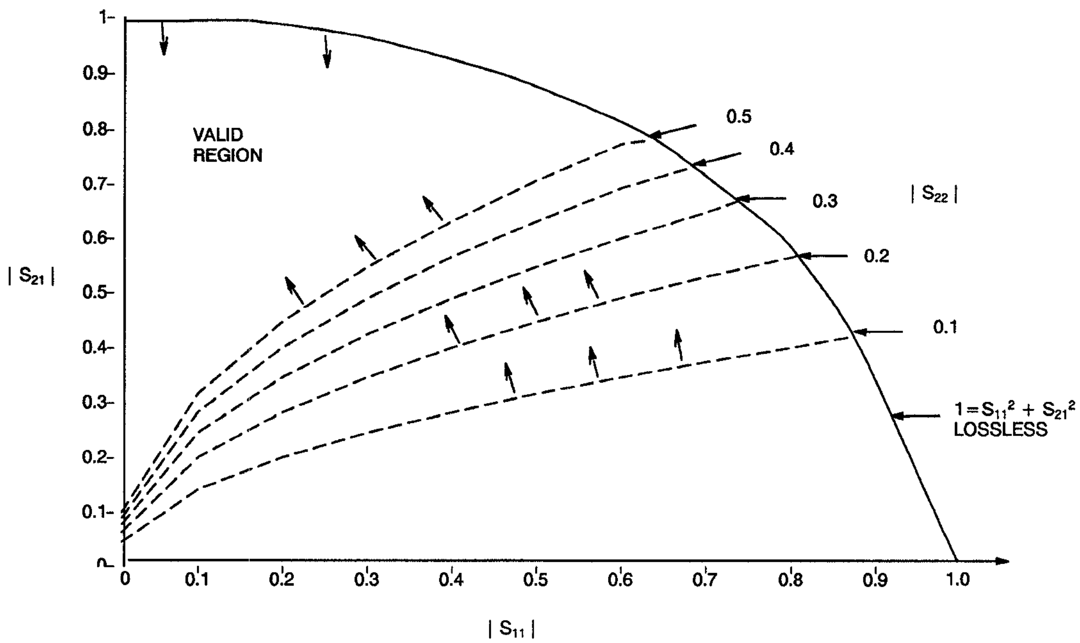

Figure 2 Users guide for physical criteria (Equation 10) of where the thru-delay quadratic root choice is valid. Arrows point towards the valid region where the criteria is met. The area enclosed by the $1 = S_{11}^2 + S_{21}^2$ curve defines the region where the embedding network is passive. ($S_{12} = S_{21}$ by reciprocity)

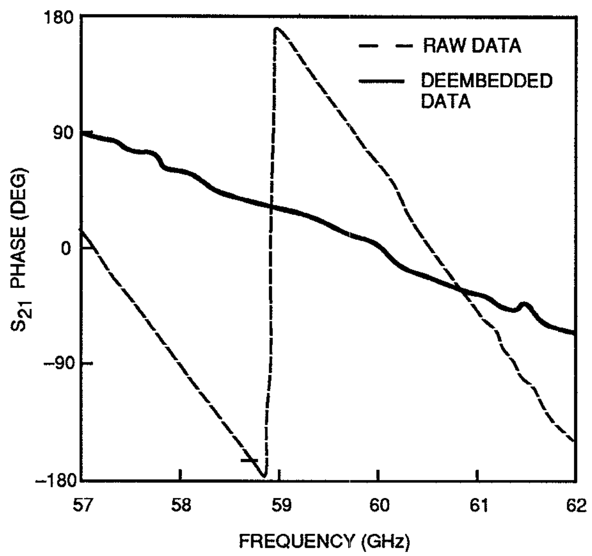

Figure 3 Verification of ETRL deembedding technique. Shown is the raw and deembedded phase data of an ideal matched line. The theoretical phase shift is 153° and experimental is 154°.

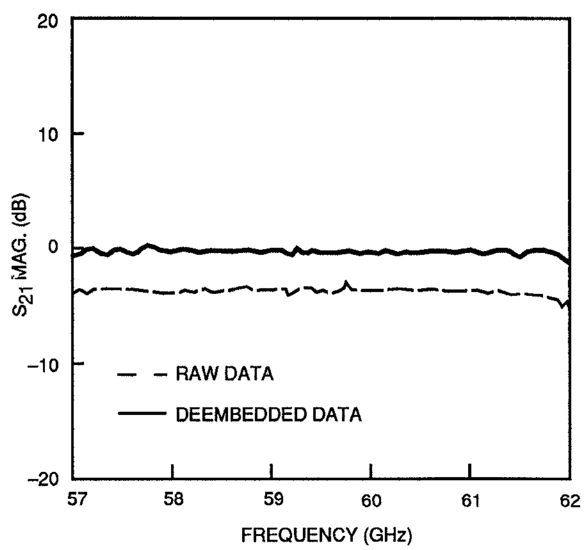

Figure 4 Deembedded and raw data for a 50-Ω transmission line. As expected the insertion loss is nominal for the device under test. The fixture loss is approximately 4 dB.

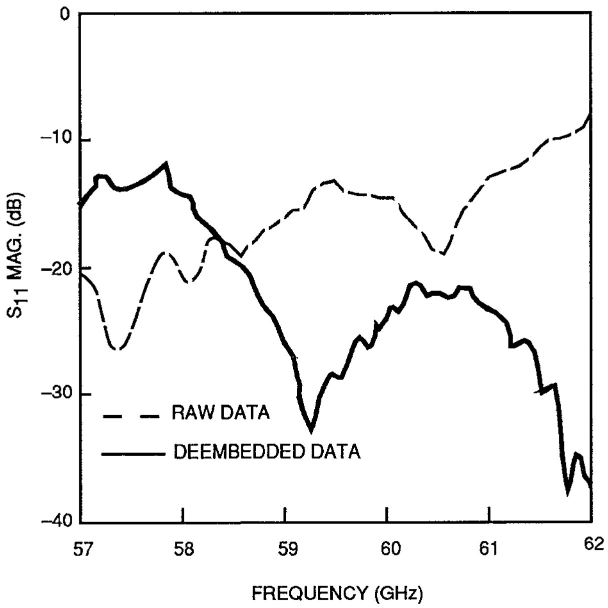

Figure 5 S_{11} of a 50-Ω transmission line. This device is most challenging for any deembedding scheme. Ideally it should be $-\infty$, however, experimental and numerical error predominates. This shows the sensitivity of the deembedding approach.

regions of degradation. This is due to the variability of the fixture assembly and experimental repeatability. In this work the emphasis has been placed on theoretical approach. We are presently improving fixture design and are extending our verification for W-band (75 to 110 GHz) MMIC characterization.

CONCLUSIONS

We have formulated a new unterminating technique, the Extended TRL method, which was used to perform millimeter-wave deembedding at V-band using a Hughes waveguide based vector network analyzer system. The ETRL approach overcomes the necessity to know the electrical characteristics of your standards which are not usually known in the millimeter-wave regime to a great degree of accuracy. This work permits accurate characterization of MMIC components into the high millimeter-wave frequency range in addition to being valid in the microwave region.

ACKNOWLEDGEMENTS

The authors would like to thank Drs. H. Bowers and T. Midford for their support of this IR&D effort. Also, we appreciate guidance and support from Dr. H. J. Kuno and Mr. R. S. Ying. Finally, we would like to thank Mr. J. Denny for data acquisition algorithms and initial test fixture characterization.

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