Naval Ocean Systems Center
San Diego, CA 92152-5000

2

Technical Document 2020
January 1991

De-Embedding Millimeter-Wave Integrated Circuits with TRL

David Rubin

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
Commander

H. R. TALKINGTON, Acting
Technical Director

ADMINISTRATIVE INFORMATION

This work was performed for the Naval Research Laboratory (NRL), 4555 Overlook Ave., S.W., Washington, DC 20375, under program element 602234N, under the direction of K. Sleger.

Released by
Harris A. Quesnell, Head
Microwave/MMW Branch

Under authority of
J. E. Griffin, Head
Electromagnetic Systems
Division

CONTENTS

DE-EMBEDDING MILLIMETER-WAVE INTEGRATED CIRCUITS WITH TRL

I. INTRODUCTION

Now that you have the use of a network analyzer that goes to 40 GHz or above, just what do you do with it? Using the calibration procedures included with the analyzer will let you look at packaged millimeter-wave circuits. The two-port parameters will include the effects of line and transition reflections and losses. Using the line extender artifice is useful only if the transitions are near ideal and the line parameters well known.

De-embedding to the circuit or device contained within the line (microstrip, coplanar, suspended substrate, etc.) usually requires ideal or measured shorts, opens, and resistive loads. At normal microwave frequencies a short may appear as such, but at millimeter wavelengths a short will surely be inductive, an open radiative, and a resistor inductive. At millimeter wavelengths one very interesting de-embedding procedure called TRL[1] (Through-Reflect-Length) seems almost magic-like in that very non-ideal elements can be used for the procedure. These elements are:

T: Through line which connects the two transitions.

R: Reflect elements which can be just about anything as long as identical ones are used to terminate the input and output transitions.

L: Length of transmission line connecting the two transitions.

TRL de-embedding is easy to implement on wafers which can use coplanar probes[2] or microstrip launchers[3,4]. The input and output probes can be moved apart thereby facilitating the "L" part of TRL.

The method to be described will allow TRL de-embedding using any type of transmission line without the use of external probes. The abilty to use waveguide input and output transitions should be of particular interest to designers of millimeter-wave hybrid integrated circuits.

II. METHOD

Figure 1 indicates the four measurements necessary for de-embedding. Note that TRL transition A and TRL transition B both include line lengths which meet somewhere in-between (reference position). The actual transitions which connect to the analyzer ports can be quite different, and may even include different bias lines.

Figure 1a. shows the basic <u>through</u> structure. S parameters are taken over the desired frequency range. The transitions can actually have poor VSWR without upsetting the de-embedding procedure.

Figure 1b. shows the <u>reflect</u> measurement used. Since any two identical reflections may be used, it is particularly simple to remove equal large sections from both sides of the reference position. The reflection elements are therefore reduced sections of line terminated with a radiative open circuit.

Figure 1c. shows the <u>length</u> measurement configuration. Note that TRL transition A and TRL transition B are the same as in the other measurements except for an added length of transmission line. This requires another fixture exactly like that of Fig. 1a. except for an extended length in the region surrounding the reference position. To insure "exactness" the fixtures are best made on a computer-controlled mill.

Figure 1d. is the same as figure 1a except that the device to be measured is shown centered at the reference position.

The four sets of measurement data should be stored in data files for manipulation by the de-embedding program. The mathematics behind the procedure, based (with exceptions) on Reference 1, is given in Appendix A. A de-embedding program which directly follows this is given in Appendix B.

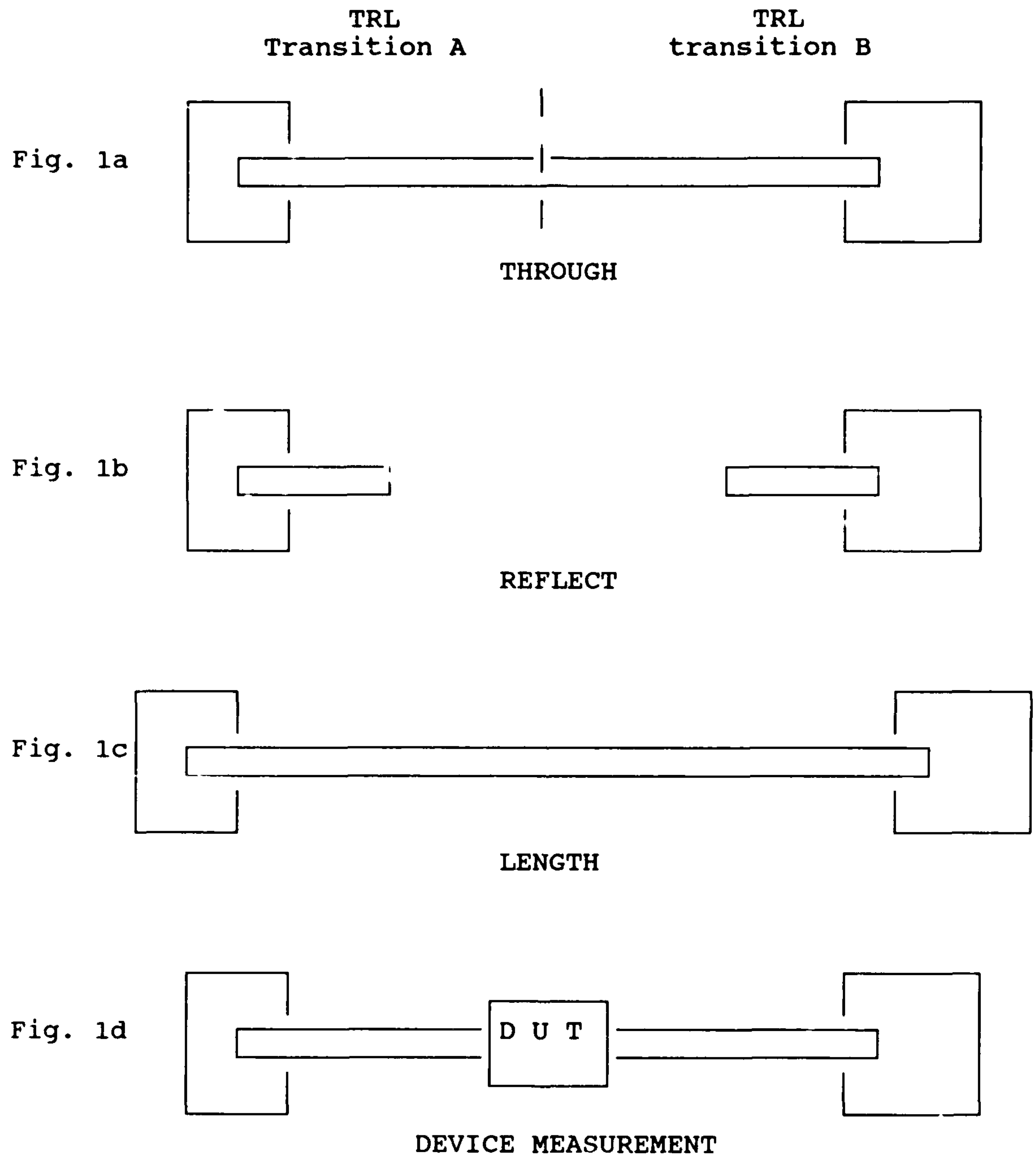


Figure 1. The four measurements required for TRL de-embedding.

III. An Example of De-Embedding

To illustrate the effectiveness of the above procedure, two Ka band suspended substrate fixtures with waveguide transitions were fabricated using a computer-controlled mill[5]. The fixtures were fabricated for line lengths (excluding probes) of 1.4 and 2.0 inches. The length difference is about twice the suspended substrate wavelength at 33 GHz. Instead of using .080" waveguide probe lengths which would have given excellent VSWR for the 92 ohm transmission lines[6], .050" probes were used. A typical suspended substrate bandpass filter was inserted in the line as the DUT. Figures 2 and 3 show the detrimental effects of using the intentionally bad probes.

The two-port S parameters for the above two cases were measured in the smaller fixture as well as the S parameters of a non-ideal open circuit (about 1 inch of line removed in the center). Next the S parameters of the 2-inch line were measured in the larger fixture. All of the measured parameters were put into computer files which were then called up by the de-embedding program. The results of de-embedding the filter are shown in Figure 4. The usual flat top and reasonable return loss are similar to measurements made with normal .080" probes.

IV. Conclusions

The use of two circuit fixtures, one larger than the other by a nominal length, leads to a de-embedding procedure which should be very useful at millimeter wavelengths. Particularly important, any type of transmission line may be used. Transitions and bias lines may be different for the input and output. A transistor chip with bond wires may be measured in the same media as its intended use. Discontinuities are therefore measured along with the chip and can be used directly in subsequent circuit design. The reproducibility of the fixtures and transmission lines will determine the upper frequency limit. Using .0005-in. tolerances, useful parameters should be obtainable to at least 100 GHz.

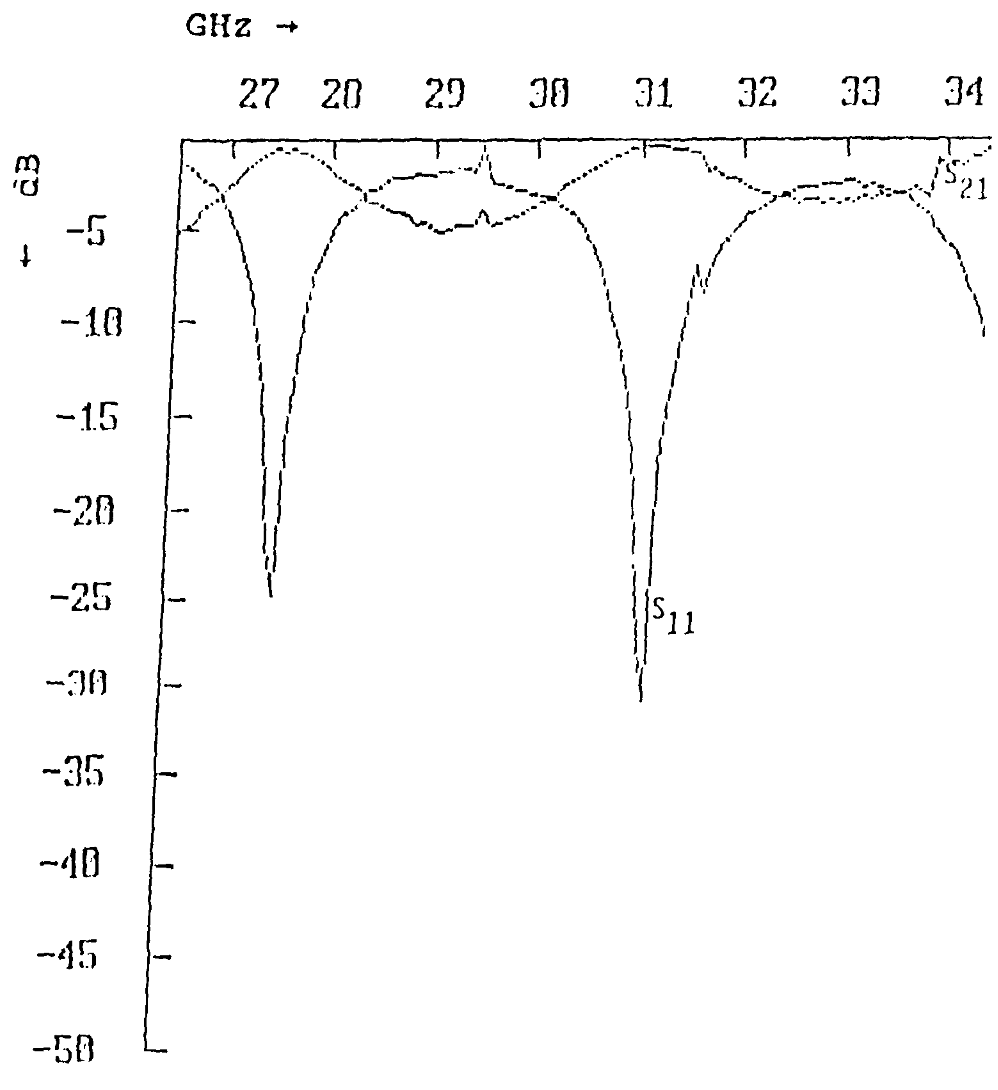


Figure 2. Measured parameters of 1.4 inch line with poor transitions

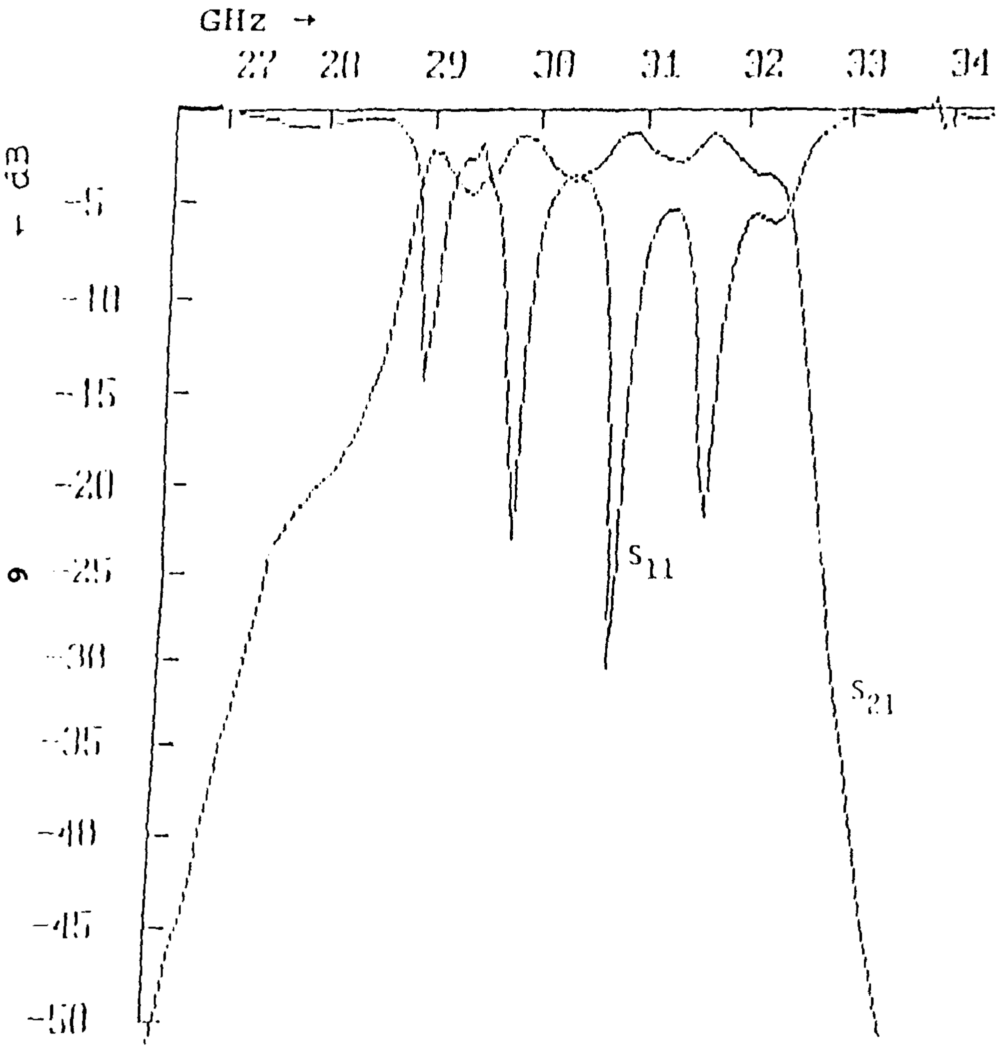


Figure 3. Measured parameters of bandpass filter with poor transitions

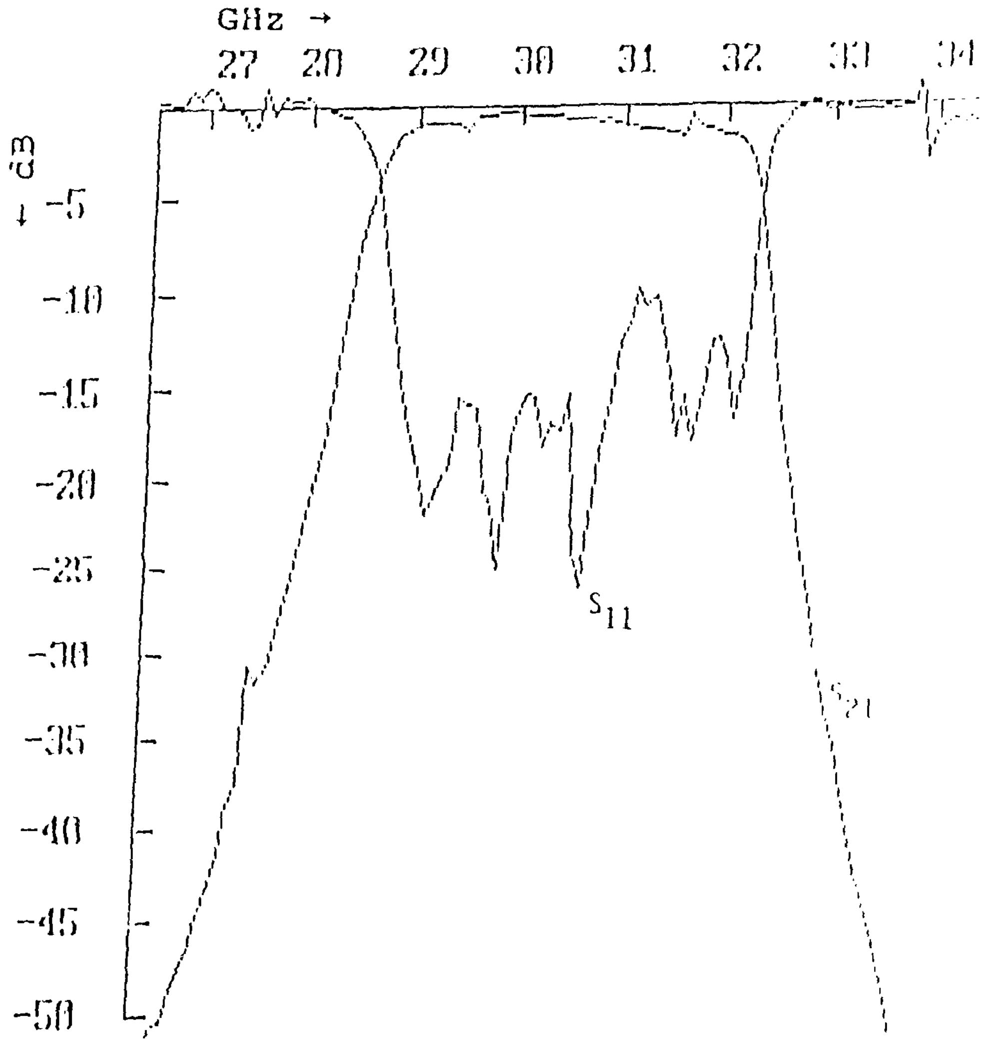


Figure 4. De-embedded filter

Appendix I: TRL De-Embedding

A. FINDING THE LINE PARAMETERS

Both the attenuation and effective dielectric properties of the transmission line may be found from the measurements indicated in figures 1a and 1c. If there were no transition reflections, then it would be simple to get these values from the two S21 measurements. However, reflections from the transitions introduce errors which can be eliminated by the first part of a TRL program.

The scattering parameters derived from each of the four steps can easily be converted to transmission parameters:

Scattering Parameters

$$b_1 = s_{11}a_1 + s_{12}a_2$$
$$b_2 = s_{21}a_1 + s_{22}a_2$$

Transmission Parameters

$$b_1 = r_{11}a_2 + r_{12}b_2$$
$$a_1 = r_{21}a_2 + r_{22}b_2$$

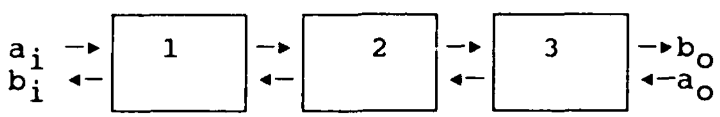
The relationship between the two parameters is

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \frac{1}{S_{21}} \begin{bmatrix} -d_s & S_{11} \\ -S_{22} & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} = \begin{bmatrix} & \mathbf{R} & \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}$$

where $d_s = s_{11}s_{22} - s_{12}s_{21}$

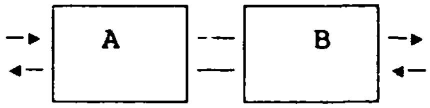
and the "**R**" matrix used here is sometimes called the "transmission" matrix.

The **R** matrix has a property similar to **ABCD** matrices; they may be multiplied in sequence (cascaded).



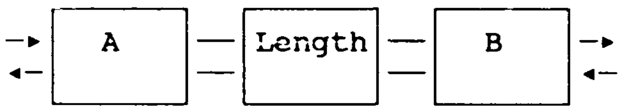
$$\begin{bmatrix} b_i \\ a_i \end{bmatrix} = \begin{bmatrix} R_1 \end{bmatrix} \cdot \begin{bmatrix} R_2 \end{bmatrix} \cdot \begin{bmatrix} R_3 \end{bmatrix} \cdot \begin{bmatrix} a_o \\ b_o \end{bmatrix}$$

1. Measure $\left[S_{AB} \right]$, the S parameters of the <u>through</u> connection.



Convert to $\left[R_{AB} \right]$, noting that $\left[R_{AB} \right] = \left[R_A \right] \cdot \left[R_B \right]$

2. Measure $\left[S_{ALB} \right]$, the S parameters of the through connection with the added **length**



Convert to $\left[R_{ALB} \right]$, where $\left[R_{ALB} \right] = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right]$

There is enough information from these two measurements to obtain the parameters of the transmission line used, i.e., the attenuation and phase velocity at each frequency. The added length must have the same characteristics as the line in which the DUT is to be embedded.

3. Find the matrix $\left[T \right] = \left[R_{ALB} \right] \cdot \left[R_{AB} \right]^{-1}$ (1)

Note that all the elements of the **T** matrix are known since the elements of R_{ALB} and R_{AB} were directly found from the S_{ALB} and S_{AB} measurements.

Using the cascade properties of the **R** matrix we have

$$\left[T \right] = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right] \cdot \left[R_{AB} \right]^{-1} = \left[R_A \right] \cdot \left[R_L \right] \cdot \left[R_B \right] \cdot \left[R_B \right]^{-1} \cdot \left[R_A \right]^{-1}$$

so that

$$\boxed{\begin{bmatrix} \mathbf{T} \end{bmatrix} = \begin{bmatrix} \mathbf{R_A} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{R_L} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{R_A} \end{bmatrix}^{-1}} \qquad (2)$$

The added line of length L is non-reflecting (same impedance as end of TRL transitions), so

$$\begin{bmatrix} \mathbf{S_L} \end{bmatrix} = \begin{bmatrix} 0 & e^{-\tau L} \\ e^{-\tau L} & 0 \end{bmatrix}$$

where $\tau = \alpha + j\beta$

α= attenuation const
β= propagation const

Therefore

$$\begin{bmatrix} \mathbf{R_L} \end{bmatrix} = \begin{bmatrix} e^{-\tau L} & 0 \\ 0 & e^{\tau L} \end{bmatrix}$$

Using

$$\begin{bmatrix} \mathbf{T} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{R_A} \end{bmatrix} = \begin{bmatrix} \mathbf{R_A} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{R_L} \end{bmatrix},$$ we have

$$\begin{bmatrix} T_1 & T_2 \\ T_3 & T_4 \end{bmatrix} \cdot \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} = \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} \cdot \begin{bmatrix} e^{-\tau L} & 0 \\ 0 & e^{\tau L} \end{bmatrix}$$

Multiplying matrices we find:

(3) $T_1 \cdot R_{A1} + T_2 \cdot R_{A3} = R_{A1} e^{-\tau L}$ (5) $T_1 \cdot R_{A2} + T_2 \cdot R_{A4} = R_{A2} e^{\tau L}$

(4) $T_3 \cdot R_{A1} + T_4 \cdot R_{A3} = R_{A3} e^{-\tau L}$ (6) $T_3 \cdot R_{A2} + T_4 \cdot R_{A4} = R_{A4} e^{\tau L}$

From 3,4 we have

$$\frac{R_{A1}}{R_{A3}} = \frac{T_2}{e^{-\tau L} - T_1} = \frac{e^{-\tau L} - T_4}{T_3} \qquad (7)$$

so that $$\epsilon^{-2\tau L} - \epsilon^{-\tau L}(T_1 + T_4) + (T_1T_4 - T_2T_3) = 0 \qquad (8)$$

From 5,6 we have $$\frac{R_{A2}}{R_{A4}} = \frac{T_2}{\epsilon^{\tau L} - T_1} = \frac{\epsilon^{\tau L} - T_4}{T_3} \qquad (9)$$

so that $$\epsilon^{2\tau L} - \epsilon^{\tau L}(T_1 + T_4) + (T_1T_4 - T_2T_3) = 0 \qquad (10)$$

The solutions for $\epsilon^{-\tau L}$ and $\epsilon^{\tau L}$ are the two solutions to the complex equation

$$G^2 - G(T_1+T_4) + (T_1T_4 - T_2T_3) = 0$$

we find

$$G = B\cdot\left[1 \pm D^{1/2}\right] \text{ with solutions } |G_1|\cdot\epsilon^{jtg1},\ |G_2|\cdot\epsilon^{jtg2} \qquad (11)$$

where $$B = \frac{T_1 + T_4}{2} \qquad C = T_1T_4 - T_2T_3 \qquad D = 1 - \frac{C}{B^2}$$

The solution for $\epsilon^{-\tau L} = \epsilon^{-\alpha L}\cdot\epsilon^{-j\beta L}$ will be

$|G_1|\cdot\epsilon^{jtg1}$ if tg1 is negative

$|G_2|\cdot\epsilon^{jtg2}$ if tg2 is negative

The attenuation (dB) in the distance L is $20*\log_{10}(G_{1,2})$ so

$$\boxed{\text{dB/inch} = \frac{20*\log_{10}(G_{1,2})}{L(\text{in.})}} \qquad (12)$$

where $G_{1,2}$ is the correct solution as found above

Also, since $\beta L = t_g = 2\pi \cdot L/\text{wavelength} = \dfrac{2\pi \cdot L \cdot f \cdot \sqrt{e_{eff}}}{c}$

$$\boxed{e_{eff} = \{\ 30 \cdot t_g/[2.54 \cdot 2\pi \cdot L(\text{in}) \cdot f(\text{gHz}]\ \}^2} \qquad (13)$$

We have found the transmission line parameters dB/inch and e_{eff} from measuring the S parameters of the two fixtures with different lengths.

For low loss media such as suspended substrate, the added length L should be large enough so that the transmission loss of the larger line will be evident. The added line may need to be a centimeter or longer. Since measurements of the phase of s11 and s22 are ambiguous by multiples of 2π radians if L is larger than 1/2 wavelength, one can resolve the ambiguity in t_g as follows:

a. Estimate e_{eff} and find an approximate t_g.

b. Use this value to calculate e_{eff}^{o}, e_{eff}^{+}, and e_{eff}^{-} for the approximated values of t_g, $t_g+2\pi$, and $t_g-2\pi$ respectively.

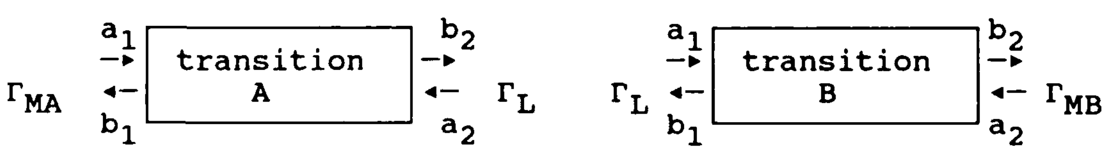
c. Choose which of the three values comes closest to the estimated e_{eff}.

Generally, for L one or two wavelengths long, the other two values will be very far off.

B. FINDING THE TRANSITION PARAMETERS

We now turn to the rest of the de-embedding process.

Using identical loads, do the <u>Reflect</u> measurements, finding Γ_{MA} and Γ_{MB}. It is not necessary to know the load value, only that it is the same for the two reflect measurements. Taking identical lengths off the ends of the TRL transitions provides the simplest of loads.



$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix}_A = \begin{bmatrix} R_{A1} & R_{A2} \\ R_{A3} & R_{A4} \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_A = R_{A4} \cdot \begin{bmatrix} A_1 & A_2 \\ A_3 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_A$$

$$(b_1/a_1)_A = \Gamma_{MA} = \frac{A_1(a_2/b_2) + A_2}{A_3(a_2/b_2) + 1} = \frac{A_1\Gamma_L + A_2}{A_3\Gamma_L + 1} \tag{14}$$

define $\boxed{X1 \equiv R_{A1}/R_{A3} = A_1/A_3}$ and (15)

$$\boxed{X2 \equiv R_{A2}/R_{A4} = A_2} \tag{16}$$

where these values were completely determined in (7) and (9).

we find from (14)

$$A_1 = \frac{\Gamma_{MA} - X2}{\Gamma_L(1-\Gamma_{MA}/X1)} \tag{17}$$

where all values are now known except Γ_L

Similarly,

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix}_B = \begin{bmatrix} R_{B1}/R_{B4} & R_{B2}/R_{B4} \\ R_{B3}/R_{B4} & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_B = R_{B4} \cdot \begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}_B$$

$$(b_1/a_1)_B = \frac{1}{\Gamma_L} = \frac{B_1 + B_2(b_2/a_2)_B}{B_3 + (b_2/a_2)_B} = \frac{B_1 + B_2 \cdot \Gamma_{MB}}{B_3 + \Gamma_{MB}} \tag{18}$$

We now find the B values, hence Γ_L, and finally, from (17), A_1.

From measurements:

$$\left[\,\mathbf{R_{AB}}\,\right] = \begin{bmatrix} R_{AB1} & R_{AB2} \\ R_{AB3} & R_{AB4} \end{bmatrix} = R_{AB4}\cdot\begin{bmatrix} AB1 & AB2 \\ AB3 & 1 \end{bmatrix} \quad \text{known, and since}$$

$$\left[\,\mathbf{R_B}\,\right] = \left[\,\mathbf{R_A}\,\right]^{-1}\cdot\left[\,\mathbf{R_{AB}}\,\right]$$

$$\left[\,\mathbf{R_B}\,\right] = R_{B4}\cdot\begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} = \frac{R_{AB4}}{R_{A4}(A_1-A_2\cdot A_3)}\begin{bmatrix} 1 & -A_2 \\ -A_3 & A_1 \end{bmatrix}\cdot\begin{bmatrix} AB_1 & AB_2 \\ AB_3 & 1 \end{bmatrix}$$

solving for RB_4, we have

$$\begin{bmatrix} B_1 & B_2 \\ B_3 & 1 \end{bmatrix} = \frac{1}{(A_1-A3\cdot AB_2)}\begin{bmatrix} 1 & -A_2 \\ -A_3 & A_1 \end{bmatrix}\cdot\begin{bmatrix} AB_1 & AB_2 \\ AB_3 & 1 \end{bmatrix}$$

$$\boxed{B_1 = \frac{AB_1 - X2\cdot AB_3}{A_1\cdot(1 - AB_2/X1)}} \qquad (19)$$

$$\boxed{B_2 = \frac{AB_2 - X_2}{A_1(1- AB_2/X1)}} \qquad (20)$$

$$\boxed{B_3 = \frac{AB_3 - AB_1/X1}{1- AB_2/X1}} \qquad (21)$$

Eliminating the unknown Γ_L from (17) and (18) gives

$$\frac{A_1}{B_1} = \frac{(\Gamma_{MA} - X2)\cdot(1 + [B_2/B_1]\cdot\Gamma_{MB})}{(1 - \Gamma_{MA}/X1)\cdot(B_3 + \Gamma_{MB})}, \quad \text{all known} \qquad (22)$$

Multiplying (22) by (19) yields two solutions for A_1

$$A_1 = \pm \left[\frac{(\Gamma_{MA} - X2)\cdot(1 + [B_2/B_1]\cdot\Gamma_{MB})\cdot(AB_1 - x2\cdot AB_3)}{(\Gamma_{MB} + B_3)\cdot(1 - \Gamma_{MA}/X1)\cdot(1 - AB_2/X1)} \right]^{1/2} \tag{23}$$

$$\begin{aligned} A_1 &= a_1\cdot\epsilon^{jTax1} && \text{for } + \surd \\ &= a_1\cdot\epsilon^{jTax1+\pi} && \text{for } - \surd \end{aligned}$$

where a_1 is a positive real number.

To find which solution is to be used, find the approximate value of A_1. If an ideal open circuit were used for the reflect measurement, $\Gamma_L = 1$. If the open circuit was at an angular distance Θ_i before the reference position, $\Gamma_L = \epsilon^{j2\Theta i}$. Substituting in (17) we find the approximate value of A_1.

$$A_1 \approx \frac{\Gamma_{MA} - X2}{\epsilon^{j2\Theta i}(1 - \Gamma_{MA}/X1)} \equiv A_{1x} = |a_{1x}|\cdot\epsilon^{jTax}, \text{ all known} \tag{24}$$

Now that we've calculated the phase angle that A_1 would have with an ideal open circuit, we can compare that phase angle with the angles derived from the non-ideal opens. The winner is the angle closest to T_{ax}. This is shown diagrammatically in Figure A1.

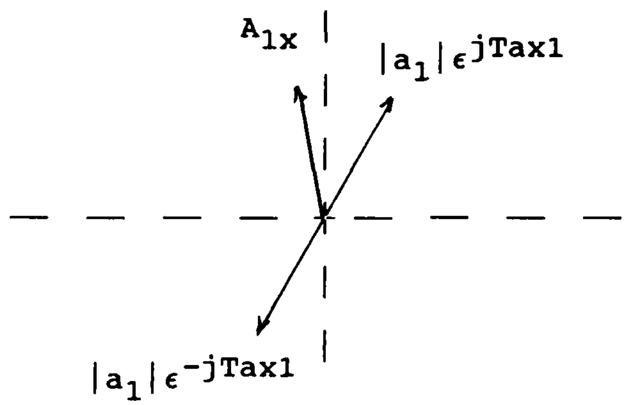


Figure A1. Determining the correct phase of A_1

All values of the **A** matrix are now known.

C. DE-EMBEDDING THE DEVICE

The device is inserted at the reference position, that is, the junction of TRL transitions 1 and 2 (Figure A2). This position need not be at the center of the line.

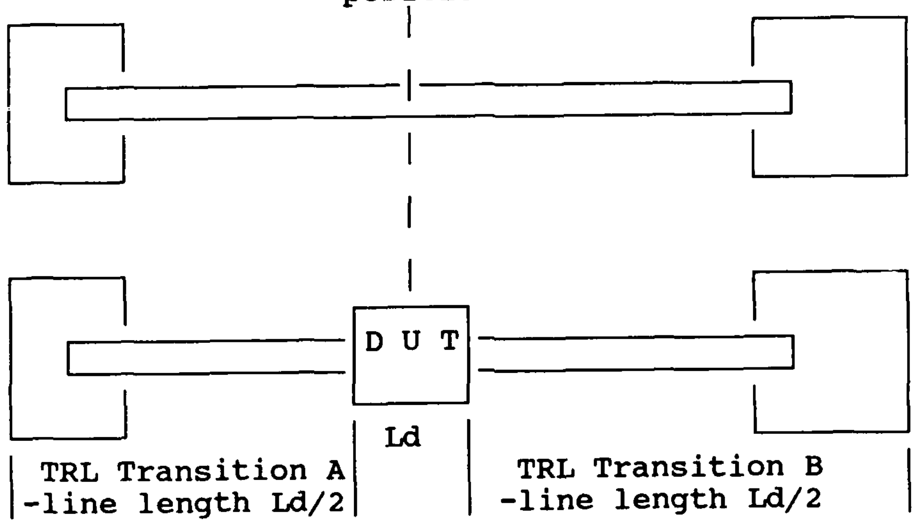


Figure A2. Inserting the device at the reference position

$\left[R_{ADB} \right]$ can be written to include the negative line lengths -Ld/2 taken by the DUT from the TRL transition line lengths.

The **R** matrix for negative line length -Ld/2 is

$$\left[R_N \right] = \begin{bmatrix} e^{\tau Ld/2} & 0 \\ 0 & e^{-\tau Ld/2} \end{bmatrix} \tag{25}$$

so

$$\begin{aligned} \left[R_{ADB} \right] &= \left[R_A \right] \cdot \left[R_N \right] \cdot \left[R_D \right] \cdot \left[R_N \right] \cdot \left[R_B \right] \\ &= R_{A4} \cdot R_{B4} \cdot \left[AR_N \right] \cdot \left[R_D \right] \cdot \left[R_N B \right] \end{aligned} \tag{26}$$

$$\left[R_D \right] = \frac{1}{R_{A4} \cdot R_{B4}} \left[AR_N \right]^{-1} \cdot \left[R_{ADB} \right] \cdot \left[R_N B \right]^{-1} \tag{27}$$

The values R_{A4} and R_{B4} have not yet been determined. We can write

$$\left[\ \mathbf{R_{AB}}\ \right] = R_{A4} \cdot R_{B4} \left[\ \mathbf{A}\ \right] \cdot \left[\ \mathbf{B}\ \right] \quad \text{which yields}$$

$$R_{AB4} = R_{A4} \cdot R_{B4} \cdot (1 + A_3 \cdot B_2). \tag{28}$$

Substituting (28) into (27) gives the result

$$\boxed{\left[\ \mathbf{R_D}\ \right] = \frac{(1 + A_3 \cdot B_2)}{R_{AB4}} \cdot \left[\ \mathbf{AR_N}\ \right]^{-1} \cdot \left[\ \mathbf{R_{ADB}} \right] \cdot \left[\ \mathbf{R_N B}\ \right]^{-1}} \tag{29}$$

Examination of this equation shows that all values to the right of the = sign have been determined; therefore the device transmission parameters can be calculated.

Finally, the 4-port device **R** parameters can be converted to the device **S** parameters by the standard *transformation methods.*

$$\boxed{\left[\ \mathbf{S_D}\ \right] = \frac{1}{R_{22}} \begin{bmatrix} R_{12} & d_r \\ 1 & -R_{21} \end{bmatrix}, \quad d_r = R_{11} \cdot R_{22} - R_{12} \cdot R_{21}} \tag{30}$$

Appendix B: STRL4, A De-Embedding Computer Routine"

The computer program listed in the following pages was written in TRUE BASIC, a compiled version of Basic which seems well suited for mathematical programming.

The first part of the program is specific for data obtained on a Wiltron 360 network analyzer. It calls up the stored S parameter data from the Transition, added Length, Reflection, and DUT measurements and filters out the garbage associated with byte file headings, spaces, etc. The four Wiltron data files are stored with file names T,L,R,and any name for the device under test. All four files are automatically given the extension .DAT by the analyzer.

Example: For TRL de-embedding if we denote a particular measurement set "B," and we call the DUT "fil," the four file names would be

```
  T_B.DAT
  L_B.DAT
  R_B.DAT
fil_B.DAT
```

For the filtering routine to work with the Wiltron, it is important that the analyzer is set to display linear magnitude and phase information such as "linear polar", and that the markers are off.

If data is obtained from another analyzer such as an H.P. 8510, a routine should be written so that data for N different frequencies ends up as

```
   f(k),    k=1 to N
 s11(k,g), k=1 to N, g=1 to 4  (1→L, 2→T, 3→R, 4→DUT)
 t11(k,g),  "    " ,  "   "
  ....
  ....
 t22(k,g),  "    " ,  "   "
```

Copies of this program may be obtained by U.S. companies by writing the author. Although every attempt has been made to assure accuracy, the author and the U.S. government do not assume any responsibility for its usage.

```
!STRL (takes 4 Wiltron byte files as input and de-embeds device
                                                  S parameters)
input prompt "device name, device length (in.)= ":dname$, Ld
input prompt "use printer (y or n) ":print$
if print$="y" then
open #10: printer
print #10: dname$&".TRL (de-embedded)","  Ld=";Ld;"in."
print #10:
end if
input prompt "include Ldb, eeff of calib. ? (y or n) ":incl$
option nolet
for g=1 to 4
if g=1 then open #1: name "salb.wil",     access input, org byte
if g=2 then open #2: name  "sab.wil",     access input, org byte
if g=3 then open #3: name  "sga.wil",     access input, org byte
if g=4 then open #4: name "dname$&".wil", access input, org byte
ask #g: filesize len1
read #g,bytes len1:file$
p1=pos[file$,chr$(10)&chr$(10)&chr$(49)]-1   !start of 1st freq.
                                              position
p2=pos[file$,chr$(10)&chr$(12)]              !end of data position
len2=p2-p1
n=int(len2/137) !number of frequencies
set #g: pointer begin
read #g,bytes p1:kill$                 !removes garbage headings
dim buf$(141,10),c$(10),d$(10),f$(10)
when error in
for k=1 to n
read #g, bytes 137: a$        !reads line of data
  b$=a$[2:137]                !removes chr$(10) symbol before
data
for j=1 to 10
    c$(1)=b$[01:03]
    c$(2)=b$[04:16]
    c$(3)=b$[17:31]
    c$(4)=b$[32:48]
    c$(5)=b$[49:63]
    c$(6)=b$[64:78]
    c$(7)=b$[79:93]
    c$(8)=b$[94:108]
    c$(9)=b$[109:124]
    c$(10)=b$[125:139]

    buf$(k,j)=c$(j)
next j
next k
use
print using "not enough data on freq line ###":k
set #g: pointer end
end when
dim f(401,4),s11(401,4),t11(401,4),s12(401,4),t12(401,4),
             s21(401,4),t21(401,4), s22(401,4),t22(401,4)
```

```
for k=1 to n
f(k,g)=val(buf$(k,2))
s11(k,g)=val(buf$(k,3))
t11(k,g)=val(buf$(k,4))
s12(k,g)=val(buf$(k,5))
t12(k,g)=val(buf$(k,6))
s21(k,g)=val(buf$(k,7))
t21(k,g)=val(buf$(k,8))
s22(k,g)=val(buf$(k,9))
t22(k,g)=val(buf$(k,10))
next k
close #g
next g
REM g=1:Salb  g=2:Sab  g=3:Sga  g=4:Sadb
REM: example:  f(20,4) is the 20th frequency of Sadb data

call trl


sub TRL ! TRL calibration and measurement
option angle degrees
option nolet
La=.1! added line (inches) used for calibration
rem Ld= length (inches) of device to be parameterized
if incl$="y" then
print "F(GHz)  Ldb   eeff     S11    A11       S12    A12
               S21    A21     S22   A22"
if print$="y" then print #10: "F(GHz)  Ldb   eeff     S11    A11
                       S12    A12      S21    A21     S22   A22"

else
print "F(GHz)    S11    A11      S12    A12       S21    A21
      S22   A22"
if print$="y" then print #10: "F(GHz)    S11    A11      S12
                               A12    S21    A21     S22   A22"
end if
FOR N=1 to 28
FOR G=1 TO 4
fr=f(n,1)
!S params with added line
!read s1,a1,s2,a2,s3,a3,s4,a4
let s1=s11(n,1)
let a1=t11(n,1)
let s2=s12(n,1)
let a2=t12(n,1)
let s3=s21(n,1)
let a3=t21(n,1)
let s4=s22(n,1)
let a4=t22(n,1)
```

```
call StoT(s1,a1,s2,a2,s3,a3,s4,a4,r1a1b,t1a1b,r2a1b,t2a1b,
          r3a1b,t3a1b,r4a1b,t4a1b) !Ra1b
!S params without added line
!read s1,a1,s2,a2,s3,a3,s4,a4
let s1=s11(n,2)
let a1=t11(n,2)
let s2=s12(n,2)
let a2=t12(n,2)
let s3=s21(n,2)
let a3=t21(n,2)
let s4=s22(n,2)
let a4=t22(n,2)
call StoT(s1,a1,s2,a2,s3,a3,s4,a4,r1ab,t1ab,r2ab,t2ab,r3ab,t3ab,
          r4ab,t4ab)!Rab

!reflection coeff. of transitions and B with identical loading
!read ga,tga,gb,tgb
let ga=s11(n,3)
let tga=t11(n,3)
let gb=s22(n,3)
let tgb=t22(n,3)

!S parameters with device inserted
!read s1,a1,s2,a2,s3,a3,s4,a4
let s1=s11(n,4)
let a1=t11(n,4)
let s2=s12(n,4)
let a2=t12(n,4)
let s3=s21(n,4)
let a3=t21(n,4)
let s4=s22(n,4)
let a4=t22(n,4)
call StoT(s1,a1,s2,a2,s3,a3,s4,a4,r1adb,t1adb,r2adb,t2adb,
r3adb,t3adb,r4adb,t4adb) !Radb

!find matrix [T]=[Ra1b]*[Rab]-1
call inv(r1ab,t1ab,r2ab,t2ab,r3ab,t3ab,r4ab,t4ab,ri1ab,ai1ab,
ri2ab,ai2ab,ri3ab,ai3ab,ri4ab,ai4ab)!(Rab)-1
call mult(r1a1b,t1a1b,r2a1b,t2a1b,r3a1b,t3a1b,r4a1b,t4a1b,
          ri1ab,ai1ab,ri2ab,ai2ab,ri3ab,ai3ab,ri4ab,ai4ab,
          t1,at1,t2,at2,t3,at3,t4,at4)

!find line coeff. ! exp(-alpha*La)*exp(-j*beta*La)=gx*exp(j*tgx)
! first solve quad. exp(-2*gamma*La)-exp(-gamma*La)*(T1+T4)
                    +(T1*T4-T2*T3)=0
call add(t1/2,at1,t4/2,at4,b,angb)
call add(t1*t4,at1+at4,-t2*t3,at2+at3,c,angc)
call add(1,0,-c/(b^2),angc-2*angb,d,angd)
```

```
call add(b,angb,b*sqr(d),angb+angd/2,g1,tg1)
call add(b,angb,-b*sqr(d),angb+angd/2,g2,tg2)
if tg1<=0 then  !correct solution is one with negative exp.
gx=g1
tgx=tg1
else

gx=g2
tgx=tg2
end if
!gx*exp(jtg)=exp(-alpha*La)*exp(-j*beta*La)
beta=-tgx/La
eeff=(30*tgx/(2*180*2.54*La*fr))^2
Ldb=20*log10(Gx)/La
!print using "f=##.###  Ldb=##.###  Eeff=##.###":fr, Ldb,eeff
!if print$="y" then print #10, using "f=##.###  Ldb=##.###
                                              Eeff=##.##": fr, Ldb,eeff

!Find X1=Ra1/Ra3, X2=Ra2/Ra4
call add( gx/t3,tgx-at3,-t4/t3,at4-at3,x1,tx1)
call add(1/(gx*t3),-tgx-at3,-t4/t3,at4-at3,x2,tx2)

a2=x2  !one of the elements of [A]: to be used later
ta2=tx2
!put [Rab] in the form const*[ab1,ab2,ab3,1]
call ratios(r1ab,t1ab,r2ab,t2ab,r3ab,t3ab,r4ab,t4ab,ab1,tab1,
            ab2,tab2,ab3,tab3)

!Rb=R4b*[B1,B2,B3,1]
!solve for B2/B1 =k1*exp(j*tk1)
call add(ab2,tab2,-x2,tx2,ka,tka)
call add(ab1,tab1,-x2*ab3,tx2+tab3,kb,tkb)
k1=ka/kb
tk1=tka-tkb

!solve for B3=b3*exp(j*tb3)
call add(ab3,tab3,-ab1/x1,tab1-tx1,ka,tka)
call add(1,0,-ab2/x1,tab2-tx1,kb,tkb)
b3=ka/kb
tb3=tka-tkb

!solve for A1*B1=k3*exp(j*tk3)
call add(ab1,tab1,-x2*ab3,tx2+tab3,ka,tka)
k3=ka/kb
tk3=tka-tkb

!solve for a1*exp(j*ta1)
call add(ga,tga,-x2,tx2,g1,tg1)
call add( 1,0,k1*gb,tk1+tgb,g2,tg2)
call add(ab1,tab1,-x2*ab3,tx2+tab3,g3,tg3)
call add(gb,tgb,b3,tb3,g4,tg4)
call add(1,0,-ga/x1,tga-tx1,g5,tg5)
call add(1,0,-ab2/x1,tab2-tx1,g6,tg6)
a1=sqr(g1*g2*g3/(g4*g5*g6))
tax1=(tg1+tg2+tg3-tg4-tg5-tg6)/2
```

```
tax2=tax1+180

!find if ta1=tax1 or ta1=tax2
!find approx value of a1, given that load was an exact open
tar=2*beta*lr/2 !increased load angle caused by missing line
call add(ga,tga,-x2,tx2,anum,tanum)
call add(1,0,-ga/x1,tga-tx1,aden,taden)
ax=anum/aden
tax=tanum-taden-tar

if abs(mod(tax,2*180)-mod(tax1,2*180))<180/2 then
   ta1=tax1 else ta1=tax2

a3=a1/x1
ta3=ta1-tx1

a4=1
ta4=0

!solve for B1=b1*exp(j*tb1)
b1=k3/a1
tb1=tk3-ta1

!solve for B2=b2*exp(j*tb2)
b2=b1*k1
tb2=tb1+tk1

b4=1
tb4=0

![Radb] is actually [RaRnRdRnRb] where [Rn] is matrix for -Ld/2
        line length
![Rn] matrix is:
rn1=exp(alpha*Ld/2)
tn1=beta*Ld/2
rn2=0
tn2=0
rn3=0
tn3=0
rn4=exp(-alpha*Ld/2)
tn4=-beta*Ld/2

! find [Ran]=[Ra]*[Rn]=R4a*[A1,A2,A3,1]  and
       [Rnb]=[Rn]*[Rb]=R4b*[B1,B2,B3,1]
! [Rd]=[Ran]-1 *[Radb]*[Rnb]-1
call mult(a1,ta1,a2,ta2,a3,ta3,1,0,rn1,tn1,rn2,tn2,rn3,tn3,
          rn4,tn4,ran1,tan1,ran2,tan2,ran3,tan3,ran4,tan4)
call mult(rn1,tn1,rn2,tn2,rn3,tn3,rn4,tn4,b1,tb1,b2,tb2,
          b3,tb3,b4,tb4,rnb1,tnb1,rnb2,tnb2,rnb3,tnb3,rnb4,tnb4)
! find [Rnb]-1 and [Ran]-1
call inv(rnb1,tnb1,rnb2,tnb2,rnb3,tnb3,rnb4,tnb4,
         nb1,tinb1,inb2,tinb2,inb3,tinb3,inb4,tinb4)
call inv(ran1,tan1,ran2,tan2,ran3,tan3,ran4,tan4,ian1,tian1,
         ian2,tian2,ian3,tian3,ian4,tian4)
!find [Radb]*[Rnb-1]=Rbb
```

```
call mult(rladb,tladb,r2adb,t2adb,r3adb,t3adb,r4adb,t4adb,
          inb1,tinb1,inb2,tinb2,inb3,tinb3,inb4,tinb4,
          r1bb,t1bb,r2bb,t2bb,r3bb,t3bb,r4bb,t4bb)
!find [Ran-1]*Rbb=Rdd
call mult(ian1,tian1,ian2,tian2,ian3,tian3,ian4,tian4,
          r1bb,t1bb,r2bb,t2bb,r3bb,t3bb,r4bb,t4bb,
          r1dd,t1dd,r2dd,t2dd,r3dd,t3dd,r4dd,t4dd)
![Rd]=1/(R4a*R4b) *[Rdd], where 1/(R4a*R4b)=(A3*B3+1)/R4ab
call add(a3*b2/r4ab,ta3+tb2-t4ab,1/r4ab,-t4ab,de,tde)
rd1=de*r1dd
rd2=de*r2dd
rd3=de*r3dd
rd4=de*r4dd

td1=tde+t1dd
td2=tde+t2dd
td3=tde+t3dd
td4=tde+t4dd

! Find device S parameters [Sd]
call TtoS(rd1,td1,rd2,td2,rd3,td3,rd4,td4,sd11,td11,sd12,td12,
                                        sd21,td21,sd22,td22)
next g
if incl$="y" then
print using  "##.### ##.##  #.##  ##.###  ####.#
              ##.### ####.#  ##.### ####.#  ##.### ####.#":
              fr,Ldb,eeff,sd11,td11,sd12,td12,sd21,td21,sd22,td22
if print$="y" then print #10, using "##.### ##.##  #.##  ##.###
          ####.#   ##.### ####.#  ##.### ####.#  ##.### ####.#":
          fr,Ldb,eeff,sd11,td11,sd12,td12,sd21,td21,sd22,td22
else
print using "##.###  ##.## ##.## ####.#  ##.### ####.#
             ##.### ####.# ##.### ####.#":
             fr,sd11,td11,sd12,td12,sd21,td21,sd22,td22
if print$="y" then print #10, using "##.###  ##.## ##.## ####.#
                   ##.### ####.#  ##.### ####.#  ##.### ####.#":
                   fr,sd11,td11,sd12,td12,sd21,td21,sd22,td22
end if
next n
end sub
end
!************* external subroutines follow **************

SUB MULT(a1,t1,a2,t2,a3,t3,a4,t4,b1,q1,b2,q2,b3,q3,b4,q4,
                                  c1,r1,c2,r2,c3,r3,c4,r4)
call add(a1*b1,t1+q1,a2*b3,t2+q3,c1,r1)
call add(a1*b2,t1+q2,a2*b4,t2+q4,c2,r2)
call add(a3*b1,t3+q1,a4*b3,t4+q3,c3,r3)
call add(a3*b2,t3+q2,a4*b4,t4+q4,c4,r4)
end sub

SUB RTP(x,y,u,i) !u*exp(j*i)=x+j(v2)  converts x,y to u*expi
option angle degrees
u=sqr(x^2+y^2)
if y=0 then
```

```
  if x>=0 then i=0 else i=180
end if
if y<>0 then
  if x=0 then i=180/2*y/abs(y)
  if x>0 then i=atn(y/x)
  if x<0 then i=atn(y/x)+180
end if
end sub

SUB ADD(u1,i1,u2,i2,u,i)  !u*exp(j*i)=u1*exp(j*i1)+u2*exp(j*i2)
option angle degrees
x=u1*cos(i1)+u2*cos(i2)
y=u1*sin(i1)+u2*sin(i2)
u=sqr(x*x+y*y)
if y=0 then

  if x>=0 then i=0 else i=180
end if
if y<>0 then
  if x=0 then i=180/2*y/abs(y)
  if x>0 then i=atn(y/x)
  if x<0 then i=atn(y/x)+180
end if
!  i=360/(2*180)*i
end sub

SUB INV(u1,i1,u2,i2,u3,i3,u4,i4,v1,j1,v2,j2,v3,j3,v4,j4)
rem u's, i's, elements of matrix, v's,j's are inverse
call add(u1*u4,i1+i4,-u2*u3,i2+i3,d,id)
v1=u4/d
j1=i4-id
v2=-u2/d
j2=i2-id
v3=-u3/d
j3=i3-id
v4=u1/d
j4=i1-id
end sub

SUB StoT(s1,a1,s2,a2,s3,a3,s4,a4,t1,b1,t2,b2,t3,b3,t4,b4)
        !S to T params
call add(s1*s4,a1+a4,-s2*s3,a2+a3,d,td)!find delta =d*exp(jtd)
t1=-d/s3
b1=td-a3
t2=s1/s3
b2=a1-a3
t3=-s4/s3
b3=a4-a3
t4=1/s3
b4=-a3
end sub

SUB TTOS(t1,a1,t2,a2,t3,a3,t4,a4,s1,b1,s2,b2,s3,b3,s4,b4)
        !T to S params
call add(t1*t4,a1+a4,-t2*t3,a2+a3,d,td)   !delta=d*exp(jtd)
```

```
s1=t2/t4
b1=a2-a4
s2=d/t4
b2=td-a4
s3=1/t4
b3=-a4
s4=t3/t4
b4=a3-a4+180
end sub

SUB Root(a1,ta1,b,tb,c,tc,x1,tx1,x2,tx2)
!solves a1(X^2)+B(X)+C=0 where a1=a1*exp(jta),..etc
!2 roots are x1*exp(jtx1), x2*exp(jtx2)
if a1<>0 then
call add(1,0,-4*a1*c/b^2,ta1+tc-2*tb,e,te)
call add(1,0, sqr(e),te/2,f1,tf1)
call add(1,0,-sqr(e),te/2,f2,tf2)
xa=-b*f1/(2*a1)

txa=tb-ta1+tf1
xb=-b*f2/(2*a1)
txb=tb-ta1+tf2
if abs(xa)>abs(xb) then
x1=xa
tx1=txa
x2=xb
tx2=txb
end if
if abs(xb)>abs(xa) then
x1=xb
tx1=txb
x2=xa
tx2=txa
end if
end if
if a1=0  then
x1=-c/b
tx1=tc-tb
x2=x1
tx2=tx1
end if
end sub

SUB RATIOS(r1,tr1,r2,tr2,r3,tr3,r4,tr4,a1,ta1,a2,ta2,a3,ta3)
!forms [R1,R2,R3,R4] matrix into R4*[A1,A2,A3,1] matrix
a1=r1/r4
ta1=tr1-tr4
a2=r2/r4
ta2=tr2-tr4
a3=r3/r4
ta3=tr3-tr4
end sub
```

References

1. G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," IEEE Trans. Microwave Theory Tech., vol MTT-27, No. 12, Dec. 1989.

2. Cascade Microtech, Beaverton, Or.

3. Inter-continental Microwave, Santa Clara, CA.

4. Wiltron Company, Morgan Hill, CA.

5. Pacific Millimeter Products, San Diego, CA.

6. D. Rubin and A. Hislop, "Millimeter-Wave Coupled Line Filters," Microwave Journal, Vol 23, No. 10, Oct. 1980.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1991	

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
DE-EMBEDDING MILLIMETER-WAVE INTEGRATED CIRCUITS WITH TRL	PE: 0602234N Proj: RS34340 Work Unit: NOSC 75–EE09750
6. AUTHOR(S) David Rubin	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Naval Ocean Systems Center San Diego, CA 92152-5000	TD 2020

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Naval Research Laboratory 4555 Overlook Ave., S.W. Washington, DC 20375	

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

Through the use of a modification of the TRL (Through-Reflect-Line) method, integrated circuits contained within transitions have been successfully de-embedded. Two waveguide-to-suspended-substrate fixtures of different lengths were fabricated on a computer-controlled mill. Printed circuit waveguide probes were intentionally shortened to make them very reactive. Transmission and reflection measurements of a filter placed between the probes highlight the differences between measured and de-embedded results.

This report reviews the theory behind TRL, explains the modifications used, and presents a computer program to de-embed measurements from a Wiltron 360 network analyzer.

14. SUBJECT TERMS	15. NUMBER OF PAGES
millimeter wave integrated circuits de-embedding	32
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

INITIAL DISTRIBUTION

Code 0012	Patent Counsel	(1)
Code 0144	R. November	(1)
Code 753	D. Rubin	(25)
Code 921	J. Puleo	(1)
Code 961	Archive/Stock	(6)
Code 964B	Library	(3)

Defense Technical Information Center Alexandria, VA 22304-6145	(4)
NOSC Liaison Office Washington, DC 20363-5100	(1)
Center for Naval Analyses Alexandria, VA 22302-0268	(1)