The Design of a TRL Calibration Kit for Microstrip and its use for Measurement and Modeling of Active and Passive RF Components

D. Elsherbeni, L. Jordan, E. Hutchcraft, D. Kajfez, and R. K. Gordon

Department of Electrical Engineering
The University of Mississippi, University, MS 38677-1848, USA
daelsher@olemiss.edu, ltjordan@olemiss.edu, eeweh@olemiss.edu, eedarko@olemiss.edu,
eegordon@olemiss.edu

Abstract − Microstrip TRL standards for the Thru, Reflect, and Line are designed, fabricated and tested. A split fixture design is built which contains microstrip to coaxial transitions to aid in measuring non-coaxial devices. With this microstrip TRL calibration kit, accurate and repeatable calibrations over a broad frequency range will be verified. This kit is used to measure and model several components such as a capacitor, an inductor, a transistor, and a radio frequency identification tag. The TRL kit allows the reference planes to be set at the device under test and allows novel modeling of the device's intrinsic and extrinsic parameters through optimization of a network to minimize the difference between S-Parameter measurements taken with the TRL kit and device under test and the proposed model.

I. REQUIREMENTS FOR TRL STANDARDS

The Short-Open-Load-Thru (SOLT) technique is the traditional calibration method used primarily for coaxial applications. In non-coaxial measurements it is more difficult to build impedance standards that are easily characterized. In microstrip, short circuits are inductive, open circuits radiate energy, and it is difficult to build a high quality purely resistive load. Because of these limitations, studies are done on an alternative method for calibration in non-coaxial environments called Thru-Reflect-Line (TRL) that uses simple, realizable standards. This form of calibration can provide more accurate results than the SOLT method even for coaxial applications. The standard SOLT calibration depends on a set of four well-defined impedance standards (open, short, load, thru), but TRL only relies on lines with a consistent characteristic impedance and a reflect that doesn't have to well defined like a short or an open circuit. Because of this, TRL calibration standards are easier to manufacture than SOLT standards, especially for in-fixture environments. In this paper, the TRL calibration technique is studied for use in testing packaged transistors and passive surface mount components that are typically used on microstrip. The device under test must be physically connected to the network analyzer by some kind of transition. As a solution, we propose the development of a TRL calibration kit in which only microstrip TRL standards are used for S-parameter characterization of non-coaxial devices. The hookup of the three different standards along with the associated error boxes is shown in Appendix I [1]. The thru is obtained by placing the two fixture halves together in between the set of coaxial connectors. The thru standard is of zero length. Its characteristics are perfect transmission (S_{21}=1 with zero degree phase shift) and reflection coefficients equal to zero. At all frequencies, an ideal short is defined to have perfect reflection in which its reflection coefficient, $S_{11,}$ is equal to negative one. The line length is designed to have an electrical length equivalent to 90° phase shift at the center frequency of the entire range. It is characterized by perfect transmission when $|S_{21}| = 1$. The major limitation of the TRL technique is the limited bandwidth of the Line standards. A single line is only usable over a maximum of an 8:1 frequency range, so multiple lines are required for broad frequency coverage. At low frequencies, Line standards can become too long for practical use [2]. In the work reported here, three different line lengths, one to cover the low frequency range of 200 MHz to 1.8 GHz, a second to cover 700 MHz to 6.3 GHz, and a third to cover 1.4 to 12.6 GHz. These three lines would allow measurement up through the X-band. Since the design was to be used in a 50 Ohm system, widths of the 50 ohm microstrip lines were found using a linecalc program with the knowledge of the dielectric constant and the thickness of the board. The board substrate used in the design of the microstrip TRL calibration kit is the RT Duroid 6002 High Frequency Laminate from Rogers Corporation with dielectric constant of 2.94 and thickness of 30 mils [3]. An example of using a linecalc program available in Agilent's Advanced Design System (ADS) is shown in Fig. 1 below [4].

The width and relative dielectric constant are then used in a set of formulas shown below to obtain different frequency Line lengths. A block for each Line length was first designed then built. These blocks represent the Line

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standard in the TRL calibration technique. Twenty percent of the center frequency defines the lower part of the operating range. One-hundred and eighty percent of the center frequency defines the upper part of the range. For example, consider the low frequency range:

center frequency, $f_c = 1$ GHz
20% of $1 < f_c <$180% of 1
200 MHz $< f_c <$ 1.8 GHz .

From the above calculations, a low frequency Line insert piece was designed to cover 200 MHz to 1.8 GHz. From LineCalc, width, w = 1.935 mm and relative effective dielectric constant, ε_{reff} = 2.383 were obtained when the center frequency was set at 1 GHz. From these values and the following set of equations we obtain the phase velocity, v_p and wavelength, λ_g . The line length is designed to be one quarter the wavelength at the center frequency as shown below,

$$v_p = \frac{c}{\sqrt{\varepsilon_{reff}}} = \frac{3x10^8}{\sqrt{2.383}} \qquad (1)$$
$$= 1.94x10^8\, m/s$$

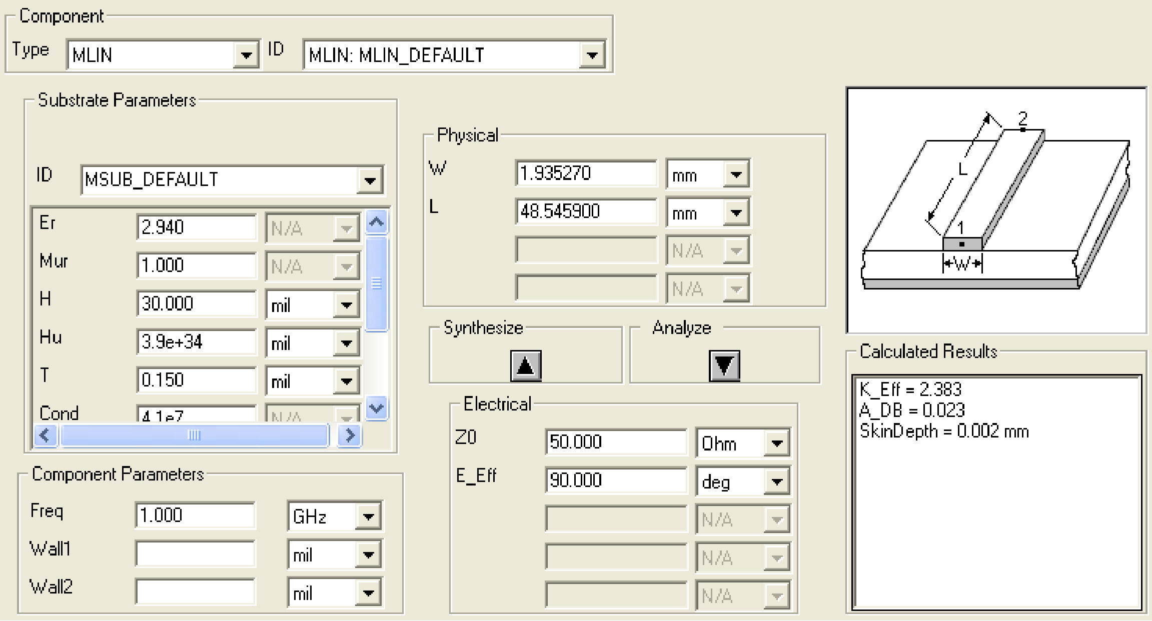
$$\lambda_g = \frac{v_p}{f} = \frac{1.94x10^8}{1x10^9} \qquad (2)$$
$$= 0.194\ m$$

lower frequency Line length,

$$L = \left(\frac{90}{360}\right)\lambda_g = \frac{\lambda_g}{4} = \frac{0.194}{4} \qquad (3)$$
$$= 0.0485\ m = 4.85cm\ .$$

Following the same calculating procedure as above, with center frequency at 3.5 GHz, a resulting span from 700 MHz to 6.3 GHz characterized a second Line length insert piece for the middle frequency range of the designed microstrip TRL calibration kit. Finally, a third line was designed with center frequency at 7 GHz and a range covering 1.4 GHz to 12.6 GHz. Typically, the VNA has calibration kits for most coaxial devices and the different standards for these kits have been defined within the network analyzer. The VNA also typically has the TRL calibration algorithm embedded into the system software. However, for the TRL algorithm to work, it is necessary to create and define each standard that will be used with the designed text fixture. The user-created standard kit includes the electrical characteristics of each calibration standard. Figure 2 shows the Standard Definition window for a VNA Calibration Kit Program used for out Agilent 8510C VNA [5].

Entered are the Short, Line, and Thru delay values in picoseconds. These values were obtained through a one-port SOLT calibration using the Agilent coaxial calibration kit. Each standard was placed on port 1 of the network analyzer, and with the port extension feature, the length of each standard was recorded and entered into the Offset Delay column in the Standards Definition window.



Type MLIN
ID MLIN: MLIN_DEFAULT

ID MSUB_DEFAULT
Er 2.940 N/A
Mur 1.000 N/A
H 30.000 mil
Hu 3.9e+34 mil
T 0.150 mil
Cond 4.1e7 N/A

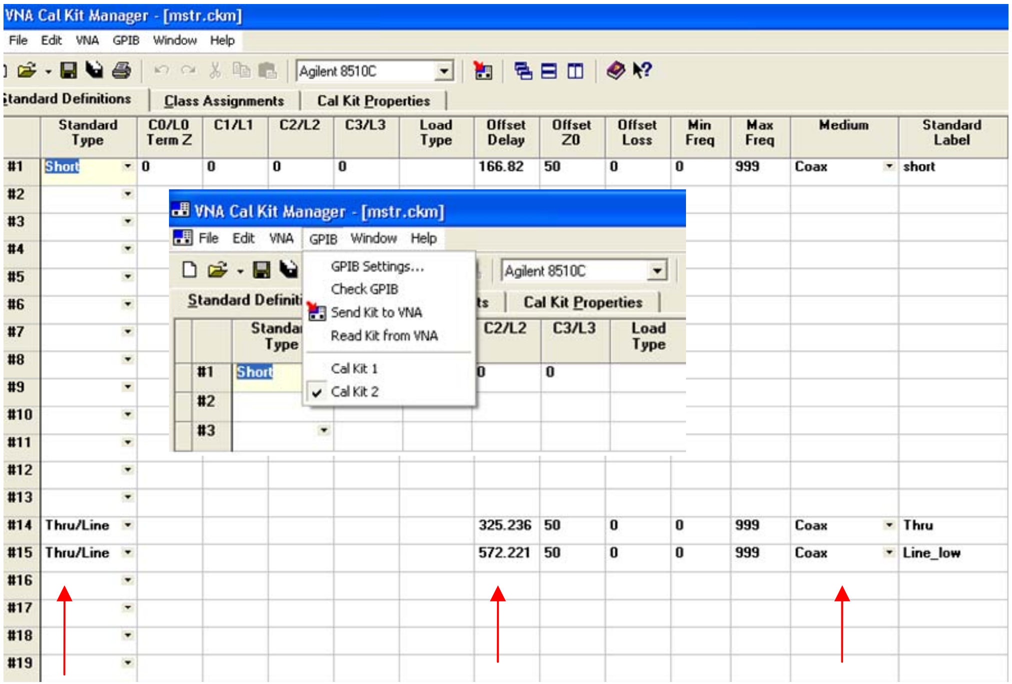
Freq 1.000 GHz
Wall1 mil
Wall2 mil

W 1.935270 mm
L 48.545900 mm

Z0 50.000 Ohm
E_Eff 90.000 deg

K_Eff = 2.383
A_DB = 0.023
SkinDepth = 0.002 mm

Fig. 1. A typical LineCalc window.



	Standard Type	C0/L0 Term Z	C1/L1	C2/L2	C3/L3	Load Type	Offset Delay	Offset Z0	Offset Loss	Min Freq	Max Freq	Medium	Standard Label
#1	Short	0	0	0	0		166.82	50	0	0	999	Coax	short
#2													
#3													
#4													
#5													
#6													
#7													
#8													
#9													
#10													
#11													
#12													
#13													
#14	Thru/Line						325.236	50	0	0	999	Coax	Thru
#15	Thru/Line						572.221	50	0	0	999	Coax	Line_low
#16													
#17													
#18													
#19													

Standard types and their corresponding numbers: Short #1, Thru#14, Line#15

Offset Delay (ps)

Coaxial or Waveguide
For microstrip, choose coaxial

Fig. 2. User-created Cal Kit standards definitions.

II. SPLIT FIXTURE DESIGN

For non-coaxial device measurement, a test fixture is needed to mount the device under test. The split design gives the ability to mount calibration standards of different lengths and non-coaxial devices to the center block which is inserted between the fixture halves. The test fixtures that represent the TRL calibration standards were made out of brass blocks and built using a CNC machine. Each block part was carefully modeled in the mechanical design software Pro-Engineer [6]. Figure 3 is a layout in Pro-Engineer showing dimensions in cm for the Reflect block, one of the required calibration standards of the TRL technique. Figure 3 simply demonstrates how each part was carefully designed and laid out for machining.

Figure 4 shows the assembled split fixture (zero length Thru standard) with the two block halves and a Teflon bridge on top. The purpose of the bridge is to insure connection between the device under test and the connecting blocks. The connection could be done with solder, but the Teflon bridge will allow connection without having to solder the leads of the device under test to the microstrip fixture leaving the calibration kit general to the various sizes and shapes of RF non-coaxial components. In the middle of the Teflon piece are two fingers. These fingers press down on the leads of the device under test so that there is good electrical connection between the device under test and microstrip line. The Teflon piece is connected to the block with screws, and these screws provide the pressure to the fingers which are lined with copper strips for conductivity. It should be pointed out that the Teflon could, in fact, introduce discontinuities, but since its dielectric constant is relatively low, and only a small portion touched the microstrip lines, it did not affect the measurement results in the frequency range of interest.

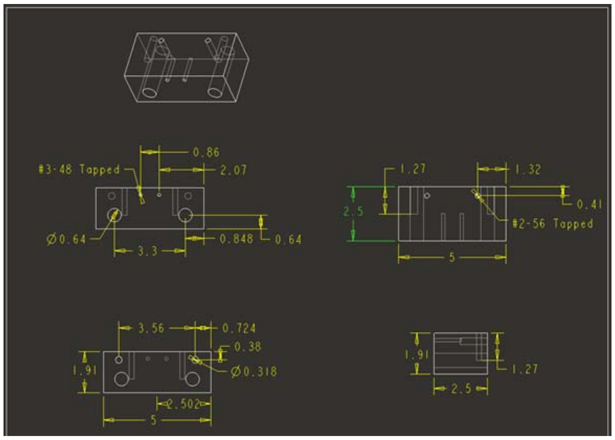


Fig. 3. Pro-Engineer layout for the Reflect standard (2.5 x 5.0 cm block half).

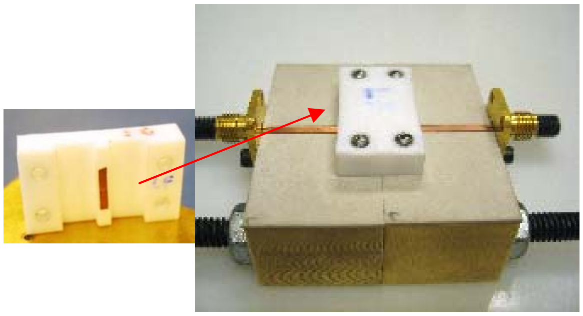


Fig. 4. Thru standard with Teflon bridge connection.

As can be seen from the Pro Engineer design, the individual blocks have assembling bolts and precision guiding pins, for accurate alignment of microstrip sections. Figure 5 points out the low frequency Line standard inserted in between the two halves with guiding pins and bolt holes to ensure a tight fit. Any high Reflect standard can be used and must be the same on port 1 and port 2 of the network analyzer.

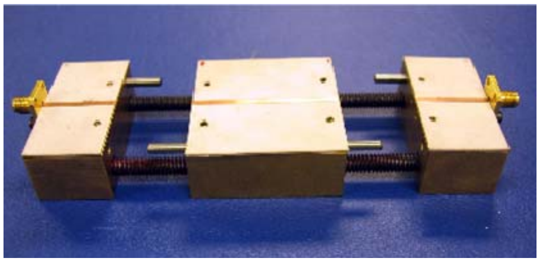


Fig. 5. Low frequency Line insert with guiding pins and bolts.

In this work, the Reflect standard is a 5 x 2.5 cm block with a wire soldered at the end of the microstrip line resembling a short circuit shown in Fig. 6.

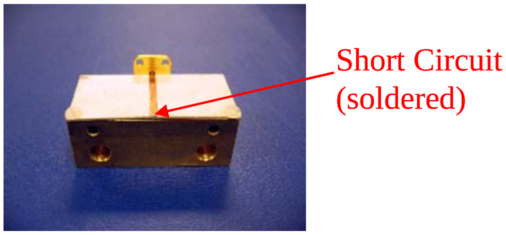


Fig. 6. Reflect standard (short circuit).

III. CHECKING THE CALIBRATION PERFORMANCE

This section below will check the performance of each TRL standard for the low frequency range. The reflection coefficient of the Reflect standard is supposed to be negative one at all frequencies. The objective is to obtain total reflection, 20 log (1) equals 0 dB. Figure 7 is a plot of the reflection coefficient in log magnitude verifying the Reflect standard requirement. Figure 8 verifies both the Line and Thru standards. The low frequency Line length is designed to have an electrical length of 90° at center frequency of 1 GHz.

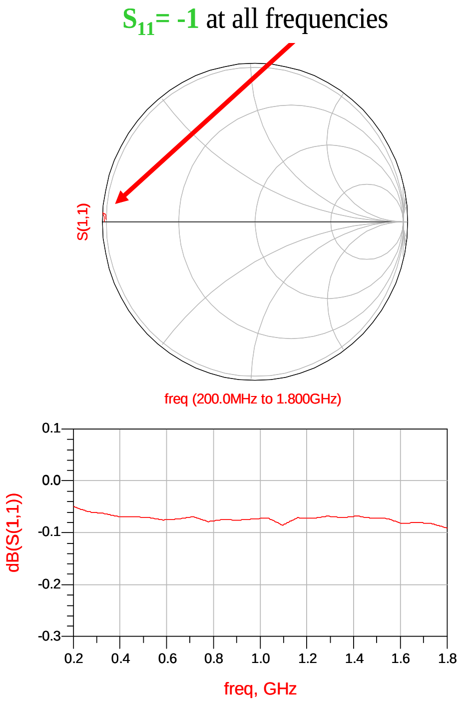
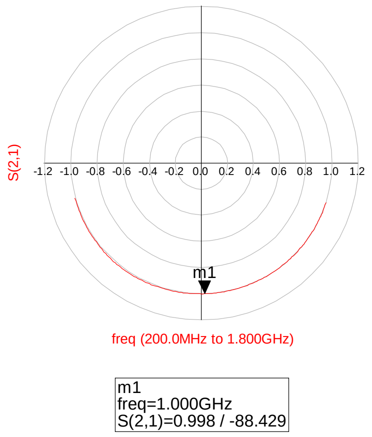


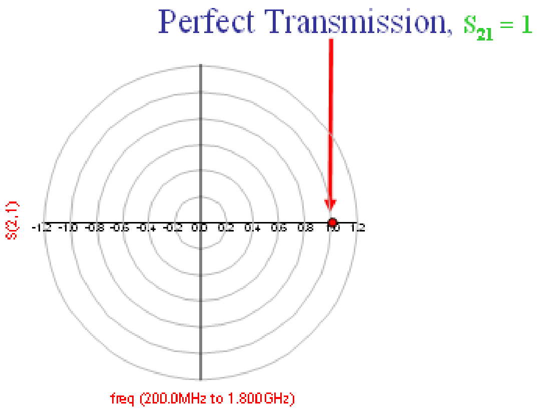
Fig. 7. Short standard verification.

The marker “m1” denotes the center frequency point. Note that the red marker on this transmission plot, is, as designed, nearly one quarter wavelength away from the Thru. The red curve is the measured range between 200 MHz and 1.8 GHz. Notice that the Line length varies as a function of frequency. The phase due to the electrical length of the line is different at each frequency and therefore the Line length is different at each frequency. The thru will remain constant at zero degrees.

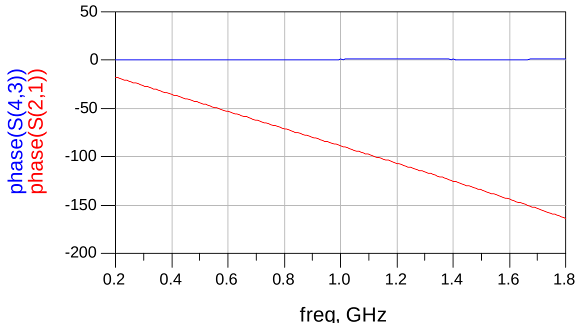
The TRL calibration kit has been tested for the lower frequency band, and the results are excellent. The results are similar for the middle and upper bands. However, some difficulties arose with the performance of the Reflect standard when calibrating with the high frequency set of blocks which results in the limitation of its use to only 9 GHz. Further studies will be done regarding the Reflect block to determine the reason for the incorrect reflection coefficient at a few specific frequencies to increase the overall working frequency range. A new Reflect board with grounding vias is being designed, and it is expected that this should cause the short circuit to appear less inductive. It is hoped that this will remedy the problem and allow the use of the high frequency block to 12.6 GHz.



(a) Line



(b) Thru



(c) Line and Thru

Fig. 8. (a)Line standard verification, (b)Thru standard verification, and (c) Line and Thru- phase in degrees.

IV. MEASUREMENT AND CHARACTERIZATION OF ACTIVE AND PASSIVE RF COMPONENTS

Calibration is necessary before taking measurements. In order to remove systematic errors the TRL calibration technique is used to setup the reference plane at the device under test. Because this TRL kit allows the reference plane to easily be set at the test device's terminals, models can easily be obtained through optimization of a model and the measured S-parameters. This section will show several measurements of non-coaxial devices such as a capacitor, an inductor, and a transistor all setup and tested using the designed microstrip TRL calibration kit. All of these were measured using the low or middle frequency ranges because they were being used in an amplifier that was being designed for the WLAN range (2.4 GHz). In addition, a radio frequency identification (RFID) tag was also measured. For all of these components, the S-parameters were measured, and these S-parameters could be used to obtain a model for the device, or the S-parameters could be used directly in a simulation.

Capacitor:

The designed microstrip TRL calibration kit can be used to assess the performance of capacitors. The capacitor used in measurement was the C06CF5R1B9U high Q Multilayer Capacitor from Dielectric laboratories, Inc. [7]. This capacitor was measured using the designed low frequency microstrip TRL calibration kit over the range of 200 MHz to 1.8 GHz. To determine the measured capacitor's value, the capacitor was modeled using an equivalent circuit and optimized in ADS. The equivalent circuit used was a series RLC circuit with another resistor in parallel with the capacitance. A simulation was run to best fit the measured data to an the capacitor circuit model. Results conclude that the optimization yields that the value of the capacitor is 5.41489 pF. It would be hard to accurately measure this capacitance this accurately with an LCR meter, but with the optimization in ADS, the result is to this number of significant digits over the frequency range measured. The data sheet provided by Dielectric Laboratories, Inc lists nominal value for the capacitor is 5.1 pF. Measured results show a good match between the data provided. Figure 9 compares the transmission results of the measured capacitor to the data provided by the manufacturing company in log magnitude format. The measured S-parameters match the model well; the two curves shown illustrated the difference between the company's nominal capacitor value and the particular one that was measured. At the higher frequencies, both are acting as short circuits, as a capacitor should.

Inductor:

A hand wound inductor coil that was to be used as an RF choke was made from 28 gauge enamel coated copper wire and soldered to the microstrip boards for measurement. A 3-turn inductor was measured using the low frequency calibration kit over the frequency range of 200 MHz to 1.6 GHz. The picture in Fig. 10 below shows the 3-turn inductor soldered to the 50 Ohm microstrip transmission lines placed on the designed test fixture which is connected to ports one and two of the network analyzer.

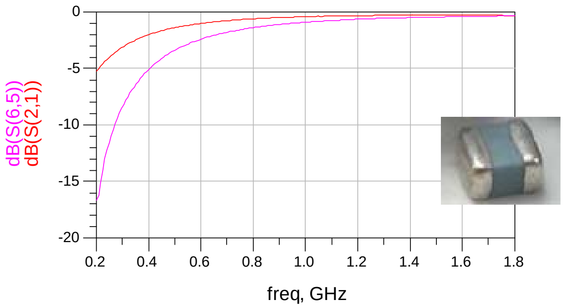


Fig. 9. S_{21} capacitor results. Red = Measured capacitance (optimized to C=5.41489 pF using an equivalent circuit with parasitics using ADS), Magenta = Typical Manufacturer's Characteristics (C=5.1 pF).

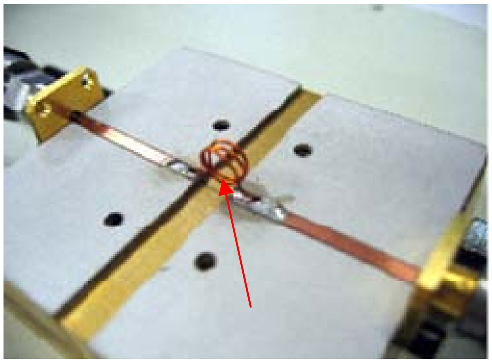


Fig. 10. 3-Turn inductor.

Results for the 3-turn inductor are shown in Fig. 11 in Smith chart form. This inductor was merely fabricated to have impedance much higher than 50 Ohms so that the RF could be blocked in the desired frequency range since it was to be used as an RF choke in an amplifier design. So, to insure the device was acting accordingly, the device was modeled in ADS as shown in Fig. 12 below. This model includes parasitic elements as well as the inductor itself. Optimization enables us to determine the value of the inductor itself. As can be seen from Fig. 12, the inductance value obtained from the equivalent circuit was in good agreement with the design as the equivalent circuit's inductance was approximately 48 nH, which by itself (not including parasitic) has an impedance that is at least ten times larger than 50 Ohms in the amplifier's frequency range of 1.9-2.6 GHz. The resulting equivalent circuit's S-parameter results are shown in blue on Fig. 11. Thus, the equivalent circuit provides an excellent model for the inductor over the desired frequency range.

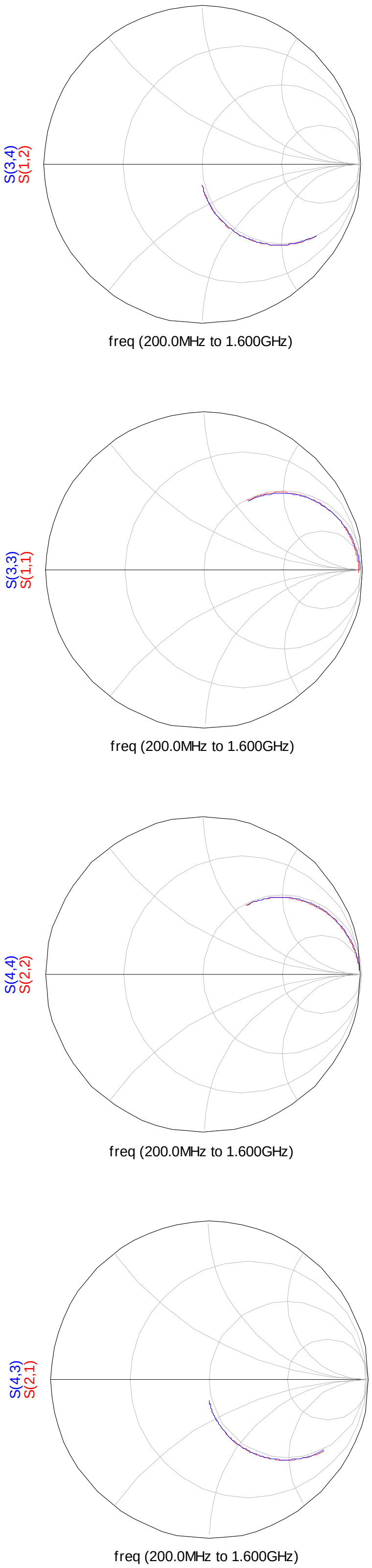


Fig. 11. 3-Turn inductor results. Red = measured, Blue = simulated model including parasitics.

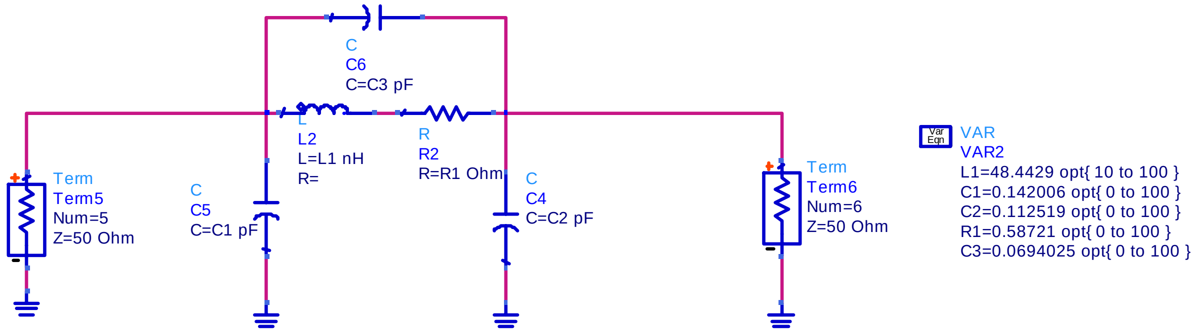


Fig. 12. ADS schematic of the equivalent circuit of an inductor.

Radio Frequency Identification (RFID) Chip:

An RFID tag is an object that can be attached to another object for the purpose of identification using radio waves. Chip-based RFID tags contain silicon chips and antennas [8]. A sample commercial RFID tag with an integrated chip was set up for impedance measurement. The setup is depicted in Fig. 13. The terminals shown in the Figure were connected to port 1 and port 2 of the network analyzer. The fingers on the Teflon bridge pressed the edges of the chip down for contact during measurement. Characteristics were not provided by the manufacturer, so the TRL calibration kit enables us to determine the input impedance of the tag.

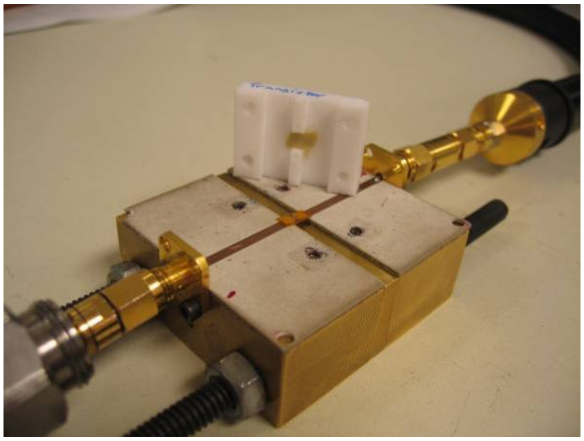


Fig. 13. RFID measurement setup.

The S-parameters were measured. A picture of the RFID chip is shown in Fig. 14 along with S_{11} data plotted on a Smith chart.

From the measured S-parameters, the RFID tag's input impedance could be obtained.

Transistor:

A silicon carbide (SiC) transistor from the manufacturing company CREE [9] is an active component used in an RF amplifier design. This small transistor has a large power output capability. So before actual measurements of the amplifier, the designed microstrip TRL calibration kit was used for testing the D.C. biasing and general behavior of the CREE transistor. For the CREE transistor a special block was made so that the bottom of the transistor can sit down into the block allowing the leads to reach the microstrip board. This block is shown in Fig. 15. The transistor leads were soldered to the board. A Teflon piece was pressed over the transistor for electrical conductivity during measurements.

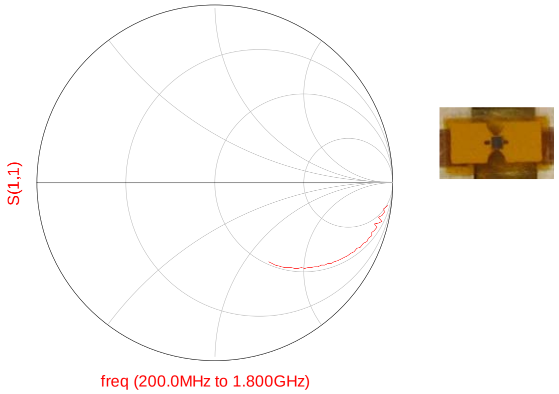
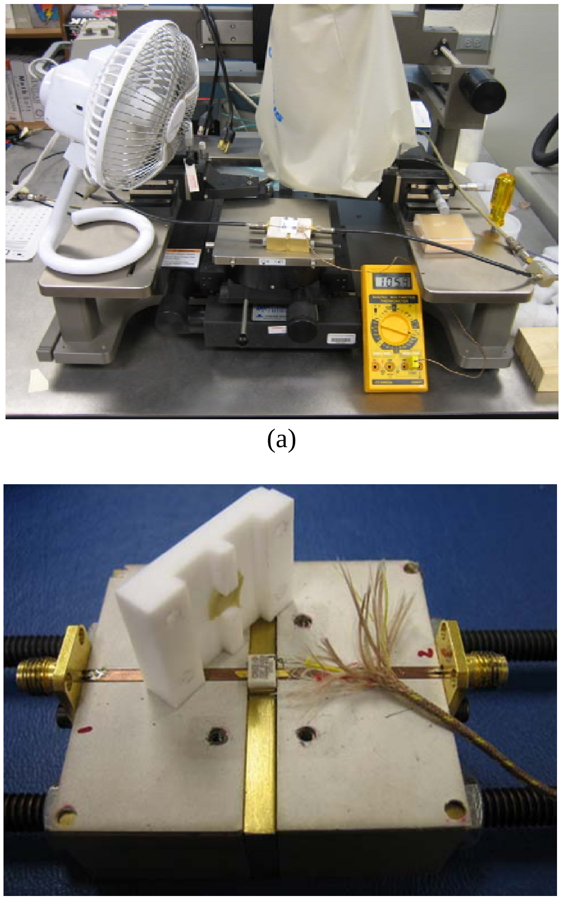


Fig. 14. Reflection, S_{11}, results and a picture of the measured RFID chip.

Fig. 15. The CREE transistor sits on this block.

The transistor was measured using the middle frequency range designed microstrip TRL calibration kit but only from 100 MHz to 4 GHz. A thermocouple wire was used to monitor the temperature as different Q-points were tested. The tip of the thermocouple wire was pressing against the top of the transistor. From above, pressure was applied by the Teflon bridge and a small piece of silicon. Figure 16 contains two pictures. The first picture, (a), is the measurement setup of the CREE SiC transistor as its temperature readings are being taken while the fan cools it off. The second picture labeled (b) is a close up of the thermocouple wire and Teflon bridge that will press over the mounted transistor during measurements.



(a)

(b)

Fig. 16. (a) Measurement of CREE SiC transistor (b) Teflon piece with silicon padding and thermocouple wire for monitoring the temperature.

The fan served as a cooling mechanism as the temperatures started to reach the maximum operating temperature of 125 ˚C. As the temperature increased, a clamp was added to create better contact with the copper block and dissipate more heat. Before applying any current, the temperature read 22.6 ˚C from the thermocouple meter. Full two-port measurements were performed at the biasing point of V_{GS}= -6.87 V, V_{DS}= 48.0 V, and I_{DS}= 249.4 mA at 139 degrees Celsius. This was near the manufacturer's provided data which was taken at V_{GS}= -6.0 V, V_{DS}= 48.0 V, and I_{DS}= 250.0 mA. Figure 17 illustrates a comparison between the S_{21} (transistor gain) of the closest fit curve that was obtained during measurement from the set of different Q-points listed in Table 1 to CREE's manufacturer's data. As seen from the S_{21} data, the results are close, and differences are likely due to device variability. The full two-port data was also used in building a circuit model for the SiC transistor.

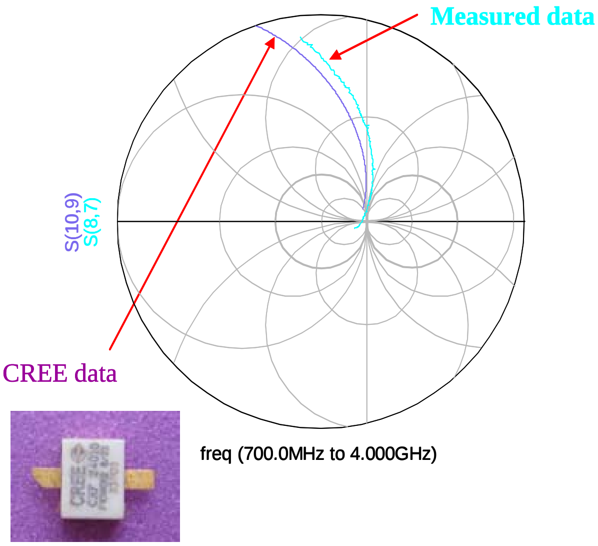


Fig. 17. Gain of measured S (8, 7) versus CREE's manufacturer's curve S (10, 9).

V. CONCLUSION

In this work, the design and fabrication of a microstrip TRL calibration kit has been developed, discussed, and proven to work for RF device measurements. The Thru, Reflect, and Line standards were verified through the TRL calibration process. The microstrip split fixture design gives ability to mount calibration devices of different lengths and packaged transistors to the center block. Several non-coaxial components such as a capacitor, an inductor, a transistor, and an RFID tag were mounted onto and measured with this split fixture design calibration kit. One key importance of this kit is that it allows extraction of both intrinsic and parasitic device parameters through the novel optimization and circuit simulation shown throughout this paper.

ACKNOWLEDGEMENTS

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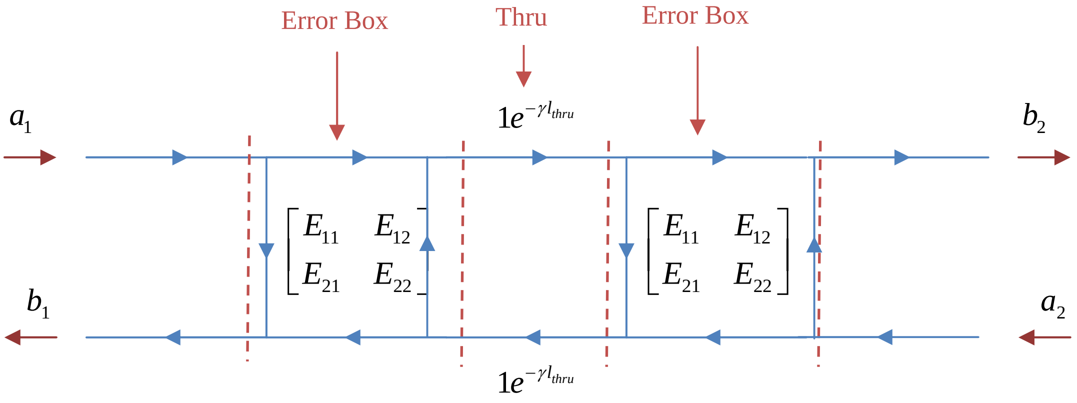
APPENDIX I

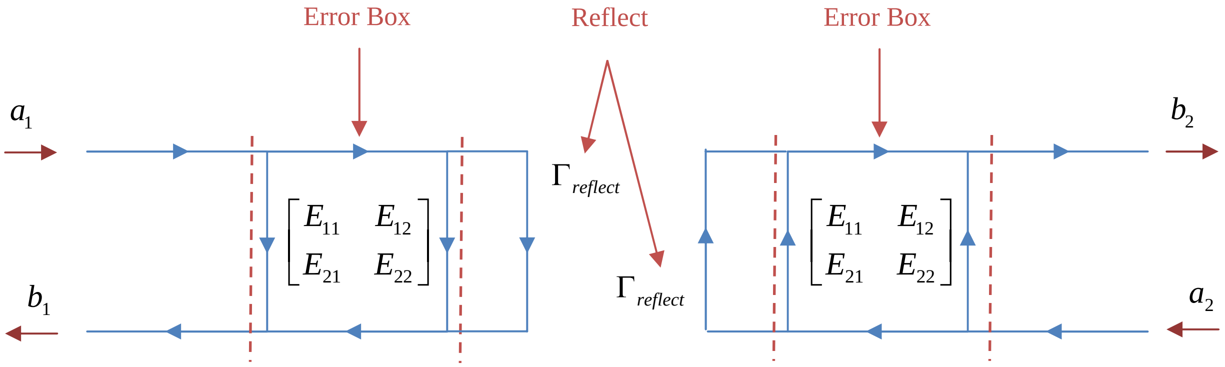
TRL Technique

The signal flow graphs of the TRL calibration technique are shown in the figures below. The Error Boxes are the errors in the measurement that are calibrated out after the TRL calibration is performed. These errors include errrors associated with directivity, source and load matching, etc. By connecting the Thru, the Reflect, and the Line standards, enough measurements are made to find the unknowns that are associated with the error boxes, the impedance of the transmission lines, and the reflection coffecient of the Reflect standard. Finally, the reference planes can be set at the DUT (where the Thru, Reflect, and Line are placed in the pictures). Notice in the Thru connection, that l_{thru} is typically zero, so the resulting terms are just 1. If a nonzero length thru is used, the technique is often called LRL due to the fact that two lines are being used in the calibration. Details of the resulting equations can be found in [1].

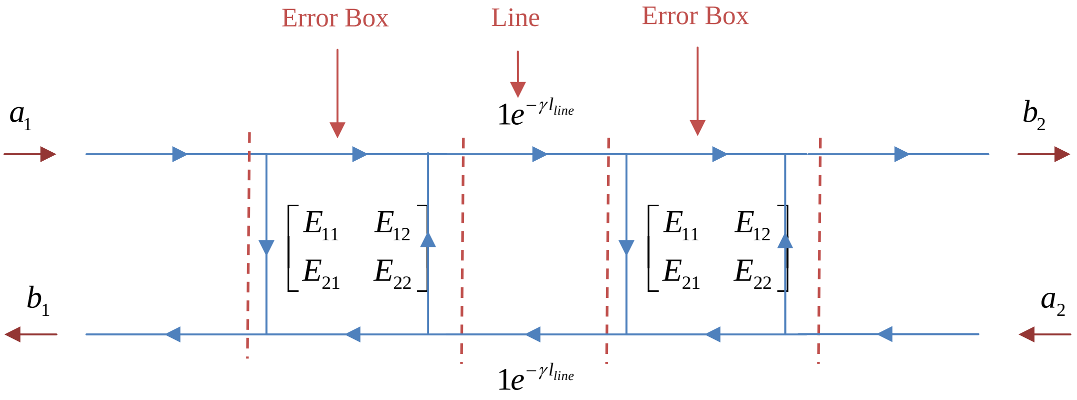
Thru Connection – [T]



Reflect Connection – [R]



Line Connection – [L]



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[7] Dielectric Laboratories, Web: www.dilabs.com/pdfs/pages_10-11_C06.pdf.

[8] Online: http://en.wikipedia.org/wiki/RFID.

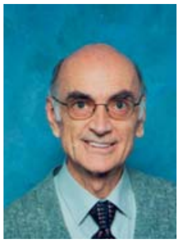
[9] CREE Part Number CRF24010, Web: http://www.cree.com/products/pdf/CRF24010-Rev1_4.pdf

Dalia Elsherbeni received an undergraduate degree in electrical engineering from The University of Mississippi in 2004. In December 2006 she received a Master's degree in electromagnetics at the University of Mississippi. Her thesis entitled, "Measurement of Non-Coaxial RF Components Using the TRL Calibration Technique" was written under her advisor Dr. Elliott Hutchcraft. Ms. Elsherbeni is a member of IEEE. She was the recipient of the Mississippi Academy of Sciences (MAS) Third Place Oral Presentation Award in Vicksburg, MS in 2006. Since 2004 she has been employed full time by Radiance Technologies working in the technology and development department.

Lisa Jordan Ewell graduated from the University of Mississippi in May of 2004 with a Bachelor of Science in Electrical Engineering. She continued her education at Ole Miss and pursued a master's degree in electrical engineering with an emphasis in electromagnetics. She received her Master of Science in December, 2006. While studying for her master's degree, she first worked as a research assistant for Dr. Elliott Hutchcraft and then began working for Radiance Technologies in Oxford, MS. She currently lives in Bangkok, Thailand, teaching English and Java programming at Mahidol Wittayanusorn School, a Thai math and science high school.

W. Elliott Hutchcraft was born in Lexington, Kentucky on April 29, 1973. He earned his B.S. in electrical engineering at the University of Mississippi, Oxford, MS in 1996, his M.S. in electrical engineering at the University of Mississippi, Oxford, MS in 1998 and his Ph. D. in electrical engineering at the University of Mississippi, Oxford, MS in 2003. He is an Assistant Professor in the Department of Electrical Engineering at the University of Mississippi in Oxford, Mississippi. Dr. Hutchcraft is a member of Eta Kappa Nu, Sigma Xi, IEEE, Tau Beta Pi, Phi Kappa Phi, and ARFTG.

Richard K. Gordon was born in Birmingham, Alabama on November 26, 1959. He earned his B.S. in physics at Birmigham Southern College, Birmingham, AL in 1983, his M.S. in mathematics at the University of Illinois, Urbana, IL in 1986 and his Ph. D. in electrical engineering at the University of Illinois, Urbana, IL in 1990. He is an Associate Professor in the Department of Electrical Engineering at the University of Mississippi in Oxford, Mississippi. Dr. Gordon is a member of Eta Kappa Nu, Phi Beta Kappa, and Tau Beta Pi.



Darko Kajfez is Emeritus Professor of Electrical Engineering at the University of Mississippi. He obtained the electrical engineer's degree (Dipl. Ing.) from University of Ljubljana, Slovenia, in 1953, and the PhD degree from U.C. Berkeley in 1967. He co-edited the book *Dielectric Resonators*, and authored the books *Notes On Microwave Circuits*, and *Q Factor*. His research interests include rf and microwave measurement and analysis. He can be reached at eedarko@olemiss.edu.