TRL CALIBRATION APPLIED TO THE MEASUREMENT OF CHIP TRANSISTOR S-PARAMETERS UP TO 40 GHz

L. Pradell, C. Sabater, E. Artal, A. Comerón, J. Bará, I. Corbella, J. Fortuny. (*)

ABSTRACT

The design of a Microstrip Test Fixture for TRL calibration, based on mobile, precisely positioned coax-to-microstrip transitions, is described. Experimental results for the measurement of GaAs FET and HEMT chips S-parameters in the 1-40 GHz frequency band are presented, and compared with the manufacturer's available data. Theoretical considerations and experimental results for the repeatability of transitions, based on a useful "error box" model, are also presented.

INTRODUCTION

The advantages of the TRL (Thru-Reflect-Line [1]) calibration method in obtaining an accurate, repeatable measurement of GaAs FETs and HEMTs S-parameters, are well known [2]. A number of Microstrip Test Fixtures using coax-to-microstrip transitions (for frequencies up to 46 GHz) have been reported in the literature, including those commercially available [3]-[7]. When using the TRL technique, the repeatability of transitions is an important factor which limits the measurement accuracy, as it has been shown for the measurement of chip GaAs FETs S-parameters up to 22 GHz [8]. However, experimental results in the millimeter-wave band using the TRL technique are not yet available.

DESCRIPTION OF THE TEST FIXTURE

A microstrip Test Fixture (figure 1) was designed to allow the measurement of GaAs FET and HEMT chip transistors S-parameters from 1 GHz to 40 GHz using the TRL calibration technique. This wide frequency band is covered in two steps, 1-6.5 GHz and 6-40 GHz. Each step requires its own LINE standard (figure 2). Two substrates were selected to implement the microstrip circuits, Cuclad 217 ($\epsilon_r = 2.17$) and Alumina ($\epsilon_r = 9.9$). The Test Fixture is composed by three separate pieces mounted on a common base: the input connector wall, the central support provided with a vertical guiding system for the three TRL calibration standards and the chip carrier (one at a time), and the output connector wall. Each connector wall can be independently, precisely positioned (to 0.01 mm) along three orthogonal axes in space by means of three micropositioning devices (figure 1). The ground contact is achieved by horizontal pressure, just below the microstrip line, thus virtually eliminating the parasitic ground paths. The *pin* contact to the microstrip line is achieved by vertical pressure. The connectors are type MACOM/OMNISPECTRA OS-50 (2.4 mm), usable up to 50 GHz. Figure 3 shows the return and insertion losses of the THRU standard (Alumina), including the microstrip-to-coaxial transitions. A worst value of 0.5 dB for the insertion loss and 17 dB for the return loss were obtained in the 45 MHz-40 GHz frequency margin. Similar characteristics were measured for both LINE standards.

"ERROR BOX" MODEL USEFUL IN REPEATABILITY MEASUREMENTS

Each calibration or measurement step requires positioning the input and output connector walls and achieving the ground and *pin* contacts. Poor contact repeatability is the main limiting factor in measurement accuracy [8], because it leads to small variations in the error coefficients e_{ij} (figure 4) during the calibration process. The Network Analyzer computes the error coefficients using the measured calibration data. Consequently, some error in computations occur (referred to as the *calibration residual error*). The residual errors, in turn, yield to S-parameters measurement errors. Figure 5 shows the decomposition of the input "error coefficients box" in three error boxes *a,b,c*. Box *a* corresponds to the Network Analyzer, cables and connectors. Box *b* models the coax-to-microstrip transition (ground and *pin* contacts). Box *c* accounts for the microstrip line going from the transition to the TRL reference plane. The same decomposition holds for the output error box.

The *repeatability of the coaxial-to-microstrip transitions* can be evaluated in the following manner. First, a coaxial Open-Short-Load (OSL) calibration is performed at the plane of connectors (m and m' in figure 5). Using this calibration, an input reflection coefficient measurement (say S_{11}) corresponding to the THRU standard (or the LINE standard), is made. With the notation of figure 5, it can be expressed as:

(*) E.T.S.E. Telecomunicació. Dept. T.S.C. - A.M.R. Group. Ap. 30002,
08080-Barcelona-Spain

$$S^{tf}_{11} = e^{b}_{00} + \frac{e^{b}_{01} e^{b}_{10} S^{p}_{11}}{1 - e^{b}_{11} S^{p}_{11}} \qquad (1)$$

where S^{p}_{11} is the S_{11} parameter corresponding to the rest of the Test Fixture (marked as "p" in figure 5). Then, both transitions are disconnected (the connector walls are separated from the central piece containing the standard), and the standard is "rotated" 180º. Thus, both ends are interchanged. Then both transitions are connected again and a new S_{11} measurement is made. It can be expressed as:

$$S^{tf'}_{11} = e^{b'}_{00} + \frac{e^{b'}_{01} e^{b'}_{10} S^{p'}_{11}}{1 - e^{b'}_{11} S^{p'}_{11}} \qquad (2)$$

where:

$$\begin{aligned} e^{b'}_{00} &= e^{b}_{00} + \Delta^{b}_{00} \\ e^{b'}_{11} &= e^{b}_{11} + \Delta^{b}_{11} \\ e^{b'}_{01} e^{b'}_{10} &= e^{b}_{01} e^{b}_{10} + \Delta(e^{b}_{01} e^{b}_{10}) \\ S^{p'}_{11} &= S^{p}_{11} + \Delta^{p}_{1} \end{aligned} \qquad (3)$$

The "Δ's" refer to the repeatability associated to each parameter, and they are supposed to be small compared with the corresponding parameter. Substituting (3) in (2), the vector difference between both measurements can be computed, in a first order approximation, as:

$$\begin{aligned} S^{tf'}_{11} - S^{tf}_{11} = \Delta^{b}_{00} &+ \left(\Delta^{b}_{01} + \frac{e^{b}_{01} e^{b}_{10} \Delta^{b}_{11} S^{p}_{11}}{1 - e^{b}_{11} S^{p}_{11}} \right) \frac{S^{p}_{11}}{1 - e^{b}_{11} S^{p}_{11}} + \\ &+ \Delta^{p}_{1} e^{b}_{01} e^{b}_{10} \left(1 + \frac{S^{p}_{11} e^{b}_{11}}{1 - e^{b}_{11} S^{p}_{11}} \right) \end{aligned} \qquad (4)$$

If the transmission lines and the transition contacts are well done (low reflection), S^{p}_{11} can be supposed to be of the same order of magnitude as "Δ's". Thus, (4) becomes, in a first order approximation:

$$S^{tf'}_{11} - S^{tf}_{11} = \Delta^{b}_{00} + \Delta^{p}_{1} e^{b}_{01} e^{b}_{10} \qquad (5)$$

The measured difference at the left hand of (5) is the repeatability associated to the transition disconnection/connection cycle and "circuit change". (5) relates the transition repeatability to the error coefficient repeatability. If an "ideal" time-domain gate is used, then (5) becomes an exact expression. From (5), the repeatability of e^{b}_{00} can be computed if we assume, for example that $\Delta^{b}_{00} = \Delta^{p}_{1}$. Then, the residual and measurement errors can be approximately computed if we assume the same repeatability for the rest of e^{b}_{ij}coefficients [9].

EXPERIMENTAL RESULTS

Four millimeter-wave chip transistors were measured using the Test Fixture with TRL calibration in the 1-40 GHz frequency band: A low noise GaAs MESFET from FUJITSU (type FSX03X), two low noise HEMTs from TOSHIBA (types JS-8901-AS and JS-8830-AS) and a power GaAs FET from TOSHIBA (type JS-8864-AS). Figure 6 shows the thermocompression bonding details for the former. An HP 8510B Automatic Network Analyzer (which includes the TRL calibration software) was used as the measurement instrument. Figures 7, 8, 9 and 10 show the measured S-parameters of the transistors, using the Test Fixture with

TRL calibration at the upper frequency step (6-40 GHz). The manufacturer's data are superimposed in dashed lines. They are specified up to 22 GHz, except for the JS-8864-AS type. The manufacturer gives the *computed* data up to 40 GHz for the former. For the FSX03X and the JS-8901, the magnitude deviation with respect to manufacturer's data is small (except for S_{12} in the second type), and the phase deviation is significant only beyond 20 GHz (26º at 22 GHz). For the JS-8830-AS, the agreement is also good except for S_{22} above 15 GHz. The measured data of these three transistors were taken on a Cuclad-217 substrate. Figure 10 shows the measured data for the JS-8864-AS mounted on Alumina substrate. The comparison with the manufacturer's data results in similar considerations as with the other transistors.

The repeatability measurements using time-domain gating show a worst value of -36 dB at 40 GHz (figure 11). Using this measured value, the TRL calibration residual errors are found to be -30 dB at 40 GHz [9]. The S-parameters measurement repeatability under the same TRL calibration can also be measured [8]. In this case, a worst value of -30 dB at 40 GHz was obtained.

CONCLUSIONS

A microstrip Test Fixture for TRL calibration has been presented, allowing the S-parameter measurement of GaAs FETs and HEMTs in the 1-40 GHz band. Each coax-to-microstrip transition is precisely positioned (to 0.01 mm) by means of three micropositioning devices. In this way, a high measurement accuracy and repeatability are achieved. Experimental results for 4 chip millimeter-wave transistors have been obtained in the 1-40 GHz band. They are in fairly good agreement with the manufacturer's data. An "error box" model has been developed which allows the evaluation of the TRL calibration residual errors and the measurement errors, from measured transition repeatability data. The transition repeatability has been measured using time-domain gating, yielding a worst value of -36 dB at 40 GHz. Thus, a TRL calibration residual error of -30 dB was computed. The repeatability for an S-parameter measurement series (under the same TRL calibration) was measured, yielding a worst value of -30 dB.

REFERENCES

[1] G.F. Engen, C.A. Hoer
"Thru-Reflect-Line: An improved technique for calibrating the dual six-port automatic network analyzer"
IEEE Trans M.T.T., vol. MTT-27, no. 12, pp. 987-993, dec. 1979

[2] HEWLETT-PACKARD Co.
Product note 8510-8
"Applying the HP 8510B TRL calibration for non-coaxial measurements"
October 1, 1987

[3] P. Bagley Ross, B.D. Geller
"A broadband microwave test fixture"
Microwave Journal, vol. 30, no. 5, may 1987, pp. 233-248

[4] H.F. Cooke
"A universal fixture for transistor chip and microwave amplifier measurement"
Microwave Systems News, vol. 17, no. 3, pp. 64-70, mar. 1987

[5] R.J. Lang, W.P. Jewett, J.D. Merrill
"Test Fixtures for frequencies from DC to 75 GHz"
Microwave Journal, vol. 31, no. 5, pp. 367-371, may 1988

[6] CASCADE MICROTECH
"MTF26. DC-26.5 GHz Microstrip Test Fixture and TRL Standards"
may, 1989

[7] INTERCONTINENTAL MICROWAVE
"Universal Test Fixture Mainframe. Series TF-2000. DC to 40 GHz"
1989

[8] L. Pradell, E. Artal, C. Sabater
"S-parameters measurement of chip GaAs FETs up to 22 GHz using the TRL calibration technique"
19th European Microwave Conference. Conference proceedings, pp. 576-581. Wembley (London), 4-7 sept. 1989.

[9] L. Pradell
"Diseño de amplificadores de bajo ruído en banda milimétrica"
Doctoral Thesis presented to the Universitat Politècnica de Catalunya. Chap. V. Barcelona, Oct. 1989

ACKNOWLEDGEMENT

This work has been carried out under the contracts "Medida de parámetros S de transistores en la banda de 30 GHz", "Caracterización no lineal de transistores MESFET en banda Ka" (1989) with Electrónica ENSA, and "Outdoor unit for the CODE earth station" (1989-1990), with Electrónica ENSA and the European Space Agency (ESA).

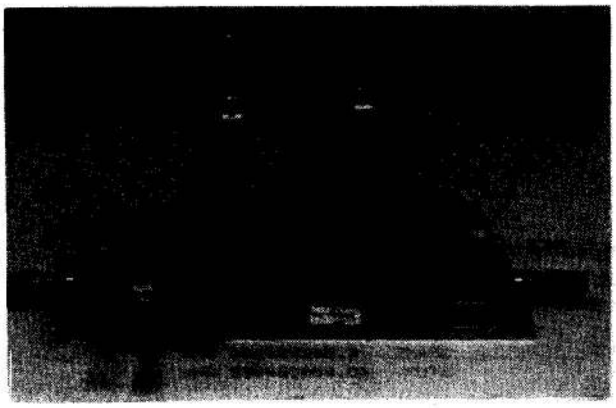


FIGURE 1 - THE MICROSTRIP TEST FIXTURE

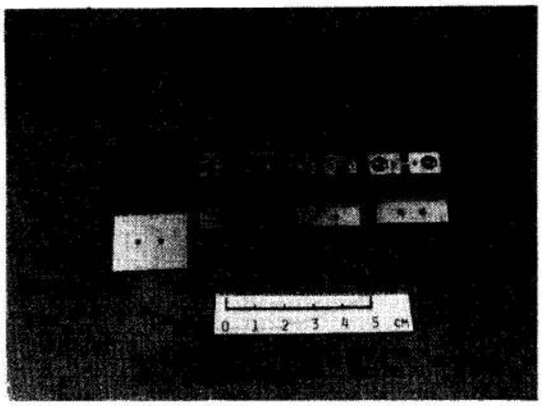


FIGURE 2 - TRL CALIBRATION STANDARDS (CuClad). BOTH LINES (1-6.5 GHz AND 1-40 GHz) ARE SHOWN

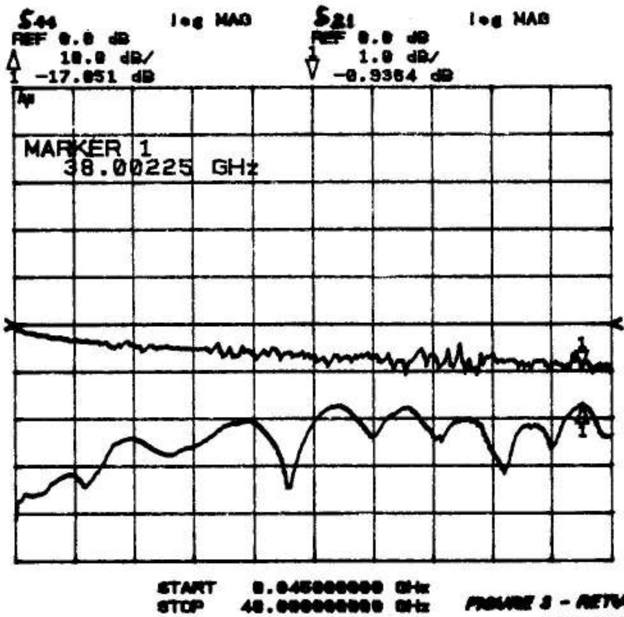


FIGURE 3 - RETURN AND INSERTION LOSSES FOR THE THRU STANDARD (ALUMINA)

FIGURE 6 - CHIP TRANSISTOR TYPE JS-8804-AS. THERMOCOMPRESSION BONDING DETAILS.

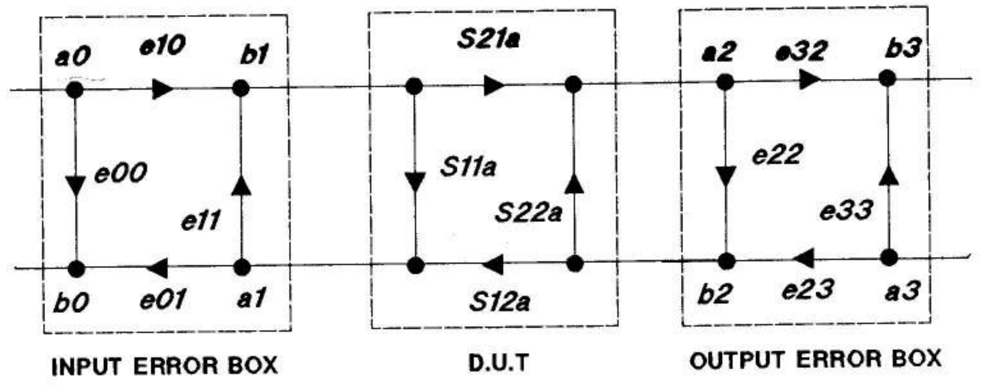


FIGURE 4 - A.N.A. ERROR MODEL FOR TRL CALIBRATION

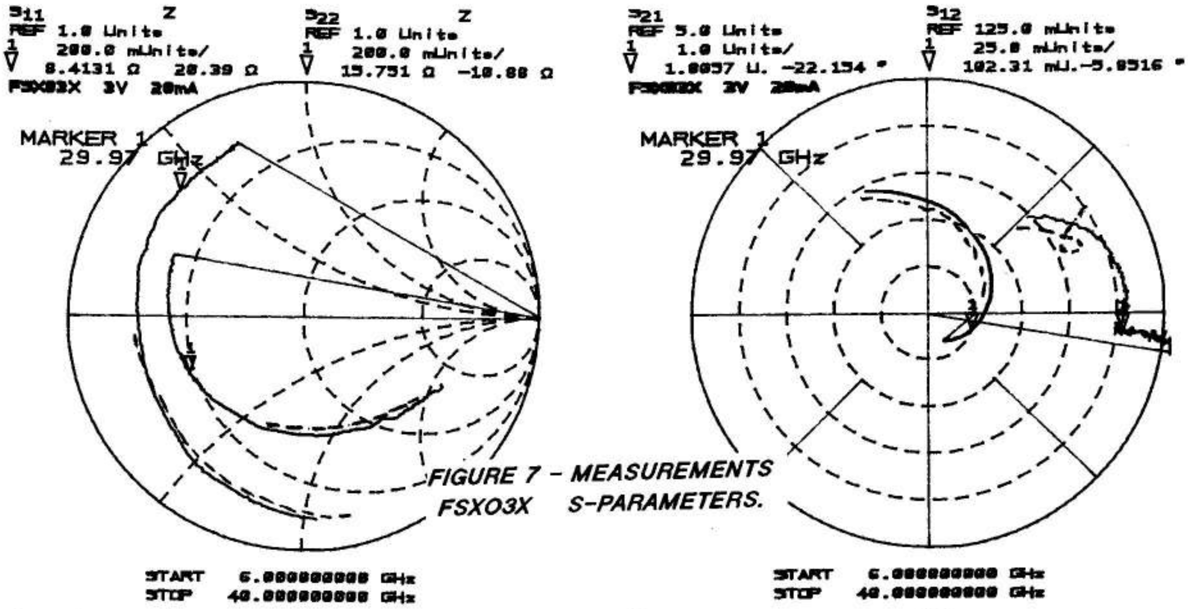


FIGURE 7 - MEASUREMENTS
FSXO3X S-PARAMETERS.

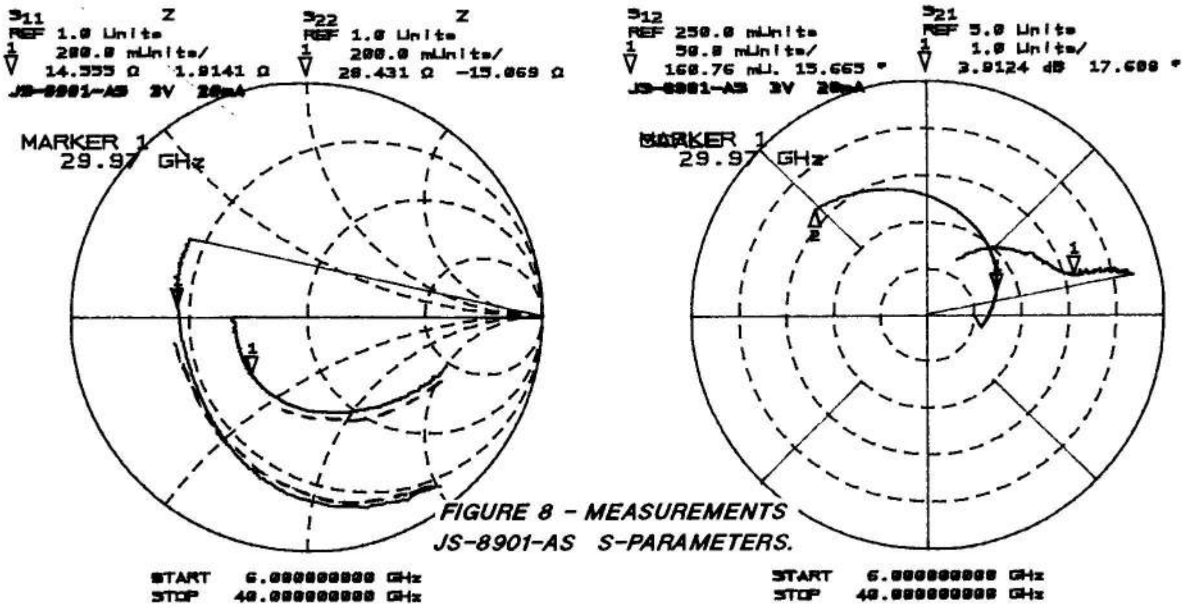


FIGURE 8 - MEASUREMENTS
JS-8901-AS S-PARAMETERS.

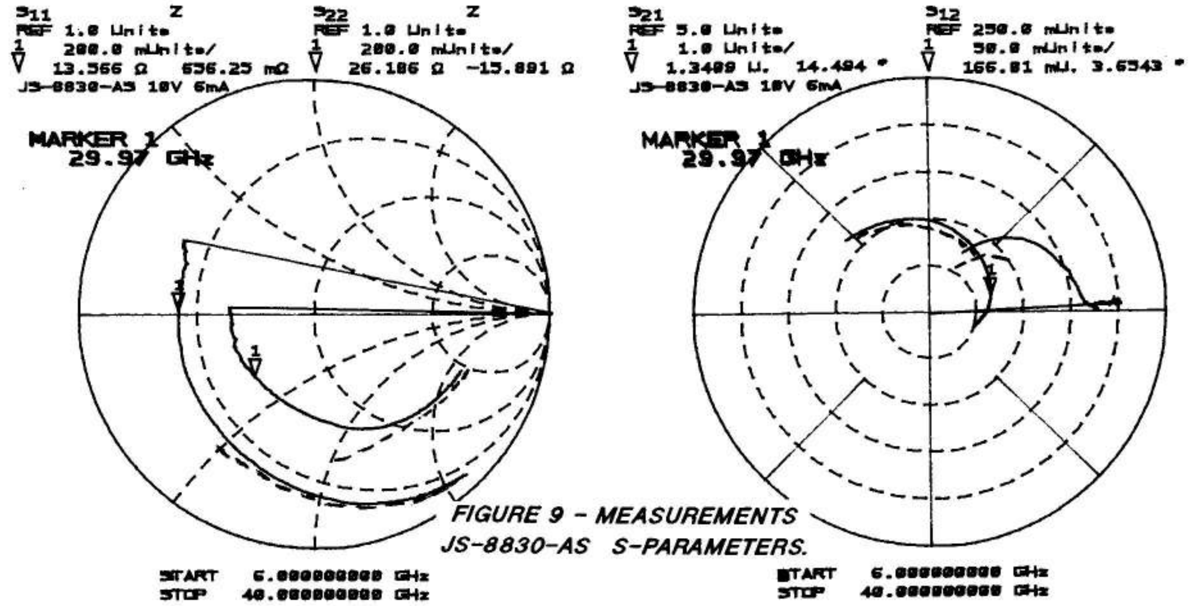
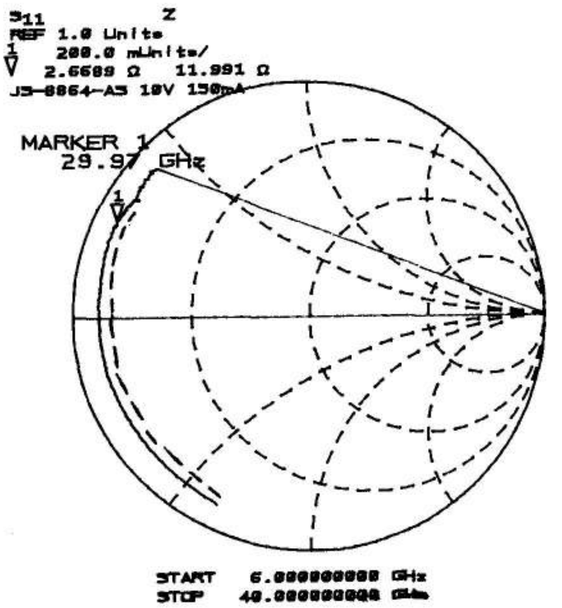
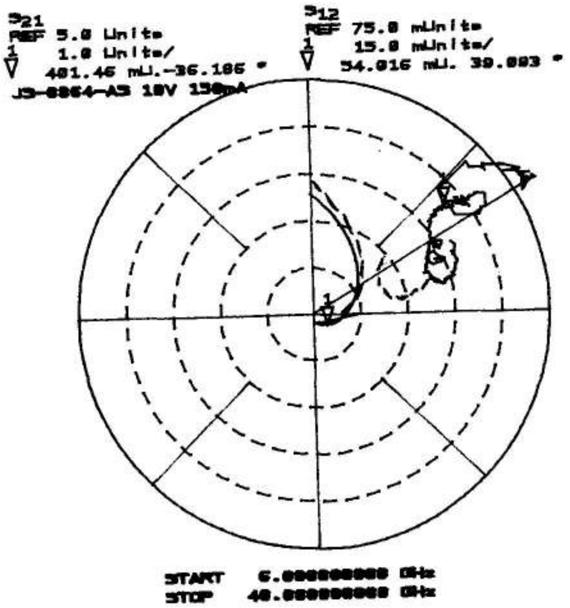


FIGURE 9 - MEASUREMENTS
JS-8830-AS S-PARAMETERS.





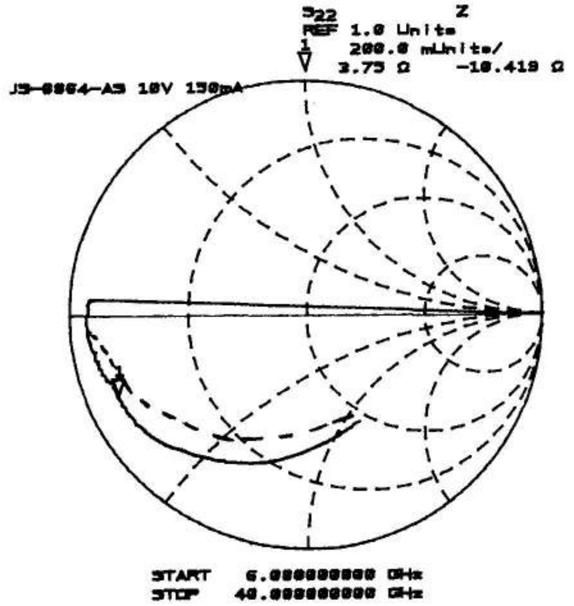
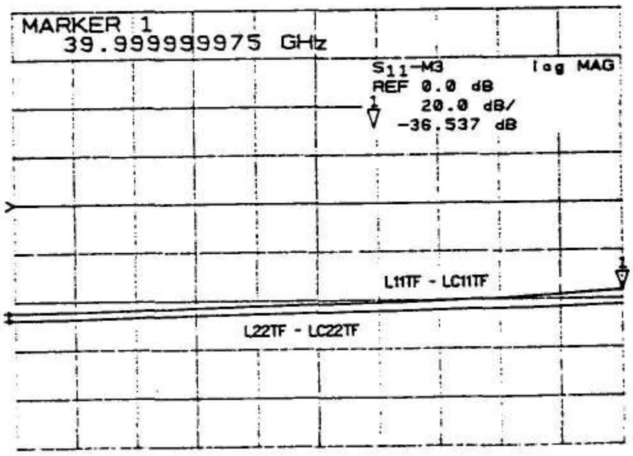


FIGURE 10 - MEASUREMENTS JS-8864-AS S-PARAMETERS.

FIGURE 11 - EXPERIMENTAL RESULTS TRANSITION REPEATABILITY



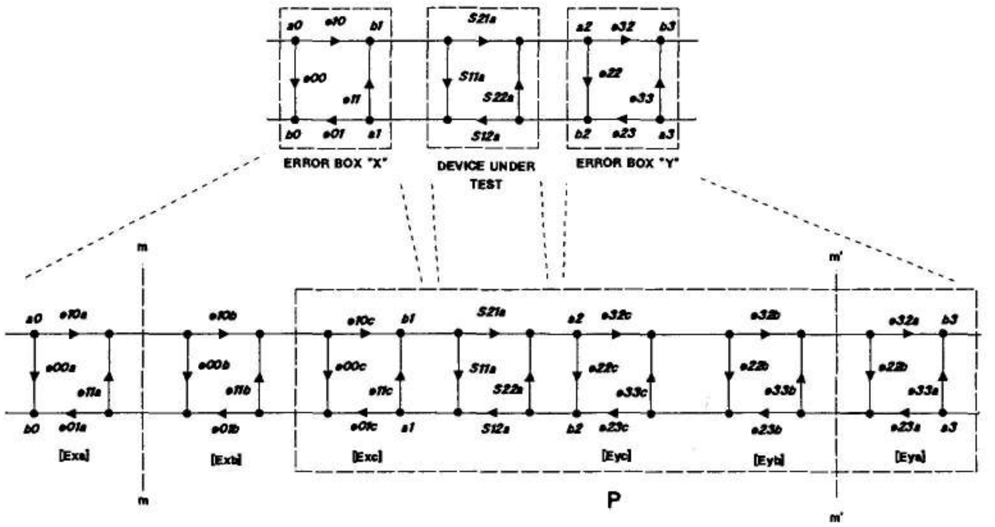


FIGURA 5 - DECOMPOSITION OF THE ERROR BOXES