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Application Note No 6

Load Pull Measurements on Very Low Impedance Transistors

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Introduction

This document describes an accurate and cost effective method for making Load Pull measurements on high power field effect (FET) and bipolar transistors in the RF and microwave frequency range.

The method is most useful for testing packaged non prematched transistors in test fixtures but has also been used for millimeter wave GaAs MMIC's 'on wafer' [1].

High power transistors are made of many individual transistor cells connected in parallel. This makes the total impedance at the in- and output port very low, of the order of 0.5 to 2 Ω (S_{11},S_{22}=0.95 or VSWR=40:1). Accurate load pull measurements can only be done if the transistor is presented, at its connections, the conjugate complex of its internal impedance. This means a tuner system, used for load pull, must generate this kind of impedance from 50 Ω, accurately enough in order to make measurements.

A study of the measurement accuracy of the available Automatic Network Analyzers shows that it is practically impossible to determine the loss of a highly reflective tuner with about 1% accuracy (±0.03dB), required for load pull measurements.

A simple and accurate way to solve this problem is to use **transforming test fixtures**. The CCMT's and MTS's software provides accurate solutions and coverage of all characterization and computing tasks used in this approach.

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The typical Load Pull Setup

A load pull setup includes

- A signal source
- A test fixture with DUT (device under test)
- A tuner (=transformer)
- A power detector

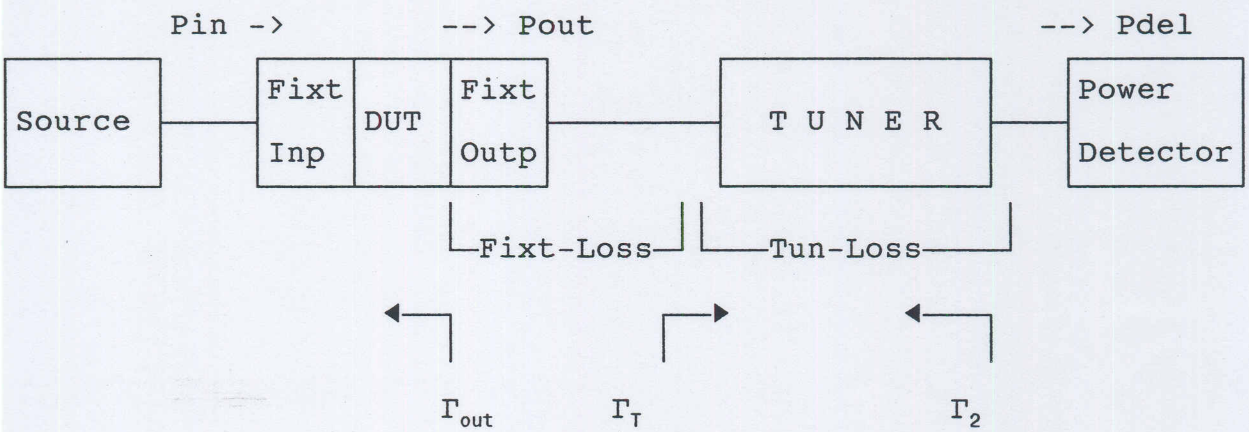


Fig. 1 Typical Load Pull setup

Inorder to compute the Power generated by the DUT (Pout) we have to multiply the power delivered to the detector (Pdel) with the power loss of the output network. This network consists of 1/2 the test fixture (Fixt-Loss) and the tuner (Tun-Loss).

The difficulty is to maintain acceptable measurement accuracy when the tuner has to generate very high Γ_T inorder to match Γ_{out} even through the lossy test fixture.

When Γ_T becomes very high (>0.85) two things happen:

1. The measurement accuracy of the Network Analyzers drops
2. The power loss of the fixture (Fixt-Loss) and the tuner (Tun-Loss) increase sharply.

Item 1. is due to normal imperfections in the RF and electronic components of any mesurement instrument, as well as the calibration method used.
Item 2. is due to sharply increasing reflection loss of any mismatched component (including test fixtures and tuners).

Let us examine these two phenomena in more detail.

Accuracy of the Network Analyzer

In load pull measurements we are concerned about how accurately the present network analyzers can measure the loss of **highly reflective-low loss** devices, such as tuners. The power loss of the tuner is calculated using the formula

$$\text{Power Loss} = \frac{1 - |\Gamma_T|^2}{|S_{21}|^2}$$

where S_{21}=insertion loss of the tuner

Depending on the Network Analyzer and the coaxial calibration method used the power loss can be measured with a guaranteed accuracy given in figure 2.

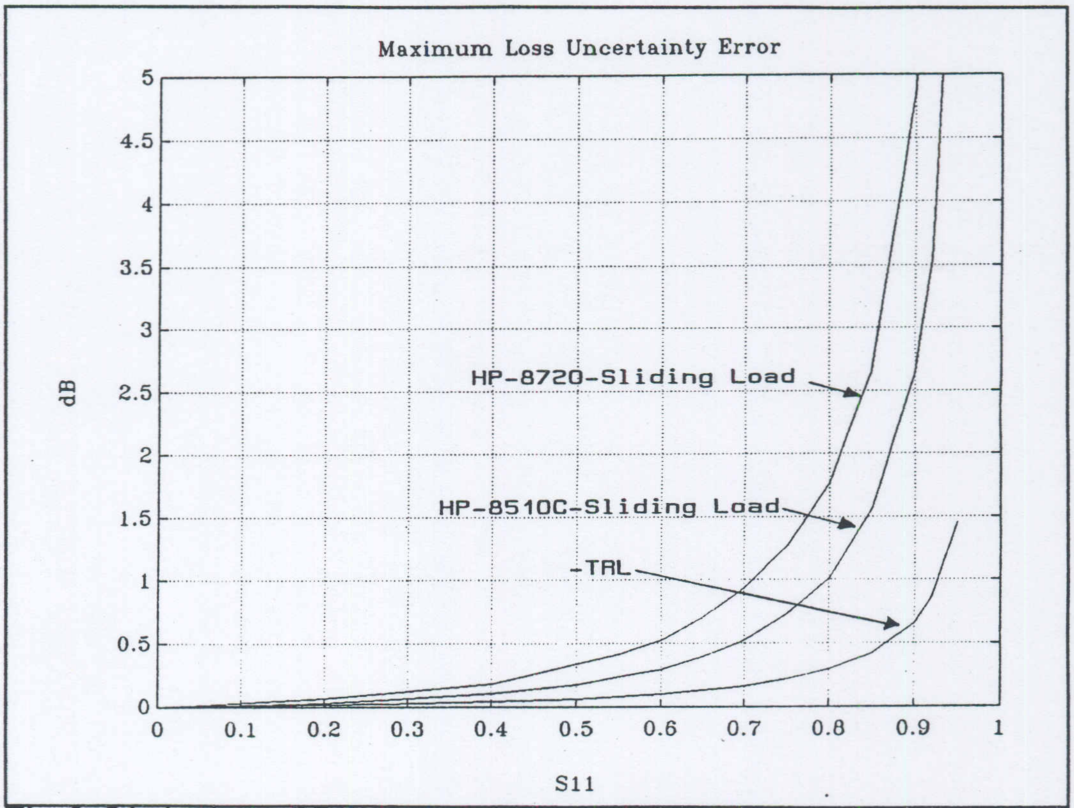


Fig. 2 Limitations of Power Loss Accuracy Measurement

As can be seen from Fig.2 the potential inaccuracies at Γ_T > 0.85 are such that a reliable measurement is not guaranteed. Only if the TRL (or LRL) calibration method is used the accuracy remains reasonable at high Γ's.
This phenomenon is well known and follows from the rule of thumb in metrology that the ratio between reference (here 50 Ω) and test object should remain less or equal to 10 (VSWR <= 10:1 or Γ <= 0.82).

Power loss of fixture (Fixt-Loss) and tuner (Tun-Loss)

The power loss of a low loss transmission line, such as a test fixture or a tuner can be calculated from

$$\text{Power Loss} = \frac{|1-\Gamma_T{*}S_{22}|^2{*}(1-|\Gamma_1|^2)}{|S_{21}|^2{*}(1-|\Gamma_T|^2)} \quad \text{and } \Gamma_1 = S_{11} + \frac{S_{12}{*}S_{21}{*}\Gamma_T}{1-\Gamma_T{*}S_{22}}$$

where S_{ij} are the S-Parameter of the transmission line (half the test fixture) and Γ_T is the reflection factor the tuner generates at the output port of the fixture (fig. 1).

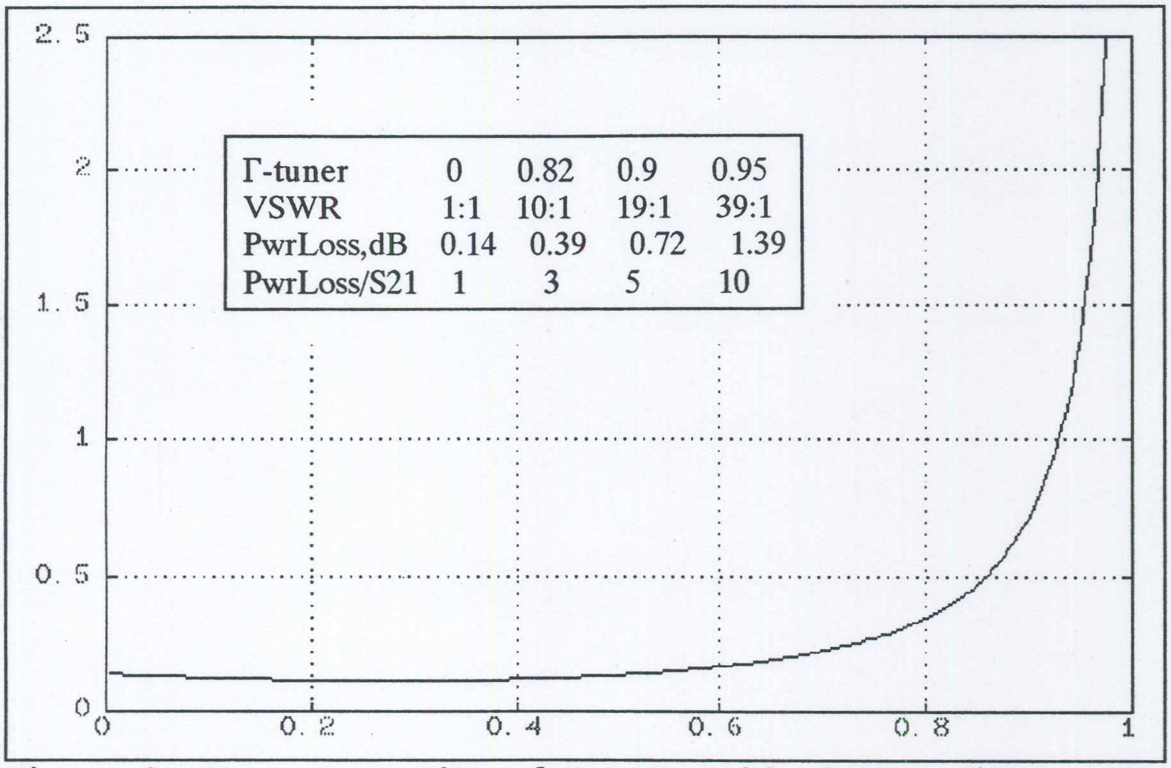


Figure 3: Power Loss (dB) of Output Half of Test Fixture as function of Γ_{Tuner}

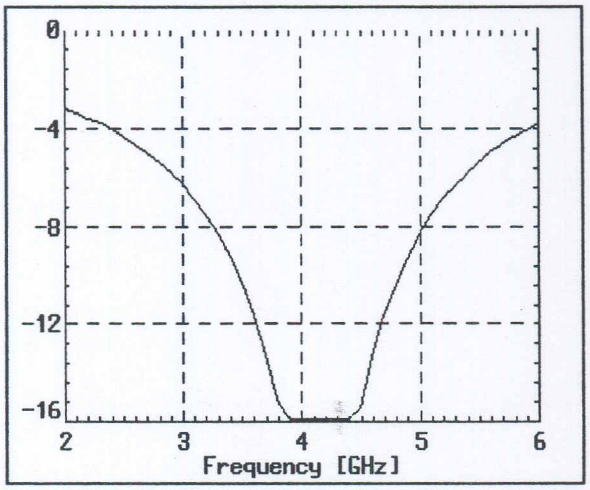
This shows that the (reflective) loss contribution of the test fixture under high reflection factor conditions is important. Since the reflection factor of the tuner itself can only be determined within $\delta S_{11} \approx \pm 0.02$ (figure 2) it follows that the **measurement error in power loss** of the test fixture will be **0.3 dB at Γ=0.9 and 1.13 dB at Γ=0.95** (figure 3).

The **conclusion** is that the impedance change from 50Ω to 1Ω (or less) should happen in 2 (or more) steps using a prematching transformer network. As such can be used the test fixture halves (figure 1).

Transforming Test Fixture

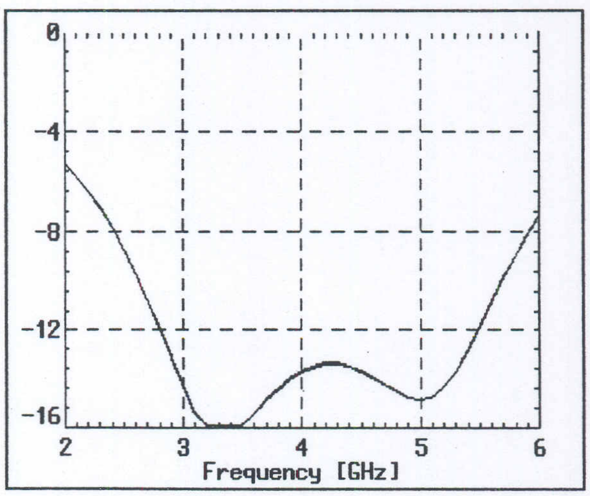
A transforming test fixture includes on one or both sides of the DUT prematching microstrip networks (in general one or more low impedance $\lambda/4$ sections). Increasing the number of sections increases the operational bandwidth but also the size of the fixture. For this reason using multisectional transformers below 2 GHz may become problematic. Figure 4 shows the relative bandwidth of some transforming fixtures.

Return Loss [dB]



Bandwidth of single section transformer (50Ω to 6.5Ω)

Return Loss [dB]



Bandwidth of 2 section transformer (50Ω to 6.5Ω)

Fig. 4:Bandwidth of transforming sections

Design a Transforming Test Fixture

The transforming sections of the test fixture should be designed for the smallest impedance to be realized at the transistor port, under consideration of the transforming effect of the tuners. We recommend to assume that the tuners realize a 6:1 ratio. This leaves enough tuning margin and guarantees very good accuracy. In order to synthesize a 1 Ω impedance at the transistor port using a one section transformer its characteristic impedance shall be:

$$Z0^2=Z_1*Z_2 \qquad (Z_1=1\ \Omega,\ Z_2=294\ \Omega \text{ gives } Z0=17\ \Omega)$$

Fig. 5 shows the transforming mechanism.

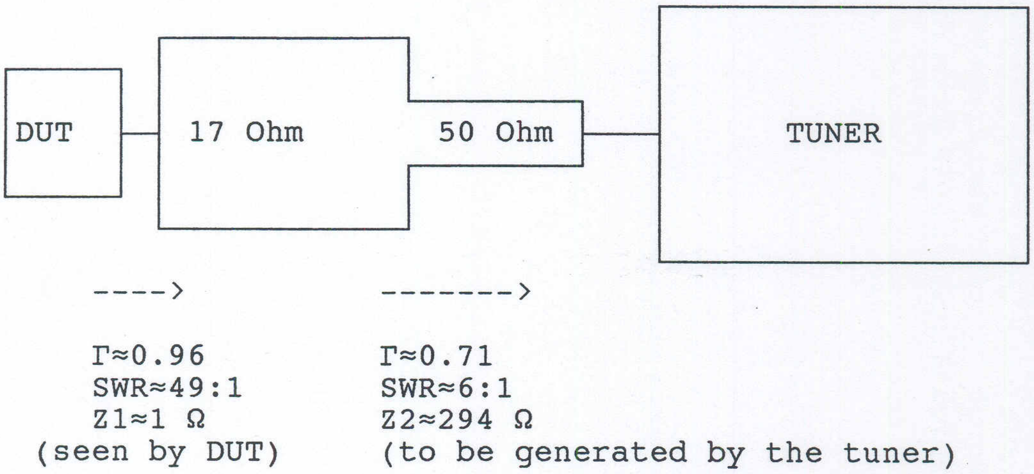


Fig. 5: Transforming a 6:1 VSWR to a 49:1 VSWR using a simple λ/4 transformer section

The advantages of this approach are easy to understand:
1. The accuracy of the tuner characterization is high (fig. 1).
2. The loss of the fixture is low, since Γ does not exceed 0.71 at any place in the transforming path (fig. 2).
3. Impedances below 1 Ω can easily be presented to the DUT port.

Using a Transforming Test Fixture

A load pull system, inorder to be able to measure using a transforming test fixture, must provide software tools that permit to characterize it and exploit the data generated. The CCMT and MTS systems both use the same approach:

1- Characterize the fixture using TRL and 50 Ohm transmission lines
2- Incorporate the S-Parameters of the transformer sections using .S2P files
3- Cascade the resulting matrices

4- Normalize the load pull calibration points with the new characteristic impedance at the end of the transformer (in the example above = 6.48 Ohms)
5- Make load pull measurements using the new pattern of points
6- Process the load pull data to ISO Contours and Graphs.

Characterizing the Test Fixture using TRL

The test fixture can be characterized using the programms SETUPL.EXE (CCMT) and SETUPCAL.EXE (MTS). In both cases generic TRL formulas are used to compute the S-Parameters of input and output section of the test fixture. These two sections do not need to be identical.

To do this characterization the following standards are required:

- A THRU Line (ie. a test fixture with 50 Ohm microstrip without DUT)
- A DELAY Line (the same as above only $\lambda/4$ longer at center frequency)
- A REFLECT (in microstrip OPEN circuits are the best standards)

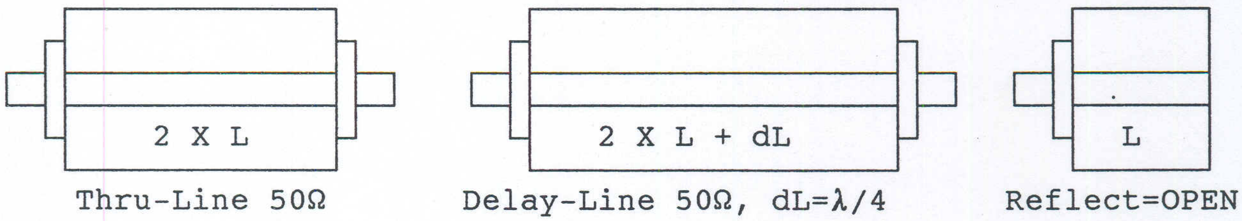


Fig. 6: TRL standards required by SETUPL.EXE & SETUPCAL.EXE

This measurement can be done using one of the above programms and one of the following Vector Network Analyzers (VNA)

Wiltron 360A/B, 37000
Hewlett Packard 8510A/B/C, 8720A/B/C and all 8753

The CCMT (and MTS) software provides additional tools to verify the validity of the computed data, as well as a Smoothing capability for problematic measurements, that can happen if the VNA calibration or the standards used are not good enough.

The following tables show examples of a test fixture characterized using the TRL method of SETUPCAL.EXE.

Accurate results have been obtained up to 40 GHz using microstrip structures and up to 75 GHz using waveguide/microstrip/finline test fixtures.

Table 3a: Example of TRL Characterization of Microstrip Test Fixture (Input)

```
! INPUT TEST JIG:
!
! PTJO,Teflon 0.031",gold,apc7-sma
!------------------------------------
 0.70  0.031    80.2  0.992  -109.5  0.992  -109.5  0.031 -121.9
 0.80  0.031    64.5  0.992  -125.1  0.992  -125.1  0.031 -141.0
 0.90  0.031    50.3  0.992  -140.8  0.992  -140.8  0.032 -158.3
 1.00  0.031    35.9  0.992  -156.4  0.992  -156.4  0.033 -174.6
 1.10  0.032    21.2  0.991  -172.0  0.991  -172.0  0.033  169.8
 1.20  0.033     6.2  0.989   172.3  0.989   172.3  0.034  154.4
 1.30  0.033   -10.0  0.989   156.7  0.989   156.7  0.035  139.7
 1.40  0.035   -23.5  0.988   141.2  0.988   141.2  0.035  124.1
 1.50  0.036   -38.3  0.988   125.6  0.988   125.6  0.036  107.6
 1.60  0.037   -51.5  0.988   110.0  0.988   110.0  0.036   89.2
 1.70  0.038   -64.3  0.986    94.4  0.986    94.4  0.037   68.9
 1.80  0.038   -71.4  0.986    78.8  0.986    78.8  0.039   48.1
 1.90  0.041   -83.4  0.985    63.2  0.985    63.2  0.042   26.0
 2.00  0.046   -92.8  0.985    47.6  0.985    47.6  0.046    4.7
 2.10  0.051  -102.0  0.983    32.0  0.983    32.0  0.051  -16.0
 2.20  0.056  -113.3  0.982    16.4  0.982    16.4  0.058  -35.6
 2.30  0.063  -125.1  0.981     0.8  0.981     0.8  0.064  -54.1
 2.40  0.069  -137.7  0.980   -14.8  0.980   -14.8  0.070  -72.3
 2.50  0.075  -150.6  0.980   -30.3  0.980   -30.3  0.075  -89.9
 2.60  0.079  -163.1  0.978   -46.0  0.978   -46.0  0.079 -107.4
 2.70  0.083  -175.6  0.977   -61.6  0.977   -61.6  0.081 -125.3
 2.80  0.085   171.5  0.976   -77.1  0.976   -77.1  0.081 -143.4
 2.90  0.085   159.4  0.975   -92.7  0.975   -92.7  0.080 -162.5
 3.00  0.084   148.1  0.974  -108.2  0.974  -108.2  0.077  177.4
```

Table 3b: Example of TRL Characterization of Microstrip Test Fixture (Output)

! OUTPUT TEST JIG:
!
! PTJ0,Teflon 0.031",gold,apc7-sma
!-----------------------------------

0.70	0.029	-118.1	0.992	-113.3	0.992	-113.3	0.032	71.8
0.80	0.029	-137.7	0.990	-129.6	0.990	-129.6	0.031	58.8
0.90	0.030	-158.5	0.989	-145.8	0.989	-145.8	0.032	44.6
1.00	0.031	-178.0	0.989	-162.0	0.989	-162.0	0.033	30.0
1.10	0.032	164.8	0.989	-178.2	0.989	-178.2	0.033	15.8
1.20	0.034	148.2	0.990	165.6	0.990	165.6	0.034	0.3
1.30	0.035	130.3	0.990	149.3	0.990	149.3	0.035	-14.2
1.40	0.038	115.6	0.989	133.0	0.989	133.0	0.037	-28.9
1.50	0.040	99.7	0.988	116.8	0.988	116.8	0.039	-46.2
1.60	0.041	83.8	0.987	100.6	0.987	100.6	0.041	-63.3
1.70	0.042	67.1	0.987	84.4	0.987	84.4	0.042	-79.1
1.80	0.045	49.2	0.986	68.1	0.986	68.1	0.042	-94.1
1.90	0.044	30.7	0.986	51.8	0.986	51.8	0.043	-107.7
2.00	0.045	11.0	0.985	35.6	0.985	35.6	0.045	-120.0
2.10	0.045	-10.7	0.985	19.3	0.985	19.3	0.046	-131.5
2.20	0.047	-32.7	0.985	3.1	0.985	3.1	0.047	-141.2
2.30	0.049	-56.8	0.984	-13.2	0.984	-13.2	0.050	-150.6
2.40	0.052	-80.4	0.983	-29.5	0.983	-29.5	0.053	-160.6
2.50	0.055	-103.5	0.982	-45.7	0.982	-45.7	0.055	-170.1
2.60	0.059	-126.1	0.981	-62.0	0.981	-62.0	0.058	-178.4
2.70	0.064	-148.2	0.981	-78.2	0.981	-78.2	0.063	172.8
2.80	0.070	-169.8	0.981	-94.5	0.981	-94.5	0.069	162.0
2.90	0.074	169.1	0.980	-110.8	0.980	-110.8	0.073	151.2
3.00	0.079	148.5	0.979	-127.0	0.979	-127.0	0.079	139.9

Incorporate the S-Parameters of the Transformer Sections

The S-Parameters of the transforming sections have to be available in .S2P ASCII format. This can be done very easily using any of the available microstrip circuit simulator programms.

After cascading with the transformer data the S-Parameters of the above test jig become:

```
! INPUT TEST JIG:
!
! Using 1 section transformer
!-----------------------------------
 0.70  0.644   103.0  0.751  -117.7  0.751  -117.7  0.654 -158.5
 0.80  0.668    82.2  0.729  -131.7  0.729  -131.7  0.679 -166.0
 0.90  0.682    61.5  0.715  -145.6  0.715  -145.6  0.694 -173.1
 1.00  0.687    41.1  0.709  -159.3  0.709  -159.3  0.699 -179.9
 1.10  0.683    20.6  0.712  -173.0  0.712  -173.0  0.696  173.3
 1.20  0.668    -0.1  0.723   173.2  0.723   173.2  0.684  166.2
 1.30  0.645   -20.9  0.743   159.1  0.743   159.1  0.660  158.8
 1.40  0.610   -41.7  0.772   144.6  0.772   144.6  0.623  151.0
 1.50  0.563   -63.2  0.810   129.6  0.810   129.6  0.574  142.3
 1.60  0.495   -85.0  0.853   113.8  0.853   113.8  0.505  132.6
 1.70  0.407  -107.2  0.898    97.1  0.898    97.1  0.414  121.4
 1.80  0.292  -128.7  0.941    79.5  0.941    79.5  0.300  107.7
 1.90  0.164  -146.3  0.972    61.0  0.972    61.0  0.165   88.2
 2.00  0.047  -108.3  0.985    41.9  0.985    41.9  0.046    9.5
 2.10  0.150   -51.2  0.972    22.8  0.972    22.8  0.155  -84.0
 2.20  0.285   -67.5  0.939     4.1  0.939     4.1  0.296 -104.7
 2.30  0.403   -88.8  0.894   -13.7  0.894   -13.7  0.416 -118.9
 2.40  0.497  -110.4  0.843   -30.5  0.843   -30.5  0.513 -130.7
 2.50  0.569  -131.6  0.795   -46.3  0.795   -46.3  0.587 -141.0
 2.60  0.621  -152.2  0.752   -61.2  0.752   -61.2  0.641 -150.2
 2.70  0.657  -172.3  0.719   -75.6  0.719   -75.6  0.679 -158.5
 2.80  0.681   168.0  0.695   -89.2  0.695   -89.2  0.703 -166.2
 2.90  0.693   148.6  0.682  -102.6  0.682  -102.6  0.717 -173.6
 3.00  0.695   129.3  0.679  -115.9  0.679  -115.9  0.719  179.3
```

Table 4a: S-Parameter of input part of test fixture (of table 3a) after cascading to a transformer section.

! OUTPUT TEST JIG:
!
! Using 1 section transformer
!----------------------------------

0.70	0.652	-158.5	0.752	-121.6	0.753	-121.6	0.646	95.2
0.80	0.677	-165.9	0.728	-136.3	0.728	-136.3	0.668	73.3
0.90	0.693	-173.1	0.714	-150.6	0.714	-150.6	0.682	51.7
1.00	0.698	-180.0	0.708	-164.8	0.708	-164.8	0.686	30.1
1.10	0.695	173.1	0.712	-179.1	0.712	-179.1	0.682	8.6
1.20	0.683	166.0	0.724	166.5	0.724	166.5	0.670	-13.1
1.30	0.659	158.6	0.745	151.9	0.745	151.9	0.647	-35.0
1.40	0.624	150.6	0.773	136.7	0.773	136.7	0.611	-57.1
1.50	0.574	141.9	0.809	121.1	0.809	121.1	0.562	-79.9
1.60	0.506	132.1	0.851	104.5	0.852	104.5	0.495	-103.0
1.70	0.416	120.8	0.898	87.2	0.898	87.2	0.407	-126.4
1.80	0.304	106.9	0.940	68.8	0.940	68.8	0.295	-149.5
1.90	0.169	88.2	0.972	49.6	0.972	49.6	0.166	-168.5
2.00	0.047	15.6	0.985	29.9	0.985	29.9	0.047	-135.6
2.10	0.148	-84.8	0.974	10.2	0.974	10.2	0.145	-75.8
2.20	0.287	-105.8	0.944	-9.1	0.944	-9.1	0.279	-92.8
2.30	0.407	-120.2	0.899	-27.4	0.899	-27.4	0.396	-115.1
2.40	0.503	-132.0	0.850	-44.7	0.850	-44.7	0.489	-137.8
2.50	0.577	-142.3	0.804	-61.1	0.804	-61.1	0.559	-160.0
2.60	0.631	-151.4	0.762	-76.4	0.762	-76.4	0.611	178.4
2.70	0.669	-159.8	0.731	-91.3	0.731	-91.3	0.647	157.4
2.80	0.694	-167.5	0.708	-105.5	0.708	-105.5	0.671	136.6
2.90	0.707	-174.9	0.695	-119.5	0.695	-119.5	0.683	116.0
3.00	0.710	177.9	0.692	-133.5	0.692	-133.5	0.685	95.5

Table 4b: S-Parameter of output part of test fixture (of table 3b) after cascading to a transformer section.

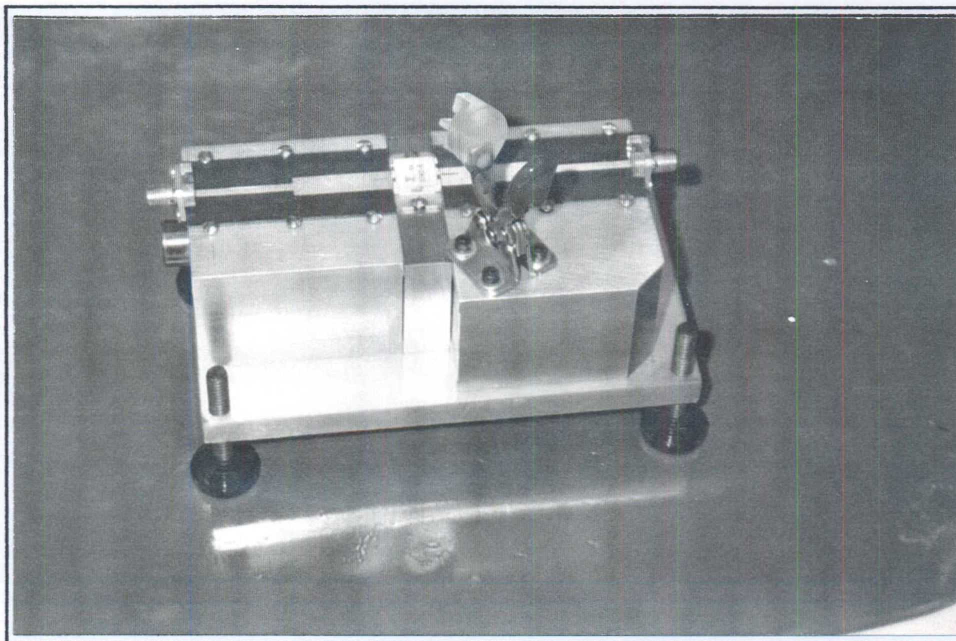


Fig. 7: The Power Test Fixture used, model PTJ0.

Effect of Transforming Fixture on Tuner Calibration

Before the test fixture has been included in the setup the tuner calibration points (at a single frequency) are equally distributed over the Smith Chart as shown in figure 8. This permits easy search for maximum power and smooth operation of the contouring software.

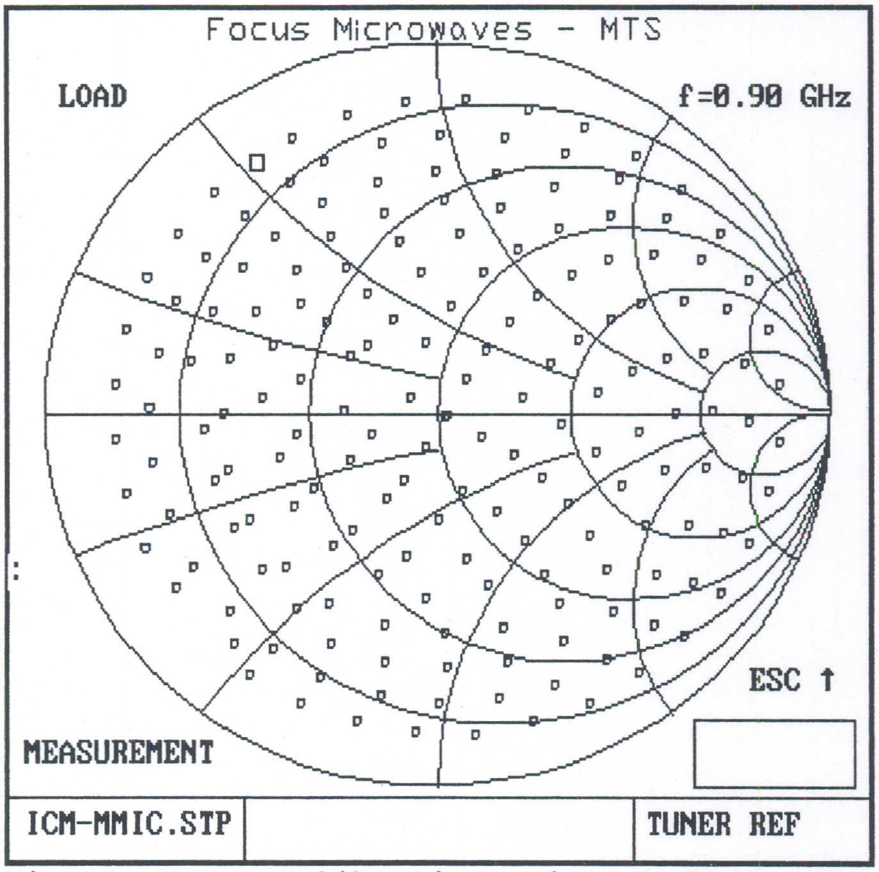


Fig. 8: Tuner Calibration points before cascading to fixture

After cascading with the transforming fixture, however, most of the calibration points are concentrated around the new characteristic impedance, which is close to 7 Ω.
This way very low impedances can be synthesized and presented to the DUT port and the setup (tuner & fixture) loss can be calibrated with good accuracy.

The problem is that this concentration of points does not permit sufficient visual resolution around the optimum Γ and, the contouring software has problems to generate well visible ISO contours, because of the unequal distribution of calibration points.

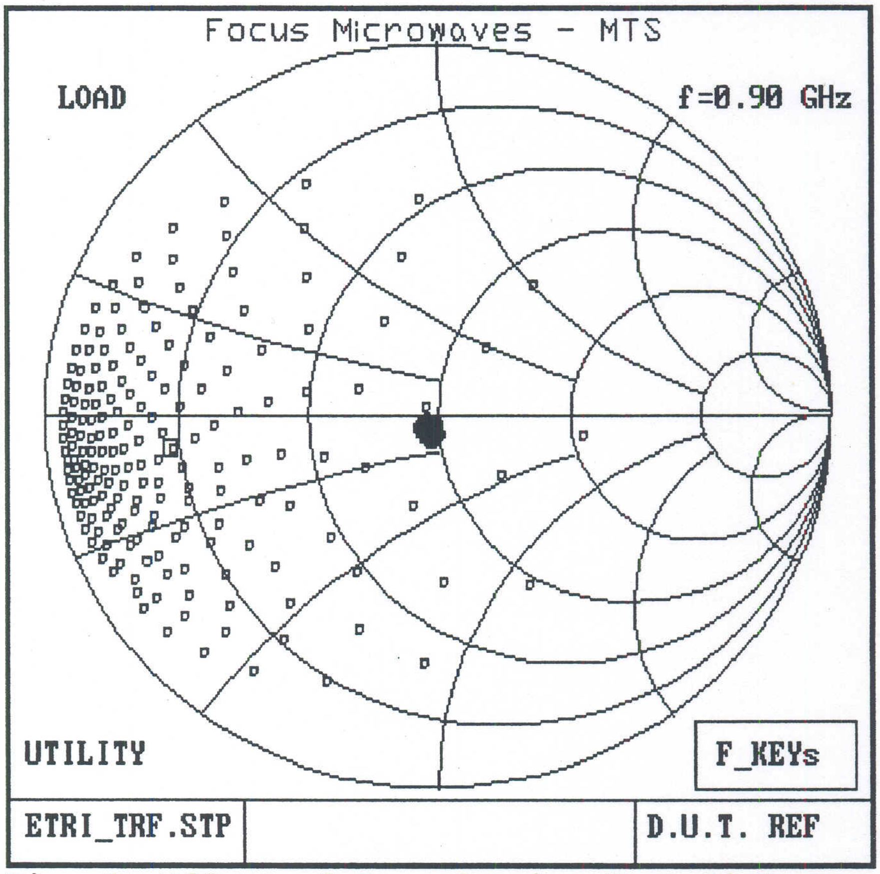


Fig. 9: Effect of Transforming Test Fixture

To solve these problems the CCMT (and MTS) software use the **Characteristic Impedance Normalization** utility.

This is a routine that computes the (real) characteristic impedance required (for each frequency) for a maximum spread of the calibration points over the Smith Chart. This is done in the measurement programms automatically by using the Softkey 'Alt-N'.

Figure 10. shows the effect of this normalization process applied to the pattern of points of figure 9.

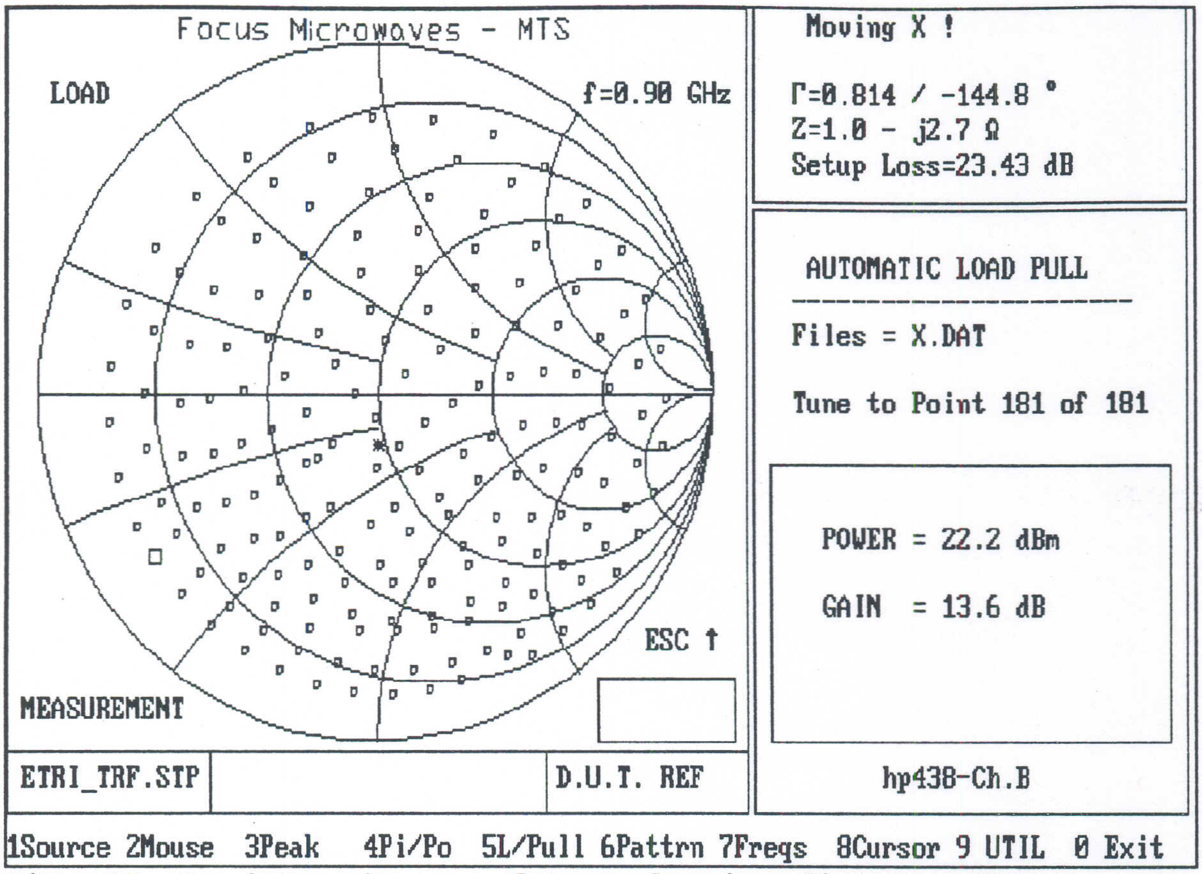


Fig. 10: Load Impedances of transforming fixture after Normalization

It is clear that the normalized pattern permits much higher visual resolution around Γ_{max}, better efficiency in the search of the optimum as well as better ISO contour data processing.

Figure 11 shows a set of ISO Output Power contours measured using the described transforming test fixture and normalized using the technique described here.

It is important to recognize that impedances as low as 0.88 Ω are synthesized at DUT level and the optimum impedance is well within the high resolution area of the Smith Chart (using the new characteristic impedance).

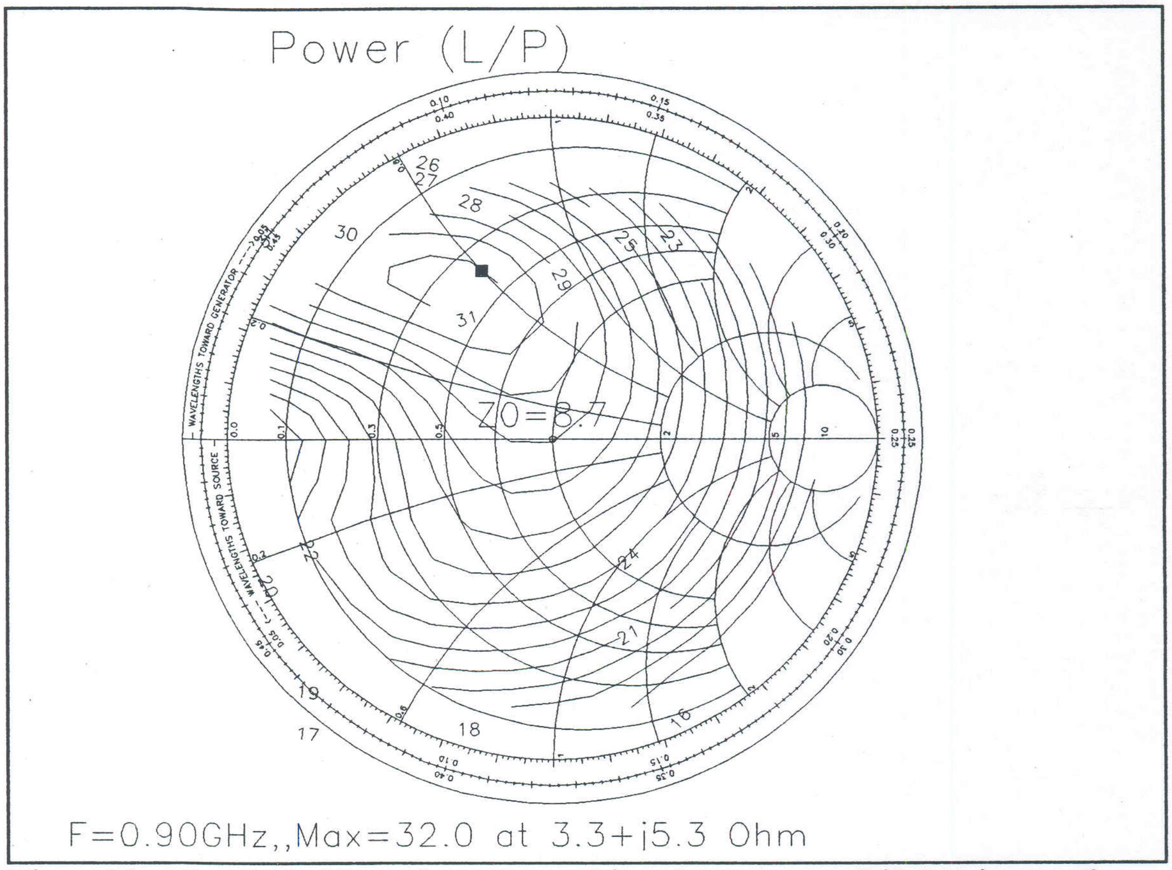


Fig. 11 Load Pull using normalized Tuner calibration. The ■ shows the Zmax=3.3+j5.3 Ω

ISO Contour plot measured using transforming test fixture (Z0 of transforming section ≈17 Ω). The Impedance points have been normalized to Z0=8.7 Ω. This is indicated in the center of the Smith Chart. The smallest impedance presented to the DUT during this test is around 0.88 Ω.

Using transforming sections with lower Z0, such as 5-10 Ω, we could present to the device impedances as low as 0.1 Ω with still acceptable measurement accuracy and full tuning capability.

Results on these tests can be supplied to interested readers on request.

References

[1] A.K.Sharma et al. "Ka-band Power PHEMT on-wafer characterization using prematched structures", Proceedings IEEE MTT-S, 1993, Atlanta Ga.