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Product Note 70

MLTF[1], Minimum Loss Test Fixture For Package De-Embedded Load Pull Testing

MLTF is a modular, extremely low loss test fixture, designed for load pull testing of very low impedance high power RF transistors. Low loss is obtained by exclusively using air as dielectric[1]. The test fixture includes a main body, coaxial connectors and flanges, test inserts and TRL calibration standards. It can be used up to 10GHz. Additional, package specific TRL calibration standards, allow package de-embedded testing to the internal chip reference plane.

Description of the Fixture

MLTF has been designed for load pull measurements of high power RF and microwave transistors with very low internal input and output impedances without using transformers. In addition for extremely low insertion loss, the fixture (≈0.025dB at 2GHz with N connectors for high power; using APC-7 connectors provides even lower insertion loss [1]) uses a rigorous slabline approach developed by Focus for its Computer Controlled Microwave Tuners, CCMT, as transmission media; the new fixture has the capability of employing 50Ω as well as non-50Ω TRL calibration standards, thus allowing for the correction of parasitic capacitances, created by the leads of the transistors package.

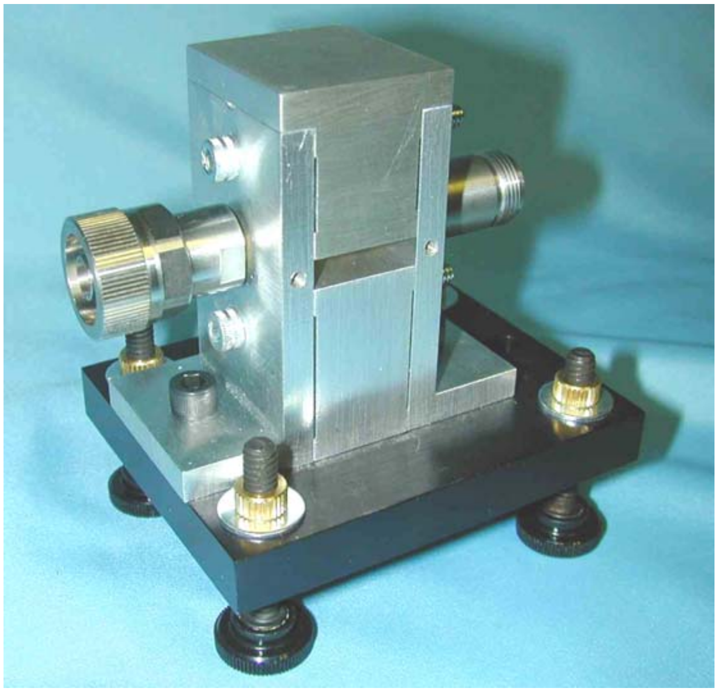

Figure 1: MLTF with N connectors for Power Transistor Load Pull Testing

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[1] *US patent in process.*

The transition technique between coaxial and microstrip structures, used also in previous MLTF designs, has been refined and can be used with a multitude of transistor packages, providing all inherent advantages of the MLTF structure of extremely low loss and high repeatability.

MLTF consists of the following parts and components:

- One fixture base with four adjustable feet,
- Two connector brackets (launchers), one fixed and one sliding on the base,
- One set of coaxial TRL calibration standards, including a Thru, a Delay Line, Inserts and associated fixture covers,
- One Thru and one Delay Line emulating the leads of any particular transistor package,
- One measurement set for each package, including a transistor insert and associated cover.

Background

Load Pull as well as Noise measurements are possible preferably using automatic tuners. Noise is a small signal phenomenon where it is possible to determine the optimum noise figure without having to tune exactly to the optimum impedance [2]. Whereas, Load pull is a non-linear phenomenon where there are no analytical formulas describing the relation between source (or load) impedance and device power, gain, PAE or other. In this case, if we want to determine the exact power or other performance of the device we must physically tune to the optimum impedance.

Modern multicell high power transistors have very low internal impedances both on the input (gate, base) and the output (drain, collector) sides, in general in the order of 1Ω or less, which must be physically matched with a tuner in order to determine the exact value of the parameter to be measured.

State of the art automatic electromechanical tuners may generate VSWR up to approximately 20:1 (R≈2.5Ω) with acceptable accuracy. Again, this would be a VSWR at the tuner reference plane and not the DUT (transistor) reference plane. De-embedded to the transistor reference plane, this reflection factor is reduced by twice the insertion loss of the test fixture and any other parts inserted between DUT and tuner, such as diplexers or triplexers in case of some harmonic load pull setups [3]. This insertion loss reduces the effective VSWR at the DUT reference plane to, generally, unacceptable levels for high power transistors, as can be seen in the lower half of table I. This table shows the reduction in effective reflection factor (or minimum tuneable impedance R_{min}) at DUT reference plane as a function of the insertion loss of the output section of the test fixture; this is shown when we connect a good mechanical tuner (CCMT) with an internal reflection factor of 0.9 (VSWR ≈20:1) to the test fixture and, alternatively, when we use a Prematching Tuner (PMT) with maximum VSWR of the order of 100:1 (Γ=0.980) or higher [4]. PMT tuners may generate VSWR close to 200:1 (Γ≈0.990 or R≈0.25Ω). Any excess insertion loss of the test fixture would, in this case, jeopardize the advantage of using these high performance tuners. In fact, it has been demonstrated using a prototype low loss MLTF with APC-7 connectors and a Prematching Tuner, which can be tuned as low as 0.3Ω at DUT reference plane [1].

The two examples in table I show why it is so important for load pull test fixtures to be designed for extremely low insertion loss **S21**.

We use a combination of the following, well known, formulas:

$$\Gamma_{DUT}= \Gamma_{Tuner}\bullet 10^{\,S21[dB]/10} \qquad [1]$$

$$\mathrm{VSWR}_{DUT} = (1+\Gamma_{DUT}) / (1-\Gamma_{DUT}) \qquad [2]$$

$$R_{min,\, DUT} = 50\ \Omega / \mathrm{VSWR}_{DUT} \qquad [3]$$

Combined to

$$R_{min} = 50\Omega \bullet (1 - \Gamma_{Tuner}\bullet 10^{\,S21[dB]/10}) / (1 + \Gamma_{Tuner}\bullet 10^{\,S21[dB]/10}) \qquad [4]$$

S21[dB]	$R_{min}[\Omega]$	Γ_{DUT} (Standard Tuner)	$R_{min}[\Omega]$	Γ_{DUT} (Prematching Tuner)	
0.00	2.63	0.900	0.251	0.990	
-0.01	2.69	0.898	0.304	0.988	
-0.02	**2.75**	**0.896**	**0.366**	**0.985**	⇦ MLTF (Coaxial)
-0.03	2.80	0.894	0.424	0.983	
-0.04	2.86	0.892	0.482	0.981	
-0.05	2.92	0.890	0.539	0.979	
-0.10	**3.21**	**0.880**	**0.827**	**0.967**	⇦ PTJ-0 (Microstrip)
-0.15	3.50	0.869	1.115	0.956	

Table I: Effect of Insertion Loss of Test Fixtures on Minimum tuneable Impedance R_{min} (or Maximum tuneable Γ) for a standard tuners (CCMT) and a prematching (PMT) tuner connected to both coaxial (MLTF) and Microstrip (PTJ-0) test fixtures.

Savings in Driver Amplifier Power due to lower MLTF Loss

Beyond maximum attainable Γ at source and load side of the DUT, the fixture insertion loss has undesired consequences on the power of the driver amplifiers used in the setup. Considering that the typical test fixture insertion loss is close to 0.1dB or lower, leads to the false assumption that its loss would not matter with regards to the input power. This is not the case since the operating loss of the test fixture is not $1/|S21|$ but $(1-|\Gamma_{tun}|)/|S21|$; as can be seen from table II. The difference in operation loss between the microstrip test fixtures (like PTJ-0) and the coaxial ones (like MLTF) can reach moderate 1.4dB at medium Γ (CCMT, $\Gamma\approx0.940$), but it reaches prohibitive values over 3dB at highest levels of reflection (PMT, $\Gamma\approx0.988$). This means that, in order to provide enough power to drive a high power transistor to saturation, we would need at least twice as much power from the driver amplifiers**.** Comparing cost of driver power amplifiers shows that the price difference between a 25Watt and a 50Watt amplifier for example may easily reach tens of thousands of dollars, all due to the apparently "negligible" difference of 0.08dB in insertion loss of the test fixture (0.1dB for microstrip against 0.02dB for coaxial).

	Γ-tuner (Standard) = 0.940 VSWR = 32:1		Γ-tuner (Prematch) = 0.988 VSWR = 167:1	
Insertion Loss S21 Of ½ Fixture	Total Available Loss (dB)	Loss due to Fixture (dB)	Total Available Loss (dB)	Loss due to Fixture (dB)
0.000dB	0.61	0.00	9.83	0.00
0.020dB *(≈MLTF, Coax)*	0.92	0.31	11.19	**1.36**
0.050dB	1.34	0.73	12.66	2.83
0.100dB *(≈PTJ-0, Mstrip)*	1.98	1.37	14.36	**4.53**

$\delta > 3$dB

Table II: Operation loss at high reflection factors (Γ-tuner) due to insertion loss of test fixture. Higher insertion loss of 0.08dB causes more than 3dB higher operation loss.

Calibration Accuracy Considerations

MLTF must be fully characterized. This can be achieved using either the TRL calibration method or an accurate equivalent circuit model. Since the insertion loss is so low and the return loss so high, one might assume that a quasi loss-less transmission line could adequately describe MLTF. This would be acceptable for S-parameter or Load Pull measurements using tuners with moderate reflection factors less than $\Gamma\approx0.82$ (VSWR=10:1). Beyond this Γ value any insertion loss, even very low, rapidly increases to significant loss with increasing Γ_{tuner}, which would falsify the measurement results, if one would adopt the "loss-less transmission line" approach.

This is particularly true if MLTF is operating in conjunction with a prematching Tuner (PMT [1]), which generates Γ up to around 0.990 (VSWR≈200:1). Table III below shows an example of operation loss of a cascade of MLTF connected to a PMT tuner with $\Gamma_{\text{tuner}} = 0.992$ for the two cases:

(a) Assuming zero insertion loss for an ideal MLTF (S21 = 0dB) and
(b) Assuming non-zero loss for a real MLTF (S21 = -0.017dB).

|S21|	Γ_{DUT}	R_{min}	Power Loss
0dB (a) MLTF assumed Loss less	0.992	0.2Ω	2.24dB
-0.017dB (b) MLTF duly calibrated	0.986	0.36Ω	4.76dB

$\boxed{\delta = 2.52\text{dB}}$

Table III: Effect of Fixture Insertion Loss on Power Loss of Tuner + MLTF combination.

In table III the first row corresponds to the "loss-less" approximation (fixture loss = 0dB) whereas in the second row the real loss is 0.017dB, which for other, non-high VSWR load pull applications, could be considered as a quasi ideal transmission line. If a PMT (with Γ_{tuner}=0.992) is used, however, the difference in calculated power loss would be ≈2.5dB thus introducing an unacceptable measurement error.

For this reason it is imperative for MLTF to be very accurately characterized using either TRL or simulated using an accurate model based on wideband S-parameters and cannot be assumed to be completely loss-less.

MLTF Calibration Procedure using TRL Standards

MLTF is supplied with both Thru and Delay calibration standards and the corresponding leads and covers. A different cover is required for each calibration standard. MLTF can be characterized using FOCUS generic TRL software. Figures 2 and 3 show MLTF with various standards inserted (covers are removed for photos). The results of a TRL calibration (one half of the fixture) are shown in figure 4.

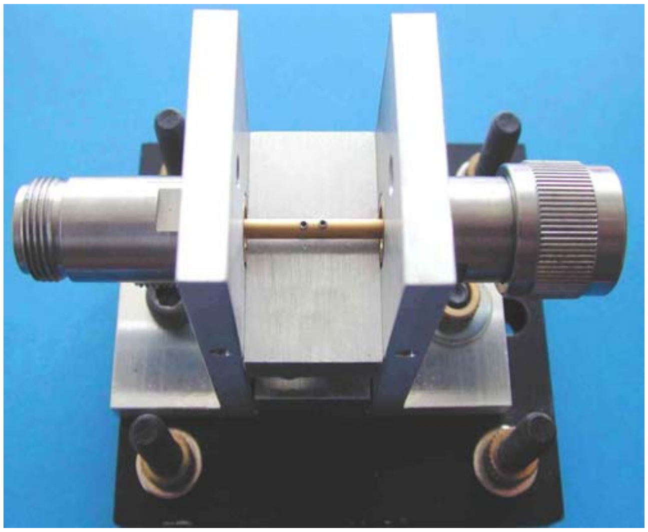


Figure 2: MLTF with THRU standard

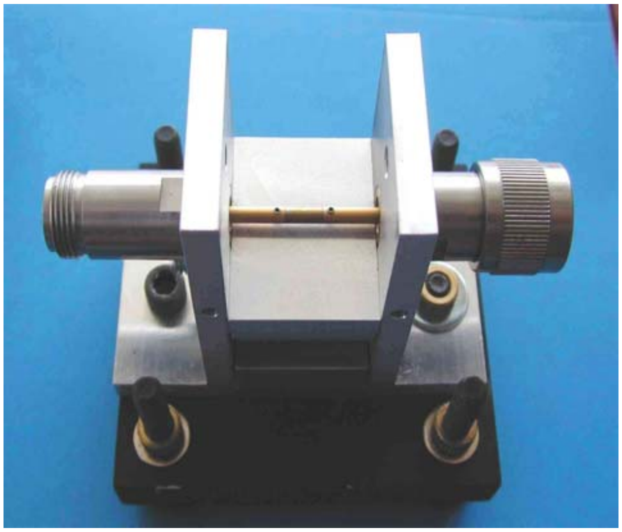
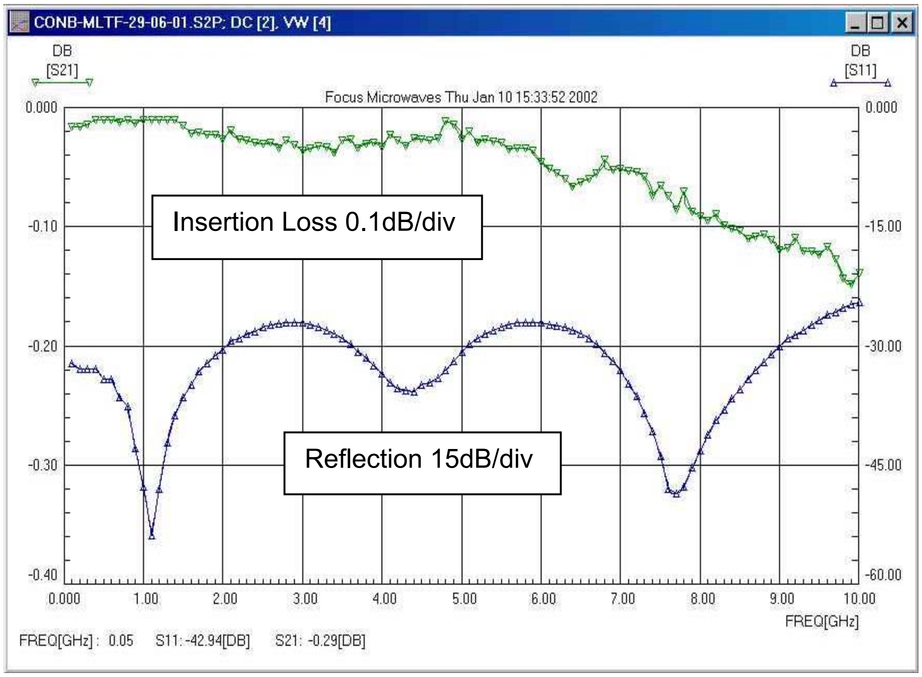


Figure 3: MLTF with DELAY standard



FREQ[GHz] : 0.05 S11: -42.94[DB] S21: -0.29[DB]

Figure 4: Insertion and return loss of one section of an MLTF. The data has been obtained using Focus TRL fixture characterization routines.

Calibrating MLTF using "package-specific" TRL Standards

An important feature of MLTF is that it is possible to be calibrated at a reference plane that includes package-specific transistor lead parasitics. Depending on the size of the transistor to be tested, their typical packages include metallic leads of various sizes (figures 5-7).

Quite often, these metallic leads are wider than the microstrip lines of the test fixtures and represent impedances lower than 50Ω; they behave as capacitive loads "C_{in}" and "C_{out}". There is also the parasitic feedback capacitor C_p, due to the ceramic cover of the package. The special calibration of MLTF allows the elimination of the elements C_{in} and C_{out}; the element C_p cannot and should not be eliminated, since it will be present when the transistor will be used in an actual circuit (figure 8).

If the amplifier Designer intends to use the transistors with the package, as is, without cutting away the leads, then he should introduce the package leads in form of transmission lines of given length and width in his design.

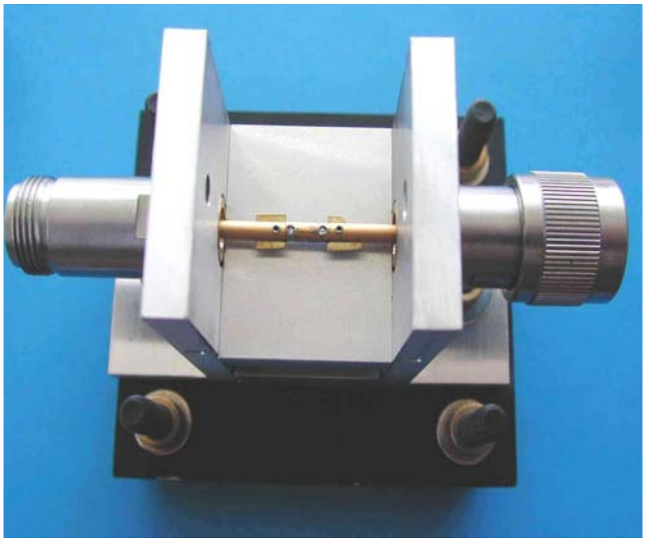


Figure 5: MLTF with DELAY standard for De-Embedding a transistor package.

Figure 6: Detail of DELAY standard for package de-embedding.

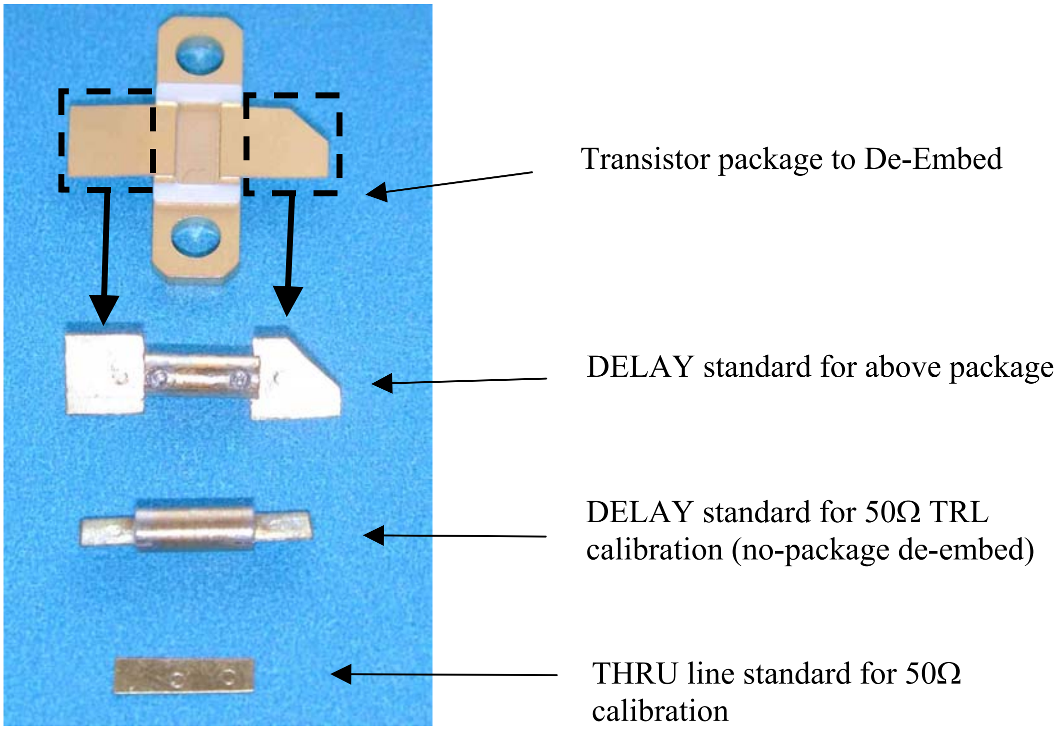


Figure 7: Package-specific and 50Ω TRL calibration standards for MLTF.

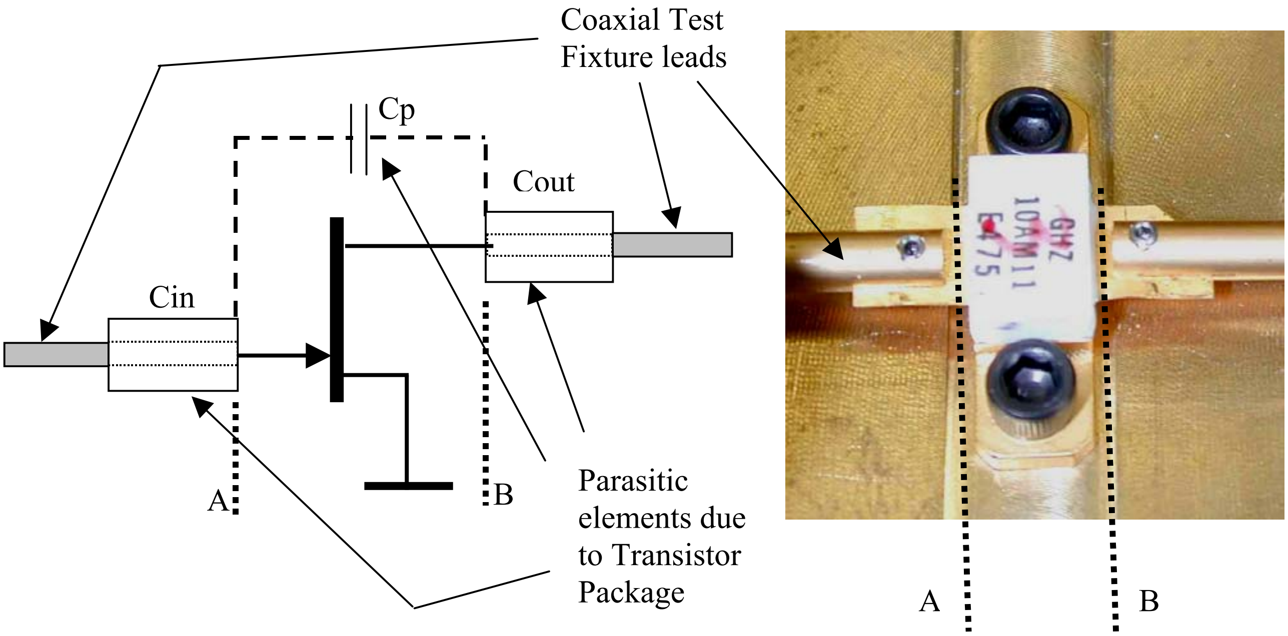


Figure 8: Transistor package mounted in MLTF and corresponding equivalent circuit, referring to calibration plane A-B.

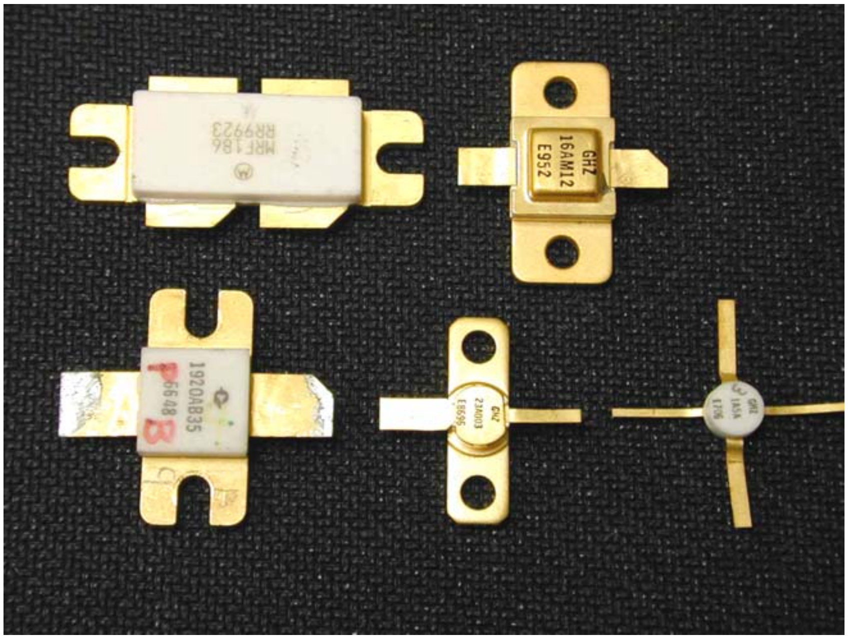


Figure 9: Various packages that can be used with MLTF

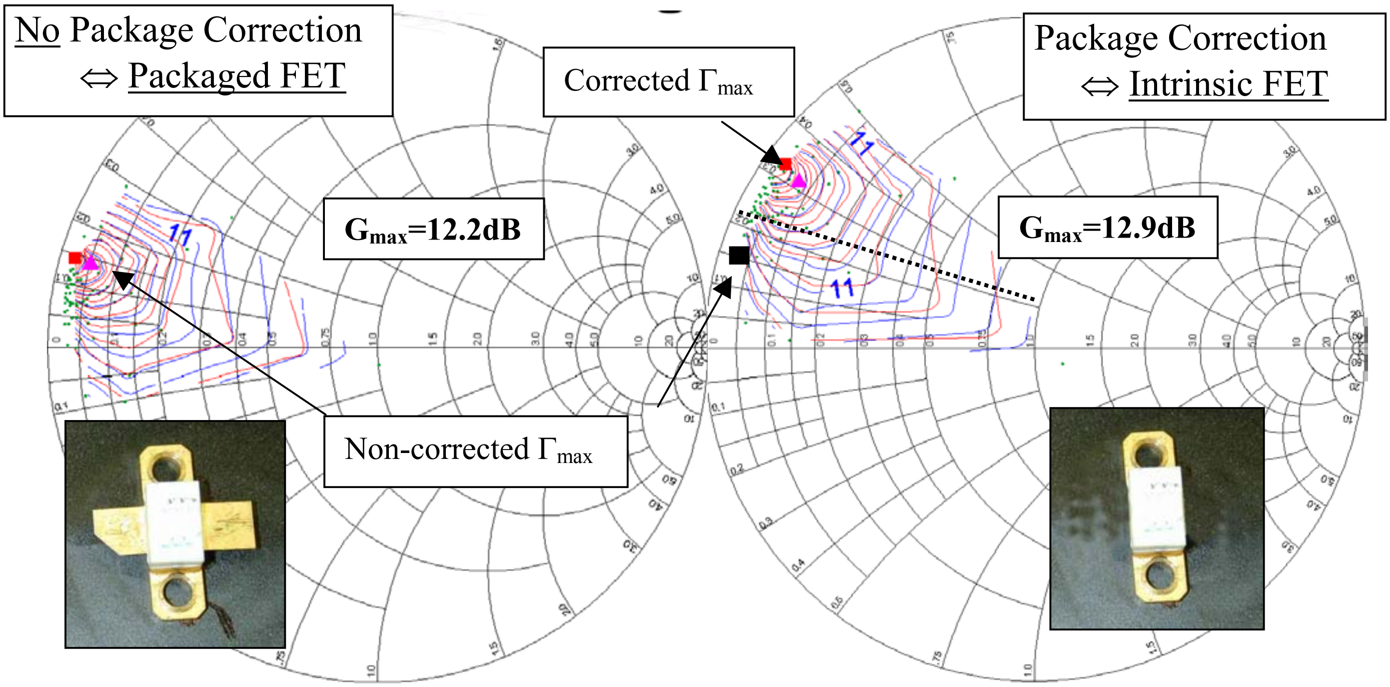


Figure 10: Effect of package de-embedding on Load Pull contours of power MOSFET at 2GHz

In Figure 10 the left plot shows data when de-embedding with a 50-Ω microstrip test fixture correction; the right plot shows the "intrinsic" transistor data, after de-embedding with fixture parameters including the package leads. Both sets of data have been measured using the same 50-Ω fixture. The transistor has more capacitive output impedance when the package is not corrected for. We also measure 0.7dB higher Gain and output Power, when correcting for the package leads.

Determining MLTF's S-Parameters with the Help of a Model

The mechanical, assembly structure and the very low loss of MLTF make it delicate to calibrate using traditional TRL methods. Because of the low loss, minor repeatability changes in the RF contacts during the assembly and disassembly of TRL THRU and DELAY standards, combined with possible drift in VNA readings may cause significant variations and possibly errors in the TRL calculations. In particular the basic TRL condition where the insertion loss of the DELAY must be higher than the THRU may be disturbed, since both such values are extremely low and within the measurement accuracy of the VNA.

For this reason it is useful to assist the calibration of MLTF by means of a wideband electrical model or equivalent circuit. If such a circuit is available and its elements can be determined using manual or automatic optimisation routines using only S-parameters measured with a THRU line connected, then determining the S-parameters of both halves of the fixture would be extremely simple and assembly – disassembly errors would be avoided. The device to describe is shown in figure 11. The basic configuration of an equivalent circuit is shown in figure 12.

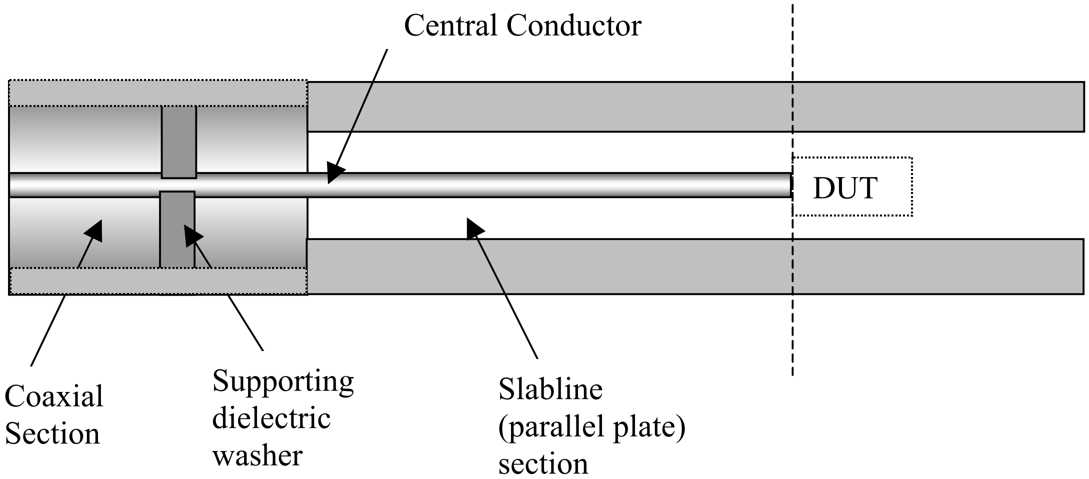


Figure 11: Physical layout (cross section) of one half of MLTF fixture.

Each half consists of a transmission line corresponding to the connector coaxial section, an inductor, corresponding to the connector recessed section to carry the central conductor supporting dielectric washer, a parallel section of a high resistor and series capacitor corresponding to the supporting washer itself and partly the transition between coaxial and slabline structures and, finally, another transmission line section, corresponding to the parallel plate transmission between the coaxial connector and the DUT at the center of the fixture.

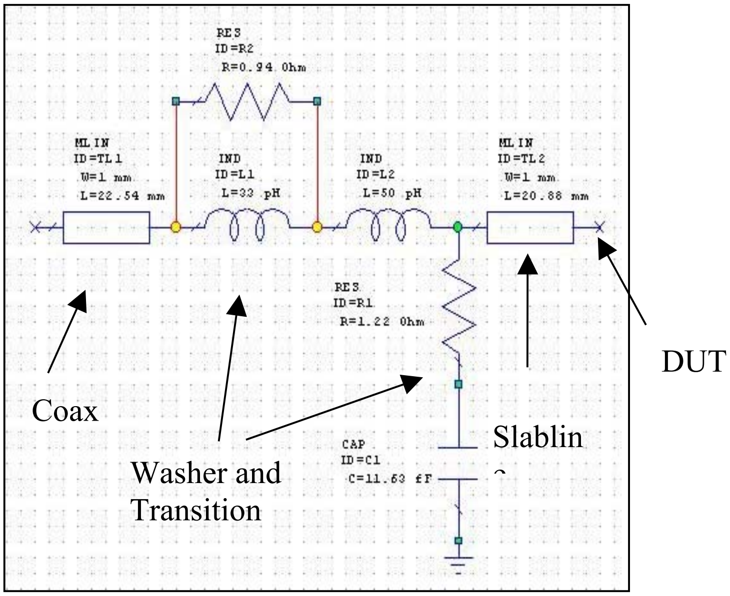


Figure 12: Wideband electrical model (equivalent circuit) of one half of MLTF

A special software has been developed, which permits to determine the values of the elements in the equivalent circuit, using only twoport S-parameters, measured with a THRU line connected in the fixture. The complete circuit used is shown in figure 13 and a comparison between measured and calculated S11, S21 and φ21 is shown in figure 14.

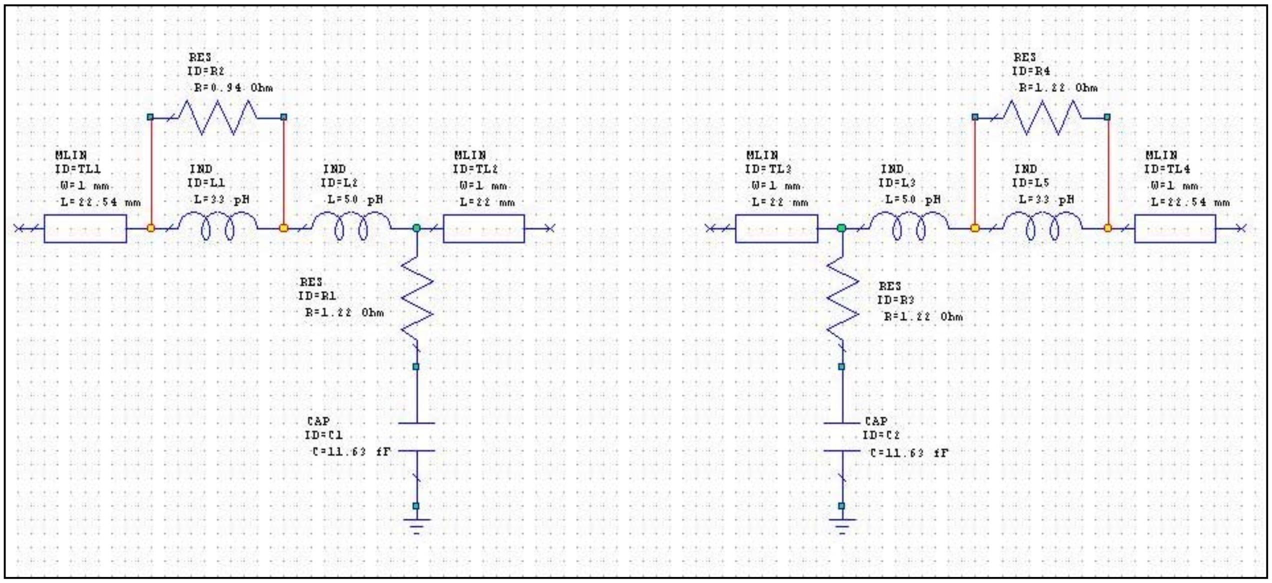
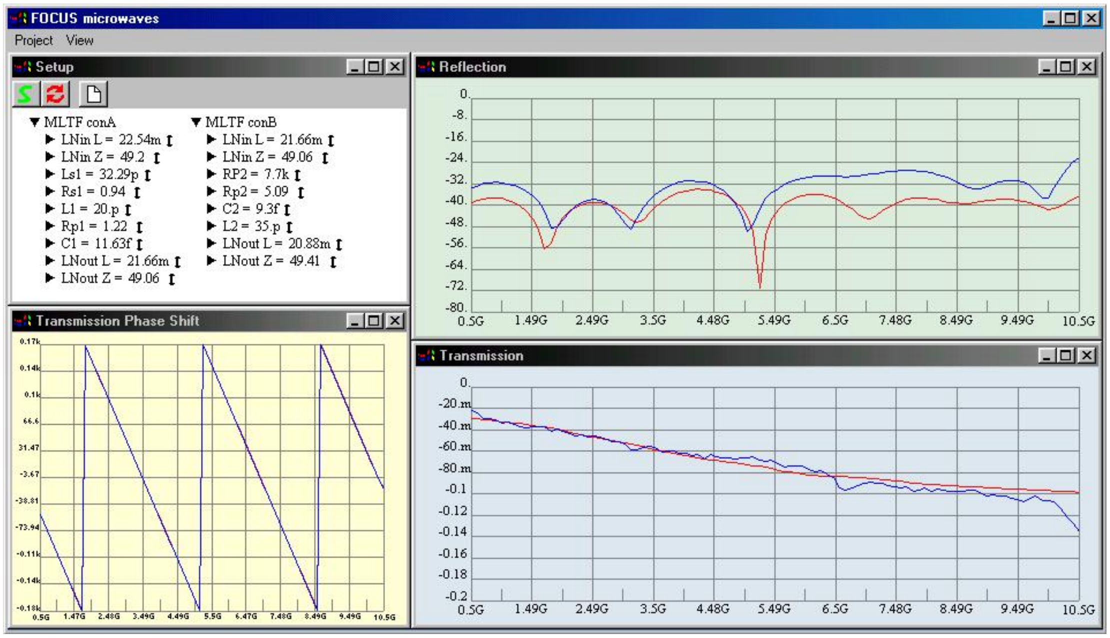


Figure 13: Complete equivalent circuit of MLTF as used for the optimisation.



▼ MLTF conA
- ▶ LNin L = 22.54m
- ▶ LNin Z = 49.2
- ▶ Ls1 = 32.29p
- ▶ Rs1 = 0.94
- ▶ L1 = 20.p
- ▶ Rp1 = 1.22
- ▶ C1 = 11.63f
- ▶ LNout L = 21.66m
- ▶ LNout Z = 49.06

▼ MLTF conB
- ▶ LNin L = 21.66m
- ▶ LNin Z = 49.06
- ▶ RP2 = 7.7k
- ▶ Rp2 = 5.09
- ▶ C2 = 9.3f
- ▶ L2 = 35.p
- ▶ LNout L = 20.88m
- ▶ LNout Z = 49.41

Figure 14: Display of operation menu with manual or automatic optimiser and comparison of measured against calculated S-parameters of MLTF. Left bottom: φ21, top right: |S11| and bottom right: |S21|. The most important parameters for load pull measurement accuracy are φ21 and |S21|.

Conclusion

MLTF is a very low loss modular test fixture, designed for load pull measurements of very low impedance transistors. It can be used up to 10GHz with APC-7 or N connectors. MLTF offers the possibility of "package-specific" TRL calibration, in order to de-embed the transistor package leads. Experimental Load Pull data to this effect are presented. TRL calibration of the 50Ω structure can be avoided when an appropriate equivalent circuit and optimising software are used.

Literature

[1] Paper presented at ARFTG, June 2000, Boston, MA: "Minimum Loss Test Fixture for Sub 1Ω Load Pull Testing".

[2] Application Note 8: "Basic Load pull and Noise Measurements", June 1994.

[3] Maury Microwave Technical data 4T-050F: "Harmonic Tuning", 2001.

[4] Product Note 52: "Prematching Tuners for Very High VSWR and Power Load Pull Measurements", February 1999.