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***Product Note 75***

# DLPS, a Differential Load Pull System

Differential amplifiers have many operational advantages, and become increasingly popular for many applications. High power single-ended devices can be accurately characterized using a traditional load pull system. For differential devices however, single-ended device characteri-zation does not provide the real performance of the device working at differential mode. Focus presents a new Differential Load Pull System, which proves to be the required means for accu-rately characterizing differential (push-pull) devices in true differential mode.

## Background

To meet today's amplifier requirements operating the transistor near saturation is always necessary and causes contradictory effects on linearity and efficiency. In this region electrical computer transistor models are not accurate enough to provide for reliable PA designs. The natural way to solve these problems is the direct measurement of all-important transistor parameters under high power excitation using a load pull system. This will provide accurate knowledge of optimum load and source impedances at all significant harmonic frequencies for all-important RF parameters such as output power, PAE, bias parameters, etc. Because all parameters can be taken into account even a complex optimum goal for the operation, which depends on more than one parameter, can be achieved. Load pull and source pull techniques are the most efficient way to determine the optimum impedance and power conditions both on input and output of the devices.

For balanced devices, there has not been a genuine and effective measurement system able to characterize devices at differential mode near saturation, so far. The major obstacles are that most test equipment are intended for testing single-ended devices. The related hardware infrastructure (cables, couplers, isolators, attenuators, test fixtures) is also unbalanced. This includes also other auxiliary components that are often taken for granted, such as calibration standards, transmission lines and connectors, and even industry-standard reference impedances.
Current approaches for the characterization of differential devices are either employing mixed mode S parameters or characterize devices half by half.
Differential circuits work best when driven by balanced inputs. The single-ended response of a circuit designed for differential circuits may generate large artifacts because parasitic components, which remain at common mode, come into play. Spurious peaks may appear in the frequency response, and the input impedance match may not be accurate.

## Differential Tuners

Differential Microwave Tuners ( DMT ) are precision microwave instruments, which contain two independent tuner units. Each DMT includes two parallel slab lines in which slugs (RF probes) are inserted in order to create a controllable microwave reflection factor. Moving the slugs up/down or left/right the impedances presented at the two ports of each slab line are adjusted and then the total impedance presented into the device (gate-to-gate or drain-to-drain) can be precisely modified. The calibration and control software include routines, which allow the total impedance presented to the device (gate-to-gate or drain-to-drain) to be actually tuned to any desired value within the calibration range of the tuner.

Figure 1 shows the internal structure of a Focus Differential Microwave Tuner (DMT). The electrical length of both individual tuners is adjustable to be exactly equal. This is very important for the proper differential mode operation of the DUT. Both individual tuner components of the DMT can be controlled and tuned by the software completely independently. This is a key requirement for differential mode operation in order to be able to compensate for symmetry imperfections of the test fixture, baluns, adapters, cables etc. in the setup.

Considering the possible imbalance caused by differences in machining of the tuner components, including adapters and connectors, DMT's use transmission airlines which are adjustable in length. The special design of such slab lines with the capability of transmission phase adjustment is shown in figure 2.

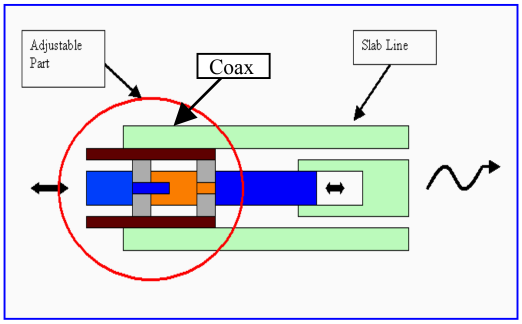


Figure 2: Phase adjustable transmission airline of DMTs.

A TRL calibrated Vector Network Analyzer is used to measure the original phase difference of, otherwise, macroscopically identical airlines, and adjust to zero, so that the phase imbalance can be eliminated.

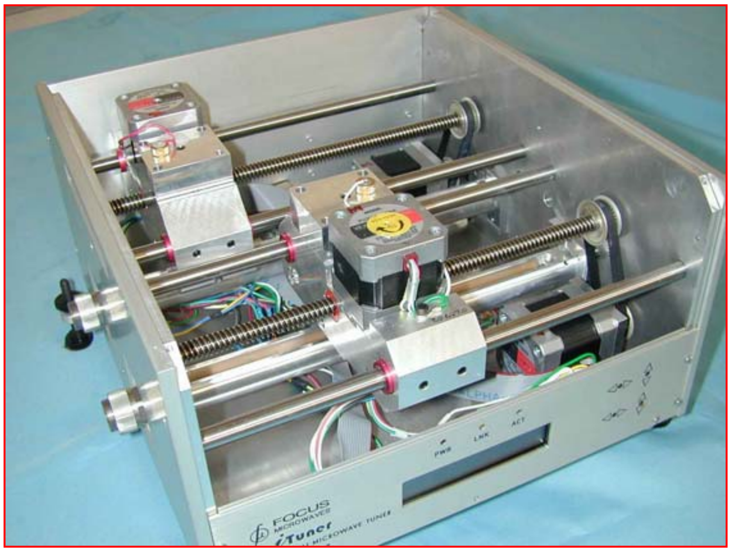

Figure 1: Internal DMT structure


Figure 3: Differential Microwave Tuner - DMT

Differential Microwave Tuners (DMT) can be controlled either via a USB port of a PC or via Ethernet (TCP/IP or *iTuner*). The specific exemplar shown in figure 3 is an intelligent tuner (*iTuner*) controlled directly via the TCP/IP network port of any PC or laptop. The on-board electronics of this unit includes a complete tuner identification and mechanical characteristics, high level communication language driver and a removable flash memory card with several tuner calibration files that can be down or up loaded to and from the tuner.
The on-board TCP/IP tuner controller eliminates all other external control electronics and hardware. It requires only an ordinary 12V/3A DC power supply in addition to the Ethernet (RJ-45) cable for full operation.

## DMT Calibration

Since the two slab lines included in the DMT are not coupled the calibration procedure can be done in two steps and remains valid, since the coupling coefficients between the two individual tuners of the DMT can be considered independent. DMT is treated as two uncoupled independent tuners, in other words it is calibrated in two sub sequential sessions by switching the VNA from one tuner (airline) to the other.

The calibration setup of a DMT is shown in figure 4.

First the VNA is connected to the first tuner and complete S parameter measurements as a function of the physical position of the RF probe moving inside slab line 1 are performed and saved in a calibration file. Then the VNA is connected to slab line 2 to do another compete tuner calibration. All measured S-parameter data are saved in calibration files, one file per tuner and frequency and are named DMT calibration files.

Figure 1.4 DMT calibration

## Differential Impedances

Differential impedances are created by the DMT tuners. Since all the measurement tools including instruments, such as VNA, Power meter, and spectrum analyzer are unbalanced, it is necessary to review the method to use standard (unbalanced) instruments to measure differential signals.

Differential components are unique in that signals are referenced not only to a common ground but to each other as well. The signals referenced to each other are called "differential mode" and the signals referenced to a common ground are called "common mode."

Bockelman and Eisenstadt have proposed a method to convert the single-ended data to mixed-mode using mathematical algorithms. These algorithms show the relationship between nodal waves generated by a standard vector network analyser and the associated common and differential waves that generate mixed mode *S*-parameters.

To develop the transformation between standard S -parameters and mixed-mode S - parameters, the mixed mode S-parameters must first be defined.

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \left[ \begin{array}{c|c} Sdd & Sdc \\ \hline Scd & Scc \end{array} \right] \begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix}$$

Where each partition represents a two-by-two S-parameter sub-matrix. The partition labeled Sdd are the differential S-parameters, Scc are the common-mode S-parameters, and Sdc (Scd) are the mode-conversion or cross-mode S-parameters, where Sdc describes the conversion of common-mode waves into differential-mode waves, and Scd describes the conversion of differential-mode waves into common-mode waves.

The transformation can be developed by considering the relationships between the standard and mixed-mode incident waves, a, which can be written as

$$\begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} a1 \\ a2 \\ a3 \\ a4 \end{bmatrix}$$

If

$$M = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

It can be shown that

$$S_{mm} = M \bullet S_{std} \bullet M^{-1}$$

Where $S_{mm}$ are the mixed-mode S-parameters and $S_{std}$ are the standard four-port S-parameters. Additionally, M has the property $M^{-1}=M^{T}$.

By applying the transformation for tuner calibration data, differential mode S parameters can be obtained.

## Microwave Balun

Microwave baluns play a very important role in push-pull amplifier design. A balun splits the signal power incident onto its port 1 equally into ports 2 and 3, but as anti phase voltages. When ports 2 and 3 are driven equally but in anti phase, the balun combines the incident powers into the load terminating port 1. If ports 2 and 3 are driven by *non-differential* signals, an internal resistor dissipates the common-mode component of the incident power.

Since differential tuners are designed with 50 Ω characteristic impedance, in order to match Baluns to tuners, two transition boards are designed with multi-section transformer (25 to 50 Ω), which can be designed using any circuit simulation software (like ADS from Agilent). Thus commercial available 50 Ω connectors can be used on Balun transition boards, which connect baluns and the airlines of the DMT tuners. The transition board is shown in figure 5.

Figure 5: Balun Transition Board

## Differential Load Pull Setup

A Differential Load Pull System (DLPS) is shown in figure 6. The DLPS is a measurement system in which the Load (or Source) total differential impedance is synthesized using a differential tuner.

The unbalanced input signal is split into two balanced signals, which are injected into differential devices through the differential tuner and the input part of the differential test fixture. Signals, amplified by the DUT, are delivered to the output differential tuner and are finally transformed by the output balun transition board to unbalanced signals, which can directly be measured by unbalanced instruments.

A Network Analyzer is not used in the setup, since all components are to pre-calibrated.

The transmission loss of the baluns, the differential tuners and the differential test fixtures are calculated from mixed mode S parameters. All RF parameters of the DUT are eventually extracted by de-embedding the losses. The optimum complex reflection coefficient of source and load can also be obtained by straightforward mathematic calculations. A PC is used to control the DMT tuners and communicate with all instruments via IEEE 488.2 (GPIB) bus. The calibration and measurement software is written in C++; it is capable of controlling the tuners, synthesize any impedance (calibrated or non), and acquire data from instruments as well as parameter extraction.

Figure 6: DLPS Setup with a DUT in Test Fixture

## Measurement Results

The differential load pull system is set up in Focus Microwave Laboratory and used to test push pull transistors provided courtesy of Fujitsu FCSI California (FLL-300IP-2). The test frequency is 2 GHz.

The optimum complex load impedance is obtained for the optimum power, power added efficiency and third order intercept (TOI). Load pull contours for output power are shown in figure 7, and the 3-D view is shown in figure 8. Power added efficiency (PAE) contours and 3-D view are shown in figure 9 and 10. Drain current 3-D contours are shown in figure 11 and show the Smith Chart area where possible oscillations occur.

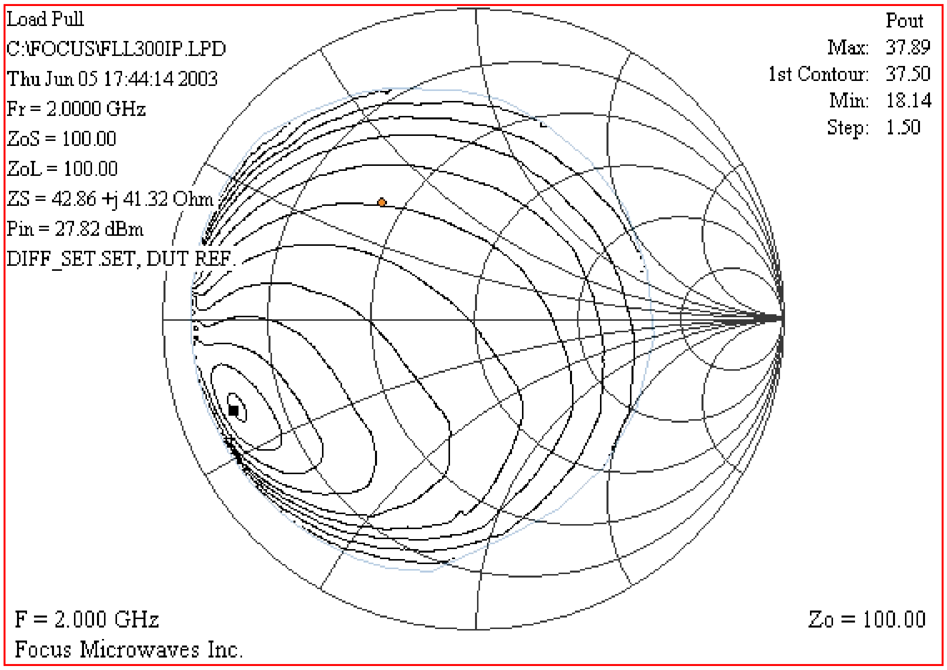


Figure 7: Output Power Contours of push-pull transistor

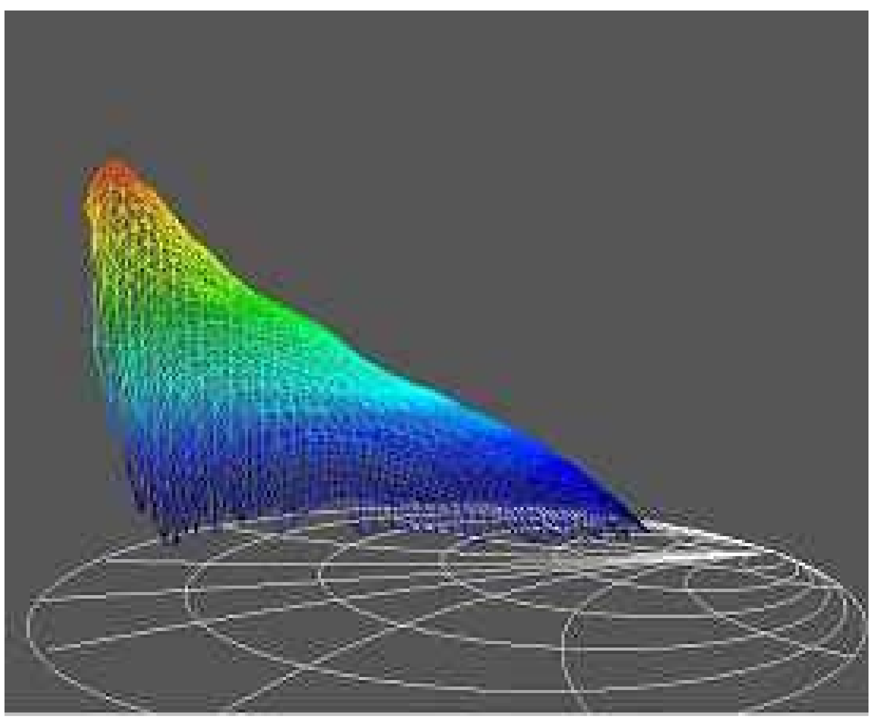

Figure 8: 3-D plot of output power of push-pull transistor

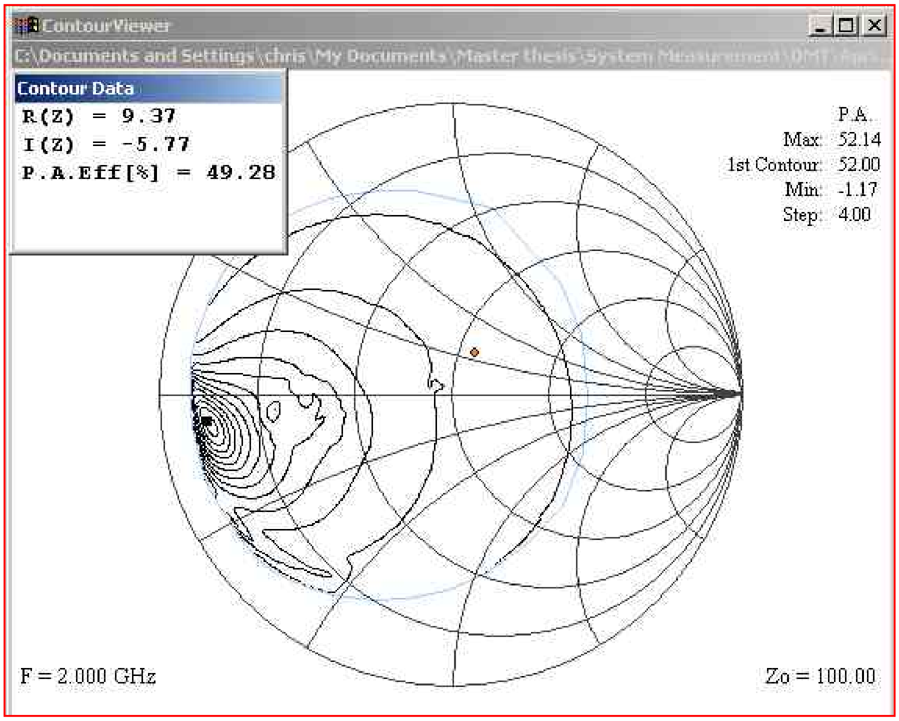


Figure 9 Contours of Power Added Efficiency

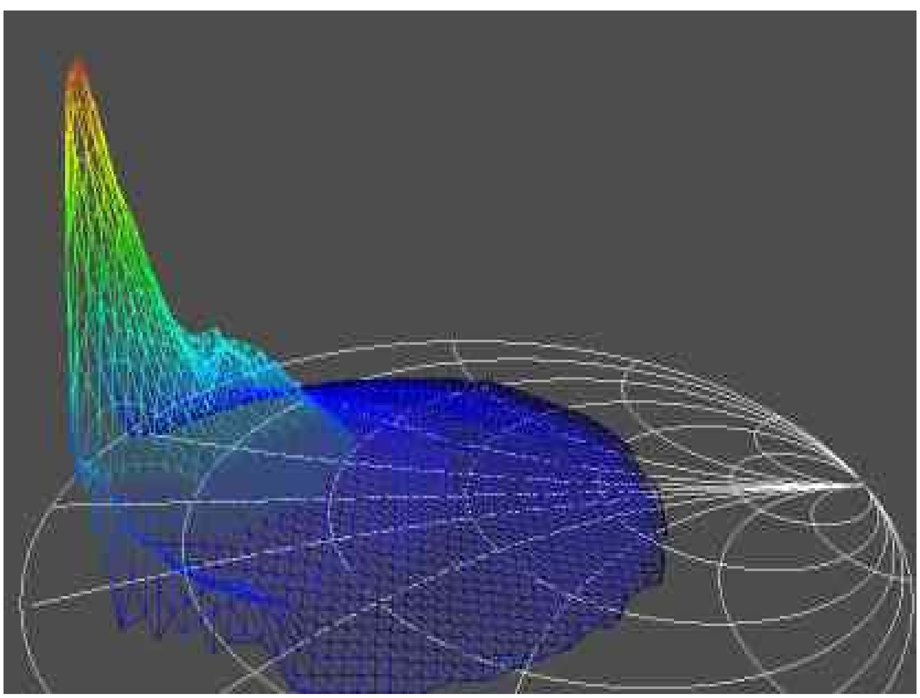

Figure 10 3-D plot of Power Added Efficiency

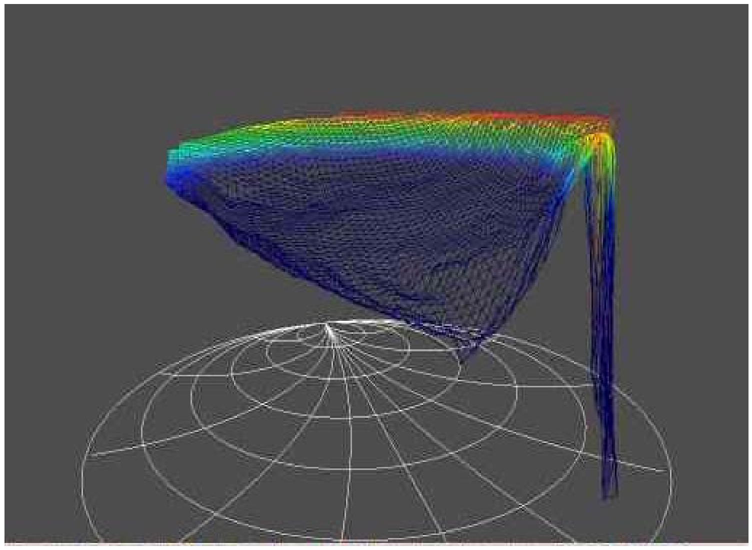

Figure 11: 3-D plot of Drain Current of a push-pull device showing possible spurious oscillation regions.

## Conclusion

A true Differential Load Pull System has been proposed and tested for the first time. The benefit of this system is that the real performance of push pull devices can be explored in true differential mode.

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