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Application Note 15

High Resolution Tuners Eliminate Load Pull Performance Errors

Measurement of Maximum Power and Gain of transistors requires **fine tuning** of source and load impedances simultaneously for which we need high resolution tuners. Digital (electronic) tuners and mechanical tuners without software interpolation between calibration points cannot always realize optimum test conditions. This causes "**performance errors**": the obtained data may not represent the best device performance and load impedance and may lead to incorrect (pessimistic) specifications.

Introduction

Accurate load pull measurements are the basis of state of the art transistor characterization and specification. Well calibrated commercial load pull systems provide device data within 1-2% error (=0.043 to 0.085dB). However, to be able to measure accurately the best performance of a transistor at a given frequency **we have to search and physically set** both source and load impedances to optimum values. A grid of a few hundred tuneable impedances is often not sufficient to accomplish this task. Especially high power devices need fine tuning within a few tenths of 1Ω to perform best. Tuning resolution Δ_ must be less than 1 degree and ΔΓ less than 0.01. This corresponds to at least 360°/0.01=36,000 tuneable impedances.

This requirement is beyond the natural limits of digitally controlled electronic tuners that can synthesize a few hundred impedance points. The same happens to stepping-motor driven mechanical tuners without impedance and loss interpolation capability between calibrated points.

The mechanical tuners of Focus Microwaves inherently fulfil this requirement: They have a tuning capability between 500,000 and 10,000,000 impedance states depending on frequency and tuner type. For all these states all four S-parameter of the tuners (and the setup) are interpolated among the nine closest calibrated points using 2nd order Lagrange polynoms, as will be described in this note, with an overall tuning accuracy better than 40 and 50 dB (0.3 to 1%).

This guarantees that the optimum impedances can be presented to the transistor tested and "performance errors" will not occur.

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Test Methodology

We verified the importance of high resolution tuning on power transistors at 900-1000 MHz, a typical frequency for PCN applications. All conclusions drawn are broadly valid for any frequency for which tuners are available and used. In this case the tuning resolution of our tuners is 5,240,000 points, because we used 1808-CCMT tuners with 25.4 µm horizontal step size (table 1).

We compared two cases:
In the first case we calibrated the tuners at 361 impedance points. The CCMT system offers the possibility to measure either at 361 points or a fraction of it (181 or 95 points). We first pre-match the output tuner to be close to the optimum load impedance. Then we run Source Pull. This automatic routine tunes only to calibrated impedance points, measures and saves in a file all measured data. Then we generate a contour plot and pick the optimum source impedance point. Subsequently we set the source tuner to this impedance and run Load Pull. Again the software tunes and measures only at the selected number of calibrated points: 361, 181, 95 etc... calibrated points. The result of these two tests is the best performance of the device, according to this "calibrated point" based test.

In the second case we alternatively match input and output tuners using high resolution Cursor (manual) tuning. The result is different from the first case, depending on the transistor, bias, frequency and input power conditions.

Even though we cannot say that the result of the first method is always wrong and by how much, the **possibility of an error exists**. If we use inappropriate hardware and software there is no practical way to be certain if this is the case or not. This is exactly the problem Engineers have when they use automatic systems: To be sure that what they measure is accurate and at the right test conditions (load/source impedances).

This phenomenon explains also the discrepancy many Engineers encounter when they test transistors using manual tuners (which have infinite resolution) and automatic tuners, which by their nature have limited resolution. The disadvantage of manual tuning, however, is that we only can optimize the overall Gain and the conclusions drawn for the de-embedded devices are wrong [1]. But still there is the feeling that we are not able to get the optimum performance out of a transistor.

Some may argue that the output power or gain of the transistors are continuous functions of impedance and therefore numerical smoothing will generate the optimum impedance for the top of the measured surface.

This is only a partial remedies. The fact is that we have to present to the transistor the exact impedance at the input and output in order to generate the right overall gain. It is not enough to be able to find out, using interpolation techniques, which the optimum impedance on one side of the device is: This is only valid for small signal operation (like Noise measurements). In the case of nonlinear or even quasi saturated operation **we must be able to tune the device to its optimum impedances physically**. For this we need high resolution tuners.

Test Results

This page summarizes the test results on a bipolar medium power transistor at 1000 MHz using the CCMT-1808 (0.8 - 18 GHz) load pull setup at three different input power levels.

Pin=6 dBm

Number of CAL Points	Z-source-opt [Ω]	Z-load-opt [Ω]	Pout-max [dBm]
95	5.9+j2.1	19.2+j36.3	21.1
181	6.1+j4.2	25.1+j60.6	22.38
361	6.1+j4.2	25.1+j60.6	22.37
Manual Fine Tuning	6.4+j5.1	25.6+j59.1	22.58

Pin=16 dBm

Number of CAL Points	Z-source-opt [Ω]	Z-load-opt [Ω]	Pout-max [dBm]
95	6.5+j3.7	19.2+j36.3	28.4
181	6.1+j7.4	25.3+j43.7	30.05
361	6.1+j5.7	36.9+j43.5	30.13
Manual Fine Tuning	6.8+j6.1	36.2+j43.0	30.80

Pin=26 dBm

Number of CAL Points	Z-source-opt [Ω]	Z-load-opt [Ω]	Pout-max [dBm]
95	7.4+j9.1	87.8+j15.4	30.20
181	7.2+j12.1	102.9+j19.3	31.40
361	6.8+j9.8	102.9+j19.3	31.50
Manual Fine Tuning	6.5+j8.4	92.3+j24.0	31.95

It is important realize that this result is rather optimistic since the tuner calibration of Focus Microwaves provides, even at low density (95 points) an equal coverage of the Smith Chart. If electronic tuners are used it may happen that **entire areas of the Smith Chart remain uncovered (blind spots)**. In this case the possible error will certainly be higher.

Tuning Resolution of Focus Tuners

Tuning resolution is determined by the horizontal and vertical step size of the tuner mechanism. CCMT tuners use a vertical step of 1.5µm and horizontal steps of 3 to 25.4µm. MTS tuners use a vertical step of 2.5µm and a fixed horizontal step of 25.4µm.

Vertical tuning is not linear. The closer the RF slug comes to the centre conductor, the higher the tuning sensitivity. Overall active vertical tuning range is about 1200 steps for CCMT tuners and 800 steps for MTS tuners. This allows us to calculate the typical tuning resolution for the different available tuner types and frequencies. In particular cases, depending on the best compromise between high resolution and tuning speed, CCMT tuners can be custom configured at the factory to meet the user's requirements.

Typical tuning resolution data of standard tuners are shown below:

Tuner Model	**Horizontal Step**	**Points at f-min**	**Points at f-max**
1. Coaxial Tuners			
MTS-308	**25.4 µm**	**5,900,000 @ 800 MHz**	**1,570,000 @ 3 GHz**
CCMT-304-CK	**25.4 µm**	**11,800,000 @ 400 MHz**	**262,000 @ 18 GHz**
CCMT-306	**25.4 µm**	**7,860,000 @ 600 MHz**	**1,570,000 @ 3 GHz**
CCMT-1808	**13.7 µm**	**11,800,000 @ 800 MHz**	**524,000 @ 18 GHz**
CCMT-1816	**6.35 µm**	**11,800,000 @ 1.6 GHz**	**1,048,000 @ 18 GHz**
CCMT-2604	**6.35 µm**	**4,720,000 @ 4 GHz**	**712,000 @ 26.5 GHz**
CCMT-4006	**6.35 µm**	**3,146,000 @ 6 GHz**	**472,000 @ 40 GHz**
2. Waveguide Tuners			
CCMT-5033	**3.0 µm**	**1,515,000 @ 33 GHz**	**1,000,000 @ 50 GHz**
CCMT-7550	**3.0 µm**	**1,000,000 @ 50 GHz**	**666,000 @ 75 GHz**
CCMT-11075	**3.0 µm**	**666,000 @ 75 GHz**	**454,000 @ 110 GHz**

Table 1: Tuning Resolution of Focus Tuners

Focus System Software (SYSOFT) generates four S-parameter for the tuners for each of the above tuneable positions based on the nine closest calibration points and second order interpolation as we will describe later in this note.

Tuning Speed of High Resolution Tuners

Tuning resolution has its price. To a great extend this is tuning speed.
The higher the number of tuneable impedances the more time it takes to go from one point of the Smith Chart to another. This is valid mostly for random tuning, ie. being able to tune from any point to any other point. In automatic load pull or peak search measurements the tuned impedances are adjacent and tuning time is much shorter.

The general relation that permits to estimate tuning time of a Focus tuner with a horizontal step size **STP [mm]** at a frequency **freq [GHz]** between two points on the Smith Chart distant by **Δ_ degrees** and **ΔΓ in amplitude** is as follows:

$$\Delta T \text{ [seconds]} \approx 8.3 \bullet 10^{-4} \bullet \Delta\_ \text{ [degr]} / (\text{STP[mm]} \bullet \text{freq [GHz]}) + 2 \bullet \Delta\Gamma$$

In a "worst case" scenario, tuning between two points one at the centre of the Smith Chart and one at $\Gamma=0.8$ and 180 degrees apart at 1 GHz using a 306-CCMT tuner, would take about 8 seconds.
Tuning time between adjacent calibrated points (≈10 degrees apart) will be 0.3 seconds.

At 40 GHz tuning between opposite points using a 4006-CCMT tuner will take 2.5 seconds whereas tuning between adjacent calibrated points will be 0.03 seconds.
At millimetre wave frequencies tuning time is even shorter.

In all these cases tuning time is not the only limitation of the system. Depending on the GPIB instruments and averaging factors used, measurement time can be of the order of a few hundred milliseconds up to one second for accurate reading of RF power using a true bolometer. These measurement delays then become of the same order of magnitude as tuning time and should be considered in order to put lower speed of high resolution mechanical tuners in true proportion to the total measurement time.

Reading Speed of GPIB Instruments

GPIB instrument reading is not instantaneous. It depends on the particular instrument and the actual reading range, averaging factor etc. We tested reading time using a 486/DX2/66MHz PC and special routines which make a large number of readings and normalize over the time past. Table 2 presents some examples.

Instrument	Reads	Average	Time/Reading
Network Analyzer (Wiltron 360)	4 S-parameter (1 frequency)	16	200 ms
Spectrum Analyzer (MS 2602A)	Peak Power	1	100 ms
Digital Multimeter (HP 34401A)	Voltage	1	360 ms
Power Meter (Boonton 4200)	RF Power	1	130 ms

Table 2: Reading time of some GPIB instruments

S-parameter Tuner Interpolation of Focus Software

CCMT tuners are calibrated for each frequency at a fixed number of impedance points covering as equidistantly as possible the whole Smith Chart. The number of calibration points can be selected between 95, 181 and 361. Optionally CCMT tuners can be calibrated at 385 points [2]. The MTS system software provides 181 calibration points.

This does not mean that only these points can be tuned. In reality any point of the Smith Chart can be tuned to, the number of tuneable states varying between 500,000 and 11 million (table 1). Obviously all these tuneable states are useless if the system software is unable to generate the four S-parameter of the tuners accurately for each of these points.

Focus' system software accomplishes this task using nonlinear numerical inter- and extra-polation routines selected to generate maximum accuracy in shortest computing time [3]. These routines have been transformed to work in a coordinate system which best fits the nature of our tuners: Phase and amplitude of the reflection factor are controlled practically independently: Horizontal movement controls the phase whereas vertical movement controls almost exclusively the magnitude of the reflection factor.

The interpolation algorithm works as follows: Each time the tuner is moved to a certain physical position X (horizontal) and Y (vertical) [motor steps] the software first identifies the closest calibrated vertical levels. It takes into account two calibration levels above (Y2 and Y3) and one level (Y1) below the actual Y value. Then it searches the S-parameter of the calibration points of the three closest horizontal levels (X1, X2, X3) to the actual X value. This generates a grid of a total of 9 calibration points around the actual point: [X1,Y1], [X1,Y2], [X1,Y3] [X2,Y1], [X2,Y2], [X2,Y3], [X3,Y1], [X3,Y2] and [X3,Y3].
In a first step virtual calibration points are generated at the vertical level Y, but at calibrated horizontal levels X1, X2 and X3: [X1,Y], [X2,Y] and [X3,Y] using 2nd order Lagrange interpolation polynoms in vertical direction:

$$S_{ij}(X_k,Y) = L_0(Y) \bullet S_{ij}(X_k,Y_1) + L_1(Y) \bullet S_{ij}(X_k,Y_2) + L_2(Y) \bullet S_{ij}(X_k,Y_3)$$

where $\{k\} = \{1, 2, 3\}$

$$L_0(Z) = \frac{Z - Z_2}{Z_1 - Z_2} \bullet \frac{Z - Z_3}{Z_1 - Z_3}$$

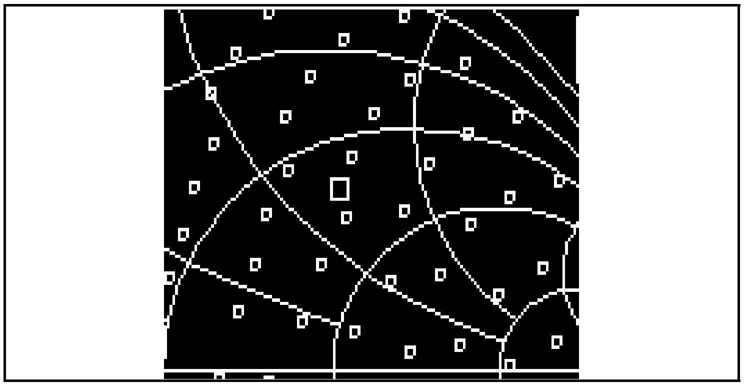
$$L_1(Z) = \frac{Z - Z_1}{Z_2 - Z_1} \bullet \frac{Z - Z_3}{Z_2 - Z_3}$$

$$L_2(Z) = \frac{Z - Z_2}{Z_3 - Z_2} \bullet \frac{Z - Z_1}{Z_3 - Z_1}$$

$Z = X$ or Y and $S_{ij}(X_k,Y_m)$ are the real and imaginary parts of the four measured S-parameter of the tuner at the calibrated points $[X_k,Y_m]$ for $\{k,m\} =\{1,2,3\}$ and $\{i,j\} = \{1,2\}$.

In a second step the calculated S-parameter at these virtual calibration points are used for a second interpolation in horizontal direction using the same formulas as before.

$$Sij\ (X,Y) = L0\ (X) \bullet Sij\ (X1,Y) + L1\ (X) \bullet Sij\ (X2,Y) + L2\ (X) \bullet Sij\ (X3,Y)$$



These two interpolation steps permit to calculate real and imaginary part of all four S-parameter of the tuner Twoport at every physical position X,Y (in motor steps). As figure 1 shows the dependence of the magnitudes of S11 and S22 of a tuner on vertical movement of the RF slug are nonlinear but still quite smooth; The phases of S11 and S22 also change with Y but quite slowly. The magnitudes of S11 and S22 do not change with horizontal movement.
S12 and S21 change only with vertical movement and remain constant for all horizontal positions. We found that this natural behaviour of Focus' tuners can be described very accurately with the formulas given.

All experimental evidence up to now shows that well adjusted and calibrated tuners permit total interpolation and tuning error between 40 and 50 dB up to 18 GHz. At higher frequencies overall accuracy slightly drops to 35-40 dB. This in general includes network analyzer drift between calibration and test of the tuners, mechanical instability and temperature effects on the tuners and the test cables. The pure mechanical resetability of the tuners is easier to test in short time and permits this way to eliminate network analyzer drift and temperature change effects. We found the pure mechanical resetability of S-parameter of the tuners, set to arbitrary impedances at different frequencies, to be between 50 and 60 dB up to 18 GHz dropping slowly at higher frequencies [4].

The difference between total error and pure mechanical resetability error can be attributed to some extend to the interpolation mathematics.
We also found some accuracy improvement when increasing the number of calibrated points from 95 to 181; further increase of calibration points to 361 also enhances accuracy but to a lesser extend.

Conclusion

We analyzed the importance of high resolution tuners with accurate nonlinear interpolation capability between calibrated points in order to eliminate "performance errors" in transistor load pull characterization. An example at 1000 MHz shows a possible error between 0.5 and 1.5 dB in Pout and 10 to 20% in Zin when high resolution tuners are not available.

There is no practical way to correct this error except by using a properly calibrated high resolution tuning system.

We also presented typical tuning resolutions and tuning speed of Focus tuners and GPIB instruments. We described and explained the basic tuner interpolation algorithm.

References

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[4] "RF-Resetability Test of CCMT's" , Appendix to CCMT 4.0 operation Manual, Focus Microwaves, 1993