A NOVEL FAST SEARCH ALGORITHM FOR AN ACTIVE LOAD-PULL MEASUREMENT SYSTEM

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ABSTRACT

In this paper a novel fast search algorithm for an active load-pull algorithm is presented. This algorithm is based on the fact that it is possible to fit, with a minimum number of measurements, the desired parameter, for instance the output power, as function of the load reflection coefficient. The fitted function is used to make a prediction of the location of the optimum load reflection coefficient. Application of the novel load-pull algorithm has resulted in a 8 time reduced measurement time. In this paper also the load-pull measurement system installed at TNO-FEL and some measurement results obtained with the described search algorithm are discussed.

INTRODUCTION

It is of vital importance for the development of High Power Amplifiers (HPAs) to have accurate information available regarding the optimum load impedance of the transistors used. At this moment this optimum load impedance is most of the time determined with the help of a load-pull measurement system.

In this paper the active load-pull system that is installed at TNO-FEL will be discussed. The drawback of the measurement system is the long measurement time necessary to find the optimum load impedance. This is due to the iterative nature of the active load-pull measurement system used. To circumvent this problem the novel fast search algorithm discussed in this paper has been developed. At the end of this paper also some measurement results are discussed that are obtained with the help of this novel fast search algorithm.

ACTIVE LOAD-PULL SYSTEM TNO-FEL

The load-pull measurement system developed at TNO-FEL is an integrated part of a larger measurement system that has been developed for the on-wafer characterisation of Microwave Monolithic Integrated Circuits (MMICs). This measurement system, see figure 1 for a block diagram, has the following measurement capabilities: S-parameter, noise figure, pulse profile, intermodulation, spectrum, power and load-pull measurements. The measurements can be performed in both the pulsed and in the CW mode.

In our measurement system the loss between the load-pull tuner and the output of the Device Under Test (DUT) is approximately 5 dB. This means that the maximum reflection coefficient that can be applied to the DUT has a maximum magnitude of 0.3. This is too low because the expected optimum load reflection coefficients are larger than 0.6. For this reason it was decided to use an active load in our load-pull measurement system. The loss between the load-pull tuner and the output of the DUT can be compensated for with such an active load. With an active load a reflection coefficient with a magnitude up to one can be applied to the output of the DUT.

The active load used in our measurement system is based on the principle first described by Takayama (1). A simplified block diagram of the load-pull system that has been implemented, is shown in figure 2. The amplitude and phase of the reflected signal are controlled with the help of a vector modulator. The performance of this vector modulator is described by Tieman (2). No feedback system has been used to realise the active load, as can been seen from figure 2. This has been done to avoid the feedback oscillations that are common for such type of the active loads. A disadvantage of the approach used, is the fact that a large number of iterations are necessary to set the reflection coefficient at every frequency and input power of the DUT. This is due to the fact that the load reflection coefficient depends on the output power and gain of the DUT which on their turn are also load reflection coefficient dependent. A long measurement time is the result from the large number of iterations necessary to set a load reflection coefficient. The measurement time at this moment is 30 s per iteration. A measurement time of 150 hours, for one frequency and one input power, is obtained, if one wants to measure all possible load reflection coefficients with an amplitude between 0 and 1 and a phase between 0° and 360° with an amplitude resolution of 0.01 and a phase resolution of 2°. This measurement time can be reduced by putting in some more intelligence in the selection of the area in the Smith chart that is load-pulled. It is for instance possible to measure the conjugated of the output reflection coefficient of the DUT and measure in a limited area surrounding this reflection coefficient. Note that it is with our measurement system possible to perform the necessary S-parameter measurement for the determination of the conjugated output reflection coefficient without reconnecting the

DUT. Nevertheless the resulting measurement time is still more than 4 hours for each frequency point. The fast search algorithm described in the next section has been developed to reduce the measurement time.

The load-pull measurement system is fully vector error corrected up to the probe tips. For performing the calibration and load-pull measurements the equations described Ferrero and Pisani (3) are used. A summary of the measurement capabilities of the load-pull measurement system is listed in table 1.

NOVEL FAST SEARCH ALGORITHM

In this section the developed novel fast search load-pull algorithm is discussed. A flow graph of this algorithm is shown in figure 3. In the remainder of this section the depicted steps shown in the flow graph are discussed.
A start reflection coefficient is selected as first step. The conjugated of the output reflection coefficient of the DUT is an example of a good starting point. With the help of this starting point the maximum one dB output power compression point or the maximum Power Added Efficiency (PAE) point of a transistor can for instance be determined.

In the following step the desired parameter, for instance the output power, is measured at a set of different load reflection coefficients. The first measurement will be performed at the load reflection coefficient that is depicted in the centre of the circle shown in figure 4. This centre point is the, at the given moment, best estimation of the optimum load reflection coefficient. As next step at least five measurements, at a circle surrounding this centre point, must be performed. For our search algorithm the radius of this circle is set to 0.1. Experiments have shown that the algorithm gives good results when six equally spaced reflection coefficients on the circle are measured. For the location of the load reflection coefficients the so called Centre Composite Inscribed selection method is used. According to Walton et al. (4) this selection method is particular appropriate for contour mapping when the relation between the measured parameter is no more than second order. In our experience this assumption is valid for the parameters measured with the active load-pull measurement system.

At this point in the search algorithm the measured parameter, for instance the output power, is fitted as function of the load reflection coefficients. The measurement data is fitted with the help of a least square method to the equation listed in 1.

$$Z = a_0 + a_1 \cdot X + a_2 \cdot X^2 + a_3 \cdot Y + a_4 \cdot Y^2 \tag{1}$$

In this equation is Z the measured parameter that must be fitted. X is the real part of the load reflection coefficient and Y is the imaginary part of the load reflection coefficient. An example of the ability to fit the measured parameters with the help of equation 1, is listed in table 2.

After the coefficients of equation 1 are determined it is possible to find the optimum load reflection coefficient for the current set of parameters. The optimum load impedance is calculated from setting the derivatives of equation 1 to 0. This gives the following optimum for the reel (X_{OPT}) and imaginary (Y_{OPT}) part of the load reflection coefficient, see equation 2 and 3.

$$X_{OPT} = \frac{-a_1}{2 \cdot a_2} \tag{2}$$

$$Y_{OPT} = \frac{-a_3}{2 \cdot a_4} \tag{3}$$

The whole procedure is repeated until one of the following criteria is met:

1. The maximum number of iterations is reached. We have set this number to eighth. This number was hardly ever reached during our experiments. Most of the time the optimum load impedance is found within 3 iterations.
2. The difference between two successively determined optimum load reflection coefficient falls inside a specified resolution. The resolution used by TNO-FEL at this moment is 0.02 for the amplitude and 2° for the phase.

With the help of the described load-pull search algorithm the measurement time, for one frequency and input power, was reduced from more than 4 hours to less than 30 minutes. Note that the described algorithm is also applicable for systems that make use of passive tuners. The speed improvement will there be less because of the absence of the iterations necessary to set a load reflection coefficient. Nevertheless also a speed improvement is found because fewer measurements will be necessary to find the optimum load impedance.

MEASUREMENT RESULTS

In this section some load-pull measurement results obtained with the measurement set-up and fast search algorithm described in the previous sections will be shown. In table 3 the large-signal measurement results obtained at the optimum load impedance of a transistor matrix are shown. The listed results have been obtained in less than 4 hours. This would have taken in the past more than 3 days, so a very significant speed improvement has been obtained.

The capability of the measurement system to measure the for a HPA design relevant parameters as function of the input power is demonstrated in figure 5. In this figure the measurement results are shown at the optimum load impedance for maximum output power.

CONCLUSIONS

A novel fast search algorithm for an active load-pull measurement system is described. With the help of this algorithm the measurement time of one DUT, at a specific frequency point and input power, has been reduced from 4 hours to less than half an hour.

The described algorithm can also be used for conventional system that make use of passive tuners.

REFERENCES

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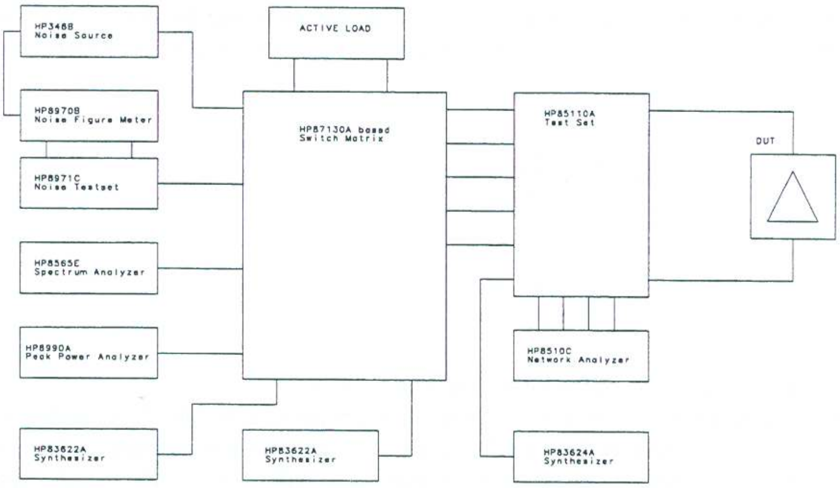

Figure 1: Block diagram of the TNO-FEL MMIC measurement system.

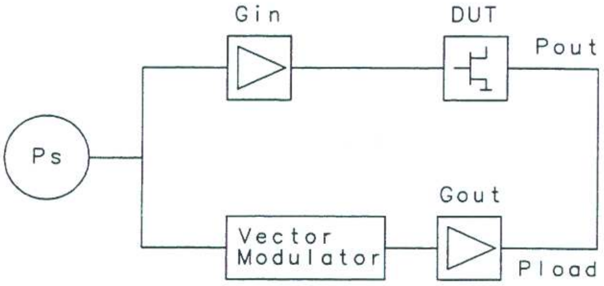

Figure 2: *Block diagram active load-pull measurement system*

Table 1: Summary measurement ranges active load-pull measurement system TNO-FEL.

	Range
Frequency	8 - 12 GHz
Input power	3 W
Output power (Γload=1)	3 W

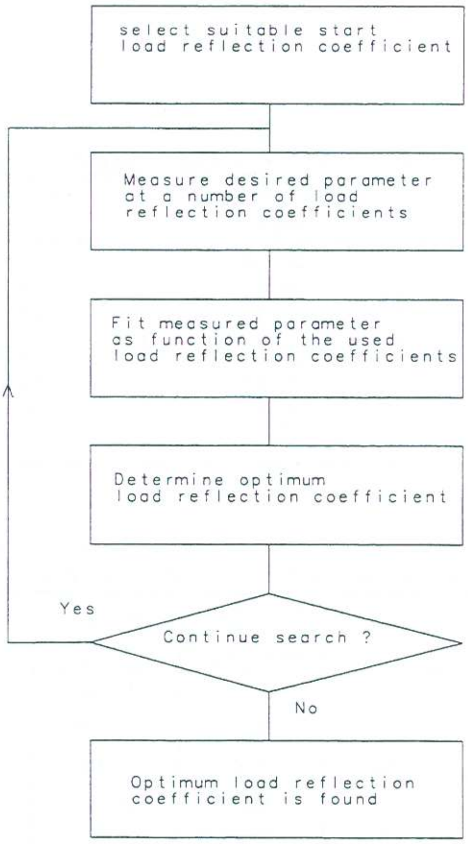

Figure 3: *Fast load-pull search algorithm*

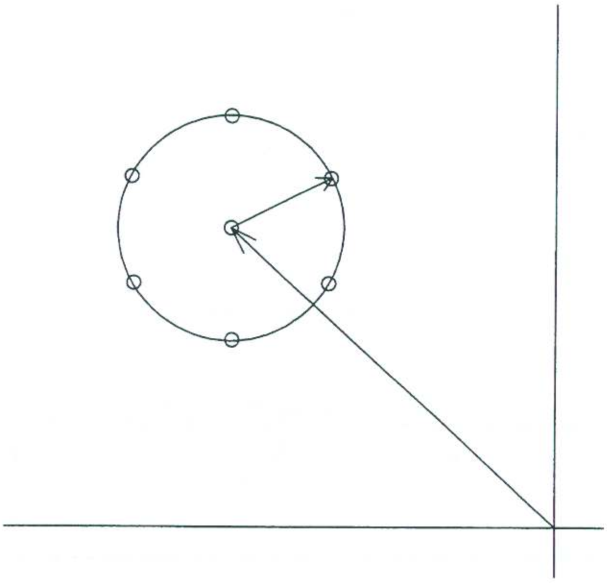

Figure 4: *Location of the measured load reflection coefficients.*

Table 2: Comparison between the measured and the with equation 1 fitted output powers.

$\lvert\Gamma_{load}\rvert$	$\varphi(\Gamma_{load})$	Pout measured [dBm]	Pout fitted [dBm]
0.647	151	28.70	28.70
0.602	143	28.36	28.27
0.701	144	27.73	27.75
0.747	151	28.03	28.09
0.704	158	28.87	28.85
0.605	159	29.19	29.18
0.547	151	28.91	28.94

Table 3: Measured large-signal parameters at the optimum load impedance. The optimum load impedance has been determined for maximum output power at f=8 GHz, Vds=9 V and Vgs=-1.25 V.

Transistor	Width [mm]	$\lvert\Gamma_{opt}\rvert$	$\varphi(\Gamma_{opt})$ [°]	Pout-1dB [mW/mm]	Gp-1dB [dB]	PAE-1dB [%]	Pout-2dB [mW/mm]
#1	1.28	0.47	138	595	11.94	48.77	677
#2	1.6	0.49	150	599	11.63	52.88	647
#3	2.0	0.55	159	598	10.88	52.43	649
#4	2.4	0.60	164	590	10.43	52.68	634
#5	2.8	0.64	167	578	9.72	51.86	615
#6	3.0	0.67	169	626	9.34	50.18	661
#7	3.2	0.68	169	628	9.06	51.27	677

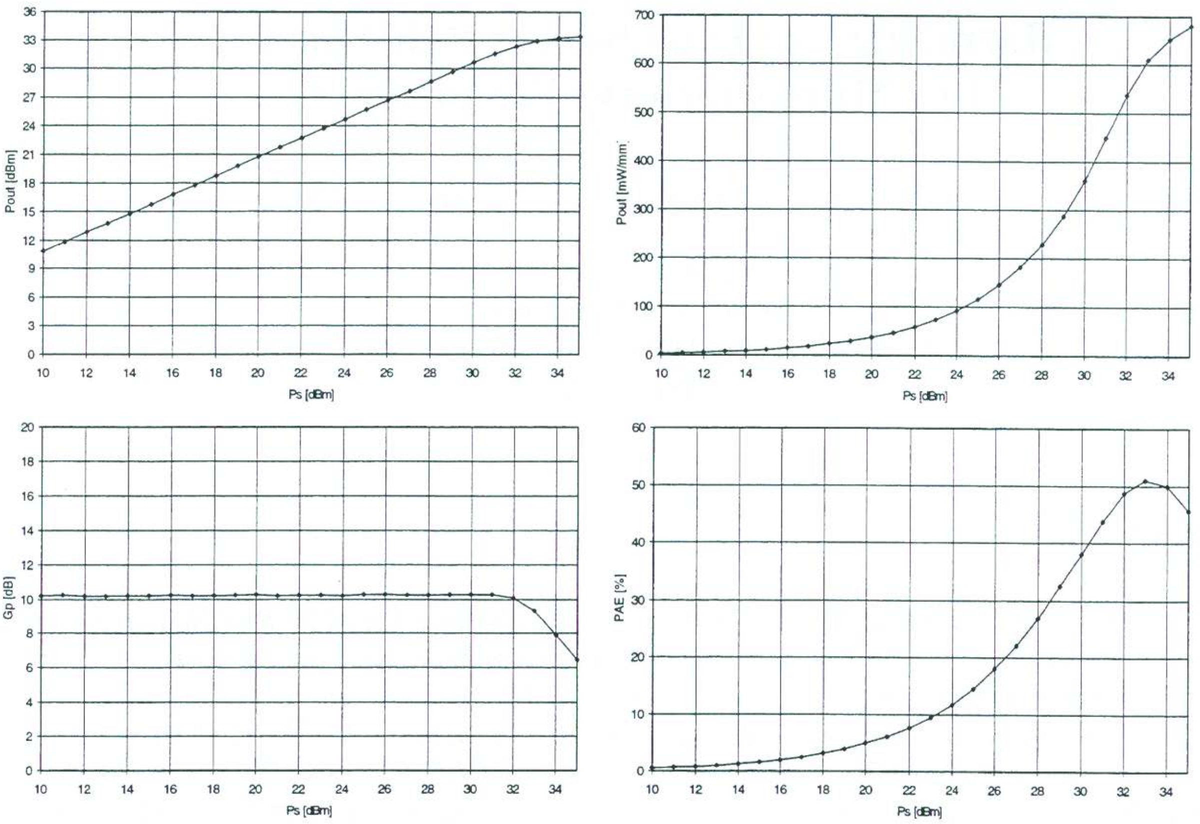

Figure 5: Measured large-signal parameters of a 3.2 mm transistor measured at the optimum load impedance at f=8 GHz, Vds=9 V and Vgs=-1.25 V.