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In Situ Waveform Measurement Approach within an inverse class F GaN Power Amplifier

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Abstract — In this contribution a gallium nitride (GaN) based inverse class F (F^{-1}) power amplifier with in situ waveform measurement capability is presented. Which the measurement approach the high frequency time domain voltages and currents in a reference plane can be measured directly in the circuit. Therefore, a directional coupler is integrated in the output matching network of the F^{-1} power amplifier. With this measurement results, a more in-depth investigation of the F^{-1} power amplifier can be carried out under operational conditions. Also it is a suitable approach for describing the non-linear behavior of RF circuits under operational conditions.

Index Terms — Efficiency, inverse class F, non-linear, time domain measurement, power amplifiers.

I. INTRODUCTION

Amplifier architectures are commonly complex circuits. Normally the amplifier can be characterised by measuring input and output quantities and the DC operation point. In [1] a two-stage GaN amplifier is presented, where the high frequency voltages in an interstage matched amplifier are measured with a calibrated high impedance probe. The authors investigated the effect of the high frequency voltage waveform on the amplifier efficiency, because knowing the voltages within the circuits is of interest for the amplifier design, characterisation and optimization. However, for a more in-depth investigation of a power amplifier, the additional knowledge of the high frequency current is necessary. In [2] the authors proposed an approach for optimizing the efficiency of a silicium (Si) LDMOS device under class F and F^{-1} condition by measuring the high frequency voltages and currents using a complex load-pull measurement system from [3]. In this contribution the high frequency voltages and currents will be measured in the output matching network within a realized F^{-1} power amplifier under operational condition. With the additional benefit of knowing the waveforms it is suitable to verify and optimize the design by the impedance, the power and the efficiency requirements.

First, the operational principle of the in situ waveform measurement approach is introduced. Furthermore, a setup for a comparison of the in situ waveform measurement approach to a direct measurement with an oscilloscope is presented in Section II. Section III shows the design of the F^{-1} power amplifier with the integrated directional coupler for the measurement of the waveforms in a reference plane. Subsequently in Section IV, the waveform measurement results of the developed F^{-1} power amplifier are discussed.

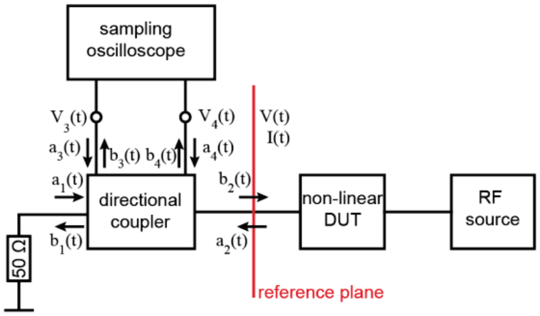

Fig. 1. Schematic of in situ waveform measurement setup.

II. IN SITU WAVEFORM MEASUREMENT

A. Concept

Using the high frequency voltages V(t) and currents I(t) in time domain [3] is a suitable approach for describing non-linear behavior of RF circuits. Fig. 1 shows the schematic of measurement setup based on a sampling oscilloscope and a directional coupler.

The directional coupler detects the incident and reflected waves of the device-under-test (DUT). The coupled waves $b_3(t)$ and $b_4(t)$ are measured in time domain with the sampling oscilloscope. The high frequency voltage V(t) and current I(t) in the DUT's reference plane can be determined from the $a_2(t)$- and $b_2(t)$-waves with the system impedance Z_0 as followed [3]:

$$V(t)=\left(a_2(t)+b_2(t)\right)\cdot\sqrt{Z_0} \quad (1)$$

$$I(t)=\left(a_2(t)-b_2(t)\right)/\sqrt{Z_0} \quad (2)$$

To calculate the V(t) and I(t) the measurement setup has to be calibrated taking into account the frequency response of the directional coupler and of the measurement setup, that can be described by a 2x2 error matrix **E**, with the error coefficients e_{xy}. The theory of the calibration is not in the scope of this paper. It is described in detail in [3].

In the following the measurement setup should be realized as a microstrip technology circuit. Therefore, the reference plane is set to be at a position on a microstrip line with a characteristic impedance of $Z_0 = 50\ \Omega$. Therefore, the calibration procedure was modified using a TRL calibration [4] with a reference plane on the microstrip line. After this step V(t) and I(t) can be calculated in the reference plane.

B. Verification

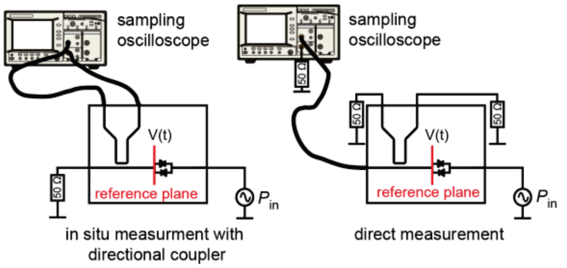

Fig. 2. Verification setups for the in situ measurement with directional coupler and direct measurement.

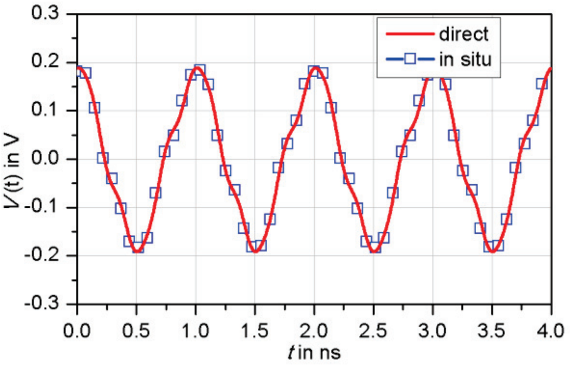

Fig. 3. Measured voltage waveform comparison at P_{in} = 6 dBm.

To determine the accuracy of the in situ measurement approach a comparison between a direct measurement and the in situ measurement approach with the coupler has been carried out. For all measurements the sampling oscilloscope 86100B from Agilent with module 86117B is used. The test circuit consists of two antiparallel diodes, which are connected over two microstrip lines with a characteristic impedance of Z_0 = 50 Ω. At the left side of the diode circuit a directional coupler is integrated into the circuit. The RF source provides an available source power of P_{in} = 6 dBm at a frequency of f_0 = 1 GHz. The resulting voltages V(t) in the reference plane are calculated in MATLAB with the predetermined error coefficients e_{xy} and the measured waves for both methods.

A comparison of the measured results in Fig. 3 shows a good agreement between both methods. The diodes clip and attenuate the input signal. As result the signal contains higher harmonics.

Fig. 3 proves the accuracy of the in situ waveform measurement system for the fundamental frequency and the higher harmonics of both methods. This is confirmed by comparing both methods in the frequency domain as well.

III. DESIGN OF AN INVERSE CLASS-F POWER AMPLIFIER

The schematic of the developed F^{-1} power amplifier for a frequency of f_0 = 1 GHz with integrated directional coupler in the output matching network is shown in Fig. 4.

In a F^{-1} power amplifier the fundamental wave is terminated with the optimal load impedance Z_{opt}. At Z_{opt} the F^{-1} power amplifier delivers the maximum power and efficiency. Furthermore, the matching network provides high impedance at the even harmonics and low impedance at the odd harmonics. With this termination a theoretical drain efficiency of η_{DE} = 100% is possible [5]. In the following only the second and third harmonic are terminated according to [6]. For this type of termination a theoretical drain efficiency of η_{DE} = 92% can be achieved [5], [7]. At the microstrip line TL1 a directional coupler with a coupling factor of -35 dB is integrated into the design, in order to measure the high frequency voltages V(t) and currents I(t) in the reference plane as it is described in the previous section.

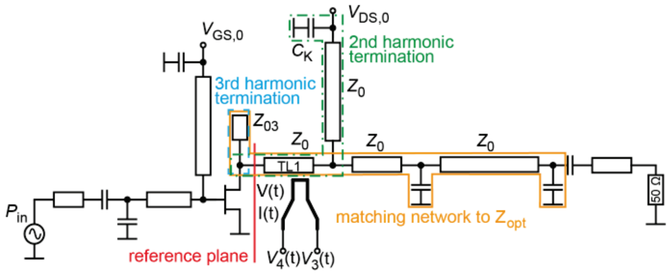

Fig. 4. Schematic of the developed F^{-1} power amplifier.

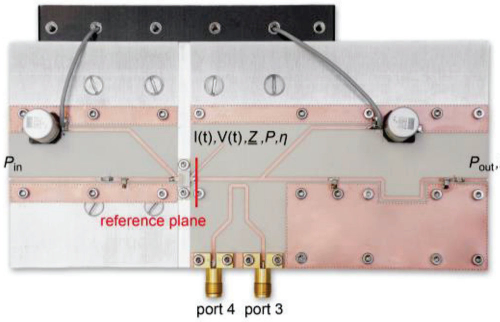

Fig. 5. Realized F^{-1} power amplifier.

IV. REALIZATION OF AN INVERSE CLASS-F POWER AMPLIFIER

The F^{-1} power amplifier uses a 10 Watt GaN HEMT device from Cree. Fig. 5 shows the realized F^{-1} power amplifier. The gate bias voltage is set to $V_{GS,0}$ = -2.9 V, which corresponds to the threshold voltage of the transistor. The DC supply for the drain bias voltage is set to $V_{DS,0}$ = 28 V.

Before starting measurement a calibration procedure of the time domain waveform measurement setup must be done with a calibration board at the fundamental and higher harmonics. After determining the error coefficients e_{xy} of the error matrix **E** waves measured in the output matching network of the F^{-1} power amplifier can be used to calculate V(t) and I(t). The resulting fundamental frequency f_0 waveforms for the high frequency voltages V(t) and currents I(t) in the reference plane are shown in Fig. 6 for a input power of P_{in} = 10 dBm and P_{in} = 21 dBm. Using V(t) and I(t) the impedance $\underline{Z}$ in the reference plane can be calculated. Fig. 7 shows the reference plane impedance Z of the frequency $f = f_0$ and $f = 2f_0$ versus the input power P_{in}.

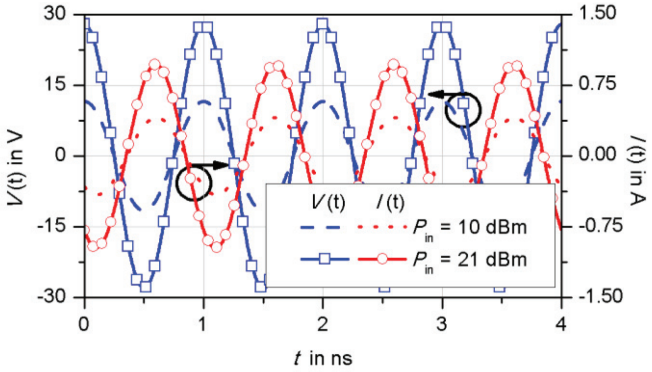

Fig. 6. Measurement results for the voltages and currents at the fundamental frequency f_0 in the reference plane for varying P_{in}.

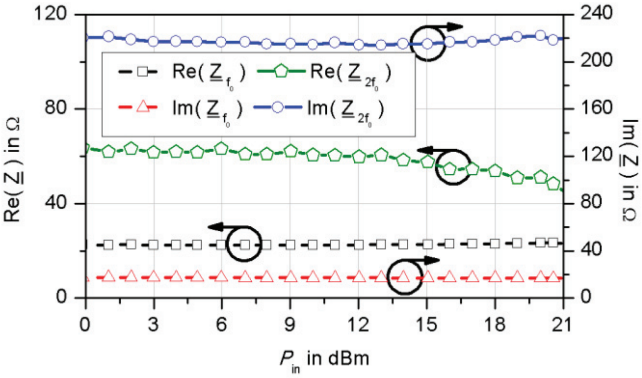

Fig. 7. Measurement results for the real- and imaginary-part of Z of the f_0 and 2 f_0 in the reference plane for varying P_{in}.

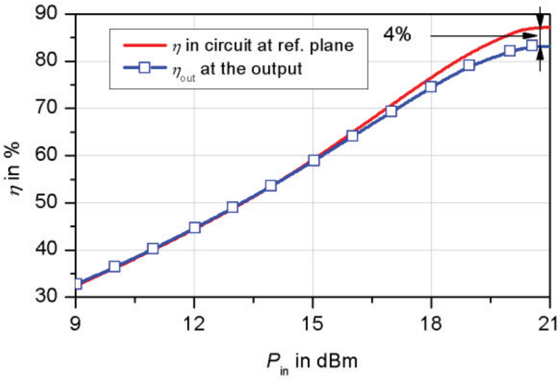

Fig. 8. Measured efficiencies.

With this knowledge the realized output matching network can be compared to the simulation results for further optimization.

Furthermore V(t) and I(t) can be transformed from the reference plane to the current source in the transistor model in order to optimize the amplifier, in [8]. Fig. 8 shows the comparison of the efficiency η in the reference plane and at the output of the power amplifier. In the reference plane the amplifier has an efficiency of η = 87% at P = 40.4 dBm. The measured efficiency η in the reference plane is close to the theoretical drain efficiency η_{DE} = 92%, which can be achieved for an ideal transistor with a termination of the second and third harmonic. At the output port of the F^{-1} power amplifier a power level of P_{out} = 40.2 dBm can be measured resulting in an efficiency of η_{out} = 83%. Both efficiency values η and η_{PA} are determined for an input power of P_{in} = 21 dBm. The difference between both power levels P and P_{out} of 0.2 dB is caused by the insertion loss of the output matching network and accord to a variation of 4% in the efficiency.

V. CONCLUSION

In this contribution a calibrated in situ waveform measurement approach, which is integrated in the output matching network of a F^{-1} power amplifier, is presented. In addition, the in situ waveform measurement approach offers the chance to get further knowledge of power, impedance and efficiency in the reference plane under operating conditions. This in situ measurement approach has an especially advantage in a more complex amplifier topology. Furthermore it is shown, that the F^{-1} power amplifier with a termination of the second and third harmonics achieves an efficiency close to the theoretical value.

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