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Investigation of the Dynamic Load Modulation of an Inverse Class-F Power Amplifier with an Adaptive Matching Network

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***Abstract*— This paper presents a 10 Watt gallium nitride (GaN) based inverse class-F power amplifier with dynamic load modulation. The designed power amplifier uses an adaptive output matching network, which is realized using MEMS switches (micro electro mechanical systems), for the enhancement of the power added efficiency over the dynamic output range. Through the load modulation achieved by the adaptive matching network an efficiency enhancement of approximately 30 pp (percentage point) at 10-dB-back-off at the drain of the transistor is achieved compared to a power amplifier without load modulation. Through the use of an *in situ* measurement approach in-depth investigations of the working principle of the realized amplifier and adaptive matching network are possible.**

***Index Terms*— Adaptive matching network, efficiency enhancement, inverse class-F, load modulation, time domain measurement, power amplifier.**

I. Introduction

Simple power amplifier structures based on a single transistor can achieve their highest efficiency only at the maximum output power. For applications with variable output power, the power amplifier is less efficient when operated at lower output powers. One possible approach to enhance the efficiency is presented in [1], where a class-F power amplifier with a manually tuned matching network is introduced. The benefit of this approach is shown through the efficiency enhancement in the back-off range. A class-AB amplifier with an adaptive matching network for load modulation is presented, e.g., in [2]. Furthermore, a multi-mode-matching output network is described, e.g., in [3] and shows the application of RF-MEMS switches for the reconfiguration of a matching network for a GaN power amplifier.

In this contribution an adaptive matching network, based on MEMS, is integrated into an inverse class-F power amplifier for an efficiency enhancement over a large range of output power. Supplementary, an *in situ* measurement approach is used to measure the high frequency voltages and currents to calculate the actual load impedance seen at the transistor package plane for an in-depth investigation of the load modulation. First, the load modulation operation principle is described. The design of an inverse class-F power amplifier with an adaptive matching network is shown in Section III. In addition the embedding of a directional coupler for the *in situ* measurement approach is described. Subsequently in Section IV, measurement results of the *in situ* measurement approach are presented proving the applicability of the proposed adaptive matching network for the load modulation.

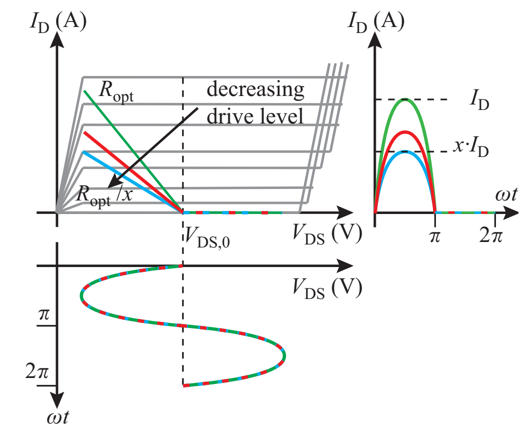

Fig. 1. Load line adaptation to achieve constant voltage swing.

II. Operation Principle of the Load Modulation

In power amplifiers with a fixed matching network between transistor and load, the maximum efficiency is only achieved at the maximum power level [4]. In an amplifier with load modulation, e.g. the Doherty amplifier, the resistance R_{opt}, seen by the transistors internal current source, is increased by the factor $1/x$ at lower power levels, whereby $0 < x \leqslant 1$. As a result the voltage swing is maximized at all output power levels, which is illustrated in Fig. 1 for the operation principle of a load modulated class-B amplifier.

In contrast to the voltage V_{DS} the current I_D is decreasing with increasing R_{opt} (cp. Fig. 1). The enhancement of the voltage V_{DS} to the maximal voltage swing for the corresponding R_{opt} is the reason of the efficiency enhancement in the back-off range.

III. Design of an Inverse Class-F Power Amplifier with Load Modulation

The transistor of an inverse class-F power amplifier operates as a saturated controlled current source with the optimal load R_{opt} at the internal current source. In order to approximate a square-wave current and a half

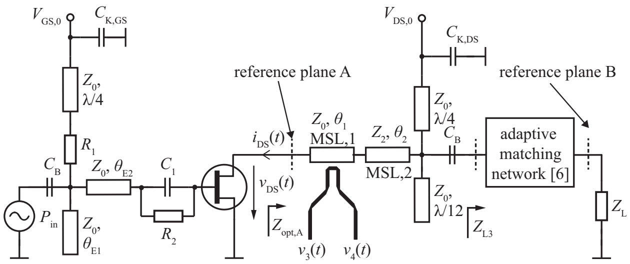

Fig. 2. Schematic of the developed inverse class-F power amplifier with the adaptive matching network.

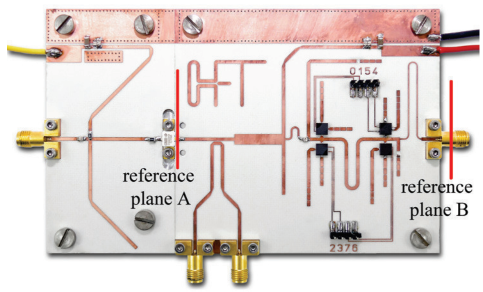

Fig. 3. Photo of the developed inverse class-F power amplifier.

sine-wave voltage waveform, as required for the inverse class-F mode, even harmonics are terminated with high impedances and odd harmonics with low impedances at the internal current source of the transistor [5].

Fig. 2 shows the schematic of the developed inverse class-F power amplifier, which satisfies the previously defined conditions for the harmonic termination.

For a center frequency of $f_0 = 800\,\mathrm{MHz}$ the inverse class-F power amplifier is terminated by the optimal load impedance $Z_{\mathrm{opt,A}}$ at the package plane of the transistor. Furthermore, the matching network in combination with the parasitics of the transistor provide high impedances at even harmonics and low impedances at odd harmonics at the internal current source plane.

The matching network is designed as an adaptive inverse L matching network based on MEMS switched capacitors for f_0. The realized load impedance, if all MEMS switches are turned off (switch open), is chosen for maximum efficiency and output power. In [6] the detailed design of the adaptive matching network is described.

Furthermore, a directional coupler is embedded into the output matching network (OMN). It is used to measure the wave quantities in reference plane A (cp. Fig. 2). Through, a calibration procedure exact measurements of the high frequency voltages and currents in the time domain can be achieved [7], [8]. In contrast to the previous work, in this paper the wave quantities are used to determine the impedance and *PAE* in plane A to investigate the properties of the adaptive OMN under operational conditions.

IV. Realization of an Inverse Class-F Power Amplifier with Adaptive Load Modulation

The introduced inverse class-F power amplifier is realized, based on the previous section, and the in [6]

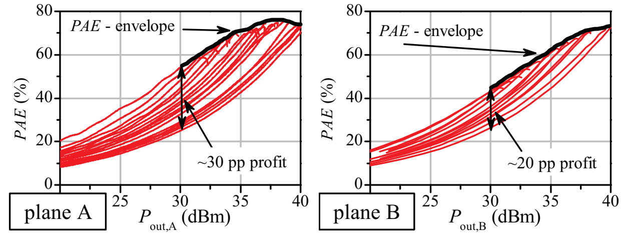

Fig. 4. Measured *PAE* in reference plane A and B versus output power P_{out} for various matching states.

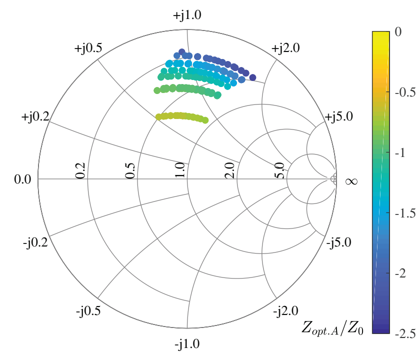

Fig. 5. Measured power gain G_{P} of the matching network for all matching states.

presented adaptive matching network. The power amplifier is fabricated on a Rogers RO4003 laminate, with a permittivity of $\epsilon_{\mathrm{r}} = 3.55$ and a thickness of $h = 508\,\mu\mathrm{m}$, which is mounted on an aluminum plate for better mechanical stability. For the inverse class-F power amplifier a 10 Watt GaN HEMT (high-electron-mobility transistor) device from Cree is used. The chosen gate bias voltage is $V_{\mathrm{GS}} = -3.1\,\mathrm{V}$ and the drain bias voltage is $V_{\mathrm{DS,0}} = 28\,\mathrm{V}$. In this configuration the power amplifier achieves a maximum output power of $P_{\mathrm{out}} = 40\,\mathrm{dBm}$.

In the following, the inverse class-F power amplifier is characterized regarding the power added efficiency in the reference planes A and B (cp. Fig. 3).

Fig. 4 shows the measured results in reference planes A and B for a continuous wave signal at the center frequency f_0 at different matching states of the adaptive matching network. For a better clarity, only the states of the optimal load impedances $Z_{\mathrm{opt,A}}$ for the maximum efficiency are shown dependant on the output power P_{out}.

The *PAE*-envelope in Fig. 4 shows an efficiency enhancement of 30 pp at 10-dB-back-off in reference plane A compared to results, which can be obtained by the fixed matching network (all MEMS switches are turned off). In the reference plane B an efficiency enhancement of 20 pp at 10-dB-back-off is achieved compared to results without load modulation.

To analyse the reasons for the *PAE* differences in both planes Fig. 5 depicts the power gain G_{P} of the adaptive output matching network of all possible matching states in the Smith-Chart ($Z_0 = 50\,\Omega$) to quantify losses at the center frequency f_0. At 0-dB-back-off (all MEMS switches

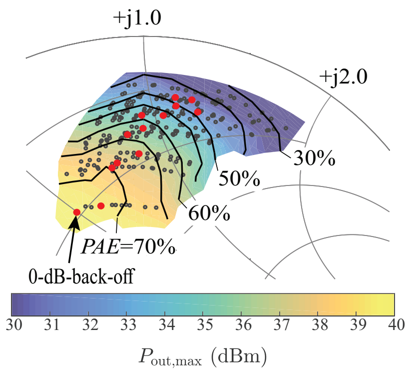

Fig. 6. Measured *PAE* and output power P_{out} depending on $Z_{\text{opt,A}}$ for all matching states.

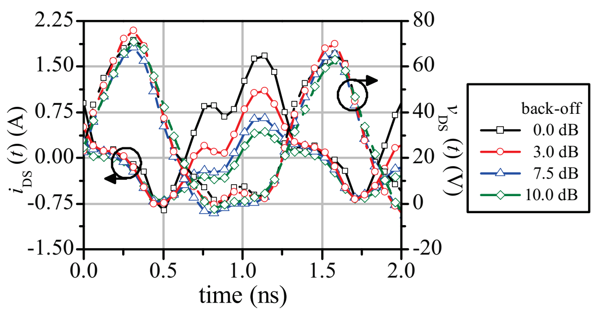

Fig. 7. Measured voltages and currents for various matching states in reference plane A.

are turned off), only the offset capacitors are used. Hence, the power gain G_{P} is $\approx -0.5\,\text{dB}$, which corresponds to a low insertion loss. For an increasing back-off range, higher capacitances are necessary, thus the appropriate MEMS switches have to be activated. Accordingly, the G_{P} decreases, respectively the losses increase with increasing back-off range. This explains the difference between the *PAE*-envelopes in Fig. 4. Nevertheless, the efficiency enhancement of the load modulated amplifier compared to the power amplifier with fixed matching network is increased in the reference plane B. The matching network still provides an optimization potential through the reduction of the insertion loss and therefore to further enhance the *PAE* over the back-off range in reference plane B.

The achieved load modulation can be further analyzed in Fig. 6. It depicts the maximal PAE in plane B (black isolines) as well as the corresponding output power levels (underlying heatmap) in dependence of the load impedance $Z_{\text{opt,A}}$ (red and black dots), which is adjusted through the adapative matching network. Illustrated this way the load line for maximal PAE is recognisable along the protrusions of the PAE isolines and the optimal matching states (red dots) can be chosen. Accordingly, the red dots also represent the matching states of the graphs in Fig. 4.

In addition, the effect of the load modulation can be evaluated from Fig. 7, where the measured high frequency voltages and currents for various matching states in reference plane A are presented. As it can be seen, the high frequency voltage has the same shape with the maximum amplitude for the presented states. Furthermore, the high frequency current decreases for an increasing back-off range, which corresponds to the theory of Section II. The waveforms from Fig. 7 could be further de-embedded to the internal current source plane of the transistor to verify the inverse class-F operation [9].

With the realized adaptive matching network, an efficiency enhancement in the back-off region is shown in both reference planes. The use of the *in situ* measurement approach allows an in-depth study of complex amplifier topologies under operational conditions.

V. Conclusion

This work introduces an inverse class-F power amplifier with an integrated *in situ* measurement capability under load modulation. Therefore, an adaptive inverse L matching network is realized, which is based on transmission lines and tunable capacitors. The tunability of the capacitors is achieved by using MEMS switches. The adaptive matching network performance is verified by measurements and exhibits an efficiency enhancement of 30 pp at 10-dB-back-off in the reference plane A. Furthermore, the time domain measurement approach provides the opportunity, to get knowledge about the high frequency voltages and currents at the transistor package plane under operational conditions. With this knowledge, the load modulation is verified and an impedance measurement for adjusting realized adaptive output matching networks becomes possible.

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