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Load Modulation with an Adaptive Matching Network Based on MEMS for Efficiency Enhancement of an Inverse Class-F Power Amplifier

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Abstract—**In this contribution a 10 Watt gallium nitride (GaN) based inverse class-F power amplifier with an adaptive matching network realized with MEMS (micro electro mechanical systems) is presented. The developed power amplifier uses an adaptive output matching network for the enhancement of the power added efficiency over the dynamic output range. With the output matching network an efficiency enhancement of 20 pp (percentage point) at 10-dB-back-off is achieved.**

Keywords*—*Inverse class-F, power amplifier, power added efficiency, load modulation, MEMS

I. INTRODUCTION

Modern communication systems use complex modulation signals with high peak-to-average power ratio (PAPR), e.g. 4G-System (LTE) with a PAPR in the range 8.5 dB to 13 dB [1]. Simple power amplifier structures based on a single transistor can achieve high efficiency only at the maximum output power. As a result, most of the time the amplifier works in a low efficiency mode when excited by a signal with high PAPR. To amplify this signals, efficient but complex structures such as Doherty-amplifiers or Chireix-amplifiers are used. From the RF point of view the envelope tracking amplifier, were the drain voltage is varied as a function of the modulated envelope is a more simple solution. Another approach is presented in [2], where a class-F power amplifier with a manually tuned matching network is introduced. The efficiency enhancement in the back-off range shows the benefit of this approach. An adaptive matching network for load modulation of a class-AB amplifier is presented in [3]. A multi-mode-matching output network presented in [4] shows the approach of RF-MEMS (micro electro mechanical systems) in matching networks for a multi-band gallium nitride (GaN) power-amplifier applications.

In the following work an adaptive matching network, based on MEMS, for an inverse class-F power amplifier with the target to increase the efficiency at low as well as high power levels of the output power is shown. First, the load modulation operation principle will be described. In Section III the design and realization of the adaptive L matching network realized with MEMS are presented. Section IV shows the design of an inverse class-F power amplifier with the adaptive matching network for efficiency enhancement in the back-off region. Subsequently in Section V, measurement results for the developed inverse class-F amplifier are presented, proving the applicability of the proposed adaptive matching network with MEMS.

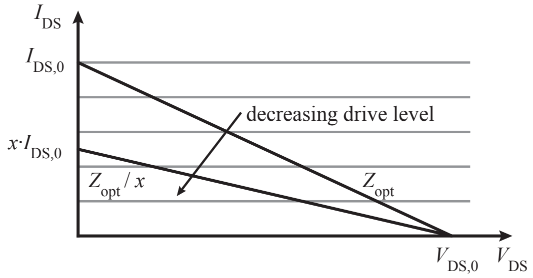

Fig. 1. Ideal load line adaptation to achieve constant voltage swing

II. OPERATION PRINCIPLE OF THE LOAD MODULATION

In traditional power amplifiers with fixed load impedance the maximum efficiency is only achieved at the maximum drive level [5]. In a load modulation amplifier the resistance R_{opt}, seen by the transistors internal current source, is increased with $1/x$ at low power levels, where x is $0 < x < 1$ such that the voltage swing is maximized at all output power levels. Fig. 1 shows the operation principle of the load modulation amplifier assuming that the transistor is a perfect transconductor. In an inverse class-F power amplifier the transistor operates as a saturated controlled current source with the optimal load R_{opt}. In order to approximate a square-wave current and a half sine-wave voltage waveform the output matching network provides high impedances at even harmonics and low impedances at odd harmonics [6].

$$Z_{\mathrm{opt}} = \begin{cases} R_{\mathrm{opt}} = \dfrac{\pi^2}{8}\dfrac{V_{\mathrm{DS,0}}}{x \cdot I_{\mathrm{DS,0}}} & \text{fundamental} \\ \infty & \text{even harmonics} \\ 0 & \text{odd harmonics} \end{cases} \tag{1}$$

III. DESIGN AND REALIZATION OF AN ADAPTIVE MATCHING NETWORK WITH MEMS

Fig. 2 shows an inverse L matching network with a tunable capacitance and inductance. In microstrip technology capacitances are preferable realized as inductances. Therefore, the series inductance is converted to a shunt capacitance with two $\lambda/4$-transformers (compare Fig. 3). The tunable capacitance can be implemented as a parallel circuit of switched capacitors. The switches are realized using MEMS from RADANT of the type RMSW220HP. The RADANT MEMS has a long

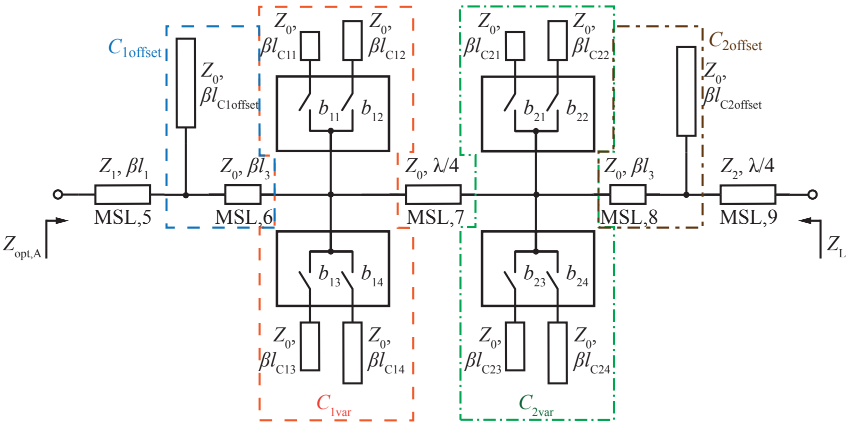

Fig. 4. Schematic of the adaptive matching network with MEMS

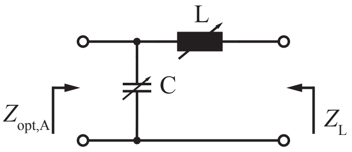

Fig. 2. Schematic of a tunable inverse L matching network

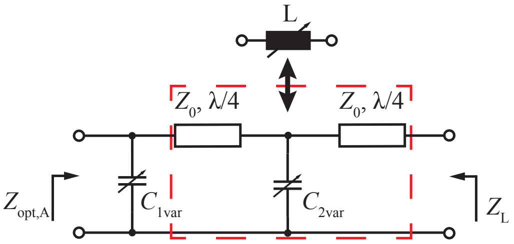

Fig. 3. Tunable inverse L matching network with converted inductance

durability with >1 billion cycles at 40 dBm cold-switched [7]. Furthermore, the MEMS offers the advantage of a good DC/RF isolation without additional components. An alternative choice to realize the switch is to use e.g. a SPDT (Single Pole Double Throw) GaN switch [8], but in the required power range there are no practical switches in a QFN-Package (Quad Flat No-lead) available only as Die. So the realization is more difficult as with the MEMS in the QFN-Package. The principle automatic tuning procedure can be investigated with the MEMS too. Before starting the design of the adaptive matching network, the MEMS were characterised with a vector network analyzer. With these measurements a S-Parameter model of the MEMS is generated to design the matching network. Fig. 4 shows the schematic of the developed adaptive matching network for the fundamental frequency $f_0 = 800\,\text{MHz}$. The matching network consists of eight MEMS, that provide $2^8 = 256$ impedance states, but not all states are required and used for the load modulation.

The values of the capacitances $C_{1\text{var}}$ and $C_{2\text{var}}$ are shown in Fig. 5. The capacitance $C_{1\text{var}}$ varies between $0.23\,\text{pF}$ and $3.38\,\text{pF}$ and $C_{2\text{var}}$ between $0.25\,\text{pF}$ and $3.75\,\text{pF}$. The first value corresponds with the values of the offset capacitances $C_{1\text{offset}} = 10.3\,\text{pF}$ and $C_{2\text{offset}} = 0.7\,\text{pF}$. For the state with all switches turned off the impedance $Z_{\text{opt,A}}$ is transformed with the offset capacitance $C_{1\text{offset}}$ and $C_{2\text{offset}}$. So that in this state (0-dB-back-off) $Z_{\text{opt,A}}$ can correspond for example to an optimal impedance for the maximum output power of an amplifier.

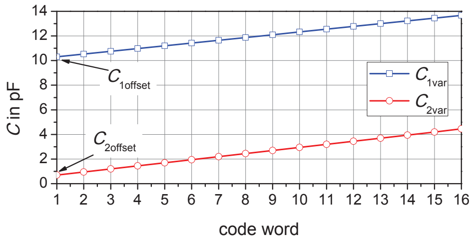

Fig. 5. Simulated capacitance $C_{1\text{var}}$ and $C_{2\text{var}}$

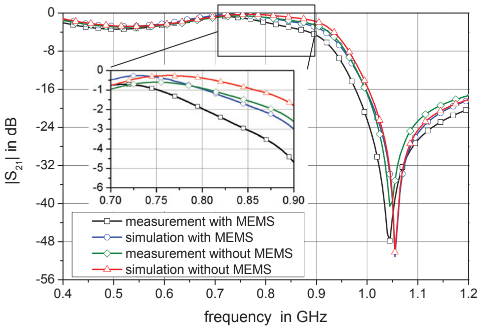

Fig. 6. The insertion loss of the output matching network

Fig. 6 shows a comparison of the insertion loss of the output matching network. The simulation and the first measurement of the insertion loss of the output matching network without MEMS exhibits a good agreement. Furthermore, the insertion loss of the output matching network with the MEMS is displayed in Fig. 6. The comparison of this results show a deviation for the insertion loss in the configuration with the MEMS. This deviation is caused by the layout of the output matching network and the inaccuracy of the MEMS placement on the board. With the objective of an application in a power amplifier for efficiency enhancement, the impedance range is chosen to be small for a refine resolution in the area of the optimal load impedance of the power amplifier. The simulation

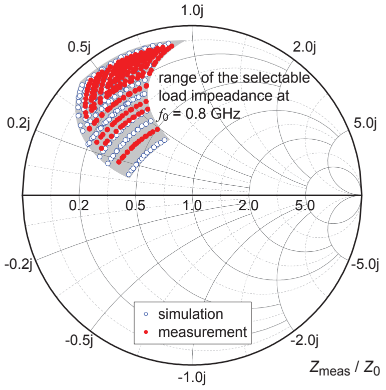

Fig. 7. Simulated and measured impedance Z_{meas} for all matching states

and measurement results for impedance Z_{meas} (compare Fig.8) are shown in Fig.7. Both, measurement and simulation results covers the required impedance range, that is needed for the the load modulation.

IV. DESIGN OF AN INVERSE CLASS-F POWER AMPLIFIER WITH LOAD MODULATION

The schematic of the developed inverse class-F power amplifier is shown in Fig. 8. The fundamental wave of an inverse class-F power amplifier is terminated by Z_{opt}. Furthermore, the matching network provides high impedance at even harmonics and low impedance at odd harmonics. In this case, the second and third harmonic is terminated [6]. The matching network is designed as an adaptive inverse L matching network based on MEMS switched capacitors for f_0. By changing the capacity $C_{1\mathrm{var}}$ and $C_{2\mathrm{var}}$ of the matching network (shown in Fig. 4), the load impedance $Z_{\mathrm{L}} = 50\,\Omega$ is matched to the optimum impedance $Z_{\mathrm{opt,A}}$. The impedance $Z_{\mathrm{opt,A}}$ is tunable by the adaptive MEMS matching network and is transformed to Z_{opt} by the microstrip lines MSL,1 and MSL,2 with the electrical lengths θ_1 and θ_2. The termination of the second harmonic is realized with a $\lambda_{f_0}/4$ short-circuited stub at f_0.The short is transformed by the microstrip lines MSL,1 and MSL,2 in an open at the drain of the transistor. The $\lambda_{f_0}/4$-microstrip line serves as DC supply of the drain source voltage $V_{\mathrm{DS,0}}$. For the third harmonic a $\lambda_{f_0}/12$ open-circuited stub is placed after the microstrip lines MSL,1 and MSL,2 to provide a short for the third harmonic at the drain of the transistor.

V. REALIZATION OF AN INVERSE CLASS-F POWER AMPLIFIER WITH ADAPTIVE LOAD MODULATION

In this section, the realization and measurement results of the inverse class-F power amplifier, based on the findings out of the previous section, are presented. The power amplifier is fabricated on a Rogers RO4003 laminate, with a permittivity of $\epsilon_{\mathrm{r}} = 3.55$ and a thickness of $h = 508\,\mu\mathrm{m}$. The printed circuit is mounted on a aluminum plate for more mechanical stability. It additively functions as heat-sink and allows an easy assemble of the transistor. The inverse class-F power amplifier uses a 10 Watt GaN HEMT (high-electron-mobility transistor) device from Cree. The optimum gate bias voltage is $V_{\mathrm{GS}} = -3.1\,\mathrm{V}$ and the DC supply for the drain bias voltage is $V_{\mathrm{DS,0}} = 28\,\mathrm{V}$.

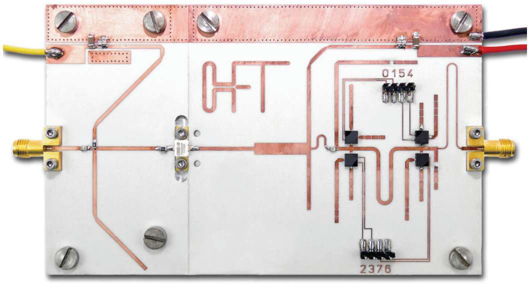

Fig. 9. Photo of the developed inverse class-F power amplifier

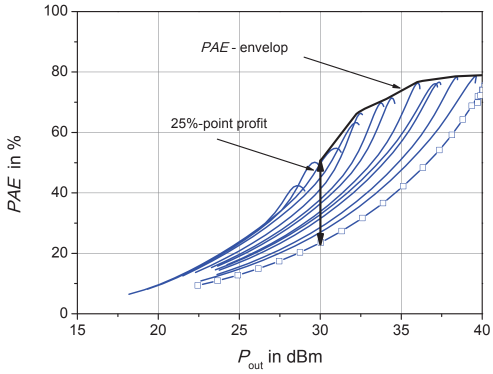

Fig. 10. Simulated *PAE* versus output power P_{out} for various matching states

Fig. 10 and Fig. 11 show the simulated and measured results for a continuous wave signal at the fundamental frequency f_0 for different matching states. For a better clarity, only the states along the optimal load impedance Z_{opt} are shown. As it can be seen the *PAE*-envelop in Fig. 10 and Fig. 11 shows an efficiency enhancement for the simulated and measured data. For 10-dB-back-off the simulation is 25 pp above the PAE of the fundamental state. In the fundamental state the power amplifier achieves the maximum output power of $40\,\mathrm{dBm}$. For the measurement the PAE at 10-dB-back-off is 20 pp higher than in the fundamental state. In Table I four matching states are presented with their capacitor values, the power added efficiency and the calculated R_{opt}. For the states listed in Table I the output power P_{out} versus the input power P_{in} is shown in Fig. 12 and Fig. 13. Both, simulation and measurement show a good agreement for all states. This shows that with an adaptive matching network a load modulation for efficiency enhancement in the back off region is possible. Power amplifier with adaptive matching networks for load modulation can be used, e.g. in handheld radio with variable output power, where the efficiency can be increased for a low output power in comparison to a simple power amplifier structure.

TABLE I. CAPACITANCE VALUES AND MEASUREMENT PERFORMANCE

State	Back-Off	C_{var1}	C_{var2}	P_{out}	*PAE*	R_{opt}
1	0 dB	10.3 pF	0.7 pF	40.0 dBm	68 %	56 Ω
2	3 dB	12.4 pF	1.7 pF	37.0 dBm	65 %	96 Ω
3	7,5 dB	13.0 pF	1.5 pF	32.5 dBm	50 %	270 Ω
4	10 dB	13.0 pF	2.9 pF	30.0 dBm	40 %	594 Ω

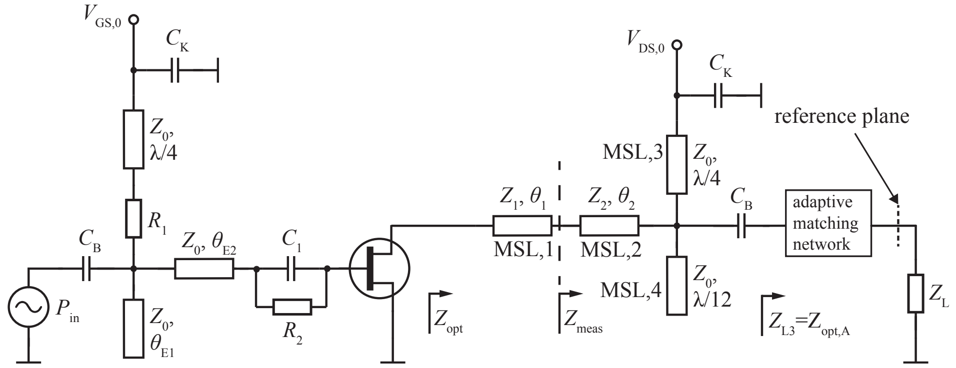

Fig. 8. Schematic of the developed inverse class-F power amplifier with adaptive matching network

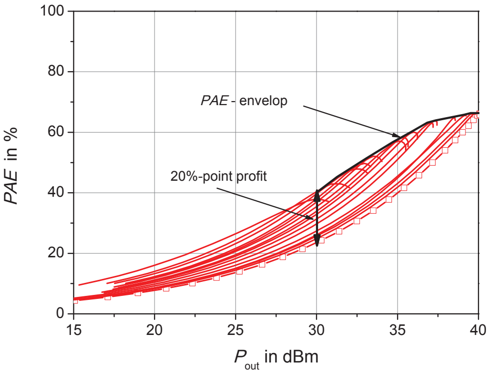

Fig. 11. Measured *PAE* versus output power P_{out} for various matching states

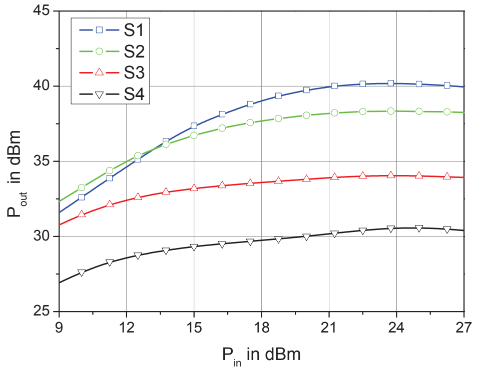

Fig. 12. Simulated output power P_{out} versus input power P_{in}

VI. CONCLUSION

In this work a 10 W GaN inverse class-F power amplifier with load modulation was introduced. An adaptive inverse L matching network, which is based on transmission lines and tunable capacitors, is demonstrated. The tunable capacitors are realized with MEMS switches. The adaptive matching network with MEMS switched capacitors was verified through measurements and exhibits an efficiency enhancement of $PAE = 20$ pp at 10-dB-back-off. Furthermore, the insertion loss of the adaptive matching network can be optimized.

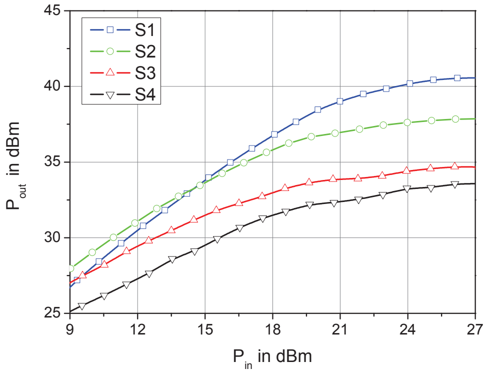

Fig. 13. Measured output power P_{out} versus input power P_{in}

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