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INFLUENCE OF THE RECONSTRUCTION FILTER ON THE PERFORMANCE OF A SWITCHED-MODE POWER AMPLIFIER

Elena Serebryakova, Kurt Blau, *Member IEEE*,
and Matthias A. Hein, *Senior Member IEEE*

Institute for Information Technology, Ilmenau University of Technology, Ilmenau, Germany, E-mails: Elena.Serebryakova@TU-Ilmenau.de, Kurt.Blau@TU-Ilmenau.de, and Matthias.Hein@TU-Ilmenau.de

Abstract: This paper presents an analysis of a reconstruction filter in a switched mode power amplifier system. Doubly and singly terminated filters for current-mode class-S power amplifiers were analysed previously through analytical, numerical, and experimental approaches, and it was shown that only singly terminated filters can fulfil the requirements of current-mode switching amplifiers, owing to their constant input resistance over the pass-band. In this paper potential effects of the parasitic components in the actual filters and the filter termination are evaluated. The simulation and measurement results of current mode class-S power amplifier systems employing GaN HEMT MMICs are presented and critically analysed.

1. INTRODUCTION

Recently, class-S power amplifiers (PAs) have become attractive for wireless communication systems operating in the UHF range, because they offer simplified transmitter architectures and increased power efficiency. Such an amplifier system is composed of three building blocks [1], as indicated in Fig. 1: a one-bit modulator, e.g., a band-pass delta-sigma modulator ($\Delta\Sigma\text{M}$) or a pulse-length modulator, a switching amplifier in a push-pull configuration, and a reconstruction band-pass filter (BPF). The reconstruction filter has to not only fulfil stringent requirements of the switching amplifier and one-bit modulators, but also be compliant with the spectral requirements of mobile communication standards. There are numerous filter architectures for class-S PA systems presented in literature [2-6], which were experimentally investigated without being connected to the system. This paper presents the potential influence of the reconstruction filters on the performance of the switched-mode power amplifier. For the purposes of the current study, a current-mode switching amplifiers operating in class-D or class-S are in the focus of this paper. A current-mode class-D PA represents a particular case of class-S PA systems, it operates with sinusoidal drain voltages and 50% duty cycle square wave drain currents. Its simulation can be considered as a necessary interim step taken in order to estimate the loss mechanisms in the switching transistors, to

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optimise the system for efficiency and output power, and to evaluate the impact of the filter termination on the PA performance. However, these power amplifier systems are quite complicated and require detailed investigation because each of its building blocks may have similar distorting effects on the whole PA system. The various separate effects have been described in [8], those related to the reconstruction filter will be considered in the following.

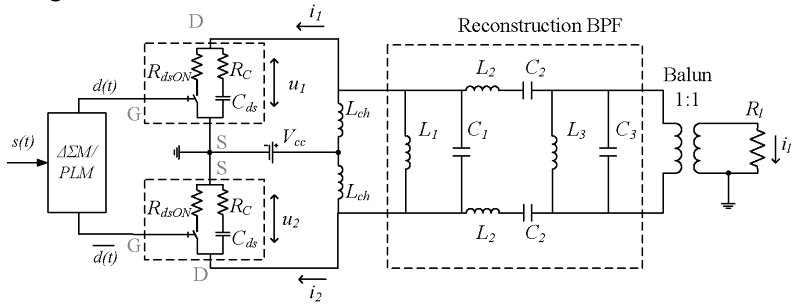

Fig. 1 Building blocks of a class-S power amplifier system comprising a $\Delta\Sigma M$ or PLM, a push-pull amplifier with an equivalent circuit of the GaN HEMTs (C_{ds}, R_C and R_{dsON}) and biasing network (RF chokes L_{ch} and voltage supply V_{cc}), blocking capacitances DC_{block} and a reconstruction band-pass filter [7]

2. RECONSTRUCTION FILTER FOR CLASS-S POWER AMPLIFIERS

The final block of a class-S PA system is a band-pass filter required for the reconstruction of the amplified step-like signal. The reconstruction filter has to shape the power spectrum resulting from the input modulator (noise-like for a BDSM or spurs for a PLM), and comply with the emission mask defined by the 3GPP standard [9] as well, as in conventional power amplifiers for communication systems. Moreover, as a building block between the final stage and an antenna, the filter has to provide low-loss power transmission and the optimal operating conditions for power transistors. Such matching conditions may become quite challenging, given potentially broadband $\Delta\Sigma M$ spectra and a current-mode push-pull configuration of the final stage, demanding balanced signal combining. In order to sustain the rectangular shape of the drain current, and, with it, high efficiency, the reconstruction filter should have low-ohmic out-of-band input impedance for the differential mode and high-ohmic for the common mode. The resulting electrical as well as geometrical constraints for the design of a reconstruction filter can be satisfied by balanced input comb-line filters [3-5]. There arises the question of which impact the actual filter characteristics have on the power amplifier performance. In order to elucidate this question, a CMCD PA system is analysed in the following section, including parasitic components of the reconstruction filter.

Turning to the in-band behaviour: because the final stage of current-mode class-S PAs acts like a current source with a virtual infinite internal impedance, a singly terminated (ST) filter is required. Previously, it was shown through analytical, numerical, and experimental approaches that only ST filters can fulfil the requirements of current-mode switching amplifiers, owing to their constant input resistance over the pass-band

[5-6]. This paper presents a potential effect of the filter termination on the power characteristics of switching mode PAs.

3. EFFECT OF PARASITIC COMPONENTS IN THE RECONSTRUCTION FILTER

Because realistic reconstruction filters contain parasitic elements, it is necessary to evaluate their influence. It has been made clear that it is necessary for the filter to have high-ohmic common-mode input impedance, which will at most be affected by capacitances against ground. It is important to note that in this section the doubly terminated (DT) filter will be the focus of investigation, but, however, capacitances to ground will have the same effect out-of-band on either DT or ST filters. To facilitate investigation of how these capacitances to ground C_g affect the shape of the drain currents, they were positioned at the filter input, as shown in Fig. 2. The input impedance for both modes of excitation was simulated with capacitances varying from 0 pF to 8 pF. The simulation results are presented in Fig. 3,a-b. The effect of these capacitances on the differential-mode input impedance out-of-band is negligible, because of the maintenance of the symmetrical filter structure. The capacitances to ground have a major influence on the common-mode input impedance out-of-band, which diminishes as C_g rises.

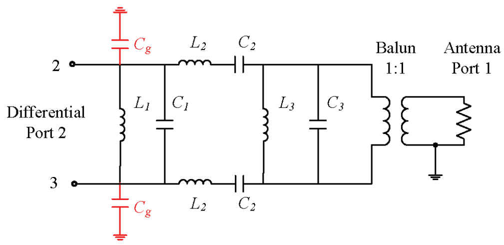

Fig. 2 Lumped-element representation of a balanced input third-order reconstruction filter with parasitic capacitances to ground C_g at the filter input

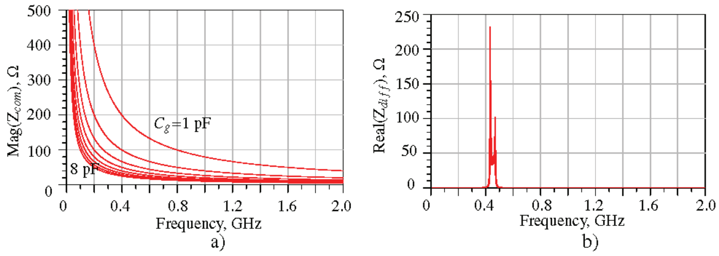

Fig. 3 ADS simulation results of the balanced input BPF at 450 MHz with parasitic capacitances to ground: Magnitude of the input impedance for the common mode (panel a) and input resistance for differential excitation (panel b). The common-mode input magnitude is infinite when C_g = 0 pF

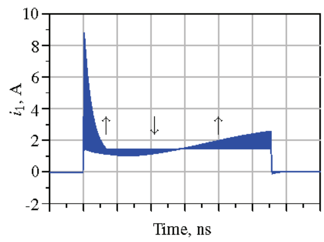

Fig. 4 Numerical simulation results: Variation of the time dependent drain currents (shown by the arrows) for a variation of the ground capacitance from 0 pF to 8 pF (the shape close to rectangular corresponds to $C_g = 0$)

Because the filter here is a device with floating ground potential, the input impedance for the common mode depends on the ground capacitance only, $Z_{com} = \dfrac{1}{2\pi f 2C_g}$. What is the effect this diminished common-mode impedance has on the power characteristics and on the shape of the drain currents? In order to answer this question, the CMCD PA system using the filter circuit from Fig. 2 was simulated with a commercial circuit simulator ADS (Advanced Design System) [10]. The results are presented in Figs. 4-5. The first figure illustrates how the capacitance to ground changes the shape of the drain currents (arrows indicate variation from 0 pF to 8 pF). As can be seen, the ground capacitance has a similar effect as that of the drain-source capacitance in the transistors investigated in [7]; the only difference is that C_g affects the drain currents in the ON-state only, whereas C_{ds} affects in both the ON-state and the OFF-state. From the figure, it can be concluded that it is not possible to compensate the drain-source capacitance C_{ds} in the first resonator of a reconstruction filter.

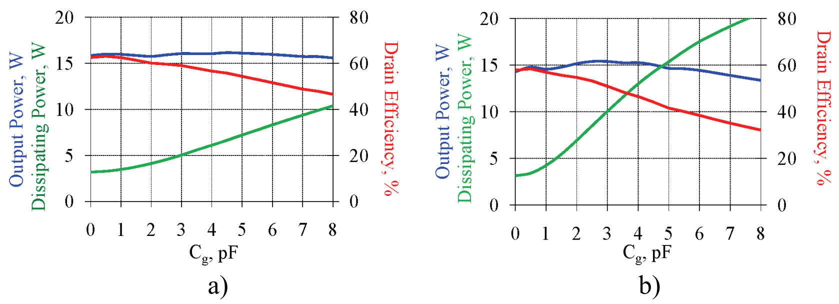

Fig. 5 ADS simulation results of the CMCD PA system operating at 450 MHz (panel a) and the CMCD PA system operating at 900 MHz (panel b): Drain efficiency (red curve), output power (blue curve) and power dissipated in the switch (green curve) as functions of the parasitic capacitance to ground C_g

The power transfer of the CMCD PA system is also affected by this capacitance, as shown in Fig. 5,a. Because the reactive currents flow through the capacitance to ground, the currents through the switches rise as C_g grows, which results in increased dissipated power in the switch ($\frac{1}{2}I_1^2 R_{dsON}$). At the same time, the output power remains constant, because it is compensated by the diminishing output voltage. The diminished drain efficiency becomes potentially significant at 45% when C_g is 8 pF, and negligible when C_g drops below 2 pF (the total capacitance to ground is then 4 pF), which corresponds to a common-mode impedance of less than 40 Ω at 2 GHz. Because the impact of these capacitances depends on frequency, the simulation of a CMCD PA system was repeated for 900 MHz. The common-mode impedance of the filter for 900 MHz is identical to that for 450 MHz, as shown in Fig. 3,a. The simulation results are presented in Fig. 5,b. The degradation of the drain efficiency is significant at 30% when C_g is 8 pF, and can be neglected for C_g below 2 pF (the total capacitance to ground is then 4 pF), again corresponding to a common-mode impedance of less than 40 Ω at 2 GHz. As can be seen, the CMCD PA system operating at 900 MHz is affected more strongly by the capacitance to ground, because all higher harmonics of the drain currents are shorted to ground, which increases the current through the switches and thus the power dissipated in these. It can, however, be concluded that because both DT and ST balanced input comb-line filters [5] demonstrated characteristics out-of-band even better than presented above, they will not significantly affect the PA performance. Nonetheless, it is necessary to avoid capacitances to ground as far as possible, for they may occur not only in a reconstruction filter, but also in a mounting board, in biasing networks, or in MMICs, are thus a challenge not to be neglected.

4. Influence of the filter termination

Another potential source of distortion is the filter termination. The fundamental distinction between DT and ST filters is in their synthesis and, consequently, their element values. The element values of ST and DT low-pass prototype LC ladders were obtained and tabulated in [11,12]. As opposed to DT filters, where in case of matching half of the generator power is absorbed in the load R_l and another half is dissipated in the generator R_g, in ST filters, except for the low insertion loss of the filter (considered negligible), the total generator power is absorbed in the load:

$$P_l = P_g, \tag{1}$$

$$\left|I_l\right|^2 \cdot R_l = \left|I_g\right|^2 \cdot Re(z_{11}),$$

where I_g and I_l are the input and load currents, respectively, and z_{11} denotes the complex-valued input impedance of the ladder network. Eq. 1 illustrates that the output power is determined entirely by $Re(z_{11})$, whose frequency dependence reflects the desired filter transmission characteristics, e.g., Butterworth, Chebyshev, etc. However, any DT filter is characterised by pronounced maxima of its input resistance, which can result in high drain voltages, potentially damaging the switching transistors [6]. In contrast, a ST filter with a constant input resistance can provide constant output power of the current-mode class-S PA. Therefore, the shape of the frequency dependent filter input resistance will be in the focus of our further investigation.

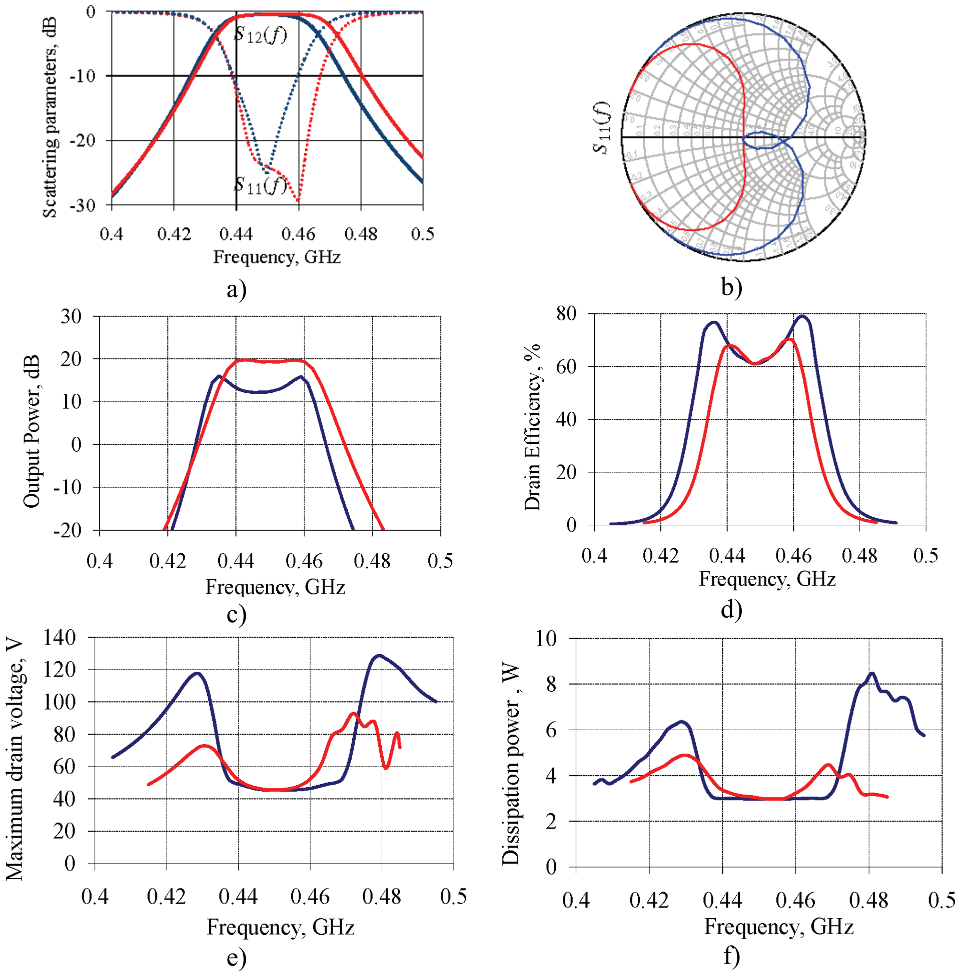

Fig. 6 ADS simulation results of the class-D PA with the ST filter (red curves) and the DT filter (blue curves) as functions of centre frequency: a) - scattering parameters, b) - Smith chart, c) - output power, d) - drain efficiency, e) - maximum drain voltage, f) - dissipated power in the switch

In order to assess the impact of filter termination on the PA performance in-band, the CMCD PA system from the previous section was again simulated with ADS, sweeping the centre frequency of the RF signal, and the results are shown in Fig. 6. It was necessary to simulate both filters in the S-parameter simulation mode first, to establish their basic characteristics. As can be seen, both filters have a flat transfer function over the operational bandwidth, as shown in Fig. 6,a. The difference in the filter terminations becomes apparent only from the simulated reflection coefficients, which is shown in the Smith Chart in Fig. 6,b. The following analysis was carried out in the transient simulation mode of ADS and all PA parameters were computed for each frequency point. Fig. 6,c shows the output power for both cases. As was expected, the double termination results in pronounced maxima in the output power. In contrast, it was found that the ST filter provides constant output power. (It is important to note that in order to simulate the ideal current source, it was necessary to choose a suitable value of RF chokes.) The drain efficiency is illustrated in Fig. 6,d. For both cases the drain efficiency has a similar shape, with the minimum at the centre frequency. The significant differences become apparent for increasing frequency. This effect can be explained by the analysis of the peak drain voltage in Fig. 6,e, where it is seen to grow rapidly at the edges of the pass-band and overdrive the transistors. In practice, such high drain voltages will damage the GaN transistors, and operation in back-off will be required. Because the drain voltages out-of-band are tripled, the DT filter represents a more critical case. At the same time, the power dissipated in the switch ($\frac{1}{2} I_1^2 R_{dsON}$) for both cases, seen in Fig. 6,f to grow with increasing offset from the centre frequency, is mainly caused by the high drain voltages. It is important to note that the PA characteristics also depend on the filter structure.

In order to provide constant output power, it is necessary not only that the reconstruction filter be singly terminated, but also that the final stage act as an ideal current source.

5. EXPERIMENTAL INVESTIGATION

After the current mode class-D and class-S PA systems have been investigated by means of computer simulation, it is necessary to analyse the measurement results of these systems and compare them with the numerical data. A demonstrator of a CMCS PA system for the GSM frequency band was designed for a centre frequency of 900 MHz [13]. The system employs GaN HEMT MMICs, supplied by Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik in Berlin, Germany, and the coaxial DT balanced input comb-line filter with an electrically-short input loop [4,5]. The measurement process of the amplifier system was described in detail in [13]. Firstly, in order to find the optimal bias points for the pre-amplifier and the final stage, the filter was tuned by means of a pseudo random bit sequence generated by a FPGA board. The broad noise spectrum of the sequence means that the output signal reflects the transfer function of the filter. Secondly, the demonstrator was tested in class-D operation. The measured output power as a function of the centre frequency is depicted in Fig. 7. As can be seen, there are unacceptable 3-dB ripples in the pass-band [6], which are caused by the double termination of the balanced input comb-line filter.

Another demonstrator for the GSM frequency band was implemented with GaN HEMT MMICs supplied by Fraunhofer Institute Applied Solid-State Physics in Freiburg, Germany and a singly terminated balanced input comb-line filter. The demonstrator was assembled by Cassidian, an EADS company in Ulm, Germany and experimentally investigated in both class-D and class-S operation at Ilmenau University of Technology, Germany. There are two steps to the measurement procedure. The first step was filter tuning, in order to find the optimal bias points for the pre-amplifier and the final stages. The filter tuning step was concluded in a class-D regime so that the centre frequency of the RF signal was swept, and the shape of the output power curve was obtained. In order to get the constant output power in-band, it was necessary to tune the filter with the aid of trimmers and a dielectric material, which served to correct the coupling coefficient [5]. The second step was to test the demonstrator in the class-D regime. The impact of the filter termination on the shape of the output power is presented in Fig. 8, where three output characteristics correspond to the different biasing points (2 V, 7 V and 15 V). As can be seen, the filter results in constant output power independently of the biasing conditions.

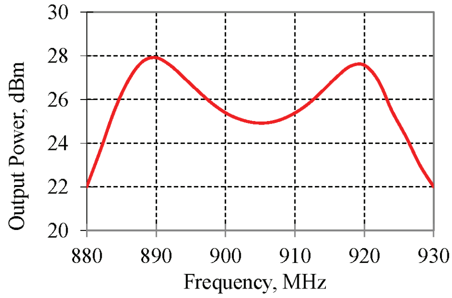

Fig. 7 Typical result for the measured output power of the class-S PA with a DT reconstruction filter, operating for test purposes in class-D over the specified bandwidth around 900 MHz centre frequency

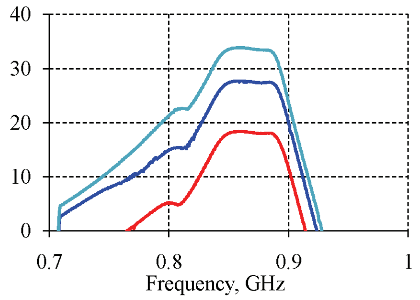

Fig. 8 Typical result for the measured output power of the class-S PA with a ST reconstruction filter, operating for test purposes in class-D over the specified bandwidth around 900 MHz centre frequency: for different biasing voltages of 2 V (red curve), 7 V (blue curve) and 15 V (light blue curve)

The impact of the filter termination on the shape of the output power has been confirmed experimentally. A singly terminated filter results in constant output power independently of biasing conditions, while doubly terminated filters result in pronounced maxima in drain voltages, in drain efficiency, and in output power. In order to provide constant output power, it is necessary not only that the reconstruction filter be singly terminated, but also that the final stage act as an ideal current source.

6. CONCLUSIONS

This paper has presented the potential effects of a reconstruction filter on the switched-mode power amplifier performance. Firstly, the effect of capacitances against ground has been investigated. These parasitic components not only affect the shape of the drain currents, but also diminish drain efficiency. It had been made clear that it is necessary to reduce capacitances to ground as much as possible. Secondly, the impact of the filter termination on the shape of the output power was confirmed experimentally. It has been found that the doubly terminated filters result not only in pronounced maxima in output power, but also increased dissipating losses in the switches. Under the same driving conditions singly terminated filters result in constant output power.

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