

## ANALYSIS OF BROADBAND GAN SWITCH MODE CLASS-E POWER AMPLIFIER

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**Abstract**—Switch mode power amplifiers offer high efficiency approaching 100% for an ideal case. This paper discusses the operation mode of broadband switch mode class-E power amplifier designed previously by the authors for UHF applications (600–1000 MHz). A method to extract the waveforms at the die reference plane from the time domain analysis using  $50\ \Omega$  environment systems is discussed. It has been observed that the designed class-E power amplifier operation was not maintained ideally over the entire band; however, it was operating close to the class-E operation.

### 1. INTRODUCTION

Broadband highly efficient Power amplifiers (PA) are of increasing interest for modern base stations in telecommunication applications. With high data rate and more users, more complex modulations are used that increase the signal crest factor and signal bandwidth and place high demands on system linearity. This often leads to amplifiers working in far back-of region with low efficiency. Increasing the efficiency is of major concern. It will reduce the thermal problems in the power devices, their size and the auxiliary cost for heat removal. A wide operational bandwidth is also important for expanding the base-station operation for multi-standard wireless system purposes.

With switch mode PAs (SMPAs) we normally refer to classes like class-F, class-E, and class-D. They have high efficiency with a theoretical drain efficiency of 100%. The transistor in SMPAs is working as a switch instead of a current source as in the classical classes. A large drive signal has to be injected into the transistor to drive it as a switch. The output side of the SMPAs includes,

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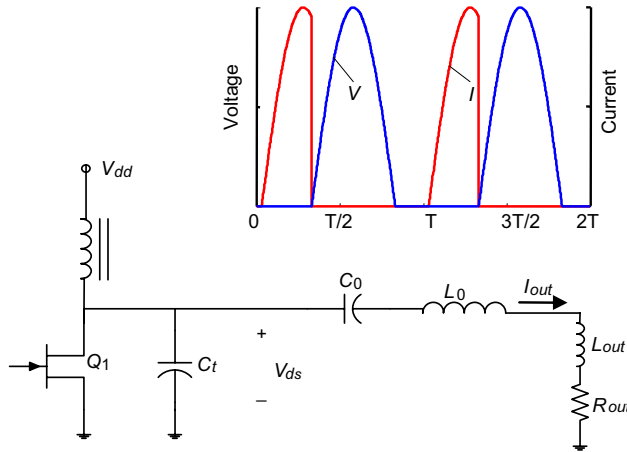
in addition to the matching network, a network of resonators which shapes the drain voltage and the drain current of the transistor. For class D usually two transistors are required and extra baluns for the input and the output sides. Class-F/ $F^{-1}$  requires a resonator for every single harmonic to give the optimum termination for that operation. For class-E only a single transistor and a simple output network is required. This makes it a first choice for broadband designs. In all switch-mode classes, a zero voltage switching (ZVS) condition is desirable to reduce power loss in the device and this is also achieved in all classes by ensuring that the drain voltage is zero just before the on period. However, for practical applications the efficiency degrades due to the parasitics of the devices, making the device choice crucial for achieving highest efficiency [1].

The recently developed GaN HEMT devices have high power density, high breakdown voltage, wide operating bandwidth, low thermal resistance and low output parasitic capacitance, making them a good candidate for SMPAs for high frequency, high power and wideband applications [2].

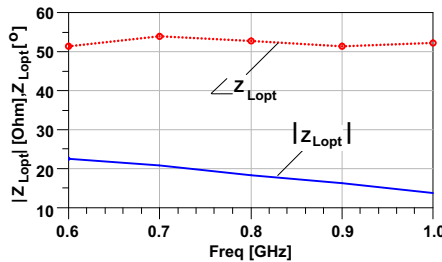
A broadband SMPA designed for class-E operation has previously been designed and fabricated at TU-Berlin [3]. It is state of the art with regards to fractional bandwidth ( $BW/f_0$ ), power and efficiency. However, it was found that the amplifier does not have a constant efficiency over the entire band. Hence the amplifier seems to not be working ideally as class-E PA over the full bandwidth. In this paper we present an analysis class of operation for this wideband switch mode power amplifier using a time-domain characterization in the simulation environment followed by de-embedding down to the switch-mode reference plane. The amplifier operation has been analyzed at three different frequencies (i.e., Lower edge frequency, center frequency and upper edge frequency) within the band of operation 600–1000 MHz. the analysis depends on the drain voltage and current waveforms for the, load impedance seen at the drain side and instantaneous power.

## 2. THEORY OF CLASS-E POWER AMPLIFIER

Class-E power amplifier was first introduced in [4]. The load network has a series resonant circuit tuned at the fundamental frequency and the fundamental load is slightly inductively tuned. The series resonant passes only the fundamental frequency, while the inductive load reduces the slope of the voltage waveform before the switch turns on (soft switching), which satisfy the zero voltage switching (ZVS). The typical circuit topology of class-E power amplifier is shown in Fig. 1, where  $C_t$  is the total output capacitance ( $C_{ds}$ ) of the transistor and external



**Figure 1.** Ideal network topology and Ideal drain voltage and current waveforms for class E PA.



**Figure 2.** Optimum load impedances over frequency for class E PA.

capacitance ( $C_{ex}$ ) needed for the design to get an optimum class E operation. The ideal voltage ( $V$ ) and current ( $I$ ) waveforms for class E, assuming square drive signal, are also shown. Class E has two main advantages:

1. Soft switching which reduces the losses.
2. Simple circuit topology compared to other switching mode PA classes.

### 3. BROADBAND DESIGN

The optimum load impedances for the operating bandwidth are shown in Fig. 2 which was taken from load and source-pull simulation using

Agilent's Advanced Design System (ADS). As can be seen the optimum impedance has a constant phase of  $52^\circ$  and its magnitude reduces with the frequency with a constant slop, which follows from (1).

$$Z_{Lopt} = \begin{cases} R_{Lopt}(1 + j1.28), & \text{at } f_o \\ \infty & \text{at } nf_o, n > 1 \end{cases} \quad (1)$$

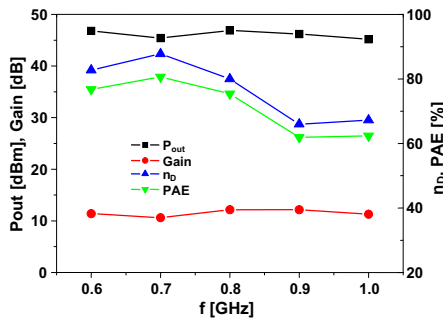
where,  $R_{Lopt}$  is the optimum impedance, and it is inversely proportional to the frequency and the output capacitance  $C_{ds}$  (i.e.,  $R_{Lopt} \propto \frac{1}{(C_{ds} \cdot f)}$ ).

### 3.1. Band-pass Filter and Output Matching Design

To realize a constant phase and magnitude of constant slope a Butterworth filter was chosen. A sharp filter that gives enough attenuation for the harmonics starting from 1200 MHz was implemented using a 3 pole filter. Moreover, to minimize the insertion loss of the filter, the 3dB bandwidth was designed for the band between 470 MHz and 1.160 GHz. The filter topology was chosen as T topology instead of Pi topology which gives an open termination for the harmonics. Further details about the realizations of the amplifier can be found in [3].

## 4. EXPERIMENTAL RESULT

The large signal performance was previously measured over the full bandwidth from 600 MHz to 1000 MHz in steps of 100 MHz. Fig. 3 presents the results of maximum output power ( $P_{outmax}$ ), the drain efficiency ( $\eta_D$ ), the power added efficiency (PAE) and the Gain.

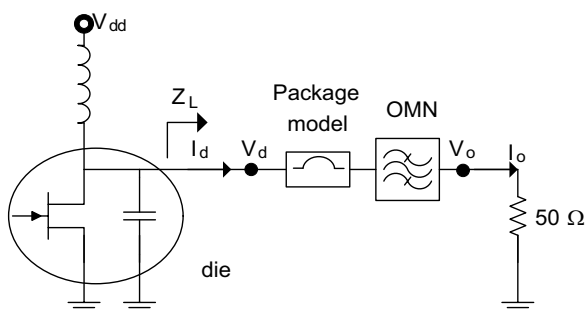


**Figure 3.** Large signal performance over the bandwidth.

As can be seen there is a clear peak in the drain efficiency at 87% around 700 MHz but further up in frequency this drops to around 80% at the center frequency 800 MHz and then further to 66% at 900 MHz. If it could be clearly understood what causes this drop it is likely that the full bandwidth response can be much improved in the future.

## 5. DE-EMBEDDING METHOD

The broadband power amplifier was designed for class-E PA operation. However, the ideal optimum load impedances for this class was extracted with ideally open termination which make it infeasible for the designed filter since the attenuation for low harmonic is not high enough. Hence, the PA operation is not optimally class-E PA for the entire frequency band. The only interface for the analysis accessible is the connector of the amplifier. For a full switch-mode analysis the time domain waveforms need to be studied in the intrinsic transistor plane. With the matching networks from ADS and the knowledge of the response from the transistor package the measured interface can be de-embedded to the  $Z_L$  plane shown in Fig. 4. To this reference plane the waveforms can be de-embedded and used to analyze the operation mode, and to extract the load impedances seen at the die reference plane.



**Figure 4.** The reference plane for the extracted waveforms.

For GaN devices, the model of the output capacitance  $C_{ds}$ , which is the main effect of the waveform shapes, is linear and has a small value. Hence the effect of this capacitance on the waveforms for the low frequency can be neglected. The de-embedding algorithm can be done simply following the previous assumption and considering the device as a source generator; then measuring the time domain either by using oscilloscope or LSNA for the output voltage. These measurement devices can produce the output voltage either in time or in frequency

domain. Time domain waveforms are obtained through sub-sampling concept. The IF filter used here is a low pass filter, which is not the same as in VNA. The resulted IF signal is the same replica as the microwave signal. The magnitude and the phase for the component of the measured voltage is obtained using the Fast Fourier Transform (FFT).

Five harmonic components can be used to give a good overview of the time domain component. The output current can be found from the output voltage component using ohm law assuming  $50\ \Omega$  impedance for the entire harmonic component. Using (2) [5] the time domain of the drain voltage and current can be extracted.

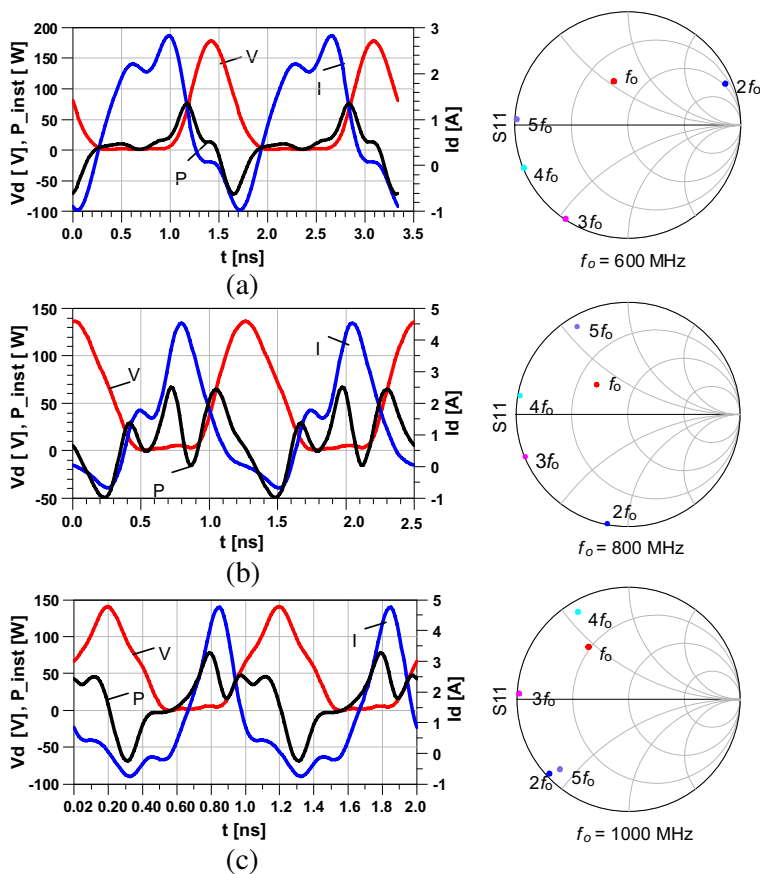
$$\begin{bmatrix} V_d \\ I_d \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_o \\ I_o \end{bmatrix} \quad (2)$$

where,  $V_o$  and  $I_o$  are the output voltage and current content, respectively, and the transmission matrix is the total transmission matrix of the matching network, filter and the package. This matrix can be acquired from the conversion of the  $S$ -matrix which is obtained from the simulation. For five harmonic component of the drain voltage and current waveform (2) should be performed five times for each component, where the value of the transmission matrix for each single harmonic is used.

The time domain extraction method was verified in the simulation environment. It showed a very good agreement between the simulated and calculated one. Fig. 5 shows the calculated waveforms for the current ( $I_d$ ) and the voltage ( $V_d$ ) at the die reference plane (on the left-hand side) and their corresponding extracted load impedances (on the right-hand side) for 3 different frequencies (i.e., 600 MHz, 800 MHz and 1000 MHz).

For further analysis of the dissipated power, the instantaneous power  $P_{inst}$  ( $P_{inst} = v(t) \cdot i(t)$ ) is shown in Fig. 5 (LHS) with the time domain of the drain current and drain voltage. This power will be further analyzed for four different switching characteristics; the turn-ON region where the transistor current start to increase, the turn-OFF region where the current drops to zero, the ON region where only the current is conducting (ideally) and finally, the OFF region where there is no current present.

The extracted waveforms do not have the same shape over the frequency band which can be concluded that the optimum class-E PA operation is not maintained ideally over the entire band. Fig. 5 (RHS) shows the calculated load impedances from the extracted waveforms ( $Z_L = V_d/I_d$ ) for the same frequencies calculated previously and the same reference plane. These impedances with the extracted



**Figure 5.** Time domain extracted waveforms at the die reference plane (LHS) and their corresponding extracted load impedances at the die reference plane (RHS) for (a) 600 MHz, (b) 800 MHz, and (c) 1000 MHz.

waveforms will guide on determining the class operation for each of these frequencies.

## 6. DISCUSSIONS

Before starting with the analysis a very important point is that the optimum load impedances in (1) excludes the effect of the intrinsic output capacitance of the die. The optimum impedance for the entire harmonic seen at the internal current source is usually a capacitive

load (i.e.,  $C_t$  in Fig. 1) which has different impedance value for each harmonic.

### 6.1. Analysis at 600 MHz

It can be seen from Fig. 5 (LHS), that the voltage shape is sinusoidal while the current is not purely as in class-E PA and not even purely square shape. However, on the RHS, the fundamental impedance is inductive and the second harmonic impedance is high and the rest of the harmonic impedances have low impedance mostly in capacitive part of smith chart which operates as an external capacitance. This concludes that the class resembles a class-E/ $F_2$  PA [6].

### 6.2. Analysis at 800 MHz

It can be seen from Fig. 5 (LHS), that the voltage shape is sinusoidal while the current is close to the current in class-E PA, also, from Fig. 5 (RHS), the fundamental impedance is inductive and the harmonics see low real impedance values and capacitive imaginary value, which is the same requirement as in class-E PA.

### 6.3. Analysis at 1000 MHz

It can be seen from Fig. 5 (LHS), that the voltage shape is sinusoidal while the current is close to the current in class-E PA, also, from Fig. 5 (RHS). The fundamental impedance is inductive and the harmonics see low real impedance values, but the imaginary value is between capacitive and inductive. This kind of operation can be stated as weak class-E PA.

It is stated previously that the efficiency at this frequency is 15% less than efficiency at 800 MHz. The calculated instantaneous power in Fig. 5 (LHS) will help in the investigation of the power loss. In the turn-ON region of the switching behavior, there is no overlapping between the drain current and the drain voltage for all the frequencies,

**Table 1.** Summary of published broad-band SMPAs performances.

Freq [MHz]	State of operation		
	$P$ at off state and turn-on state [W]	$P$ at on state [W]	$P$ at turn-off state [W]
800	-0.04	1.24	6.07
1000	-0.18	1.70	10.42



Fig. 5 (LHS) because the voltage at the capacitor  $C_t$  is zero just prior the turn-ON state. Hence, the OFF state and the turn-ON will be analyzed together. Table 1 presents the calculated average power for each of the three states at 800 MHz, which has high efficiency and the PA is working as class-E PA, and at 1000 MHz, where the PA works as weak class-E PA and it has the lowest efficiency. The result in Table 1, shows that the major part of the losses is during the OFF-state of the operation, it is 6 W at 800 MHz and 10 W at 1000 MHz. for this state it need to have a zero current switching (ZCS) which require that the switch (in this case the transistor) to be zero just prior to the turn-OFF state. This yield to that the second harmonic impedance seen at the transistor at 1000 MHz is smaller than the second harmonic impedance seen at the transistor reference plane at 800 MHz, Fig. 5 (RHS).

## 7. CONCLUSION

A previously designed SMPA in [3] has been analyzed. The SMPA showed maximum drain efficiency of 87.8% and the maximum output power of 46.9 dBm (49 W), while the minimum drain efficiency was 66%. Analysis based on time domain waveforms has been presented.

Extraction method of the time domain waveforms was discussed. The de-embedded waveforms are based on the sub-sampling theorem which is filtered again using low pass filter. The extracted waveforms are taken from first five harmonic components. The resulted IF waveform is exactly the same replica of the microwave waveforms. The extracted magnitude and phase are used for the time and frequency domain analysis.

The analysis was based on three different characteristics at the die reference plane; the time domain drain current/voltage, the time domain power and the load impedances. The power amplifier showed different operational mode over the entire frequency, however, it started from class-E/ $F_2$  PA (i.e., at 600 MHz) passing by optimal class E PA (i.e., at 800 MHz) and ending with weak class-E PA (i.e., at 1000 MHz). Over all, the broadband PA operation is maintained within the class-E PA mode of operation that is designed for (i.e., either weakly or strongly).

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