A GaN HEMT Class AB RF Power Amplifier

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Abstract — **In this article, an RF power amplifier which has a crucial importance for RF transceivers is designed and implemented. The main aim of the design is making the power amplifier linear at the center frequency 1.8 GHz. Linearity was measured with two tone test and according to the result of the test, the Carrier-to-Intermodulation (C/I) ratio should have been above 30 dB and two fundamental carriers with the 5 MHz space should be at least 1.25 Watt. Also, efficiency was tried to be kept as high as possible. Considering the three issues; linearity, output power and efficiency; the circuit was biased to the conditions of deep class AB. GaN transistor which has been very popular in recent years was used as an active device. The simulations and the layout of the circuit were all done with AWR Microwave Office. Taconic TSM30 600 was used as a substratum in the circuit. After the circuit was implemented, the measurements results were compared to simulations.**

Keywords-component; formatting; RF Power Amplifier, Linearity, GaN HEMT.

I. INTRODUCTION

A power amplifier is basically an electronic circuit which transfers the RF power to the load by amplifying the input power. RF transceivers send RF signals kilometers away. With regard to the "Free Path Loss" equation, RF signals are attenuated at the transmission lines such as air or coaxial cable. The RF signals should be higher than a specific level not to be lost in noise signals at the receiver. For this reason, the last stage of the transceivers must be a power amplifier to deliver high amount of power.

The power amplifier design involves many challenging concerns at the same time such as output power, efficiency and linearity. Therefore simulation programs and accurate models of transistor are essential to overcome the design issues. The whole design was completed with AWR. The nonlinear model of chosen transistor for AWR was provided by the vendor.

The technology and type of transistor is also important in power amplifiers. GaN HEMT was chosen as the parasitic capacitances of GaN HEMTs are lower than GaAs MESFETs and their power density and voltage operation are higher too. GaN HEMTs is used in wider bandwidth applications owing to their high load-line dynamic resistance [5].

II. THEORY

A. *Carrier-to-Intermodulation Ratio*

Carrier-to-Intermodulation ratio (C/I) is a common method to determine nonlinear behaviour of a PA. The ratio between the desired output power and IMD output power is defined as the carrier-to-intermodulation ratio.

$$C/I \triangleq \frac{P_{out}}{P_{IMD}} \tag{1}$$

Because of the several reasons such as matching network components and memory effects, C/I is defined and measured in four possible ways [3]:

$$C/I \triangleq \frac{P_{out}[f_{n(m)}]}{P_{out}[2f_{2n(2m)} - f_{m(n)}]} \qquad n, m = 1, 2 \tag{2}$$

Change of the input power strongly affects the carrier-to-intermodulation ratio. The ratio is could be written in terms of $IP3_{out}$ which was explanied next title [3]:

$$\left(C/I\right)_{dBc} = 2 \cdot \left(IP3_{out} - P_{out,dBm}\right) \tag{3}$$

III. DESIGN

The power amplifier design involves a lot of trade – offs such as linearity, output power, efficiency, power gain etc. The designer should determine the general structure of the PA, biasing point selection, class of operation and technology of the active device.

In order to determine the class of operation, firstly, it has to be taken into account that the power amplifier has to be linear. It seems that class A, AB and B are appropriate selections. It is also desired the efficiency should be as high as possible. Class B has the highest efficiency but at higher frequency applications, deep class AB is the most suitable operation for single ended power amplifiers [4]. To obtain high efficiency as high as class B, the gate bias voltage will be selected very close to the threshold voltage. The bias point selection is done by looking the $I_{DS} - V_{GS}$ graph of the transistor.

Considering the requirements of power amplifier, a GaN HEMT transistor was used in the design. GaN HEMTs are offering high linearity and efficiency including high output power [6]. Cree's GaN HEMT transistor CGH40010F was chosen as an active device. The large signal model of the transistor is available for AWR Microwave Office.

A. *Output Network*

In RF circuits the input and output impedances should be matched to 50Ω. At the output, optimum impedance should be found for the requirements. At first, the optimum impedance for efficiency was determined. In order to find the optimum impedance for best efficiency, a method known as "Load Pull" is applied. The optimum impedance value for the best efficiency is (0.53+j0.84).50 = 26.5+j*42 Ω. If this impedance had been used as seen impedance from the output of the transistor, the efficiency could be quite high; however the linearity was far less than desired. After making some compromise for required linearity, the most appropriate impedance was decided to be 25 Ω. This impedance value was an outcome of an optimizing of both linearity and efficiency. Now, the output network is a simply passive circuit transforms the 25 Ω to 50 Ω. The most widely used solution is a single section low-pass network which consists of a capacitive reactance shunting the higher load resistance, along with a series resonant inductive reactance [1]. In this work, only microstrip lines are used to transform the impedance.

B. *Stability and Input Network*

Unlike the output network, the aim of the input network is to match the impedances between ports. In order to match the impedances, only the distributed elements were used except DC block capacitor and stabilization network. After the transistor was biased; the stability of the device was analyzed. The transistor is unstable over a wide range of frequencies even at the operating frequency, therefore the stabilization network was included to the input network [4]. The gate bias voltage was -3V which was decided before for deep class AB operation. The input network including microstrips, DC blocking capacitors and stabilization network. The width of microstrip were kept constant and lengths of microstrips were optimized according to the s_{11} value at the operating frequency.

C. *Biasing*

A biasing network generally consists of a DC block and RF choke. The purpose of the RF Choke is to have very high impedance at the operating frequency to block the RF from leaking through the biasing network. The RF Choke prevents the RF signal while acting as a DC short. The RF choke at microwave frequencies is generally realized by using a high impedance λ/4 line, also known as a shunt stub terminated by an RF bypass capacitor. In order to further increase in bandwidth, two sections of quarter-wave long transmission lines are used. If an open circuit is required across the main line for RF signals, a quarter wave high impedance line followed by an open-circuited quarter wave low impedance line are connected [2].

The circuit was designed with microstrip lines except DC block capacitors. According to the simulation results; the width and length of the lines were optimized again.

IV. SIMULATION RESULTS

The first measurement was stability. At the operating frequency the the Rollett factor (K) must be greater than unity The amplifier is unconditionally stable at the operating frequency.

The power gain of the circuit was analyzed and the value of linear power gain and 1 dB compression point were investigated.

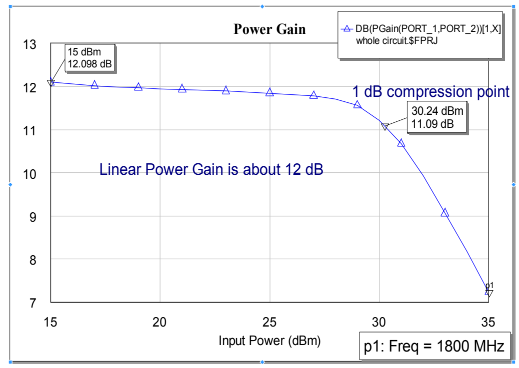

Figure 1: The power gain of the circuit

The amplifier can give about 12.0 dB constant linear output power up to 30 dBm input power. The 1 dB compression. point of output and input power was shown in figure 1.

The power added efficiency is strongly depends on input power. As the input power increases, the power added efficiency increases as well. However, after a certain point the PAE becomes constant and even decreases. The power added efficiency graph is shown in figure 2.

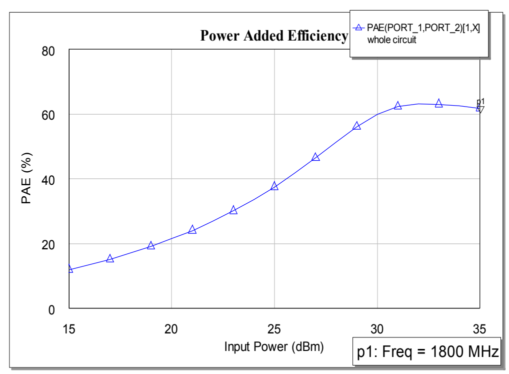

Figure 2: Power Added Efficiency

When the power of tones were 23 dBm, the value of the fundamental carriers were 34.75 dBm and 34.81 dBm respectively. The nearest intermodulation products were -3.795 dBm and -0.168 dBm as seen in figure 3.

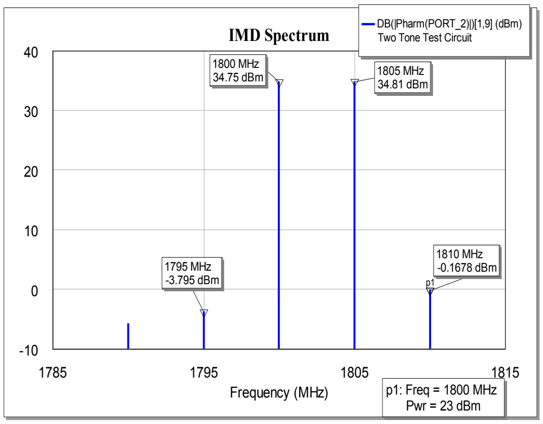

Figure 3: Intermodulation Spectrum (P_{IN}=23 dBm)

When the power of tones were 24 dBm, the intermodulation products risen rapidly as expected. The fundamental carriers were 35.54 dBm and 35.6 dBm respectively and the intermodulation products were 3.84 dBm and 6.04 dBm. Thus the carrier-to-intermodulation ratio was 35.54 dBm - 6.04 dBm = 29.5 dBm as shown in figure 4.

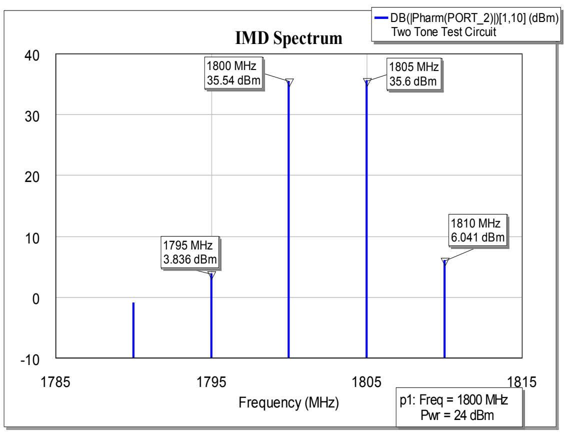

Figure 4: Intermodulation Spectrum (P_{IN}=24 dBm)

According to linearity criterion, the maximum input power should be under 23 dBm. When the input power was 23 dBm, the power added efficiency was 30.1%. This was a quite good result for a linear power amplifier.

V. MEASUREMENTS and CONCULUSION

After the circuit was fabricated, it settled on an aluminum layer and screwed on it. Between the transistor and aluminum layer thermal paste was rubbed to expel the heat. The circuits dimensions are 11.4x10.3 cm^2 (Figure 5).

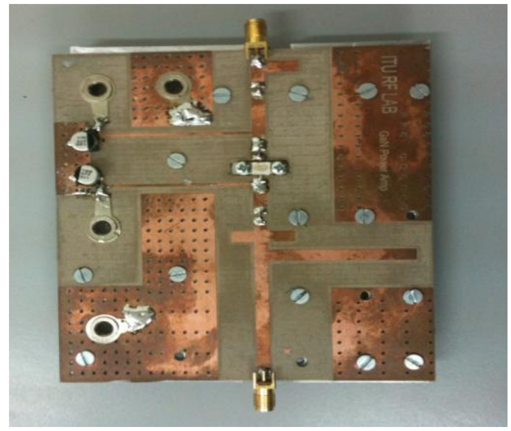

Figure 5: The fabricated circuit

The circuit was biased and single tone was exerted from the signal generator to the input. The offset value of the device was changed due to the loss of the attenuator. The input power was changed from 20 dBm to 25 dBm, the output power and power gain was observed. The linear gain of the amplifier was measured about 10 dB. This was 2 dB low compared to simulation result. When the input power was 23 dBm, the output power was 33 dBm. The output signal was seen on the frequency spectrum as in Figure 6.

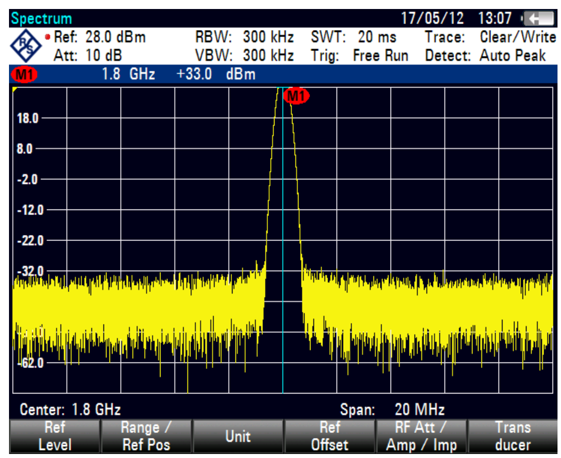

Figure 6: The measured output signal when P_{IN} = 23 dBm

When the input power was 24 dBm, the output signal was measured as 33.8 dBm as seen in figure 7.

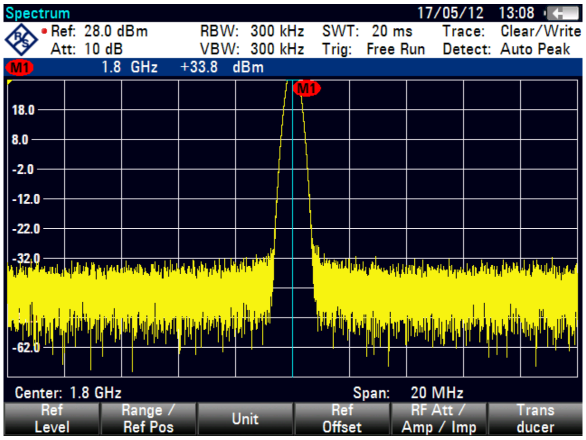

Figure 7: The measured output signal when P_{IN} = 24 dBm

Table 1: Measurement results for single tone test

P_{IN} [dBM]	P_{OUT} [dBm]		Power Gain [dB]		PAE (%)	
	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
20	30.0	32.0	10.0	12.0	15.31	21.48
21	31.0	33.0	10.0	12.0	17.93	24.06
22	32.0	34.0	10.0	12.0	18.86	26.94
23	33.0	35.0	10.0	12.0	21.38	30.12
24	33.8	36.0	9.8	12.0	23.24	33.64
25	34.4	37.0	9.4	12.0	24.19	37.53

The two tone signals were exerted to the input port and carrier-to-intermodulation ratio was calculated. When the input power was 24 dBm, the spectrum was like in figure 8. The fundamental carriers were 30.2 dBm and the closest intermodulation product was -0.3 dBm. According to this result, the carrier-to-intermodulation ratio was calculated 30.2 dBm - (-0.3) dBm = 30.5 dB. This result was above desired conclusion however the output power was less than expected.

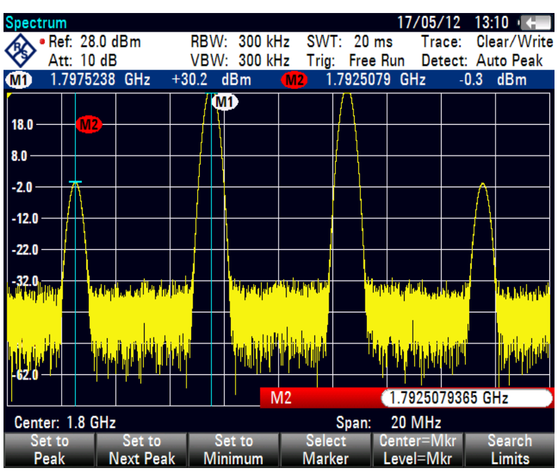

Figure 8: Two tone test measurement when P_{IN} = 24 dBm

When the two tone input power were 25 dBm, the spectrum was like in figure 9. The fundamental carriers were 30.9 dBm and the closest intermodulation product was 7.3 dBm. According to this result, the carrier-to-intermodulation ratio was calculated 30.9 dBm - (7.3) dBm = 23.6 dB. The C/I ratio was below than 30 dB and the amplifier was not linear enough for design criterion. On the other hand, each of the fundamental carriers were 30.9 dBm which was equal to output power criterion, 1.25 Watt.

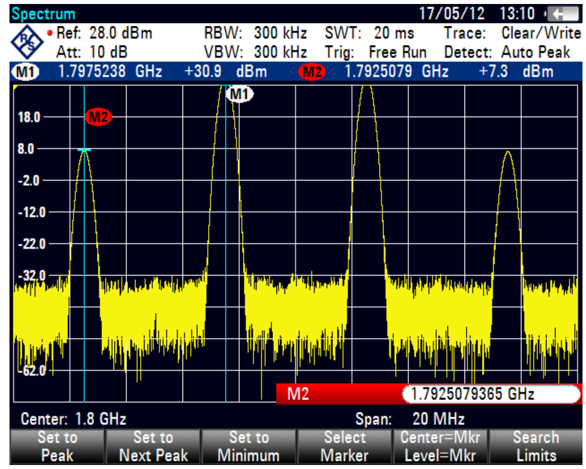

Figure 9: Two tone test measurement when P_{IN} = 25 dBm

The implemented circuit fullfilled two of three criterions. While the input power 23 dBm and 24 dBm, the carrier-to-intermodulation ratio were 34.8 dB and 30.5 dB respectively. The linearity criterion was satisfying since C/I was desired above 30 dB. On the other hand, the power of fundamental carriers during the two tone test were below 1.25 Watt while C/I was above 30 dB. For a linear operation, at most 24 dBm power could be exerted to the input. Therefore, the highest power added efficieny could be optained 23.24 %.

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