Uneven Doherty Amplifier Based on GaN HEMTs Characteristic

K. Pushyaputra, T. Pongthavornkamol, N. Puangngermak and S. Chalermwisutkul
The Sirindhorn International Thai-German Graduate School of Engineering (TGGS)
King Mongkut’s University of Technology North Bangkok (KMUTNB)
1518 Pibulsongkram Road, Bangsue, Bangkok 10800, Thailand

Abstract. To enhance the average efficiency of high frequency power amplifier, enhancement technique such uneven Doherty amplifier and high performance material such a GaN HEMT are interesting solutions. In this report, the uneven Doherty amplifier based on NPT00004 GaN HEMTs from Nitronex at 2.45 GHz is proposed with the assumption that it would give superior average efficiency compared to conventional class AB. However, these transistor model used in the design process are not extracted in house. Hence, the characteristic of used transistors might cause discrepant results between simulation and measurement especially when biased point is below threshold voltage. The measurement result gives power added efficiency (PAE) about 32% at 1dB compression point with linear power gain of 7.11dB whereas the simulation result shows PAE of 56% at 1dB compression point and approx. 38.8% at 6dB back off power (BOP).

Keywords: Uneven Doherty amplifier, GaN HEMTs

1. Introduction

Demands of wireless communication such as increasing users and complex applications are rapidly grown every day. The channel bandwidth is still not expanded to serve those requirements due to limitations of available bandwidth. Therefore, in-band utilized techniques are critical methods to respond to such demands. The spectrum utilization is comprised of linearization techniques such as feed-forward, in-line predistortion and digital predistortion and efficiency enhancement techniques such as envelope elimination and restoration (EER), envelope tracking (ER) and Doherty amplifier (DA) which are important techniques to achieve high spectrum efficiency. However, these techniques require suitable device to satisfy the specifications e.g. bandwidth and the flexibility to support versatile usages. As an emerging wide-bandgap semiconductor material for power device technology, Gallium Nitride (GaN) enables larger operating bandwidth and frequency as well as high power density. Although, GaN is still immature technology but this technology usage inclines increasing in the future which is applied to spectrum enhancement techniques for modern communication.

Doherty power amplifier, one of efficiency enhancement techniques used in wireless communications, can offer high average efficiency for new wireless and mobile standards with non-constant signal envelope while is still maintained. Doherty power amplifier is comprised of two amplifiers i.e. main amplifier operated in class AB and peaking amplifier operated in class C. In addition, Wilkinson divider, tee power combiner and other microstrip structures are used to provide the Doherty amplifier’s operating conditions.

2. AlGaN/GaN HEMTs

Aluminum Gallium Nitride/ Gallium Nitride (AlGaN/GaN) is a new device technology which shows superior advantages beyond other materials such as GaAs, SiC and Si in terms of high power and frequency operation range[1]. The high charge density of this material and capability of making High Electron Mobility Transistors (HEMTs) result in higher power and wider bandwidth due to higher input and output
impedances[1]. Moreover, GaN HEMTs still keep their advantages at high frequencies (>4GHz) when proper gate lengths are used [1]. GaN technology is also designed to operate at high power levels with wider bandwidth which is adopted by commercial efficiency power amplifier design markets [1]. However, this technology is still immature due to e.g. trapping effects. Trapping effects in GaN technology impact directly to the performance including isothermal of the current lag, low frequency dispersion, current collapse, gate lag effect and drain lag effect [2], [3].

Fig. 1: Equivalent-circuit model of an GaN HEMT [4].

The equivalent-circuit of GaN HEMT in Fig.1 is not only used to explain the nonlinearity of this device but also shows the physics of this device over a frequency range and wide biasing point [4]. Moreover, the complexity of this analysis is limited by numerical calculation. In general, it hardly achieves the maximum efficiency of amplifier at high frequency. This is because the parasitic reactive elements of the device i.e. device on-resistance, non-zero transition time, non-zero knee voltage and finite resonator Q-factor [5].

3. Uneven Doherty Amplifier

In general, Doherty technique uses two unequal-sized devices for operation. This is because its mechanism needs optimum load modulation with higher power at peaking amplifier (PA) and lower power at main amplifier (MA). However, it is possible to use two equal-sized devices in Doherty operation that referred to uneven Doherty amplifier. The critical point of this architecture is biased voltage of PA that needs to be trigged at right back-off power (BOP) [6]. In order to simplify the circuit, this design will activate MA and PA as class AB amplifier and class C respectively. As a result of this scheme, this design will reduce unnecessary external circuit used in control biased voltage of PA due to class C operation. Doherty operation can be explained in three region of operation by considering the input power level [6].

3.1. Low power level

Only MA is operated while PA is turned-off. Linearity and efficiency of this region are based on class AB operation since MA is operated to its saturated point. Theoretically, when MA reaches to saturation, its maximum efficiency is achieved.

3.2. Medium power level

PA starts to operate while MA is still operated as current source, the load impedance of MA is modulated resulting in combined output power and efficiency.

3.3. High power level

At this region, both amplifiers are saturated and maximum efficiency of Doherty operation is achieved.

4. Uneven Doherty Amplifier Design

In this work, four sub-circuits were designed and fabricated separately. The advantage of this procedure is each measurement result can be compared to simulation and it would be easier to analyze. The conventional operation classes of NPTB00004 GaN HEMT can be classified at \( V_{ds} = 24 \) V in Fig.2. MA circuit operated in class AB and PA circuit operated in class C were designed on NPTB00004 model.
Main amplifier (MA) for Doherty operation designed in class AB is chosen to operate between 5% and 10% of maximum drain current for high efficiency while linearity is acceptable. Hence, the biased point of MA should operate at \( V_{gs} = -1.3 \) V at \( I_{dsq} = 65 \) mA. For input matching network design, S parameter of device can be applied whereas source-pull method is possible. However, this design also concern about unconditional stability case that result in adding the 10 \( \Omega \) resistor at input matching network to achieve stable condition. Although the resistor reduces the input power but it offers the advantage of noise floor suppression that comes up with pre-amplifier. This resistor is not only lump element at input matching network because the capacitor added in parallel with resistor is also used for efficiency enhancement. In the similar way, output matching network can be designed by Load-pull method. Load-pull not only provides impedances of maximum efficiency but also offers impedances of maximum output power which will be chosen in this design. The schematic of MA is shown in Fig. 3 as well as the simulation result and measurement result are shown in Fig. 4.

![Fig. 3: Schematic circuit of MA.](image)

In the same procedure as MA, peaking amplifier (PA) is designed to operate at class C operation. As shown in Fig. 2, a class C gate bias voltage should be below \( V_{gs} = -1.4 \) V. To achieve a suitable biased point at 6 dB back-off power (BOP), PA is activated automatically due to class C operation at \( V_{gs} = -2.6 \) V. It is obvious that the measurement result deviates from simulation result when the biased voltage is activated deeply in class C operation. The measurement result and simulation result are shown in Fig. 5.

![Fig. 4: Measurement result and simulation result of MA.](image)
5. Performance

In this work, NPTB00004 GaN HEMTs model provided by Nitronex was used during the design. To scrutinize the results, at 1 dB compression point of MA, drain current is 267 mA at $P_{out} = 35.11$ dBm that gives PAE around 46%. In case of simulation, drain current of the simulation result is 239 mA at $P_{out} = 35.54$ dBm that gives PAE around 50.3%. On the other hand, designed PA gives discrepant result between measurement and simulation when drain current of PA is 119 mA at $P_{out} = 30$ dBm with PAE around 23.4% whereas the simulation result shows 100 mA at $P_{out} = 30.3$ dBm that gives PAE around 63%. As a consequence, the Doherty PA shows PAE only 32% at $P_{out} = 35.51$ dBm. The main reason for the discrepancies between simulation and measurement is the inaccurate simulation of the class-C amplifier caused by effects which are not described by the model e.g. trapping & package [5]. The measurement result and fabricated circuit are shown in Fig. 6 and Fig. 7 respectively.

![Fig. 5: Measurement result and simulation result of PA.](image1)

![Fig. 6: Performance of uneven Doherty amplifier.](image2)

![Fig. 7: Fabricated circuit of uneven Doherty amplifier.](image3)

To support this argument, the NPTB00004 class-C model extracted by Institute of Electromagnetic Theory (ITHE), RWTH Aachen, Germany which was extracted from the pulse measurement data with class-C quiescent point was used to replace conventional model from manufacturer to repeat the simulation. The result is shown in Table I. Moreover, the simulation of uneven Doherty amplifier that use class-C model from RWTH Aachen is compared to measurement result is shown in Fig. 8 compared to Fig.6, an obvious improved agreement between simulation and measurement can be observed.
TABLE I
COMPARISON RESULT BETWEEN USED MODEL AND CLASS-C EXTRACTED MODEL.

<table>
<thead>
<tr>
<th>Class</th>
<th>$V_{gs}$ (V)</th>
<th>Impedance at $\text{PAE}_{\text{max}}$ (Ω)</th>
<th>PAE by used model (%)</th>
<th>PAE by class-C extracted model (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>-1.6</td>
<td>12.3+j22.2</td>
<td>53.4</td>
<td>19.8</td>
</tr>
<tr>
<td>C</td>
<td>-2</td>
<td>10.4+j25.7</td>
<td>55.9</td>
<td>14.9</td>
</tr>
</tbody>
</table>

a) Class-C peaking amplifier
b) Entire uneven Doherty amplifier

Fig. 8: Measurement result and simulation result with class C model.

6. Acknowledgements
The authors would like to express their gratitude to the colleagues at TGGS RF laboratory who have provided great support. This project was supported with the class-C quiescent pulsed EEHEMT1 model extracted by Institute of Electromagnetic Theory (ITHE), RWTH Aachen, Germany.

7. References