Development of a GaN HEMT Class-AB Power Amplifier for an Envelope Tracking System at 2.45 GHz

P. Suebsombut*, O. Koch**, S. Chalermwisutkul*

*The Sirindhorn International Thai-German Graduate School of Engineering (TGGS),
King Mongkut's University of Technology North Bangkok,
1518 Pibulsongkram Rd., Bangsue, Bangkok, Thailand
e-mail: suramate.c.ce@tggs-bangkok.org

**Institute for High Frequency Technology (IHF)
RWTH-Aachen University
Melatenerstr.25,
D-52074 Aachen, Germany
e-mail: Koch@ihf.rwth-aachen.de

***Abstract* – A class-AB power amplifier was designed for an envelope tracking (ET) application. Class-AB amplifier is widely used in wireless communication systems due to the compromise between linearity and efficiency. As a power device, Cree Gallium Nitride High Electron Mobility Transistor (GaN HEMT) CGH4010F was chosen. The input and output matching networks were designed and simulated with Advanced Design System (ADS). After some optimization, the amplifier was fabricated using a Rogers RT/Duroid 5880 substrate. The amplifier together with a MAX2247 preamplifier as a driver was measured. A good agreement between the simulation and measurement results was observed. The maximum power added efficiency (PAE) is around 50 percents with the supply voltage V_{sup}= 10V and the maximum drain efficiency is around 75 percents with V_{sup}= 5V. An output power up to 42 dBm and good linearity of the output voltage with respect to the supply voltage in the range $0<V_{sup}<20V$ were achieved. Thus, the amplifier is suited for ET applications.**

***Keywords* – class-AB operation, envelope tracking, amplifier, linearity, input and output matching network, GaN HEMT**

I. Introduction

Nowadays, the electrical power consumption is increased every year. One of the reasons is the increasing need of telecommunication infrastructure and server farms. An observation has shown that the rise of the power consumption in the ICT sector is doubling every 4-5 year [4]. Therefore, the power consumption in this sector is required to be reduced by the innovation of tools or technologies, which can increase the energy efficiency and are capable of serving wide range of applications [4].

High efficiency power amplifiers (PAs) are desired both to increase battery lifetime in mobile systems and to reduce the power costs of base station operation. The main issue of modern communication systems is that there is a trade-off between high data rates, a cheap transmitter architecture and power-efficient amplification. Modern modulation schemes based on Orthogonal Frequency Division Multiplex (OFDM) require highly linear transmitters over a wide dynamic range of signal power due to the fact that the signal envelope is non- constant. To meet these requirements, class-AB architectures with sufficient back-off are usually chosen. For the peak power level of the signal, class-AB can offer an acceptable combination of linearity and relatively high efficiency from 50 to 78.5 percent. However, during the most operating time, the power level of the signal is lower than the peak level. As a result, the power efficiency decreases drastically compared to the peak efficiency. Thus, to reduce the necessary back-off and to increase the power efficiency while still meeting the linearity requirements, envelope tracking (ET) architectures can be used. In these architectures, the power supply of the final PA stage is modulated, providing a part of the signal envelope.

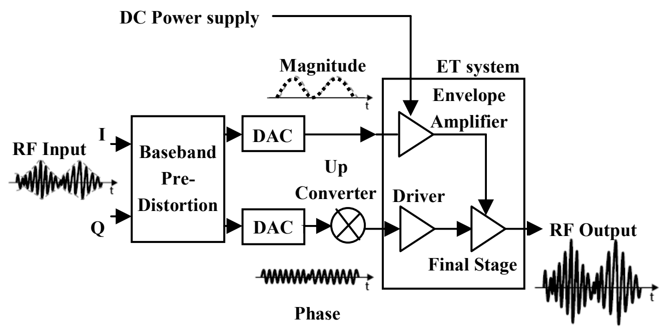

Figure 1. Envelope Tracking Architecture [1], [5]

It was demonstrated in the literature that the envelope tracking system can improve the average power-added efficiency (PAE) of a power amplifier [5]. The main concept of the envelope tracking technique is the superposition of the envelope signal with the drain supply voltage (see Figure 1). Therefore, the RF power transistor is persistently operated in a high efficiency region. Drawbacks of ET are the sensitivity to time misalignment between RF and envelope signals and nonlinearity due to dynamic supply voltage [6]. However, it has been already proven in the literature that these drawbacks can be compensated with optimal or adaptive predistorters as described in [6].

II. Efficiency Terms

In this work, two efficiency terms—*power–added efficiency* (PAE) and *Drain efficiency*—will be used. PAE is defined by the ratio between the difference of RF input and output power and the DC power supplied to the amplifier. Thus, the equation of PAE is:

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \tag{1}$$

Where $\boldsymbol{P_{out}}$ is the output power of power amplifier;
$\boldsymbol{P_{in}}$ is the input power of the power amplifier;
and $\boldsymbol{P_{DC}}$ is the DC power of the power amplifier.

In case of drain efficiency, the ratio between the RF output power to input DC power is considered. Thus, the formula of drain efficiency is:

$$\eta_{drain} = \frac{P_{out}}{P_{DC}} \tag{2}$$

III. Design of the Microstrip Class-AB Power Amplifier for an ET System

For an ET system, class-AB is the most appropriate operating class of the power amplifier due to the flexibility to maintain linearity and efficiency when the supply voltage at the output side of the PA is varied. Considering high efficiency switch-mode PAs e.g. class E, they are more prone to nonlinearity and require more complicated optimum tuning of load and source impedance for the fundamental and the harmonics. Thus, they are not appropriate for an ET system, but for another efficiency enhancing technique, namely the Envelope Elimination and Restoration (EER) [2].

In this work, a class-AB microstrip power amplifier with the operating frequency of 2.45 GHz was developed and verified for the suitability for an ET system. In order to enable the drain supply voltage to vary in a wide range, a power device with a high breakdown voltage [7] should be chosen. This device property can be offered by transistors based on wide-band gap semiconductor material e.g. Gallium Nitride (GaN). The power device chosen for this work is CGH40010F GaN HEMT from Cree [3].

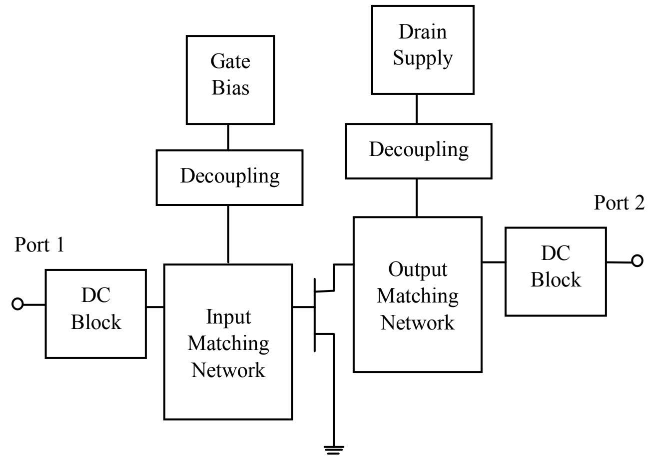

Figure 2. Block diagram of the designed class-AB power amplifier

Agilent's Advanced Design System (ADS) was used as the design tool for the class-AB amplifier. Large signal model of the GaN HEMT from Cree was included into the amplifier circuit on ADS. Input and output matching networks realized by microstrip line steps as well as bias networks at the device's gate and drain sides were designed for optimum power matching. The substrate parameters were set according to Roger 5880 RT/Duroid datasheet [8] which was used later for the fabrication of the power amplifier. The block diagram of the designed amplifier is shown in Figure 2.

IV. Simulation Results

Harmonic balance simulations were performed in order to predict the performance of the amplifier circuit shown in Figure 3. **In the first step, the amplifier circuit was simulated with a constant drain supply voltage V_{sup}= 28V** and the gate bias voltage V_g= -1.8V which represent a bias condition of a conventional class-AB amplifier. By feeding the amplifier input with a 2.45 GHz, 26.5 dBm sinusoidal signal, the output power of the amplifier circuit was simulated to 42.98 dBm as illustrated in Figure 3. From the simulation, the power added efficiency (PAE) is around 55 percent and the drain efficiency η_{drain} is around 55.73 percent (see Table I).

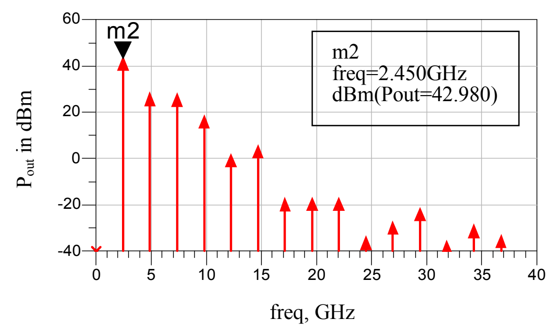

Figure 3. Output power of the designed amplifier at 2.45 GHz

TABLE I

SIMULATION PARAMETERS, SIMULATED OUTPUT POWER AND EFFICIENCIES

freq.	V_g	V_{sup}	P_{RFin}	P_{RFout}	Gain	PAE	η_{drain}
2.45 GHz	-1.8 V	28V	26.5 dBm	42.98 dBm	21.20 dB	55%	55.73%

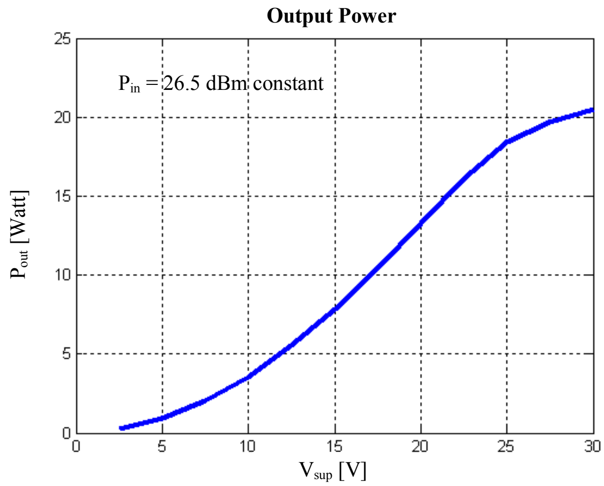

Figure 4. Output power versus drain supply voltage

In the second step, the drain supply voltage V_{sup} was swept from 2.5V to 30V during the simulation, whereas the RF input power P_{in} is fixed at 26.5 dBm. The relation between the drain supply voltage V_{sup} and the RF output power is depicted in Figure 4, whereas the dependency of the PAE and η_{drain} on V_{sup} is shown in Figure 5.

The PAE and drain efficiency with supply in Figure 5 shows the efficiency of the amplifier depending of the drain supply voltage from 2.5 to 30 Volts. The peak of PAE from the simulation is around 67 percents at V_{sup}= 12.5V whereas the peak of η_{drain} is about 78.94 percents at V_{sup}= 2.5V.

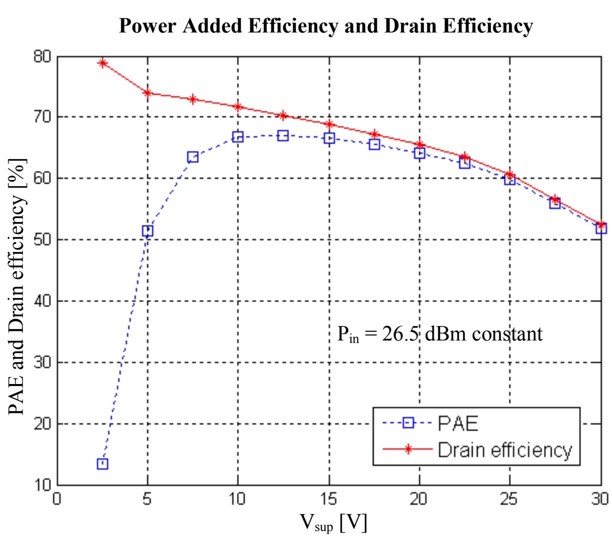

Figure 5. PAE and drain efficiency as functions of V_{sup}

V. MEASUREMENT RESULTS

The designed class-AB amplifier circuit was fabricated on 5880 RT/Duroid substrate. Figure 6 shows a photograph of the fabricated power amplifier for an ET system. In order to provide sufficient RF input power of 26.5 dBm to the fabricated power amplifier, MAX2247 (28 dB gain@2.45 GHz) was used as a driver [9]. The small signal gain ($|S_{21}|$) of the fabricated amplifier together with the driver was measured with a variation of the drain supply voltage 2.5V<V_{sup}<30V. From the measurement results shown in Figure 7, it is obvious that the gain of the fabricated class-AB power amplifier can be varied by varying the drain supply voltage V_{sup}. However, when V_{sup} exceeds around 25V, the gain is not significantly changed at 2.45 GHz.

Another measurement was set up to verify the dependency of the power amplifier's output power on V_{sup}. During the measurement, the input power of the fabricated amplifier provided by the driving stage (MAX2247) is fixed to 26.5 dBm. When V_{sup} was varied in the range of 2.5V<V_{sup}<30V, the output power shows the expected dependency on V_{sup} as depicted in Figure 8. With V_{sup}= 25V, the output power was maximum at 8.7 Watts for the signal frequency of 2.45 GHz.

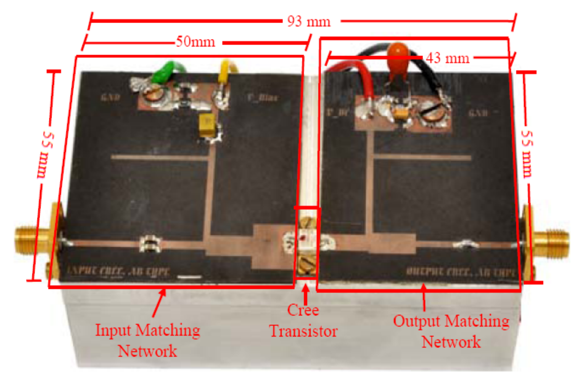

Figure 6. Fabricated class-AB power amplifier

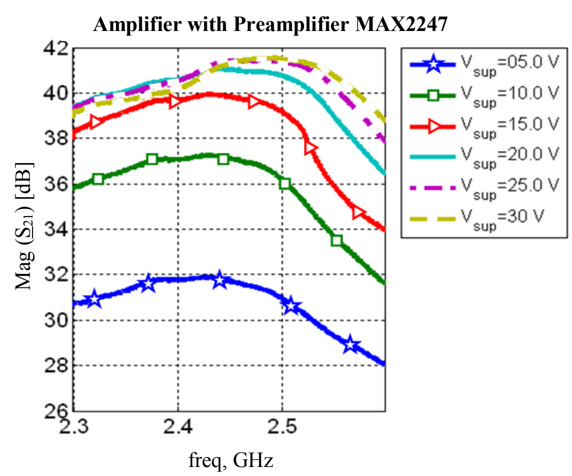

Figure 7. Measured $|S_{21}|$ of the fabricated amplifier with preamplifier MAX2247

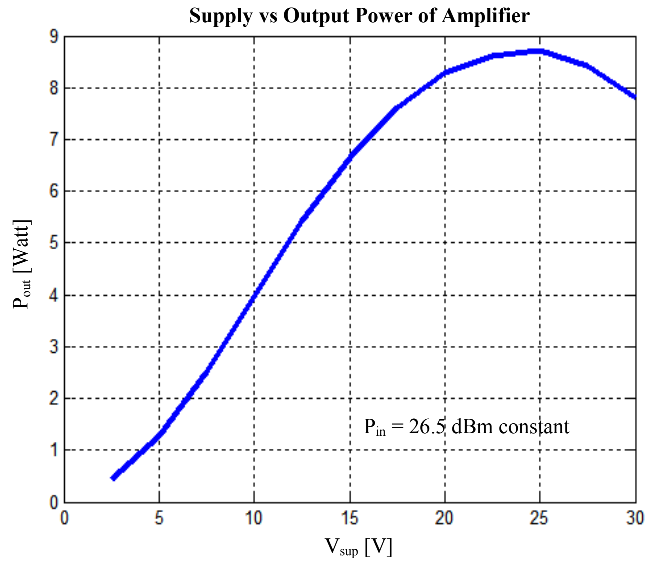

Figure 8. Measured dependency of P_{out} on the drain supply voltage V_{sup}

From the measured output power, PAE and η_{drain} were calculated and plotted as functions of V_{sup} (see Figure 9). From Figure 9, differences are observed between simulated and measured PAE and η_{drain} . Possible reasons of the differences are inaccurate fabrication process or losses which were not taken into account in the simulation. However, the measurement results show the expected dependency between the efficiencies and the drain supply voltage. The fact that the output power can be varied by varying the drain supply voltage whereas PAE is relatively high (>40%) over a wide range of V_{sup} confirms that the fabricated amplifier is appropriate for an ET system.

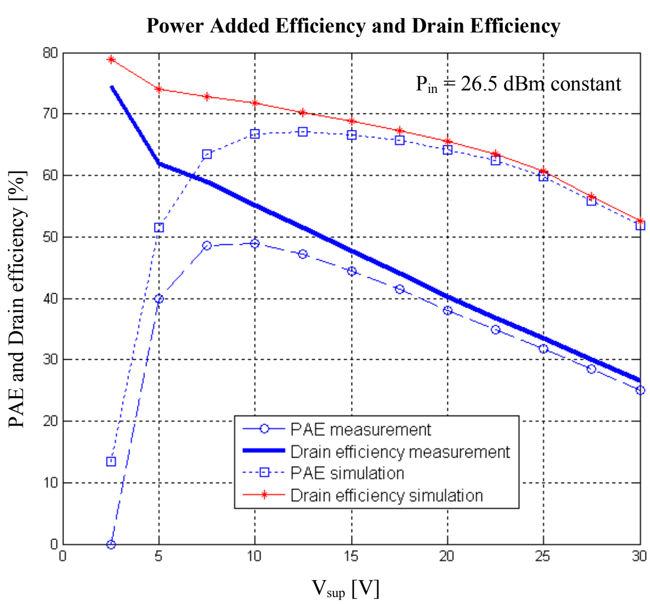

Figure 9. Comparison between simulation and measurement regarding calculated PAE and $\eta_{DC\,to\,RF}$ as functions of V_{sup}

VI. COMPARISON WITH A CONVENTIONAL BACK-OFF AMPLIFIER

The PAE of the fabricated class-AB amplifier is plotted once more as a function of the output power (see Figure 10 a)). **In this case, the RF input power is fixed at 26.5 dBm, whereas the drain supply voltage is varied causing the RF output power to change.** From the measurement result, PAE is higher than 40% for the output power range 31 dBm<P_{out}<39 dBm. Thus, when a PAE of 40% or higher is desired, a 8 dB back-off is allowed. As a result, a high average efficiency can be achieved for signals with non-constant envelope. Assuming that a power amplifier with the performance near to our simulation was fabricated, even greater signal back-off is allowed while a high PAE is still maintained (see PAE simulation in Figure 10 a)). To make it more obvious, a simulation was done for a conventional solution with a class-AB back-off power amplifier where efficiency can only be optimized for the signal's peak power. **In this case the drain supply voltage is fixed at 28V where the RF output power is varied by varying the RF input power.** The simulation result depicted in Figure 10 b) shows that the PAE is reduced more than 30% when the output power is backed-off by 8 dB from the peak power.

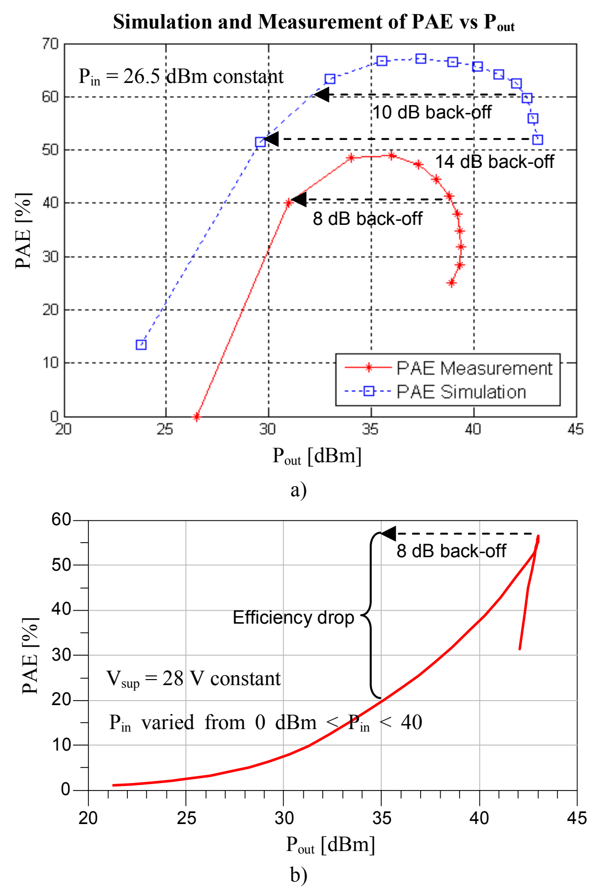

Figure 10. PAE versus P_{out} : a) proposed amplifier with varied V_{sup}, b) conventional back-off amplifier with varied P_{in} and fixed V_{sup}= 28V

VII. Measurement Results of the Fabricated Amplifier with OFDM 802.11g Input Signal

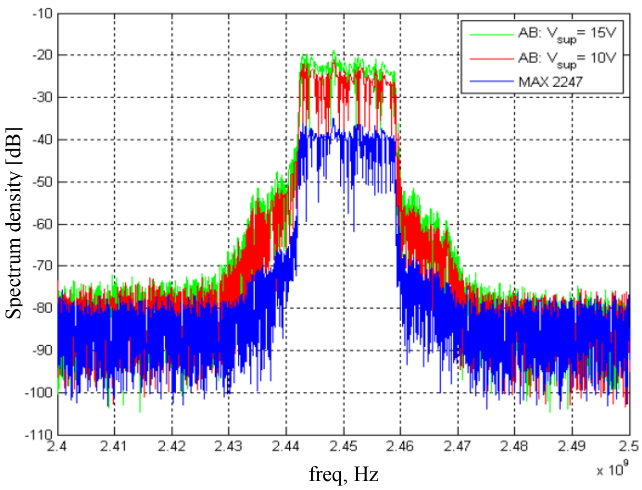

Figure 11. Spectrum density of the driver and main amplifier output

The fabricated amplifier with MAX2247 preamplifier was used to amplify an OFDM 802.11g signal and the spectrum was monitored. Center frequency of the signal is 2.45 GHz, whereas the bandwidth is 18 MHz. The gate bias voltage was -1.8V and the drain supply voltage V_{sup} was set to 10V and 15 V, respectively. Figure 11 shows the measured spectrum density. The spectrum with the lowest in-band power level is the spectrum density of MAX2247 preamplifier output. The one with the middle in-band power level is the spectrum density of OFDM 802.11g with the fabricated amplifier supplied with 10V DC at the drain side. The gain is about 14 dB. The one with the highest in-band power level is the spectrum density of OFDM 802.11g with fabricated amplifier supplied with 15V DC at the drain side. The gain is about 15 dB. The input signal has no harmonics. The spectral regrowth was caused by the transmitter.

VIII. Conclusion

In this work, a class-AB power amplifier for envelope tracking system was designed and fabricated. From simulation results, the attained peak output power was 42.98 dBm. By observing $|S_{21}|$ over a range of drain supply voltage $5V<V_{sup}<30V$, it is obvious that the gain of the designed amplifier can be varied by varying V_{sup}. However, the gain is not significantly increased in case that V_{sup} exceeds 20V. A peak power added efficiency of about 50% occurred at a drain supply voltage of 7.5V. The difference of the PAE between the measurement and the simulation might be due to some cable and other losses. Despite of lower PAE of the fabricated amplifier compared to the simulation, this amplifier allows a signal back-off of 8 dB while the PAE is maintained higher than 40%. Thus, it has been proven that the fabricated amplifier is appropriate for an ET system which can enhance the average efficiency compared to a conventional back-off amplifier without variation of the DC supply voltage.

The amplifier together with its driver was used to amplify an OFDM 802.11g signal and the spectrum was monitored. The spectral requirements were met. Thus, the amplifier is suitable for the ET application.

Acknowledgement

The authors wish to express acknowledgement to all technicians at the Institute for High Frequency Technology (IHF), RWTH Aachen University, Germany for their supports during the fabrication of the power amplifier. Also, the authors thank all research assistants at IHF for the fruitful discussions. Last but not least, the first and the third authors would like to express their special appreciation for all the supports from the RF team members at The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), KMUTNB in Bangkok, Thailand.

References

[1] D. K. Su, and W.J. McFarland, "An IC for Liberalizing RF Power Amplifiers Using Envelope Elimination and Restoration", IEEE Journal of Solid-State Circuit, Vol. 33, No. 12, December, 1998, pp. 2252 - 2258

[2] Ph.D. Frederick H. Raab, "Drive Modulation in Kahn-Technique Transmitters", Microwave Symposium Digest, IEEE MTT-S International, 1999, pp. 811 - 813

[3] Cree Co. Ltd., CGH40010F GaN HEMT datasheet

[4] G. Fettweis, and E. Zimmermann, "ICT Energy Consumption-Trends and Challenges", the 11th International Symposium on Wireless Personal Multimedia Communication (WPMC), 2008

[5] F. Wang, A. Ojo, D. Kimball, P. Asbeck and L. Larson, "Envelope Tracking Power Amplifier with Pre-Distortion Linearization for WLAN 802.1 1 g", Microwave Symposium Digest, IEEE MTT-S International, 2004, pp. 1543 - 1546

[6] A. Hekkala, M. Lasanen, and A. Kotelba, "Adaptive Time Misalignment Compensation in Envelope Tracking Amplifiers", IEEE Spread Spectrum Technique and Application , 2008, pp. 761 – 765

[7] N. Ikeda, S. Kaya, Jiang Li, Y. Sato, S. Kato, and S. Yoshida, "High power AlGaN/GaN HFET with a high breakdown voltage of over 1.8 kV on 4 inch Si substrates and the suppression of current collapse", IEEE Power Semiconductor Devices and IC, May, 2008, pp. 287 - 290

[8] Roger Corporation, RT/duroid 5880 datasheet

[9] Maxim innovation delivered company, MAX 2247 datasheet