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Gallium Nitride-Based Power Amplifiers for Future Wireless Communication Infrastructure

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1. Introduction

Progress in wireless communication technology has enabled applications which were unthinkable as the first digital mobile phone came into the market. Integration of digital camera into a mobile phone was an important step of the convergence between telecommunication and information technology as users started to require transfer of digital pictures besides conventional voice and text information. In addition, fast progress in digital technology has been an immense driving force of the needs for high data rates in telecommunications. Digital multimedia contents e.g. pictures, music, video clips are expected to be available anytime and anywhere which results into tremendous requirements in research and development in wireless technology.

Even though the industry tends to be majorly driven by software applications as well as “look and feel” of mobile devices, enabling hardware technologies in the background also deserve appropriate attention from R&D engineers. As soon as the performance of mobile communication systems cannot fulfil the expectation of users in terms of data rate and error robustness, the importance of the enabling hardware technology becomes obvious.

In order to cope with the rapid growth of the needs in wireless data transmission with constantly increasing data rates, new technical challenges arise perpetually on every layers of the OSI reference model. Whereas new modulation and multiple access techniques e.g. OFDM and OFDMA are introduced to support higher data rates and intelligent network configuration deals with the optimization of routing to increase the capacity and to improve load distribution, progress in hardware components in mobile devices and mobile base stations on the physical layer is also required to serve the needs of the higher OSI layers. Such progress on the physical layer includes techniques and hardware architectures which can enhance power efficiency of the system components while still complying with other specifications regarding linearity, noise, interference, etc.. Also, novel semiconductor device technology provides improved power handling capability resulting in smaller hardware size and high impedance which simplifies the design of matching networks. Moreover, large bandwidth and high impedance offer the possibility to create multiband components by designing the matching networks to be reconfigurable (Fischer, 2004).

This chapter aims to review state-of-the-art research in power amplifiers for wireless communication infrastructure featuring advantages of Gallium Nitride (GaN)-based power

devices including large bandwidth capability, high power density and high output impedance. Regarding the issues of power amplifier design, state-of-the-art power amplifier architectures will be discussed with various prospects. For wireless communication standards with high data rates e.g. WCDMA, WiMAX and LTE, their modulation schemes and multiple access techniques lead to non-constant signal envelope with high peak to average power ratio. As a consequence, power amplifiers in wireless communication infrastructure are required to operate in a wide dynamic range making it difficult to maintain high average efficiency over time. This chapter will discuss widespread techniques for average efficiency enhancement including Doherty power amplifier concept and envelope tracking (ET) with state-of-the-art results. Another possibility for power efficiency improvement is the switched-mode power amplifier where the waveforms of the voltage and current are optimized to achieve low power dissipation at the power transistor. GaN-based power transistors have demonstrated in numerous research works to be suitable power devices for the switched-mode architecture as well as for average efficiency enhancement techniques e.g. Doherty power amplifier and envelope tracking. As examples, results of 2.45 GHz GaN class AB power amplifier and GaN VHF class E power amplifier will be presented in this chapter. The wide band capability of GaN-based devices also supports design of reconfigurable and wideband power amplifiers. With all advantages of GaN-based devices, they are still not a mature technology in terms of reliability and memory effects. Results from investigation on memory effects and parasitics of GaN-based devices will also be discussed in the chapter showing promising improvements in these regards which make GaN-based devices interesting and promising power devices for future wireless communication infrastructure.

2. Power amplifiers in the wireless communication infrastructure

In a mobile communication system, power amplifier is an important component which boosts the transmitted signal power before it is sent via the antenna to the receiving device through wireless channels (see Fig. 1.). In a base station for mobile communication standards e.g. GSM, UMTS or LTE, power amplifier is the part which consumes the largest portion of power. Thus, the efficiency of power amplifier has the greatest influence on the entire system's efficiency. In addition, cooling requirement of a base station is also dominated by its power amplifier. In terms of cost, power amplifier is also the most expensive part of a base station. For the first generation of UMTS base stations, the costs of power amplifier and cooling are about 30%-35% of the cost of an entire base station (Chalermwisutkul, 2007). Besides the efficiency, linearity is also an important specification of power amplifiers which ensures that the transmitted signal is not distorted by the nonlinearity to an unacceptable level causing excessive bit errors.

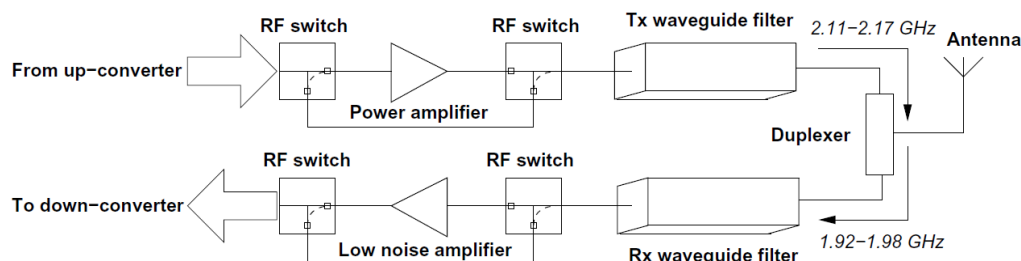


Fig. 1. Block diagram of a UMTS base station transceiver showing power amplifier and other system components.

2.1 Typical architecture and power device for base station power amplifier

In general, power amplifiers in mobile base stations are class AB amplifiers which offer both acceptable power efficiency and linearity. The operating point for the power device of this amplifier class is a compromise between those of highly efficient class B and highly linear class A. The conduction angles, output drain current waveforms, active load-lines and operating points of class A, AB, B, C, E and F amplifiers are depicted below in Fig. 2.

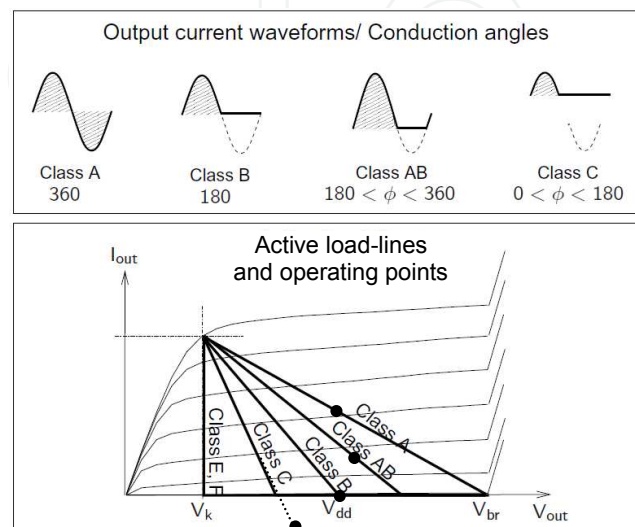


Fig. 2. Conduction angles, output drain current waveforms, active loadlines and operating points of class A, AB, B, C, E and F amplifiers. V_{out} , I_{out} , V_k , V_{dd} and V_{br} are drain output voltage, drain current, knee voltage, drain voltage supply and drain breakdown voltage, respectively (source (Chalermwisutkul, 2007)).

Typically, lateral diffused metal oxide semiconductor (LDMOS) field effect transistors based on Silicon are used as power devices for base station power amplifiers. Silicon LDMOS is considered a mature power device technology for mobile base station amplifiers due to its high efficiency, high power density and high thermal conductivity. However, main reasons which make LDMOS standard device technology for base station amplifiers are its low cost and high reliability. Although it is known that the operating frequency of LDMOS devices is limited to a few GHz, progress in LDMOS technology is still ongoing and new LDMOS devices are continuously introduced into the market with higher operating frequency and other progresses in terms of power efficiency, linearity, etc. (Ma et al, 2005). Due to this fact, the dominance of LDMOS devices in low GHz high power applications has been ensured since the first devices came into the market. However, new challenges in power device technology keep emerging as modern wireless communications are required to cope not only with higher data rates at limited frequency resource, but also with energy saving issues. In other words, there are increasing demands in high power efficiency besides spectrum efficiency for the wireless communication infrastructure. In this regard, there are several cases where it is worth to look for alternative power device to overcome limitation of existing device technologies.

Despite of all advantages of LDMOS, the main drawback of this device is the bandwidth capability. Due to high output capacitance of LDMOS device, the Q factor tends to be high and the bandwidth is small. Also, the operating frequency limit hinders this device from

being used in high frequency applications which are served with other device technology e.g. GaAs MESFET and HEMT. The research interest has been then attracted by wide-bandgap semiconductor materials for high frequency power devices. Silicon Carbide (SiC) is superior in thermal conductivity compared to other wide-bandgap semiconductors. However, the cost of SiC is relatively high. Moreover, this material is not appropriate for applications with very high operating frequencies. For Indium Phosphide (InP), another wide-bandgap compound semiconductor, the focus of research is on extremely high-speed digital applications where high power is not required.

The most prominent wide-bandgap semiconductor is Gallium Nitride (GaN). Comparing with Silicon device technology which is mainly driven by microprocessor and computer industries, GaN found its applications in screen industries enabled by GaN OLED (organic light emitting diode) technology and data storage industries utilizing blue laser produced by GaN laser diode to read out the data from a Blue-ray Disc™. In automotive applications and power electronics, GaN devices are attractive due to high operating temperature and high breakdown field for switching power supply. For RF power amplifiers, GaN-based power devices offer extremely large bandwidth, high power density, high operating frequency and high output impedance. The advantages of GaN-based power devices for wireless communications will be discussed more thoroughly in the next section.

2.2 Techniques for enhancement of average power efficiency

Modulation schemes and multiple access techniques allowing high data rates in wireless communication standards lead to non-constant signal envelope with high crest factor or peak to average power ratio (PAPR). Since a typical class AB power amplifier in mobile base station offers highest power added efficiency (PAE) about at one dB compression area in the power sweep plot, high peak to average power ratio leads to power back-off from the peak efficiency point which leads to efficiency reduction (see Fig. 3.). As a result, average efficiency over time is much lower than the peak efficiency. From the system point of view, reduction of peak to average power ratio can be done with different techniques at the cost of

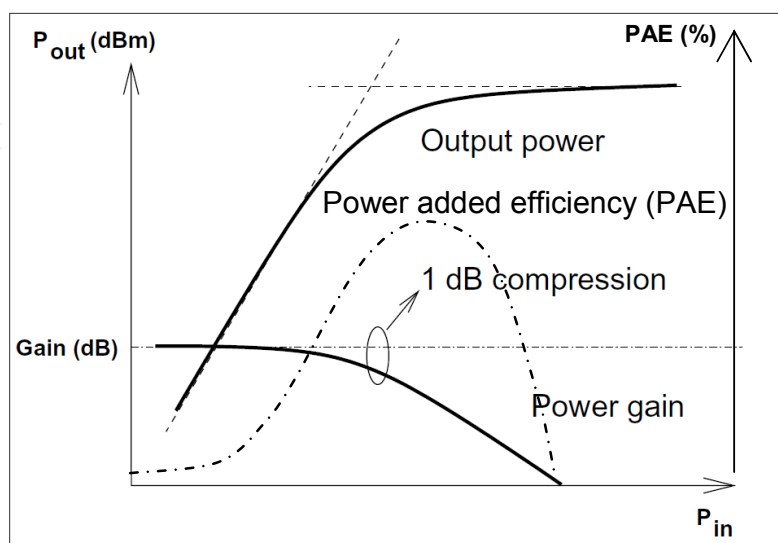


Fig. 3. Typical power sweep plot of a class AB power amplifier showing efficiency degradation when the power is backed-off from 1 dB compression point.

reduced data rate, transmit signal power increase, BER performance degradation, computational complexity increase, and so on (Jiang and Wu, 2008). Independent of the reduction techniques, rest of the peak to average power ratio still exists, so that for further average efficiency improvement, power amplifier architecture which can keep power efficiency high also when the transmitted power is backed-off must be considered.

Envelope elimination and restoration (EER) or Kahn technique

This average efficiency enhancement technique is based on the idea to separate the amplitude modulated envelope from the constant envelope, phase modulated carrier signal. The envelope is amplified with high efficiency envelope amplifier, whereas the carrier is amplified with nonlinear but highly efficient power amplifier. The output of the envelope amplifier is supplied to the carrier amplifier which reconstructs the typical signal with non-constant envelope of modern wireless communication standards (Diet et al, 2004).

Envelope Tracking (ET)

Similar to Kahn technique, supply voltage level of the RF amplifier is dynamically modified depending on the level of the signal envelope. A slight difference is that the input of the RF amplifier is still amplitude and phase modulated. Only with excessive signal power, the supply voltage of the RF amplifier is modified. The RF amplifier of this technique operates also in a linear mode unlike the Kahn technique, where the RF amplifier operates solely in a nonlinear mode.

Outphasing or Chirix technique

Also known as linear amplification using nonlinear components (abbr. LINC), this technique uses two nonlinear high efficiency power amplifier to boost up two signals with differently controllable phases. The two amplified signals are then combined with vector addition and the phase difference between the two signals defines the power level of the resulting signal. Compared to EER and ET, phase is the dynamically changing quantity and not the supply voltage of the RF amplifier (Helaoui et al, 2007).

Doherty technique

The concept of Doherty power amplifier utilizes two power devices which are operated as main and auxiliary amplifiers. As soon as a certain level of input power is reached, main amplifier—normally class B — is running into saturation providing its maximum efficiency. As the main amplifier starts to saturate, the auxiliary amplifier starts to conduct current. The saturation condition of the main amplifier is maintained by load modulation caused by the current from the auxiliary amplifier, so that the main power device acts like a voltage source. At peak output power, the auxiliary amplifier just begins to saturate and high efficiency is ensured for both amplifiers. Block diagram of a Doherty power amplifier is depicted in Fig. 4.. Details about Doherty amplifier can be found in the literature (Raab, 1987).

Compared to other efficiency enhancement techniques, Doherty concept has gained its popularity due to simple architecture which deals with RF circuit design issues only, whereas other techniques make use of digital signal processing to improve average efficiency. Thus, it is more straightforward to design a Doherty power amplifier to cope

with new peak to average power ratio value where high average efficiency is desirable. This can be simply achieved by modifying the input power division ratio between main and auxiliary amplifier. If necessary, three amplifiers can also be used in order to maintain high average efficiency over a high dynamic range.

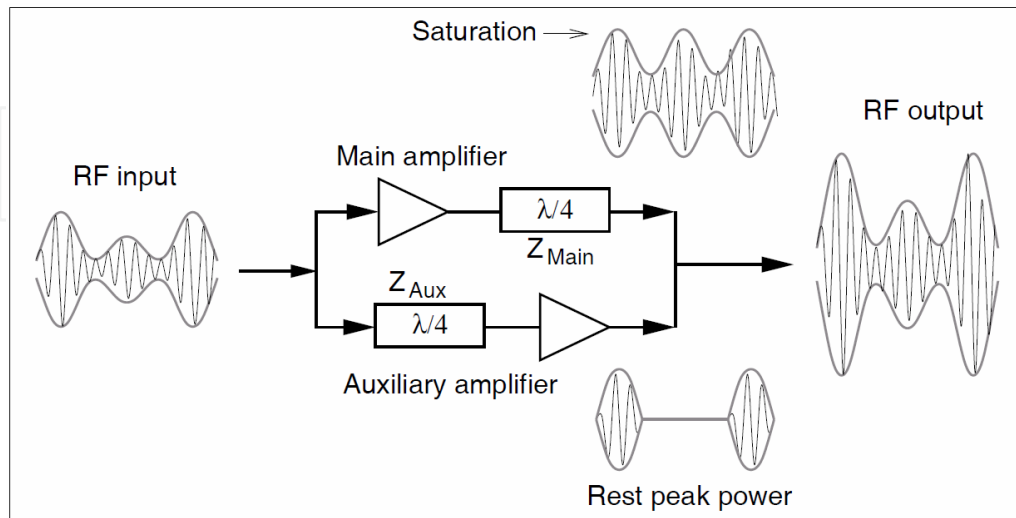


Fig. 4. Block diagram of a Doherty amplifier.

2.3 Switched-mode power amplifiers

In subsection 2.2, average efficiency enhancement techniques with the goal of maintaining high efficiency over a wide range of input power have been described. Considering peak efficiency at peak output power, switched-mode power amplifiers can achieve higher efficiency than widespread class AB power amplifiers. In case of switched-mode, the power transistor operates as a switch so that output voltage and current of the device (drain of FETs and HEMTs or collector for BJTs and HBTs) do not have high values at the same time. For the “off” state, the current is near to zero and the voltage is high and vice versa for the “on” state resulting in theoretical efficiency of 100%. In the following, switched-mode class E, F and D will be briefly described.

Class E

The first class E amplifier has been proposed by Sokal in 1975 (Sokal, 1975). Thereafter, other variations of class E amplifiers have been constantly presented with higher operating frequency where not only class E operation is ensured, but also, practical issues such as small circuit size and simple matching have been taken into account. A good example of such progress in class E amplifier design was represented by the class E amplifier with parallel circuit proposed by Grebennikov (Grebennikov, 2002). Class E offers high efficiency by avoiding simultaneous existence of high drain voltage and high drain current and thus, avoiding power dissipation of the power transistor. Control of the output current and voltage waveforms at drain or collector node of the device is achieved using an output load network. Theoretically, as the transistor turns on, the voltage drops to zero and the current starts to flow so that the output capacitance is gradually charged. As soon as the control voltage of the switch is lower than the switching voltage threshold,

the transistor is turned off and the current drops to zero while the output voltage of the device starts to increase. The ideal class E voltage and current waveforms are depicted in Fig. 5. Variations of class E amplifiers are reported to offer high power as 1 kW for switching applications at low frequency, whereas for RF applications, operating frequency of 10 GHz was already presented (Weiss, 1999). Class E is a promising switched-mode amplifier concept due to its simple architecture and flexibility compared to other switched-mode classes. Combination of a class E amplifier with average efficiency enhancement techniques e.g. EER or Doherty has been reported in the literature (Diet et al, 2004 and Kim et al 2010).

Class F

High efficiency of class F amplifiers is achieved by shaping the wave forms of output current and voltage of the power transistor which operates as a switch. Compared to class E, where load network is required to ensure the ideal switching condition (on state with high current, zero voltage and off state with high voltage and zero current), load network of class F has additional function which attempts to shape the output voltage and current waveforms at the device's drain or collector node. For conventional class F, odd harmonic peaking of the device's output voltage is realized by providing high impedance (open circuit condition) at the odd harmonic frequencies. As a result, the voltage waveform approximates a square wave. For the drain current, even harmonics are provided in addition to the fundamental by offering the device a short circuit condition at even harmonic frequencies. As a result, the current waveform approximates a half wave signal. Ideal current and voltage waveforms of a class F amplifier are shown in Fig. 5. Another alternative variation of class F is the inverse class F where the current waveform approximates a square wave, whereas the voltage waveform approximates a half wave signal. Efficiency of class F amplifiers can be increased by offering appropriate termination (open or short) at higher harmonics. However, this occurs at the cost of circuit's complexity. Similar to class E, class F and inverse class F amplifiers can be combined with Doherty technique to obtain high average efficiency for wireless communication signals with high peak to average power ratio. By using class F or inverse class F in a Doherty transmitter, peak efficiency is increased compared to the variation with class B main amplifier (Goto et al, 2004).

Class D

Unlike other switched-mode amplifier classes, class D uses at least two transistors as switches. In case of current mode class D (CMCD), the transistor's output current has a form of a square wave whereas the voltage mode class D (VMCD) shows a square output voltage of the transistor (see Fig. 5.). For both CMCD and VMCD, a tank filter is required to obtain the sinusoidal signal at the load. For CMCD, additional BALUN is also required, whereas for VMCD, two supply voltage sources are needed (see Fig. 6.). When one of the switches is turned on, the other one is turned off, so that high current and high voltage cannot exist at the same time. Theoretically, 100% efficiency can be achieved. In practice, the efficiency is compromised by limited switching speed and device's output capacitance. Due to these reasons, frequency of operation is limited for class D amplifiers. Experimental, state-of-the-art RF class D power amplifiers can operate at frequencies in the region near to 1 GHz (Aflaki et al, 2010).

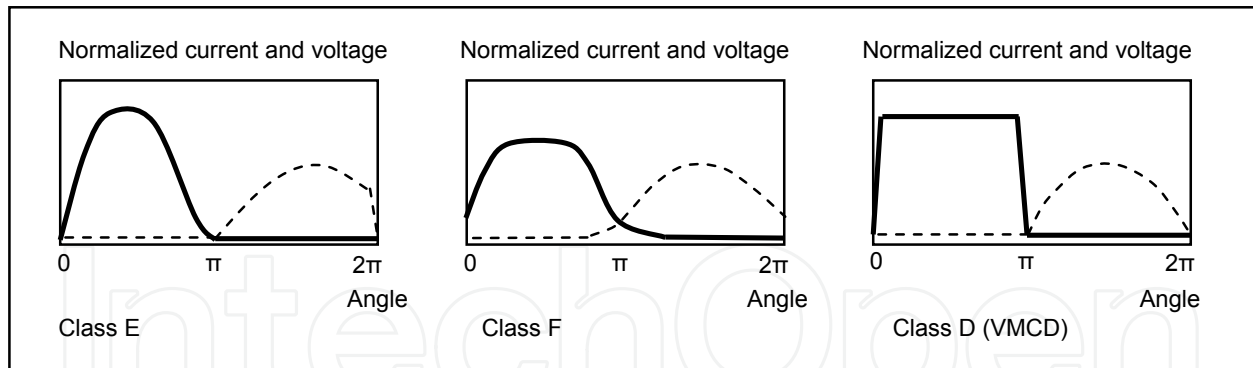


Fig. 5. Ideal current and voltage waveforms of class E, F and D switched-mode amplifiers (Raab et al., 2002). Broken lines represent the device's output current and the solid lines represent the device's output voltage.

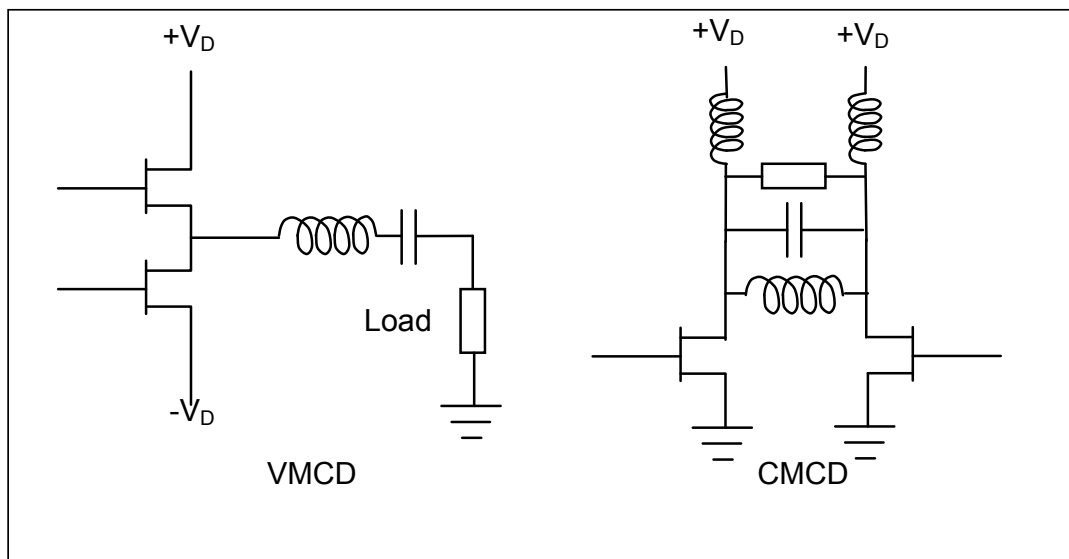


Fig. 6. Configurations of voltage mode class D (VMCD) and current mode class D (CMCD) amplifiers.

2.4 Linearization techniques

In general, a trade-off exists between efficiency and linearity of power amplifiers. For conventional transconductance amplifier classes e.g. class A, AB and B, it is obvious that high efficiency classes are nonlinear. In subsection 2.2, average efficiency enhancement techniques aiming to keep the efficiency high over a wide dynamic range have been discussed. Even though efficiency is the main goal of such techniques, linearity was also taken into consideration so that none of such techniques would have severe impact to linearity. However, when the desired efficiency profile is achieved, linearity might not comply with wireless communication standards leading to unacceptable error vector magnitude and bit error rates. In such a case, linearity improvement techniques can be utilized to eliminate the excessive nonlinearity of the amplifier. Widespread linearization techniques are reviewed below.

Feedback linearization

In order to force the RF output to follow the input, feedback of the RF signal is realized using a directional coupler. The simplest variation of this technique subtracts the RF feedback from the input signal. However, the compensation of the non linearity with this technique is not very efficient as the transmitter's gain is reduced. Another variation detects the envelope of the RF feedback and the input signal and subtracts the first from the latter to realize the linearization of the amplitude. For the compensation for both phase and amplitude nonlinearities, another variation called Cartesian feedback was conceived that the feedback signal is down converted to I and Q values which are used to compensate the I and Q of the input signal. For a relatively small bandwidth, the two tone IMD can be reduced by 10 to 35 dB with this technique.

Feedforward linearization

This linearization technique is excellent in terms of bandwidth and IMD reduction. In order to generate the error signal, the power amplifier's output and the input signal are sampled using directional couplers and the first is then subtracted from the latter (see Fig. 7.). The error signal is then amplified and subtracted from the power amplifier's output to obtain the linear output signal. Since this technique utilizes an open loop concept, additional loop control is required in order to compensate the degradation of the power device over time to ensure the right settings of phase shift and gain for maximum linearity. IMD reduction of 20-40 dB can be achieved for bandwidth up to 100 MHz. The drawback of this technique is the complexity of the system.

Digital predistortion

In order to obtain undistorted signal at the transmitter output, the input signal can be intentionally distorted before being fed to a nonlinear power amplifier. The predistorter generates nonlinearities which operate in the opposite way to the nonlinearities generated by the power amplifier, so that the overall response at the PA-output is linear (see Fig. 8). The linearization is done in the digital regime using FPGA which makes the system very flexible and adaptive for changes in power device over time to ensure linear output. As computational power of FPGA is continuously increasing, linearization over larger bandwidth can be realized with this technique. In the literature, linearization with digital predistortion technique which can cope with dynamic nonlinearity caused by electrical memory effects has also been reported (Lee et al, 2009).

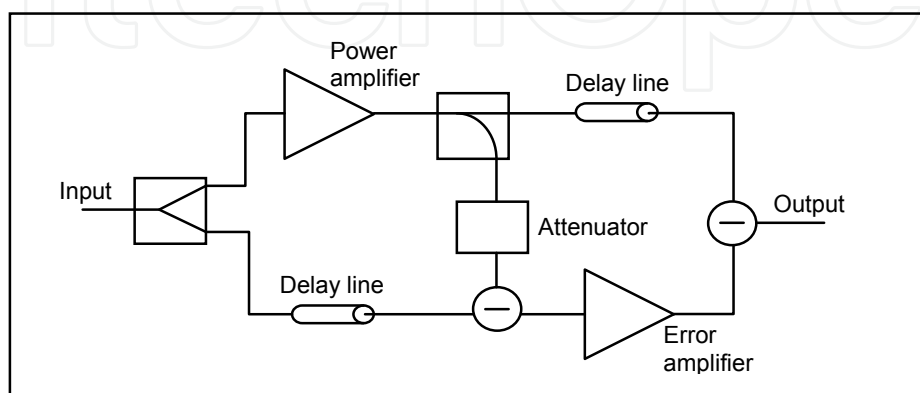


Fig. 7. Block diagram of a feedforward transmitter.

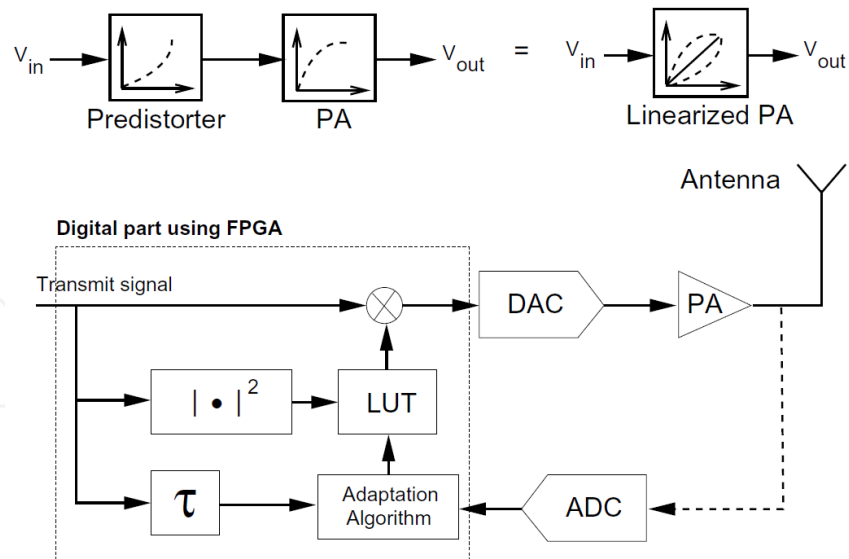


Fig. 8. Principle and block diagram of digital predistortion for linearization of power amplifiers.

In comparison to other techniques, digital predistortion offers higher efficiency and greater flexibility at low cost and represents a mature linearization technique for mobile base stations. Due to the mentioned flexibility and simple architecture, digital predistortion has gained its popularity in the power amplifier design community. In most of the cases where no extremely large bandwidth is required, high efficiency amplifiers e.g. Doherty and switched-mode amplifiers are combined with digital predistortion to improve the linearity.

3. GaN-based power amplifiers

As mentioned in section 2.1, GaN is a promising semiconductor material for high power and high frequency power transistors which are used as power devices in mobile base station power amplifiers. The advantages of GaN originate from physical properties of this wide-bandgap semiconductor. Table 1 shows physical properties of various semiconductor materials including GaN.

| Material/Properties | Si | GaAs | InP | SiC | GaN |
|---|------|------|------|-----|------|
| Bandgap (eV) | 1.1 | 1.4 | 1.3 | 3.2 | 3.4 |
| Saturation Velocity (*10 ⁷ cm/s) | 1.0 | 2.1 | 2.3 | 2.0 | 2.7 |
| Thermal Conductivity (W/cmK) | 1.3 | 0.46 | 0.7 | 4.9 | 1.7 |
| Breakdown Field (*10 ⁶ V/cm) | 0.3 | 0.4 | 0.7 | 2.0 | 2.7 |
| Electron Mobility (cm ² /Vs) | 1350 | 8500 | 5400 | 800 | 1500 |

Table 1. Physical properties of semiconductor materials for RF and microwave applications.

From table 1, advantages of GaN compared to other semiconductor materials for RF and microwave applications are obvious. GaN offers very high saturation velocity leading to high operating frequency up to 100 GHz or higher. High breakdown field allows GaN-based devices to operate with high supply voltage which is advantageous for the off state of switched mode amplifiers and for obtaining high output power with high output impedance. Due to higher supply voltage, efficiency is also improved due to the reduction of the need for voltage conversion. For extreme operating environment e.g. for automotive applications, GaN offers wide bandgap and high thermal conductivity leading to the capability to operate at high temperature.

The most prominent GaN-based device for RF and microwave applications is GaN-based high electron mobility transistor (GaN HEMT). This kind of device offers extremely high operating frequency due to high electron mobility in the so-called 2DEG channel (Smorchkova, 2001). Moreover, one of the most impressive features of this device is the extremely high power density meaning that the device's size can be much smaller compared to other device technology for the same output power. With size reduction, output impedance becomes larger and parasitic capacitances smaller leading to large bandwidth and uncomplicated matching to 50 Ohm. It was also mentioned in the literature that GaN HEMT can offer better noise performance than that of MESFET's (Mishra et al, 2007).

For wireless communication infrastructure, GaN HEMT has proven itself to be an attractive alternative power device besides LDMOS FET for base station power amplifiers. For WCDMA base station, a GaN HEMT-based transmitter with output power higher than 200 W and supply voltage of 50 V was published in 2004 (Kikkawa et al, 2004). Reliability--one of the biggest concerns regarding GaN HEMT compared to LDMOS--was also presented in that work. However, at this point, it is not possible to foresee when GaN HEMT's will take the place of LDMOS FET's in base station power amplifiers. Even if the frequency of operation is limited to a few GHz for LDMOS, this device technology is continuously developed regarding power, reliability, linearity, etc.. Moreover, LDMOS is considered a cost-effective and mature power device technology with a large LDMOS amplifier designer community. Consequently, knowhow and design experience for this device is available to a great extent. Regarding this consideration, GaN HEMT will find its importance first in applications where large bandwidth is required or high power is desirable at high frequency. Besides reliability, charge carrier trapping in GaN HEMT has been a big issue for device technology improvement. Numerous investigations have been done regarding trapping effects of GaN devices. Charge carrier traps can cause dependency of the pulse-measured I-V characteristic on the quiescent point. This is a phenomenon of the so-called electrical memory effect (Chalermwisutkul, 2008). Other phenomena of memory effects are gate lag and drain lag in time domain where the drain current reaches its final value after some delay as the bias voltages are abruptly changed. In frequency domain, dispersion of output impedance is the consequence of electrical memory effect leading to dynamic nonlinearity with a large bandwidth of spectral regrowth (Fischer, 2004). Improvement of GaN device technology regarding charge carrier trapping and reliability has been reported occasionally e.g. SiN passivation or use of the field plate for traps reduction (Mishra, 2007). In this section, results from the works regarding GaN device modeling and GaN power amplifier design in which the author has been involved will be presented.

3.1 GaN device modeling

Computer simulation of the performance belongs to a typical design flow of power amplifiers. As many as possible components in the amplifier circuit should be characterized and described by models in order to obtain accurate prediction of circuit's performance from the simulations. As the main component of a power amplifier, quality of power transistor model plays a significant role in the accuracy of circuit simulation. Especially for power amplifier design, nonlinearities of the device must also be described by the device model unlike for small signal amplifiers, where it is sufficient to have the device's S-parameter sets of a few bias points of interest.

Even for one device technology, it is not practical to create a universal model which can describe the device's behavior under all operating conditions. In order to describe more effects and dependencies of the device's behavior on dynamic thermal and electrical conditions, more and more model parameters and nonlinear equations are required. In that case, the model would become very complex and long simulation time is needed. Though computational resource can be increased, complex device models suffer from poor robustness, that the simulation would be often terminated without convergence and reasonable results. For switched-mode power amplifiers e.g. class E, F, inverse F or D, a concept of using switch model in combination with the "on" state resistance R_{on} and output capacitance C_{ds} instead of empirical transistor model exists (Negra et al, 2007). This simple model is capable of providing good trend of power and efficiency and of verifying switched-mode operating conditions. At this point, there exist some discussions regarding the accuracy of such switch model for switched-mode power amplifier applications. Especially for power devices with charge carrier trapping and thus, memory effects, the switch model is not able to describe such effects which can have influence in efficiency and output power of switched-mode amplifiers (Chalermwisutkul, 2008).

Electrical memory effects

Even when electrical memory effects of GaN HEMT are still not negligible compared to those of GaAs HEMT, but the benefit of high power density, high output impedance, high frequency, etc. of GaN HEMT can be used, when the device is accurately described including the memory effects by the device model. First of all, the extraction of model parameters should be done using multibias pulsed measurement data. In such a measurement process, the bias voltages of the transistor is pulsed starting from the so-called quiescent point to other bias points in the I-V characteristics and drain current I_{ds} as well as S-parameters of that bias point are measured. Pulsed measurement has a significant advantage which is the isothermal measurement condition. The measured I-V characteristic of a pulsed measurement does not contain the self-heating of the transistor at high V_{ds} and I_{ds} as seen in DC measurement which is more familiar to the realistic operating condition. Moreover, quiescent point of pulsed measurement can be chosen equal to the operating point of the amplifier class of interest in order to create a device model which corresponds to the behavior of the device under realistic operating condition. In particular, the quiescent point dependent device model is necessary for a power device with significant trapping effects (see Fig. 9.). Theoretically, the dependence on quiescent point could be included into the model making the device model a general purpose one. However, as described above, this would increase the complexity and decrease the robustness of the model. Promising results of high power GaN HEMT have been published in 2004 showing the progress in

GaN device technology in term of reduction of trapping effects where the DC measurement of I-V curves shows no significant difference in the level of drain current compared to a pulsed measurement with a quiescent point at high drain voltage region (Kikkawa et al, 2004). In such a case, the quiescent point dependence of the device model would not be so critical. For power transistor manufacturers, normally, only one device model is provided to the circuit designer. As a result, the model of a mature power device regarding trapping will offer more accurate results for arbitrary classes of amplifiers.

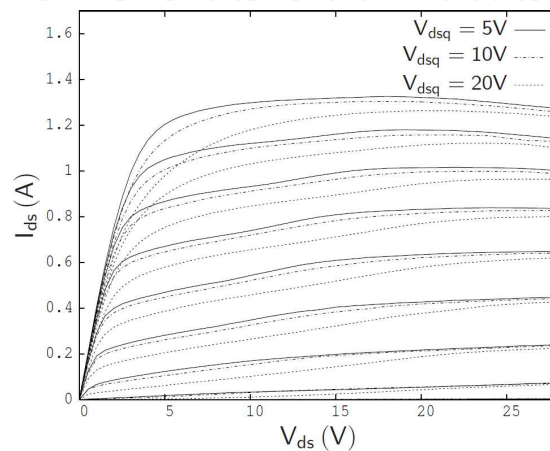


Fig. 9. Dependence of I-V characteristic of a GaN HEMT on quiescent point. The quiescent voltage was constant at a pinch-off value (no quiescent current) whereas the drain quiescent voltage V_{dsq} was varied.

Knee walkout

In contrast to GaAs HEMT and MESFET, the knee voltage of a GaN HEMT depends on the gate voltage and the drain quiescent voltage. With high gate voltage, the knee of the I-V curve becomes more round than at lower gate voltage where the knee is relatively angular. In addition, the knee voltage is shifted to the right toward higher drain voltage when gate voltage is high. This so-called *knee walkout* effect observed only with GaN HEMT and not with GaAs HEMT or MESFET cannot be modeled with standard EEHEMT model. By adding dependency of the knee voltage on the gate voltage and the drain quiescent voltage, the knee region of the I-V curve with high gate voltage can be better described (see Fig. 10.). As a result more accurate power and efficiency simulation can be done (see Fig. 11.) (Chalermwisutkul, 2007).

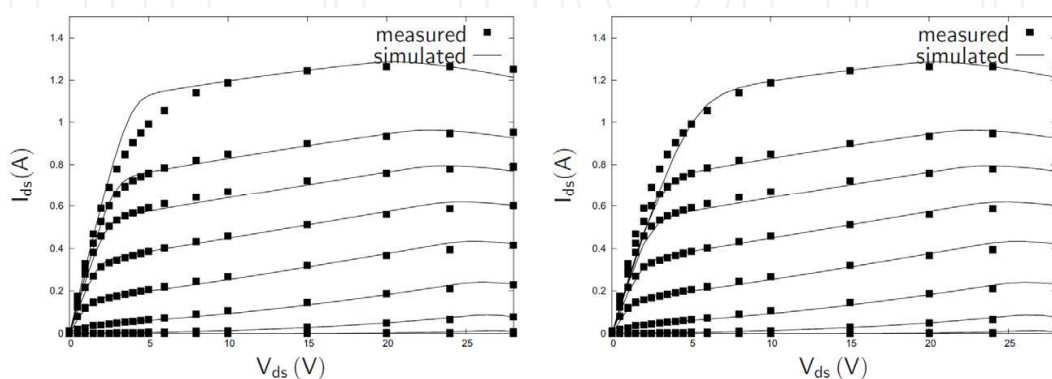


Fig. 10. I-V curves fitting results without (left) and with (right) the description of the knee-walkout.

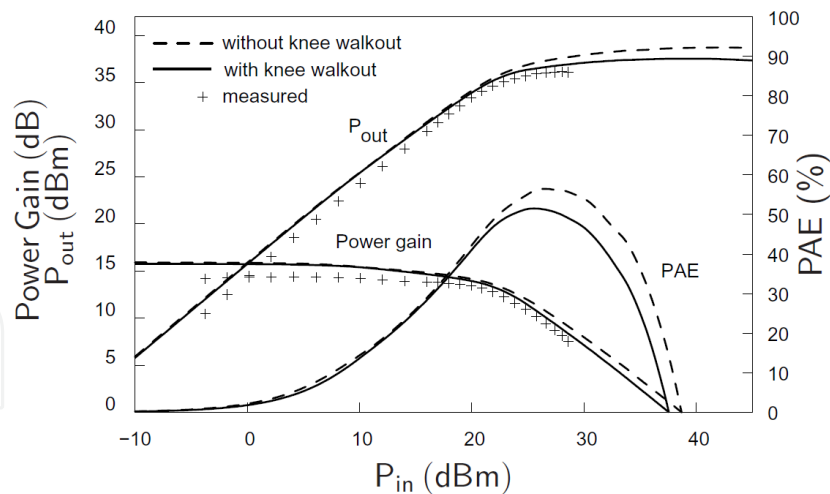


Fig. 11. Power sweep simulation without and with the description of the knee-walkout compared to measured values.

Large signal behavioral model

As discussed before, large signal model is required in order to describe nonlinearities of the power device. However, device modeling is a complex task which requires extensive experience of modeling engineers and special modeling software, so that power amplifier design engineers are mostly forced to rely on the large signal model provided by device's manufacturer. Due to progress in RF measurement techniques, a measurement system has been developed which allows measurement of the so-called X-parameters (Betts et al, 2011). Unlike with S-parameters, not only small signal behavior of the device can be described, but also nonlinearities arising under large signal conditions. In general, the input signal power is swept and the output response at the fundamental as well as at higher harmonics is measured. The measured information is then concluded into the X-parameter set which can be directly used in the circuit simulation software as the device's behavioral model. This kind of device modeling is very convenient and can be combined with source and load tuners to obtain load dependence of the X-parameters. In addition, the extracted behavioral model is accurate, robust and does not require large computational resource. However, the behavioral model cannot provide insights into physical properties of the device and the measurement setup is relatively expensive for small companies and educational institutions with low budget.

Package modeling

Packaged transistors comprise also parasitic components of the package and bond wires. These typical parasitic inductance and capacitance can compromise the performance of the amplifier circuit especially at high frequencies. For example, for class F amplifiers where short or open circuit must be provided at the drain node of the transistor at harmonic frequencies in order to shape the output current and voltage waveforms for high efficiency. Optimization for efficiency can be done best, if the package model of the transistor is known. The current and voltage waveforms which are optimized for minimum overlap should be presented at the internal drain node of the device inside the package and not at the external drain port (Schmelzer and Long, 2007).

Design examples of GaN HEMT power amplifiers

As examples, two GaN power amplifiers are presented. The first one is a 2.45 GHz GaN HEMT class AB power amplifier (Monprasert et al, 2009). This power amplifier is intended for the use in a WLAN system. The power transistor used in this amplifier is NPTS00004 GaN HEMT from Nitronex Corporation. The performance of the 2.45 GHz power amplifier is shown in Table 2. The drain supply voltage was varied with $V_{dsq}=20V$ and $28V$. For the drain supply voltage of $28V$, the output power is not as high as in the case with $V_{dsq}=20V$ since the drain current was increased as the device started to be saturated. The DC power exceeded the limit of 7 Watts given in the datasheet and the device was damaged. Fig. 12 shows a photograph of the fabricated class AB amplifier.

| Drain quiescent voltage | $V_{dsq} = 20 V$ | $V_{dsq} = 28 V$ |
|--------------------------------|------------------|------------------|
| Maximum output power | 34.68 dBm | 30.93 dBm |
| Maximum Power Added Efficiency | 42.5 % | 20.8% |
| Small signal gain | 12.27 dB | 13.69 dB |

Table 2. Measured performance of 2.45 GHz GaN HEMT class AB power amplifier.

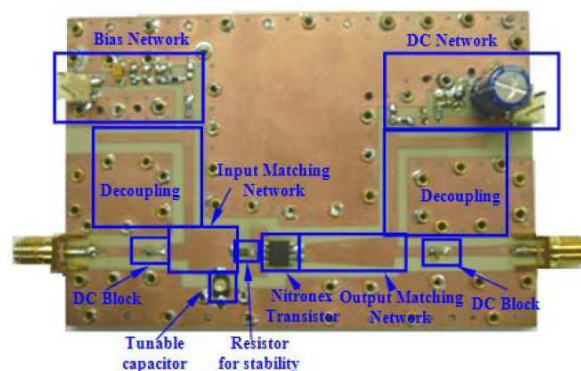


Fig. 12. Fabricated 2.45 GHz GaN HEMT class AB power amplifier.

Another design example is the VHF class E power amplifier (Khansalee et al, 2010). Using the same GaN power device Nitronex NPTB00004, a class E power amplifier for the operating frequency from 140 MHz to 170 MHz has been designed and fabricated. The values of load network L , C , L_0 and C_0 (see Fig. 13.) were determined using equations in the work published by Gebrennikov (Gebrennikov, 2002).

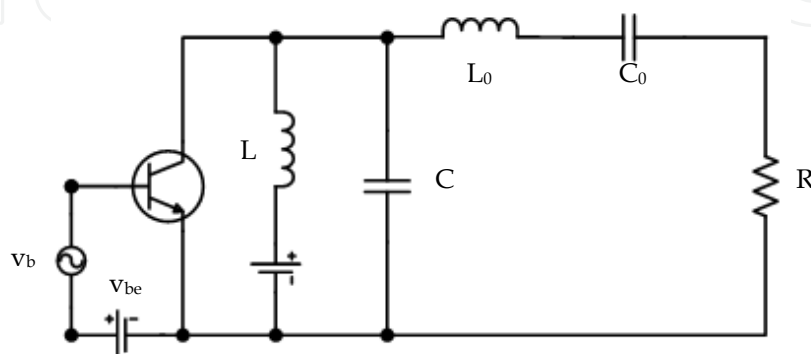


Fig. 13. Schematic of class E power amplifier with parallel circuit.

The optimal load impedance was determined using load pull simulation in Advance Design System (ADS). Simulated drain voltage and current waveforms show that class E operation is achieved (see Fig. 14.).

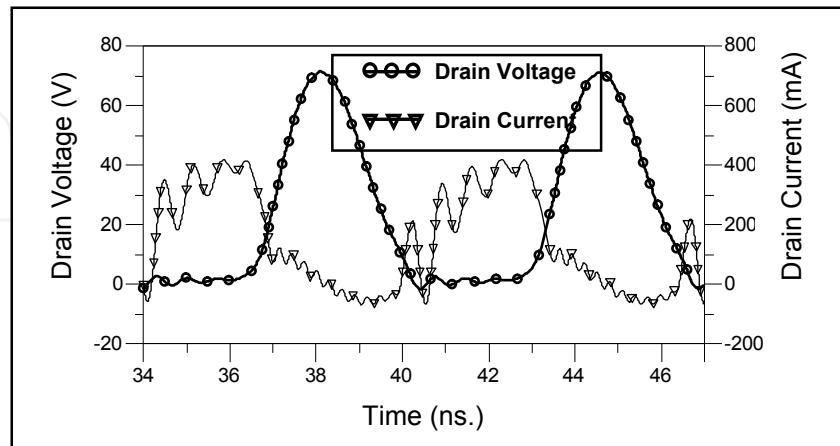


Fig. 14. Simulated drain current and voltage waveforms of the class E amplifier.

The fabricated class E power amplifier delivers maximum output 33.9 dBm, peak Power-Added Efficiency (PAE) of 72.5% and power gain of 16.4 dB at the center frequency of 155 MHz. Fig. 15. shows output power, efficiency and gain over the required operating frequency from 140 MHz to 170 MHz. A photograph of the fabricated GaN class E amplifier is depicted in Fig. 16.

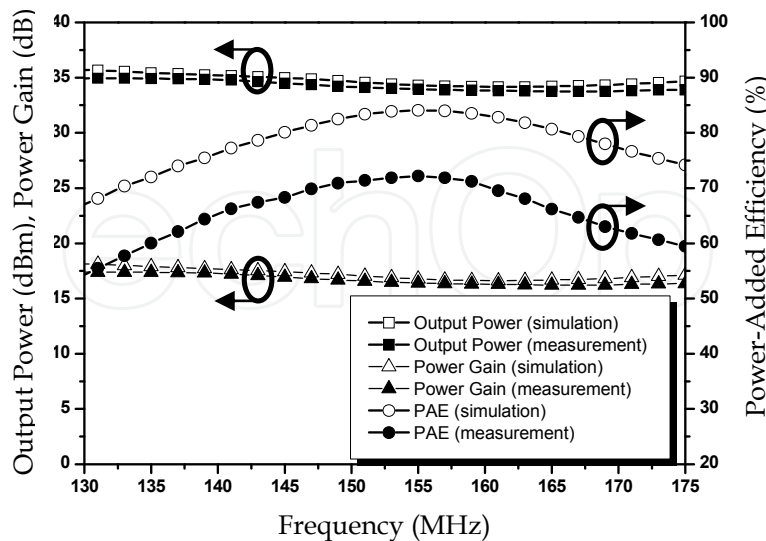


Fig. 15. Simulation and measurement results of power gain, output power, and PAE over the frequency 140 MHz to 170 MHz at input power of 18 dBm with the drain supply voltage of 24 V and gate supply voltage of -1.4 V over frequency.

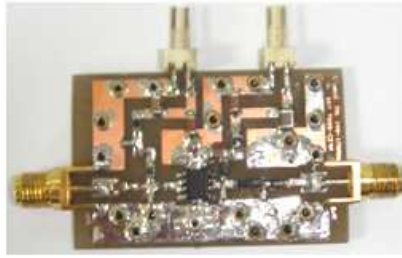


Fig. 16. Fabricated class E GaN VHF power amplifier.

4. Future research in power amplifiers for wireless communications

Needs for high data rates anywhere and anytime while the spectrum resource is limited will be a great challenge for future mobile and wireless communications. In order to utilize the bandwidth efficiently, new approaches on the network layers are being standardized and conceived including opportunistic, software defined and white space radio. The challenge of such frequency agile concepts will be not only be on the network and system layers e.g. spectrum sensing for vacant frequency slots, but also on the physical layer regarding the need of transmitters which can cope with extremely wide band or can be reconfigured for dynamic band migration. Regarding efficiency and power management, issues on every layer must be taken into consideration which would lead to interlayer optimization from network over system to physical layers. Active antenna and multiple inputs, multiple outputs (MIMO) concept will also be important topics which will require co-design and integration of amplifiers and antennas.

Energy saving is and will be a big issue not only in automotive and electrical power areas but also in wireless communications. To fulfil the intention for the “green transmission”, high efficiency must be provided by all infrastructure components e.g. base stations. Also, the trend of modern wireless communication standards is going in the direction of low power and small base stations will small cell size. This means that not only the mobile devices e.g. smart phone or tablets require aesthetic design but also the infrastructure components which should be well integrated into the environment. High efficiency will contribute to this requirement by offering small size of base stations. Regarding efficiency, research and development efforts will be spent in high efficiency signal transmission including design of switched-mode high efficiency power amplifiers with modulated input for improved efficiency e.g. class S amplifiers for delta sigma modulated signal (Pivit et al, 2008). Considering the demand of wide bandwidth and the capability to deliver high switching speed at high power, GaN-based devices are promising device technology for future wireless communications.

5. Conclusion

In this chapter, GaN-based power amplifiers for wireless communication infrastructure have been discussed. GaN HEMT's offer superior performance compared to state-of-the-art power devices for base station power amplifiers e.g. LDMOS. Especially high power density and high supply voltage of GaN HEMT's leads to smaller size of the device and thus, to lower parasitic capacitance, higher output impedance and large bandwidth which are advantageous for switched-mode and reconfigurable power amplifiers. In addition, wide

range of operating frequency can be covered by GaN-based power devices. The concerns of GaN transistors regarding charge carrier trapping and reliability is gradually extenuated by the progress in GaN device technology.

Device modelling is another important issue which ensures the power amplifier design community fast design process and accurate simulations. As examples, VHF class E amplifier and 2.45 GHz class AB amplifier have been presented.

6. Acknowledgment

The author would like to thank his family for the support and understanding during the preparation of the manuscript. Also, the author would like to express his appreciation to the research assistants, staffs and students of the RF and Microwave Laboratory, the Sirindhorn International Thai-German Graduate School of Engineering, King Mongkut's University of Technology North Bangkok for their interest in RF and microwave topics as well as for their support.

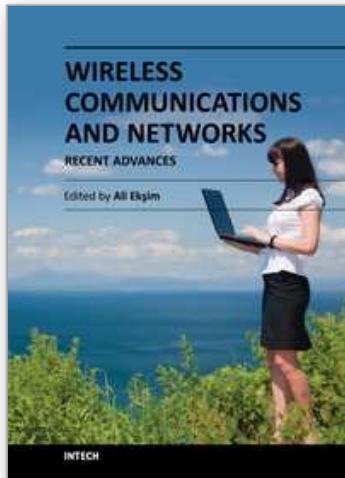
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Wireless Communications and Networks - Recent Advances

Edited by Dr. Ali Eksim

ISBN 978-953-51-0189-5

Hard cover, 596 pages

Publisher InTech

Published online 14, March, 2012

Published in print edition March, 2012

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