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Review

A review of GaN HEMT broadband power amplifiers

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ABSTRACT

The unique material properties of GaN, wide bandgap, high thermal conductivity, high breakdown voltage, high electron mobility and the device properties of GaN HEMT (High Electron Mobility Transistor) namely low parasitic capacitance, low turn on resistance and high cut off frequencies make it a good choice to use in a power amplifier. During this era of wire- less communication with complex modulation schemes having high peak to average power ratio, maintaining the efficiency and linearity of power amplifier is a tough task. In this paper an extensive review of GaN HEMT based power amplifier is presented. First of all, GaN technology is described and compared with other semiconductor technologies. The different classes of power amplifier like class B, C, D, E, F and J with GaN is discussed. Efficiency and linearity enhancement techniques like envelope tracking, Doherty power amplifier and digital predistortion used in applications with high PAPR waveforms is described. The advantages of GaN MMIC (Microwave Monolithic Integrated Circuit) are reviewed. Finally different thermal management solutions used for GaN power amplifier to cope with its self heating phenomenon are explained.

Contents

1. Introduction

Wireless communication, military applications, satellite communication and TV broadcasting are some of the areas which demands high power and high frequency power amplifiers for their efficient operation. The data rate and number of consumers for mobile communication is continuously increasing and the consumer market demand lower power consumption and higher throughput. The fourth generation wireless communication will shift to up- coming fifth generation. Apart from telecommunication industry, this change from 4G to 5G will influence a wide range of areas like robotics, health- care, automobiles, education, agriculture and healthcare. Power amplifiers also plays an important role in any radio transmissions. With the development of semiconductor technologies, different power amplifier architectures have evolved to meet the constantly increasing system level require-

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Table 1
Properties of GaN compared with Si, SiC and GaAs [13–16,20].

Property	GaN	Si	SiC	GaAs
Bandgap E_g (eV)	3.4	1.12	3.2	1.4
Breakdown field E_{br} [mv/cm]	3.3	0.3	3.5	0.4
Electron mobility μ_n [cm^2/V s]	2000	1500	650	8500
Hole mobility μ_p [cm^2/V s]	300	480	120	400
Saturation electron drift velocity v_{sat} (cm/s)	2.5×10^7	10^7	2.7×10^7	1.2×10^7
Transit frequency f_T (Ghz)	150	20	20	150
Dielectric constant	9.5	11.9	10	12.5
Thermal conductivity K [W/mC]	130	150	450	550

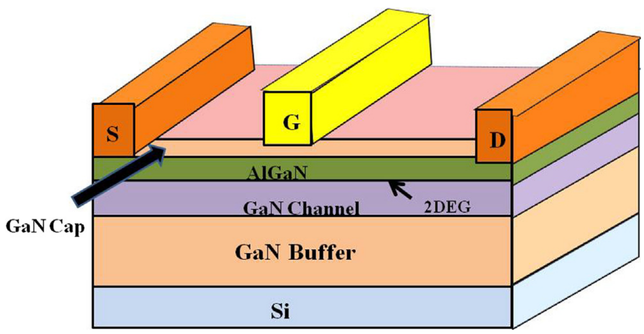

Fig. 1. Three dimentional schematic of AlGaN/GaN HEMT.

ments like number of antennas, power level, modulation bandwidth operating over a wider frequency range [1–3]. The vacuum tube microwave devices used in high power electromagnetic systems have been replaced by solid state power amplifiers. This is due to the fast advancement in solid state device technology. Thus power amplifier is the governing device in the transmitter output stage, and it determines the system characteristics like efficiency, linearity and gain. In some of the applications efficiency is important than linearity and gain. For example in a Base Station [4] a highly efficient power amplifier can help reduce the power dissipation and thus the need for cooling. Most of the cooling system are complex to design as well as expensive and can occupy huge space [5,6]. Output power is an important factor in long range communications in a noisy environment rather than efficiency. High linearity is necessary to minimize the interchannel interference [7,8] as the communication channel is becoming narrower. For higher power and higher frequency applications, semiconductors with high electron mobility, wide band gap energy and high breakdown voltage are preferred [9–12].

GaN exists in three different crystalline structures, namely wurtzite, zinc blende and rock salt. The thermodynamically stable structure is wurtzite for bulk GaN. The material properties of GaN with wurtzite crystal structure, [13–16] compared to Si, SiC and GaAs are given in Table1. GaN power amplifiers provide better efficiency, gain and thermal performance when compared to other semiconductor technologies. Also it has the potential to operate at power densities far higher than SiC and GaAs. Due to its high efficiency GaN is a promising technology in green ICT (green IT or green computing) systems. The three dimentional schematic of AlGaN/GaN HEMT is shown in Fig. 1.The two dimensional electron gas (2DEG) is formed at heterojunction between AlGaN and GaN. The GaN cap layer can increase the maximum transconductance and saturation current, it also helps to reduce the series resistance between source and drain compared with HEMT without GaN cap layer. The sheet charge density of AlGaN/GaN hetero-structure in the two dimensional electron gas (2DEG) is very much higher than AlGaAs/GaAs HEMT. This high 2DEG density is obtained because of the strong piezoelectric and spontaneous polarization effects [17–19] and the large conduction band offset between the AlGaN and GaN. The Ga—N and Al—N bonds are highly ionic and they carry a strong dipole. The electronegativity of N is higher than that of Ga and the electron wave function around the Ga—N pair is offset to the nitrogen side. Due to the very high electronegativity of N, the degree of spontaneous polarization is more than five times greater in III-nitrides than in most III-V semiconductors.

The GaN properties listed in the Table 1 [20], are exploited to design RF microwave integrated circuits like power amplifiers [21], switches [22], low noise amplifiers [23] and many other applications [16]. The bond length between the atoms in GaN is much smaller when compared with Si—Si bond length. For ionic bonds like Ga—N, the lattice energy is the energy required to separate one mole of a compound into its gaseous phase ions. Ions with higher charges and shorter distance will have higher lattice energy, which is a measure of stability of the compound. Smaller bond length between Ga and N indicates higher lattice energy and thus higher stability. This explains the more stable and inert nature of GaN when compared with Si. AlGaN/GaN HEMTs [24–37] have very high breakdown voltage. Thus large drain voltages can be used in power amplifiers, which give high output impedance that aids in easier matching and lower loss matching circuits. The high sheet charge results in large current densities and minimizing the transistor area results in high watts per millimetre of gate periphery [38,39]. This paper explores the pros and cons of GaN power amplifier and gives a brief review of the efficiency and linearity enhancement technique used. The thermal management techniques used in GaN is explained and also the GaN MMIC development is reviewed.

2. GaN HEMT power amplifier

The distinct advantages of GaN such as high output power density and high operational voltage make GaN a game changer in radar and satellite communication. The output power can be increased about four times when compared with GaAs, with the same transistor size [40–42]. The advantages of higher power density are less circuit complexity, higher efficiency and wider bandwidth. Increased power density indicates more power per unit area and thus more functionality can be implemented in the same area, hence lesser circuit complexity and smaller die size. Also GaN is now qualified for space applications. Airborne and space applications which have limited prime energy requires the development of highly efficient power amplifier. The very high power density of GaN enables it to use in high operating voltages and thus improved DC to RF efficiency and wider bandwidth were achieved. The first demonstration of GaN broad band power amplifier was done in 1999 [43]. The circuit was fabricated on an AlN substrate using AlGaN- GaN power high-electron mobility transistors, grown on sapphire substrates, which were flip-chip bonded for thermal management. Most of the semiconductor companies have now access to GaN MMIC (monolithic microwave integrated circuits) technology [44–46] having high performance processes with gate lengths less than 150 nm. GaN based MMIC have many advantages. For example, in space and airborne systems the high operation bias close to the onboard power supply helps to reduce the extra energy for DC to DC conversion [47–50].

Maximum efficiency of a power amplifier is achieved when it operates at its peak output power, while lowering the output power significantly reduces efficiency. For linearity, the opposite is true; the maximum linear operation is obtained at low output power. To rectify the impairments that come along with high efficiency operation, digital predistortion (DPD) techniques are used. Digital predistortion techniques can compensate for power amplifier nonlinearities [51,52]. The radio base stations have power amplifiers that are optimized for high efficiency and high power-added efficiencies as high as 50–70 percent. A DPD technique is then used to recover the linearity. A highly efficient base station system thus leads to a significant reduction in power consumption and cooling requirements. Similarly in space and aircraft environments which have limited primary energy for cooling, a small percentage change in power added efficiency can make a huge positive impact. GaN technology has made a bigger impact on the power amplifier concept when compared with Si technology. Transit frequency fT, which is a measure of intrinsic speed of a transistor is high for GaN than Si, and also GaN have higher breakdown voltage than Si, which makes it more suitable to use in high power and high frequency applications. The Doherty configuration of GaN power amplifier exhibits higher off state impedance and lower output capacitance when compared with Si technology.

In GaAs technology, the bandwidth of a high power amplifier is limited due to the large input capacitances of large periphery devices providing high power [53]. Also, the impedance transformation from low optimum load impedance up to the 50 Ω environment limits the bandwidth. To get wide bandwidth and high power simultaneously, a device with low device capacitance and high optimum load impedance is needed [54–56]. As GaN devices exhibit high output-power density and good thermal properties, the fabrication of smaller devices with the same output power when compared to the much larger GaAs counterparts is possible. As the smaller size of GaN devices leads to a reduction in terminal feedback capacitance and an increase in the output impedance for a given output power, they can operate effectively over a wider bandwidth.

2.1. Power amplifier classes

Different classes of operation of power amplifier are class A, B, AB, C, D, E, F and J [57]. The theoretical maximum efficiencies of the power amplifier are given in Table 2. Theoretical efficiency calculation is based on the ideal physical model equations. There are number of losses in a practical power amplifier, like discharge losses, conduction losses, Vknee losses and passive component losses [58]. Due to these circuit losses, the amplifier fails to achieve the maximum theoretical efficiency. For example in a Class D switching amplifier, the theoretical efficiency would be achieved if the transistors could switch instantaneously. That is, the transistors are in either their fully on or fully off state, where almost no power is consumed. But practically, it takes a little time for the voltage to swing, and during this time some power is dissipated. Thus practical efficiency is always lesser than theoretical efficiency. Power amplifiers can be categorized as. the linear Class A, the non-linear Class AB, B, C then the switching type amplifiers, Class E, F, etc. The Class A amplifier has the highest linearity among all the classes, at the expense of efficiency. And for switching amplifiers, linearity is traded for efficiency, which is suitable for the applications that does not require high linearity.

Class A power amplifier has the maximum linearity with only 50% theoretical efficiency. They can be used for applications like audio sound systems which require linear and distortion less operation and does not give much importance to efficiency. Class B power amplifiers are used in low cost systems and it is more efficient than class A. In [64] highly linear common source and common drain class B power amplifier in GaN was reported. The common source amplifier exhibited a PAE of 34% and linearity greater than 35 dBc of third order intermodulation suppression. The combination of class A and B gives class AB. The efficiency of class C amplifier is high and they are highly nonlinear, thus they are not used in audio amplifiers. The high performance two stage pulsed class C power amplifier in GaN HEMT was reported in [65] used for radar applications. The measured RF peak power was 39dBm, in an operating frequency range of 2.45–2.75 Ghz. Class D amplifiers are nonlinear switching amplifiers also called as digital amplifiers with theoretical efficiency of 100%. A Doherty transmitter architecture was implemented using class D GaN power amplifier in [66]. Class E power amplifiers used in RF applications are highly efficient tuned power amplifiers. In [67] a broadband class E GaN power amplifier was designed and an average drain efficiency of 68% was observed. Class F amplifiers uses selected harmonics to shape their drain voltage and drain current waveform to improve their efficiency and power output capability. A class F GaN power amplifier was fabricated in [68] which exhibited a power added efficiency (PAE) of 85% with an output power of 16.5 W. Class J amplifier is similar to Class AB power amplifier with a capacitive harmonics termination such that the collector voltage and current waveform have minimum intersect. In [69] the design and implementation of highly efficient class J GaN power amplifier was done for base station application.

3. Analysis of efficiency improvement in GaN power amplifiers

Wide modulation bandwidth and high PAPR (peak to average power ratio) is the characteristics of modern wireless communication system. Different methods to reduce the PAPR have already been adopted [70]. Power amplifiers are compelled to operate at a large back off because of this high PAPR signals. This degrades the power amplifier efficiency. Particularly in 4G/5G systems, modulated signals with more complex scheme and higher bandwidth are used to achieve higher data rate, and the demand is increasing for flexible multiband, multimode operation [71–74]. Various approaches such as Doherty amplifiers [75–78], envelope tracking (ET) amplifiers [79–81], and digital transmitters with superior GaN properties are now used, to efficiently and flexibly amplify the signals.

3.1. GaN Doherty power amplifier

Modern base stations depends on Doherty architecture to implement linear, efficient and broadband power amplifiers (PAs) [82–106]. Doherty power amplifier (DPA), combines two power

Table 2
Theoretical maximum efficiencies of various power amplifier [59–63].

Class	A	B	C	D	E	F	J
Efficiency%	50	78.5	100	100	100	100	78.5

Table 3
Performance of GaAs power amplifiers.

Ref	Freq (GHz)	Saturated output power (dBm)	P1dB (dBm)	Power added efficiency forlinear operation (%)	Supply voltage (v)
[123]	7	35	34	5	6
[124]	23	33	31	3	6
[125]	38	28	27	<2	4
[126]	31–41	37	–	26	4
[127]	42–46	34.5	–	23–26	5
[128]	13.6–14.2	38.1	–	24.6	8

Table 4
Performance of GaN power amplifiers.

Ref	Freq (Ghz)	Saturated P_{out} (dBm	Drain) efficiency at $P_{AV\ tt}$ (	PAE (%)	PAPR (dBm)	Modulation	ACLR (dBc)	Gate length (μm)
[109]	1.65–2.75	44.5–46.3	46.0–62.0	–	7.5	LTE	−45.0	0.4
[130]	1.5–2.4	43.1–44.4	45.3–53.6	–	6.7	LTE	−45.6	0.4
[131]	1.7–2.6	44.9–46.3	>45.0	–	6.5	WCDMA	−50	0.4
[132]	1.7–2.8	44.0–44.5	50.0–55.0	–	6.5	LTE	−47.8	0.25
[133]	0.75–0.95	48.0–48.8	>44.0	–	9.5	LTE	<−22.2	0.4
[134]	0.9–1.8	49.7–51.4	41.3–57.4	–	9.5	LTE	<−22.5	0.4
[135]	5.5	–	29.5	25.6	6	LTE	−48	0.25
[136]	0.7–0.95	44.7	78.3	–	9.65	LTE	−45.6	0.4
[137]	8–12	40	–	44.7	–	LTE	–	0.25
[138]	75–110	28.6	–	6.5	–	LTE	–	0.1
[139]	1.68–2.12	48	77–84	70–79	–	LTE	–	0.25
[140]	2.14	–	44	40	8.6	LTE	−47.9	0.4
[141]	1.85	–	–	31	–	LTE	<−30	0.4
[142]	2.35	–	46.1	40.1	11	LTE	−38.8	0.4
[143]	0.65–1.95	>39	25–42	–	7.2	WCDMA	−50	0.4
[144]	2.14	50	33.7	–	6.5	LTE	−38 ?	0.4
[145]	2.4	44	86.7	–	6.6	LTE	−30.2	–
[146]	6–18	3.7–5.6	–	13–21	–	LTE	–	0.25
[112]	2.6	37.6	54.4	–	6.5	LTE	−27	0.4
[147]	1.5–3.8	43.4	63	–	–	LTE	–	0.4
[148]	2.4	45.6	67	47	7.5	LTE	−27	0.4
[149]	1.63–1.98	31–34	–	944–60	–	WCDMA	–	0.4
[150]	2–19	5.5–12.3	–	22–49	9.5	LTE	–	0.1
[67]	9.57	–	–	32	11.4	LTE	-33	0.15

amplifiers to optimize the power efficiency at the average and peak powers. For single-band LTE signals, DPAs can exhibit an average efficiency around 50%. To maximize the power efficiency of the main and peaking PAs used in DPA, waveform engineering is used [107,108]. The voltage and current swings on the drains of GaN HEMT devices far exceed than other RF power semiconductor technologies. This enables the use of waveform engineering techniques which employs a suitable harmonic manipulation on both source and load harmonics. Tables 3 and 4 provide the performances of GaAs power amplifier and GaN Doherty power amplifier as available in the references. The first three rows of Table 3 data has been taken from vendor datasheets [123–125] and these are the best examples for the current state of point to point communication, that is linear operation at the expense of efficiency. The bandwidth of GaAs technology is from 10 Khz up to 150 Ghz. In [126], 0.1 μm GaAs PHEMT was used to design a power amplifier which delivers 5 W saturated output power and 28% maximum power added efficiency. The authors of [126] claim this amplifier to be of maximum bandwidth in the Ka band.

Doherty power amplifiers has been an inevitable part of wireless base station for a long time as they achieves high efficiency in both saturation and in back-off [109–113]. The basic Doherty amplifier improves efficiency in back-off by using two branch amplifiers, a peaking amplifier and a carrier amplifier. The carrier amplifier is connected to the peaking amplifier through an impedance inverter and the peaking amplifier is then connected to the load. At low power, this arrangement presents high impedance to the carrier amplifier. The impedance decreases as the power increases. Over a wide range of output powers, typically 6 dB or more, the load modulation makes sure that the carrier amplifier operates at saturation and also at high efficiency. Theoretically Doherty amplifier is a linear amplifier, but the practical realization is inevitably nonlinear. Therefore, a digital pre distortion system is needed in the radio base station, which provides linear operation. As the Doherty amplifiers are successfully implemented in radio base stations, next attempt was made to carry over the Doherty technology to the point-to-point communication. The challenges

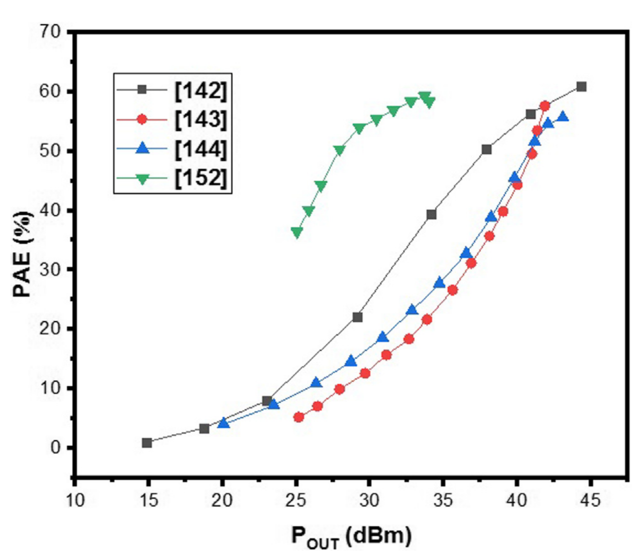

Fig. 2. Power added efficiency versus output power.

at circuit level are the shorter wavelengths in the point-to-point communication bands and the low power density of GaAs. Shorter wavelengths need an integrated solution in contrast to the sub-6 GHz Doherty amplifiers, where the combiner and splitting networks are implemented on the amplifier printed circuit board. But the maximum output power that can be achieved is restricted due to low power density of GaAs. Doherty power amplifiers beyond 6 GHz can be realized with short gate length GaN MMIC technology, which can deliver more than 10 W in saturation. The difficulty in using GaAs material is the low power density which reduces the peak power handling of the system.

Works that was done with GaN Doherty power amplifiers which operates in the 7 GHz bands [114–120] and at 23 GHz [121] shows that state-of-the-art GaN technology is capable of achieving a power-added efficiency of 30 percent and more than 20 W of saturated output power. In 2012, Gustafsson [116] demonstrated the performance of a GaN MMIC Doherty power amplifier operating in a microwave radio band. Using a digital predistortion system, the amplifier achieved an average efficiency of greater than 35 percent while keeping its adjacent channel leakage power ratio (ACLR) below 48 dB for a 10 MHz 256-QAM signal. More recently, Gustafsson [122] demonstrated the performance of a GaN hybrid Doherty amplifier. The hybrid approach with passive GaAs for matching circuits limits the GaN content, which has the potential to lower the cost of the Doherty amplifier. In [129], PAE and gain of symmetrical GaN Doherty power amplifier is compared with balanced class AB power amplifier. The Doherty configuration gives an improved PAE when compared to class AB configuration for a continuous wave input.

The performance outcome of recent research on GaN is given in Table 4. Different modulation schemes like LTE (long-term evolution) and WCDMA (wide band code division multiple access) were used with the given PAPR. The data in Table 4 indicates that the PAE of the GaN power amplifier tend to decrease above 20Ghz. In Fig. 2 the PAE of GaN power amplifiers in [140], [141], [142] and [149] are analysed against the output power and compared. The details of GaN HEMT power amplifiers compared in Fig. 2 are given in Table 5. From the analysis it is evident that the PAE and output power has a linear relationship until the PAE saturates at the maximum output power. Also the highest PAE is achieved in [149] in the frequency range of 1.63–1.98 Ghz. The plot between gain of the GaN power amplifiers and their output power as in [138], [140], [142] and [148] is shown in Fig. 3. Table 6 gives the details of the GaN HEMT power amplifiers compared in Fig. 3. As shown in the figure, the gain decreases rapidly after output power reaches the saturated output power. It is due to this phenomenon the power amplifier is compelled to operate at backoff to maintain high efficiency. Also its clear from the plot that GaN power amplifiers operating at high frequency tend to have low saturated output power than those operating at lesser frequencies. The analysis of gate length of GaN HEMT and maximum gain achieved by the power amplifiers as available in [67,112,146,150] is shown in Fig. 4. A peak is obtained at 0.15 μm, which indicates that maximum gain can be achieved at 0.15 μm gate length technology when compared to other gate lengths. This observation was made at a bandwidth of 2–20 Ghz. The maximum drain efficiency of GaN HEMT power amplifier reported was 82% as in [151].

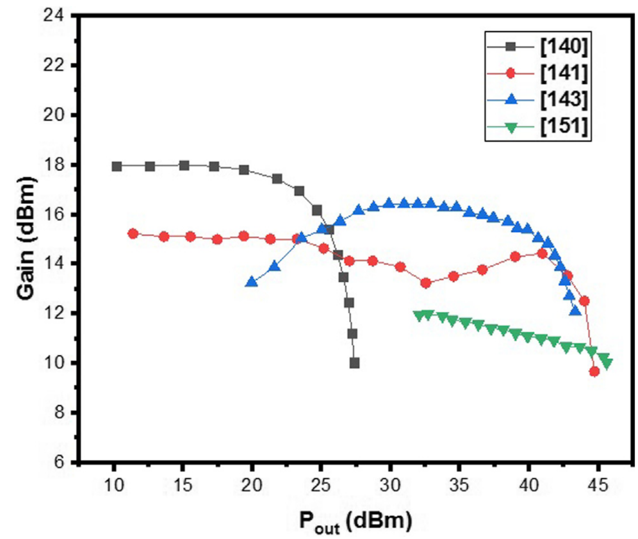

Fig. 3. Gain versus output power.

3.2. GaN envelope-tracking amplifiers

Similar to Doherty architecture, envelope tracking is also an important option to increase the power amplifier efficiency. In fact they are considered as an effective way for greener wireless communication [152] as they ensure efficiency even the power amplifier operates at backoff. An envelope tracking amplifier is made up of a RF power amplifier and an envelope amplifier/modulator (EA) to track the signal envelope. In envelope tracking amplifiers, the supply voltage of the RF power amplifier is modulated dynamically by the envelope amplifier, so that the RF power amplifier operates at compression, resulting in high average efficiency even with high peak to average power ratio signals. The block diagram of an envelope tracking power amplifier [153] is shown in Fig. 5 and the power supply modulation is shown as Vdd (t).

To realize an efficient broadband envelope amplifier, GaN with its higher- speed operation and higher voltage is an attractive option, and thus an envelope tracking amplifier with GaN has been realized in [157]. The power-added efficiency (PAE) and output power of the envelope tracking power amplifier were 35.3% and 30.7 dBm, respectively. Table 7 shows the state-of-the-art performance of envelope tracking power amplifiers. Compared with CMOS, the envelope tracking power amplifier reported in [157] has the highest efficiency and widest modulation bandwidth. This shows that the envelope tracking power amplifier is one of the most useful architectures for 4G/5G systems which require multimode, multiband operation [73,158,159].

4. Analysis of linearity improvement in GaN power amplifier

Power amplifiers play an inevitable role in determining the overall performance and throughput of the wireless communication system. But they are inherently nonlinear and this nonlinearity causes distortion and spectral regrowth which lead to adjacent

Table 5
Details of the GaN HEMT power amplifiers compared in Fig. 2.

Ref	Remarks	Frequency (GHz)	Average PAE (%)	Modulation	Gate length (μm)
[140]	Doherty power amplifier	2.14	40	LTE	0.4
[141]	Doherty power amplifier	1.85	31	LTE	0.4
[142]	Envelope tracking power amplifier	2.35	40.1	LTE	0.4
[149]	Doherty power amplifier	1.63–1.98	44–60	LTE	0.4

Table 6
Details of the GaN HEMT power amplifiers compared in Fig. 3.

Ref	Remarks	Frequency (GHz)	Average PAE (%)	Modulation	Gate length (μm)
[138]	WBand GaN power amplifier MMIC	75–110	6.5	LTE	0.1
[140]	Doherty power amplifier	2.14	40	LTE	0.4
[142]	Envelope tracking power amplifier	2.35	40.1	LTE	0.4
[112]	Load modulated balanced amplifier	2.4	47	LTE	0.4

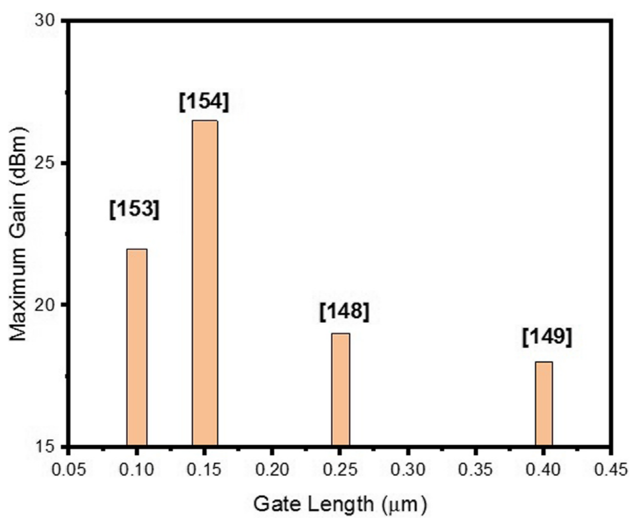

Fig. 4. Maximum gain versus gate length.

channel interference. If the power amplifier operates at the linear portion of its operating curve (that is at backoff), the power amplifier operates at lower power and thus at lower efficiency. Moreover new modulation schemes like wideband code division multiple access (WCDMA) and orthogonal frequency division multiplexing (OFDM, WLAN/3GPP LTE) are complex and they have high PAPR (Peak to average power ratio), that is very large fluctuation in their signal envelope. This demands the power amplifiers to operate at back off far below its saturated power level resulting in very low efficiency. A lot of linearization methods have been introduced such as adaptive baseband predistortion, Cartesian feedback, envelope elimination and restoration, feedforward and linear amplification with nonlinear components [73,159–163]. All these methods have resulted in improving the linearity, but many of them suffers from bandwidth limitations and lack of precision and stability. This is where adaptive digital predistortion comes into picture. Digital predistortion is one of the linearization techniques used by power amplifiers to obtain good quality transmission with high PAPR and wideband signals [161–164]. The other linearization techniques and their comparison with digital predistortion [165–167] are given in Table 8. The measure of linearity is given by intermodulation distortion (IMD), 1db compression point (P1dB), spectral regrowth and noise power ratio (NPR). The lesser the value of IMD, the higher the linearity. Predistortion is achieved by reducing phase and gain distortions or by cancelling the intermodulation products. In [168], a digital predistortion linearizer was used in a highly efficient GaN power amplifier. WCDMA (wide band code division multiple access) signal was used as the input with PAPR of 9.8 dB. A power added efficiency of 21% was achieved at 10 dB output power back off with 53dBc ACLR.

5. Thermal analysis of GaN power amplifier

Self heating is one of the main problems faced by GaN technology. GaN can reach 5–10 times of higher power densities compared with GaAs and thus results in higher operating channel temperature. Growing GaN on SiC substrate is adopted as one of the method of thermal management. This is due to high thermal conductivity of SiC. SiC keeps the channel temperatures of GaN HEMT beneath the maximum temperature for safe operation. As the channel temperature is exponentially related to the device reliability, a change of 15–20 degree celsius can decrease the mean time to failure by an order of magnitude. Also different cooling strategies of GaN HEMT are introduced like passive remote cooling, active remote cooling, passive near junction cooling and active integrated cooling [169,170]. DARPA (Defense Advance Research Projects Agency) have launched the TMT (Thermal Management Technologies) program [171] to address the thermal management issues in semiconductors. This program introduced attached cooling and embedded cooling technologies to address the heat management in active regions of semiconductors. [172,173]. The reliability of GaN devices is mainly effected by the junction temperature. The highest magnitude of junction temperature occurs on the drain side edge of the gate called the hotspot. Therefore moving the thermal management solutions closer to the heat generation region is critical in order to reduce the overall junction temperature of the device. The use of embedded microfluidic thermal management is more effective than passive remote cooling strategies. The traditional passive remote cooling techniques are now replaced by near junction embedded microfluidic cooling

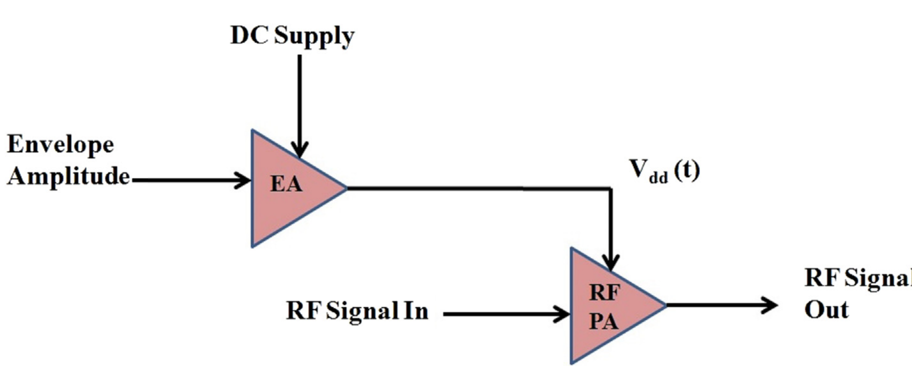

Fig. 5. Block diagram of envelope tracking power amplifier [153].

Table 7
Performance comparison of GaN and CMOS Envelope tracking amplifier.

Ref	Device for EA	Freq (Ghz)	Modulation band width (Mhz)	PAPR (dB)	Total efficiency (%)	ACLR (dBc)
[154]	CMOS	0.5–1.75	5	6.6	25–31	−47.5
[155]	CMOS	1.85	5	6.5	30	–32
[156]	GaN	1.84	10	11.7	23.9	−38.7
[157]	GaN	0.9–2.15	80	6.5	32.1 – 35.5	−45

Table 8
Linearity enhancement methods [165–167].

	Feedback	Feed forward	Analog predistortion	Digital predistortion
Bandwidth	Narrow	Wide	Very wide	Moderate
Linearity	Good	Very good	Good	Very good
Complexity	Medium	High	Medium	High
Power efficiency	High	low	High	High

methods [174–179]. GaN on diamond substrate is also used to achieve a good thermal management where diamond act as the electrical substrate and heat spreader. Diamond microfluidics based intrachip cooling is used in [180] to affect scalable, low thermal resistance die level heat removal. In [181], application of microfluidic technology on GaN on Diamond devices is explored. The tradeoff between passive and active remote cooling techniques used in GaN on SiC and GaN on Diamond device technologies are presented in [182].

6. GaN MMIC and applications

Microwave Monolithic Integrated Circuit (MMIC) power amplifier where the transistor and the matching network are integrated in a single platform is of crucial importance to minimize weight and component count, and also to improve reliability and repeatability of the microwave front-ends. Applications like solid state power transmitters, radar, electronic warfare, high speed communications and compact receivers would benefit from the implementation of MMIC, and GaN HEMT technology has been identified as a suitable technology for this. The first GaN MMIC was reported in 2000 [183,184]. Sapphire substrates were initially used, later Si or SiC substrates were used for the fabrication of GaN high electron mobility transistors. Both Si and SiC technologies have their relative strengths and weaknesses [185,186]. Si-based technology has several limitations as compared to the SiC-based technology especially for MMIC realizations due to the higher losses of the passive components and the lower working frequency of the active devices [187,188]. Si based technology offers low cost and high wafer diameter when compared with SiC. Many GaN MMICs are produced in bulk by the vendors and they have performed remarkably well.

GaN on SiC MMIC processes have been developed and can practically make use of the same passive structures used for GaAs MMICs that have attained a good technological maturity. The high output power density of GaN allows the fabrication of much smaller size devices compared to GaAs with the same output power. Smaller size leads to higher impedance which facilitates lower loss matching in power amplifiers. The high operating voltage of GaN due to its high breakdown electric field reduces the need for voltage conversion and also provides the potential to obtain high efficiency, which is a crucial for power amplifiers. The wide bandgap also enables it to operate at high temperatures. The GaN-on-SiC based MMICs enable the state-of-the-art high frequency performance and bandwidth to be extended into Ka-Band and Ku-Band applications [189]. The design and measured performance of two MMIC power amplifiers (based on GaAs PHEMT and GaN HEMT) is given in [40]. The operating frequency is over 4 to 18 GHz with approximately 4 Watts of output power. For the same output power, the ratio of output periphery of the devices is about 1:7 (GaN:GaAs).

Diamond has the highest thermal conductivity of any known material at temperatures above 100 K. Due to its high thermal conductivity, diamond is also considered as a substrate to grow GaN devices [190–192]. It can effectively remove heat from active region of GaN device and thus enables the improvement in lifetime and reliability of the amplifiers and also increase the power. A comparative analysis of GaN on SiC and GaN on Diamond technologies is given in [193].

As GaN material properties are more suitable for high frequency and high power operation, they cause an unwanted issue like electromagnetic emission that can affect the performance of nearby integrated circuits [194–196]. So handling these emissions in such a way that they cause less damage is done in many ways. Some of them are shielding the source [197,198], suppressing the electromagnetic emissions using absorbent materials [199,200] and filtering out the emissions by adding filtering components [201,202]. But all these methods turned out to be costly and failed to address the root cause of the emissions. In [203], a simulation method is developed using Advanced Design System. The simulated electromagnetic emission results were used to optimize it using response surface methodology.

7. Conclusion

Solid state amplifiers with high output power and operating at high frequency plays an inevitable role in the modern wireless communication. Complex modulation schemes with high PAPR signals demand power amplifiers with high efficiency and linearity at both saturation and backoff. The material properties of GaN makes it a good choice for the fabrication of high power and high frequency power amplifiers. Different efficiency enhancement technique like Doherty configuration and envelope tracking can be used to ensure high efficiency. Analysis of efficiency was done in GaN power amplifier and the PAE was found to be far higher in GaN Doherty power amplifier than in conventional GaN power amplifier. Thus GaN Doherty power amplifiers are best suited for Base station application as the highly efficient power amplifier helps to reduce the power dissipation and thus the need for cooling. Linearization technique like digital predistortion is used in GaN power amplifiers to obtain linearity at high efficiency. Growing GaN on SiC and on Diamond was found to be effective for thermal management of the power amplifier. SiC is used more extensively than diamond due to cost issues. The microwave monolithic integrated circuit technology in GaN has its own advantages. GaN have an immense potential which helps in the development of high frequency and high power devices due to its high thermal conductivity. Also due to its wideband gap advantages over other semiconductor technologies, GaN technology and applications are the most exciting in RF and microwave industry.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeue.2019.153040.

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