Gallium Nitride HEMTs for High Efficiency Power Amplifiers

by Aethercomm

Introduction

Gallium nitride has numerous physical properties that result in transistors with greatly increased power density compared to established technologies. Increasing power density results in smaller transistor die with higher output power. Compared to silicon LDMOS FETs and GaAs MESFETs of similar output power, GaN HEMTs have smaller parasitic capacitances. The result is transistors that have higher gain with larger input and load impedances. The matching networks have fewer sections and exhibit broader bandwidth than those required for other technologies.

Table 1: L-band amplifier swept power measurements

Output Power (dBm)	Gain (dB)	DC Power (W)	PAE (%)
38.3	53.3	34.7	19.5
40.7	53.7	44.3	26.5
42.9	53.9	56.6	34.5
44.9	53.9	71.6	43.2
46.6	53.6	88.5	51.7
47.8	52.8	103.9	58.0
48.2	52.2	110.1	60.0
48.5	51.5	114.6	61.8
48.7	50.7	117.8	62.9
48.8	49.8	120.0	63.2

Advantages and Disadvantages

Gallium nitride is a wide bandgap material, which enables operation at higher drain voltages. This further increases the transistor's impedances relative to LDMOS and GaAs. Another benefit is tolerance of open and short circuited outputs, as well as operation into high VSWR loads. This is advantageous for applications where use of a circulator is not feasible. An example is when a multi-octave amplifier is used to directly drive a broadband antenna.

Currently, the principle disadvantage of gallium nitride technology is cost. The majority of GaN HEMTs are produced on silicon carbide substrates, which are both costly and limited in size. In spite of the smaller die, they cost five to ten times more than LDMOS transistors of comparable output power. GaN HEMTs grown on silicon substrates potentially offer substantial cost savings over ones grown on silicon carbide. The drawback is reduced thermal conductivity of silicon substrates, which limits the power density of the transistor.

The increased transistor cost in a GaN HEMT amplifier is somewhat offset by several factors. In applications where multiple lower power LDMOS FETs or MESFETs would need to be paralleled to achieve the required power and bandwidth, a single pair of higher power GaN HEMTs could be used. For example, an 80W amplifier covering 800MHz to 2500MHz using GaAs MESFET technology would require paralleling eight 10W transistors. Three stages of power combining would also have to be implemented. The GaN solution would require using only two 45W transistors parallel. There are considerable savings in size, complexity, and tuning time, which lower the cost of the GaN amplifier, particularly as the power level and bandwidth are increased.

GaN HEMTs exhibit a soft power compression characteristic. LDMOS FETs and GaAs MESFETs typically exhibit gains identical to their small signal gains over most of their drive range. When producing the rated output power, the gain typically drops by 1dB. This is called the P1dB output power. Output power will saturate at a power approximately 1dB greater than P1dB, while the gain will have typically decreased by 3dB compared to the small signal gain. By comparison, GaN HEMTs driven even 10dB below their rated output power will exhibit a decrease in gain compared to the small signal gain. This results in a lower value for P1dB than the rated power might indicate. GaN HEMT output powers are therefore usually specified where the gain drops by 3dB, or P3dB. When GaN HEMTs are used in multiple stages of a power amplifier, greater levels gain compression can occur before the maximum output power is reached.

The soft compression characteristic also impacts the linearity of GaN HEMT amplifiers. LDMOS and MESFET amplifiers usually exhibit third order output intercepts (OIP3), 10dB greater than their P1dB when measured at output powers 10dB or greater backed off from P1dB. At output powers closer to P1dB, OIP3 generally degrades due to the compression of the transistors. Aethercomm typically measures differences of 6dB to 8dB between OIP3 and P1dB for GaN HEMT amplifiers under backed off conditions. Under moderate levels of drive, the OIP3 generally improves 2dB to 3dB before falling again as the amplifier compresses.

Class E and Class F High Efficiency Modes

The low parasitic capacitance and high breakdown voltage of GaN HEMTs makes them ideal for realizing the class E and class F high efficiency amplifier modes. Both modes have theoretical efficiencies of 100%. Recently, several GaN transistor vendors have implemented class E amplifiers in hybrid form. Typical results are ten watts output power at L-band with efficiencies from 80% to 90%.

Aethercomm recently delivered a class F high efficiency amplifier module operating at L-band to a major defense contractor. The desired output power was to exceed 50W with an efficiency of 60% for the entire amplifier. Due to the tight delivery schedule, it was necessary to use off the shelf packaged transistors rather than developing a custom hybrid solution.

The power amplifier final stage was implemented using a balanced pair of packaged GaN HEMTs operating in class F. Matching networks supplying the harmonic terminations necessary for class F operation were designed by starting with an idealized model of the transistor. The parasitic capacitance and inductance of the transistor package was then added and the matching networks modified appropriately to maintain the required harmonic terminations at the transistor die. The amplifier was then simulated using a nonlinear model of the transistor, and the matching networks modified to optimize efficiency and power.

A single-ended prototype of the class F output stage was constructed. Drain efficiency of 75%, output power of 40W, and gain of 16dB were obtained with only minor bench tuning. The results tracked the simulation closely.

Low power GaN devices suitable for the driver stage were not available. The three stage driver was designed using GaAs MESFETs, which were operated in class A. Initially it was believed that the driver stages would have to be operated in a high efficiency mode in order to achieve the required PAE; however, analysis indi-

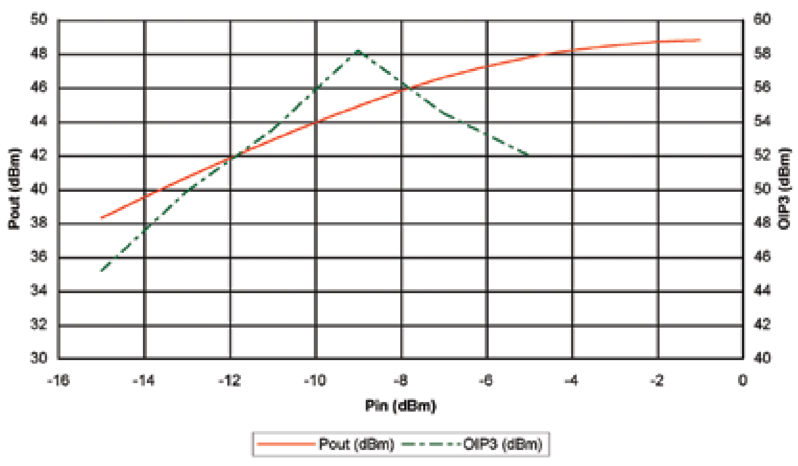

Figure 1: L-band amplifier output power versus OIP3

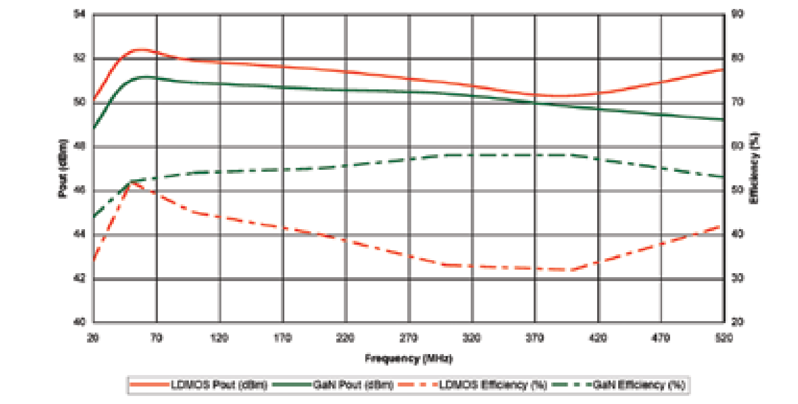

Figure 2: VHF/UHF amplifier LDMOS versus GaN comparison

cated that with proper sizing of the transistors, class A operation was permissible. The driver had 40dB gain and 10W power consumption.

The final configuration of the power amplifier exhibited a peak PAE of 63% at an output power of 75W. At P2dB, the amplifier had an output power of 65W and 61% PAE. Table 1 gives the characteristics of the power amplifier under different drive levels. Since the class F final stage is biased at threshold, with no quiescent current, the amplifier has gain expansion at low drive levels. The amplifier gain peaks, then compresses as the maximum output power is approached. Table 1 demonstrates the efficiency of this design.

The OIP3 of the amplifier is shown in Figure 1. Degraded linearity is exhibited at low drive powers because of the class F bias level. The maximum linearity occurs at an average output power of 45dBm, with OIP3 measuring over 58dBm. At higher drive levels, the amplifier is compressed by the peak level of the two input tones, with lower OIP3 resulting. The soft compression characteristic can also be observed in Figure 1. Detailed OIP3 data is given in Table 2.

Table 2: OIP3 versus output power

Average Output Power (dBm)	OIP3 (dBm)
35.6	44.1
37.7	46.2
39.0	47.7
40.0	49.3
41.1	50.5
42.1	52.0
43.2	54.0
44.1	56.2
44.9	58.2
45.6	57.5
46.3	55.7
46.7	54.5
47.1	53.0

Broadband VHF/UHF High Efficiency Amplifier

Aethercomm has delivered power amplifiers operating from 20MHz to 520MHz to several customers. The amplifiers currently use silicon LDMOS transistors to achieve an output power of 100W with an efficiency across the band of approximately 40%. Recently, a customer requested a modified amplifier which would be able to directly drive their high VSWR antenna over the full bandwidth. Although gallium nitride technology is not normally considered for VHF/UHF applications, its high breakdown voltage gives an advantage over a LDMOS solution.

The new amplifier was implemented using a GaN HEMT driver and final stage operating at 28V. The transistors were biased Class AB, and driven with packaged MMIC components. The amplifier had 50dB gain, saturated output power of 50dBm, and an efficiency of 53% over the 20MHz to 520MHz band. In addition to being more rugged than the LDMOS solution, the GaN solution demonstrated a significant efficiency improvement. Under full drive, this results in approximately 100W savings in DC power consumption across the band, allowing a smaller power supply to be used. This also translates directly into a reduction in heat dissipated by the amplifier, with significant

Table 3: VHF/UHF amplifier LDMOS versus GaN comparison

Frequency (MHz)	LDMOS Pout (dBm)	LDMOS DC Power (W)	LDMOS Efficiency (%)	GaN Pout (dBm)	GaN DC Power (W)	GaN Efficiency (%)
20	50.1	303	34	48.8	173	44
50	52.3	324	52	51.0	241	52
100	51.9	342	45	50.9	228	54
200	51.5	356	40	50.6	207	55
300	50.9	368	33	50.4	188	58
400	50.3	340	32	49.8	165	58
520	51.5	340	42	49.2	157	53

reductions in the heat sink size and air flow required. Detailed data comparing the two solutions are given in Table 3. Figure 2 demonstrates this in a graphical form.

Conclusion

Gallium nitride transistors are in production and are available from several vendors. The increased power density of GaN HEMTs enables the creation of power amplifiers with higher output power, smaller size, and greater efficiency than existing technologies. Aethercomm has put this technology to use, delivering a high efficiency class F power amplifier at L-band with over 60% efficiency. A broadband VHF/UHF power amplifier with over 50% efficiency has also been achieved over a decade bandwidth.

AETHERCOMM