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Wideband 400 W Pulsed Power GaN HEMT Amplifiers

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Abstract

RFMD has developed 400W pulsed output power GaN HEMT amplifiers operating over 2.9GHz to 3.5GHz band or 17% bandwidth. Under pulsed RF drive with 10% duty cycle and 100μs pulse width, the amplifier delivers output power in the range of 401W to 446W over the band, with drain efficiency of 48% to 55% when biased at drain voltage of 65V. The amplifier uses AlGaN/GaN HEMTs with a total device periphery of 44.4mm and advanced source connected field plates for high breakdown voltage. These wideband high power amplifiers are suitable for use in frequency agile pulsed applications such as military radar, air traffic control radar, and communications jamming.

Introduction

The high power and wide bandwidth potential of GaN HEMT devices is well known.[1] RFMD has been developing high power amplifiers using GaN HEMTs for various applications. A 250W amplifier in the 2.14GHz to 2.5GHz band for wireless infrastructure applications in the WCDMA and WiMAX bands was reported earlier.[2] Such wide bandwidth is essential for next generation frequency agile software-defined radio architectures that use reconfigurable radios to support multiple frequency bands and various standards.[3]

This paper presents 400W pulsed power amplifiers operating in the 2.9GHz to 3.5GHz band that find use in high power pulsed radars for surveillance and air traffic control systems. Such amplifiers could be used for 3.5GHz WiMAX infrastructure under less stringent conditions, as they can support high peak to average digitally modulated signals while providing good linearity.[4]

The military and commercial community requires high power and broadband modules for pulsed radar surveillance and air traffic control applications. The market is looking for next generation devices that provide higher power and broader bandwidth able to support 1.2GHz to 1.4GHz L-band for IFF, TACAN, TCAS pulsed applications and 2.7GHz to 3.5GHz S-band pulsed applications. These devices will enable suppliers to power and combine fewer devices, and reduce size and weight for >1kW power modules used in radar systems.

To obtain high power, large periphery devices are required and the resulting high device parasitics lead to low device input and output impedances. Matching to such low impedance from a 50Ω system severely limits the bandwidth achievable. Wideband gap material systems like Gallium Nitride that have low parasitic capacitances and can be operated at high drain voltage can obtain a combination of wide bandwidth and high output power compared to Silicon or Gallium Arsenide technologies.

GaN technology has been used to implement several amplifiers with pulsed output power higher than 400W. Output power of 750W using 1% duty cycle pulses at 2.14GHz has been reported over a narrow bandwidth.[5] Push-pull power combining topologies have been employed on the board to obtain 500W at 1.5GHz.[6] 550W output power over 3.3GHz to 3.6GHz has been demonstrated using 2% duty cycle and 2μs pulse width.[7]

AlGaN/GaN HEMT devices are used with source connected field modulation plates, which can be operated at drain voltages up to 65V. This high operating voltage increases the device's optimum impedance and lowers parasitic capacitance for a given output power requirement. This allows a broader band match resulting in a wider bandwidth. High output power densities up to 32W/mm at 4GHz[8] have been reported using AlGaN/GaN HEMTs with field plates. Here we demonstrate the capability of the field plate devices to provide broad bandwidth of 600MHz at high power levels >400W while maintaining good efficiency over the bandwidth.

Theory

In theory, purely real impedances can be matched to a 50Ω system over any bandwidth using an infinite number of matching elements. Actual devices have device optimum impedances with a reactive component. Complex loads can be matched only over a limited bandwidth as defined by Fano's limit.[9] The maximum bandwidth ratio achieved using an infinite lossless matching network is given by:

$$\frac{F_{HIGH} - F_{LOW}}{F_O} = \frac{\pi}{-Q_L \cdot \ln(\Gamma)} \qquad (1)$$

where Q_L is the Q-factor of the device optimum source or load impedance to be matched, and Γ is the minimum reflection coefficient needed over the band. This bandwidth is further limited in practice due to the finite number of matching sections and the matching network losses. For these reasons, low Q-factor for the optimum source and load impedances are critical to obtaining broad bandwidth. A suitable figure of merit for high power broadband capability of a device technology is a low pF/W gate and drain capacitance.

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GaN HEMT Technology

RFMD's baseline AlGaN/GaN HEMT technology is based on devices with a standard 0.72 μm gate length and an advanced source connected field plate to obtain breakdown voltages in excess of 200V. To be able to handle the high power densities in excess of 10W/mm, a SiC substrate is used that provides excellent thermal conductivity and minimizes temperature dependent memory effects. The device topology and the baseline fabrication process are detailed in an earlier publication.[10]

A typical device biased at a drain voltage of 65V exhibits a pinch-off voltage of about -5V and a peak current density of 0.9A/mm. The current and power gain cutoff frequencies (ft and fmax) as measured from small periphery devices are 11GHz and 18GHz, respectively.

Under class-AB bias and CW operation at 3.3GHz a typical 2.2mm unit cell device obtains 56% peak power-added efficiency (PAE) and a peak output power of 21.9W. This corresponds to a power density of 9.9W/mm. This is about three times the 3.2W/mm power density obtained at 28V drain bias from a device without the field plate. The series equivalent optimum source and load impedances are $Z_S = 3.8 + j10.5\Omega$ and $Z_l = 30 + j47\Omega$, respectively. These indicate low gate and drain capacitances of ~0.46pF/W and 0.07pF/W, respectively, which is about one-fifth of equivalent silicon devices. Using this series-equivalent source impedance, the theoretical maximum bandwidth ratio for a -15dB return loss can be calculated to be 57%. These low capacitances contribute to the higher bandwidth obtained compared to other device technologies.

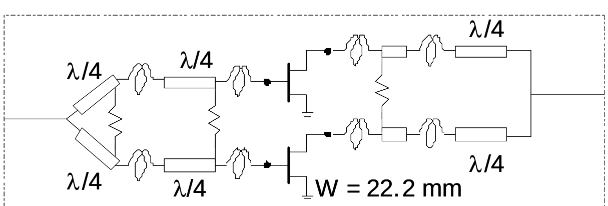

Figure 1. Amplifier Circuit Schematic

Circuit Design

The amplifier circuit (Figure 2) uses two 22.2mm periphery devices combined using a Wilkinson power divider/combiner[11] on the input and output. This topology achieves wider bandwidth than would be obtained using a single 44.4mm device. Along with the power division/combination function, the Wilkinson combiners also perform the impedance transformations required to provide the optimum source and load impedance to the devices. The unit cell source and load pull impedance measurements mentioned earlier were used to estimate the large periphery device's source and load optimum impedances. Due to the higher gate capacitance, a two-stage impedance transformation was used at the gate to obtain broader bandwidth. The drain section consists of an inductive element to provide the reactance needed for the optimum load and a single stage Wilkinson combiner/transformer. Electromagnetic field models were used extensively to model the frequency performance of the combiner transformer elements.

Extensive stability analysis and odd mode oscillation loop analysis were conducted. This type of combining network is prone to the formation of out-of-frequency band oscillation loops. The design needs significant analysis over a wide frequency range to determine if any potential odd mode oscillation loops exist. Previous work[12] provides detailed descriptions applying stability analysis to multidevice amplifiers using linear analysis and S-parameters. An extensive analysis of odd mode oscillation loops is provided in an earlier paper applying this methodology to GaN-based amplifiers.[13] For an odd mode loop to cause stability issues the following conditions must be met:

To provide adequate design margin loop gain, <-2dB should be maintained across a frequency band where G_{MAX} is greater than 0dB.

This methodology was applied to the amplifier's loop gain and phase using Wilkinson combiner networks not employing an isolation resistor between the ports. The loop phase angle meets the criteria for oscillation at two distinct frequencies, 3.685GHz and 8.536GHz. Loop phase is close to the criterion at low frequency. In all three cases the loop gain requirement is not met; however, the loop gain margin is less than the adequate limit defined.

The loop stability can be increased by adding an isolation resistor to the Wilkinson combiner and by optimizing the gallium nitride device layout. Isolation resistors at the input and output were used between the two devices to curb odd mode oscillations.

The devices come in a 15mmx17mm package (Fig. 2). The combiner/dividers were implemented on high dielectric constant substrates to achieve the small dimensions required for the package. The quarter-wave transformations were designed to obtain 35Ω impedance at the package. The evaluation board used for testing further transforms the impedance to 50Ω.

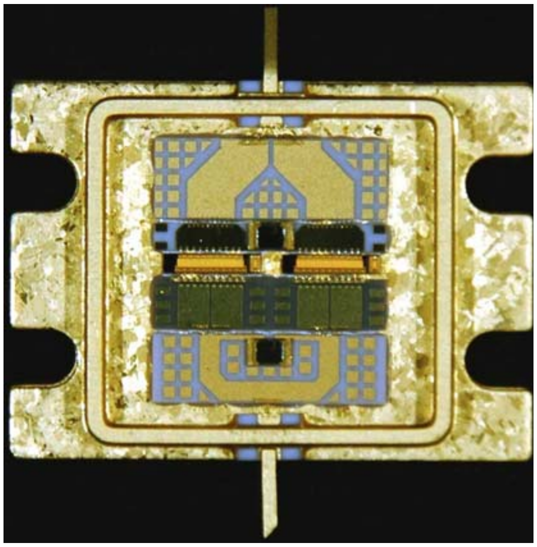

Figure 2. 400W GaN HEMT Amplifier Photograph

Pulse Power Performance

RF performance was evaluated after optimizing on-board matching. The amplifier was biased in class A-B mode at a fixed drain voltage of 65V and a drain current of 440mA. RF input was pulsed using a 100µs wide pulse with 1ms period. Output power was measured at the center of the pulse. The drain current pulse waveform was monitored to calculate drain efficiency. The amplifier was tested over the frequency range of 2.9GHz to 3.5GHz.

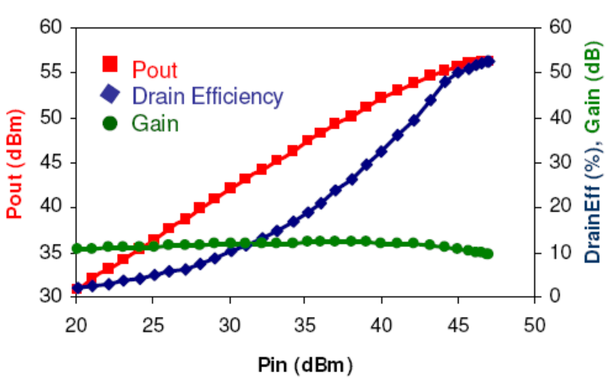

Figure 3. RF Ouput Power at Midpoint of the Pulse (Drain Efficiency and Gain at 3.4GHz)

Figure 3 shows measured output power at the pulse mid-point, drain efficiency, and gain at 3.4GHz as a function of input power. Peak output power of 434W was obtained at 3.4GHz with drain efficiency of 52.6%. Figure 7 shows measured output power over frequency for a range of input power, illustrating broadband power capability.

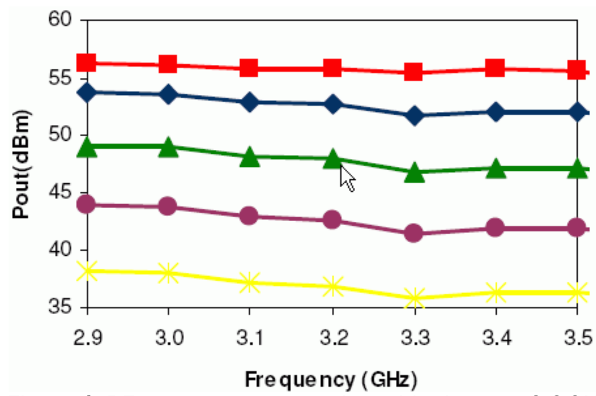

Figure 4. RF output power at pulse midpoint over 2.9GHz to 3.5GHz band for P_{IN} of 25, 30, 40, and 45dBm.

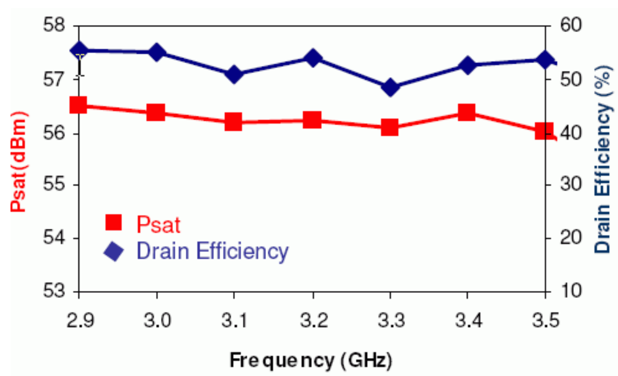

Figure 5. Measured saturated output power, and drain efficiency over the 2.9GHz to 3.5GHz frequency band.

Fig. 5 shows the peak saturated output power and drain efficiency over the frequency band and Table I summarizes the data. Output power in excess of 401.5W was obtained over the entire band, with better than 48.4% drain efficiency.

Table 1. Summary of RF Performance

Frequency (GHz)	Pk P_{OUT} (W)	Drain Eff (%)	PAE (%)
2.9	446.4	55.5	49.1
3.0	432.9	55.1	49.0
3.1	414.8	50.8	44.6
3.2	419.3	54.0	47.3
3.3	405.4	48.4	42.4
3.4	434.1	52.6	46.5
3.5	401.5	53.8	47.9

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The pulse droop performance at 56.4dBm output power shows about 0.25dB droop over the complete 100µs pulse, and less than 0.15dB across the middle 50% of the pulse. This confirms the excellent thermal capability of the GaN on SiC dies in the package, even under the high power density at which they operate.

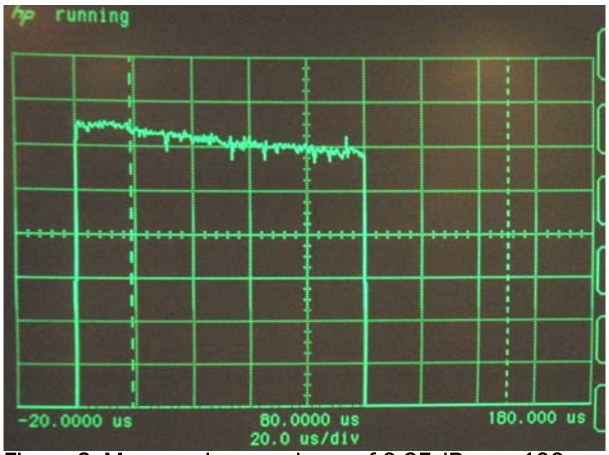

Figure 6. Measured power droop of 0.25dB over 100µs pulse at 56.4dBm output power (at the center of the pulse) with 10% duty cycle.

Conclusion

RFMD has demonstrated a compact >400W wideband AlGaN/GaN HEMT power amplifier operating at 65V with better than 48.4% drain efficiency over a 600MHz bandwidth from 2.9GHz to 3.5GHz, under pulsed condition with 10% duty cycle and 100µs pulse width. RFMD has also successfully demonstrated a >400W wideband AlGaN/GaN HEMT power amplifier operating at 65V with better than 48.4% drain efficiency over a 600MHz bandwidth from 2.9GHz to 3.5GHz, under pulsed condition with 10% duty cycle and 100µs pulse width. The combination of GaN HEMT device technology and the impedance matching topology, achieves high power and broad bandwidth in a small package. These amplifiers are well suited for pulsed applications including advanced radar systems.

Acknowledgement

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