Hybrid and Monolithic GaN Power Transistors for High Power S-Band Radar Applications

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***Abstract*—this paper presents the design, development and characterization of three products for S-Band Radar applications. These products include two 240 Watt hybrid power transistors and a fully integrated 75 Watt packaged MMIC.**

Keywords-GaN; HEMT; Power Amplifier; Radar, MMIC

I. Introduction

Today's military, civilian, and commercial radar systems largely rely on either traditional vacuum tube-based implementations using centralized transmitters or various distributed architectures (including electronically scanned arrays) employing solid state amplifiers using silicon or GaAs device technology. These radar systems service a number of applications areas including threat detection, precipitation tracking, and maritime vessel traffic management. As the next generation of these systems nears production readiness, gallium nitride (GaN) devices promise to play a large role due to their ability to produce higher RF output power at higher temperature and high efficiency over larger bandwidths than traditional semiconductors. These attributes directly support systems with higher sensitivity, increased detection range and improved reliability with lower cost and weight.

Over the last six years, GaN has rapidly matured from a promising new device technology to a production ready, mainstream reality. At Cree, over the last five years, we have shipped over 600,000 GaN devices and multi-stage MMICs ranging in output powers from 15 to 240 Watts covering operational frequencies from DC through 18 GHz.

In this paper, we focus on three new S-band product offerings that promise to dramatically improve the performance of S-band radar systems for both military and commercial applications. The first two products are the CGH35240 and CGH31240 which are fully matched 240 Watt packaged GaN transistors covering 3.1 GHz to 3.5 GHz and 2.7 GHz to 3.1 GHz respectively. These parts are ideal for radar system designers looking to replace traditional travelling wave tubes (TWTs) or cross field amplifiers (CFAs) with a solid state approach.

The third product is the CMPA2735075F which is a two stage packaged GaN MMIC PA covering 2.7 GHz to 3.5 GHz. It produces 75 Watts of RF output power at greater than 50% PAE. This product is ideal for active electronically scanned arrays (AESAs) requiring a small form factor.

II. Design and Development of a 240W Hybrid Transistor

A. Design Overview

S-Band radar transmitters often require very high output power in a very small form factor due to limited available space in the installation. The frequency allocation for S-Band radar is from 2.7 to 3.5 GHz. We chose to subdivide the band in two to optimize performance of the 240W transistor. It was determined that the power transistor should be matched to 50 ohm and that it should have as small a footprint as possible [1], [2].

The initial design specification was to achieve 240 W of power over 3.1 to 3.5 GHz with a power added efficiency of 50 to 60 %. The product was also required to be designed to be robust and be able to be manufactured in high volumes with no additional adjustment.

The first task in designing this hybrid transistor was to determine the best topology for the input and output matching networks for the GaN HEMT die. The die used for this design was a pair of CGH60120D devices which have a unit gate width of 360um and have 28.8mm in total. These die have a typical performance of 120 W output power and drain efficiency typically greater than 65 %. These die are from the G28V3 process, which has been proven to be extremely robust with excellent reliability. The die model was first load-pulled over 3.1 to 3.5 GHz to determine the impedances.

	Die Impedances			
	Input		***Output***	
Freq. (GHz)	Mag	Ang	Mag	Ang
3.1	0.982	177.6	0.913	176.5
3.3	0.981	178.1	0.919	176.4
3.5	0.984	178.6	0.916	175.8

Table 1. Impedances at die

Large signal simulation of the die model with the source and load impedances as shown in table 1 achieved output power greater than 125 W with 10 dB gain and a power added efficiency of 63 %.

B. Topology Selection

In a hybrid transistor assembly basic microwave circuit elements are implemented as follows. Bond-wires are used as inductive elements where the value can be adjusted by their height and length. Single layer capacitors are used as the capacitor matching elements. Splitting and combining of the RF input and output is implemented using microstrip lines on an alumina substrate. Matching networks can also be included on these substrates. The interface to the transistor package also needs to be taken into consideration and was included in the analyses of the different topologies. Three different topologies were analyzed for the realization of the output matching network, direct bonding, shunt-C, and shunt-L.

- **Direct Bonding:** In this approach the transistor die is connected directly to the alumina substrate. The direct output match is the circuit with least complexity and also can be realized in the smallest space. The drawback is the limitation of performance over the full bandwidth.
- **Shunt-C:** The transistor is connected to the output combining alumina substrate through a PI network consisting of a series inductor, shunt capacitor and series inductor. The shunt-C match circuit uses the same topology as the input match. It is more complex and requires more space. It has better performance over the full bandwidth
- **Shunt-L:** In this realization two sets of bond wire are used for matching. One set of bond wires connects the die to the output alumina substrate while a second set of wires is connected to a DC blocking capacitor effectively creating a shunt-L. This topology provides the most tuning flexibility. It is, however, the most complex topology in physical implementation. It also has better performance over the full bandwidth.

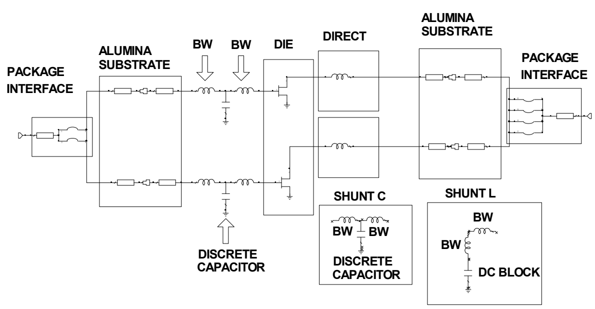

Figure 1. Hybrid transistor output matching topologies

Figure 1 above details the three discussed topologies. Simulations of the different realizations are shown in figure 2 and summarized in table 2.

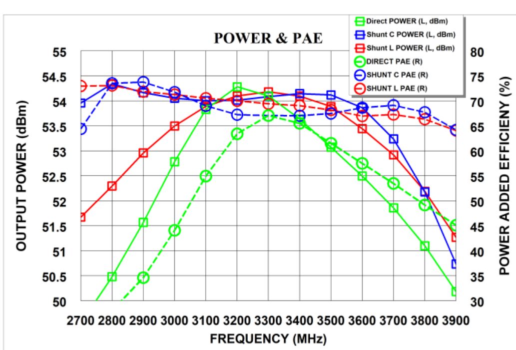

Figure 2. Simulations comparing the relative bandwidth of three different matching topologies

	RF Performance					
	Power (dBm)			*PAE (%)*		
Freq. (GHz)	3.1	3.3	3.5	3.1	3.3	3.5
Shunt C	54.0	54.1	54.1	69.0	67.1	67.5
Shunt L	53.9	54.1	53.9	70.5	69.7	68.2
Direct	53.8	54.1	53.1	55.6	67.1	61.5

Table 2. Comparison of performance of different topologies

The Shunt-C topology was selected for this design as it gave best performance over the desired frequency band as well having the same topology for both input and output match.

C. *Detailed Design of CGH35240F*

The detailed design of the circuit was performed using the Microwave Office design environment. Electromagnetic (EM) simulations of the alumina substrates, capacitors and package interface were used to ensure that all coupling effects were accounted for. Bond wires were simulated using the standard AWR model [3]. The capacitor was modeled as a 16 port single layer dielectric structure. The input and output alumina substrates design were first simulated using simple transmission line models. The final iterations of the design were checked with full EM mode. Both input and output alumina substrates were designed to optimize the phase balance across the HEMT die. This was achieved by adjusting the feed structure and removing some metal. The phase balance across the manifold was improved from 11 to 3 degrees.

The integrated design environment allows for a visualization of the complete hybrid assembly. This attention to layout based design has been proven to provide the best chance of first pass success [4]. Figure 3 shows the full hybrid amplifier model.

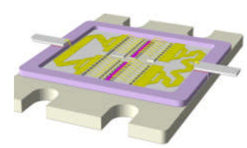

Figure 3. Layout view of power transistor

D. *Measured and Modeled Performance*

The device was characterized in a test fixture designed for pulsed condition. A pulse width of 300us and 20% duty cycle was used for all large signal testing. The agreement between the large signal model is excellent considering the complexity of this hybrid design using a total GaN HEMT gate width of 57.6mm. Modeled and measured results are shown in figures 4 and 5.

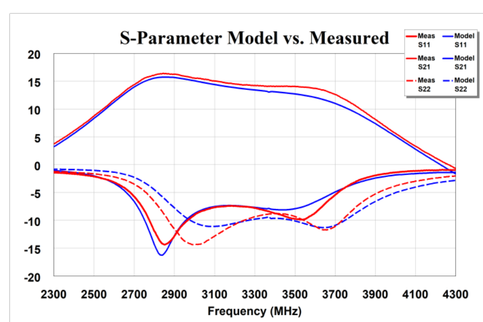

Figure 4. Small signal performance of CGH35240F

In summary the CGH35240F product design achieved excellent performance characteristics with output power greater than 220 Watts with a power added efficiency of better than 55% over the full 3.1 to 3.5 GHz band.

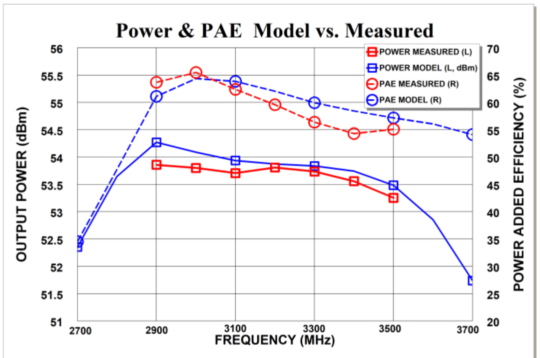

Figure 5. Large Signal performance of CGH35240F

III. Thermal and Stability Performance Considerations for a 240W Hybrid Transistor

A. Overview of CGH31240F

The CGH31240F was designed as an output stage to cover the 2.7 to 3.1 GHz part of S-band for civilian marine and aviation radar systems. Design of this hybrid transistor followed the same flow as the previously described transistor. The CGH31240F also combines two 120 W GaN-on-SiC die to generate 240 W when using a 300 us and 20 % duty cycle. The excellent thermal properties of GaN-on-SiC allow the device to maintain its performance over a wide variety of pulse widths and duty cycles [5]. Typical performance characteristics can be seen below in figure 6.

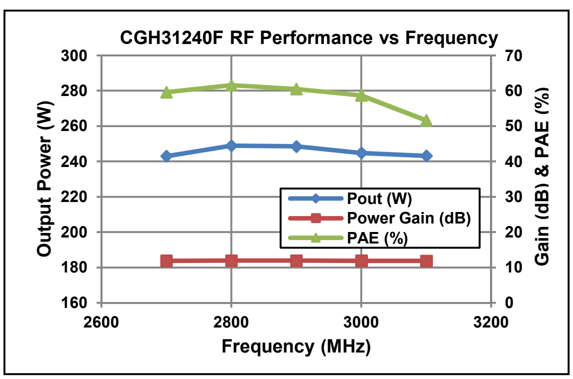

Figure 6. Typical performance of CGH31240F

B. Thermal Attributes of GaN based Radar Products

ANSYS Thermal was used to determine the thermal resistance of the device over various pulse widths and duty cycles. These results were verified with IR results using a Quantum Focus Thermal Imaging camera [6]. It can be seen in figure 7 that there is a dramatic reduction in thermal resistance when operating under pulsed conditions compared with continuous wave (CW) operation. This is due to the excellent thermal properties of GaN-on-SiC technology. The theta-jc for a pulse width of 300 us and 20 % duty cycle of 0.5 °C/W allows the device to run up to a max case temperature of 150°C.

Thermal performance of solid state devices is well understood to be linked to the lifetime of any transmitter. In radar applications thermal performance is also important in terms of maintaining high output power throughout the length of a pulse.

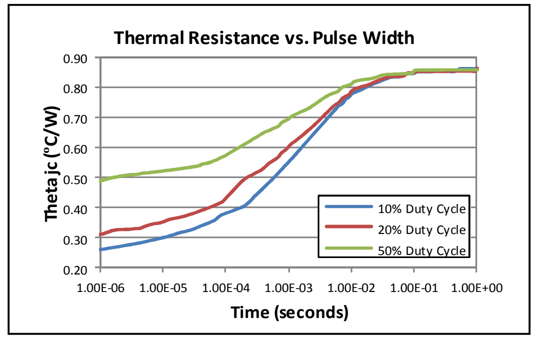

Figure 7. Transient thermal behavior of CGH31240F

It can be seen from the radar range equation [7] that the range of radar, R, is directly proportional to the total output power, P_t, of the transmitter

$$R = \sqrt[4]{\frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}}}$$

Given that radar systems use pulsed signals the output power of a system is then defined by how long a pulse and duty cycle the power amplifier can support. If the solid state transistor gets too hot during the pulse the power will drop versus time. This is normally referred to as pulse droop. This droop is of course affected by the thermal response of the device. With the low thermal resistance of the CGH31240F the droop is less than or equal to 0.6 dB even for a pulse width of 5ms of less and a duty cycle of 25 % as shown in figure 8.

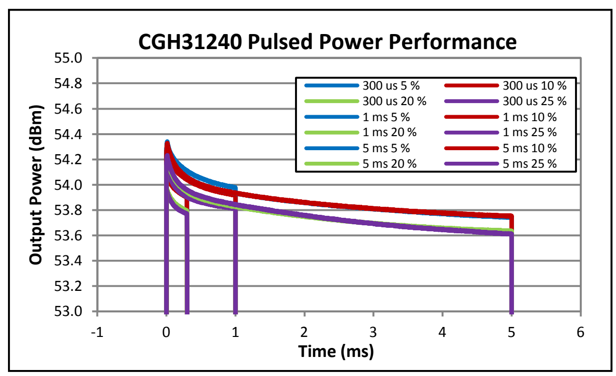

Figure 8. Amplitude droop performance of CGH31240F

C. Stability

All three product designs presented in this paper are fully matched to 50 ohm. This places an important requirement on the designer, that of stability. Given that there is no additional matching required at the system level it would be difficult to affect the stability of the transistor, the only tool to do so would be to add series resistance into the input network. This would be very undesirable since this would simply degrade the system performance by adding unnecessary loss. One of the design goals of these radar products was to achieve a very small size and high performance simultaneously. This required the use of high Q matching networks and a careful trade of performance versus stability. To improve device stability with the 240 Watt hybrid designs a high pass low frequency stabilization network consisting of a 511 Ohm resistor and a 6.8 pF capacitor was included on the input RF trace of the supporting test fixture. A 5.1 Ohm resistor was also included in the gate bias circuit to mitigate the high amount of low frequency gain associated with GaN HEMTs. The impact of these stabilization networks can be seen in figure 9 below.

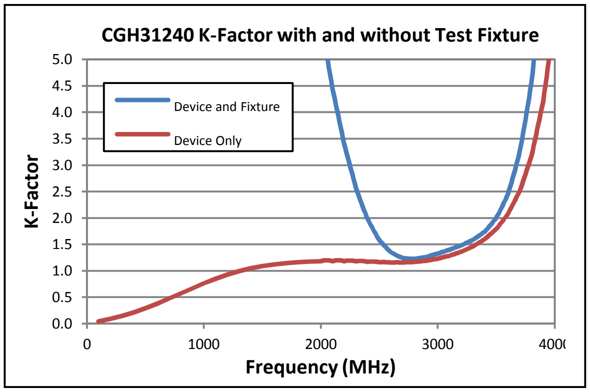

Figure 9. K-Factor analysis of CGH31240F.

IV. Characterization of a Radar Power Amplifier

A. Overview of CMPA2735075F

Cree has developed a 75 W S-band MMIC based amplifier to act as an output stage of a phased array radar system or as a driver for higher power fixed antenna systems. The MMIC uses a two stage reactively matched design to enable wide bandwidths and achieve the output power, gain and efficiency requirements for the desired application.

The amplifier has an associated gain of 21 dB and typical output power of 75 W and PAE of 55 % from 2.7 to 3.5 GHz. The MMIC and alumina substrates are attached to a metal carrier which is only 12.5 x 12.5 mm. The pulsed RF pulsed power droop of less than 0.6 dB at a 5 ms pulse with 25 % duty cycle is evidence of the state of the art thermal characteristics and power density of the two stage MMIC.

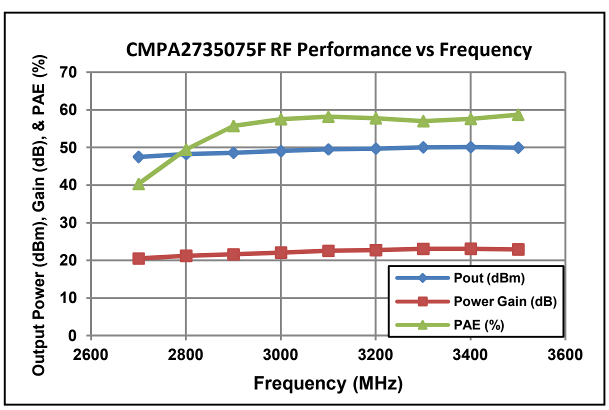

Figure 11. Typical performance of the CMPA2735075F

The gate, drain and input power pushing factors were also measured on this MMIC. The gate and drain pushing factors [8] describe the sensitivity of the output power of the device due to changes or noise on the gate or drain bias lines, while input power pushing characterizes the output power changes due to noise from the input power. The radar system designer needs to know the typical change in magnitude and phase in output power from the noise in the bias supplies as well as the input power. Measuring these factors under a large signal RF and DC pulsed environment requires specialized measurement equipment like the Agilent PNA-X microwave network analyzer and a pulsed DC supply. Figure 11 shows the behavior of this MMIC based amplifier to changes in input power in 0.5 dB steps.

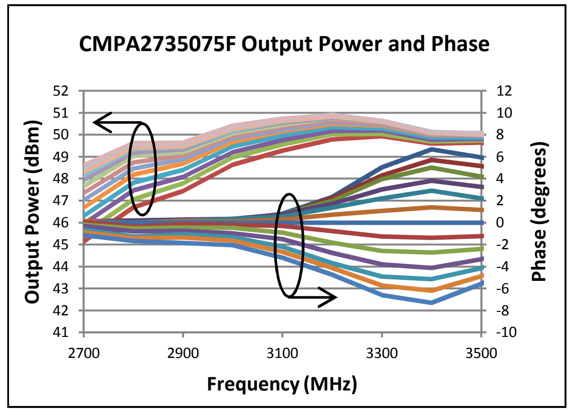

Figure 11. Variation in magnitude and phase due to changes in input power

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