Wideband Power Amplifier MMICs Utilizing GaN on SiC

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***Abstract* — The application of GaN on SiC technology to wideband power amplifier MMICs is explored. The unique characteristics of GaN on SiC applied to reactively matched and distributed wideband circuit topologies are discussed, including comparison to GaAs technology. A 2 – 18 GHz 11W power amplifier MMIC is presented as an example.**

***Index Terms* — broadband power amplifiers, MMIC power amplifiers, Gallium Nitride, Silicon Carbide.**

I. Introduction

The advantageous characteristics of GaN, particularly GaN on SiC substrates, for power amplifiers are well known and documented. These attributes include high breakdown voltage, current carrying capability, frequency of operation and thermal conductivity. The great majority of demonstrated power amplifier examples are narrowband. Here we consider the case of wideband power amplifiers, for the purposes of this discussion considered as instantaneous bandwidth of greater than both 1 octave and 10 GHz. A significant number of applications require large instantaneous bandwidths, particularly electronic warfare (EW) and an increasing number of communication systems. Those same high power density, frequency range and thermal conductivity characteristics that make GaN on SiC well suited for narrowband power amplifiers are also attractive for wideband amplifiers. However, the additional circuit constraints of wideband operation present additional challenges to the device technology.

Wideband power amplifiers using GaAs technology have been developed over the past two decades yielding commercially available 2-18 GHz distributed power amplifier topology MMICs [1] delivering > 1W and reactively matched topology 6-18 GHz MMICs [2] and [3] delivering 3W and 5W respectively. More recent publication of development work [4] has realized a non-uniform distributed power amplifier (NDPA) MMIC delivering > 4W over 4-18 GHz combining multiple NDPA sections and impedance transformation up to 50 ohms. GaAs-based wideband power amplifiers covering this frequency range must operate at a significantly lower voltage, 5 – 12 V in these examples, than GaN technology could allow.

What advances in wideband power amplifier performance will GaN-based technology enable? Recent work [5] has already shown significant improvements. As shown in Fig. 1 a GaN NDPA demonstrated a MMIC, Fig. 2, with > 8W and 20% power-added-efficiency (PAE) over 1.5-17 GHz utilizing a production 0.25um GaN on SiC process, [5]. This paper will show further improvement in wideband power amplifier performance and discuss the special considerations necessary for this application.

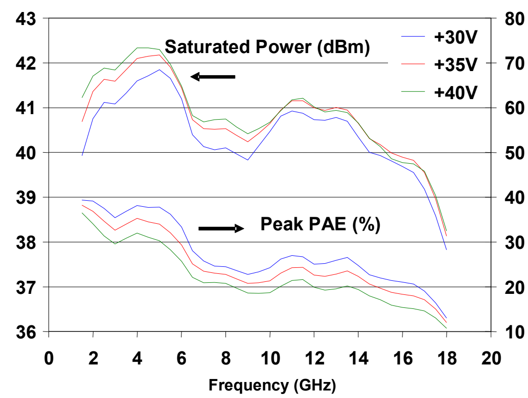

Fig. 1. Power Output and Power Added Efficiency of an 8W 1.5-17 GHz GaN on SiC Non-uniform Distributed Power Amplifier.

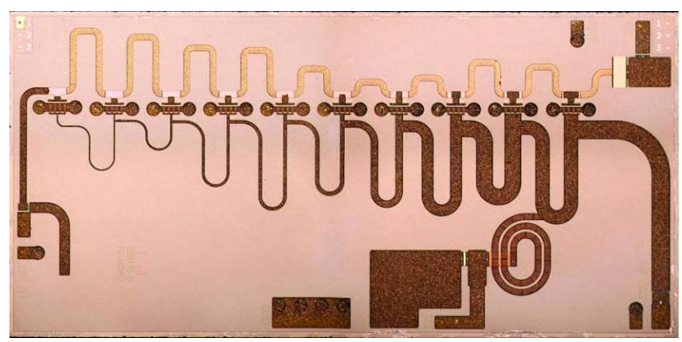

Fig. 2. Photograph of 8W 1.5-17 GHz GaN on SiC Non-uniform Distributed Power Amplifier.

II. The GaN on SiC MMIC Process

Wideband power amplifiers of this frequency range require implementation in an MMIC process with suitable passive elements in addition to the GaN transistors. Each of the appropriate circuit topologies require low interconnect parasitics, precise control of low loss capacitance and inductance elements and suitable voltage and current handling. These are supported well with an MMIC process incorporating three metal levels, air bridge interconnect, three capacitance densities and through-substrate plated vias which can be implemented directly under capacitors. The substrate is thinned to 100um. The capacitors in the process must be suitable for appropriate voltage levels and the metal layers for appropriate current levels for the high power capabilities of GaN transistor technology. The chosen GaN on SiC process implements capacitors of 1200, 300 and 240 pF/mm^2. Three independent interconnect metal levels of 0.7, 2.0 and 4.0um provide low loss interconnect and may be stacked to maximize current handling.

Active device power, efficiency and gain characteristics for this level of wideband power amplifier performance may best be assessed at the highest frequency of operation for the amplifier. GaN device performance as a function of drain bias voltage at 18 GHz from TriQuint's 0.25um GaN production process is shown in Fig 2.

Realizing improvement to the previously demonstrated results of [5] is aided by some improvements in the process specifically useful for this application. The DARPA WBG-RF phase III program is incorporating these improvements for the 2-20 GHz HPA development activities [6]. Desired improvements to active devices include higher gain @ 18GHz and greater voltage handling. To achieve the gain improvements, optimized gate and field plate geometries have been developed. Voltage handling is improved by a combination of both material and channel geometry. Maximum safe operating channel temperature is also improved through a combination of factors.

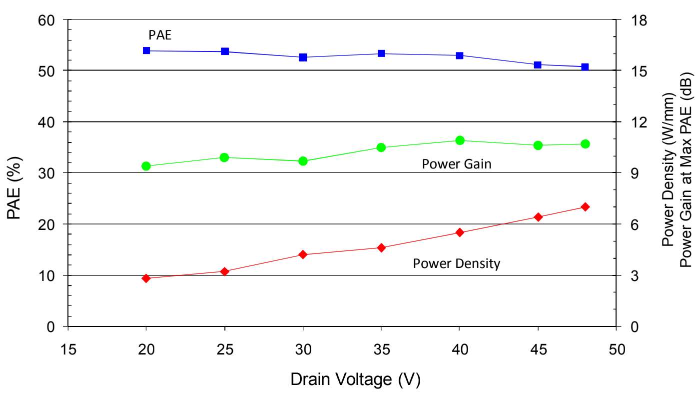

Fig. 3. 18 GHz load pull performance as a function of drain voltage for a 400um unit cell from the 0.25um GaN on SiC process.

III. Wideband Circuit Considerations

Two circuit topologies have successfully been used for GaAs pHEMT MMIC wideband power amplifiers (WBPA) as noted previously, [1] – [4]. The Non-uniform Distributed Power Amplifier (NDPA) topology has successfully demonstrated full decade bandwidths at power levels above 1W. Higher power levels but reduced bandwidths have been demonstrated with reactive matching techniques, such as the 2.5W 6-18GHz WBPA in [2]. The two approaches are well documented in the literature, and a detailed discussion will not be repeated here. There are some noteworthy points worth emphasis when applying either to GaN devices.

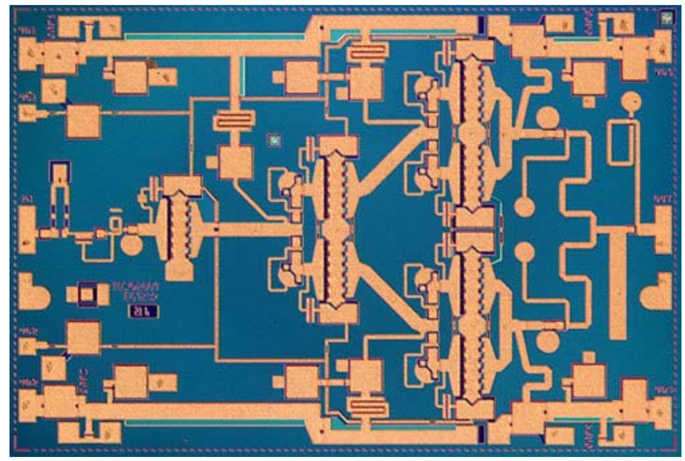

Fig. 4. Photograph of 3W 6-18 GHz GaAs reactively matched wideband power amplifier.

The reactive matching techniques are subject to the classic Bode-Fano limitation. A typical GaAs pHEMT operating at 6 to 8V may have an optimum load impedance of R_p~20-25Ω-mm and C_p~0.3pF/mm. A typical GaN HEMT operating at 30 to 40V may have an optimum load impedance of R_p~120-160Ω-mm and C_p~0.5pF/mm. Thus, an equivalent limitation will be observed for a 1.2 GHz instantaneous bandwidth in GaN as for 12 GHz in GaAs. Clearly, the reactive matching technique is not well suited to GaN WBPAs of the intended bandwidth.

The NDPA circuit topology, Fig. 4, is not subject to the same limitations. The capacitance of individual transistor cells is absorbed in the construction of a quasi-lumped element transmission line with series inductive elements provided by microstrip transmission lines interconnecting transistor cells in both the gate and drain artificial transmission lines. More details of this approach are described in [5].

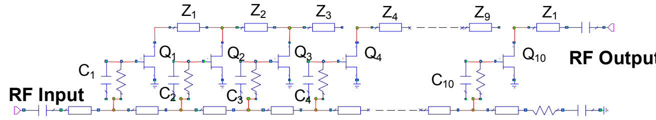

Fig. 5. Circuit topology for non-uniform distributed power amplifier (NDPA)

There are several noteworthy considerations to be emphasized. As the reactive components of the devices are absorbed into the artificial transmission lines, the remaining reactance approaches zero, the Bode-Fano bandwidth limit approaches infinity. However, impedance transformation is no longer realized. Consequently, the simple relation limiting output power by supply voltage and load impedance, V_d^2/R_L, becomes a dominant factor. Further limitations result from the need to present appropriate impedances to each transistor cell in order to realize maximum output power. As the number of transistor cells increases, the first cell must be loaded with an increasingly higher impedance for optimum power delivery. Increasing the operating voltage of the GaN devices, and thus the optimum load impedance, exacerbates this fundamental problem. The microstrip transmission line impedances available on the SiC substrate may not be high enough to provide the appropriate load impedances to the initial cells of the NDPA. Consequently, the practical bias voltage may be limited to less than the active device alone could accommodate. Another significant consideration is thermal management. Many applications for this type of amplifier require CW operation, so the circuits are designed to reliably accommodate that. At some point in the operating drive frequency and power level conditions for the amplifier, each of the unit cells will perform inefficiently, in some cases severely. The thermal design of the unit cell must accommodate the worst case conditions imposed by the circuit design and operating requirements. The conflicting motivation of minimizing cell area to periphery ratio is desirable to reduce parasitics and improve cell performance; which must now be done with careful thermal analysis and design.

III. DEMONSTRATED PERFORMANCE

The initial portion of the DARPA WBG-RF phase III program has demonstrated significant improvement in wideband 2-20 GHz power amplifiers. One such circuit uses the NDPA topology of Fig. 5. The MMIC is fabricated in the 0.25um GaN on SiC process described earlier. A photograph of the device is shown in Fig. 6.

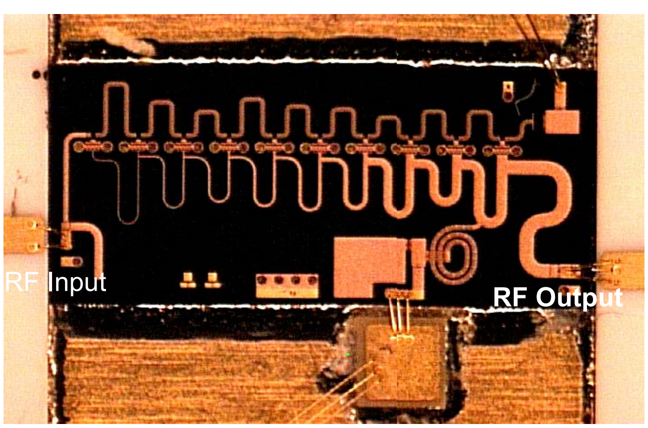

Fig. 6. Photograph of 11W 2-18 GHz GaN Non-uniform Distributed Power Amplifier.

The resulting device delivers a minimum 11W, average 14W Pout with an associated minimum 24%, average 28% PAE across 2-18 GHz with a bias voltage of 35V. Reducing the bias to 30V yields an average 1 point improvement in PAE but a 2 W reduction in output power. These results are shown in Fig. 7. Increasing the bias voltage to 40V provided a slightly higher peak power of 18W with no improvement in average output power. Efficiency was reduced an average 2 points and as much as 4 points. the band, and at some frequencies a reduction in output power as well. All the measurements referenced are CW.

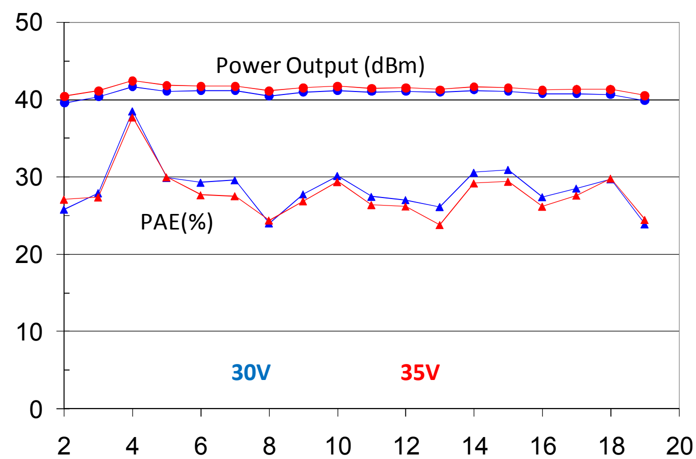

Fig. 7. Power output and associated PAE versus frequency for 11W 2-18 GHz GaN Non-uniform Distributed Power Amplifier at 30 and 35V bias.

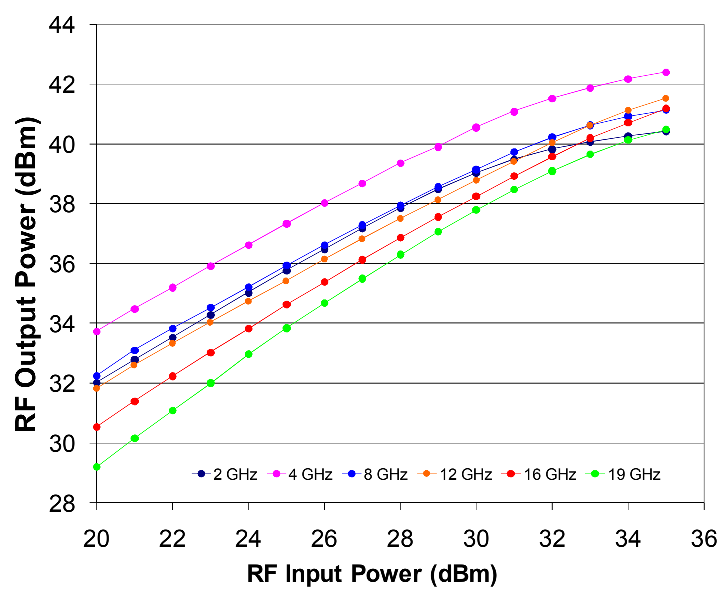

Fig. 8. Pout versus Pin characteristics at selected frequencies for 11W GaN Non-uniform Distributed Power Amplifier at 35V bias.

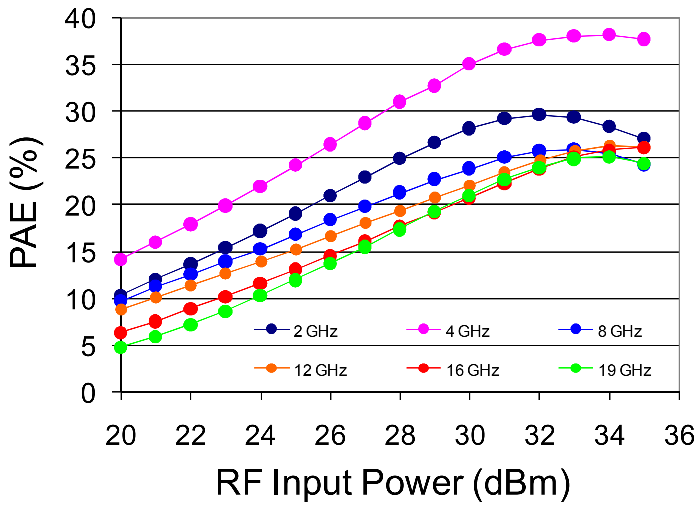

Fig. 9. PAE versus Pin characteristics at selected frequencies for 11W GaN Non-uniform Distributed Power Amplifier at 35V bias.

Power output and Power Added Efficiency as a function of input drive is shown in Figs. 8 and 9. In summary, these results represent more than a 35% increase in output power, a 4 point improvement in efficiency and an improvement in power flatness to +/- 1dB across a wider bandwidth of 2-18 GHz.

IV. Future Work

Further WBPA improvement can be achieved beyond the present results. Several process modifications have been identified to address characteristics highlighted in the NDPA development. Key among those in passive elements are higher impedance transmission lines and higher current handling capability for a given impedance level. Suspended microstrip lines may be implemented with posted airbridges toward this end. Increased gain and voltage handling at the device unit cell may be addressed by factors of gate length, field plate geometries, material specifications and cell geometry. Thermal management concerns may be addressed with unit cell layout, worst case power dissipation control and reliable tolerance of higher channel temperatures. Beyond the advances at the active and passive component level, further improvement at the overall circuit level may be achieved with more effective design tradeoffs, implementation and simulation. These factors and others are being addressed both in DARPA WBG-RF phase III and internal research and development activities.

V. Conclusion

GaN on SiC device and MMIC technology has been explored in the context of wideband power amplifiers. The two commonly used circuit topologies for WBPAs in GaAs pHEMT MMIC technology are evaluated for GaN devices, yielding only one, the nonlinear distributed power amplifier, suitable for GaN. Examples of the NDPA are discussed, with the latest result showing 35% increase in output power, 20% improvement in PAE and superior power flatness over a wider frequency range than prior reported results. The NDPA considerations discussed reveal the opportunity for further power amplifier improvement with changes to passive and active components in the existing GaN on SiC MMIC process. These improvements serve as the basis for future work pursuing higher power wideband amplifiers.

Acknowledgement

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