Broad-band Microwave Power Amplifiers in GaN Technology

K. Krishnamurthy, S. Keller, U.K. Mishra, M.J.W. Rodwell, S.I. Long
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106, USA.
Phone: 805-893-8044, Fax: 805-893-3262
Email: karthik@vsat.ece.ucsb.edu

Abstract— **We report lumped power amplifiers with > 4.4 W saturated output power over 2 – 8 GHz bandwidth in a GaN HEMT technology. Peak output power and *PAE* are 5.12 W and 21 % respectively at 6 GHz, under class-A operation. Also reported are GaAs MESFET / GaN HEMT cascode distributed amplifiers with 1 – 9 GHz bandwidth and with peak output power and *PAE* of 1.35 W and 14% respectively at 8 GHz.**

I. INTRODUCTION

PHASED -array radar and instrument applications require power amplifiers (PA) with high output power and power-added efficiency (*PAE*) over wide bandwidths. AlGaN / GaN HEMTs have high $f_\tau V_{br}$ products [1], and can provide high power at microwave frequencies [2], [3].

f_τ-doubler power amplifiers [4] have shown better gain-bandwidth product than simple lumped PAs, and higher *PAE* and smaller die area than distributed PAs. Cascode-delay-matched distributed power amplifiers [5] can provide gain-bandwidth product limited by the power-gain cut-off frequency, f_{max} with efficiencies up to the theoretical class-A limit of 50%. Since neither circuit requires high impedance lines which would limit the peak current, they are realizable for high output powers.

We had earlier reported power amplifiers based on these topologies in a GaAs MESFET technology [4], [5]. Here we report results of implementation in GaN HEMT technology.

II. f_τ-DOUBLER POWER AMPLIFIERS

0.75μm gate-length AlGaN / GaN HEMTs were fabricated on epitaxial material grown by MOCVD on C-plane sapphire. The layer structure and process details are discussed elsewhere [6]. Peak output power density of 3.92 W/mm and 36% *PAE* were obtained at 8 GHz (fig.1). Circuits were realized by flip-chip bonding the GaN HEMTs to 10 mil thick AlN substrates, which have the passives (NiCr resistors, Si_3N_4 capacitors) and CPW interconnects. The AlN substrate also provides a low resistance thermal path for efficient heat-sinking. The GaN die provides a second plane of wiring for cross-overs. The AlN substrates were bonded to a copper block using silver epoxy to provide a good thermal path.

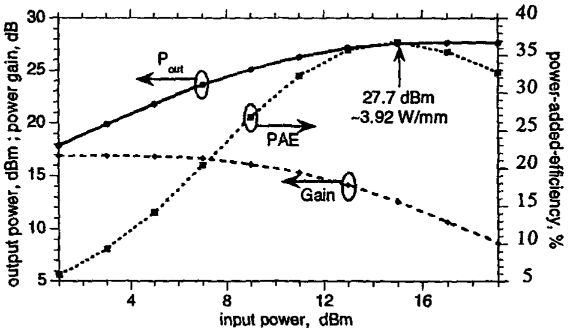


Fig. 1. Measured power performance of a 150 μm periphery device at 8 GHz.

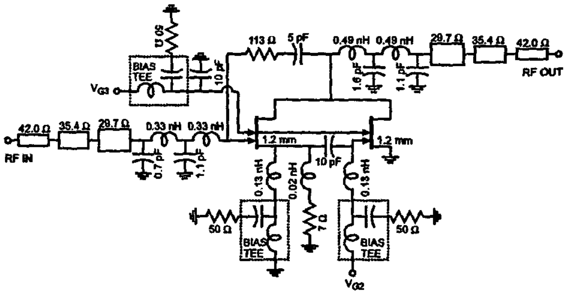
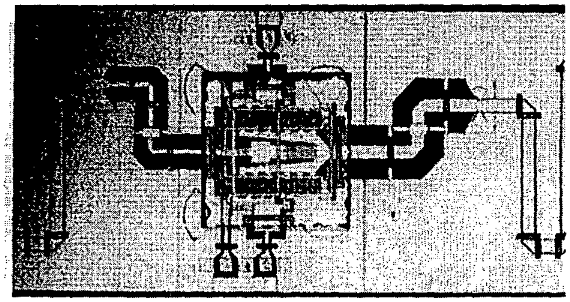


Fig. 2. Complete schematic of GaN dual-gate cascode f_τ-doubler resistive feedback power amplifier.

The f_τ-doubler PA [7] uses dual-gate devices with a net periphery of W = 2.4 mm (fig.2). Circuits were designed for 10 dB gain, 2 - 9 GHz bandwidth and 6 W output power. Capacitive division [8] and resistive feedback are used for varying gain and matching the input and output to 25Ω. Broad-band π-sections at the input and output improve matching. Inductances were implemented using a 90Ω CPW transmission line at the input and using a 75Ω line at the output to accommodate the higher current capacity at the output. A four-section quarter-wave transformer is used to transform to a 50Ω system. External bias tees were used to independently bias the two devices for maximum output power.



Die Area : GaN : 1.38 mm x 1.38 mm
AlN : 7.25 mm x 2.20 mm

Fig. 3. Die photograph of the f_T-doubler power amplifier.

The GaN and AlN die sizes are 1.38 mm × 1.38 mm and 7.25 mm × 2.20 mm respectively (fig.3). Power measurements were done in a 50Ω system without any external tuning. Peak output power and PAE are 5.12 W and 21 % at 6 GHz, under class-A operation at 28 V drain bias (fig.4). Saturated output power is > 4.4 W over 2 - 8 GHz (fig.5).

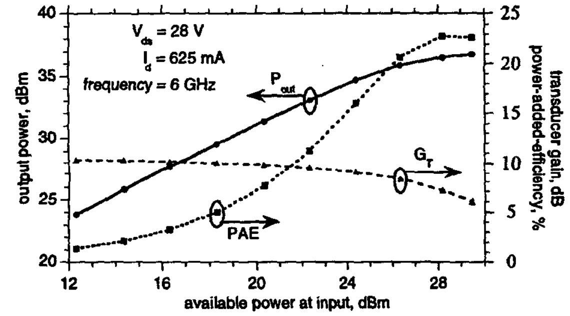


Fig. 4. Power performance of the f_T-doubler power amplifier at 6 GHz.

III. Cascode-Delay-Matched Distributed Power Amplifiers

Cascode-delay-matched traveling-wave amplifier (CDMTWA) [5] is a distributed amplifier having no output synthetic transmission line. The drain-line reverse wave is eliminated, and class-A efficiencies could be obtained. Delay equalization is instead provided by impedance-matched line (fig.6) between the common-source (CS) and common-gate (CG) devices within a cascode cell, where high impedance lines are not required. The equalizing line sections have delay increments of $\tau_s = \tau_g$, the loaded delay per section of the gate line.

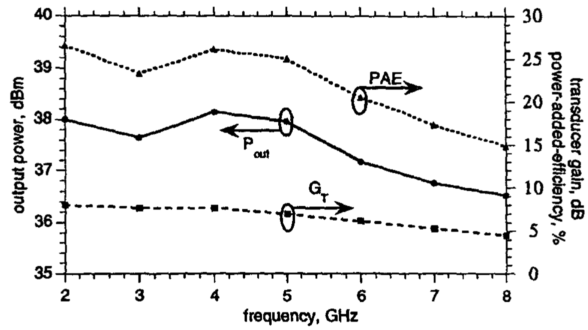


Fig. 5. Power performance of the f_T-doubler power amplifier from 2 - 8 GHz.

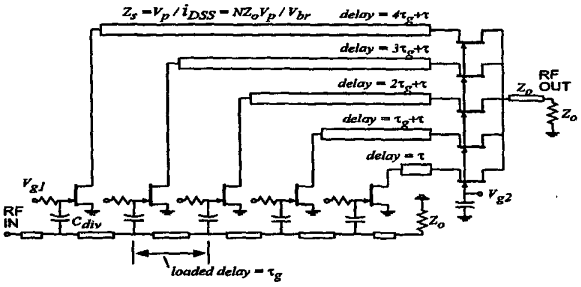


Fig. 6. Simplified schematic of GaAs MESFET / GaN HEMT cascode-delay-matched distributed amplifier.

Besides the higher efficiency the CDMTWA has other advantages. In a cascode cell most of the output voltage swing appears across the CG device. The CS device drives the gate-source junction of the CG device and has a peak-peak V_{ds} swing of V_p, while the CG device has a peak-peak swing of $(V_{br} - V_k)$. This allows the use of low breakdown and possibly high f_T devices for the CS distributed stage and a high breakdown device for the CG stage. Also since the inputs to the CG devices are phase and amplitude matched, and the drains are connected together, a single lumped large periphery device could be used. Thus the problems in power TWAs due to mismatch in load seen by the individual devices are eliminated. However the output capacitances cannot be absorbed into a synthetic drain line and the effect of output capacitance on bandwidth and efficiency is an issue.

A 10 cell cascode-delay-matched distributed power amplifiers was designed using GaAs MESFETs from Triquint's TQTRx process ($W = 3$ mm) for the CS distributed stage and GaN HEMT ($W = 2$ mm) for the lumped CG stage. As most of the output voltage appears across the CG device, GaAs MESFETs with $V_{br} \sim 12$ V are sufficient for driving the CG GaN HEMT. The gate line impedance of 90Ω was used, with a gate line Bragg frequency of 13 GHz. Interstage delay matching was done using 60 Ω lines to match to the input impedance of the CG device. To partially absorb the parasitics of the lumped CG device, inductive networks were used at its source and drain.

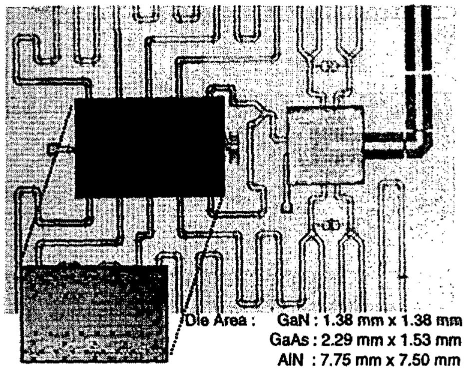


Fig. 7. Die photograph of GaAs MESFET / GaN HEMT cascode-delay-matched distributed amplifier (GaAs MESFET die shown as inset).

The GaAs and GaN dice are flip-chip bonded to the AlN substrate (fig.7). The GaAs die has the MESFETs, biasing resistors and capacitors. The GaN die contains only the HEMTs. All CPW transmission lines, matching networks and additional bias and termination resistors and capacitors are on the AlN substrate. Air-bridges are used for connecting ground planes in the CPW layout. For regions under the bonded dice, metalization on the die along with the bump bonds are used as cross-overs. The die area for the GaN HEMT, GaAs MESFET and AlN dice are 1.38 mm × 1.38 mm, 2.29 mm × 1.53 mm and 7.75 mm × 7.50 mm respectively.

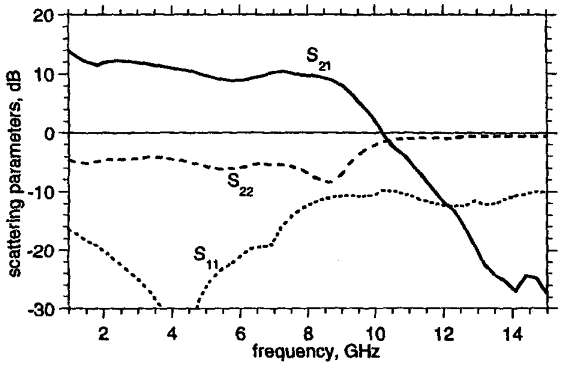


Fig. 8. Small-signal performance of the distributed amplifier.

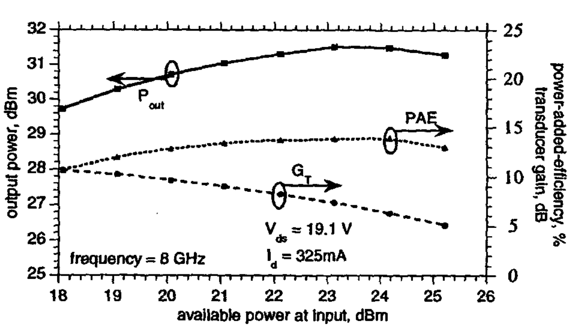


Fig. 9. Power performance of the distributed amplifier at 8 GHz.

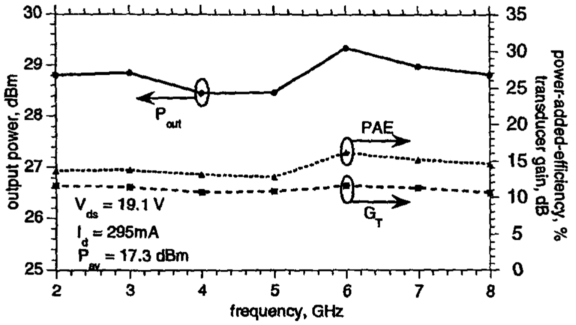


Fig. 10. Power performance of the distributed amplifier from 2 - 8 GHz.

Measured small signal scattering parameters at a drain bias of 15 V (fig.8) shows ~ 11 dB small-signal gain over 1 - 9 GHz bandwidth with input reflection coefficient lesser than -10 dB. At a reduced drain bias of 19 V, peak output power and *PAE* are 1.35 W and 14% (fig.9). Over 2 - 8 GHz output power and *PAE* are > 28 dBm and > 10% with a flat gain of 11 dB (fig.10). Failure of GaAs MESFETs was observed beyond 19 V drain bias, possibly due to thermal or electrical breakdown. Though these output powers are far less than what is expected at higher bias voltages, they correlate well with 1.6 W maximum power expected from 25 V swings at this bias.

IV. CONCLUSIONS

GaN f_T-doubler power amplifiers achieve high power over a bandwidth of two octaves using a lumped circuit. 2 – 8 GHz power amplifiers with > 4.4 W saturated output power were obtained. Cascode-delay-matched distributed amplifiers incorporate GaAs MESFET and GaN HEMT devices to realize broad bandwidth and high power. 1 – 9 GHz power amplifiers with > 1 W output power were obtained. With better devices, improved thermal design, and better modeling, significantly improved performance could be achieved from these circuits.

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REFERENCES

[1] Y.-F. Wu., B.P. Keller, S. Keller, N.X. Nguyen, M. Le, C. Nguyen, T.J. Jenkins, L.T. Kehias, S.P. Denbaars, U.K. Mishra, "Short channel AlGaN/GaN MODFETs with 50 GHz f_T and 1.7 W/mm output power at 10 GHz", *IEEE Electron Device Letters*, Sept. 1997, vol. 18, no. 9, pp. 438-440.

[2] Wu Y.-F., et. al., "3-watt AlGaN-GaN HEMTs on sapphire substrates with thermal management by flip-chip bonding", *56th Annual Device Research Conference Digest*, Charlottesville VA, June 22-24, 1998.

[3] Y-F. Wu, B.J. Thibeault, J.J. Xu, R.A. York, S. Keller, B.P. Keller, U.K. Mishra, "GaN HEMTs Grown on Sapphire Substrates for Microwave Power Amplification", *IEEE 1999 Device Research Conference*, 1999, pp. 50-51.

[4] K. Krishnamurthy, M.J.W. Rodwell, S.I. Long, "A > 25% *PAE* 0.2 - 6 GHz Lumped Power Amplifier in a 18 GHz MESFET Technology", *IEEE 1999 GaAs IC Symposium Digest*, Oct. 1999, pp.81-84.

[5] K. Krishnamurthy, S.I. Long, M.J.W. Rodwell, (Edited by: M. Matloubian, E. Ponti), "Cascode-Delay-Matched Distributed Amplifiers for Efficient Broadband Microwave Power Amplification" *IEEE 1999 Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest*, 1999, pp. 819-822.

[6] B.J. Thibeault, B.P. Keller, Y-F. Wu, P. Fini, U.K. Mishra, C. Nguyen, N.X. Nguyen, M. Le, "High Performance and Large Area Flip-Chip Bonded AlGaN / GaN MODFETs", *IEEE 1997 International Electron Device Meeting*, 1997, pp. 569-572.

[7] K. Krishnamurthy, R. Vetury, S. Keller, U. Mishra, M.J.W. Rodwell, S.I. Long, "Broadband GaAs MESFET and GaN HEMT power amplifiers", to be published in *IEEE Journal of Solid State Circuits*, Sep. 2000.

[8] Y. Ayasli, S.W. Miller, R. Mozzi, L.K. Hanes, "Capacitively coupled traveling-wave power amplifier" *IEEE Transactions on Electron Devices*, vol. 31, (no. 12), 1984, pp. 1937-1942 .