A 3-10 GHz LCR-matched Power Amplifier using Flip-Chip Mounted AlGaN/GaN HEMTs

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ABSTRACT

We report a GaN-based broadband power amplifier using AlGaN/GaN-HEMTs, grown on sapphire substrates, as the active devices. The circuit topology used novel LCR-matching networks in a 4-way binary-Wilkinson combiner structure. The devices were flip-chip bonded onto the AlN circuit for thermal management. Using devices with 0.7-μm gate length and 4-mm gate width, a small-signal gain of 7 dB was obtained with 3-10 GHz bandwidth. The saturation power level was 8.5 W at 8 GHz, which is the highest for a power amplifier using GaN-HEMTs-on-Sapphire.

I INTRODUCTION

GaN HEMTs have enormous potential for realizing high-power solid-state amplifiers at microwave frequencies. GaN epitaxial layers can be grown either on SiC or single-crystal sapphire (Al_2O_3) substrates. Sapphire has the advantage of lower cost and availability in larger wafer size than SiC, but it is a poor thermal conductor. GaN HEMTs on SiC have achieved a power density of 6.9 W/mm, while GaN HEMTs on sapphire have demonstrated 3.3 W/mm, and the difference is believed to be due to the higher thermal conductivity of SiC over sapphire. However, by paying close attention to thermal management, GaN-HEMT-on-Sapphire can have competitive performance. In particular, adequate thermal management can be achieved through flip-chip bonding of the device onto a thermally-managed substrate, such as ceramic Aluminum Nitride (AlN), which also hosts the matching networks and combiner networks. Using this technique we have demonstrated single-device results of 4.4 W output power (CW) with a 1mm-wide GaN HEMT on sapphire (Fig. 1). In this paper, we present the results of an ongoing effort at UCSB to realize high power, broadband microwave amplifiers using such flip-chip mounted GaN devices.

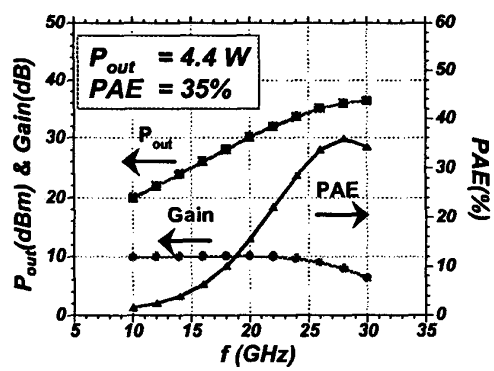

Fig. 1. Power performance of a 1-mm-wide GaN-HEMT-on-sapphire. (L_g = 0.7μm, W_g = 1 mm, f = 8 GHz, biased at V_{ds} = 27V, class AB mode)

II AMPLIFIER DESIGN AND FABRICATION

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We have previously reported a Modified Traveling Wave Power Amplifier circuit (TWPA)[1][2] for realization of wideband power amplifiers. This topology can achieve good input matching and gain flatness since it employs the input artificial transmission line technique of a conventional TWA circuit to accommodate the large input capacitance of the power HEMTs. Higher efficiency was achieved as compared with a conventional TWA by replacing the output artificial drain line with a more efficient corporate combiner structure, thus eliminating the "backward" wave. However, the frequency-dependent loss on the input artificial transmission line made it difficult to uniformly drive each device over the entire operating bandwidth, even using non-uniform capacitive division along the line. Such uneven input drive will reduce the efficiency and reliability of the circuit, especially at higher frequency of the band. In this study, we circumvent the problem by employing novel LCR matching networks and multi-section quarter-wave transmission lines to realize the input broadband matching.

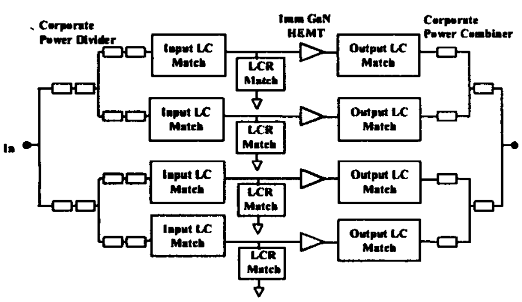

Fig. 2. Schematic of the 3-10 GHz LCR-matched GaN power amplifier.

The circuit schematic is shown in Fig.2. Due to difficulties in flip-chip mounting a large-area HEMTs device, our design used two separate 2mm-wide HEMTs, for a total of 4mm of gate periphery. A multistage corporate power divider and combiner were employed at the input and output, respectively, to distribute and collect power from these devices. The combiner networks used multiple-stage quarter-wave transformers to achieve the desired bandwidth and impedance transformation ratios (the desired impedance levels are naturally different at input and output). Input and output LC match networks were then utilized to reactively compensate for C_{gs} and C_{ds}, and provide additional impedance transformation. A lossy LCR network (reported in [3] for a single-device amplifier) was used at the input of the device to achieve the desired gain flatness over the design bandwidth.

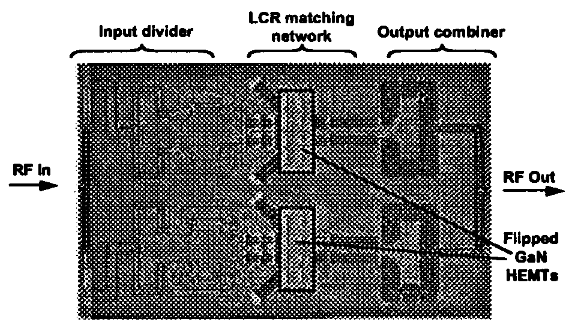

Fig. 3. Photograph of the fabricated amplifier.

The circuit was designed to operate over 3-11.5 GHz frequency range, with small-signal gain S_{21} of 8 dB, input match S_{11} of −10 dB and output match S_{22} of −6 dB. The GaN HEMTs used in this work were fabricated using Stepper lithography with a 0.7 μm gate-length, each gate finger length is 75 μm, and gate-to-gate spacing is about 50 μm. The device has characteristics of I_{max} = 1000 mA/mm, $g_{m\_intrinsic}$ = 320 mS/mm, V_{knee} = 5 V, $V_{pinch\text{-}off}$ = - 4 V, $V_{break\text{-}down}$ = 40 - 50 V. The current gain and power gain cutoff frequencies were about 20 and 40 GHz respectively. The optimum load for the maximum output power of the device was obtained from load-pull measurement using ATN LP1 system (fundamental tuning only), for

1mm-wide 0.7 µm-long device, $R_{opt} = 32\ \Omega$, $C_{ds} = 0.32$ pF. Due to the relatively low f_{max} and high C_{gs} of these devices, it proved more challenging to achieve the desired low input reflection throughout the bandwidth with this reactively-matched circuit topology as compared with the earlier TWPA design.

Fig.3 shows the photo of the finished amplifier, the circuit dimension was 12mm × 8mm. Fabricated on a 10-mil thick polished AlN substrate, the circuit components include NiCr resistors, MIM capacitors using SiN as the insulating layer, air bridges and two flipped 2mm-wide GaN HEMTs chips. All the device and ceramic circuit processing was carried out at UCSB.

III AMPLIFIER PORFORMANCE

Fig.4 shows the small-signal performance of the circuit. The measured S_{21} is about 7 dB with 3dB-bandwidth of 3-10 GHz. We expect to extend the bandwidth to above 11 GHz by shrinking the gate length to 0.6 µm. The measured S_{11} is less than –8 dB and S_{22} is less than –5 dB over the band; both are close to the simulation mentioned earlier.

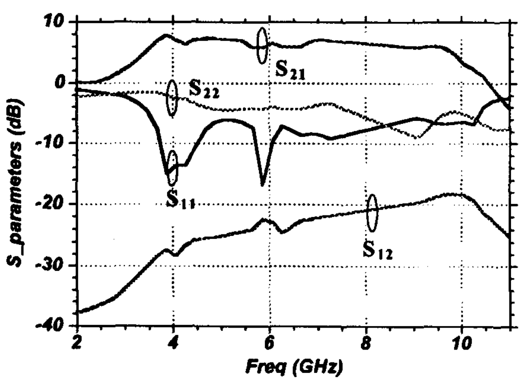

Fig. 4. Small-signal performance of the circuit.

Fig.5 shows the power performance at 8 GHz, when biased at V_{ds} =16 V, I_{ds} = 500 mA (class AB mode). We achieved output power of 8.5 W with power-added efficiency (PAE) of 20%. To our knowledge, this power level is the highest for a power amplifier using GaN-HEMTs-on-sapphire. The PAE is also improved by about 10% compared with the previous 1-8 GHz TWPA [1]. Power measurement over the whole bandwidth is not available due to the limit of the equipment. More detailed characterization is under way and will be reported in the symposium.

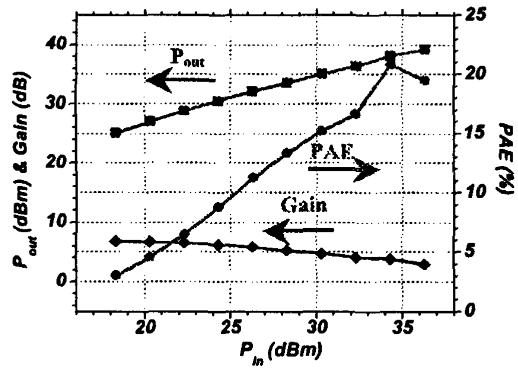

Fig. 5. Large-signal performance at 8 GHz.

CONCLUSIONS

We have successfully designed and fabricated a second-generation GaN-based broadband power amplifier with improved output power and power-added efficiency (PAE). Compared with the previous design of Modified Traveling Wave Power Amplifier (TWPA) topology [1], this LCR-matched circuit topology eliminates the problem of uneven input drive of the devices, The trade-off is the increased input return loss. The circuit had about 7dB small-signal gain with 3-dB bandwidth of 3-10 GHz, the input return loss was about –8 dB and output return loss was about –5 dB. At 8 GHz, the circuit was able to generate about 8.5 W output power using total of 4mm–wide devices which corresponds to more than 2 W/mm output power density. Although lower than 4.4 W/mm results using 1mm-wide devices, which is due to the increased complexity in thermal management and matching network as the device size increases, this power density is nonetheless about twice as high as what GaAs-based counterparts with the same size devices can achieve.

However, these initial demonstrations of GaN-based power amplifiers are still at very early stage and rapid progress is expected in the near future as GaN material and device technology matures.

ACKNOWLEGMENT

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