Broadband GaN HEMT Push-Pull Microwave Power Amplifier

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***Abstract*—We report a broadband, linear, push-pull amplifier that utilizes GaN-based HEMTs grown on SiC substrates. The high power density capabilities of these devices can be enhanced by the high efficiency achievable with push-pull operation. Good amplifier performance is facilitated by use of a new low-loss balun that is implemented with three symmetric coupled lines and which showed insertion loss of less than 0.5 dB per balun. The bias was injected through the baluns, thereby simplifying the amplifier design and reducing loss associated with dc decoupling capacitors. Using two 1.5 mm HEMTs with 0.35-μm gate length, a push-pull amplifier produced a small-signal gain of 8 dB at 5 GHz, a 3 dB bandwidth of 3.5–10.5 GHz, and a PAE of 25%.**

***Index Terms*—Balun, broadband, GaN, push-pull.**

I. INTRODUCTION

HIGH voltage and current bias of microwave wide bandgap GaN high electron mobility transistors (HEMTs) has resulted in power densities of 6.9 W/mm at 10 GHz and 9.1 W/mm at 8.2 GHz [1], [2]. Early GaN HEMTs were grown on sapphire substrates. Use of high thermal conductivity silicon carbide (SiC) substrates paves the way for higher power density amplifiers. These devices are, therefore, candidates for compact, light-weight, and high power amplifier systems. Recent applications of GaN HEMTs have included broadband Class A amplifiers, such as a monolithic distributed amplifier [3], an amplifier with distributed input and corporate output combining that employed flip-chip bonded devices [4], and an amplifier with LCR-matching having an input power splitter and an output combiner [5]. In all of these amplifiers, the power-added-efficiency (PAE) is rather poor, due in part to the immature device technology, but also due to designs based on linear Class A operation. Many applications require high power, high efficiency linear amplifiers, i.e., push-pull amplifiers [6]–[9]. Push-pull Class B operation can yield higher PAE, reduced sensitivity to source grounding, and direct drive capability for antennas requiring balanced feeds. Also, thermal dissipation can be significantly reduced with Class B operation. To date, the challenge of realizing low-loss microwave baluns and the more complex biasing and testing has impeded the widespread application of push-pull amplifiers.

Manuscript received March 7, 2001; revised July 6, 2001. This work was supported by the Office of Naval Research under Contracts N0014-99-C-0172 and N00014-98-1-0371 (John Zolper). The devices were fabricated by Cree, Inc., under contracts from ONR (N0014-99-C-0172, John Zolper) and AFRL (F33615-99-2-1472, Tom Jenkins). The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

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Publisher Item Identifier S 1531-1309(01)08082-5.

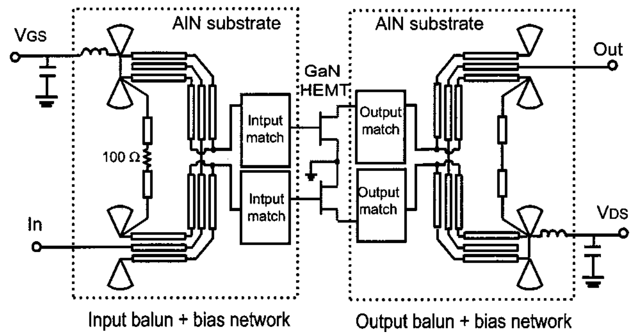

Fig. 1. Schematic of the push-pull amplifier with a new balun and biasing scheme.

We report the development of a broadband push-pull amplifier based on AlGaN/GaN HEMTs on SiC and having low loss baluns with an integrated biasing scheme. This circuit design could form the basis of linear amplifiers that will yield tens of watts of output power at high PAE. The new balun structure with integrated biasing can be also used for efficient power combining with multiple MMIC amplifiers, where discrete transistors are replaced with MMIC amplifiers [10].

dc isolation and bias injection through a conventional transformer-coupled amplifier have been utilized in push-pull amplifiers [11]. We demonstrate a comparably simple push-pull design based on a Marchand balun, which is preferred for low loss, broadband, and high frequency operation. The schematic of the balun-combined push-pull amplifier is shown in Fig. 1, illustrating two 1.5 mm GaN HEMTs as gain elements, three symmetric coupled line baluns for input and output 180° phase shifting, and integrated biasing elements. The radial stub provides the RF grounding for the balun resonators and also a suitable place for bias injection.

II. GaN HEMTs ON SEMI-INSULATING SiC

The device fabrication and dc and RF testing results have been reported previously [1]. The AlGaN/GaN HEMTs were grown on a semi-insulating SiC substrate. The amplifier used 1.5-mm periphery devices (12×125 μm) having 0.35 μm gate lengths and source ground via holes. These devices had a maximum of about 600 mA/mm drain current, an f_T of 26 GHz, and an $f_{\max}$ of 48 GHz. The devices were measured with Class B bias to determine a large-signal device model for the amplifier design. A power sweep yielded a power density of about 2 W/mm, a PAE of more than 48% and a gain of 12.5 dB at 4 GHz, when biased at $V_D = 18$ V, $V_G = -2.47$ V, and using input/output tuners.

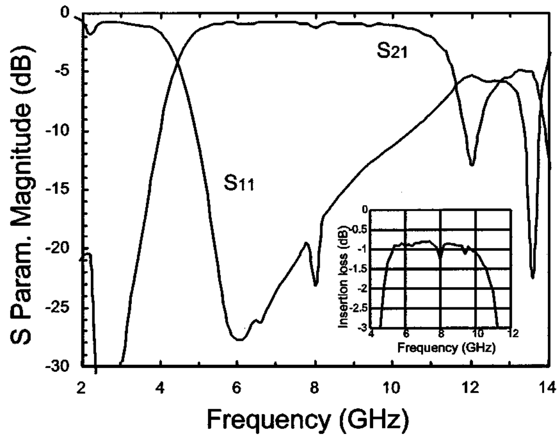

Fig. 2. Measured back-to-back performance for two cascaded baluns.

III. Low Loss Planar Broadband Balun Design

A low-loss balun is critical for microwave push-pull operation, and, for many applications, microstrip is the preferred transmission line. Broadband operation can be achieved using the reactance slope compensation proposed by Marchand [12]. Linear push-pull performance requires good amplitude and phase balance over several octaves in order to aid in even harmonic cancelation [6].

The initial design of a symmetric three-coupled-line balun was achieved using Agilent EEsof ADS [13]. The result was a balun having relaxed inter-line coupling by using three coupled lines rather than two lines, where the outer resonators are connected using air bridges. Analysis showed that the use of three symmetric coupled lines can achieve tight coupling with a relatively large 20 μm inter-line spacing, which is desirable for ease of fabrication. For high (bias) current, large conductor cross-section is needed. To achieve wide lines, a thick substrate was used [in our case a 380 μm high thermal conductivity AlN ($\epsilon_r = 8.5$) substrate]. The line widths were all 100 μm and the resonator lengths were 3500 μm; the complete coupled line lengths are twice this. The design achieved with ADS/LIBRA was verified using Agilent Momentum, a full-wave electromagnetic simulator. The influence of layout discontinuities was also evaluated numerically. A description of the balun synthesis and measurement details are given elsewhere [14]. The measured back-to-back balun performance, i.e., for two cascaded baluns, is shown in Fig. 2. The insert in Fig. 2 shows that the insertion loss is less than 0.5 dB per balun over 4.5–10 GHz, and the 3-dB bandwidth of the balun is 4.5–11.5 GHz.

IV. Amplifier Design and Fabrication

The balun that yielded the results of Fig. 2 was designed to transform from an unbalanced 50 Ω to a balanced 25 Ω impedance, in order to ease the matching requirements for high power devices. Additional input/output matching elements, realized by open-circuit stubs, were designed to be placed in the balanced transmission line between the baluns and the devices. The devices were not unconditionally stable, and the stability circles encroached into the Smith chart further at the lower frequencies. The matching networks were designed for good broadband performance, with consideration of stability, rather than for optimization of gain or PAE over a narrow frequency range.

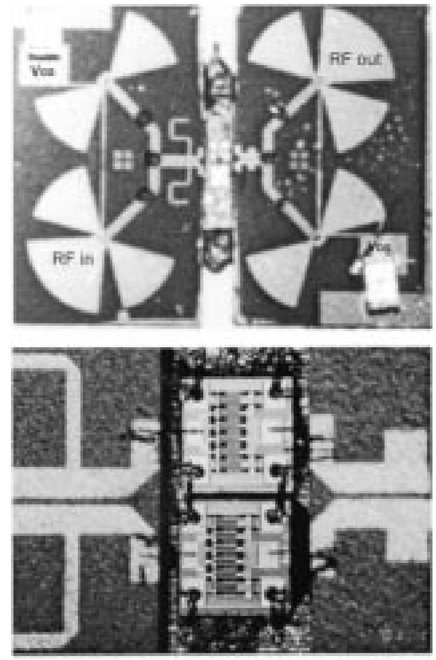

Fig. 3. Photograph of the fabricated amplifier and a detailed view.

HEMTs with source ground via holes were used. Wirebonds were used between the two devices. Additional wire bonds were placed to ground to further ensure source grounding.

The bias is injected through a radial stub, which also acts as the balun resonator RF ground. This scheme takes an advantage of the dc isolation provided by the coupled line structure and also eliminates the need for RF-dc decoupling capacitors. Using the high impedance line between RF ground points provided by the radial stubs, as shown in Fig. 1, dc bias is supplied to both active devices a with single bias injection. For stable biasing, a 100 Ω TiW resistor was included in the center of the high impedance shunt connection line of the input balun, and a 100 pF chip capacitor was used for additional RF bypassing in both the input and output baluns. This results in a balun structure with an integrated biasing network which provides both a simplified circuit design and lower loss.

The fabricated amplifier is shown in Fig. 3. A hybrid approach was taken, considering the rather large balun size for 4–12 GHz operation. The balun and input/output matching networks were fabricated on the AlN substrate, metallized with 2.5 μm-thick gold. There are additional radial stubs at the input and output to provide top-side RF grounding for on-wafer probing. An expanded view in Fig. 3 shows the wire-bonded HEMTs. Thermal-conducting epoxy was used to attach the HEMTs to the gold-plated brass fixture, and 1-mil Au bond wire was used for device to balun connection. Each substrate containing a balun and matching network is approximately 0.5 in by 0.4 in.

V. Measured Results

After amplifier dc testing showed the correct gate control of the drain current, RF characteristics were measured. The small-signal S-parameter results for the push-pull amplifier at $V_D =$

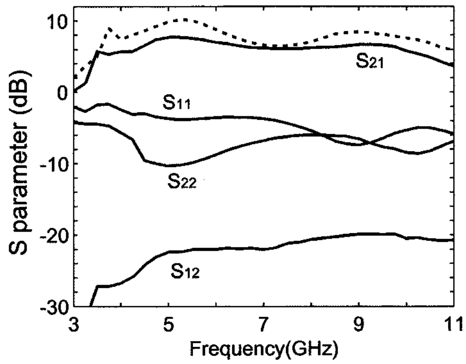

Fig. 4. Measured small-signal S-parameters. The dotted line is the simulated S_{21}.

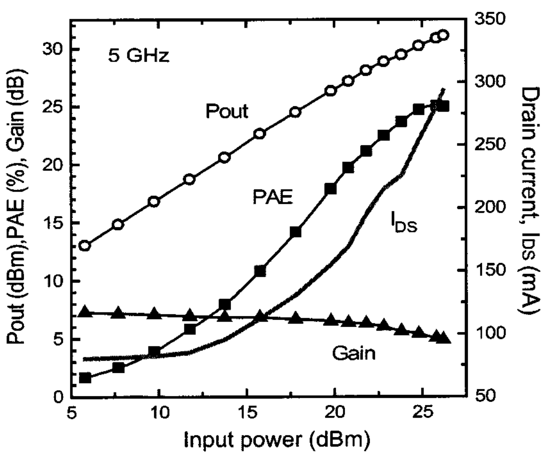

Fig. 5. Measured power sweep at 5 GHz in push-pull mode.

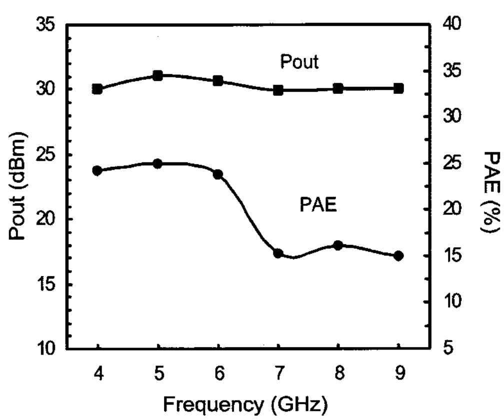

Fig. 6. Measured power output and PAE versus frequency at approximately the 2 dB gain compression point.

15 and $V_G = -3.5\ V$ are shown in Fig. 4. The gain at 5 GHz is 8 dB and the 3 dB bandwidth is 3.5–10.5 GHz, and the simulated S_{21} is shown as the dotted line. Fig. 5 shows the continuous wave (CW) power sweep at 5 GHz, with the HEMTs biased at $V_D = 12$ and $V_G = -3.6\ V$. With 26 dBm of input power, a PAE of 25% was measured. This corresponds to a PAE of 31% after the balun loss is de-embedded. The increase in I_{DS} with input power shown in Fig. 5 is characteristic of Class B operation. A sweep to higher power was not performed because of the limitation of the driver. Fig. 6 shows the output power and PAE measured at approximately the 2 dB gain compression point. The PAE ranged from 25% to 15% over 4–9 GHz.

VI. Conclusion

A broadband, push-pull amplifier based on GaN HEMTs on SiC has been demonstrated using a low-loss, planar, broadband balun. The concept of injection of the bias through the baluns was successfully demonstrated, thereby simplifying the amplifier structure and reducing the loss.

Acknowledgment

The authors wish to thank B. M. Green (Cornell University) for helpful discussion on the balun layout, M. Hargis (IBM) for fabrication information related to the AlN substrates, and S. T. Sheppard (Cree Inc.) for providing the GaN HEMTs.

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