

Power Combined Gallium Nitride Amplifier with 3 Watt Output Power at 87 GHz

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Abstract — Many terahertz frequency signal sources that are derived from frequency multiplication with Schottky diodes utilize W-band power amplifiers. In this report we present measured results for powered combined gallium nitride (GaN) W-band power amplifier modules. An individual module contains a single three stage GaN MMIC. GaN modules are power combined separately with 2-way and 4-way WR10 waveguide hybrid couplers to increase output power. At a drain operating bias of 12 V, the highest measured output power from a single MMIC module, 2-way power combined modules, and 4-way power combined modules are 0.78, 1.29, and 2.28 W, respectively. Further increasing drain bias to 15 V on the 4-way power combined module produced 3 W peak output power. We discuss the GaN package module, the modular WR10 waveguide power combiners, the power characterization test set, and our measured results.

Index Terms — gallium nitride, W-band, MMIC, power amplifier, power combining.

I. INTRODUCTION

W-band power amplifiers are currently used in many high frequency local oscillator (LO) sources for terahertz heterodyne receivers to study molecular spectra. Information obtained can be used to remotely detect the presence and quantity of molecules, and to determine the pressure, temperature, and Doppler velocity of gases (see ref. 1 and 2 for a review of terahertz technology and applications). The availability of higher W-band power amplifiers can simplify future array heterodyne systems that will require more LO power, and enable new higher frequency radar and communication systems.

W-band power amplifiers have been largely developed from technologies such as gallium arsenide (GaAs) pseudomorphic high electron mobility transistors (pHEMTs) [3] and indium phosphide (InP) HEMTs [4]. Advances in gallium nitride (GaN) HEMTs have demonstrated W-band operation with output power density per unit gate width surpassing that

of GaAs and InP HEMTs by about a factor of 7.5 [5]. Recent progress in GaN amplifiers have now demonstrated output power over a watt level from single chip MMICs; 1.3 W at 75 GHz [6] and 1.7 W at 91 GHz [7] have been measured. By power combining MMIC chips in waveguide, earlier efforts using GaAs pHEMTs and InP HEMTs in an 8-way waveguide power combiner have demonstrated output power levels of 2.4 W and 2.24 W. These correspond to power density per unit gate width of the output PA stage of 0.23 and 0.175 W/mm, respectively [8]. Recent efforts in a 12-way radially power combined GaN PA produced 5.2 W at 95 GHz while operating the output stage at a power density of 0.72 W/mm [9]. In this effort, we report on a 4-way power combined GaN PA that resulted in 3 W of output power at 87 GHz with a higher output stage power density of 1.25 W/mm. These new GaN efforts demonstrate state-of-the-art W-band operation of GaN PAs with greater output power and greater power density capability than other compound semiconductor technologies that we are aware of to date. Additional benefits of GaN are that it is mechanically more robust and can operate at higher temperatures than GaAs and InP [10-12].

II. MMIC AND MODULE

The GaN MMIC chip we use has 0.15 μm T-gate length transistors with f_T and f_{max} of 90 and 200 GHz, respectively. The basic transistor unit cell consists of 4 x 37.5 μm wide gate fingers. The MMIC PA has three stages. Stage 1, 2 and 3 have 1, 2, and 4 transistor units each, respectively. Optimum

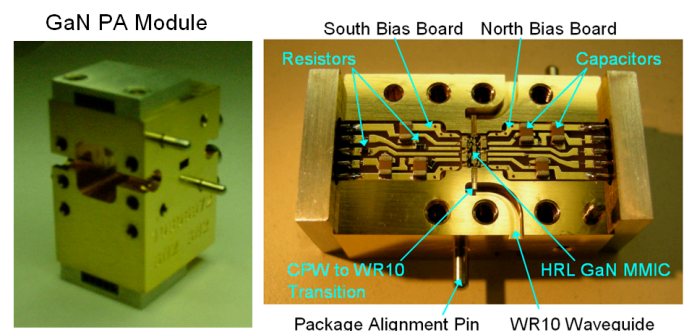


Fig. 1. The GaN PA module is a split block package with RF input and output WR10 ports compatible with MIL Spec MIL-F-3922/67B-010.

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gain 50 ohm inter-stage matching is used to minimize potential issues from uncertainties in the transistor model. The net output stage gate periphery is $600 \mu\text{m}$. The MMIC PA was designed and fabricated by HRL Laboratories under HRL internal research and development efforts [13]. The single chip GaN PA MMIC is packaged in a split block W-band amplifier module. The module has two separate bias boards for the drain (north side) and gate (south side) bias lines of the MMIC. Figure 1 shows the general layout of the package. The GaN MMIC chip resides in a cavity in which waveguide modes are ideally cut off. Off-chip bias line capacitors and resistors are added near the MMIC and on the DC bias boards for decoupling. The bias boards are fitted with a socket receptacle for easy connection to voltage bias supplies. For transmitting RF signal from the MMIC to the input and output WR10 waveguides of the module, microstrip to waveguide transitions are used. Wirebonds complete all chip to RF transitions and DC bias board connections.

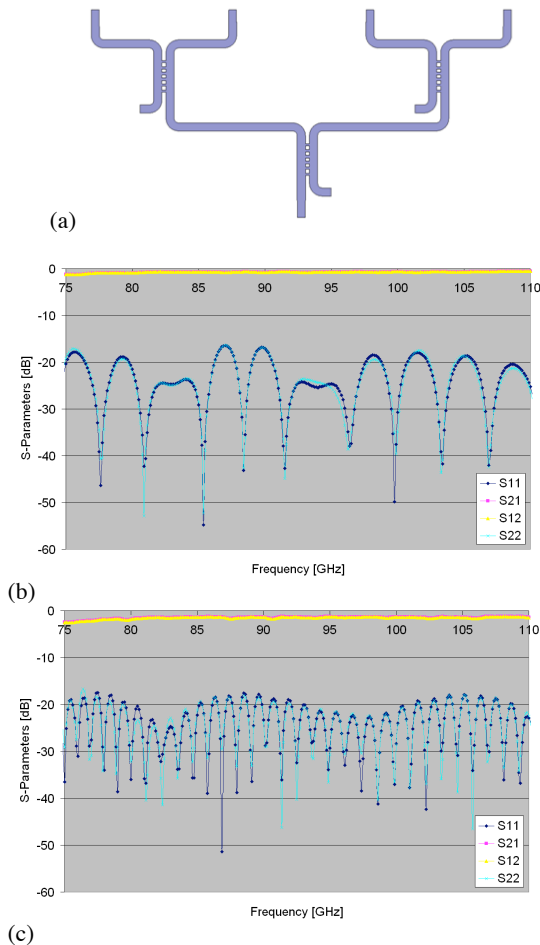


Fig. 2. Characteristics of the 2- and 4-way power combiners (splitters). (a) Diagram of the 4 to 1 port power combiner (splitter). Internal ports are terminated by matched absorber loads. The 2 to 1 port power combiner (not shown) is a special case of the 4 to 1 port design. (b) S-Parameters of the back-to-back 2 to 1 port combiners. (c) S-Parameters of the back-to-back 4 to 1 port combiners.

III. WAVEGUIDE HYBRID COUPLER POWER COMBINERS

The 2- and 4-way power combiners (splitters) examined in this study utilize waveguide hybrids [14] and are designed to function over the full W-Band. A waveguide hybrid is a four-port directional coupler. Ideally, power incident on any port is divided equally between two other ports with a 90° phase difference, and the fourth port is isolated. The waveguide form of quadrature hybrid consists of two parallel waveguides coupled through a series of apertures or branch waveguides. The number of waveguide branches determines the fractional bandwidth of the coupler. Hybrid couplers used as power splitters and combiners have an advantage over traditional waveguide Y-splitters in that the hybrid couplers are balanced and offer better return loss.

In the 2- and 4-way waveguide hybrid coupler power combiners (splitters), 6-branch couplers allow for full W-band (75-110 GHz) operation. The designs are optimized using a 3-D electromagnetic simulator (Ansoft's High Frequency Structure Simulator – HFSS) and Agilent's linear circuit simulator (Advanced Design System – ADS) using an iterative technique known as space mapping [15]. The parameters that are optimized in the two hybrid coupler designs are the amplitude and phase imbalance at the output ports and the return loss performance at all the ports. We designed the couplers to have less than ± 0.5 dB of amplitude imbalance and $90^\circ \pm 1^\circ$ phase shift over the entire W-band. Figure 2 shows the schematic of the 4-way hybrid coupler power combiner and measured S-parameters of both the 2- and 4-way combiners measured back-to-back in pairs. For the 2 to 1 hybrid coupler combiner measured back-to-back, insertion loss is less than 1.2 dB and return loss is greater than 16.4 dB across the band. For the 4 to 1 hybrid coupler combiner measured back-to-back, insertion loss is less than 2.5 dB and return loss is greater than 17.5 dB.

IV. POWER PERFORMANCE MEASUREMENTS

The power-in versus power-out (PiPo) characterization test set consists of a frequency multiplied signal source. An Agilent 20 GHz signal synthesizer is used as the initial signal generator. A Millitech sextupler is used to multiply the synthesizer signal to W-band frequency. Different custom JPL packaged PAs are used to provide adequate input test power at various W-band frequencies. A variable attenuator is used to change the test signal power level. An isolator is used to improve matching for the test PA output and the GaN PA device under test (DUT) input. Couplers allow for the input and output test signal power levels to and from the DUT to be sampled. An Agilent W-band and an Erickson broadband power meter monitor the input and output power levels of the DUT. A high power load terminates the output of the test set.

Output power as a function of frequency has been measured at various input power levels for the 2- and 4-way power combined GaN PAs that are constructed from multiple units of the single chip module. The power combined PA's saturated

output power increases while the unsaturated gain remains essentially the same as a single amplifier module except for slight losses due to non-ideal amplitude and phase combining, and passive losses in the combiner waveguides themselves.

The 2- and 4-way power combined GaN PAs are shown in Figures 3 (a) and 4 (a). Operating at 12 V drain bias, for the 2- and 4-way power combined GaN PAs respectively, the maximum output powers are 1.29 and 2.28 W; corresponding gains are 8.1 and 6.7 dB; and power added efficiencies (PAEs) are 13.7 and 11.2 %. The maximum output power achieved in this study is 3 W with 6.6 dB gain and 10.2 % PAE at 15 V drain bias with the 4-way GaN PA (see Fig. 4 (c)).

2-Way Combiner GaN PA Module

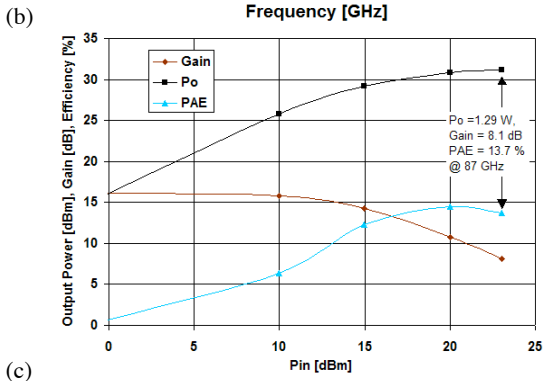
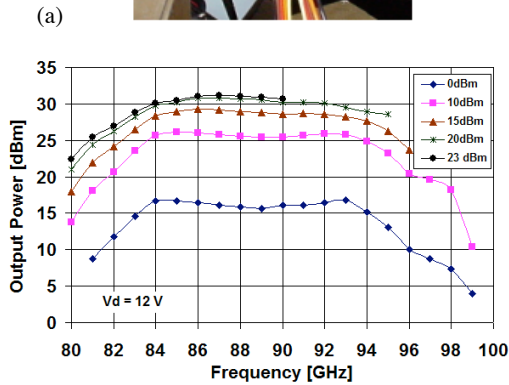
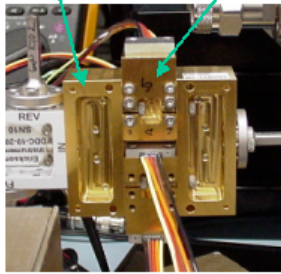


Fig. 3. 2-way waveguide power combined GaN PA results. (a) Photo of the power combined GaN PA. (b) Output power measured at input power levels of 0, 10, 15, 20 and 23 dBm as a function of frequency. (c) PiPo, gain and PAE of the 2-way power combined PA at 87 GHz.

4-Way Combiner GaN PA Module

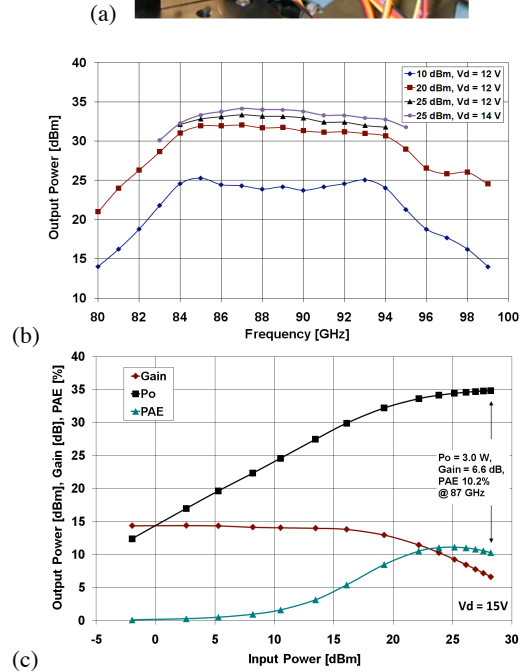
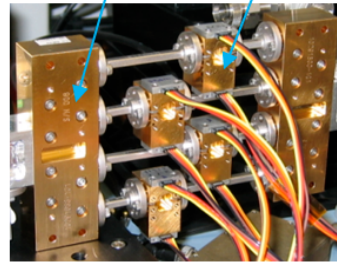


Fig. 4. 4-way waveguide power combined GaN PA results. (a) Photo of the power combined GaN PA. Individual amplifier modules are staggered with waveguide sections to prevent mechanical interference and are not intended to add any net phase shifts at the input of the power combiners. (b) Output power measured at input power levels of 10, 20 and 25 dBm as a function of frequency. (c) PiPo, gain and PAE of the 4-way power combined PA at 87 GHz.

V. THREE MONTH POWER-ON TEST

We examined the characteristics of a single MMIC chip module under continuous input power at ambient temperature. The amplifier was DC biased where the gain S21 is approximately optimized, peaking slightly at 86 GHz. For the extended time power-on response test, the amplifier is driven into compression with 22 dBm at 86 GHz. During the test, output power, input power, and the bias conditions of each of the three stages of the MMIC amplifier are recorded (see Fig. 5). Measurements indicate there is a settling time for the output power of the amplifier to reach a steady value from the initial power on value. The packaged amplifier MMIC was not subjected to a burn-in period prior to the test. Output power and also PAE show some fluctuations that coincide in time with drain current bias fluctuation changes. The cause of the drain current bias fluctuations is still under

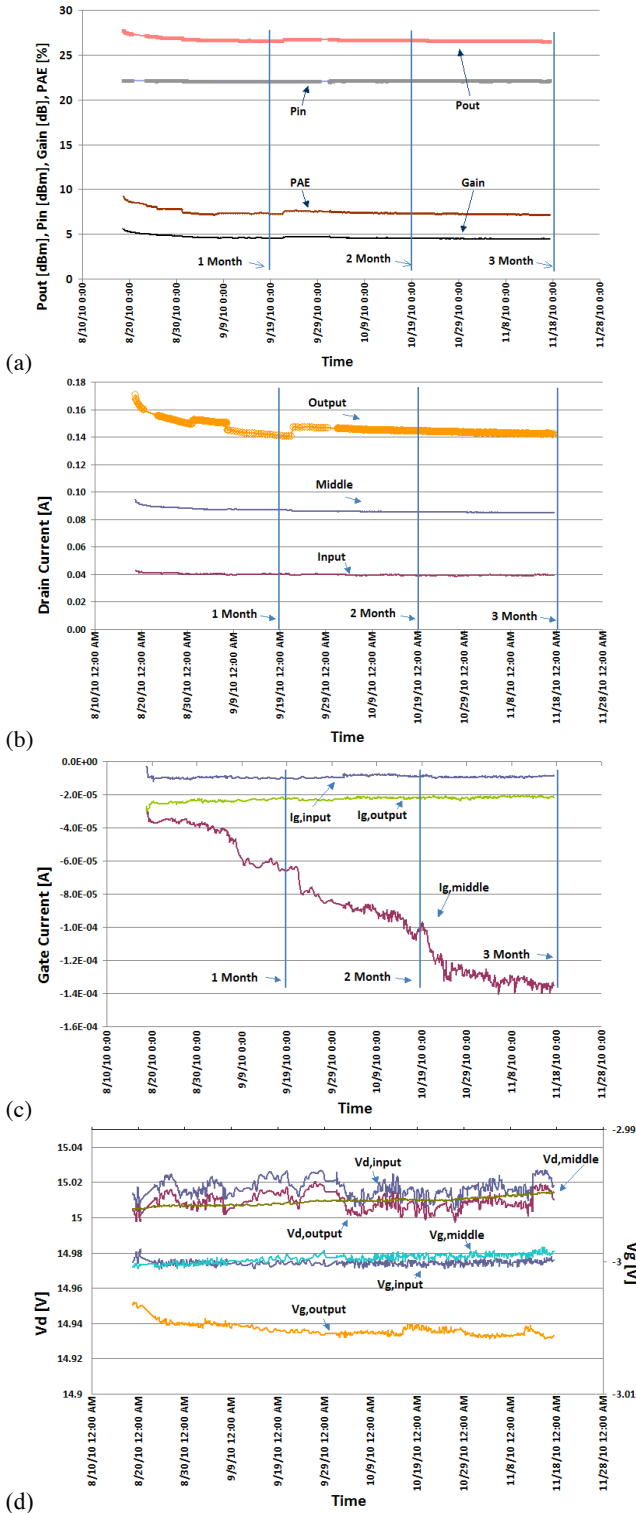


Fig. 5. Extended time power-on test results for a packaged single MMIC chip module. (a) Plot of output power, input power, PAE and gain versus time. (b) Plot of drain current of each of the three stages of the MMIC amplifier versus time. (c) Plot of gate current of each of the three stages of the MMIC amplifier versus time. (d) Plot of drain and gate voltage supply values versus time.

investigation. Gate current of the middle stage of the amplifier increases in magnitude while the input and output stages remain essentially constant during the three-month test. The output power level doesn't appear to be greatly affected by the measured bias changes and remains fairly constant after the initial settling period. The test data we present here is our first examination of extended power-on performance of one amplifier module. More effort in accelerated lifetime testing at elevated temperatures with additional test samples would benefit determination of mean time to failure (see ref. [10] for more discussions).

VI. CONCLUSION

We report results on waveguide power combined GaN MMIC modules for W-band operation. By power combining four GaN modules with waveguide hybrid couplers, a maximum output power of 3 W, with 6.6 dB gain and 10.2 % PAE was measured. An extended power on-test of three months duration was performed on a single MMIC chip module. After an initial settling period of the output power level and drain currents, the output power remained essentially constant. It is expected future W-band PAs will migrate towards GaN based semiconductors as the technology matures in terms of reliability and cost.

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