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**GaN WIDE BAND POWER
INTEGRATED CIRCUITS (PREPRINT)**

**J.P. Conlon, N. Zhang, M.J. Poulton, J.B. Shealy, R. Vetry,
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GaN Wide Band Power Integrated Circuits

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Abstract — Gallium Nitride (GaN) amplifiers have demonstrated very high power density as well as wide band width in previous research. This paper examines their use in supplying flat gain, power, and linearity across a large band width. It demonstrates two types of power amplifiers: a Ft Doubler (FT2) amplifier and a Cascode amplifier, both of which require a simple PCB tune. Both amplifiers show 0.2 to 4GHz bandwidth with 30 dBm P1dB output power. The 3GPP WCDMA output power is 20 dBm at -45 dBc ACLR.

Index Terms — Gallium Nitride (GaN), High Electron Mobility Transistor (HEMT), Linearity, Power Amplifiers, Software Defined Radio, Wide Band.

I. INTRODUCTION

GaN HEMT amplifiers have been of keen interest in recent years. Their inherent high voltage operation, high power handling capability and their accompanying high impedances offer much promise for use both in military and commercial telecommunications, especially when fabricated on high thermal conductivity substrates such as SiC [1]. In such applications, gain and power are often optimized, and the band widths of interest are relatively narrow compared to the potential of GaN, though they are wide compared to other technologies such as LDMOS.

GaN amplifiers have also been developed to address high linearity needs. The performance of a class B amplifier in standard double ended configuration is reported in [2] and a single ended push pull configuration is reported in [3]. The results showed that GaN could provide not only large gain and power but also good linearity in a wide band. Additionally, the use of flip-chip integration of GaN HEMTs mounted to SiC substrates which contain the necessary passive elements for amplifier construction has been demonstrated in [4].

Several methods to produce wide band GaN HEMT amplifiers are described in [5] – [8]. This paper investigates such wide band GaN amplifiers like Ft doubler (FT2) and Cascode amplifiers that provide not only flat gain and power over its operating band, but also flat linearity in the same band, which would be ideal for modern communication systems, regardless of modulation type that is employed. These wide band power amplifiers promise significant inventory reduction and cost saving as compared to multiple LDMOS or GaAs devices required to address the same bands. Furthermore, they enable seamlessly frequency hopping for emerging software defined radio applications.

The second part of this paper describes the construction of FT2 and Cascode amplifiers using discrete GaN HEMT devices and GaAs IPC (Integrated Passive Components) dice in an AlN SO8 package. The third part discusses measured results from the amplifiers, and is followed by conclusions.

II. AMPLIFIER DESCRIPTIONS

The amplifiers employed a hybrid construction: passive matching and stabilization components were made on GaAs dice (IPC process) and these dice were then wire bonded to discrete GaN HEMT dice to form the amplifier. By using these IPC dice, a large area of expensive SiC substrate is saved from a true MMIC configuration. Additionally, large quantities of IPC variations can be made for one amplifier to ensure the optimum performance. Finally, the turn time of the IPC process is much shorter than that for a GaN MMIC, thus enabling fast design iterations. In order for the devices to meet thermal requirements for continuous wave applications, high-K conductive epoxy was used to mount the devices to a high thermal conductivity AlN SO8 package that is also being used for higher power GaAs amplifiers [9].

The GaN ICs were unconditionally stable and were fully matched to 50 ohm to the package pins. The inherent high port impedances of GaN HEMTs enables simple, wide band matching structures: only DC blocking capacitors are needed on evaluation boards. The drain bias voltage Vdd was 28V.

(a) Ft Doubler Amplifier

The amplifier was constructed using two separate GaN HEMTs with an individual gate periphery of 2 x 400 um thus yielding 1600 um total gate periphery. This type of amplifier is a modified Darlington amplifier and it makes use of a common Vdd connection for each GaN HEMT as shown in Fig. 1a. The picture of a finished FT2 in package is shown in Fig. 1b. Its input stage is a common drain device whose source connects to the gate of the output device via a coupling capacitor and shunt resistor / inductor combination. The overall amplifier design was patterned after similar multi-die GaN FT doubler amplifier designs of K. Krishnamurthy [6] & [7] along with the inductive compensation of the feedback loop as suggested by Chung et.al. [8].

The function of the coupling capacitor and of the shunt resistor / inductor combination is to not only adjust the band width but also to ensure that stability is achieved and to ensure that each GaN HEMT contributes equal output power over as wide a frequency as possible so as to achieve flat gain, power, and linearity [6]

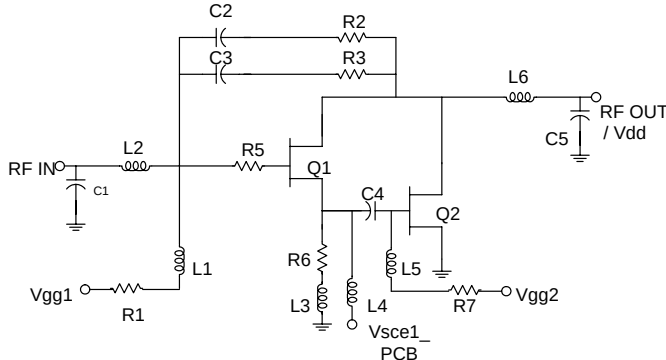


Fig. 1a. Ft Doubler amplifier schematic

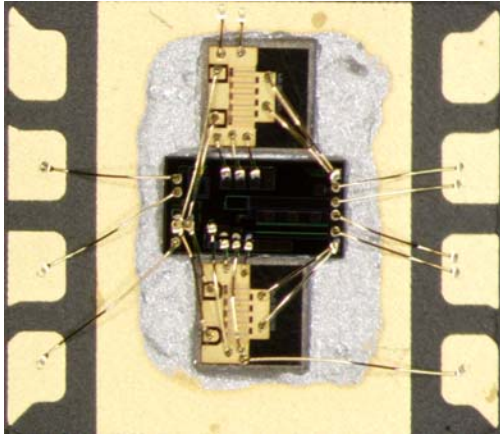


Fig. 1b. Ft Doubler amplifier photograph

This coupling capacitor value is chosen to be the same value as the C_{gs} of the following, output stage, accounting for any parasitic capacitances and stray inductances, so that the effective C_{gs} of the output stage is halved or nearly halved and its F_t is effectively doubled so that a wide, effective operating bandwidth may be achieved. This value is determined through both simulations and on-safer measured data for the $2 \times 400 \mu\text{m}$ stage GaN HEMTs. In so doing, band width is extended at the expense of gain, since the gain-bandwidth product must be maintained.

Additionally, the shunt series resistor and inductor combination values were selected so as to not only provide stability to the amplifier but also to provide equal or nearly equal distribution of power between the input and output FETs over frequency, in order to produce gain and output power as flat as possible across the frequency band:

$R = 2/G_m$ and $L = 2 \times C_{gs} \times R_i / G_m$ where G_m and C_{gs} are properties of the input HEMT, which is also the same as the output HEMT in this design. [6].

(b) Cascode Amplifier

This GaN cascode amplifier is basically two FETs stacked atop each other, such that the drain of the input FET connects to the source of the output FET. Thus, a common source amplifier feeds a common gate amplifier. Fig. 2 shows the schematic of a Cascode amplifier.

In the construction of this amplifier, all GaN HEMTs were constructed on one die, and two integrated passive dice were used along with this GaN die in order to construct the amplifier. The total gate periphery is $800 \mu\text{m}$. This cascode amplifier design offers a higher output impedance than other amplifier types, thus perhaps offering even wider band width potential than that of the FT doubler amplifier. As with the FT doubler amplifier, the drain voltage V_{dd} was 28 V.

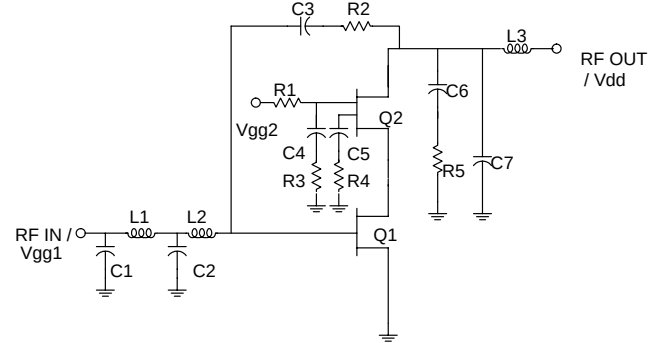


Fig. 2. Cascode amplifier schematic

Much attention was given to the proper on-die bypassing and stabilization of the output stage, as well as correctly biasing this output stage, since it is challenging to establish the best I_{dd} through the input FET and the output FET. In order to set not only the best output power but also the best dynamic range since for a given V_{dd} , the input FET voltage swing is limited by the V_{ds} of the output FET.

Yet perhaps an even larger challenge is ensuring that the input impedance of the common-gate second stage is zero, which is also the load to the first stage. In this case the load line is vertical and power transfer between stages is at a maximum.

Again for stabilization drain to gate negative feedback is used, along with several shunt resistive feedback structures, which sacrificed some gain for the resulting unconditional stability and wider band width. The input prematch is a two stage design, using low Q stages to further ensure a broad operating band width.

III. RESULTS

(a) FT Doubler Amplifier

All measured results were obtained using an evaluation PCB with AC coupling capacitors and a single shunt 0.5 pF capacitor in both the input matching network and the output matching network. The printed circuit board (PCB) is not shown.

The circuit is presented in Figure 1a. The dice were mounted to the AlN package die flag in the conventional active-side up configuration. A photograph shows a complete amplifier (Figure 1b).

The small and large signal results show the comparison between simulated results and measured results (Figure 1c). The major difference between the two data sets is a difference in gain, which is attributed to the package ground / mounting plane inductance. The chosen package, one made of AlN ceramic, provides a ground path through vias from the backside metal to the die mounting flag, and the inductance of these vias causes gain to degrade especially at frequencies higher than 2 GHz. This gain degradation leads to the use of a shunt 0.5 pF capacitor in the input match and also a shunt 0.5 pF capacitor in the output match, and the simulated and measured data both reflect the use of these two external parts.

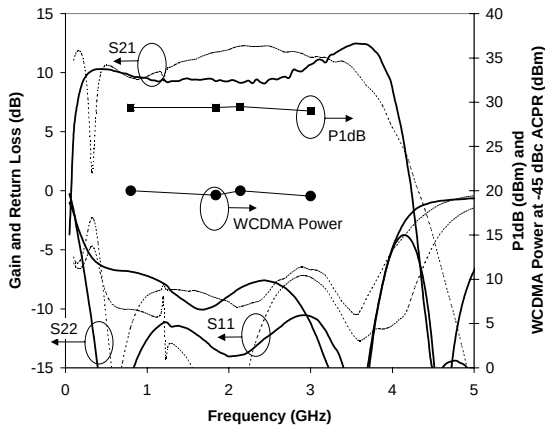


Fig. 2. FT Doubler amplifier small signal s-parameters and large signal data (solid lines are measurements)

The large signal data over frequency show that the compression point of nearly 1 W is very flat from 800 MHz to 3 GHz, as is the output power required for -45 dBc. The WCDMA 3GPP ACLR data shows some degradation at 3 GHz due to the 3.3 GHz upper limit of the signal generator. However, the s-parameters show the wider bandwidth that is available.

(b) Cascode Amplifier

All measured results were obtained using an evaluation PCB with AC coupling capacitors and a single shunt 0.5 pF capacitor in both the input matching network and the output matching network. The PCB is not shown. The circuit is presented in Figure 1a. The dice were mounted to the AlN package die flag in the conventional active-side up configuration. A photograph shows a complete amplifier (Figure 2).

The small and large signal results show the comparison between simulated results and measured results (Figure 3). As with the FT doubler amplifier which also uses the same package type, the major difference between the two data sets

is a difference in gain, which is attributed to the package ground / mounting plane inductance.

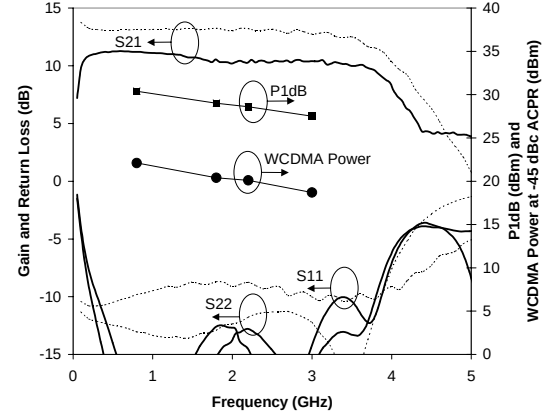


Fig. 3. Cascode amplifier small signal s-parameters and large signal data (solid lines are measurements)

The large signal data over frequency show that the compression point of nearly 1 W is very flat from 800 MHz to 3 GHz, as is the output power required for -45 dBc. The WCDMA 3GPP ACLR data shows some degradation at 3 GHz due to the 3.3 GHz upper limit of the signal generator. However, the s-parameters show the wider bandwidth that is available.

III. CONCLUSIONS

Wide band width power IC amplifiers made of GaN HEMTs show much promise to deliver flat gain, power, and linearity across all major analog and digital communications frequency bands. Since they run off the standard system 28V and require only a single, simple PCB tune, these GaN HEMT amplifiers offer an extremely easy to use solution for modern communications. Further process improvements to performance in future designs will be made possible by the incorporation of an improved, second generation GaN process that includes ground vias, as well as passive matching elements on the GaN HEMT substrate.

Another planned process improvement is to optimize the compression characteristics by reducing RF dispersion within the GaN die. These two improvements will not only increase gain, power, and linearity, but also they will further extend band width and stability.

A major package level improvement that is planned is the transition from a high thermally conductive epoxy and package to standard epoxies and plastic packages. This transition will be possible due to extensive in-house research that investigates the best combination of package type and plating with available standard epoxies that will deliver the lowest Tj for a given output power.

Once the transition to standard epoxies and packages is complete, further continuous price reductions will be possible, which coupled with the inherent wide band width of GaN

HEMTs, will provide a simple low cost solution to allow a single amplifier chain to meet multiple communications and modulation standards and frequencies.

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