MMIC class-F power amplifiers using field-plated GaN HEMTs


Abstract: Class-F microwave monolithic integrated circuit (MMIC) power amplifiers (PA) fabricated in a GaN technology are reported. Field-plated GaN HEMT devices are used for high-power performance. Two MMICs are reported. The first class-F MMIC PA operating at 2.0 GHz achieved a power-added efficiency (PAE) of 50% with 38 dBm output power and 6.2 W/mm power density. A second class-F PA operating at 2.8 GHz achieved a PAE of 46% with 37 dBm output power and 7.0 W/mm power density.

1 Introduction

High-efficiency and high-power amplifiers are required in most wireless communications and radar systems. High efficiency leads to low power consumption, reduced cooling requirements, small size and low cost. Class-F PAs use multiple-resonator output filters to control the harmonic content of their drain voltage and drain current waveforms. The efficiency of an ideal PA is increased from the 50% limit of class-A operation towards 100% in class-F operation [1–3]. Many class-F RF/microwave power amplifiers in hybrid circuits using printed circuit board (PCB) technologies have been reported [1–5]. Recent years have seen various implementations of high-efficiency class-F PAs in MMIC using GaAs FET [6, 7], GaAs pHEMT [8], CMOS [9] and SiGe HBT [10] technologies. In this paper, we present the first class-F MMIC PAs using field-plated GaN HEMT devices. GaN HEMTs are promising for high-power applications due to a high intrinsic breakdown field, and recent advances using field-plate over the gate electrode have led to record power densities exceeding 30 W/mm. Thus, by combining GaN HEMT technology with high-efficiency circuit techniques, very compact high-efficiency power-amplifier MMICs can be implemented.

2 2.0 GHz class-F MMIC PA design and simulation

In class-F PA design, the even harmonics are shorted, and the odd harmonics are open-circuited in the output stage. High efficiency is achieved by minimizing the overlap between the drain voltage and current waveforms. The transistor in the 2.0 GHz class-F PA is a field-plated GaN HEMT device with a 0.7 μm gate length, 8 × 125 μm gate width and 0.7 μm field-plate length [11]. Figure 1 shows the schematic of the PA. The harmonic trap (L3, C3) at the drain is used to tune the second harmonic, and the output network (L2, C2, L4, C4) is used to terminate the third harmonic and transform the 50Ω load to optimum impedance at the drain output, as required for class-F operation. A harmonic trap (L1, C1) at the gate is employed for input harmonic tuning. As the device is potentially unstable, a stability resistance (R1) is added at the input. The circuit was simulated using the harmonic-balance simulator in ADS from Agilent Technologies. A bias-dependent and scalable large-signal EEHEMT1 model was used for simulations.

Simulated drain voltage and current waveforms are shown in Fig. 2. The waveforms deviate from ideal class-F operation. The reasons for this include nonideal characteristics of the transistor, nonoptimum output network due to
limited Q values in spiral inductors and, in particular, the limited values of components realisable through MMIC. This discrepancy leads to degradation in efficiency.

3 Measurements of the 2.0 GHz class-F MMIC PA

The class-F amplifier was fabricated on a SiC substrate for better thermal conductivity. AlGaN/GaN HEMT devices were grown by metal organic chemical vapour deposition (MOCVD). The epitaxial structure consisted of a semi-insulation Fe-doped GaN base layer, followed by a 290 Å-thick Al0.27Ga0.73N barrier layer. The room temperature sheet electron concentration and Hall mobility were $\sim 1.12 \times 10^{13} \text{cm}^{-2}$ and $\sim 1430 \text{cm}^2/\text{Vs}$, respectively. The GaN HEMT device has a breakdown voltage greater than 100 V and $I_{dss} = 1 \text{A/mm}$. The measured unit current gain cutoff frequency $f_t$ of the device is 18 GHz. Figure 3 shows a photo of the circuit, which measures a size of 1.9 × 1.5 mm.

Figure 4a shows the results of output power, gain and PAE, which are measured at a drain voltage of 28 V. A maximum power of 36 dBm is achieved, corresponding to a power density of 4.0 W/mm. The maximum PAE is 50.4%, and the gain is about 10 dB. Simulated results of PAE and output power are also shown in dashed lines in Fig. 4a. The simulated and measured results of output power match well. There is about a 10% discrepancy between simulated and measured PAE, which is attributed to the simplistic large-signal device model that was used.

Figure 4b shows the measured power, gain and PAE against input power when the drain voltage is 35 V. The circuit achieves a maximum power of 38 dBm, corresponding to a power density of 6.2 W/mm. The gain is about 10 dB, and a maximum PAE of 50% is achieved in this case.

4 2.8 GHz class-F PA design and results

Based on the same principle, another class-F MMIC PA was designed at the higher frequency of 2.8 GHz. Figure 5 show the schematic of the PA. Its simulated drain voltage and current waveforms are shown in Fig. 6. The peak of the drain voltage waveform is flattened, close to the ideal class-F case. However, in this case there is a greater overlap between the drain voltage and current waveforms, leading to performance degradation relative to the first design. Again, this is due to the combined effects of device nonidealities and the limited range of inductor values that can be realised in the MMIC process.

The 2.8 GHz class-F PA was similarly fabricated on a SiC substrate with MOCVD-grown GaN. Figure 7 shows the photo of the PA, which occupies an area of 2.1 × 1.5 mm. The transistor used is a field-plated GaN HEMT device with a 0.7 mm gate length, 6 × 125 mm gate width and 0.7 mm field-plate length. Figure 8a shows the output power, gain and PAE against input power, which is measured at a drain voltage of 35 V. It achieves a maximum
PAE of 46.1%, a gain about 10 dB and a maximum power of 36.5 dBm, corresponding to a power density of 6.0 W/mm.

Figure 8b shows the measured results of output power, gain and PAE at a $V_{ds}$ of 40 V. It achieves a gain of 10 dB, and a maximum output power of 37.2 dBm, corresponding to a power density of 7.0 W/mm.

Figure 9 shows the output power and PAE against frequency when the $V_{ds}$ is 35 V. The PAE is over 42% within the range 2.7–2.9 GHz. Simulation results are shown by dashed lines for comparisons. Measured results of output power are close to the simulated results, while there is about a 14% discrepancy between simulated and measured PAE.

To further illustrate the advantages of GaN technology, Table 1 gives a comparison amongst the class-F RF/microwave MMIC power amplifiers using GaN in this work and other technologies [6–9]. The MMIC amplifiers are compared in terms of frequency, drain bias voltage, output power, maximum PAE, gain and power density. As we can see, our amplifiers have achieved comparable efficiency performance with significant improvement in output power and power density. In particular, its power density is at least ten times higher than that of other technologies [6–9]. This clearly demonstrates the potential of GaN RF class-F PA for high-efficiency high-power applications.

Class-F design technique has the potential of achieving very high efficiency in RF/microwave PAs. It is noted that

The PAE of these amplifiers here is still much lower compared to that of the ideal case (100%). However, with the improvement in the GaN MMIC process and optimised circuit designs, we believe higher efficiency in RF/microwave PAs can be achieved using the GaN technology combined with class-F design techniques.
5 Conclusions

The first class-F MMIC PAs using field-plated GaN HEMT devices are reported. The class-F PA at 2.0 GHz achieves a PAE of 50%, 38 dBm output power and 6.2 W/mm power density. The PA at 2.8 GHz achieves a PAE of 46%, 37 dBm output power and 7.0 W/mm power density. State-of-the-art performance in output power and power density are achieved. It is also noted that these class-F PAs, though having a high efficiency, are basically nonlinear amplifiers due to power compressions. Further ongoing work is to employ the GaN class-F MMIC PAs in LINC (linear amplification using nonlinear components) configurations or EER (envelop elimination and restoration) to achieve both high efficiency and high linearity, which are key requirements in future broadband mobile communication systems[12, 13].

6 Acknowledgments

This work is funded by HEFCE (UK) under the Promising Research Fellowship Scheme, EPSRC (UK) under the grant GR/S42538/01, and in part by the Office of Naval Research under contract #N00014-01-0764.

7 References

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Table 1: Comparison amongst class-F MMIC RF PAs using different technologies

<table>
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<tr>
<th>Frequency, GHz</th>
<th>Drain bias voltage, V</th>
<th>Output power, dBm</th>
<th>Maximum PAE, %</th>
<th>Gain, dB</th>
<th>Power density, W/mm</th>
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