High Power GaN Amplifier for High Efficiency Applications

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Abstract

Design and measured results of a single stage S-Band high-efficiency GaN-HEMT power amplifier is presented for continuous wave (CW) applications. The power amplifier employs Class-F harmonic processing technique to shape the current and voltage waveforms to enhance the amplifier's efficiency performance. The GaN-HEMT device constituting the amplifier is a commercial off-the-shelf device that is designed for high voltage operation. The fabricated GaN-HEMT power amplifier operating under continuous wave mode achieved a nominal gain of 18 dB with an output power of 130 Watts, a drain efficiency of 73%, and power-added efficiency (PAE) of 64% across 2.35 to 2.55 GHz.

Introduction

The paper describes the design and measured results of a single stage S-Band high-efficiency power amplifier that uses state-of-the-art GaN-HEMT (Gallium Nitride high electron mobility transistor). The amplifier's efficiency performance is enhanced using Class-F harmonic processing technique. The GaN-HEMT device employed is a commercial off-the-shelf (COTS) device that is designed for high voltage operation under continuous wave mode. To the authors knowledge the best power-added efficiency (PAE) reported to date from a power amplifier at 2 GHz is 80% for output power of 16.5 W [1]. The proposed power amplifier design has a measured drain efficiency of 73%, and power-added efficiency of 64% across 2.35 to 2.55 GHz.

Harmonic processing techniques have been extensively studied in the design of high efficiency power amplifiers. A Class F amplifier can theoretically achieve 100% drain efficiency by wave shaping the intrinsic drain voltage and current waveforms [2]. When the amplifier is driven into saturation and the device is biased at cutoff, the voltage waveform is clipped. Hence, the voltage waveform can be shaped like a square wave and the current waveform can be shaped like a half sine wave with proper harmonic terminations. As the voltage and the current waveforms do not overlap this minimizes the power dissipation. The squared voltage waveform contains only odd harmonic frequencies. Ideally it must have all of the odd harmonics terminated with an open circuit at the intrinsic drain of the transistor. The half sine wave current waveform only contains even harmonics, and all the even harmonics need a short circuit termination for the harmonic current to flow through. For an RF amplifier, it is not practical to terminate an infinite number of harmonics. The author in [2] has shown that most of the increase in efficiency resulting from wave shaping can be achieved with just the first few harmonics correctly terminated. For example, with up to and including the fourth harmonic present and terminated correctly, the efficiency of an ideal amplifier can be as high as 86%.

Power Amplifier Design

The GaN-HEMT device employed in the power amplifier is fabricated on SiC substrate. This transistor has a breakdown voltage greater than 150 V. The power amplifier was designed for maximum power-added efficiency while maintaining a high output power over the operating frequency range of 2.35 to 2.55 GHz based on under Class F. Small and large-signal device models for the GaN-HEMT device were obtained from the device manufacturer. Figure 1 shows the circuit schematic of the proposed power amplifier. Small-signal simulations were carried out using the small-signal GaN-HMET device model. Figure 2 shows the simulated small-signal gain, and input/output return loss. When carrying out the small-signal design, it is crucial to maintain circuit stability. Additional lumped element components were incorporated into the design in order to ensure the circuit stability was over a larger frequency range.

The Class F amplifier is a reduced angle amplifier with load harmonic modulation control to shape the drain voltage in a way that it does not or rarely coincide with drain current. Hence Class F amplifier greatly reduces the power dissipated by the GaN-HMET device, and hence further improves its efficiency performance without having to drive the amplifier into compression. Class F amplifier involves designing matching network at the fundamental frequency, and load harmonic tuning network up to a higher order harmonic. The common practice is to present a short circuit at the even order harmonic, and an open circuit at the odd order harmonic.

Large-signal simulations of the power amplifier were carried out using the large-signal model of the GaN-HEMT device. This enabled the optimization of the amplifier for output power and power-added efficiency performance. Non-linear harmonic balance simulations were also carried out using the large-signal model of the GaN-HEMT device in order to synthesize the output matching circuit. Additionally, the input harmonic matching technique described in [3] has been used to realize proper harmonic terminations, which was necessary to preserve a sinusoid drive at the gate terminal in spite of the nonlinear capacitance C_{gs}. Figure 3 shows the simulated output power and power-added efficiency at 2.45 GHz.

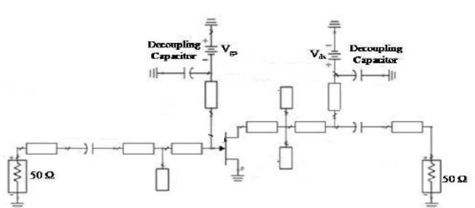

Figure 1 Power amplifier circuit schematic

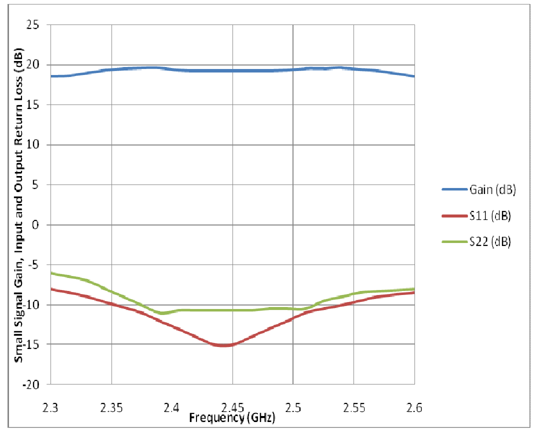

Figure 2 Simulated small signal gain, input and output return loss

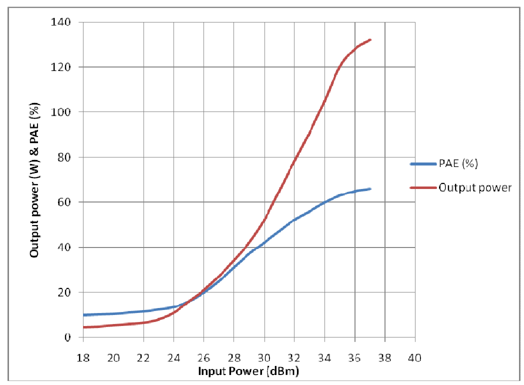

Figure 3 Simulated output power and PAE

Measured Performance

The fabricated high power amplifier is shown in Figure 4. The RF material used in the fabrication of the power amplifier was a low loss, high thermal conductivity Rogers 6035 with a thickness of 20 mil. The 6035 material was attached onto a high thermally conductivity carrier that was employed to provide the heat sinking for the GaN device. The carrier was designed so that it could be attached onto a heat sink that was liquid cooled in order to ensure that the carrier temperature was maintained at 25 °C, -40 °C and 80 °C during the RF testing.

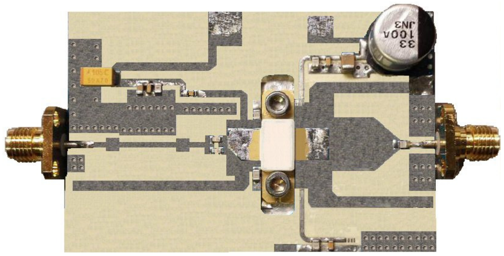

Figure 4 Fabricated GaN power amplifiers

The fabricated power amplifier, shown in Figure 4, was measured for small-signal performance with the base plate temperature at -40 ℃, +25 ℃ and +80 ℃, when operated under continuous wave (CW) mode. The measured nominal small-signal gain was 18 dB with a gain variation of less than 2 dB across the operating frequency range, as shown in Figure 5. The measured small-signal input return-loss is around a nominal value of 9.5 dB over the operating temperature and frequency range, as shown in Figure 6. The measured small-signal output return-loss is around a nominal value of 8 dB over the operating temperature and frequency range, as shown in Figure 7.

The measured large-signal performance for output power and power-added efficiency was carried out on the fabricated amplifier with the base plate temperature set at -40 ℃, +25 ℃ and +80 ℃, and when operated under continuous wave mode. Figure 8 shows the maximum measured output power at 2.45 GHz is 130 Watts and the corresponding power-added efficiency at 2.45 GHz, shown in Figure 9, is 64 %. The measured drain efficiency at 2.45 GHz is 73 % as shown in Figure 10. Output power and power added efficiency were measured across frequency and are shown in Figure 11.

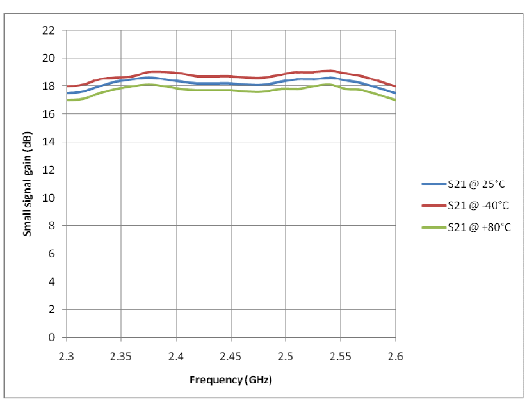

Figure 5 Measured small signal gain

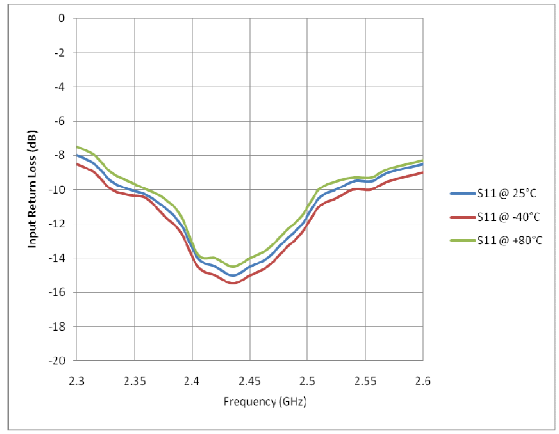

Figure 6 Measured input return loss

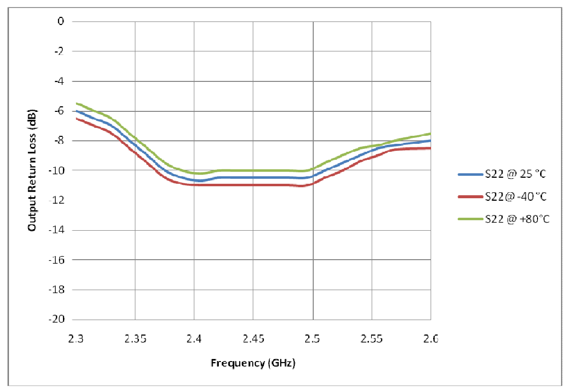

Figure 7 Measured output return loss

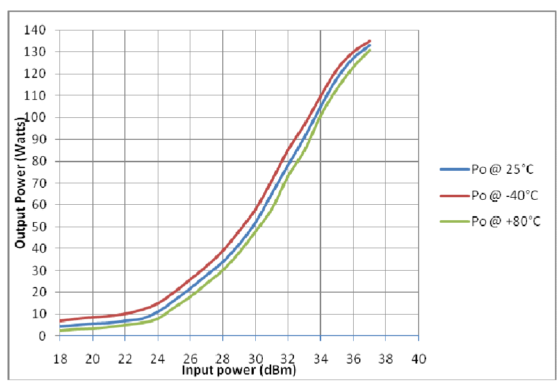

Figure 8 Measured output power @ 2.45 GHz

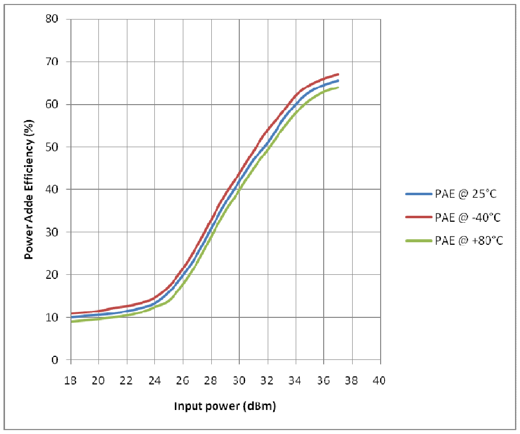

Figure 9 Measured power-added efficiency @ 2.45 GHz

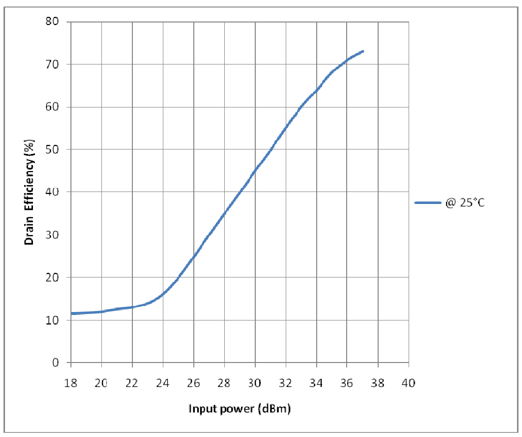

Figure 10 Measured drain efficiency at 2.45 GHz

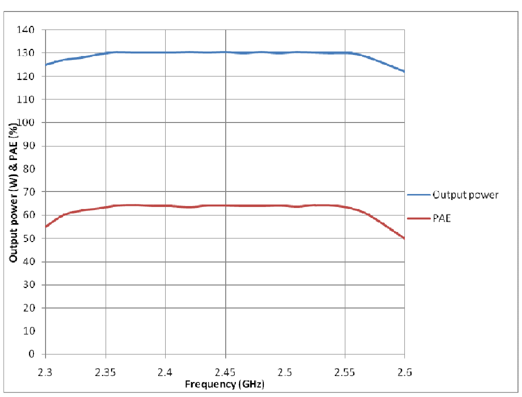

Figure 11 Measured Output Power and PAE @ 25 °C

Summary

The paper described the design, manufacture and testing of an RF power amplifier based on a GaN-HEMT for operation in Class F over 2.35 to 2.55 GHz. Measured results confirm the power amplifier exhibits excellent RF performance. The single stage power amplifier achieved a nominal small-signal gain of 18 dB, with an output power of 130 Watts and power-added efficiency of 64 % under CW mode.

Acknowledgement

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References

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