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High-Dynamic Range Pulse Profile Comparison for a GaN Power Amplifier in Different Operating Modes

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***Abstract* — The Class E amplifier is an attractive amplifier topology for fast pulse-mode systems because it can generate a high-isolation radio frequency pulse without an external pulse modulator. The pulse profile, or the power behavior versus time, is studied for amplifiers targeted for high-dynamic range fast pulse-mode applications. In these systems, the pulse must turn off at a rate compatible with the lowest system sensitivity at the receive time. A high-dynamic range pulse profile system is used to characterize the amplifier with a dynamic range of over 160 dB. The pulse profile of an example Class E amplifier is examined and compared to the results for the same amplifier operating in a linear mode. It is discovered that the inherent trapping properties of the active device technology limit the usefulness of this specific amplifier in a high-dynamic range pulsed system.**

***Index Terms* — Dynamic range, gallium nitride, measurement, power amplifiers, pulse measurements, transmitters.**

I. Introduction

The transmitter in a typical communication or radar system is operated in either a continuous wave (CW) or a pulse-mode, where the transmitter is periodically turned on for a portion of time. There exist high-dynamic range pulse-mode systems with a sensitivity of over 120 dB [1]. The transmitted pulse must turn off at a rate compatible with the minimum system sensitivity during the receive time so that the overall system performance is not degraded. Therefore, it is important to characterize the pulse profile, or the output power versus time, of amplifiers over a range even greater than the maximum system sensitivity.

The output power amplifier in a high-dynamic range pulsed system must be pulsed so that the output noise during the receive time does not affect the overall system performance. There are numerous techniques available to provide pulse modulation for an amplifier. Two popular techniques used in field-effect transistor (FET) amplifier designs use a pulsed gate or drain voltage to control the gain of the device.

The Class E amplifier is a high-efficiency nonlinear operating mode [2]. This amplifier mode provides gain only when an input RF signal is present and forces the transistor into the switch mode. Therefore, it is possible to provide high-isolation pulse modulation simply by pulsing the radio frequency (RF) input signal, similar to a pulsed Class C operation mode [3]. The Class E amplifier operating in a fast pulse-mode is previously unstudied in the literature. This mode is attractive since it is easier to generate a pulsed RF signal farther back in the transmitter chain because the power levels are lower and alternative pulse modulation techniques are available. As an added bonus, the amplifier does not dissipate power during the dead time of the pulse. The standard linear amplifier requires the use of a modulator to provide this behavior. However, the modulator itself will likely dissipate some power and tend to reduce the overall efficiency.

An example proof-of-concept Class E amplifier is designed and fabricated using a gallium nitride (GaN) heterojunction field-effect transistor (HFET). The amplifier is baseline tested using standard characterization techniques to show functionality. The amplifier is then tested using a high-dynamic range pulse profile measurement (HDRPPM) system to analyze the pulse behavior with over 160 dB dynamic range in a fast pulsing environment with a 250 ns pulse width [4], [5].

II. Amplifier Design

A Nitronex GaN on silicon 2 mm HFET is used as the active device in the amplifier design. The amplifier is biased at a drain voltage of 15 V and a gate voltage of -1.7 V, which is below pinch-off. The Class E design requires setting the fundamental impedance of the device and controlling the impedance presented to the harmonics [2]. A basic topology, as shown in Fig. 1, uses a high-impedance, quarter-wavelength stub at the second and third harmonics to control the phase at the harmonic frequencies. The high-impedance stub provides minimal interaction with the fundamental match.

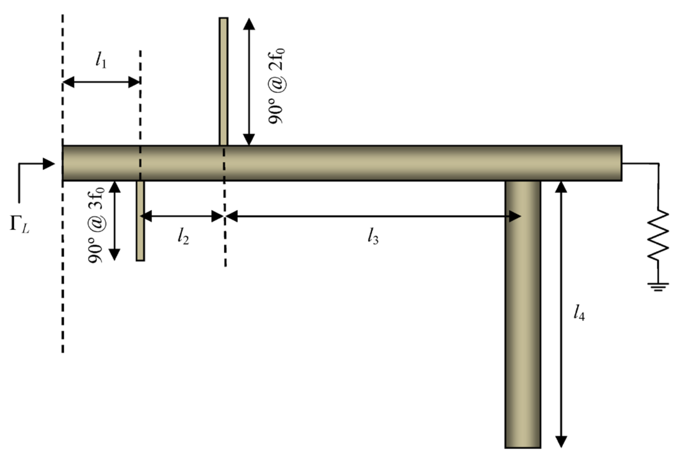

Fig. 1. General amplifier multiharmonic matching network topology.

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The fundamental impedance is set using the length l_4 of the fundamental stub and the combination of the series lengths l_1-l_3.

III. Fabrication

The amplifier is fabricated on a 5 mil thick Duroid 5880 substrate with 35 mil brass backing. A hole is milled in the substrate for the die. The physical dimensions of the test board are 3.3 in x 2.0 in. The assembled amplifier test board is shown in Fig. 2. The GaN die is attached using a high thermal conductivity Diemat DM6030Hk epoxy. A zoomed view of the die attach area is shown in Fig. 3.

IV. Drain Modulator

The Class E amplifier designed in this work is also compared to a linear operating. An amplifier biased at a Class A operating point provides linear gain to input signals with a power level below the input compression point. Therefore, for a pulsed RF input signal, the thermal noise is amplified during the dead time of the input pulse.

This situation is rectified by introducing a drain modulator onto the linear amplifier. The modulator pulses the drain voltage from 0 V to 15 V, matching the bias voltage used for the Class E amplifier. The linear amplifier does not have gain when the drain voltage is zero. An example of the drain voltage waveform is shown in Fig. 4. A totem-pole output configuration is used that allows the drain voltage to be switched on quickly and provides a low-side device to pull charge out of the amplifier HFET.

V. Standard Measurement Results

The amplifier is measured in a standard CW configuration to validate the performance of the amplifier. The measured performance for a swept input power at 2.9 GHz is shown in Fig. 5. The fundamental output power is approximately 34 dBm and the harmonic power levels are suppressed by more than 20 dB by the output matching network.

The power amplifier is also tested with a pulsed RF input to validate the pulse-mode performance. The input pulse width is 250 ns with a duty factor of 12.5 %. The maximum output power and PAE are plotted versus frequency in Fig. 6 using peak power results. The Class E amplifier generates an output pulse that follows the input pulse without the requirement for an external pulse modulator.

VI. High-Dynamic Range Pulse Profile Measurement Results

The primary interest in this work is to study the fast pulse-mode Class E amplifier behavior. However, this mode is previously unstudied over a very wide dynamic range.

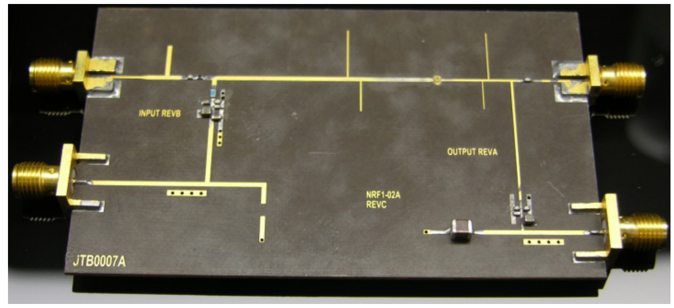

Fig. 2. Assembled amplifier test board.

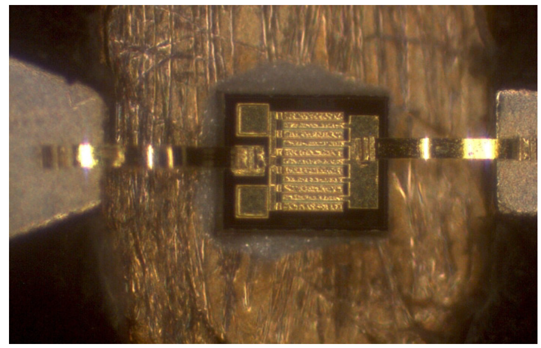

Fig. 3. Zoomed view of amplifier die attach location.

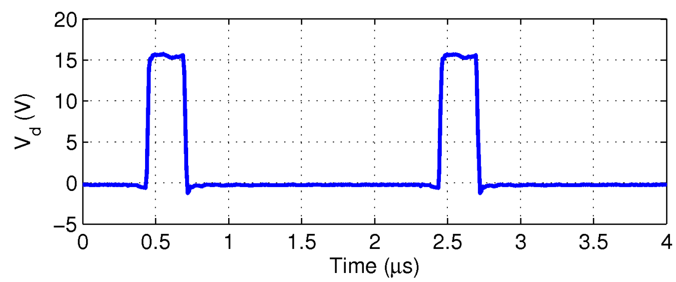

Fig. 4. Drain modulator output voltage pulse waveform.

Therefore, it is important to measure the amplifier pulse profile operating in a linear mode for a direct comparison. A linear mode amplifier typically has a better behaved pulse profile [4].

A Microwave Power, Inc. (MPI) L0203-41 amplifier is used as the preamplifier stage before the device under test. The amplifier pulse profile behavior is different when operating in either a Class E or Class A mode. A summary of the pulse profile results for each of the amplifier modes is plotted in Figs. 7 and 8 for the measurement frequencies of 2.9 GHz and 3.0 GHz, respectively. The pulse profile of the MPI driver amplifier is also included as a reference for the pulse behavior. The results are normalized to allow a direct comparison of the decay rates for the different amplifier modes. The results using a peak power meter are also included to demonstrate that the standard measurement techniques do not sufficiently reveal the pulse behavior.

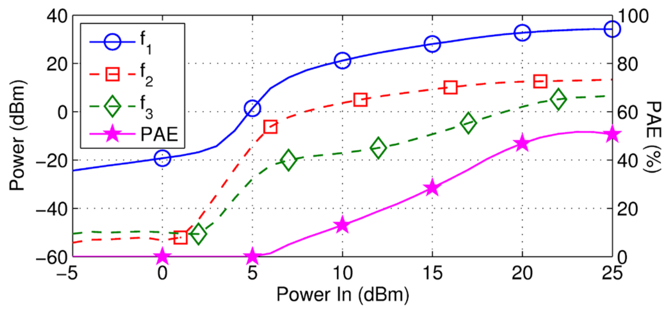

Fig. 5. Measured amplifier CW performance at f_1 = 2.9 GHz. The results for the second and third harmonic power are shown in f_2 and f_3, respectively.

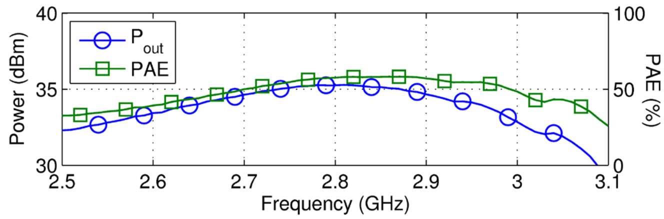

Fig. 6. Maximum output power and PAE versus frequency in pulsed Class E operating mode.

The Class E mode amplifier shows a very slow initial rate of decay compared to the linear operating mode. The drain modulator is added to the Class E amplifier design in an attempt to improve the pulsing characteristics. However, the addition of the drain modulator does not affect the pulse profile of the amplifier. The two cases for the Class E amplifier are nearly identical.

It appears that there are multiple rates of decay in the amplifier response for this operating mode. A linear least-squares curve fit is applied over three regions. Region 1 is defined as the time range from 215-280 ns, Region 2 is defined from 280-530 ns, and Region 3 is defined from 685-1500 ns. The Class E amplifier curve fit at 2.9 GHz is plotted in Fig. 9(a).

Region 1 has a fast time constant and decays at a rate of 0.89 dB/ns. A longer time constant effect takes over in Region 2 and shows a decay rate of only 0.07 dB/ns. Finally, a very long time constant behavior is observed in Region 3 that has a decay rate of only 0.02 dB/ns.

The amplifier is tested in a Class A mode to provide a direct comparison for the impact of bias on the amplifier turn-off characteristics. The gate is biased at a higher voltage to change the operating mode of the amplifier. The same drain modulator is used to provide the pulse modulation of the amplifier. The pulse profile of the Class A amplifier has a much faster decay characteristic as compared to the Class E amplifier. A linear least-squares curve fit is performed for two different regions. Region 1 is defined as the time range from 215-260 ns and Region 2 is defined from 345-800 ns. The Class A amplifier curve fit at 2.9 GHz is plotted in Fig. 9(b). The decay rate in Region 1 is fast with a decay rate of

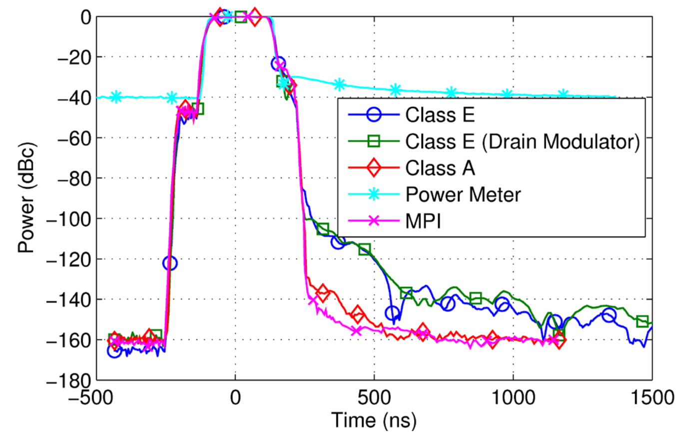

Fig. 7. Normalized amplifier pulse profile results for different operating modes in comparison to MPI driver amplifier at 2.9 GHz.

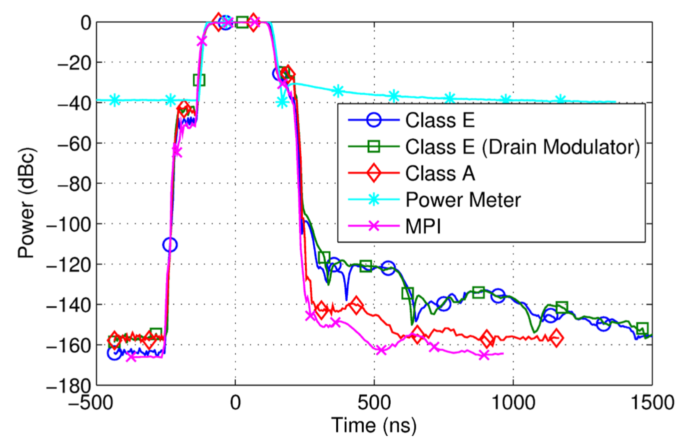

Fig. 8. Normalized amplifier pulse profile results for different operating modes in comparison to MPI driver amplifier at 3.0 GHz.

2.35 dB/ns. The response in Region 2 exhibits a much slower decay rate, similar to the decay rate of the Class E amplifier for the same time range.

The amplifier pulse behavior can be attributed to trapping in the device, or the formation of quasi-static charge distributions [6]. It is shown that the different sources of traps in a FET have different associated time constants. It is demonstrated that slow traps are associated with the channel, intermediate time constant traps are related to the deep levels in the buffer layer, and fast traps are attributed to the surface states [7]. The channel is modified by the change in bias on the amplifier and accounts for the drastic difference in decay rate in the initial turn-off region. Electrons can be trapped near the channel for large negative gate bias voltages [7]. This condition corresponds to the Class E amplifier bias and the behavior that is observed. The intermediate time constant effects could account for the similar decay rate in the final region of the pulse profiles for the various amplifier modes since the state of the buffer layer remains relatively unchanged for changes in gate bias. It is shown that the traps in the buffer layer vary little with changes in drain bias [7]. Further work is

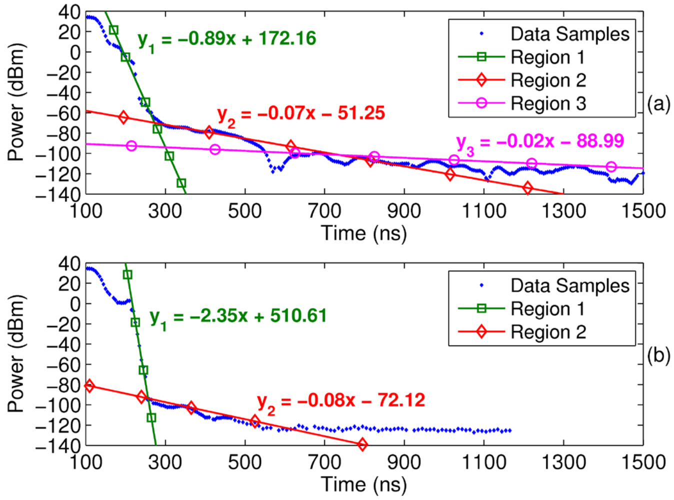

Fig. 9. Amplifier pulse profile curve fit regions with f_{RF} = 2.9 GHz for (a) Class E mode and (b) Class A mode.

required to validate the exact nature of the trapping behavior in the device.

VII. Conclusion

The first-ever high-dynamic range pulse profile results for a pulse-mode Class E amplifier are presented. The amplifier is first tested in a CW Class E mode to validate that the test board is functional. The amplifier is then tested with a pulsed RF input to validate that it operates with a high on/off isolation that follows the input pulse, as measured by a peak power meter.

The standard peak power meter is limited in dynamic range and does not reveal the full characteristics of the pulse profile for the Class E amplifier. The amplifier is tested in a pulsed Class E mode using the HDRPPM system. The measurement results reveal a very long time constant behavior in the turn-off characteristics of the amplifier. The decay rate is so slow that energy is still detectable by the time the next pulse is generated. This behavior is not observable using the standard power meter measurement technique. The slow decay rate is seen at all of the measurement frequencies. Therefore, the effect does not appear to be fundamentally frequency dependent, although the power does vary somewhat with frequency.

A drain modulator is added to the Class E amplifier design to aid in removing charge from the drain as the amplifier is pulsing. However, the addition of the drain modulator has no impact on the measured pulse profile. This effect is interesting and leads to the belief that deep charge traps within the device are responsible for the slow energy decay rate. The trapping in an active device is dependent on the DC bias applied [6].

The bias on the device is changed to validate this assertion. The pulse profile for the linear operating mode is much better behaved than the Class E mode. The initial decay rate of the amplifier pulse is nearly two and a half times faster, resulting in a much lower final power level.

The baseline Class E design does provide an attractive amplifier for standard pulse-mode applications. The amplifier is effectively off when an input signal is not present. Therefore, the amplifier is not drawing supply current and it is not dissipating any power. This fact is important in comparison to the Class A amplifier that burns power even when an input signal is not present.

However, the Class E amplifier tested in this work has a very slow turn-off characteristic. It is likely that the only solution for improving the turn-off rate is to eliminate the sources of trapping in the GaN HFET device. The trapping behavior of GaN is widely studied, although there is not a consensus on what are the direct causes of trapping behavior [6], [8]. The pulsed Class E amplifier examined in this work may not provide suitable performance for use in a fast-pulsed, very high-dynamic range application due to the slow time constant behavior observed in the turn-off characteristics of the pulse profile.

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