Output Harmonic Termination Techniques for AlGaN/GaN HEMT Power Amplifiers Using Active Integrated Antenna Approach

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***Abstract* — In this paper, effects of output harmonic terminations on PAE and output power of AlGaN/GaN HEMT power amplifier are investigated. Using a traditional method of harmonic termination, we observe a substantial increase in PAE and output power. Further, we demonstrate the high efficiency AlGaN/GaN HEMT power amplifier with harmonic termination characteristics by using the active integrated antenna approach. For the microstrip-based AlGaN/GaN HEMT power amplifier, large signal measurements and comparisons of PAE and output power were done in class-AB operation with and without output harmonic terminations. For the antenna integrated power amplifier using an AlGaN/GaN HEMT with 1 mm gate periphery, output power of 30 dBm and peak PAE of 55 % with a power gain of 14 dB were achieved at a drain voltage of 18 V and a gate voltage of -2.8 V.**

I. Introduction

With increasing demands being placed upon phased array radar systems, space technology applications, and wireless communication systems to provide high power and high efficiency, new approaches to power amplifier (PA) are gaining attention. Recently, high power amplifiers have been investigated using GaN-based transistors due to high breakdown voltage and high current density [1-2].

One technique for improving efficiency which allows for smaller and light weight power sources, reduced cooling requirements, and enhanced reliability is to tune output harmonics of amplifiers. High efficiency operation ideally occurs when the harmonics of the output voltage have the right magnitudes and phases to form a square wave. This effect can be realized by placing short circuits at the even harmonics and open circuits at the odd harmonics [3]. Practically, the 2nd harmonic is designed to be short circuited suppressing the second harmonic component and the 3rd harmonic, which is the open circuited component, makes the output voltage waveform

Using active integrated antenna (AIA) approach, the PA is directly integrated with the antenna which serves as a frequency-dependent load as well as a radiator. Antenna characteristics become a part of PA design process. It has been demonstrated to be an effective method for performing harmonic terminations depending on the characteristics of the antenna instead of using an output matching network with harmonic termination characteristics [4]. This results in a functional compact design, eliminating the effect of any cable and feedline loss that would affect overall system efficiency and power if an external antenna was used.

In this paper, we study the effects of output harmonic terminations on power added efficiency (PAE) and output power (P_{out}) of AlGaN/GaN high electron mobility transistor (HEMT) PA through comparison of measured performances with and without output harmonic terminations. We will also present an effective method to terminate output harmonics by using the concept of AIA, which relies on the antenna to serve as both output load with harmonic termination characteristic and a radiator.

II. AlGaN/GaN Power Amplifier with Output Matching Network

For the PA with output harmonic terminations, a low pass filter was employed to terminate output harmonics properly. Specifically, the 2nd harmonic was designed to be short circuited while the 3rd harmonic was designed to be open circuited [3].

AlGaN/GaN HEMTs were fabricated on SiC substrate through device isolation, ohmic metallization, gate metallization, Si_3N_4 passivation, and air-bridge processes. The design of the amplifier utilizing an AlGaN/GaN HEMT with gate width of 1 mm and gate length of 0.8 μm was done based on measured small signal S-parameters. The input matching network was fabricated on Alumina

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while the output matching network was built on Duroid with dielectric constant of 2.33 and thickness of 0.775 mm, respectively. In practice, we have also considered the effect of Au bonding wires with equivalent inductance of 0.5 nH/mm to connect circuit components. The fabricated PA was mounted on a metal fixture for heat sinking. Large-signal measurements were performed using a microwave synthesizer in conjunction with a microwave amplifier as a power source.

The measured peak PAE and P_{out} performances versus frequency are shown in Fig. 1 and Fig. 2, respectively, with harmonic terminations and without harmonic terminations at input power of 21 dBm. The amplifier was biased in class-AB mode with drain voltage (V_{ds}) of 18V and gate voltage (V_{gs}) of -2.8V corresponding to 10 % of DC drain saturation current (I_{dss}). From 1.25 GHz to 2.5 GHz, about 10 % PAE and 0.5 dBm P_{out} have been improved due to proper harmonic terminations. We achieved 57 % PAE and 31 dBm P_{out} at 1.5 GHz for the PA with harmonic terminations.

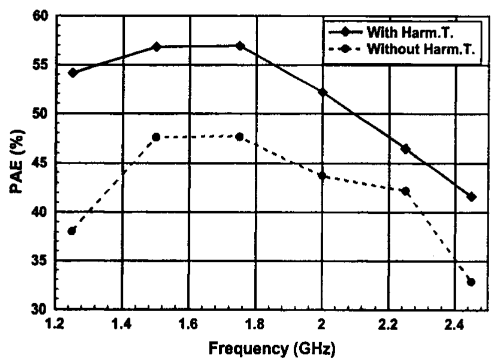

Fig. 1 Measured PAE performances with and without harmonic terminations (Harm. T.)

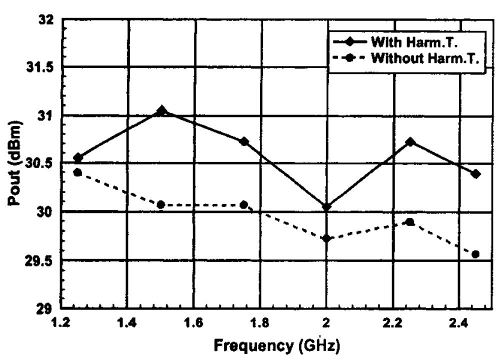

Fig. 2 Measured output power (P_{out}) performances with and without harmonic terminations (Harm. T.)

III. AlGaN/GaN Power Amplifier integrated with Antenna

The amplifier design approach based on the AIA concept minimizes the antenna feedline loss and reduces the complexity of the output matching network. Besides those merits, the antenna with harmonic termination characteristics acts as an output load and a radiator at the fundamental frequency only.

Circular sector microstrip antennas have the radiation characteristics not to radiate power at harmonic frequencies of the fundamental frequency [4 -5]. Due to the antenna characteristics, output harmonics are terminated by the circular sector antenna itself without additional output matching networks. The circular sector antenna was designed and fabricated on duroid substrate with dielectric constant of 2.33 and thickness of 0.775 mm at the resonant frequency of 2.45 GHz. The fabricated antenna was combined with AlGaN/GaN HEMT. The PA was designed at fundamental frequency including a circular sector antenna as a part of the output matching network. The photograph of the fabricated the antenna integrated PA is shown in Fig. 3.

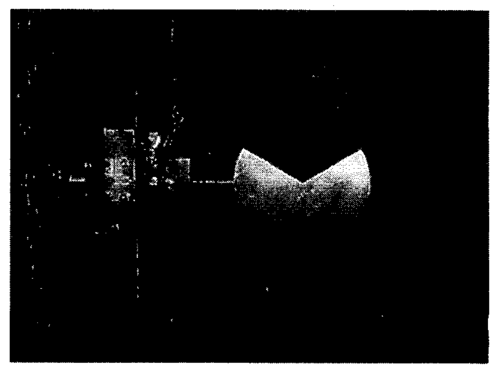

Fig. 3 Photograph of AlGaN/GaN power amplifier integrated with the circular sector antenna

Measurements were done in an anechoic chamber based upon the Friis transmission equation (1) [6]. Radiated power from a passive antenna was measured in the broadside direction. Then, the passive antenna was replaced by PA with antenna and the measurement was repeated for determining all PA performances.

$$P_{rec} = (1-|\Gamma_{trans}|^2)G_t \frac{P_{in}}{4\pi R^2}(1-|\Gamma_{rec}|^2)\frac{\lambda^2}{4\pi}G_r \quad (1)$$

In equation (1), P_{rec} and P_{in} are received power and input power from the output of HEMT to antenna and Γ_{trans} and Γ_{rec} are reflection coefficients of transmitting and receiving side, respectively. G_t and G_r are transmitting and receiving antenna gain and $1/4\pi R^2$ presents free space loss. This allows us to get the output power just before the antenna after de-embedding the receiving and the passive antenna gain.

For testing power performances of antenna integrated PA, the bias voltages were set to V_{ds} of 18 V and V_{gs} of -2.8 V at 2.45 GHz. Fig. 4 shows the measured PAE with respect to input power (P_{in}). The measured P_{out} and power gain are shown in Fig. 5 as a function of P_{in}. A peak PAE of 55 % at an input power level of 19 dBm, P_{out} of 30 dBm, and power gain of 14 dB were obtained.

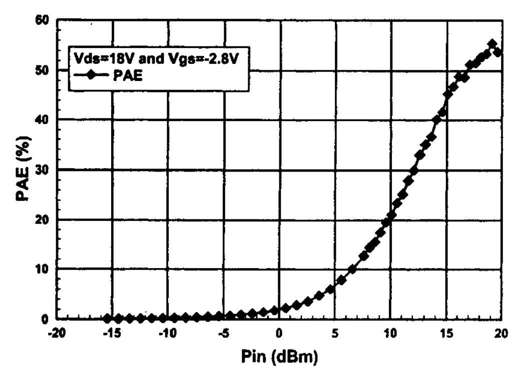

Fig. 4 Measured PAE performance for the AlGaN/GaN PA integrated with circular sector antenna at 2.45 GHz.

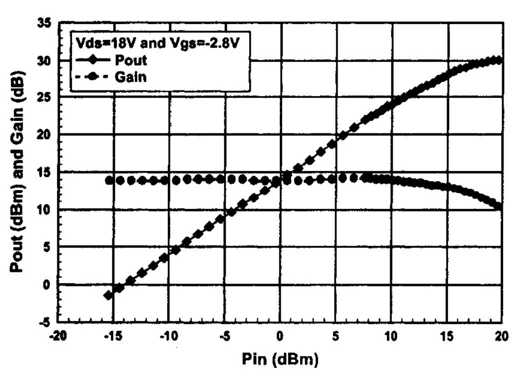

Fig. 5 Measured output power (P_{out}) and gain for the AlGaN/GaN PA integrated with circular sector antenna at 2.45 GHz.

Harmonic terminations reduce radiating power at harmonic frequencies and increase PAE. It is observed through measured radiation patterns of the 2nd and 3rd harmonic frequencies shown in Fig. 6 and Fig. 7 for H- and E-plane, respectively. Note that the radiation power at fundamental frequency of 2.45 GHz is normalized to 0 dB. Due to harmonic termination characteristic of a circular sector antenna, radiation powers at the 2nd and 3rd harmonic frequencies are below -30 dB and -20 dB, respectively, for each polarization in broadside direction.

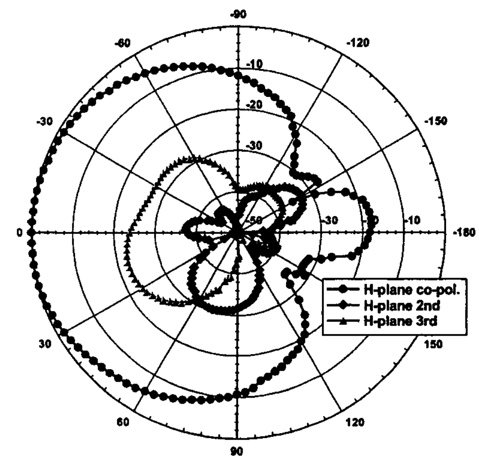

Fig. 6 Measured H-plane radiation patterns at fundamental, the 2nd, and 3rd harmonics

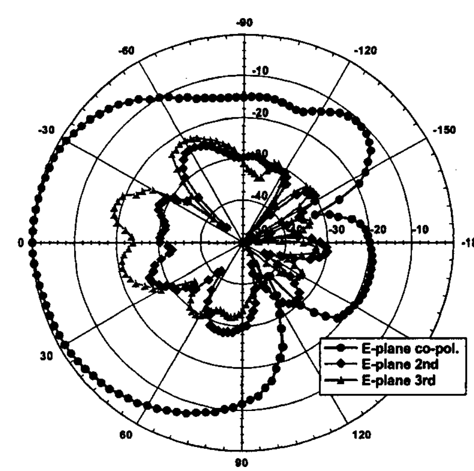

Fig. 7 Measured E-plane radiation patterns at fundamental, the 2nd, and 3rd harmonics

From the comparison of measured performances between PAs with output harmonic termination characteristics implemented by a filter and a circular sector antenna, large signal performances such as the peak PAE and output power are quite similar. Especially, 55 % PAE means that the antenna is a good harmonic termination element if we compare it to the PAE of the PA with harmonic terminations. In addition AIA design approach is very useful concept in the design of high efficiency power amplifiers for radar and wireless communication systems in terms of complexity of PA design as well as PAE and P_{out}.

IV. Conclusion

The effects of output harmonic terminations on PAE and P_{out} of an AlGaN/GaN HEMT PA have been investigated in class-AB operation. By employing a low pass filter, output harmonics have been properly terminated. From these harmonic terminations, about 10 % PAE and 0.5 dBm P_{out} over the frequency range from 1.25 GHz to 2.5 GHz have been improved. The antenna integrated AlGaN/GaN PA has been implemented. For the antenna integrated PA utilizing an AlGaN/GaN HEMT, output harmonics have been terminated using the circular sector antenna. In class-AB operation P_{out} of 30 dBm and peak PAE of 55 % with a high power gain of 14 dB were achieved.

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