AlGaN/GaN HFET Power Amplifier Integrated With Microstrip Antenna for RF Front-End Applications

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***Abstract*—In this paper, a high-efficiency and compact AlGaN/GaN heterojunction field-effect transistor (HFET) power amplifier integrated with a microstrip antenna at 7.25 GHz is presented for RF front-end circuit applications. A microstrip circular sector antenna is employed as both a radiator and frequency-dependent output load. Higher order harmonics from the HFET in nonlinear operation are reactively terminated because of the harmonic termination characteristic of the antenna. Based on the optimum load impedance measured by a load–pull measurement setup, the AlGaN/GaN HFET power amplifier has been designed and fabricated at 7.25 GHz using the active integrated antenna concept. In this design approach, the measured antenna impedance is directly transformed to the optimum load impedance for maximum efficiency. The power amplifier with 1-mm gate periphery shows 42% peak power-added efficiency and 30.3-dBm saturated output power with a linear gain of 8 dB, which is in reasonably good agreement with measured discrete HFET load–pull data. Due to the antenna's characteristics, better than 30-dB harmonic suppression has been achieved at both the second and third harmonic frequencies in both the E- and H-planes. To the authors' best knowledge, this is the first demonstration of a high-frequency AlGaN/GaN HFET power amplifier integrated with an antenna.**

***Index Terms*—Active integrated antenna (AIA), AlGaN/GaN, heterostructure field-effect transistor (HFET), harmonic termination, load–pull, microstrip circular sector antenna, power-added efficiency (PAE), power amplifier, radiation pattern.**

I. Introduction

FOR HIGH-FREQUENCY and high power-amplifier applications, the AlGaN/GaN heterojunction field effect transistors (HFETs) have shown remarkable potential since the first demonstration of a GaN-based HFET was done on a sapphire substrate in 1993 [1]–[3]. This is due to the high breakdown voltage and high carrier velocity, as well as good thermal conductivity of the HFET. The HFETs on a sapphire substrate are commercially attractive due to the low cost of growing the heterojunction epitaxial layer on a larger wafer. This provides potential applications for the commercial implementation of AlGaN/GaN HFET monolithic microwave integrated circuits (MMICs). On the other hand, the HFETs on SiC offer better performance because of higher thermal conductivity and better crystal quality compared to that of the sapphire substrate. Thanks to steadfast progress in AlGaN/GaN HFET technologies, impressive improvements have been achieved [1]–[3], allowing emerging advancements to arise in microwave and millimeter-wave system applications.

In advanced wireless communication and phased-array radar systems, which require highly compact and lightweight transmitters, power amplifiers are one of the most important circuit components. Since the power amplifier consumes the majority of the dc power in the transmitter, much attention has to be paid to maximizing the efficiency of the power amplifier. High-efficiency power amplifiers allow smaller and lightweight power sources, longer battery lifetimes, and reduced cooling requirements. Over the past years, high-efficiency power amplifiers have been investigated and realized via controlling higher order output harmonics from the nonlinear active device [4]–[7]. 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 [5], [6]. Specifically, the second harmonic is designed to be short circuited, while the third harmonic is open circuited, making the output voltage waveform closer to a square waveform. In [7], high efficiency was achieved by terminating higher order harmonics reactively so that only fundamental signal power is delivered to the output load, while other higher order harmonics are reflected reactively. When the power amplifier is connected with a transmitter antenna, most of these widely used design methodologies inevitably suffer from cable or feedline losses. For the power amplifier that is operating at the saturated output power range, the loss of even a small amount of power from the cable or feedline degrades the total system efficiency. For high-performance RF front-end applications, a new power-amplifier design methodology based on the active integrated antenna (AIA) design concept has been proposed and demonstrated [8]–[10].

Unlike conventional transmitters, which assume a 50-Ω interface, in the AIA design approach, both the active device with input matching network and the antenna are treated as a single entity. The antenna, which operates as both a radiating element and a frequency-dependent output load in the circuit, provides various circuit functionalities such as filtering and harmonic tuning. This results in a functional compact design, eliminating the effect of any cable and feedline loss associated with the use of an external antenna that would affect

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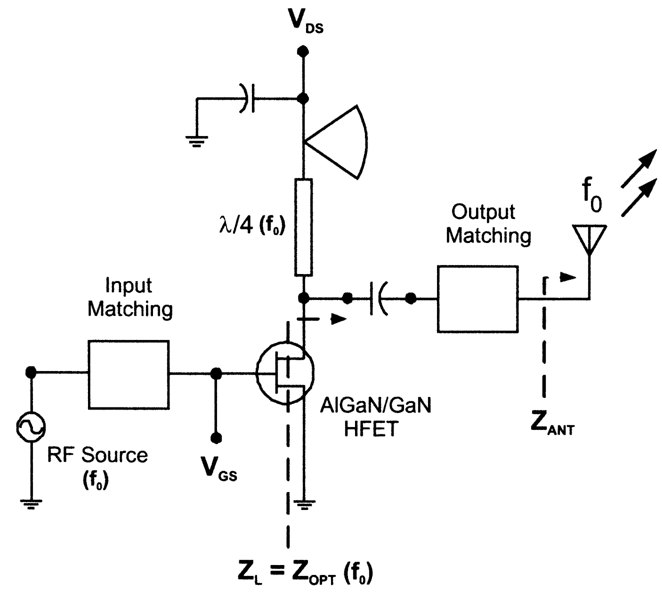

Fig. 1. Schematic of the AlGaN/GaN HFET power amplifier integrated with a microstrip antenna as a RF front-end application. Measured antenna impedance $(Z_{\rm ANT})$ is directly transformed to optimum load impedance $(Z_{\rm OPT})$ for efficiency.

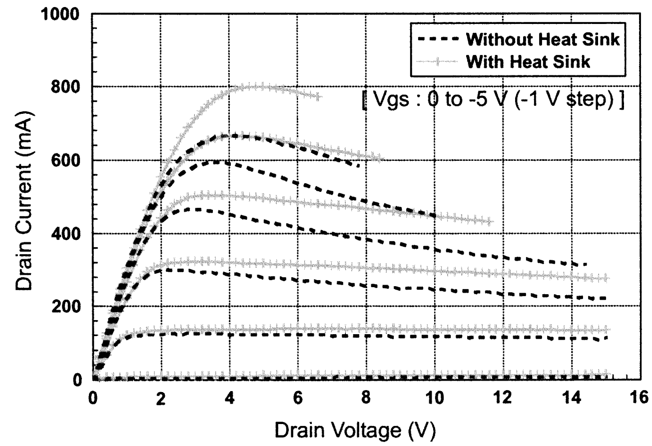

Fig. 2. DC I–V characteristic for a 1-mm-wide AlGaN/GaN HFET with and without a metal heat sink.

overall system efficiency and output power. In this paper, the AlGaN/GaN HFET power amplifier integrated with an antenna, as shown in Fig. 1, is demonstrated for high-efficiency and compact RF front-end applications. Based on the AIA design concept, the measured passive antenna impedance $(Z_{\rm ANT})$ is directly transformed to the optimum load impedance $(Z_{\rm OPT})$ for maximum efficiency. Recently, high-performance RF front-end circuits using the AIA design concept have been reported. Deal *et al.* demonstrated AIA push–pull GaAs FET power amplifiers at 2.5 and 2.46 GHz. Peak power-added efficiency (PAE) of 55% and 63% was demonstrated at 25- and 26-dBm output powers, respectively [8]. Radisic *et al.* showed a high-efficiency GaAs FET amplifier for wireless applications. A maximum PAE of 63% and output power of 24.4 dBm were reported at 2.55 GHz [9]. Hang *et al.* presented GaAs FET push–pull power amplifier with 60.9% peak PAE and 28.2-dBm output power at 4.15 GHz [10]. Unlike AIAs with a commercial GaAs-based FET presented in the literature [8]–[10], when a commercial large-signal device model is not available, the large-signal behavior of an FET has to be accurately characterized to maximize PAE and output power. As an empirical technique, load–pull measurement has been successfully used for this purpose [2], [11].

In this paper, the first 7.25-GHz high-efficiency and compact AlGaN/GaN HFET power amplifier integrated with an antenna has been developed for RF front-end applications by employing the AIA design concept. A load–pull measurement technique was utilized to accurately evaluate the $Z_{\rm OPT}$ of the AlGaN/GaN HFET and design a power amplifier. The microstrip circular sector antenna printed on a high dielectric-constant substrate was employed so that harmonic power was efficiently suppressed by the antenna itself without additional tuning circuits. This resulted in a highly efficient and compact AlGaN/GaN HFET power amplifier. The AlGaN/GaN HFET technology is presented in Section II, followed by the circuit design and fabrication of the antenna integrated AlGaN/GaN HFET power amplifier in Section III. The experimental results and discussions are described in Section IV.

II. AlGaN/GaN HFET Technology

The AlGaN/GaN HFET layer structure was grown using metallic organic chemical vapor deposition (MOCVD). The HFET epitaxial layer was composed of an undoped 50-Å $\rm Al_{0.25}Ga_{0.75}N$ layer followed by 150-Å Si-doped to a 4.15×10^{18} $\rm cm^{-3}$ $\rm Al_{0.25}Ga_{0.75}N$ layer that provides two-dimensional electron gas, 30-Å undoped $\rm Al_{0.25}Ga_{0.75}N$, and 1-μm intrinsic GaN buffer layers grown on an SiC substrate. The AlGaN/GaN HFET fabrication process includes ohmic metallization formed by Ti/Al/Ni/Au with 900 °C and 40-s rapid thermal annealing, yielding a typical resistance of $0.4\,\Omega \cdot$ mm [12]. Device isolation is realized by ion implantation using $\rm As^+$ and $\rm He^+$, followed by a gate metallization process utilizing a Pd/Au bilayer and $\rm Si_3N_4$ passivation. An air–bridge process completes the fabrication. The drain-to-source space of the HFET was 3 μm, while the gate-to-source space was 1 μm. In Fig. 2, the measured I–V characteristics are shown for a 1-mm-wide AlGaN/GaN HEFET grown on an SiC substrate with and without a metal heat sink under the device. A saturated drain current $(I_{\rm DSS})$ of 640 mA and knee voltage of approximately 3 V were observed without the heat sink. With the heat sink, on the other hand, the $I_{\rm DSS}$ was increased to 800 mA due to heat dissipation through the heat sink. Gate-to-drain breakdown voltage is typically around 40 V for these devices. From the measured frequency characteristic of the HFET with a gate length of 0.25 μm, a 25-GHz cutoff frequency and 30-GHz maximum oscillation frequency were recorded at a drain voltage $(V_{\rm DS})$ of 18 V and a gate voltage $(V_{\rm GS})$ of -3 V.

III. Circuit Design and Fabrication

The power amplifier was designed at 7.25 GHz using Agilent Technologies' ADS simulator. A load–pull measurement to extract $Z_{\rm OPT}$ for maximum efficiency from the HFET with 1-mm gate periphery and 0.25-μm gate length was done using the Maury Microwave load–pull measurement setup. For the load–pull measurement, bias voltages were set as $V_{\rm DS} = 18$ V

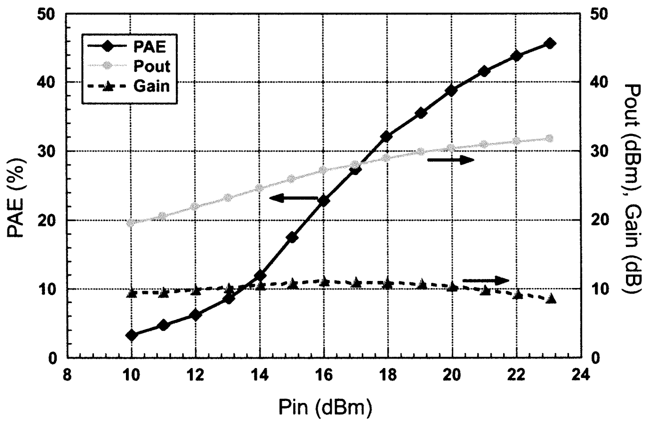

Fig. 3. Measured load–pull large-signal performance with Z_{OPT} load impedance for a 1-mm-wide AlGaN/GaN HFET.

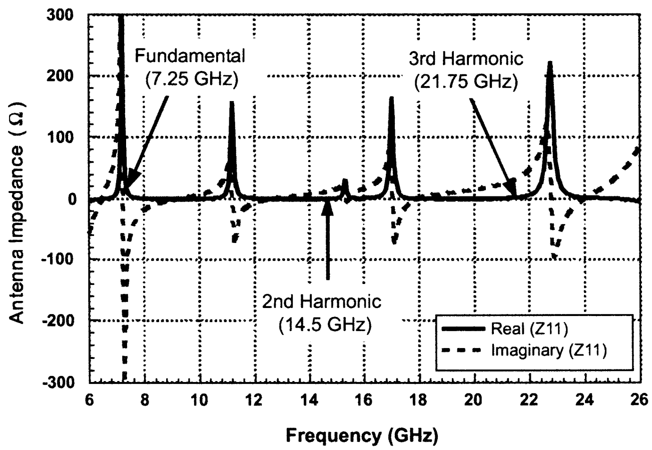

Fig. 4. Resonant characteristic of the microstrip circular sector antenna on an RT/Duroid substrate with a dielectric constant of 10.2 and a thickness of 10 mil ($Z_{11} = Z_{\mathrm{ANT}}$).

and $V_{\mathrm{GS}} = -5$ V, which corresponds to close to device pinchoff operating condition. The measured load–pull large-signal performance with Z_{OPT} load impedance for a 1-mm-wide device is shown in Fig. 3. The saturated output power reaches 1.48 W/mm. The associated power gain of 8.7 dB and peak PAE of 45% are observed.

The microstrip circular sector antenna with a 120° cut-out has the interesting characteristic not to exhibit radiating modes at higher order harmonics of the first resonant frequency [9], [13]. The cut-out circular sector antenna thus provides an efficient way to suppress higher order harmonic power as compared to a rectangular-type patch antenna. The microstrip circular sector antenna was designed at 7.25-GHz operating frequency, which is slightly off the exact resonant frequency, enabling easy output matching to avoid the high impedance at the exact resonant frequency. The designed antenna was fabricated on a Duroid substrate with a dielectric constant of 10.2 and a thickness of 10 mil. The resonant characteristic of the microstrip circular sector antenna is shown in Fig. 4. Clearly, no power radiation characteristic at higher order harmonics is observed from the Z_{ANT} in Fig. 4. The Z_{ANT} was then embedded into the simulator as one-port data at the final output terminal instead of a 50-Ω load in the design of the conventional amplifiers.

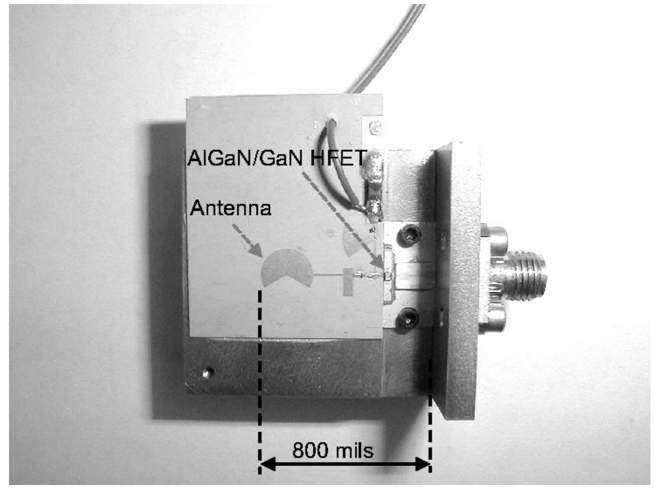

Fig. 5. Photograph of the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna on the test jig.

Since the output matching is critical in determining the output power and efficiency, the circuit design was carefully done. In this study, the measured Z_{ANT} is directly transformed to the Z_{OPT} for optimum efficiency at the fundamental frequency, bypassing the conventional intermediate 50-Ω line stage. No additional output matching network is needed to tune higher order harmonics due to the intrinsic harmonic termination characteristics of the antenna. Thus, the signal power at the fundamental frequency is radiated through the antenna while signal power at higher order harmonics is not due to the reactive termination. The designed output matching network including a bias circuit was fabricated on the RT/Duroid substrate with a dielectric constant of 10.2 and a thickness of 10 mil.

The input matching circuit was designed to transform the low gate impedance of the HFET to 50-Ω, the same as done in the design methodology of conventional amplifiers. The input matching circuit was built on the Alumina substrate with a dielectric constant of 9.8 and a thickness of 15 mil. The fabricated individual input and output matching integrated with an antenna, as well as the AlGaN/GaN HFET were combined and mounted on a test jig. The metal fixture efficiently dissipates heat generated from the AlGaN/GaN HFET so that accurate power performance measurements can be made. We have also considered the effect of the Au bonding wire by factoring in an equivalent inductance [14]. A photograph of the fabricated AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna is shown in Fig. 5.

IV. Experimental Results and Discussions

Since the circuit is terminated with a radiator rather than a 50-Ω load, the measurement of this circuit is much more complicated when compared to a standard active circuit. To correctly evaluate the output performance of the power-amplifier integrated antenna, care must be taken to calibrate the measurement setup systematically. Employing the Friis transmission equation (1) [15], the measurements in an anechoic chamber have been done in the following order [8]–[10]. First, to deembed the antenna gain and mismatch loss, measurement of the passive microstrip circular sector antenna as a reference is done in the broadside direction. The passive antenna is then replaced by the power amplifier integrated with the same type of antenna and the measurement is repeated in the same direction. While compensating for the measured mismatch loss and the antenna gain from the measurement data of the passive antenna, all output performance of the power amplifier is correctly obtained. Note that, for all of these measurements, the cable loss and receiving antenna gain are accounted for as follows:

$$P_{\rm rec} = \left(1 - |\Gamma_{\rm trans}|^2\right) G_t \frac{P_{\rm av\_HFET}}{4\pi R^2} \left(1 - |\Gamma_{\rm rec}|^2\right) \frac{\lambda^2}{4\pi} G_r. \tag{1}$$

In (1), $P_{\rm rec}$ is the power received by the spectrum analyzer and $P_{\rm av\_HFET}$ represents the available power from the output of the HFET. $\Gamma_{\rm trans}$ and $\Gamma_{\rm rec}$ are reflection coefficients of transmitting and receiving antennas to quantify the mismatch losses, respectively. By considering both $P_{\rm av\_HFET}$ and the transmitting reflection coefficient, the delivered power to the antenna can be obtained as the output power of the AlGaN/GaN HFET power amplifier. In addition, G_t and G_r are the transmitting and receiving antenna gain and $\lambda^2/4\pi R^2$ represents free-space loss.

Based on the measurement technique, large-signal measurements for the antenna integrated AlGaN/GaN HFET power amplifier mounted on the test jig were performed in the anechoic chamber using a microwave synthesizer in conjunction with a microwave amplifier as a power source to provide sufficient drive power. A spectrum analyzer was used to monitor oscillations over the entire frequency range during the measurement to confirm the stability of the power amplifier. The HFET was first biased at $V_{\rm DS}$ of 18 V and $V_{\rm GS}$ of -5 V, the same as in the load–pull measurement bias setup. In Fig. 6, the measured PAE, output power, and gain are shown as a function of input power for the power amplifier at 7.25 GHz. PAE of 42% at an input power level of 23- and 30.3-dBm output power with 8-dB linear gain are observed. These measured data show reasonably good agreement with discrete HFET device load–pull measurements, as shown in Fig. 3. Compared to the measured discrete device load–pull data, the deviation can be attributed to circuit fabrication variation such as imperfections in etching of the matching circuits and connections and inaccurate bonding wire length, which may affect circuit performance. Poor thermal management can especially be one of main reasons for measurement discrepancies. The device is active for a longer period of time in the anechoic chamber measurements with a relatively small heat sink under the device, while load–pull power sweep measurements are performed much faster while using a chuck as a better heat sink. The large-signal performance with respect to frequency is shown for the power amplifier in Fig. 7. Peak PAE from 26% to 42% is observed for output power ranging from 28- to 30.3-dBm output power at an input power of 23 dBm. The relatively narrow frequency bandwidth can be explained by the resonant characteristic of the microstrip circular sector antenna, which ideally radiates at single designed resonant frequency. In Fig. 8, the $V_{\rm DS}$ dependent large-signal performance of the power amplifier at 7.25-GHz and 23-dBm input driving power is shown. Output power continues to increase up to 30.5 dBm at 25 V, while efficiency decreases. 45% peak PAE is observed at 15 V. This trend can be explained by dc power consumption and consequent thermal degradation encountered when choosing different operating conditions.

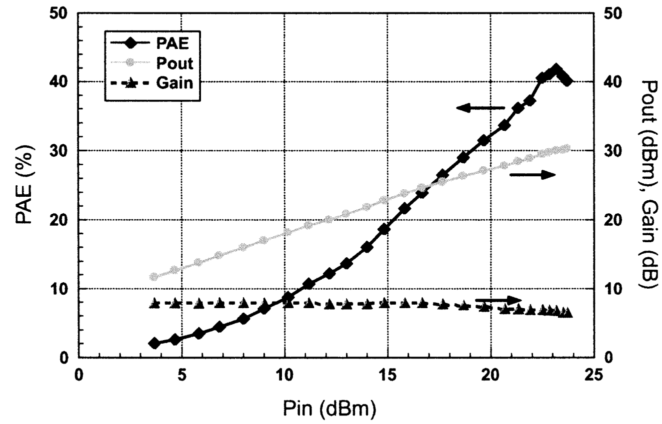

Fig. 6. Measured large-signal performance as a function of input power for the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna at 7.25 GHz (load impedance $= Z_{\rm OPT}$, $V_{\rm DS} = 18$ V, and $V_{\rm GS} = -5$ V).

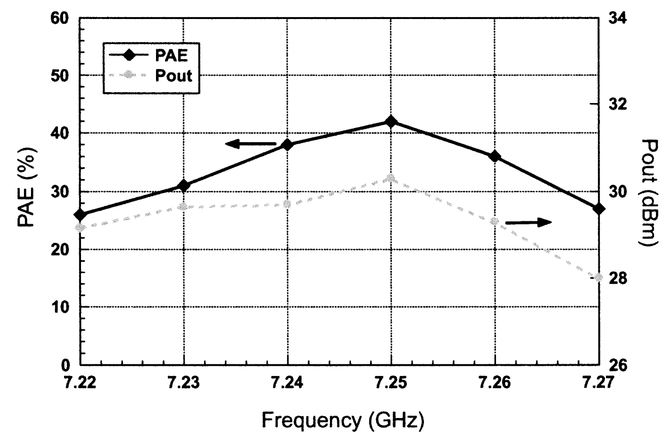

Fig. 7. Measured large-signal performance with respect to frequency for the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna ($V_{\rm DS} = 18$ V, $V_{\rm GS} = -5$ V, and $P_{\rm in} = 23$ dBm).

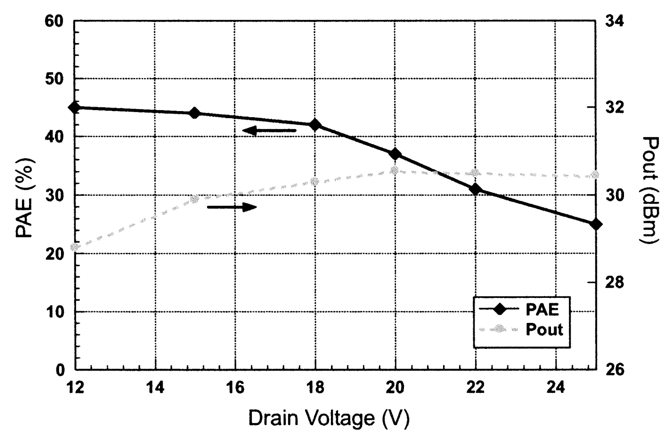

Fig. 8. Measured large-signal performance versus drain bias voltage at 7.25 GHz for the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna ($P_{\rm in} = 23$ dBm).

High-efficiency power amplifiers, which are normally biased at class AB or class B, generate substantial higher order harmonics. For a power amplifier integrated with an antenna,

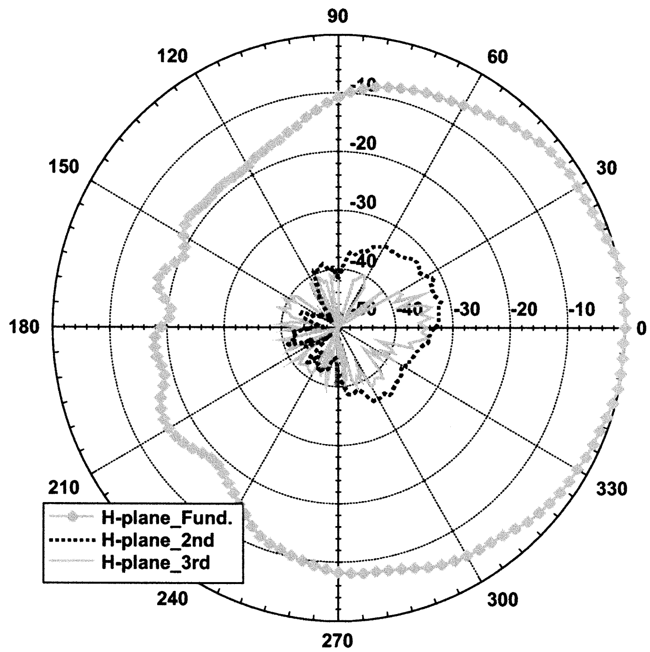

Fig. 9. Measured H-plane radiation patterns at the fundamental of 7.25-GHz, second, and third harmonic frequencies for the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna.

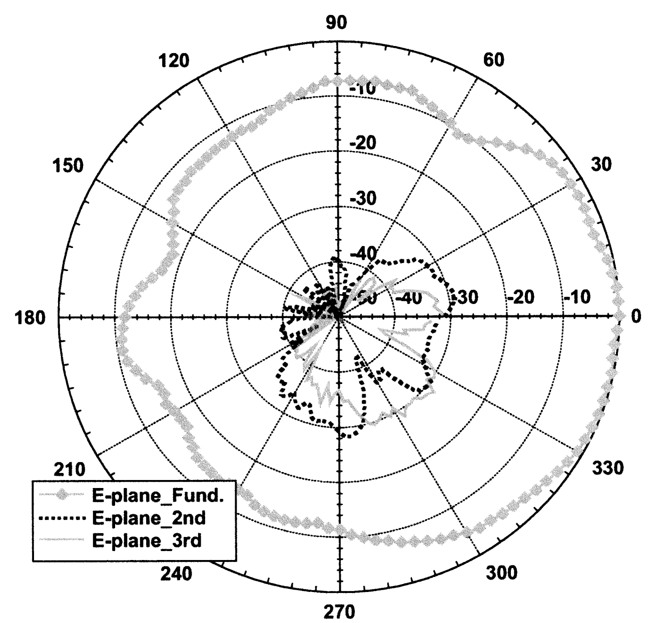

Fig. 10. Measured E-plane radiation patterns at the fundamental of 7.25-GHz, second, and third harmonic frequencies for the AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna.

these harmonics can radiate out through the antenna and overall system performance can be significantly degraded by these undesired higher order harmonics. In this study, high-efficiency performance has been realized via suppression of the higher order harmonics by employing the microstrip circular sector antenna. The higher order harmonic suppression characteristics of the power amplifier can be observed by measuring the second and third harmonic radiation. Figs. 9 and 10 show the H- and E-plane radiation patterns at fundamental, second, and third harmonics, respectively. The measurement was done at the input power level corresponding to the peak PAE and the maximum power was normalized to 0 dB. As shown in Figs. 9 and 10, second and third harmonic suppression better than 30 dB has been measured in both the H- and E-planes. Note that, in this measurement, output power levels at all the frequencies were referred to the reference plane at the output of the AlGaN/GaN HFET power amplifier. This is done by taking into account the cable and free-space losses, receiving antenna gain, and mismatch loss at the corresponding frequencies.

The compactness of the implemented AlGaN/GaN HFET power amplifier integrated with the microstrip circular sector antenna is realized by employing 10.2-high dielectric-constant substrate, as well as the AIA design approach, which eliminates the unnecessary connecting components between the power amplifier and antenna in conventional transmitters. As GaN-based device technology matures, a power amplifier integrated with an antenna or a transmitter in next-generation wireless systems will be able to be integrated together on a sapphire substrate with a high dielectric constant of 11.6 in parallel and 9.4 in the perpendicular direction.

V. Conclusion

In this study, the first AlGaN/GaN HFET power amplifier integrated with a microstrip antenna for RF front-end applications has been developed at 7.25 GHz based on the measured optimum impedance Z_{OPT} by a load–pull measurement setup. The microstrip circular sector antenna that effectively radiates the fundamental frequency signal while simultaneously suppressing higher order harmonic radiation was integrated with the AlGaN/GaN HFET based on the AIA design concept. This enabled a compact power-amplifier design, which was further enhanced by using a high dielectric-constant substrate. The compact size enables potential implementation of AlGaN/GaN HFET MMICs for compact transmitters in next-generation microwave wireless systems.

A peak PAE of 42% and the output power of 30.3 dBm with linear gain of 8 dB have been achieved from the antenna integrated AlGaN/GaN HFET power amplifier with 1-mm gate periphery at 7.25 GHz. These measured PAE, output power, and gain of the power amplifier designed at a load impedance of Z_{OPT} agreed reasonably well with load–pull measurement of the HFET discrete device. Up to 45% in PAE and 30.5 dBm in output power were achieved by varying the V_{DS} dc-bias conditions in the 15–25-V range. Peak PAE greater than 26% and output power greater than 28 dBm are maintained over the considered frequency bandwidth. Due to the harmonic termination characteristics of the microstrip antenna, radiation power levels at the second and third harmonics are suppressed by better than 30 dB in both the E- and H-planes. This study has demonstrated that, with proper harmonic termination, AlGaN/GaN HFETs can be successfully used to produce high-efficiency power amplifiers required for phased-array radar and wireless communication systems. Power-amplifier design based on the AIA concept has been shown to provide an efficient and successful method for the design of high-efficiency and compact AlGaN/GaN HFET power amplifiers. In addition, the anechoic chamber measurement technique verifies the design methodology using load–pull measurement.

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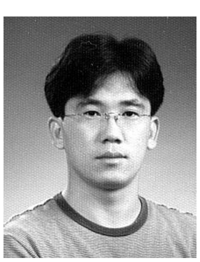

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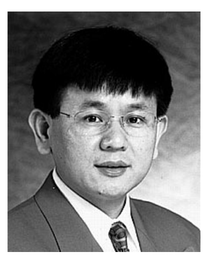
He has authored or coauthored 30 technical papers. His research interests are solid-state electronics technology, design and fabrication for microwave high-power applications.



Yongxi Qian (S'91–M'93–SM'00) was born in Shanghai, China, in 1965. He received the B.E. degree from Tsinghua University, Beijing, China, in 1987, and the M.E. and Ph.D. degrees from the University of Electro-Communications, Tokyo, Japan, in 1990 and 1993, respectively, all in electrical engineering.

From 1993 to 1996, he was an Assistant Professor with the University of Electro-Communications. From April 1996 to January 2001, he was a Post-Doctoral Fellow, Assistant Research Engineer, and Lecturer with the Electrical Engineering Department, University of California at Los Angeles (UCLA). In February 2001, he joined the MicroWaveSys Division, Microsemi Corporation, Los Angeles, CA, where he is currently Director of Technology and Applications with a focus on advanced HBT integrated circuits (ICs) for third-generation (3G) wireless local area network (LAN) and high-speed fiber-optic applications. His research interests have included numerical techniques for microwave and millimeter-wave circuits and antennas, generation and transmission of picosecond electrical pulses, crosstalk problems in high-density MMICs, miniature circuits for mobile communications, 60-GHz millimeter-wave focal plane imaging array, broad-band planar antennas, smart antennas and arrays for wireless communications, high-efficiency microwave power amplifiers, RF interconnect for mixed-signal silicon MMICs, quasi-optical power combining, photonic bandgap (PBG) structures, AIAs for indoor LANs, and high-power broad-band RF photonic devices for millimeter and submillimeter-wave photomixing. He has authored or coauthored over 200 refereed journal and conference papers, two books, and several book chapters.

Dr. Qian was the recipient of the 1998 Japan Microwave Prize presented at the Asia–Pacific Microwave Conference, the 1999 Best Student Paper presented at the 29th European Microwave Conference, and the 2000 ISAP Paper Award presented at the International Symposium on Antennas and Propagations.

Cheng P. Wen (S'54–M'63–SM'74–LS'97–LF'97) received the Ph.D. degree from The University of Michigan at Ann Arbor, in 1963.

He is currently a Technical Consultant with the Device Research Laboratory, University of California at Los Angeles (UCLA), where he is involved with GaN HFET technology. In 1998, he retired as Department Manager/Chief Scientist with the Hughes Aircraft Company, and was with Rockwell International and RCA Laboratories. He invented coplanar waveguide (CPW) and pioneered the development of high-power flip-chip MMICs. His wide-ranging research included ultra-low-noise traveling-wave amplifiers, gas laser color switching, surface acoustic wave (SAW) devices, magnetic semiconductors, millimeter-wave IMPATT diodes, long-wavelength infrared detectors, short-range automotive radar, hybrid and MMICs. He holds 45 U.S. patents.

Kang L. Wang (S'68–M'70–SM'78–F'92) received the B.S.E.E. degree from the National Cheng Kung University, Taiwan, R.O.C., in 1964, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1966 and 1970, respectively.

Since 1979, he has been with the Electrical Engineering Department, University of California at Los Angeles (UCLA). From 1993 to 1996, he was Chair of the Electrical Engineering Department.

Prof. Wang is a member of the American Physical Society, the Materials Research Society, Eta Kappa Nu, Sigma Xi, and Phi Tau Phi. He has chaired many international conferences and symposia. He has been the recipient of numerous awards, which include the Semiconductor Research Corporation Inventor Award (consecutively from 1989 to 1994, and again from 1996 to 1998). In 1995, he was also honored with the Semiconductor Research Corporations Technical Excellence Award and the Best Paper Award presented by the European Material Research Society. His other awards include the J. H. Ahlers Achievement Award and the Guggenheim Fellow Award presented by the Max Planck Institute, Stuttgart, Germany.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois at Urbana-Champaign. From April 1976 to August 1977, he was a Senior Research Engineer with the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor at the University of Kentucky, Lexington. In July 1978, he joined the faculty at The University of Texas at Austin, where he became a Professor of electrical engineering in 1981 and Director of the Electrical Engineering Research Laboratory in 1984. During the summer of 1979, he was a Guest Researcher at AEG-Telefunken, Ulm, Germany. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at The University of Texas at Austin. In September 1984, he was appointed Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department, The University of Texas at Austin. In January 1991, he joined the University of California at Los Angeles (UCLA), as Professor of electrical engineering and Holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He was an Honorary Visiting Professor at the Nanjing Institute of Technology, Nanjing, China, and at the Japan Defense Academy. In April 1994, he became an Adjunct Research Officer for the Communications Research Laboratory, Ministry of Post and Telecommunication, Japan. He currently holds a Visiting Professorship at The University of Leeds, Leeds, U.K., and is an External Examiner of the Graduate Program of the City University of Hong Kong. He has authored or coauthored 274 journal publications, 540 refereed conference presentations, and 30 books/book chapters in the area of microwaves, millimeter-waves, antennas and numerical electromagnetics. He has generated 49 Ph.D. students.

Dr. Itoh is a member of the Institute of Electronics and Communication Engineers of Japan and Commissions B and D of USNC/URSI. He became an Honorary Life Member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) in 1994. He was the editor-in-chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1983–1985) and the IEEE MICROWAVE AND GUIDED WAVE LETTERS (1991–1994). He serves on the Administrative Committee of the IEEE MTT-S. He was vice president of the IEEE MTT-S in 1989 and president in 1990. He was the chairman of USNC/URSI Commission D (1988–1990), and Chairman of Commission D of the International URSI (1993–1996). He is the chair of the Long Range Planning Committee of URSI. He serves on advisory boards and committees of a number of organizations. He has been the recipient of a number of awards, including the 1998 Shida Award presented by the Japanese Ministry of Post and Telecommunications, the 1998 Japan Microwave Prize, the 2000 IEEE Third Millennium Medal, and the 2000 IEEE MTT-S Distinguished Educator Award.