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A 20 W GaN-based Power Amplifier MMIC for X-band Radar Applications

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Abstract

In this paper, we demonstrated a power amplifier monolithic microwave integrated circuit (MMIC) for X-band radar applications. It utilizes commercial 0.25 µm GaN-based high electron mobility transistor (HEMT) technology and delivers more than 20 W of output power. The developed GaN-based power amplifier MMIC has small signal gain of over 22 dB and saturated output power of over 43.3 dBm (21.38 W) in a pulse operation mode with pulse width of 200 µs and duty cycle of 4% over the entire band of 9 to 10 GHz. The chip dimensions are 3.5 mm × 2.3 mm, generating the output power density of 2.71 W/mm^2. Its power added efficiency (PAE) is 42.6–50.7% in the frequency bandwidth from 9 to 10 GHz. The developed GaN-based power amplifier MMIC is expected to be applied in a variety of X-band radar applications.

Key words : Power amplifier, MMIC, GaN, HEMT, X-band

Ⅰ. Introduction

Phased array systems were initially invented for use in military radar applications to detect aircrafts and missiles. However, these phased array systems are now also widely used in various civilian radar applications such as medical imaging scanners, meteorological radar systems, and so on. Phased array systems provide improvement in radar functionality and performance in terms of beam agility, effective radar source management, and conservative degradation with module failure. The current trend is toward active phased-array systems with a large number of distributed transmitter and receiver (T/R) modules. The active phased array is typically an active electronically scanned array (AESA), and this is a phased array in which each antenna element has its own T/R module.

A high power amplifier is one of the most important components in these T/R modules for an AESA system. In particular, solid state power amplifiers (SSPAs) are receiving much attention because they can replace electronic tube amplifiers now widely used in conventional radar applications, such as a magnetron tube and a traveling-wave tube amplifier (TWTA). These tube-type amplifiers

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have limitations such as low linearity and a high failure rate, although they can deliver very high output power. Moreover, they are bulky and heavy. For these reasons, SSPAs are replacing tube-type amplifiers.

The device technology platforms for SSPAs have been constantly improved in the past decades to include materials such as indium phosphide (InP), gallium arsenide (GaAs), and gallium nitride (GaN). Among these new options, the most promising candidate is the GaN-based high electron mobility transistor (HEMT) technology. Due to its inherent and outstanding material properties, such as a high breakdown electric field and a high saturation carrier velocity in comparison with those of GaAs-based and InP-based devices, a GaN-based power amplifier monolithic microwave integrated circuit (MMIC) has the potential to fulfill demands for high output power in various applications [1-2]. Although the GaN-based HEMT technologies are well developed, higher-performance GaN-based power amplifiers at higher operating frequencies are still popular research topics. Over the last few years, GaN-based power amplifier MMICs for X-band radar applications have been demonstrated [3-8].

In the work reported in this paper, we demonstrated a high performance power amplifier MMIC based on 0.25 μm GaN-based HEMT technology for X-band radar applications. The design specifications provide a small signal gain of more than 20 dB, a power added efficiency (PAE) of more than 35 %, and output power of more than 42 dBm in the frequency bandwidth from 9 to 10 GHz.

Ⅱ. Power Amplifier MMIC Design

The GaN-based power amplifier MMIC was designed using the 0.25 μm GaN HEMT process, and performed by a Wireless Information Networking (WIN) Semiconductor foundry. The 0.25 μm GaN HEMT at WIN shows a breakdown voltage of 120 V, a cutoff frequency of 24.5 GHz, a maximum oscillation frequency of 86 GHz, a PAE of 64%, a power density of 4.7 W/mm, and a small signal gain of 19 dB at 10 GHz with an operating voltage of 28 V.

The power amplifier MMIC consists of two stages, with a first stage 1.2 mm gate-width periphery, and a second stage 4.8 mm gate-width periphery. The second stage is called the power cell and is composed of four unit HEMTs for an output power above 42 dBm. The output was thus designed as a 4-to-1 combiner. The output power of the each unit HEMT device (eight fingers and gate width of 150 μm) was about 37 dBm from load-pull simulation at a center frequency. The first stage was composed of one unit HEMT in order to achieve high efficiency and proper overall gain response characteristics.

The schematic diagram of the designed two-stage power amplifier MMIC is shown in Fig. 1. The output matching network was synthesized for optimum output impedance. The input matching network was designed for small signal gain response and high efficiency. The inter-stage matching network was designed for considering proper small signal gain, power efficiency, and power matching, simultaneously.

In order to ensure unconditional stability of the power amplifier MMIC, a parallel RC network is adopted at the input of the each unit HEMT device [9] and series resistors are added to the gate bias lines. An odd mode oscillation is suppressed by a resistor connected in series between each adjacent unit HEMT device.

The circuit was then refined using an electromagnetic simulation tool, NI's AWR, in order to ensure minimum deviation between the model and the actual circuit layout. From the EM simulation results, output power of over 42.5 dBm and small signal gain of over 23 dB were obtained in the frequency bandwidth from 9 to 10 GHz.

III. Experimental Results

The standard process for AlGaN/GaN HEMTs is fabricated on 100 mm GaN-on-SiC wafers and GaN process platforms are fully capable of enabling MMICs design. Front-side processing includes active-layer isolation, ohmic contact, 1^{st} silicon nitride (SiN) passivation, NiAu-based T-gate, 2^{nd} SiN passivation, source-coupled field-plate formation, thin-film tantalum nitride (TaN) resistor, two interconnect metal layers, and metal-insulator-metal (MIM) capacitors. After front-side processing, wafer are thinned to 100 μm thickness. The back-side processing features via-holes [10]. The fabricated two-stage GaN-based power amplifier MMIC is shown in Fig. 2. The chip dimensions are 3.5 mm×2.3 mm.

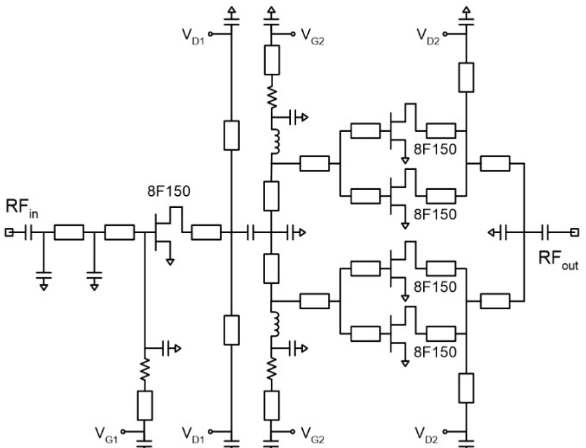

Fig. 1. Schematic diagram of the designed two- stage GaN-based power amplifier MMIC.

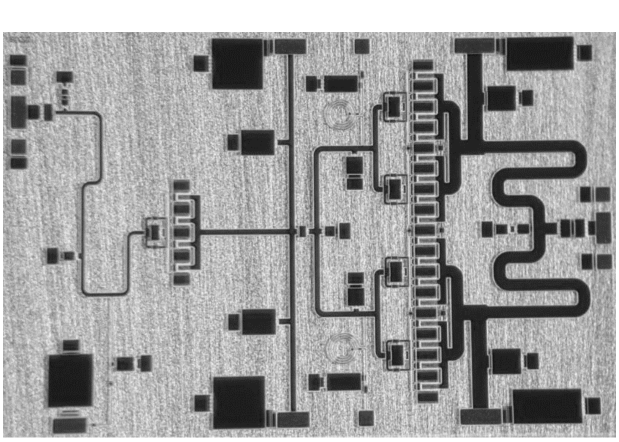

Fig. 2. Chip photograph of the fabricated two-stage GaN-based power amplifier MMIC.

The fabricated GaN-based power amplifier MMIC was soldered to a 40 mil-thick copper molybdenum (CuMo) carrier plate using AuSn eutectic bonding. Then, the CuMo carrier plate was assembled in an aluminum test fixture. The input and output bond pads of the fabricated power amplifier MMIC were connected to 50 Ω microstrip lines on a 10 mil-thick alumina substrate using Au wire bonding. The inductance of the bonding wires at input and output ports was considered during the circuit simulation. The other ends of the 50 Ω microstrip lines were connected to K-type connectors. A single layer capacitor (SLC) of 100 pF was mounted at the DC bias pads as a bypass capacitor. The in-fixture measurements were performed under pulsed test conditions with a pulse width of 200 μs and a duty cycle of 4% at room temperature.

Typical S-parameters of the fabricated two-stage GaN-based power amplifier MMIC are shown in Fig. 3 at drain bias of 28 V with a quiescent drain current of 0.3 A. The measured results are reasonably consistent with the simulated results. The small signal gain (S_{21}) is greater than 22 dB from 9 to 10 GHz. The input return loss (S_{11}) and output return loss (S_{22}) are better than -13 and -6.5 dB, respectively.

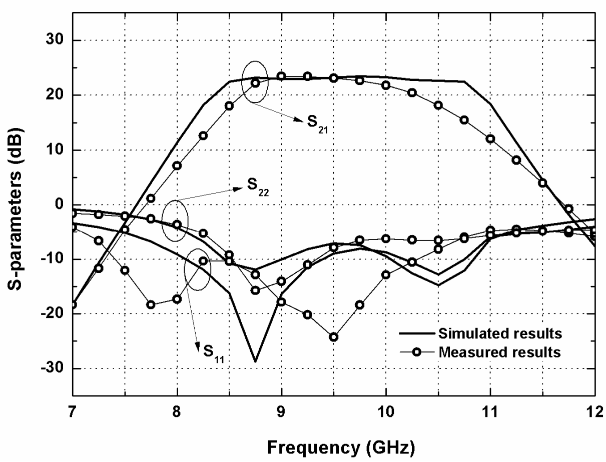

Fig. 3. Measured S-parameters characteristics of the fabricated two-stage GaN-based power amplifier MMIC.

Output power and power gain characteristics of the fabricated two-stage GaN-based power amplifier MMIC are shown in Fig. 4. Measured data shows that the saturated output power is better than 43.3 dBm at drain bias of 28 V in the frequency bandwidth from 9 GHz to 10 GHz.

Fig. 5 shows the drain current characteristics versus input power over the entire band of 9 to 10 GHz. The drain current at saturated output power (P_{sat}) is a typical 1350 - 1600 mA.

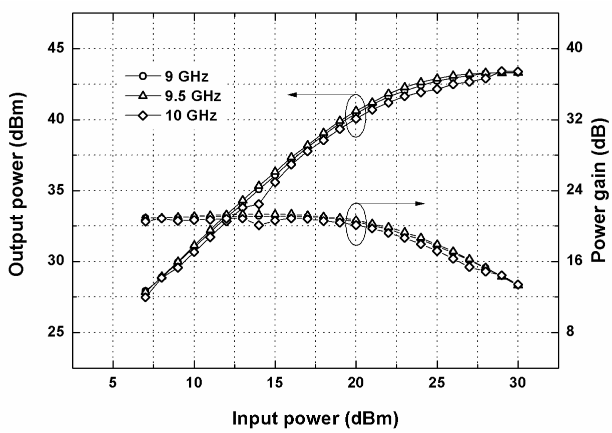

Fig. 4. Measured output power and power gain characteristics of the fabricated two-stage GaN-based power amplifier MMIC.

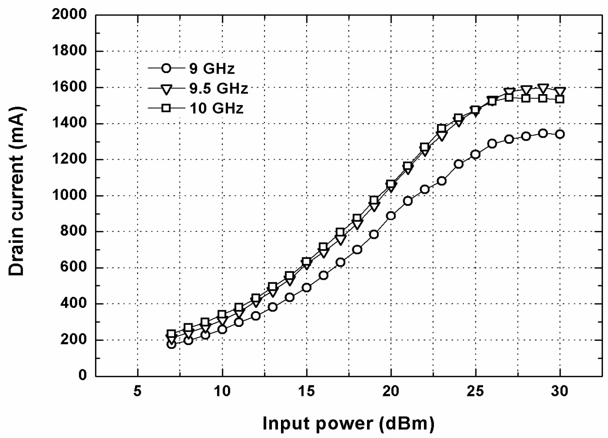

Fig. 5. Measured drain current characteristics of the fabricated two-stage GaN-based power amplifier MMIC.

Fig. 6 shows the saturated output power and power added efficiency (PAE) characteristics of the fabricated GaN-based power amplifier MMIC. The saturated output power is greater than 43.3 dBm (21.38 W), and the PAE is 42.6 - 50.7% over the entire band of 9 to 10 GHz.

All measured results of the fabricated power amplifier MMIC satisfied the design specifications.

Table I shows a comparison of the fabricated

Table 1. The comparison of the developed X-band GaN-based power amplifier MMICs with other reported data.

Frequency (GHz)	Device technology	Drain bias voltage (V)	Small signal gain (dB)	Saturated output power (dBm)	Power added efficiency (%)	MMIC area (mm^2)	Power density (W/mm^2)	Ref.
8.8-10.8	0.25 μm GaN	28	24-26	46	38-44	20.7	1.92	[3]
8.5-10.5	0.25 μm GaN	28	> 20	44.7	35-37	13.26	2.19	[4]
8.5-10.5	0.25 μm GaN	30	21.5-24	42.5	37.3	9.13	1.95	[5]
8.8-10.4	0.25 μm GaN	26	> 25	41.6	38-43	18	0.79	[6]
8.6-10.6	0.5 μm GaN	25	18.5	42	33	9.25	1.71	[7]
9-12	0.25 μm GaN	30	24	41.7	38.6-51.1	7.25	2.05	[8]
8.5-10.5	0.25 μm GaN	25	14-20	46.3	34-52	18	2.39	[11]
8.5-11.5	0.25 μm GaN	28	22	43.4	35-40	13.5	1.62	[12]
8-10	0.25 μm GaN	25	14-16.5	46	20-38	18	2.22	[13]
8.8-10.2	0.25 μm GaN	30	24-27	45	36-37	22	1.44	[14]
9-10	0.25 μm GaN	30	20	44.77	40	9.8	3.06	[15]
8-11	0.25 μm GaN	28	28	45.44	40	17.28	2.02	[16]
9-10	0.25 μm GaN	28	35	42.5	> 40	13.1	1.35	[17]
8.5-11	0.25 μm GaN	30	24	41.76	40	13.97	1.07	[18]
9-10	0.25 μm GaN	28	22-23.5	43.4	42.6-50.7	8.05	2.71	This work

GaN-based power amplifier MMIC results with those reported about other devices. The developed GaN-based power amplifier MMIC is very competitive in all performance aspects, including power density, compared with the previous state-of-the-art results, thus it is expected to be applied for a variety of X-band radar applications.

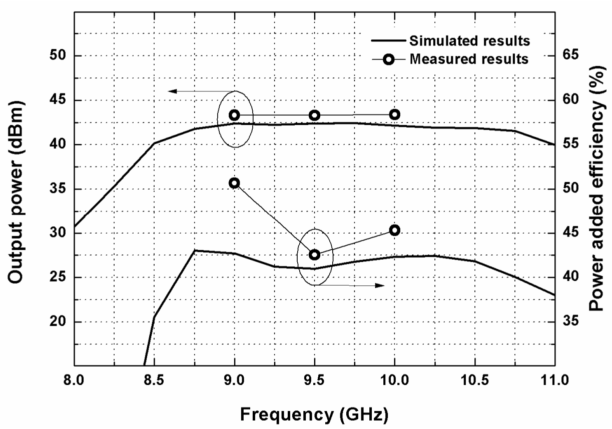

Fig. 6. Measured saturated output power and power added efficiency characteristics of the fabricated two-stage GaN-based power amplifier MMIC.

We expect the developed GaN-based power amplifier MMIC to be developed as a manufactured good using MMIC packaging technology.

IV. Conclusion

In this paper, we presented a GaN-based power amplifier MMIC for X-band radar applications. The device technology relies on the 0.25 μm GaN HEMT process. The developed power amplifier MMIC has a small signal gain of over 22 dB and saturated output power of over 43.3 dBm (21.38 W) in the frequency bandwidth from 9 to 10 GHz with pulse width of 200 μs and duty cycle of 4%. The PAE is 42.6 - 50.7% and the final chip dimensions are 3.5 mm × 2.3 mm. The developed two-stage GaN-based power amplifier MMIC is very competitive in all performance aspects, including power density, compared with previous state-of-the-art results, thus it is expected to be applied in a variety of X-band radar applications.

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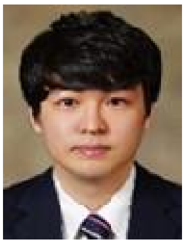

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