A 77-GHz MMIC Power Amplifier for Automotive Radar Applications

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***Abstract*—A MMIC 77-GHz two-stage power amplifier (PA) is reported in this letter. This MMIC chip demonstrated a measured small signal gain of over 10 dB from 75 GHz to 80 GHz with 18.5-dBm output power at 1 dB compression. The maximum small signal gain is above 12 dB from 77 to 78 GHz. The saturated output power is better than 21.5 dBm and the maximum power added efficiency is 10% between 75 GHz and 78 GHz. This chip is fabricated using 0.1-μm AlGaAs/InGaAs/GaAs PHEMT MMIC process on 4-mil GaAs substrate. The output power performance is the highest among the reported 4-mil MMIC GaAs HEMT PAs at this frequency and therefore it is suitable for the 77-GHz automotive radar systems and related transmitter applications in W-band.**

***Index Terms*—Millimeter wave, MMIC, PHEMT, power amplifier.**

I. Introduction

THE MOST commonly used frequencies in W-band (75–110 GHz) transceiver systems are 77 GHz and 94 GHz. The spectrum around 94 GHz is a well-known window for millimeter-wave (MMW) propagation in the atmosphere and has been used for a number of system applications for a long time [1]–[3]. Quite a few power amplifiers around 94 GHz have been reported using GaAs or InP-based PHEMT MMIC processes in recent years [4]–[10]. Most of them were fabricated using 0.1-μm gate-length PHEMT on 4-mil GaAs substrates [4]–[7]. The power amplifiers using more advanced MMIC processes, such as GaAs PHEMT on 2-mil thick substrate and InP-based HEMT, demonstrated better performance [8]–[10]. However, the standard 4-mil GaAs PHEMT MMIC process still has the advantage of lower cost at present, especially for the high volume applications.

Recently, the 77-GHz automotive radars became popular and can be found in literatures [11]–[16]. Power amplifiers were also designed and fabricated for these radar systems. The output power of the most reported 77-GHz power amplifiers were below 15 dBm [9], [11]–[16] except the one using 2-mil GaAs PHEMT [9]. In a typical automotive radar application, the transmitting power from the transceiver is 10 dBm at antenna port [20]. The worst case is that we have to consider the LO power to mixer, switch loss, and etc. Therefore, the required output power of the power amplifier is usually 17 to 19 dBm. A higher output power in the radar systems can certainly enhance the SNR and thus extend the detected range and range resolution. In this letter, we present a power amplifier using 4-mil GaAs 0.1-μm PHEMT MMIC process, which demonstrated an output power of 140 mW (21.5 dBm) and a power gain of 12 dB at 77-78 GHz. This output power result is the highest among all the reported 77-GHz power amplifiers designed for automotive radar systems using 4-mil GaAs-based HEMT MMIC processes [11]–[16].

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II. Circuit Design

In this power amplifier design, we used a 0.1-μm AlGaAs/InGaAs/GaAs PHEMT MMIC process on 4-mil GaAs substrate provided by TRW. The four-finger 80-μm device is selected for the power amplifier design. This device exhibits a typical gate-to-drain breakdown voltage of 6 V, peak dc transconductance of 600 mS/mm, maximum current of 600 mA/mm, unit current gain frequency f_T of 120 GHz and maximum oscillation frequency $f_{\max}$ of greater than 250 GHz at 4-V drain bias [17].

The power amplifier is a two-stage design, as shown in the block diagram of Fig. 1, with a single-end driver stage and the balanced configuration for the output stage. It comprises three identical PA units and utilizes two 3-dB Lange couplers to combine the two output PA units. The driver stage uses one PA unit to drive output stage.

The PA unit employs four cells of four-finger 80-μm HEMT devices and therefore the first stage has a total gate periphery of 320-μm and the output stage has a 640-μm gate periphery. The isolation resistors are placed between every pair of parallel devices to prevent the odd-mode oscillation. The output match was designed according to the power contour to achieve the maximum RF output power, while the input match is simply conjugate matched for input return loss. The dc blocking in the output is accomplished with a metal–insulator-metal (MIM) capacitor and a pair of coupled lines is used for input dc block as well as input matching. The radial stubs are used for in-band RF bypass network, and a 1-pF capacitor together with a shunt RC bypass network are used to ensure low frequency stability and out-of-band RF bypass.

The transmission lines, coupled lines, radial stubs, MIM capacitors and combining structures are simulated using the full-wave EM-simulator (Sonnet Software) [18]. The complete circuits are simulated using HP Series IV circuit design software

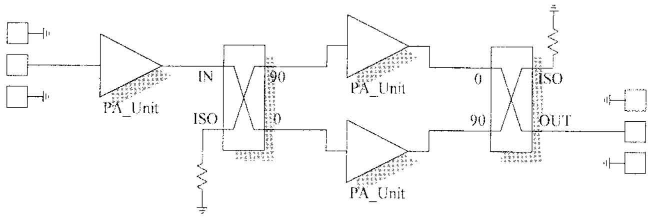

Fig. 1. Block diagram of the 77-GHz two-stages power amplifier.

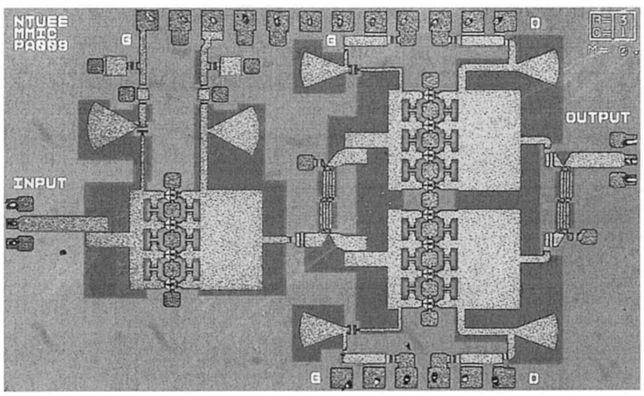

Fig. 2. Microphotograph of the MMIC power amplifier with a chip size of 3 × 2 mm.

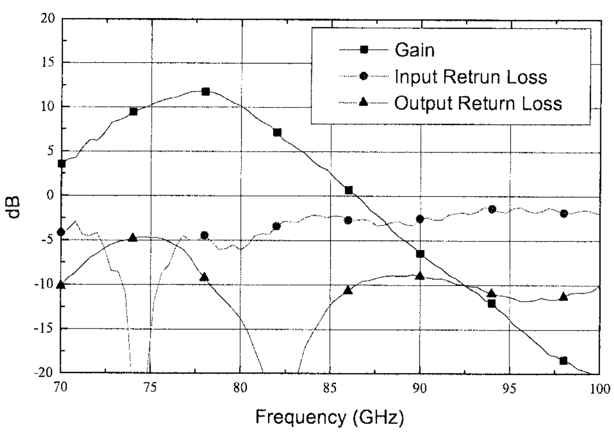

Fig. 3. Measured small signal gain and input/ouput return loss from 70 to 100 GHz for the power amplifier.

with the nonlinear HEMT model provided by TRW Inc. Fig. 2 is the microphotograph of the PA chip with a chip size of 3 × 2 mm^2.

III. MEASUREMENT RESULTS

The S-parameters measurements of the power amplifier were performed via on-wafer probing using Agilent V85104A millimeter-wave S-parameters test-set for 50 to 75 GHz and Agilent W85104A millimeter wave S-parameters test-set for 75 to 110 GHz.

The measured small signal gain and input/output return loss of the PA are plotted in Fig. 3. The small signal gain is above 10 dB and input/output return losses are better than 5 dB from 75 to 80 GHz, respectively, at the drain voltage of 4 V with gate voltage set 0 V for both of the two stages. The drain currents are 100 mA for the driver stage and 200 mA for the output stage.

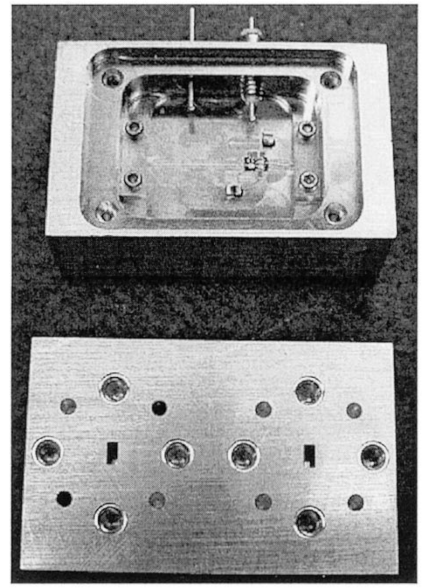

Fig. 4. Photograph of the packaged power amplifier module.

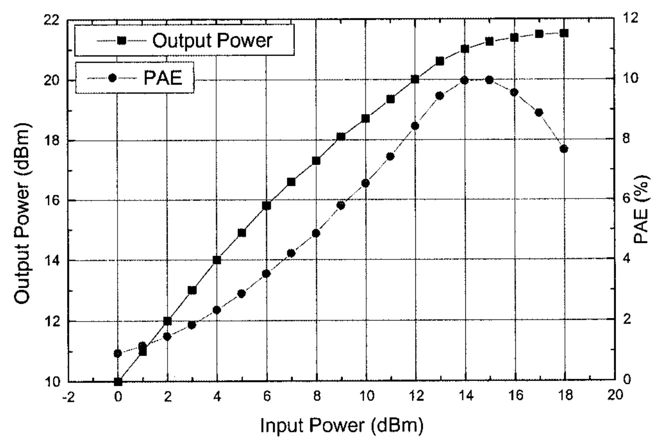

Fig. 5. Measured output power and power added efficient vs. input power plots at 77 GHz for packed power amplifier module. The data are corrected by the insertion loss of the transitions.

The PA chip was then tested in a packaged module with a pair of microstrip-line to WR-10 waveguide transition for output power measurement. The photograph of the package module is shown in Fig. 4. The microstrip line is constructed on a 0.005-in thick alumina substrate while the transition is on a 0.004-in thick alumina substrate. The thru line insertion loss of the test fixture with two microstrip-line to waveguide transitions is about 4 dB and the insertion loss of a single microstrip-line to waveguide probe transition is about 1.2 dB. The return loss is better than 10 dB cross entire W-band in room temperature.

The power measurements were performed with a Gunn source and a W-band power meter. The drain voltage is 4 V for both of the two stages with the drain currents of 100 mA for the driver stage and 200 mA for the output stage. The measured output power and power added efficient vs. input power results at 77 GHz for the monolithic power amplifier are plotted in Fig. 5, with all the data corrected by the insertion loss of the

TABLE I
COMPARISON OF PREVIOUSLY PUBLISHED 77-GHz POWER AMPLIFIER AND THIS WORK

MMIC TECHNOLOGY (All GaAs based)	CHIP SIZE	FREQUENCY	OUTPUT-STAGE TOTAL GATE PREIPHERY	SMALL SIGNAL GAIN	P-SAT /GAIN	PAE	OUTPUT-STAGE POWER DENSITY
2 mil 0.1-μm HEMT [9]	2.3 x 1.6 mm^2	72-81 GHz	1280-μm	8 dB	22 dBm	11 %	123 mW/mm
4 mil 0.15-μm HEMT [11]	1.5 x 1.2 mm^2	76.5 GHz	N/A	13 dB	14 dBm / 5 dB		
4 mil 0.15-μm HEMT [13]	0.5 x 0.6 mm^2	77 GHz	240-μm	8.5 dB	14.5 dBm / 2 dB		117 mW/mm
4 mil 0.15-μm HEMT [14]	1.5 x 1.2 mm^2	71-80 GHz	100-μm	13.5 dB	12 dBm / 9 dB		159 mW/mm
4 mil 0.13-μm HEMT [15]	2 x 1 mm^2	76.5 GHz	240-μm	10 dB	15 dBm / 7 dB		132 mW/mm
4 mil 0.12-μm HEMT [16]	2 x 1 mm^2	76 GHz	N/A	11 dB	13 dBm		
4 mil 0.1-μm HEMT (this work)	3x2 mm^2	77-78 GHz	640-μm	12 dB	21.5 dBm / 4 dB	10 %	219 mW/mm

transitions. It demonstrates 21.5 dBm (140 mW) output power with about 4 dB saturation power gain and 18.5-dBm output power at 1 dB compression. The maximum PAE is above 10% at 21 dBm output power and 7 dB power gain. The output power results at 75 GHz, 76 GHz and 78 GHz are similar to that of 77 GHz, as shown in Fig. 5. Those output saturation power levels are also greater than 21.5 dBm with PAE better than 10%. Recently reported 77-GHz power amplifiers results and this work are summarized in Table I. This power amplifier demonstrated the highest output power among all the reported 77-GHz MMIC power amplifiers for automotive systems using 4-mil GaAs HEMTs. The power amplifier has the highest power density compared with other reported 77-GHz MMIC PA results owing to its narrow bandwidth design and the process technology. Compared with the 94-GHz discrete power PHEMT results in [19], the discrete PHEMT showed an even higher power density (62.7 mW out of a 160-μm PHEMT, which is 392 mW/mm) at a higher frequency. This is due to that tuning for the optimal performance in a hybrid MIC amplifier is easier than doing that in an MMIC. The chip size of this amplifier is relatively large since it is a two-stage design with balanced architecture in the output stage.

IV. CONCLUSION

In this letter, we reported a W-band two-stage power amplifier using a 0.1-μm AlGaAs/InGaAs/GaAs PHEMT MMIC process on 4-mil GaAs substrate. A small signal gain of 10 dB, a maximum output power of 140 mW and maximum PAE of 10% have been achieved with a chip size of 3×2 mm^2. This power amplifier MMIC chip is suitable for automotive radar applications with requirements of longer range and higher range resolution.

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