A 77 GHz SiGe Power Amplifier for Potential Applications in Automotive Radar Systems

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***Abstract*—In this paper we present the performance of a 77 GHz power amplifier for potential applications directed towards automotive radar systems. The circuit was fabricated in a SiGe bipolar pre-production technology. A balanced two-stage common emitter circuit topology was used to achieve 6.1 dB of power gain at 77 GHz and 11.6 dBm output power at 1dB compression. The power amplifier uses a single 2.5 V supply and was fully integrated (including matching elements) to demonstrate its low-cost potential. First experimental results show its broad-band characteristic from 40 GHz to 80 GHz and its temperature dependence up to 130 °C.**

***Index Terms*—power amplifier, W-band, 77 GHz, automotive radar**

I. Introduction

The W-band frequency range is becoming increasingly important due to applications like 60 GHz personal area networks, IEEE 802.15, 77 GHz vehicular radar and growing military applications. Advanced SiGe bipolar technologies demonstrate promising operation at these millimeter-wave (MMW) frequencies due to continued improvement in their cutoff frequencies (f_T, f_{max}). However, the scaling of these processes to smaller dimension leads to lower breakdown voltages (BV_{CEO}, BV_{CBO}). This breakdown limit, caused by impact ionization, can be overcome to a certain extent if the bias circuit provides a low enough external resistance seen from the transistor's base [1], [2], [3]. Although the W-band is presently dominated by III-V semiconductor technologies, e.g. GaAs or InP-based PHEMT MMIC processes [4], SiGe is becomming increasingly important because it meets the demands of relatively high output powers while maintaining high integration levels at low cost [5]. In a typical automotive radar application the transmit power from the transceiver is 10 dBm at the antenna port [6]. But to overcome losses between the power amplifier and the antenna, even higher powers are considered. Higher output powers can also be used to improve the SNR, thus extent the detection range and the resolution. To investigate the potential of silicon technology in the W-band, a 77 GHz power amplifier has been implemented. This paper will present the design methodology, circuit architecture, and measured results.

II. SiGe Technology Used

The power amplifier was designed based on IBM's pre-production bipolar technology SiGe8T [7]. It is a 0.12 μm SiGe technology with a cutoff frequency $f_T \approx 207$ GHz and $f_{max} \approx 285$ GHz. The four-layer back-end of the line has three copper layers with thick aluminum as last metal for low loss interconnects available. The breakdown voltages are $BV_{CEO} \approx 1.7$ V and $BV_{CBO} \approx 5.5$ V.

III. Circuit Concept

The balanced power amplifier was designed to operate from a 2.5 V supply. The die size is 2.1 x 0.75 mm^2 and it draws 130 mA quiesent current. A two-stage circuit topology was used in order to feed a differential antenna structure directly, providing a 100-Ω differential impedance at the ampifier's input and output. Figure 1 shows a simplified schematic diagram of one half-circuit of the symmetrical class-AB biased balanced power amplifier. An on-chip feedback bias circuit is used to compensate for process and temperature variations as well as to smooth bias and gain control [8]. Each of the four power transistors has its own bias circuit. The bias transistor is closely spaced to the power transistors for good thermal coupling. The input transistor T1 has half the size of the output transistor T2, which defines a DC bias current ratio of 1:2 between the devices.

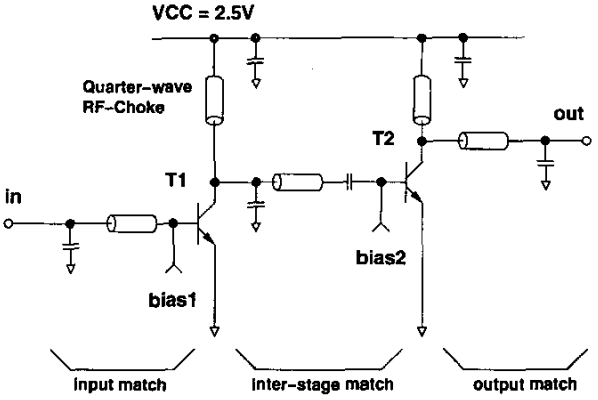


Fig. 1. Simplified schematic diagram of one side (half-circuit) of the balanced power amplifier.

Two major problems associated with the design of on-chip power amplifiers in an advanced SiGe bipolar technology are the low breakdown voltages and the high loss of the on-chip impedance transformation. The latter is caused by the conductive substrate, as well as thin metal and dielectric layers. In order to operate the transistor above breakdown, each bias circuit provides about a 300-Ω impedance seen from the transistor's base. This allows the collector-emitter voltage to swing $\pm$ 1.5 V around the 2.5-V DC bias voltage ($V_{CE,max} \approx 4$ V) without causing the device to break down. Note that this voltage is well above BV_{CEO}.

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Transmission line sections and shunt metal-insulator-metal (MIM) capacitors are used as (LC) resonant matching networks to provide the necessary impedance transformation from the external 50 Ω (half-circuit) to about 7 Ω at the collector of the output transistors. At 77 GHz a quarter-wavelength is ~480 μm, hence transmission lines are extensively used throughout the design. They have been implemented as 10 μm wide microstrips with side shields to minimize coupling to adjacent structures. Top layer metalization was analog-metal (AM, 4 μm thick) over a 0.3-μm thick copper ground-plane (MT) with a characteristic impedance of 50 Ω to comply with current density and electro migration design rules. Wide MT ground-planes have been used where possible to avoid electromagnetic fields to reach into the lossy silicon substrate, to minimize coupling and to limit the loss of the on-chip impedance transformation. Figure 2 shows a chip micrograph of the design.

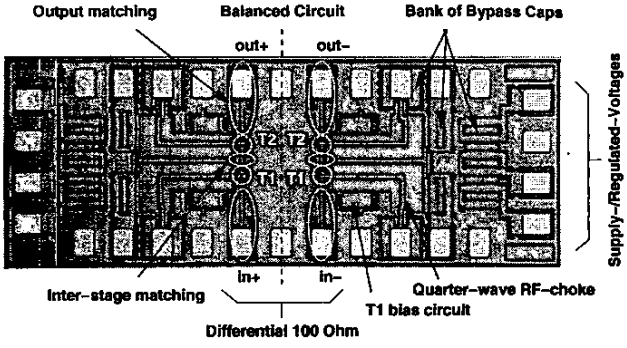


Fig. 2. Chip micrograph of the balanced power amplifier. The size of the power amplifier is 2.1 x 0.75 mm^2.

IV. First Experimental Results

In some radar systems the use of differential antennas is preferred because they provide a convenient way of power combining the outputs of two amplifiers at the antenna port. Therefore, a balanced circuit has been implemented to increase the total output power by 3 dB. Nevertheless, in a millimeter-wave measurement system a differential signal generation make high demands on equipment and external baluns are not readily available. To overcome that problem a wave-guide balun has been build to provide differential signals for the input to the power amplifier as well as for power combining the signals again at its output. Since the implemented circuit is balanced, symmetric, and well isolated from each other (see chip micrograph in Fig. 2) a common-mode to differential-mode conversion can be neglected, and it has been found that adding 3 dB to single-ended measurements give rise to the same results as a fully differential measurement with the external waveguide baluns. Therefore, all measurements presented in this paper have been measured on-wafer, single-ended into 50 Ω, and are representative for a differential operation of the power amplifier since 3 dB has been added to its input and output power. The input power was generated using an Anritsu synthesizer (69347B) in combination with an Anritsu millimeter-wave ×6 multiplier (54000-4WR10) followed by an external 77 GHz amplifier (Spacek) mounted closely to the probe. For on-wafer probing of the device, 110-GHz Picoprobes in GSGSG configuration have been used and the output power was detected with an calibrated Agilent 75–110 GHz power sensor (W8486A) at the output. Figure 3 shows the measured output power (P_{out}) and transducer power gain (GT) versus input power at 77 GHz. A transducer power gain of 6.1 dB has been achieved and the output power at 1dB compression (P_{1dB}) was 11.6 dBm. The highest output power was measured at 12.5 dBm, which was limited by the available input power to the device. A complete saturation of the amplifier is expected to be at least 3 dB higher than the 1dB compression (≥14.6 dBm). The power added efficiency at 1dB compression was 2.5 % and is peaking at 3.5 % at the highest measured output power of 12.5 dBm.

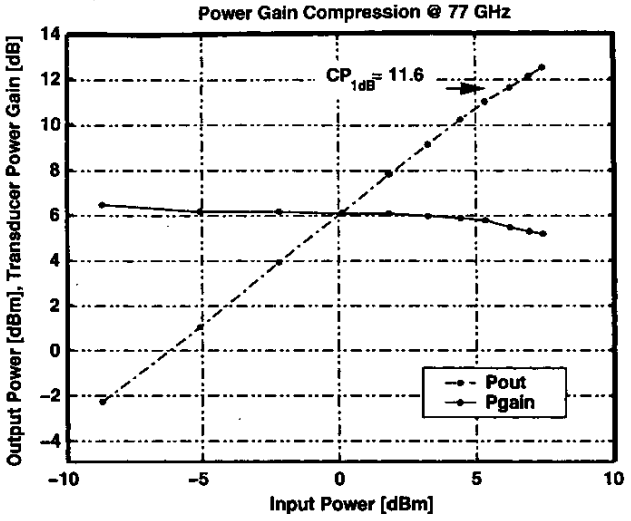


Fig. 3. Power Gain Compression at 77 GHz. A transducer power gain of 6.1 dB has been achieved and the output power at 1dB compression (P_{1dB}) was 11.6 dBm.

The temperature stability of the output power at 1dB compression has been measured and is shown in Figure 4. Good temperature stability of ±1.8 dB has been found between 5–135 °C even though the device is operated close to the peak of its (f_T,f_{max}) curve.

Figure 5 and Figure 6 show the small-signal S-parameters measured from 40 GHz up to 80 GHz. The maximum transducer power gain (GT_{max}) has been calculated and included in Figure 6 for comparison with the small-signal gain (S21). GT_{max} shows the maximum achievable small-signal gain if the amplifier would have been conjugately matched externally. The S21 is 13 dB at 40 GHz and drops down to 4 dB at 80 GHz. At 77 GHz the amplifier has a small-signal gain of 5.6 dB (GT_{max}=7.4 dB). Note that a power amplifier design for maximum power delivered to a load and optimum operation within breakdown limits requires a non-conjugated

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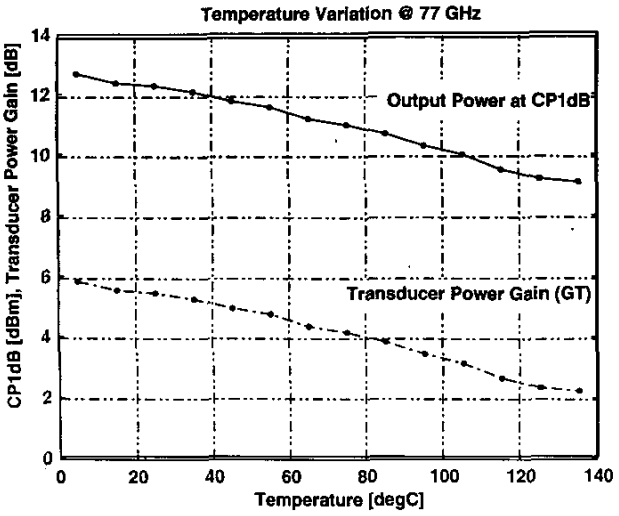


Fig. 4. Compression Point (P_{1dB}) vs. temperature at 77 GHz. A variation of ±2 dB has been measured.

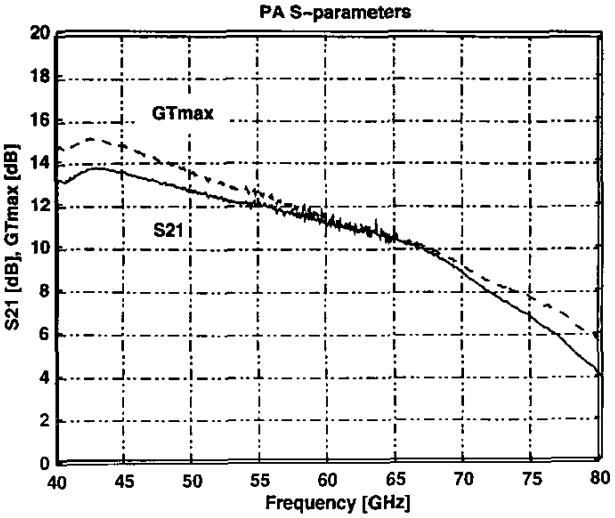


Fig. 6. Small-signal gain (S21) and maximum transducer gain (GT_{max}).

match. At 77 GHz the difference between GT_{max} and S21 has been traded for higher output power. Overall, the matching is rather broad-band and allows an operation over a wider frequency range from 40 GHz up to 80 GHz. The output match is below -10 dB from 40 to 75 GHz and the input match is better than -10 dB from 55 GHz up to 72 GHz.

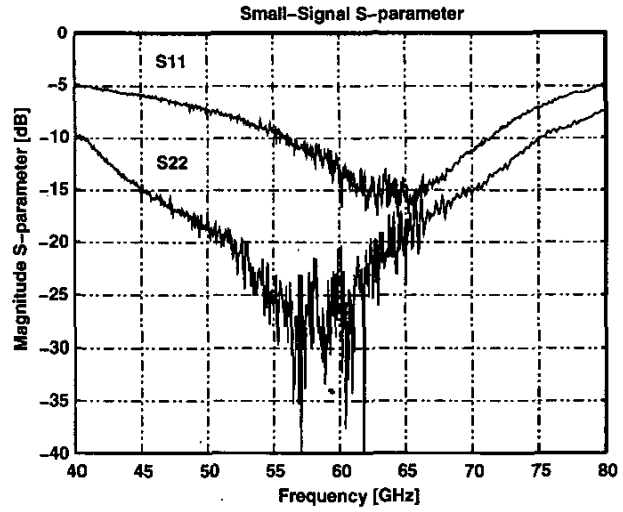


Fig. 5. Return loss (S11, S22) of the single-ended power amplifier.

V. Summary

The measured results for the power amplifier are summarized in Table I. All measurements have been measured on-wafer, single-ended into 50 Ω. The table lists the measured, single-ended, large-signal parameters separately from the differential operation (where 3 dB has been added to its input and output power). The small-signal S-parameters are shown at 76, 77, and 78 GHz. Lowest input return loss (-14.8 dB) was achieved at 63.7 GHz, and the output return loss minimum (-26 dB) was achieved at 58 GHz. The simulation results are shown for a 1.1-V supply, where the simulator converged and showed reliable compression point data. Addition measured results for a 60-GHz power amplifier, previously published in the visual supplements of [5], have been included in Table I for comparison purposes. The 60-GHz power amplifier has a similar circuit topology and bias condition, although it uses open-stub transmission lines instead of MIM capacitors in its (LC) resonant matching networks. The comparison shows similar gain compression for the 60 GHz power amplifier, a higher saturation power and transducer power gain was achieved at 60 GHz. In both cases the power added efficiency is low due to the class-AB bias condition. Future improvements will focus on different bias conditions and high-efficient circuit architectures.

VI. Conclusion

It has been demonstrated that SiGe pre-production technologies are well suited to generate high output powers at 77 GHz, which are required for automotive radar systems. The power amplifier has been fully integrated on-chip which shows its high integration and low-cost potential. For achieving maximum output power the output transistors have to be operated close to their breakdown and current density limits. First measurement results have been presented showing that SiGe based transistors in common emitter bias configuration are able to generate 11.6 dBm at their 1dB compression point with reasonable transducer power gain of 6.1 dB. This performance is comparable to power levels achieved in other Si-based technologies [9].

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TABLE I

SUMMARY OF MEASURED 77-GHz PA PERFORMANCE. THE 60-GHz DATA HAS BEEN PUBLISHED PREVIOUSLY AND IS INCLUDED HERE FOR COMPARISON PURPOSES.

DC Specification (T_A = +25°C,unless otherwise noted)

PARAMETER	Circuit			Units
	77 GHz PA		60 GHz PA	
	measured	simulated[1]	measured	
DC POWER REQUIREMENTS				
Voltage Supply, VCC	+2.5	+1.1	+2.5	V
Cuiesent Current[2], I_{DC}	130	75	150	mA
AC TEST CONDITION				
Frequency[3]	77	77	61.5	GHz
DFFERENTIAL LARGE SIGNAL[4]				
Compression Point, CP_{1dB}	11.6	9.5	11.2	dBm
Transducer Power Gain, GT	6.1	7.0	10.8	dB
Saturated Output Power[5], P_{sat}	12.5	13.5	16.2	dBm
Max Power Added Efficiency, PAE	2.5	6.5	3.0	%
SINGLE-ENDED LARGE SIGNAL				
Compression Point, CP_{1dB}	8.6	6.5	8.2	dBm
Transducer Power Gain, GT	6.1	7.0	10.8	dB
Saturated Output Power, P_{sat}	9.5	10.5	13.2	dBm
Power Added Efficiency, PAE	2.5	6.5	3.0	%
TEMPERATURE CHARACTERISTIC				
CP_{1dB}over Temperature [5,135]°C	±1.8	-	±2.0	dB
SINGLE-ENDED SMALL SIGNAL				
Frequency test condition[6]	[76, 77, 78]	[76, 77, 78]	[59, 61.5, 64]	GHz
Return Loss, S11	[-6.6,-6.2,-5.8]	[-13.2,-11.9,-10.8]	[-6.6,-6.2,-5.8]	dB
Output Match, S22	[-9.5,-9.1,-8.6]	[-18.8,-16.2,-14.2]	[-11.4,-8.9,-6.8]	dB
Reverse Isolation, S12	[-53,-46,-46]	[-44,-45,-46]	[-35,-33,-35]	dB
Small Signal Gain, S21	[6.1, 5.6, 5.0]	[7.7, 6.9, 6.1]	[11.8,10.2,8.3]	dB
Maximum Transducer Power Gain, GT_{max}	[7.8,7.4,6.9]	[8.0,7.3,6.7]	[12.4,11.6,10.9]	dB
S11 Notch	-14.8, 63.7	-18.3, 72.4	-23.6, 55.4	dB,GHz
S22 Notch	-26.0, 58.0	-25, 73.8	-20.8, 49.7	dB,GHz

[1] Shown for a 1.1-V bias, where the CP_{1dB} simulation converged

[2] Assumes balanced operation, single-ended operation will be half

[3] Unless otherwise noted

[4] Assumes balanced operation (inc. +3dB for P_{sat}, and CP_{1dB})

[5] Limited by available input power of the measurement equipment ($\geq$ 14.6 dBm expected)

[6] S-parameters listed below are given at this frequency test condition

VII. ACKNOWLEDGMENT

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