A Low-Voltage 77-GHz Automotive Radar Chipset

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Abstract — This paper presents the first complete 2.5V, 77GHz chipset for Doppler radar and imaging applications fabricated in 0.13µm SiGe HBT technology. The chipset includes a voltage-controlled oscillator with -101.6dBc/Hz phase noise at 1MHz offset, an 25dB gain low-noise amplifier, a novel low-voltage double-balanced Gilbert-cell mixer with two mm-wave baluns and IF amplifier achieving 12.8dB noise figure and an OP1dB of +5dBm, a 99GHz static frequency divider consuming a record low 75mW, and a power amplifier with 19dB gain, +14.4dBm saturated power, and 15.7% PAE. Monolithic spiral inductors and transformers result in the lowest reported 77GHz receiver saturated power, and 15.7% PAE. Monolithic spiral inductors and transformers result in the lowest reported 77GHz receiver saturated power, and 15.7% PAE. Monolithic spiral inductors and transformers result in the lowest reported 77GHz receiver saturated power, and 15.7% PAE.

Index Terms — Automotive radar, millimeter-wave receivers and transmitters, millimeter-wave imaging, low-noise amplifiers, power amplifiers, monolithic inductors and transistors.

I. INTRODUCTION

Using the latest SiGe processes with fT/fMAX above 200GHz [1], circuits for W-band radar and millimeter-wave imaging are under development. State-of-the-art demonstrations of silicon technology in W-band applications include circuit blocks at 77GHz [2]-[6], and 94GHz [7]-[9], [19], and 77GHz receivers and transmitters [10]-[14], [18].

A transceiver array is required in imaging applications, and therefore power consumption and reliability are critical. The power supply voltage of the SiGe mm-wave transceiver must be reduced from the nominally used values of 5.5V/3.3V [3]-[6], [8]-[14], to 2.5V, or even 1.8V [2]. Circuit architectures must be simplified to decrease the device count, further reducing power consumption, and improving reliability. Furthermore, the HBTs must be optimized for mm-wave performance. The simultaneous mm-wave and DSP demands of W-band imaging and radar systems make a fine lithography SiGe BiCMOS process [16] an attractive technology choice at mm-waves [15].

This paper presents a 2.5V, 77GHz SiGe BiCMOS chipset for automotive and mm-wave imaging applications. Unlike other efforts to date, this chipset contains all critical blocks (VCO, LNA, PA, mixer, and static frequency divider) required to fabricate a fully integrated 2.5V, 77GHz transceiver with PLL. In the following sections, an overview of the transceiver architecture is given, the novel aspects of each circuit block are described, and circuit measurement results over wafer splits and temperature are presented.

II. TRANSEIVER ARCHITECTURE

A block diagram of the direct conversion Doppler transceiver is shown in Fig. 1, where boxes with dashed lines indicate circuit blocks. The transceiver employs mm-wave baluns for single-ended to differential conversion, similar to [17]. The first stage of a static frequency divider is demonstrated to show that a robust PLL can be added to the transceiver. A robust, low phase noise PLL and VCO require MOSFETs, once again pointing to the need for a BiCMOS process for mm-wave radar and imaging systems [15], [16].

Fig. 1. 77GHz Doppler transceiver architecture.

III. CIRCUIT BUILDING BLOCKS

A. Low Noise Amplifier and Power Amplifier

The schematic of the LNA is shown in Fig. 2. The first two stages are common-emitter (CE) to allow 1.2-1.8V operation, and to minimize the noise figure. All stages are simultaneously noise and impedance matched using the techniques described in [9]. The LNA consumes a total of 40mW from 1.5V/1.8V supplies or 60mW from 1.8V/2.5V supplies. The simulated noise figure and gain are 5.3dB and 21dB, respectively.

Fig. 3 illustrates a simplified PA schematic. The later stages are common-emitter to minimize power consumption and maximize power-added-efficiency (PAE); the transistors and bias currents are scaled by a factor of 2 from stage to stage. In simulation, the PA achieves 23dB gain, 14.5dBm saturated output power, and 16.4% PAE.

Fig. 2. 1.8V/2.5V, 3-stage, 77GHz LNA schematic.
C. Voltage-controlled oscillator

The VCO schematic is shown in [7], along with the design methodology for minimum phase noise. In this bipolar-only version, the VCO is designed to provide 5dBm of differential output power and 4GHz of tuning range (5%) using HBT varactors, and consumes 135mW from a 2.5V supply.

D. Mixer, Balun, and IF Amplifier

A novel low-voltage, mm-wave, Gilbert cell mixer is illustrated in Fig. 4. To allow reduction of the supply voltage down to 2.5V, the RF pair is replaced by the secondary coil of a transformer, and the primary coil becomes the load inductor of the final LNA stage. A current source biases the mixing quad through the center tap of the secondary winding. The 2.5V design used here allows 1.5V swing per side (1.2dBm) at the mixing quad output, and consumes only 12.5mW. Using this mixer topology, the bias current in the mixing quad can be set independently without added current sources, unlike the conventional Gilbert cell.

The IF amplifier is a resistively degenerated differential pair with 50Ω load. Consuming 66mW, it provides 3dB of power gain and a simulated OP1dB of 6.5dBm at 1GHz IF. In simulation, the transformer, mixer, and IF amplifier together have conversion gain of 12dB at 1GHz IF, using a +1dBm 77GHz LO. Optimization of degeneration resistances and bias currents achieves high linearity without resorting to complex circuit topologies [4] that require higher supply voltage.

IV. MEASUREMENT RESULTS

The circuit blocks were fabricated in a 0.13µm SiGe HBT process (no MOSFETs) with several HBT profile splits with varied collector doping and emitter-base junction engineering. The SiGe HBT \( f_T / f_{MAX} \) for the technology splits are illustrated in Table 1. A die photo of the receiver, including LNA, VCO, and mixer with baluns and IF amplifier, is shown in Fig. 6. Measurement results are reported for wafer 5 (the “reference” split), except where explicitly indicated.

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>( f_T ) (GHz)</th>
<th>( f_{MAX} ) (GHz)</th>
<th>Collector doping</th>
<th>EB Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>250</td>
<td>290</td>
<td>Reference=C</td>
<td>Reference</td>
</tr>
<tr>
<td>3</td>
<td>245</td>
<td>280</td>
<td>C+</td>
<td>Reference</td>
</tr>
<tr>
<td>7</td>
<td>265</td>
<td>255</td>
<td>C++</td>
<td>Reference</td>
</tr>
<tr>
<td>2</td>
<td>260</td>
<td>240</td>
<td>C+++</td>
<td>Reference</td>
</tr>
<tr>
<td>6</td>
<td>275</td>
<td>275</td>
<td>C+</td>
<td>Scaled</td>
</tr>
</tbody>
</table>

A. Low-Noise Amplifier and Power Amplifier

The LNA gain (\( S_{21} \)) is shown in Fig. 10, measured at 1.8V/2.5V and 1.5V/1.8V supplies. The input return loss is shown in the same plot for different bias currents of the input transistor \( Q_1 \). The LNA gain was also measured over temperature, and over the wafer splits corresponding to Table 1, as illustrated in Fig. 11 and Fig. 12, respectively. The 3dB bandwidth extends from 81GHz to 90GHz with the highest gain of 25dB centered at 86GHz. Measured \( S_{11} \) and \( S_{12} \) are better than -20dB and -50dB, respectively. The measured OP1dB is +4dBm at 86GHz. Because a standalone down-converter was not available for W-band noise measurement, the LNA noise figure cannot be measured.

The saturated PA gain and output power were measured from 75-95GHz over temperature, as illustrated in Fig. 13, and, along with \( S_{11} \), across the technology splits, as shown in Fig. 14 and Fig. 16. In Fig. 15, measurements at 77GHz show the PA achieves small-signal \( S_{21} \) of 19dB, saturated output power of +14.4dBm, an OP1dB of 12dBm, and PAE of 15.7% (based on 161mW \( P_{DC} \)). \( S_{11} \) and \( S_{22} \) in the PA remain below -10dB from 64-89GHz on all splits; \( S_{11} \) is illustrated in Fig. 16.
B. Voltage-Controlled Oscillator

The VCO provides +5dBm differential output power at 77GHz (measured using a power meter), a tuning range of 4GHz, and as shown in Fig. 7 has a phase noise for W-band VCOs of -101.6dBc/Hz at 1MHz offset, or approximately -99.1dBc/Hz with linear averaging.

C. Mixer, Balun and IF amplifier

Depending on bias conditions, the mixer, with LO and RF baluns, achieves a differential to single-ended conversion gain of 8-11dB, and a noise figure of 12.5-14.5 dB for a -2dBm, 73GHz LO signal and a 1 GHz IF, as shown in Fig. 8 (a). The mixer noise figure is DSB but its value is pessimistic because the RF input of the mixer is broadband (50 GHz to 80 GHz) and multiple signal source harmonics (multiplier source) are present at the LO port of the mixer which have not been filtered out. The noise figure also includes the insertion loss of the transformer, larger than 2dB, at RF port of the mixer.

With a -2dBm LO signal at 77GHz, the OP1dB of the IF amplifier is +5dBm, as illustrated in Fig. 8 (b).

E. Static Frequency Divider

The static frequency divider achieves a self-oscillation frequency of 83.5GHz at 25°C and 66.9GHz at 125°C, the highest ever reported for a silicon frequency divider, while consuming a record low 75mW from a 2.5V supply. The previous silicon record was 76GHz at 25°C and 122mW from 3.3V [8]. The divider operates correctly up to 99GHz, as illustrated in Fig. 9.

V. CONCLUSION

A state-of-the-art low-voltage, small form factor chipset for 77GHz automotive and imaging applications has been reported. Measured results indicate excellent performance for all circuit blocks across temperature and process at 1.8V/2.5V. Table 2 summarizes the expected performance of a 500mW, 77GHz transceiver made using the circuit blocks presented. Results also show that the LNA and PA gains closely track the HBT $f_{MAX}$ across wafer splits. Wafer 5, with the highest $f_{MAX}$, shows the best overall circuit performance for all blocks.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Result</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Receiver IP1dB (1GHz IF)</td>
<td>-33 dBm</td>
<td>+5dBm OP1dB minus receiver conversion gain</td>
</tr>
<tr>
<td>Receiver conv. Gain (1GHz IF)</td>
<td>36 dB</td>
<td>With -2dBm 70GHz LO and (+-2dBm 77GHz LO)</td>
</tr>
<tr>
<td>Receiver noise figure</td>
<td>5.4 dB</td>
<td>LNA NF sim. Mixer NF meas.</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>&gt;2GHz</td>
<td>LO -2dBm, 73GHz</td>
</tr>
<tr>
<td>RF input bandwidth</td>
<td>9 GHz</td>
<td>-3dB bandwidth of LNA $S_{21}$</td>
</tr>
<tr>
<td>$S_{11}/S_{22}$ matching</td>
<td>&lt; -15 dB</td>
<td>Worst case for LNA and PA</td>
</tr>
<tr>
<td>Transmitter OP1dB</td>
<td>12 dBm</td>
<td>77 GHz meas.</td>
</tr>
<tr>
<td>Transmitter $P_{out}$ sat.</td>
<td>14.6 dBm</td>
<td>77GHz meas. &amp; PAE is 15.5%</td>
</tr>
</tbody>
</table>
Fig. 10. LNA S-parameters over supply.
Fig. 11. LNA $S_{21}$ over temperature.
Fig. 12. LNA $S_{21}$ for technology splits.

Fig. 13. PA gain over temperature.
Fig. 14. PA gain across technology splits.

Fig. 15. PA $S_{21}$, OP1dB, and $P_{SAT}$ at 77GHz

Fig. 16. PA Input return loss across technology splits.

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REFERENCES


