

# A Highly Linear SiGe Double-Balanced Mixer for 77 GHz Automotive Radar Applications

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*Student Paper*

**Abstract**—An active double-balanced mixer for automotive applications in the 77 GHz range is presented. The circuit includes on-chip baluns both at the RF and the LO port. The mixer was designed and fabricated in a 200 GHz  $f_T$  SiGe:C bipolar technology. The chip was characterized by on-wafer measurements. At 77 GHz, the conversion gain of the mixer is 11.5 dB. The single sideband noise figure at 77 GHz is 15.8 dB. The input-referred 1 dB compression point at 75 GHz is -0.3 dBm. Measurements across the wafer verified that this mixer circuit is robust against wafer inhomogeneities. The size of the chip is  $700\mu\text{m} \times 900\mu\text{m}$ . The circuit was designed for a supply voltage of 5.5 V and draws 75 mA.

## I. INTRODUCTION

The well-known advantages of Silicon-Germanium bipolar technology, like low-cost, small size, or high integrability, have recently been expanded to highest-frequency applications [1], [2], [3], [4]. The main application in the 77 GHz frequency range is automotive radar from 76 GHz to 77 GHz. Several building blocks have been published in III-V technology [5], [6]. Also front ends [7] or complete systems [8] in these technologies are available. Published mixers around 77 GHz show a moderate noise figure (SiGe:  $NF_{SSB} = 14$  dB,  $P_{In,1dB} = -30$  dBm, [9]) or a high input-referred compression point (GaAs:  $P_{In,1dB} = -6$  dBm, no noise figure reported [7]). Also at other frequencies, good results have been obtained (60 GHz, SiGe:  $P_{In,1dB} = -7$  dBm,  $NF_{SSB} = 13$  dB, [10]).

In this paper, a double balanced mixer with on-chip baluns in SiGe technology for a 77 GHz automotive radar system is presented. Due to the hard specifications of the automotive environment, a high dynamic range of the input signal must be expected. Therefore, high linearity of the mixer is a major design goal. On the other hand, since the mixer immediately follows the antenna, the noise figure of the mixer must stay at a reasonable level. Good temperature behavior is another demand from the strict automotive requirements.

## II. CIRCUIT DESIGN

The mixer presented in this work consists of a Gilbert-type mixer core, emitter followers as a buffer for the local

oscillator, and on-chip baluns for single ended to differential conversion. An RC - lowpass with a cut-off frequency of 5 GHz is the load of the mixer, improving the LO-IF isolation. A simplified schematic of the mixer is depicted in Figure 1. The mixer core cell is based on the Gilbert mixer presented

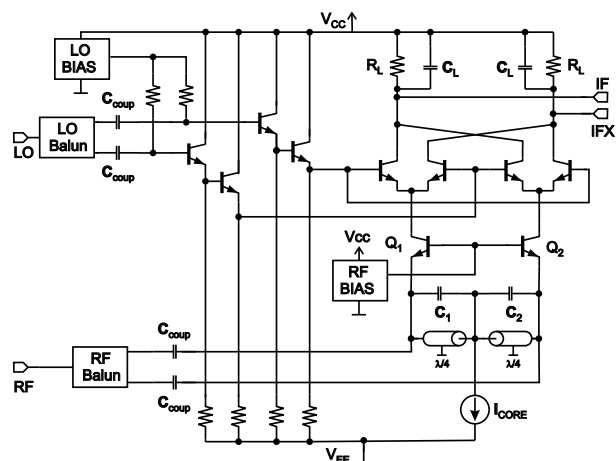


Fig. 1. Schematic of the Mixer.

in [11]. The LO signal is decoupled from the four switching transistors of the Gilbert cell by an LO buffer that consists of two emitter followers. The switching behavior of the four upper transistors in the Gilbert cell has a large influence on the noise figure of the mixer. Thus, the current density in the switching quad was chosen to result in maximum  $f_T$ . Two transistors in common-base configuration are used at the RF input of the mixer core. This topology increases the linearity. Opposed to the common-emitter configuration with resistive degeneration, the common-base configuration does not add noise contributors. Without the capacitors  $C_1$  and  $C_2$ , the RF input impedance of the mixer core is inductive in the frequency range from 75 GHz to 80 GHz. The capacitors  $C_{1,2}$  transform this inductive impedance to a real value. In this way, the matching of the RF path is improved significantly. Quarter-wavelength transmission lines are used to decouple the virtual

ground node from the RF signal path.

The LO and the RF baluns are LC-baluns where the inductors have been replaced with transmission lines [12]. With this type of balun, a single ended to differential conversion and impedance matching is achieved simultaneously. Figure 2 shows a schematic of the balun.

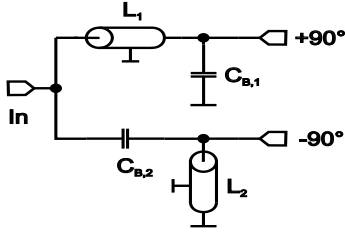


Fig. 2. Schematic of the Balun.

The current source of the mixer core is a current mirror. It feeds the mixer current of 20 mA through the virtual ground node to the mixer. This high current leads to higher linearity, a major design goal of this mixer. A drawback from this demand is the increased noise figure, resulting from the shot noise that is proportional to the current. Simulations show that 51% of the total noise power at the IF output come from the shot noise of the collector-emitter current in the common-base transistors and in the switching quad. The noise of the base resistances of these transistors add 28% to the total output noise power, which is the second largest component.

The bias networks at the LO port as well as at the RF port consist of level shifting diodes and resistors. High impedance resistors decouple the bias network from the signal paths.

### III. TECHNOLOGY

The mixer was implemented in an advanced 200 GHz  $f_T$  SiGe:C bipolar technology, based on the technology presented in [1]. The maximum oscillation frequency  $f_{max}$  is 275 GHz. Shallow and deep trench isolation are used. The transistors are fabricated with a double-polysilicon self-aligned emitter base configuration with a SiGe:C base. This base is integrated by selective epitaxial growth. The transistors have a minimum emitter mask width of  $0.35 \mu\text{m}$ , resulting in an effective emitter width of  $0.18 \mu\text{m}$ . The collector-emitter breakdown voltage of the HBTs at open base is 1.7 V. This technology provides four metal layers, MIM-capacitors, and different types of resistors.

Metal layer M4 over metal layer M2 is used for the design of the transmission lines. A  $5 \mu\text{m}$  wide metal M4 signal path over a metal M2 ground path yields a  $50 \Omega$  microstrip line. The maximum width of metal M2 is limited to  $15 \mu\text{m}$ . Therefore, a cheesed structure is used to expand the ground plane. A Matlab tool based on a 2D field simulator is used to model the transmission lines. Simulations show that the transmission lines at 77 GHz have a loss of 1 dB per millimeter, and an effective dielectric constant of 3.9.

### IV. EXPERIMENTAL RESULTS

Figure 3 shows a photograph of the fabricated mixer. The balun structures at the LO and the RF side and the quarter-wavelength transformers occupy most of the chip area. All

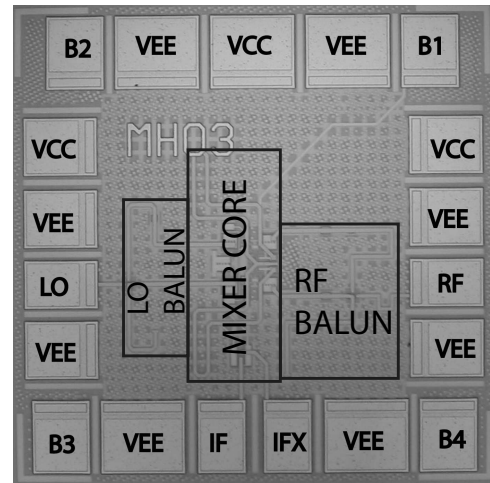


Fig. 3. Die photograph of the Mixer. Die size is  $700 \mu\text{m} \times 900 \mu\text{m}$ .

measurements were done on-wafer with probes. The temperature was kept at a constant level of  $25^\circ\text{C}$ , except otherwise mentioned. HP's 83650A synthesizer and appropriate frequency extenders were employed for the local oscillator (V and W band). The LO power level was set to 0 dBm. The mixer is designed for high impedance external loads, thus external voltage followers with an input impedance of  $100\text{k}\Omega$  were attached to the output of the mixer. This provides matching to the  $50 \Omega$  measurement environment. The differential IF signal was combined with a  $180^\circ$  low frequency hybrid from Minicircuits. All off-chip losses from the test setup have been de-embedded from the measurement results.

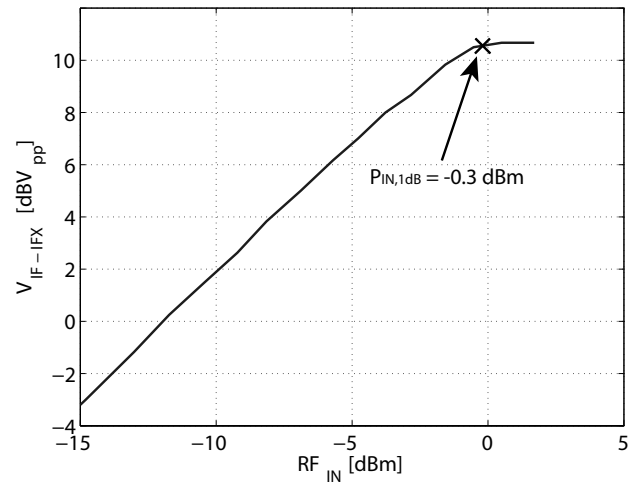


Fig. 4. Differential IF Output Voltage versus Input Power at 75 GHz, IF = 10 MHz

The plot of the differential IF output voltage versus the RF input power is shown in Figure 4. A  $\times 4$  frequency extender from Spacek Labs Inc. and a variable attenuator were used to measure the 1 dB compression point. At the output, HP's 8565EC spectrum analyzer was used to measure the output power. A 10 MHz IF was chosen for this measurement. Due to the external high impedance load of the mixer, the output voltage is depicted instead of the output power. The compress-

sion point was measured at 75 GHz because of the limited output power of the RF signal source at other frequencies in the desired range. The input-referred 1 dB compression point is -0.3 dBm, which is the highest value that has been reported for mixers operating in this frequency range so far. The differential saturated output voltage is 10.7 dBV<sub>pp</sub>, which is equal to a linear differential output voltage of 3.43 V<sub>pp</sub>. These values agree very well with the simulated results ( $P_{In,1dB} = 0$  dBm).

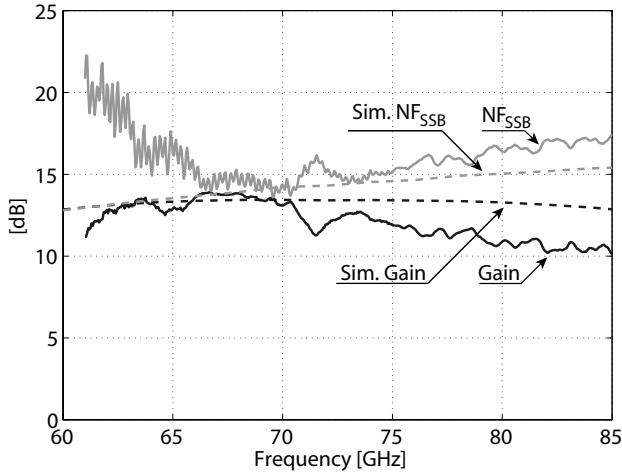


Fig. 5. Measured (solid lines) and Simulated (dashed lines) Single Sideband Noise Figure and Conversion Gain of the Mixer (IF = 10 MHz).

The noise figure was measured using HP's 8970B noise figure meter. The noise source was NoiseCom's NC5110. Due to the high ENR values (larger than 18 dB), an isolator (insertion loss < 2 dB) was used to improve the output matching of the noise source. The single sideband (SSB) noise figure and the conversion gain are depicted in Figure 5. The conversion gain is larger than 11 dB from 62 GHz to 79 GHz. The SSB noise figure is lower than 16.5 dB from 67 GHz to 79 GHz. The noise figure results mainly from the high current, see Sect.II. Regarding the application, the noise figure is at a reasonable level.

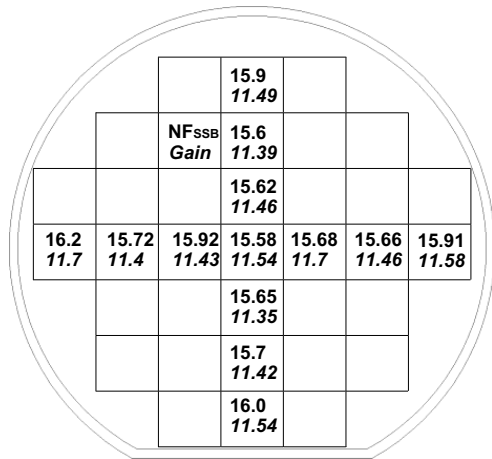


Fig. 6. Measured Samples of the SSB Noise Figure and Conversion Gain in [dB].  $f_{LO} = 77$  GHz,  $f_{IF} = 10$  MHz.  $\mu_{NF_{SSB}} = 15.78$  dB,  $\sigma_{NF_{SSB}} = 0.18$  dB,  $\mu_{Gain} = 11.5$  dB,  $\sigma_{Gain} = 0.11$  dB

Measurements across the wafer give information about the robustness of the circuit design against inhomogeneities of the wafer. Moreover, the reproducibility of the measurements can be determined. The conversion gain and the SSB noise figure were measured over 13 representative samples across the wafer, see Figure 6. At 77 GHz, the average SSB noise figure is 15.78 dB with a deviation of 0.18 dB. The average conversion gain is 11.5 dB with a deviation of 0.11 dB. The variations between the individual measurements are very low, demonstrating the homogeneity of the fabrication process and the robust circuit design.

The dependency of the SSB noise figure and the conversion gain on the local oscillator's power level is also important for the application. In Figure 7, these parameters are depicted for representative frequencies. The mixer works without perfor-

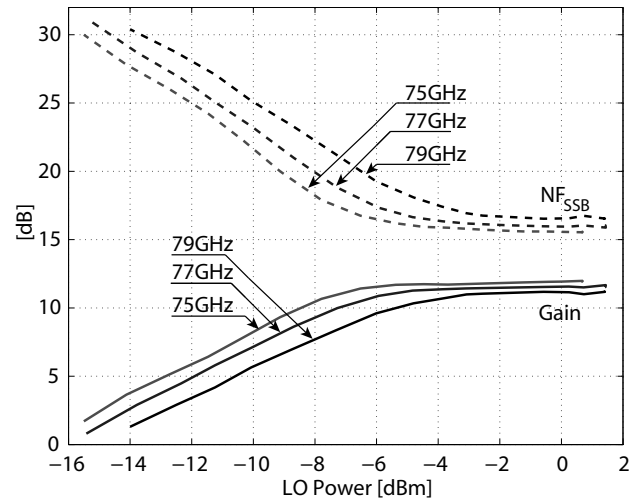


Fig. 7. Measured Single Sideband Noise Figure and Conversion Gain versus LO Power.

mance degradation down to an LO power level of -3 dBm or less, depending on the operation frequency.

The temperature behavior of the SSB noise figure and the gain are shown in Figure 8. In the desired frequency range, an increase in temperature from 10°C to 75°C leads to a noise figure degradation of 1.7 dB, while the gain decreases by 0.8 dB. This is a good result, regarding the large temperature span of 65°C. For higher temperatures, the noise figure and the conversion gain degenerate significantly. This results from the decrease in  $f_T$  and additional thermal noise.

The RF and LO port matching and isolation were measured using millimeter-wave probes and a 110 GHz network analyzer from Agilent. The results are shown in Figure 9. The RF port has a return loss larger than 10 dB (VSWR < 2 : 1) at a frequency range from 62.5 GHz to 83 GHz. The return loss of the LO port is larger than 10 dB at a frequency range from 68 GHz to 78 GHz. The LO to RF isolation is better than 19 dB in the target frequency range from 75 GHz to 79 GHz.

## V. CONCLUSION

A double balanced mixer with on-chip baluns was designed, fabricated in a SiGe:C bipolar technology, and characterized.

TABLE I  
PERFORMANCE SUMMARY OF PUBLISHED MIXERS

Reference	[4]	[10]	[7]	[9]	This Work
Technology	SiGe	SiGe	GaAs	SiGe	SiGe
Frequency Range [GHz]	122 – 124	57 – 64	76 – 77	76 – 81	75 – 79
NF <sub>SSB</sub> [dB]	-	< 13	-	< 14	< 16.5
Conversion Gain [dB]	23	> 9	-3	> 24	> 11
P <sub>In,1dB</sub> [dBm]	-	-7	-6	-30	-0.3
min. LO Power [dBm]	-4	-4	4	0	-3
Supply voltage [V]	-	2.7	-	-5	5.5
DC current [mA]	-	19.2 (with buffer)	-	60 (with buffer)	75
Chip size [mm <sup>2</sup> ]	-	2.5 × 1	1.24 × 1.8	0.55 × 0.45	0.7 × 0.9

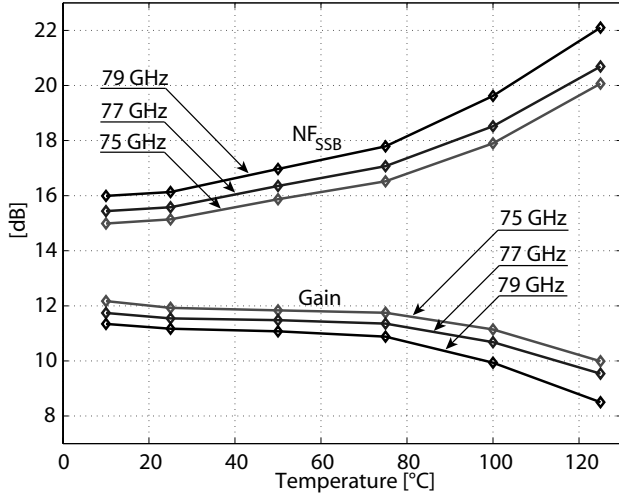


Fig. 8. Measured Temperature Dependency of the SSB Noise Figure and the Conversion Gain.

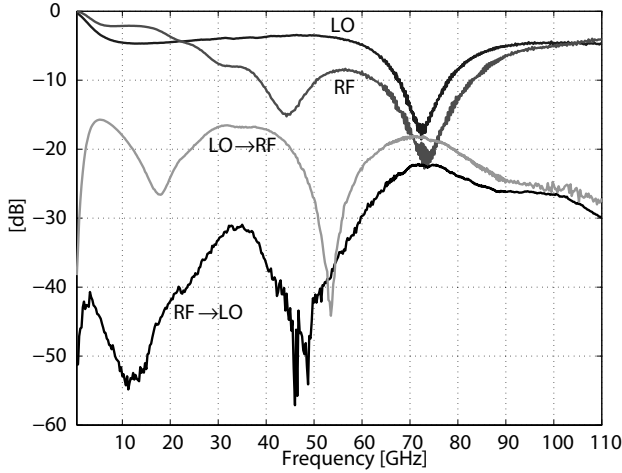


Fig. 9. Measured LO and RF Port Matching and Isolation of the Mixer.

The results are summarized in Table I. A comparison with state of the art mixers is also given there. The mixer features an input-referred 1 dB compression point of -0.3 dBm. The conversion gain of the mixer is between 11 dB and 12.5 dB in the target frequency range from 75 GHz to 79 GHz. The single sideband noise figure is between 15.3 dB and 16.5 dB in the same frequency range. The maximum differential IF output voltage is  $3.43 V_{pp}$ . The design of this mixer is robust against

wafer inhomogeneities.

The overall performance of this mixer shows that it is well suited for automotive radar applications. To the best of the author's knowledge, this is the first time that an integrated chip combining these good gain and noise figure values with such excellent linearity properties is presented at these high frequencies.

## VI. ACKNOWLEDGEMENT

The authors thank Infineon's technology team for the fabrication of the chips, and the team of DICE in Linz, Austria, for their measurement support. This work was supported by the German Bundesministerium fuer Bildung und Forschung (BMBF) under contract 10 M3161A (KOKON).

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