A Multi-Channel Rx for 76.5GHz Automotive Radar Applications with 55dB IF Channel-to-Channel Isolation

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***Abstract* — A multi-channel RX for automotive radar applications at 76.5GHz is presented. The chip uses a LO input signal at 38.25GHz which is multiplied on chip. The single-ended IF outputs show a noise density of -143dBm/Hz at 100kHz with a typical conversion gain of 18dB. The large signal IF channel-to-channel isolation is > 55dB. The 14mm^2 chip consumes 520mA from +3.3V supply in a 200GHz f_T SiGe BiCMOS process.**

***Index Terms* — Multi-channel, receiver, mm-wave, automotive radar, beam forming.**

I. INTRODUCTION

Recently transceiver chipsets for 77-79GHz automotive radar applications have been presented [1, 2, 3, and 4]. Automotive radar systems are designed to measure the distance to, the azimuth, and the relative speed of an object present ahead of an automotive vehicle for cruise control and/or anti-collision control. The detectable range of the radar system is defined geometrically by a beam emitted from or received by an antenna. Multiple beams increase the angular resolution. Beam forming, and in the special case digital beam forming, is achieved using multiple antennas, multiple receiving channels (phased array [2, 3]) and digital signal processing. No on-chip phase shifter needs to be controlled, thus the beam forming depends only on post processing algorithms. Presented in Fig. 1 is a typical radar system used for, but not only, digital beam forming. It consists of a transmitter with on-chip PLL [5], a control unit (MCU) [6] and a multi-channel receiver. This paper presents the design of a multi-channel receiver.

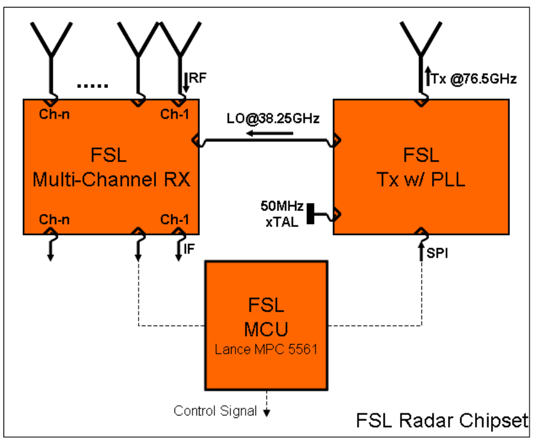


Fig. 1. Block diagram of a radar system example.

II. MULTI CHANNEL RX

The block diagram of the chip is shown in Fig. 2. The development of the topology used for this multi-channel RX was driven by the need to have a flexible RX-chip in terms of number of channels integrated on a single die, low power consumption, high channel-to-channel isolation, single-ended or differential IF output usage, and low LO input power level needed. The multi-channel receiver uses an LO signal at 38.25GHz. This signal is provided by the Tx chip presented in [5]. The usage of the LO at half of the Tx frequency (Fig. 1) allows to reduce the loss on board and of the bond transitions. The paper shows, as one possible realization, the performance of a 6-channel RX.

III. RX-CHANNEL

Each receiving channel consists of an input LC-balun, a low-noise mixer, and a two stage LO buffer. The balun is an LC-type structure where the inductors are implemented as transmission lines (TL). This enables simultaneous impedance matching and phase and amplitude symmetry.

The RX-channel does not use a LNA. Automotive radar systems require highly linear RXs which show also low gain variation over temperature. The IF range of a RX used for automotive radar applications is usually between few Hertz and 10MHz. Thus, the corner frequency for the noise figure (NF) of the receiver should be in the range of 10kHz. Due to pad limitation, only single-ended outputs are available for the presented multi-channel RX version.

The double balanced topology developed for the mixer is presented in Fig. 3. Compared to a standard Gilbert cell the RF-pair was split from the LO switching quad (as shown in [7]). This has several advantages. The current in the input RF-pair can be optimized to reduce the input referred noise and to increase the linearity. Thus, the transistors in this pair are biased with the current density needed to get the highest stable gain over temperature (60% of current density for maximum f_T). The LO switching quad is biased with much lower current in order to reduce the 1/f noise injected by the

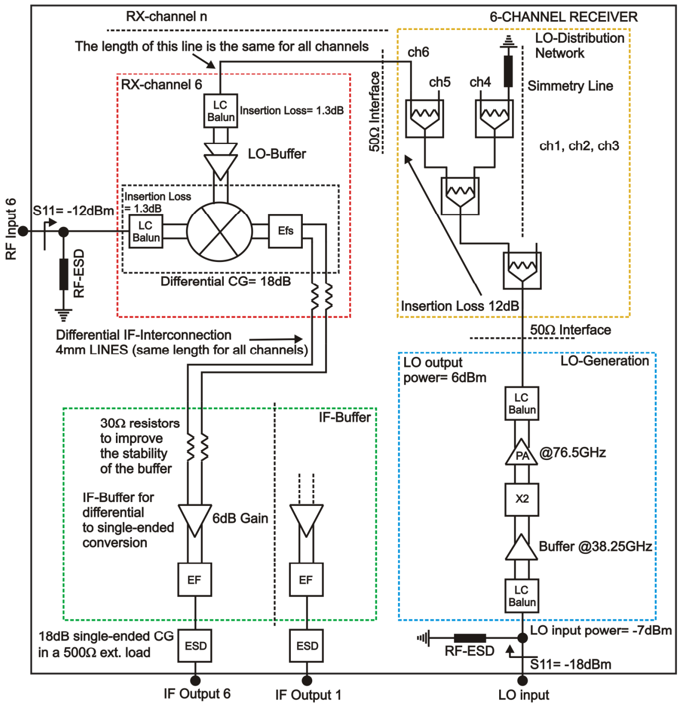


Fig. 2. Simplified block diagram of the 6-channel receiver.

four transistors (10% of current density for maximum f_T). The 2V headroom available at the IF output help to avoid the clipping in the mixer core. An extended transmission line (TL) network, consisting of $Z_{L6\text{-}8\text{-}12}$, between the RF-pair and the LO switching quad is employed for matching, and improved gain, linearization, and NF instead of a single TL as used in [5]. A 100Ω resistor is used as current source for the LO-pairs. The output impedance of the current source for the LO-pairs has a large impact on the noise performance of the RX in case of single-ended output. A low impedance results in a poor rejection of imbalance and mismatch. Thus, an increase of the NF of 5 to 10dB for IF below 200kHz is observed in case of single-ended output. By using a current mirror for the switching quad with 6mA in the reference path would have increased the output impedance of the current source. Thus, it could improve the imbalance rejection but at the cost, anyway, of an increase of the NF due to the noise injected by the current mirror itself. The linearity would have been also reduced due to the lower headroom available. Therefore, an IF buffer is used for differential to single-ended conversion. This buffer consists of two input emitter followers (EFs) and a differential pair extended with EFs at the output (Fig. 2).The first EFs are used for level shift and to buffer the 4mm lines which apply the signal to the differential pairs that are close to the pads. The differential pair with 200Ω emitter degeneration is driven by a current mirror with high output impedance and low impedance in the reference path. The EFs at the output can drive an external load larger than 500Ω. The differential conversion gain (CG) generated by the mixer is 18dB, enough to de-embed the noise of the IF-buffer. The differential voltage gain of the IF buffer is 6dB. The overall differential gain of one RX-channel is 24dB. This yields a single-ended gain of

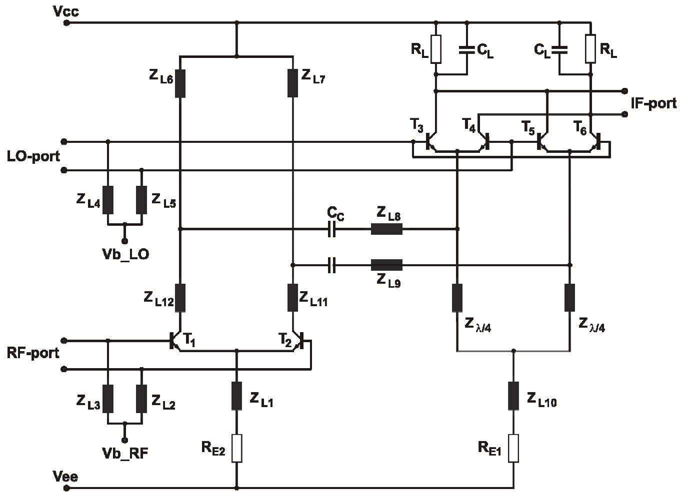


Fig. 3. Simplified schematic diagram of the proposed mixer. Bias network for Vb_RF and Vb_LO not shown. Z_L= transmission line implemented as microstrip line. $Z_{\lambda/4}$= λ/4@76.5GHz

18dB at the IF-output. λ/4 TLs are extensively used as RF-chokes to bias the RF and the LO pairs. This reduces the signal loss, improving the NF and CG. The two stages LO buffer included in each RX-channel consists of two cascode stages. The first stage amplifies the LO signal. The second stage limits the LO power to a level which saturates the CG over temperature but not overdrive the mixer. An RX-channel including IF and LO buffers draws 72mA from a 3.3V supply.

IV. LO GENERATION

Each Rx channels' LO signal is provided by an LO stage consisting of balun, 38.25GHz amplifier, frequency doubler, 76.5GHz PA, balun, and a highly symmetrical, passive LO distribution network (see Fig. 2). The 38.25GHz buffer consists of a cascode stage with inductive load. As shown in Fig. 4, a differential pair with connected emitters and collectors is the core of the LO doubler circuit. The antisymmetry (180° phase shift) of the signals taken from the collectors and from the emitters is forced by an AC-coupled λ/2 transmission line at 76.5GHz. The differential signal is then fed into a common-base stage that drives the 76.5GHz PA. Compared to the doubler with stacked cascode configuration [9], the presented topology has the advantage of equal bias conditions for the devices in the cascode stage, further improving differential operation, stability and signaling. The biasing circuits of all stages are again decoupled from the signal path by λ/4 at 76.5GHz TLs (except for the 38.25GHz path). The 76.5GHz PA consists of a differential cascode. The emitter-coupled pair and the common-base stage are AC coupled, allowing for operation under different bias conditions. As in the mixer-core, due to the split of the stacked configuration, a 2V headroom at the output of the PA is available. This allows achieving high output power with low voltage supply. Transmission lines at the output together with the LC-balun provide the load.

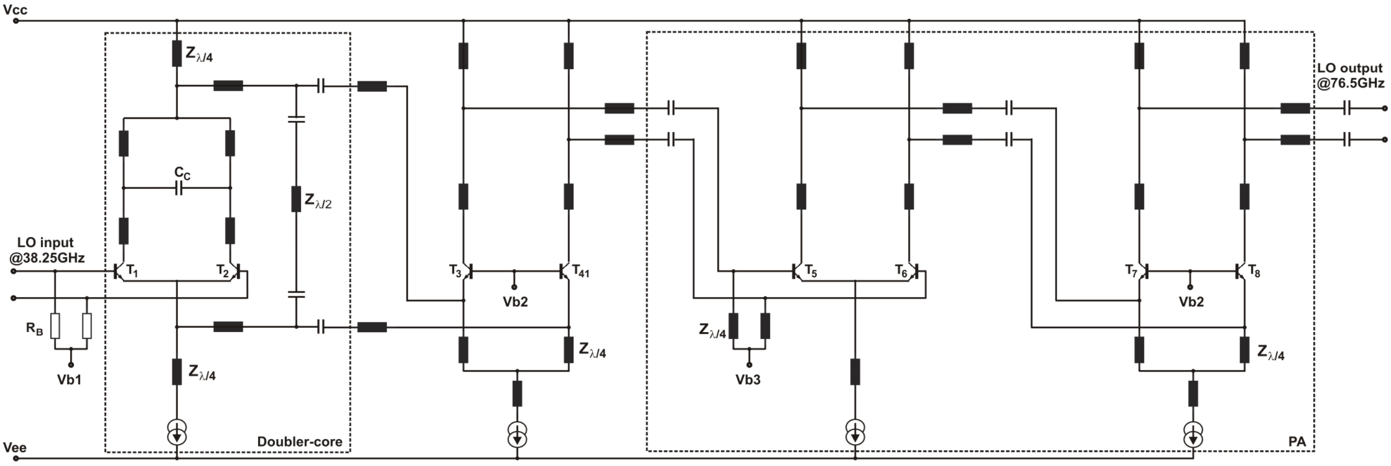


Fig. 4. Simplified schematic diagram of the proposed LO doubler and its output buffer. $Z_{\lambda/4}$= λ/4@76.5GHz. $Z_{\lambda/2}$= λ/2@76.5GHz

Separate measurements on a standalone doubler show a saturated output power between 8dBm at -40° C and 5dBm at 125°C for input power levels larger than -10dBm. The amplifier, doubler, and PA consume 90mA from a 3.3V supply. While the absolute phases of the received signals are of minor importance (they can be calibrated in the digital domain), changes in the phases due to the receivers changing characteristics must be identical for each channel. Thus, each receive channel must behave exactly as all the others under all operation conditions. Thus, all mixers are oriented in the same direction. Also, the LO distribution network (Fig. 2) exhibits exactly the same lengths, number of corners, and power division stages (Wilkinson dividers). The same number of corners is important since any corner adds an additional capacitance that causes a phase shift. The insertion loss of the LO distribution network is12dB.

V. Measurement Results

The 14mm^2 6-ch RX is fabricated in a 200GHz fT SiGe BiCMOS process [10]. It draws 520mA from 3.3V supply. A die photo is shown in Fig. 5. The IF pads and the Vcc pads are all on the bottom side of the chip. This allows an easier design of the board matching structure for the RF-paths. Each pad on chip is ESD protected.

A typical single-ended CG of 18dB is measured (this means that on chip the RX-channel generates 24dB). The drop of the gain at 125°C is max 2dB while at -40°C the gain increases by max 1dB. This temperature deviation can be improved by 1dB using a current mirror instead of the resistor R_{E1} in Fig. 3. In this case also the noise figure rises by 3dB for IF <100 kHz due to the noise injected by the current mirror itself. The input referred 1-dB compression point (P1-dB) is -8dBm. This value is only due to the clipping in the IF-buffer. The RX-channel without IF-buffer was measured on a separate test circuit. The differential CG and P1-dB are 18dB and -2dBm, respectively. This value for the linearity along with this gain represents a

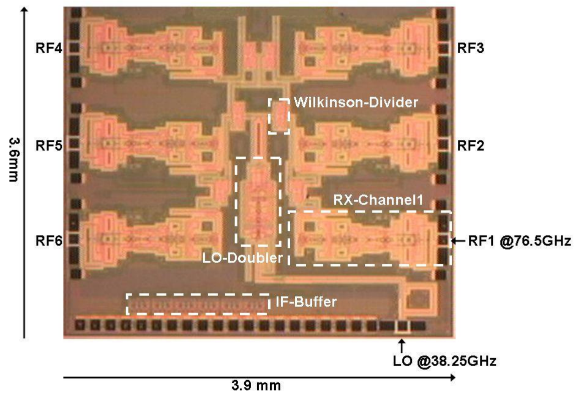


Fig. 5. Die Photo of the 6-channel RX chip.

record value for a 3.3V SiGe RX. The deviation of the CG between the channels is 0.5dB. These results were due to the symmetric LO and Vcc distribution on chip. The IF noise density at 100kHz is -143dBm(Hz). Using the gain method yields a single-side band NF (NFssb) of 13dB (Fig. 6) at 27°C at 100kHz which is 4 dB better than the previous reported value for a multi-channel RX without LNA [1]. At 125°C the NFssb raises up to 15dB only. At -40°C the NF is also degraded by 2dB. This is due to the larger LO signal generated at low temperature which slight overdrive the mixer. At 27°C the corner frequency for the noise figure is at 12kHz. The residual 76.5GHz LO power at the RF-port is at 27°C worst case -35.5dBm. This value does not change if the LO input power is swept from -10dBm up to 0dBm since the LO generation chain saturates the LO output power on chip. The split of the LO and RF pairs in the mixer was useful to reach such level. The large signal channel-to-channel isolation is presented in Fig. 7. The RX-channel is driven close to the compression. The isolation in this condition is still better then 55dB. The small-signal S_{12} between two channels on opposite sides, ch2 and ch5 e.g., is lower then 60dB. The S_{12} for two adjacent channels is lower than 42dB. This state-of-the-art isolation is achieved placing each Rx channel 1mm apart from the next channel and using a fully differential symmetrical design also for the IF signaling on chip.

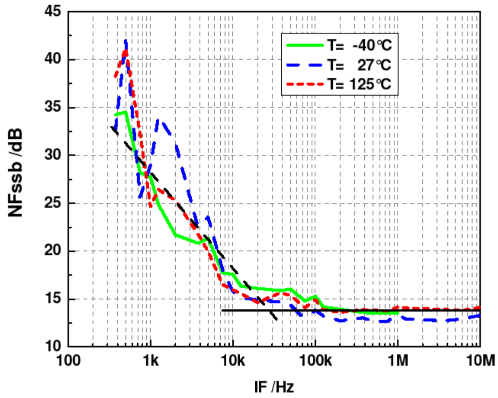
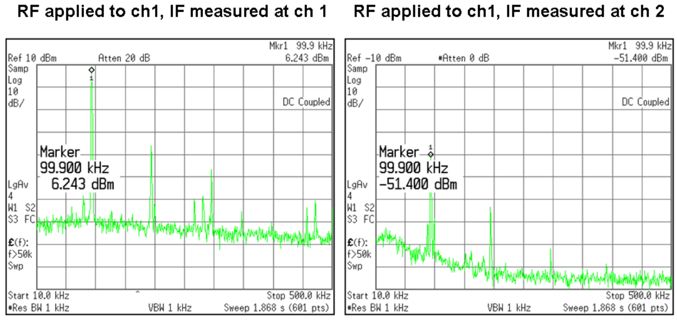


Fig. 6 NFssb measurement results.

TABLE I.
MULTI-CHANNEL RX FEATURES

Multi-channel RX Performance @ f_{IF}= 100kHz			
	-40°C	27°C	125°C
Nr. of RX-channel		6	
ESD [kV] (HBM)		1	
Voltage Supply [V]		3.3 ± 5%	
Current Consumption [mA]	580	520	470
Current Consumption for each RX-channel [mA]		72	
Current Consumption for the LO generation chain [mA] (to drive into saturation up to 8ch)		90	
Conversion Gain [dB] (single-ended gain; differential on chip is 6dB higher)	20 (26)	18 (24)	16 (22)
Ext. Load [Ω] (that can be driven by the IF buffer)		≥500	
P1dB [dBm] (input referred)	-9.8	-7.8	-6.4
Gain Saturation [dBm] (min needed LO power @38.25GHz)	<-20	-16	-10
IF Noise Density [dBm(Hz)]	-139.92	-142.83	-141.6
Noise $Figure_{ssb}$ [dB]	15	13	15
Corner Frequency Noise Figure [kHz]	12	12	12
S_{11} [dB] (LO-port @ 38.25GHz)		-18	
S_{11} [dB] (RF-port)		-12	
S_{12} [dB] (RF-ports, adjacent channels)		42	
S_{12} [dB] (RF-ports, channels on opposite sides)		60	
Large Signal ch-to-ch Isolation [dB]		55	
Max residual LO-power @76.5GHz @RF-port [dBm]		-35	
Max residual LO-power @38.25GHz @RF-port [dBm]		-80	



f_{RF} = 76.50001GHz, P_{RF} = -12dBm, f_{LO} = 38.25GHz, P_{LO} = -7dBm

➔ **Isolation = 57 dB**

Fig. 7. Large signal IF channel-to-channel isolation.

VI. CONCLUSION

A 6-channel RX for automotive radar systems has been presented. The chip has been fabricated in a low-cost SiGe BiCMOS technology which allows high level of integration. The performance of the chip are summarized in table I. The flexibility of the used circuit topology allows the implementation of a different number of RX-channel on a single die to satisfy the requirements of different radar systems.

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