75–85 GHz Flip-Chip Phased Array RFIC with Simultaneous 8-Transmit and 8-Receive Paths for Automotive Radar Applications

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Abstract **— This paper presents the first simultaneous 8-transmit and 8-receive paths 75–85 GHz phased array RFIC for FMCW automotive radars. The receive path has two separate I/Q mixers each connected to 4-element phased arrays for RF and digital beamforming. The chip also contains a build-in-self-test system (BIST) for the transmit and receive paths. Measurements on a flip-chip prototype show a gain >24 dB at 77 GHz, -25 dB coupling between adjacent channels in the transmit and receive paths (<-45 dB between non-adjacent channels), and <-50 dB coupling between the transmit and receive portions of the chip.**

Index Terms **— Automotive radar, Phased array, SiGe BiCMOS, transmitter, receiver, 77 GHz circuits.**

I. Introduction

Automotive radars have seen a lot of advances in the past 5 years due to the high degree of SiGe BiCMOS integration as demonstrated by Tyco, Infineon and Freescale [1]–[4]. SiGe is the preferred technology due to its high f_t/f_{max} (~200 GHz), very low $1/f$ noise (kHz corner frequencies), and high temperature operation (up to 120^oC) which are essential for automotive systems. In fact, SiGe is the only silicon technology which is currently approved for automotive radars, both at 24 GHz and at 77 GHz [1]–[4]. Phased arrays with 16–32 elements can enhance the performance of automotive radars by providing a narrow scanned beam before the receiver.

Recently, UCSD has shown a 16-element phased array receiver for automotive radars capable of scanning to $\pm 50^o$, and this receiver has demonstrated state-of-the-art FMCW imaging capabilities in real-time scenarios [5], [6].

This work presents the first simultaneous 8-transmit and 8-receive paths phased array RFIC for 75–85 GHz FMCW automotive radars (Fig. 1). The chip contains two separate I/Q mixers each connected to a 4-element array for RF and digital beamforming. The chip also contains a build-in-self-test system (BIST) following the principles introduced in [5]. The BIST determines the amplitude and phase of each channel, a normalized frequency response, and the system gain control using RF or IF gain control.

The chip is EM modeled and packaged using C4 flipchip techniques, and measurements are done at the board level which take into account all the coupling effects between the different channels (ground and supply inductance, LO feed-through, etc.). Also, extensive measurements are done to determine the coupling between the Tx and Rx paths, which can be detrimental in automotive radars.

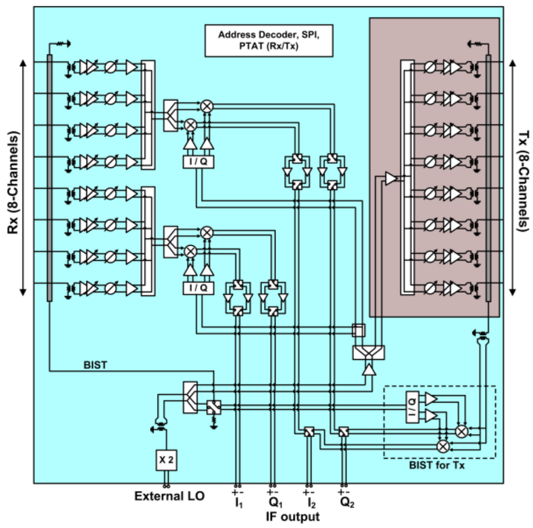


Fig. 1. Block diagram of the 8Tx+8Rx automotive radar chip with built-in-self-test for Tx and Rx channels.

II. Design

The block diagram of the 8-Tx and 8-Rx paths chip is shown in Fig. 1. The chip is fabricated in the IBM8HP SiGe BiCMOS process with f_t/f_{max} of 200 GHz and 0.13μm CMOS transistors. The transmitter is an 8-element phased array with amplitude (3-bit, 10 dB) and phase (5-bit) control, and is fed using a 37–43 GHz local oscillator using a doubler/amplifier chain. The transmitter output P_{sat} is designed to be 5 dBm per channel and 14 dBm in total. The receiver is divided into two separate 4-element phased arrays, each with its own I/Q mixer. This results in two distinct advantages as compared to an 8-element phased array receiver: 1) 4 distinct beams can be simultaneously formed at any angle in the azimuthal plane with sum and difference properties as shown in Fig. 2, which is essential in tracking systems, and 2) the equivalent receiver input P_{1dB} is improved by 3 dB as compared to an 8-element array if the linearity is limited by the mixer and not the

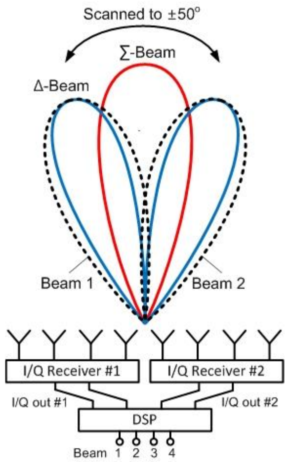
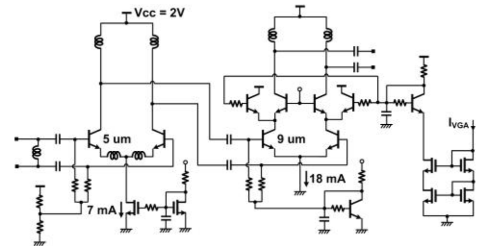


Fig. 2. Formation of 4 simultaneous beams using the two I/Q receivers.

channel (which is the case in this design). The channel (amplifier/phase shifter/amplifier) has a gain of 15 dB, a total NF of 9.5 dB and an input P_{1dB} of -11 dBm at 80 GHz.

Fig. 3 presents some of the building blocks used in the transmitter and high linearity receiver. The LNA uses inductive degeneration for improved linearity, and the phase shifter (used in both Rx and Tx path) is a high-linearity vector modulator with a gain of -3 dB and an input P_{1dB} of 1 dBm. The mixer also employs inductive degeneration with a separate gm-cell and a quad-cell so as to improve the voltage swing and increase the mixer linearity. The mixer consumes 18.5 mA from a 2 V supply, and results in a gain of 7 dB, a NF of 14 dB, and an input P_{1dB} of -1 dBm. Each mixer is followed a DC–5 MHz operational amplifier with a gain of 20 dB for FMCW radars and an output impedance of 150 Ω. Also, a DC–3 GHz differential amplifier can be connected using a pair of CMOS switches for UWB radar applications (this wideband IF is also suitable for Gbps communication systems). The entire system NF is 17 dB at an IF frequency of 100 kHz which is standard for automotive radars. The chip power consumption is 1.9 A from a 2 V supply.

The BIST of the receive path is accomplished using -26 dB couplers at each channel and the same receive I/Q mixers (see Fig. 1). However, in the transmit path, a separate I/Q mixer circuit is used for the BIST due to routing and crossover concerns. Also, the BIST distribution is done using a single-ended GCPW line for reduced loss and higher dynamic range as compared to [5]. Two different power supply planes and ground planes implemented on the chip: One for the Tx path, and another for the Rx path including the mixers, IF amplifiers, local oscillator and multiplier. This is essential for reducing the



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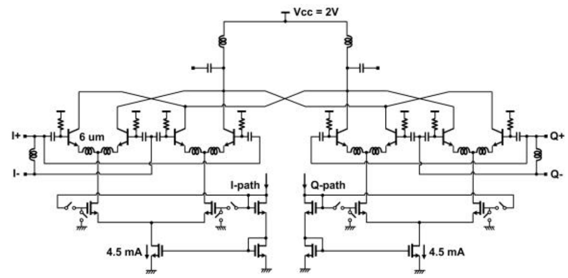

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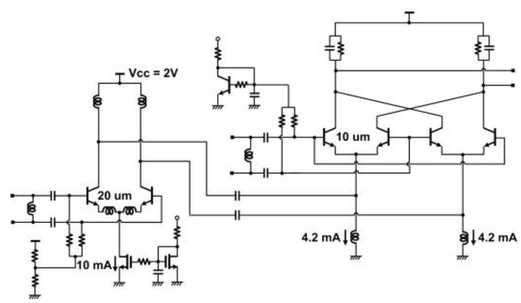


(c)

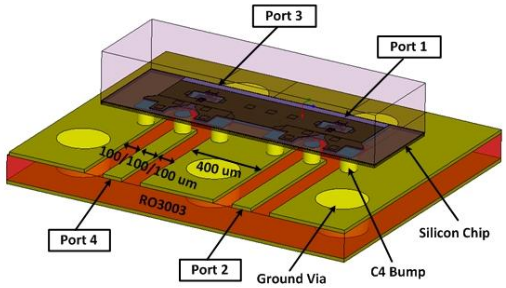
Fig. 3. Schematic of (a) the LNA/VGA, (b) high linearity vector-modulator (phase shifter), and (c) high-linearity mixer.

coupling between the Tx and Rx paths, and these blocks are connected with each other using differential RF lines. Finally, the chip is bumped using C4 bumps and flipchipped on a Rogers substrate. Full EM simulations is done using HFSS to estimate the bump inductance and its effect on the coupling between adjacent channels in the Rx and Tx paths (Fig. 4) The simulated coupling is <-35 dB at 80 GHz due to the low bump inductance. The flip-chip process also lands the chip on 2 different power supply rails which are each bypassed to ground using a set of small and large value capacitors.

III. MEASUREMENTS

Due to space limitations, measurements will be presented on the entire chip and not on the test circuits.

The flip-chip 8-Tx and 8-Rx phased-array RFIC is shown in Fig. 5 together with the reference planes defined on the Rogers substrate. Fig. 6 presents the measured receive gain (defined as voltage out at the IF port divided



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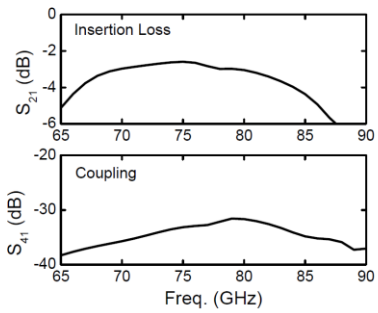
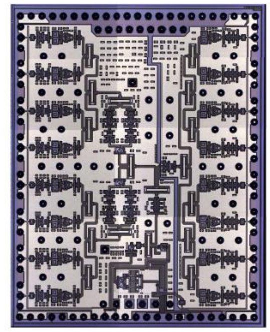


(b)

Fig. 4. (a) HFSS simulation set-up and (b) simulated S_{21} (insertion loss) and S_{41} (coupling) between the channels. The insertion loss includes the $|S_{11}|^2$ mismatch and is -1.7 dB when the ports are matched on the RO3003 substrate.



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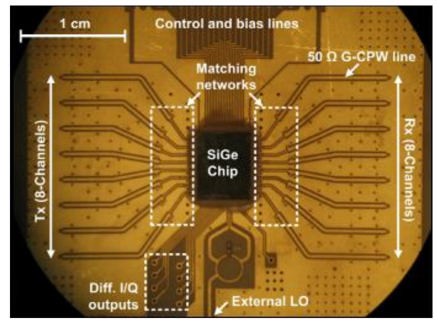


(b)

Fig. 5. (a) Microphotograph of the chip (4.5 x 5.8 mm^2), and (b) printed circuit board.

by voltage at the RF GSG port, where $P_{RF} = V^2/Z_o$), IF bandwidth for the DC–5 MHz amplifier, and gain control on the RF and IF paths. The gain includes 2.5 dB loss due to the ~2 cm long CPW line on the RO3003 substrate and the flip-chip transition. The I/Q mismatch was <0.5 dB and <10^o at 75–85 GHz. The phase shifter was tested separately (breakout circuit) and resulted in an rms amplitude and phase error of <1.5 dB and <10^o at 37–43 GHz was sufficient to achieve these values.

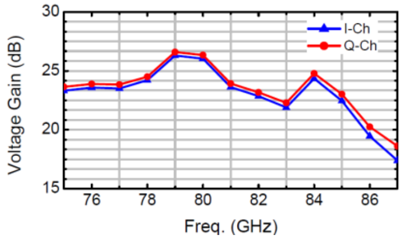
The measured output power vs. frequency at the GSG probes on the RO3003 substrate is shown in Fig. 7 for a representative channel, together with the measured output power for all channels at 77 GHz (2±1 dBm). This agrees with simulations for a P_{sat} = 5 dBm at the balun output (on-chip GSG pads), and 2.5 dB board loss. Again, an LO power of -4 dBm was sufficient to achieve these values, and there is ±1 dB difference vs. frequency over the 8 channels. The transmitter channels have the same phase response as the receive channels since similar phase shifters are used in both circuits. BIST measurements are not presented due to space limitations.

The coupling between neighboring channels located in the Tx and Rx paths is done using the technique introduced in [7], where one channel gain is measured with a fixed phase setting while the phase of the other channels are changed. The change in phase of the other channel modulates the gain of the test channel and this can determine the coupling factor. Measurements in both the Tx and Rx paths indicate a near neighbor coupling of -25 dB and a far channel coupling of <-45 dB (Fig. 8).

In order to determine the coupling between the Tx and Rx, two experiments were done: First, a receive channel gain (for example, channel 2) is measured while all 8 elements in the Tx section are toggled in phase from 0–360^o. The effect on the receive channel gain was minimal (<±0.03 dB variation), indicating a coupling <-55 dB which is much lower than the Tx antenna to Rx antenna coupling. Another test was to offset the Rx test signal from the 2 x LO signal by 5 kHz and 100 kHz, and measure the IF spectra at 5 kHz and 100 kHz with the transmitter section turned on or off. Again, no effect was seen on the phase noise at 5 kHz or 100 kHz IF showing no injection of signals from the transmitter section into the Rx section (Fig. 9).

IV. Conclusion

A 75–85 GHz phased array RFIC with simultaneous 8-transmit and 8-receive paths has been designed, fabricated, bumped, flip-chipped, and measured. EM simulation was used to design the flip-chip environment. Measurements indicate that all Tx and Rx channels perform as predicted,



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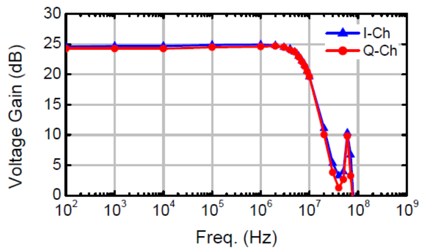
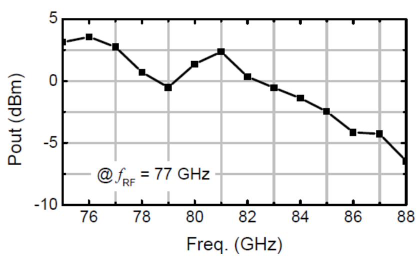


(b)

Fig. 6. Measurement results of the receiver. (a) Voltage gain versus frequency, and (b) IF amplifier bandwidth.



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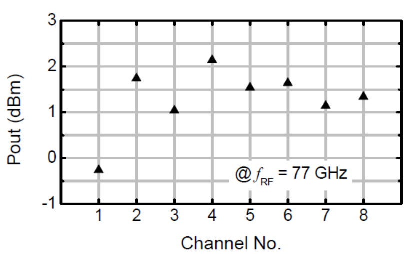

(b)

Fig. 7. Measurement results of the transmitter: (a) Output power versus frequency, and (b) output power for different channels at 77 GHz.

and that the coupling between the first neighboring channels in the Tx and Rx sections is -25 dB, and is -45 dB for all other channels Also, extensive measurements were done to determine the coupling between the transmit and receive sections of the chip, and was found to be <-50 dB at 75–85 GHz, which is excellent for FMCW radars.

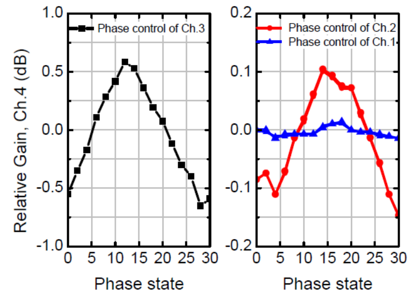

Fig. 8. Coupling measurement between different Rx channels. Similar results are achieved for the Tx channels.

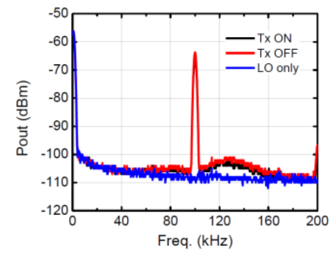

Fig. 9. IF spectrum with transmitter (8 ch) turned ON and OFF.

ACKNOWLEDGEMENT

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