# Advances in Compact Integrated Multichannel Millimeter Wave Radar Systems using SiGe BiCMOS Technology

(Focused Session on Highly-Integrated Millimeter-Wave Radar Sensors in SiGe BiCMOS Technologies)

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***Abstract*—In this publication an overview of the recent developments regarding compact multichannel radar systems is given. The chosen radar systems are all based on custom integrated circuits reported in literature from 2010 to 2017. Important specifications of the radar systems are compared to a 120 GHz SiGe:C based 2x8 FMCW MIMO radar sensor reported by us in in 2017 [1]. The technological differences of the integrated circuits used throughout the compared radar systems are discussed with respect to their advantages and disadvantages.**

## I. Introduction

The ongoing trend in Silicon based integrated circuits gave rise to many new technologies in recent years. The reduction in feature size on integrated circuits results in lower power consumption as well as higher transit-frequency and maximum frequency of oscillation $f_T/f_{max}$ of transistors in a given technology. As commonly known these advances enabled the availability of incredibly high digital processing power and vast amounts of memory in modern days. Less commonly known however is that this trend also gave rise to highly integrated RF systems such as integrated millimeter wave radio communication and multichannel radar systems. In this paper we present the recent advances in multichannel radar systems with ever increasing levels of integration by employing state-of-the-art SiGe BiCMOS technologies in particular.

The idea of using a multichannel radar system to allow the estimation of angle-of-arrival dates back to the early days of radar development in the 1940s [2]. These first systems used active switches for monostatic beamsteering. For historical reasons this was mainly driven by military applications resulting in large and expensive system approaches. Nevertheless aperture antennas have quickly been a crucial part of radar system development so that significant effort was invested in complete theoretical description and modelling of aperture radars [3]. The main draw-back of the phased array pushed forward at those days was the large effort required for calibration of hundreds of cascaded phase shifter all realized in hardware. With the availability of digital-processing in the 1970s digital-beam forming got into focus [4]. The estimation-of arrival was now not dependent on the realization of hundreds of phase-shifters. Instead the imaging could be separated from the actual data-acquisition process. Signal-processing quickly advanced driven by the increased need for data-capacity and the awareness of the limitations arising from the limited available bandwidth as described by Shannon. To deal with Shannon's limit spatial multiplex was seen as a possible way. It was discovered that not only the spectrum of the signal, but also the waveform's shape can be used to carry information. First Multiple-Input-Multiple-Output systems were established mid of the 1970s [5]. From that point it took several decades to transfer the MIMO approach to the field of radar imaging. In 2004 Fishler et al. stated that time has come to use the MIMO concept for modern radar system approaches [6].

In contrast to phased arrays, MIMO systems allow sparsening of the antenna array. The key feature of such systems is that each receiver can differentiate between the signals originating from different transmitter elements. This can be implemented by using one of the many multiplexing schemes that are also used for radio communication purposes. For $N$ transmitters every receiver sees $N$ different signals per measurement. Therefore, the effective number of measurements of a MIMO array is the number of transmitters $N$ times the number of receivers $M$. In fact, each transmitter-receiver combination can be seen as a so-called virtual element making a MIMO array with $N + M$ transmitters and receivers equivalent to a classical (non-sparse) array of $N \times M$ antennas. Especially for large numbers of elements this dramatically decreases the number of antennas and thus the system hardware effort. Naturally this improvement comes at the cost of reduced RF dynamic range compared to a non-spare phased array. However indoor and close-range application scenarios do allow trading off power budget in order to simplify the RF module design. The MIMO technology has scaled down the effort for radar based imaging to a level where it gets feasible to be used for commercial applications. One of the most prominent example are the MIMO body scanners now used at airport checkpoints first reported in 2011 [7]. Full 3D body imaging is obtained with no need for mechanical movement while obtaining a resolution of a few millimeters. More compact designs were developed for environmental screening for automotive or airborne applications in 2017 [8], [9].

To miniaturize radar imaging modules the frequency of operation has to scale up accordingly to maintain the image resolution. Angular resolution of a radar is given by the

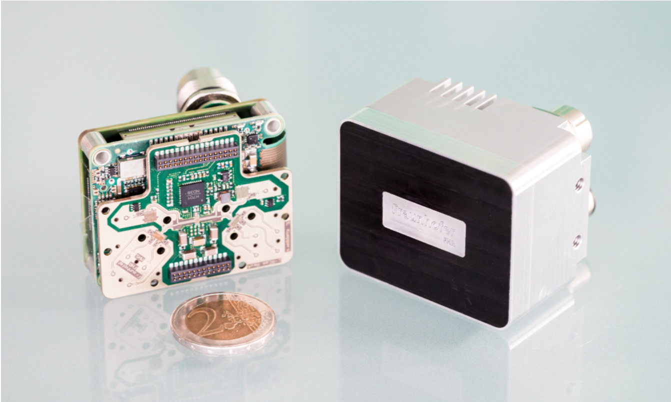

Fig. 1: Photograph of 2 × 8 MIMO radar system demonstrator from [1]

aperture of the radar in wavelengths [10]. For high resolution imaging with small modules millimeter wave technology can be used. The technological limit arises from the fact that the virtual element spacing should not get larger than half a wavelength to avoid grating lobes in a traditional MIMO radar design. This can be overcome by further sparsening the elements. Depending on the position of the elements grating lobes can be smeared to maintain a given suppression. For arrays with randomly distributed elements the mean sidelobe level scales inversely with the number of elements [10]. However, the actual sidelobe distribution depends on the individual aperture design. The design challenge is therefore to find a distribution of transmitter and receiver elements which fulfills the requirements with respect to image dynamic range, and feasibility regarding front-end realization with acceptable effort thus keeping the number of transmitters and receivers to a minimum. An innovative approach realizing this trade-off at 120 GHz is presented in this paper. This will be compared with competing approaches to provide a brief technological review over todays state of the art in MIMO radar imaging.

## II. Reference System

In 2017 we presented a multichannel radar system [1] using a novel MIMO antenna array aperture as described in [11] that has been designed for emergency service robots to explore low visibility environments using the MIMO imaging technique. The radar sensor is shown in Fig. 1 and measures 50 mm × 40 mm × 30 mm. The device contains all required RF and digital circuits to operate as a standalone system connecting to the outside world using a Gigabit Ethernet connection. The utilized antenna array provides 30° field-of-view with a spatial resolution of 15 cm in 1 m distance and a maximum sidelobe level of −8 dB. The total power consumption of the system is 7 W at 12 V.

Fig. 2 (left) shows the topmost RF circuit board containing the integrated circuits and RF components required to implement the 120 GHz radar operation. To achieve the required degree of system integration three different custom integrated circuits have been developed (blue rectangles). The development of the custom integrated circuits has been carried out in the B11HFC 130 nm SiGe:C BiCMOS technology by Infineon Technologies AG [12]. The technology features 130 nm SiGe:C heterojunction bipolar transistors with 250 GHz/370 GHz $f_T/f_{max}$, RF capacitors and resistors, 4 thin and 2 thick copper metal layers as well as an aluminium pad layer.

In the center of the RF circuit board a 30 GHz oscillator circuit from [13] has been used achieving a phase noise of −107 dBc Hz$^{-1}$ with 1 MHz offset frequency at 30 GHz and provides a tuning range of 6.78 GHz (24.5 %). This VCO is used to provide the generated chirp signal for each RX and TX circuit in the radar system frontend. Besides a fundamental VCO this integrated circuit contains a divide-by-8 frequency divider to allow frequency stabilization using a commercial off-the-shelf phase locked loop IC (yellow rectangle). The generated reference clock is distributed to the single-channel transmitter and 4-channel receiver circuits. Each of those integrated circuits contains a frequency quadrupler from [14] in order to regenerate the 120 GHz local oscillator for radar operation. To reduce complexity of the distribution network the frequency quadrupler building block has been designed to work from a single-ended source with as low as −20 dBm input power at a total power consumption of 132 mW. This on-chip frequency quadrupler block is used to drive the downconversion mixer in the integrated receive circuits for homodyne FMCW operation. In the single-channel transmit

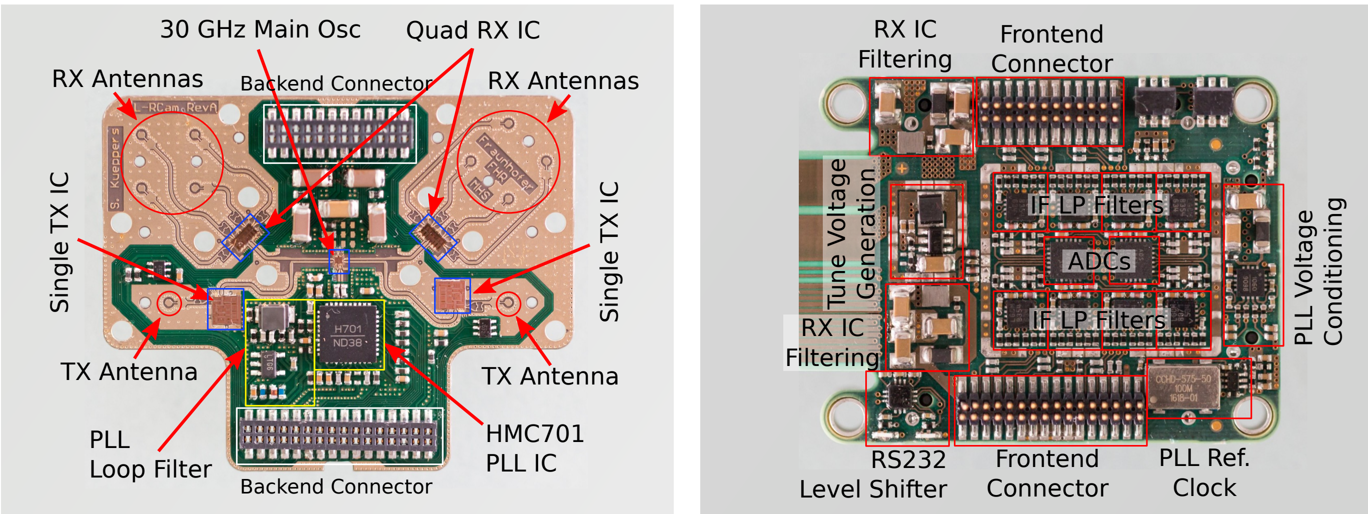


Fig. 2: Radar System Hardware (Left: Frontend, Right: Backend)

| Ref. | Operating Freq. | Physical Size | TX/RX Channels | Multiplex Mode | Technology | Year |
|---|---|---|---|---|---|---|
| [15] | 77 GHz | 4 cm × 4 cm | 4 × 4 | Time Division | Infineon B7HF200 300 nm SiGe:C | 2010 |
| [16] | 72 – 80 GHz | 200 cm × 100 cm | 3008 × 3008 | Time Division | Infineon B7HF200 300 nm SiGe:C | 2011 |
| [17] | 77 GHz | 9 cm × 6 cm | 6 × 8 | Frequency Division | Infineon B7HF200 300 nm SiGe:C | 2014 |
| [18] | 77 GHz | 16 cm × 16 cm | 16 × 4 (x4) | Time Division | Infineon B7HF200 300 nm SiGe:C | 2015 |
| [19] | 100 GHz | 35 cm × 35 cm | 22 × 22 | Time Division | Fraunhofer IAF 100 nm InGaAs mHEMT | 2016 |
| [20] | 61 GHz | 4 cm × 3 cm | 2 × 2 | Freq./Code Division | IHP SG13G2 130 nm SiGe:C BiCMOS | 2017 |
| [1] (This) | 120 GHz | 5 cm × 4 cm | 2 × 8 | Time Division | Infineon B11HFC 130 nm SiGe:C BiCMOS | 2017 |

TABLE I: Comparison of MIMO systems between 2010 and 2017

circuit the frequency quadruplers can be disabled to allow for time-division multiplex operation. In contrast to frequency-division or code multiplex, time-division multiplex minimizes hardware complexity at the cost of increased measurement time due to its sequential nature of operation. Minimizing the frontend hardware and routing effort as much as possible allows this design to be expanded above $16 \times 16$ TX and RX channels in a future compact system implementation.

In Fig. 2 (right) the backend part of the radar system is presented. It mainly consists of commercial integrated circuits for intermediate frequency signal conditioning such as high-pass and low-pass filters, amplifiers and analog-to-digital converters. Once the IF signal has been digitized it is preprocessed and made available on the integrated Gigabit Ethernet interface using a Xilinx Zynq® System-on-Chip on a commercial off-the-shelf module mounted on the backend circuit board. The raw data can be obtained from the device so that further image reconstruction algorithms can be run on an external processing computer.

## III. Comparison of MIMO Radar technology

From Table I the pervasiveness of SiGe based technologies in multichannel radar systems in recent literature can clearly be observed. The key reason for this trend is the ability to develop highly integrated high-frequency RF circuits containing multiple channels per integrated circuit without suffering from a drastic penalty on production yield which is often the case with III-V based semiconductor technologies. Systems [15], [16], [17], [18] use the B7HF200 SiGe:C technology by Infineon Technologies AG providing 180 GHz/250 GHz $f_T/f_{max}$. This mature technology is predominantly used in automotive radar sensors thus providing a stable and reliable technology for implementing complex integrated millimeterwave circuits. In 2016 Fraunhofer IAF presented a multichannel radar system [19] using their in-house 100 nm InGaAs mHEMT technology providing $22 \times 22$ channels. While RF performance with this technology is excellent circuit yield has to be considered. This inevitably leads to a reduction in the circuit complexity for each integrated circuit. In this particular case the problem has been alleviated by implementing only a single TX or RX channel path per chip, forcing severe limits upon the maximum achievable integration due to the increased assembly complexity.

In recent years a trend towards CMOS integration into bipolar technologies can be observed [20], [1]. This enables the use of high-performance SiGe:C heterojunction bipolar transistors for fast, reliable and complex RF circuits while also integrating digital logic for auxiliary purposes such as builtin self-test or on-chip signal synthesis. These techniques can be used to reduce labor and cost on system level during production, assembly and testing stages by using automation techniques. In addition, CMOS integration can be used to implement data acquisition and digitization circuits directly into the RF integrated circuit. This not only reduces the cost from avoiding using external IF filters, amplifiers and ADCs but also decreases overall system size and circuit-board level complexity.

Another trend that can be observed from Table I is the rise in operating frequency over the years. As the relation between operating frequency and aperture size is given by [10] the size required for the antenna array reduces with increasing operating frequency maintaining the same imaging resolution. When the physical size of the radar system is limited by the antenna array size increasing the operating frequency consequently allows the reduction in overall system size. With the development of SiGe:C technologies and their improvements regarding RF performance in recent and future years, the feasibility of generating and processing RF signals with even higher frequencies improves constantly.

An often overlooked fact is that system complexity plays a big role in reducing overall system size. MIMO radar systems have to distribute reference signals over electrically large distances using suitable RF interconnects. In most experimental systems commercial off-the-shelf coaxial cables and connectors are used prohibiting compact module designs. A key to decreasing system level complexity to a minimum is reducing the number of required RF and IF interconnects by employing modular design only where it is unavoidable. Therefore future systems are expected to constantly increase the level of integration targeting designs with a small number of board-to-board interconnects or even on-chip integrated systems for higher frequencies to avoid high system costs.

## IV. Summary

Since the first formulation of the MIMO idea the trend has continued to advance in favor of increasing operating frequency and reducing radar system size. Looking back at the development of SiGe:C HBT technologies and their impact on multichannel radar systems over recent years an interesting future lies ahead. In the time from the first use of angle-of-arrival estimation to high-performance millimeter-wave imaging radar systems today, the technology has come a long way. We presented an innovative implementation of a MIMO radar demonstrator by Fraunhofer FHR along with its physical, performance and power specifications and compared it to similar radar systems in literature. The demonstrator has been realized using custom integrated RF integrated circuits in Infineon's B11HFC 130 nm SiGe:C technology. It is our estimation that the past and future improvements especially in SiGe:C based technologies are and will be responsible for the tremendous growth in radar multichannel radar systems. Not only will operating frequencies of radar systems increase along with rising $f_T/f_{max}$ of semiconductor technologies but also integration of digital circuits for data acquisition for example will reduce hardware and financial efforts in the future.

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