A Compact 120 GHz SiGe:C based 2 × 8 FMCW MIMO Radar Sensor for Robot Navigation in Low Visibility Environments

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***Abstract*—In this publication, a compact and low power radar sensor that can be used for 3D imaging purposes applications is presented. By providing two transmit channels and eight receive channels the MIMO principle for data reconstruction has been realized. A custom integrated chipset has been specifically developed for this application allowing a space saving hardware implementation. The system allows for a near-realtime reconstruction of 3D information that is suitable to be used for robot navigation in low-visibility environments. The 3 dB cross range resolution realized with the sensor shown here is 15 cm in 1 m distance with a total field-of-view of 30°. The used circular antenna array topology provides a maximum sidelobe level of −8 dB. The total hardware power consumption is 7 W at 12 V supply voltage and the physical dimensions are 50 mm × 40 mm. Radar operation is performed around 120 GHz with a measured on-chip output power of 4 dBm.**

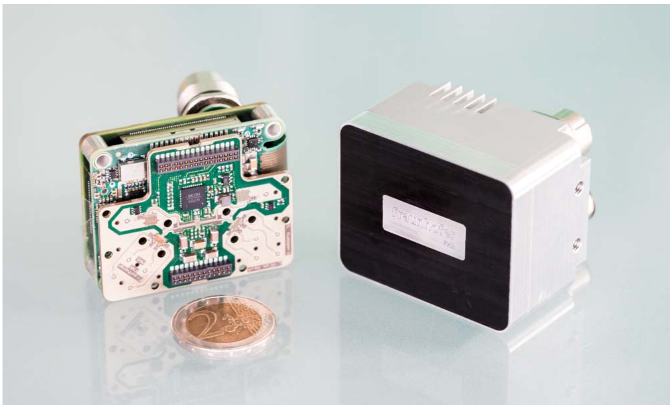

Fig. 1: Photograph of 2 × 8 MIMO radar system demonstrator

I. Introduction

In many emergency scenarios, the availability of precise information about the conditions directly at the center of the disaster site is crucial for guiding rescue actions as well as potential counter-measures. However, the critical sites are often hard to reach as well as restricted in visibility by dangerous gases, smoke or dust. In these cases unmanned vehicles have proven to significantly lower the risk for the emergency team. Remotely driven robots can access places where the conditions do not allow sending people for investigation.

We propose that the ability to obtain reliable information for planning and coordination of countermeasures at a disaster site can be improved by the use of millimeterwave imaging techniques. This is due to the fact that sensor modalities typically used for robotic applications involve laser scanners and video cameras, both of which fail to operate under low visibility conditions. This is not the case for sensors operating in the millimeterwave range of the electromagnetic spectrum due to the longer wavelength compared to the optical spectrum.

Many techniques used for radar imaging such as SAR can be found in literature [1]. However a problem with similar measurement setups is that the time to acquire the 3D image is in the range of minutes to even hours. Clearly, mechanical scanning approaches are not suitable to be used as a realtime navigation aid for robots. Historically, the solution to this problem was the use of Phased Array Radar Systems. Here the scene is scanned by an electronically formed beam using phase shifters that are inserted directly into antenna feedlines within the antenna array. However in the past few years, a different kind of radar imaging principle gained popularity in literature, namely the MIMO approach. The MIMO principle is a well-known technique [2] risen to popularity due to the ever decreasing cost of digital processing power and is now used in several applications (e.g. [3]). Employing the MIMO principle has two main advantages for the application shown in this publication. Firstly, by the introduction of orthogonal transmit channels a so-called virtual array is produced by the convolution of RX and TX antennas. This way, data for $N_{TX} \times N_{RX}$ virtual antenna elements can be acquired with only $N_{TX} + N_{RX}$ antenna elements. Thus by employing the MIMO principle, the hardware effort is much more managable compared to the phased array approach allowing for a compact hardware implementation. The second main advantage of the MIMO principle is avoiding the use of complex RF-circuits such as phase shifters. Instead, each receive channel is downconverted and digitized simultaneously such that any phase shifting can be done in the digital domain instead. However MIMO sensors

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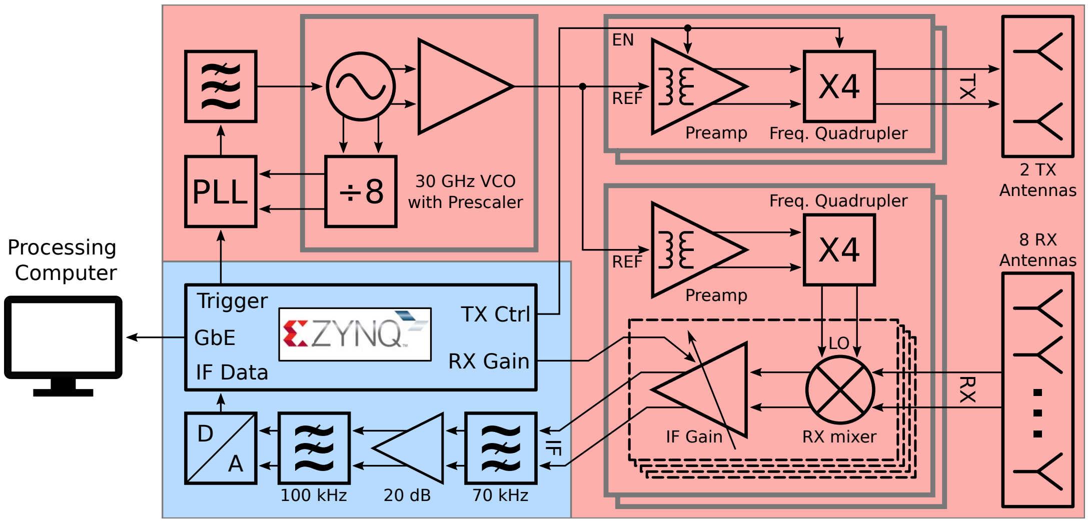

Fig. 2: Radar Hardware Concept (Blue: Backend, Red: Frontend)

currently reported in literature (such as [4]) are not very well suited for being used on space and power limited mobile platforms due to their size or the requirement of external digitizer hardware. Thus a key effort in the development was the reduction of the physical size to be compatible with mobile operation.

II. Radar System Hardware

A compact 2 × 8 MIMO radar system demonstrator has been developed as presented in Fig. 1. It is capable of producing a near-realtime stream of the data processed by the MIMO algorithm of the scene in the radar's field-of-view. The robot platforms used in this application typically use rechargable batteries to provide power to the onboard electronics. Thus, the system also has to be power efficient, so that a long battery lifetime is achieved.

The developed hardware concept shown in Fig. 2 is divided into the frontend (red) and backend (blue) part serving different purposes. The frontend hardware contains circuits required to implement the FMCW radar operation such as power amplifiers and receive mixers as well as the generation of a stable reference chirp reference. In contrast, the backend hardware is responsible for controlling the radar operation and the acquisition of the IF data generated by the radar frontend.

A. Frontend Hardware

To achieve the required degree of system integration required for a compact overall system realization, three different custom integrated circuits have been developed (grey boxes in Fig 2). The development of the custom integrated circuit has been carried out in the 3.3 V B11HFC 130nm SiGe:C BiCMOS technology by Infineon Technologies AG for implementing RF function blocks as well as digital logic for auxiliary purposes. 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 layers as well as an aluminium pad layer. By relying on a robust and mature SiGe:C technology, we expect high reliability and integrated circuit yield thus lowering the total cost of the system especially when using these chips multiple times throughout the system.

As the main radar reference clock, a 30 GHz oscillator has been developed providing the generated signal to each RX and TX circuit in the radar system frontend. Besides a fundamental VCO, this integrated circuit additionally contains a divide-by-8 frequency divider so it can be stabilized with a commercial off-the-shelf PLL IC. Additionally, two amplifiers are implemented in order to provide the required output power such that the reference signal can be split up to multiple RX and TX circuits.

Although the actual radar operation has been designed for 120 GHz, a 30 GHz reference clock has been chosen. This is due to the fact, that RX and TX circuits are typically distributed over electrically large distances in case of a MIMO antenna topology. Thus to reduce wiring losses and achieve a good board-to-chip impedance match at the reference clock inputs, a reference frequency that is one fourth of the final radar operation frequency has been chosen. By doing so, a frequency multiplier has to be used for each RX and TX circuit to regenerate the local oscillator signal. The regenerated signal is then used to drive power amplifiers or receive mixers in case of the TX or RX integrated circuit. To achieve a low overall system power consumption, a high conversion efficiency as well as a high conversion gain has been realized.

In a first step, a power efficient frequency quadrupler at the operating frequency of 120 GHz has been developed and published in [5]. The radar sensor shown in this publication uses this frequency quadrupler as a single channel TX circuit without additional power amplification, thus delivering an onchip peak output power of 4 dBm and more than 0 dBm in a 40 GHz wide frequency band.

Secondly, an integrated receive downconversion mixer for FMCW operation has been implemented. The frequency quadrupler circuit from [5] has been used to generate the 120 GHz local oscillator signal for homodyne downconversion of the

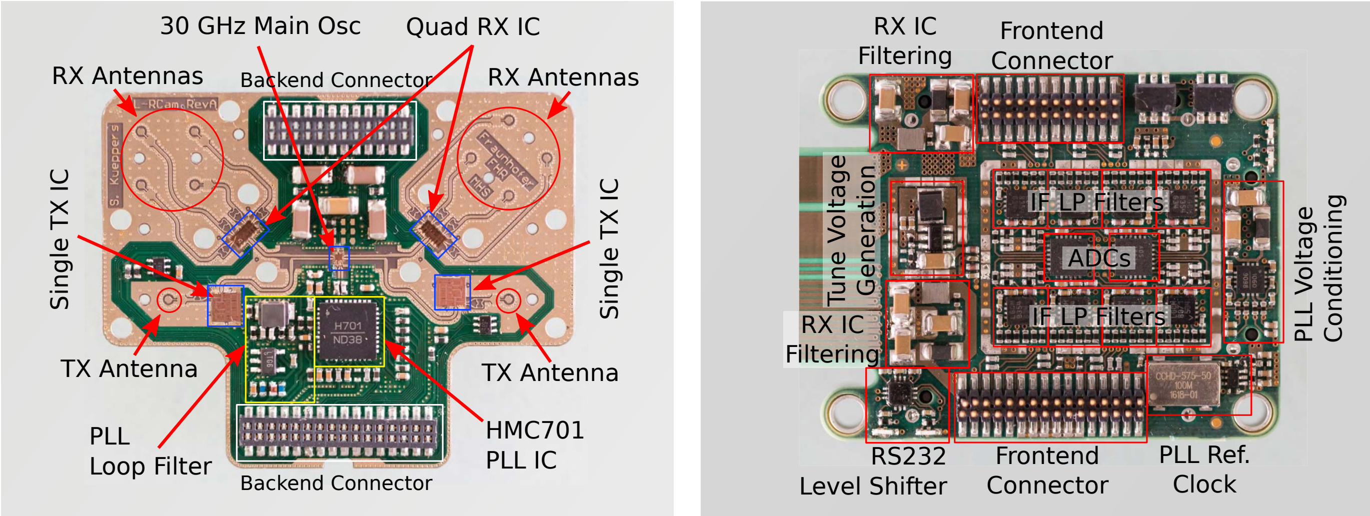

Fig. 3: Radar System Hardware (Left: Frontend, Right: Backend)

received radar signal. A gilbert-cell style frequency mixer has been realized providing a noise figure of approximately 12 dB and a conversion gain of 16 dB. The intermediate frequency information generated by the downconversion mixer is further processed by an on-chip programmable gain amplifier in order to fully utilize the dynamic range of the ADC on the backend.

The developed integrated circuits have been integrated on a Rogers RT/duroid 5880 substrate as shown in Fig. 3 (left). In addition to the integrated circuit chipset a novel circular antenna topology has been realized on the frontend substrate. The chosen antenna topology features eight receive antennas clustered up into two circles and two transmit antennas oriented on the same vertical axis as the center points of the receive antenna clusters. Further details and experimental evaluation of the antenna topology have been published under [6].

B. Backend Hardware

Since the intermediate frequency signals downconverted by the radar frontend have frequency contents of below 1 MHz, further signal conditioning can be performed on the backend of the radar system as shown in Fig. 3 (right). In the first stage, low frequency content is removed by means of a high-pass filter with a cutoff frequency of 70 kHz. The reason for these low frequency signals are diverse and can be due to imperfections in the RF chip-to-board interconnects, antenna input matching or direct TX to RX crosstalk. Since these interfering signals can be quite strong in amplitude the maximum allowable IF amplification is limited by the allowable dynamic range when they are not sufficiently suppressed. As a side-effect of the high-pass filtering, a simple amplitude shaping of the baseband frequency response can be achieved. This is useful as targets that are close to the radar system and thus show at low IF frequencies do not experience as much free space path loss as targets that are further away. After the amplitude shaping, 20 dB fixed gain operational amplifiers have been used to maximize the utilization of the available dynamic range.

In order to avoid range ambiguities of targets in front of the radar sensor, 3rd order antialiasing filters with a cutoff frequency of 100 kHz are used. Following these low-pass filters the signals are digitized using two ADS7863A analog to digital converters providing eight 1 MSPS channels with 12 Bit resolution. The digital data is then fed into a Xilinx Zynq® System-on-Chip on a TE0720 commercial off the shelf module made by Trenz Electronic (not shown in Fig. 3). It is used for coordinating the timing of the transmit channels and the data acquisition required in the time-multiplexed MIMO approach. These low-level functionalities have been implemented in the programmable logic part of the SoC such that the control logic can be clocked by a common 100 MHz crystal oscillator that is also used to provide the reference clock for the phase locked loop on the radar frontend. By employing a single reference clock for the entire radar subsystem, high acquisition stability and a low acquisition jitter can be achieved. Once the digital data has been stored an embedded linux running on the Zynq® programming system provides the data over a Gigabit Ethernet data link to a processing computer.

III. System Evaluation

In order to evaluate the radar system performance a realistic scenario has been chosen for measurement. Fig. 4 shows the measurement setup with the radar system located in the front, pointing at a door leading to the kitchen on the Fraunhofer FHR premises. A trihedral reflector on a post has been used in a separate calibration measurement and has been removed before the actual measurement of the scene has been carried out. The measurement parameters have been 5 GHz sweep bandwidth with a sweep duration of 1 ms, mainly limited by the bandwidth of the individual antenna elements.

The data acquired by the measurement shown in the photograph in Fig. 4 has been reconstructed using the backprojection algorithm in order to produce three-dimensional information about the scene. The acquisition of the measurement data took

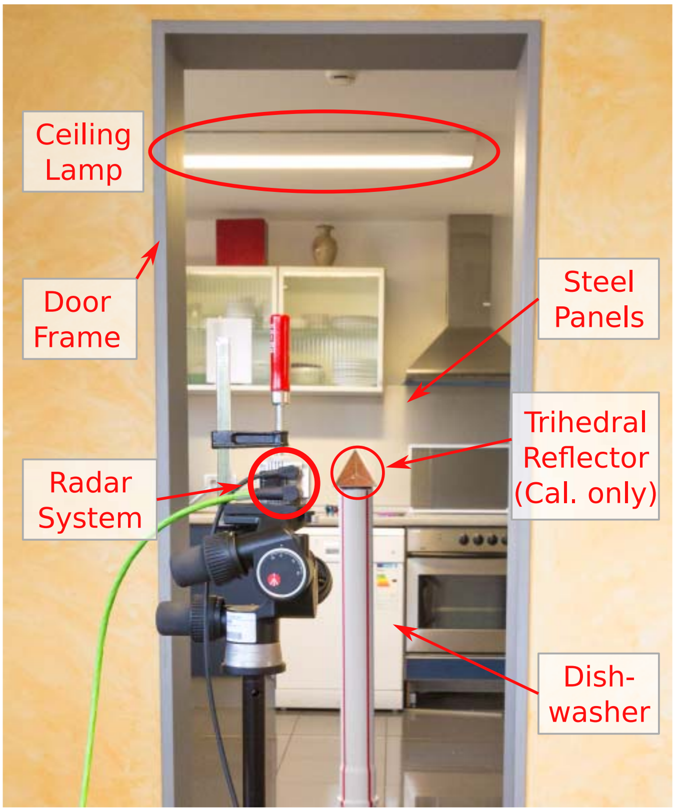

Fig. 4: Photograph of measured scenario (Front View)

less than 100 ms and the total processing time for the generation of the image shown in Fig. 5 was less than 5 seconds using MATLAB®. The reconstructed three dimensional data has been processed for 2D visualization by summing up the amplitudes of all horizontal slices and displaying them using a greymap. This effectively generates a top-down view of the scene by compressing the data along the vertical axis. As shown in Fig. 5 several strong amplitudes can be observed corresponding to physical objects seen in the photograph in Fig. 4. In addition to these objects the image also shows the clutter generated by the antenna topology that corresponds well to the simulated -8 dB maximum side lobe level.

IV. Conclusion

In this publication, a compact, lightweight and low power radar system for 3D imaging applications has been shown. By employing the MIMO radar principle a low hardware effort has been achieved allowing a technically feasible realization. A system concept for the radar system hardware has been developed and realized using an application specific custom integrated RF chipset on the radar frontend. For characterization of the hardware implementation a realistic scenario has been chosen for measurement and the data provided by the measurement has been processed and visualized showing the expected functionality of the hardware.

The measurement results shown here demonstrate the suitability of the compact millimeterwave MIMO radar system

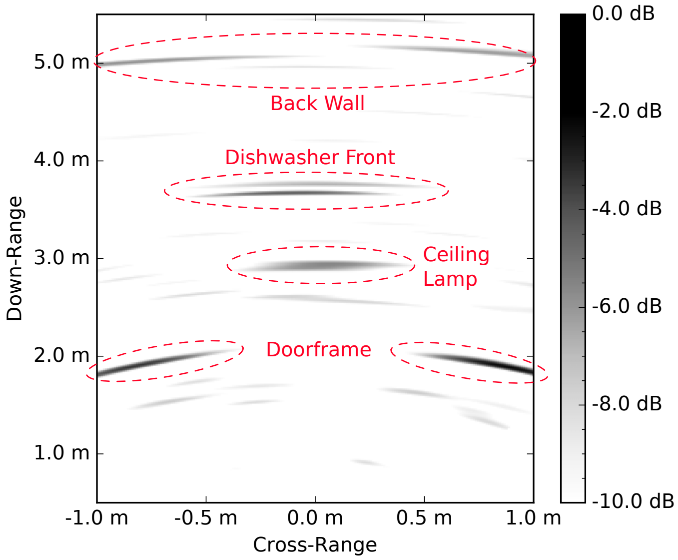

Fig. 5: Reconstructed image (Top View) of scenario in Fig 4

hardware for use in robotic applications. The RF chipset developed for the radar system is a well suited basis for building more complex MIMO radar sensors using a larger number of TX and RX channels and thus increasing cross-range resolution and decreasing the maximum side lobe level providing higher quality image reconstruction.

Acknowledgment

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