A Radar System Concept for 2D Unambiguous Angle Estimation Using Widely Spaced MMICs with Antennas On-Chip at 150 GHz

Patrik Grüner, Markus Klose, and Christian Waldschmidt

A Radar System Concept for 2D Unambiguous Angle Estimation Using Widely Spaced MMICs with Antennas On-Chip at 150 GHz

Patrik Grüner^{#1}, Markus Klose[#], Christian Waldschmidt[#],

[#]Institute of Microwave Engineering, Ulm University, Germany

¹pgruener@ieee.org

Abstract—The system concept of a compact three-dimensional (3D) imaging radar in the millimeter-wave range around 150 GHz is presented. The multiple-input multiple-output (MIMO) radar system is composed of two identical two-channel radar monolithic microwave integrated circuits (MMICs) with on-chip antennas arranged perpendicular to each other. Typically, such arrangements suffer from angular ambiguities due to large antenna spacings that come along with the MMIC footprint and printed circuit board (PCB) routing constraints. The concept of biomimetic antenna arrays (BMAAs) is used to mitigate the problem of ambiguities. The influence of applying a spherical lens to the radar system is discussed in the paper, and radar measurements show the applicability of the proposed concept.

Keywords—biomimetic antenna arrays, direction-of-arrival estimation, frequency-modulated continuous-wave (FMCW) radar, imaging radar, radar MMIC

I. INTRODUCTION

Increasingly smaller and cheaper radar sensors allow for more and more new applications [1]–[3]. This is possible due to the advances in semiconductor technology, like e.g. in the silicon-germanium (SiGe) technology [4], that enable the integration of complete radar sensors on a single monolithic microwave integrated circuit (MMIC). The demand for high range resolution and thus high absolute bandwidths in the RF domain pushes the carrier frequencies of these radar sensors beyond 100 GHz. With increasing frequencies above 100 GHz, the integration of antennas directly on the radar MMIC is a necessity in order to avoid losses due to bond transitions to printed circuit boards (PCBs) [5].

The composition of a radar system consisting of multiple transmit and receive channels in order to measure the angle of a target is then achieved by placing multiple MMICs—each equipped with a small number of transmit-receive channels—side by side to form a larger antenna array [6]. An antenna spacing of half a wavelength or less at the carrier frequency is required to ensure a non-ambiguous angle estimation. However, when building radar systems composed of several MMICs with integrated antennas, it is often not feasible to ensure these spacing requirements due to the size of the chip and the required external connections that have to be routed from or to every single MMIC. In applications with a one-dimensional aperture this can be achieved by designing the MMIC in a way that the bond connections are only on one side of the chip [6]. When considering two-dimensional apertures this is more difficult to achieve since the spacing constraint for non-ambiguous angle

Fig. 1. Block diagram of a single MMIC. Components belonging to channel 1 are highlighted in green, whereas those of channel 2 are marked in blue.

estimation must be fulfilled in both dimensions, and therefore, a violation of the spacing constraint can hardly be avoided.

This paper proposes a new system concept to place radar MMICs at a distance larger than half a wavelength but still ensure an ambiguity-free angle estimation by exploiting biomimetic antenna arrays (BMAAs) [7]. The concept is demonstrated by means of the design and measurement of a compact 3D-imaging radar at 150 GHz. The radar system is based on two MMICs each of which having two transmit-receive channels and forming a two-dimensional aperture. The chips are arranged perpendicularly and are separated by a distance of λ . The system components are described in this paper, the system setup is discussed, and radar measurements are presented.

II. SYSTEM COMPONENTS

A. MMIC

The basis of the presented radar system is a monostatic two-channel radar MMIC at 150 GHz with integrated antennas. It is similar to the MMIC used in [8] and its block diagram is shown in Fig. 1. The offset-synthesizer based signal generation is optimized for low phase noise and relies on a reference frequency around 920 MHz and a frequency ramp signal in the range of 8–12 GHz which both have to be supplied from external sources. The MMIC is built up as a homodyne radar and the two channels are composed of a power amplifier (PA) in the transmit path, a low noise amplifier (LNA) in the receive

Fig. 2. Phase progressions at the output of a conventional antenna array (---) consisting of two antennas spaced at a distance $d = 0.37\lambda$ and a BMAA (—) with identical d and a phase gain of $\eta = 3$.

path, and a compact rat-race coupler as transmit-receive coupler (TRC). A biomimetic coupling (BMC) is implemented in the receive path of the chip. Both PAs can be switched on and off individually to allow for a MIMO operation with time-division multiplexed (TDM) transmitters. The overall chip occupies an area of $2.48 \text{ mm} \times 1.21 \text{ mm}$ with an antenna spacing of 0.37λ .

B. Biomimetic Antenna Array (BMAA)

The BMAA consists of a conventional antenna array and a specifically designed biomimetic coupling network and is capable of improving the angle estimation performance for electrically small apertures by mimicking the hearing system of the fly *Ormia ochracea* [7]. First applications in radar systems were presented recently [8]. The effect of using BMAs is illustrated in Fig. 2. In conventional antenna systems, the phase progression between two antennas spaced at a distance d is given by $\phi_{\text{in}} = kd \sin \theta$, with $k = 2\pi/\lambda$ being the wavenumber, λ the wavelength in free space, and θ the incidence angle. After the biomimetic coupling this phase progression is steeper in the vicinity of the boresight direction (cf. ϕ_{out} in Fig. 2) and therefore appears like a larger array. The scaling factor is referred to as the phase gain η [7]. The trade-off of the antenna system is a lower signal-to-noise ratio (SNR) which is quantified by the normalized output power L_{out} [7].

The presented MMIC is equipped with a BMAA designed for a phase gain of $\eta = 3$ at a normalized output power of $L_{\text{out}} = -9.5 \text{ dB}$. Because the biomimetic coupling is placed only in the receive path of the monostatic MMIC (cf. Section II-A) and consequently, only the receive antennas experience the enhanced phase difference, they appear to be spaced at a larger distance than the transmitter antennas. However, the TX and RX antenna of one channel is at the same physical position.

C. Dielectric Lens

In order to improve the SNR and therewith the detection range of the radar system, a dielectric lens is placed over the MMICs. Whereas in 1D-applications a cylindrical lens can be used where the signal is focused only in the non-scanning

Fig. 3. Measured 2D-radiation pattern of the spherical lens with one transmitting antenna placed off the focal axis with (a) the transmitter placed at the focal distance of the lens ($h = 25 \text{ mm}$) and (b) the transmitter placed out of the focal distance towards the lens ($h = 15 \text{ mm}$).

Fig. 4. (a) Simulated 2D-phase progression ϕ (in degree) of two antennas ($\theta = -90^\circ \dots 90^\circ$) and (b) measured 2D-phase progression ϕ of the same antenna configuration but placed beneath a spherical lens ($\theta = -14^\circ \dots 14^\circ$).

plane, a spherical lens is applied in this work. Spherical lenses usually lead to very narrow beams, and sources placed away from the focal axis lead to a tilting of the main beam. As a consequence, if several antennas are placed underneath a spherical lens, the single channels have very narrow beams and are inevitably tilted in opposite directions. Hence, the virtual aperture of the MIMO radar cannot be built up. To mitigate this effect in this work, the MMICs were placed out of the focal plane of the lens, i.e., the lens was placed closer to the MMICs. This broadens the beam at the cost of gain. Fig. 3 shows the measured 3D-radiation diagrams (in spherical coordinates with boresight at $\theta = 0^\circ$) of the spherical lens used in this work fed by a transmit antenna placed in the focal plane (Fig. 3(a)) at 25 mm and placed out of the focal plane towards the antenna at 15 mm (Fig. 3(b)). The beam is broadened from $2.8^\circ/2.3^\circ$ to $10.6^\circ/7^\circ$ for $\varphi = 0^\circ/90^\circ$ and now enables the formation of a MIMO aperture because each transmit signal is able to reach every receive antenna. Based on this results, in the remainder of this work the lens is used at a distance of 15 mm to the MMIC.

As a next step, the influence of the spherical lens

Fig. 5. (a) Placement of the two MMICs with degrees of freedom d_x and d_z and actual positions of transmit antennas ($\times$) as well as apparent positions of receive antennas ($\circ$) due to biomimetic coupling and (b) photograph of the bonded MMICs arranged perpendicularly and separated by a distance of $d_x = d_y = \lambda$.

on the phase progressions is discussed using a practical example. Fig. 4(a) shows the simulated 2D-phase progression of two antennas placed in the x - z -plane. The measured phase progression in Fig. 4(b) uses the same antenna positions, but a spherical lens is mounted on top of the antennas. By comparing the measured and the simulated phase progression ϕ it can be noted, that the measured graph is not only a cutout of the simulated graph for $\theta = \pm 14^\circ$, but a steeper phase progression in the considered angular region is obtained. Moreover, the two diagrams show the same course, but for different angular ranges of θ . This can be quantified by introducing a compression factor that relates the different angular regions with and without lens. In general, this factor depends on the focusing characteristics of the lens; in this work it is calculated from Fig. 4 to a value of around 3.3.

III. RADAR SYSTEM CONCEPT

The system concept of the presented 3D-imaging radar relies on the perpendicular arrangement of coherently coupled two-channel radar MMICs with on-chip antennas at 150 GHz. The aperture of the first chip is aligned in x -direction, that of the second chip in z -direction, cf. Fig. 5(a). In order to increase the overall aperture size, the radar is operated in a MIMO configuration. However, the placement of the MMICs is subject to constraints, such as the size of the chip and the number of signals that must be routed to it. Two degrees of freedom result for the perpendicular placement of two MMICs, namely an x -offset d_x and a z -offset d_z , see Fig. 5(a). Simulations of different antenna array geometries showed that with the designed phase gain of $\eta = 3$, ambiguities occur close to the main lobe if d_x or d_z exceed 1.2λ . To ensure an ambiguity-free angle estimation despite manufacturing tolerances in the placement of the chips, the spacing in this work was chosen to $d_x = d_z = \lambda$. A photograph of the realized arrangement is shown in Fig. 5(b).

The resulting MIMO aperture ($\diamond$) consisting of 16 virtual antenna positions, and calculated by a spatial convolution of the transmitting ($\times$) and the receiving ($\circ$) aperture, is depicted in Fig. 6. Fig. 6(a) shows the virtual aperture if

Fig. 6. Positions of TX antennas ($\times$), RX antennas ($\circ$), and virtual antennas ($\diamond$) in the MIMO aperture of (a) the conventional and (b) the biomimetic radar system in boresight direction ($\lambda \approx 1.95$ mm).

conventional radar MMICs of the same type but without biomimetic coupling were used. Some positions in the virtual aperture are redundant and therefore, only 10 unique antenna positions are visible. The aperture apparently contains several gaps with a size bigger than $\lambda/2$ between the antennas that inevitably lead to ambiguities in the angle estimation. In contrast, the use of biomimetic MMICs fills the large gaps in the virtual aperture, resulting in an angle estimation without ambiguities (cf. Fig. 6(b)). Thus, the additional elements in the virtual aperture contribute significantly to the unambiguity of the antenna arrays, and reduced sidelobe levels in the angle estimation are to be expected in MIMO operation. Additionally, the resulting MIMO aperture occupies a larger area, leading to a smaller main lobe in the angle estimation and thus to a higher angular resolution.

IV. RADAR MEASUREMENTS

A. Measurement Setup and Calibration

The complete radar system consists of several printed circuit boards (PCBs) stacked above each other. Each of the PCBs serves a specific purpose like FMCW ramp generation, IF signal amplification and filtering, and power distribution. The uppermost circuit board is the radar front-end on which the MMICs are accommodated and above which the spherical lens is mounted at a distance of 15 mm to the MMICs.

The angle estimation is performed by means of a maximum likelihood (ML) method which correlates the measured values with a prerecorded set of calibration data of all incidence angles θ_r and φ_r . This calibration data set was generated by moving a corner reflector mounted on a robotic arm [9] along a 3D-trajectory around the radar at a constant distance of 1 m, cf. Fig. 7. Radar measurements were performed at discrete points along the surface of the sphere. The complex values of the radar response of each virtual channel at each target position were extracted and stored in the calibration data matrix. The modulation parameters used in the radar measurements are summarized in Tab. 1.

B. 2D-Angle Estimation

In order to evaluate the performance of the radar system in terms of angular estimation, an exemplary radar measurement

Fig. 7. Measurement setup for the radar measurements using a robotic arm. The radar is arranged in the x - z -plane with the y -axis corresponding to the focal axis of the spherical lens, and $\theta_r = \varphi_r = 90^\circ$ corresponds to the boresight direction.

Table 1. Radar Modulation Parameters

Ramp duration T_{up}	100 μs
Ramp repetition time T_r	150 μs
Center frequency f_c	152.92 GHz
RF bandwidth B	8.24 GHz
Number of ramps N_r	1024

for a target placed at around 1 m under an angle of $\theta_r = 90^\circ$ and $\varphi_r = 87^\circ$ was performed. Fig. 8(a) shows the maximum likelihood (ML) spectrum calculated from the measured radar response correlated with the prerecorded calibration matrix. The target can clearly be located at the correct angles with no ambiguity (i.e. correlation > 0.7) besides the main peak. Figs. 8(b) and 8(c) show the simulated ML spectra without and with using biomimetic MMICs, respectively, for the presented radar system. The reduction in sidelobe level achieved with the biomimetically coupled MMICs can clearly be recognized. The comparison between the simulation and the measurement verifies the working principle of the presented system concept. The main lobe in Fig. 8(a) has a 3 dB-width of 4.6° and 2.8° in θ_r and φ_r direction, respectively.

V. CONCLUSION

A new system concept for a 3D-imaging radar based on widely spaced two-channel radar MMICs at 150 GHz was presented in this paper. The new concept applies the method of biomimetic antenna arrays to fill the gaps of the potentially ambiguous aperture. The effects of adding a spherical lens to the radar system were discussed and a compression factor was introduced to compare measurements with and without dielectric lenses. Radar measurements proved the theory and showed an ambiguity-free angle estimation in two dimensions.

Fig. 8. (a) Measured angle estimation using ML in comparison to simulated maximum likelihood angle estimation for (b) the conventional and (c) the biomimetic radar system. The true direction of arrival is marked by a red cross.

ACKNOWLEDGMENT

This work was funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) – WA 3506/6-1.

REFERENCES

- [1] Z. Peng and C. Li, "A Portable K-Band 3-D MIMO Radar With Nonuniformly Spaced Array for Short-Range Localization," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 11, pp. 5075–5086, Nov. 2018.
- [2] S. Kueppers, H. Cetinkaya, and N. Pohl, "A compact 120 GHz SiGe:C based 2×8 FMCW MIMO radar sensor for robot navigation in low visibility environments," in *Europ. Radar Conf. (EuRAD)*, Oct. 2017, pp. 122–125.
- [3] D. Bleh *et al.*, "W-Band Time-Domain Multiplexing FMCW MIMO Radar for Far-Field 3-D Imaging," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 9, pp. 3474–3484, Sep. 2017.
- [4] S. P. Voinigescu, S. Shopov, J. Bateman, H. Farooq, J. Hoffman, and K. Vasilakopoulos, "Silicon Millimeter-Wave, Terahertz, and High-Speed Fiber-Optic Device and Benchmark Circuit Scaling Through the 2030 ITRS Horizon," *Proc. IEEE*, vol. 105, no. 6, pp. 1087–1104, Jun. 2017.
- [5] B. B. Adela, P. T. M. van Zeijl, U. Johannsen, and A. B. Smolders, "On-Chip Antenna Integration for Millimeter-Wave Single-Chip FMCW Radar, Providing High Efficiency and Isolation," *IEEE Trans. Antennas Propag.*, vol. 64, no. 8, pp. 3281–3291, Aug. 2016.
- [6] A. Dürr *et al.*, "High-Resolution 160-GHz Imaging MIMO Radar Using MMICs With On-Chip Frequency Synthesizers," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 9, pp. 3897–3907, Sep. 2019.
- [7] P. Grüner, T. Chaloun, and C. Waldschmidt, "A Generalized Model for Two-Element Biomimetic Antenna Arrays," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1630–1639, Mar. 2019.
- [8] —, "Enhancing Angle Estimation Accuracy of Ultra Compact Two-Channel Radar MMICs at 160 GHz Using a Biomimetic Antenna Array," in *IEEE MTT-S Int. Microw. Symp. (IMS)*, Boston, Jun. 2019.
- [9] L. Boehm, F. Boegelsack, M. Hitzler, and C. Waldschmidt, "The Challenges of Measuring Integrated Antennas at Millimeter-Wave Frequencies [Measurements Corner]," *IEEE Antennas Propag. Mag.*, vol. 59, no. 4, pp. 84–92, Aug. 2017.