Enhancing Angle Estimation Accuracy of Ultra Compact Two-Channel Radar MMICs at 160 GHz Using a Biomimetic Antenna Array

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***Abstract*— An ultra compact monostatic two-channel radar MMIC at 160 GHz with enhanced angle estimation accuracy is presented. The MMIC is built up of two transceivers as well as two chip integrated antennas. The small antenna aperture of a quarter wavelength is enhanced by applying a biomimetic antenna array. As a consequence, the MMIC only occupies a chip area of 2.40×1.15 mm^2. Radar measurements are performed to evaluate the angle estimation capability of the MMIC and it is shown that the accuracy of the angle estimation is enhanced by a factor of 2.2 by using the biomimetic antenna system.**

***Keywords*— MMIC, radar sensor, SiGe, FMCW radar, biomimetic antenna array, direction of arrival.**

I. Introduction

Advances in silicon-germanium (SiGe) technology enable the integration of complete FMCW radar frontends on MMICs. For frequencies above 100 GHz it is also possible to integrate the antennas together with the active components on the MMIC. Several single channel radar chips with on-chip antennas were presented recently in monostatic and bistatic configurations [1], [2], [3]. While these MMICs exhibit a high bandwidth and therefore a high range resolution it is often desirable to additionally sense the angle of the incoming signal. Therefore, it is necessary to consider multichannel radar sensors [4], [5], [6] to evaluate the phase progression between the multiple antennas and estimate the angle of incidence. The key parameter for decent angle estimation capabilities is the aperture size of the underlying antenna array. This size has to be as large as possible for accurate measurements and high resolution. When integrating antennas on-chip this increases the cost of the chips enormously as a lot of additional space on the wafer is needed. A technology to overcome this issue is using biomimetic antenna arrays [7], [8], [9]. This kind of antenna systems which is inspired by the hearing system of a fly couples two adjacent receive antennas in a specific way and enlarges the phase progression between the antennas. By applying this concept, the aperture of the radar system seems to be enlarged and, therefore, it allows for an improved angle estimation capability.

In this paper, an ultra compact radar MMIC with two fully integrated transceivers and integrated antennas at 160 GHz is presented. To reduce the overall chip size the antennas are spaced only $\lambda/4$ apart. It is shown that by applying the biomimetic antenna system the MMIC has a very good angle estimation capability despite its small size of 3 mm^2 only. Section II gives a short overview over the biomimietic antenna arrays while Section III presents the MMIC concept. The Sections IV and V show the measurement setup used to evaluate the angle estimation accuracy and present the measurement results.

II. Biomimetic Antenna Arrays

Biomimetic antenna arrays (BMAAs) have been presented recently. A conventional antenna array is hereby followed by a coupling network inspired by the hearing system of the fly *Ormia ochracea* [8], [10]. This coupling network enlarges the phase difference between two adjacent antenna elements and thus improves the angle estimation capability of the system regardless of the antenna element spacing. This is advantageous especially for applications where only little space is available. The trade-off for enhancing the phase difference is a loss in power level at the output. On system level, the properties of the biomimetic antenna array can be described by the parameters phase gain η and normalized output level L_{out} [8], [9]. Each of them compares the BMAA to a conventional antenna array with the same radiating elements and the same antenna element spacing but without the coupling network. The parameters are defined as follows where ϕ_{in} is the phase progression of the uncoupled antenna array and ϕ_{out} the phase difference at the BMAA output ports:

$$\eta = \frac{\left.\frac{\mathrm{d}\phi_{\text{out}}}{\mathrm{d}\theta}\right|_{\theta=0}}{\left.\frac{\mathrm{d}\phi_{\text{in}}}{\mathrm{d}\theta}\right|_{\theta=0}} \tag{1}$$

$$L_{\text{out}} = \frac{P_{\text{out,BMAA}}}{P_{\text{out,reg. Array}}} \ . \tag{2}$$

The phase gain basically describes the increase in steepness of the ϕ_{out} curve compared to the ϕ_{in} curve. The reduction in power level is given by L_{out} and is always less than 1. Examples of the phase difference curves and the normalized output level can be found in Fig. 1 for an exemplary phase gain of η=5 and L_{out}=−10 dB.

III. MMIC Concept

In this work a two-channel radar MMIC has been developed using a SiGe process with $f_{\text{T}}/f_{\text{max}}$ of 300 GHz / 500 GHz. The main objective was to make the chip as compact as possible to save wafer area and therefore costs. Several points were considered to achieve this objective. The chip is realized as a monostatic radar to keep the numbers of antennas as low as possible as the on-chip antennas are typically the largest single components on the chip. Furthermore, the antenna element spacing was chosen

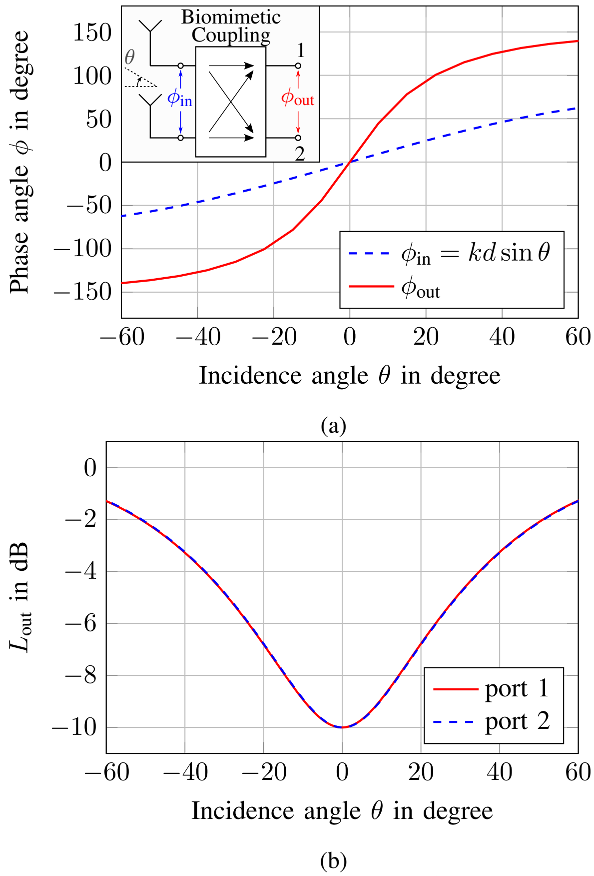


Fig. 1. Exemplary curves for (a) the phase difference and (b) the output power level L_{out} of a biomimetic antenna array with phase gain η=5 and normalized output level L_{out}=−10 dB. The two curves for L_{out} are identical and lie on top of each other.

to only $\lambda/4$ at 160 GHz. Placing dielectric resonator antennas on top of the on-chip patches increases the antenna aperture to 0.3737λ. In order to enable a decent angle estimation capability despite the small antenna element separation, biomimetic coupling was applied to the antenna array. The designed coupling results in an phase enhancement factor of η=4, leading to an effective aperture size of $\eta(0.3737\lambda)$. This is nearly six times the physical aperture size on the chip. A block diagram of the realized MMIC is depicted in Fig. 2.

The chip is based on the single-channel monostatic chip presented in [3]. Besides the bias voltages two signals are generated externally and are fed to the chip: the reference frequency f_{ref}=916 MHz and the ramp frequency f_{ramp} between 8 GHz and 12 GHz. f_{ref} is fed as reference into an integer-N-PLL on the chip. The output of the PLL is a signal at around 60 GHz which is then doubled in frequency and mixed with the ramp signal whose frequency has been multiplied by 4 before. This setup represents an offset-synthesizer which is optimized for low phase noise. The resulting signal is split among the two channels by an active power splitter and afterwards split again to generate the transmitted signal and the local oscillator (LO) signal for the receiver mixer of each channel. For separating the

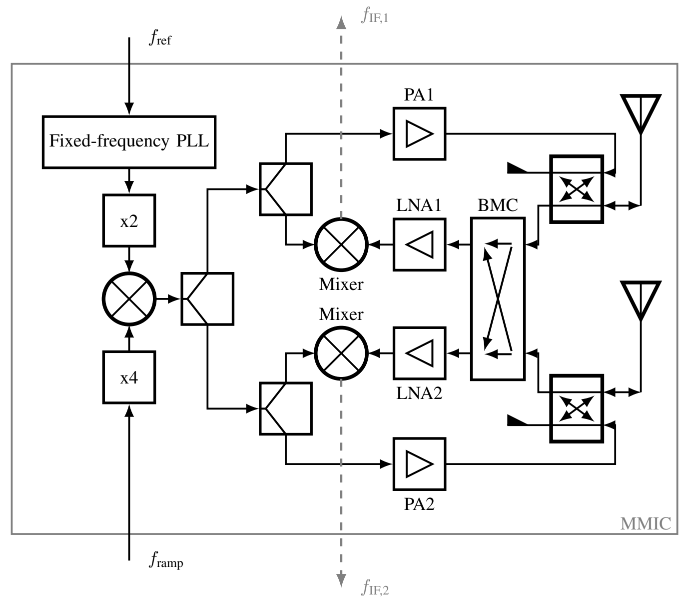


Fig. 2. Block diagram of the presented MMIC.

transmitted and the received signal in the monostatic radar a Tx-/Rx coupler is implemented by means of a compact rat-race coupler [3]. The integrated antennas are realized as shorted patches being a quarter wavelength long. To increase the antenna efficiency a dielectric resonator of height 825 µm and diameter 515 µm is placed on top of each antenna element. In the receive path between the Tx-/Rx coupler and the LNA, the biomimetic coupling is implemented by means of a transformer coupling both RX signals. The biomimetic coupling in this MMIC is designed to exhibit a phase gain of η=4 and a normalized output power level of L_{out}=−5 dB leading to a quality criterion of 2.25 [9]. This means, the angle estimation accuracy is expected to be 2.25 times better than without using the biomimetic coupling. A photograph of the bonded MMIC including the dielectric resonators is shown in Fig. 3.

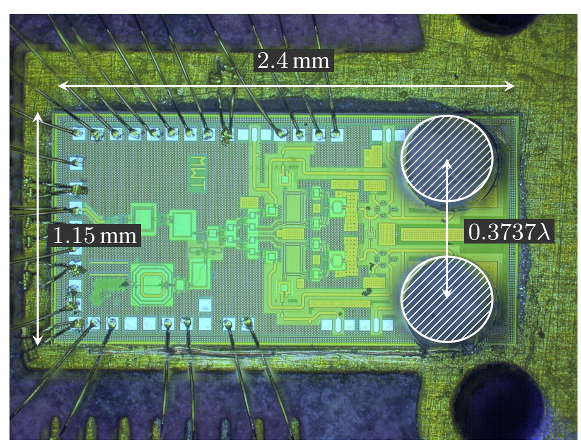


Fig. 3. Bonded MMIC with on-chip antennas and dielectric resonators (marked by the shaded circles).

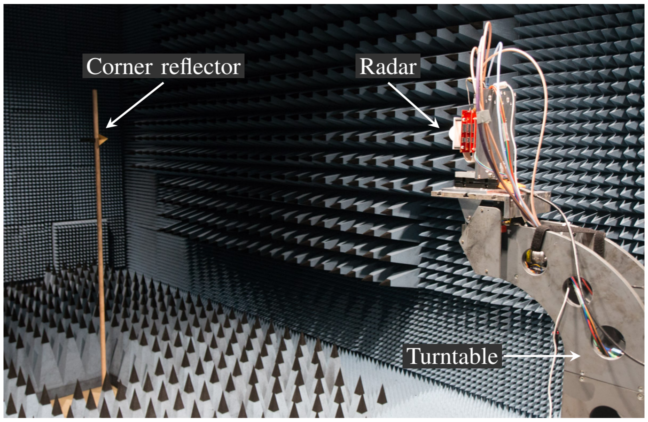


Fig. 4. Photograph of the measurement setup in the anechoic chamber. The corner reflector is placed at a distance of 2.2 m from the radar.

IV. Measurement setup

For evaluating the angle estimation accuracy of the presented chip, radar measurements in an anechoic chamber were performed. The measurement setup is depicted in Fig. 4. The radar consists of a modular stack of PCBs each of which has a special purpose like power supply, IF signal amplification and filtering, and generation of the ramp and the reference frequency. On the topmost board, the MMIC is mounted. In order to increase the antenna gain, a cylindrical lens was mounted above the radar MMIC focusing only in the elevation plane where the radar is not turned.

The radar stack was placed on a turntable in the anechoic chamber and was configured in a way that TX1 was transmitting and both receivers were active. A corner reflector with a radar cross section (RCS) of $10\,\mathrm{m}^2$ was placed in front of the radar at a distance of approximately 2.2 m. By using the turntable, the radar was rotated in the angular range of $-35°$ to $35°$. For every angle a radar measurement was performed and the target phases at the desired range cell were extracted. Using this procedure, the calibration data set for the maximum likelihood angle estimation was generated.

The same setup was used to evaluate the variance of the angle estimation. The radar was placed pointing into a specific direction. Subsequently, 100 radar measurements were performed for each angle of interest ($0°$, $\pm 5°$, $\pm 10°$).

V. Measurement Results

In Fig. 5 a typical radar response is plotted recorded with the measurement setup described in Section IV. 512 ramps were transmitted with a length of $12\,\mu\mathrm{s}$ each and an RF bandwidth of 1 GHz. The IF signal was amplified by 30 dB and a low pass filter with a corner frequency of 5 MHz was applied. A target peak at a distance of 2.2 m with an SNR of approximately 22 dB can be noticed.

By performing this radar measurement for every angle in the desired angular range, the calibration data set is recorded. Fig. 6 shows the phase difference at the receivers extracted from this data set. The measured phase difference curve is significantly steeper than the theoretical phase progression

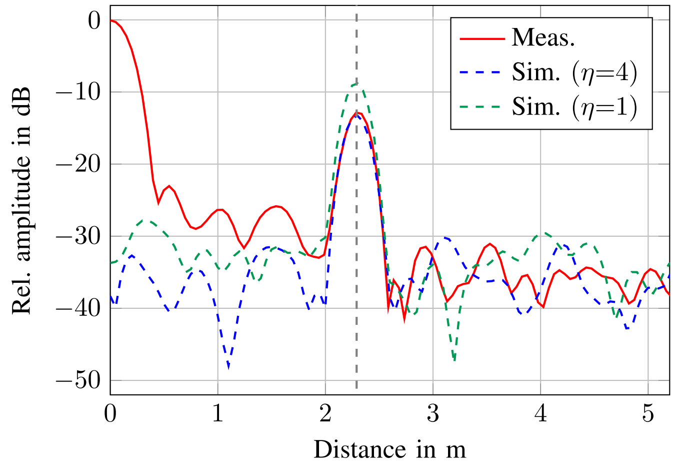


Fig. 5. Radar measurement for a target at 2.2 m under $-5°$ for the MMIC with biomimetic coupling. Non-coherent integration was performed over the two receive channels.

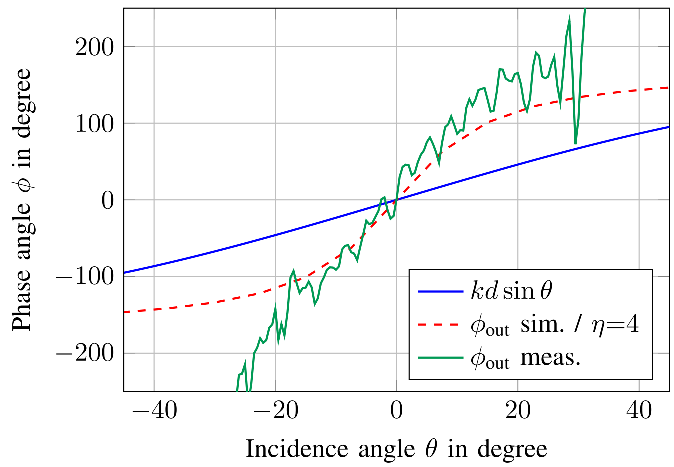
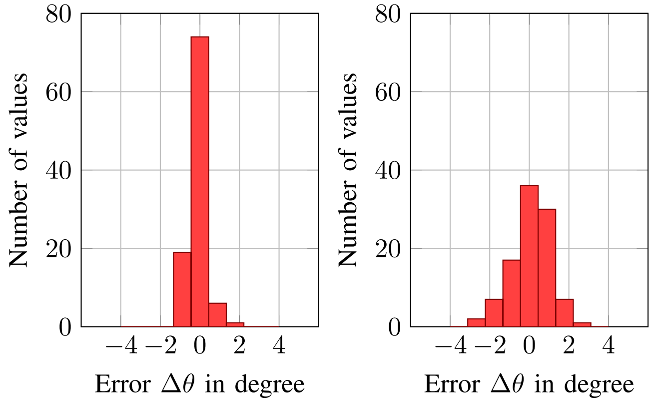


Fig. 6. Measured and simulated phase progression ϕ_{out} of the presented MMIC. For comparison, the theoretical phase progression $kd\sin\theta$ between the centers of the dielectric resonators is also given.

$kd\sin\theta$ and matches well to the calculated ϕ_{out} curve with a phase gain of η=4.

Using this recorded calibration data set, the investigation on angle estimation accuracy was carried out. In this paper the results for an exemplary incidence angle (θ=$-5°$) are shown. These measurements are compared to simulations of the MMIC without biomimetic coupling. The simulation parameters were carefully adjusted to match the simulations to the measurements (cf. Fig. 5, simulation with η=4). In a next step, the parameters η and L_{out} were removed from the simulation model (i. e. η=1, L_{out}=0 dB). This means, the effective aperture for this setup is now four times smaller but the SNR is increased by 5 dB. Using this modified simulation model (cf. Fig. 5, simulation with η=1), 100 simulations were performed for the MMIC without biomimetic coupling.

A maximum likelihood angle estimation was performed for every measured and simulated sample, respectively. The estimation error $\Delta\theta$ is plotted with its occurrence



(a) MMIC with BMAA - meas. (b) MMIC without BMAA - sim.

Fig. 7. Error distributions out of 100 radar measurements/simulations and subsequent ML angle estimation for the MMIC (a) with and (b) without biomimetic coupling.

in the histograms of Fig. 7. As can be seen from Fig. 7 the biomimetic coupling leads to a more accurate angle estimation. The standard deviation of the MMIC with the BMAA is $0.47°$ whereas for the MMIC without BMAA the standard deviation is calculated to $1.02°$. The lower standard deviation originates from the increased phase progression (cf. Fig. 6) leading to a smaller lobe in the angle spectrum. This also overcompensates the loss in SNR given by the L_{out} parameter.

Applying the biomimetic coupling to the MMIC therefore leads to an angle estimation accuracy being factor 2.17 better than the MMIC would exhibit with a conventional antenna system of the same size.

VI. Conclusion

In this paper an ultra compact radar MMIC at 160 GHz is presented. While occupying a chip area of $3\,\text{mm}^2$ only it comprises two transceivers and two antennas, all integrated on the chip. Biomimetic coupling was added to the antenna system to improve the angle estimation accuracy despite the small antenna aperture of $\lambda/4$ only. It was shown that the angle estimation accuracy is improved by about the factor 2.2 when using BMAAs.

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