

# Fully Integrated Automotive Radar Sensor with Versatile Resolution

Carsten Metz<sup>1</sup>, Jens Grubert<sup>1</sup>, Johann Heyen<sup>1</sup>, Arne F. Jacob<sup>1</sup>,  
Stephan Janot<sup>2</sup>, Ernst Lissel<sup>3</sup>, Gerald Oberschmidt<sup>4</sup>, Leif C. Stange<sup>1</sup>

<sup>1</sup>Institut für Hochfrequenztechnik, TU Braunschweig, Germany

<sup>2</sup>now with: Rhode&Schwarz, München, Germany

<sup>3</sup>Volkswagen AG, Wolfsburg, Germany

<sup>4</sup>now with: Siemens AG, Bruchsal, Germany

**Abstract** — A planar radar sensor for automotive application is presented. The design comprises a fully integrated transceiver multi-chip module (MCM) and an electronically steerable microstrip patch array. The antenna feed network is based on a modified Rotman-lens. An extended angular coverage together with an adapted resolution allows for the integration of automatic cruise control (ACC), precrash sensing and cut-in detection within a single 77 GHz frontend. For ease of manufacturing the interconnects between antenna and MCM rely on a mixed wire bond and flip-chip approach. The concept is validated by laboratory radar measurements.

## I. INTRODUCTION

Millimeterwave monolithic integrated circuit (MMIC) technology and low profile antennas with high resolution capability as well as wide angular coverage are keys for future low cost radar systems with high customer acceptance. Due to advanced MMIC production technologies complete 77 GHz transmit/receive-chipsets are readily available for system application [1–5]. Here, usually modular approaches are pursued in order to allow maximum flexibility in circuit design. Depending on the desired circuit structure only few components like couplers and resonators have to be added. Hence, the engineering tasks focus on the conception of the system architecture including the antenna, the design and optimization of proper MCM, and the chip assembly and characterization. Despite this, most today's radar-frontends still comprise high-cost packaged Gunn diodes. Present antenna systems mainly rely on quasi-optical concepts or mechanical scanning which generally implies rather bulky structures [6–8]. Only few reports on planar antennas were published [9, 10]. Except for increased losses, such concepts are superior with respect to both system integration in the car and low cost production. Still, additional features like parking aid, precrash sensing, and cut-in detection are presently not integrated in the known 77 GHz antenna designs. Often these tasks are performed by separate 24 GHz modules [11], which complicates the system integration and increases the cost significantly.

This paper reports on a new planar, fully integrated and

frequency-modulated continuous wave (FMCW) radar sensor for automotive application. Besides a PLL stabilized MMIC chipset it combines ACC, parking aid, precrash sensing, and cut-in detection capability within a single 77 GHz front-end. To keep the circuit effort reasonably low this first prototype system was designed for sequential lobing, only. However, parallel lobing can easily be incorporated in future designs because of the flexibility of the present approach. The actual planar, electronically steerable antenna with its versatile resolution already exhibits the required functionality. In the following, the transceiver unit and the phase lock loop are discussed in detail. Because of its complexity the antenna system will only be sketched very briefly, here. The physical structure of the complete front-end will be presented next. Finally, preliminary operational tests of the overall system are reported.

## II. SENSOR HARDWARE DESIGN

### A. Transceiver Unit

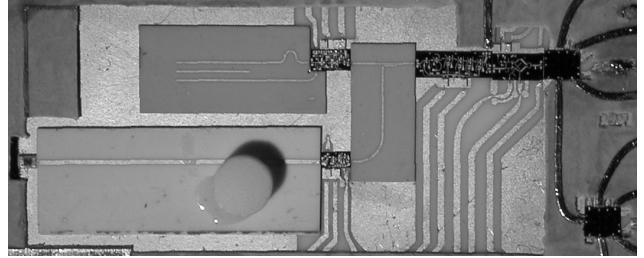


Fig. 1. Multi-chip module

The assembled MCM is shown in Fig. 1. It consists of a 630  $\mu$ m thick alumina substrate and incorporates four commercially available MMIC of high functionality [1], two MMIC PIN-switches [5], and various passive circuit components, designed and manufactured in-house. The gold plated alumina substrates are structured and shaped employing photolithography and laser material processing, respectively. The MCM is assembled using pick and place

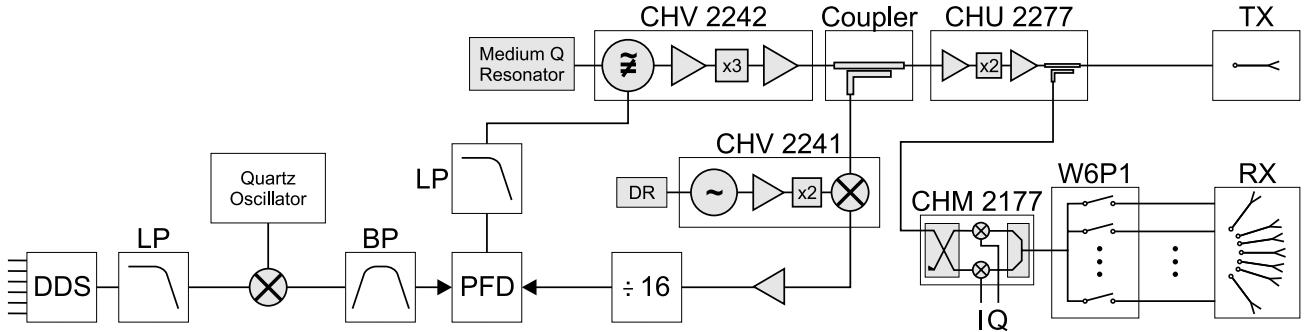


Fig. 2. Block diagram of the sensor

utilities with a split field optic for highly accurate chip placement ( $\pm 4 \mu m$ ). The components are connected by wire bonds. In order to reduce the inductance of the bond wire the passive drop-on components, e.g. an  $8 dB$  microstrip coupler and a medium Q resonator, were designed on  $127 \mu m$  thick alumina substrate, comparable in height to the  $100 \mu m$  thick MMIC. The transceiver unit was characterized by means of a Cascade Microtech Probe Station with W-band coplanar waveguide probes.

Fig. 2 illustrates the architecture of the transceiver unit. A voltage controlled oscillator (VCO) generates a  $12.75 GHz$  signal which is amplified and tripled on-chip (CHV2242) to  $38.25 GHz$ . The oscillator is coupled to a medium Q feedback circuit consisting of three coupled half-wave lines, as suggested in [1]. The oscillator exhibits a free running phase noise of  $-55 dBc/Hz@10 kHz$  and a tuning range in excess of  $150 MHz$ .

The multifunction chip (CHU2277) combines a frequency doubler and a four-stage amplifier. It has two  $76.5 GHz$  ports with an output power of  $13 dBm$  and  $9 dBm$ , respectively. These feed the transmit antenna and the local oscillator port of the receiving mixer, respectively.

The integrated I-Q mixer (CHM2177) downconverts the signal of the receiving antenna to an in-phase (I) and a quadrature (Q) IF-port for further signal processing. Sequential lobing of the seven antenna beams is provided by means of PIN-switch MMIC. Because single-chip  $77 GHz$  SP7T PIN-switches are currently not available two W6P1 PIN-switches [5] had to be cascaded. This leads to different power levels for the individual beams; this drawback will eventually be overcome in a later parallel lobing design.

#### B. Phase lock loop (PLL)

In order to suppress VCO phase noise and improve frequency chirp linearity it is essential to employ phase-lock techniques as a part of the radar synthesizer. An especially demanding requirement for the stepped FMCW approach is the short settling time of  $3.5 \mu s$  in combination with small

frequency steps (approx.  $20 kHz$ ) [12]. Typical solutions to this problem include the utilization of multiple-loop architectures or single-loop PLLs with fractional dividers [13].

The synthesizer architecture chosen here comprises a single-loop PLL driven by a direct digital synthesizer (DDS) as a reference source. The circuit complexity of this approach is relatively low and enables the selection of standard IC components. DDS exhibit good phase noise performance, fast switching capabilities and extremely fine frequency resolution. The main problem associated with these devices is their high spurious signal content at higher output frequencies. To alleviate this drawback the DDS is operated at lower frequencies ( $4.9 MHz$ ), where the spurious free dynamic range (SFDR) is sufficiently high: typ.  $80 dB$  within  $\pm 100 kHz$  around the carrier. This output is then up-converted, filtered and fed to the phase/frequency detector (PFD).

The VCO output at  $38.25 GHz$  is partially coupled into the feedback path and downconverted by an integrated oscillator/mixer MMIC (CHV2241). The oscillator is stabilized by means of an external high-Q dielectric resonator (DR) at  $19 GHz$  [1]. Its frequency is doubled internally giving a phase noise of  $-100 dBc/Hz@100 kHz$ . The output IF signal in the frequency range  $704..784 MHz$  is amplified and fed to the PFD through a prescaler/divider chain ( $N=16$ ) for comparison with the reference signal at  $44..49 MHz$ . At  $10 kHz$  offset from carrier the VCO phase noise can be suppressed by approximately  $15 dB$ . The transient behaviour of the loop is determined by the bandwidth of the following loop filter. The selected filter bandwidth of  $1 MHz$  allows the PLL to settle within less than  $3.5 \mu s$ .

Only the DR has to be tuned here making this approach suitable for automatic alignment.

#### C. Antenna System

The sensor comprises a bistatic antenna system based on a planar microstrip patch array. Similarly to [9] the receiving antenna is scanned via a planar Rotman-lens. As shown

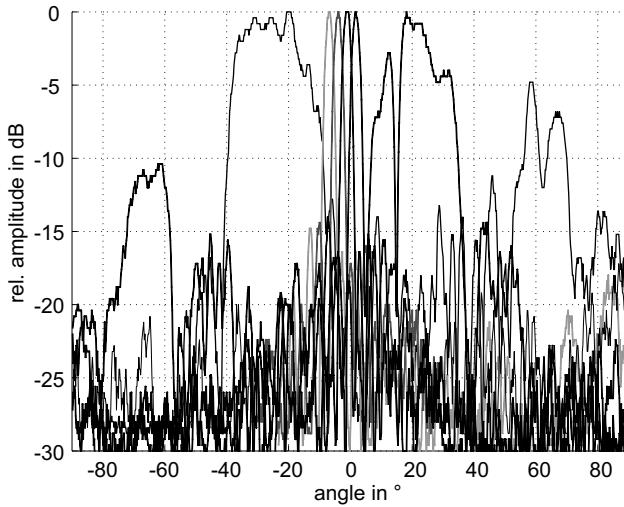


Fig. 3. Measured antenna pattern

in Fig. 3 it possesses five beams of  $2.7^\circ$  width at  $26.6\text{ dBi}$  average gain (for mechanical reasons the waveguide measuring equipment could only be connected to four beams in this setup). Two additional beams provide cut-in detection and precrash sensing capability. While narrow beam mode is achieved by feeding the beamports of the lens, broad beams are realized by distributed sidewall feeding with secondary lenses. A fresnel-lens-like delay network is introduced in the design to reduce the sidelobe level.

In contrast to [9] where transmit and receive antenna were scanned simultaneously, here the entire field of view is illuminated permanently. The radiation pattern of the transmit antenna is formed so as to emphasize ACC detection. Besides offering highest SNR this approach also minimizes the complexity of the RF circuitry and allows a smaller transmit antenna. This significantly reduces the size of the complete sensor.

#### D. Physical Structure of the Frontend

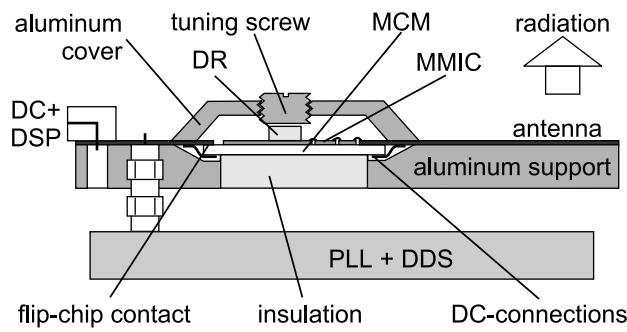


Fig. 4. Physical structure of the frontend

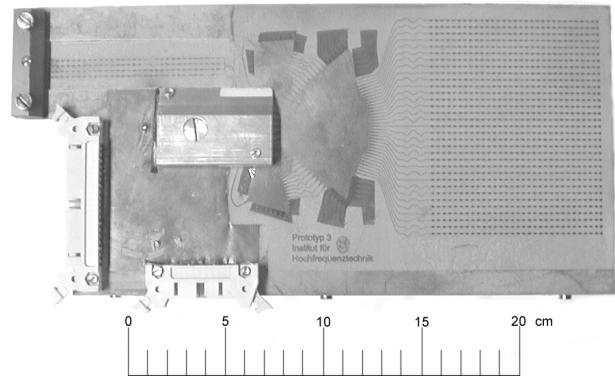


Fig. 5. Photograph of the planar sensor

Fig. 4 shows a cross-sectional view of the whole prototype frontend. An aluminum plate supports the antenna substrate and the MCM. Due to the absence of moving parts the design is rugged and durable. For operation in the field the sensor will be equipped with a radome, which was omitted in the laboratory setup. The MCM/antenna support measures only  $24.9\text{ cm} \times 12.2\text{ cm} \times 1\text{ cm}$  (see Fig. 5) whereas the overall size of the sensor including the PLL is  $24.9\text{ cm} \times 12.2\text{ cm} \times 12.2\text{ cm}$ , leaving great potential for optimization.

To avoid the intersection of RF and DC traces the latter are partly configured on the backside of the MCM. All RF connections are wire bonded, whereas the DC and IF interconnects between MCM and antenna substrate are flip-chipped using conductive adhesives. Besides ease of manufacturing this also provides mechanical stability. To minimize the bond length and thus, transmission losses the antenna substrate and the MMIC have comparable thickness.

### III. RESULTS

First functionality tests of the radar frontend were conducted in a laboratory environment. The digital signal processing (DSP) was run on a standard personal computer (PC). This includes all necessary FMCW-waveform settings for the DDS and the data acquisition. The measurements are performed as follows. Before down-conversion the received RF signal is chopped by a  $20\text{ kHz}$  "on-off-keying" of the MMIC switches in the receiving path. The modulated base-band signal is measured with a commercial lock-in-amplifier (Stanford Research Systems SR-510), which is synchronized to the chopper signal. The measured data are transferred to the PC for further signal processing which allows online radar measurements of stationary targets. Since the used PC interfaces are too slow doppler processing is not feasible in this test setup. For illustration, Fig. 6 shows the processed signal obtained from a corner reflector lo-

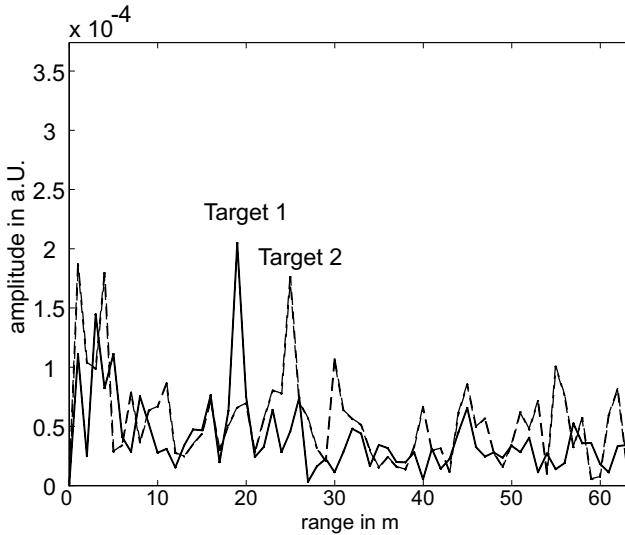


Fig. 6. Radar measurements with targets at 18 and 23m

cated at 18 and 23m, respectively. An appropriate DSP architecture will now be added to the frontend in order to allow velocity measurements. Its improved offset-correction will increase the sensitivity.

#### IV. CONCLUSION

In this paper a fully integrated, planar radar sensor for automotive application was presented. ACC, precrash sensing and cut-in detection were integrated within one 77GHz frontend to replace today's hybrid approaches based on separate 24 and 77GHz modules. Commercially available MMIC and self made components were employed for the transceive-module. A detailed description of the technological fabrication process is given. The electrical interface between antenna and MCM was realized in mixed flip-chip and wire-bond technology to reduce the number of bond wires. For phase noise reduction the oscillator was stabilized by a PLL. Simple radar measurements prove the functionality. A DSP unit is now being attached to the frontend for high performance detection and field application.

#### V. ACKNOWLEDGEMENT

The authors wish to acknowledge the continuous and generous support by United Monolithic Semiconductors (UMS) and Tyco Electronics M/A-COM regarding the supply of MMIC.

#### REFERENCES

- [1] M. Camiade, D. Domnesque, Z. Quarch, and A. Sion, "Fully MMIC-Based Front End for FMCW Automotive Radar at 77 GHz," in *Proceedings of the European Microwave Conference*, vol. 1, (Paris), pp. 9–12, 2000.
- [2] H. J. Siweris, A. Werthof, H. Tischer, U. Schaper, A. Schafer, L. Verweyen, T. Grave, G. Bock, M. Schlechtweg, and W. Kellner, "Low-cost GaAs pHEMT MMIC's for millimeter-wave sensor applications," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2560–2567, Dec. 1998.
- [3] H. Mizutani, N. Shida, T. Saryo, T. Kuwabara, T. Eda, T. Matsumura, and M. Funabashi, "76-GHz MMIC chip set for compact, low cost and highly reliable automotive radar system," in *Radio Frequency Integrated Circuits (RFIC) Symposium, 1999 IEEE*, pp. 91–94, 1999.
- [4] H. Kondoh, K. Sekine, S. Takatani, K. Takano, H. Kuroda, and R. Dabkowski, "77 GHz fully-MMIC automotive forward-looking radar [using pHEMTs]," in *GaAs IC Symposium, 1999. 21st Annual*, pp. 211–214, 1999.
- [5] J. Putnam, M. Barter, K. Wood, and J. LeBlanc, "A monolithic GaAs PIN switch network for a 77 GHz automotive collision warning radar," in *Microwave Symposium Digest, 1997., IEEE MTT-S International*, vol. 2, pp. 753–756, 1997.
- [6] L. H. Eriksson and B.-O. As, "Automotive radar for adaptive cruise control and collisions warning/ avoidance," in *Radar 97*, (Järfälla, Sweden), pp. 16–20, Oct. 1997.
- [7] W. Menzel, D. Pilz, and R. Leberer, "A 77-GHz FM-CW radar frontend with a low-profile low-loss printed antenna," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2237–2241, Dec. 1999.
- [8] K. Winter, B. Lucas, H. Olbrich, T. Beez, H. Mayer, and K. Lehre, "A compact radar sensor and control unit for adaptive cruise control," in *International Radar Symposium*, vol. 1, (Munich), pp. 355–362, 1998.
- [9] M. E. Russell, A. Crain, A. Curran, R. A. Campbell, C. A. Drubin, and W. F. Miccioli, "Millimeter-wave radar sensor for automotive intelligent cruise control," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2444–2453, Dec. 1997.
- [10] D. D. Li, S. C. Luo, and R. M. Knox, "Millimeter-wave FMCW radar transceiver/ antenna for automotive applications," *Applied microwave & wireless*, vol. 11, no. 6, pp. 58–68, 1999.
- [11] P. Heide, M. Vossiek, M. Nalezinski, L. Oreans, R. Schubert, and M. Kunert, "24 GHz short-range microwave sensors for industrial and vehicular applications," in *Workshop "Short Range Radar"*, (TU Ilmenau), 1994.
- [12] R. Mende and H. Rohling, "A high performance AICC radar sensor-concept and results with an experimental vehicle," in *Radar 97 (Conf. Publ. No. 449)*, pp. 21–25, 1997.
- [13] T. v. Kerssenbrock, T. Musch, B. Schiek, and P. Heide, "Novel 77 GHz low-cost automotive radar module with Fractional-PLL frequency linearizer," in *Proceedings of the European Microwave Conference*, pp. 5–8, 1999.