A 94 GHz Single-Chip FMCW Radar Module for Commercial Sensor Applications

A. Tessmann, S. Kudszus*, T. Feltgen, M. Riessle, C. Sklarczyk**, W. H. Haydl

Fraunhofer Institute for Applied Solid State Physics (IAF), Tullastrasse 72, D-79108 Freiburg, Germany

*now with: BigBear Networks, 1591 McCarthy Blvd, Milpitas, CA 95035

**Fraunhofer Institute for Non-destructive Testing (IZFP), D-66123 Saarbruecken, Germany

***Abstract* — A single-chip 94 GHz frequency modulated continuous wave (FMCW) radar module has been developed for high resolution sensoring under adverse conditions and environments. The monolithic microwave integrated circuit (MMIC) includes a varactor tuned VCO with injection port, very compact transmit and receive amplifiers and a single-ended resistive mixer. To enable bidirectional operation of a single transmit-receive antenna a combination of a Wilkinson divider and a Lange coupler was integrated. The circuit features coplanar technology and cascode HEMTs for compact size and low cost. These techniques result in a particularly small over-all chip-size of only 2 x 3 mm^2. The packaged 94 GHz FMCW radar sensor achieved a tuning range of 6 GHz, an output power of 1 mW and a conversion loss of 5 dB. The RF performance of the radar module was successfully verified by real-time monitoring the time flow of a gas-assisted injection molding process.**

I. Introduction

In addition to the forward looking automotive radar, compact and efficient industrial sensors are the most promising commercial applications at W-band frequencies. They are suitable to control industrial manufacturing processes by contactless real-time monitoring the fabrication flow. Further applications are surface analysis, characterization of thin films on coated windows, quality control of welded joints and level sensing. In contrast to ultrasonic, video, infrared and laser sensors, radar sensors are less sensitive to environmental conditions, so they can be used to penetrate vapor, heat and dust. Signal frequencies at W-band are very attractive due to their high spatial resolution, the resulting compact chip-size and small antenna dimensions [1]-[3]. For short distance sensing the signal output power is small, which helps to reduce heating of both, the test object and the sensor itself.

In this work, we present a low-cost single-chip 94 GHz FMCW radar module. The monolithically integrated coplanar FMCW radar chip includes four active circuits, two hybrids and an additional injection port. The coplanar waveguide (CPW) technology is very attractive at millimeter wave frequencies, due to the simplified fabrication process and its potential for flip-chip packaging [4]. The cascode devices offer twice the gain of a conventional HEMT in common-source configuration, requiring the same chip area. The assembled W-band FMCW radar MMIC was packaged in a WR-10 waveguide module, using CPW-to-waveguide transitions, realized on 127 μm thick quartz substrates. In addition to the conventional face-up mounting technique, we also investigated flip-chip packaging of the radar MMIC on doped silicon (n-Si) carriers [5].

The monolithically integrated multifunctional radar chip, low fabrication cost, small module size and low weight combined with improved assembly techniques allows for the realization of a high performance W-band sensor highly suitable for commercial applications and industrial markets.

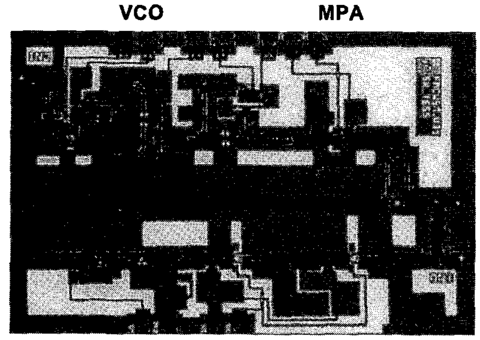

Fig. 1. Chip photo of a 94 GHz single-chip FMCW radar MMIC. The chip size is 2 x 3 mm^2.

II. 94 GHz FMCW Radar MMIC

For manufacturing the radar chip, we used an MBE grown double doped pseudomorphic AlGaAs/InGaAs/GaAs

HEMT technology on semi-insulating 4-inch wafers. The T-shaped 0.15 μm gates were written with e-beam, and the recess was dry etched.

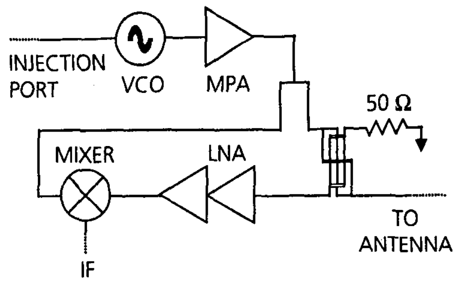

Fig. 2. Block diagram of the 94 GHz FMCW radar MMIC.

The devices typically achieve a transit frequency f_t = 100 GHz and a maximum oscillation frequency f_{max} = 180 GHz. With 25 % indium in the channel, a current density I_{sat} of 1000 mA/mm is achieved. The extrinsic maximum transconductance is 800 mS/mm.

The chip photo in Fig. 1 illustrates the circuit topology, using coplanar transmission lines with a metalization thickness of 3 μm and a ground to ground spacing of 50 μm. The block diagram in Fig. 2 shows the configuration of the 94 GHz FMCW radar MMIC. A newly developed varactor tuned VCO offers both, large tuning range and the possibility to reduce the phase noise by injection locking, as demonstrated in [6]. A very compact MPA, based on space-saving dual-gate devices, was used to amplify the oscillator signal. The directivity and the isolation for separating the transmit and receive paths, which are feeding a single transmit-receive antenna, were achieved by combining a Wilkinson power divider and a Lange coupler.

This approach enables broadband modulation and provides the functionality of a circulator, which had to be added externally in an earlier design of the radar MMIC [7]. The receive path consists of a two-stage cascode LNA and a single-ended resistive mixer. The entire chip-size of the FMCW radar is only 2 x 3 mm^2.

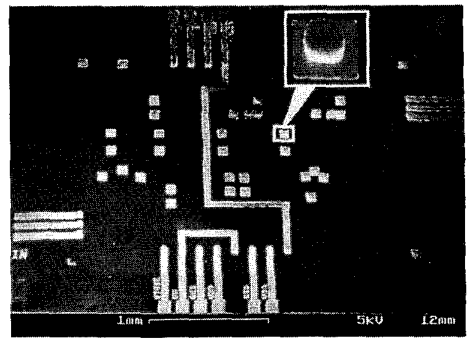

Fig. 4. Flip-chip substrate for the 94 GHz FMCW radar MMIC. The substrate size is 3 x 4 mm^2.

III. PERFORMANCE AND ASSEMBLY

Figure 3 shows the on-wafer measured output power and the signal frequency of the radar MMIC as a function of the tuning voltage. A tuning bandwidth of 6 GHz and an output power of about 2 dBm were measured by varying the varactor voltage between – 3 V and + 1 V.

In addition to the face-up mounting technique, we also investigated flip-chip packaging of the 94 GHz MMIC on doped n-Si substrates to further improve reproducibility and to ease fabrication. Figure 4 shows the layout of a typical carrier substrate.

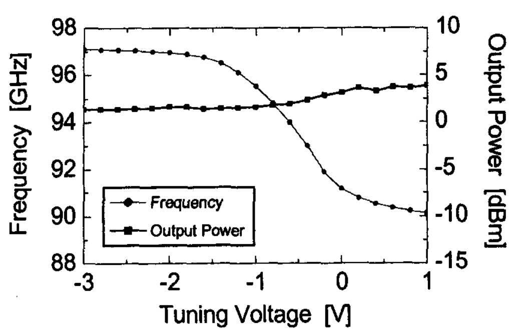

Fig. 3. 94 GHz radar MMIC: On-wafer measured output power and signal frequency as a function of the tuning voltage.

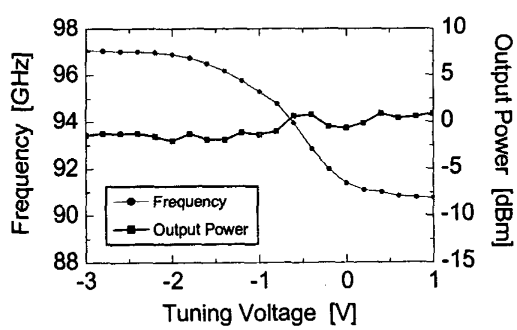

Fig. 5. Flip-chip packaged 94 GHz radar MMIC: Measured output power and signal frequency as a function of the tuning voltage.

The transmission lines on the substrate were realized as finite-ground coplanar waveguides (FGCPW), to reduce the excitation of parallel-plate modes in the flip-chip substrate [8]. For good heat dissipation, the 28 µm high galvanic gold bumps were placed close to the active devices. Additional bumps were used to realize the RF and DC contacts and to improve the mechanical stability, counteracting the different thermal expansion coefficients of GaAs and Si. In Fig. 5 the RF performance of a flip-chip mounted radar MMIC is shown. The measured tuning bandwidth and output power correspond to the on-wafer measurement results.

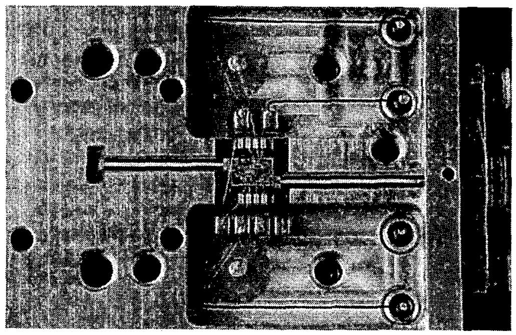

Fig. 6. Inside view of the face-up mounted 94 GHz FMCW radar module with injection port.

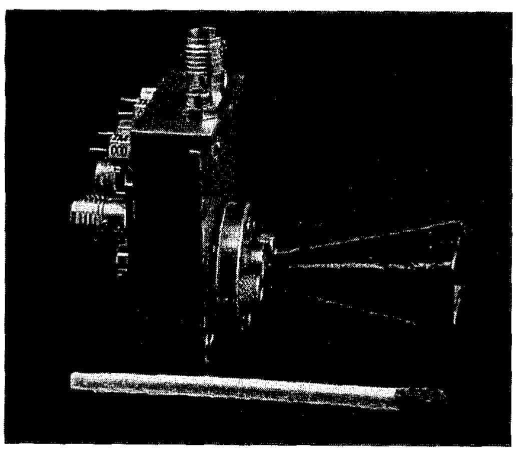

Fig. 7. Photo of the 94 GHz FMCW radar module.

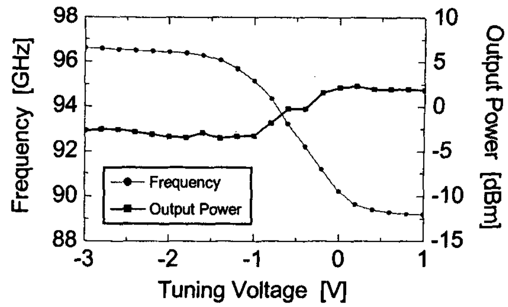

Fig. 8. 94 GHz radar module: Measured output power and signal frequency as a function of the tuning voltage.

In Fig. 6 and Fig. 7 an inside view and a photograph of the 94 GHz FMCW sensor module are shown. For this module the conventional face-up mounting technique was utilized, with wedge-bonded interconnects using 17 µm gold wires. To prevent low frequency oscillations, we integrated 120 pF chip capacitors, 10 nF SMD ceramic capacitors and filters in the bias connections. The transition from the coplanar output of the MMIC to the waveguide of the module was realized with a microstrip line on 127 µm thick quartz substrates [9]. The over-all module size was 34 x 24 x 10 mm^3. The radar module achieved a modulation frequency range of 6 GHz, an output power of about 0 dBm and an average conversion loss of 5 dB, as shown in Fig. 8 and Fig. 9, respectively.

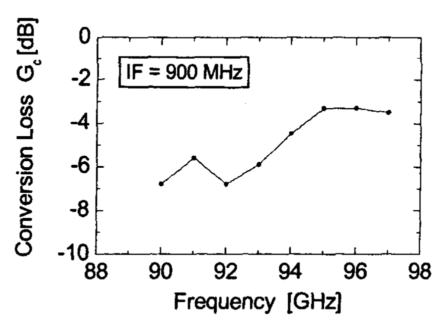

Fig. 9. Measured conversion loss of the 94 GHz radar module.

IV. EXPERIMENTAL RESULTS

To verify the functionality of the FMCW sensor in a production environment, the module was used to monitor the quality of polymeric products. As an example, Fig. 10 shows two plastic rods which were manufactured by gas-assisted injection molding. During the fabrication process,

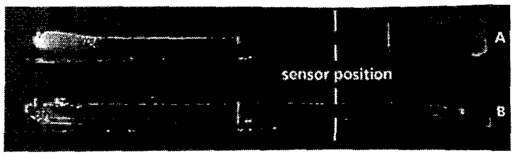

Fig. 10. Photo of two plastic rods realized by gas-assisted injection molding.

first, liquid plastic was filled into the mold. Then, to reduce weight and material, gas was injected forming an inner cavity in the plastic rod. The radar sensor was used to monitor the gas injection process through a teflon window in the mold. Two experiments are represented by the two rods shown in Fig. 10. In Fig. 10A the gas injection stopped, before the gas reached the sensor position. Figure 10B shows a successful injection of the gas, that has passed the sensor and thus, led to a completely hollow plastic rod. This is illustrated furthermore in Fig. 11 by monitoring the amplitude of the IF signal during the process, indicating clearly the time flow of the injection.

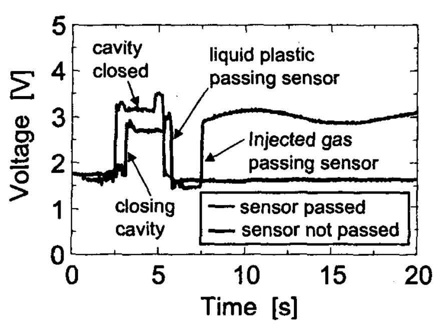

Fig. 11. IF signal of the 94 GHz FMCW radar sensor representing the time flow of the polymeric injection molding process.

V. Conclusion

A very compact single-chip 94 GHz FMCW radar sensor was demonstrated, achieving a tuning range of 6 GHz and an output power of 1 mW. The coplanar radar MMIC contains four active circuits occupying a chip-area of only 2 x 3 mm^2 and enables bidirectional operation of a single transmit-receive antenna. The FMCW radar chip was successfully packaged in a WR-10 waveguide module and used to real-time monitor the time flow of a gas-assisted injection molding process. These results demonstrate the potential of compact, high resolution W-band radar sensors to improve process control, even under adverse conditions like dust, fume, heat or vapor. Additionally, the advanced and mature circuit and assembly technique allow for a commercial high performance sensor.

VI. Acknowledgement

The authors would like to thank their colleagues from the technology department for the fabrication of the coplanar devices, H. Massler and M. Kuri for measurements and M. Schlechtweg and G. Weimann for support.

References

[1] D. C. W. Low, K. W. Chang, R. Lin, E. W. Lin, H. Wang, M. Biedenbender, G. S. Dow, and B. R. Allen, "A Single-chip W-band Transceiver with Front-end Switching Receiver for FMCW Radar Applications", *1995 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium Digest*, pp. 225-228, June 1995.

[2] K. W. Chang, H. Wang, G. Shreve, J. G. Harrison, M. Core, A. Paxton, M. Yu, C. H. Chen, and G. S. Dow, "Forward-Looking Automotive Radar Using a W-band Single-Chip Transceiver", *1995 Transactions on Microwave Theory and Techniques*, vol. 43, no. 7, pp. 1659-1668, July 1995.

[3] M. Vossiek, T. v. Kerssenbrock, and P. Heide, "Novel Nonlinear FMCW Radar for Precise Distance and Velocity Measurements", *1998 IEEE MTT-S International Microwave Symposium Digest*, pp. 511-514, June 1998.

[4] T. Hirose, K. Makiyama, K. Ono, T. M. Shimura, S. Aoki, Y. Ohashi, S. Yokokawa, and Y. Watanabe, "A Flip-Chip MMIC Design with Coplanar Waveguide Transmission Line in the W-Band," *1998 IEEE Transactions on Microwave Theory and Techniques*, vol. 46, pp. 2276-2282, Dec. 1998.

[5] A. Tessmann, W. H. Haydl, T. v. Kerssenbrock, P. Heide., S. Kudszus, " Suppression of Parasitic Substrate Modes in Flip-Chip Packaged Coplanar W-Band Amplifier MMICs," *2001 IEEE MTT-S International Microwave Symposium Digest*, pp. 543-546, May 2001.

[6] S. Kudszus, T. Berceli, A. Tessmann, M. Neumann, and W. H. Haydl, " W-band HEMT-Oscillator MMICs Using Subharmonic Injection Locking," *2000 IEEE Transactions on Microwave Theory and Techniques*, vol. 48, no.12, pp. 2526-2532, Dec. 2000.

[7] W. H. Haydl, M. Neumann, L. Verweyen, A. Bangert, S. Kudszus, M. Schlechtweg, A. Hülsmann, A. Tessmann, W. Reinert, and T. Krems, "Single-Chip Coplanar 94-GHz FMCW Radar Sensors," *1999 IEEE Microwave and Guided Wave Letters*, vol. 9, no. 2, pp. 73-75, Feb. 1999.

[8] M. Yu, et al., "W-Band InP HEMT MMICs Using Finite-Ground Coplanar Waveguide (FGCPW) Design," *1999 IEEE Journal of Solid-State Circuits*, vol. 34, pp. 1212-1217, Sept. 1999.

[9] A. Tessmann, W. H. Haydl, M. Neumann, and J. Rüdiger, "W-Band Cascode Amplifier Modules for Passive Imaging Applications," 2000 IEEE Microwave and Guided Wave Letters, vol. 10, pp. 189-191, May 2000.