Microwave and Millimeterwave Sensors Based on Flip-Chip and SAW Technology

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Wireless sensing plays an important role in industrial automation, domestic systems and transportation. Microwave and millimeterwave sensors offer high resolution and reliable operation in rough environments. Novel attractive sensor modules for the 24, 61 and 77 GHz frequency bands are feasible by the use of flip-chip (FC) and Surface Acoustic Wave (SAW) devices.

Drahtlose Sensorik spielt eine wichtige Rolle in der industriellen Automatisierung, im privaten Haushaltsbereich und in der Verkehrstechnik. Mikrowellen- und Millimeterwellen-Sensoren bieten hohe Auflösung und arbeiten selbst unter rauhen Umgebungsbedingungen zuverlässig. Der Einsatz von Flip-Chip- und Oberflächenwellen-Bauelementen ermöglicht die Realisierung neuartiger, attraktiver Sensormodule für die Frequenzbereiche bei 24, 61 und 77 GHz.

1. Introduction

Multiple wireless sensor functions will be implemented in future railroad and automotive traffic management systems [1], in the field of industrial process automation [2] and in domestic environments [3]. A particular advantage of microwave sensors is their robustness with regard to variable environmental conditions, such as dirt and temperature. Microwave technology is opening up important commercial applications [4], including

- position and speed measurements for railroad vehicles,
- forward-looking radar and park distance control for cars,
- liquid-level sensing for industrial process control,
- presence detection and object recognition for intelligent domestic systems,
- vehicle identification and traffic monitoring systems,
- on-line diagnosis of turbine engines in power engineering.

Up to 100 GHz, high-resolution sensors can be operated in the ISM (industrial, scientific, medical) frequency bands at 24.0 - 24.25 GHz and 61.0 – 61.5 GHz. For automotive radar, the range 76.0 – 77.0 GHz is designated. Higher frequencies offer better resolution and small antenna size; however, technical realization usually becomes more expensive with increasing frequency, which stands in contrast to the low-cost requirements in high-volume sensor applications.

2. Flip-Chip Technology

The engineering potential of microwave sensors can be better and more cost-effective utilized by combining the specific advantages of different component and material technologies. Among other things, this results from the fact that the different and partly competing technologies in many cases offer complementary technical properties. The combination of these features into a functionally optimized microwave system requires reliable and reproducible assembling technologies [5].

At very high frequencies, a conventional SMD production, being used in high-volume consumer electronics (e.g. satellite receivers), encounters technical limitations. The mechanical dimensions of the package and the related parasitic electrical effects (e.g. phase shift, attenuation) are no longer negligible. Even when using wirebonded chips, additional compensation networks are needed. Generally, the lack of reproducibility, caused by varying interconnection length and coarse placement accuracy, often requires expensive circuit tuning. Although recently developed adaptive bonding techniques [6] can correct rough mismatching, they do not solve the problem of attenuation and radiation of wirebonds and are tuning methods themselves.

These constraints are overcome by using flip-chip assembly, which provides extremely short connections. As shown in Fig. 1, the microwave devices are directly connected face-down onto a ceramic or glass substrate. Small gold bumps with a typical diameter of 50 µm are providing the contact. The substrate, processed in thin film technology, includes all passive structures. Before flip-chip bonding, the bumps are applied to the substrate. The flip-chips are then connected to the substrate with thermocompression.

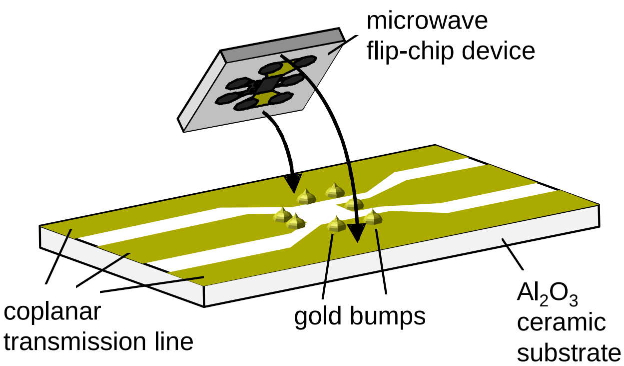

Fig. 1: Flip-chip bonding of microwave devices.

Flip-chip technology has been used in the production of digital circuits (e.g. ball grid arrays, FC soldering) for some time now, whereas FC bonding of microwave and mm-wave devices is still new. The technological basis for this progressive technique is currently in development [7 – 9].

FC bonding demands no special chip devices. By using a coplanar design, via holes are avoided. Besides the advantages of coplanar circuits at millimeterwaves, their design requires sophisticated field simulation [10] and experimental work. The main critical effects are the ohmic losses and the dispersion of coplanar waves [11]. In addition, parasitic modes (surface waves and parallel plate modes) could be excited. These parasitics exhibit a strong dependency on the chosen coplanar configuration (backside metallization, inner conductor width, gap width, width of ground metallization, dielectric constant, substrate height), but can be minimized in a proper circuit design.

3. Flip-Chip Sensor Modules

Different chips, ranging from diodes and discrete HEMTs [12] to MMICs [13, 14] have been used in the development of new flip-chip sensor modules at 24, 61 and 77 GHz. The results illustrate the excellent performance of flip-chip assembly.

Figure 2 shows a single stage K-band amplifier. The active flip-chip device is a discrete GaAs PHEMT chip (Siemens T409D). The transistor chip is very small (300 x 300 μm^2). The amplifier module (12 x 6 mm^2) is realized in coplanar waveguide with a inner conductor width of w = 130 µm and a gap width of g = 65 µm on a 635 µm thick alumina substrate. A tapered transition connects the amplifier input and output to coaxial ports. The bias network incorporates radial inductors. The simulated and measured gain curves S21(f) are plotted in Fig. 3. At the center frequency, a maximum gain of 9 dB is obtained. Experimental characterization of 10 identical flip-chip amplifier modules proved a very high circuit reproducibility.

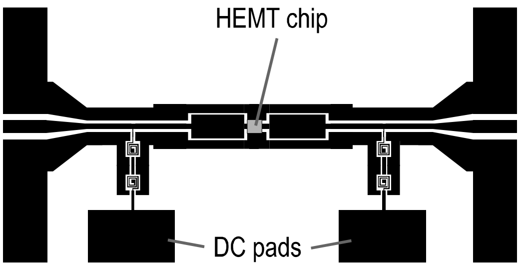

Fig. 2: K-band FC amplifier.

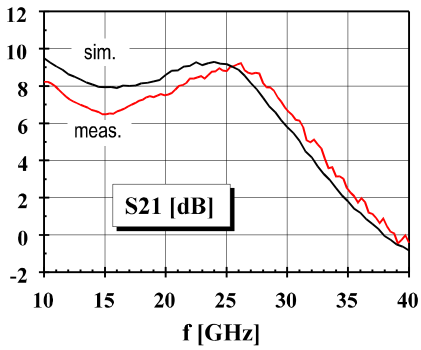

Fig. 3: Simulated and measured gain (S21).

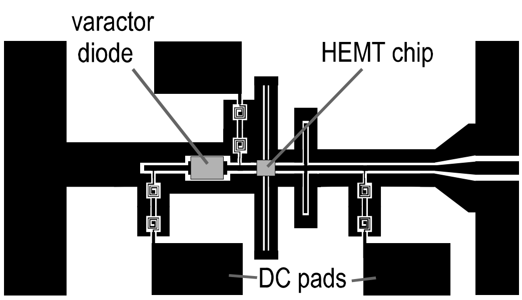

Fig. 4: K-band VCO module.

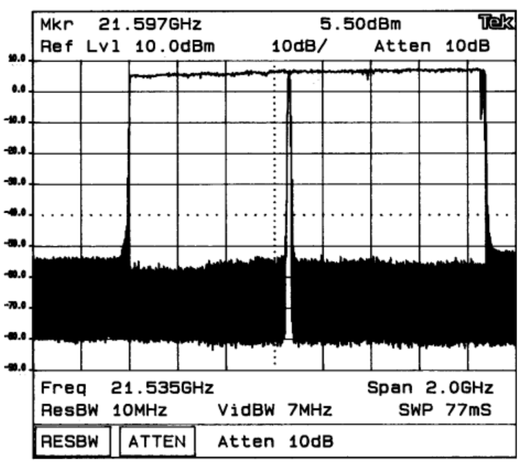

Fig. 5: Swept VCO output spectrum.

The K-band VCO, depicted in Fig. 4, is a reflection-type oscillator also utilizing the Siemens T409D chip. The size of the module is 12 x 6 mm^2. In the VCO design, we optimized for maximum reflection gain (S11) and moderate transmission (S21) in order to get a broad tuning bandwidth and small load pulling. Sweeping of the VCO is obtained by using a varactor tuning diode in a serial feedback configuration. The assembled FC VCO achieved a sweep bandwidth of 1.5 GHz and an output power of +5 dBm (Fig. 5).

By cascading the VCO, a buffer amplifier and a receiver, a compact K-band flip-chip FMCW sensor is realized (Fig. 6). A simple coplanar single diode detector receiver, depicted in Fig. 7, has been built. Through radial inductors, the sensor signal d(t) is taken from the detector DC pad, while interdigital capacitors (IDCs) provide the DC decoupling of the VCO, the buffer amplifier and the receiver.

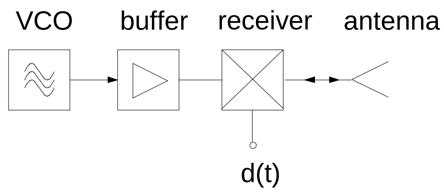

Fig. 6: Schematic of a FMCW sensor.

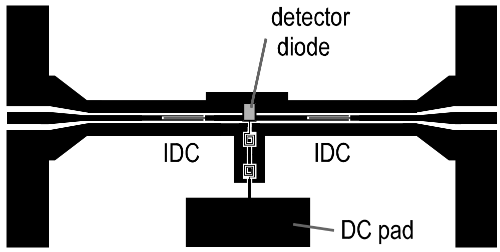

Fig. 7: Flip-chip detector.

Similar sensor modules for millimeterwave frequencies are in development. Figure 8 shows the photo of a 77 GHz flip-chip oscillator (chip size $2.4 \times 0.9 \times 0.1$ mm^3). The GaAs MMIC VCO [15] incorporates the oscillator and two additional buffer stages. The chip is connected to the alumina substrate by a total of about 20 bumps with additional bumps for mechanical stabilization. The assembled FC VCO module includes the transition to a W-band coaxial connector. Typical VCO output power is +3 dBm (Fig. 9).

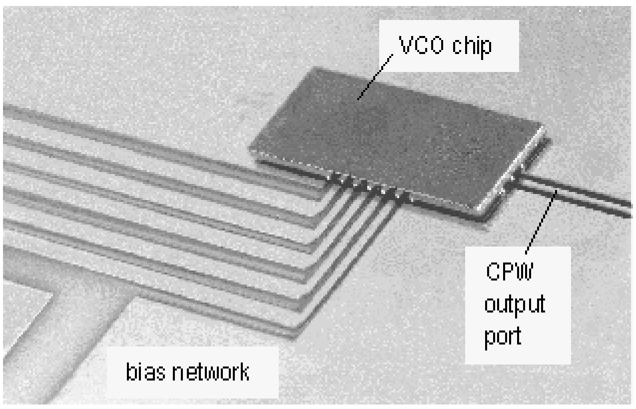

Fig. 8: 77 GHz flip-chip VCO.

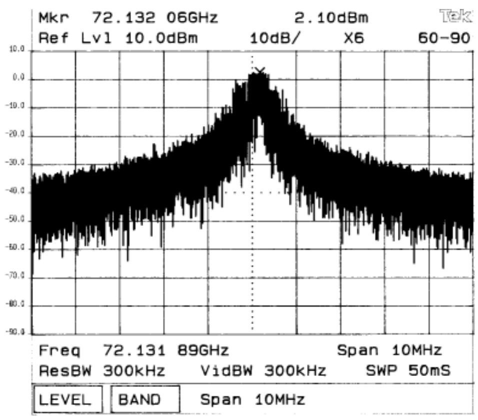

Fig. 9: VCO output spectrum

4. FMCW Sensor with SAW Reference

For commercial microwave applications, inexpensive sensors are needed. The FMCW principle is well established for radar distance measurements, because it offers high sensitivity and is thus suitable for high distance measurements and objects with low reflectivity. However, the performance of a FMCW sensor is limited by the sensor hardware: Typical effects, such as drifting, aging, nonlinearity and noise of the VCO will cause phase errors and thus limitations in measurement sensitivity and accuracy [16].

The basic idea behind a new patented FMCW sensor concept is that the measured distance is compared with an internal reference length [17]. To accomplish this, the IF section of the microwave sensor incorporates a highly precise reference path (Fig. 10) — a small 2.45 GHz SAW delay line [18]. Phase effects occur in the target path and in the reference path in an analogous way. These phase errors are detected and adaptively compensated *by software*. With the internal SAW reference, a self-calibration of the sensor hardware is achieved, which proved to work excellent for precise distance measurements at 24 GHz [19].

In the millimeterwave range, oscillator phase noise is a crucial sensitivity limitation in FMCW sensors [20]. For high-distance measurements, a good phase noise behavior is essential. Currently, monolithically integrated oscillators do not fulfill this requirement. The phase noise level of chip VCOs is typically at about -70 dBc/Hz @ 1 MHz (see Fig. 9). The corresponding limited coherence length of the radar signal is equivalent to a marked reduction in sensor sensitivity with respect to distant objects.

The stabilization of chip VCOs with a feedback loop is very critical and necessitates considerable additional hardware costs. As a cost-effective alternative, the phase noise related deterioration in system dynamics can be eliminated with the aid of the SAW reference. A possible sensor topology of a millimeterwave FMCW sensor with SAW reference is depicted in Fig. 11. A small part of the millimeterwave VCO signal is downconverted to the IF level and drives the 2.45 GHz reference path. Target and reference signal are fed into the DSP section, which removes all phase errors [17].

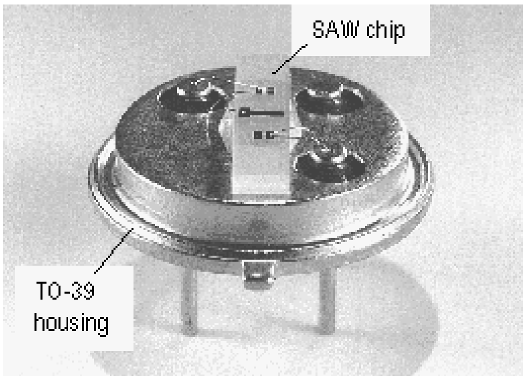

Fig. 10: High-Precision 2.45 GHz SAW reference.

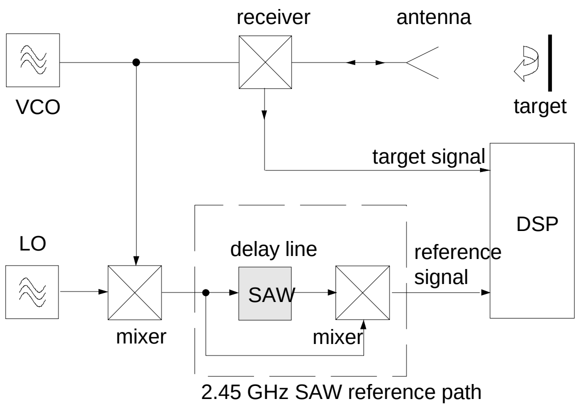

Fig. 11: FMCW sensor with SAW reference. Phase errors are compensated by software.

In experiments, performed with noisy millimeterwave MMIC VCOs, the reference technique proved to significantly enhance the dynamic range of the FMCW sensor, particularly for long-distance targets. Figures 12 and 13 illustrate the effect of phase errors on the FFT echo spectrum corresponding to a target at 100 meter distance. Due to these phase errors, the raw target echo is spread over a wide bandwidth. After phase error compensation, the same echo is compressed to a narrow peak.

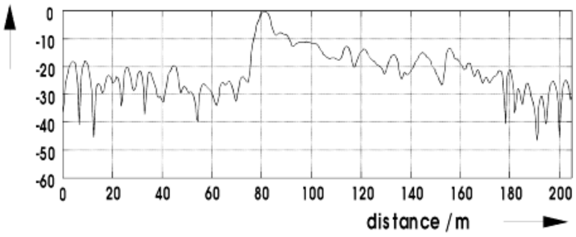

Fig. 12: Raw target signal (100 m distance).

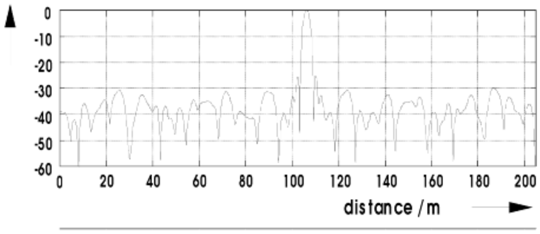

Fig. 13: Same target signal after phase error compensation.

The SAW reference obviates expensive demands on the quality of the oscillators, thus low-cost MMICs or planar Gunn elements can be used — an important prerequisite for opening up large-quantity commercial millimeterwave applications, such as 77 GHz automotive radar.

5. Conclusion and Outlook

New modules for microwave and millimeterwave sensor applications have been developed. It has been demonstrated that sensors can be significantly improved by utilizing the specific features of FC and SAW devices, while cost and size is reduced. The reported sensor modules prove the feasibility and attractiveness of flip-chips. To establish coplanar FC modules into high-volume production, however, further efforts are needed with respect to advanced production processes for thin-film ceramics with integrated bumps and airbridges.

References

[1] H. Meinel: "State of the Art and Future Development Trends in the Area of Automotive Radar Applications", *MIOP '97 Int. Microwave and Optronics Conf.*, Stuttgart, Germany, to be published.

[2] W. Boyes, R. Jean: "Look at Your Process Non-Invasively — Microwave Radar is the Rising Star among Noninvasive Sensing Techniques for Flow, Level or Composition", *Chemical Engineering*, June 1994, pp. 84 – 88.

[3] "Tischlein Deck Dich" (Technik und Innovation — Wohnen 2000), *Wirtschaftswoche*, Nr. 40 (1996).

[4] P. Heide, V. Mágori: "Microwave Sensors for Industrial and Transportation Systems", *Siemens Review*, R&D Special, Fall '96, pp. 30 – 32.

[5] P. Heide, F. Schmidt, V. Mágori: “New Concepts and Key Technologies for Microwave Sensor Systems: Flip-Chip & SAW Devices”, *26th European Microwave Conference (EuMC’96),* Prague, Workshop Proc. pp. 60 – 65.

[6] U. Goebel: “DC to 100 GHz Chip-to-Chip Interconnects with Reduced Tolerance Sensitivity by Adaptive Wirebonding”, *IEEE 3rd Topical Meeting Electrical Performance of Electronic Packaging,* Monterey, CA, 1994, pp. 182 – 185.

[7] G. Baumann, D. Ferling, H. Richter: “Comparison of flip-chip and wire bond interconnections and the technology evaluation on 51 GHz transceiver modules”, *26th European Microwave Conference (EuMC’96),* Prague, pp. 98 – 100.

[8] T. Krems, W. Haydl, H. Massler, J. Rüdiger: “Millimeter-Wave Performance of Chip Interconnections Using Wire Bonding and Flip-Chip”, *1996 IEEE MTT-S Int. Microwave Symposium,* San Francisco, USA, pp. 247 – 250.

[9] J. Eldring, E. Zakel, H. Reichl: “Flip-Chip Attach of Silicon and GaAs Fine Pitch Devices as well as Inner Lead TAB Attach Using Ball Bump Technology”, *Hybrid Circuits,* 34 (1994), pp. 20 – 24.

[10] M. Naghed: “Analyse koplanarer Mikrowellenstrukturen mit der Methode der quasistatischen Finiten Differenzen”, Dissertation, Universität Duisburg, 1992.

[11] M. Riaziat, R. Majidi-Ahy, I.-J. Feng: “Propagation modes and dispersion characteristics of coplanar waveguides”, *IEEE Trans. on MTT,* Vol.38, no.3, 1990, pp. 245 – 251.

[12] F. Ponse, O. Berger: “HEMT Evaluation for Space Applications”, *Proc. of 2nd ESA Electronic Components Conf.,* Noordwijk, 1993, pp. 95 – 101.

[13] J.E. Müller et.al.: “A GaAs Chip Set for Automotive Radar Systems fabricated by Optical Stepper Lithography”, *1996 IEEE GaAs Symposium,* Orlando, FL (USA), pp. 189 – 192.

[14] A. Springer, C.G. Diskus, K. Lübke, H.W. Thim: “A 60 GHz MMIC-Compatible TED-Oscillator”, *IEEE Microwave and Guided Wave Letters,* Vol. 5, No. 4 (1995), pp. 114 – 116.

[15] A. Bangert, M. Schlechtweg, M. Lang, W. Haydl, W. Bronner, T. Fink, K. Köhler, B. Raynor: “Monolithic Integrated 75 GHz Oscillator with High Output Power Using a Pseudomorphic HFET”, *1994 IEEE MTT-S Int. Microwave Symposium,* San Diego, CA, USA, pp. 135 – 138.

[16] H.D. Griffiths: ”The Effect of Phase and Amplitude Errors in FM Radar”, *IEE Colloquium on High Time-Bandwidth Product Waveforms in Radar and Sonar,* London, UK, 1991, pp. 9/1 –9/5.

[17] M. Vossiek, P. Heide, M. Nalezinski, V. Mágori: “Novel FMCW Radar System Concept with Adaptive Compensation of Phase Errors”, *26th European Microwave Conference (EuMC’96),* Prague, Czech Republic, pp. 135 – 139.

[18] C. Ruppel, L. Reindl, S. Berek, U. Knauer, P. Heide, M. Vossiek: “Design, Fabrication and Application of Delay Lines at 2.45 GHz”, *1996 IEEE Ultrasonics Symposium,* San Antonio, Tx, USA, to be published.

[19] M. Nalezinski, M. Vossiek, P. Heide: “Novel 24 GHz FMCW Front-End with 2.45 GHz SAW Reference Path for High-Precision Distance Measurements”, *1997 IEEE MTT-S Int. Microwave Symposium,* Denver, Co, USA, to be published.

[20] P. Lowbridge, P. Brigginshaw, B. Kumar: "A Low Cost mm-Wave Cruise Control System for Automotive Applications", *Microwave Journal*, October 1993, pp. 24 – 36.