24 GHZ SHORT-RANGE MICROWAVE SENSORS FOR INDUSTRIAL AND VEHICULAR APPLICATIONS

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Abstract

Microwave sensors are well suited for robust non-contact measurements of distance and velocity. The use of radar technology in sensor applications is steadily increasing [1]. The higher the radar frequency, the better the resolution and the smaller the size of the sensor. This paper gives a status report on the development of 24 GHz short-range radar sensors for industrial and vehicular applications. System and technology aspects are considered. Several commercial radar systems are presented.

A. Industrial Tank Level Measurement

The measurement of level in tanks (see fig. 1) is a significant industrial market [2]. The process control industry needs to measure the level of a wide range of different products stored in tanks throughout chemical and pharmaceutical plants, power plants, oil refineries, pulp and paper mills and cement mills. The industrial customer prefers level instruments with capabilities like

- wide application range (different materials and tank geometries, diverse environmental conditions)
- high reliable, repeatable and accurate measurement
- easy installation, operation and maintenance
- self-calibration and self-diagnosis
- process not to be influenced by the measurement; instrument to be installed in existing tank opening

Traditional level instruments (e.g. float gauges, capacitance probes, difference pressure transmitters) require a mechanical contact to the process. These sensors have several limitations regarding to the diverse process conditions (e.g. corrosive media and changes in density, pressure, dielectric constant, temperature).

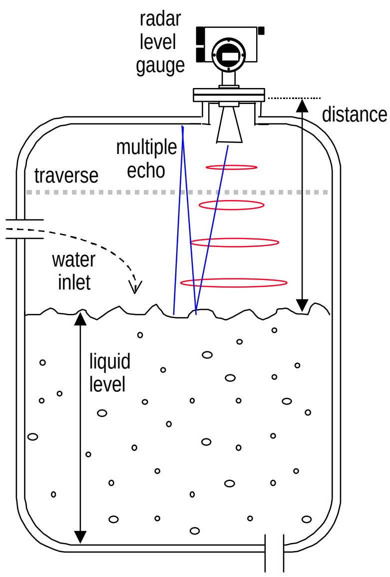

Fig. 1 Radar tank level measurement.

Microwave technology has proved to be well suited for tank level measurement, due to the non-contact sensing principle, its reliability in a wide measuring range and its robustness against temperature, pressure, steam and dust. The market share of radar level gauges increases steadily. Most of today's radar systems operate at 5.8 GHz or 10 GHz [3]. However, the next product generation will use 24 GHz technology [2,4] because of two main reasons:

- ✓ A 24 GHz level gauge is smaller and easier to handle
- ✓ it provides higher sensitivity, reliability and accuracy.

The radar propagation with respect to reflection and absorption of the tank media is not significantly different at 5.8, 10 or 24 GHz. The main impact on the radar performance comes from the antenna directivity and the radar bandwidth – and here 24 GHz technology provides distinct benefits: 1. Sharp antenna patterns are feasible (even with small antennas) and 2. the possible higher modulation bandwidth allows to obtain a good axial resolution (i.e. the ability the separate two closely spaced echoes). As a result, the narrow antenna beam and the high axial resolution make the 24 GHz level gauge less susceptible to false returns from obstructions like e.g. agitator blades, inlet valves and ladders.

The directivity is proportional to the antenna diameter and inverse proportional to the radar wavelength. A 24 GHz antenna achieves the same directivity pattern with a quarter of the antenna diameter compared to 5.8 GHz (see fig. 2). Thus, 24 GHz level gauges provide more flexibility, because they fit into narrow tank flanges even when located at the side of the tank.

In spite of these significant advantages, 24 GHz sensors were barely applied in the level industry up to now due to a lack of technical maturity and the high cost of the microwave components. The new Siemens radar level gauge SITRANS-LR overcomes these limitations by an innovative approach.

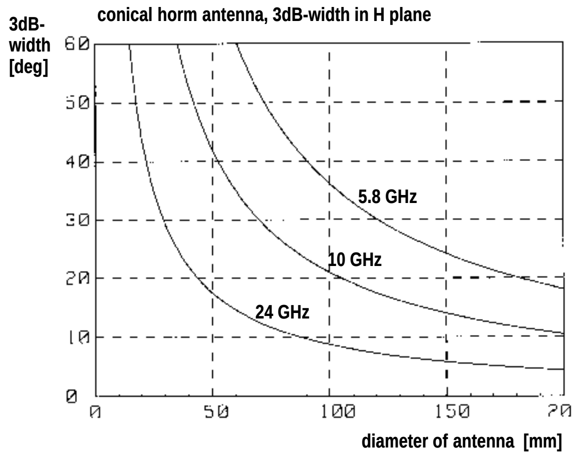

Fig. 2 Antenna directivity as a function of antenna diameter.

Siemens 24 GHz Tank Level Gauge

A FMCW radar concept has been chosen, which is advantageous with respect to the applicability of advanced digital signal processing. The schematic of the sensor electronic is shown in fig. 3. The frequency modulation is realized with a 2.4 GHz VCO controlled by a ramp generator (FGEN). One part of the VCO signal is fed to the reference block comprising a SAW (surface acoustic wave) delay line and an IF mixer (IMIX) yielding a reference signal (REF). The transmitted 24 GHz signal is generated by an upconversion of the 2.4 GHz FM signal. The SSB upconverter comprises a highly stable 21.7 GHz local oscillator (LO), a mixer (TXMIX) and a filter/amplifier (BP,AMP). The 24 GHz receiver (RXMIX) diplexes the transmit and receive signals, down-converts them with a single-balanced mixer and provides the target signal (MEAS) to be processed in the digital signal processor (DSP).

The strategy behind the applied concept was to reduce the complexity of the sensor electronic by realizing critical functions at the IF or the software level rather than at 24 GHz. The reference signal (REF), that is a replica of the transmitted radar signal, is used to calibrate the sensor. The calibration, which removes unwanted drift and non-linearity effects from the target signal (MEAS), is done with the constant phase interval sampling algorithm (CPIS) described in [5]. The calibration accuracy severely depends on the quality of the reference. The SAW chip [6], embedded in a DCC6 surface mount package (see figure 4), represents a miniature 100 meter radar path with a precision comparable to that of a quartz oscillator. With the use of this device, an excellent radar performance is obtained.

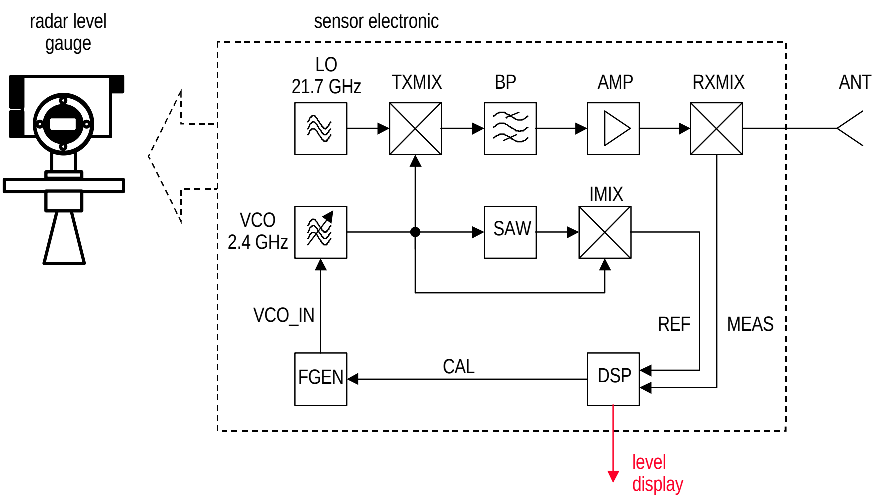

Fig. 3: 24 GHz FMCW tank level gauge.

Field Application

While the primary signal processing comprises the calibration of the measured raw data and

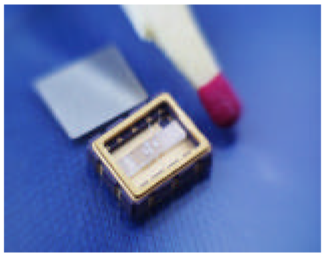

Fig. 4: High-precision SAW reference device.

the calculation of the FFT echo profile, the secondary data processing goes far beyond this. Powerful algorithms were developed for intelligent echo profile evaluation, run time diagnosis and automatic parameter setup. This add-on software is an essential part of the system, because it significantly improves the consistency and reliability of the radar level measurement within the diverse range of industrial applications.

A lot of application-oriented a-priori knowledge has been embedded in fuzzy rules. The fuzzy toolbox is based on the expertise from ultrasonic distance sensors and was adapted and improved with respect to the specific circumstances of radar level measurements. The fuzzy procedure is able to identify fixed targets like traverses or depositions, multiple echoes or false echoes caused by noise or the filling process. As a result of the fuzzy evaluation, a probability value is assigned to each measured echo. The echo with the highest probability value is taken as the actual tank level.

The signal processing concept has been extensively tested and optimized during field tests in a variety of different industrial process tanks. Figure 5 shows one example of a tank application, where the level of lime dust had to be measured. This measuring task is very difficult, because lime dust has a low dielectric constant and thus causes only weak reflections (especially if the dust is not compressed and a lot of air is enclosed). Since there is no total reflection on a lime dust surface, further reflections can occur at inhomogenities in lower layers or at the tank bottom. Density changes often occur at layers corresponding to different filling processes. During the filling process lime dust is blown from the top into the tank, so that the lime dust crosses the radar beam. If lime is drained out of the tank the cone of the bulk material collapses from time to time such that different surface structure and density profiles arise.

In the depicted test measurement the lime tank was monitored for 16 hours. During the first 14 hours only a small amount of lime was taken out of the tank – apparently the lime cone collapses after 9 hours. After 14 hours the tank was filled up. A constructive element of the tank, located at the outer side of the radar beam, caused a weak fixed echo at a distance of about 2 m. This distance value was slightly varying with time because the lime dust was settling on the objects’ surface and the thickness of this deposit changed.

With the developed echo evaluation it was possible to reliably detect the filling level at any time. No complicated parameter setting had to be performed by the user, since most of the parameter settings were adjusted automatically. This measurement and other tests in industrial process and storage tanks proved the good performance of the new radar system and the reliability of the applied signal processing concept.

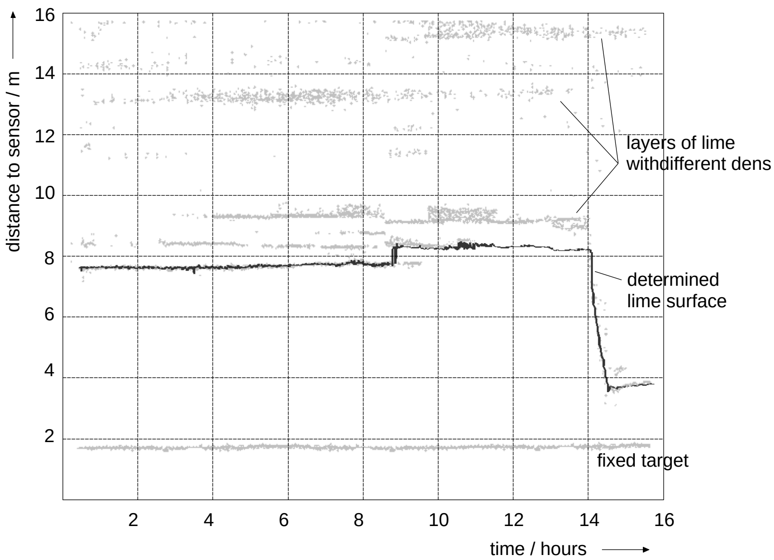

Fig. 5: Measurement in a lime tank. The grey dots mark the unprocessed echoes, detected within a single measurement. The solid black line illustrates the final result of data processing i.e. the distance of the echo that was classified to be the actual lime surface. The results demonstrate, that the weak echo of the lime surface can be clearly detected in spite of several misleading echoes. The measurement was not disturbed by the filling process.

B. Vehicular Radar Applications

Besides the industry, radar technology is interesting for vehicular applications as well. For the improvement of traffic efficiency in railway networks it is important to know the speed and the driven distance of trains. A practical solution, which works independent from the wheel radius, wheel slippage and wheel blocking of the locomotive, is provided with non-contact speed measurements by using a Doppler radar as shown in figure 6. Due to the statistical character of the Doppler signal, a minimum measurement distance is necessary to achieve a specified accuracy. The smaller the wavelength of the microwave, the higher the number of Doppler cycles are averaged and the better the measurement accuracy. Thus, the use of a high radar frequency at 24 GHz is again helpful. An advanced sensor concept is necessary to maintain a good accuracy and reliability in a wide range of different measurement conditions. The speed estimation has to be independent from the ground properties – this is the key issue. A dual-sensor approach is taken as the solution to compensate the influence of changing ground conditions. More detailed reports on the Siemens Railway Radar SRR II product have been published in [7,8].

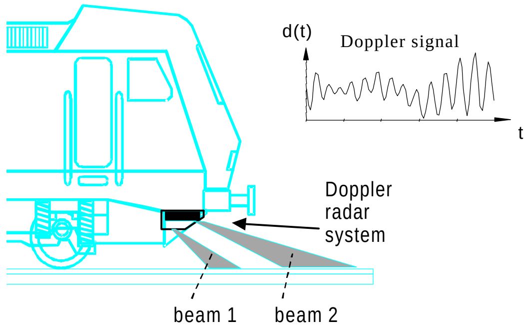

Fig. 6: Dual-beam Doppler sensor installed on a locomotive.

Radar technology also has a strong support of the automotive industry [9]. This market is of special interest due to its potential high volume. Automotive distance warning systems are using front, side and back radar sensors to monitor the distance and speed of adjacent objects and alert the driver, if he gets too close to an obstacle (fig. 7). Radar appears to be the best sensor principle, because alternatives like laser and ultrasound fail under bad weather conditions, when they are needed most. First generation forward-looking ACC radars are currently in market release.

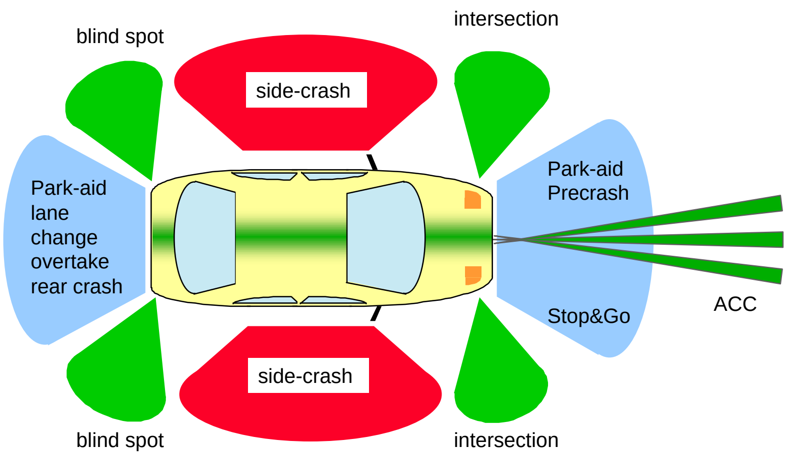

Fig. 7: Innovative car sensor functions.

The next product generation will probably bring short-distance sensor functions into the car, for example lane-change aid, park distance control (PDC), precrash detection, blind spot sensing, side-crash detection and stop & go distance control. Different automotive sensor functions implemented with 24 and 77 GHz modules (figure 8) are currently under evaluation in the car [10].

Park distance control systems have been using ultrasonic technology, but low-cost microwave sensors are likely to replace ultrasound. As a major customer benefit, radar is more robust and the microwave modules can be mounted invisible behind plastic bumpers.

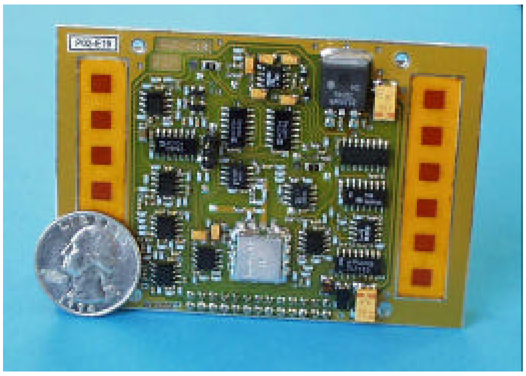

Fig. 8: Siemens short-distance automotive radar module.

Radar precrash detection is foreseen to be able to increase the passenger safety. One possible new function is the „smart airbag“, that is inflated adaptively by taking into account manifold sensor information on the collision and occupant situation. Conventional airbag systems are triggered by acceleration or pressure sensors. The radar precrash sensor helps to improve the reliability of the airbags, especially with respect to the side airbag, which is the most critical one.

In the future, radar precrash sensors could also be used to activate reversible safety systems like pneumatic airbags and electronically activated safety belts, neck restraints and knee pads. In addition to the various radar sensors around the car, further in-car sensors will support the safety and the comfort of the passengers. New techniques for optical 3D cameras for reliable passenger detection (determination of type and position of occupants on each seat) are under development.

HF Production Technology

Traditionally, high frequency components have been expensive. However, communication applications like mobile phones, satellite downconverters, point-to-point- and point-to-multipoint radios meanwhile have created high-volume HF products and hereby promoted a significant progress in the commercialization of microwave and millimeterwave components [11,12]. Due to demands on higher circuit integration, the sizes of semiconductor packages have been dramatically reduced during the last few years. Surface mount assembly with ultra small SMD devices (i.e. 0204 or even 0201 packages) now becomes the standard, that can be handled in an automated production. This technical trend has moved up the upper frequency limit, that can be reached with conventional production means.

24 GHz sensor circuits using planar microstrip technology and SMD packaged devices are available as laboratory prototypes for some time [13]. Although the use of SMD technology seems to be the best approach for a low-cost product, it required considerable industrialization work to assemble K-Band components on a standard SMD production line. It is absolutely necessary to have a production-specific design of the HF board to be able to achieve a high yield under actual production conditions. The radar modules used in the described Siemens 24 GHz sensor products were optimized to be insensitive to the typical tolerances corresponding to a spread in semiconductor device parameters and mechanical tolerances.

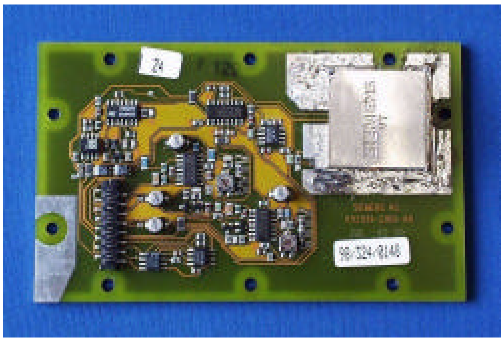

Fig. 9: Commercial 24 GHz radar module.

A highly stable dielectric resonator oscillator is implemented as a local oscillator in all modules. Due to this patented DRO concept, the resonator is operated in a higher order mode. With the DRO as a local oscillator, the radar carrier frequency is very stable. For very high precision measurements, the temperature can be measured on board such that drift effects can be further reduced. Due to the sensor system concepts that include a self-calibration, no tuning of the microwave assembly is required. The complete microwave assembly can be realized as a compact block using state-of-the-art multilayer boards (fig. 9). These printed circuit boards are realized as a sandwich structure combining different layers of FR4, metal and RT/Duroid. Due to this simple mechanical construction, there is no need for further board-to-board solder interconnections, expensive milled metal housings or other complicated manufacturing steps.

Conclusion

In this paper, several commercial short-distance radar sensors for industrial and vehicular applications have been described. A common 24 GHz hardware platform is used for these products. The authors believe, that the chosen technical and technological approach is superior to former solutions in terms of performance and cost. The Siemens 24 GHz technology is now in production.

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