A Low Cost W-Band Multi-Beam Doppler Radar for Automotive Applications

Ralph H. Rasshofer and Erwin M. Biebl

Institut für Hochfrequenztechnik der Technischen Universität München
Arcisstraße 21, 80333 München, Germany

ABSTRACT

For automotive millimeter wave applications, SIMMWIC technology provides a low cost alternative to conventional GaAs MMICs. In this paper, we present a 76 GHz radar system adopting the classic principle of multi-beam Doppler navigation systems for automotive applications. Exclusively low cost SIMMWIC components have been employed in the millimeter wave front-end.

INTRODUCTION

The steadily increasing traffic density demands an efficient traffic management, which is based on automatic acquisition of information about the traffic situation by the vehicle itself as well as information exchange between vehicles and base stations. Millimeter wave systems are ideally suited to deal with these tasks. Thus, short range millimeter wave communication links and automotive radar systems have been discussed extensively in the last years. Economic analyses predict a huge market for automotive sensor and communication systems [1]. However, in such a mass-market only the most cost-effective system will be successful.

Silicon **m**onolithic **m**illimeter **w**ave **i**ntegrated **c**ircuits (SIMMWIC) provide a low cost alternative to conventional GaAs MMICs. Transmitters for the automotive bands at 77 GHz based on silicon Impatt-diodes provide high output power and low phase noise [2]. Planar millimeter wave Impatt oscillators in self mixing operation have been used as very simple CW-Doppler velocity sensors [3]. However, more complex systems have not been reported yet. Using four Doppler sensors, we built an integrated multi-beam Doppler radar system. The principle of multi-beam Doppler radar is known as „Doppler navigation system“ and has been used extensively in aircraft navigation for the last 30 years [5]. A low cost automotive multi-beam Doppler radar based on SIMMWIC components is presented in this paper. In contrast to automotive multi-beam Doppler radar systems reported earlier [4], our system requires no hollow waveguide or horn components. The millimeter wave front-end of our sensor is a planar low cost solution capable to measure a vehicle’s speed in cruising and transversal direction. This information could be especially valuable for automotive navigational equipment, lane-change aids, airbag systems, and brake and traction control, as the system allows precise two dimensional ground-speed measurement even without turning of the vehicle’s wheels [7].

PRINCIPLE OF OPERATION

Following the classic principle of airborne Doppler navigation systems [5], four millimeter wave beams (frequency f_{0i}, radiation vector $\boldsymbol{k}_i$) are directed towards the road surface under a tilt angle α as shown in Fig. 1.

The movement of the sensor is characterized by the three dimensional velocity vector $\boldsymbol{v}$. The Doppler-shift of the i^{th} transmitted signal seen by the i^{th} velocity sensor can be calculated as:

$$f_{Di} = \frac{2 f_{0i}}{c}\left(\boldsymbol{v} \cdot \boldsymbol{k}_i^0\right); \quad \left|\boldsymbol{k}_i^0\right| = 1 \qquad (1)$$

0-7803-4603-6/97/$5.00 (c) IEEE

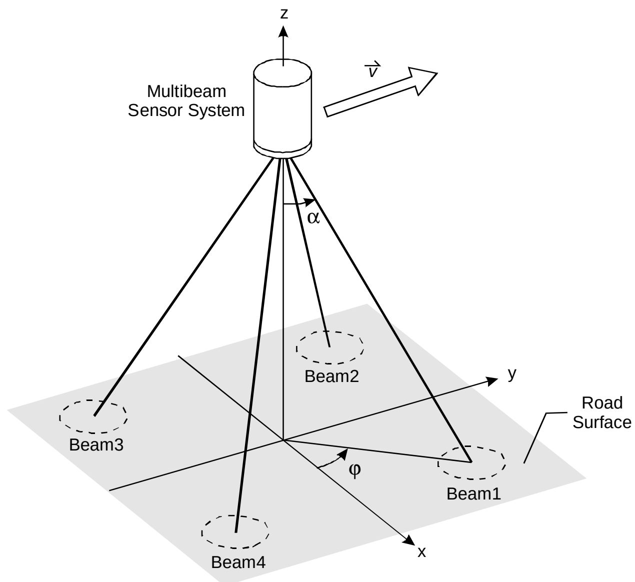

Fig. 1. Basic Beam Configuration in a Multi-Beam Doppler Radar System.

If three or more sensors are used, the complete three dimensional vector ***v*** can be determined. The use of more than three sensors provides an opportunity to minimize measurement errors by solving eqn. (1) for the three components of ***v*** with minimal error.

However, using the very low cost and simple configuration of Impatt diodes in self-mixing operation, no information about the sign of the Doppler frequency is available. In this case - assuming v_z=0 and φ=0 - only the absolute value of the vehicle's ground speed in *x*- (cruising) and *y*- (transversal) direction can be calculated, which is sufficient for many automotive applications. As speed in one direction is measured by two sensors, an improved speed information can be calculated.

In future applications, the sign of the velocity value might be obtained by the use of subharmonically synchronized front-ends [6] driven with 90 degree phase shift. This provides the I and Q component of the doppler signals and hence information about the sign of the velocity value measured.

SYSTEM DESIGN

The millimeter wave front-end contains four SIMMWIC active antennas placed on an aluminum heatsink in a ring-shaped configuration with a diameter of 36 mm (Fig. 2). The active antennas consist of an Impatt diode integrated in a planar resonator. The resonator acts simultaneously as an antenna. The outstanding advantages of the active antenna concept are low loss, low parasitic radiation, minimal chip size, and, thus, low cost. The radiation pattern of the active antennas is shaped by a specially designed polystyrene dielectric lens (52mm diameter and 35mm focal length) having a partial monofocal and bifocal characteristic. This lens launches beams with an opening angle of Θ_{3dB} = 5.4 degree while providing a scanning angle of α=30 degree [8].

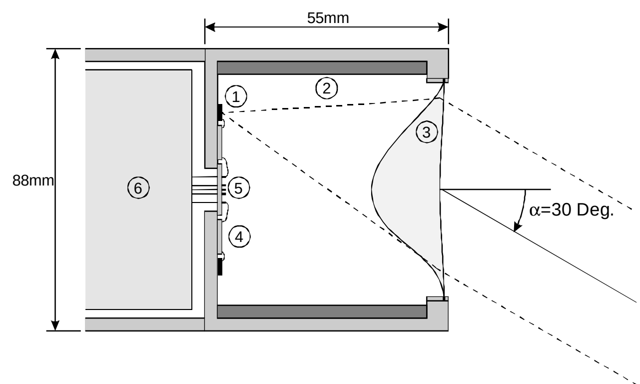

Fig. 2. RF Front End and Beam Shaping Principle using a Bifocal Dielectric Lens.
(1) Planar Oscillator (2) Absorber
(3) Dielectric Lens (4) Connection PCB
(5) Connector (6) Detector Amplifier

A bias supply unit drives a constant current of 20 mA through each of the Impatt diodes (U_{impatt}=18V) keeping them just beneath the oscillating threshold. Pulsing the bias current to 35mA starts the oscillation, and the active antenna radiates with an output power of +4dBm at 76GHz.

The detected Doppler signals are amplified by a low-noise amplifier (LNA) with a gain of 20dB and an input impedance of 200 Ohms. This impedance was chosen as a compromise between the low noise amplifier's minimal noise source impedance (300 Ohms) and the small signal video-impedance of the self-mixing Impatt-oscillator (100 Ohms) which provides optimal conversion gain.

Gain control and further amplification of +20..30dB is added by a voltage controlled amplifier.

The Doppler signals of each sensor are fed sequentially into the audio-input of a standard 16-bit PC sound-card. A sampling rate of 10kHz ($f_{d,max}$ = 5 kHz) and 8 bit resolution are used, dataframes of 100ms length are sampled into the PC's memory. Subsequently, a FFT algorithm transforms the sampled data to frequency domain. The strongest spectral line is selected from the Doppler spectrum and the radial velocity between sensor and ground is calculated [9].

The measured radial velocities are used to calculated the vehicles ground speed via geometrical equations, error minimization takes place by taking the mean value of redundant sensor information as discussed above.

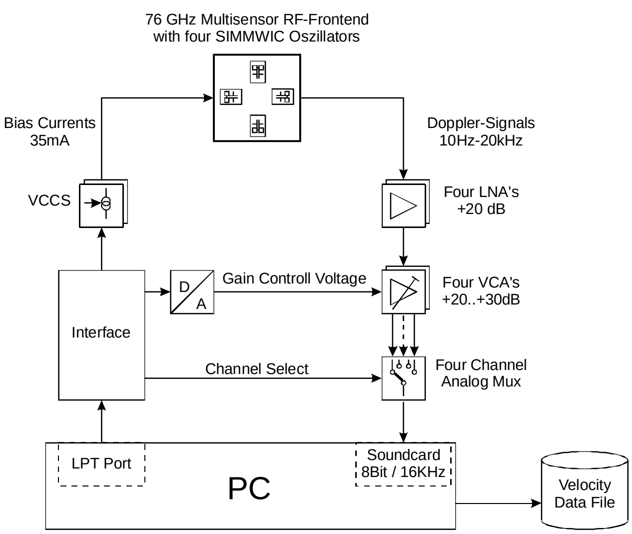

Fig. 3. Functional Diagram of the Low Cost Four Beam Doppler Radar System.

MEASURED RESULTS

To characterize the multi-beam Doppler radar system, the radiation pattern of each sensor was measured with only one Impatt oscillator active. Measured results showed the predicted beam tilt angle of 30 degree and a 3dB beam width of 5.3 degree (Fig. 5).

Fig. 4. Millimeter Wave Camera with Lens.

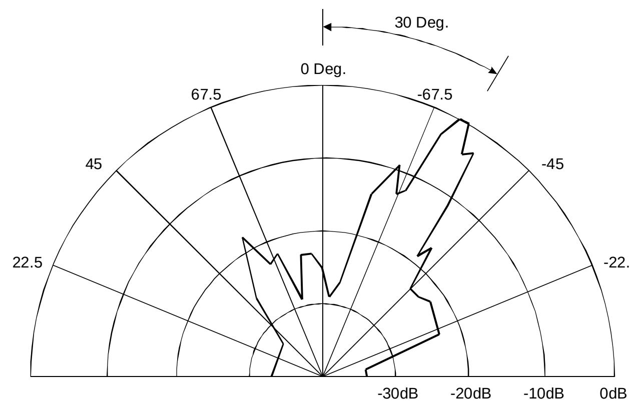

Fig. 5. Measured, Normalized Sensor Radiation Pattern with One Sensor Active. α=30 Deg., θ_{3dB}=5.3 Deg.

As velocity measurement precision in Doppler sensor systems depends on the sensor's radiation footprint [9], the sensor's impulse response in space domain, i.e. the system's response to a uniform point scatterer was measured. The measurement was performed using a free falling steel ball with a diameter of 2cm as a model for a uniform point scatterer (Fig. 6).

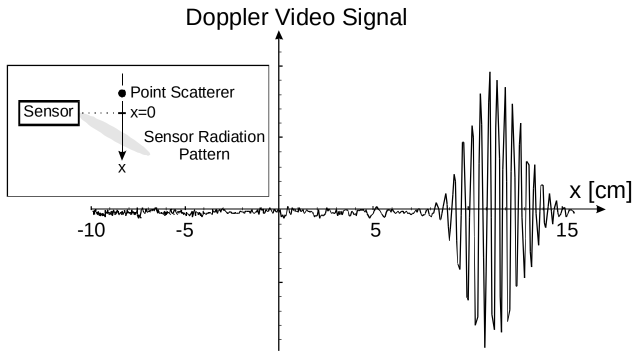

Fig. 6. Measured Impulse Response of the Sensor System in Space Domain.

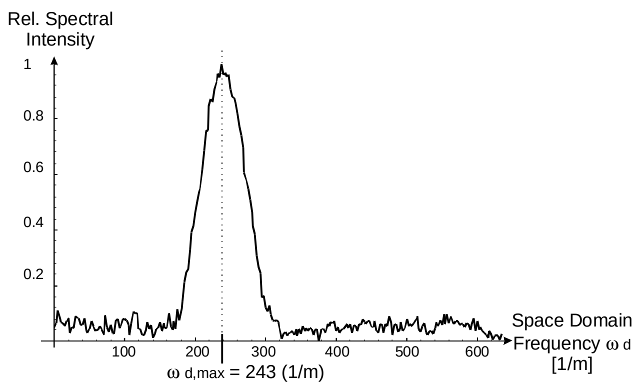

Fig. 7. Calculated Space - Frequency Spectrum of the Sensor System.
λ_0=0.441cm; $\omega_{d,max} = (1/\lambda_0) = 243\ ^1/_m$.

The received impulse function data will be used to predict the detected Doppler spectra when sensing road surfaces modeled by a statistical distribution of uniform point scatters. Using a correlation technique between predicted and actually detected spectra, a further improvement of velocity measuring precision seems possible [10].

CONCLUSION

A multi-beam Doppler radar system for automotive applications is presented. The radar front-end contains exclusively very low cost SIMMWIC active antennas, which are the simplest millimeter wave generators or detectors imaginable. Our results show that very low cost millimeter wave sensor systems based on silicon are now feasible.

REFERENCES

[1] IEEE MTT-S Microwave/MMW Technology For Intelligent Vehicles Workshop, June 21. 1996, San Francisco, 1996.

[2] M. Singer, A. Stiller, K.M. Strohm, J.-F. Luy and E.M. Biebl, "A SIMMWIC 76 GHz Front-End with High Polarization Purity", *1996 IEEE MTT-S Int. Microwave Symp. Digest*, (San Francisco), pp. 1079-1082, 1996.

[3] V.F. Fusco, „Self detection performance of active microstrip antennas", *Electr. Lett.*, vol. 28, no. 14, pp. 1362-1363, July 1992.

[4] N. Kees, M. Weinberger, and J. Detlefsen, „Doppler Measurement of Lateral and Longitudinal Velocity for automobiles at Millimeter-waves", IEEE MTT-S International Microwave Symposium Digest, pp. 805-808, 1993.

[5] W.R. Fried, „Principles and Performance Analysis of Doppler Navigation Systems", *IRE Transactions on Aeronautical and Navigational Electronics*, December 1957, 1957.

[6] M. Singer, K.M. Strohm, J.-F. Luy and E.M. Biebl, "Active SIMMWIC-Antenna for Automotive Applications", *1997 IEEE MTT-S Int. Microwave Symp. Digest*, (Denver), 1997.

[7] P. Heide et al., "A High Performance Multisensor System for Precise Vehicle Ground Speed Measurement", *Microwave Journal*, July 1996, 1996.

[8] T. Müller, G. Friedsam, R.H. Raßhofer and E.M. Biebl, „Computer-Aided Design of a Dielectric, Bifocal Lens with Extreme Wide Scanning Angle", *Progress in Electromagnetic Research Symp. (PIERS) Digest*, p.630, (Hong Kong), 1997.

[9] C.L. Everett, "Phase Noise Contamination to Doppler Spectra", *Microwave Journal*, September 1996, 1996.

[10] M. Joppich, „Schätzverfahren zur Genauigkeitssteigerung der Geschwindigkeitsmessung über Grund nach dem Dopplerprinzip", *VDI Fortschritt-Berichte Reihe 8*, Nr. 440, VDI Verlag Düsseldorf / Germany, 1994.