A Direction Sensitive, Integrated, Low Cost Doppler Radar Sensor for Automotive Applications

Ralph H. Rasshofer and Erwin M. Biebl

Institut für Hochfrequenztechnik, Technische Universität München
Arcisstraße 21, 80333 München, Germany

ABSTRACT

We fabricated and tested an integrated, low cost, W–Band Doppler radar sensor, capable to provide direction sensitive velocity information. The front–end consists of an active integrated antenna in self–mixing operation and a surface–wave coupled, mixing rectenna, providing full homodyne *I*/*Q*–detection. In the front–end, we employed only low cost silicon monlithic millimeter wave integrated circuits (SIMMWIC). Measured results show excellent performance of the sensor.

INTRODUCTION

With increasing traffic density on today's roads, a rapidly growing interest in intelligent transportation systems (ITS) can be noticed. One key component in ITS technology today are highly sophisticated radar sensor systems. As ITS applications intend to serve a mass–market, the costs of the sensor systems should be as low as possible. Cost reduction by the use of active integrated antennas has been proposed by several authors [1]. A very simple possibility for automotive speed measurement is provided by self–oscillating, active integrated antennas in self–mixing configuration [2]. As active elements, Impatt diodes [3], Gunn devices [4], HEMT's [5] and HBT's [6] have been reported. However, one major drawback of these designs is, that only the absolute value of the velocity can be measured. For automotive Doppler navigation aids [7], traffic monitoring systems and motion sensors, information whether a target is approaching or receding is crucial. In this paper, we describe a simple, low cost device for precise homodyne *I*/*Q* detection of a Doppler signal. Furthermore, our new sensor concept may serve as a simple add–on to already existing self–mixing active antennas. The new approach is based on an active integrated antenna in self–mixing configuration and a rectenna, used as a surface–wave coupled mixer. Due to the spacing between active antenna and rectenna, the surface–wave coupled LO signal of the rectenna has a certain phase shift compared to the active antenna's signal. By properly adjusting the distance between active antenna and rectenna, a 90 degrees LO phase shift can be accomplished, leading to homodyne *I*/*Q* detection. Taking advantage of this principle, a W–Band (76 GHz) Doppler radar front–end, consisting of an active integrated, self–oscillating antenna on a silicon substrate and a silicon Schottky rectenna has been assembled. Measured results showed that an exact 90 degrees LO–phase shift, leading to high–quality *I*/*Q* signal detection, can be realized. A sharp decision between approaching and receding target could be taken from the received signals, using a simple digital phase comparator and a low–pass filter.

PRINCIPLE OF OPERATION

Classically [8], velocity sign information is extracted from CW Doppler radar return signals by means of a SSB receiver technique. As shown in Figure 1, the LO signal taken from the transmitter is fed into two mixers *A* and *B*. The LO signal of mixer B has a phase offset of ϕ_{LO} .

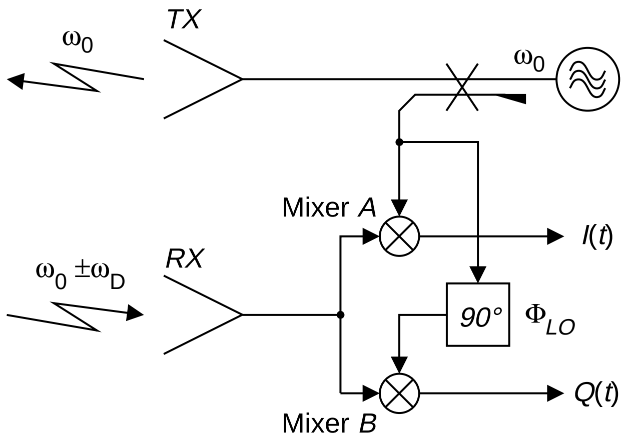


Figure 1: Operation principle of classic direction sensitive CW Doppler radar [8].

For optimal I/Q detection,

$$\Phi_{LO} \overset{!}{=} \Phi_{IQ} = \left(\tfrac{1}{2} + n\right) \cdot 180^\circ \, ; \, n \in \{0, \pm 1, \pm 2, \ldots\} \quad (1)$$

has to be chosen. If the LO phase shift is exactly 90 degrees (Figure 1), the associated Doppler signals for a Doppler frequency $+\omega_D$ (approaching target) are:

$$I(t) = I_0 \cdot \cos \omega_D t \quad (2)$$

$$Q(t) = -Q_0 \cdot \sin \omega_D t \quad (3)$$

From the phase relationship between I and Q signal, the sign of ω_D can easily be deduced. In our proposed sensor system, an active antenna, based on a monolithically integrated Impatt diode coupled to a resonant patch dipole antenna is used as RF source [2]. The active antenna is operated in self–mixing configuration, providing the in–phase (I–) component of the Doppler signal. To get the quadrature (Q–) component of the signal and hence the sign of the velocity, we employ a resonant Schottky rectenna as surface–wave radiation coupled mixer. The rectenna is mounted in a certain distance s from the radiating active antenna. Theoretically, the free space LO signal (wavelength: λ_0) phase shift, seen by a rectenna located in a distance s from the active antenna is:

$$\Phi_{LO} = \Phi_0 + 360^\circ \cdot \frac{s}{\lambda_0} \; . \quad (4)$$

The phase correction Φ_0 takes into account the displacement between the phase center and the geometrical center of the antenna due to reactive near field effects in the vicinity of the active antenna. For exact I/Q detection, the LO signal should have a phase shift of ϕ_{IQ}. For free space radiation coupling,

$$s_{IQ} = s_0 + \left(\tfrac{1}{2} + n\right) \cdot \frac{\lambda_o}{2} \quad , \quad n \in \{0, 1, 2, \ldots\}, \quad (5)$$

has to be chosen. In the work reported in this paper, the active antenna is separated from the rectenna by free space because only two separate chips were available, but integration of both the active antenna and the rectenna on a single substrate is straightforward. In our case, (4) holds exactly. If the rectenna and the active antenna are located on the same substrate, the wavelength of the fundamental surface–wave mode λ_s has to be inserted instead of λ_0. For a back side metalized substrate, the TM_0 mode is the fundamental surface–wave mode. For active integrated dipole antennas, the substrate has to be electrically thin ($h/\lambda_0 < 0.05$) to reduce losses due to excessive surface–wave excitation [9]. In this case, we can assume $\lambda_s \approx \lambda_0$. As the two wavelengths are almost equal in both cases, the results from the free space experiments reported in this paper may easily be adopted for a fully integrated front–end where active antenna and rectenna are located on the same substrate. In (5), a periodical nature of s_{IQ} is shown. However, for optimal detection, the LO signal coupled to the rectenna should be a strong as possible. In practice, $n = 0$ or $n = 1$ are chosen. If active antenna and rectenna are located on the same substrate, even stronger LO coupling, resulting in increased rectenna sensitivity is expected.

TEST SETUP

To show the capabilities of the described front–end, a simple demonstration system has been build and characterized (Figure 2). The active antenna's Impatt diode is supplied with a constant DC bias current of 37 mA, resulting in an EIRP of +6.5 dBm at 76 GHz. From numerical modeling based on the method of moments, the RF power coupled to the surface–wave field was calculated to be +1.2 dBm.

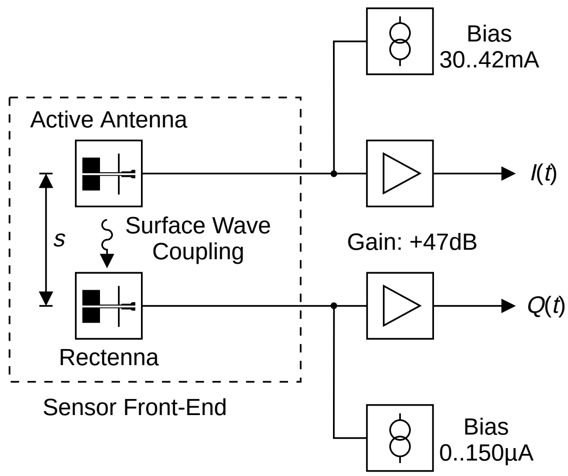


Figure 2: Test setup used to characterize the novel direction sensitive CW Doppler radar module.

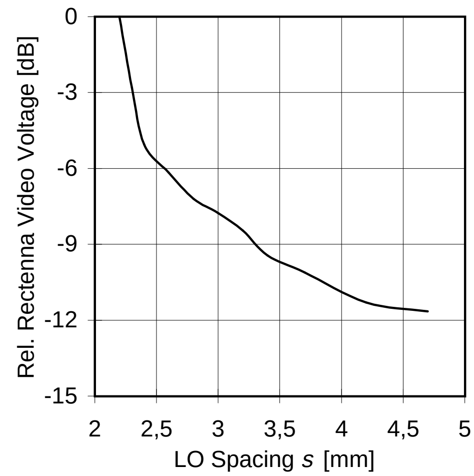


Figure 3: Measured rectenna's video signal amplitude, depending on the space s between active antenna and rectenna, normalized on maximum video amplitude. For s = 2.2 mm, both chips are touching each other.

The rectenna's bias current was chosen to be 60µA as a compromise between minimal video noise (optimum: zero bias) and large sensitivity (large bias current, i.e. 150µA). The signals provided from both RF front–end chips are fed into two video amplifiers with matching input impedances (Z_{Impatt}=200 ohms, Z_{Rectenna}=2000 ohms) and equal video gain (+47dB). As the expected velocities are below 80 m/s, a bandwidth limitation of BW = 20 kHz is chosen.

As simple radar target, a movable brass trihedral reflector with a side length of 4.9 cm and an approximate bore–side radar cross section σ =1 m^2 is located 12 cm from the sensor. The amplified signals of both front–ends are fed into a transient recorder. As a simple way to detect the velocity sign, I and Q component of the Doppler signal (2,3) are amplified and limited to a TTL logic level. The use of a simple PLL type digital phase detector provides the sign information.

MEASURED RESULTS

For exact I/Q detection, a LO phase shift of ϕ_{IQ} (2) is necessary. With increasing distance s between active antenna and rectenna, the radiation coupled LO signal applied to the rectenna decreases, resulting in a decrease of sensitivity. To get rough information how strong this effect would be, the rectenna's video signal amplitude was measured for various values of s (Figure 3).

From (5), $s_{IQ} \cong$ 3mm can be deduced. As can be seen from Figure 3, the rectenna's sensitivity is below it's maximum value for this position. However, the –8dB lag of sensitivity should not degrade then system's functionality in short–range applications where strong Doppler return signals are expected.

To get the exact rectenna position s_{IQ} for a ϕ_{LO} phase shift, the phase difference of the Doppler signals was measured for various rectenna positions s. In Figure 4, the small triangles show measured data while the solid line shows values calculated from (5). For exact I/Q detection, s_{IQ} = 3.2 mm was chosen (n = 1).

The front–end under test was assembled on a TO–8 header. Without any beam–shaping components, the amplified I and Q signals detected by the front–end have been recorded by a digital scope for an approaching and a receding target (Figure 5 a,b).

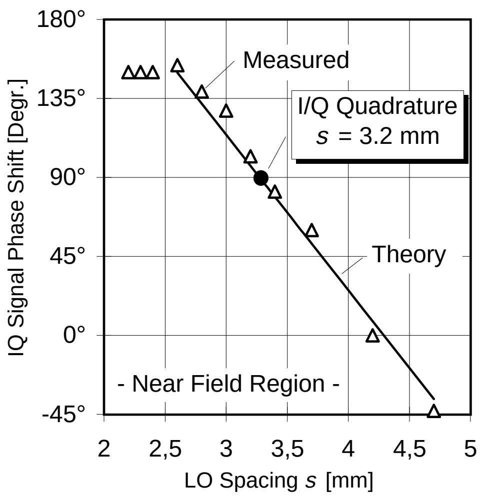
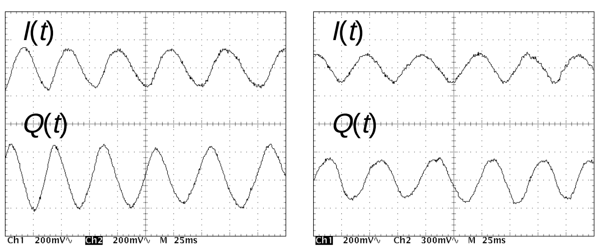


Figure 4: Measured and calculated *I*/*Q*–phase difference, depending on the space *s* between active antenna and rectenna. For *s* = 3.2 mm, an exact 90 degrees *I*/*Q*–phase shift is provided.



(a) (b)

Figure 5: (a) Measured *I* and *Q* signal for approaching target. (b) Measured *I* and *Q* signal for receding target.

In Figure 5a (approaching target), the phase difference between *I*– and *Q*– Doppler signal is –90 degrees while in Figure 5b (receding target) the phase difference is +90 degrees. This significant phase difference can easily be detected by means of a commercially available phase comparator IC.

CONCLUSION

We presented a novel direction sensitive W–Band CW Doppler radar sensor in purely planar technology. The velocity sign information is provided by a homodyne *I*/*Q* receiver principle. As quadrature signal receiver, a surface–wave coupled rectenna is employed. Measured results showed the excellent ability of the front–end to distinguish between approaching and receding targets. The whole front–end is very low cost and ready for monolithic integration. The technique described in this paper can easily be used as low cost add–on for already existing Doppler radar front–ends.

REFERENCES

[1] K. D. Stephan , and T. Itoh, „Recent efforts on planar components for active quasioptical applications“, *1990 IEEE MTT–S Int. Microwave Symp. Digest*, pp. 1205–1208, 1990.

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

[3] 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.

[4] C.M. Montiel, L. Fan, and K. Chang, “A Novel Active Antenna with Self–Mixing and Wideband Varactor–Tuning Capabilities for Communication and Vehicle Identification Applications“, *IEEE Trans. Microwave Theory Tech.*, vol. MTT–44, no.12, pp. 2421–2430, Dec. 1996.

[5] O.–P. Lundén, “Power Combining of Ku–band Active Dipoles in a Cylindrical Resonant Cavity“, *1995 IEEE MTT–S Int. Microwave Symp. Digest*, (Orlando), pp. 701–704, 1995.

[6] M.J. Kelly, J.A.C. Stewart, and A.D. Patterson, “HBT Active Antenna as Self Oscillating Doppler Sensor“, *1997 IEEE MTT–S Int. Microwave Symp. Digest*, (Denver), pp. 1065–1068, 1997.

[7] R.H. Rasshofer, and E.M. Biebl, „A Low–Cost W–Band Multi–Beam Doppler Radar for Automotive Applications“, *1997 IEEE MTT–S Int. Microwave Symp. Digest*, (Denver), pp. 971–974, 1997.

[8] M.I. Skolnik, „Introduction to Radar Systems“, *McGraw–Hill*, 1982.

[9] N.G. Alexopoulos, P.B. Katehi, and D.B. Rutledge, “Substrate Optimization for Integrated Circuit Antennas“, *IEEE Trans. Microwave*

Theory Tech., vol. MTT–31, no.7, pp. 550–557, July, 1983.