W-Band Substrate Integrated Waveguide Radar Sensor based on Multi-Port Technology

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***Abstract*— A 94 GHz collision avoidance radar sensor based on multi-port technology is proposed. This sensor makes use of substrate integrated waveguide (SIW) multi-port circuit fabricated on alumina substrate. The use of integrated waveguide allows for a full integration of the radar sensor front-ends. A specific base-band circuit generates in-phase and in-quadrature signals used to obtain the relative speed of target (including the moving direction) and the distance by elementary signal processing. Simulation and measurement results validate the operating principle of the proposed sensor and also indicate excellent results for relative velocity measurement together with good accuracy of distance measurement.**

I. Introduction

In spite of a long history of automotive radar design, the development of a reliable, compact and environmentally safe millimeter-wave radar sensor for various automotive applications is still a challenging problem for today's radar technologies. Millimeter-wave radar sensors are currently considered the preferred technology for vehicle-based ranging applications due to high range resolution and good performances even in adverse weather conditions.

In the last decade, various design techniques of radar sensor based on multi-port (mainly six-port) technology were proposed using different architectures and/or operating principles at lower frequencies [1] -[3].

Recently, the multi-port technology has successfully been used in the design of a 94 GHz continuous wave (CW) collision avoidance radar sensor. The sensor is intended to be used in an Adaptive Cruise Control (ACC) System. The block diagram and the operating principle including related design equations were presented in details in our previous paper [4].

Low-cost, high reliability and compact size achieved together with high velocity and distance measurement accuracy are crucial for system implementation. However, problems related to integration at millimeter-wave frequencies require more investigations.

This paper presents theoretical and experimental investigations of a 94 GHz radar sensor based on a multi-port prototype designed and realized using the substrate integrated waveguide (SIW) technology [5], [6], which allows for a high quality circuit integration. The SIW multi-port represents the main element of the proposed radar sensor. We believe that the use of integrated waveguides opens up the possibility of designing a fully integrated radar front-end.

The relative velocity of target can be obtained with excellent accuracy by measuring the Doppler frequency shift of reflected signal. In addition, the multi-port technology allows, using a simple method, obtaining the direction of target movement. This presents an important feature compared to conventional architectures, where the sign of the Doppler frequency is lost in down conversion process. Furthermore, the distance to the target can be obtained with good accuracy by a simple technique based on phase measurements using two separated CW frequencies [1], [4]. It was previously demonstrated that the phase of a specific baseband signal (generated using multi-port output detected voltages) is equal to the phase difference between the input millimeter-wave signals [7], [8]. We note that a conventional FMCW approach can also be used because the multi-port with related circuits plays the role of a millimeter-wave I/Q mixer.

II. Simulation Results

System simulations were performed using Advanced Design Systems (ADS) software of Agilent Technologies. In order to validate the operating principle of the proposed radar sensor, a computer model of the SIW multi-port circuit based on Ansoft High Frequency Structure Simulator (HFSS) simulation results was initially developed.

The block diagram of the radar sensor is presented in Fig.1. A part of the transmitted CW signal is injected at the reference port of the multi-port using a directional coupler. The power amplifier (PA) gain is a function of the distance to the target. The sensor uses separate antennas in order to increase the isolation between the transmitted and received signals. The received signal is amplified by a low-noise amplifier (LNA) and injected to the RF port of the multi-port. Using the differential approach, as presented in [7] and [8], two in-phase and in-quadrature signals, I and Q respectively, are generated. As demonstrated in [8], the multi-port with related circuits acts as a millimeter-wave I/Q mixer.

In practice, for this multi-port heterodyne receiver, the carrier frequency ω is close to the local oscillator frequency ω_0 (relative speed measurements) [9]. Therefore, this receiver is a low IF heterodyne. However, if $\omega_0 = \omega$ (distance measurements), I/Q direct conversion is obtained in a homodyne architecture. This aspect is an important advantage of the proposed receiver compared to the conventional down-conversion scheme. In addition, signal to noise ratio is improved using a multi-port circuit compared to conventional mixers.

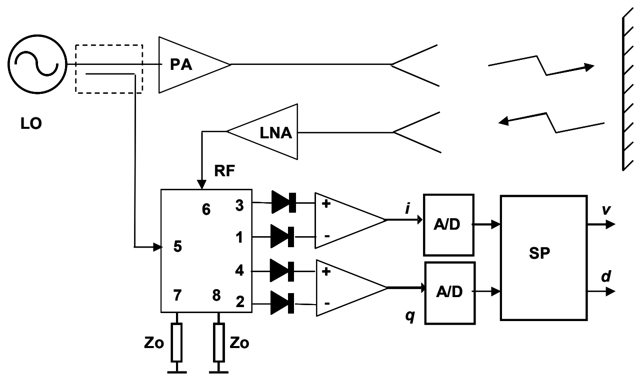

Fig. 1. The radar sensor block diagram

The relative speed of the target is obtained by measuring one of the I or Q signal frequency, according to the equation:

$$v = \frac{c}{2} \cdot \frac{\omega - \omega_0}{\omega_0} \tag{1}$$

The direction of target movement is obtained by a simple observation; the sense of rotation of $\Gamma = I + jQ$ phasor in the complex plane, clockwise or counter clockwise, is related to the sign of the Doppler frequency.

Distance measurement is obtained using two adequately spaced CW frequencies ω_{01} and ω_{02} [4]. The distance to the target is calculated using the measured difference between the phases of the two corresponding echo signals $\Delta\theta_1$ and $\Delta\theta_2$ respectively:

$$d = \frac{c}{2} \cdot \frac{\Delta\theta_1 - \Delta\theta_2}{\omega_{01} - \omega_{02}} \tag{2}$$

An important theoretical aspect is presented in [10]. It is demonstrated that the distance equation can be also used for a moving target, with an excellent approximation, because the received Doppler frequency is almost the same for both transmitted CW signals. In addition, our previous paper [4] shows that for short-range measurements (up to 75 m) an additional 1 % measurement error corresponds to a millimeter-wave oscillator stability of 10^{-6}.

As mentioned, ADS simulations are performed using an SIW multi-port computer model based on Ansoft HFSS S-parameter simulation results of the complete 3D structure including transitions to the WR-10 standard rectangular waveguide, as shown in Fig. 2.

In order to make relative speed and distance estimations by system simulations (see Fig. 1), a CW signal power of 0 dBm, a 25 dB directional coupler, a PA of 15 dB, a LNA of 10 dB together with two identical antennas of 30 dBi are used. The CW frequencies are chosen function of the distance to the target in order to avoid phase ambiguities.

A distance measurement procedure starts by assuming a long range and then continues by successive adjustment of the CW frequency shift (which is increased for a shorter maximal range). We highlight that more accurate measurements are obtained if the distance to the target represents more than 20 % of the maximal range [4].

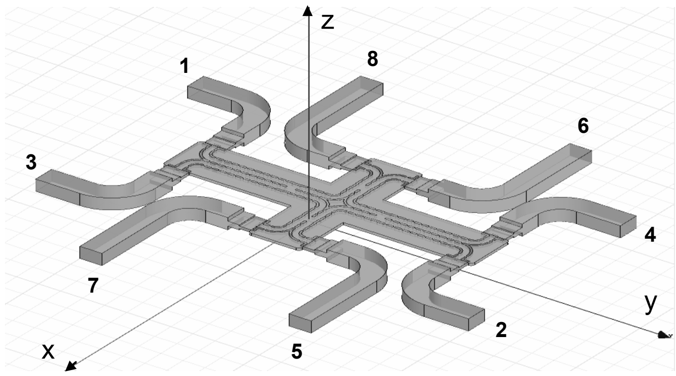

Fig. 2. The Ansoft HFSS 3D structure of the multi-port circuit

Figures 3 and 4 show typical I or Q output signals in the case of the relative speed measurement. The output signal frequency represents in fact the Doppler frequency due to the movement of target. For example, a 1.740 KHz signal (Fig. 3) corresponds to a 10 Km/h relative speed and a 17.406 KHz signal (Fig. 4) corresponds to a 100 Km/h relative speed, in excellent agreement with equation (1).

The phase shift between I and Q output signals is ± 90° depending on the sense of rotation of the Γ phasor in the complex plane, clockwise or counter clockwise, in accord to the movement direction of the target.

The distance to the target is evaluated according to equation (2). In order to obtain some interesting statistical results, a distance resolution equal to about a half of the wavelength is used in simulations.

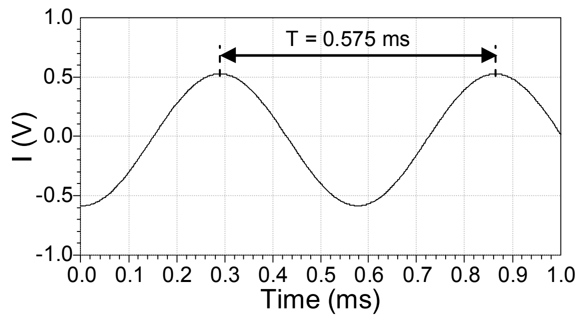

Fig. 3. The in-phase output signal for a relative speed of 10 Km/h

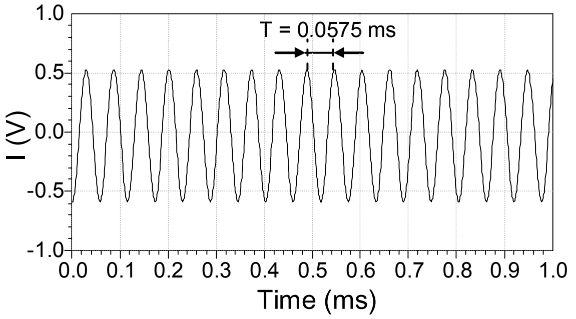

Fig. 4. The in-phase output signal for a relative speed of 100 Km/h

Fig. 5 shows a linear variation of the phases of the baseband complex signals $\Delta\theta_1$ (circle symbol at data) and $\Delta\theta_2$, corresponding to two different CW transmitting signals, function of the distance resolution. According to the multi-port theory, $\Delta\theta_i$ represents the phase difference between the two input millimeter-wave signals at ports 5 and 6 at the operating frequency ω_{0i} (see equation (2)). In this example, the frequency shift of 2 MHz between the CW transmitted signals corresponds to a maximum unambiguous range of 75 m and a target situated at 25 m.

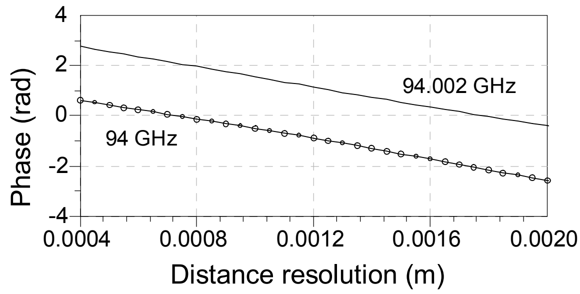

Fig. 5. The phase of the base band complex signals versus the distance resolution

The histogram presented in Fig. 6 indicates the dispersion of the distance to the target evaluated by simulations, corresponding to a target situated at 25 m. The mean of 100 estimations is 24.916 m, which corresponds to a standard deviation of 0.5 m. The related standard error is 2%.

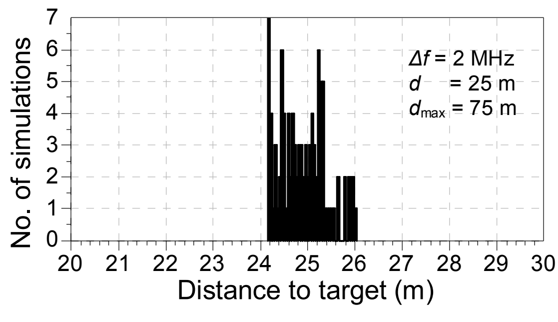

Fig. 6. Histogram of the distance to the target estimations obtained by system simulations for a target situated at 25 m

As these results show, even if an individual measurement supposes an increased error, the mean of consecutive measurements dramatically increase their precision. This measurement procedure is therefore strongly recommended.

III. Measurement Results

Measurements are performed on a test bench using a radar sensor prototype based on the SIW multi-port.

Fig. 7 shows the W-band SIW multi-port on the brass structure including SIW to WR-10 transitions. This circuit is the core of this radar sensor and the measurement precision is related to the magnitude and phase of the S-parameter results.

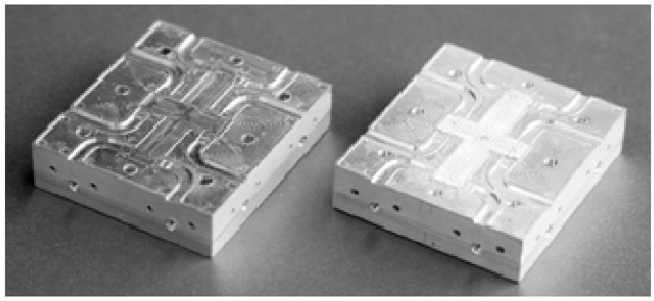

Fig. 7. The W-band SIW multi-port metallic structure

A photograph of the first SIW radar sensor prototype, in accord with the block diagram of Fig. 1, is shown in Fig. 8. The millimeter-wave CW signals are obtained by using a 6x multiplier and a microwave source. High gain antennas are used in the transmitter (Tx) and the receiver (Rx) modules. The multi-port (MP) inputs corresponding to the reference and echo signals are connected at a directional coupler and a LNA respectively. Four waveguide power detectors and two loads are connected to the MP outputs. All millimeter-wave connections are made using standard WR-10 waveguides. The baseband circuit (BBC) generates the output signals using power detectors, according to the multi-port equations.

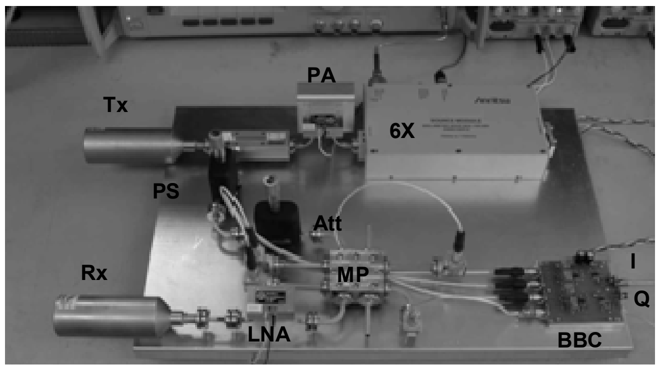

Fig. 8. The W-band SIW radar sensor prototype

The photograph of the radar sensor prototype test bench for short distance measurements is presented in Fig. 9. The metallic target is placed in the vicinity of the sensor. Therefore the CW signal frequencies are spaced by 50 MHz, corresponding to a maximum unambiguous range of 3 m. A waveguide phase shifter PS (see Fig. 8) was used in order to obtain the equivalence to the distance resolution of simulations. The PS will also increase the measurement precision due to some weakness of the waveguide power detectors, as explained further.

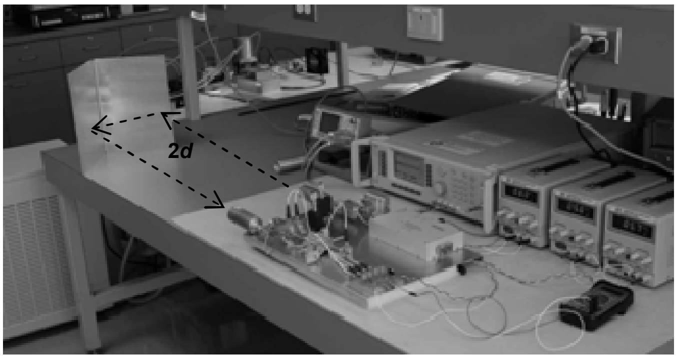

Fig. 9. The radar sensor prototype test bench

Fig. 10 shows the variation of the I output signal for both CW frequencies versus the phase shift of the reference signal. The curves were obtained trough point by point in both cases. The minimum are relatively flat due to the low sensitivity of the waveguide power detectors. However, using the maximum values of these curves a $\Delta\theta_1$ - $\Delta\theta_2$ value of around 100° is obtained. According to equation (2), the measured distance to the target is 0.833 m. The physical distance measured on the set-up of Fig. 9 is 2d = 1.7 m, which corresponds to a distance to the target equal to 85 cm. Therefore the measurement error is around 2%.

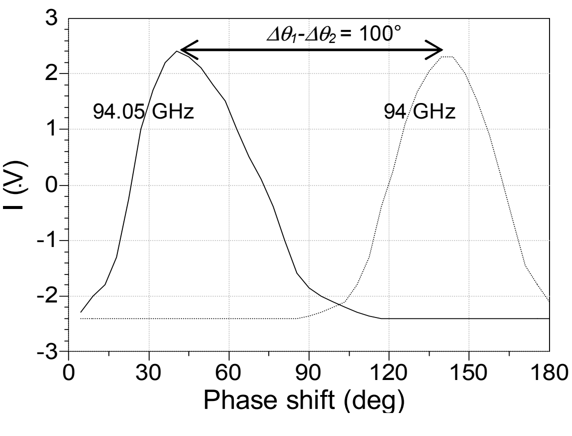

Fig.10. The I output signal for both CW frequencies versus the phase shift at the reference port

A prototype of a W-band collision avoidance radar sensor has been proposed. The radar sensor makes use of an SIW circuit as a first step in order to develop a complete integration. A considerable cost reduction can be made by using SIW integrated antennas, multi-port and power detectors, thus avoiding all SIW to standard WR-10 waveguide transitions and components.

IV. CONCLUSIONS

The relative velocity, the moving direction and the distance to the target are obtained by using one of both baseband in-phase and in-quadrature signals generated according to the multi-port equations. The relative velocity of the target is obtained with excellent accuracy using the measurement of Doppler frequency shift of the reflected signal. Because the multi-port is a millimeter-wave I/Q mixer, the moving direction of the target is not lost in down conversion process.

The distance to the target is obtained with good accuracy by a simple technique based on phase measurements using two adequately spaced CW signals. Statistical evaluations of the distance estimations have shown low measurement errors.

It must to be highlighted that the conventional FMCW approach can also be used in order to obtain the distance to target, because the multi-port with related circuits acts as a millimeter-wave I/Q mixer.

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