A New 94 GHz Collision Avoidance Radar Sensor Using Six-Port Phase Frequency Discriminator

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Abstract - **A new prototype of collision avoidance radar sensor at 94 GHz is proposed. The receiver front-end module is realized using a six-port phase/frequency discriminator (SPD). The SPD is composed of four 90° hybrid couplers fabricated in metal blocks using Computer Numerically Controlled (CNC) milling machine. System simulations to obtain the relative speed of the target and the distance to the target using a SPD model based on 90° hybrid coupler measurement results, are presented. Statistical evaluations of the proposed radar sensor performances are also discussed.**

I. Introduction

Automotive radar applications and other millimeter wave sensors attract great interest and investments. Several operating autonomous cruise control (ACC) systems have been developed and demonstrated. Most of these applications are based on the FM/CW [1] or pulse techniques [2]. In the last years, various designs and prototypes of collision avoidance radar sensor based on a SPD technology were proposed [1,3,4]. Low cost, compact size and great accuracy of range and relative speed measurements are the most significant requirements for commercial deployment. All proposed designs are focused on solving these problems. However, problems related to integration and packaging processes require more investigations [2].

The intent of this paper is to present the principle of a new continuous wave (CW) radar sensor based on a SPD. The proposed SPD is composed of four 90° hybrid couplers fabricated in metal blocks using a CNC milling machine, at 94 GHz. The theoretical principle of relative speed and distance measurements is available from previous publications [3,4]. However, in the present paper, analog signal processing (ASP) instead of digital signal processing (DSP) is used to obtain low cost SPD collision avoidance radar sensors.

System simulations results to obtain relative speed and distance to the target are presented. The SPD model is based on S parameter measurement results of the 90° hybrid coupler at 94 GHz. The design of this coupler was realized using the High Frequency Structure Simulator (HFSS) software, version 5.6, of Agilent Technologies. System simulations were performed using the Advanced Design System (ADS) software of the same company.

II. The Six Port Phase/Frequency Discriminator Operating Principle

The six-port is a passive linear component, first developed in the 70's for accurate automated measurements of the complex reflection coefficient in microwave network analysis [5].

The complex reflection coefficient can be calculated using the output power readings at the four output ports.

$$|b_i|^2 = P_i = |A_i a_6 + B_i b_6|^2, \; i = 1,\ldots,4 \qquad (1)$$

where a_6 and b_6 are the incident and emergent waves of the unknown RF signal and A_i, B_i are the six-port network parameters. These parameters can be obtained through an appropriate calibration procedure of the six-port junction. The signal generator is connected at port 5. The complex reflection coefficient Γ can be written as the vector ratio of the incident and emergent waves:

$$\Gamma = \frac{a_6}{b_6} \qquad (2)$$

A number of six-port phase/frequency discriminators (SPD) were developed in our laboratory, and used in direct conversion receivers [6]. Phase measurements can be performed at microwave and millimeter wave frequencies by making only amplitude measurements using power detectors at four SPD output ports.

Fig.1 shows the block diagram of the SPD circuit. The power to each output port can be expressed as:

$$P_i = \left|S_{5i}|a_5|\exp(j\varphi_5) + S_{6i}|a_6|\exp(j\varphi_6)\right|^2, \; i=1\ldots4 \quad (3)$$

For the same amplitude of the two RF input signals, the output signal powers become:

$$P_i = K|a|^2\left|\exp\left[j\left(\frac{\pi}{4} + \varphi_6 - \varphi_5\right)\right] - q_i\right|^2, \; i=1\ldots4 \quad (4)$$

where K is a constant and q_i are the q points of the SPD:

$$q_i = \exp\left\{ j\left[\frac{\pi}{4} + (i-1)\frac{\pi}{2} \right] \right\},\ i=1\ldots4 \qquad (5)$$

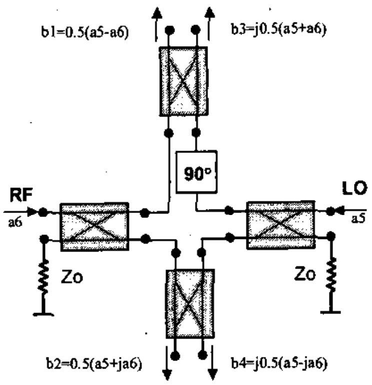


Fig.1. The block diagram of the SPD circuit

III. SPD RADAR SENSOR OPERATING PRINCIPLE

When the two RF input signals have different frequencies, the six-port actually becomes a frequency discriminator. The expression contained in the module of equation (3) represents a vector rotating in the complex plane. The Doppler frequency f_D can be obtained by measurement of the rotating velocity of this vector:

$$f_D = \Delta f = \frac{\Delta\varphi}{2\pi * \Delta t} \qquad (6)$$

where $\Delta\varphi = \varphi_6 - \varphi_5$ is a function of time.

The sign of f_D, witch indicates the sense of target movement, is given by the sense of the vector rotation (clockwise or counter clockwise) [3].

Distance measurements are achieved by using two different CW properly spaced frequencies f_1 and f_2. The distance to the target is obtained by calculating the difference between the phases of the two reflected signals:

$$d = \frac{c(\Delta\varphi_1 - \Delta\varphi_2)}{4\pi(f_1 - f_2)} \qquad (7)$$

The maximum unambiguous range is obtained for a maximum phase difference $\Delta\varphi_1 - \Delta\varphi_2 = \pi$.

IV. THE PROPOSED RADAR SENSOR

The block diagram of the proposed radar sensor is presented in Fig.2. A VCO is used to generate two different CW signals f_1 and f_2 for distance measurements. A part of the transmitted signal is injected at SPD as a reference signal. A power amplifier (PA) is used to increase the power of the transmitted signal. Equal power levels to the SPD inputs improve the measurement accuracy. Therefore, a low noise amplifier (LNA) and a RF amplifier (A) with an automated gain control (AGC) circuit are used. The four SPD output signals are detected and amplified using video amplifiers. An ASP and a frequency counter are used to obtain the relative speed and the distance to the target. To increase the isolation between the transmitted and received signals, two separate antennas are used, instead of a single antenna and a duplexer.

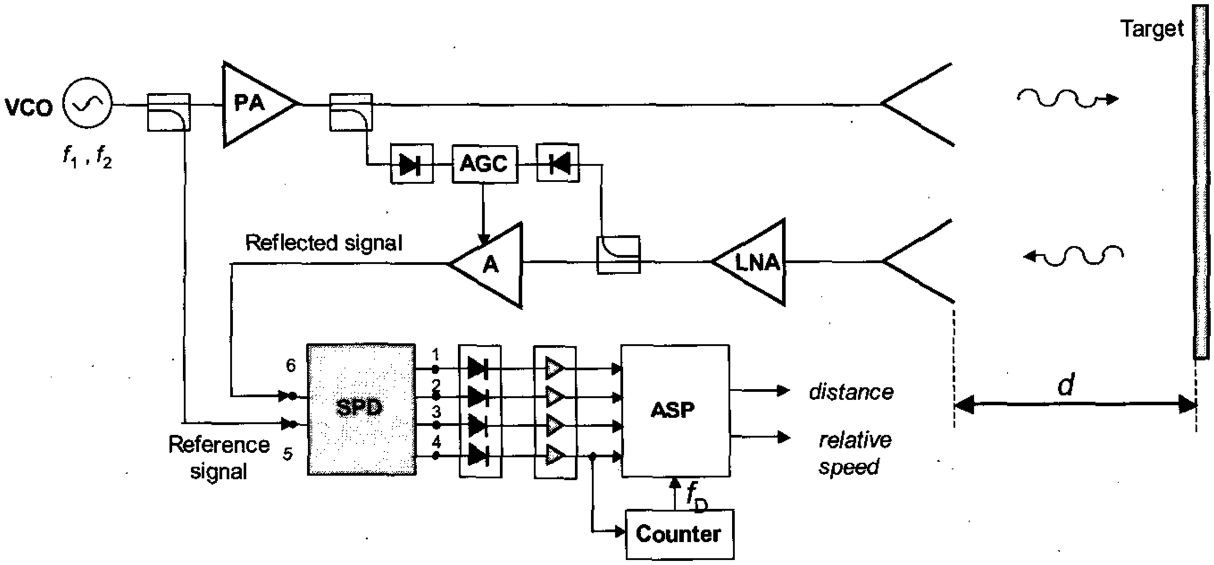


Fig.2. The block diagram of the proposed radar sensor

V. Test Results

A SPD model based on measurement results of the 90° hybrid coupler at 94 GHz was used to perform the system simulations. The coupler was fabricated in a small metal block of brass and good S parameter measurement results were obtained (return loss and isolation above –20 dB and an equal power split of -3.5 dB at 94.8 GHz).

In order to perform relative speed measurements a frequency counter measure the Doppler frequency f_D using an output SPD signal, as shown in Fig. 2.

Fig. 3 shows the waveform of a SPD output signal having a period of 100 μs, corresponding to a measured Doppler frequency of 10 KHz. The relative speed of the target v can be obtained using this measured Doppler frequency as follows:

$$v = \frac{c}{2f} f_D \tag{8}$$

where c is the speed of the light and f is the frequency of the transmitted CW signal. For a f_D = 10 kHz and f = 94.8 GHz, the value of the relative speed is 15.822 m/s.

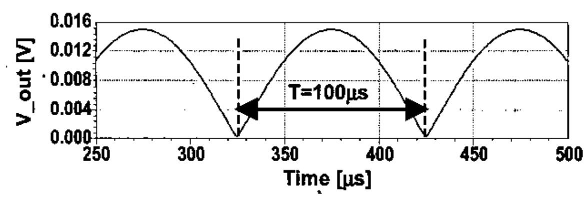


Fig.3. The waveform of a SPD output signal for f_D=10 KHz

To obtain the distance to the target system simulations using two properly spaced CW signals f_1 and f_2, transmitted one after other, were performed. The corresponding phase difference is measured and the distance is obtained using equation (7). For example a maximum unambiguous range of 50 m gives an Δf = 1.5 MHz frequency difference between the two CW signals. In order to obtain a statistical evaluation of distance measurements a distance resolution equal to about the half of the 94 GHz wavelength was chosen and 400 measurements were performed for each measured distance. The dispersion of the measurement results is a function of the accuracy of the phase measurements using the proposed SPD. Fig. 4 shows the variation of the SPD output voltages over the distance resolution values.

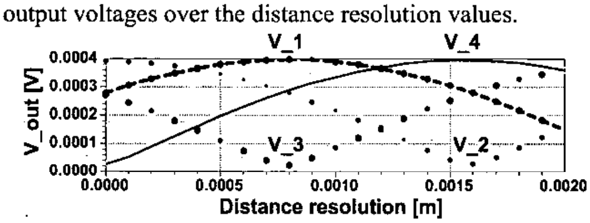


Fig.4. The output voltages vs. the distance resolution values

The ASP uses the four output SPD signals to obtain a phase to voltage conversion. A linear combination between these SPD output voltages is used to provide a low cost implementation of ASP. The conversion result versus the distance resolution is very close to a linear variation, as shown in Fig. 5.

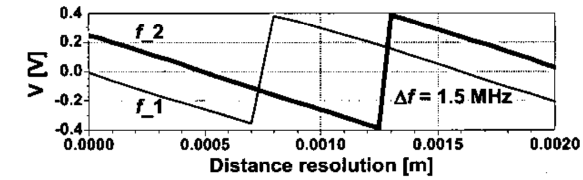


Fig.5. The ASP phase to voltage converted signal vs. the distance resolution values (for two CW signals $f1$ and $f2$).

The imperfect conversion linearity caused by non-ideal couplers determines the spread of the measured distance. Histograms presented in Fig.6 indicate the dispersion of the measured distance values for a 25 m and 45 m distance to the target, with an acceptable measurement mean square error of 2.8% and 1% respectively. In these measurements, a maximum unambiguous range of 50 m (Δf = 1.5 MHz) was considered.

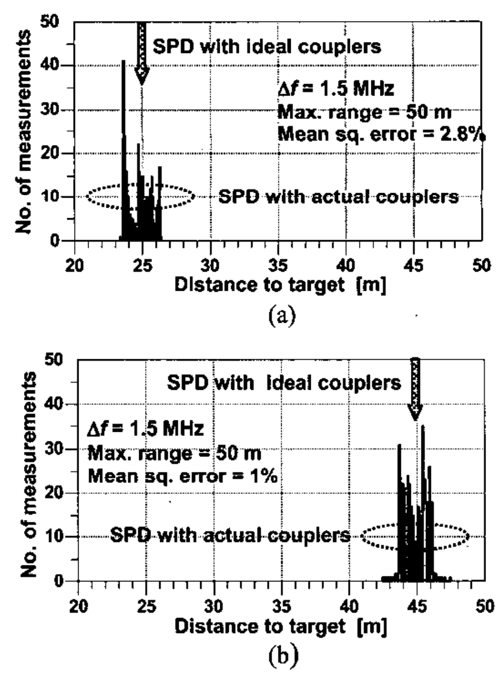


Fig.6. Histograms of measured distance for: a) 25m; b) 45m.

Fig.7 shows the mean square error of the measured distance values versus the distance to the target if the maximum unambiguous range is 50 m.

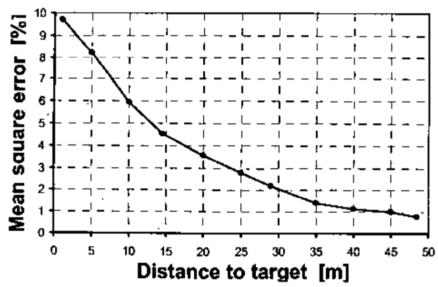


Fig.7. The mean square error of the measured distance

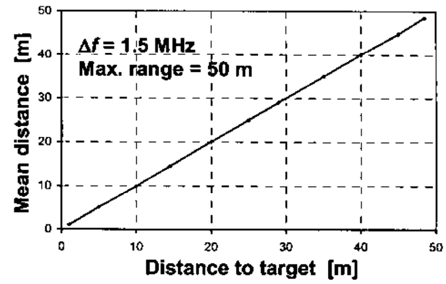
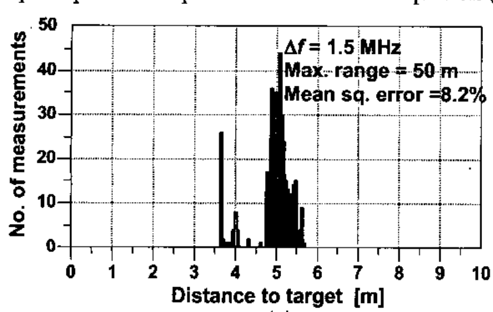
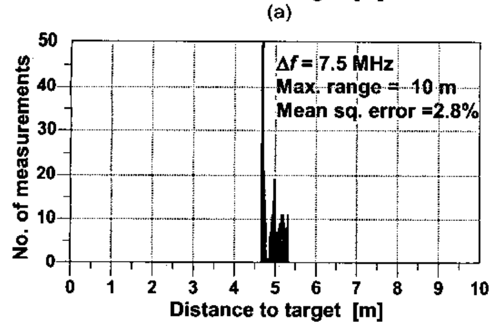


Fig.9. The mean of measured distance vs. the distance to the target

In order to decrease the measurement error for the small distances, the difference between the two CW transmitted frequencies must increase. For example, for a 5 m measured distance, the mean square error of measurement is 8.2% if $\Delta f = f_1 - f_2 = 1.5$ MHz (max. range 50 m) and 2.8% if $\Delta f = 7.5$ MHz (max. range 10 m) as seen in Fig. 8. Therefore, a good correlation between the maximum range and the measured distance must be considered using an adequate pair of frequencies as shown in equation (7).



(a)



(b)

Fig.8. Histograms of 5m measured distance for: a) Δf = 1.5 MHz, b) Δf = 7.5 MHz using non-ideal couplers

Fig.9 shows the mean of the measured distance versus the distance to the target. A number of 400 measurements were considered in each point. The average substantially improves the distance measurements. However, good results were obtained even if a lower number of measurements (between 10 and 100) are performed.

VI. Conclusions

A new low cost prototype of a collision avoidance radar sensor at 94 GHz using a SPD is proposed. The proposed radar sensor uses analog signal processing to obtain relative speed and distance measurements. The relative speed is proportional to the measured Doppler frequency and the distance to the target is proportional to the phase difference between two reflected signals.

The uses of ASP and a passive, linear circuit (SPD) instead of a classical architecture of the receiver determine a considerable diminution of the radar sensor cost. However, size limitations are imposed by the uses of power detectors, connected by standard WR-10 flanges at the machined waveguide SPD circuit.

The system simulations using a SPD model based on a 90° hybrid coupler measurement results are presented. Excellent relative speed measurement results were obtained. Statistical evaluations of the distance measurement results show an acceptable error for this low cost radar sensor.

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