Novel Nonlinear FMCW Radar for Precise Distance and Velocity Measurements

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ABSTRACT

A new nonlinear FMCW radar concept for precise distance and velocity measurements is presented. The radar system incorporates a surface acoustic wave (SAW) reference device used for an online detection of oscillator phase errors. With a specific Doppler/distance ambiguity function, that is continuously adapted to the measured phase error, the target signal is evaluated. By applying this novel technique the optimal distance resolution at a given sweep bandwidth is obtained independently of the Doppler resolution. The proposed system approach has been evaluated with a 77 GHz radar incorporating a flip-chip MMIC VCO.

INTRODUCTION

Millimeterwave systems are currently being established in commercial applications in the automotive and industrial field. Fully integrated MMIC solutions can be fabricated at very low cost in high volumes. However, there persist serious technical problems, such as a high phase noise level or a significant FM nonlinearity.

Phase error effects severely degrade the performance of FM radar systems [1,2]. So, phase locked loops are frequently used to linearize the radar sweep. In recent articles we presented a FMCW radar concept with integrated SAW reference that uses a software approach for phase error compensation [2,3]. This method determines and reduces not only systematic phase errors, which occur mainly due to the nonlinear voltage-to-frequency characteristic of the VCO, but also compensates the oscillator phase noise. However, the reported algorithms had several limitations when moving targets with significant Doppler frequency shift were evaluated. In this paper a novel nonlinear FMCW radar approach with advanced digital signal processing is proposed, that overcomes these limitations.

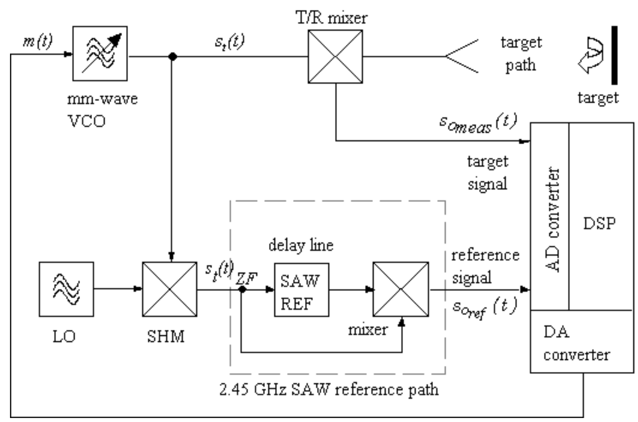

Fig. 1: Nonlinear FMCW radar system with internal SAW reference path (2.4 GHz) and DSP unit.

SYSTEM SETUP

The schematic of the developed nonlinear FMCW radar system is depicted in Fig. 1. The radar signal source (Fig. 2) is a millimeterwave flip-chip MMIC VCO module [4,5] with a rather high phase noise level, typically between -50 and -70dBc/Hz @1MHz. A measurement of the oscillator phase noise using an 354 ns SAW delay line is shown in Fig 3. For this delay the radar signal phase jitter is approx. $\pm 0.5\pi$. The histogram of the phase jitter change shows an instantaneous frequency distribution of approx. 600 kHz bandwidth.

The oscillator is frequency tuned with a nonlinear modulation signal *m(t)*. For continuous online measurement of phase errors, the common FMCW radar setup is extended by a SAW reference path [2,3]. The complex reference signal $\underline{s}_{o_{ref}}(t)$ as well as the target signal $\underline{s}_{o_{meas}}(t)$ are digitized for further computer based signal processing.

PHASE ERROR EFFECTS IN FM DOPPLER / DISTANCE RADAR

The oscillator signal $s_t(t)$ is described as an ideal linear sweep with sweep rate μ that is distorted by a time dependent phase error $\xi(t)$.

$$s_t(t) = \cos\left[(\omega_0 + 0.5\mu \cdot t) \cdot t + \xi(t)\right] \qquad (1)$$

Provided the common phase error theory [1], the phase error term $\xi(t)-\xi(t-\tau) \approx \tau\, d/dt[\xi(t)]$ of the downconverted signal $s_o(t)$ can be treated as linear within the transmission time τ and thus the phase difference between transmit and receive signal including the phase error is proportional to τ, i.e.:

$$\varphi(t) = \tau \cdot [\omega_0 + \mu \cdot t + \dot{\xi}(t)]$$

$$with \quad \dot{\xi}(t) = \frac{d}{dt}\left[\xi(t)\right]$$

$$\Rightarrow \quad \varphi_{dist\_i}(t) = \tau_{dist\_i} / \tau_{ref} \cdot \varphi_{ref}(t). \qquad (2)$$

It has been shown in [2] that any phase error distortion can be equalized by reassembling the measured signal in a way, that sampling is not performed at fixed time intervals dt, but at fixed reference signal phase intervals $d\varphi_{ref}$. When If these extracted samples are rearranged sequentially using a constant new sampling interval dt', the resulting signal

$$s_{o_{meas}}'(n \cdot dt') = s_{o_{meas}}\left(t_n = t\big|_{\varphi_{ref}(t) = n \cdot d\varphi_{ref}}\right) \quad (3)$$

CPIS formula

can be converted into a combination of ideal sinewaves with constant instantaneous frequency $f_{oi} = \mu \cdot \tau / 2\pi$. However, an ideal phase error compensation is only achieved with the CPIS (constant phase interval sampling) technique, if a fixed target is observed.

If the object and the sensor are moving relative to each other with speed v_i, not only the radar

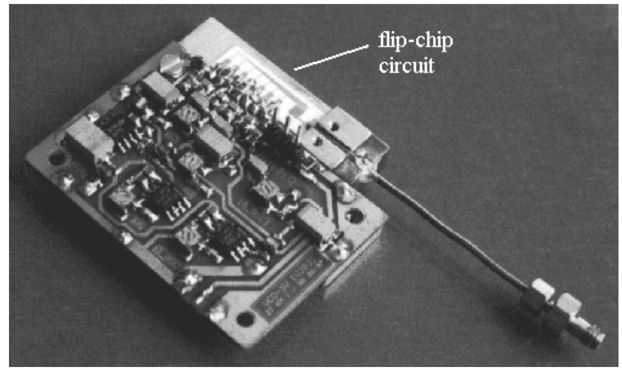

Fig. 2: Flip-Chip Module with 77 GHz GaAs MMIC VCO.

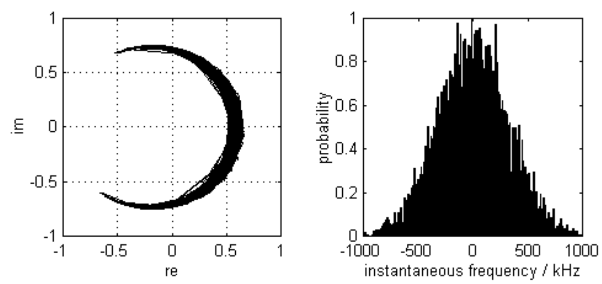

Fig. 3: Phase noise of 77 GHz GaAs MMIC VCO measured using a 354 ns SAW delay line.
a) Complex reference signal $\underline{s}_{o_{ref}}(t)$ illustrating phase jitter
b) Histogram H of instantaneous frequency distribution

frequency and the phase error but also the target distance $d_i(t)$ is a function of time and the target signal phase term Eq. (2) alters to:

$$\varphi_{meas\_i}(t) = \varphi_{dist\_i}(t) + \varphi_{dop\_i}(t) =$$

$$[\omega_0 + \mu \cdot t + \dot{\xi}(t)] \cdot \left(\tau_{oi} + \frac{2 \cdot v_i \cdot t}{c}\right). \qquad (4)$$

↑ ↑
distance and Doppler term

This equation shows that the radar signal phase error has an effect which is directly dependent on the target speed. Now, the main idea of the novel nonlinear radar approach is to use this phase error effect to determine the target speed.

Doppler/distance ambiguity function

If the measured target signal is extended with a Doppler phase compensation term as follows:

$$\varphi_{meas\_i}(t)_{corr} = \varphi_{meas\_i}(t) - \varphi_{dop_{corr}}(t,v)$$
$$\textit{with} \quad \varphi_{dop_{corr}}(t,v) = \qquad (5)$$
$$\left([(\omega_0 + \mu \cdot t + \dot{\xi}(t)] \cdot \frac{2 \cdot v \cdot t}{c} \right) \approx \frac{2 \cdot v \cdot \omega_c \cdot t}{c}$$

and if v is chosen equal to the real target speed v_i, the Doppler dependent phase term (ref. Eq. (4)) would be compensated and consequently the CPIS equation Eq. (3) will lead to an optimal phase error suppression, i.e. a Fourier spectrum with a very narrow and high echo peak. In contrast, if v is selected different to the ideal value v_i, a phase error will be induced and the target signal power will be spread over a broad spectral bandwidth. The larger the radar signal phase error and the difference between the hypothetical and the real target speed are, the more the target spectrum will be blurred. Hence, the strategy is to generate an extremely nonlinear VCO signal and perform a single measurement. After that, the measured target signal is successively extended with a set of Doppler phase correction terms (as described in Eq. (5)) for several hypothetical target speeds v. The value of v that leads to the best CPIS result corresponds to the real target speed.

A useful Doppler/distance ambiguity function $\Psi(d_{0i},v)$ can be defined as follows:

$$\Psi(d_{0i},v) = \left| \mathfrak{F}\left\{ CPIS\left\{ s_{o_{meas}}(t) \cdot e^{-j \cdot \varphi_{dop_{corr}}(t,v)} \right\}\right\}\right|$$

with

target Distance: $\quad d_{0i} = f_{0i} \cdot \pi \cdot c / \mu \qquad (6)$

target speed: $\quad v$

where $\mathfrak{F}(.)$ and CPIS(.) denote the Fourier-Transform and the constant phase interval sampling algorithm respectively.

Results

Figure 4 illustrates the result of an evaluation with the proposed algorithm. A modulation signal *m(t)* with a quadratic time dependency was used. In addition to the inherent MMIC oscillator phase noise the modulation was also corrupted by some low frequency noise terms. The sweep had a bandwidth of 450 MHz, the sweep duration was 20 ms. Two targets were present. One target was located at 164.5 m, slowly moving away with a speed of -8.6 m/s. The other target at 39 m was moving towards the

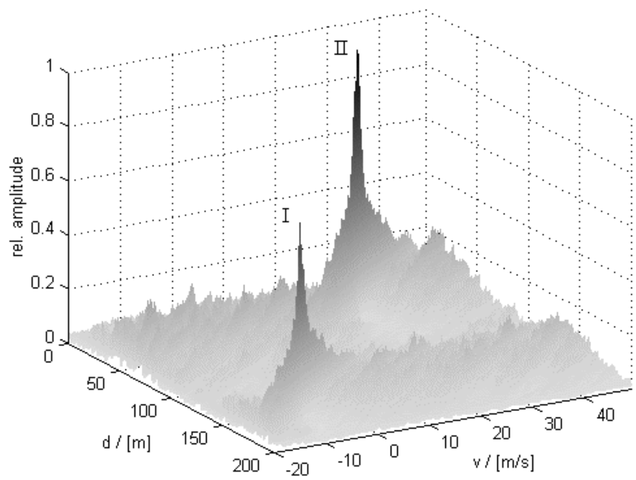

Fig. 4: Doppler/distance ambiguity function obtained from a two-target scenario.
Target I: distance 164.5 m; speed -8.6 m/s
Target II: distance 39 m; speed 28.3 m/s

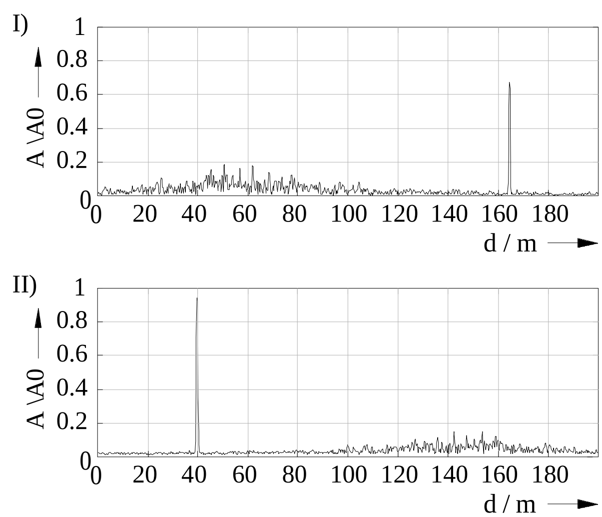

Fig. 5: Intersection of Doppler/distance diagram Fig. 4 at the target maxima (optimum value of *v*).
I) v=-9m/s; best result for target I
II) v=28m/s; best result for target II

sensor with 28.3 m/s. In the evaluation v was chosen in 1 m/s steps from -20 m/s up to 50 m/s. In the resulting Doppler/distance diagram the two targets can be identified clearly. The maxima are located at $v = -9$ m/s for the first and 28 m/s for the second target. This corresponds to the actual target speeds. The intersections (Fig. 5I and Fig. 5II) in the diagram at the positions of the maxima are providing the exact distance information. The advantage of the developed Doppler/distance evaluation technique on the basis of a nonlinear FMCW radar is, that it yields unambiguous target scenarios. The optimal distance resolution at a given sweep bandwidth is obtained independently of the Doppler resolution.

A drawback of the concept can be seen in the fact that it provides a rather low dynamic range for special multi-target scenarios. The noise induced by strong target signals can hide small signals if the targets differ in speed and are located close to each other. To overcome this limitation iterative techniques that successively subtract identified spectral components can be used.

CONCLUSION

Millimeterwave systems are currently established in commercial applications in the automotive and industrial field. However, fully integrated MMIC solutions, which could be fabricated at very low cost in high volumes, still have some technical problems. It is emphasized in this paper, that advanced digital signal processing can establish effective strategies for the improvement of radar performance. On the basis of the proposed phase error adapted ambiguity function, an optimal distance and Doppler resolution is obtained in spite of non-ideal radar characteristics like oscillator phase noise or sweep non-linearity.

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