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Fully Integrated, Multipurpose Low-Cost K-Band FMCW Radar Module with Sub-Milimeter Measurement Precision

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***Abstract*—A design of a low-cost K-band FMCW radar module with integrated microstrip antenna arrays and onboard digital signal processing has been presented. The radar utilizes antenna arrays with series feeding network which minimizes dissipation losses and allows for realization of high-gain antennas. The radar's microcontroller unit is able to perform complete signal processing at real time which makes the presented sensor suitable for fully autonomous operation. Moreover, the presented radar module is capable of performing interferometric measurements. The interferometric capability of the developed unit allows for measurements of object displacement with precision on the order of tens of micrometers.**

***Index Terms*—FMCW radar, integrated radar sensor, series-fed microstrip antenna array.**

I. INTRODUCTION

Many fields of engineering require dynamic distance measurements in multiple target situations, frequently in harsh environmental conditions and with obscured field of view. Frequency-Modulated Continuous-Wave (FMCW) radars are an optimum solution for such tasks. In opposition to ultrasound or laser measurement systems, the FMCW radars are mostly unaffected by dust, vapor or debris while maintaining the required measurement precision. Also, as the FMCW radars are not pulsed radars, they do not require complex circuitry to achieve ranging precision on the order of centimeters. For these reasons the FMCW radars have been frequently used in e.g. automotive [1]-[7] or industrial [8]-[13] applications.

FMCW radars utilize sawtooth or triangle frequency modulation ramp. As the radar's received signal is an attenuated and delayed copy of the transmitted signal, the difference between instantaneous frequencies of the transmitted and received signals Δf is directly proportional to the distance to the static target R, due to the frequency ramp:

$$\Delta f = \frac{2RB}{vT} \tag{1}$$

where B is bandwidth of the transmitted signal, T – modulation period, v – phase velocity of the signal (typically assumed to be equal to the speed of light). If the target is not stationary, the frequency difference is additionally influenced by the Doppler shift f_D:

$$\Delta f = \frac{2RB}{vT} \pm f_D \tag{2}$$

By utilizing the triangle sweep instead of the sawtooth ramp, the speed of the moving target can be obtained, as the Doppler frequency shift has different sign for up-ramp and down-ramp parts of the triangle sweep. However, if the modulation period is relatively short and the target does not move very fast, the Doppler shift has a negligible effect on the frequency difference Δf. For this reason, the frequency shift f_D is usually omitted and only the sawtooth ramp is utilized as modulation waveform. By performing spectral analysis of the IF signal, ranges to targets located within radar's beam can be obtained. Most common method of spectral analysis of FMCW signal is computation of Fast Fourier Transform (FFT) due to its relatively low complexity and high efficiency. Ranging accuracy ΔR of the FMCW radar with FFT signal processing is dependent only on the bandwidth B of the radar signal and phase velocity of the electromagnetic wave v, and can be expressed as:

$$\Delta R = \frac{v}{2B} \tag{3}$$

In a typical case, the bandwidth of radar signal is few hundreds MHz, which yields accuracy ΔR on the order of tens of centimeters, e.g. bandwidth of 500 MHz produces ranging accuracy ΔR = 30 cm. Whereas in automotive applications such ranging accuracy is usually satisfactory, which in most cases is easily feasible, certain industrial applications like level gauging, machine control or structural health monitoring (SHM) require precision well below millimeters [14], [15]. In such cases the frequency evaluation of the radar's intermediate frequency (IF) signal cannot provide the required precision. To overcome this problem, interferometric measurement can be used, where phase term of the beat signal is utilized to determine distance to the target. The phase of the IF signal φ is directly proportional to distance to target R as given:

$$\phi = \frac{4\pi R}{\lambda} \tag{4}$$

where λ is wavelength of the transmitted radar signal. Accuracy of ranging by phase determination is independent from signal bandwidth; it is proportional to precision of

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radar's phase detection circuit $\Delta\varphi$, and is inversely proportional to signal wavelength. For an exemplary radar system with $\Delta\varphi = 1^{\circ}$ and carrier frequency $f_0 = 24$ GHz (thus wavelength $\lambda = 12.5$ mm) ranging precision as high as 17 µm can be achieved. However, as in real systems phase can be only determined within $[0, 2\pi]$ limits and unambiguous range measurement by phase evaluation is restricted to only $\lambda/2$ distance. For this reason, FMCW radars use frequency evaluation algorithms to obtain coarse range to the target, and afterwards track changes in the IF signal's phase to measure displacement of the target with micrometer precision.

In this paper we present a newly developed, low cost, compact FMCW radar sensor operating at 24 GHz frequency band with integrated antennas for variety of applications, capable of conducting interferometric measurements (phase evaluation), while featuring overall low hardware complexity as well as embedded digital signal processing, which makes the radar capable of fully autonomous operation. This work is an extension to the radar sensor presented in [16], which lacks integrated antennas.

II. RADAR SYSTEM OVERVIEW

Schematic block diagram of the presented radar module is shown in Fig. 1. The sensor consists of separate Tx/Rx antennas, synthesized signal source, homodyne receiver, IF gain and filtration stage, and an ARM-core microcontroller that controls the radar system.

A. Hardware Overview

Signal generation is performed in phase-locked loop (PLL), which consist of an SPI-programmable frequency synthesizer integrated circuit and a microwave voltage-controlled oscillator (VCO) chip. The VCO has three outputs: fundamental frequency output, halved frequency output, and divided-by-16 frequency output. The latter output is used as PLL feedback signal. The halved frequency output functions as local oscillator (LO) signal for the radar's sub-harmonic mixer. The VCO's fundamental frequency output is connected to the transmit antenna array. Signal from the receive antenna array is mixed with the transmitted signal in the sub-harmonic mixer. The mixer's intermediate frequency (IF) signal is then amplified by variable gain amplifier (VGA) and filtered by a band-pass filter (BPF). These two components are controlled by the radar's microcontroller unit, which also configures frequency synthesizer and communicates with PC host via USB interface.

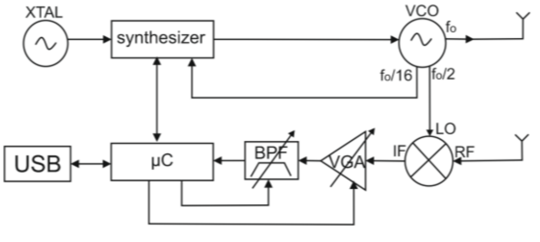


Fig. 1. Schematic block diagram of the presented radar sensor.

B. Signal Processing Overview

Signal processing is based on FFT. Presence and distance of targets is identified by properties of peaks in the calculated signal spectrum. To minimize the spectral leakage effect, which can lead to small targets being totally obscured by presence of a strong target, a Hann window function is utilized. Targets' displacement is measured by tracking phase changes of the appropriate discrete frequencies in the FFT spectrum. To ensure that the phase changes are caused only by target's displacement, the sampling of the IF signal must be strictly synchronized with the FMCW frequency modulation ramp. If this condition wasn't met, the phase changes would reflect variation of sampling start time relative to the modulation ramp. This phenomenon especially affects measurements of distant targets, as they are represented by higher frequencies in the IF signal.

The signal processing is performed entirely onboard by the microcontroller with ARM Cortex-M4F core running at 168 MHz clock. The Cortex-M4F core features SIMD-type instructions (Single Instruction, Multiple Data) and floating-point unit, which, combined with high operating frequency, results in very efficient data handling. FFT composed of 1024 samples of single precision (32 bit) floating point type is calculated in slightly less than 1 ms. This allows the presented radar sensor to measure displacement at real time with rate up to 1 kHz, which satisfies requirements of demanding applications like vibration measurements of structures or machinery.

C. Antenna Array

In the first stage of the radar sensor's antenna design process a 7-element linear antenna array has been designed operating at the center frequency of 24.25 GHz. The linear antenna array utilizes series feeding technique which allows to minimize the overall feeding network length, and thus reduces the feeding network losses [17]-[22]. In the presented solution a "through-element" feeding technique has been applied in which the excitation signal is guided through consecutive radiating elements with the use of either direct or electromagnetic coupling [20]-[22]. In order to obtain appropriate transmission coefficients between consecutive radiating elements, galvanic connections as well as electromagnetic couplings have been used. Electromagnetic simulations have been performed in Ansoft Ensemble design environment, which utilizes method of moments and assumes infinite ground plane. The final antenna array utilized in the presented radar module is composed of 4 parallel-fed linear arrays connected together by three T-junctions as shown in Fig. 2. The measured radiation pattern of the complete 7×4 array is presented in Fig. 3, whereas the measured gain of the array equals 17 dBi.

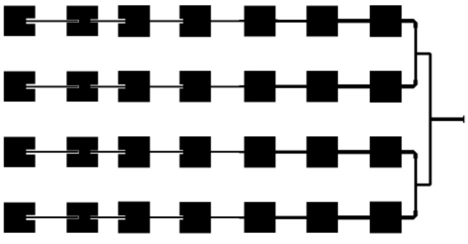
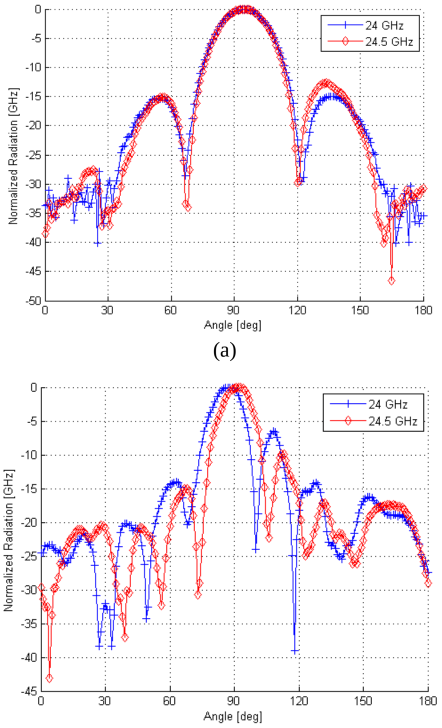


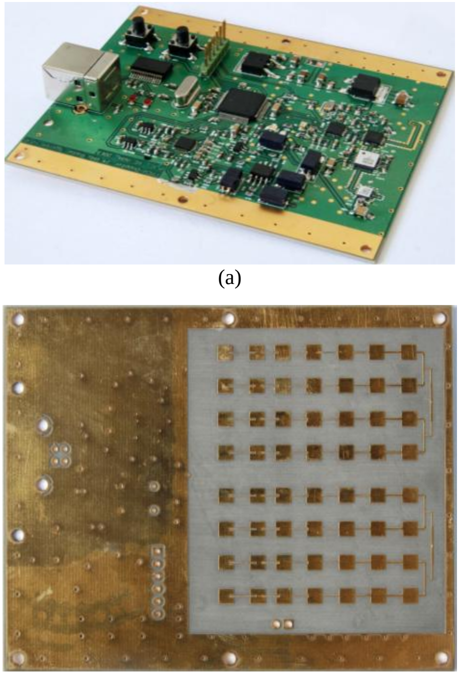
Fig. 2. Layout of the designed series-parallel fed antenna array for application in radar sensor.



(a)

(b)

Fig. 3. Radiation pattern of the 7 ×4 antenna array in the H-plane (a) and E-plane (b).



(a)

(b)

Fig. 4. The photograph of the manufactured radar sensor.

III. RADAR DESIGN

The presented integrated radar sensor has been designed on a 4 layer PCB, composed of 12 mils-thick Arlon 25N laminate, sized 75 × 93 mm. The photograph of the manufactured radar unit is shown in Fig. 4. The electronic components occupy the top layer, while the antenna arrays are located on the bottom layer. For the purpose of connecting the Tx/Rx antenna arrays with coplanar waveguide with ground (CPWG) Tx/Rx lines placed on the top side, a dedicated broadband transition has been designed for the given antenna array and the layer stack. To minimize the overall length of microwave transmission lines, the transition has been composed directly into the antenna array and functions as a first T-junction for the antenna's feeding network. The transition has been designed and simulated electromagnetically in AWR design environment. Fig. 5 shows the picture of the transition, while Fig. 6 shows the transition's simulated reflection coefficient.

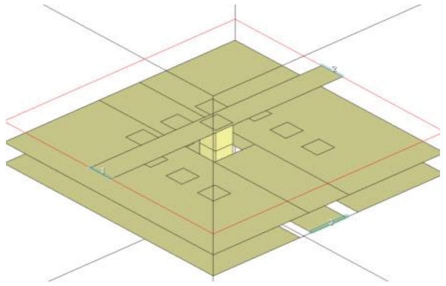


Fig. 5. 3D view of the designed CPWG – antenna array transition. Only metal layers are visible, dielectric is transparent, square shapes are vias.

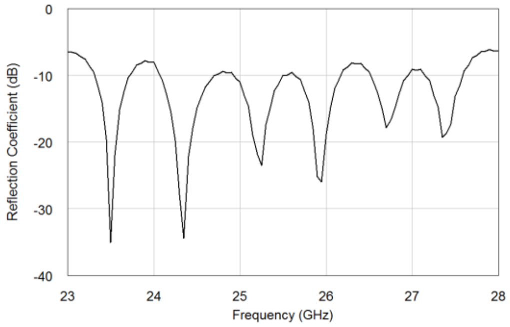


Fig. 6. Reflection coefficient of the inter-layer CPWG – antenna array transition.

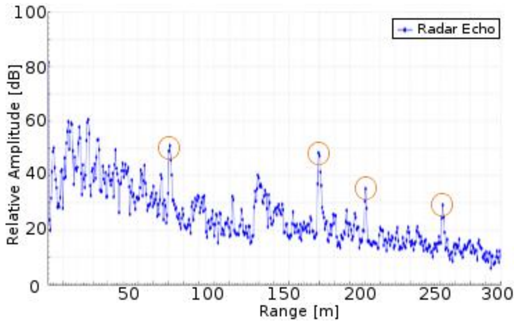


Fig. 7. Screenshot taken from PC application during traffic monitoring test.

IV. EXPERIMENTAL SETUP

A. *Traffic Monitoring Test*

An experimental traffic monitoring test has been set up, with the radar positioned on a roadside facing the road. The radar has operated in 24 – 24.25 GHz ISM band. Signals caused by passing vehicles have been registered. Detection range exceeding 300 m for passenger car-sized target (~ 5 m^2 RCS) has been achieved. Such a long detection range resulted from the radar's high gain antennas as well as fast onboard signal processing, which allows to calculate hundreds of FFTs per second, average tens of signal spectrums to lower noise level and still being able to display several measurements per second, which is essential to keep up with dynamic traffic situations. Fig. 7 presents an exemplary screenshot taken from PC application, where the spectrum of the registered IF signal is plotted. The frequency has been converted to the corresponding distance using eq. (1). In the presented figure four peaks (marked with circles) pointing out from clutter and noise can be seen, which are corresponding to four vehicles registered by the radar. Ranges to the vehicles are approx. 80 m, 180 m, 210 m and 260 m. Apart from the spectrum peaks corresponding to the vehicles, multiple clutter can be seen. In the distance range of about 10 – 40 m strong parasitic reflection from a nearby metal fence is visible, at 140 m a building reflection can be seen, the remaining spectrum "floor" is composed of smaller objects and ground reflections combined with noise.

B. *Displacement Measurement Test*

In order to verify the radar's precise displacement measurement capability an experimental measurement in laboratory conditions has been set up. In the test a limited prototype with externally attachable antennas has been used. In the measurement a metallic plate of 81 cm^2 surface has been placed 5 meters away from the radar and then successively displaced with 0.1 mm steps. The radar operated with following parameters: frequency sweep range: 24 – 24.4 GHz, modulation period: 1.7 ms, IF frequency corresponding to the target: 7.8 kHz, Rx/Tx antennas: 10 dBi gain. Phase of the IF tone was registered after each movement of the target. The registered phase difference has been converted to displacement of the target, according to (3). The obtained results are shown in Fig. 8. The mean measurement error is 28 μm, while maximum error equals 78 μm.

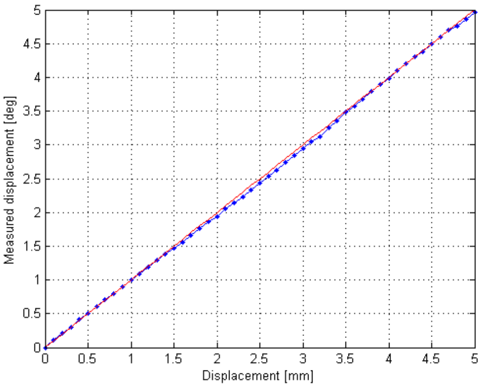


Fig. 8. Displacement measured by the radar sensor (blue dotted line) compared with actual displacement (red solid line).

V. CONCLUSIONS

An integrated, low-cost, multirole compact FMCW radar sensor with interferometric capability has been shown. The radar features high gain, series-fed antenna arrays which minimizes feeding network losses, and fast onboard digital signal processing. These properties resulted in outstanding detection range, which was experimentally verified in a non-laboratory test. The radar's phase evaluation capability has also been verified experimentally, which resulted in the radar achieving micrometer precision. Currently, the work on the presented radar sensor is focused on developing angle of arrival (AoA) detection capability. To obtain a high angular accuracy together with the wide field of view it is planned to utilize on the Tx side a multiple beam antenna fed by a Butler matrix, and on the Rx side a monopulse technique. This capability would make the presented radar system suitable for applications in such demanding systems as automotive collision warning and avoidance, naval monitoring and guiding, or airport traffic control.

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