Next Generation Ultra-Low-Power Radar Sensors and Systems

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***Abstract*—This report provides a brief summary of the outcomes of the research project on next generation ultra-low-power radar sensors and systems that was supported through a 2016 IEEE MTT-S Graduate Fellowship Award. Main objective was to perform research on energy-efficient continuous wave radar systems to build next-generation systems with highly accurate absolute distance measurements and an aimed average power consumption in the one-digit milliwatt range or even lower.**

I. Introduction

High-accuracy, low-power radar systems play an increasingly important role in contemporary society and can be used in various areas. Short-range radar sensors are, e.g., more and more employed for wireless distance measurement and vibration-monitoring in industrial as well as medical applications [1]. Some of these tasks require particularly energy-efficient devices, especially when they are operated in an always-on scenario. Up to now radar systems either used a free-running voltage controlled oscillator (VCO) and are thus not suited for dual- or multi-tone measurements or could not reach the desired power consumption in the one-digit milliwatt range. This report summarizes the outcomes of the conducted research project, presenting the final hardware demonstrator and the underlying system and circuit design considerations with their inevitable tradeoffs for lowest power consumption.

II. Project description and research outcome

A. Ultra-low-power system concept

A detailed analysis of various radar principles and implementation possibilities were carried out, finally leading to the proposed system concept in Fig. 1. A continuous wave (CW) radar approach was chosen as it requires neither a high bandwidth nor complex signal processing routines. Especially systems based on microwave interferometry can be implemented very energy-efficiently as the whole receiver can be realized by passive planar microwave structures and diode power detectors [2]. The whole system consists of three core components: An optimized radio frequency (RF) synthesizer to generate the RF transmit and reference signals, a purely passive RF frontend for phase evaluation between the received signal (S_{RX}) and a reference signal (S_{REF}) and an active baseband circuit with an ultra-low-power micro-controller scheduling the whole system for maximum efficiency. To overcome the inherently limited unambiguous range of only half a wavelength for CW radar systems the RF synthesizer must be fine-grain adjustable

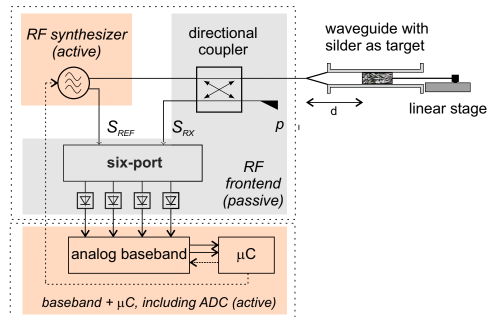

Fig. 1. Block diagram of the the proposed low-power radar system concept.

to perform dual- or multi-tone measurements [3] that can significantly enhance an unambiguous measurement range.

B. Hardware building blocks

1) RF synthesizer: The RF synthesizer is crucial in the proposed system concept as it's the only active RF component and will thus be the biggest contributor to the total power consumption. Therefore an optimized 24 GHz frequency synthesizer was designed, simulated, built up and experimentally verified using a fast locking phase locked loop (PLL) with a 24 GHz VCO and a temperature compensated crystal oscillator as reference.

The system showed a total turn-on and lock time below 50 µs and, due to range-correlation in CW short-range radar systems, still a good phase noise for this application with a resulting effective RMS position error contribution below 10 µm [4]. A paper presenting more details, the optimization criteria and various tradeoffs for, e.g., the PLL phase frequency detector, the loop filter as well as the baseband filter bandwidths has been submitted to the 2017 European Microwave Conference (EuMC) [4].

2) RF frontend: A purely passive 24 GHz six-port interferometer with diode power detectors is used as receiver for phase evaluation between a reference signal S_{REF} and the received signal S_{RX}. The video bandwidth of the power detectors is again a tradeoff between power consumption and measurement precision and has been chosen to approximately 300 kHz. This has shown to be a good compromise between settling time and noise contribution. A microstrip (MSL) to WR-42 waveguide (WG) transition has been built up using firstly a MSL to substrate-integrated-waveguide (SIW) transition and then an SIW-to-WG transition to allow a direct mounting of the WG to the printed circuit board. The transition was optimized for

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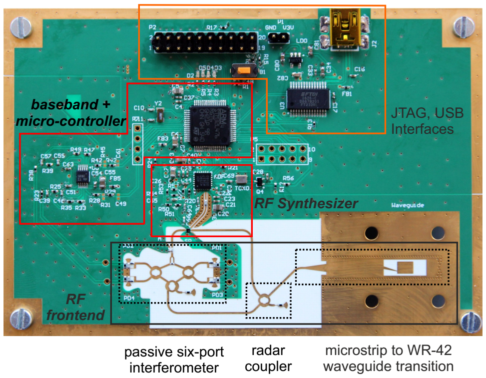

Fig. 2. 24 GHz ultra-low-power radar system for multi-tone measurements.

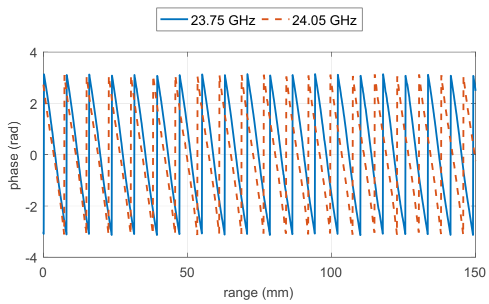

Fig. 3. Reconstructed phase for a dual-tone measurement over the range of 150 mm with a frequency difference f_d =300 MHz.

minimal return loss in order to minimize static offsets and enhance the isolation between transmit and receive path.

3) Baseband and micro-controller: The analog baseband circuitry amplifies the weak detector output signals and also performs an additional filtering for anti-aliasing and noise suppression. 2nd-order active Bessel filters, matched to the detector bandwidth, showed the best tradeoff in the overall system view as they have an optimal step response behaviour due to a constant group delay in the passband. An ultra-low-power micro-controller is responsible for setting the required PLL frequencies and the analog-to-digital conversion of the baseband signals. It can furthermore put every active component into a shutdown mode with minimal power consumption. This is realized through dedicated enable-pins and through additional P-MOS transistors that can completely disconnect the supply voltage of the component.

C. Hardware demonstrator and measurements

A photo of the latest hardware demonstrator is depicted in Fig. 2. By intermittently transmitting, the system is capable to perform dual- and multi-tone measurements in the 24 GHz ISM-frequency band with an average power consumption, verified by measurements, of only slightly above 1 mW (performing 20 position measurements per second). Fig. 3 depicts the phase measurement results for a dual-tone measurement over the range of 150 mm with a frequency difference $f_d = 300$ MHz as a first proof-of-concept. As expected, the phase difference increases with measurement range. Using this information the unambiguous range could be enhanced, however, some phase-nonlinearities still occur that would degrade the final position results. For a practical application it is thus advisable to use multiple frequencies with different spacings. This way all frequency differences can be evaluated, leading to a more robust and accurate position measurement.

III. Conclusion

During the project a big step towards next-generation ultra-low-power radar sensors and systems has been made. An optimized system concept has been proposed, using a fast-locking frequency synthesizer for the generation of multi-tone measurement signals [4] to circumvent the unambiguous range limitations of CW radar systems. A purely passive RF frontend, realized by a six-port interferometer, reduces the power requirements. Every active component is individually scheduled by an ultra-low-power micro-controller so that an overall power consumption of approximately 1 mW for 20 dual-tone measurements per second has been reached.

IV. Impact statement, IMS2016 impressions and next career plans

I would like to express my sincere gratitude to the IEEE MTT-S for the support of my research activities through this prestigious MTT-S Graduate Fellowship Award in 2016. This recognition encouraged me to work even more intensively towards next generation ultra-low-power radar systems and I am sure it will have a very positive impact on my future career. Furthermore, it allowed me to travel to the 2016 International Microwave Symposium (IMS) in San Francisco, CA, which was a very valuable experience for me that I can recommend to anyone involved in microwave technology. The conference attendance not only provided me the opportunity to meet experts and researchers from all over the world but also gave me a deep insight into the latest academic research results. The industrial exhibition was also very impressive and allowed me to receive first-hand information about cutting-edge developments and products. My future plan is to continue the research in the field of RF sensors and radar systems with the next short-term goal finishing my Ph.D. After that I am strongly interested in continuing my career in an environment focused on creating technical innovations. Finally, I would like to encourage any eligible microwave graduate student to apply for the next round of MTT-S Graduate Fellowships.

References

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