A Low-Power and Low-Cost Monostatic Radar Based on a Novel 2-Port Transceiver Chain

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***Abstract* — A low-power and low-cost 5.8-GHz 2-port monostatic Doppler radar was designed, fabricated and tested for small motion detection. The implemented RF board is based on a new radar architecture that features a compact size and only one active device. Unlike conventional board level radar systems, it does not use separate Tx/Rx signal chains. With a single antenna for Tx/Rx, it does not use any low noise amplifier (LNA) or circulator in the RF front-end. Besides the local oscillator (LO), there is no more active device that consumes DC power. The fabricated radar system has dimensions of 20.6 mm × 26.5 mm (L×W) and a power consumption of 290 mW in continuous operation, which could be significantly reduced based on duty cycling. In addition, a low conversion loss of 3.6 dB was achieved. The high sensitivity of the proposed architecture was demonstrated by successfully measuring a 50 µm sinusoidal movement.**

***Index Terms* — Doppler radar, Interferometric radar, Internet of things, Schottky diode.**

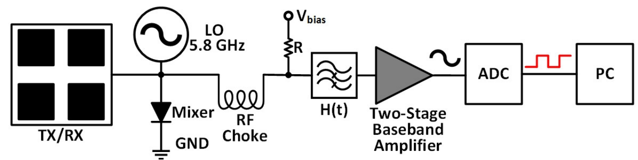

Fig. 1. Proposed radar system block diagram.

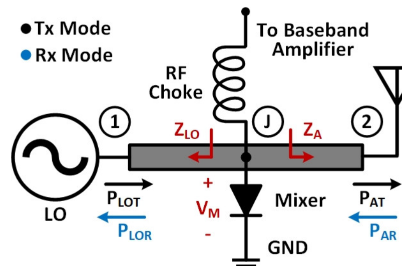

Fig. 2. 2-port transceiver chain schematic and power flow diagram.

I. Introduction

Portable radar sensors are being widely studied and used due to their versatility in various applications such as vital signs detection, human tracking, gesture recognition, speech sensing, concealed weapon detection, and traffic safety monitoring [1]-[4]. The interest on low-power and self-powered smart sensors with small form factor has increased in the last few years to fulfill the internet of things (IoT) requirements [5], [6]. Additionally, in order to make feasible the deployment of the high number of sensors demanded in the IoT era, it is imperative to pursue the design of ultra-low-cost on-board electronics [7].

For many portable radar sensors, the quadrature direct down-conversion architecture has been widely used due to its low complexity and easy on-chip integration. However, this architecture uses several active components which increase its power consumption, form factor, as well as cost. In order to overcome these issues, a simplified 25 cm^2 (including the radiating element but not the baseband circuit) radar front-end was proposed in [8]. A hybrid coupler was used to split the local oscillator (LO) power between the transmitting/receiving (Tx/Rx) antenna and the down-conversion mixer. As the hybrid is a bidirectional passive device, the signal received by the antenna was also divided between the RF port of the mixer and the system LO, introducing an undesired 3 dB loss but avoiding the use of expensive components such as a circulator. Nevertheless, as the size of the hybrid coupler is highly dependent on the wavelength λ, there is a limitation on the minimum size of the system.

In this work, a novel, low-cost, low-power 2-port monostatic radar suitable for massive fabrication and array implementation is proposed. Unlike conventional radar systems, this architecture does not use separate Tx/Rx signal chains, just counts on a single antenna for Tx/Rx, and does not use a hybrid or circulator in the RF front-end. Besides the LO, there is no other active device consuming any DC power. The fabricated radar system has dimensions of 20.6 mm × 26.5 mm (L×W) or 5.47 cm^2 without the antenna but including a two-stage baseband amplifier.

The rest of the paper is organized as follows. Section II details the design principles of the system. In Section III, the results of the experiments are shown demonstrating the system's capability to detect small motions even with a well-designed ultrasimple structure. Finally, a conclusion is drawn in Section IV.

II. Design Principle

Fig. 1 shows the schematic of the implemented 5.8-GHz radar system. A Schottky diode is used as a down-conversion mixer and it forms a 4-ports junction along with the LO, the Tx/Rx antenna, and the RF choke. This 4-port junction can be analyzed as a 2-port transceiver chain since there are just two RF ports in the oscillator and antenna ends of the structure. The LO (Analog Devices HMC358MS8G) is the only active device in the proposed architecture and it

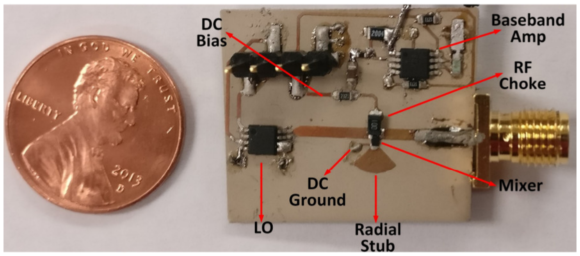

Fig. 3. Fabricated radar system.

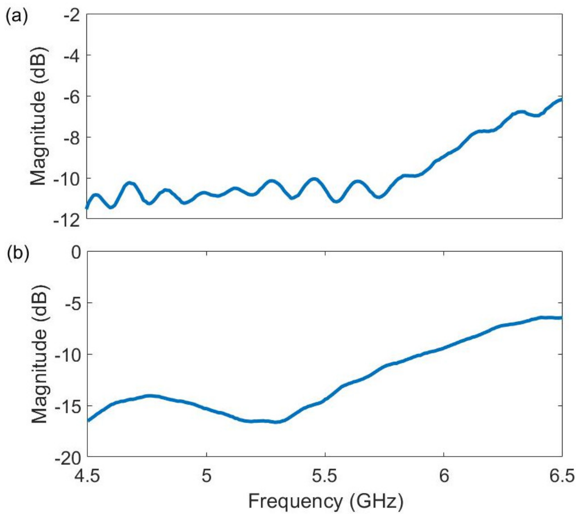

Fig. 4. Measured S-parameters for the 2-port transceiver chain without the LO: (a) measured S_{11}, and (b) S_{22}.

fixes the overall power consumption of the 2-port monostatic front-end to 290 mW. The entire system was designed and implemented using a 1.27 mm 3210 Rogers substrate.

A. 2-Port Transceiver Chain

The 2-port transceiver chain was designed to achieve the power division ratio that optimizes the radar performance. Its power flow is depicted for the Tx/Rx modes in Fig. 2. In order to optimize the performance of the proposed front-end, it is necessary to maximize the AC voltage on the mixer since the transmission line (T-line) effect is not pronounced when comparing physical size with wavelength. As the position of the mixer changes along the T-line, it will see different signal amplitudes V_M. Therefore, by using this principle the LO and the received signal strength can be optimized at the mixer location leading to the optimal conversion loss. Additionally, low reflection at each port and low insertion loss between the ports are desirable to maximize the transmitted power.

It is important to mention that by using a 2-port transceiver chain, the size limitations of [8] can be relieved since the form factor of the 2-port transceiver chain is not limited to $\lambda/4$ in the two axes. Although it reduces the isolation between the ports. Conversely, it may not be

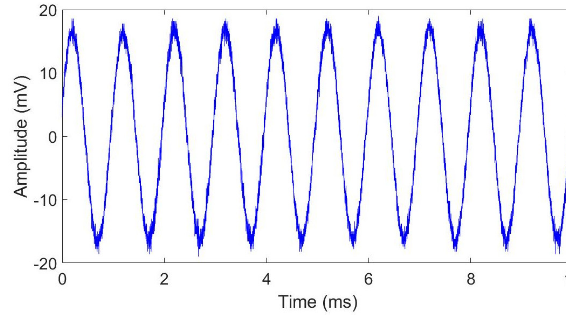

Fig. 5. Measured baseband signal for conversion loss characterization.

convenient to implement these minimalistic architectures in very high frequencies (i.e., deep millimeter-wave region) since a low path loss is necessary to overcome the lack of an LNA and the high noise figure of the system (e.g., low/intermediate frequencies and short-range applications).

B. Diode Based Mixer

The mixer was designed using the Infineon BAT15-02L Schottky diode. A 90° radial stub with a shunt DC line was designed and simulated in order to provide an AC and DC ground to the cathode of the diode. Additionally, as shown in Fig. 1, a bias voltage V_{bias} and a bias resistor R were added after the RF choke in order to tweak the diode S-parameters improving the matching of the system.

C. Baseband Circuit

For the baseband circuit, a two-stage inverting amplifier was designed. The gain of each stage was set to 10 and 20 respectively. A RC high-pass filter was used to decouple the DC in order to simplify the amplifier design. Additionally, the baseband signal was taken from the RF isolated port of the system to avoid high frequency signals from going to the baseband amplifier.

III. Experiment and Result Analysis

The fabricated radar system is shown in Fig. 3. It has dimensions of 20.6 mm × 26.5 mm (L×W) or 5.47 cm^2 without the antenna but including the two-stage baseband amplifier. An SMA connector was placed in one of the 2-ports of the system in order to use an external 2 by 2 patch antenna array. The RF choke value was chosen to be 480 nH, and the LO output power was measured as 11 dBm.

A separate 2-port transceiver chain without the LO was fabricated to characterize the proposed structure. The S-parameters were measured for different values of V_{bias}, obtaining the best results for $V_{bias} = 0\ V$. The measured S_{11} and S_{22} are shown in Fig. 4. Moreover, $S_{21} = S_{12}$ were recorded as -2 dB, achieving a high Tx power. The conversion loss of the system was measured by feeding a

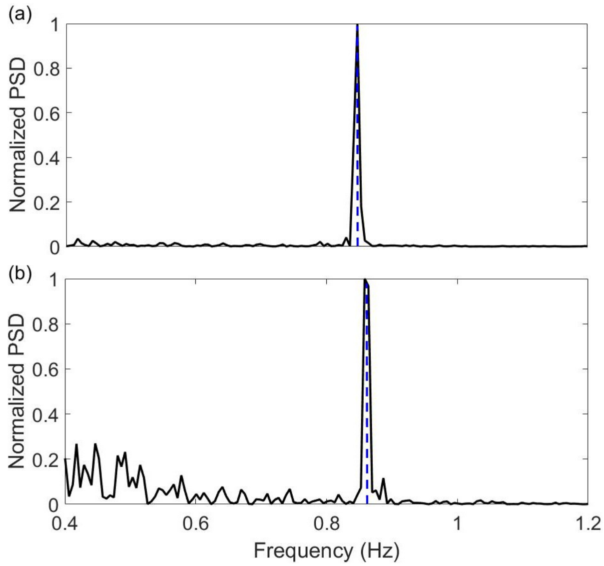

Fig. 6. Power spectral density of: (a) 100 µm sinusoidal movement at 0.85Hz, and (b) 50 µm sinusoidal movement at 0.9 Hz.

11 dBm 5.8-GHz signal into port 1 and a -21 dBm RF signal with 1-KHz offset into port 2. The down-converted 1-KHz baseband signal is shown in Fig. 5. It was measured with an RMS value of 13.15 mV, corresponding to 22.4 dBmV. In order to calculate the conversion loss of the system, the supplied -21 dBm were converted to 26 dBmV using a 50 Ω load reference. Therefore, the conversion loss of the 2-port monostatic transceiver is given by $C_L = 26\ dBmV - 22.4\ dBmV = 3.6\ dB$.

To benchmark the performance of the proposed 2-port monostatic transceiver front-end, the system was placed 1-m away from a linear actuator (Zaber T-NAOSA50) to measure mechanical movements of an 11 cm edge corner reflector. The actuator was programmed to produce sinusoidal movements of 0.85 and 0.9 Hz with amplitudes of 100 and 50 µm respectively. A National Instruments USB-6009 was used to digitize the signal with a sampling frequency of 6-KHz and the Welch's power spectral density estimation was used to recover the motion frequency. The experimental results for 100 µm and 50 µm movements are depicted in Fig. 6(a) and (b), respectively. As can be seen, the frequency of the programmed movements was successfully recovered, showing the high sensitivity of the proposed architecture. Table. 1 shows a comparison with previously reported motion sensing radars using more complex architectures. As the sensitivity of a particular radar is highly dependent on its operation frequency, the ratio of the smallest detected amplitude (A) and the system' wavelength (λ) was calculated as a metric to allow a fair comparison between radars working at different carrier frequencies. A smaller ratio corresponds to a better performance.

TABLE I
COMPARISON OF INTERFEROMETRIC RADARS FOR SMALL MOTION DETECTION

	This work	[9]	[10]	[11]
Displacement	50 µm	10 µm	20 µm	95 nm
Freq (GHz)	5.8	24	60	125
A/λ (µm/m)	967	800	4000	39.5

IV. CONCLUSION

A 2-port monostatic transceiver front-end was proposed, implemented and tested. Its reduced size, low-cost, and good performance make this architecture potentially suitable for large scale deployment and array implementation, which is very important for the ongoing IoT missions. Experiments with an implemented 5.8-GHz 2-port monostatic radar verified the high sensitivity of the proposed architecture, showing great potential for smart motion sensing applications.

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