

A Ka-Band Low Power Doppler Radar System for Remote Detection of Cardiopulmonary Motion

Yanming Xiao¹, Jenshan Lin¹, Olga Boric-Lubecke², Victor M. Lubecke²

¹University of Florida, Gainesville, FL, 32611, USA

²University of Hawaii, Honolulu, HI, 96822, USA

Abstract—A low power Ka-band Doppler radar that can detect human heartbeat and respiration signals is demonstrated. This radar system achieves better than 80% detection accuracy at the distance of 2-m with 16- μ W transmitted power. Indirect-conversion receiver architecture is chosen to reduce the DC offset and 1/f noise that can degrade signal-to-noise ratio and detection accuracy. In addition, the radar has also demonstrated the capability of detecting acoustic signals.

Keywords—Acoustic signal detection, cardiopulmonary motion, Doppler radar, heartbeat, indirect-conversion receiver, Ka-band, remote monitoring, respiration, sensors.

I. INTRODUCTION

Microwave Doppler radar has been used for wireless sensor applications for many years. Since the 1970s, microwave Doppler radar has garnered attention for new applications on human healthcare because it offers a non-contact alternative for healthcare monitoring and detection, such as physiologic movement and volume change sensing [1], life detection for finding human subjects trapped in earthquake rubble [2], and cardiopulmonary monitoring for sleep apnea syndrome detection [3].

This paper demonstrates a Ka-band Doppler radar system, which can detect human heartbeat, respiration signals, and acoustic signals. This is the first time that Ka-band Doppler radar has been demonstrated for cardiopulmonary motion detection, although a 35.6-GHz sensor has been reported for displacement sensing and low-velocity measurement [4]. Ka-band Doppler radar offers several advantages over lower frequency systems [1]-[3]. First, lower frequency bands are crowded and occupied by many other applications. For example, the 2.4-GHz ISM band is used for wireless LAN, cordless phones, Bluetooth, etc. In contrast, the Ka-band frequency spectrum is still sparsely used and has less interference. Second, the shorter wavelength is more sensitive to small displacement. The modulated phase in the baseband output is inversely proportional to the wavelength [3]. For the same displacement, the shorter wavelength will generate a larger phase modulation. Ka-band spans from 26-GHz to 40-GHz, corresponding to wavelengths from 11.5-mm to 7.5-mm. Therefore, the phase generated by a 30-GHz ($\lambda = 10$ -mm) wave is 12.5 times (about 22-dB) larger than that at 2.4-GHz ($\lambda = 125$ -mm). Finally, due to short wavelength at Ka-band, the antenna can be made very

small and can possibly be integrated on-chip in the future [5].

The Ka-band Doppler radar described in this paper shows excellent results on detecting human heartbeat and respiration signals. With a very low transmitted power of 16- μ W, the detection accuracy is 100% at a distance of 0.5-m. The accuracy is still better than 80% even when the distance is as far as 2.0-m. To further test the system robustness, an experiment was carried out with a 2-cm-thick wood board standing between the subject and the radar. A detection accuracy of more than 80% was still achieved at 1-m distance.

To explore more applications for Ka-band Doppler radar, the system was also tested for detecting acoustic signals. The radar successfully detected the 100-Hz vibrations of an audio speaker. Potentially, this Ka-band radar monitoring system can be used to retrieve acoustic information remotely by detecting vibrations of musical instruments or human vocal folds as illustrated in [11].

In this paper, the Ka-band Doppler radar system and circuits are shown in Section II, and measurement results are presented in Section III.

II. KA-BAND DOPPLER RADAR SYSTEM AND CIRCUITS

The block diagram of the Ka-band Doppler radar remote monitoring system is illustrated in Fig. 1. The receiver chain includes a receiving antenna (Rx_Antenna), a low noise amplifier (LNA), two down-converters (Rx_Mixer1 and Rx_Mixer2), and an IF amplifier (IF_AMP). The transmitter chain contains a transmitting antenna (Tx_Antenna) and two up-converters (Tx_Mixer1 and Tx_Mixer2). Baseband circuits are composed of a preamplifier (PreAMP), a band pass filter (BPF), and a low frequency amplifier (LF_AMP). Two 3-dB power splitters are used to divide the power of $S_1(t)$ and $S_2(t)$, with half of the power fed to the transmitter chain and the other half to the receiver chain. The input of Tx_Mixer1 is terminated with a 50- Ω resistor so that this general-purpose Ka-band transceiver can function as a Doppler radar sensor.

As shown in Fig. 1, the circuits inside the dashed box form a Ka-band radio, which uses commercial parts as individual building blocks. The Ka-band radio is an indirect-conversion transceiver that employs two-step conversion to mitigate the severe DC offset problem that occurs normally

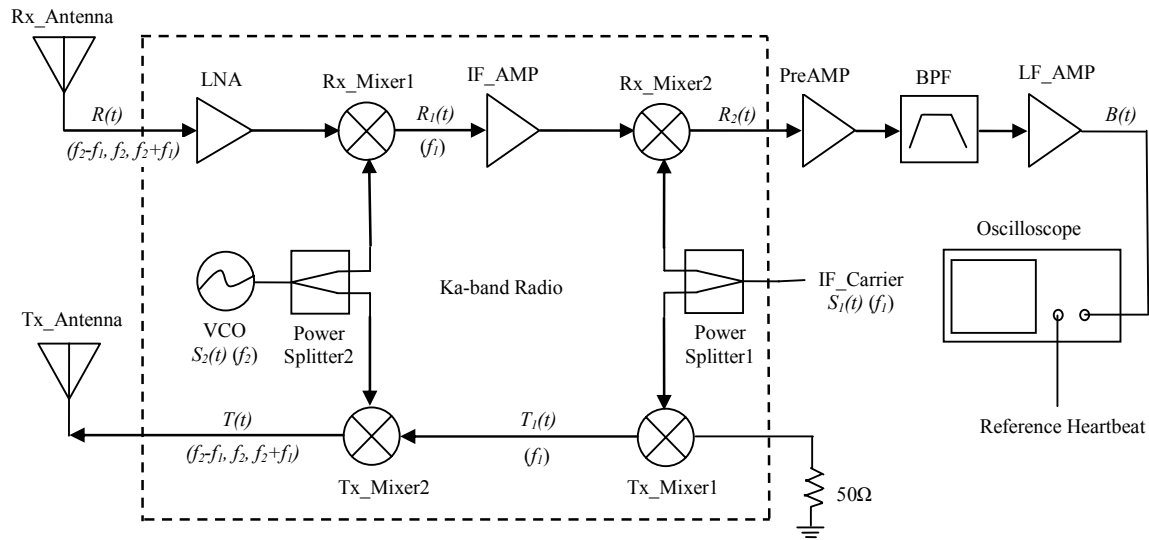


Fig. 1. Block diagram of the Ka-band Doppler radar remote monitoring system.

in the direct-conversion receivers. This is because the mixer and VCO at the last stage of the indirect receiver operate at low frequency, which reduces the DC offset and the associated $1/f$ noise at baseband [3] [6]. The frequency of the RF and IF can be tuned to avoid the “null” points in measurement.

The transmitting and receiving antennas are both 4×4 printed patch antenna arrays fabricated on Rogers RO3003 PTFE/Ceramic laminates with dielectric constant $\epsilon_r = 3.0$ and a substrate thickness of 0.5-mm. They have a maximum antenna gain of 12.9-dB at 28-GHz, and an estimated beamwidth of $10^\circ \times 10^\circ$. Compared to a single patch antenna, the antenna array has higher directivity gain, thereby increasing the detection distance and reducing interference from other directions. The baseband circuits are designed using LM324 low power op-amp. The bandpass filter BPF can pass signal frequency from 0.1-Hz to 10-Hz, and the preamplifier PreAMP, same as the low frequency amplifier LF_AMP, has a variable gain from 20-dB to 40-dB. When the measurement was performed, an Agilent 54622D oscilloscope displayed and recorded the baseband signal, and a MATLAB program was used to further processes the recorded data.

When the same LO source is used for the transmitter and the receiver, the range correlation effect greatly decreases the noise spectrum at baseband [7]. For this reason, the VCO can be used as a source in the Ka-band Doppler radar despite VCO high phase noise [3].

III. MEASUREMENT RESULTS

The Ka-band Doppler radar remote monitoring system was tested in the lab environment. The subject, facing the antenna, was seating at a distance away and breathing normally. A wired finger-pressure pulse sensor (UFI_1010

pulse transducer) was attached to the index finger during the measurement to provide the reference heartbeat signal.

When performing signal processing using MATLAB, the heartbeat and breathing signals were first separated by a 4th order Butterworth low-pass filter with cut-off frequency at 0.7-Hz and a 4th order Butterworth band-pass filter with pass band from 0.9-Hz to 3-Hz. Then these two filtered signals were windowed and then autocorrelated to find the periodic breathing and heartbeat signals simultaneously. Finally, the detected heartbeat signal was evaluated by “heart-rate accuracy”. Heart-rate accuracy was calculated as the percentage of time the calculated rate was within 2% of the reference rate. Because there was no reference available for a breathing signal, its detection accuracy was not calculated [8] [9].

A. Heartbeat and breathing signals measured at 0.5-m

The heartbeat and breathing signals were measured with a VCO frequency $f_2 = 27.1$ GHz, IF frequency $f_1 = 560$ MHz, and the subject seated approximately 0.5-m from the antenna. This “best” frequency was determined experimentally by tuning the VCO frequency of the Ka-band radio, and was the result of the antenna bandwidth in combination with transceiver gain. The output power from the transmitter at this frequency was only 16- μ W. The baseband signal detected by the Doppler radar monitoring system (solid line) and the reference heartbeat signal (dashed line) are shown in Fig. 2(a). Their frequency spectrums obtained by using the fast Fourier transform (FFT) are shown in Fig. 2(b). The horizontal axis represents breathing and heartbeat rates per minute instead of frequency for reading easily. From the plot, the respiration rate is about 21 breaths per minute. The heartbeat rate is about 75 beats per minute, which matches the reference heartbeat rate. To assess the detection accuracy, the detected

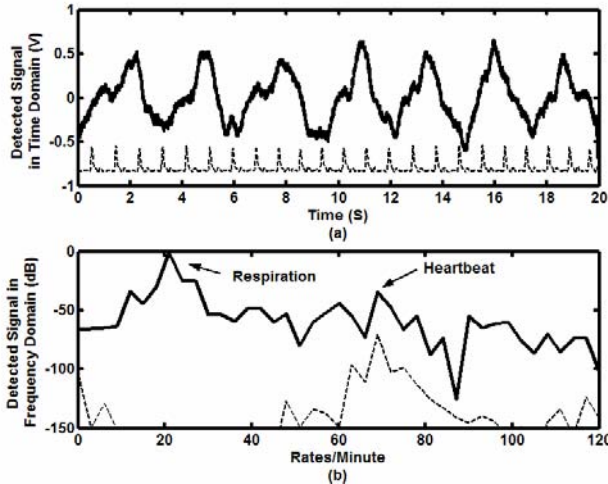


Fig. 2. Detected (solid line) and reference (dashed line, not in the same scale) signals in (a) time domain and (b) frequency domain. The respiration signal peak shows a rate of 21 breaths per minute, and the heartbeat signal peak shows a rate of 75 beats per minute which matches with the reference heartbeat signal.

signal was further processed by utilizing an autocorrelation function to find the periodic heartbeat and breathing signals in it. The results are shown in Fig. 3. The heartbeat signal after autocorrelation matches the reference heartbeat with an accuracy of 100% for the 0.5-m distance.

B. Heartbeat and breathing signals measured over variable distance

With the same setup as in the 0.5-m measurement, heart-rate accuracy at different distances was measured. The results of heart-rate accuracy versus distance are shown in Table I.

As the distance is increased, the amplitude of the detected signal becomes smaller and harder to detect due to the increased signal loss when propagating over a longer distance, thus reducing heart-rate accuracy. The longest distance to achieve better than 80% heart-rate accuracy is 2.0-m.

C. Heartbeat and respiration measurement with a wood board between the subject and the radar

The measurement setup was the same as the above experiments, except that a large 4'x4' 2-cm-thick wood board was inserted between the subject and the radar. The purpose of this experiment is to find the penetration capability of the high frequency electromagnetic wave and the robustness of this system. The measurement results are shown in Fig. 4, which illustrates that a heart-rate accuracy of 81.8% was achieved at a 1-m distance. Microwave penetration depth is proportional to its wavelength and square root of its dielectric constant, but inversely proportional to its loss factor. The penetration depth in wood for a 2.45-GHz wave is from 3-cm to 350-cm depending on the dielectric constant and loss factor [10].

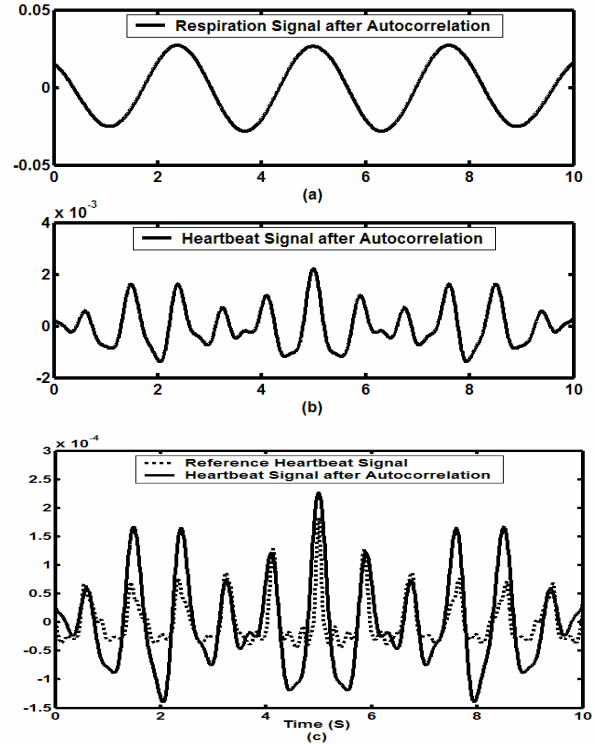


Fig. 3. Respiration and heartbeat signals after autocorrelation are shown in (a) and (b), respectively. (c) The comparison of heartbeat signal with the reference shows a 100% match.

TABLE I
HEART-RATE ACCURACY MEASURED BY KA-BAND DOPPLER RADAR SYSTEM AT DIFFERENT DISTANCES FROM 0.5 METER TO 2.5 METER.

Distance Between the Subject and the Radar (m)	Heart-Rate Accuracy (%)
0.5	100
1	96
1.5	89.3
2	81.5
2.5	64.6

Although the loss factor of the wood board used in this measurement is unknown, the measurement results demonstrate that this Ka-band Doppler radar is relatively robust for wood ($\epsilon_r = 2.0\text{--}2.6$). More investigations on different materials with different dielectric constants are being carried out.

D. Single-tone sound measurement at 0.3-m distance

To explore more applications for the Ka-band Doppler radar system, an experiment of detecting acoustic signal was designed. In this measurement, the system was the same as those used to detect the heartbeat and breathing signals except for the band pass filter (BPF) in the baseband circuits. The BPF was substituted with a low pass filter (LPF) that had cut-off frequency at 1-KHz. When a single-tone 100-Hz

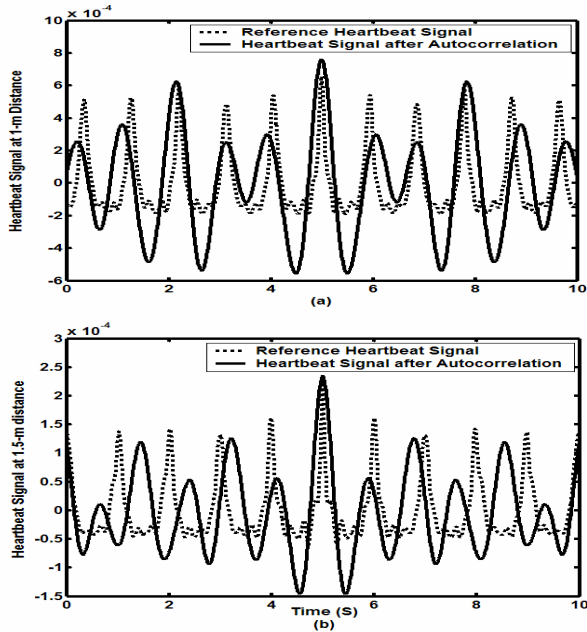


Fig. 4. Heartbeat-rate accuracy measured through 2-cm-thick wood board at (a) 1-m distance (81.8% accuracy) (b) 1.5-m distance (45.4% accuracy).

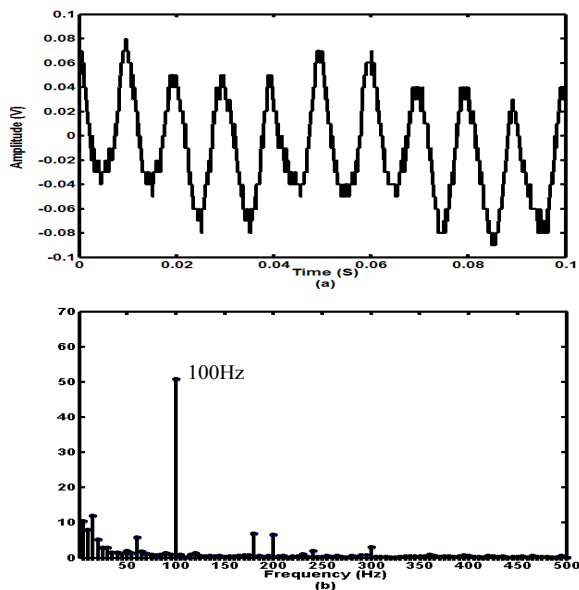


Fig. 5. Result of Doppler radar sensor used for sound detection, (a) time-domain, (b) frequency-domain.

sound signal was sent to a speaker, the speaker was humming, and its surface was vibrating at the same frequency accordingly. Similar to the heartbeat and respiration detection, the Doppler radar can detect the small displacement due to the speaker surface vibration as well. The recorded time-domain signal and its frequency spectrum are shown in Fig. 5. The 100-Hz tone was detected clearly, while the much weaker second and third harmonics were also detected. More experiments on acoustic signal

detection will be carried out in the future work. One potential application for this is remote sensing of human speech pattern by detecting the surface vibration of throat [11].

IV. CONCLUSION

For the first time, human heartbeat, breathing signals, and acoustic signals have been successfully detected by a low-power Ka-band Doppler radar. The short wavelength at Ka-band increases the sensitivity of phase shift due to small displacement and therefore improves the signal-to-noise ratio and detection accuracy. An antenna array transmitting radio waves in a narrow beam also contributes to the improvement.

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