

A Doppler radar vital sign detection system using concurrent dual-band hybrid down conversion architecture

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Abstract In this paper, a concurrent dual-band hybrid down conversion architecture based on continuous-wave (CW) Doppler radar is demonstrated. The proposed system operates at 2.05-/1.64-GHz simultaneously. The dual-band can solve the null detection point problem generated at quarter-wavelength distance between the target and antenna. The detection results from different channels can be mutually verified to improve the system accuracy. The vital sign can be detected by the radar through the wooden board at higher transmit power. For satisfying the requirements of dual-band RF transmitters, and a two-stage dual-band power amplifier is designed. Experimental results have demonstrated the feasibility of the system.

Keywords: continuous-wave (CW), Doppler radar, dual-band, null point, vital sign

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Vital signs detection has always been a hot spot in real-time monitoring, such as medical supervision, assisted driving, and so on [1, 2, 3, 4]. The most important vital signs include respiration and heartbeat signals for organisms [5, 6]. The technology of vital signs detection includes contact vital signs detection and non-contact vital signs detection. Currently contact monitoring devices are still widely used in the hospital. The electrodes of these devices are attached directly to the skin of the patient for vital signs detection [7]. However, the process of detection will put pressure on the patient, which will affect the patient's psychological activities, and ultimately lead to inaccurate result. In addition, the technology of contact vital signs detection is limited in some special applications, such as burns, infections, search and rescue. Therefore, it is very meaningful to study the technology of non-contact vital signs detection.

The technology of non-contact vital sign detection, especially based on Doppler radar, has unique advantages in obtaining vital signs. No electrodes or equipment are required to contact the organism, and even small movements of the organism can be detected. Therefore, a lot of

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DOI: 10.1587/elex.16.20190665 Received October 29, 2019 Accepted November 22, 2019 Publicized December 13, 2019 Copyedited January 10, 2020 attention has been paid to the research of Doppler radar to detect vital signs [8, 9, 10, 11, 12, 13]. Although the continuous-wave (CW) Doppler radar [14, 15, 16, 17, 18, 19] and the ultra-wideband (UWB) Doppler radar [20, 21, 22, 23, 24, 25] are often used to detect vital signs. When the cardiopulmonary signal is detected, it is usually difficult to distinguish the echo of target from the clutter, so the advantage of UWB radar to suppress the clutter is limited. Moreover, the CW Doppler radar features simple structure and strong anti-interference ability with narrow bandwidth.



Fig. 1. The structure of concurrent dual-band hybrid down conversion vital sign detection system.

At present, the technology of the vital sign detection based on Doppler radar also faces many problems, such as null detection point [26, 27, 28, 29, 30]. In order to solve the problem of null detection point and improve the accuracy, many experimental methods have been proposed. For example, a method of arctangent demodulation is proposed, but a complex calibration of the DC offset is required [27]. A complex signal demodulation technique is proposed, but it is susceptible to interference by higher harmonics [28].

The conventional single-channel heterodyne radar has the null detection point problem [1] and image problem [31], and the typical homodyne receiver architecture has also the null detection point problem and DC offset [1]. In order to improve the accuracy of the detection results, a dual-band dual radar is proposed [32], but the clutter signals that from antenna coupling and the reflected signals from the stationary objects can degrade the performance of the system [33].

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To overcome the above problem, as shown in Fig. 1, this paper proposes a concurrent dual-band hybrid down conversion vital sign detection system based on CW Doppler radar. Two sensors with two different carrier frequencies are used for detection to avoid the problem of null detection point related to the detection distance. Compared to the conventional Doppler radar, an extra heterodyne quadrature receiver architecture is chosen to reduce the DC offset and 1/f noise that can degrade signalto-noise ratio and detection accuracy. As another point of view, the extra homodyne receiver architecture does not

have image interference, so the image rejection filter is avoided. Moreover, the results of the two sensors can be mutually verified to improve the accuracy of the results, and when the system operates at high transmit power, vital signs can be also detected through the wooden board.

2. System design

2.1 Method

The system structure of the concurrent dual-band hybrid down conversion architecture is presented in Fig. 1. According to [1], the null detection point occurs when the echo and the LO are either in-phase or 180° , and the movement x(t) is much smaller than the wavelength λ . At this time, θ is equal to $k\pi$ (k is a natural number), as shown in formula (1) and (2). d_0 is a fixed distance from target to the antenna.

$$\theta = \frac{4\pi d_0}{\lambda} + \theta_0 \tag{1}$$

$$d_0 \simeq \frac{k\lambda}{4}$$
 (k is a *natural number*) (2)

The null detection point is only related to the $\lambda/4$ distance between the target and the antenna. Therefore, the dualband detection can avoid the occurrence of the null detection point. In order to verify the feasibility of the scheme, the structure of Fig. 1 is proposed.

2.2 System structure and analysis

The system structure of the concurrent dual-band hybrid down conversion architecture is presented in Fig. 1. This receiver architecture has a mixed double- and direct-conversion capability and does not require high image rejection SSB mixer. The first baseband signal and the IF signal are generated by the Mixer1. In the receiving chain, the RF signals f_1 and f_2 are first down-converted into DC and (f_1-f_2) . Then IF signal (f_1-f_2) is further down-converted into quadrature baseband signals. To improve the linearity of the secondary mixing, a band-pass filter (BPF2) is inserted after the first mixer and the high-frequency interferences, such as $(2f_1)$ and $(2f_1-f_2)$, are filtered out. Two different carrier frequencies guarantee a continuous vital sign monitoring with a simple, low-cost and compact design.

Since the null detection point occurs with a target distance every quarter-wavelength distance from the antenna. The frequency of f_1 and f_2 is carefully chosen to avoid the "null points" in measurement. Considering the third-order intermodulation of the two carrier frequencies, the following relationship is obtained:

$$f_2 < f_1 < \frac{3}{2}f_2 \tag{3}$$

According to the formula (3) and the bandwidth of the dual-band power amplifier (DB_PA), 2.05-/1.64-GHz are selected as the carrier frequencies.

2.3 Circuit design

The radar consists of a concurrent dual-band RF module and a data acquisition module. The transmitter chain contains two phase locked loops (PLLs), a power splitter, a power combiner, a frequency divider, a wide-band transmitting patch antenna (Tx_Antenna) and DB_PA. The transmitter generates two carrier frequencies by two PLLs respectively. One of the PLLs (PLL2) with two output channels, which can output two identical carrier frequencies simultaneously. In order to ensure that the two carrier frequencies generated in the same phase, and two PLLs share a crystal. The power splitter is used to split a carrier frequency with half of the power fed to the transmitter chain and the other half to the receiver chain. The power combiner is used to combine the two carrier frequencies so that the carrier frequencies can be amplified by the DB_PA and transmitted by the patch antenna concurrently.



Fig. 2. The circuit of harmonic control and output matching of DB_PA

In order to meet the requirements of dual-band and high output power RF transmitters, a two-stage DB harmonictuned PA is designed. The DB_PA operates at 1.7 and 2.14 GHz concurrently using Class-F as the power stage and the inverse class-F as the driver stage. The measured output power of the two-stage DB_PA reaches two peaks of 40.2 and 40 dBm at 1.62 and 2.08 GHz, and the maximum PAEs are 71.5% and 73%, respectively [34]. The schematic of the harmonic control circuit and output matching circuit of the DB_PA, as shown in Fig. 2. The patch antenna has an impedance bandwidth of 52.7% (from 1.62 to 2.78 GHz) and the measured average gain is 6 dBi [35], as shown in Fig. 3.

The receiver chain includes a receiving antenna (Rx_Antenna), a low noise amplifier (LNA), two bandpass filters (BPF1 and BPF2), two down-converters (Mixer1 and Mixer2), and an IF amplifier (IF_AMP). Baseband circuits are composed of three low pass filters (LPF). When selecting the LNA, pay special attention to the its bandwidth and linearity, and minimize the interference. Furthermore, it needs to notice the isolation between the RF module and

other modules and the isolation between the transceiver antenna. Therefore, the RF module is isolated by the shielding cavity to prevent interference with other modules, and the tin foil plate is also added to the transceiver antenna.

The Fig. 4 shows the radar test platform, which includes radar board, DB_PA, Patch antenna and NI data acquisition card. Table I shows the main components selected for the radar board.

Table I. List of selected components.

Block	Manufacturer	Specifications
PLL1	ADI	0.37~6.39 GHz; P _{out} : -9~3 dBm; Phase noise: -132 dBc/Hz@1 MHz;
PLL2	ADI	53.125 MH~6.8 GHz; P _{out} : -4~5 dBm; Phase noise: -137 dBc/Hz@1 MHz
Power Splitter	Anaren	0.95–2.15 GHz; Insertionloss: 0.5 dB; Isolation: 10 dB
LNA	ADI	1.2–2.2 GHz; Gain: 13.5~23 dB; NF: 0.65~1.15 dB; P _{out} 1 dB: 16.5~20 dBm
Mixer1	ADI	LO/RF: 1.6~3 GHz; IF: dc~1 GHz; Conversion loss: 8~10 dB; P _{in} 1 dB: 16 dBm
IF_AMP	NXP	dc~750 MHz; Gain: 31.1 dB; P _{out} 1 dB: 4 dBm
Mixer2	Linear	RF: 40 MHz~900 MHz; LO: 80 MHz~1.8 GHz; Conversion Gain: 0~3.3 dB; P _{in} 1 dB: 10 dBm
Frequency divider	ADI	$0.2 \sim 2 \text{ GHz}; P_{out}: -3 \sim 12 \text{ dBm};$ $P_{in}: -2 \sim 10 \text{ dBm};$ Frequency Divider, N = 1, 2, 3, 4
BPF1	AVX	1.27–2.05 GHz; Insertionloss: 1.88 dB; Out-of-band rejection: 20 dB@1.07/2.04 GHz
BPF2	EPCOS	410~420 MHz; Insertionloss: 2.4 dB; Out-of-band rejection: 37 dB@500 MHz
LPF	TDK	dc~10 MHz; Insertionloss: 0~0.5 dB; Out-of-band rejection: 20 dB@100 MHz



Fig. 3. Block figure of Patch Antenna, DB_PA



Fig. 4. Block figure of the radar test platform

3. Measurement results

In order to verify the performance of the system, three experiments were performed. The subjects of the three experiments were the same man aged 26. The electronic bracelet was chosen to provide the reference heartbeat signal in the three experiments. In the first experiment, the subject facing the antenna sat quietly at 20 $\lambda/4$ distances (74 cm) from the antenna. The output power from the transmitter at the 2.05-/1.64-GHz were 10.74 dBm and 14.65 dBm, respectively. The baseband signal detected by the Doppler radar monitoring system were shown in Fig. 5.

After performed a fast Fourier transformation, the normalized spectra of channel I1 was shown in Fig. 5(a). After the complex signal demodulation, the normalized spectra of channel I2 &Q2 was shown in Fig. 5(b).

The demodulation ability was very poor for channel 11, and the useful information was not obtained. Another channel I2 &Q2 could obtain the useful information. The respiration was 0.3906 Hz, and the heartbeat de-modulation result was 1.392 Hz. Compared to the reference heartbeat, the error was 3.11%. Therefore, the null detection point problem could be solved well by the proposed system.



Fig. 5. The result of respiration and heartbeat at 74 cm (sit quietly): (a) Result of the channel I1, (b) Result of the channel I2 &Q2.

In the second experiment, the subject facing the antenna sat at 1 m from the antenna after doing exercise. The output power and the demodulation algorithm were the same as the first experiment. The baseband signal detected by the Doppler radar monitoring system was shown in Fig. 6.

At this time, the detection distance was not the $\lambda/4$ distance of the two carrier frequencies. Therefore, the valid information could be obtained from channel I1 and channel I2&Q2. The respiration (0.6348 Hz) and heartbeat (1.636 Hz) information were also obtained. Compared to the reference heartbeat, the error was 4.43%. The signal loss increased as the signal propagated over a longer distance, and the detected signal became more difficult to detect, resulting in an increase in the error rate. The results of the channel I1 and the channel I2&Q2 were consistent, so that they could mutually check each other.

In the third experiment, the subject facing the antenna sat quietly at 1 m from the antenna, but a 106 cm * 63.5 cm black wooden board with a thickness of 1.6 cm was inserted between the target and the radar. The output power at the 2.05-/1.64-GHz were 20.2 dBm and 23.7 dBm, respectively. The demodulation algorithm was the same as the first experiment. The detection results were shown in Fig. 7.



Fig. 6. The result of respiration and heartbeat at 1 m (after doing exercise): (a) Result of the channel 11, (b) Result of the channel I2&Q2.

The configuration program of PLLs was adjusted to maximize the output power. The board was inserted between the target and the antenna, and the target was completely obscured. The purpose of this experiment was to find human subjects trapped in earthquake rubble. The respiration (0.415 Hz) and heartbeat (1.416 Hz) information was also obtained. Compared to the reference heartbeat, the error was 6.64%. The depth of microwave penetration is related to its wavelength, dielectric constant and loss factor. Although the loss factor of the board used was unknown, the system could still accurately detect vital signs.



Fig. 7. The result of respiration and heartbeat at 1 m (in the presence of obstacles): (a) Result of the channel I1, (b) Result of the channel I2 &Q2.

4. Conclusion

The Doppler radar with a concurrent dual-band hybrid down conversion for vital sign detection is demonstrated. The experimental study on the proposed radar demonstrated that the radar sensor is capable of avoiding null detection problem by transmitting two different carrier frequencies and improving the accuracy by autocorrelating the detection results from different channels. In addition, the system can also penetrate the wooden board to detect vital signs at higher transmit power. Three experiments have shown the ability of radar systems to detect vital signs in indoor or obstacle environments.

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