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DC Coupled Doppler Radar Physiological Monitor

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Abstract — **One of the challenges in Doppler radar systems for physiological monitoring is a large DC offset in baseband outputs. Typically, AC coupling is used to eliminate this DC offset. Since the physiological signals of interest include frequency content near DC, it is not desirable to simply use AC coupling on the radar outputs. While AC coupling effectively removes DC offset, it also introduces a large time delay and distortion. This paper presents the first DC coupled IQ demodulator printed circuit board (PCB) design and measurements. The DC coupling is achieved by using a mixer with high LO to RF port isolation, resulting in a very low radar DC offset on the order of mV. The DC coupled signals from the PCB radar system were successfully detected with significant LNA gain without saturation. Compared to the AC coupled results, the DC coupled results show great advantages of less signal distortion and more accurate rate estimation.**

I. Introduction

Direct-conversion quadrature (IQ) transceivers are commonly used in wireless communications to avoid image rejection filters and enable a higher level of integration with lower power dissipation [1-2]. Direct-conversion radio architecture is also commonly used for microwave Doppler-radar non-contact cardiopulmonary monitoring [3-4]. The performance limitations of quadrature systems include IQ imbalance, LO leakage, flicker noise, and DC offset at the receiver output [1-2]. In wireless communications, DC offset is typically removed using AC coupling; however, in radar systems, with high-speed response time or signal content near the DC, AC coupling results in unacceptable time delay and signal distortion. DC offset usually limits the amplifier gain at the baseband stage to levels that are too low to produce meaningful data. In [3], a DC cancellation method was proposed to overcome this issue; however, this technique is cumbersome to implement and requires continuous adjustment during measurement.

In this paper, a low DC offset quadrature demodulator is described that enables DC-coupled measurements. Experimental results indicate that this IQ demodulator can be used for Doppler radar motion detection, and that DC coupling provides outputs with significantly less distortion.

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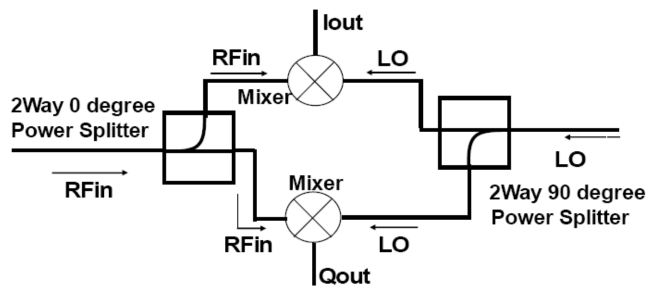
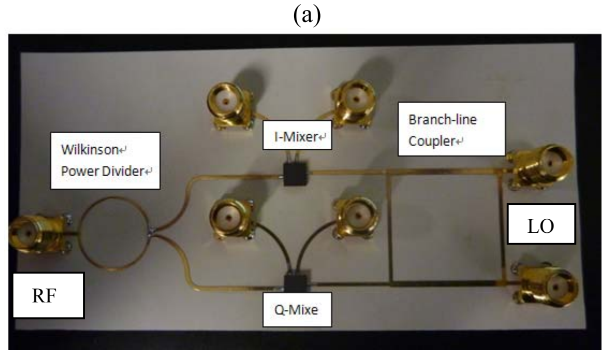
II. IQ Demodulator Design

The IQ demodulator was designed to work at 2.4 GHz as its center frequency. As seen in Fig. 1, the RF signal is injected into the board from the Wilkinson power divider and then split equally to feed the RF inputs of the I and Q mixers; the LO signal is injected through the branch-line coupler and splits equally in amplitude with a 90-degree shift to feed the LO inputs of the I and Q mixers. The overall dimension of the PCB is 100mm by 50mm. The PCB was fabricated on the Rogers R3003 substrate (thickness 0.25mm) with surface mounted mixers and SMA connectors.



(a)



(b)

Fig. 1. (a) IQ demodulator diagram; (b) Photo of IQ demodulator PCB

The key for the low DC offset design is the mixer with high LO-RF isolation. The mixer [5], which was used in the IQ demodulator, is a 2.4 GHz resistive ring mixer with on-chip baluns. They are fully integrated on chip by a 0.18um IBM7HP process and packaged as QFN01603 by the Kansas City Plant (KCP) using 7HP technology. The mixer die was initially tested on the Cascade probe station. This mixer exhibits broadband RF impedance matching with return loss better than -10 dB through the RF frequency range from 2 to 6 GHz. The conversion loss of 7.8 dB is achieved at the RF frequency 2.4 GHz. The LO-RF isolation of -52.7 dB and the LO-IF isolation of -30 dB are achieved at 2.4 GHz. Very high

LO-RF isolation of this mixer results in low DC offset, making the DC-coupled measurements possible.

III. Lo Leakage and Dc Offset

The imperfections in circuit components and clutter reflections from stationary objects will cause the DC offset in the radar system. The most serious problem is the generation of a DC offset in the baseband section following the mixer. The DC offset arises from many causes: the largest offset typically comes from a signal at the LO frequency that is not the desired signal. In communication receivers, there is no transmitted signal, so the offending offset is usually caused by the LO coupling to the RF input port. This may happen by the LO signal exiting through the antenna, reflecting off an object, and returning to the receiver through the RF input port, or by the LO coupling to the RF input through the chip substrate, the bond wires, or the package leads. When this signal is mixed to baseband, it may cause a DC offset. Additionally, a large undesired interfering signal at the RF input can leak into the LO port of the mixer, causing additional down-conversion to DC. This DC offset results in flicker noise, which limits system sensitivity. The LO leakage and DC offset were measured with respect to the IQ demodulator.

From the signal generator (Agilent E4433B), a 0 dBm input signal was provided to the LO port of the receiver, and the spectrum analyzer (Agilent E4448A) was connected at the RF input port to measure the LO leakage power. At 2.4 GHz, the LO leakage was determined as -45.3 dBm.

The DC offsets caused by hardware imperfection and clutter reflections were measured for IQ demodulator. The signal, which was generated by an Agilent E4433B signal generator, was first divided by a two-way 0° power splitter (Mini-Circuits ZX10Q-2-27) with one port terminated by a 50 ohm terminator, and the other port connected to the LO input port of the IQ demodulator. The RF input port of IQ demodulator was terminated by a 50 ohm terminator, as well. The IF outputs from I and Q mixers were low-passed with a cut-off frequency 30Hz of LNA (Stanford Research Systems SR560). The DC offset in each channel was obtained with an oscilloscope (Tektronix TD8 3014B). The DC offset due to the clutter reflections was measured in the same way. Instead of termination of the transmit and receiver port, the antennas (ASPPT2988 2.4-GHz ISM-band patch antenna) were connected. The DC offset cancellers were applied at the IF baseband outputs to cancel the DC offset caused by hardware. The DC offsets were measured at different power levels from 15 dBm to 10 dBm from signal generator.

Fig.2 shows the measurement results for the DC offset in the IQ demodulator at different power level. At 15 dBm, DC offset due to clutter reflection is larger than the DC offset due to hardware imperfection. After a 1 dBm power decrease, the DC offsets due to clutter and hardware are decreased significantly to only a couple of mVs. This low DC offset level enables DC-coupled measurements.

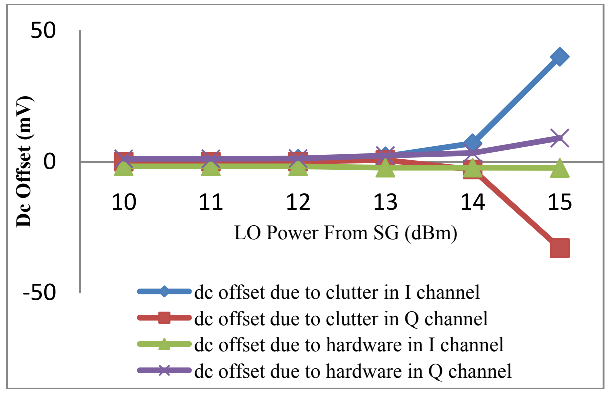


Fig. 2. Dc offset measurement result

IV. Experimental Results

The IQ demodulator was tested in a Doppler radar set-up as shown in Fig. 3. Measurements were made with the input power from the signal generation of 14 dBm at 2.4 GHz, and the small motion from the target was detected with a LNA gain of 500 with from LNA in good resolution. The input power from the signal generator was split to feed the RF out chain and LO port of the radar receiver. The transmitted signal was reflected back from the moving target to the receiving antenna, and then fed to the RF input of the radar receiver.

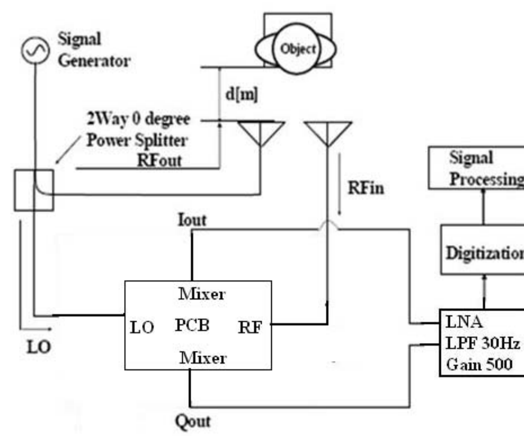


Fig. 3. Doppler measurement set-up

The artificial moving target, shown in Fig. 4, is placed in front of the antennas at about a one meter distance. The target is programmed to follow a square-wave motion with an amplitude of about 1.5cm at 0.1 Hz. The output signals were DC coupled with the maximum gain without LNA saturation, and then recorded in the DAQ for further signal processing. The DC-coupled system was tested with several different input power signals, and the output signals were recorded at the maximum gain for each. The AC-coupled data was taken for comparison.

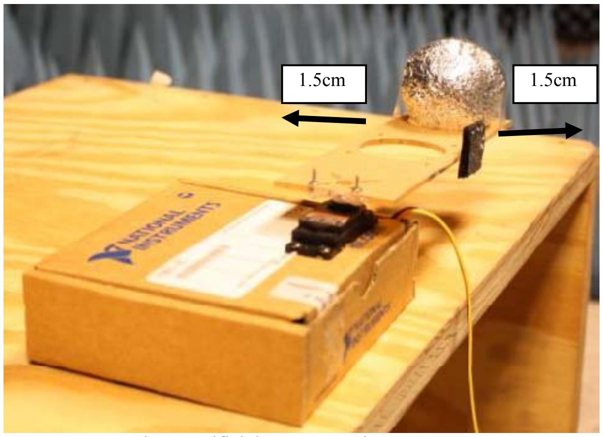


Fig.4. Artificial Target Moving at 0.1Hz

Fig. 5. shows the AC-coupled and DC-coupled baseband signals without any processing. The DC-coupled data shows the DC offset at each channel.

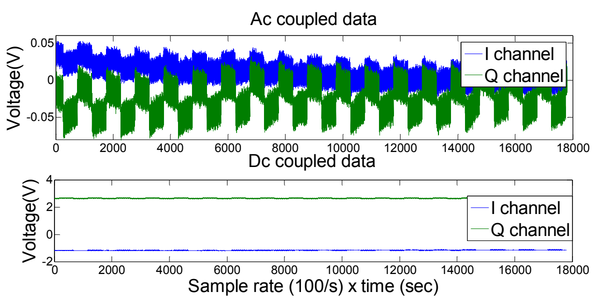


Fig. 5. Original baseband signals

Applying arctangent demodulation to the ratio of the quadrature outputs, phase information linearly proportional to target's motion can be extracted as [3]:

$$(t) = \arctan\left(\frac{B_Q(t)}{B_I(t)}\right) = \arctan\left(\frac{A_r \sin(\theta + p(t))}{A_r \cos(\theta + p(t))}\right)$$
$$= \theta + p(t) \quad (1)$$

$$p(t) = \frac{4\pi\Delta x(t)}{\lambda} \quad (2)$$

The output of non-linear demodulation is phase in radians, which can be easily converted into distance by multiplying by $\lambda/4\pi$. The linear demodulation [4] is the only way to process the AC-coupled data, since AC-coupling removes all the DC information. However, for DC-coupled data, either linear or non-linear modulation can be applied. Fig. 6 shows the comparison of DC and AC-coupled data after signal processing. The output of the linear demodulation is proportional to the output power, while the output of the non-linear demodulation yields the absolute displacement of the target. The advantage of the DC-coupled data, besides less signal distortion compared with AC-coupled data, is that the absolute displacement can be detected as well.

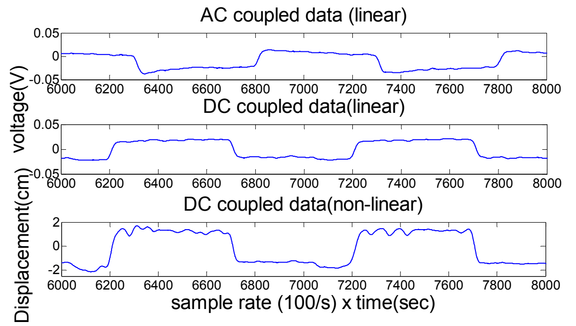


Fig. 6. Demodulated ac and dc signals

Fig.7 shows the estimated target rate of motion from AC and DC-coupled signals, and Table I. shows the data statistics for the measurement results. The AC-coupled data shows the lowest detection accuracy. For the DC-coupled data, the measurement result for the rate of motion is similar for linear and non-linear demodulaton, and the non-linear demodulation provides a slightly lower standard deviation.

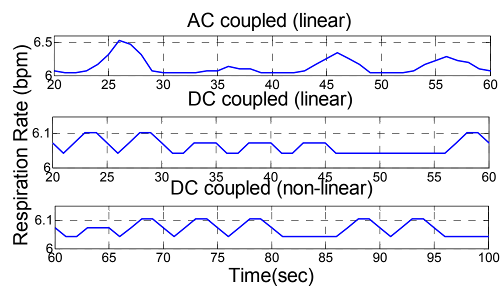


Fig. 7. Detected moving rate for ac and dc coupled signals

TABLE I

MEASUREMENT RESULTS STATISTICS

Moving Rate(bpm)	Ac coupling (linear)	Dc coupling (linear)	Dc coupling (non-linear)
Mean	6.142	6.069	6.064
Std	0.1156	0.0256	0.0228

A human test was also done using in this radar system. A subject sat at the front of the antennas at a distance of about one meter, repeatedly holding and releasing their breath. The piezo-electric chest band was placed on the upper chest of the subject to provide a reference signal, and AC and DC-coupled data was taken at the same time. The waveforms of demodulated signals are shown in Fig. 8 with the reference respiratory signal obtained using the piezo-electric belt. Due to the capacitive nature of the piezo-electric belt, this measurement is inherently AC-coupled and exhibits distortion. The DC-coupled data, after non-linear demodulation, provides the output with the least amount of distortion.

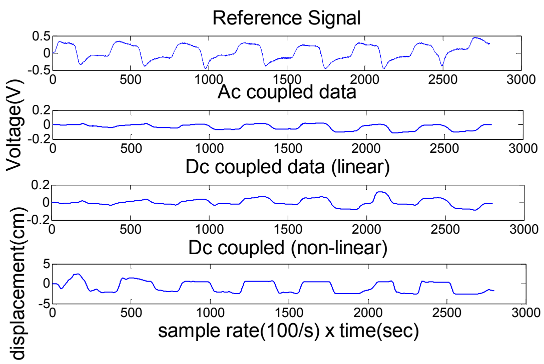


Fig. 8. Human test measurement results

V. Conclusion

One of the limitations of quadrature receivers is the DC offset resulting mainly from finite LO-RF isolation. In this paper, a low DC offset IQ demodulator is introduced. A high LO-RF isolation mixer was used to minimize DC offset and enable DC-coupled measurements. The LO leakage was measured for the IQ demodulator, which was -45.3 dBm at 2.4 GHz. The DC offsets of both channels, due to hardware imperfections and clutter reflections, were determined to be on the order of mW. The DC-coupled signals from the IQ demodulator system were successfully detected without LNA saturation, and AC-coupled data was acquired simultaneously for comparison. The DC-coupled results show the great advantages of less signal distortion and higher accuracy in rate estimation of periodic motion.

To the best of the authors knowledge, this is the first reported IQ demodulator whose DC offset is small enough to record DC-coupled signals with significant gain and without any DC cancellation. The measurement results indicate that this technique is effective for avoiding AC-coupling in Doppler radar measurements of periodic motion.

Acknowledgment

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