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A NOVEL 10 GHZ SUPER-HETERODYNE BIO-RADAR SYSTEM BASED ON A FREQUENCY MULTIPLIER AND PHASE-LOCKED LOOP

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Abstract—This paper presents a novel 10 GHz bio-radar system based on a frequency multiplier and phase-locked loop (PLL) for non-contact measurement of heartbeat and respiration rates. In this paper, a 2.5 GHz voltage controlled oscillator (VCO) with PLL is employed as a frequency synthesizer, and 10 GHz continuous wave (CW) signal is generated by using frequency multiplier from 2.5 GHz signal. This paper also presents the noise characteristics of the proposed system, and the analysis result shows that the same signal-to-noise-ratio (SNR) performance can be achieved with the proposed system based on the frequency multiplier compared with the conventional system with identical carrier frequency. The experimental results shows excellent vital-signal measurement up to 100 cm without any additional digital signal processing (DSP), thus proving the validity of the proposed system.

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1. INTRODUCTION

The bio-radar based on Doppler effect has inspired a great deal of interests in measuring vital signals, such as heartbeat and respiration, due to its simplicity as well as non-invasive non-contact measurement scheme. Droitcour showed that the phase noise of local oscillator (LO) signal source is greatly reduced with the range correlation effect based on Budge's study [1–3]. As a result, it has been considered that the phase noise from the VCO is not an important parameter in bio-radar system, even though the heartbeat and respiration signals are in very low frequency regime ranging from 1 Hz to 30 Hz and the phase noise at that offset frequency of a conventional VCO is very high. So, direct conversion transceiver architecture has been generally employed with a shared LO for up- and down-conversion mixers, and most of recently reported bio-radar systems are based on free running VCO [4–7]. However, the team of authors carefully analyzed the phase noise effect with conventional parameters of commercial components with respect to antenna as well as mixer leakage effects, and the analysis result shows that the phase noise of LO is still dominant factor of the SNR degradation in a bio-radar system due to the low isolation between Tx and Rx blocks [8]. Moreover, the bio-radar system with PLL has been proposed, and the experimental results showed the validity of the bio-radar system with improved LO source [9]. In this paper, performance of a 10 GHz Doppler-effect-based bio-radar system with a PLL is presented based on 10 GHz super-heterodyne architecture with PLL and frequency multiplier for the new frequency band a primary basis worldwide [10] from 10.45 to 10.5 GHz. Moreover, the noise mechanism in the proposed super-heterodyne architecture is analyzed, and the validity of the proposed bio-radar system is presented with the noise analysis and experimental results.

2. 10 GHZ SUPER-HETERODYNE BIO-RADAR

2.1. Bio-radar System Topology

Figure 1 shows the block diagram of the proposed 10 GHz super-heterodyne bio-radar system. As presented in [9], the performance of bio-radar system can be greatly improved with PLL employment. The frequency synthesizer in 2.5 GHz is designed with PLL, and 10 GHz source signal is generated by using a frequency multiplier (quadrupler). So, it is possible to generate very stable CW signal with extremely low phase noise characteristics. The receiver consists of the IQ-demodulator and down-conversion mixer, where the IQ-demodulator is driven by 2.5 GHz signal generated by the LO, while the down-

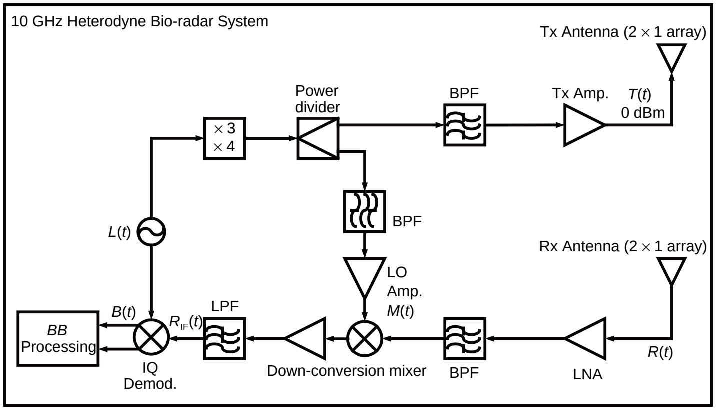

Figure 1. The block diagram of the proposed 10 GHz bio-radar system.

conversion mixer employs the 7.5 GHz signal generated by another frequency multiplier (tripler). This receiver topology is a super-heterodyne architecture with 2.5 GHz intermediate frequency (IF), which is the PLL operating frequency or the fundamental frequency of the frequency synthesizer. With the proposed topology, the IQ-demodulator requirement can be less strict, and IF band filtering with relatively sharp skirt characteristics is possible. These advantages are the common characteristics of a super-heterodyne architecture. By using the frequency multipliers, tripler as well as quadrupler, only one signal synthesizer with PLL is necessary.

In the proposed super-heterodyne bio-radar system, the output of the signal synthesizer ($L(t)$) as well as the multiplied signals ($T(t)$ and $M(t)$) in Figure 1 can be expressed as followings:

$$L(t) = \cos(2\pi f_c t + \phi(t)) \tag{1}$$

$$T(t) = \cos(8\pi f_c t + 4\phi(t)) \tag{2}$$

$$M(t) = \cos(6\pi f_c t + 3\phi(t)) \tag{3}$$

where, f_c and $\phi(t)$ are the fundamental frequency and phase noise of the frequency synthesizer, respectively.

The received signal, reflected and modulated by human body, can be expressed as a function of the time-varying distance between the bio-radar and target human body ($d(t)$) as following equations:

$$R(t) = A_1 \cos\left[8\pi f_c \left(t - \frac{2d\left(t - \frac{d(t)}{c}\right)}{c}\right) + 4\phi\left(t - \frac{2d\left(t - \frac{d(t)}{c}\right)}{c}\right)\right] \tag{4}$$

where, c is the speed of light.

The distance ($d(t)$) can be decomposed with the constant distance from the bio-radar system to the human body (d_0) and very small variation of chest ($x(t)$) due to heartbeat and respiration. With the small angle approximation, the down-converted baseband signal ($B(t)$) in Figure 1 can be calculated as followings:

$$\begin{aligned} B(t) \; = \; & A_2 \cos\left[\frac{16\pi d_0}{\lambda} + \frac{16\pi x(t)}{\lambda} - 4\phi\left(t - \frac{2d_0}{c} - \tau_m\right)\right. \\ & \left. +3\phi(t-\tau_m) + \phi(t) + \theta_1 + \theta_2\right] \end{aligned} \tag{5}$$

where, θ_1 and θ_2 are the phase delays from LO to down-conversion mixer and to IQ-demodulator, respectively, and τ_m is the time delay from RF to IF due to the down-conversion mixer.

The phase term of the above baseband signal, $B(t)$, consists of three parts, which are followings:

$$\frac{16\pi d_0}{\lambda} + \theta_1 + \theta_2 \tag{6}$$

$$\frac{16\pi x(t)}{\lambda} \tag{7}$$

and

$$-4\phi\left(t - \frac{2d_0}{c} - \tau_m\right) + 3\phi(t-\tau_m) + \phi(t) \tag{8}$$

The first term is constant, and it does not affect the bio-radar system operation. The second and third terms are the measured bio-signal and down-converted phase noise in baseband, respectively. The measured signal amplitude by the proposed bio-radar based on the frequency multiplier is increased by four times compared with the signal measured by the conventional bio-radar system due to four times higher carrier frequency. The phase noise is also increased due to frequency multiplier, but it is considered that the degree is not serious. For example, if the time delay due to the down-conversion mixer is negligibly small compared with the time delay of the signal propagation from Tx to Rx, the phase noise in (8) and baseband signal in (5) can be approximated as followings:

$$-4\phi\left(t - \frac{2d_0}{c}\right) + 4\phi(t) \tag{9}$$

$$B(t) \approx \cos\left(\theta + \frac{16\pi x(t)}{\lambda} - 4\phi\left(t - \frac{2d_0}{c}\right) + 4\phi(t)\right) \tag{10}$$

The phase noise in (8) is exactly four times of the phase noise in the conventional direct conversion bio-radar system employing the fundamental signal of the frequency synthesizer. Finally, there is not any SNR degradation due to frequency multiplier of the proposed super-heterodyne bio-radar system due to the fact that the phase noise power and the signal power are increased by the same ratio, four times in this case.

2.2. Noise Analysis

In this paper, the SNR analysis is focused on the respiration signal, since the respiration signal is generally the main issue of bio-radar system design. The received signal power in the I-channel (S_I) of the conventional bio-radar system based on direct conversion architecture can be calculated as following [8]:

$$\begin{aligned} S_I &= \frac{2P_{Tx}G_TG_RG_{Rx}\lambda^2\sigma_hL_h\overline{\cos^2\left(\theta_h+\frac{4\pi x(t)}{\lambda}\right)}}{(4\pi)^3d_0^4} \\ &\approx \frac{P_{Tx}G_TG_RG_{Rx}\sigma_hL_h\overline{x^2(t)}}{2\pi d_0^4} \end{aligned} \tag{11}$$

The received signal power in the I-channel (S_I') of the proposed bio-radar system based on the frequency multiplier, quadrupler, can also be derived by using (11), and it is the same as that of the conventional system as shown in the following equation:

$$S_I' \approx \frac{P_{Tx}G_TG_RG_{Rx}\sigma_hL_h\overline{x^2(t)}}{2\pi d_0^4} \tag{12}$$

To analyze the noise mechanism of the prosed bio-radar system, the residual phase noise of the LO in baseband is the most important parameter. In this paper, the power spectral density of the residual phase noise in baseband is calculated by using the autocorrelation of the residual phase noise in time-domain as well as Fourier transform of the calculated autocorrelation. The residual phase noise ($R_{\Delta\phi}(\tau)$) and its power spectral density ($S_{\Delta\phi}(f)$) in the conventional bio-radar system are [1, 2]:

$$\begin{aligned} R_{\Delta\phi}(\tau) &= E\{[\phi(t+\tau-\tau_d)-\phi(t+\tau)][\phi(t-\tau_d)-\phi(t)]\} \\ &= 2R_\phi(\tau)-R_\phi(\tau-\tau_d)-R_\phi(\tau+\tau_d) \end{aligned} \tag{13}$$

$$S_{\Delta\phi}(f) = \mathfrak{F}\{R_{\Delta\phi}(\tau)\} = S_\phi(f)(4\sin^2\pi f\tau_d) \tag{14}$$

where

$$S_\phi(f) = \mathfrak{F}\{\phi(t)\} \tag{15}$$

and

$$\tau_d = \frac{2d_0}{c} \tag{16}$$

and it has to be noticed that f in (14) and (15) is not the carrier frequency but the offset frequency.

The autocorrelation ($R'_{\Delta\phi}(\tau)$) of the residual phase noise in the baseband of the proposed bio-radar system summarized in (8) and its power spectral density ($S'_{\Delta\phi}(\tau)$) can be calculated by using (8) by the same procedure with the conventional system as following:

$$\begin{aligned} R'_{\Delta\phi}(\tau) &= 26R_\phi(\tau) - 12R_\phi(\tau-\tau_d) - 12R_\phi(\tau+\tau_d) \\ &\quad -4R_\phi(\tau-\tau_d-\tau_m) - 4R_\phi(\tau+\tau_d+\tau_m) \\ &\quad +3R_\phi(\tau-\tau_m) - 3R_\phi(\tau+\tau_m) \end{aligned} \tag{17}$$

$$\begin{aligned} S'_{\Delta\phi}(\tau) &= \mathfrak{F}\{R'_{\Delta\phi}(\tau)\} \\ &= S_\phi(f)(48\sin^2\pi f\tau_d + 4\sin^2\pi f(\tau_d+\tau_m) \\ &\quad +12\sin\pi f\tau_d \cdot \sin\pi f(\tau_d+2\tau_m)) \end{aligned} \tag{18}$$

If $\tau_m \ll \tau_d$, then the above equation can be further simplified as follows:

$$S'_{\Delta\phi}(f) \approx 64\sin^2\pi f\tau_d \tag{19}$$

The analyzed residual phase noise spectral density in baseband of the proposed super-heterodyne bio-radar system in (19) is greatly reduced from the LO phase noise ($S_\phi(f)$) with very small delay time (τ_d and τ_m) in nano-second order. It means that the range correlation is still available and stable vital signal acquisition is possible with the proposed system.

The main noise sources in the Doppler effect based bio-radar system are the thermal noise (N_T), residual phase noise due to antenna leakage ($N_{\Delta\phi_{L1}}$), clutter reflection ($N_{\Delta\phi_c}$), human body back-scattering ($N_{\Delta\phi_h}$), mixer leakages through down-conversion mixer ($N_{\Delta\phi_{L2}}$), as well as IQ-demodulator ($N_{\Delta\phi_{L3}}$) [8]. From the analysis result in [8], the main noise sources can be summarized as followings:

$$N_{\Delta\phi_h} = \frac{2P_{Tx}G_TG_RG_{Rx}(\lambda/4)^2\sigma_hL_h\overline{\Delta\phi_h(t)^2}}{(4\pi)^3d_0^4} \tag{20}$$

$$N_{\Delta\phi_c} = \frac{2P_{Tx}G_TG_RG_{Rx}(\lambda/4)^2\sigma_cL_c\overline{\Delta\phi_h(t)^2}}{(4\pi)^3d_0^4} \tag{21}$$

$$N_T = G_{Rx}\cdot kTB\cdot NF \tag{22}$$

The above noise power can be calculated by using (19) as following:

$$\begin{aligned} N_{\Delta\phi_h} &= \frac{P_{Tx}G_TG_RG_{Rx}\sigma_hL_h}{\pi f^2}S_\phi(1)(1\,\mathrm{Hz})^3\ln\left(\frac{f_H}{f_L}\right) \\ &\quad \cdot\left(\frac{1}{2d_0^2}+\frac{c}{8d_0^3}\tau_m+\frac{c^2}{128d_0^4}\tau_m^2\right) \end{aligned} \tag{23}$$

$$N_{\Delta\phi_c} = \frac{P_{Tx}G_T G_R G_{Rx}\sigma_c L_c}{\pi f^2} S_\phi(1)(1\,\mathrm{H}z)^3 \ln\left(\frac{f_H}{f_L}\right) \cdot \left(\frac{1}{2d_0^2} + \frac{c}{8d_0^3}\tau_m + \frac{c^2}{128d_0^4}\tau_m^2\right) \tag{24}$$

The phase noise power from antenna leakage, which is one of the most important and dominant parameters, can be easily calculated by using replacement of the delay of the signal back-scattered by human body, τ_d, into the delay from Tx antenna to Rx antenna by direct coupling, τ_a. The calculated residual phase noise power is as follows:

$$N_{\Delta\phi_{L1}} = 2\pi^2\eta_a P_{Tx}G_{Rx}S_\phi(1)(1\,\mathrm{Hz})^3 \ln\left(\frac{f_H}{f_L}\right) \cdot \left(256\left(\frac{\tau_a}{2}\right)^2 + 64\frac{\tau_a}{2}\frac{\tau_m}{2} + 4\left(\frac{\tau_m}{2}\right)^2\right) \tag{25}$$

The received signal power of the proposed system in (12) is the same as that of the conventional bio-radar system with the carrier frequency in (11), which is the same as the fundamental frequency of the proposed system based on multiplier, because the relative chest variation to wavelength as well as propagation loss are increased by the same ratio with frequency multiplication. On the other side, the residual phase noise power of the proposed system in (25) is larger compared with the conventional low frequency direct conversion system in [8] by about 4 times. As a result, the the SNR of the proposed bio-radar system with the multiplied carrier frequency is degraded by about 4 times. However, it has to be noticed that the phase noise of the general VCO is proportional to the oscillation frequency, and the phase noise of the VCO oscillating at four times higher frequency is larger by 4 times or 12 dB. It means that the proposed multiplier based bio-radar system using the carrier frequency generated by frequency multiplication from lower LO signal is the same in terms of SNR performance compared with the conventional bio-radar system with the same carrier frequency generated at higher frequency. Moreover, the frequency synthesis in lower frequency is not only stable but also economical.

The phase noise power due to the down-conversion mixer as well as IQ-demodulator can be calculated by the same manner. However, it is very interesting to note that the phase noise down-converted by the down-conversion mixer does not affect the performance of the proposed super-heterodyne bio-radar system, because the leakage signal is down-converted to DC and the down-converted signal is filtered by IF filter and modulated again by IQ-demodulator. So, the phase noise due to down-conversion mixer ($N_{\Delta\phi_{L2}}$) does not need to be considered for this noise analysis. Moreover, the phase noise effect by leakage of the IQ-demodulator is exactly the same as the leakage effect of the mixer in the conventional direct-conversion based bio-radar system, because there is no frequency multiplication for the leakage signal of the IQ-demodulator. As a result, the residual phase noise of the leakage signal of the IQ-demodulator ($N_{\Delta\phi_{L3}}$) can be expressed as following:

$$N_{\Delta\phi_{L3}} = 32\pi^2 \eta_{IQ} S_\phi(1)(1\,\mathrm{Hz})^3 \ln\left(\frac{f_H}{f_L}\right)\left(\frac{\tau_{IQ}}{2}\right)^2 \tag{26}$$

where, τ_{IQ} is the delay of the leakage signal, and the other parameters are summarized in Table 1.

Table 1. Simulation parameters, symbols, and values of the proposed bio-radar system.

Parameter	Symbol	Value
Fundamental frequency of LO	f_c	2.5 GHz
LO phase noise at 1 Hz	$S_{\phi(t)}(1)$	+58 dBc/Hz
Carrier frequency of LO	-	10 GHz
Filter low-cutoff frequency	f_L	0.5 Hz
Filter high-cutoff frequency	f_H	30 Hz
Receiver gain	G_{Rx}	10 dB
Tx Antenna gain	G_T	8 dBi
Rx Antenna gain	G_R	8 dBi
Output power	P_{Tx}	0 dBm
Heart RCS	σ_h	$6.8e-3$
Body clutter RCS	σ_c	0.5
Heart reflectivity	L_h	−60 dB
Human body reflectivity	L_c	−3 dB
Receiver noise figure	NF	6.0 dB
Antenna leakage	η_a	−20 dB
Mixer RF-LO isolation	η_m	−50 dB
IQ-demodulator isolation	η_{IQ}	−50 dB

The identical residual phase noise of the leakage signal of the IQ-demodulator with the conventional system with lower carrier frequency means that the mixer leakage effect is negligible. Finally, the received SNR can be calculated as following:

$$\mathrm{SNR} = \frac{S_I}{N_T + N_{\Delta\phi_h} + N_{\Delta\phi_c} + N_{\Delta\phi_{L1}} + N_{\Delta\phi_{L3}}} \tag{27}$$

To compare the system performance of the proposed bio-radar system with that of the conventional direct-conversion based bio-radar system using the same carrier frequency without any frequency multiplication, the system simulation using MATLAB are performed. The phase noise of 10 GHz LO in the conventional system is assumed as +70 dBc/Hz, which is 12 dB higher than that of the proposed bio-radar system with the 2.5 GHz frequency synthesizer frequency, since the phase noise is proportional to VCO oscillation frequency. Except for the fundamental frequencies and their phase noise characteristics, it is assumed that all the other parameters of the proposed and conventional systems are identical. The simulation parameters are utilized as summarized in Table 1, and they are based on the conventional and commercial components. Note that the phase noise value of a free-running VCO may be a positive dBC/Hz value with a extremely small offset frequency [8].

Figure 2 shows the simulated SNR due to the antenna leakage and clutter scattering, which are the most dominant factors in the system performance, and the overall SNR of the proposed bio-radar system. As shown in Figure 2, the total SNR of the proposed bio-radar system is high enough to measure the vital signal up to about 1 m. The calculated SNR of the proposed system is exactly same with that of the conventional direct conversion bio-radar system, and the calculated SNR traces of the conventional system are abbreviated to avoid repetition and confusion. This simulation result means that the additional IF band signal processing and beneficial low frequency PLL implement can be employed without any system performance degradation, and the validity of the proposed bio-radar system based on a super-heterodyne architecture with PLL and frequency multiplier is shown.

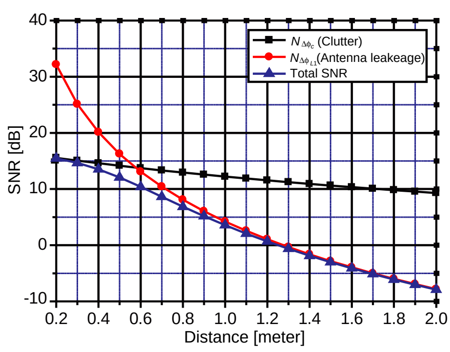

Figure 2. The simulated SNR with respect of antenna leakage and clutter scattering in the conventional and proposed bio-radar system.

3. EXPERIMENTAL RESULTS

Figure 3 shows the photographs of the fabricated bio-radar system. The designed bio-radar is realized in triple layered printed circuit boards (PCB). On the top board, Tx as well as Rx array antennas are integrated. The second board consists of RF components including frequency multiplier, RF bandpass filters, power divider, Tx amplifier, and LNA. The bottom board hosts frequency synthesizer with PLL, IQ demodulator, and IF filter. The size of the fabricated 10 GHz super-heterodyne bio-radar system is $40 \times 46\,\mathrm{mm}^2$.

Figure 4 shows the measured return loss and isolation of the fabricated antenna. The measured return loss is about -30 dB at 10.2 GHz frequency band. Moreover, the isolation between Tx-Rx antennas at 10.2 GHz, best matching frequency of the antennas, is about 20 dB.

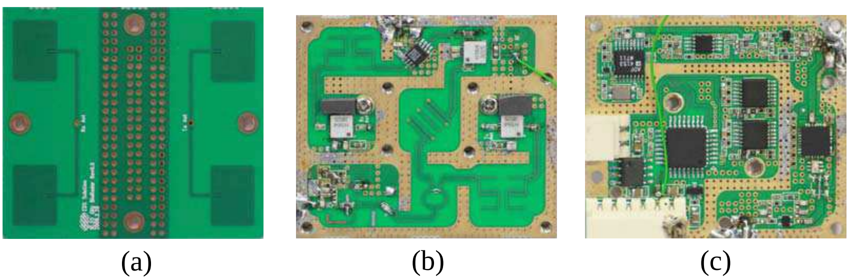

Figure 3. The photographs of the fabricated bio-radar system ($40 \times 46\,\mathrm{mm}^2$). (a) Antenna board (top board). (b) RF board (second board). (c) Baseband board (bottom board).

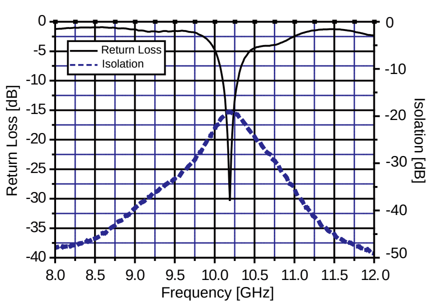

Figure 4. The measured return loss and isolation of the fabricated antenna.

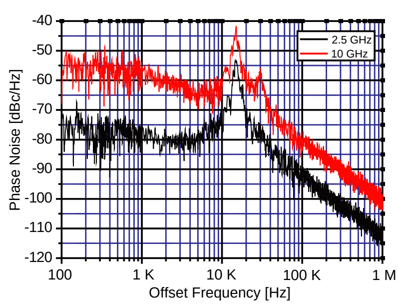

Figure 5. Measured phase noise characteristics of 2.5 GHz LO and 10 GHz multiplied signals.

Figure 5 shows the measured phase noise characteristics of the 2.5 GHz LO and 10 GHz multiplied signals. The phase noise characteristics depicted in Figure 5 show that the designed PLL is well locked, and the measured phase noise value of the 2.5 GHz LO is about −75 dBc/Hz and −112 dBc/Hz at 100 Hz and 1 MHz offset frequencies, respectively. For the 10 GHz multiplied signal, the measured values are −55 dBc/Hz and −100 dBc/Hz at 100 Hz and 1 MHz offset frequencies, respectively. The theoretical increment of the phase noise due to the quadrupler is 12 dB. This phase noise increment is well matched for the phase noise for the higher offset frequency, but the phase noise of the 10 GHz multiplied signal for the lower offset frequency is rather larger than theoretical prediction. It is strongly believed that the main reason of higher phase noise increment compared with theoretical increment is the noise added by the frequency multiplier. However, the 10 GHz signal shows stable locking operation as well as phase noise characteristics.

Figures 6(a) and 6(b) show the measured bio-signals at 50 cm and 100 cm, respectively. With the 10 GHz radar system the bio-signal measurements are performed in two different ways. First, the bio-signal is measured for normally breathing condition. In this case, the measured bio-signal in I and Q channels (I (Res.) and Q (Res.) in Figures 6(a) and 6(b)) include heartbeat signals. Next, the bio-signal is measured on the same human body without respiration. In this case, the measured bio-signal in I and Q channels (I (Non-res.)

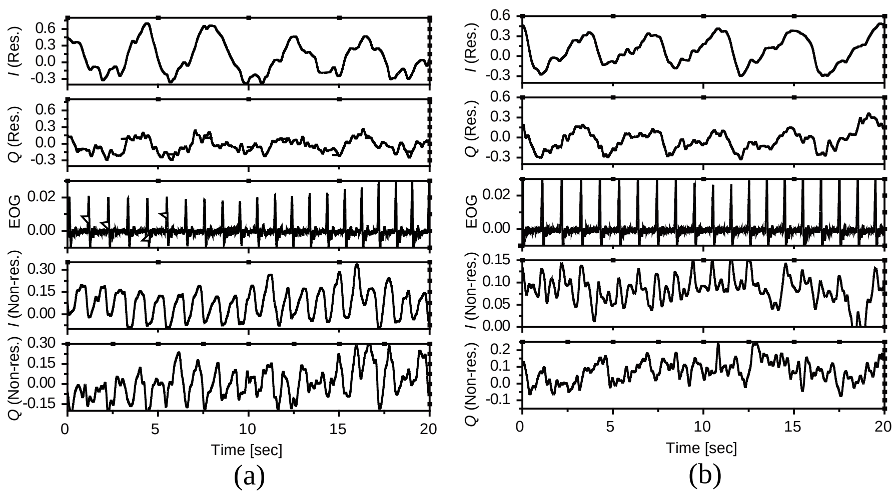

Figure 6. Measurement measured bio-signals at 50 cm and 100 cm. (a) 50 cm. (b) 100 cm.

and Q (Non-res.) in Figures 6(a) and 6(b)) include only heartbeat signal. Since the heartbeat signal is relatively weak compared to the respiration signal and the respiration signal consists of many harmonic components close to heartbeat signal frequency region, the measured heartbeat signal without respiration may provide more objective bio-radar system performance measurement before applying any additional signal processing. It should be noted that the heartbeat signals are measured by electrocardiogram (ECG) for reference signals to verify the proper operation of the proposed bio-radar system. It is clear that the respiration signals are clearly observed in all of the measurement results. It is apparent that the proposed system works very well for close-in subject considering that there are large amount of Tx to Rx coupling. The heartbeat signals measured at the distance of 50 cm is also very clear in I channel (I (Non-res.)) as well as Q channel (Q (Non-res.)) as shown in Figure 6(a). Moreover, the number and position of the peaks of the heartbeat signal measured at the distance of 100 cm also accords with the measured result by ECG, especially in I channel (I (Non-res.)) as shown in Figure 6(b). It is worth to note that in this work any additional signal processing is not employed to process these experimental results.

4. CONCLUSIONS

This paper presents a new 10 GHz super-heterodyne bio-radar system based on frequency multiplier and phase-locked loop. Since the phase noise of local oscillator is still dominant factor due to the low isolation between Tx and Rx antennas, the PLL employment can greatly improve the performance of Doppler-effect-based bio-radar system. Moreover, the PLL in this paper is realized at 2.5 GHz, and the 10 GHz signal is generated by the frequency multiplier or quadrupler to achieve best phase noise performance. The proposed bio-radar system has a super-heterodyne architecture, and it has distinct advantages over conventional super-heterodyne architecture, such as less stringent requirement of IQ demodulator and IF filtering for required noise figure performance. To verify the validity of the proposed system, the noise characteristics of the proposed system is carefully analyzed, and the result reveals that the same SNR performance are achieved with the proposed system based on the frequency multiplier compared with the conventional system employing identical signal frequency. This means that the additional IF band signal processing as well as economical realization can be achieved with the proposed system without any sacrifice of the system performance. The experimental results demonstrate the excellent detection performance of respiration as well as heartbeat signals up to 100 cm without any additional signal processing technique. The presented bio-radar can be employed for future medical system, and the proposed super-heterodyne architecture based on PLL and frequency multiplier can also be employed for higher frequency bands, such as 24 GHz or 60 GHz industrial, scientific, and medical (ISM) radio band systems.

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