An Ultra-Low-Supply Dual-Band VCO for Wireless Sensor Networks

Bo Zhao, Yongpan Liu, Pengpeng Chen, Tao Chen, Huazhong Yang, Hui Wang

Abstract— **Aggressive scaling down reduces the supply voltage of digital integrated circuits continuously. In order to realize Systems-On-a-Chip (SOC), analog and RF circuits should also work under the reduced voltage. For Wireless Sensor Networks (WSN), low supply is important for communication nodes as the supply voltage must be low enough under a single solar cell as power source. Besides, the future transceiver system for WSN must be able to adapt itself to various applications and environments, so multi-mode is the trend. In multi-mode systems, it would be ideal to use a signal oscillator which can generate multiple frequencies. Therefore, a Ultra-low-supply Dual-band Voltage-Controlled Oscillator (UDVCO) is proposed here. The presented UDVCO can be dynamically switched between two bands near 2.4-GHz and the 5-GHz. Its minimal operating voltage is 0.5 V by connecting the substrate of the cross-coupled NMOSFETs to the supply. A mathematical model is built for the low-supply VCOs, whose accuracy is validated by $SpectreRF$ simulation. A series of LC tank is used as a noise filter for both the two bands. The chip is fabricated in the 0.18-μm CMOS HJTC technology. Our measurement results show that the low-frequency band can be tuned from 2.01 GHz to 2.08 GHz and the phase noise is about -82.17 dBc/Hz@1MHz; while the high-frequency band ranging from 3.24 GHz to 3.44 GHz and the phase noise is about -74.33 dBc/Hz@1MHz.**

I. INTRODUCTION

In modern communication systems, Voltage-Controlled-Oscillator (VCO) is the heart of a radio transceiver. Not only for signal generation in transmitter, but also for local oscillator implementation in receiver. There have been plenty of previous works on VCOs. Hajimiri raised a general theory of phase noise in electrical oscillators [1]. Later on, Rael studied the physical processes of phase noise in differential LC oscillators [2]. Recently, various designs of VCOs appear with advanced features for different applications, such as wide tuning range [3], low phase noise [4], low frequency-to-voltage gain [5] and high linearity [6]. Aiming at the wireless sensor network (WSN) usage, the VCO should be both low-supply and tunable due to the following reasons: (1) A WSN node is typically solar-cell powered [7], thus minimizing supply voltage of VCOs to reduce power in WSN is preferred. (2) Low-supply VCOs can be compatible with digital modules in future WSN SOC chips. (3) In order to avoid the communication collisions, multi-band transceivers tends to be used in future WSNs.

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In traditional multi-mode transceivers, a number of oscillators are needed. However, individual oscillators consume a substantial part of chip area and battery power. One solution to the power overhead is to turn the inactive ones off when an oscillator is working. However, transition time is wasted during the VCOs' power on/off periods. It will cause power wasting. To address this problem, Goel gave an oscillator circuit which can switch between two resonant frequencies efficiently [8]. However, there are two shortcomings: (1) It does not support low supply voltage for future WSN SOC chips. (2) Goel's oscillator can't be tuned. It is dual-resonance but not dual-band;

This paper presented a low voltage methodology and design a tunable dual-band VCO. The main contribution of this paper is listed as the followings:

- Observing that a NMOS transistor's threshold can be lowered by increasing the substrate bias, we design and tape out a Ultra-low-supply Dual-band VCO (UDVCO) for WSN usage. Measurement results show that its minimum operating supply voltage is 0.5 V.
- A novel phase noise mathematical model is built for the proposed low-supply VCOs, and the $SpectreRF$ simulation displays that the maximum error between the results of our model and simulation results is 6.34 dB for the 2.4-GHz frequency and 1.89 dB for the 5-GHz frequency while the maximum error between the results of Leeson's model and simulation results is 13.72 dB for the 2.4-GHz frequency and 17.12 dB for the 5-GHz frequency.
- A tunable dual-band VCO structure is implemented and a new circuit structure to filter out the second harmonic in both bands is presented.

The rest of our paper is organized as follows. Section II gives an brief review of typical frequency-switching and low-supply technologies. The architecture of our UDVCO is described in detail in Section III. Section IV displays the measuring results to validate our ideas and mathematical models. Section V concludes the paper.

II. A BRIEF REVIEW OF FREQUENCY-SWITCHING AND LOW-SUPPLY TECHNOLOGIES

For modern WSN usage, multi-mode and low-supply are two main focus in transceiver design. We first give a brief review of frequency-switching and low-supply technologies for VCOs.

In the frequency-switching aspect, Fig. 1(a) shows that tradition VCO switches capacitors to change the total capacitance in the LC tank so as to realize frequency switching. The

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main limitation of such architecture is that the band selecting switch such as $S1$, $S2$ is placed in the signal path, both the loss and noise of the switches deteriorate the phase-noise performance. Goel raises a switching method that the switch $S1$ or $S2$ is tuned on only in switching process and there is no signal going through any switch under steady working condition [8]. As shown in Fig. 1(b), both of switches are opened when any of the desired oscillations is established. The loss, noise and nonlinearity of switches do not degrade the steady state response.

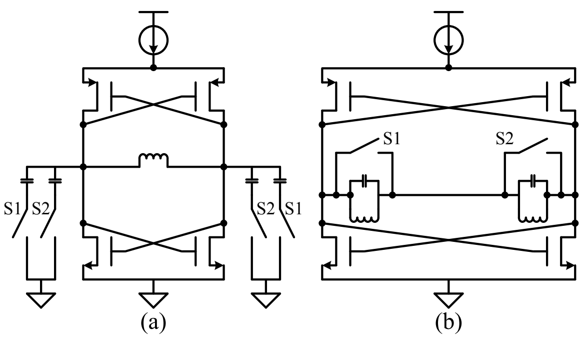


Fig. 1. (a) The traditional frequency switching method. (b) The switching method proposed by Goel [8]

In the low-supply aspect, the VCO's supply voltage is mainly determined by the adopted architecture. Generally, CMOS LC VCOs can be divided into two kinds: One is the current-biased VCO, which uses a tail-current MOSFET to supply current [9]. The other is the voltage-biased VCO, in which there is no tail-current transistor, and the supply voltage is directly set on the cross-coupled MOSFETs [10]. The voltage-biased VCO that has only NMOS cross-coupled transistors is adopted as it consumes the least voltage headroom. For this kind of VCOs, Hegazi raised a noise-filter technology to reduce the phase noise [11]. The voltage-biased VCO with a LC noise filter and NMOS cross-coupled transistors is shown in Fig. 2. The resonant frequency of the LC tank in noise filter is two times the resonant frequency of the VCO, then the second harmonic of the oscillation is filtered out, so the noise performance is improved [11].

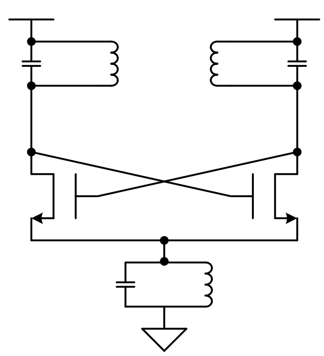


Fig. 2. The noise filter technology proposed by Hegazi [11].

According to Leeson's theory [12], the phase noise in the area of $1/f^2$ is [1]:

$$S_\phi(\omega_m) = \big(\frac{\omega_o}{2Q}\big)^2 \frac{2FkT}{P_s\omega_m^2} \tag{1}$$

in which ω_o is the central frequency of the oscillator, Q is the quality factor of the LC tank, k is the Boltzmann constant, T is the temperature, ω_m is the offset frequency, F is the effective noise figure, P_s is the power of the output signal, which is proportional to the output amplitude:

$$P_s = \frac{V_o^2}{8R(1+Q^2)} \approx \frac{V_o^2}{8RQ^2} \tag{2}$$

in which V_o is the output amplitude (peak-to-peak). From equations (2)(3), a common phase noise model of such voltage-biased VCO can be deduced as shown in equation (3):

$$S_\phi(\omega_m) = 4FkTR\big(\frac{\omega_o}{V_o\omega_m}\big)^2 \tag{3}$$

Based on Goel's switching method and Hegazi's noise filter technology, we will propose our UDVCO in the next section; Furthermore, we will built a mathematical phase-noise model which is more accuracy than Leeson's theory for such low-supply VCOs.

III. DESIGN OF THE UDVCO

The structure of our UDVCO is demonstrated here, the circuit implementation is shown in Fig. 3. Full-differential architecture is adopted here to reduce the phase noise. L1, C1 and L2, C2 are two LC tanks for the two frequency bands. The 5-GHz LC tank (L2 and C2) is set below the 2.4-GHz LC tank (L1 and C1) for two reasons: (1) the parasitics of pads will greatly reduced the resonant frequency of the 5-GHz tank if the 5-GHz tank is set close to the power pads; (2) the high-frequency tank is more sensitive to power noise. S1 and S2 are switches used for frequency selecting. M1 and M2 is a couple of cross-coupled MOSFETs, their substrate is not grounded but connected to the supply. LC tanks L3, C3 and L4, C4 compose a noise filter for dual-band. Next we describe our low-supply technology and dual-band implementation respectively.

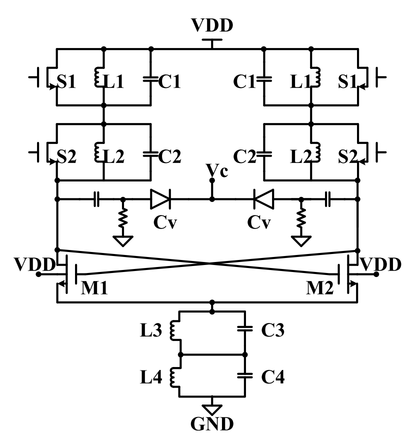


Fig. 3. The proposed UDVCO.

A. The low-supply technology

The low-supply technology is described in details as below. In order to further decrease the supply voltage of voltage-biased VCO, the substrate of the cross-coupled NMOSFETs is not grounded but connected to the supply, as shown in Fig. 3. The threshold voltage of NMOSFETs is [13]:

$$V_{th} = V_{th0} + \gamma\left(\sqrt{|2\phi_f + (V_s - V_{bulk})|} - \sqrt{|2\phi_f|}\right) \quad (4)$$

in which V_{th0} is the threshold voltage under the condition of zero voltage across source and substrate of a MOSFET, ϕ_f is the Fermi electromotive force, γ is the coefficient of substrate modulation effect, and V_s is the source voltage, and V_{bulk} is the voltage at substrate.

We choose a NMOSFET with a 0.18-μm channel length and 40×8-μm width which is the same as the cross-coupled MOSFETs in our UDVCO for experiment. The gate-to-source voltage V_{gs} and the drain-to-source voltage V_{ds} are both set to 0.5 V. We change the substrate-to-source voltage V_{bs} from 0 V to 1.5 V. The variety of transconductance is shown in Fig. 4. We can see that the transconductance g_m rises normally as the substrate-to-source voltage V_{bs} increases from 0 V to 1.2 V. However, when V_{bs} exceeds 1.2 V, there is a large leakage current. So under the condition of low supply (below 0.5 V), connecting the substrate to supply is safe.

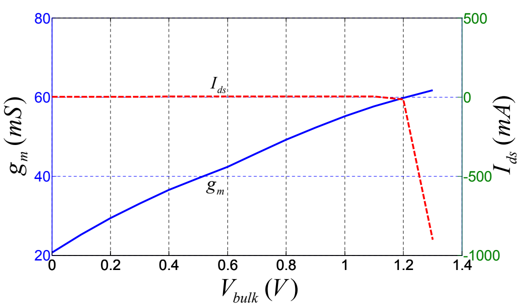


Fig. 4. The variety of transconductance g_m versus the substrate-to-source voltage V_{bs}.

Through equation (4), we can see that the threshold voltage falls as the substrate voltage V_{bulk} is raised. As a result, the architecture we proposed can start up under a lower supply than Hegazi's work.

The circuit is simulated under both conditions that the substrate is grounded and connected to the supply. If the substrate is grounded, the supply voltage must be at least 0.47 V for 2.4-GHz band, and 0.51 V for 5-GHz band; while the supply can be as low as 0.43 V for 2.4-GHz band, and 0.47 V for 5-GHz band with the substrate connected to the supply. As the relationship among the phase noise, resonant frequency, and frequency offset is always accuracy, then how phase noise changes with supply voltage V_{dd} and bulk-biased voltage V_{bulk} is studied here, as shown in Fig. 5.

Based on Leeson's theory [12] and our simulation results, the phase-noise mathematical model can be built:

$$\begin{aligned} S_\phi(\omega_m)(dBc/Hz) &= 10lg[FkTR(\frac{\omega_o}{\omega_m})^2 f(V_{dd}, V_{bulk})] \\ f(V_{dd}, V_{bulk}) &= (-2.1141V_{dd} + 1.2468)V_{bulk}^2 \\ &+ (1.6541V_{dd} - 0.9635)V_{bulk} \\ &+ (-0.9284V_{dd} + 0.6097) \quad (5) \end{aligned}$$

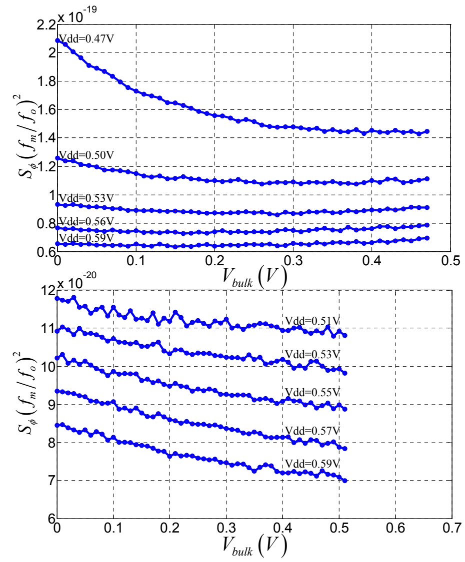


Fig. 5. The variety of phase noise versus the supply voltage and the bulk-biased voltage.

in which V_{dd}, V_{bulk} are the supply voltage and the bulk-biased voltage respectively, other parameters are the same as in equation (3). And we can use this model to guide our circuit design and predict the phase noise at any resonant frequency in the two bands, and any low supply voltage.

The phase noise under both the conditions of substrate connected to supply and substrate grounded is shown in Fig. 6: We can see that the phase noise of VCO with substrate

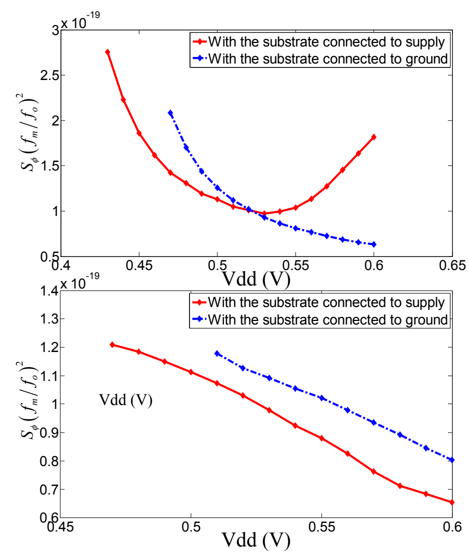


Fig. 6. The variety of phase noise versus the supply voltage.

connected to supply is always lower than that with substrate grounded for 5-GHz band; but for 2.4-GHz band, the phase noise of VCO with substrate connected to supply is lower than that with substrate grounded only when the supply voltage is below 0.53 V. Therefore, our method is more suitable for an ultra-low supply below 0.53 V than for a normal supply.

B. The dual-band realization

The dual-band realization and noise filter implementation is analyzed in this subsection. The resonant frequency of the UDVCO can be selected by switches as shown in Fig. 3. When switch $S1$ is tuned on and $S2$ is tuned off, the UDVCO outputs a frequency at $f_2 = 1/(2\pi\sqrt{L_2C_2})$; then $S1$ is tuned off, the UDVCO still oscillate at the frequency f_2 because the impedance of L1-C1 tank is very low at the resonant frequency of L2-C2 tank. When $S1$ is kept off and $S2$ is switched, for the same reason, the UDVCO oscillate at the resonant frequency $f_1 = 1/(2\pi\sqrt{L_1C_1})$.

The problem of lossless frequency switching has been solved, and then we need to design a dual-band noise filter. One way to realize the noise filter for the two bands may be using switches to select the right filter for each band. However, noise, nonlinearity and loss are the three problems difficult to solve in MOS switches, so it's better not to use switches. As shown in Fig. 3, two series LC tanks are adopted here to filter out the second harmonic of both the two bands. The resonant frequencies of the two LC tanks in the noise filter are:

$$\begin{aligned} f_3 &= 2f_2 \\ f_4 &= 2f_1 \end{aligned} \tag{6}$$

Then the value of the elements in the noise filter can be got from:

$$\begin{aligned} \frac{1}{2\pi\sqrt{L_3C_3}} &= \frac{2}{2\pi\sqrt{L_2C_2}} \\ \frac{1}{2\pi\sqrt{L_4C_4}} &= \frac{2}{2\pi\sqrt{L_1C_1}} \end{aligned} \tag{7}$$

As the high-frequency tank is more sensitive to parasitics and ground noise, the L4-C4 tank is set more close to the ground, as shown in Fig. 3. With the noise filter, the noise figure in equation (5) is $F = 1 + \gamma$ in which γ is the channel noise coefficient [11]. And the different parameter for 2.4 GHz and 5 GHz is R which is the equivalent parallel resistance of the LC tanks. The value of R in two tanks is $R_1 = 70.27$ (For 2.4-GHz tank) and $R_2 = 164.02$ (For 5-GHz tank) respectively. With the substrate connected to supply, the $spectreRF$ simulation is done and the comparisons are made among the results our model, Leeson's model and simulation results, as show in Fig. 7. Under the

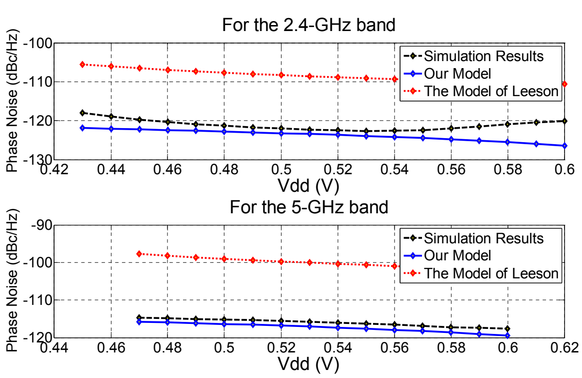


Fig. 7. The comparisons among simulation results, our model and Leeson's model.

ultra-low supply voltage below 0.6 V, the maximum error between the results of our model and simulation results is 6.34 dB for the 2.4-GHz frequency and 1.89 dB for the 5-GHz frequency while the maximum error between the results of Leeson's model and simulation results is 13.72 dB for the 2.4-GHz frequency and 17.12 dB for the 5-GHz frequency. It's obvious that for the low-supply VCOs our model is much more accuracy than Leeson's.

IV. MEASURE RESULTS

The UDVCO is designed and taped out, and the testing result is displayed in this section. The circuit of Fig. 3 is implement using HJTC 0.18-μm CMOS technology. The technology has six metal layers with a top metal layer 8 KA thick. The inductors are built as square spiral inductors using four metal layers in parallel and were simulated with Berkeley's software 'Asitic'.

The layout pattern of our UDVCO is shown in Fig. 8. The measured resonant frequency is about 2.05 GHz and

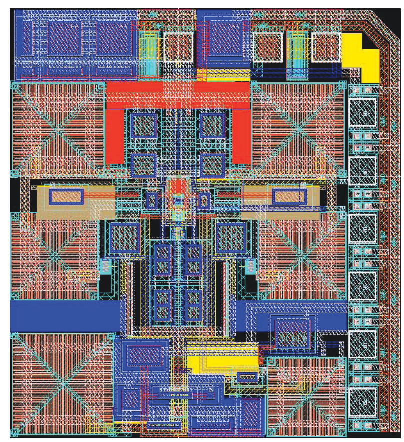


Fig. 8. Layout pattern of our UDVCO.

3.44 GHz respectively, as shown in Fig. 9. The frequency reduction is caused by parasitics of PCB and pads. And because of the parasitics, the switching to high-frequency band must be done by keep $S1$ on. However, the phase noise can be measured for both frequency bands. The minimum supply voltage for VCO to start on both bands is $V_{min} = 0.50V$ and $V_{min} = 0.53V$ respectively. Under the minimum supply, the measure phase noise of the UDVCO is shown in Fig. 10.

In order to make a comparison, the chip is measured with the bulk connected to the supply ($V_{bulk} = V_{dd}$) and ground ($V_{bulk} = 0$) respectively. The testing results are summarized into Table I.

As we can see, our three main ideas are proved: (1) The UDVCO can work under a ultra-low supply voltage at about 0.50 V; (2) The UDVCO can be switched between two frequency bands; (3) The UDVCO can be tuned in both frequency bands. However, the measured phase noise is worse than expected. We think that it is caused by the following reasons: (1) The self designed inductors has a much poor quality value Q than we expect; (2) The PCB seriously affect the noise performance, because the supply

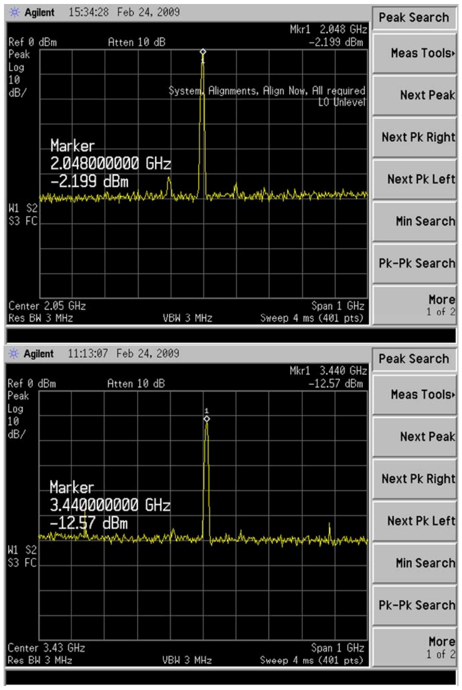
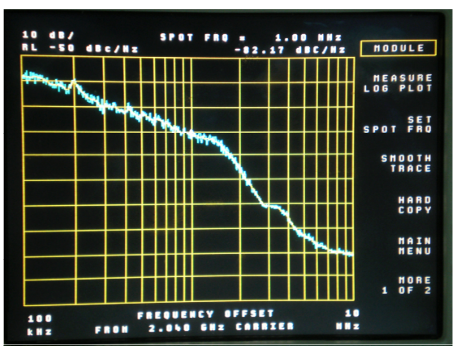
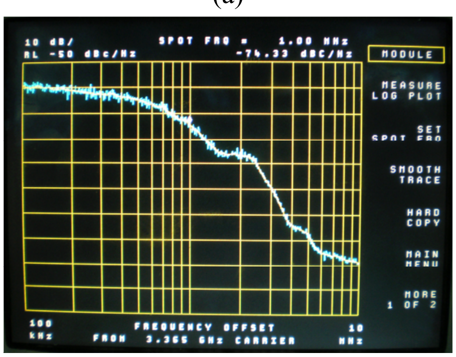


Fig. 9. The resonant frequency of the two modes.



(a)



(b)

Fig. 10. The phase noise of the UDVCO: (a) For the low-frequency band; (b) for the high-frequency band.

line on PCB is too long and the noise on the supply is too large; In a ultra-low supply VCO, the power noise impact is particularly serious. Therefore, we will redesign the PCB and get better measurement results in future.

TABLE I

THE TESTING RESULTS

The Testing Results	For low-frequency band	For high-frequency band
$V^{a}_{min,1}$	0.59 V	0.60 V
$V^{b}_{min,2}$	0.50 V	0.53 V
Phase noise[c]	-82.17dBc/Hz@1 MHz	-74.33dBc/Hz@1 MHz
The tuning range[c]	2.01 GHz∼2.08 GHz	3.24 GHz∼3.44 GHz

[a]The minimum supply voltage with the substrate grounded.

[b]The minimum supply voltage with the substrate connected to the supply.

[c]The phase noise and tuning range is tested under the minimum supply $V_{min,1}$.

V. CONCLUSION

A 0.5-V ultra-low-supply multi-band VCO is designed and taped out in this paper. The VCO can be switched between two bands near 2.4 GHz and 5 GHz. A dual-band noise filter technology is presented to eliminate the second harmonic by two LC tanks connected in series. A phase noise model for low-supply VCOs is proposed and validated. Measurement results shows that the tuning frequency band of the two mode is 2.01 GHz∼2.08 GHz and 3.24 GHz∼3.44 GHz respectively. The phase noise is -82.17dBc/Hz@1 MHz at the low-frequency band and -74.33dBc/Hz@1 MHz at the high-frequency band.Our future work is to redesign the PCB by better technology and layout.

VI. ACKNOWLEDGMENT

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