A MULTIBAND CMOS VCO WITH SWITCHING BONDWIRE INDUCTOR FOR BIOMEDICAL WIRELESS FREQUENCY BAND

Design and Performance Analysis

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Abstract: This paper presents a multiband low phase noise CMOS VCO with wide frequency tunability using switched bondwire inductor bank, for operation in the medical wireless frequency band. The combination of bondwire inductor and CMOS switch transistor enhances frequency tunability and improves phase noise characteristics. All most of the medical wireless frequency bands can be covered by the single VCO proposed in this paper. The proposed multiband VCOs, VCO1 operates from 2.3 GHz to 6.3 GHz with phase noise of -136 and -122 dBc/Hz at 1 MHz offset frequency, respectively, and VCO2 operates from 4.9 GHz to 12.7 GHz with phase noise of -122.3 and -111.8 dBc/Hz at 1 MHz offset frequency, respectively. Switched bondwire inductor bank shows high quality factor Q at each frequency band, which allows better tradeoff between phase noise and power consumption. The proposed VCO1 is designed in TSMC 0.18um CMOS process and consumes 7.2 mW power resulting in figure of merit(FOM) of -189.3 dBc/Hz at 1 MHz offset from 6 GHz carrier frequency, and the proposed VCO2 is designed in SEC 65nm CMOS process and consumes 8 mW power resulting in figure of merit(FOM) of -184.6 dBc/Hz at 1 MHz offset from 12 GHz carrier frequency.

1 INTRODUCTION

These days, wireless technologies have been widely used for medical applications including measuring physiological signals, intelligent mobile emergency response systems and patient monitoring both inside and outside the hospital, etc. In biomedical application, devices using wires are not suitable for signal detection, record and transmission because human behaviour is restricted by wires. Wireless solution is also favored for infection free and cosmetic point of view. Therefore, a single chip solution including RF transceiver is becoming more prevalent in biomedical application, considering size, power consumption and economic issues. Among the efforts for the single chip radio integration, the low phase noise VCO implementation gets a lot of attentions because the phase noise of the VCO is one of the most critical parameters for the information transfer achievement. A major challenge in the single chip solution for biomedical application is the establishment of low cost communication terminals, which is highly integrated and can support multi-band and multi-standards. Table 1 shows the different frequency bands, which is used for medical applications both on U.S. and Europe(Mohamed *et al*, 2009).

Table 1: Summary of Medical Wireless Frequency Bands.

Location	Frequency Band	Frequency [MHz]
U.S.	Medical Implant Communications Service	402 - 405
U.S.	Wireless Medical Telemetry Service	608 - 614 1395 – 1400 1427 - 1432
U.S.	Instrumentation, Scientific, and Medical (ISM)	315 902 - 928 2400 - 2483.5 5150 - 5875
Europe	ISM	433.05 – 434.79 868 – 870 (short -range) 2400 – 2483.5
U.S.	UWB	3.1 – 10.6 GHz 22 - 29 GHz, center freq > 24.075 GHz
Europe	UWB	4.2 – 4.8 GHz 6 – 8.5 GHz 3.4 – 4.2 GHz (Pending)

Multiband radio using multiple transceivers can satisfy these demands, however the complexity and

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chip area should be increased. Though design research for RF building blocks with wide frequency operability has been progressed, single low phase noise multiband CMOS VCO design is still remain as challenging work (S. Ryu *et al*, 2005), (K. Lee *et al*, 2008). The multiband VCO with wide frequency tunability needs large capacitor banks and varactor diodes, large capacitor banks results area occupation issue and high VCO gain of varactor results phase noise degradation issue. Though these problems can be solved by allowing higher power consumption, this is not desirable for biomedical application which requires low power consumption for long lifetime of implantable and wearable devices.

This paper describes design of a low phase noise CMOS VCO with very wide frequency tunability using switched bondwire inductor bank. All most of the medical wireless frequency bands can be covered by the single CMOS VCO proposed in this paper, with just simple divide-by-two prescaler.

With a 1.2 V power supply, this VCO1 consumes a 6 mA bias current at VCO core and shows frequency tunability from 2.3 to 6.3 GHz, and VCO2 consumes a 6.7 mA bias current at VCO core and shows frequency tunability from 4.9 to 12.7 GHz with low phase noise characteristics

2 MULTIBAND VCO ISSUE

Multiband multi-standard RF transceiver for biomedical application requires the LO block with very wide tuning range and low phase noise, therefore LO block structure based on only divide-by-two prescaler is favored these days, since side effects of other structures such as self-mixing, DC-offset and frequency pushing/pulling can be minimized. In addition, this simple LO chain structure is the optimum solution to minimize the cost in terms of system complexity, power consumption and area in comparison with other solutions such as quadrature VCO (QVCO) and a polyphase filter (A. Koukab *et al*, 2006). For this simple LO structure, VCO core itself should have very wide tuning range. A usual way to achieve a wide tuning range is adopting a switched capacitor bank in a VCO resonator for coarse tuning. For fine tuning, a large varactor with high VCO gain, K_{vco}, also helps to enlarge VCO frequency tuning band. However, smaller varactor with low K_{vco} enables low phase noise and switched capacitor bank is more suitable for small frequency changes (Z. Li *et al*, 2005). Therefore the utilization of both capacitor and inductor switching can be an optimum solution for wide frequency tunability. The switched inductor bank can be composed of planar spiral inductors and MOS switch (S. Yim *et al*, 2006).

Considering the size and Q factor of the on-chip spiral inductor, single-turn inductor of about 1 nH is favored for 2 ~ 6 GHz operation. A custom - designed single - turn inductor shows Q of around 15 ~ 20. However, relatively large inductor size, out - diameter of around 400 ~ 500 µm, is required. Switched inductor bank with these inductors is not desirable solution due to area issue. The proper sized conventional planar spiral inductor of CMOS process provides Q of about 10. Therefore, VCO phase noise characteristics may be severely degraded by switched inductor bank using conventional spiral inductor due to MOS switch parasitics, such as on resistance, R_{on}.

3 LOW PHASE NOISE VCO WITH BONDWIRE

To resolve this problem, bondwire inductor is proposed in this work. Bondwire inductor shows good quality factor above 25 in the frequency range of interest. The inductance of bondwire structure is linearly increased with the bondwire length and can be modified with changing the distance between two bondpads and bondwire height. We have recently reported a bondwire inductor VCO with low phase noise characteristics (K. Lee *et al*, 2008). This VCO exhibits good phase noise performance while simultaneously achieving enough tuning range.

Though the variation of the bondwire inductance is higher than that of on-chip spiral inductor, more than 20% of the inductance value can be tuned even after chip fabrication by inserting dummy tuning pads in circuit layout and changing bondwire length or height. Therefore, the bondwire inductor VCO is one of the best solutions for low noise and low cost RF transceiver of biomedical devices.

4 DESIGN OF THE TEST VEHICLE: MULTIBAND VCO WITH SWITCHING BONDWIRE INDUCTOR

The proposed VCO adopts a switched bondwire inductor bank, which is composed of three bondwire inductors with different length. Fig. 1 and Fig. 2 shows simulated inductance value and Quality factor of the bondwire inductor, respectively. 3D - EM simulator, HFSS is used for this characterization. In these figures, _long, _mid and _short exhibit bondwire inductor simulation results for length of 700, 525 and 350 um respectively, and _all depicts simulation results for shunt connection of all three bondwire inductors. As depicted in Fig. 2, the frequency for maximum Q factor can be varied with bondwire inductance switching, which can improve VCO phase noise characteristics at each frequency band.

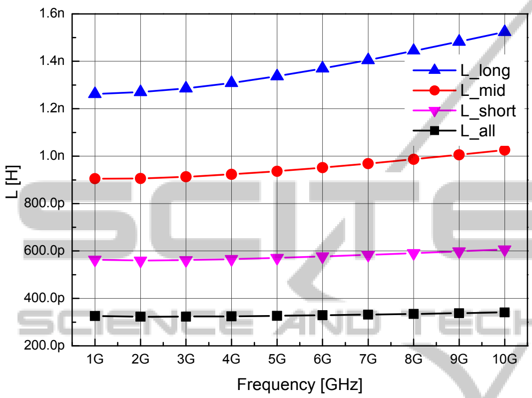


Figure 1: Simulated inductance of switched bondwire inductor.

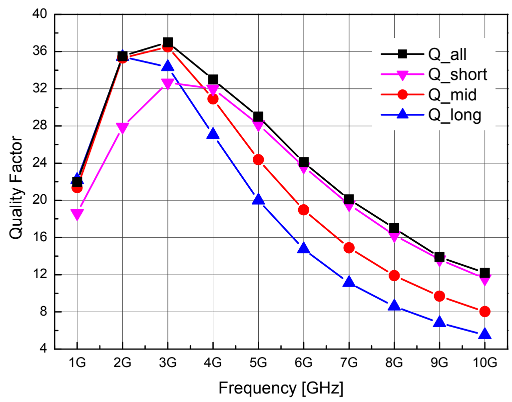


Figure 2: Simulated Q factors of switched bondwire inductor.

The proposed VCO structure is shown in Fig. 3. An accumulation-type MOS varactor is used for fine tuning. A switched bondwire inductor bank is used for wide frequency tenability.

As depicted in Fig. 3, mid and short length bondwire inductors are shunt - connected to long bondwire inductor when all MOS switches are on state, and switched inductor bank has lowest total inductance value in that case. When all MOS switches in switched inductor bank are off, mid and

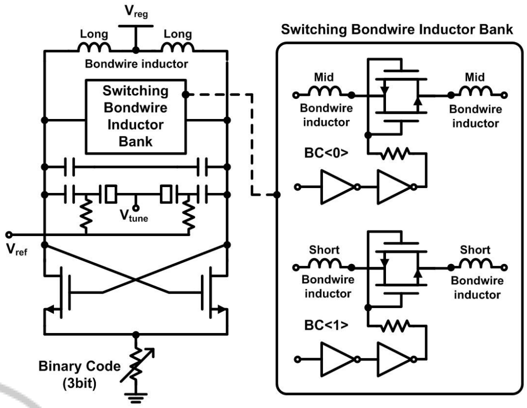


Figure 3: Proposed VCO structure with bond-wire inductors.

short length bondwire inductors are disconnected and highest inductance value can be achieved.

Though bondwire inductors are connected through MOS switches at on state, the Q factor degradation from MOS R_{on} resistance can be mitigated due to shunt connection with long bondwire inductor which is directly connected to VCO oscillation node without MOS switch.

To design a wide frequency tuning range VCO with good phase noise performance and low power dissipation, a complementary structure and an NMOS-only structure are compared. These two types depicted in Fig. 4 are mostly favored for differential CMOS VCO.

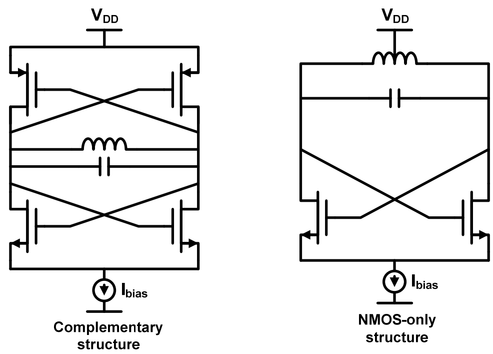


Figure 4: Comlementary and NMOS-only VCO structure.

The well-known phase noise model for an oscillator is Leeson's proportionality (D. B. Leeson *et al*, 1966).

$$L\{\Delta\omega\} \propto \frac{1}{V_o^2} \cdot \frac{kT}{C} \cdot \left(\frac{\omega_o}{Q}\right)^2 \cdot \frac{1}{\omega_m^2}$$

Where the phase noise is given by *kT/C* noise that is shaped in frequency domain by LC tank and normalized to the power in the tank. This expression reveals the dependency of the phase noise upon the signal amplitude V_o. For the complementary type VCO, as the bias current increases, signal amplitude is limited by V_{DD} in the voltage limited regime, while the NMOS-only type VCO enables higher voltage swing above V_{DD} limit. Therefore, the phase noise of the complementary type at each offset frequency may become worse than that of the NMOS-only type as the bias current increases(S. Ryu, 2009).

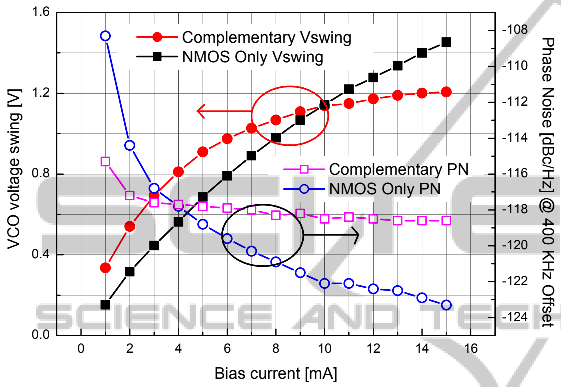
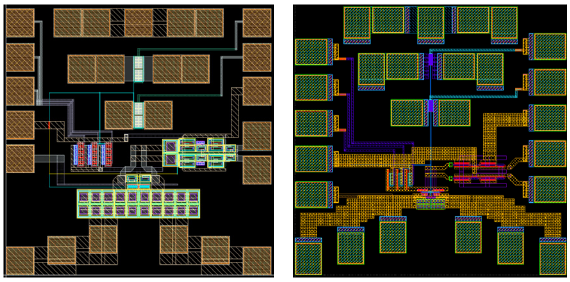


Figure 5: Simulated VCO voltage swing amplitude and phase noise at 400 KHz offset from 4GHz carrier frequency as a function of bias current.

Although the complementary type still maintains better phase noise performance for relatively small bias current, below 4 mA, with V_{DD} of 1.2V as depicted in Fig. 5, this bias current is not enough to satisfy the requirements for multi-band/multi-standard operation. In addition, considering various lossy components of the real circuits, enough phase noise margin is necessary. Accordingly, the NMOS-only type is adopted.

For minimizing power consumption, the VCO bias current is varied between each frequency band by controlling the 3-bit binary weighted bias resistors. This programmability allows the trade-off between power consumption and phase noise, which is necessary for multi-band/multi-standard VCOs.

Considering these multiband low phase noise VCO design issues, the proposed VCOs, VCO1 and VCO2 is designed in 0.18 µm and 65nm CMOS technology, respectively. Fig. 6 shows the complete layout of the VCOs. The chip size is 0.75 × 0.75 mm^2 for each.



(a) VCO1, 0.18um TSMC (b) VCO2, 65nm SEC

Figure 6: Complete layout of the proposed CMOS VCO.

5 SIMULATION RESULTS

The carrier signal frequency of the VCO1 is tunable between 2.28 GHz and 2.33 GHz when all MOS switches are at off state, and when all MOS switches are at on state, the carrier signal frequency is tunable between 6.1 GHz and 6.38 GHz. The frequency band between 2.33 GHz and 6.1 GHz can be covered by controlling each MOS switch in the inductor bank, separately. The full tuning range can also be covered by utilizing both switched capacitor bank and switched inductor bank. Fig. 7 and Fig. 8 depict the simulated frequency tuning range and the phase noise for the VCO1. The VCO1 exhibits a phase noise of -127 and -136 dBc/Hz at 400 KHz and 1 MHz offsets from the 2.3 GHz Carrier. For the 6.2 GHz carrier, a phase noise of -113.8 dBc/Hz and -122 dBc/Hz at 400KHz and 1MHz offsets are attained, respectively. The VCO core operates from 1.2V supply and biases at 6 mA.

The simulation results of both VCO1 and VCO2 are summarized in table 1.

A widely used figure of merit (FOM) (A. Waemans *et al*, 1998) for the VCO is defined as

$$FOM = L\{f_{offset}\} - 20\log\left(\frac{f_o}{f_{offset}}\right) + 10\log\left(\frac{P_{DC}}{1mW}\right)$$

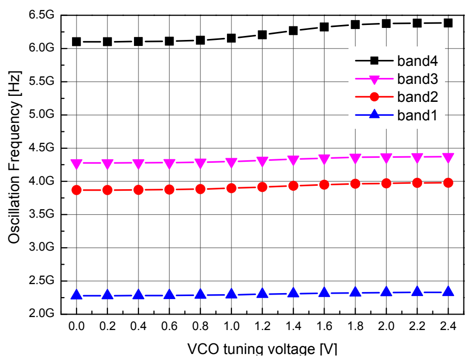


Figure 7: Simulated frequency tuning range of the proposed VCO1.

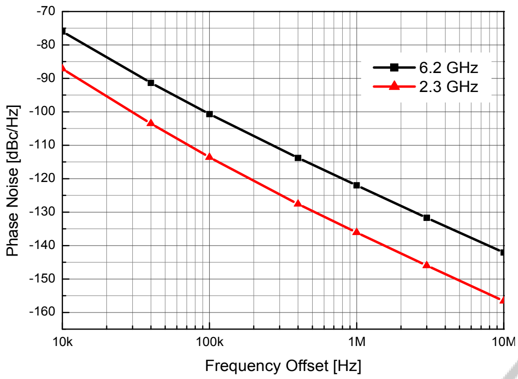


Figure 8: Simulated phase noise of the proposed VCO1 at 2.3 and 6.2 GHz carrier frequency.

Here, $L\{f_{offset}\}$ is the measured phase noise at offset frequency f_{offset} from the carrier frequency f_o. P_{DC} is VCO power consumption in mW. The worst simulated FOMs for the VCO1 and VCO2 are -189.3 dBc/Hz at 6 GHz and -184.6 dBc/Hz at 12 GHz carrier frequency, respectively. Table 2. shows the summary of the simulation results compared to those of other low phase noise VCOs.

Table 2: VCO performance summary and comparison.

VCO	Tech.	Freq. [GHz]	Power [mW]	P/N [dBc/Hz]	FOM
Ham 2001	0.35um Bi-CMOS	1.91	10	-121 @600KHz	-181.1
Astis 2005	0.35um Bi-CMOS	5.6	13.5	-117 @1MHz	-180.7
Fong 2003	0.13um CMOS	3.0-5.6	2	-114.5 @1MHz	-186.5
Adreanj 2001	0.35um CMOS	2.19	12.6	-139 @3 MHz	-185.3
VCO1	0.18um CMOS	2.28-2.33 3.88-3.91 4.27-4.31 6.10-6.38	7.2	-122 @1 MHz [6GHz]	-189.3
VCO2	65nm CMOS	4.93-5.07 8.34-8.60 9.48-9.75 12.21-12.74	8.0	-111.8 @1 MHz [12GHz]	-184.6

6 CONCLUSIONS

In this work, a low phase noise, multiband CMOS VCO for biomedical wireless frequency bands, with wide frequency tunability through switching bondwire inductor, has been presented. All most of the medical wireless frequency bands can be covered by the single CMOS VCO proposed in this paper.

The design has been achieved with TSMC 0.18 µm and SEC 65nm CMOS process. An NMOS-only structure and high Q bond wire inductor are adopted for enough phase noise margin, wide frequency tunability, and chip area efficiency. In addition, programmable 3-bit bias resistors are used for a trade-off between phase noise and power consumption. Proposed switched bondwire inductor bank is composed of CMOS switch and bondwire inductors, which enable very wide frequency tunability and low phase noise characteristics.

The simulation results show that the tuning ranges are from 2.3 GHz to 6.4 GHz for VCO1 and from 4.9 GHz to 12.7 GHz for VCO2. The phase noise performance of the VCO1 is -122 dBc/Hz at 1 MHz offset from the 6 GHz Carrier. For the VCO 2, a phase noise of -111.8 dBc/Hz at 1MHz offset from 12 GHz carrier is achieved. The simulated FOM for the VCOs are -189.3 dBc/Hz and -184.6 dBc/Hz for VCO1 and VCO2, respectively. These FOM values confirm that a good tradeoff among phase noise, wide tunability and power consumption is achieved from the proposed CMOS VCOs.

REFERENCES

Mohamed R. Mahfouz, "Integration of UWB and Wireless Pressure Mapping in Surgical Navigation," *IEEE Trans. Microw. Theory Tech.* vol. 57, no. 10, pp. 2550-2564, Oct.2009.

S. Ryu, Y. Chung, H. Kim, J. Choi, and B. Kim, "Phase noise optimization of CMOS VCO through harmonic tuning," in *IEEE Radio Freq. Integr. Circuits Symp.*, Long Beach, CA. pp. 403–406, Jun. 2005.

K. Lee, H. Yu, H. Ahn, H. Oh, S. Ryu, D. Keum and B. Park, "A0.13-um CMOS Σ-Δ Frequency Synthesizer with an Area Optimizing LPF, Fast AFC Time, and a Wideband VCO for WCDMA/GSM/GPRS/ EDGE Applications," in *IEEE Radio Freq. Integr. Circuits Symp.*, Atlanta, GA. pp. 299–302, Jun. 2008.

A. Koukab, Y. Lei, M. J. Declercq, "A GSM-GPRS/UMTS FDD-TDD/WLAN 802.11a-b-g Multi-Standard Carrier Generation System," *IEEE J. Solid-State Circuits*, vol. 41, pp. 1513-1521, July. 2006.

Z. Li and K.K.O, "A Low-Phase-Noise and Low-Power Multiband CMOS Voltage-Controlled Oscillator," *IEEE Trans. Microw. Theory Tech.* vol. 40, no. 6, pp. 1296-1302, Jun. 2005.

S. Yim and K.K.O, "Switched Resonators and Their Applications in a Dual-Band Monolithic CMOS LC-Tuned VCO," *IEEE Trans. Microw. Theory Tech.,*

vol. 54, no. 1, pp. 74-81, Jan. 2006.
D. B. Leeson, "A Simple Model of Feedback Oscillator Noise Spectrum," *Proceedings of the IEEE*, vol. 54, pp. 329–336, 1966.
S. Ryu, "Multi-standard carrier generator with CMOS logic divider," in *IEEE Int. Midwest Symp on Circuit and Systems.,* Cancun. pp. 1059–1062, Aug. 2009.
A. Wagemans, "A 3.5 mW 2.5 GHz diversity receiver and a 1.2 mW 3.6 GHz VCO in silicon-on-anything," *IEEE Int. Solid-State Circuits Conf. Tech. Dig.*, pp. 250-251, Feb. 1998.
D. Ham and A. Hajimiri, "Concepts and methods in optimization of integrated *LC* VCOs," *IEEE J. Solid-State Circuits*, vol. 36, pp. 896–909, Jun. 2001.
G. De Astis, D. Cordeu, J. Paillot, and L. Dascalescu, "A 5-GHz fully integrated full pMOS Low-phase-noise *LC* VCO," *IEEE J. Solid-State Circuits*, vol. 40, pp. 2087–2091, Oct. 2005.
N. Fong, "Design of wideband CMOS VCO for multiband wireless LAN applications," *IEEE J. Solid-State Circuits*, vol. 38, pp. 1333–1342, Aug. 2003.
P. Adreanj and H. Sjoland, "A 2.2 GHz CMOS VCO with inductive degeneration noise suppression," in *Proc. IEEE Custom Integrated Circuit Conf.*, San Diego, CA, pp. 197–200, May. 2001.