Dual Band CMOS Quadrature VCO using Reconfigurable LC Tank and Coupled Transistors

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Abstract: To qualify the condition of a multi standard and a multi band transceiver, a quadrature voltage controlled oscillator (VCO), which has a wide and proper tuning range, is necessary, while providing high phase noise performance and consuming low current. In this paper, a dual band quadrature VCO in 0.18 μm CMOS process is proposed. To attain the dual band operation, a reconfigureurable LC tank is adopted. To generate quadrature phase signal with low phase noise and low power consumption, series coupling transistors are attached. To enhance the phase noise performance, a current source of the source of the nmos transistor is excluded, and a filter inductor at the common source node is included. The measured phase noises of low frequency band and high frequency band are -123.8 dBc/Hz and -115.06 dBc/Hz at 1 MHz offset frequency and figureure-of-merit (FoM) of -181.8 dB and -180.5 dB with 4 mA current consumption with a 1.7 V supply.

1. Introduction

Recently, the research on multistandard and multimode transceiver chipset is vastly carried out to come up with the demands for a wireless communication satisfying various situations such as operation at multi frequency bands and standards. For meeting these conditions, a multistandard and a multiband transceiver with low power consumption and low phase noise should be considered.

In conventional VCO, a varactor is used to adjust the frequency band. But controlling the varactor cannot support sufficient tuning range. To support multiband operation and achieve proper frequency tuning range, a reconfigureurable LC tank is adopted. This structure composed of the varactor and components which are capable of band selection. Active inductor has a high Q factor and high flexibility, but it has disadvantage that extra power consumption is noticeably large. Switchable passive LC tank has frequency selectivity and does not increase extra power consumption. The LC tank can simply control frequency band selection by the combination of switchable inductor and capacitors. Operation of the LC Tank, however, may decrease quality factor because of channel resistance of transistors used in the switched LC tank. Thus, appropriate architectures are essential to improve phase noise performance [1].

In this paper, a dual band CMOS QVCO supporting multistandards is presented. For reconfigureurability, designed QVCO adopts switched LC tank. Cross coupled series transistors are used to generate quadrature phase signal. Plus, an inductor is added instead of a tail current source as a role of a filter to enhance the performance of QVCO.

Next section of this paper deals with the design of the presented QVCO and related theory. In section 3 and 4 circuit design and experimental results measured on the design are provided. Finally, Section 4 will summarize this paper.

2. Consepts of the presented Quadrature VCO

2.1 Switched LC tank for reconfigureurability

The oscillation frequency of the conventional LC VCO can be determined by varying L or C value of the LC tank.

$$f_{osc} = \frac{1}{2\pi\sqrt{L_{total}C_{total}}} \quad (1)$$

Where L_{total} and C_{total} are inductance and capacitance of LC tank including parasitic inductance and capacitance. Each part of the VCO circuit - inductor, transistor, tuned varactor - can be sources of parasitic components. By containing these parasitics, equation (1) can be rewrite. By introducing reconfigureurable LC tank concept, equation (1) can be modified as follows

$$f_{osc} = \frac{1}{2\pi\sqrt{L_{ind} + L_{line}(C_{ind} + C_{load} + C_{MOS} + C_{tune,\mathrm{var}})}} \quad (2)$$

Where L_{line} is the inter-connection inductance between inductor and transistors, C_{ind} is the parasitic capacitance of the inductor, C_{MOS} is the parasitic capacitance of the transistor and $C_{tune,var}$ is the capacitance of the varactor as a resonator capacitor. In equation (2), we can vary the inductance L_{ind} and $C_{tune,var}$ by adopting switched LC tank for changing operation frequency as shown in Figure 1.

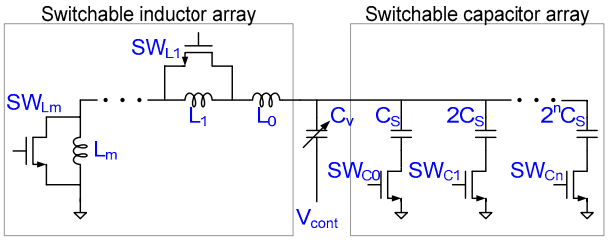

Figure.1. Half circuit of the switched LC Tank

And also the multiband operation is possible by using this concept. Selection of a frequency band is done by switching

the inductor on and off. Because the order of magnitude between capacitance and inductance in the LC tank is quite different. The unit of the inductance is nano(10^{-12}) and the capacitance is femto(10^{-15}). The difference of unit in inductor and capacitor makes the inductor to have a large effect on changing the frequency band.

The role of switched array capacitors is corse tuning at each frequency band. the Fine tuning can be done by controlling the overdrive voltage, V_{CONT}, of the varactor. Switching operations can be done by turning transistors, SW_{C1}~SW_{C4} and SW_L, on and off. However, channel resistance and parasitic capacitance at drain node fo the transistor should be optimized when switches are turned on and off. The quality factor of switched capacitor array(Q_{SCA}) is mainly controlled by the on-state resistance(R_{ON}) of the transistor in the triod region, given by

$$Q_{SCA} = \frac{1}{2\pi f_o \cdot R_{ON} \cdot C} = \frac{\mu_n C_{ox} W (V_{gs} - V_{th})}{2\pi f_o \cdot R_{ON} \cdot C} \quad (3)$$

Where f_o is the oscillation frequency, C the determined capacitance, μ_n the mobility of the NMOS transistor, V_{gs} the gate source voltage and V_{th} the threshold voltage of the device. For a higher Q factor, a on-state resistance should be made up as small as possible when the switch is turned on. That is, wide transistor can rise the overal Qualty factor of the LC tank.

However, this makes the parasitic drain capacitance(C_d) of the switch to be increased when it is off sate as the width is enlarged. The increase of the drain capacitance declines the rate of total capacitance variation. To reduce the disadvantage, the widths of the transistors must be designed as binary weighted like capacitance of array capacitors [2]. Table 1 presents the summary of the designed LC tank's reactances. The maximum and minimum reactances of switched LC tank are as follows.

Table 1. Reactance equations of switched LC tank

Total Inductance of switchable inductors(L_{SL})
$L_{SL-\min} = L_1$, with $R_{on} = R_{on,SW_L}$ $L_{SL-\max} = L_1 + L_2$
Total capacitance of switchable capacitors (C_{SCA})
$C_{SCA-\min} = [\frac{1}{C_S} + \frac{1}{C_d}]^{-1} + [\frac{1}{2^1 C_S} + \frac{1}{2^1 C_d}]^{-1} + [\frac{1}{2^2 C_S} + \frac{1}{2^2 C_d}]^{-1}$ $= (2^0 + 2^1 + 2^2) \cdot \frac{C_S C_d}{C_S + C_d}$ $C_{SCA-\max} = \left(2^0 + 2^1 + \cdots + 2^{n-1}\right) \cdot C_S$

2.2 Cross-coupled series transistor for quadrature signal

There are several techniques for generating quadrature phase signals; poly phase filter, digital frequency divider, a passive RC complex filter and cross-coupled transistors, etc. In the proposed design, the pairs of cross coupled transistors in seriese with complementary switching transistors are adopted because it shows lower phase noise performance compared to above methods. This circuit is similar to the cascode configureuratuion that is able to reduce the noise due to isolation between input and output. Figure 2 shows the proposed cross coupled transistor architecture. In the proposed design, coupling transistors, PM5-8, are adopted in seriese with switching transistors to produce quadrature phase signal outputs. And this architecture achieves low phase noise and phase robustness compared to the parallel coupled QVCO [3].

Switching transistors constructing negative-gm circuit provide power to oscillate the LC resonator. That is, negative conductances of the transistors cancle out parasitic conductance of LC tank. Thus, it leaves L and C only, leading to oscillation. Total transconductance of of the circuit is the parallel combination of each of the cross coupled active devices.

$$R_{negative} = -(\frac{2}{G_{M_N}} \| \frac{2}{G_{M_P}}) = -\frac{2}{G_{M_N} + G_{M_P}} \quad (4)$$

Where G_{MN} and G_{MP} is the transconductance of the NMOS and PMOS transistor respectively. From Hajimiri's theory reported in [4], by matching the each transconductance (G_{MN}=G_{MP}), the fall time and rising time of the output signal can be equal. Consequently, symmetricity of the signal enhances the phase noise performance. By using equation (5), the matching can be done.

$$\frac{W_N}{L_N} \cdot K_N = \frac{W_P}{L_P} \cdot K_P \quad (5)$$

Where $W_{N(P)}$ and $L_{N(P)}$ are the width and length of the NMOS, PMOS transistor respectively, $K_{N(P)}$ is the process parameter of the each transistors.

In designed QVCO, complementary stages, PM1-4 and NM1-4, take the role as above. In this architecture, crossed coupled PMOS transistors determine rising time of output signals and NMOS transistors control the falling time of the signals. If the width of each transistors are same, the falling time is lowered than the rising time because of differences of the mobility between NMOS and PMOS transistors. Therefore, the phase noise performance of the VCO can be lowered [4]. To overcome this problem, widths of NMOS transistors (NM1-4) should be bigger than that of PMOS transistors (PM1-4) which create output signals more symmetrically.

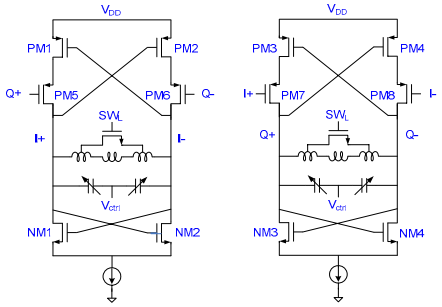

Figure 2. Cross-coupled series QVCO

3. Circuit design

A series coupled quadrature VCO using LC tank for dual band application is designed in 0.18 μm CMOS technology. The half schematic of the reconfigureurable LC tank for

dual band operation is shown in Figure 3. The LC tanks are composed of three inductors and six capacitors and two varactors in each differential VCO. The value of center-tapped inductor, *L1*, is 1.2 nH and symmetric inductor, *L2*, is 3.6 nH. Binary weighted capacitors, *C1, C2* and *C3*, are 60 fF ,120fF and 240 fF respectively. The capacitance range of varactor is from 145 fF to 430 fF. To determine frequency band seven switches and a control voltage are used in each VCO. One inductance switch, SW_L, is used for band selection; three capacitance switches on each output node, SW_{C1}, SW_{C2} and SW_{C3} are used for coarse tuning; and a varactor, C_v, is used for fine tuning as the variation of the overdrive voltage, V_{CTRL}. The Inductance can be varied to 1.2 nH and 4.8 nH by controlling inductance switch. eight types of capacitance can be by combination of three capacitor of the LC tank

The full schematic of designed VCO is shown in Figure 4. The designed circuit consists of two symmetric differential VCOs which are coupled each other directly and crossly. The designed VCO has complimentary switching stage, PM_S and NM_S. PM_C is coupled with two differential VCOs.

To achieve the quadrature phase outputs, series coupling transistors, PM_C, are used to achieve better output performances such as phase noise and phase accuracy than the conventionally used parallel coupled quadrature VCO without consuming more current as shown in Figure 4. The designed VCO adopts complimentary stage, NM_S and PM_S, compensating the loss of LC tank to keep continuing oscillation with low power consumption. In the designed circuit, current source is reduced to increase oscillation voltage swing level and to eliminate one of the noise sources. Moreover, filter inductors, L_f, are adopted to optimize the phase noise at the common source node. When doing a layout of the circuit, two filter inductors, L_f, are put together as a center tapped inductor to take the advantege of downsizing the chip size.

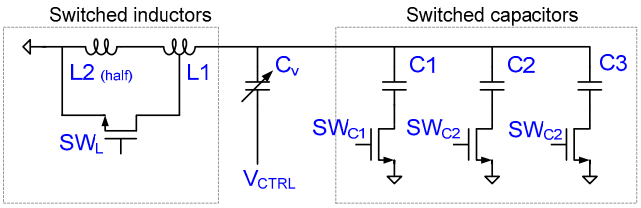

Figure. 3. Half schematic of Reconfigureurable LC tank

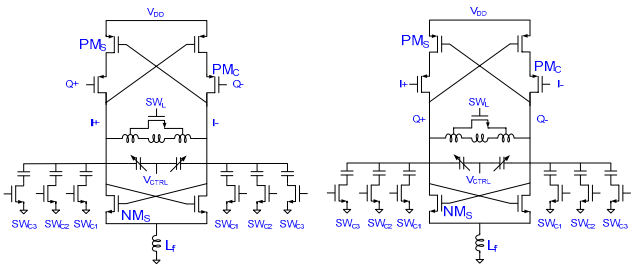

Figure. 4. Full schematic of designed QVCO

4. Experimental Result

Designed QVCO is fabricated by TSMC 0.18um RF CMOS 1P6M process. Chip dimension of the fabricated S-QVCO is 1.17 mm×0.89 mm. When inductor switch, SW_L is off, the QVCO is operated in low frequency band. And tuning on the switch let the QVCO operated in high frequency band. Tuning range of each frequency band is determined by controlling switched capacitor array. Therefore, designed QVCO can be tuned with the ranges of 1.80~2.06GHz and 4.12~4.89GHz as shown in Figure 5. The measured phase noises of low frequency band and high frequency band are -123.8 dBc/Hz and -115.06 dBc/Hz at 1 MHz offset from each carrier frequency repectively. Each result is measured at the highest frequency in each band as shown in Figure 6.

The figureures of merit (FoM) of the frequency bands are -181.8dB and -180.5dB with consuming 6.8mW. All of measured performances of proposed circuit are summarized in Table 2. The comparison with state-of-the-art about LC QVCO is in the Table 3. The photo view of the fabricated circuit is shown in Figure 7.

When comparing with other QVCO, the figureure of merit(FOM) is commonly used, defined as

$$FoM(\Delta\omega) = L(\Delta\omega) - 20\log\left(\frac{\omega_o}{\Delta\omega}\right) + 10\log(P_{mW}) \quad (6)$$

Where $L(\Delta\omega)$ is the phase noise at offset frequency, $\Delta\omega$, from the center frequency, ω_o. P_{mW} is power consumption expressed in mW.The unit is dB.

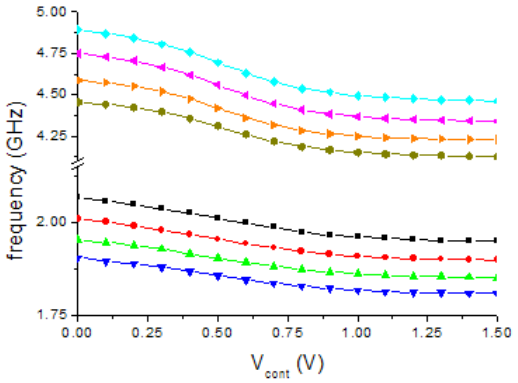

Figure. 5. The tuning characteristic of the QVCO

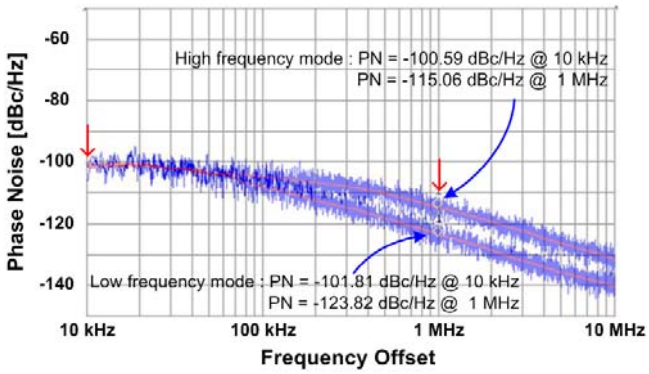

Figure. 6. the measured phase noise of the QVCO

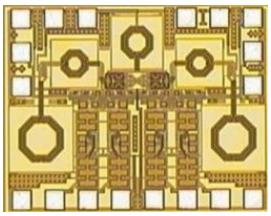

Figure. 7. Die photo of the fabricated QVCO

Table 2. Performance summary

Mode	Low Freq Band	High Freq Band.
Frequency	1.80~2.06 GHz	4.12~4.89 GHz
Phase Noise	-123.83 dBc/Hz	-115. 6dBc/Hz
Off Set	1 MHz	
Power	6.8mW	
FoM	-181.80	-180.5
Technology	TSMC 0.18 μm CMOS	

Table 3. VCO performance Comparison

Ref.	Tech. [μm]	Freq. [GH]	Power [mW]	PN [dBC/Hz]	Tuning Range Ratio	FoM (dB)
[1]	0.18 CMOS	1.73~2.49	15	-112 @ 1MHz	36%	-169.6
		4.13~4.89	15	-112 @ 1MHz	17%	-163.0
[5]	0.35 CMOS	1.91~2.27	20.8	-140 @ 3MHz	17%	-184
		1.8~2.08	32	-140 @ 3MHz	14%	-182
[6]	0.18 CMOS	4.8	14.4	-127.7 @ 3MHz	N/A	-180.2
		5.6	14.4	-127.5 @ 3MHz	N/A	-181.3
[7]	0.18 CMOS	0.82~0.87	16	-125 @ 600kHz	5.9%	-176
		1.64~1.81	16	-123 @ 600kHz	9.8%	-181
This work	0.18 CMOS	1.80~2.06	8.6	-123.83 @ 1MHz	13%	-181.8
		4.12~4.89	8.6	-115.06 @ 1MHz	19%	-180.5

5. Conclusion

By combining switched inductor and switched capacitor, a dual band reconfigureurable QVCO is designed. The reconfigureurable LC tank consists of switched inductors, switched capacitors and varactors. To generate quadrature phase signals, series coupling transistors are adopted. The performance of the proposed QVCO can be enhanced by excluding the current source. Consuming 6.8mW, the proposed QVCO achieves 1.80-2.06 GHz and 4.12-4.89 GHz tuning range, and the phase noise (1 MHz offset) is -123.8 dBc/Hz at low frequency band, and -115.6 dBc/Hz at high frequency band.

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References

[1] J.H. Kim and H.J. Yoo, “Low power low phase noise LC quadrature VCO topology,” *IEICE Trans. Fundamentals*, vol. E89-A, no. 6, pp. 1547–1551, Jun. 2006.

[2] A. Fard, T. Johnson and D. Aberg, “Design of a Dual Band 5/2.4GHz CMOS VCO for 802.11 A/B/G WLAN Transceivers,” *APCCS2004*, pp. 429-432, Dec. 2004.

[3] P. Andreani, “A low phase noise, low phase error 1.8GHz quadrature CMOS VCO,” *ISSCC2002*, pp. 290–291, Feb. 2002.

[4] A. Hajimiri and T. H. Lee, “Design Issues in CMOS Differential *LC* Oscillators,” *IEEE J. of Solid State Circuits*, vol. 34, pp. 717-724, May. 1999

[5] A. Rofougaran, J. Rael, M. Rofougaran, and A. A. Abidi, “A 900 MHz CMOS LC-oscillator with quadrature outputs,” *ISSCC1996*, pp. 392–393, Feb. 1996.

[6] A. Fard and P. Andreani, "A low-phase-noise wide-band CMOS quadrature VCO for multi-standard RF front-ends," *IEEE RFIC Symposium2005*, pp. 539-542, Jun. 2005.

[7] S. M. 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, pp. 74-81, Jan. 2006.