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CMOS Active Inductor Based Voltage Controlled Oscillator

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ABSTRACT

A Tunable Active Inductor (TAI) based Voltage Controlled Oscillator (VCO) for Radio Frequency (RF) applications ranging from 670 MHz-1.53 GHz is presented. A design of low phase noise and compact VCO is proposed. In order to lower the phase noise of VCO, its RF output power has been improved. The use of low voltage active in-ductor circuit reduces the power dissipation of VCO. The single ended CMOS active inductors with minimum number of transistors are used to consume less die area of VCO circuit. The low power dissipation of the circuit have high efficiency to generate output RF power. A supply independent variable current source tunes the VCO. The post layout design is simulated in Cadence spectreRF using TSMC 180 nm process libraries. The VCO circuit shows the phase noise variation from -124 to -126 dBc/Hz and an active area of 0.0049 mm^2. The VCO core circuit, excluding output buffers, consumes 10 mW at 1.8 V supply voltage.

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1. INTRODUCTION

Today the emerging field of wireless communication has resulted into number of services from several megahertz to multi-gigahertz frequency bands. The performance of RF front-end mainly relies on the performance of the individual RF blocks. The frequency synthesizer is used to generate the multiple numbers of frequencies from a reference frequency. The voltage controlled oscillator is most pertinent block of frequency synthesizer. Low phase noise of VCO shows better spectral purity of frequency synthesizer. LC resonator based VCOs are widely used for RF applications instead of ring oscillators due to better phase noise performance [1]. To achieve low phase noise VCO, various techniques have been used such as switched capacitors [2] switched inductors [3], [4], and high K transformers [5]. But, due to the passive component like inductor, LC resonator based VCO consumes more die area. Therefore, to make the VCO compact, gyrator based active inductor technique is preferable [1]. The presented VCO shows high RF output power. The high output power VCO also reduces the driver stages of the power amplifier block of the transmitter. Subsequently, it reduces the size and power dissipation of the whole transmitter.

To tune the active inductor based VCO, various methods have been proposed as discussed in literature. In [1], voltage controlled passive resistor was used in conventional single ended cascode active inductor topology. It showed the high quality factor but the price paid was low phase noise. The tunable differential active inductor circuit was implemented in [6] and [7] to enhance the phase noise performance. But the differential configuration consumes more die area. The results of active and passive inductor based VCO(s) are also compared in literature. Proposed circuit exhibits low phase noise with consumption of less die area.

The organization of paper is as follows. The conventional VCO topology is described in section 2. The active inductor is described in section 3 and the tuning mechanism is discussed in section 5. The proposed VCO circuit is presented in section 4. The design and simulation results of VCO are presented in section 5. Finally, conclusions are summarized in section 6.

2. ACTIVE INDUCTOR

The active inductor presented in Figure 1 was used for reducing the supply noise in PC boards [8]. The single-transistor current sources in the circuit can be used for low voltage designs. The negative transconductance is realized by using M2 which is NMOS based common source configuration. Transistors M1, M3 and M4 form the positive transconductance where the current mirror contained of M3-M4 is used to invert the negative transconductance of M1, also configured in common source connection. M2 converts the voltage across C1 to a current and makes it to flow at the input port.

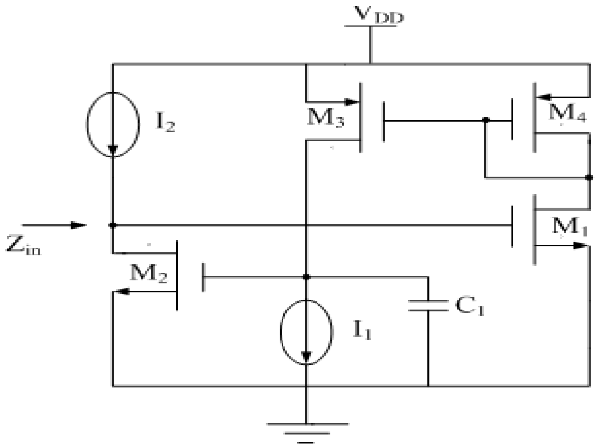

Figure 1. Low voltage active inductor [8]

The current reuse method has been used in modified low voltage active inductor as shown in Figure 2. The negative transconductance is realized by using M_2 which is PMOS based common source configuration. The gate terminals of transistors M_5 and M_6 are tied together at node V_o.

2.1. Small signal analysis

The inductive behaviour of the modified active inductor circuit has been verified through the small signal analysis. Figure 2 shows the small signal model of proposed circuit shown in Figure 1.

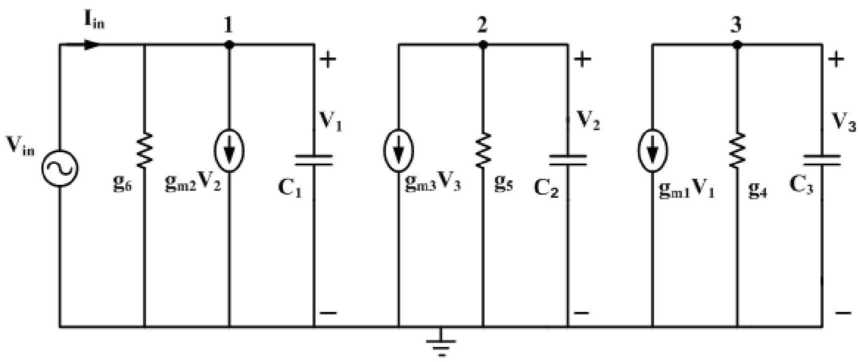

Figure 2. Small signal equivalent circuit of Figure 2

The input admittance at the input port can be expressed as,

$$Y_{in} = \frac{[s(C_2g_4+C_3g_5)g_6+C_1g_4g_5]+ g_{m1}g_{m2}g_{m3}}{s(C_2g_4+C_3g_5)+ g_4g_5} \quad (1)$$

From the rational function as shown in equation 1, the equivalent components as inductance (L), series resistance (R_s), capacitance (C_p), and parallel resistance (R_p) can be expressed as,

$$L = \frac{C_2g_4+C_3g_5}{g_{m1}g_{m2}g_{m3}} \quad (2)$$

$$R_s = \frac{g_4g_5}{g_{m1}g_{m2}g_{m3}} \quad (3)$$

$$C_p = C_1 \quad (4)$$

$$R_p = \frac{1}{g_6} \quad (5)$$

The bode plot of the modified active inductor exhibits an inductive characteristics in the frequency range $\omega_z < \omega < \omega_p$.

$$\omega_z = \frac{g_{m1}g_{m2}g_{m3}}{(C_2g_4+C_3g_5)g_6+C_1g_4g_5} \quad (6)$$

$$\omega_p = \frac{g_4g_5}{C_2g_4+C_3g_5} \quad (7)$$

where $C_j = C_{gsi}$i (i = 1,2,3) and $g_i = g_{dsi}$ (j =4,5,6).

Equation 2 shows that the equivalent inductance depends on the circuit parameters including C_2, C_3, g_4, g_5, g_{m1}, g_{m2} and g_{m3}. It is also observed that the equivalent inductance is strongly dependent on gm_1, gm_2, and gm_3. As the voltage V_0 increases transconductance of M_1, M_2 and M3 increases and equivalent inductance decreases. In presented circuit, single tuning is provided to tune the inductance. To tune inductance and quality factor separately, capacitor C_1 at node 1 can be replaced with varactor.

3. VARIABLE CURRENT SOURCE

One key advantage of active inductors over their spiral counterparts is the large tuning of their inductance. The gyrator-C based active inductors can be tuned either by changing the load capacitance or by varying the transconductances of the tranconductors [10]. A novel approach to use a supply independent current source to tune the active inductor circuit is proposed here. Figure 3 presents a supply independent current generator with degeneration source resistor R_d. The self biased circuit is supply independent but still dependent on process and temperature variation. To minimize the channel length modulation, the channel length of all the transistors in Figure 4 has been considered higher. The degenerated resistor of variable current source can be defined as,

$$R_d = \frac{1}{\mu_n C_{ox}\left(\frac{W}{L}\right)_c (V_{ctrl}-V_{thn})} \quad (9)$$

$$I_{out} = \frac{2}{\mu_n C_{ox}\left(\frac{W}{L}\right)_9} \frac{1}{R_d^2}\left(1-\frac{1}{\sqrt{K}}\right)^2 \quad (10)$$

Where K shows the size ration of transistors M_9 and M_{10}. The current will flow as long as the K is not equal to zero. In presented work, K is chosen as 1.5. Over the entire controlled voltage (V_{ctrl}) range, M_c remains in triode region and transistors of NMOS and PMOS current mirrors in saturation region. With increased value of V_{ctrl}, voltage at V_o increases and provides the variable voltage at gate terminals of M_5 and M_6.

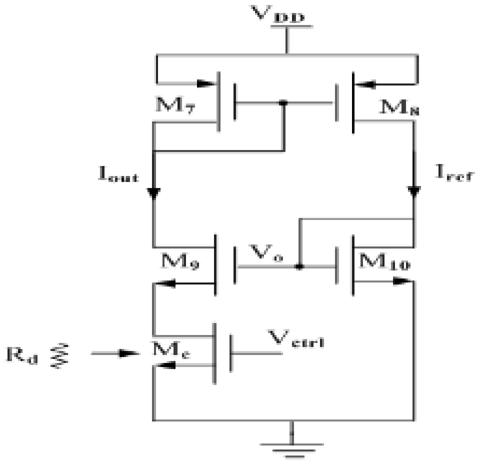

Figure 3. Variable current source [9]

4. PROPOSED VCO CIRCUIT

The distinct illustration of the proposed differential mode active inductor based VCO is shown in Figure 4. The modified active inductor as presented in Figure 2 has been used in VCO circuit. A variable current source controls the VCO frequency. At zero differential voltage, both switching MOSFETs of cross coupled pair remain in saturation. Furthermore, the cross coupled pair shows a small signal negative conductance that initiates the oscillations. As the control voltage (Vctrl) gradually increases, the differential voltage drives one MOSFET of cross coupled pair into triode and tuns off the other one. The FET in triode region loads the active inductor/resonator circuit.

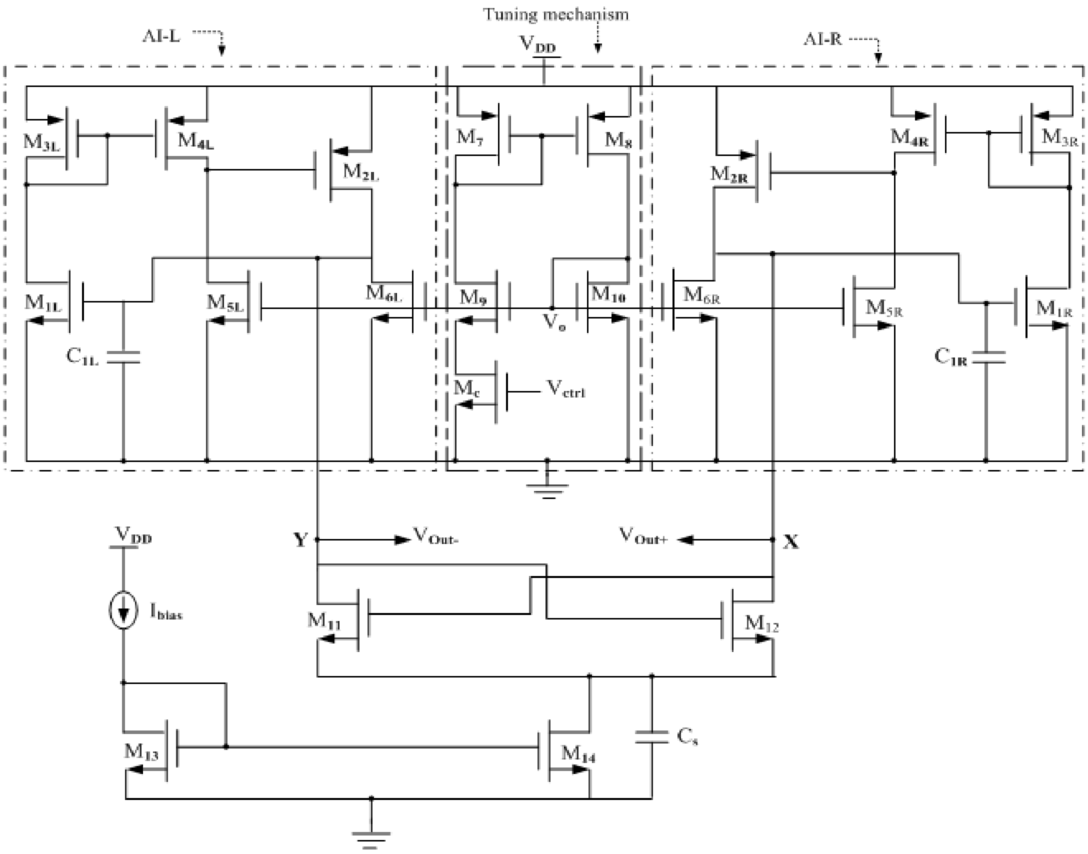

Figure 4. Proposed tunable active inductor based voltage controlled oscillator

4.1. VCO Start-up Conditions

A simplified equivalent circuit of the VCO is illustrated in Figure 5. To start the oscillation, the negative conductance provided by cross coupled transistor pair (M_{11} and M_{12}) should be sufficiently large to compensate the loss of active inductor/-resonator circuit. To ensure about the oscillations, the negative conductance of cross coupled pair is set three times larger than the required one.

$$\frac{1}{g_{m11}} \approx 3R_{p1} \tag{11}$$

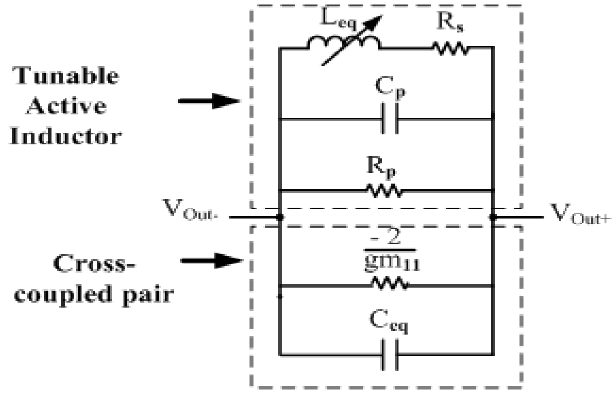

Figure 5. Simplifed VCO circuit

4.2. VCO Frequency Tuning

In VCO design, variable current source is used to tune the coarse frequency. As V_{ctrl} increases, it increases the gate voltage of M_9 and M_{10} and hence provides the biasing to AI-L and AI-R. The resonance is measured between X and Y. Variable capacitor at node X and Y can be used for fine tuning of VCO. The operating oscillation frequency can be calculated as,

$$\omega_{osc} = \frac{1}{\sqrt{L\,(C_{gs12}+C_p)}} \tag{12}$$

4.3. Phase Noise

Phase noise defines the spectral purity of the VCO output frequency. It is a important design param eter of VCO for RF applications. From Leeson's model, phase noise can be defined as,

$$£_{(\Delta\omega)} = 10\log\left[\frac{2\,k\,T}{P_{sig}}\left(\frac{\omega_0}{2\,Q\,\Delta\omega}\right)^2\right] \tag{13}$$

Where $£_{(\Delta\omega)}$the single ended spectral noise density at a frequency is offset $\Delta\omega$ away from the fundamental frequency ω_0 and P_{sig} is the power of signal [11]. Eq. (13) shows that a very efficient way to reduce the phase noise of VCO is increasing the signal power.

4.4. DC-to-RF Power Efficiency

The RF to DC power ratio of VCO is expressed as,

$$\eta = \frac{P_{RF}}{P_{DC}}$$

Low power dissipation of active inductor helps to reduce the power dissipation of VCO. Subsequently,high DC to RF power efficiency has low level of power dissipation.

5. SIMULATION RESULTS

The layout of proposed core VCO circuit is shown in Figure 6. VCO transistor dimensions are shown in Table 1. The post layout simulations of proposed VCO circuit are presented. Figure 7 and Figure 8 depict the variation of VCO output frequency and phase noise variation as a function of Vctrl. VCO frequency tuning range is found as 78 %. Due to the higher output impedance at X and Y, VCO output power is found between +21 dBm to +22 dBm. Using Equation 14, the DC-to-RF power efficiency is obtained as 15.84 % which is observed highest among reported VCO circuits. Along with the higher power efficiency, the proposed circuit shows the output swing of +/- 600 mV.

Table 1. Circuit Parameters of VCO

Transistors	W/L (μm/μm)
M_{1L},M_{4L},M_{2L},M_{1R},M_{4R},M_{2R}, M_9	15/0.18
M_{3L},M_{3R}, M_7, M_8, M_{10}	10/0.18
M_{5L},M_{6L}, M_{5R}, M_{6R}	5/0.25
M_c	8/0.25
M_{11}, M_{12}	40/0.18
M_{13}, M_{14}	10/0.25

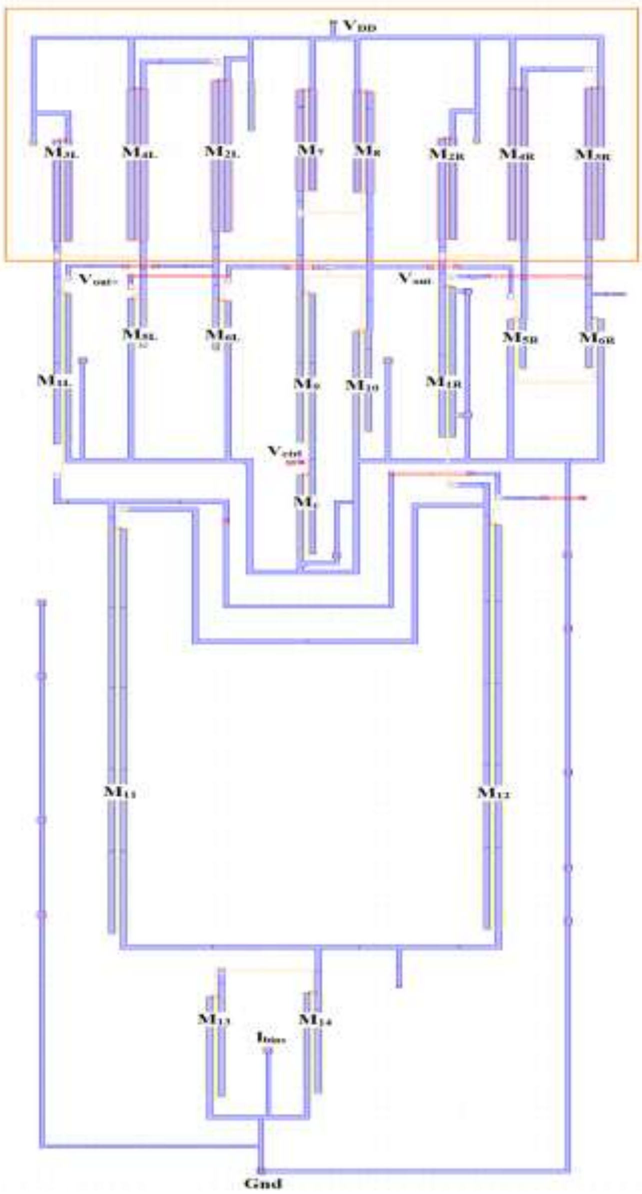

Figure 6. Proposed VCO layout

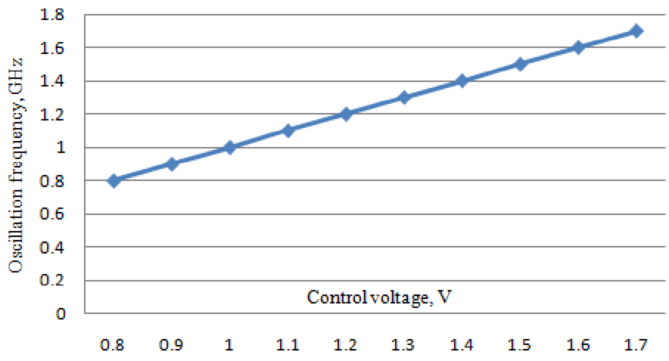

Figure 7. VCO output frequency as a function of control voltage V_{ctrl}

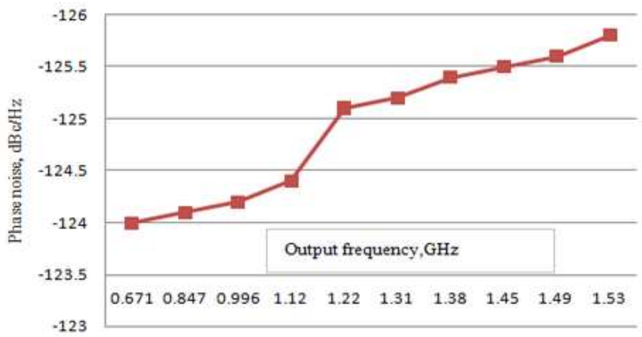

Figure 8. VCO phase noise (at 1MHz offset frequency) as a function of control voltage V_{ctrl}

Table 2 shows measured parameters of presented active inductor based VCO as well as that those of other reported work. The phase noise at 1MHz frequency offset is significantly lesser in the proposed VCO. It also demonstrates better DC to RF power efficiency and consumes less area.

Table 2. VCO Performance and Comparison

	This work	R.Mukho 2005 [1]	L.Lu 2006 [6]	Xu 2011 [7]	Roy 2015 [12]
Process	0.18-µm CMOS	0.18-µm CMOS	0.18-µm CMOS	0.18-µm CMOS	0.18-µm CMOS
Tuning range (GHz)	0.6-1.53	0.5-2	0.5 -3	0.83 -3.72	0.98 -1.1
Phase noise (dBc/Hz)	-124 ~ -126 @1MHz offset	-79 ~ -90 @1MHz offset	-101 ~ -118 @1MHz offset	-104 ~ -109 @1MHz offset	-125 @1MHz offset
Power dissi-pation(mW)	10.2	13.8	6~28	13	48
DC-RF power efficiency (%)	15.84	0.09	0.14	6.25	5.7
Area $(mm)^2$	0.0049	0.09	0.045	0.108	0.455
Technique	Active Inductor	Active Inductor	Active Inductor	Active Inductor	Passive Inductor

6. CONCLUSION

A conventional low voltage active inductor circuit has been modified to use the current reuse technique. A new mechanism to tune the active inductor is used. Low voltage active inductor and less number of transistors consume less power and enhance the output RF power. Subsequently, phase noise of VCO is significantly decreased compared to passive inductor based VCO.

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