Active Inductor with Feedback Resistor Based
Voltage Controlled Oscillator Design for
Wireless Applications

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Abstract—This paper presents active inductor based VCO design for wireless applications based on analysis of active inductor models (Weng-Kuo Cascode active inductor & Liang Regular Cascode active inductor) with feedback resistor technique. Embedment of feedback resistor results in the increment of inductance as well as the quality factor whereas the values are 125.6@2.4GHz (Liang) and 98.7@3.4GHz (Weng-Kuo). The Weng-Kuo active inductor based VCO shows a tuning frequency of 1.765GHz -2.430GHz (31.7%), while consuming a power of 2.60 mW and phase noise of -84.15 dBc/Hz@1MHz offset. On the other hand, Liang active inductor based VCO shows a frequency range of 1.897GHz -2.522GHz (28.28%), while consuming a power of 1.40 mW and phase noise of -80.79 dBc/Hz@1MHz offset. Comparing Figure-of-Merit (FoM), power consumption, output power and stability in performance, designed active inductor based VCOs outperform with the state-of-the-art.

Keywords—VCO, active inductor, inductance, quality factor, phase noise, figure-of-merit

I. INTRODUCTION

In the modern wireless communication system, the voltage controlled oscillator (VCO) exhibits a very outstanding contribution and has become counterpart in this sector [1]. VCO is a fundamental comprising element of PLL (Phase Locked Loop), which is the basic building block of RF transceiver [2]. Furthermore, the frequency synthesizers, high efficient transmitter, ADC (analog-to-digital converter), local oscillator have a fundamental inclusive part, VCO [3-6]. Small silicon area, low power consumption, low phase noise and wide tuning range are the basic performance parameters of a VCO. Ring Oscillator and LC oscillator are mostly used for high frequency applications. Small silicon area consumption and wide frequency range are the two key advantages of the ring oscillator. But it has a main drawback of poor phase noise performance, whereas LC VCO has the ability to surmount this drawback.

However, LC VCO exhibits a low tuning scope and has a very high silicon area consumption which emerges due to spiral or passive inductor [7]. This drawback can be overcome by replacing the passive inductor with active inductor. Moreover, in perspective of quality factor, silicon area consumption and tunability the active inductor outperforms the spiral inductor [8]. The active inductor basically utilizes the gyrator-C topology, which is in feedback configuration. By embedding a resistor ($R_f$) in the feedback path a good contribution in the improvement of quality factor can be achieved, thereby in phase noise performance.

This writing has a seven consisting section where section II expatiates various active inductor topologies with and without feedback resistor. Section III explicates the simulation and corresponding results, graphs. The designs are proposed at section IV. Section V contains a broad clarification, discussion and comparison of simulation results of the proposed VCOs, which is concluded by section VI.

II. ACTIVE INDUCTOR TOPOLOGIES

A. Basic Gyrator- C Active inductor:

A Gyrator-C active inductor is formed by two consecutive transconductors (for example MOSFET) with one terminal is connected to a capacitor. It can be designated as single ended if one port is connected to a ground or any power supply [9]. The schematic representation (Fig.1) and the corresponding equations are given below.

\[ Z_{in} = \frac{g_{ds2}g_{ml2}}{s(C_{gd2}g_{ml2}+C_{gd2}+C_{gd1})} + \frac{s(C_{gs2}+C_{gd2}+C_{gd1})}{(sC_{gd2}+g_{ds2}+g_{m2})(s(C_{gs2}+C_{gd1})+g_{m2})} \]

\[ G = g_{ds2} + g_{ml2} \quad L = \frac{g_{ds2}}{g_{m1}g_{m2}} \]

\[ R_s = \frac{g_{ds1}}{g_{ml2}g_{m2}} \quad C = C_{gs1} \]

The self-resonant frequency is given by, $\omega_o = \frac{g_{m1}g_{m2}}{\sqrt{C_{gs1}C_{gd2}}}$

The equations stated above are the expressions for equivalent input impedance, conductance, inductance, series resistance, parallel capacitance and self-resonant frequency. As the Q factor is the ratio of the imaginary part and real part of
 impedance, then by improving the inductance without affecting others a high-Q factor active inductor can be accomplished. Therefore, a new technique, that is employment of a feedback resistor from the drain output of $M_1$ to the gate input of $M_2$, shows a tremendous contribution in this case. [9]

$$G = g_{ds2} + \frac{g_{m1}}{1 + R g_{ds1}}$$

$$L \approx \frac{C_{gs2} \left( 1 + R g_{ds1} \right)}{g_{m1} g_{m2}}, \quad R_s \approx \frac{g_{ds1}}{g_{m1} g_{m2}} \quad \text{and} \quad C \approx C_{gs1}$$

(2)

Now the new analyzed resonant frequency can be expressed by the equation given below

$$\omega_o = \sqrt{\frac{g_{m1} g_{m2}}{C g_{gs1}}}$$

Equations (2) are the corresponding equations of $G \omega L$, $R_s$ and $C$. It is clear that the inductance is increased by a factor of $(1 + R g_{ds1})$ which results in the increment of the quality factor. Moreover, another major contributing factor of quality factor $R_s$ remains constant and so it has no impact on the quality factor. [9]

B. Weng-Kuo Cascode Active Inductor:

An active inductor which utilizes the current reuse cascode was introduced by Weng and Kuo. The noteworthy advantage of this topology is that, it provides the scope of tuning inductance and quality factor independently [10]. The schematic representation of Weng-Kuo Cascode Active Inductor is depicted in Fig. 2.

Fig. 2. Weng-Kuo Cascode active inductor. (a) Without feedback resistor. (b) With feedback resistor.

Here $g_{m1}$ is relative to $J_1 + J_3$ but $g_{m3}$ just corresponding to $J_1$. The other equations are cited below

$$L = C_{gs1}, \quad G = g_{ds2} + g_{m1} \approx g_{m1}$$

(3)

The resonant frequency and the quality factor at resonant frequency are given by

$$\omega_o = \sqrt{\frac{g_{m1} g_{m2}}{C g_{gs1}}}$$

and

$$Q(\omega_o) = \frac{g_{m1} L}{R_s} = \frac{g_{m1} g_{m2} C_{gs2}}{g_{ds1} g_{ds3} C_{gs1}}$$

Tunibility of $\omega_o$ can be achieved by variation of $g_{m1}$ and $g_{m2}$, but for $Q$ variation of $g_{m1}$ is enough. So the tunibility of $Q$ will no longer depends on $\omega_o$ [10].

Now introduction of a feedback resistor as in the previous case will generate a quite different condition. The analyzed equations for employing the feedback resistor from the drain output of $M_3$ to the gate input of $M_2$ are given below.

$$L \approx \frac{C_{gs2} \left( 1 + R g_{ds1} \right)}{g_{m1} g_{m2} g_{m3}}, \quad R_s \approx \frac{g_{ds1} g_{ds3}}{g_{m1} g_{m2} g_{m3}} \quad C \approx C_{gs1}, \quad G \approx g_{ds2} + \frac{g_{m1}}{1 + R g_{ds1}}$$

(4)

$$\omega_o = \sqrt{\frac{g_{m1} g_{m2}}{C g_{gs1}}} \quad \text{and} \quad Q(\omega_o) = \frac{g_{m1} L}{R_s} = \frac{g_{m1} g_{m2} C_{gs2} \left( 1 + R g_{ds1} \right)}{g_{ds1} g_{ds3} C_{gs1}}$$

C. Liang Feedback resistance regular cascode active inductor:

The performance of Weng-Kuo active inductor can be further improved by replacing the cascode with a regular cascode. The idea of using regulated cascade was introduced in Manetakis Regulated Cascode Active Inductor [11]. Again it was further upgraded by J. Liang, where a feedback resistor was embedded [12]. The analysis of both cases will show the effect of regulated cascade and regulated cascode with feedback resistor.

![Diagram](image-url)

Fig. 3. (a) Manetakis regular cascode active inductor. (b) Liang feedback resistor regular cascode active inductor.

Manetakis regulated cascode active inductor employs two MOSs $M_3$ and $M_4$ which will ultimately reduce the series resistance $R_s$ cause the increment of the $Q$ factor [11]. The corresponding equations are given below

$$L = C_{gs2}, \quad G = g_{ds2} + g_{m1} \approx g_{m1}$$

(5)

The resonant frequency and the quality factor at resonant frequency are given by
\[ \omega_o = \frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}} \]

and

\[ Q(\omega_o) = \frac{\omega_o L}{R_s} = \frac{g_{ds1}g_{ds2}}{g_{ds1}g_{ds2} + \frac{g_{m1}}{1+R_g g_{ds1}}} \frac{g_{m1}g_{m2}g_{m3}g_{m4}}{C_{gs1}} \]

The employment feedback resistor \( R_s \) will cause further improvement in the \( Q \) factor due to increment of the inductance [12]. The corresponding equations are given below.

\[ L \approx \frac{C_{gs2}(1+R_g g_{ds1})}{g_{m1}g_{m2}} \frac{g_{ds1}g_{ds2}}{C_{gs2}(1+R_g g_{ds1})} \]

\[ C \approx \frac{C_{gs1}}{g_{m2}} \quad G \approx g_{ds2} + \frac{g_{m1}}{1+R_g g_{ds1}} \quad \omega_o = \frac{g_{m1}g_{m2}}{C_{gs1}(1+R_g g_{ds1})} \]

\[ Q(\omega_o) = \frac{\omega_o L}{R_s} = \frac{g_{ds1}g_{ds2}g_{ds4}}{g_{ds1}g_{ds2} + \frac{g_{ds3}}{1+R_g g_{ds1}}} \frac{g_{m1}g_{m2}g_{m3}g_{m4}}{C_{gs1}} \]  

### III. SIMULATION OF ACTIVE INDUCTOR

Since the ideal current sources \( I_1, I_2 \) and \( I_3 \) are impractical, so these will be replaced by saturated MOSs, which act as current source. The s parameter simulation was performed to achieve the graph of inductance and \( Q \) factor. The value of feedback resistor is 1KΩ. The new schematic diagram of Weng-Kuo Cascade Active Inductor and Liang Feedback resistance regular cascade active inductor with saturated MOS as current source along with W/L ratios are shown in Fig. 4.

The simulation is performed with a power supply of \( V_{DD}=1V \) and a biasing voltage of \( V_b=0.5 \) V. For all saturated pMOSs as current sources the \( \frac{W}{L} = 4\mu m/120nm \) and nMOSs \( \frac{W}{L} = 6\mu m/300nm \) are used.

<table>
<thead>
<tr>
<th>MOS</th>
<th>Width(μm)</th>
<th>Length(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>12</td>
<td>120</td>
</tr>
<tr>
<td>M2</td>
<td>22</td>
<td>140</td>
</tr>
<tr>
<td>M3</td>
<td>25</td>
<td>140</td>
</tr>
<tr>
<td>M4</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>M5</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>M6</td>
<td>4</td>
<td>300</td>
</tr>
<tr>
<td>M7</td>
<td>4.2</td>
<td>300</td>
</tr>
</tbody>
</table>

Fig. 5 (a). Graphical representation of inductance vs frequency of selected active inductors.

Fig. 5 (b). Graphical representation of quality factor vs frequency of selected active inductors.

From fig. 5(b), it can be seen that the quality factor of Liang regular cascade active inductor is greater than the Weng-Kuo active inductor. It occurs as the inductive value is greater in case of first one than the second. Again the series resistance \( R_s \) is divided an additional terms \( g_{ds1}, g_{m3} \) and \( g_{m4} \) due to regular cascode in Liang regular cascade active inductor. These two effects have an overall contribution in the increment of \( Q \) factor for Liang regular cascade active inductor. The maximum inductive values are 12.86nH@3.8 GHz (Liang) and 7.94nH@5.2GHz (Weng-Kuo). Similarly, the maximum \( Q \) factors are 4.26@1.5 GHz (Liang) and 3.69@2.1GHz.

Figure 6 depicts the case where the resistor is imbedded. As the inductance is increased by a factor of \((1 + R_f g_{ds1})\), so the numerical values of maximum inductance increase to 30.9nH and 27nH in both cases. Now the upgraded values of quality factors are 125.6@2.4GHz (Liang) and 98.7@3.4GHz (Weng-Kuo). The power consumption is 429.9μW for Liang regular cascode, where it is 474.1μW for Weng Kuo cascode active inductor.
Fig. 6 (a). Graphical representation of quality factor vs frequency of selected active inductors with feedback resistor.

Fig. 6 (b). Graphical representation of quality factor vs frequency of selected active inductors with feedback resistor.

Fig. 7: Simplified Schematic of NMOS cross coupled LC VCO topology.

IV. NMOS LC VCO TOPOLOGY AND PROPOSED ACTIVE INDUCTOR BASED VCOs

LC VCO topology is formed by inductors in differential configuration, cross-coupled NMOS transistor’s pair, a varactor and a current source as shown in Fig. 7. Every section of this formation has its particular contribution. The inductor’s own parasitic capacitance and the varactor form the LC tank where the varactor is used to vary the oscillation frequency. In practical case, the LC tank has its own resistance which is responsible for the diminishing of the oscillation. Therefore, a high gain amplification, which is the fundamental requirement for sustaining the oscillation.

The cross-coupled NMOSs ($M_1$ and $M_2$), which are back to back connected in common source configuration provide the large voltage gain. This configuration has another major duty that it provides a phase shift of -360 degree that is one of the basic postulates of Barkhausen Criteria. Therefore two basic conditions first one is a large voltage gain and the second one is total phase shift of -360 are fulfilled by this cross coupled configuration. The residuum, that is the tail current source $I$ is used to regulate the resistance of the MOSs, so that the desired voltage gain can be accomplished for sustaining the oscillation [13]. This topology will be used for the subsequent design purpose.

Figure 8(a) and 8(b) represents the schematics of the designed active inductor based VCOs employing feedback resistors that use the previously described cross-coupled NMOS topology for VCO. The dotted section represents the active inductor’s portion, where two single ended inductors
form the differential configuration. MOS $M_{neg}$ is used as negative resistance network which provides the high gain and it utilizes saturated MOS $M_8$ (acts as current source) to regulate the resistive value of $M_{neg}$. MOS $M_{cap}$ is used as MOS capacitor where changing of $V_{con}$ engenders the alternation in capacitive value of $M_{cap}$. Out1 and Out2 are the differential ports where outputs are taken and the supply voltage $V_{DD} = 1\text{V}$ is used to drive the network. Fig. 8(a) is VCO network that employs Weng-Kuo cascode active inductor, while Fig. 8(b) employs the Liang Feedback resistance active inductor topology. Table II represents the W/L ratios for all MOSs.

V. SIMULATION RESULTS FOR THE PROPOSED VCOs

TABLE II
WIDTHS AND LENGTHS OF IMPLEMENTED TRANSISTORS
FOR THE PROPOSED VCOs

<table>
<thead>
<tr>
<th>MOS</th>
<th>Width(µm)</th>
<th>Length(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>12</td>
<td>120</td>
</tr>
<tr>
<td>$M_2$</td>
<td>22</td>
<td>140</td>
</tr>
<tr>
<td>$M_3$</td>
<td>25</td>
<td>140</td>
</tr>
<tr>
<td>$M_4$</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>$M_5$</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>$M_6$</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>$M_7$</td>
<td>4.2</td>
<td>300</td>
</tr>
<tr>
<td>$M_{cap}$</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>$M_8$</td>
<td>30</td>
<td>100 (multipliers=3)</td>
</tr>
</tbody>
</table>

The designed active inductor based VCO is simulated in 90nm CMOS process with Virtuoso Cadence 6.1.6 environment. Fig. 9(a) and 9(b) show the differential output oscillation in case of control voltage $V_{con} = 0.4\text{V}$. Simulated results indicate that Weng-Kuo based oscillator yields a differential output of 0.468V to -0.468 V, whereas the other one (Liang) has the value of 0.330 V to -0.330 V. This is because the power consumption of Liang Active Inductor based oscillator (1.4 mW) is less than other (2.6 mW).

The corresponding value of phase noises are -84.15 dBc/Hz (Weng-Kuo) and -80.79 dBc/Hz (Liang). Similarly, the corresponding output powers in dBm are 3.15 and 0.073 respectively.

![Fig. 9(a). Differential output voltage vs time for Weng-Kuo cascode active inductor based VCO.](image1)

![Fig. 9(b). Differential output voltage vs time for Liang regular cascode active inductor based VCO](image2)

Table III and Table IV represent the performance parameters for both of the designed active inductor based VCO for different tuning voltage ranging from 0V to 0.7 V. The first one has tuning frequency of 1.77 GHz to 2.43 GHz with a tuning scope of 31.7%. Similarly, the second one has a tuning range of 1.9 GHz to 2.52 GHz and in percentage form it is 28.28%. Both of the designs produce a frequency range that covers the operating frequency (2.4 GHz) for Bluetooth applications.

TABLE III
PERFORMANCE PARAMETERS FOR DIFFERENT TUNING VOLTAGE $V_{con}$
(WENG-KUO CASCODE ACTIVE INDUCTOR BASED VCO)

<table>
<thead>
<tr>
<th>$V_{con}$ (V)</th>
<th>Freq. (GHz)</th>
<th>Differential Output (P-P) mV</th>
<th>Voltage (PSS) mV@f</th>
<th>Phase Noise@1MHz offset (dBc/Hz)</th>
<th>Power Diss. @1V (mW)</th>
<th>Differential Output Power (50 Ω) @f (dBm)</th>
<th>Figure of Merit(FoM) @1MHz Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.765</td>
<td>482 to -482</td>
<td>444.9</td>
<td>-86.38</td>
<td>2.60158</td>
<td>2.965</td>
<td>-147.163</td>
</tr>
<tr>
<td>0.1</td>
<td>1.772</td>
<td>485 to -485</td>
<td>447.7</td>
<td>-86.22</td>
<td>2.60158</td>
<td>3.021</td>
<td>-147.037</td>
</tr>
<tr>
<td>0.2</td>
<td>1.817</td>
<td>483 to -483</td>
<td>454</td>
<td>-85.92</td>
<td>2.60158</td>
<td>3.142</td>
<td>-146.955</td>
</tr>
<tr>
<td>0.3</td>
<td>1.961</td>
<td>476 to -476</td>
<td>458.8</td>
<td>-85.17</td>
<td>2.60158</td>
<td>3.233</td>
<td>-146.867</td>
</tr>
<tr>
<td>0.4</td>
<td>2.216</td>
<td>468 to -469</td>
<td>454.6</td>
<td>-84.15</td>
<td>2.60158</td>
<td>3.153</td>
<td>-146.909</td>
</tr>
<tr>
<td>0.5</td>
<td>2.396</td>
<td>469 to -469</td>
<td>447.9</td>
<td>-83.84</td>
<td>2.60158</td>
<td>3.023</td>
<td>-147.277</td>
</tr>
<tr>
<td>0.6</td>
<td>2.438</td>
<td>469 to -469</td>
<td>445.3</td>
<td>-83.92</td>
<td>2.60158</td>
<td>2.974</td>
<td>-147.508</td>
</tr>
<tr>
<td>0.7</td>
<td>2.430</td>
<td>471 to -471</td>
<td>444.6</td>
<td>-83.90</td>
<td>2.60157</td>
<td>2.959</td>
<td>-147.459</td>
</tr>
</tbody>
</table>

![TABLE III](image3)

![TABLE IV](image4)
The phase noise varies from -86.38 dBc/Hz to -83.90 dBc/Hz for the first case, where -81.95 dBc/Hz to -81.04 dBc/Hz for the second case (Fig. 10). These values imply the lower sensitivity of the phase noise on the variation of tuning voltage.

A parameter that describes performance based on the three basic performance parameters phase noise, power consumption and oscillation frequency is Figure of Merit (FoM), which is given by

\[ FoM = L(\Delta \omega) + 10\log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) - 20\log_{10} \left( \frac{V_{\text{os}}} {\omega_0} \right) \]

Where \( L(\Delta \omega) \) is the phase noise at particular offset \( \Delta \omega \), \( \omega_0 \) is the oscillation frequency, \( V_{\text{os}} \) is the DC power consumption \([14]\). FoM can also be defined as \([15]\):

\[ FoM(dBF) = 20\log_{10}(\text{freq}) - \text{phase noise} - 10\log_{10}(P_{\text{diss}}) \]

Figure 11 shows the variation of frequency for different control voltages. The Weng-Kuo active inductor based oscillator has a frequency range of \((1.77 \sim 2.43)\) GHz and Liang active inductor based oscillator has a frequency range of \((1.9 \sim 2.52)\) GHz

Figure 12 shows the variation of Figure-of-Merit(FoM) with the change of tuning voltage. It is clear from the figures that the FoM is almost constant in spite of the change of tuning voltage, which indicates that the designed active inductor based oscillators have stability in performance.

The designed VCOs use active inductor that utilizes feedback resistance topology. They consume very low power along with stability of performance which is clearly illustrated from the phase noise and FoM graph. The positive value of the output power in dBm indicates the high output power of the oscillators. Table V compares the key performance parameters of the designed VCOs with other references. Though the tuning scope is less than other references, the designed oscillator outperform the other references in terms of power consumption, output power and finally the major performance parameter FoM.
VI. CONCLUSION

Active inductor with feedback resistor based VCOs have been designed and simulated efficiently for wireless applications in 90 nm CMOS technology. Starting from the basic Graytor-C active inductor, Weng-Kuo cascode active inductor (with and without feedback resistor) and Liang regular cascode active inductor (with and without feedback resistor) topologies have been analyzed and simulated to show the inductance and quality factor. Addition of feedback resistor results in the increment of inductance as well as the quality factor whereas the values are 125.6@2.4GHz (Liang) and 98.7@3.4GHz (Weng-Kuo). The active inductor with feedback resistor techniques are then applied to design NMOS cross-coupled LC VCOs and performances are verified by simulation. Simulated results show that the Weng-Kuo active inductor based VCO has tuning frequency of 1.765GHz to 2.430GHz (31.7%), while consuming a power of 2.60 mW and phase noise of -84.15 dBc/Hz@1MHz offset, while Liang active inductor based VCO has tuning frequency of 1.897GHz to 2.522GHz (28.28%), consuming a power of 1.40 mW and phase noise of -80.79 dBc/Hz@1MHz offset.

REFERENCES


