Performance Analysis of Tunable Band Pass Filter and VCO for Multiband RF Front End

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Abstract: This paper presents a design and performance analysis of tunable RF front end circuits such as RF band pass filter and VCO for multiband applications. The tunable element is an active inductor, built by MOS transistors. It is attractive due to its tunable and larger inductance values. The RF band pass filter is realized using active inductor with suitable input and output buffer stages. The tuning of center frequency for multiband operation is achieved through the controllable current source of the active inductor. The tunable range of the band pass filter varies from 3.9 GHz to 12.3 GHz. The simulation results of band pass filter have minimum noise figure of 23 dB and has less power dissipation of 2.83mW. The simulated IIP3 is -9.6dBm for 1st and 3rd order frequency of 7.94 GHz and 7.93 GHz respectively. The VCO designed using active inductor has the tuning range of 0.384 GHz to 1.620 GHz with the phase noise of -139dBc/Hz at the offset of 1MHz. It consumes less power of 1.754mW with the figure of merit of 189dBc/Hz. The designed active inductor, RF band pass filter and VCO are simulated in 180nm CMOS process using Synopsys simulation tool.

Keywords: Active inductor; Input impedance; Phase noise; Multi band RF front end

1. Introduction

The design of multi-band RF front end has stimulated the development of compact and hardware sharing transceivers in RF systems. CMOS technology plays a vital role in the design of highly integrated, low power and low cost RF systems. The block diagram of a multi-band RF front end is shown in Fig.1. An analog RF band pass filter is an essential block of RF front end to select interested band in the received signal over entire spectrum. Low noise figure, low power consumption, tuning center frequencies and better linearity are some of the major challenges in the design of multiband RF band pass filter. Voltage controlled oscillator (VCO) is an important block of the RF front end which is used in frequency synthesizers to achieve absolute synchronization of local oscillator (LO) signals. The important specifications of VCO are center frequency, tuning range, power supply voltage, power consumption and phase noise. Most of the RF band pass filters and VCO are implemented using on-chip spiral inductors [1]. But the spiral inductors cannot be realized for larger inductance values, high quality factor and smaller chip area [2]. On the other hand, active inductors can be realized for large inductance value with high resonance frequency, high quality factor, small chip area and wide range of tuning ability [3-6].

Active filters in GHz range have been designed in [7-8] and are not able to achieve the wide range of operating frequencies needed for multi standard RF systems. Widely tunable filters using varactors to change the operating frequencies have been designed in [9]. However, the varactors consume larger area and have less tuning range [10]. A fully integrated active LC band pass filter based on triple coupled spiral inductor topology has high power dissipation and less center

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frequency tuning range [11]. A second-order active band pass filter using integrated inductors implemented in Si bipolar technology consumes high power dissipation of 68mW [12].

VCOs designed using active inductors are discussed in [13-16] have wide frequency tuning ranges and consume small amounts of power has shown an interest in the design of VCOs using active inductors. Furthermore, active inductor tuned VCOs are highly integrated and more cost effective than varactor tuned VCOs [17].

This task is to design a low power, low noise tunable RF band pass filter and VCO using active inductor for center frequency tuning. Section 2 briefly describes design and simulation results of active inductor, band pass filter and VCO.

![Block diagram of multi band RF front end](image)

**Figure 1** Block diagram of multi band RF front end

## 2. Design and Simulation Results

### 2.1 Active inductor

A single ended active inductor is realized using gyrator-C topology [5] is an impedance inverter consisting of positive transconductor $G_{m1}$ and negative transconductor $G_{m2}$ connected back to back converts the port (parasitic) capacitances into an equivalent inductance. The proposed single ended active inductor with the aspect ratios in $\mu$m is shown in Fig. 2. It consists of differential pair M1 and M2 which represents the positive transconductor $G_{m1}$ between the input (node 1) and the output (node 3). The cascode pair M3 and M4 represents the negative transconductor $-G_{m2}$ between the input (node 3) and the output (node 1). Thus the $G_{m1}$ and $-G_{m2}$ forms the gyrator which converts the parasitic capacitance $C_3$ at node 3 to an equivalent inductance $L_{eq} = C_3 / G_{m1}G_{m2}$. The passive equivalent circuit of the proposed single ended active inductor is shown in Fig.3.

The differential configuration of $G_{m1}$ makes the proposed active inductor, less sensitive to noise and interference. The PMOS cascode structure of negative transconductor $-G_{m2}$, leads to possible negative resistance in series with the equivalent inductor to compensate the inductor loss. Thereby, it enhances the quality factor of the active inductor. Also, the cascode structure provides frequency range expansion by lowering the lower bound of the frequency range, thus increases the inductive bandwidth. The p-channel transistors are preferred for cascode structure as they have low noise and can be placed in separate n-wells, thus eliminating the non-linear body effect [4]. Thus, the combination of the differential configuration of $G_{m1}$ and cascode configuration of $-G_{m2}$ offers higher inductive bandwidth, higher resonance frequency and less noise.

The equivalent input impedance $Z_{in}$, can be obtained from the small signal equivalent circuit of the active inductor where $g_{m1-4}$ are the transconductances of $M_{1-4}$, $C_{1-4}$, $g_{1-4}$ are the total parasitic capacitances and conductances at nodes 1-4 respectively.

![Circuit diagram of proposed single ended active inductor](image)

**Figure 2** Circuit diagram of proposed single ended active inductor (with biasing arrangement) with the aspect ratios (W/L in $\mu$m) are M1(2.25 /0.18), M2 (2.25 /0.18), M3(4.5/0.18) & M4(4.5/0.18).

![Passive equivalent circuit](image)

**Figure 3** Passive equivalent circuit
\[ Z_{\text{in}}(s) = \frac{s^2 + \frac{g_4}{C_1} + \frac{g_1g_3C_3}{Gg_3 + g_4} + \frac{g_3}{C_1}}{s^2 + \frac{g_4}{C_1} + \frac{g_3}{C_1} - \frac{g_3}{G} + \frac{g_1g_2g_3g_4 + g_1Gg_3[gm_4 + g_4]}{Gg_3}} \]

Where \( G = gm_1 + gm_2 + g_2 \).

The format of \( Z_{\text{in}} \) shows that it is equivalent to an RLC network, as shown in Fig. 3. Theesf term in the numerator indicates the equivalent inductance and the real term indicates series resistance. From equation (1), \( L_{\text{eq}} \) and \( R_s \) can be written as,

\[ L_{\text{eq}} = \frac{g_3GC_3}{gm_1gm_2gm_3gm_4 + g_1Gg_3[gm_4 + g_4]} \]

\[ R_s = \frac{Gg_3g_4}{gm_1gm_2gm_3gm_4 + g_1Gg_3[gm_4 + g_4]} \]

The parallel capacitance \( C_p = C_1 \) and the parallel resistance \( R_p = 1/g_2 \).

The active inductor of Fig.2 with the given aspect ratios is simulated in 180nm CMOS process using Synopsys HSPICE simulator. The gate bias voltages are kept as \( V_{b1} = 0.2V \) and \( V_{b2} = 0.25V \). The controllable current sources are \( I_1 = 90\mu A \), \( I_2 = 80\mu A \) and \( I_3 = 100\mu A \). The small signal parameters, \( gm_1 = 523\mu S, gm_2 = 724\mu S, gm_3 = 273\mu S, gm_4 = 873mS, g_1 = 91\mu S, g_2 = 84\mu S, g_3 = 769\mu S, g_4 = 109\mu S, C_1 = 1.87fF, C_2 = 1.53fF, C_3 = 4.03fF, C_4 = 3.81fF \) and \( G = 1331\mu S \) are found from the operating points.

The quality factor \( Q_0 \) at \( \omega_0 \) is given as

\[ Q_0 = \sqrt{\frac{gm_1gm_2gm_4 + g_1Gg_3[gm_4 + g_4]}{Gg_3}} \]

(4)

From the real and imaginary values of the simulation results, the quality factor \( Q_0 \) is calculated to be 497 at the frequency of \( f_0 = 7.94GHz \). Fig. 6 shows the variation of \( Z_{\text{in}} \) for different values of controllable current source \( I_2 \). When \( I_2 \) is varied from 50\mu A to 120\mu A, the \( Z_{\text{in}} \) brings corresponding changes in \( R_s \) and \( L_{\text{eq}} \). Therefore, the quality factor is tuned through the controllable current source \( I_2 \). The resonance frequency \( \omega_0 \) is given as

\[ \omega_0 = \sqrt{\frac{gm_1gm_2gm_4 + g_1Gg_3[gm_4 + g_4]}{Gg_3}} \]

(5)

The center frequency \( f_0 \) is tuned through the current source \( I_3 \) of Fig. 2. Fig. 7 shows the tuning of
the active inductor for various centre frequencies. The controllable current source \( I_3 \) is varied from 30\( \mu \)A to 100\( \mu \)A for tuning the centre frequency of the active inductor. The designed active inductor has wide tuning range of 3.9GHz to 12.3 GHz. Table 1 shows the tuning of active inductor for various center frequencies for different values of controllable current source \( I_3 \).

Table 1 Center frequency tuning of active inductor

<table>
<thead>
<tr>
<th>Controllable current source ( I_3 (\mu A) )</th>
<th>Center frequency ( F_0 )(GHz)</th>
</tr>
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<tbody>
<tr>
<td>72</td>
<td>3.99</td>
</tr>
<tr>
<td>67</td>
<td>4.99</td>
</tr>
<tr>
<td>64</td>
<td>6.3</td>
</tr>
<tr>
<td>61</td>
<td>7.94</td>
</tr>
<tr>
<td>55</td>
<td>9.9</td>
</tr>
<tr>
<td>42</td>
<td>12.3</td>
</tr>
</tbody>
</table>

7.93GHz respectively and has higher spurious free dynamic range of 118.7dB. The layout of the active inductor is shown in Fig. 11.

The designed active inductor also features low power dissipation of 0.6mW. The noise output voltage varies from of 21nV/\( \sqrt{\text{Hz}} \) to 7nV/\( \sqrt{\text{Hz}} \) for the tuning range 3.9GHz to 12.3GHz. Fig. 8 shows the noise voltage \( (V^2/\text{Hz}) \) as a function of frequency. Fig. 9 shows the simulated noise figure of 3.5dB for the entire tuning range 3.9 GHz to 12.3 GHz. Fig. 10 shows IIP3 of -7.39dBm or 0.126Vpp, which has been simulated for 1st and 3rd order frequency of 7.94GHz and

2.2 Multi band RF band pass filter

The second order RF band pass filter of Fig. 12 is based on the active inductor topology. It consists of two resonators (M1, M2, M3, M4 and M5, M6, M7, M8) which are made up of single ended active inductors, coupled through the capacitance C [6]. Most of the band pass filter topologies used in thin film technology is of the coupled resonator type [18]. The advantage of coupled resonator filters is that they do not require a wide range of inductance values and are often realized using the same inductance for all resonators. The top coupled topology is one of the most commonly used. It is especially suitable to attenuate strong blocking signals in the cellular communications bands. However, in this type of filter the resonators operate in single ended mode. Min (W/L =1/0.18 in \( \mu \)m) is the common gate transistor, is used as the input buffer stage for input matching. A source follower stage Mout (W/L=1/0.18 in \( \mu \)m), is used as
an output buffer stage for output matching and to reduce the loading effect. \(R_{\text{in}}\) and \(R_{\text{out}}\) are the input and output resistances which are selected to be 1k\(\Omega\).
The controllable current source \(I_6\) is used for tuning the center frequency of the band pass filter.

The frequency response of the band pass filter with 1k\(\Omega\) at both ends (\(R_{\text{in}}\) at source and \(R_{\text{out}}\) at load) is shown in Fig. 13. It is simulated for center frequency of 7.94GHz with gain of 28dB and narrow bandwidth of 200MHz with less power consumption of 2.83mW.

With fixed \(V_{\text{b1}}\) and \(V_{\text{b2}}\), the center frequency can be tuned by varying controllable current source \(I_6\) from 5\(\mu\)A to 110\(\mu\)A. The tuning range of the band pass filter is 3.99 GHz to 12.3 GHz. The tuning can be done through the single current source which adds advantage to this band pass filter.

Table 2 lists the tuning of band pass filter for various center frequencies. Fig. 14 shows the simulation result of tuning of band pass filter for various center frequencies.

The simulated noise figure ranges from 27dB to 23dB for the entire tuning range 3.9 GHz to 12.3 GHz as shown in Fig. 15. The noise figure is 23dB for 7.94GHz. The IIP3 is -9.6012dBm or 0.1Vpp which has been simulated for 1st and 3rd order frequency of 7.94GHz and 7.93GHz respectively as in Fig. 16. The \(P_{1dB}\) compression point is -9.6dBm or 0.1Vpp from 50\(\Omega\) source and higher spurious free dynamic range 94.101(dB) has been obtained.

### 2.3 Tunable VCO

The design of VCO is shown in Fig. 17. The topology of the VCO consists of cross coupled PMOS transistors to generate negative resistance and the resonant tank circuit [19]. The cross coupled PMOS transistors have smaller 1/f noise due to lower mobility comparing to NMOS transistors, and they have less hot carrier effect [20]. Thus PMOS VCO can achieve better phase noise performance and suppression of power supply noise than NMOS VCO. The resonant tank
circuit is composed of a capacitor C and the active inductors L1 and L2. Active inductors are tunable and consume less power than spiral inductors. M3, M4, M5 and M6 forms the current reuse resistive feedback variable gain stage provides better output impedance matching. The oscillation frequency is given as equation (6) where \( L_{eq1} \) and \( L_{eq2} \) are the equivalent inductance of the active inductors L1 and L2 respectively. The equivalent inductances can be tuned through the controllable current source \( I_2 \) of the active inductors which in turn vary the oscillation frequency.

Fig. 18 shows \( V_{out^+} \) and \( V_{out^-} \) of VCO at \( f_{osc} = 1.62\text{GHz} \) for \( I_2 = 50\mu\text{A} \). Fig. 19 shows the VCO output waveforms for the different frequencies with respect to the current source \( I_2 \) of the active inductors. The tuning range of the VCO is 0.384GHz to 1.62GHz. Fig. 20 shows the simulated phase noise of -139dBc/Hz at the offset of 1MHz. It consumes less power of 1.754mW as shown in Fig 21, with the figure of merit of 189dBc/\( \sqrt{Hz} \).
3. Performance Comparison

Table 3 compares the performances of band pass filter with reported works in the literatures [21, 22] of R-F band pass filters. The comparison results show that the band pass filter features wide range of center frequency tuning capability, less power dissipation and better linearity. Table 4 compares the performances of the VCO with the reported works in the literatures [23, 24, 25] of VCOs. The comparison results show that the designed VCO features better tuning range and low power consumption.

Table 3 Comparison of band pass filter performances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ref[21]</th>
<th>Ref[22]</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>90nm 1.2V</td>
<td>0.25μm 1.8V</td>
<td>0.18μm 1.8V</td>
</tr>
<tr>
<td>Filter order</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ω0(GHz)</td>
<td>3.46</td>
<td>1.6-2.45</td>
<td>3.99 -12.3</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>1.4</td>
<td>8.6</td>
<td>2.83</td>
</tr>
<tr>
<td>NoiseFigure (dB)</td>
<td>5(at 3.46GHz)</td>
<td>17(at 2.45GHz)</td>
<td>23(at 7.94GHz)</td>
</tr>
<tr>
<td>IIP3 (dBm)</td>
<td>-10.29</td>
<td>-2.1</td>
<td>-9.6</td>
</tr>
</tbody>
</table>

4. Conclusions

The tunable RF band pass filter and VCO based on CMOS active inductor are simulated in 180nm CMOS process. The simulation results of active inductor show that the circuit has wide inductive bandwidth and high resonance frequencies. The simulation results of RF band pass filter prove that it has better tuning of center frequencies, less noise and lower power dissipation. The simulation result of VCO features lower power and better tuning range. The designed RF band pass filter and VCO are more suitable to design low power RF front end circuits.

References

Figure 20 Simulated phase noise of VCO

\[ \text{Avg. Power} = 1.754 \, \text{mW} \]

Figure 21 Average power consumption of VCO

Table 4 Comparison of VCO performances

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<thead>
<tr>
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<tbody>
<tr>
<td>Supply voltage (V)</td>
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<td>1.8</td>
<td>1.8V</td>
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<tr>
<td>Technology (µm)</td>
<td>0.25</td>
<td>0.18</td>
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<td>0.18</td>
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<tr>
<td>Frequency (GHz)</td>
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<td>2/5.8</td>
<td>2.97</td>
<td>0.384</td>
</tr>
<tr>
<td>Phase Noise (dBc/Hz)</td>
<td>-130</td>
<td>-112/-107</td>
<td>-124.2</td>
<td>-139</td>
</tr>
<tr>
<td>at 1MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (mW)</td>
<td>9</td>
<td>11.7/9.3</td>
<td>7</td>
<td>1.754</td>
</tr>
</tbody>
</table>


