# **Constant-Power CMOS LC Oscillators Using High-Q Active Inductors**

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*Abstract:* - CMOS LC oscillators using high-Q active inductors with constant-power consumption are presented. The active inductor with one feedback resistor results in a gain-boosting factor to improve the Q-value and the inductance (L) of the active inductor. Based on this high-Q active inductor, a negative resistance LC-tuned oscillator with low constant-power consumption and wide tuning-range can be achieved. Simulation results show that the improved active inductor can achieve the maximum Q-value of 1E8 and dissipate 2.5mw power consumption under 2.5 V power supply. The die size included bounding pad is about 853um × 413um. In the wide-tuning frequency range oscillator, low constant power consumption at 2.5 V power supply around 10mW is observed. This oscillator also depicts a reasonable phase noise performance of -91dBc/Hz at 600 kHz. The phase noise from 0.8GHz to 3GHz tuning-range is less than 6dBc/Hz phase noise deviation. The small die size included bounding pad is about 965um × 482um.

Key-Words: - CMOS, Active Inductor, Q-value, LC Oscillator, Phase Noise, and Power Consumption.

## **1** Introduction

The quarter-micron or below complementary metal oxide semiconductor (CMOS) technology has found an attractive alternative to GaAs and BiCMOS technologies for implementation of integrated radio frequency (RF) transceivers due to the lower cost and the possibility for integration of RF front-end and digital circuits on the same chip. Among the CMOS RF front-end blocks, the oscillator circuit is the major challenge for implementing a fully integrated transceiver. То achieve а high-performance oscillator, low power consumption, wide tuning-range, and stringent phase noise should be simultaneously considered in the RF circuit applications [1, 2]. However, a low Q-value passive spiral inductor in fabricating CMOS process will seriously limit the wide tuning-range and the phase noise. The lower Q-value spiral inductor will limit the wide tuning-range [3] and result in lower phase noise [4]. Although the low power consumption is one of the most considerations of the subjects in RF applications, the constant power consumption, which is independent of the frequency, is also a significant factor that improves the noise

production of the circuit. Recently, wide tuning-range ring oscillators in digital circuit and low phase noise LC oscillators using passive spiral inductors have been demonstrated [5]. On the other hand, CMOS active inductors have been applied in microwave/RF amplifier and oscillator designs to achieve high power gain, wide tuning-range and save chip area [6-8]. The ring oscillator circuits can achieve wide tuning-range, but the larger phase noise exits in ring oscillator circuit [9]. The LC-tuned oscillator circuits can achieve lower phase noise, but the low Q-value passive inductor limits the frequency tuning-range [10]. In addition, the oscillators using active inductors have wide tuning-range and small chip area, but the large phase noise is also encountered due to the O-value of the active inductors is not high enough [11-12]. Also, the power consumption of these oscillators will be sensitively influenced by the frequency tuning as well, resulting in extra circuit noise in different operating frequency. Therefore, it is desired to design an oscillator using high-Q active inductor to improve wide tuning-range, reasonable phase noise, and small chip area. Besides, constant power

consumption and low deviation of phase noise in target wide frequency band can be achieved.

In this paper, we propose a CMOS wide tuning-range LC oscillator using high-Q active inductors. The active inductor, simpler than the circuit of [11], results in improving both Q-value and inductance (L) of the active inductor. Based on this inductor, a negative resistance LC-tuned oscillator with wide tuning-range, reasonable phase noise, constant power consumption, and low deviation of the phase noise has been designed. These results are carried out in Agilent-ADS simulator using TSMC 0.25um CMOS process model at 2.5V.

# 2 Improving High-Q Active Inductor Design

Based on the gyrator theory [12], the simple grounded active inductor circuit and its equivalent circuit are shown in Fig. 1 (a) and (b). Each MOS transistor is modeled by the equivalent device components including  $g_m$ ,  $g_{ds}$ ,  $C_{gs}$ , and  $C_{gd}$ . Assuming  $g_m >> g_{ds}$  and  $C_{gs}$ ,  $>> C_{gd}$ , then the equivalent input impedance ( $Z_{in}$ ) of this circuit can be derived as below. The component values of the inductor are also expressed from Eq. (2) to Eq. (5).



Fig. 1 Simple active inductor and equivalent circuit

$$Z_{in} \approx \frac{(g_{ds2} + g_{m1}) + S(C_{gs2} + C_{gd1} + C_{gd2})}{(SC_{gd2} + g_{ds2} + g_{m1})(S(C_{gs2} + C_{gd1}) + g_{m2})} (1)$$

$$G \approx g_{ds2} + g_{m1} \approx g_{m1} \tag{2}$$

$$R_s \approx \frac{g_{ds1}}{g_{m1}g_{m2}} \tag{3}$$

$$L \approx \frac{C_{gs2}}{g_{m1}g_{m2}} \tag{4}$$

$$C \approx C_{gs1}$$
 (5)

where  $g_{mi}$ ,  $g_{dsi}$ , and  $C_{gsi}$  are the transconductance, output conductance, and gate-source capacitance of correspondence transistors, respectively. From Eq. (2), the increasing parallel conductance loss of G will reduce the Q-value of the active inductor. Therefore, in order to improve the performance such as the Q-value and the inductance (L), we propose high-Q active inductors with a feedback resistor. The improved high-Q active inductor circuit is illustrated in Fig. 2 (a). This circuit is composed of common source transistor  $M_1$ , common drain transistor  $M_2$ , feedback resistor  $R_f$  and two biasing current sources  $I_1$  and  $I_2$ . Feedback resistor  $R_f$  and transistor  $M_1$ construct a gain network. This network produces a gain factor to reduce the parallel conductance (G) in such a way that the internal loss of the inductor will be decreased, and then the Q value is increased. Therefore, the inductance (L) is also increased due to the feedback resistor. At high frequency, this circuit is equivalent to a lossy resonator as well, which is shown in Fig. 2 (b). The values of each component including three parameters,  $C_{gsi}$ ,  $g_{dsi}$ , and  $g_{mi}$ , are derived from Eq. (6) to Eq. (9).



Fig. 2 High-Q active inductor and equivalent circuit

$$G \approx g_{ds2} + \frac{g_{m1}}{1 + R_f g_{ds1}} \tag{6}$$

$$R_s \approx \frac{g_{ds1}}{g_{m1}g_{m2}} \tag{7}$$

$$L \approx \frac{C_{gs2}(1 + R_f g_{ds1})}{g_{m1}g_{m2}}$$
(8)

$$C \approx C_{\rm gsl}$$
 (9)

$$\omega_{0} \approx \sqrt{\frac{g_{m1}g_{m2}}{C_{gs1}C_{gs2}(1+R_{f}g_{ds1})}}$$
(10)

$$Q \approx \sqrt{\frac{g_{m1}g_{m2}C_{gs2}}{g_{ds1}^{2}C_{gs1}}} \times \left(1 + R_{f}g_{ds1}\right)$$
(11)

From Eq. (6), the effect of the factor,  $(1+R_fg_{dsl})$ , is designed to be a value greater than unity. This factor will result in the equivalent conductance loss to be minimized, as well as an increase of the equivalent inductance by  $(1+R_fg_{dsl})$  factor. The result of scattering parameter (S11) performance of the inductor is illustrated in Fig. 3. This figure can be treated as the curve following the increase of the feedback resistance  $R_f$  between 0.5GHz and 2.5GHz.



Frequency (0.5GHz to 2.5GHz)

Fig. 3 Microwave performance of the proposed high-Q active inductor (S11)

Figs. 4, 5, and 6 show the Q-value, the inductance, and the equivalent loss comparisons between the active inductor with feedback resistor  $R_f$  and the one without it.

Figure 4 and 5 indicate that in the range of 0.5GHz to 2.5GHz, the maximum Q-value is around 1E8 and the inductance changes from 5nH to 7.5nH.

The Q-value and the inductance of the active inductor with feedback resistor are higher than that of the one without it.



Fig. 4 Q-value of the proposed active inductor circuit



Fig. 5 Inductance of the proposed active inductor circuit



Fig. 6 Equivalent loss of the proposed active inductor circuit

Fig. 6 shows the minimum equivalent loss of a proposed active inductor with feedback resistor is  $1.2E-8\Omega$  and it is much smaller than that of the one without the feedback resistor between the frequency ranges of 0.5GHz and 2.5GHz. Consequently, the

active inductor has shown а significant improvement. The power consumption is only about 2.5mW under 2.5 V supply voltage, and there is lesser power consumption in this active inductor. Furthermore, in this active inductor, the external bias voltages are used to tune the characteristics of the active inductor due to the variation in the circuit implementation. Therefore, it can be achieved the performances that independent of the process variation. The comparisons between improved and original at 1.5GHz is shown in TABLE I.

Table 1 Comparisons between improved and original @1.5GHz

	Original	Improved	
Q-Value	1.4	1E8	
Loss $(\Omega)$	8	1.2E-8	
Inductance (nH)	2	5.8	
Power			
Consumption	3	2.5	
(mW)			

The moving trend of this curve inclines to the outside of the circle, indicating that the loss is decreased, but the Q-value is increased. Fig. 7 shows the curves of the S11, which the curves are move outside of the circle as the feedback resistor is increased.



Frequency (0.8GHz to 3GHz)

Fig. 7 Microwave performance of high-Q active inductor (S11) in different resistance

The Q-value at self-resonant frequency  $\omega_0$  (Eq. (10)) can be written as Eq. (11). Therefore, the Q-value is promoted with the feedback resistance  $R_f$  by  $\sqrt{(1 + R_f g_{ds1})}$  factor and the trend variation of

the Q-value is shown in Fig. 8. The Q-value is increased with the increasing feedback resistance. In Fig. 9, according to Eq. (8), the inductance of the inductor is also increased by the increasing feedback resistance  $R_f$  in the range of 0.8GHz to 3GHz. As a result, the performances of the proposed active inductor containing the Q value and the inductance may be tremendously improved with a simple loss compensation network. The layout of the proposed active included bounding pad is 853um × 413um.

Because the dc current does not pass through the feedback resistance  $R_f$ , the voltage drop of the feedback resistance is zero, and then the voltage will not be changed when the resistance  $R_f$  is varied. Consequently, power consumption of the improved active inductor can be retained constant.



Fig. 8 Q value of high-Q active inductor in different resistance



Fig. 9 Inductance of high-Q active inductor in different resistance

Therefore, the unchanged power consumption characteristic can be applied to design a constant power consumption oscillator circuit with wide tuning-range.



Fig. 10 Layout of the proposed active inductor

### **3** Oscillator Circuit Design

The chief design considerations of the oscillator are to obtain a low constant-power consumption, wide tuning-range and low phase noise. The circuit diagram of the proposed oscillator shown in Fig. 11 has a cross-coupled connection of NMOS transistors  $M_{NR}$  and  $M_{NL}$  to form a positive feedback loop for providing negative resistance, called negative impedance converter (NIC) to compensate the loss of the active inductor in the LC tank. Two improved high-Q active inductors depicted in Fig. 2 replace the conventional inductors of the LC tank. Through these active inductors a superior oscillator, being composed of M<sub>1R</sub>, M<sub>1L</sub>, M<sub>2R</sub>, M<sub>2L</sub>, M<sub>SR</sub>, M<sub>SL</sub>, M<sub>PR</sub>,  $M_{PL}$ ,  $R_{fR}$  and  $R_{fL}$ , can be completely designed. These active inductors are behaved as the equivalent inductance in this oscillator.

Because the oscillator circuit is symmetric and the Q value of the active inductor is high enough, all transistors only have the same minimum dimension, where the length and the width of each MOSFET are 0.24um and 40um, respectively. No varactors are employed in this oscillator; the oscillator frequency modulation function will be constrained. To provide an adjustable frequency range, the feedback resistance  $R_f$  of the active inductor is added to tune the desired oscillator frequency. Though the capacitance is kept unchanged, the equivalent inductance values are deviated by the resistance  $R_{f}$ . Thus, the output frequency of the oscillator will only be adjusted by  $R_{f}$ . Assume the total equivalent capacitance from the output node of the NIC is  $C_T$ , then the output oscillating frequency can be expressed as:



Fig. 11 Proposed LC voltage controlled oscillator

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{(C_{gs1} + C_T)[C_{gs2}(1 + R_f g_{ds1})]}}$$
(12)



Fig. 12 The frequency of output v.s. feedback resistance  $R_{\rm f}$ 

From Eq. (12), the frequency  $\omega_0$  is the inverse proportion of the feedback resistance  $R_{f}$ . In other words, when the feedback resistance is decreased, then the frequency will be increased, and vice versa. The output frequency shows a wide tuning frequency range. The result between the output frequency and the feedback resistance is given in Fig. 12. This figure points out the frequency has wide tuning-range, from 0.8GHz to 3GHz. Although the wide tuning frequency range is achieved, the power consumption is still constant.



Fig. 13 Oscillator power consumption v.s. tuning frequency



Fig. 14 Output amplitude v.s. tuning frequency

Fig. 13 shows that the constant power consumption of 10mW is constantly maintained in this range, 0.8GHz to 3GHz. The relationship between the output amplitude and the output frequency is appeared in Fig. 14. It indicates that the variation of the output amplitude is about 15dBm during the wide tuning-range. Besides, the phase noise in the wide tuning-range is exposed in Fig. 15. It explores that the variation of the phase noise during 0.8GHz to 3GHz is around 6dBc/Hz and the phase noise almost retains a constant value between 1.5GHz and 3GHz. Moreover, the oscillator has the reasonable phase noise below -91dBc even though the active inductors have the higher noise than the passive counterparts. Finally, this proposed circuit exhibits wider tuning-range, constant power consumption, and reasonable phase-noise. Fig. 16 is showed the layout of the oscillator. The small die

size included bounding pad is only 965 $um \times$  482um.



Fig. 15 Phase noise v.s. tuning frequency

### **4** Conclusion

A CMOS LC oscillator using an improved high Q-value active inductor is proposed. Only using a feedback resistor  $R_{f}$ , a tunable high-Q active inductor can be achieved. The power consumption of the oscillator can be retained as a constant value in a wide frequency tuning range. The phase noise depicts the uninfluenced value even though the active inductor has larger noise than the passive inductor counterparts. These simulation results of the proposed circuit are better than those of earlier publications [10-12]. Therefore, this study shows that the proposed circuit can achieve constant power consumption, wide frequency tuning-range and reasonable phase noise to fit RF requirements. The comparisons between this work and other works are shown in TABLE II.



Fig. 16 Layout of the oscillator

Table 2 Comparisons between this work and other works

	Xibo	Jo-Yi	This
	Zhang <sup>13</sup>	Foo <sup>14</sup>	Work
Frequency(Hz)	2.4G	5G	3G
Phase	-79.49	-74.6	-91
Noise(100KHz)	dBc/Hz	dBc/Hz	dBc/Hz
Power(mW)	26.25	6.86	10
Tuning Range(GHz)	0.96	0.18	2

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