# A Wide Tuning Range Voltage-Controlled Oscillator with Active Inductors for Bluetooth Applications

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*Abstract:* - In this paper, a fabricated voltage-controlled oscillator (VCO) with active inductors using TSMC 0.18µm CMOS process is presented. By employing an improved high-Q active inductor to improve the circuit tuning range, the measurement results of the VCO tuning range from 1.26GHz to 2.98GHz with circuit operating frequency at 2.4GHz achieves 71% tuning range and phase noise obtains -90dBc/Hz within 1 MHz frequency offset. The power consumption including buffer is 44.6mW in 1.8V power supply. Occupied chip area is around 0.585 × 0.679 mm$^2$.

*Key-Words:* - VCO, Tuning Range, Active Inductor, Phase Noise

## 1 Introduction

In recent years, the rapid development of wireless communication, such as WLAN, GSM and DVB is demand for integrating systems. Indeed, the fast emerging wireless technology demands low cost and low power integrated RF transceiver. Therefore, at present the popular research for the CMOS process to implement of the radio frequency integrated circuit (RFIC) [1-2]. The benefit of using standard RF CMOS process can cause integrating the whole RF transceiver on a single chip at lower cost. However, a key building block in RF transceivers is the voltage-controlled-oscillator (VCO).

It is main role is to provide a clean source of high-frequency signals in the voltage-controlled oscillator (VCO) block for RF integrated circuits [3]. The indicators of performance requirements have to be making a VCO suitable for wireless applications which low phase noise and large frequency tuning range. In the existing CMOS VCO topologies, a passive planar spiral inductor is used in tune tank of VCO, but the spiral inductors will result in many disadvantages such as large chip area and low quality factor. These issues can be overcome by using an active inductor. An active inductor has higher quality factor and smaller chip area than a spiral inductor and electrical tunable exist in an active inductor. In this paper, we propose a CMOS wide tuning-range VCO based on an improved high-Q active inductor and a NMOS cross-coupled configuration. Using external voltage, the characteristics of VCO can be tuned. The measurement results of the VCO show that the design can obtain well performance in Bluetooth applications.

## 2 Architecture

### 2.1 Active Inuctor Design

The most common one-port active inductor topology is the grounded active inductor, which is based on the "gyrator theory" containing only two transistors, which generate inductance. It is small-signal equivalent circuits based on a gyrator topology are shown in Fig.1.

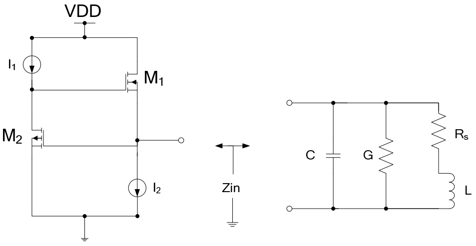

Fig.1 active inductor and equivalent circuit

$$
\begin{aligned}
&Zin \approx \frac{(g_{ds1}g_{m2}) + S(C_{gs1} + C_{gd1} + C_{gd2})}{(SC_{gd1} + g_{ds1} + g_{m1})(S(C_{gs1} + C_{gd2}) + g_{m1})} \\
&G \approx g_{ds1} + g_{m2} \approx g_{m2} \\
&L \approx \frac{C_{gs1}}{g_{m1}g_{m2}} \\
&R_s \approx \frac{g_{ds2}}{g_{m1}g_{m2}} \\
&C \approx C_{gs2}
\end{aligned}
\qquad (1)
$$

Equation (1) is expression of 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 using the high-Q active inductors with a feedback resistor [3]. The improved high-Q active inductor circuit is illustrated in Fig.2. In this design, by feedback resistance method of based on gyrator theory then to increase Q-factors and reduce the loss, the active inductor is combined with two transistors, a feedback resistor, and current sources. The characteristics of the active inductor can be improved by using the feedback resistance ($R_f$). By derived, the component value of the equivalent circuit can be expressed refer to (2).

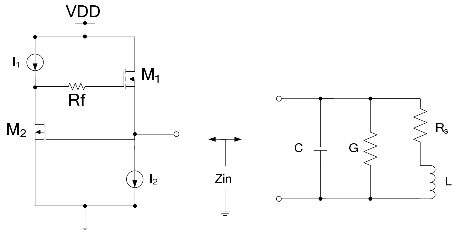

Fig.2 High-Q active inductor and equivalent circuit

$$\begin{aligned} G &\approx g_{ds1} + \frac{g_{m2}}{1+R_f g_{ds2}} \\ L &\approx \frac{C_{gs1}(1+R_f g_{ds2})}{g_{m1} g_{m2}} \\ R_s &\approx \frac{g_{ds2}}{g_{m1} g_{m2}} \\ C &\approx C_{gs2} \end{aligned} \qquad (2)$$

From equation (2),the effect of the factor, $(1+R_f g_{ds2})$ designed to be a value greater than unity. This factor will result in the equivalent conductance loss (G) to be minimized, as well as an increasing of the equivalent inductance (L) by $(1+R_f g_{ds2})$ factor. The result of scattering parameter (S11) performance of the inductor is exposed in Fig.3. It can be seen that between 1GHz and 5GHz, the curve is inclined to the outside of circle, indicating that the loss is decreased, and the smallest loss at frequency 2.4GHz.

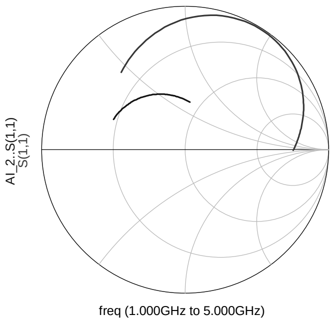

Fig.3 Simulated S-parameters of feedback resistance active inductor ($R_f$) and active inductor (without $R_f$); the frequency region is form 1GHz to 5GHz.

This active inductor was fabricated by a TSMC 0.18μm RF CMOS process with using ADS EDA tool to required frequency 2.4GHz for the application of low-frequency band 2.4 GHz Bluetooth systems, as shown in Fig.4. It has maximum 90 with scan frequency 1GHz to 5GHz at the 2.4GHz and Fig.5 show the frequency is tuned of inductance for 3.6nH to 11nH.

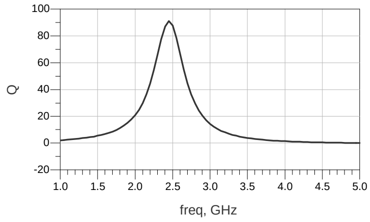

Fig.4 Maximum Q-factor at the required frequency 2.4GHz.

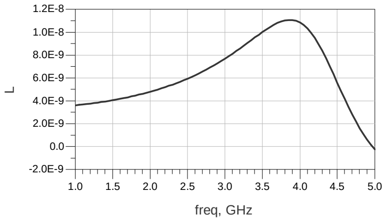

Fig.5 The Simulated inductance of feedback resistance active inductor

## 2.2 Voltage Controlled Oscillator with Active Inductors

Fig.6 shows the proposed VCO, it is composed with two active inductors and cross-coupled configuration. In this VCO circuit, involving transistors ($M_1$-$M_8$) and feedback resistor ($R_{f1}$ and $R_{f2}$) emulate tunable active inductors. The active inductors are combined with the parasitic capacitors to form the resonator.

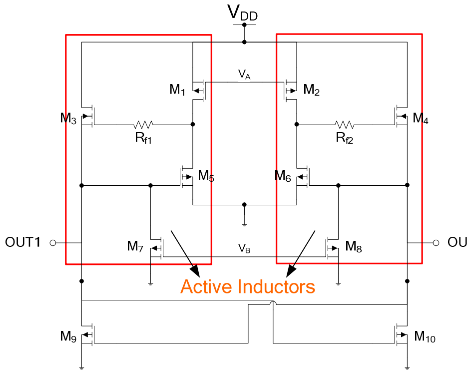

Fig.6 Schematic of proposed LC Oscillator

Transistors M1, M2 and M7, M8 are formed current source to vary the oscillated frequency. The voltage VA and VB of the current source are used to control transistors M1, M2 and M7, M8, respectively. The bias of the VA and the VB are tuned then the inductance of the active inductors will be changed. The various range of oscillated frequency will be achieved. In the 2.4GHz oscillated frequency, the bias VA and VB are 1V and 0.667V at VDD = 1.8V, respectively. Furthermore, the oscillation frequency and tuning range will be affected by the value of the selected feedback resistance (Rf1, 2). Assume the total equivalent capacitance from the output node of the NIC is $C_T$, and then the output oscillating frequency can be expended as refer to Eq. (4), the frequency $\omega_0$ is the inverse proportion of the feedback resistance $R_f$, which oscillation frequency will be decreased if the feedback resistances are increased. The cross-coupled configuration, including transistors M9 and M10 produce negative conductance to compensate the loss of the LC-tank.

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{(C_{gs2} + C_T)[C_{gs1}(1 + R_f g_{ds2})]}} \qquad (4)$$

## 3 Measurement Results

The proposed circuit has been fabricated in the TSMC 0.18μm CMOS technology. Fig.7 showed the photograph of the VCO chip. The chip area including pads is 0.585 x 0.679 mm$^2$. The designed VCO including two active inductors operates at a supply voltage of 1.8 V with the total current consumption of 24.6mA.

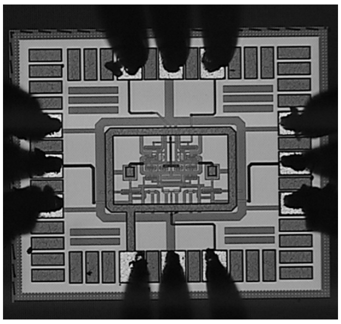

Fig. 7 Micro photo of VCO

As the VDD = 1.8V and VA = 1V, Vb is swept from 0 to 1 V, the VCO frequency can be tuned from 1.26 to 2.98 GHz, showing in Fig.8.

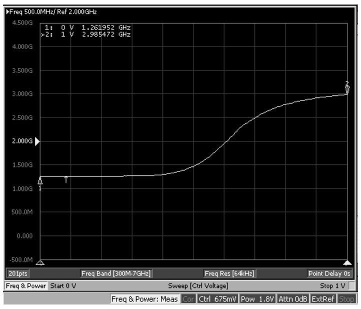

Fig. 8 Measured oscillation range at $V_{DD}$ = 1.8V, $V_A$ = 1V, $V_B$ = 0 to 1

Fig.9 and 10 plots the measured output power and phase noise by using the Agilent E4407B spectrum analyzer and E5052A signal source analyzer, respectively. The VCO oscillated at 2.4 GHz (VB = 0.667 V) delivers an output power of -6 dBm to the 50-Ω test instrument with a phase noise of -90 dBc/Hz at 1MHz offset frequency.

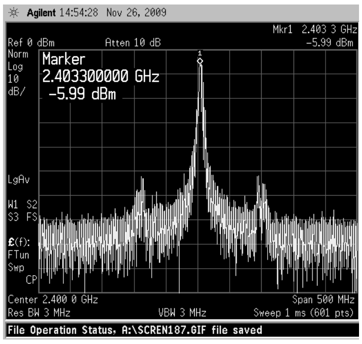

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Fig.9 Measured output spectrum at 2.4GHz

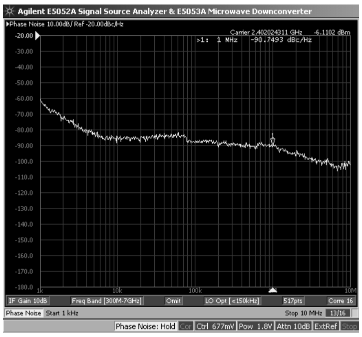

Fig.10 Phase noise of the VCO at 2.4GHz

Brief characteristic of the proposed VCO of measurement results oscillators are shown in Table 1. Table 2 compares with the wideband VCOs published over the past few years. It shows that the tuning-range of the VCO with active inductor owns the wide-band of above 1 GHz.

## 4 Conclusion

An active inductor LC-tank voltage-controlled oscillator with a wide frequency tuning range has been proposed and implemented in the TSMC-0.18μm 1P6M RF CMOS technology. The wide-band tuning provides a frequency tuning range from 1.26GHz to 2.98GHz and output power -5.3dBm to -18.7dBm. The phase noise with the VCO tuned to 2.4GHz is -90dBc/Hz at 1 MHz frequency offset and the total current consumption of the core with output buffers are 24.6mA. The designed VCO can be used for the applications in low-frequency band of Bluetooth system.

# 5 Acknowledgment

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**Table 1** Performance Summary of the Wide-Tuning-Range VCOs

| | |
|---|---|
| Process | TSMC 0.18-um RF CMOS technology |
| Power Supply | 1.8V |
| Power Dissipation | 44.6mW |
| Frequency Range | 1.26GHz to 2.98GHz |
| Tuning Range | 1.72GHz |
| Phase Noise | -90 dBc/Hz@ 1 MHz offset at 2.4GHz |
| Output Power | -5.3dBm to -18.7dBm |

**Table 2** Performance Summary of the Wide-Tuning-Range VCOs

| ***Ref.*** | ***Process*** | ***Frequency (GHz)*** | ***Tuning range (GHz)*** | **** Phase-Noise (dBc/Hz)*** |
|---|---|---|---|---|
| **This work** | 0.18-μm CMOS | 1.26-2.98 | 1.72 | -90 |
| [5]<br>C. C. Wei | 0.18-μm CMOS | 2.16–6.16 | 4 | -65 – -85 |
| [6]<br>L. H. Lu | 0.18-μm CMOS | 0.5–3.0 | 2.5 | -101– -118 |
| [7]<br>R. Mukhopadhyay | 0.18-μm CMOS | 0.5–2.0 | 1.5 | -78– -90 |
| *** dBc/Hz at 1 MHz offset frequency** | | | | |

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