High Q Active Inductors Apply in A 2.4GHz Bandpass Filter

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Abstract: - In this paper, we investigate high Q (quality factor) active inductors to apply in a 2.4GHz bandpass filter design with 0.18μm CMOS process integrated into the system-on-chip (SoC) concept. Simulation results show the bandpass filter circuit obtaining good performance, such as input return loss (S_{11}) of -34.703dB, output return loss (S_{22}) of -34.315dB, loss (S_{21}) of -0.213dB, noise figure (NF) of 10.156dB, 1-dB compression point (P_{1dB}) of 3dBm, third-order intercept point (IIP_3) of -3.151dBm, and 1.872mW power dissipation under 1.8V power-supply. The dimension of this circuit occupyes approximate to 450×390 μm^2.

Key-Words: - bandpass, filter, quality factor, active inductor, SoC

1 Introduction

In recent years, most RF building blocks have been successfully implemented in CMOS process. The wireless communication design, especially in RFIC applications, the device component, inductor, dominates the visibility of the radio frequency (RF) circuit performance.

Most of the previously inductors with spiral shapes were passive structures and the size of occupied chips are big. The quality factor (Q-value) of the spiral inductors is too small to fit in the design of high frequency circuits. In order to overcome these weaknesses, the active inductor is intensively applied in this RF design field. Of course, the active inductor has the higher Q-value, smaller size and tunable inductance more than spiral inductors. RF CMOS active inductors have been used in RF circuit, due to the advantages of small size, high Q-value, and tunable characteristic [1]-[2]. The application of the active inductors will possibly come through SoC easier.

Recently, there has been an increasing interest in the design and implementation of CMOS inductors, compare to the spiral inductors in the RF bandpass filters [3]-[6].For the bandpass filter, generally, most of designers adopt the surface acoustic wave (SAW) filter in radio frequency integrated circuit (RFIC) design. However, the SAW filter is not easy to be integrated into the CMOS process to achieve a SoC IC. Here, we propose a suitable solution to integrate the bandpass filter into SoC and reduce the filter chips size, increasing the application competition.

The high Q active inductors to employ in a 2.4GHz bandpass filter by using simple cascade RC feedback compensation technique and design circuit operation of the inductor includes negative feedback, positive feedback, and current pumping to obtain inductivity impedance and reduce loss of the active inductor, and enhance Q-value. We utilize the active inductors in the characteristic at 2.4GHz to the bandpass filter.

In this paper, the active inductors not only provide the smaller size, but display the good Q-value, lower loss, and the tunable ability in filter functions.

2 High-Q Active Inductor Design

The organization of this chapter is as follows. In section 2.1, we will describe the active inductor using simple CMOS architecture to design an active inductor. In section 2.2 we will describe the improved High-Q active inductor principle and the characteristics of a RF CMOS active inductor for inductance impedance is presented and the discussion of the advantages will also be explained.

2.1 Simple CMOS Active Inductor

Fig. 1 shows an active inductor based on CMOS generalized impedance converter (GIC) proposed [7], where the inductor loss is reduced by cascade technique of enhancement DC gain. Fig. 2 shows of the Fig. 1 small-signal equivalent circuit. Fig. 1 to the equivalent input conductance is shown in Fig. 2.

This circuit depicts the latent issue. Simple CMOS active inductor only produce a very small Q-value, which is still inferior to the circuit application.

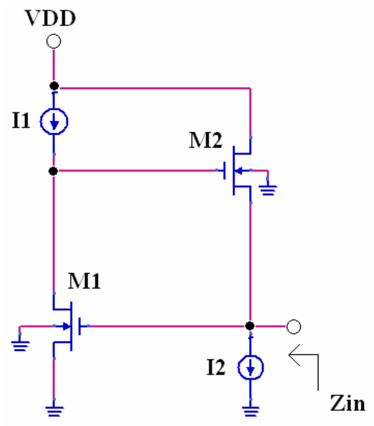

Fig. 1 The simple active inductor

The current source equivalent input impedance of the GIC circuit shown in Fig. 1 is expressed as [8].

$$Zin = \frac{g_{dsp} + g_{ds1} + S(C_{gs2} + C_{gd1} + C_{gd2})}{(SC_{gd2} + g_{dsp} + g_{ds1} + g_{m1})(S(C_{gs2} + C_{gd1}) + g_{m2})} \quad (1)$$

In Eq.(1), the conductance loss g_{dsp} and g_{ds1} reduces the performance of the active inductor. Furthermore, the Q-value, inductance, and operating frequency of the Fig. 1 active inductor become degraded seriously as the ideal current sources are replaced by CMOS current source devices. The circuit is equivalent to a loss resonator at high frequency, seen in Fig. 2. If based on the assumption of *Cgsi* >> *Cgdi*, the equivalent input conductance (*Yin*) can be illustrated as following (2).

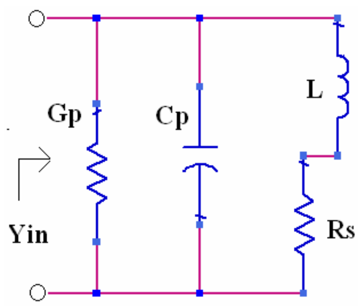

Fig. 2 The small signal equivalent circuit of simple active inductor.

$$Y_{in} \approx Gp + sCp + \frac{1}{sL + Rs}$$

$$\approx (g_{dsM2} + g_{mM1}) + sC_{gsM1} + \frac{g_{mM1} g_{mM2}}{sC_{gsM2} + g_{dsM1}} \quad (2)$$

$$Gp \approx (g_{dsM2} + g_{mM1}) \quad (3)$$

$$L \approx \frac{C_{gsM2}}{g_{mM1} g_{mM2}} \quad (4)$$

$$Rs \approx \frac{g_{dsM1}}{g_{mM1} g_{mM2}} \quad (6)$$

$$C_P \approx C_{gsM1} \quad (7)$$

Here, g_{mMi}, g_{dsMi}, and C_{gsMi} are the transconductance, output conductance, and gate-source capacitance of correspondence MOSFET transistors, respectively. The increasing parallel conductance loss of *Gp* will reduce the Q value of the active inductor, shown in (3).

2.2 Improved High-Q Active Inductor

Fig. 3 and Fig. 4 show the active inductor and the small-signal equivalent circuit, respectively, based on the literature [9], but the ideal current sources of this active inductor circuit are replaced with MOSFET active devices (M3 and M4).

The performances collapsed when the ideal current sources were substitute for the practical MOSFET active devices (M3 and M4) for integrated circuit (IC) fabrication.In order to improve the performances, a schematic diagram of our proposed active inductor circuit shown in Fig. 3.

Except for adding capacitor *Cn*, the active inductor is similar to the previous active inductor, given in Fig. 3. In Fig. 3 , the non-ideal characteristics of the transistors M3 and M4, such as the g_{ds} (the conductance of drain to source of the transistor) and the capacitance *Cgs* (between the gate and the source of the transistor) increase the parallel loss (*Gp*) and the active inductor, shown in Fig. 4.

For a small signal, the finite conductance (g_{ds}) and the capacitance (*Cgs*) of the transistors (M3 and M4) form the loss paths from the drain of MP and M2 to the ground, this signal of generating the inductance characteristic of the active inductance will lose through the loss paths. Therefore, the loss paths arise in the increase of the parallel loss and the series loss. Consequently, the performances of the active inductor in the literature [9] that the practical MOSFETs current sources replace the ideal current sources will cause seriously decay.

Fig. 3 and Fig. 4 show the proposed improve active inductor and the small-signal equivalent circuit, respectively. In Fig. 3 only using feedback capacitor (*Cn*) is designed for compensating the loss caused by MOSFETs current source implementation (M3 and M4). Transistors M1, M2, capacitor *Cn* resistor RG, and transistor MP form an active inductor circuit. Transistors M3 and M4 are the current source of the inductor. The circuit operation of the inductor includes negative feedback, positive feedback, and current pumping to obtain inductivity impedance and reduce loss of the active inductor, and enhance Q-value.

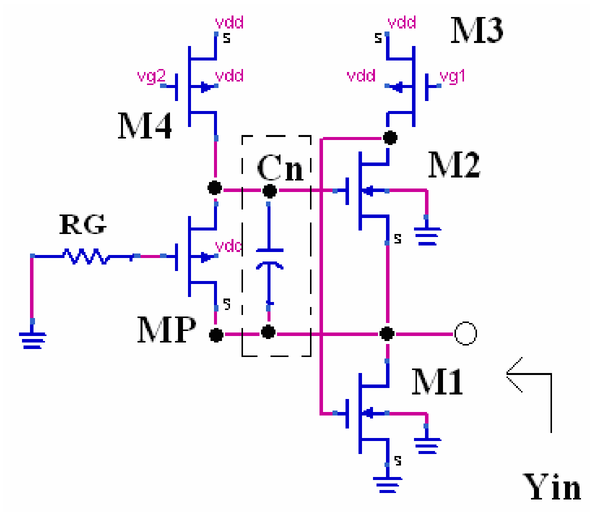

Fig. 3 The improved active inductor circuit.

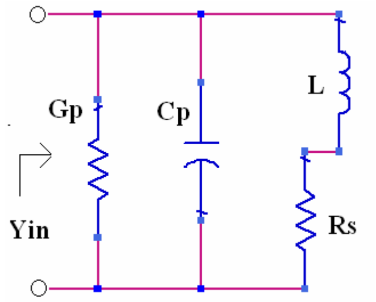

Fig. 4 The small signal equivalent circuit of improved active inductor.

Therefore, the increasing Q-enhancement of the active inductor is accomplished by adding an equivalent negative conductance into the input terminal. This negative conductance is generated through the interaction between *Cn* and the current pumping circuit comprising MP and RG. Consequently, the loss is significantly reduced, but the Q-value is enormously improved. Including the parameters, *Cgs*, g_{ds}, g_m, and *Cn* to analyze the proposed circuit, and based on these assumptions of all identical MOSFETs dimensions, $\omega RGC_{gs} \ll 1$, $C_{gsM1} = C_{gsM2} = C_{gsM3} = C_{gsM4} = C_{gsMP} = C_{gs}$, and $\omega \gg \frac{g_{mP}}{C_{gs} + Cn}$, $g_{mi} \gg g_{dsi}$, the equivalent input conductance (*Yin*) of the active inductor, shown in Fig. 3.

According Fig. 3 to the equivalent input conductance is shown in Fig. 4, where the corresponding component value can be expressed as below :

$$Gp \approx (g_{dsM1} + g_{dsM2} + g_{dsM4} + g_{mM4}) - \frac{\omega^2 C_{gs} Cn}{g_{mMP}}$$

$$(g_{dsM1} + g_{dsM2} + g_{dsM4} + g_{mM4} \approx g_{mM4})$$

$$\approx g_{mM4} - \frac{\omega^2 C_{gs} Cn}{g_{mMP}} \qquad (8)$$

$$Rs \approx \frac{(g_{dsM2} + g_{dsM3} + g_{mM3}) - \frac{\omega^2 C_{gs} Cn}{g_{mMP}}}{g_{mM1} g_{mM2} + g_{dsM2} g_{mMP}} \qquad (9)$$

$$C_P \approx \frac{C_{gs}}{3} \qquad (10)$$

$$L \approx \frac{(C_{gs} + Cn)}{g_{mM1} g_{mM3} g_{mM4} g_{mMP}} \qquad (11)$$

Integrating (8), (9), (10) and (11), we are able to obtain the equivalent input conductance (*Yin*) of the active inductor, shown in Eq. (12):

$$Y_{in} \approx G_P + sC_P + \frac{1}{sL + Rs} \qquad (12)$$

In Eqs. (8) and (9) the parallel loss (G_P) and series loss (Rs), respectively, owing to the negative term in the equation, result in the parallel loss and series loss reducing, respectively. In Eq. (10) the capacitance is become $C_P \approx \frac{Cgs}{3}$ such that the capacitance is reduced, but the operating frequency is increased. In Eq. (11) the equivalent inductance will be also increased.In consequence, the performances of the active inductor are improved by using a capacitor (*Cn*). If the circuit components are properly chosen, a higher Q-value, and higher operating frequency can be realized.

Nevertheless, while the tunable RG with a passive resistor and *Cn*, and an active transistor M1~MP is contained, we are able to obtain a high efficient filter, providing the regulative inductance and the high quality factor at the desired center carrier frequency.

3 High Q Active Inductor Application Bandpass Filter

Basically, the basspass filter is used to passive spiral inductor as the load. However, the low Q, and the large occupied chip of passive inductor reduce the performance and increase the cost. In order to improve the performance of the filter, an input active inductor apply in the filter design. The active inductor has the higher Q, smaller size, more tunable inductance, especially less loss than spiral inductor.

The bandpass filter circuit architecture of an active inductor from Fig.3 is modified and combined into Fig.5 as a basic bandpass filter. This bandpass filter equivalnt simple circuit is shown in Fig. 6. It is a feasible solution to integrate the bandpass filter into a SoC design requirement. The loss of the bandpass filter can be reduced.

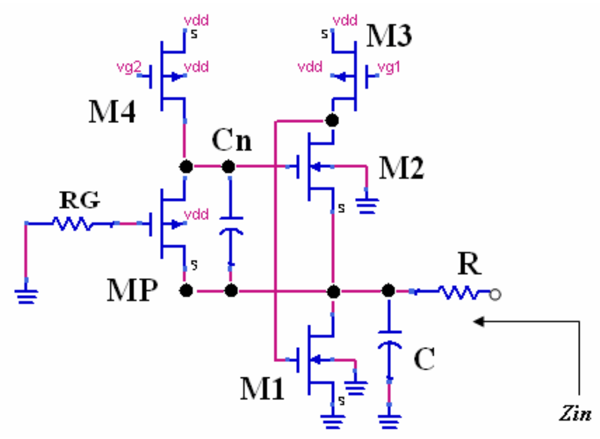

Fig. 5 Implementation of the bandpass filter using improved active inductor.

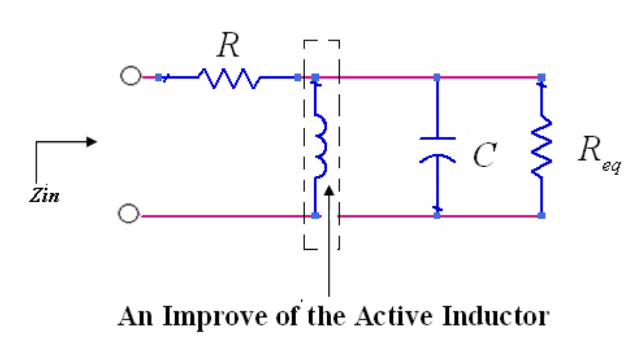

Fig. 6 Bandpass filter equivalnt simple circuit.

4 Simulation Results

All simulation are carried out in an Aligent-ADS simulator. The active devices are modeled by TSMC 0.18µm CMOS process at 1.8V.

4.1 Simulation Results of the Improved Active Inductor

The active inductor all transistors have the same dimensions, where the length and width of each MOSFET are 0.18µm and 1.5µm, respectively. The improve CMOS active inductor value of the components are designed to have R_G = 3.6Ω and *Cn* = 0.24 pF.

The simulation results of active inductors are show in the Fig. 7, 8, and 9 respectively. In the Fig. 7, 8, and 9 are show the curves of the inductance, the equivalent loss, and the Q-value respectively. The improved CMOS active inductor that in the range of 1GHz to 5GHz, the inductance value ranges from 4.4nH to 11.56nH, which has large enough inductance for bandpass filter circuit applications. Its minimum equivalent loss is about 2.064E-5Ω, and maximum Q-value is about 4.431E6 in 2.4GHz. Furthermore, Fig. 4 to the Fig. 6 exhibit the comparisons of the Q-value (Q), the inductance (L), and the equivalent loss in center frequency of the 2.4GHz.

The performance comparisons of the simple and improved active inductor are in Table1.

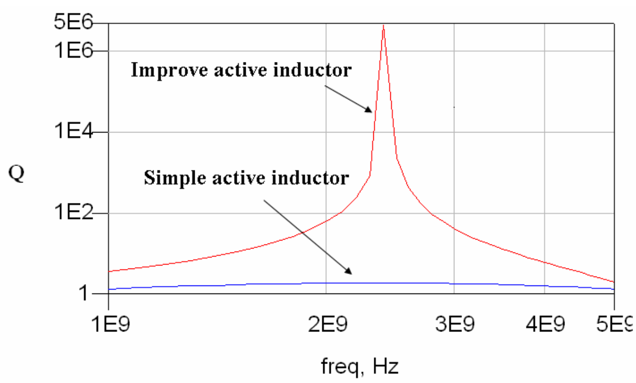

Fig. 7 Q-value of the active inductor circuit.

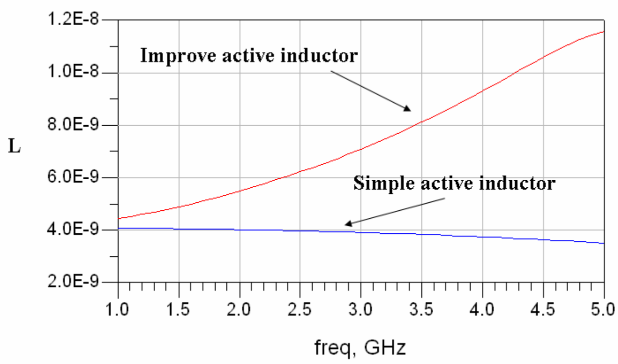

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Fig. 8 Inductance of the active inductor circuit.

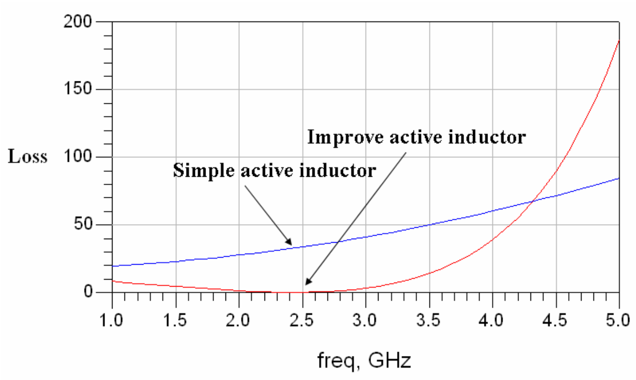

Fig. 9 Equivalent loss of the active inductor circuit.

Table 1 Performance comparisons of the simple and improved active inductor.

Performance	Simple	Improve
Frequency	2.4GHz	
Q-value	2.363	4.431E6
Inductance	3.108nH	6.064nH
Equivalent loss	19.833Ω	2.064E-5Ω

4.2 Simulation Results of the Bandpass Filter

We take the improved active inductor in the characteristic at 2.4GHz to the bandpass filter. The bandpass filter value of the components are designed with R = 1 Ω and C = 1 pF.

As this result the simulation outworks with bandpass filter are depicted in Fig. 10, 11, 12, and 13 respectively. In the Fig. 10, 11, 12, and 13 are shown the curves of the bandpass filter parameter, the input return loss (S_{11}), the output return loss (S_{22}), the loss (S_{21}), and the noise figure (NF) respectively. The bandpass filter circuit exposes the performance such as an input return loss (S_{11}) of -34.703dB, an output return loss (S_{22}) of -34.315dB, a loss (S_{21}) of -0.213dB, a noise figure (NF) of 10.156dB, a 1-dB compression point (P_{1dB}) of 3dBm, a third-order intercept point (IIP_3) of -3.151dBm, and the power dissipation in 1.872mW under 1.8V power-supply operation. These simulated parameters in the demand of a bandpass filter design are valuable. The loss of the bandpass filter can be reduced shown in Fig. 12.

The layout of the bandpass filter is shown in Fig. 14. The chip area included bounding pad is around 450×390 μm^2. There are clear comparisons with other papers and the simulation results from [10]-[11] in Table 2.

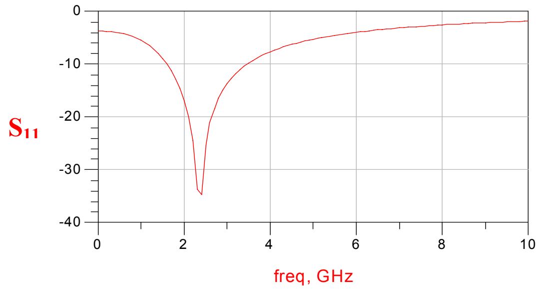

Fig. 10 Input return loss (S_{11}).

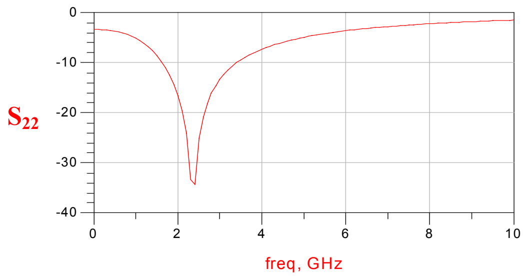

Fig. 11 Output return loss (S_{22}).

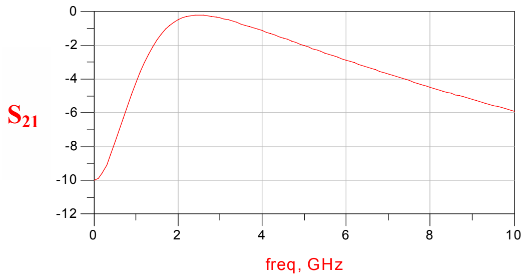

Fig. 12 Loss (S_{21}).

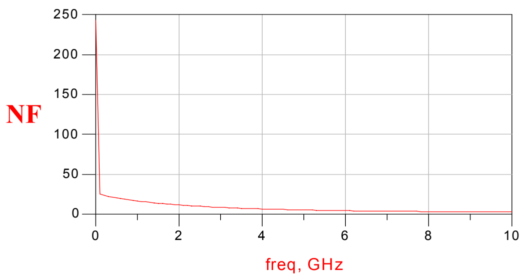

Fig. 13 Noise figure (NF).

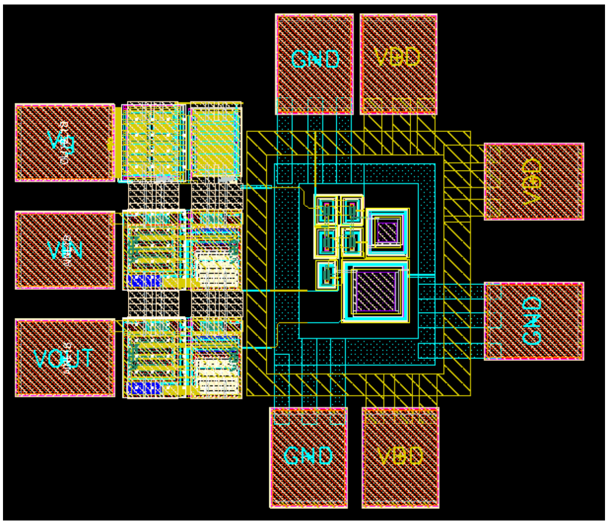

Fig. 14 Layout of the bandpass filter.

TABLE 2 Comparisons with other papers.

Performance	[10]	[11]	This work
Supply voltage	**1.8V**	**NA**	**1.8V**
Input return loss (S_{11}).	**-17.85dB**	**-15.7dB**	**-34.7dB**
Output return Loss (S_{22}).	**-16.07dB**	**NA**	**-34.31dB**
Loss (S_{21}).	**-2.14dB**	**-4.2dB**	**-0.21dB**
NF	**21.93dB**	**7.9dB**	**10.15dB**
Power consumption	**13.14 mW**	**9 mW**	**0.9 mW**
P_{1dB}	**-30dBm**	**2dBm**	**3dBm**
IIP_3	**-23.6 dBm**	**NA**	**3.15 dBm**
Frequency	**2.4GHz**	**5.4GHz**	**2.4GHz**
Process	**0.18 μm CMOS**	**0.18 μm CMOS**	**0.18 μm CMOS**
Chip size (μm^2)	**NA**	**910×530**	**450×390**

5 Conclusion

Via the simulation results with ADS software, we observe that there are several advantages adopting the active inductor design in radio frequency filter circuit, such as high Q-value, tunable inductance value , low power consumption, small chip size , and less loss. Besides these, filter is easy to be integrated into IC construction.

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