High-Q 2-Port active inductors Using Tunable Resistance

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***Abstract*—This review paper presents a gyrator based active inductor using conventional grounded active inductor, differential pair active inductor and symmetric 2-port active inductors. This paper presents a novel 2-port high-Q active inductor using LC parallel resonator. The proposed 2-port high-Q active inductor consists of the feedback parallel resonance circuits that comprises of low-Q spiral inductor and capacitor. This structure can improve its Q-factor due to decrease of the parasitic capacitances and extend high-Q operating frequency range. A feedback resistance is added to improve the quality factor, while the tuning range of the desired inductance value is achieved by using a network of capacitance.**

***Keywords*—Active inductor, feedback parallel resonance circuit, *Q*-factor, spiral inductor.**

I. INTRODUCTION

Inductors are the most important circuit elements for high frequency and RF systems. The RF circuit includes resonant circuits for frequency tuning, where inductor plays a vital role. Inductors are used in RF filtering, RF choke, impedance matching networks, etc. Traditionally passive inductors were used as off-chip discrete component. The off-chip passive components limits the operative bandwidth, increases the cost and size of the RF system. Lack of high quality factor inductors is perhaps, “the most conspicuous shortcoming of standard IC processes” for CMOS RF integrated circuit designers. A significant effort has been taken to fabricate inductors on a silicon substrate, so that a wireless transceiver can be integrated on a single substrate monolithically.

Passive on-chip inductors such as bond wire inductors and spiral inductors were made available in standard silicon CMOS process. But, mutual coupling effects of adjacent wires, difficulty in tuning and non-guaranteed bonding process of repeated inductor makes the semiconductor industry not to use bond wire inductor for mass production. Drawbacks of the spiral inductors are low resistivity substrates of CMOS technology led a significant loss and also it occupies large die area. Moreover, passive inductor has a fixed inductance value, thus it tends to give a single band operation for the design. Also, it complicates the design and fabrication and extends the range of applicable process technology. Limitations of passive on-chip inductor motivated the researchers to consider active circuitry for synthesizing the integrated inductors.

In this paper we have discussed about conventional grounded active inductor and some modified active inductor circuits by adding arbitrary circuit to enhance Q-factor (GAI) in chapter II.GAI shows 2-port characteristic components of the transistors but employ an unsymmetrical circuit structure with narrow bandwidth for high-Q factor. To solve this problem, some 2-port active inductors have been discussed in chapter III. The above discussed 2-port active inductors didn’t have symmetric structure that shows somewhat different characteristics from each port, and deviates from the behavior of an ideal inductor.2 -port active inductor designed by cascading two gyrators and Symmetric 2-port active inductor with parallel LC resonator to increase Q-factor has been discussed in chapter IV. Finally 2-port active inductor using tunable resistance to obtain required inductance value has been discussed in chapter V.

II. BASIC STRUCTURE OF CONVENTIONAL GROUNDED ACTIVE INDUCTORS (GAI)

One important issue related to the standard CMOS technology is low-resistivity silicon substrate that results in low Q-factor for the passive spiral inductor. Thus, in spite of the inherent drawbacks of the active inductor such as noise, linearity and power consumption, it have been studied and applied to many RF circuit designs because of its several advantages of low insertion loss, small size, and tunability of inductance.

The conventional grounded active inductor (GAI) is realized with basic gyrator-C structure [1] is shown in figure 1. The gyrator-C consists of two transistors, and generates inductive reactance from parasitic capacitance of those transistors. But the conventional GAI has limitation to increase the Q-factor and frequency tuning range with high Q-factor.

The performance of the active inductor typically depends on following [10]:

- Frequency range
- Inductance tenability
- Quality factor
- Noise
- Linearity
- Stability
- Supply voltage sensitivity
- Parameter sensitivity
- Signal sensitivity
- Power consumption

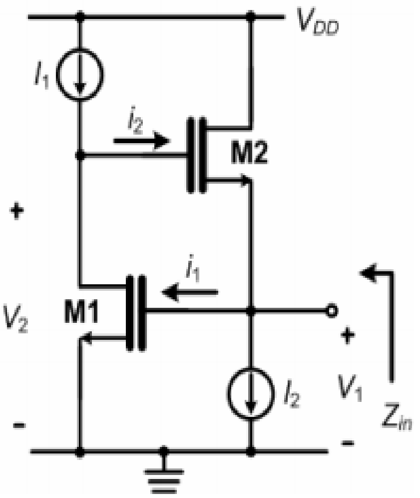


Figure 1 Schematic of GAI

There have been some works by adding arbitrary circuit into the conventional GAI to enhance Q-factor [1][2] and GAI with cascode structure to enhance Q-factor was proposed in [3] shown in figure 2 and figure 3.

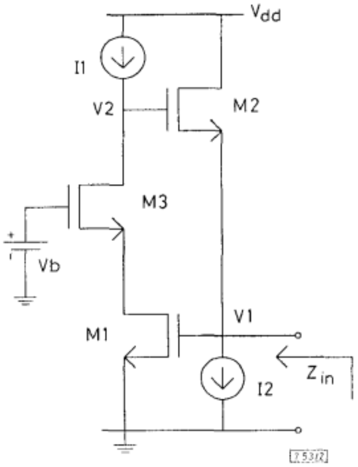


Figure 2 Schematic of simple cascode GAI

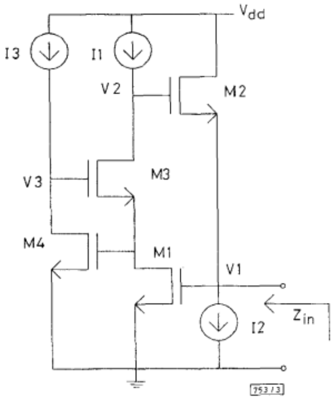


Figure 3 Schematic of regulated cascode GAI

However, as the CMOS process becomes smaller with the development of CMOS process technology, it has a drawback of consuming much DC power by voltage headroom. An optimum design method of tunable inductor with high Q-factor by feeding feedback parallel resonance circuit into the conventional GAI structure is proposed.

2.1. Prototype inductor (PI) using feedback spiral inductor.

A prototype inductor (PI) to improve Q-factor by adding the feedback spiral inductor (Lf) between the source of M2 and the gate of M1 of the conventional GAI. As Q-factor is decreased by parasitic capacitance [4] shown in figure 4. If parasitic capacitance is reduced by adding the spiral inductor to the source of M2, we can compensate the degradation of Q-factor by parasitic capacitance. The spiral inductor can occupy an additional space, but we have a high Q-factor using only small inductance as a compensation for parasitic capacitance of M2 transistor in the conventional GAI. Moreover, a parasitic resistance of the spiral inductor is useful the improvement of Q-factor due to increasing inductance of GAI.

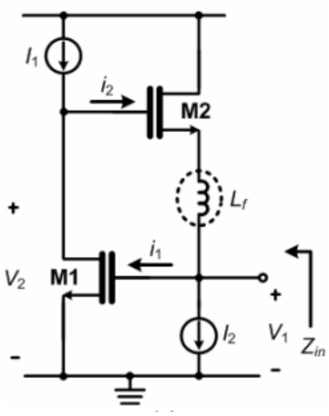


Figure 4. Schematic of Prototype inductor (PI) using feedback spiral inductor.

2.2. High-Q inductor using feedback LC resonance circuit

The spiral inductor of over 2.3 nH occupies an extensive space and causes the size problem. To overcome this problem, we used LC parallel resonance circuit ($L_{pf}C$) instead of spiral inductor (Lf) as shown in Figure 5.

The spiral inductor (L_{pf}) of the feedback resonance circuit is smaller than L_f of the PI. Fig. presents a high inductor (HI) using parallel feedback LC resonance circuit. The impedance of parallel LC resonance circuit ($L_{pf}C$) can be explained and the equivalent inductance explained with Eq. From Eq., resonator was designed to exhibit large inductance value by small spiral inductor.

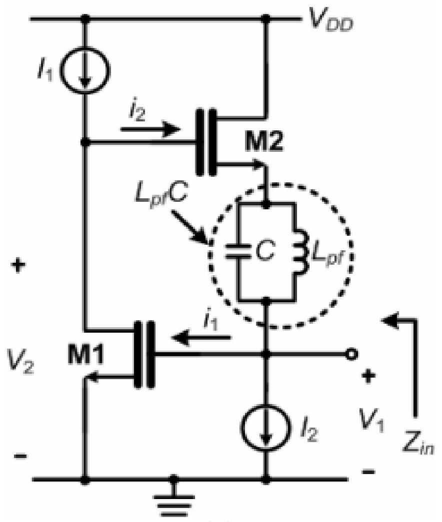


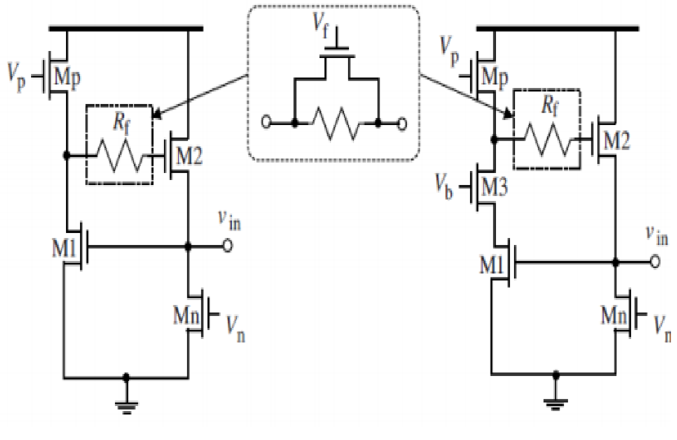
Figure 5 Schematic of High-Q inductor using feedback LC resonance circuit

$$Z_{resonance} = sL_{resonance} = \frac{j\omega L_{pf}}{1-\omega^2 L_{pf} C_v}$$

The fabricated PI has Q-factor above 50 at 6 GHz, and the maximum inductance about 100 nH at 7 GHz, also HI has Q-factor of 250 around 5 GHz, and maximum inductance is 45 nH. This high-Q inductor provides high Q-factor and large inductance using the small value spiral inductor. However, the proposed HI has two a drawbacks. Those problems are large power consumption and narrow frequency range of high Q-factor.

2.3. Hsiao feedback resistance active inductors

The feedback resistor Rf does not consume any static power and can be tuned by connecting a nMOS transistor in parallel with a poly resistor shown in figure 6.



(a) (b)

Figure 6. Schematic of (a) Feedback resistance active inductor. (b)Cascode Feedback resistance active inductor.

III. STRUCTURE OF DIFFERENTIAL PAIR ACTIVE INDUCTORS.

As seen conventional configuration of the active inductor based on the basic grounded-type active inductor shows 2-port characteristic components of the transistors but employ an unsymmetrical circuit structure with narrow bandwidth for high-Q factor. To solve this problem, some 2-port active inductors have been designed.

3.1. Symmetric differential-pair active inductor.

Figure 7 shows the proposed symmetric differential-pair active inductor configuration. From a DC-point-of view, Q3 and Q 4 form a cross-coupled pair, while Q1 and Q2 are in the common-drain configuration. It is obvious that transistors Q1 - Q 4 are saturated. As for Q5 and Q6, they can operate either in the saturation region or in the triode region, depending on the controlled voltage at the gate (V_{ctrll}). Therefore, Q5 and Q6 are modeled as G_{ds5} and G_{ds6}, respectively. By deriving the port voltage V_{in} for a given input current I_{in}, the input impedance Z_{in}, as well as equivalent inductance and resistance [5] can be expressed as

$$i_{in} = g_{m5}v_{gs5} + g_{m3}v_{gs3}$$

$$v_{in} = \frac{2i_{in}}{[j\omega(c_{gs3}+c_{gs5})+g_{m1}+g_{m3}]//g_{ds1}}$$

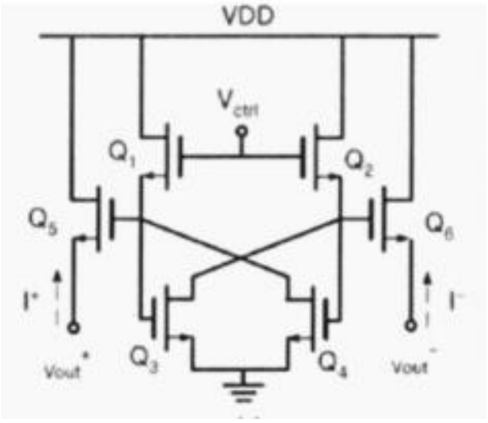


Figure 7. symmetric differential-pair active inductor

From above Equations, it is observed that the equivalent inductance depends on the circuit parameters C_{gs3}, C_{gs5}, G_{ds1}, G_{m3}, and G_{m5}. In conclusion, by reducing the G_{ds} in transistor Q1, the equivalent resistance decreases, and the equivalent inductance increases.

3.2. Symmetric differential-pair active inductor with a feedback resistance.

In order to further enhance the inductance and quality-factor of the active inductor, a feedback resistance R_f has been added between Q1 - Q4 and Q2 - Q3 in cross-coupled line.

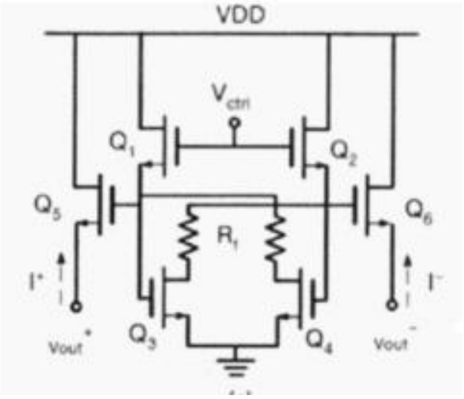


Figure 8.schematic of differential-pair active inductor with a feedback resistance.

$$L_{eq} = \frac{g_{m3}g_{m5}c_{gs3} + \omega^2 c_{gs3}^2 c_{gs5}(R_f g_{ds1} + 1)}{g_{m3}^2 g_{m5} + \omega^2 g_5 c_{gs3}^2}$$

$$G_{eq} = \frac{2g_{ds1} + R_f g_{ds1}^2}{R_f g_{ds1} + 1}$$

$$R_{eq} = \frac{g_{m3}g_{m5}g_{ds1} + \omega^2[g_{m5}c_{gs3}^2 - g_{m3}c_{gs3}c_{gs5}(R_f g_{ds1} + 1)]}{g_{m3}^2 g_{m5} + \omega^2 g_5 c_{gs3}^2}$$

This proposed a new symmetric differential 2-port active inductor shown in figure 8 is a novel configuration in a 0.18- 11m CMOS technology. The inductance and quality-factor is 27nH and 28, where this active inductor also consumes 4mW de power. This configuration is especially appropriate for highly integrated microwave circuit. Also, it has one hundredth of the chip size of a spiral inductor and it also shows more than ten times wide dynamic range and twice higher Q-factor compared to the conventional I-port active inductor circuits. In addition, this configuration can be easily implemented using the series circuit.

IV. SYMMETRIC 2-PORT ACTIVE INDUCTORS

However, the above discussed 2-port inductor requires the differential input ports [5], [6] or the grounded node is usually floated simply by additional current source and bypass capacitor [7]. The above discussed 2-port active inductors didn't have symmetric structure that shows somewhat different characteristics from each port, and deviates from the behavior of an ideal inductor. As the CMOS process becomes smaller with the development of CMOS process technology, it has a drawback of consuming relatively much DC power by voltage headroom.

4.1. Symmetric 2-port active inductor

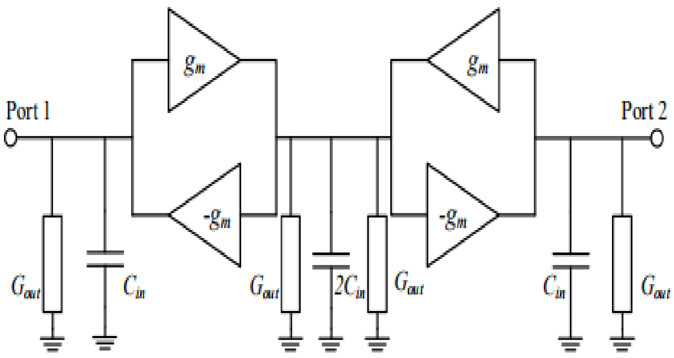


Figure 9.structure of gyrator based 2-port active inductor

The above 2-port active inductor can be designed by cascading two gyrators as shown in Figure 9. In this structure, we assume that the two gyrators have same input and output parasitic components. The parasitic components of the transconductance can be expressed as G_{out} and C_{in}. From this circuit, we can obtain Y-parameters as below.

$$Y_{11} = Y_{22} = \left(G_{out} + j\omega C_{in} + \frac{g_m^2}{2G_{out} + 2j\omega C_{in}} \right)$$

$$Y_{21} = Y_{12} = \frac{-g_m^2}{2G_{out} + 2j\omega C_{in}}$$

$$R_s = 2G_{out} / g_m^2$$

$$L_s = 2C_{in} / g_m^2$$

$$C_p = C_{in}$$

$$G_p = G_{out}$$

This above 2-port active inductor has symmetric structure about ports but has several drawbacks such as low Q-factor, high power consumption, and narrow operating range.

4.2. Symmetric 2-port active inductor with parallel LC resonator.

As the Q-factor is mainly determined by the series resistance Rs and shunt conductance Gp and these values are related to the output admittance G_{out} as shown in above equations. The new proposed the novel high Q-factor active

2-port inductor by decreasing output admittance with the parallel LC resonator.

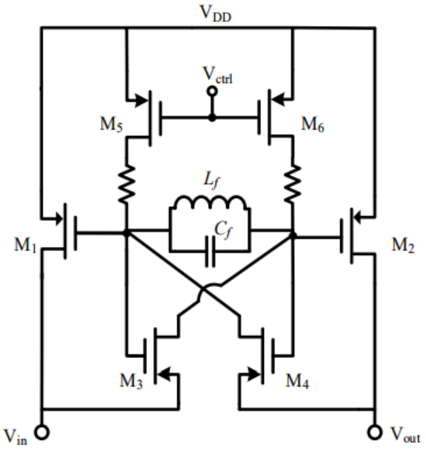


Figure 9.Symmetric 2-port active inductor with parallel LC resonator.

The proposed circuit is shown in Figure 10. above in which M1 and M2 are operating with positive Gm whereas M3 and M4 with negative Gm. NMOS transistors M5-M8 are connected for bias current sources. Similarly, M3 and M4 are connected with cross coupled pair and can produce inductance value.

4.2. Symmetric 2-port active inductor using feedback resistor

The 2-port active inductor using feedback resistance is shown in Fig. 5. In this structure, transistors M1 and M2 are operating with positive transconductance amplifier whereas M3 and M4 with negative transconductance amplifier. Transistors M5-M6 are connected for bias current sources, and M3 and M4 are connected in cross coupled pair.

The feedback resistor Rf has been added between drain of M3 and M4. Figure 10.Shows small-signal model of proposed active 2-port inductor

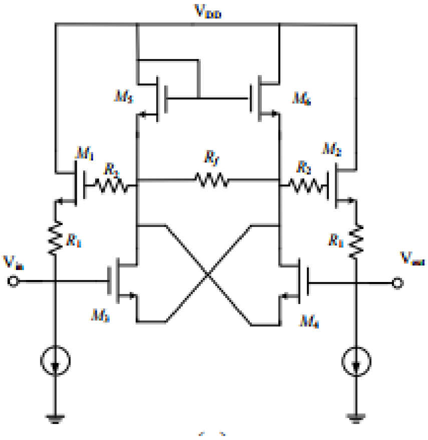


Figure 10.Symmetric 2-port active inductor with parallel LC resonator.

. By deriving the port voltage Vin and input current Iin, the input impedance Zin can be obtained as below.

$$Z_{in}=2\frac{(g_{m1}+g_{m3})\left[g_{ds5}-g_{m1}\left(R_f g_{ds5}+1\right)\right]+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\left(R_f g_{ds5}+1\right)}{g_{ds5}\left[\left(g_{m1}+g_{m3}\right)^2+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\right]}$$
$$+j2\frac{\omega\left(C_{gs1}+C_{gs3}\right)\left[\left(R_f g_{ds5}+1\right)\left(2g_{m1}+g_{m3}\right)-g_{ds5}\right]}{g_{ds5}\left[\left(g_{m1}+g_{m3}\right)^2+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\right]}$$

From Zin, the equivalent R and L can be obtained as

$$R_{eq}=2\frac{(g_{m1}+g_{m3})\left[g_{ds5}-g_{m1}\left(R_f g_{ds5}+1\right)\right]+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\left(R_f g_{ds5}+1\right)}{g_{ds5}\left[\left(g_{m1}+g_{m3}\right)^2+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\right]}$$
$$L_{eq}=2\frac{\left(C_{gs1}+C_{gs3}\right)\left[\left(R_f g_{ds5}+1\right)\left(2g_{m1}+g_{m3}\right)-g_{ds5}\right]}{g_{ds5}\left[\left(g_{m1}+g_{m3}\right)^2+\omega^2\left(C_{gs1}+C_{gs3}\right)^2\right]}$$

The Q-factor of the active inductor is also calculated from the small signal model analysis and is given as

$$Q=\left(\frac{\omega L}{R_s}\right)\frac{1}{1+R_s G_P\left[1+\left(\frac{\omega L}{R_s}\right)^2\right]}$$

As observed from above equation, the value of the feedback resistor Rf effects to decrease the equivalent resistance which results in improvement of the Q-factor.

V. STRUCTURE OF 2-PORT ACTIVE INDUCTOR USING TUNABLE RESISTANCE

The 2-port active inductor with tunable résistance is shown in Figure 11.In this structure, tunable resistance is connected instead of the feedback resistance. This feedback resistance can vary the inductance of proposed circuit and an opposite pair is also connected to get a symmetric characteristic. Figure12. shows the equivalent circuit of tunable feedback resistor. When the gate voltage is changed, current of current source is changed; therefore equivalent resistance of feedback resistance can be change.

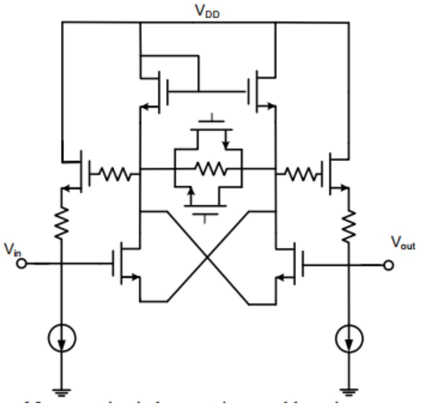


Figure 11.Symmetric 2-port active inductor with tunable résistance

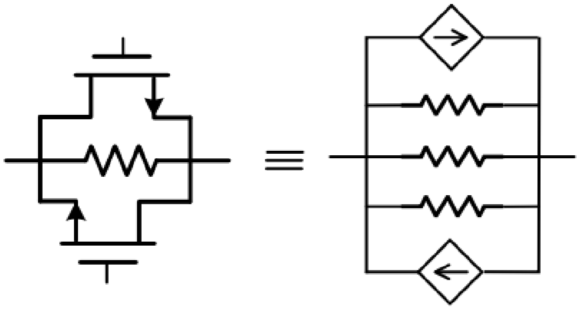


Figure 12.Equivalent circuit of tunable feedback resistor

The 2-port active inductor with tunable résistance circuit shows inductance of 2 nH and Q-factor higher than 35 at in frequency range of 3~10 GHz. Also, circuit provides high Q-factor and small variance inductance in wide frequency range. The overall circuit size of proposed active inductor is reduced by 25% for the same inductance of spiral inductor.

VI. CONCLUSION

In this paper we have reviewed various 2-port inductors. Though discussed active inductor designs occupy a smaller area because of CMOS technology, it has poor noise performance. Hence an effort is needed to design a 2-port active inductor with less noise, high quality factor and less power consumption. These features should prove valuable in designing smaller and more efficient microwave IC's. In future, we can apply the new active inductor in designing RF circuits and systems such as Wilkinson power divider, directional coupler, RFIC filters, and LC-VCO.

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