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Wideband CMOS High-Q 2-port Active Inductor using Parallel LC resonance Circuit

Jageon Koo #1, Boram An#2, Yongchae Jeong #3
Division of Electronics and Information Engineering, Chonbuk National University
567 Baekjae-daero, Deokjin-gu, Jeonju-si, Republic of Korea
1zxsq123@jbnu.ac.kr
2work0265@jbnu.ac.kr
3ycjeong@jbnu.ac.kr

Abstract- **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. The novelty of the proposed structure can improve its Q-factor due to decrease of the parasitic capacitances and extend high-Q operating frequency range. For an experimental validation, the 2-port active inductor was fabricated wit 65 nm Samsung CMOS technology. The fabricated circuit shows inductance of above 2 nH and Q-factor higher than 35 in the frequency range of 3 ~ 10 GHz.**

I. INTRODUCTION

Typically, the spiral inductor is commonly used in monolithic microwave integrated circuit (MMIC) because of simple structure and no DC power consumption. However, this structure has several drawbacks such as additional resistance due to the long line length, a low Q-factor, and a large circuit size [1]. To compensate these disadvantages, the grounded active inductor realized with basic gyrator-C structure was presented in [2]. The active inductor has several advantages with low insertion loss, small size, and high-Q factor. However the conventional grounded active inductor has narrow bandwidth for high-Q factor and can be implemented as grounded 1-port network [3].

To solve this problem, some 2-port active inductors have been studied. However, the conventional 2-port active inductor requires the differential input ports [4], [5] or the grounded node is usually floated simply by additional current source and bypass capacitor [6]. These 2-port active inductors didn't have symmetric structure that showed non-reciprocal characteristics, and deviated from the behavior of an ideal inductor. And the active inductor has a drawback of much DC-power consuming when compared the spiral inductor.

In this paper, we propose a 2-port active inductor to compensate the disadvantages of conventional grounded active inductor and spiral inductor. The proposed 2-port active inductor is based on the connection of the two basic grounded active inductors and added feedback LC resonator between two transistors to increase the Q-factor and bandwidth.

II. GROUNDED ACTIVE INDUCTOR

The gyrator structure is typically used in the grounded active inductor, which consists of two transistors and generates an inductive reactance from parasitic capacitances of those transis-

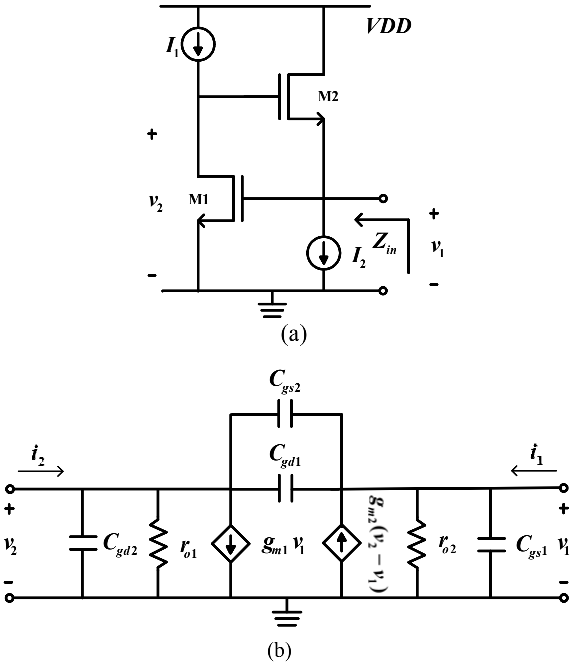

Figure 1. (a) Schematic of grounded active inductor and (b) its small signal equivalent circuit.

-tors. Fig. 1 shows a conventional grounded active inductor structure and its small signal equivalent circuit. From the small signal equivalent circuit, we can derive the 2-port impedance matrix. The input impedance of grounded active inductor shown in Fig.1 is represented as (1).

$$Z_{in} = \frac{\frac{1}{r_{o1}} + s\left(C_{gs2} + C_{gd1} + C_{gd2}\right)}{\left[g_{m2} + \frac{1}{r_{o2}} + s\left(C_{gs1} + C_{gs2} + C_{gd1}\right)\right]\left[\frac{1}{r_{o1}} + s\left(C_{gs2} + C_{gd1} + C_{gd2}\right)\right] + \left[g_{m2} + s\left(C_{gs1} + C_{gd1}\right)\right]\left[g_{m1} - s\left(C_{gs2} + C_{gd1}\right)\right]} \quad (1)$$

Using the approximate relationship, $sC_{parasitic} > g_m \gg 1/r_o$, the input impedance of the grounded active inductor presented in (1) can be simplified as (2). Using (2), we can know this structure can be operated as the inductance.

$$Z_{in} = \frac{s\left(C_{gs2} + C_{gd1} + C_{gd2}\right)}{g_{m1} g_{m2}} = sL \quad (2)$$

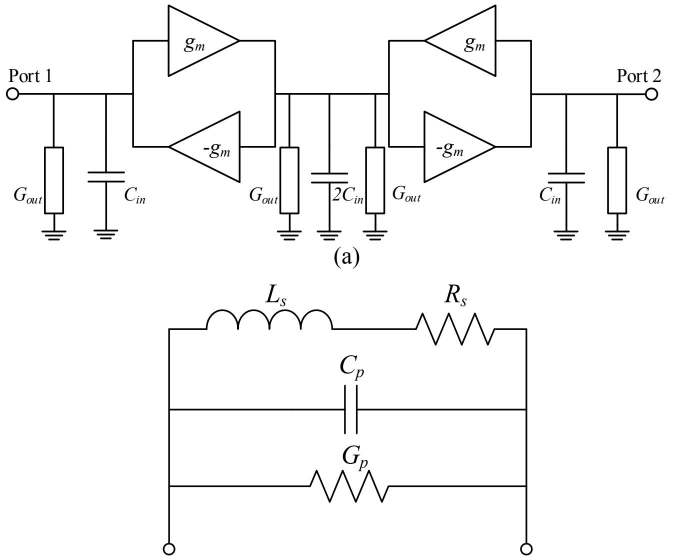

Figure 2. (a) Gyrator-based 2-port active inductor and (b) its equivalent circuit.

However, the conventional grounded 1-port active inductor cannot be used with other circuits in series. Therefore, in this work, we propose the 2-port active inductor which can be used in series with other circuits.

III. Proposed 2-Port Active Inductor

The conventional 2-port active inductor can be designed by cascading two gyrators as shown in Fig. 2(a). The parasitic components of the transconductance can be expressed as G_{out} and C_{in}. From this circuit, we can obtain Y-parameters as (3a) and (3b).

$$Y_{11} = Y_{22} = \left(G_{out} + j\omega C_{in} + \frac{g_m^2}{2G_{out} + 2j\omega C_{in}} \right) \tag{3a}$$

$$Y_{21} = Y_{12} = \frac{-g_m^2}{2G_{out} + 2j\omega C_{in}} \tag{3b}$$

The equivalent circuit of the 2-port active inductor is shown in Fig. 2(b). In this structure, we assume that the two gyrators have same input and output parasitic components. The circuit element values of the equivalent model can be found as (4).

$$R_s = 2G_{out} / g_m^2 \tag{4a}$$

$$L_s = 2C_{in} / g_m^2 \tag{4b}$$

$$C_p = C_{in} \tag{4c}$$

$$G_p = G_{out} \tag{4d}$$

The Q-factor is mainly determined by the series resistance R_s and shunt conductance G_p. These values are related to the output admittance G_{out} as shown in (4a) and (4d). This conventional 2-port active inductor has several drawback such as low Q-factor, high power consumption, and narrow operating frequency range. In this paper, we propose the novel high Q-factor active 2-port inductor by decreasing output admittance with the parallel LC resonator.

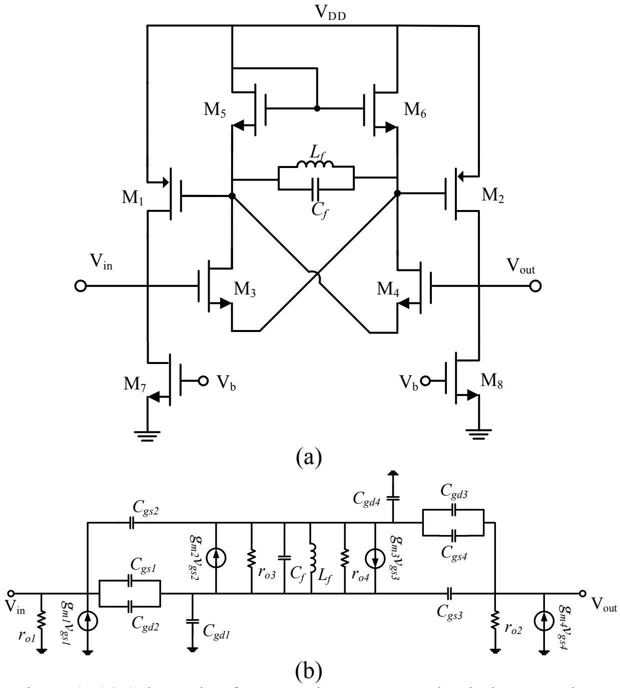

Figure 3. (a) Schematic of proposed two ports active inductor and (b) its small signal model.

The proposed circuit is shown in Fig. 3; in which M_1 and M_2 are operating with positive g_m, whereas M_3 and M_4 with negative g_m. NMOS transistors $M_5 \sim M_8$ are connected for bias current sources. Similarly, M_3 and M_4 are connected with cross coupled pair and can produce some inductance. The LC resonator is connected between drain of M_3 and M_4 to improve Q-factor. Each transistors M_1 to M_4 are operated in the saturation region.

From the small signal equivalent circuit of the proposed active inductor in Fig. 3(b), we can derive input admittance of the RLC equivalent model as (5).

$$Y_{in} = -\frac{1}{r_{o1}} + 2g_{m1} + 1 \Bigg/ \left[\frac{\omega^2 C_{gs1} L_f r_{o1} g_{m1} \left(r_{o1} + \omega^2 r_{o1} L_f C_f \right) - 2\omega^4 C_{gs1}^2 L_f^2 r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f \right)^2 + \omega^2 L_f} + s \frac{2L_f r_{o1}^2 g_{m1} + r_{o1}^2 g_{m1} C_f - C_{gs1} r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f \right)^2 + \omega^2 L_f} \right] + \frac{sC_f}{r_{o1}} + 4sC_{gs1} + \frac{1}{2sL_f} \tag{5}$$

From (5), we can find element values of RLC equivalent circuit of the proposed active inductor as (6).

$$G_p = 2g_{m1} - \frac{1}{r_{o1}} \tag{6a}$$

$$R_s = \frac{\omega^2 C_{gs1} L_f r_{o1} g_{m1} \left(r_{o1} + \omega^2 r_{o1} L_f C_f \right) - 2\omega^4 C_{gs1}^2 L_f^2 r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f \right)^2 + \omega^2 L_f} \tag{6b}$$

$$C_p = \frac{C_f}{r_{o1}} + 4C_{gs1} - \frac{1}{2L_f} \tag{6c}$$

$$L_s = \frac{2L_f r_{o1}^2 g_{m1} + r_{o1}^2 g_{m1} C_f - C_{gs1} r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f \right)^2 + \omega^2 L_f} \tag{6d}$$

In equation (6c), the parallel capacitance C_p can be reduced by feedback LC resonator which can be increased the bandwidth.

The Q-factor of an inductor is defined as the ratio of energy stored in the inductor to power loss during one cycle. The Q-factor of the proposed active inductor can be given as (7) by [5].

$$Q = \left(\frac{\omega L}{R_s}\right)\frac{1}{1+R_s G_P\left[1+\left(\frac{\omega L}{R_s}\right)^2\right]} \tag{7}$$

As shown in (7), the Q-factor of active inductor can improved by minimizing R_s. To realize smaller series resistance R_s and maintain high inductance, the series resistance should be as small as possible by optimizing circuit parameters. As seen from (6b), the R_s can be reduced by feedback LC resonator, which results in the improvement of the Q-factor of the active inductor. Also we should choose the small g_m so that the G_p can be reduced.

IV. Experimental Results

The proposed circuit was fabricated using 65 nm Samsung CMOS process. The simulation was performed in Cadence Spectre by using SP simulation. Fig. 4 shows the layout of the proposed circuit. The overall circuit size of the designed 2-port active inductor core is 0.2 mm × 0.3 mm. The proposed circuit consumes 3.6 mW DC power at 1.2 V supply voltage. On wafer probing was used to characterize 2-port *S*-parameters of the proposed circuit and also a pad de-embedding method was used for accurate measurements.

Fig. 5 and 6 show the simulated and measured inductances and Q-factors of the fabricated circuit. From the experiment, it is found that the inductance and Q-factor are higher than 2 nH and 35, respectively, in the frequency range of 3 ~ 10 GHz.

The maximum inductance is 22 nH at low frequency and maximum Q-factor is 450 at 2.7 GHz. The performance comp arison of the proposed CMOS active inductor with state-of art is summarized in Table I. The operating frequency of proposed circuit is wider than previous ones [4], [5], [7]. Also the proposed circuit has low power consumption, high Q-factor, and small chip size. Moreover, although the maximum inductance (L_{max}) is slightly lower than previous works, the proposed circuit provides constant inductance over the widest frequency range and can be used higher frequency range.

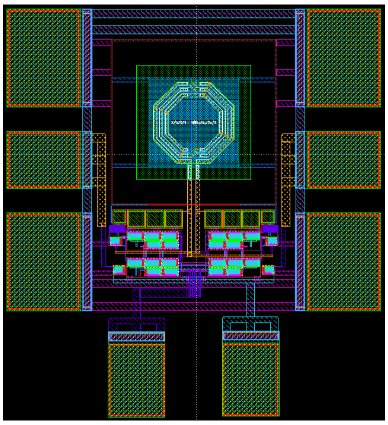

Figure 4. Layout of proposed active inductor.

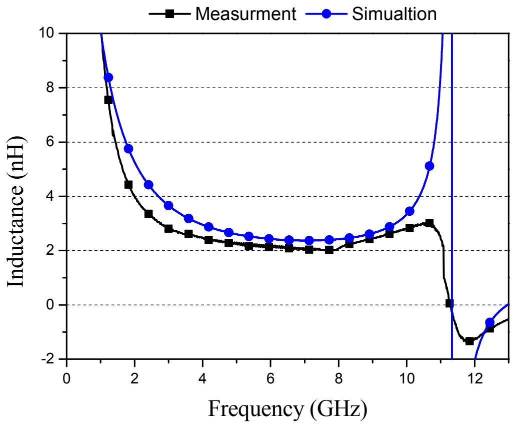

Figure 5. Simulated and measured inductances of the proposed active inductor.

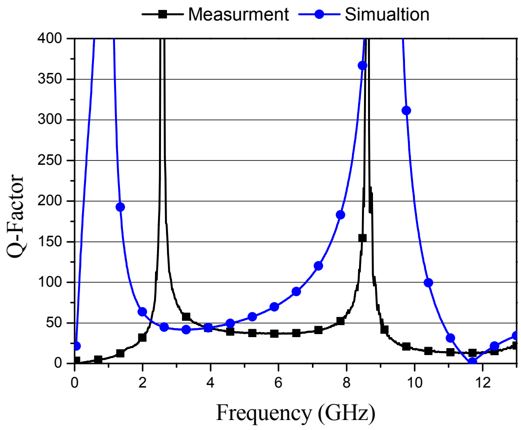

Figure 6. Simulated and measured Q-factors of the proposed active inductor.

TABLE I
PERFORMANCE COMPARISON OF CMOS 2-PORT ACTIVE INDUCTOR.

Items\Ref.	[4]	[5]	[7]	this work
Technology (nm)	180	180	180	65
Freq. range (GHz)	1-2	1-5	1-5	3-10
$L_{max.}$ (nH)	27	35	22.4	22
Q-factor	28	68	500	450
Size (mm^2)	0.01	0.16	0.075	0.06
P_{DC} (mW)	4	3.6	4.5	3.6

V. CONCLUSION

In this paper we proposed the novel 2-port inductor using feedback LC resonator. The proposed circuits shows inductance of 2 nH and Q-factor higher than 35 at in frequency range of 3 ~ 10 GHz. Also, the designed circuit provides high Q-factor and small inductance variation in wide frequency range. The overall circuit size of proposed active inductor is reduced by 25% for the same inductance of spiral inductor. In a future, we will apply the proposed 2-port active inductor in designing RF circuits and systems such as Wilkinson power divider, directional coupler, RFIC filters, and LC-VCO

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