CMOS 2-port Active Inductor using LC Resonance Circuit

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***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 comprise of low-Q spiral inductor and capacitor. The novelty of the proposed structure can improve its Q-factor decreased by the parasitic capacitance and extend high-Q operating frequency range. For experimental validation, the 2-port active inductor was fabricated with 65 nm Samsung CMOS technology. The fabricated circuit shows inductance of above 2nH and Q-factor higher than 35 for 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 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 value. However, the conventional grounded active inductor has narrow bandwidth for high-Q factor and can be implemented as grounded-type 1-port network [3].

To solve this problem, some 2-port active inductors have been studied. However, the conventional 2-port 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 shows somewhat different characteristics from each port, and deviates from the behaviour 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.

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-type active inductor and added a feedback LC resonator between two transistors to increase the Q-factor.

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

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

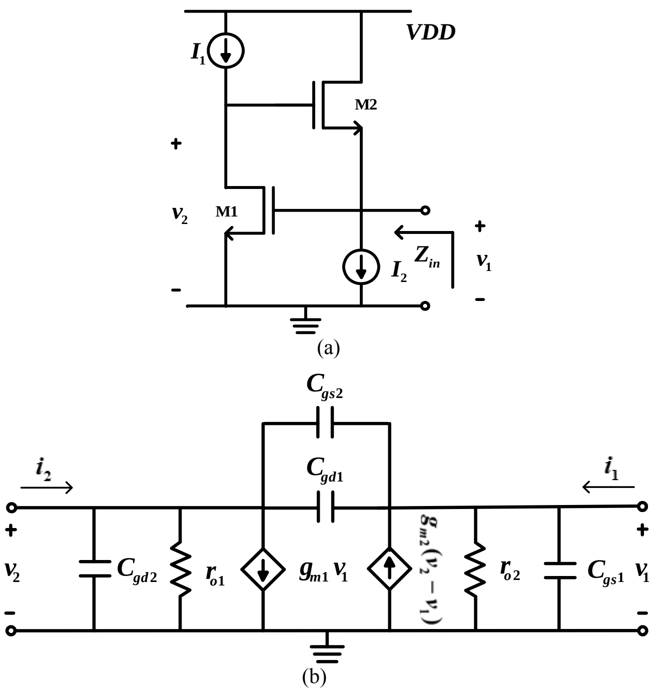

Fig. 1. (a) Schematic of grounded active inductor and (b) its small signal equivalent circuit.

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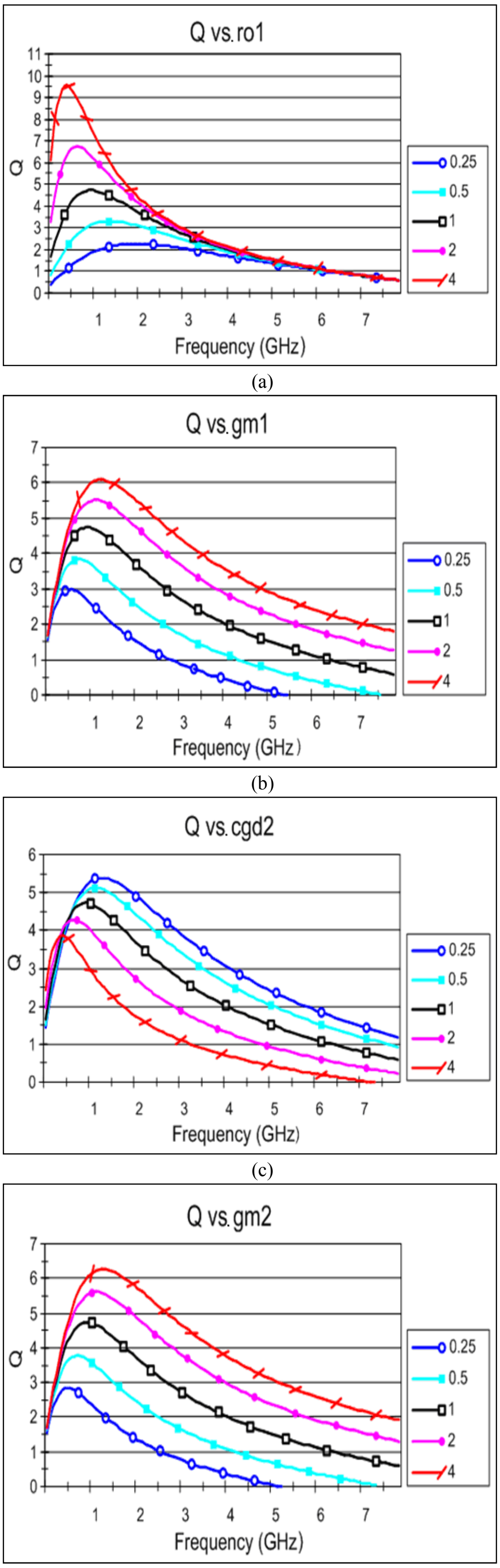


Fig. 2. The simulated Q-factor of the conventional grounded active inductor for (a) ro1 variation, (b) gm1 variation, (c) Cgs1 variation and (d) Cgs2 variation.

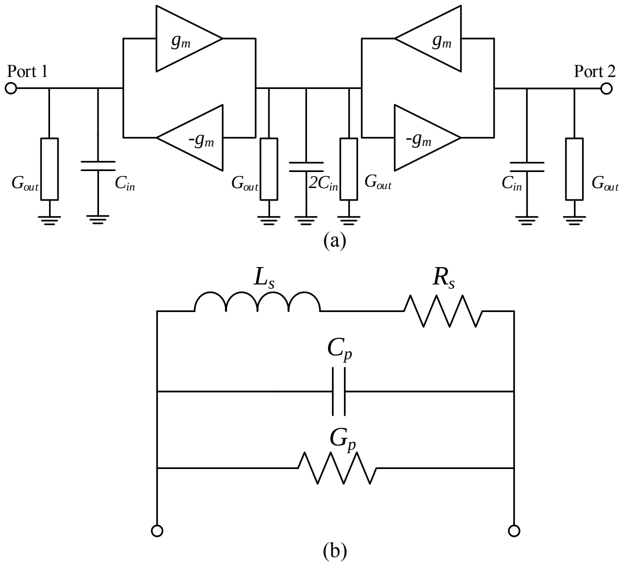


Fig. 3. (a) Gyrator-based 2-port active inductor and (b) its equivalent circuit.

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.

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

However, we cannot say that those parameters have an effect on Q-factor from Eq. (2). So, we can observe the variation of Q-factor through frequency by varying typical parameters in Eq. (3) from mathematical simulation.

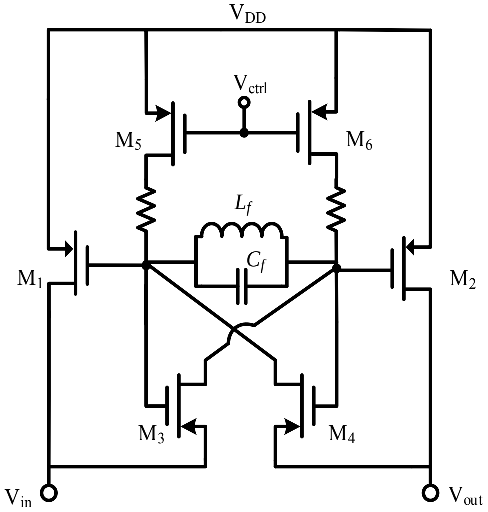
$$Q = \frac{\omega L}{R} = \frac{\omega\left[\left(C_T + C_{ds2}\right)\left(C - \omega^2 A\right) - \left(B / r_{o1}\right)\right]}{\omega^2 B\left(C_T + C_{ds2}\right) + \left(C - \omega^2 A\right) / r_{o1}} \qquad (3)$$

The simulation results are shown in Fig. 2. Fig. 2(a) shows that Q-factor can be enhanced by increasing r_{o1} of transistor M1. Fig. 2(b) shows that Q-factor is proportional to gm1, although the inductance value is inverse proportional to gm1 as it is represented in Eq. (2). Fig. 2(c) and Fig. 2(d) shows that Q-factor can be decreased by increasing C_{gs2}. We can find that Q-factor is changed dynamically by the effect of parasitic capacitance of M_2 at high frequency.

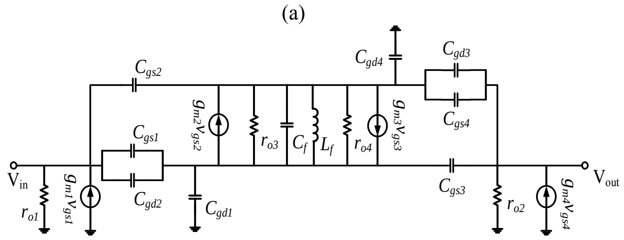
However, the conventional grounded active inductor topologies cannot be used with other circuits in series. Therefore, in this work, we propose the 2-port active inductor which can be used in series with other circuits.

III. THEORY OF 2-PORT ACTIVE INDUCTOR

The conventional 2-port active inductor can be designed by cascading two gyrators as shown in Fig. 3(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 (4).



(a)



(b)

Fig. 4. (a) Schematic of proposed two ports active inductor and (b) its small signal model.

$$Y_{11} = Y_{22} = \left(G_{out} + j\omega C_{in} + \frac{g_m^2}{2G_{out} + 2j\omega C_{in}} \right) \quad (4a)$$

$$Y_{21} = Y_{12} = \frac{-g_m^2}{2G_{out} + 2j\omega C_{in}} \quad (4b)$$

The equivalent circuit of the 2-port active inductor is shown in Fig. 4(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 (5).

$$R_s = 2G_{out} / g_m^2 \quad (5a)$$

$$L_s = 2C_{in} / g_m^2 \quad (5b)$$

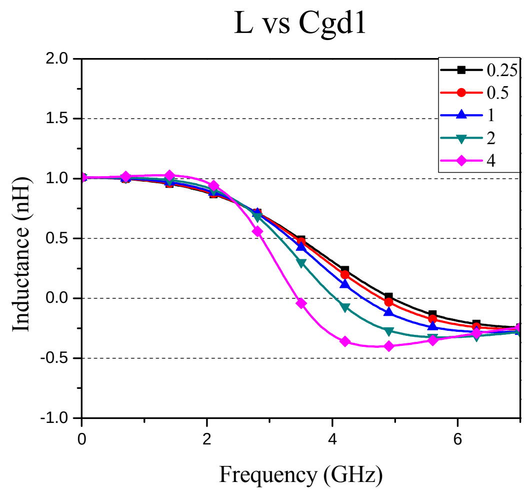
$$C_p = C_{in} \quad (5c)$$

$$G_p = G_{out} \quad (5d)$$

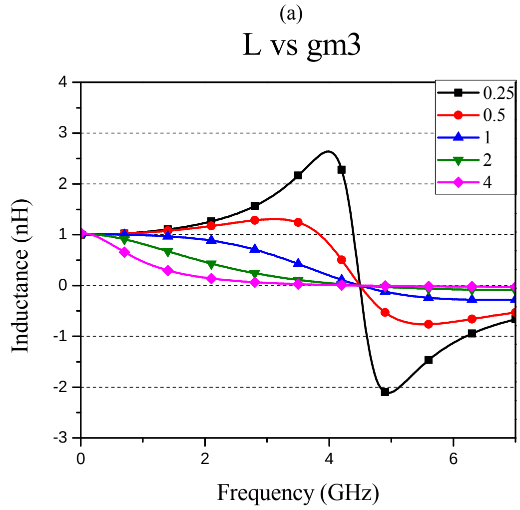
The Q-factor is mainly determined by the series resistance R_s and shunt conductance G_p. These values are related to the output admittance G_{out} as shown in (5a) and (5b). This conventional 2-port active inductor has several drawbacks such as low Q-factor, high power consumption, and narrow operating range. In this paper, we proposed the novel high Q-factor active 2-port inductor by decreasing output admittance with the parallel *LC* resonator.

IV. PROPOSED 2 PORTS ACTIVE INDUCTOR

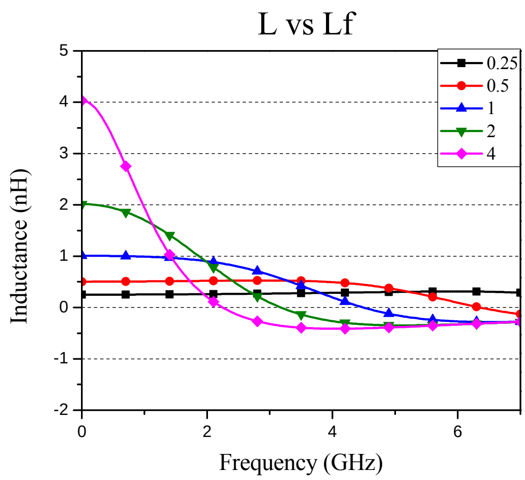
The proposed circuit is shown in Fig. 4; in which M_1 and M_2 are operating with positive g_m whereas M_3 and M_4 with negative g_m. NMOS transistors M_5-M_8 are connected for bias current sources. Similarly, M_3 and M_4 are connected with cross coupled pair and can produce inductance value.



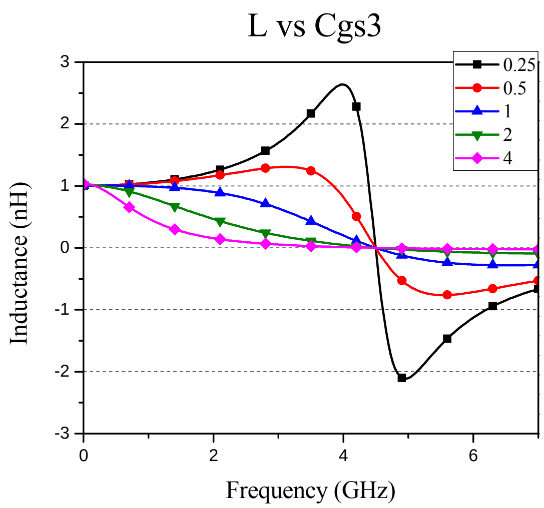
(a)



(b)



(c)



(d)

Fig. 5. The simulated inductance of the proposed grounded active inductor for (a) Cgd1 variation, (b) gm3 variation, (c) Cgs3 variation and (d) Lf variation.

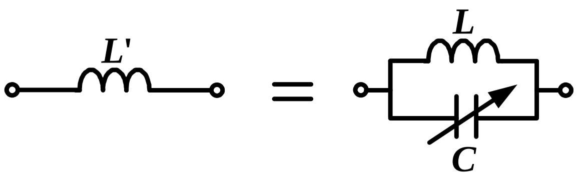


Fig. 6. LC parallel resonator.

From the small signal equivalent circuit of the proposed active inductor in Fig. 4(b), we can derive input admittance of the RLC equivalent model as Eq. (6).

$$Y_{in} = -\frac{1}{r_{o1}} + 2g_{m1} + \frac{\omega^2 c_{gs1} L_f r_{o1} g_{m1}\left(r_{o1} + \omega^2 r_{o1} L_f C_f\right) - 2\omega^4 c_{gs1}^2 L_f^2 r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f\right)^2 + \omega^2 L_f} + \frac{sC_f}{r_{o1}} + 4sc_{gs1} + \frac{s}{2s^2 Lf} + \frac{2L_f r_{o1}^2 g_{m1} + r_{o1}^2 g_{m1} C_f - c_{gs1} r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f\right)^2 + \omega^2 L_f} \quad (6)$$

From Eq. (6), we can find values of RLC equivalent model the proposed active inductor as Eq. (7).

$$G_p = 2g_{m1} - \frac{1}{r_{o1}} \quad (7a)$$

$$R_s = \frac{\omega^2 c_{gs1} L_f r_{o1} g_{m1}\left(r_{o1} + \omega^2 r_{o1} LC\right) - 2\omega^4 c_{gs1}^2 L_f^2 r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f\right)^2 + \omega^2 L_f} \quad (7b)$$

$$C_p = \frac{sC_f}{r_{o1}} + 4sc_{gs1} - \frac{1}{2\omega L_f} \quad (7c)$$

$$L_s = \frac{2L_f r_{o1}^2 g_{m1} + r_{o1}^2 g_{m1} C_f - c_{gs1} r_{o1} g_{m1}}{\left(r_{o1} + \omega^2 r_{o1} L_f C_f\right)^2 + \omega^2 L_f} \quad (7d)$$

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 follows.

$$Q = \left(\frac{\omega L}{R_s}\right) \frac{1}{1 + R_s G_P\left[1 + \left(\frac{\omega L}{R_s}\right)^2\right]} \quad (8)$$

So, we can observe the variations of inductance and Q-factor through frequency by varying typical parameters in Eq. (7) and Eq. (8) from mathematical simulation as shown in Fig. 5.

From Fig. 5, we found that C_{gs3} of M_3 has the decisive effect on Q-factor. So we tried to enhance Q-factor by adding L_f at the source of M_3 to decrease C_{gs3}, as shown Fig. 5(c). Moreover parasitic resistance of L_f contributed to the increase of inductance of the proposed 2 ports active inductor, and improving Q-factor. Q-factor enhancement has the basis on the increase of output resistance of M_3 due to the parasitic resistance. However the spiral inductor become larger, it occupies extensive place, giving rise to the size problem. To overcome this problem, *LC* parallel feedback resonance circuit is used instead of L_f. Eq. (6) shows the input impedance and equivalent inductance of *LC* resonator.

$$Z_{in} = j\omega L' = j\omega L // -j\frac{1}{\omega C} \quad (6a)$$

$$= \frac{j\omega L}{1 - \omega^2 LC}$$

$$L' = \frac{L}{1 - \omega^2 LC} \quad (6b)$$

But in practical case inductor and capacitor has parasitic resistance, it can effect equivalent inductance of *LC* resonator. So we add the parasitic resistance of inductor and capacitor Eq. (6) which can rewrite by

$$Z_{eq} = j\omega L' = \frac{R_L + j\omega L}{1 - \omega^2 LC + j\omega R_L C} \quad (7a)$$

$$L_P = L\left(1 + \frac{R_L^2}{(\omega L)^2}\right) \quad (7b)$$

$$R_P = R_L\left(1 + \frac{(\omega L)^2}{R_L^2}\right) \quad (7c)$$

This parasitic resistance will increase output resistance of transistor. From Fig. 5, we can know increasing the output resistor can improve Q-factor. Therefore, the *LC* resonator is connected between drain of M_3 and M_4. This resonator can increase output impedance of M_3 and M_4 as well as it can reduce parasitic capacitances of M_1 and M_2, and decrease the equivalent parallel capacitance. When parallel capacitance decreases, the operating frequency range is also increased.

The power consumption is one of the important issues for the active inductor. If the power consumption of active-inductor increases, the overall systems power consumption will also be increased. Therefore, in this work we chose small g_m for small power consumption. However, the small g_m can increase the equivalent series resistance, as result decreases the Q-factor. Therefore, it improves the Q-factor of the proposed circuit.

V. 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. 7 shows the layout of the proposed circuit. The overall circuit size of the designed 2-port active inductor including pad is 0.4 mm X 0.45 mm and core is only 0.2 mm X 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 for de-embedding the parasitic components.

Fig. 7 and 8 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 comparison of the proposed CMOS active inductor with state-of art is summarized in Table I. The operating frequency of proposed circuit is wider than conventional ones [4], [5],

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

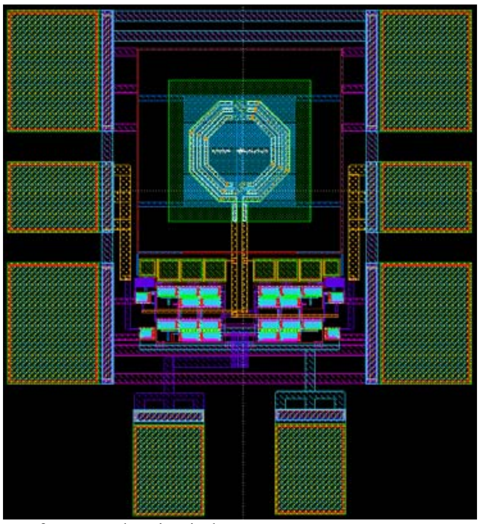


Fig. 7. Layout of proposed active inductor.

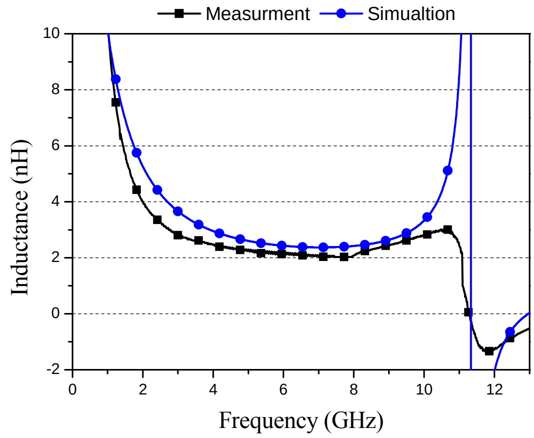


Fig. 8. Simulated and measured inductance of the proposed active inductor.

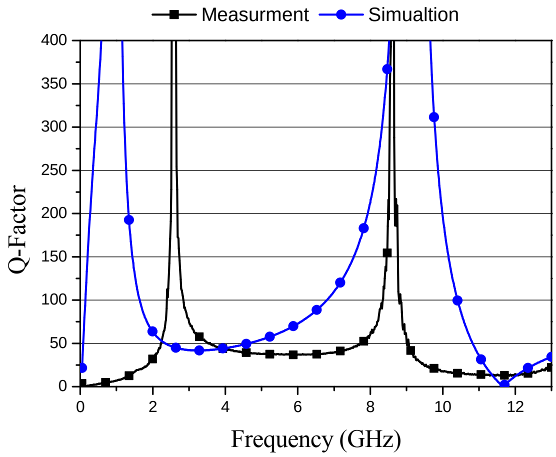


Fig. 9. Simulated and measured Q-factor of the proposed active inductor.

[7]. Also the proposed circuit has low power consumption, high Q-factor, and small chip size. Moreover, although inductance is lower than previous works, the proposed circuit provides constant inductance over wider frequency.

VI. CONCLUSIONS

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 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. 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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