High Quality-Factor and Inductance of Symmetric Differential-Pair Structure Active Inductor Using a Feedback Resistance Design

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Abstract—This paper proposes a new symmetric differential-pair structure for the active inductor. The CMOS spiral inductor occupies a large chip size and is difficult to obtain a high Q-factor. A symmetric differential-pair active inductor circuit topology with feedback resistor is proposed, which can substantially improve its equivalent inductance and quality-factor. This feedback resistance differential-pair active inductor was implemented by using 0.18-μm TSMC RF CMOS technology, which demonstrates a maximum quality-factor of 28 with a 27-nH inductance. The proposed active inductor has one hundredth of chip size of a spiral inductor and it also shows more than ten times wider 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.

Index Terms—Active inductor, CMOS, feedback resistor

I. INTRODUCTION

In the near decade, for the increasing demands of wireless personal communication system, low cost and high integration process technologies are required to reduce the production cost and the system dimension. According to these requirements, CMOS technology has become the best choice for wireless communication systems operating below 5 GHz. However, a major issue using standard CMOS technologies in spiral inductor design cannot easily achieve good performance. Recently, considerable effort has been devoted to the realization of very high Q-value active inductor [1]-[3]. Compared to a typical on-chip spiral inductor, advantages of an active inductor are large inductance value, high Q, small die area and tunability. However, most of the previously proposed active inductors are originally grounded-type 1-port network. When the 2-port floating characteristics are required, the grounded node is usually floated simply by additional current source and bypass capacitor. However, since these floating active inductors do not have symmetric structure, they show somewhat different characteristics from each port, which deviates from the behavior of an ideal inductor. In this paper, we propose a circuit configuration for the symmetric differential-pair active inductor by feedback resistor, which is based on the differential-pair connection of the two basic grounded-type active inductors [1],[4]. Also, this scheme proposes circuit with cross-connecting the two feedback resistors [5]. The proposed circuit is designed in a 0.18-μm CMOS process, which is well suited for system integration. This paper is organized as follows, Section II describes the conventional cascode grounded active inductor topology. The theoretical analysis and circuit design of the high-Q-value symmetric differential-pair active inductor are presented in Section III. The measurement results of the proposed circuit are shown in Section IV. Finally, conclusion is given in Section V.

II. THEORY OF ONE-PORT ACTIVE INDUCTOR

The conventional active inductor topology is the grounded active inductor as shown in Fig.1(a). This circuit topology is based on the gyrator theory, containing only two transistors, generating an inductive impedance. This architecture of the active inductor is possible to obtain several nH of inductance operating at a few GHz region, with the grounded-type active inductor topology. If each transistor is modeled by $C_{gs}$, $C_{ds}$, $g_m$ and $g_{ds}$, as shown in Fig.1(b), the equivalent circuit model of grounded gyrator active inductor is used. We can analyze the small signal equivalent model, and the values of each component are expressed as follows [6].

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A cascode-grounded circuit topology has been proposed to reduce output conductance \( g_{ds} \) by CMOS technology. However, cascode-grounded active inductor topologies could not be easily implemented due to the drawback of configuration to make use of series inductor. Therefore, we propose the symmetric differential-pair active inductor using two-port network.

### III. THEORY OF SYMMETRIC DIFFERENTIAL-PAIR ACTIVE INDUCTOR

The conventional configuration of the active inductor based on the basic grounded-type active inductor shows that the 2-port characteristic components of the transistors employ an unsymmetrical circuit structure [1],[7]. This derivation makes it difficult to use the circuit in some bilateral circuit application or fully optimize the characteristics of the active inductor circuit.

Fig. 1. (a) Schematic of the conventional grounded active inductor. (b) Equivalent circuit small signal model of the conventional active inductor.

By deriving the port voltage \( v_1 \) for a given input current \( i_1 \), the input impedance \( Z_{IN} \) can be expressed as

\[
Z_{IN} = \frac{v_1}{i_1} = \frac{Y_{22}}{Y_{11}Y_{22} - Y_{12}Y_{21}}
\]

The above expression shows that the impedance characteristic has single zero and two poles. The zero is at the frequency \( \omega_z = \frac{g_{ds1} + g_{ds2} + g_{ds1} + g_{ds2}}{2(g_{ds1} + g_{ds2} + g_{ds1} + g_{ds2})} \), and the dominant pole is approximately at the \( f_T \) of the transistor \( Q_2 \), \( \omega_P = g_{m2}/c_{gs2} \) and \( c_{gs2} \gg c_{gd1} \). The input impedance is thus inductive from \( \omega_z \) up to almost the \( f_T \) of the transistor \( Q_2 \). To achieve a wider inductive range, the zero frequency must be reduced by minimizing the conductance \( g_{ds1} \). Unfortunately, these topologies could not compensate output conductance for loss. Also, for achieving a higher inductance and a higher quality-factor,
From the Eqs. (7), (8) and (9), the simplified equivalent circuit model is derived as shown in Fig. 3. From Eq. (2), 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 $Q_1$, the equivalent resistance decreases, and the equivalent inductance increases. In order to further enhance the inductance and quality-factor of the active inductor, a feedback resistance $R_f$ has been added between $Q_1 - Q_4$ and $Q_2 - Q_3$ in cross-coupled line. As shown in Fig. 4(a), the equivalent circuit model of the added $R_f$ active inductor as shown in Fig. 4(b), including three parameters, $c_{gs}$, $g_{ds}$, and $g_{m}$, is expressed below.

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

(12)

In Eqs. (10) and (12), the effect of feedback resistor is $(R_f g_{ds1} + 1)$, which is designed to be a value larger than unity. By decreasing the equivalent resistance $R_{eq}$, with the help from the $R_f$, increase of the equivalent inductance $L_{eq}$ is realized. Therefore, the inductance and quality-factor can be improved in consequence [5], [8].

### IV. EXPERIMENTAL RESULTS

The designed circuit has been simulated for realizing the symmetric differential-pair active inductor with the Cadence Spectre RF using SP simulation. The proposed symmetric differential-pair active inductor with feedback resistors has been realized in TSMC RF CMOS 0.18-μm process with the bias of $V_{DD} = 1.8V$, $V_{ctrl} = 0.6V$. Fig. 5 shows the photograph of the proposed the symmetric differential-pair active inductor. Its size is...
Fig. 6. Measured resistance and inductance of a feedback active inductor.

Fig. 7. Simulated quality-factor and inductance of a feedback resistance differential-pair active inductor.

Fig. 8. Measured quality-factor and inductance of a feedback resistance differential-pair active inductor.

0.1mm × 0.1mm. Fig. 6 shows the simulated and measured equivalent series inductance and resistance. The simulated quality-factor and inductances are shown in Fig. 7. Maximum simulated quality-factor of feedback resistance and differential-pair model (without $R_f$) are 28 and 8, corresponding to the inductance of 27 nH and 18 nH, respectively. Because of the increased inductance, the self-resonant frequency of feedback resistance active inductor is lowered, i.e., 1.5 GHz versus 1.7 GHz. Fig. 8 shows the measured quality factor of proposed active inductor is approximately 28 at 1 GHz, and the measured inductance is observed approximately 27 nH at 1.5 GHz.

V. CONCLUSION

This paper proposed a new symmetric differential active inductor with a novel configuration in a 0.18-μm CMOS technology. The feedback resistor $R_f$ is applied to a differential-pair cross-coupled line. The inductance and quality-factor is 27 nH and 28, where this active inductor also consumes 4mW dc power. The proposed 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 1-port active inductor circuits. In addition, this configuration can be easily implemented using the series circuit.

REFERENCES


