A New 0.25–12.5 GHz High Quality Factor Low-Power Active Inductor Using Local RC Feedback to Cancel Series-Loss Resistance

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Abstract In this paper, the analysis and design of a new active inductor (AI) with a very high quality factor (QF) in 90 nm CMOS technology and frequency range of 0.25–12.5 GHz are presented. Using local resistive-capacitive (RC) shunt feedback, the QF of this AI could be improved more than what has been achieved in previous reports. The proposed circuit structure allows independent adjustment of the QF and self-resonance frequency (SRF). A very high QF of 13,159 is obtained at the frequency of 6.6 GHz with a 2.2 nH inductance; while noise voltage and power dissipation are less than 4.6 nV/√Hz and 4 mW, respectively. To the best of authors’ knowledge, this is the first time that an RC shunt feedback is used to cancel the series-loss resistance of an AI.

Keywords Active inductor · High quality factor · Local RC feedback · Series-loss resistance cancellation · Single-ended

1 Introduction

In 2002, Federal Communications Commission (FCC) approved the unlicensed use of the ultra-wideband (UWB) range of 3.1–10.6 GHz. Since then, UWB range has attracted the attention of many research groups worldwide, especially in the field of wireless communications. Most analog radio frequency (RF) designers use on-chip passive inductors (PIs) in their circuits. PIs have a low quality factor (QF) and dominate the die area of the chip, resulting in higher fabrication costs [1]. On the other hand, some other designers benefit from the use of active inductors (AIs), which have higher inductance and QF values and occupy less area of the chip. However, AIs introduce higher noise and consume more power than PIs [2,3].

AIs are divided into two major structures: single-ended AIs (SEAs) and differential AIs (DAIs). SEAs are utilized in applications such as filters and amplifiers; and DAIs are used in oscillators [4–6]. An AI has a tunable self-resonance frequency (SRF) in comparison with the on-chip PI. To the best of authors’ knowledge, the highest SRF range (SRFR) reported so far is 10.7 GHz, with the highest QF of about
3,000; however, the power consumption of the reported circuit is substantial [7]. Therefore, the main issues in the design of an AI are high power consumption [7], low QF [3], and an SRFR which is typically lower than 5 GHz [8,9].

Some AIs benefit from a cross-coupled transistor structure. Since this structure creates a negative resistance at its output, the equivalent series-loss resistance at the AI’s input node decreases [3,10]. In order to increase the inductance and hence the QF, a feedback resistor has been utilized in both the SEAI and DAI [3,7,9]. This resistor adds a positive term to the inductance equation so that the inductance and QF values are increased. However, this method does not yield a QF higher than 400, and an SRFR higher than 5 GHz.

In [11], a simple basic cascode structure was reported for the AI, which is an SEAI with low series-loss resistance and high inductance. Hsiao et al. [9] added a feedback resistance to further improve the cascode AI’s performance. This feedback resistance results in a higher inductance and therefore a higher QF. However, in these reports, no effort has been made to cancel the series-loss resistance. In this work, the mentioned problem is remedied by adding a local resistive-capacitive (RC) feedback, which results in a very high QF. The proposed AI circuit is designed using the TSMC 90 nm 1P9M RF CMOS process.

Subsequent sections of this paper are organized as follows. Section 2 describes the circuit structure in an SE mode. In this section, the equations governing the circuit are evaluated in order to predict the results and obtain a starting point for the design. HSPICE simulations accompany the second section for comparison purposes. Section 3 is devoted to the conclusion.

2 Investigation of the AI Structure

In this section, AI basics are explained and the cancelling method of the series-loss resistance, using the local RC feedback, is discussed. In order to evaluate the equations governing the circuit, the simulation results are given in each part.

2.1 Basic Concepts of AIs

An operational transconductance amplifier (OTA), whose electrical characteristics emulate a voltage-controlled current source, has a forward gain \((G_m)\), which is the ratio of the OTA output current to its input voltage. An ideal OTA is schematically depicted in Fig. 1a. The basic structure of an AI, known as gyrator-C, can be constructed using two ideal OTAs, depicted in Fig. 1b [12]. By assuming ideal OTAs, the following formulation describes the main concept of gyrator-C:

\[
v_2 = G_{m1}v_{in} \frac{1}{sC_2}; \quad i_{in} = G_{m2}v_2
\]

where \(s\) is the Laplace transform variable, equal to \(j\omega\), and \(\omega\) denotes the angular frequency. Therefore, input impedance \(Z_{in}\) and equivalent input referred inductance \(L_{in,eq}\) are given by Eq. (2):

\[
Z_{in} = \frac{v_{in}}{i_{in}} = \frac{1}{sC_2}/(G_{m1}G_{m2})
L_{in,eq} = C_2/(G_{m1}G_{m2})
\]

In practical cases, parasitics deteriorate the performance of the circuit. Therefore, in order to have pure inductance at the input node, namely node 1, the phase of this node’s impedance should be adjusted to be exactly 90°. In other words, if the phase can be somehow adjusted, the input series-loss resistance can be zero. According to [12], the condition for the stability of the circuit is \(G_{m2} < G_{m1}\), which will be discussed later in this section.

2.2 Description of the Proposed AI

Figure 2 shows the proposed AI structure. Transistors \(M_1\) and \(M_2\) create \(G_{m1}\) and transistor \(M_3\) creates \(G_{m2}\). Transistors \(M_{B1}\) to \(M_{B4}\) provide bias currents. Figure 3 depicts the simplified small-signal model of the proposed AI. In this figure, \(C_{gs1}\) and \(g_{mi}\) indicate the gate-source capacitance and transconductance of the \(i\)th transistor, respectively. The input admittance of the circuit of Fig. 3, regardless of the feedback network inclusion of \(R_f\) and \(C_f\), can be evaluated as:

\[
Y_{in} = \frac{1}{Z_{in}} = C_{gs1}s + g_{m1} + \frac{g_{m1}g_{m3}}{C_{gs3}s}
\]