A Modular Approach For High Q Microwave CMOS Active Inductor Design

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ABSTRACT

In this paper, a modular approach for the L-band CMOS Active Inductor (AI) is proposed and designed based upon a connection in series of conventional low Q-factor gyrator-C basic cells. The Q-factor can then be tuned by the number of AI cells in order to offer simplicity in terms of pole/zero cancellation, while maintaining in each gyrator-C inductor cell low values of the Q. In order to demonstrate the proposed architecture usefulness, a prototype L-band active inductor is designed in a 0.6μm CMOS process. The simulated results show that a high Q value of 972 is obtained @2GHz and an average Q-factor value of 200 is also achieved in the frequency range of 1-2GHz.

1. INTRODUCTION

Recent inductor integration with other mobile communication functional blocks into a single CMOS chip can obviate the need for external connections, thus avoiding problem of electrical and magnetic coupling, and also pad and bond wire parasitics [1-4]. In addition, this also allows implementing low power and reduced weight mobile communications units. However, the main drawback of the CMOS technology employment in high frequency applications is the low value of the Q factor in the implementation of the inductor. Because of undesirable resonance due to parasitic capacitance and parasitic series resistance in CMOS inductors no matter they are implemented by planar spiral or by simulation, the Q factor value cannot reach values larger than 10 [2]. Recent developments have lead to a significant increase of interest in Active Inductors (AI) which can be designed based on gyrator type impedance conversion [5]. Using the Active Inductor (AI) approach, the quality factor Q can be increased by employing an active circuit to compensate resistive losses. This paper describes the design and simulated performance of a modular approach for a differential CMOS Active Inductor (AI) based on a typical gyrator-C, which is expected to offer high Q factor.

2. MODULAR ACTIVE INDUCTOR APPROACH

Traditional gyrator-C based active inductor, as depicted in Fig. 1, mainly relies on the use of load capacitances C's and differential transconductances g_{m1} and g_{m2} to simulate the inductance. The input impedance can be represented by the following 4[th] order function [5-8]:

$$Z_{in}(s) \approx \frac{(s+\omega_{z1})(s+\omega_{z2})(s+\omega_{Z3})}{(s+\omega_{p1})(s+\omega_{p2})(s+\omega_{p3})(s+\omega_{p4})} \qquad (1)$$

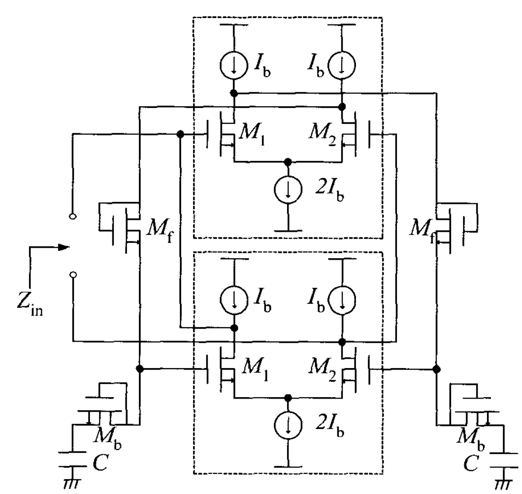

Fig. 1 Gyrator-C based active inductor.

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It can be also rewritten in terms of the even (f_{11}, f_{21}) and odd $(g_{11},\ g_{21})$ functions in the numerator and denominator as shown in the following:

$$Z_{in}(s) \approx \frac{f_{11} + g_{11}}{f_{21} + g_{21}} \tag{2}$$

where

$$\begin{aligned}
f_{11} &= s^2(\omega_{Z1} + \omega_{Z2} + \omega_{Z3}) + (\omega_{Z1} + \omega_{Z2} + \omega_{Z3}) \\
g_{11} &= s^3 + s(\omega_{Z1}\omega_{Z2} + \omega_{Z1}\omega_{Z3} + \omega_{Z2}\omega_{Z3}) \\
f_{21} &= s^4 + s^2\begin{pmatrix} \omega_{P1}\omega_{P2} + \omega_{P1}\omega_{P3} + \omega_{P2}\omega_{P3} \\ + \omega_{P1}\omega_{P4} + \omega_{P2}\omega_{P4} + \omega_{P3}\omega_{P4} \end{pmatrix} \\
&\quad + (\omega_{P1}\omega_{P2}\omega_{P3}\omega_{P4}) \\
g_{21} &= s^3(\omega_{P1} + \omega_{P2} + \omega_{P3} + \omega_{P4}) \\
&\quad + s\begin{pmatrix} \omega_{P1}\omega_{P2}\omega_{P3} + \omega_{P1}\omega_{P2}\omega_{P4} \\ + \omega_{P1}\omega_{P3}\omega_{P4} + \omega_{P2}\omega_{P3}\omega_{P4} \end{pmatrix}
\end{aligned}$$

As the product of two even functions or two odd functions is an even function, whilst the product of an even and an odd function yields odd, the real part and imaginary part of Z_{in} can be then derived:

$$\textbf{Re}\ \{Z_{in}(s)\} = \frac{f_{11}f_{21} - g_{11}g_{21}}{f_{21}^2 - g_{21}^2} \tag{3}$$

$$\textbf{Im}\ \{Z_{in}(s)\} = \frac{f_{21}g_{11} - f_{11}g_{21}}{f_{21}^2 - g_{21}^2} \tag{4}$$

In order to minimize the resistive loss, one can determine one of the high Q conditions

Numerator even function $f_{11} = 0$ *&*

Denominator odd function $g_{21} = 0$

After some algebraic steps, this leads to an equivalent Z_{in} given by:

$$\begin{aligned}
Z'_{in}(s) &= \frac{g_{11}}{f_{21}} \\
&\approx \frac{s^2 + (\omega_{Z1}\omega_{Z2} + \omega_{Z1}\omega_{Z3} + \omega_{Z2}\omega_{Z3})}{s^3 + s\begin{pmatrix} \omega_{P1}\omega_{P2} + \omega_{P1}\omega_{P3} + \omega_{P2}\omega_{P3} \\ + \omega_{P1}\omega_{P4} + \omega_{P2}\omega_{P4} + \omega_{P3}\omega_{P4} \end{pmatrix}}
\end{aligned} \tag{5}$$

Thus $Z'_{in}(s)$ becomes a third order function through one pole/zero cancellation. This means that a high Q inductor could be simulated by proper pole/zero cancellation.

In this paper, a modular approach is proposed so as to offer the above cancellation with ease. This structure relies on some reasonable (small) active inductor cells connected in series as shown in Fig. 2.

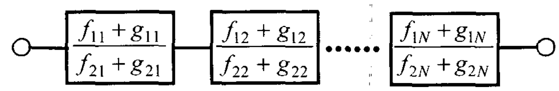

Fig. 2 Modular approach for high Q active inductor.

The resultant input impedance of active inductor of Fig. 2 can be then determined as

$$Z_{in}(s) \approx \sum_{i=1}^{N} \frac{f_{1i} + g_{1i}}{f_{2i} + g_{2i}} \tag{6}$$

When $N = 2$, the high Q condition becomes

Numerator even function =

$$\begin{aligned}
& f_{12}f_{21}(f_{21}f_{22} + g_{21}g_{22}) + f_{11}f_{22}(f_{21}f_{22} + g_{21}g_{22}) \\
& - f_{22}g_{11}(f_{22}g_{21} + f_{21}g_{22}) - f_{21}g_{12}(f_{22}g_{21} + f_{21}g_{22}) \\
& - f_{12}g_{21}(f_{22}g_{21} + f_{21}g_{22}) + g_{12}g_{21}(f_{21}f_{22} + g_{21}g_{22}) \\
& - f_{11}g_{22}(f_{22}g_{21} + f_{21}g_{22}) + g_{11}g_{22}(f_{21}f_{22} + g_{21}g_{22}) = 0
\end{aligned}$$

Denominator odd function =

$$f_{22}g_{21} + f_{21}g_{22} = 0$$

Because the orders of both numerator even function and denominator odd function have been significantly raised, there may exist some frequency ω in the frequency range of concern such that the above condition satisfied. Similarly, we can analyze the cases of three active inductors connected in series and they are:

When $N = 3$, the high Q condition becomes

Numerator even function =

$$\begin{aligned}
& f_{13}f_{21}f_{22}(f_3) + f_{12}f_{21}f_{23}(f_3) + f_{11}f_{22}f_{23}(f_3) - f_{22}f_{23}g_{11}(g_3) \\
& - f_{21}f_{23}g_{12}(g_3) - f_{21}f_{22}g_{13}(g_3) - f_{13}f_{22}g_{21}(g_3) - f_{12}f_{23}g_{21}(g_3) \\
& + f_{23}g_{12}g_{21}(f_3) + f_{22}g_{13}g_{21}(f_3) - f_{13}f_{21}g_{22}(g_3) - f_{11}f_{23}g_{22}(g_3) \\
& + f_{23}g_{11}g_{22}(f_3) + f_{21}g_{13}g_{22}(f_3) + f_{13}g_{21}g_{22}(f_3) - g_{13}g_{21}g_{22}(g_3) \\
& - f_{12}f_{21}g_{23}(g_3) - f_{11}f_{22}g_{23}(g_3) + f_{22}g_{11}g_{23}(f_3) + f_{21}g_{12}g_{23}(f_3) \\
& + f_{12}g_{21}g_{23}(f_3) - g_{12}g_{21}g_{23}(g_3) + f_{11}g_{22}g_{23}(f_3) - g_{11}g_{22}g_{23}(g_3) \\
& = 0
\end{aligned}$$

Denominator odd function =

$$
\begin{aligned}
&-f_{13}f_{21}f_{22}(g_3)-f_{12}f_{21}f_{23}(g_3)-f_{11}f_{22}f_{23}(g_3)+f_{22}f_{23}g_{11}(f_3)\\
&+f_{21}f_{23}g_{12}(f_3)+f_{21}f_{22}g_{13}(f_3)+f_{13}f_{22}g_{21}(f_3)+f_{12}f_{23}g_{21}(f_3)\\
&-f_{23}g_{12}g_{21}(g_3)-f_{22}g_{13}g_{21}(g_3)+f_{13}f_{21}g_{22}(f_3)+f_{11}f_{23}g_{22}(f_3)\\
&-f_{23}g_{11}g_{22}(g_3)-f_{21}g_{13}g_{22}(g_3)-f_{13}g_{21}g_{22}(g_3)+g_{13}g_{21}g_{22}(f_3)\\
&+f_{12}f_{21}g_{23}(f_3)+f_{11}f_{22}g_{23}(f_3)-f_{22}g_{11}g_{23}(g_3)-f_{21}g_{12}g_{23}(g_3)\\
&-f_{12}g_{21}g_{23}(g_3)+g_{12}g_{21}g_{23}(f_3)-f_{11}g_{22}g_{23}(g_3)+g_{11}g_{22}g_{23}(f_3)\\
&=0
\end{aligned}
$$

where

$$f_3 = f_{21}f_{22}f_{23} + f_{23}g_{21}g_{22} + f_{22}g_{21}g_{23} + f_{21}g_{22}g_{23}$$
$$g_3 = f_{22}f_{23}g_{21} + f_{21}f_{23}g_{22} + f_{21}f_{22}g_{23} + g_{21}g_{22}g_{23}$$

3. Simulation Results

In order to demonstrate the proposed modular structure, 3 active inductors were designed and simulated in 0.6μm CMOS technology. The simulation results were obtained by using the SpectreS simulation package of CADENCE. Biased currents of 10mA supplied by conventional current-mirror based current-source are used in these 3 active inductors and the average value of *W/L* is scaled to 12. The simulated input impedances are shown in Fig. 3 (a) and (b), respectively. It is observed that the Q-factor was increased when an additional active inductor cell is added. In fact, the value of Q can reach 11.8 @2GHz when N=1, whilst it is increased to 574 when N=2. Specially, the value of Q can reach as high as 972 when N=3 @ 2GHz.

In order to show the advantages of using the proposed approach, a detailed analysis of the frequency range between 1.85GHz - 2.003GHz is further investigated in Fig. 4, that shows a substantial decrease of the real part of the input impedance @1.885GHz. The minimum value is closed to 5Ω @2GHz with an imaginary part as large as 5kΩ. This indeed confirms the contribution of pole/zero cancellation by using this modular series approach.

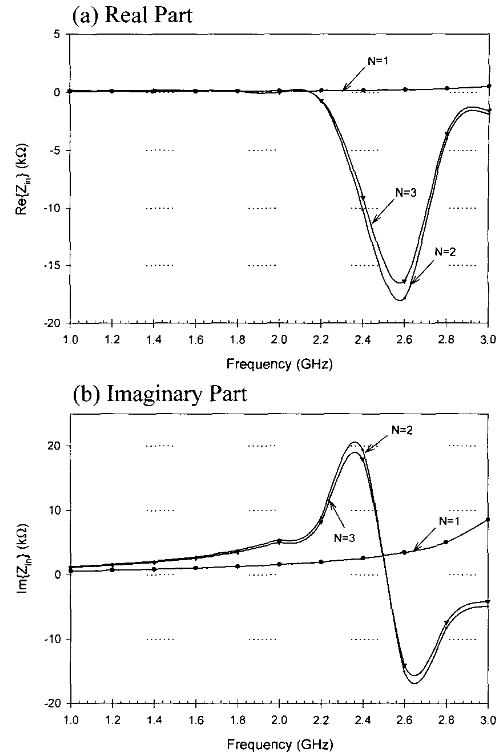

Fig. 3 Simulated CMOS AI impedance (1-3GHz).

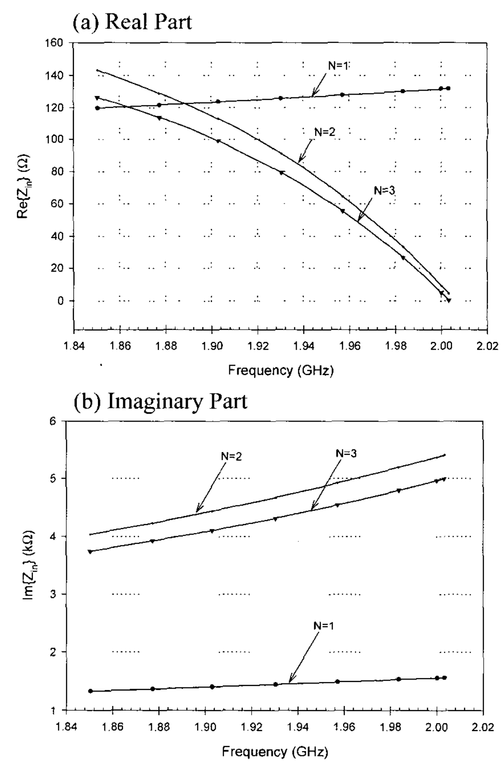

Fig. 4 Simulated CMOS AI impedance (1.885-2.003GHz).

4. CONCLUSIONS

This paper has presented the design of a modular CMOS active inductor in L-band. The simulated results demonstrate that a high Q-factor value of 972 is obtained @2GHz. When the modular series connection changes from N=1 to 3, the value of Q-factor can be tuned from 11.8 to 972. It shows that the modular method may offer some pole/zero cancellation in order to tune a high Q-factor. It is envisaged that the application of this CMOS active inductor structure will be a good candidate for the implementations of narrow band-pass filter in mobile communication.

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