Study of Design Parameter Variations in Simple Grounded Active Inductor

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Abstract— This paper presents a fundamental active inductor topology named Simple Grounded Active Inductor (SGAI) for analyzing variations in Q factor and inductance. Design parameters like aspect ratios and biasing of the transistors are varied and the Q factor and inductance variations are measured at 2.4GHz. The SGAI structure is simulated using Cadence Virtuoso spectre using 180nm technology and a supply voltage of 3.3 V. For a biasing current of 500µA and aspect ratio of 5µm/0.18µm, the Q factor is 2.45, inductance is 2.5nH, and the self resonating frequency is 23.47GHz at 2.4GHz. The designed SGAI circuit consumes a power of 3.3mW.

Keywords— SGAI, SRF, Q factor, SCAI, Regulated Cascode, CMOS, RFIC

INTRODUCTION

In order to make Moore's low pronouncing in radio frequency integrated circuits (RFIC), the RF components can no more be passive in nature. RFIC normally work between 300MHZ to 30GHZ. High Q factor inductor is a major parameter that determines the reliability and efficiency of CMOS RF blocks. Usually inductors are realized on chip as spiral inductors. But they consume a higher area and also has a limited Q factor due to various losses. The inductance and q factor of spiral inductors is determined by design parameters like total length, width, thickness of wire, number of loops, conductivity of the metal etc. Even though passive inductors are simpler to design, they possess a low Q factors in the range of 5 for bulk CMOS and 20 for SOI at GHz frequencies [1].

As the RFIC performance is mainly determined by the tank circuit, a reliable inductor design is inevitable. Active inductors are a promising solution in this scenario. They offer many advantages over their passive counter parts like small chip area, tunable inductance, high Q factor etc [2]. Even though there are several active inductor topologies in the literature most of them are based on gyrator-C configuration [3]. An ideal gyrator is a linear two port network that neither stores nor dissipates energy.

BASIC ACTIVE INDUCTORS

Usually active inductors are build on gyrator type configuration where two transistors are connected in a back to back fashion [5]. The topology utilizes the parasitic capacitance of the transistors in order to make the overall circuit to behave inductive. Simple Grounded Active Inductor (SGAI) is the fundamental topology that uses two transistors to mimic the inductive behavior [10]. However the Q factor that can be achieved is limited and for improving the same, Simple Cascoded Active Inductors (SCAI) can be used. Problem with SCAI is the reduction in the frequency range of the operation. To alleviate that drawback, regulated cascode active inductors [6] are there which provide a better performance compared to SGAI in terms of Q factor and SCAI in terms of frequency range.

A. Theory of operation of SGAI

Input voltage V_{in} is applied to the gate of M_1 which converts the voltage into a current that charges C_{gs2}. The voltage across C_{gs2} is then translated into current by M_1 that maintain I_2 as a constant [5]. Initially, $I_{d2}=I_2$. Increasing I_{in} causes voltage across C_{gs1} to increase. This increases I_{d1} and since I_1 is a constant current source, charges from C_{gs2} is extracted out to meet the increased current demand of M_1. Reduction in gate voltage along with increase in source voltage of M_2 reduces I_{d2}. Now to hold KCL, the increase in input current is utilized by I_2 to remain constant. In this manner SGAI resist the changes in current thereby mimicking inductive behavior.

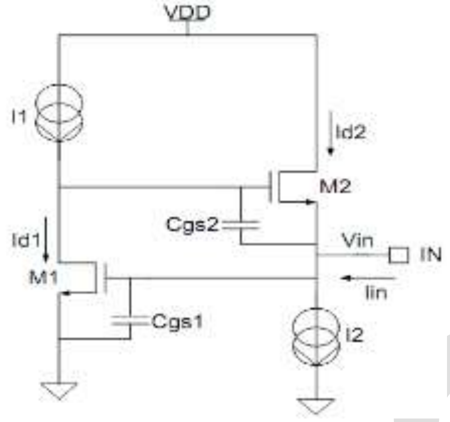


Fig1: Circuit Schematic of SGAI illustrating parasitic capacitances.

B. Figure of merits of inductors

Frequency range

A gyrator-C based active inductor exhibits inductive characteristics over a specific frequency range[8]. Lowest frequency bound is determined by the zero (ω_z) and upper bound by the pole (ω_o) of impedance transfer function. Gyrator-C network will be resistive when $\omega < \omega_z$, inductive when $\omega_z < \omega < \omega_o$ and capacitive when $\omega > \omega_o$. ω_o is also referred to as Self Resonating Frequency (SRF) [4] where the magnitude of impedance is at its peak.

Q factor

The Quality factor or Q factor is a performance indicator that indicates the energy losses within a resonant element. It is dimensionless frequency dependent parameter and can be defined as the ratio of inductive reactance to resistance.

Inductance Tunability

Inductance value can be tuned by varying the transconductance and biasing currents [11]. Since aspect ratio of inductor cannot be tuned once it is fabricated, it is done with biasing currents. So active inductors are beneficial in reconfigurable systems [1].

Chip Area

Active inductors being implemented with active devices, reduces the chip area to a greater extend when compared with their passive versions.

Linearity

Linearity defines the ability of active inductor to sustain a constant inductance and Q factor over a wide input power range [1]. Square law relationship followed by gate source voltage and drain current is the reason for nonlinearity in active inductors [11].

Noise

Active inductors exhibit a higher noise level compared to their passive counterparts [1]. The dominant contributors of noise are thermal noise in the transistor channel and flicker noise due to dangling bonds near the surface [12].

C. Design considerations in SGAI

When the transconductors used for the synthesis of AI has finite input and output impedance, there will be parasitic capacitive (parallel capacitance C_p) and resistive effects (parallel resistance R_p & series resistance R_s) which make the structure lossy. Fig2 below shows the equivalent structure of AI with parasitic effects. Applying KCL at nodes 1 and 2 gives

$$\text{Node1} \Rightarrow (sC_1 + G_{o1})V_1 - g_{m1}V_2 = 0 \qquad (1)$$

$$\text{Node2} \Rightarrow -I_{in} + (sC_2 + G_{o2})V_2 - g_{m2}(-V_1) = 0 \qquad (2)$$

Admittance looking into node 2 is given by

$$Y = \frac{Iin}{V2} = sC_2 + G_{o2} + \frac{1}{s\left(\frac{C1}{gm1gm2}\right) + \frac{Go1}{gm1gm2}} \qquad (3)$$

Above equation can be represented by an equivalent RLC network (Fig2) with following parameters.

$$R_p = \frac{1}{Go2} \qquad (4)$$

$$C_p = C_2 \qquad (5)$$

$$R_s = \frac{Go1}{gm1gm2} \qquad (6)$$

$$L = \frac{C1}{Gm1Gm2} \qquad (7)$$

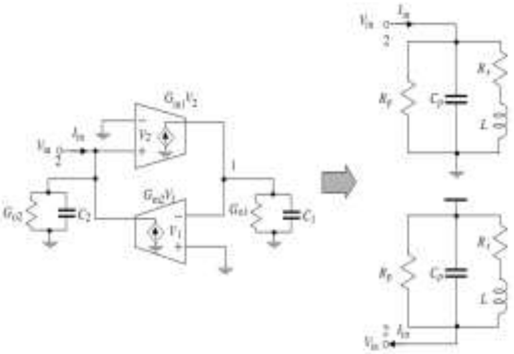


Fig2: Lossy single-ended gyrator-C active inductors. C_1 and G_{o1}, C_2 and G_{o2} denote the total capacitance and conductance at nodes 1 and 2, respectively.

Theoretical equations relating figure of merits and design parameters of active inductors are [7][9]:

$$L = \frac{cgs2}{(gm1gm2)} \qquad (8)$$

$$Q = \sqrt{\frac{gm2cgs1}{gm1cgs2}} \qquad (9)$$

$$Q = \frac{\mathrm{im}\{Z\}}{\mathrm{re}\{Z\}} \qquad (10)$$

$$Q = \frac{wL}{Rs} \qquad (11)$$

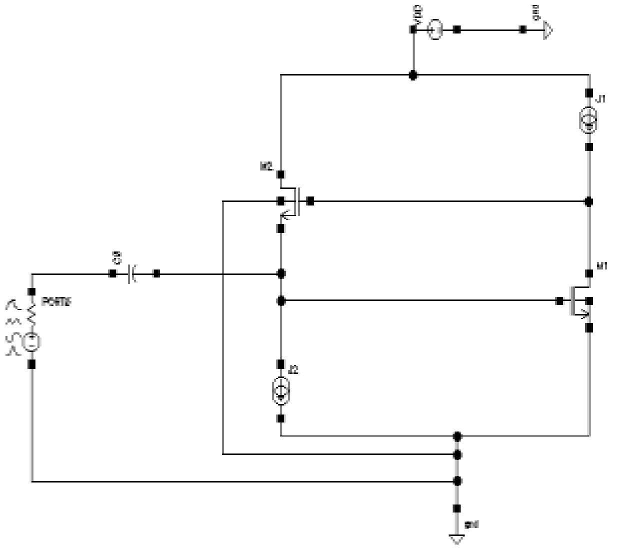
$$R_s = \frac{Go1}{gm1gm2} \qquad (12)$$

DESIGN METHODOLOGY

In this section, we discuss the design considerations and simulation results of SGAI. As many of the wireless communication techniques are operating in 2.4GHz, it is kept as the frequency of concern and L & Q factor are measured and optimized for 2.4GHz. For this frequency Q factor and inductance are measured by varying aspect ratios and biasing and dependency pattern in theoretical and practical cases are compared. For measuring SRF the design parameters are set meeting the following criteria.

TABLE I SGAI DESIGN REQUIREMENTS

Technology	180nm
V_{DD}	3.3V
Frequency	2.4GHz
Q factor	2-3
Inductance	2-3nH



.Fig3: Experimental setup of SGAI

A. Varying the aspect ratios

To understand the variations in Q factor and inductance with respect to aspect ratios, biasing currents J_1 and J_2 are arbitrarily fixed and aspect ratios of both transistors are varied in equal fashion.

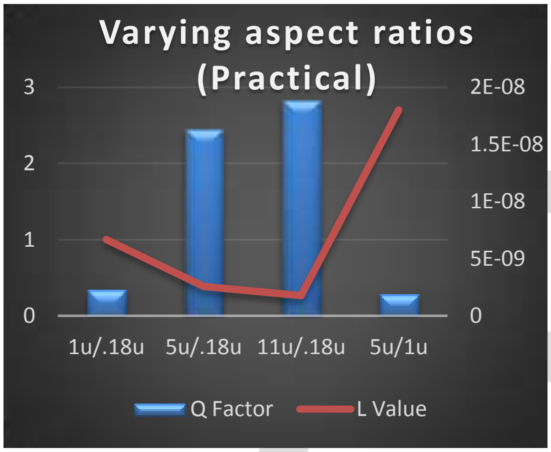


Fig4: Q factor & L for varying aspect ratios- practical case

From the above figure, it can be concluded that increasing the aspect ratios of transistors increases the Q factor and reduces the inductance. As width of M_1 &M_2 increases for a fixed length, g_{m1} and g_{m2} increases. Since L is inversely proportional to both g_{m1} and g_{m2} (eq.8), increasing width reduces L. Increase in g_{m1} and g_{m2} reduces effective series resistance Rs due to inverse proportionality (eq.12). Q factor which is inversely related to R_s thus increases for increasing width (eq.11). From the two graphs that have been plotted it is found that both L and Q factor follows the same pattern theoretically and practically. Variations in the values of theoretical and practical cases are due to the frequency of operation. Theoretical values are measured under its dc operating point and practical values are measured under the required operating conditions. So it can be concluded that both Q factor and L of the SGAI follows the basic relationships as defined in theory and practical values are used for verifying the design.

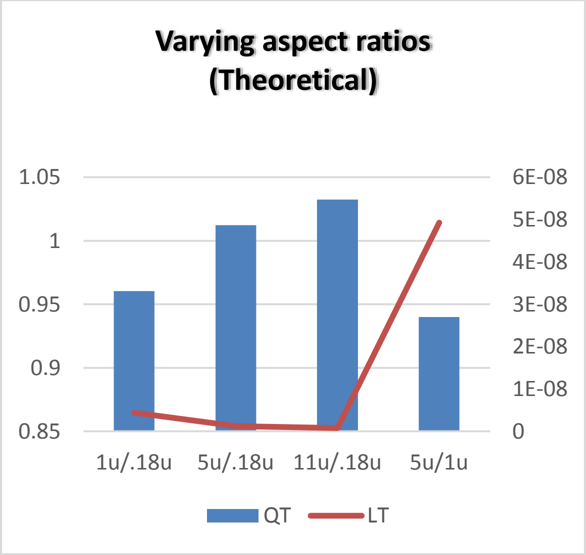


Fig5: Q factor & L for varying aspect ratios- theoretical case

B. Varying biasing currents

Increase in J_2 increase transconductance of M_1 thereby improving Q factor and reducing L. As J_1 is the bias for M_2, increase in J_1 increases transconductance of M_2 and since there is no change in aspect ratio of the transistor, c_{gs2} remains almost constant. Also g_{m2} and c_{gs1} are almost constants. Thus increasing J_1 enhances Q factor and degrades L.

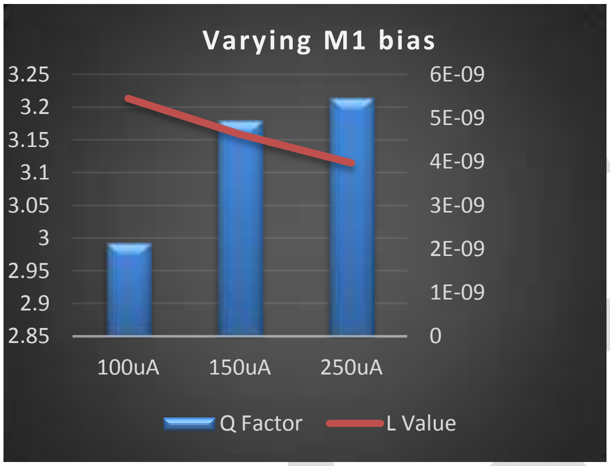


Fig6: Q factor & L for varying M_1 bias

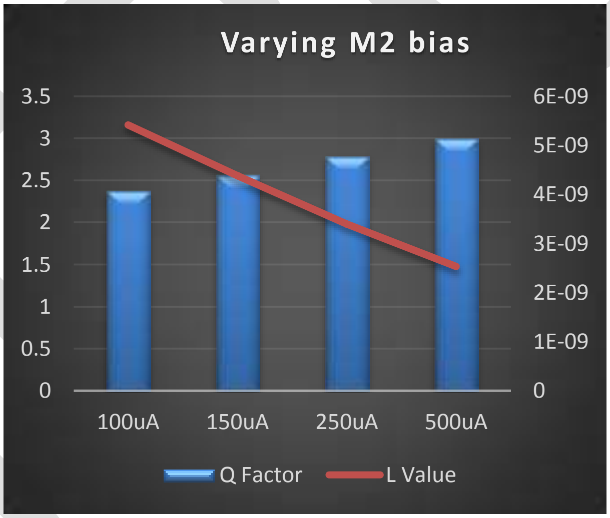


Fig7: Q factor & L for varying M_2 bias

C. Frequency range and power consumption

From the analysis carried out, parameters are fixed for obtaining an inductance of 2.5nH and Q factor in the range 2-3 for analyzing the frequency range and power consumption. . Between ω_z & ω_0 ph{Z} is greater than 0° denoting an overall inductive nature. At SRF mag{Z} is at its peak, ph{Z} is zero (crossing from positive (inductive) to negative (capacitive)) and im{Z} becomes zero thereby making Q factor to be zero. The circuit draws a current of 1.003mA from power supply thereby consuming a power of 3.3mW.

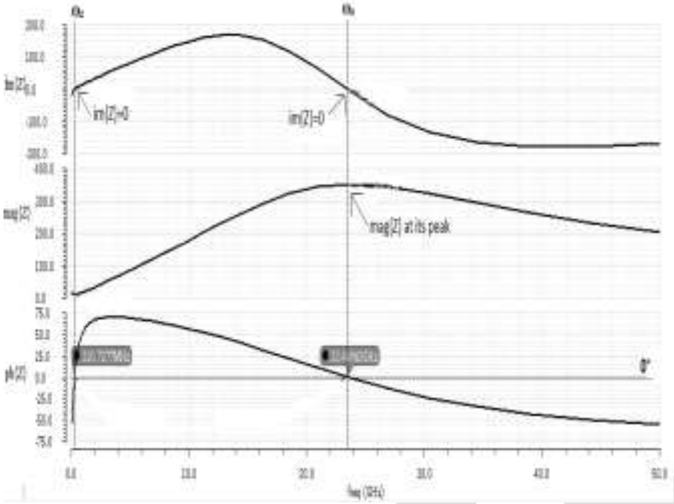


Fig8: Inductive frequency range of SGAI

TABLEII SGAI PERFORMANCE SUMMARY

Technology	180nm
V_{DD}	3.3V
Frequency	2.4GHz
Q factor	2.45
L	2.5nH
ω_z	310.73MHz
ω_o	23.47GHz
Power	3.3mW

CONCLUSION

Through transistor level simulation, we have verified relationship between the design parameters and figure of merits of a basic active inductor topology named Simple Grounded Active Inductor both theoretically and practically. The structure is then optimized for an inductance of 2.5nH and Q factor of 2.45 for analyzing its inductive frequency range and power consumption. The analysis has shown a SRF of 23.47GHz which is around ten times the required frequency of operation.

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