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ON THE DESIGN AND OPTIMIZATION OF CMOS ACTIVE INDUCTOR FOR RF APPLICATIONS

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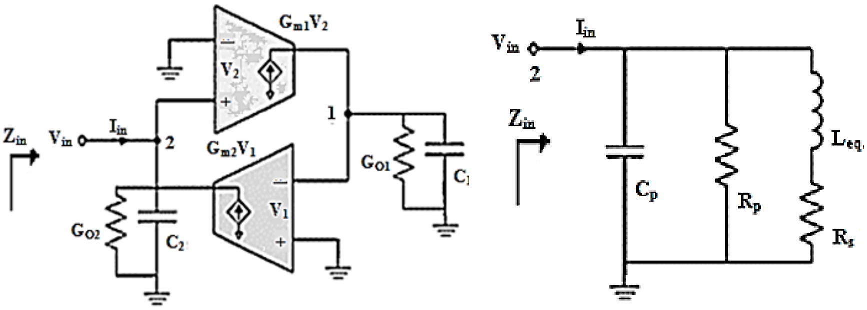
Abstract

A design and optimization of an active inductor (AI) for a 2.4 GHz RF application is presented in this paper. A Genetic Algorithm (GA) optimization technique is realized and applied to improve the active inductor performances. The active inductor performance parameters concerned include inductance value range, quality factor, device dimensions, and required power consumption. Different fitness functions are formulated and used in a multi-objective function fashion using MATLAB environment. . It is shown the use of inductance–quality factor product (LQ) in fitness function formulation provides a significant increase in inductance value range and improve quality factor (LQ = 68.6), as well as reduction in power consumption (P = 0.453 mW).

Keywords: AI, GA, LQ, LNA, RFIC.

1. Introduction

The most important and critical component in most analogue integrated circuits is the inductor realization and fabrication. This may include applications in mixer, voltage control oscillators, and in low noise amplifier. It is well known that analogue integrated circuit design are required to minimize chip area, cost, power consumption, etc. In wireless communication and radio frequency IC, there are two methods of inductor realization that are passive (Spiral) and active structure [1]. Active inductor realization provides high quality factor and occupies small chip area, on the other side, passive realization has limited quality factor tuning and required large chip area [2, 3]. The most common realization of active inductor is based on the Gyrator-C configuration as shown in Fig. 1(a) and its equivalent circuit in Fig. 1(b) [4-6], this structure consists of back to back transconductors. The gyrator-C active inductor is simulated when a capacitor is connected to one port of the gyrator, then the other terminal is resembling inductance [4]. This type of realization has been utilized for applications that required high quality factor and required inductive characteristic such as in low noise amplifier and RF band pass filters [7, 8].



(a) Model. **(b) Equivalent circuit.**

Fig. 1. The Gyrator-C active inductor configuration [4].

In this paper, genetic algorithm (GA) is applied to improve design performances for CMOS active inductor for the RF applications required at frequency 2.4 GHz. The most important parameters concerned and optimized include quality factor, self-resonant frequency, inductor value and power consumption.

The genetic algorithm is one of the most popular optimization tool used to find the proper and optimum solutions. GA is based on biological evolution where, over successive generations, individuals who are best suited to survive in an environment live on reproduce, while other individuals die off gradually [9].

2. Literature review

Passive on chip inductor realization has limited application since of its practical limitations and its fabrication difficulties. Active inductor simulation has been extensively introduced by researchers. According to Pramanik [10], Operational transresistance amplifier (OTRA) that is substantial building block in many analog signal processing has presented, this is based on grounded CMOS AI in the domain of high frequency for bandpass filter. One of the most important feature of CMOS active inductor (AI) is the capability of working at low voltages in radio frequencies. A novel low voltage floating AI has been used as a tuned load for *RF* band pass amplifier is presented by Thanachayanont [11]. Improvements on Q-factor and the impedance have been proposed by Hsiao et al. [12] using AI with feedback resistor. Mehra et al. [13] have presented a four-bit capacitor bank, two buffers and an active inductor are included for the design realization. The design of a resistor-less voltage controlled oscillator (VCO) with tuning range is realized using the proposed structure of active inductor in order to minimize the noise and chip area.

3. A Single-Ended Active Inductor Realization

The general single ended gyrator-C lossy active inductor with its equivalent circuit is shown in Figs. 1 (a) and (b) respectively. The lossy parameter is due to (input/ output) impedances of the network are not zero and have infinite value. The parasitic elements ($C_{1,2}$, G_{01} and G_{02}) included in the equivalent circuit as shown in Fig. 1(a) limits the ranges of operational frequency for the simulated inductor. The input admittance for the gyrator-C topology looking into port 2 using standard circuit analysis is given by the Eqs. (1) to (6) [4]

$$Y_{in} = \frac{1}{Z_{in}} = \frac{\mathrm{I_{in}}}{\mathrm{V_{in}}} = sC_2 + G_{o2} + \frac{1}{s\left(\frac{C_1}{\mathrm{G_{m1}G_{m2}}}\right)+\left(\frac{G_{O1}}{\mathrm{G_{m1}G_{m2}}}\right)} \tag{1}$$

Equation (1) can be represented and modeled by an RLC network that is shown in Fig. 1(b), where:

$$R_p = \frac{1}{G_{o2}} \tag{2}$$

$$R_s = \frac{G_{O1}}{\mathrm{G_{m1}G_{m2}}} \tag{3}$$

$$C_p = C_2 \tag{4}$$

$$L_{eq} = \frac{C_1}{\mathrm{G_{m1}G_{m2}}} \tag{5}$$

Therefore, the existence of these paracitics leads to lossy inductor behaviour. Hence eliminating or reducing these paracitics is the most significant criteria to approach the ideal behaviour.

The existence of the parasitic parallel resistance (R_p), parallel capacitance (C_p), and series resistance (R_s) leads to make the network of gyrator-C have same behaves a lossy inductor. Therefore, maximizing R_p and minimizing R_s should be taken into consideration to minimize the ohmic loss. However, the finite values of the input and output impedances of the transconductors of the gyrator-C network have no influence on the inductance of the active inductor (AI). The self-resonant frequency (SRF) of this active inductor is given by [2, 4]

$$\omega_0 = \frac{1}{\sqrt{L\,C_p}} = \sqrt{\frac{\mathrm{G_{m1}G_{m2}}}{C_1C_2}} \tag{6}$$

A single-ended active realization for grounded inductor **(**SGAI) simulation is shown in Fig. 2 [4].

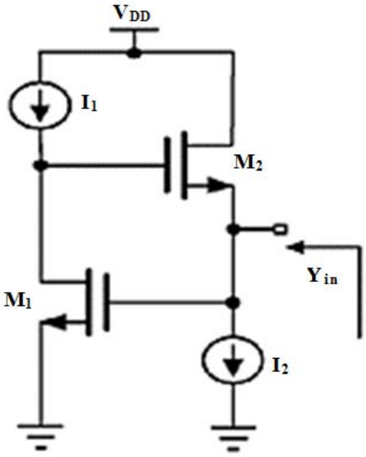


Fig. 2. Schematic diagram of Grounded single-ended active inductor.

Transistor M_2 is configures as common drain and this realize the positive transconductance. Whereas, M_1, realizes the negative transconductance in a common source configuration. M_1 and M_2 must be biased to operate in active region using two current sources I_1 and I_2 in addition to supply voltage V_{DD}.

Based on the Fig. 2 and using small signal analysis leads to the equivalent inductance and quality factor of the grounded inductor are given in Eqs. (7) and (8).

$$L = \frac{C_{gs1}}{g_{m1}\, g_{m2}} \tag{7}$$

$$Q = \frac{g_{m2}\, C_{gs1}}{C_{gs2}\, g_{m1}} \tag{8}$$

Moreover, the self-resonance frequency (SRF) can be written as in Eq. (9).

$$\omega_0 = \sqrt{\frac{1}{C_p\, L_{eq}}} = \sqrt{\frac{g_{m1}\, g_{m2}}{C_{gs1}\, C_{gs2}}} = \text{SRF} \tag{9}$$

Where g_m represent the transconductance of the device and given by Eq. (10).

$$g_m = \sqrt{2 \times \mu_n C_{ox} \times \left(\frac{W}{L}\right) \times I_D} \tag{10}$$

The total power consumption is therefore given by Eq. (11).

$$P = (I_1 + I_2) \times V_{DD} \tag{11}$$

4. Active Inductor Optimization Based on Genetic Algorithm (GA)

The design and optimization of grounded active inductor is considered in this section. The design procedure is aimed to obtain a high-quality factor over a wide range of inductance value for specified self-resonant frequency for RF applications at 2.45 GHz. It is obvious from Eqs. (7) to (9) that g_{m1} and g_{m2} determine the quality factor and the value of inductance in opposite behaviour. However, the transconductance g_{m1} and g_{m2} determine the transistor dimension W/L Eq. (10). It is means that a trade-off is required between quality factor and inductance. This can be achieved by optimization. Thus, the genetic algorithm in this work is used as optimization tool.

The main performance parameters that are to be optimized based on this approach (GA) includes Q, L, power consumption and transistor active area. These performances are designed to be controlled by four variables, and these variables may include current source (I_1), current source (I_2), transistor width (W_{t1}), and transistor width (W_{t2}) which are inherently determines g_{m1} and g_{m2}. Since, design performances that achieve using analytical solution may take too many time and also may not lead to desired specifications. Therefore, GA is applied to search for optimum design variables that provide the optimum performances. Table 1 summarized the specified performances that have to be optimized for 2.4 GHz operating frequency.

Table 1. Active inductor design goal specifications for 0.18 μm process.

Technology	**Specifications Required**
V_{DD} (V)	1.8
Frequency (GHz)	2.4
Resonant frequency (F_0) GHz	Maximize
Q-factor	Maximize
Inductance value "L" (nH)	Maximize
LQ-Product	Maximize
Power consumption (mW)	Minimize
Transistor width(W_{t1}) (μm)	Minimize
Transistor width(W_{t2}) (μm)	Minimize
I_1(mA)	Minimize
I_2(mA)	Minimize

4.1. Case study: Single-ended grounded active inductor (SGAI) design for RF applications at 2.4 GHz

A genetic algorithm (GA) procedure is written in MATLAB environment and can be summarized as follow:

Step1- Initialization of the first binary population of N random individual solutions.

Step2- Converting the current binary population to real.

Step3- Each individual (chromosome) asses by the fitness function and constraints.

Step4- Test if the fitness function, constraints are satisfied.

Step5- If the step number 4 is satisfied, then print the design variables (chromosome) and end the procedures (jump to step 9).

Step6- Test stop conditions (number of generations).

Step7- If the step number 6 is satisfied, then jump to step 9.

Step8- Apply genetic operators (selection, crossover, mutation) on the population then back to step number 3.

Step9- Stop the algorithm.

4.2. Design variables as chromosome

The design variables are selected to be I_1, I_2, W_{t1}, and W_{t2}. Thus, these variables are represented as chromosome containing for four variables as genes.

Table 2 illustrates these variables and constrained values in addition to their corresponding binary representation. The binary representation is determined by the accuracy of real values corresponding to the selected variables.

Table 2. Design Parameters of AI based on GA.

Variables	Constrained Values	Binary representation
W_{t1}(μm)	1 to 1000	20
W_{t2}(μm)	1 to 1000	20
I_1(mA)	0.1 to 5	13
I_2(mA)	0.1 to 5	13

4.3. Fitness function formulation

The fitness or objective function is a numerical quantity that measure the chromosome approximation to the desired specifications [14]. Single and multi-objective functions are explained in this paper. The design of fitness function is based on what performance parameters are selected to be optimized and therefore include in the total fitness function (F_T). The total fitness function (F_T) as multi-objective function is defined as in Eq. (12) [15, 16].

$$F_T \ \sum_{j=1}^{m} W_j \times F_j \tag{12}$$

where:

F_T : is the total fitness function.
F_j : indicate to the goal value for object "*j*".
W_j : indicate to the weight factor of object "*j*".
m : indicate to the number of objects.

When $m = 1$, the Eq. (12) will lead to formulate of single fitness (objective) function. Table 3 presents different fitness function with their corresponding concentrated parameter.

Table 3. Formulation different fitness function.

Total fitness function	Formulation	Constrained parameter
1	$F_T = (L \times W_1) + (Q \times W_2)$	Improves (*L* and *Q*). (*P* and W_t) are as constraints
2	$F_T = \left(\frac{1}{L} \times W_1\right) \times \left(\frac{1}{Q} \times W_2\right)$	Improves (*L* and *Q*). (*P* and W_t) are as constraints
3	$F_T = \left(\frac{1}{P} \times W_1\right) + (W_{t1} + W_{t2}) \times W_2$	Improves (*P* and W_t). (*L* and *Q*) are as constraints
4	$F_T = (L \times W_1) \times (Q \times W_2)$	Improves (*L* and *Q*). (*P* and W_t) are as constraints
5	$F_T = \left(\frac{1}{L} \times W_1\right) + \left(\frac{1}{Q} \times W_2\right)$	Improves (*L* and *Q*). (*P* and W_t) are as constraints
6	$F_T = (L \times W_1) + (Q \times W_2) + \left((W_{t1} + W_{t2}) \times W_3\right) + (P \times W_4)$	Improves (*L*, *Q*, *P* and W_t)

where: F_T is the total fitness function, L is the inductance value, Q is the Q-factor, P is the power consumption, W_j is the weight factor of "j" object, W_{t1} is the transistor width number 1 in Fig. 2 and W_{t2} is the transistor width number 2 in Fig. 2.

It is shown that application of each fitness function has an influence on quality factor, range of inductance values, power consumption, or on device dimensions. Moreover, the effect of these fitness function influences each parameter individually or combination of other performance parameter.

4.4. Proposed LQ product

It is clear from the above table that the application of each fitness function in the designed GA has improved certain performance parameters. Since, the most important parameters in active inductor is to maximize quality factor, maximize inductance value range to cover the operating frequency and minimize power consumption. The LQ product is introduced in the formulation of fitness function F_{T4}. The maximization this fitness function leads to improve the range and inductance value as well as the quality factor improvement. In addition to that the power consumption and devices width are constrained to certain specified values.

4.5. Performing GA on Single-ended active inductor

The genetic algorithm steps previously mentioned are simultaneously executed using the fitness functions formulated above to generate new population. Hence performing selection, crossover, and mutation to obtain new chromosome. The GA stop searching for optimum when the desired fitness function and hence constraints are met.

5. *GA* Results

The genetic algorithm using designed fitness functions is applied to grounded single-ended active inductor (operating at 2.4 GHz) as a case study. Table 4 presents GA results that illustrates the optimum values of the chromosome variables selected for different fitness function.

Table 4. Real values of the optimum selected variables of Active inductor.

Variables	F_{T1}	F_{T2}	F_{T3}	F_{T4}	F_{T5}	F_{T6}
W_{t1}(μm)	5.366	4.12	9.94	11.9	8.82	10
W_{t2}(μm)	1.256	1.017	1.4	1.07	1.06	1
I_1(mA)	0.257	0.113	0.11	0.102	0.102	0.1
I_2(mA)	0.101	0.156	0.319	0.149	0.351	0.268

The resultant GA variables obtained determine the performances required to be improved. Table 5 presents the active inductor optimum performances obtained for 0.18 μm CMOS technology.

Table 5. Results of the optimum requirements.

	Specifications Required	F_{T1}	F_{T2}	F_{T3}	F_{T4}	F_{T5}	F_{T6}
V_{DD} (V)	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Frequency (GHz)	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Resonant frequency (F_0) GHz	Max.	24	23	15.8	12.1	15.4	13.6
Q-factor	Max.	3.12	4.7	6.66	6.36	6.8	6.7
Inductance values "L" (nH)	Max.	4.86	7	7	10.8	8.5	9.8
LQ-Product	Max.	15.168	32.9	46.6	68.68	57.8	65.65
Power consumption (mW)	Min.	0.645	0.48	0.77	0.453	0.82	0.663

6. Simulation Results

The results obtained from GA are used and applied into active inductor simulation to verify these results. Advance design system (ADS) simulation environment supplied by Keysight Technologies is employed in the simulation purposes. Figures 3 to 5 present the inductance values, quality factor, and LQ product respectively as a function of frequency for proposed fitness functions. As reported earlier that fitness function (F_{T4}) provides a significant improvement on parameters performance.

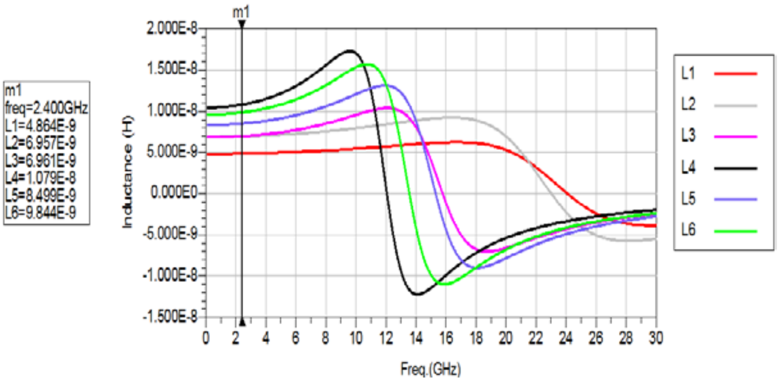


Fig. 3. Inductance values for six fitness functions.

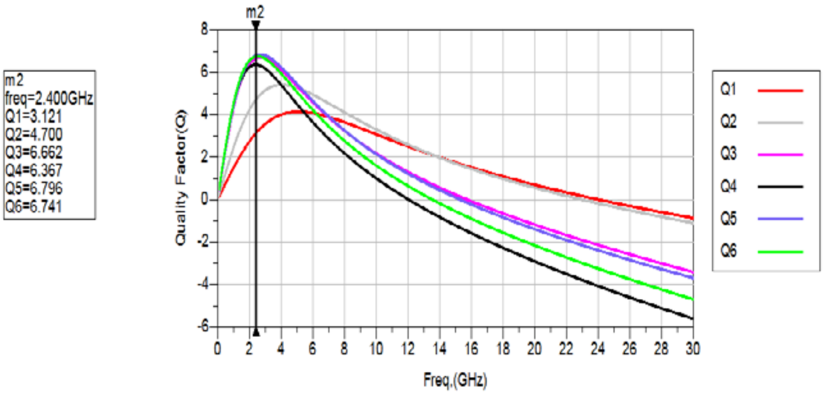


Fig. 4. *Q*-factor values for six fitness functions.

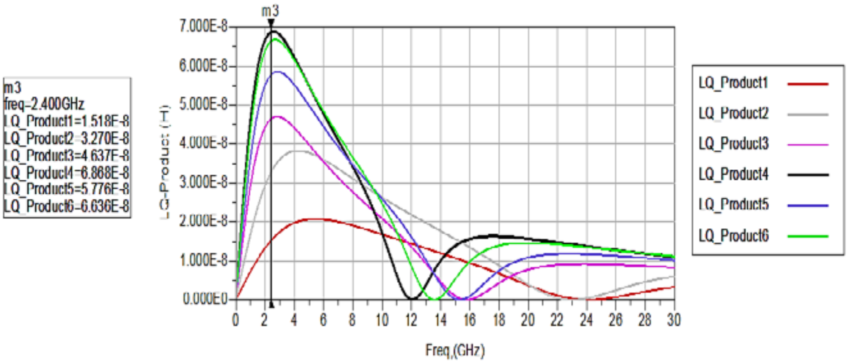


Fig. 5. LQ-Product for six fitness functions.

Figures 3 to 5 illustrate the behaviour of inductance values, quality factors and LQ products respectively under the application of various fitness function. Figure 5 presents and illustrates the improvement of LQ products as a function of frequency.

As shown earlier that fitness function F_{T4} provides a significant improvement in L and Q compared with other fitness functions used. Figures 6 to 8 illustrate that using this fitness function results in a wide and extended values of operating frequency range. In addition to that the self-resonance frequency (SRF) is extended to about 12.1 GHz.

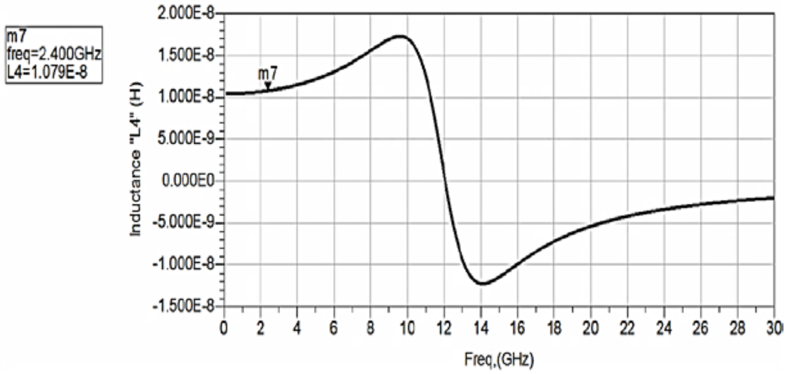


Fig. 6. Inductance value versus frequency using F_{T4}.

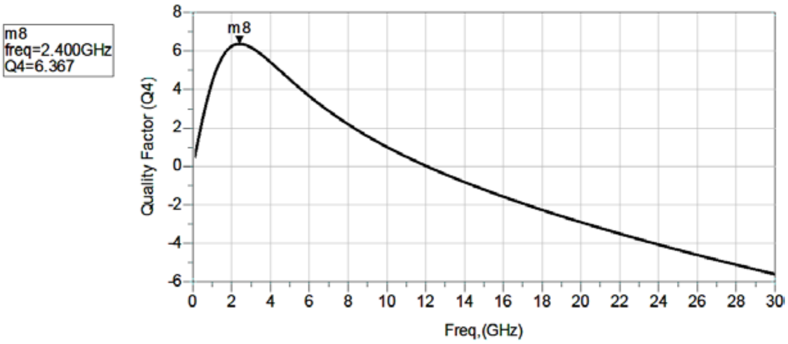


Fig. 7. Quality factor value versus frequency using F_{T4}.

The tradeoff between inductance value (L) and quality factor (Q) is treated by formulation the LQ product. Figure 8 illustrates that the LQ product values of approximately 69 nH at 2.4 GHz frequency can be obtained. It is also important to note that at this value of frequency the quality factor has acceptable value.

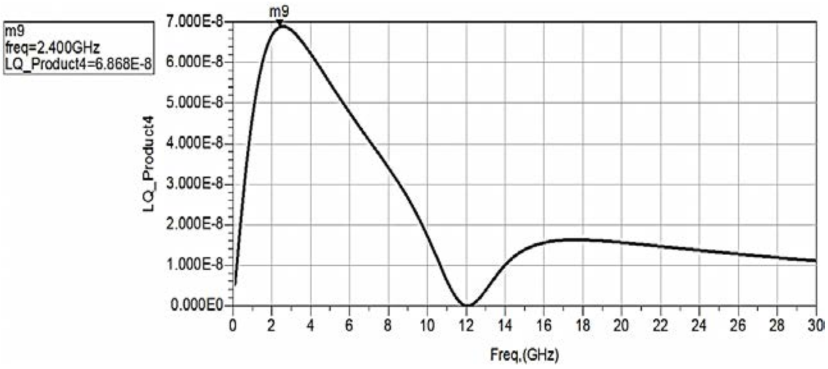


Fig. 8. LQ-Product value versus frequency using F_{T4}.

Comparison between GA Performances and other Design Techniques

To illustrate the efficiency of applying GA to improve performances of an active inductor realization a comparison is made between the existing technique [17] and the genetic algorithm approach. Table 6 presents the results of comparison at the same technology of 0.18 μm and the same topology.

Table 6. Comparison results with other design technique

	Ref. [17]	This work
Topology	SGAI	SGAI
Technology	0.18 μm	0.18 μm
V_{DD} (V)	3.3	1.8
Frequency (GHz)	2.4	2.4
Q-factor	2.45	6.36
Inductance value “L” (nH)	2.5	10.8
LQ-Product	6.125	68.688
Power consumption (mW)	3.3	0.453
W_{t1} (μm)	500	11.9
W_{t2} (μm)	500	1.07
I_1 (mA)	0.5	0.102
I_2 (mA)	0.5	0.149

7. Conclusions

A genetic algorithm optimization method was applied to design of single ended active inductor for RF applications that operate at 2.4 GHz frequency. The design performances include inductance value range, quality factor, power consumption, and transistors area were significantly improved. The design variables that form the GA chromosome and determine the above performances are selected to be the currents I_1 and I_2 as well as the device widths W_{t1} and W_{t2}. Multi-objective fitness functions are formulated to obtain the optimum variables the translated into optimum performance parameters. Different formulations of fitness function were designed and employed. It was shown the use a combination of inductance value and quality factor as LQ product in representing the fitness function resulted in a significant improve in inductance value and quality factor with minimum power consumption compared with other functions. A comparison with other existing method was presented and showed the powerful of GA technique over other methods. ADS simulation for the single ended active inductor with using the obtained parameter values from GA illustrates a good agreement with the specified performances.

Nomenclatures

$C_{1,2}$	Parasitic capacitances at node 1 and 2, F
$C_{gs1,2}$	Gate to source capacitance of transistor 1 and 2, F/m
C_{OX}	Capacitor per unit area of the gate oxide, F/m^2
C_p	Parallel Capacitance, F
F_0	Self-resonant frequency, Hz
F_{TX}	Fitness functions
G_{01} ,G_{02}	Parasitic conductances at node 1 and 2, S
g_m	Transistor’s transconductance, S
$I_{1,2}$	Drain current of transistor 1 and 2, A
L	Length channel of the transistor, m
L	Inductance, H
L_{eq}	Equivalent Inductance, H
$M_{1,2}$	Transistor number 1and 2
P	Power consumption, W
Q	Quality factor
R_p	Parallel Resistance, Ω
R_S	Series Resistance, Ω
V_{DD}	Drain voltage, V
W_{tx}	Width of the transistor, m
W_X	Weight factors
Y_{in}	Input admittance, S
Z_{in}	Input impedance, Ω
μ_n	Electron mobility, m^2/V. s

Abbreviations

ADS	Advance Design System
AI	Active Inductor
CMOS	Complementary Metal-Oxide Semiconductor
GA	Genetic Algorithm
LQ-Product	The process of multiplying value inductance with quality factor
MATLAB	Math Laboratory
RF	Radio Frequency
SGAI	Single-ended Grounded Active Inductor

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