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Synthesis of a microwave CMOS active inductor using simple current mirror-based operational Transconductance Amplifier (OTA)

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Abstract— This paper deals with the design of a microwave active inductor using 0.18 µm CMOS technology. The proposed circuit configuration is based on the Gyrator-C topology relying on new OTA circuits that can function efficiently in the microwave domain. Such circuits are mainly made out of simple current mirrors requiring essentially low power consumption. Compared to typical spiral inductors, circuits of active inductors provide small tuning inductance values, high quality factor and tiny chip area.
Several simulations have been carried out by means of PSPICE software leading in the configuration of the expected high standard performances.
The comparison between simulated and calculated inductor's parameters validates the proposed design process and allows several microwave applications to be implemented.

Index Terms— active inductor, CMOS, OTA, Transconductance, current mirror, Gyrator-C, 0.18µm technologie

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1 Introduction

Inductors are amongst the most important elements in integrated circuits such as filters, oscillators, matching networks etc.… For several years designers have widely used spiral inductors in a large number of applications, thanks particularly to their planers structure and low power consumption.

Unfortunately, there are some constraints that must be overcome for better circuit performances. Among these major problems, we have high series resistance, large chip area and crosstalk that lead inevitably to poor circuit responses.

Therefore, there is a great interest in a good alternative that consists of implementing active inductors. This solution has been adopted in microwave circuit designs and has become more and more appropriate for many applications with a huge range of topologies resulting in high quality factor. Designers rely on several architectures based upon CMOS technology for implementation.

Since the gate length of CMOS devices was substantially reduced to sub-micron, sensitive microwave applications have been developed and well achieved.

Thus, the use of Operational Transconductance Amplifiers (OTA) is one of numerous possibilities which have successfully been explored and led to high standard performances [1].

OTAs are, in most cases, implemented by means of MOSFET transistors that represent voltage-controlled current devices.

Currently, OTA circuits have various simple configurations depending on the concept of Input/Output (I/O). On one hand, there are common source transconductors with negative transconductance. On the other hand, common gate, common drain and differential pair OTA circuits have a positive transconductance [2].

As indicated, one of the three configurations is an OTA topology based on current mirrors. Generally, such a structure guarantees the required conditions, which are mentioned above, to be fully satisfied.

Under these circumstances, we have proposed a synthesis of grounded inductors by means of a Gyrator-C network. The main circuit is made of two 0.18 technology CMOS connected back-to-back having one port terminated with a capacitor [3].

The proposed document is organized as follows. Section 2 discusses three current mirrors MOSFET configurations, Simple, Wilson and Cascode with the emphasis on simple current mirror circuit. The use of simple current mirrors in the OTA circuit is given in Section 3. Section 4 presents an evaluation of the transconductance Gm and discusses the design of a lossy active inductor, also analyses of circuits and simulation results are presented in Section 5. Finally, a conclusion is given in Section 6

2 MOSFET current mirrors:

As well known, a current mirror copies the current flowing in one active device in other, providing at the same time a constant current regardless of loads. Among the most chosen current mirrors, we have simple, Wilson and cascode devices as shown in figure 1[4]. The simple current mirror consists of two saturated transistors M1 and M2 whose drain are connected. Another transistor M3 is added to the previous circuit in order to form the Wilson current mirror as illustrated in figure 1.b.

The cascode configuration is a sort of two stages of simple current mirror shown in figure 1.c. All the transistors must be in saturation region.

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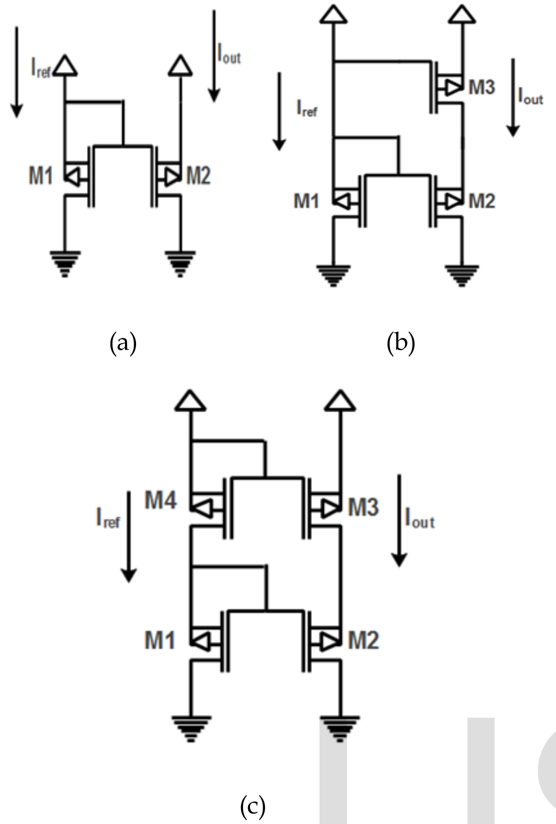

Fig1: Different configurations of current mirror circuit.
(a) Simple current mirrors.
(b) Wilson current mirrors.
(c) Cascode current mirrors.

As such, throughout the present work, we have developed a synthesis method of the proposed OTA circuit on the bases of current mirrors as building blocks. There is a wide spread demand amongst several types of OTA circuits for topologies that can provide low power consumption. As a consequence, we have chosen a simple current mirror as a basic element of the synthesized OTA circuit allowing us to reduce greatly the number of transistors in the whole circuit. In addition the design process uses current mirrors made from identical MOSFET transistors.

According to a theoretical development [5], the transconductance of MOSFET transistors is given by:

$$g_m = \sqrt{2.k_p.\frac{W}{L}.I_{SS}} \quad (1)$$

Where K_p is the Boltzmann's constant, W and L are respectively the width and the length of the transistor and I_{ss} is the biasing current that can also control the transconductance.

3 CMOS DIFFERENTIAL OTA

In this section, we deal with an OTA circuit behaving as a voltage-controlled current source (VCCS) with respect the overall transconductance Gm. Figure 2 describes the simplified configuration of such a circuit.

To further focus on this point, we emphasize that the topology of the designed OTA consists of a simple current mirror connected to an NMOS differential pair. Both transistors M1 and M2 are identical and biased by a constant current source Ibias. The whole circuit is based on 0.18µm MOSFET transistors.

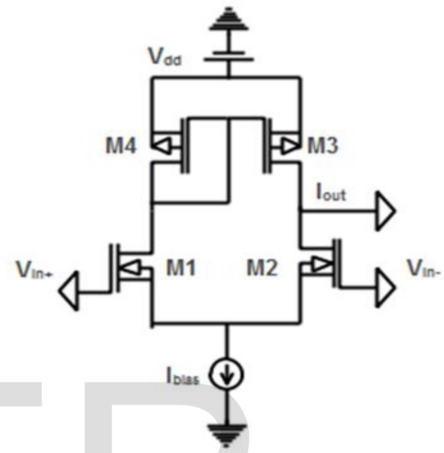

Fig 2: Simple current mirror

We also point out that this structure has the advantage to suppress common mode gain and requires simple biasing conditions.

Referring to figure 3 and taking into account the features mentioned above, the OTA circuit can be modelled as indicated in figure 3

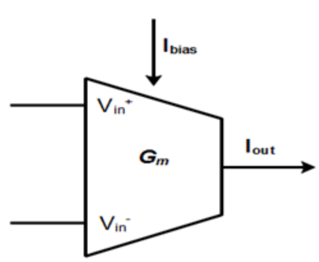

Fig 3: OTA model

Where the transconductance Gm is given by:

$$G_m = \frac{I_{out}}{V_{in}^{+} - V_{in}^{-}}$$

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4 Evaluation of the Transconductance Gm:

Considering the fact that all the MOS transistors of the OTA circuit are identical, we can find that both transconductances gm and Gm are equal that is:

$$G_m = g_m \tag{3}$$

We can also calculate the OTA's transconductance G_m through simulating the circuit of figure 4. The simulations are carried out by means of the SPICE software on the basis of 0.18µm CMOS technology at level 8.

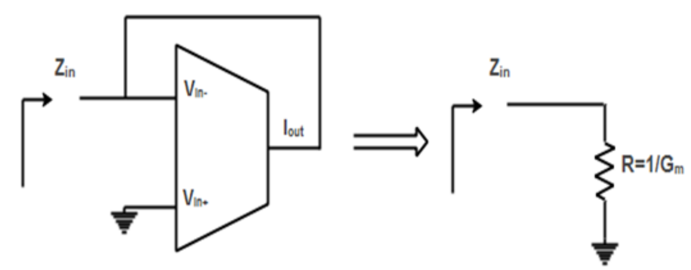

Fig 4: Circuit for calculating the OTA's transconductance

So, to obtain the input admittance of the circuit, we take into account the following simulation parameters:
L=2µm, W=4µm and V_{dd}=5V.

Table 1 show different values of G_m determined by means of (1) with respect to I_{bias}, whereas simulation results are given in figure 5 with the frequency varying from 0.8GHz to 3GHz.

TABLE 1
Different calculated values of the transconductance with different current I_{bias}

Ibias(µA)	Gm(mS)
240	28.89
250	29.49
260	30.07

We clearly notice that there is a good level of agreement between simulated values and those obtained by (5). Moreover, the curves of figure 5 show a very small variation, so that the G_m can be considered as constant.

As previously indicated, the proposed active inductor is made from Gyrator-C circuit, that is we can connect two back-to-back identical simple current mirrors based OTAs to a grounded capacitor.

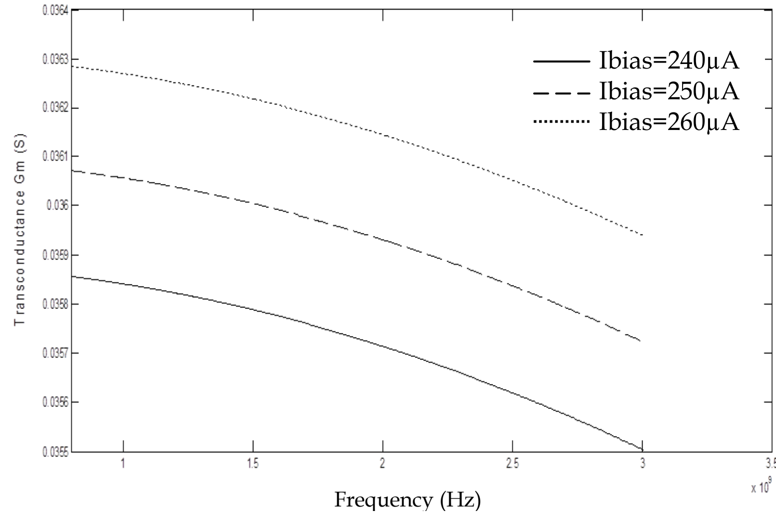

Fig 5: values of simulated Gm with different current Ibias.

Figure 6 shows a single ended active inductor circuit illustrating both the model (figure 6-a) and the real structure (figure 6-b). C_{gs} stands for C in the circuit model.

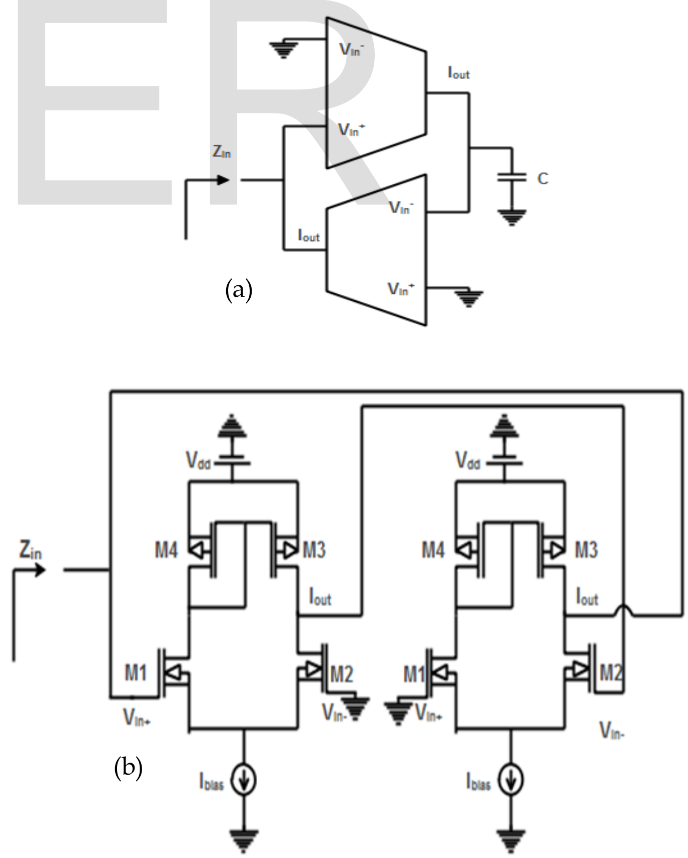

Fig6: Active inductor model and real structure
(a) Active inductor model
(b) Real structure of the proposed active inductor

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On one hand, a positive transconductor is obtained by means of a common drain and a common gate configuration. On the other hand, a common source and a common gate stage leads to a negative transconductor.

The small signal analysis enables us to determine the input Gyrator-C admittance [6] which is given by:

$$Y_{in} = \frac{I_{in}}{V_{in}} = G_m + \frac{G_m^2}{j\omega C_{gs} + G_{ds}} + j\omega C_{gs} \quad (4)$$

From relation (4), we can easily identify the equivalent resonant circuit, shown in figure 7 that models the proposed lossy active inductor.

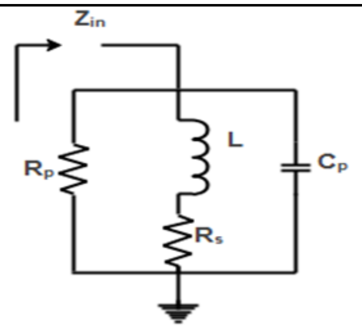

Fig7: Equivalent resonant circuit

The expressions of L, R_s, R_p and C_p are:

$$L = \frac{C_{gs}}{G_m^2} \quad (5)$$

$$R_s = \frac{G_{ds}}{G_m^2} \quad (6)$$

$$R_p = \frac{1}{G_m} \quad (7)$$

$$C_p = C_{gs} \quad (8)$$

There is clear note that all these elements are frequency independent and tunable via specific parameters.

So, the equivalent inductance L of the circuit is tunable via the transconductance G_m with respect to the biasing current I_{bias}, while the shunt conductance C_p stands for the active inductor losses. C_p is a parasitic element and R_s is a series loss resistance.

As a result, and taking into account the model structure, the resonant frequency of the active inductor is expressed as follows:

$$f_0 = \frac{1}{2\pi\sqrt{LC_p}} \quad (9)$$

This is obviously adjusted by the bias current I_{bias}. The proposed design is also aimed to illustrate another important advantage, which must be pointed out, that is the quality factor Q of the circuit whose expression is givel by (10):

$$Q = \frac{IMG[Z_{in}]}{REAL[Z_{in}]} \quad (10)$$

Where IMG [Z_{in}] and REAL [Z_{in}] are the imaginary and the real parts of the input impedance, respectively. They are functions of the transconductance G_m of the circuit. As a result, the Q factor is tuned by means of the current I_{bias} leading to a change in the equivalent inductance L and the resistances.

Circuit sensitivities:

All circuits have performances that varie as the values of the components change, the mathematical definition of the sensitivity is given by equation (11), where x stands for the variable component and y is the inductor characteristic.

$$S_x^y = \lim_{\Delta x \to \infty} \left\{ \frac{\frac{\Delta y}{y}}{\frac{\Delta x}{x}} \right\} = \frac{x}{y}\frac{\partial y}{\partial x} \quad (11)$$

The different sensitivity functions are:

$$S_{C_{gs}}^{L} = \frac{C_{gs}}{L}\frac{\partial L}{\partial C_{gs}} = 1 \quad (12)$$

$$S_{G_m}^{L} = \frac{G_m}{L}\frac{\partial L}{G_m} = -2 \quad (13)$$

$$S_{G_{ds}}^{R_s} = \frac{G_{ds}}{R_s}\frac{\partial R_s}{\partial G_{ds}} = 1 \quad (14)$$

$$S_{G_m}^{R_s} = \frac{G_m}{R_s}\frac{\partial R_s}{\partial G_m} = -2 \quad (15)$$

$$S_{C_{gs}}^{C_p} = \frac{C_{gs}}{C_p}\frac{\partial C_p}{\partial C_{gs}} = 1 \quad (16)$$

$$S_{G_m}^{R_p} = \frac{G_m}{R_p}\frac{\partial R_p}{\partial G_m} = -1 \quad (17)$$

From the results, we conclude that L and Rs are the most sensitive to variation of G_m , if we increase G_m by 10%, L and R_s values will drop by 20%.

5 Simulations and performances.

Using 0.18µm technology as the main bulging block component, PSPICE based simulations have been carried out with the same electrical parameters as those of paragraph IV within the frequency range 1GHz -3GHz.

Serval responses related to inductance, quality factor and input impedance's real part are obtained enabling us to con-

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clude on the circuit performances.

Figure 8 shows the simulation results of the active inductor, from these results we see that the values of the inductance decreases as the biasing current increases.

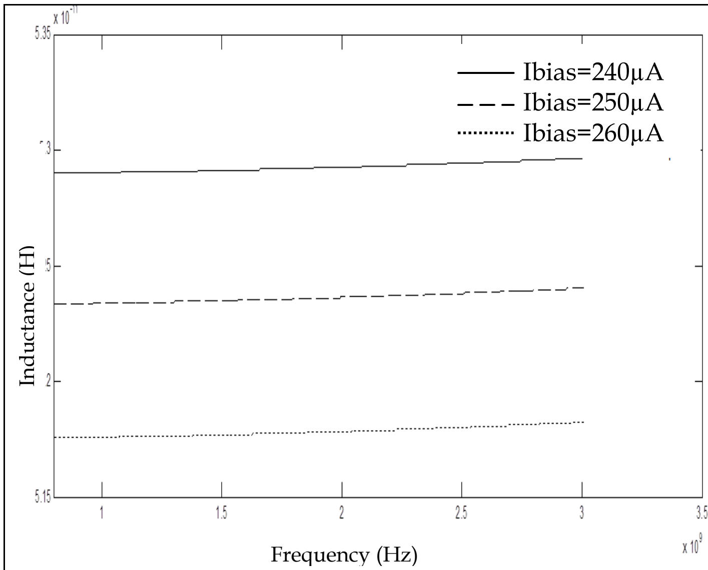

Fig 8: Different values of the active inductor varying the current bias I_{bias}

We also notice, from figure 9 that there is a good agreement between both simulated and equivalent circuit values. We present an example for I_{bias} =250µA.

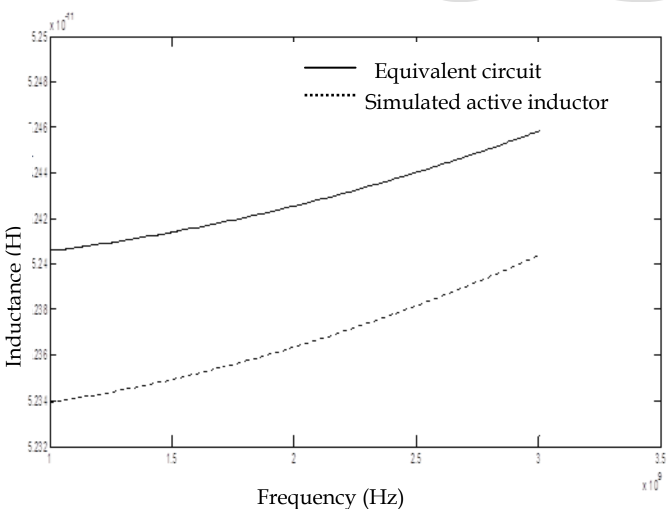

Fig 9: Comparison between the OTA active inductor and the equivalent RLC circuit

Under the same conditions, simulated and calculated real and the imaginary parts of the input impedance are compared in figure 10 and figure 11 respectively showing almost identical values.

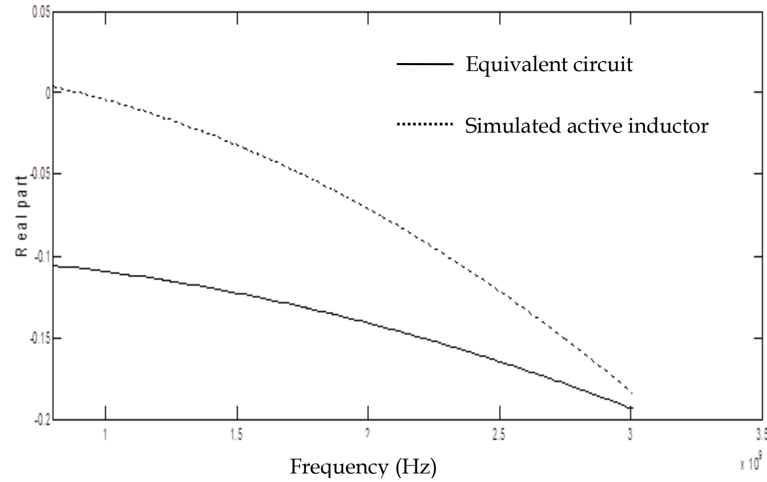

Fig 10: Simulated and equivalent circuit realparts of the input impedance.

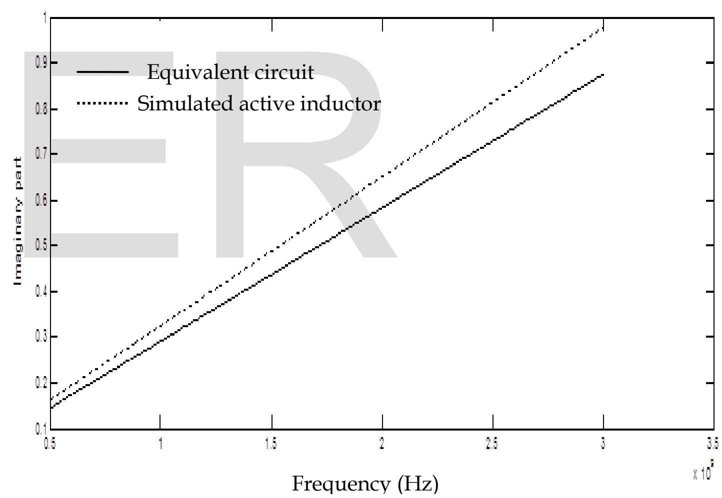

Fig 11: Simulated and equivalent circuit imaginary parts of the input impedance.

Finally, as expected, the proposed active inductor produces a high quality factor which represents one of its major advantages. From 12 we can see that the quality factor approaches high values as the biasing current increases. Figure 12 shows the different values of the quality factor with different bias current.

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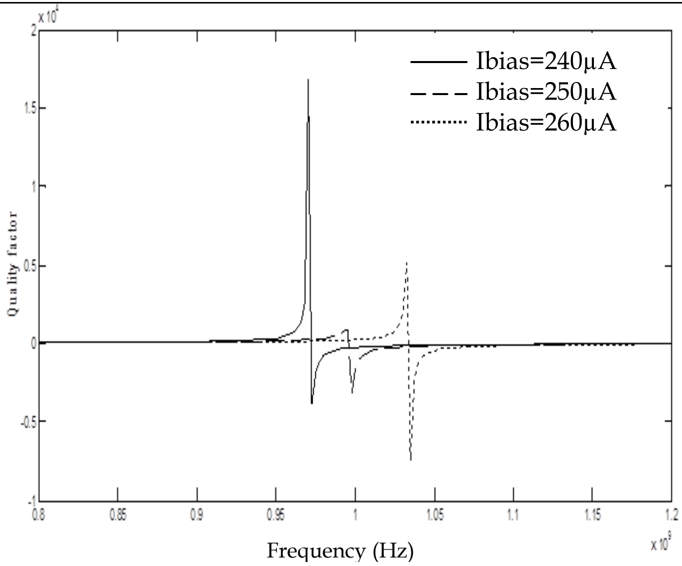

Fig 12: Quality factor with different bias current.

6 Conclusion

This work has presented an alternative solution to overcome the problems of spiral inductors especially those encountered at microwave frequencies. An efficient active inductor circuit has been designed using 0.18µm-CMOS technology.

Simple current mirrors have been the key elements in the synthesis process. As a result, they were used to build new operational transconductance amplifier (OTA) circuits operating in the microwave field. The back-to-back configuration of two OTA circuits with a connection of a grounded capacitor to one port represents the gyrator-C structure of the entire grounded active inductor.

In order to analyze such a circuit and illustrate its performances, we carried out both the elecritical small signal study and simulation process through PSPICE software. So, there has been a good level of agreement in terms of inductor's parameters such as the transconductance, the inductance value and the input impedance real part.

The analysis has also confirmed that critical issues of spiral inductors were completely addressed.

The results of this work show that the proposed active inductance produces a good performance in terms of inductance values and the quality factor. Indeed, we obtain small inductance tunable values that can reach a minimum of 51.5pH.

Besides these advantages, the proposed active inductor has small size and requires low power consumption. Consequently, this device is greatly suitable for numerous microwave applications providing particularly appropriate solutions for wireless systems.

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