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A New Grounded Current Controlled Inductor Based on Simplified Current Conveyors

Zineb M'harzi, Mustapha Alami, and Farid Temcamani

Abstract—In this paper, a new active grounded inductor controlled in current is described. This structure is realized using negative second generation current controlled conveyors and a single grounded capacitor, with no external resistance. The proposed circuit offers many advantages, such as: operation at high frequencies, simple circuit, tuning by the bias current, low power dissipation, etc. Comparison between this topology and those presented in literature is done to highlight the benefits of our structure. As an application, a bandpass filter based on the proposed active inductance is constructed to confirm the usability of the circuit and illustrate these performances. The filter center frequency and quality factor can be tuned independently. Simulation results, given under PSPICE software, present good agreement with the theoretical ones.

Keywords—Active inductor, bandpass filter, BiCMOS technology, Integrated Circuit (IC), Second Generation Current Controlled Conveyor (CCCII).

I. Introduction

THE electronic devices integration constitutes a permanent challenge in order to reduce the size and the cost, and to increase the frequency capability. Impressive progress was obtain these last decades, particularly to integrate active devices as bipolar or CMOS circuits. Passive elements such as inductors [1] still constitute a real problem to an efficient integration. The inductor is widely used in the implementation of several analog circuits for various applications such as oscillators, active filters, analog phase shifters and cancellation of parasitic inductances [1]-[2]. However, the inductor used in their conventional manufacturing technology presents many problems [1]-[4]:

- It occupies a large chip,
- It includes more parasitic elements,
- It cannot operate at very low and very high frequencies,
- It spreads magnetic energy,
- It does not allow an electronic tuning.

On the other hand, the current mode circuits have known a considerable attention for their interesting advantages. Compared to classical voltage circuits, they have a wider bandwidth, a lower power dissipated, a simpler topology, a higher linearity, etc [2], [5]. Particularly, several inductance simulators operating in current mode have been implemented [1]-[20]. These structures are based on second generation current conveyors [2], [12]-[15].

The main objective of this paper is to present a new active grounded inductor controlled in current. The novel structure

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uses a minimal number of active and passive elements, which make it a suitable circuit for IC implementation. Furthermore, this circuit has several advantages compared to other circuits proposed in the literature, and the inductance value can be tuned electronically by changing the bias current.

The organization of this paper is as follows. Section II gives an overview of a simplified negative second generation current controlled conveyor (CCCII$^-$) used in this work. Section III presents the inductor structure and the theoretical study. In Section IV, a second order bandpass filter which is a simple application of this inductance is described. PSPICE simulations, performed using the parameters of $0.35\mu m$ BiCMOS technology of ST [21], are included in Section V.

II. Current controlled conveyor

The second generation current controlled conveyor with negative transfer of current (CCCII$^-$) used in this paper was introduced recently [22], [23].

The CCCII$^-$ equivalent model comprises essentially three inputs-outputs terminals denoted X, Y, and Z referenced to the ground. A fourth terminal is relative to the bias current I_0 (Fig. 1).

The conveyor electrical schematic is presented in Fig. 2. This circuit is implemented from two NPN transistors and four DC current sources. These sources will be, in the real circuit replaced by CMOS current mirrors.

The CCCII$^-$ current-voltage matrix relationship is:

$$\begin{bmatrix} i_Y \\ v_X \\ i_Z \end{bmatrix} = \begin{bmatrix} 1/Z_Y & 0 & 0 \\ \beta(s) & Z_X & 0 \\ 0 & -\alpha(s) & 1/Z_Z \end{bmatrix} \cdot \begin{bmatrix} v_Y \\ i_X \\ v_Z \end{bmatrix} \quad (1)$$

$\beta(s)$ and $\alpha(s)$ are the conveyor voltage and current gains. $Z_Y(R_Y//C_Y)$ and $Z_Z(R_Z//C_Z)$ are respectively the high input and output impedances at terminals Y and Z (ideally infinite). The node X is represented by a low impedance Z_X (R_X in series with L_X), where the resistance R_X is inversely proportional to the bias current I_0 according to the equation [23]:

$$R_X = \frac{V_T}{I_0} \quad (2)$$

Where, V_T is the thermal voltage ($\approx$26mV at 27°C).

The variation of the parasitic resistance R_X versus the bias current I_0 is shown in Fig. 3. The values obtained by simulation match well with the theoretical ones.

Moreover, this conveyor is characterized by simple structure, low supply voltage equal to ±0.75V; and it can be controlled by the bias current I_0.
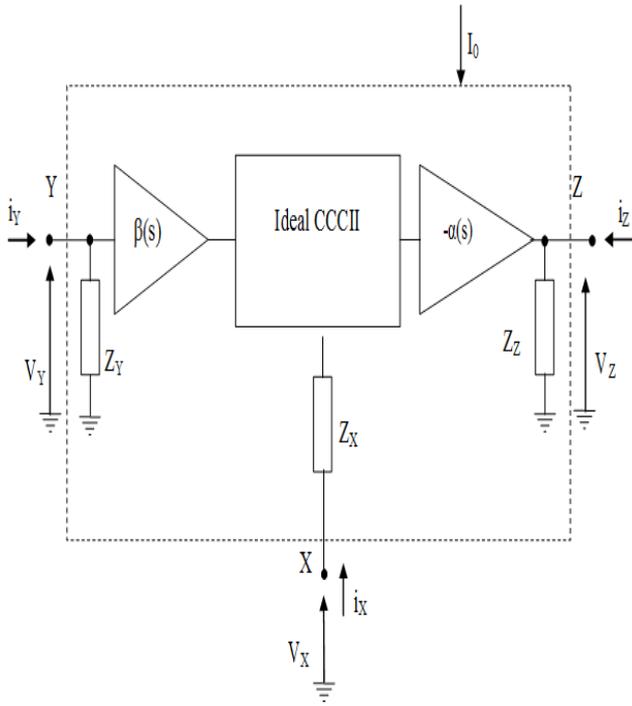
Fig. 1.   CCCII$^-$ equivalent model with all parasitic elements
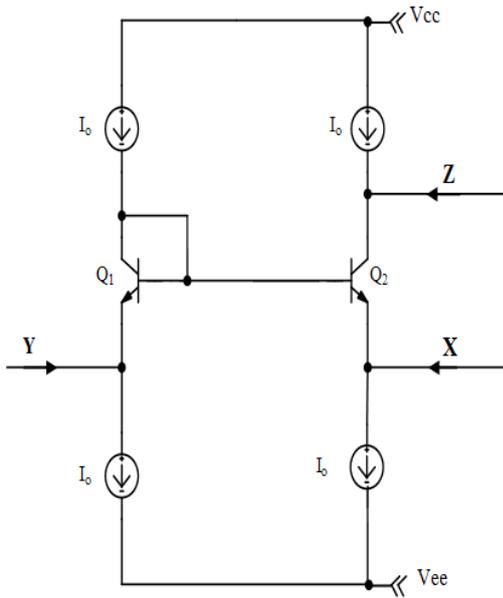
Fig. 2.   CCCII$^-$ electrical schematic

Furthermore, the minimum number of active elements used leads to a small silicon area, a low power consumption and an excellent frequency behavior in comparison with previews proposed solution, which make it an ideal choice for the tuned analog functions in current and voltage modes [22], [23].

III. CURRENT CONTROLLED INDUCTOR

A. Circuit description

The proposed current controlled inductor is shown in Fig. 4. It consists of two CCCII$^-$ conveyors, buffer cells and a
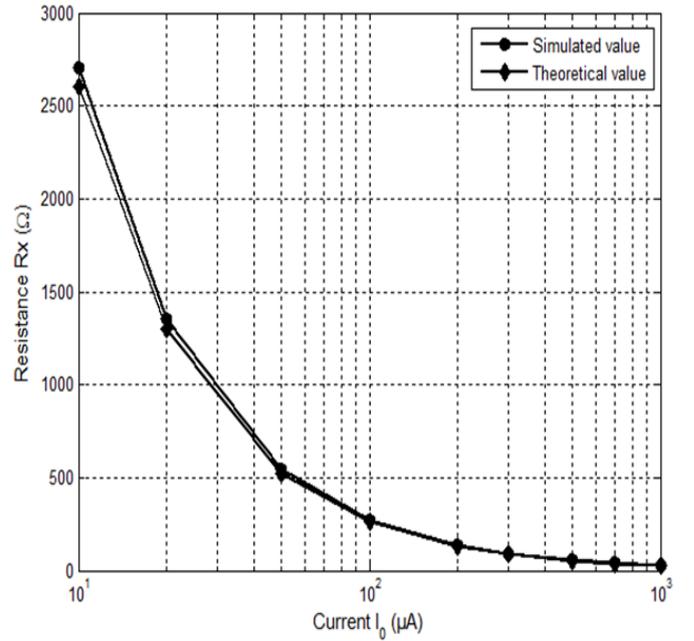
Fig. 3.   Variation of resistance R_X versus I_0
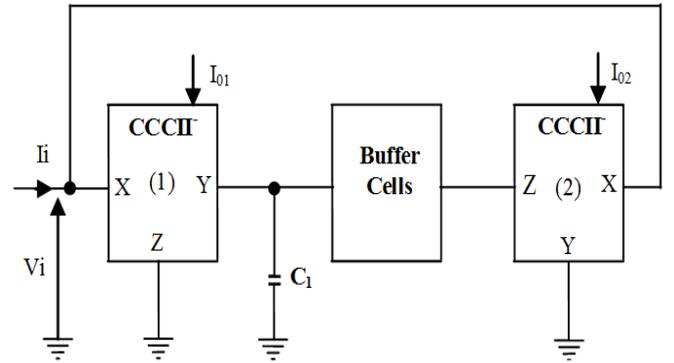
Fig. 4.   Current controlled inductance circuit

grounded capacitor. This structure uses no external resistor and does not require any condition of components matching. Moreover, the buffer cells, used in the circuit, are added in order to change the second conveyor sign.

Figure. 5 presents the complete schematic of the inductance circuit. When the both conveyors are supposed ideals, the input impedance of the circuit is expressed as:

$$Z_i = (R_{X1})//(R_{X2})//(R_{X1}R_{X2}jC_1\omega) \qquad (3)$$

The impedance Z_i is equivalent to the active inductance $L_i = R_{X1}R_{X2}C_1$ in parallel with the resistance $R_i = R_{X1}//R_{X2}$, where the indexes 1 and 2 refer to the conveyors of Fig. 4.

If the both conveyors have the same bias current ($I_0 = I_{01} = I_{02}$) and from (2), the equivalent equation of the inductance becomes:

$$L_i = \left(\frac{V_T}{I_0}\right)^2 C_1 \qquad (4)$$
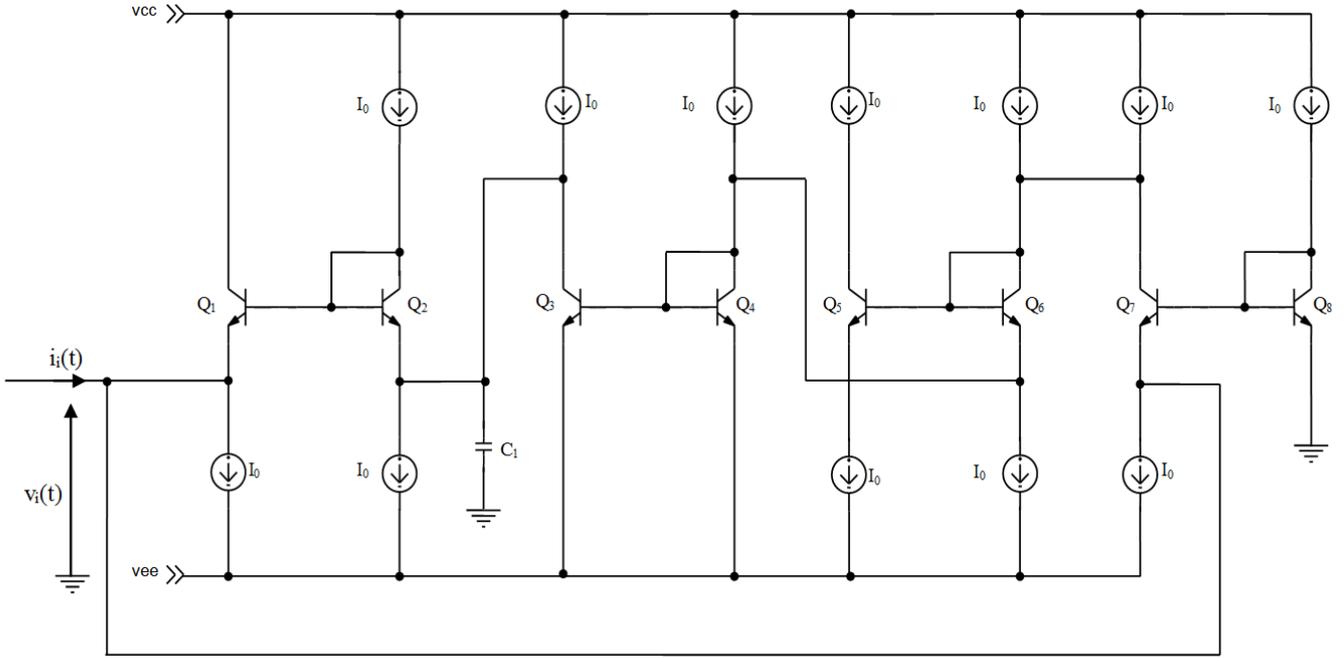
Fig. 5.   Current controlled inductance schematic implementation

From this equation, we can clearly conclude that the inductance can be controlled by the bias current of the conveyors (I_0).

B. Non ideality analysis

Taking into account all the parasitic elements of the conveyors (Fig. 1), the non-ideal input impedance of the inductor circuit (Fig. 4) becomes, where $s = j\omega$:

$$Z_i = (R_{X1} + L_{X1}s)//(R_{X2} + L_{X2}s)//Z_{eq} \qquad (5)$$

With:

$$Z_{eq} = \frac{(R_{X1} + L_{X1}s)//(R_{X2} + L_{X2}s)}{\beta_1(s)\alpha_2(s)} \cdot \frac{1 + R_P C_P s}{R_P} \qquad (6)$$

The R_P ($R_{Y1}//R_{Z2}$) and C_P ($C_{Y1} + C_{Z2} + C_1$) are respectively the equivalent parasitics resistor and capacitor of the conveyors at Y_1 and Z_2, which appear in parallel with the capacitor C_1.

Moreover, the impedance Z_{eq} is composed of the inductance L_i in series with a parasitic resistance r_s:

$$r_s = \frac{R_{X1}R_{X2}}{R_P} \qquad (7)$$

Figure 6 shows the equivalent diagram of the impedance Z_i, taking into account the parasitic elements of the conveyors.

C. Comparison with literature

The proposed grounded simulated inductor is compared with previously published structures.

The majority of the recent inductor presented in the literature [2]-[6], [8], [10], [14]-[20] are electronically voltage or current tunable, and do not require matching conditions.
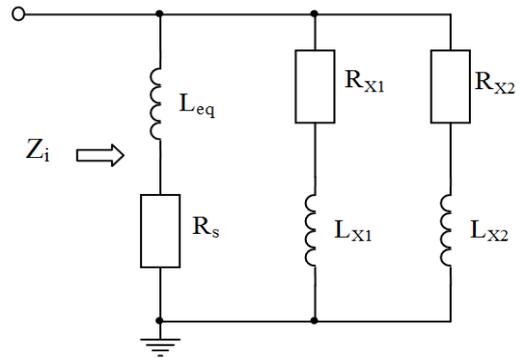
Fig. 6.   Equivalent diagram of Z_i

Moreover, some of them use commercially available devices such as AD844 [2], [6], [19], and the others use other active components, like:

- Second generation current conveyors (CCIIs) [2], [14], [15],
- Fully differential second generation current conveyor (FDCCII) [4],
- Third generation current conveyor (CCIII) [5],
- Negative-type modified inverting current conveyors (MICCI$^-$s, MICCII$^-$s) [3], [20],
- Current feedback operational amplifier (CFOA) [6], [18],
- Voltage differencing differential input buffered amplifiers (VD-DIBA) [8],
- Dual X second generation current conveyor (DXCCII) [16], [19],
- Current Amplifier [17],
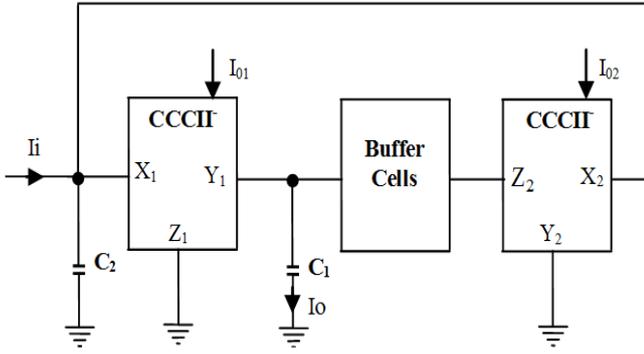
Fig. 7.   Current mode second order bandpass filter

- Current differencing transconductance amplifiers (CD-TAs) [11].

Nevertheless, these structures suffer from many problems:

- Use of a large number of passive elements [2]-[6], [14], [16], [18]-[20],
- Use of many active elements which affect the power consumption and the area of the circuits [4], [8], [10], [14], [16], [17], [20],
- Use of floating passive components which is not suitable for the integrated circuit implementation point of view [3], [5], [6], [14], [16], [18]-[20],
- Use of PNP transistors which affect the circuit frequency performance [5], [15].

Whereas, the proposed grounded inductance has much more advantages as these structures presented in literature. It has a simpler structure thanks to the simplified current controlled conveyor topology. It uses only a single grounded capacitor with no floating components, which allows it to have a small area, low power consumption and a high frequency performance. In addition, our structure can be controlled in current. With these features, the proposed inductor is an attractive element for many applications.

IV. Second order bandpass filter

To evaluate the performance of the proposed inductance, a current mode second order bandpass filter is presented (Fig. 7).

The filter transfer function is given by:

$$H(s) = \frac{I_o}{I_i}(s) = \frac{-R_{X1}C_1 s}{1 + (R_{X1} + R_{X2})C_1 s + R_{X1}R_{X2}C_1 C_2 s^2} \quad (8)$$

The filter characteristic parameters can be written as:

$$\omega_0 = \sqrt{\frac{1}{R_{X1}R_{X2}C_1 C_2}} \quad (9)$$

$$Q = \frac{\sqrt{R_{X1}R_{X2}}}{R_{X1} + R_{X2}} \cdot \sqrt{\frac{C_2}{C_1}} \quad (10)$$

$$H_0 = \frac{R_{X1}}{R_{X1} + R_{X2}} \quad (11)$$

Where: $f_0 = \omega_0/2\Pi$ is the filter center frequency, Q denote the quality factor and H_0 represents the gain.

Note that in calculation, we need to take into account the parasitic capacitances that appear in parallel with C_1.

When both conveyors are assumed to be identical, we have:

$$\omega_0 = \frac{1}{R_X \sqrt{C_1 C_2}} \quad (12)$$

$$Q = \frac{1}{2} \cdot \sqrt{\frac{C_2}{C_1}} \quad (13)$$

$$H_0 = \frac{1}{2} \quad (14)$$

From these equations, we can see that the quality factor Q is independent of the resistance R_X, which is inversely propositional to the bias current I_0. In opposite, the center frequency f_0 depends on the resistance R_X and can be controlled by varying the current I_0. Moreover, the filter center frequency and quality factor can be tuned independently of each other, which means that we can have high Q and f_0 at the same time.

V. Simulation results and discussion

Simulation results of the various circuits presented in this paper have been obtained using PSPICE software with the parameters of 0.35μm BiCMOS technology from ST [21], and the circuits are supplied with $\pm0.75V$.

A. Current controlled inductor

The proposed inductor structure is simulated for an equal bias current for the both conveyors $I_{01} = I_{02} = I_0 = 100\mu$A and the capacitance equal to $C_1 = 10pF$.

The magnitude and the phase of the input impedance are represented in Fig. 8. In this figure, we compare simulated results obtained with the global electrical circuit (Fig. 5), and the ideal results obtained with its equivalent circuit (Fig. 6). The both magnitude curves are in perfect agreement for frequencies between 200KHz and 20MHz, and for the other frequencies the difference is less than 10%. For the phase figure, both curves are almost identical up to frequencies of the order of 20MHz.

In addition, the values of the inductance and the series resistance found by simulation (Fig. 9) are in good agreement with theoretical ones calculated from (4) and (7). They are respectively equal to 0.77μH and 1.5Ω for simulated values, against 0.74μH and 1.7Ω for the theoretical ones. Figure 10 shows the theoretical and the simulated evolutions of the inductance as a function of the bias current $I_0 = I_{01} = I_{02}$. It is clear that the simulated values are well correlated with theoretical ones. Therefore, this result confirms that, the inductance values can be tuned by changing the bias current of the conveyors. Moreover, the power consumption of this circuit is equal to 1.13mW.

(a) Magnitude
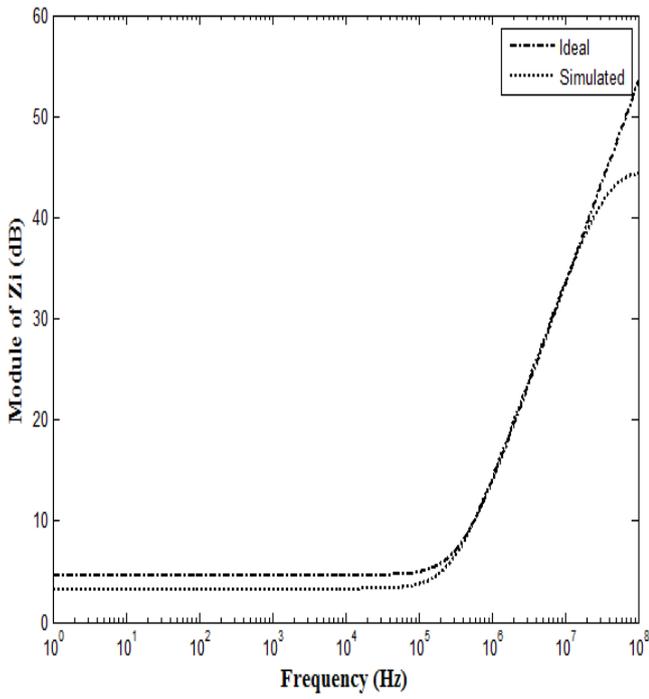
Fig. 9. Real and imaginary parts of the simulated inductance

(b) Phase

Fig. 8. Input impedance of the grounded inductor circuit
(a) Magnitude   (b) Phase
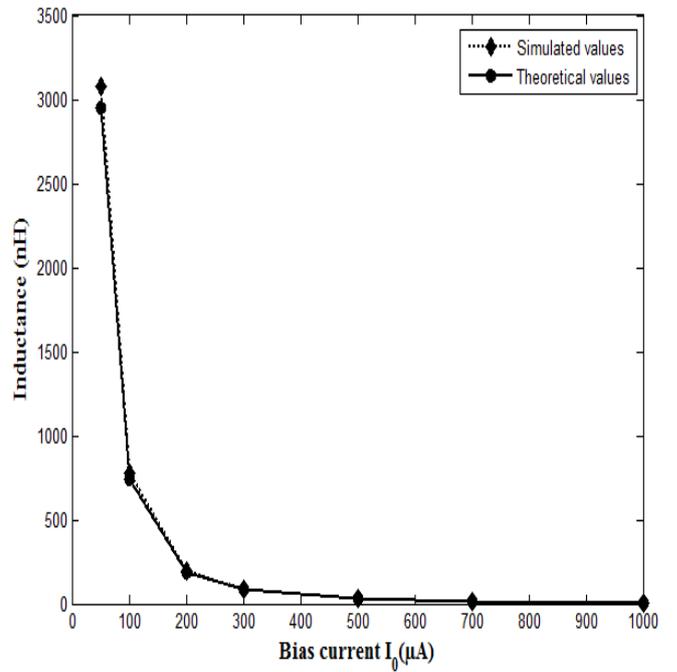
Fig. 10. Evolution of the inductance simulated and theoretical values as a function of bias current $I_0 = I_{01} = I_{02}$

TABLE I
FILTER CHARACTERISTICS

Parameter	Simulated results
f_0	17.6 MHz
Q	2.5
H_0	0.53
Power consumption	1.13 mW

B. Current mode bandpass filter

To validate the theoretical analysis, we simulated the second order bandpass filter (Fig. 7) under the following conditions $I_0 = 100\mu A$, $C_1 = 8pF$ and $C_2 = 130pF$. The main characteristics of this filter are summarized in Table I.

Figure 11 shows the simulated values of the bandpass filter for different values of I_0. The center frequencies of the filter are 17.6MHz, 35MHz, 52.24MHz and 69.4MHz, respectively
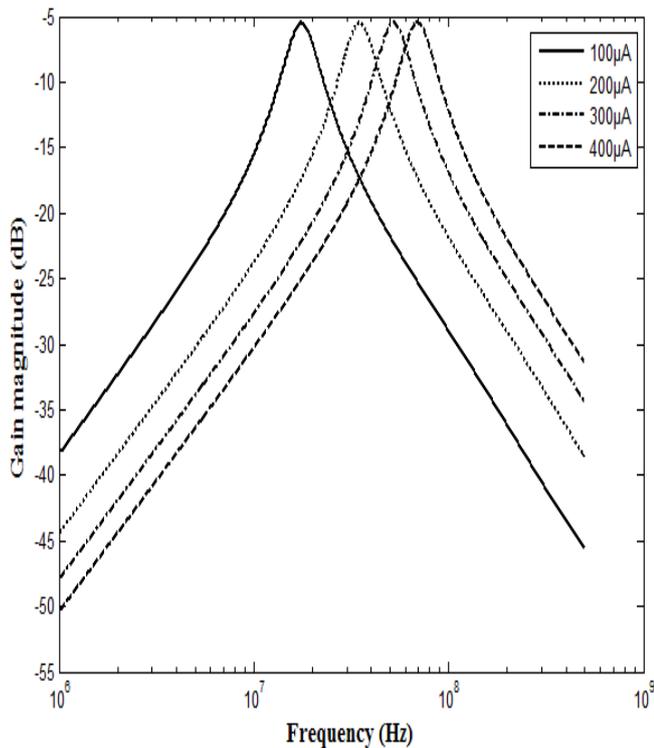
Fig. 11.   Frequency response of the filter for different values of I_0

for I_0 equal to $100\mu A$, $200\mu A$, $300\mu A$ and $400\mu A$. These values are very close to the theoretical ones (18MHz, 36MHz, 54MHz and 72MHz, respectively).

Moreover, the simulated quality factors for the same bias currents are about 2.5, whereas the theoretical values are equal to 2.

To summarize, we notice that the theoretical and simulated values of the center frequency and the quality factor of the filter are very close; and that, the f_0 and the Q can be tuned independently. The variation of the bias current of the conveyors allows the control of the frequency values but not the Q-factor values.

VI. Conclusion

An active grounded inductance simulator controlled in current is presented in this paper. This circuit uses a minimum number of active and passive components. It is composed of two second generation current controlled conveyors and a grounded capacitor. The proposed structure presents several features, such as: simplicity, low supply voltage, low power consumption, possibility of tuning, and use of a single grounded passive component which make it a suitable element for the IC manufacturing. Due to these advantages, the presented inductor is an attractive component for several applications in analog communication systems.

As an application, a current mode second order bandpass filter is realized to illustrate the practical use and the benefits of the proposed inductor structure. This filter is characterized by low power dissipation (1.13mW), low supply voltage ($\pm 0.75V$), and the possibility of tuning the frequency independently of the quality factor, which means that we can have a high frequency and a high Q-factor with the same circuit.

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