Current Feedback Operational Amplifier(CFOA) Based Programmable Lossless Floating Inductor Realization

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***Abstract*—A CMOS digitally programmable lossless floating inductor is proposed. The proposed inductor is based on current feedback operational amplifier and resistor array to provide digital tuning of the inductance value. The presented block realizes a programmable floating inductor tuned from 0.4167mH to 5.67 mH. As an application for the proposed circuit a resonant circuit and low pass filter have been realized using the digital programmable circuit. The simulation results has been demonstrated and discussed using a SPICE simulation for 0.18 µm TSMC CMOS technology and dual supply voltages ±1.5 V.**

***Keywords-** Active filters; CFOA; Current mode; Digitally programmable*

I. INTRODUCTION

The current-feedback operational amplifiers (CFOAs) [1-4] have been paid great attention that’s due to better performance, particularly higher speed, high slew-rate, and better bandwidth [5], than classic voltage-mode op-amps, which are limited by a constant gain-bandwidth product. It has been applied in lots of active filters applications, in [3] the CFOA is used to realize all-pass filters. New MOS-C band pass-low-pass filter using the CFOA is presented in [6]. A systematic method for deriving CFOA-based all-grounded-capacitor filters from current mode RLC prototype ladder has been given in [7]. A fully integrated Tow-Thomas (TT) bi quad is generated using CFOA based integrators is presented in [8].

In recent years, there has been an intensive search for a practical method of making inductor less filters. Lots of active blocks have been used to simulate floating and grounded inductor [9-12]. CFOA based inductor simulator introduced in [13].

In this paper, a digitally programmable lossless floating inductor realization is introduced. The realization involves the CFOA as an active block and the programmability is achieved through array of resistor and NMOS switches. To show the reliability of the proposed design, the presented inductor realization is applied on a series RLC resonance circuit and a 5th order Chebyshev low pass filter which can be used in various applications.

The paper is organized as follows section II presents the CMOS CFOA, section III illustrates the circuit realization of the digitally programmable lossless floating inductor simulator, section IV introduce some applications of the digitally programmable block and finally section V drawn the conclusion.

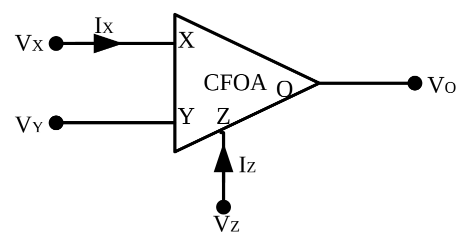

Figure 1. CFOA building block.

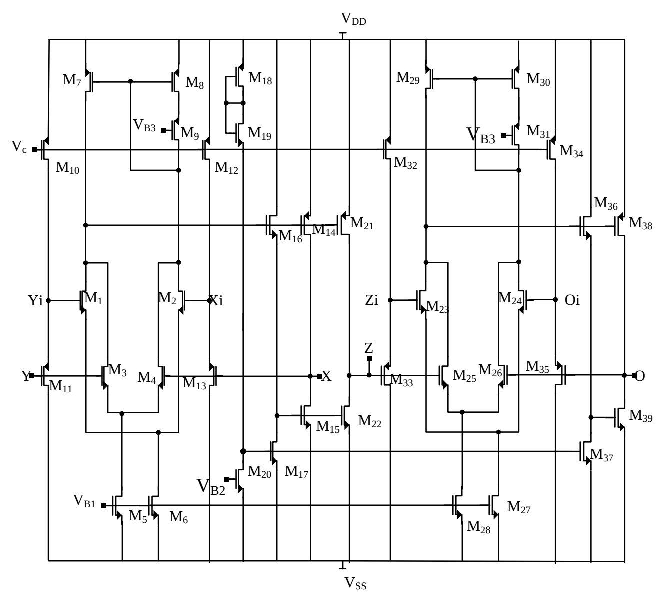

Figure 2. CMOS implementation of CFOA [4].

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II. CURRENT FEEDBACK OPERATIONAL AMPLIFIER (CFOA)[1-4]

The current feedback operational amplifier is a four port network with terminal characteristics described by the following matrix:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \\ V_O \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \\ I_O \end{bmatrix} \quad (1)$$

Where V_X, V_Y, V_Z and V_O, I_X, I_Y, I_Z and I_O are voltages and currents of X-, Y- , Z- and O-terminals. The basic building block of CFOA is shown in Fig.1. While Fig.2 shows the CMOS implementation of the CFOA block given in [4].

III. CIRCUIT REALIZATION

The circuit as shown in Fig.3 [14-15] uses three CFOA, grounded capacitor and two resistors to realize a floating inductor. The CFOA based floating inductor shown in Fig.2 is based on the four CCII floating inductor circuits presented in [16-18].The admittance matrix can be written as in eqn. (2):

$$[Y] = \frac{1}{CR_1R_2}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad (2)$$

The equivalent inductance can be represented as in eqn. (3):

$$L_{equ} = CR_1R_2 \quad (3)$$

The active inductor realization shown in Fig.3 [14-15] has been modified to be digitally tuned by replacing resistor R_1 by array of resistors and controlled NMOS switches as shown in Fig.4. Each branch contains different resistor value and NMOS transistor acts as a switch.

Depending on the applied voltage on switch gate the switch is on or off and as well the resistor is connected or not and that is determined logically through values of b_i which is integer may take value of 0 or 1 where i=0,1,2,3, 4.

IV. APPLICATIONS AND SIMULATION RESULTS

In this section the proposed digitally programmable inductor realization is used to implement a programmable resonator circuit and a programmable low pass filter.

A. Programmable resonator

The RLC series resonance circuit shown in Fig.5 with center frequency 159 KHz has been simulated using floating inductor realization shown in Fig.3.The floating inductor circuit is realized with R_1 = 10k Ω, R_2 =1k Ω and C=100pF. Fig.6 shows the actual inductor response relative to ideal.

Varying resonator frequencies by using tunable inductor realization shown in Fig.4 with array of resistors equals to R_1 = 100k Ω, R_2 =50k Ω, R_3 =25k Ω, R_4 =12.5k Ω and R_5 =6.25k Ω.Table I contain the different values of simulated inductance and its corresponding resistor array values.

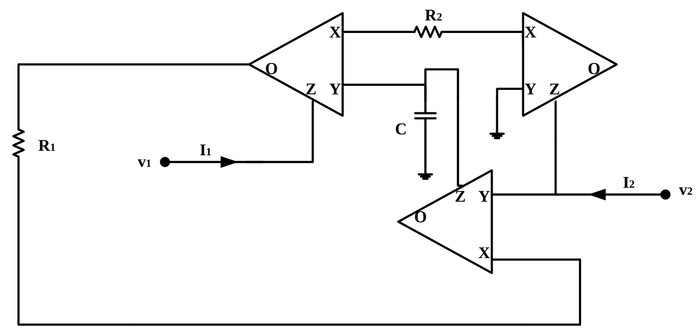

Figure 3. Floating inductor realization [14-15].

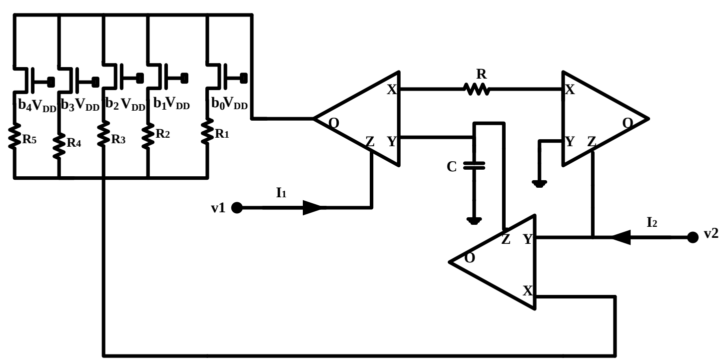

Figure 4. Digitally programmable Inductor realization.

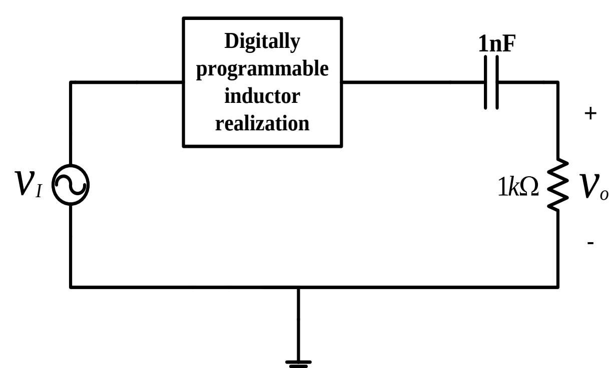

Figure 5. Passive circuit for a resonator.

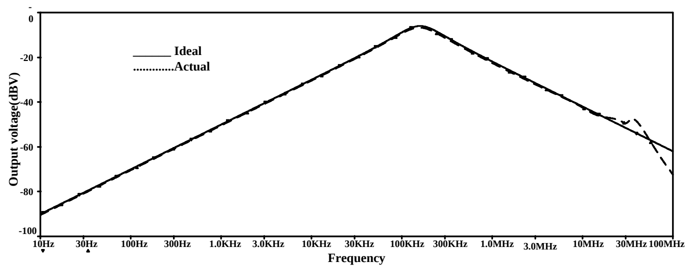

Figure 6. Ideal and actual frequency response of output voltage for the resonator circuit.

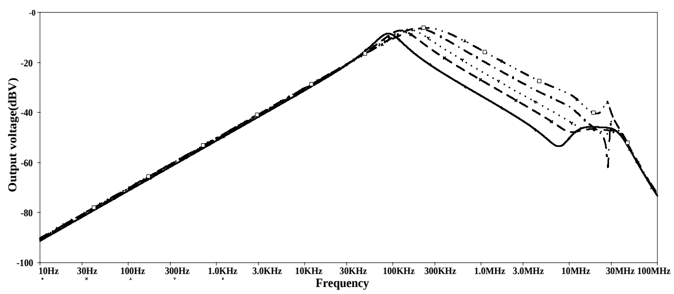

Figure 7. Frequency response of output voltage for different center frequency of the resonator circuit F_{center} =100 kHz, 124 kHz, 151 kHz, 197 kHz and 249 kHz

TABLE I. THE TUNABLE INDUCTOR VALUES USED IN RESONATOR CIRCUIT.

Inductance value (mH)	Frequency (KHz)	b's values				
		b_0	b_1	b_2	b_3	b_4
3.333	100	1	1	0	0	0
1.67	124	0	1	1	0	0
1.11	249	1	0	0	1	0
0.67	151	1	1	1	1	0
0.4167	197	0	0	0	1	1

TABLE II. SUMMARY FOR SIMULATION RESULTS FOR THE RESONATOR

Simulation parameter	Value
Simulated freq.	197kHz
Power dissipation	8.42mW
Total harmonic distortion (THD) @freq 190kHz	35.7902%
3rd order inter modulation (IM3) @ F_1 =170KHz , F_2 = 190 KHz	-69.8 dBm

The active inductor realization is simulated using SPICE based on 0.18 µm TSMC CMOS technology parameters. The current feedback operational amplifier (CFOA) realizations are simulated by using the schematic implementation shown in Fig.2 and aspect ratios given in Table III together with the MOS switch aspect ratio.

TABLE III. TRANSISTORS ASPECT RATIOS

Transistor	W (µm)	L (µm)
M1- M4	1.8	0.72
M5 , M6, M26, M27	5.2	0.72
M9-M12, M31-M34	140	3.6
M17- M19	3.6	3.6
M15 , M16, M35, M36	1	1
M7 , M8, M28, M29	110	3.6
M13, M20, M37	37	3.6
M14, M21, M38	30	3.6
M Switch	36	0.18

B. Programmable low pass filter

A 5th order Chebyshev low pass filter with cutoff frequency 1 MHz and the pass-band ripple is 1dB is shown in Fig.8 [19]. It has been simulated using the floating inductor realization shown in Fig.3 with R_1 = 1kΩ , R_2 =1kΩ and C= 170pF. Fig.9 shows the actual inductor response relative to ideal response. Taking the values of the resistors as in section A and the capacitance C= 170pF. Varying inductor value relative to Table IV the filter cutoff frequency will be changed as well. Fig. 10 shows the response of filter due to the cutoff frequency changes. Summary for simulation results; performance analysis has been done in Table V.

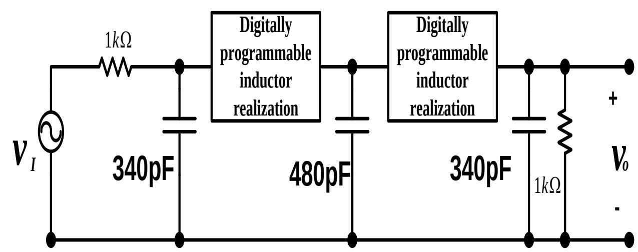

Figure 8. Fifth order Chebyshev low pass Ladder filter [11].

TABLE IV. THE TUNABLE INDUCTOR VALUES USED IN THE LOW PASS FILTER CIRCUIT.

Inductance value (mH)	Frequency (KHz)	b's values				
		b_0	b_1	b_2	b_3	b_4
5.67	139	1	1	0	0	0
2.83	194	0	1	1	0	0
1.89	237	1	0	0	1	0
1.13	316	1	1	1	1	0
0.7083	412	0	0	0	1	1

V. CONCLUSION

In this paper, using the concept of CFOAs, NMOS switch and a resistor array a digitally tunable floating inductor realization has been proposed. As an application of the proposed inductor, a resonator circuit and a low pass filter have been designed and realized. SPICE simulation has been done to verify the usefulness of the proposed tunable floating inductor realization in the building active filter implementations. The proposed inductor simulator is expected to be useful in designing of analog signal processing applications.

TABLE V. SUMMARY FOR SIMULATION RESULTS FOR THE LOW PASS FILTER CIRCUIT.

Simulation parameter	**Value**
Simulated freq.	316 kHz
Power dissipation	16.8m W
Total harmonic distortion (THD) @freq 190kHz	5.17903%
3rd order inter modulation (IM3) @ F_1 =170KHz , F_2 = 190 KHz	-68.0644 dBm

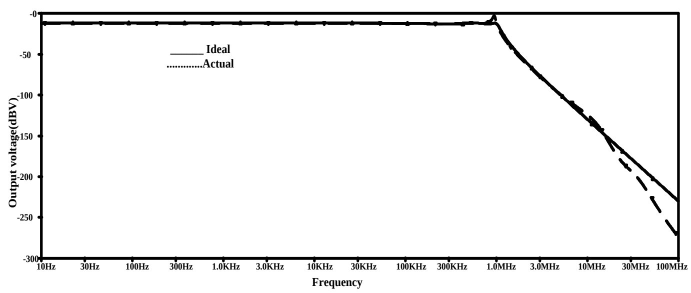

Figure 9. Ideal and actual frequency response of output voltage for the filter circuit.

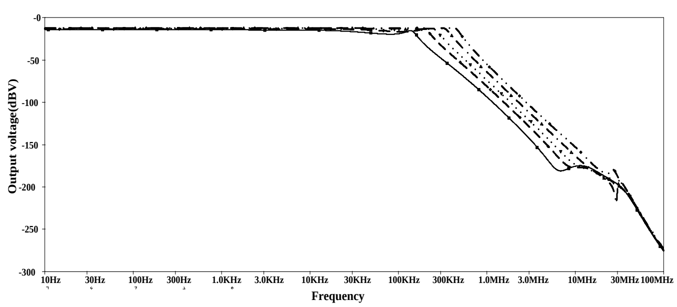

Figure 10. Frequency Frequency response of output voltage for different cut off frequency of the filter circuit F_{Cutoff} = 139 kHz, 194 kHz, 237 kHz, 316 kHz and 412 kHz.

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