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ELECTRONICALLY TUNABLE LC HIGH PASS LADDER FILTER USING OTRA

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Abstract

This paper presents Operational trans-resistance (OTRA) based electronically tunable high pass L-C based ladder filter. The proposed high pass filter is designed by following a systematic approach using leap frog simulation for ladder filters. The cut-off frequency of the proposed filter can be varied with the application of appropriate voltages to the gate of MOSFETs hence making the design electronically tunable. Therefore, it can be used for RF applications at 455kHz and 1MHz (intermediate frequencies for RF applications). Performance of the proposed circuit is verified through SPICE simulations employing a 0.5μm MOSIS AGILENT CMOS realization of OTRA.

Keywords:

OTRA, High Pass Filter, Tunable

1. INTRODUCTION

The conventional voltage mode circuits and filters realized using operational amplifiers suffer from limitations which include lower bandwidth for higher gains. On the contrary, current-mode circuits offer several advantages as compared to voltage mode circuits such as higher bandwidth, increased linearity and reduced power consumption [1]-[4]. Continuous Time (CT) filters find extensive applications in fields like communication, measurements, and instrumentation and offer simplicity, low power and no sampling noise as compared to the discrete time filters. High pass filters form a key component in R/F microwave wireless applications [5]. Hence design of a current mode high pass filter has been proposed in this paper.

The main approach for designing of filters involves the following steps: (a) choice of an appropriate order according to the required design specifications, (b) the derivation of the corresponding transfer function, (c) synthesis and implementation of the required circuit from the obtained transfer function [6]. The synthesis of CT filters generally follows the approach of doubly terminated lossless LC ladder realization [7]-[8]. The resulting filter is tolerant to component variations, and offers an improved dynamic range performance and enhanced accuracy of passband magnitude response. Inductors are bulky and their use in integrated circuits is costly [7]. We can overcome this non-feasibility of inductor realization in conventional LC ladder realization approach by using leap frog method, in which the relationship between various components is established through the signal flow graphs (SFG). Lossy and lossless active differentiators are then used to realize the obtained SFGs to implement the proposed design in this paper.

Literature survey of L-C ladder filters with different orders and approximation functions using leapfrog method [9]-[29] has been carried out. These configurations use variants of second generation current conveyors (CCII) namely dual/multiple output current controlled CCII (DOCCCII/ MOCCCII) [11]-[12], multiple output CCII (MOCCII) [10], differential voltage CC (DVCC) [14], differential voltage current controlled Current Feedback Operational amplifier (DVCCCFOA) [15] and differential voltage current controlled CCII (DVCCC), current feedback amplifier (CFA) [17], current feedback operational amplifier (CFOA) [16], current differencing buffer amplifier [18]–[20], current controlled current differencing buffer amplifier (CCCDBA) [21], operational trans-conductance amplifier [24]-26], current backward trans-conductance amplifier [27], current differencing trans-conductance amplifier (CDTA) [22]-[23], CMOS based differential integrators [9], CMOS based lossy and lossless integrators [28]-[29].

From the available pool of literature, it can be summarized that, Configurations [15], [16], [21], [24]-[26] and [9]-[14], [17]-[20], [22], [23], [27]-[29] provide voltage and current outputs respectively. There is no appropriate impedance level for the configurations [13]-[15], [17]-[20], [24]-[26]. Thus an additional active block may be required to access the output. There is a limited literature is available on structures providing voltage output [15]-[17], [21], [24]-[26]. Furthermore, these structures do not provide output at low impedance except for those presented in [16], [21].

Table.1. Full form of some acronyms

Acronym	Full form
OTRA	Operational Trans-Resistance Amplifier
SFG	Signal Flow Graphs
CCII	Second generation Current Conveyors
DVCC	Differential Voltage Current Conveyor
DVCCFOA	Differential Voltage Current Controlled Current Feedback Operational Amplifier
DVCCC	Differential voltage current controlled CCII
CFA	Current Feedback Amplifier
CFOA	Current Feedback Operational Amplifier
CCCDBA	Current Controlled Current Differencing Buffer Amplifier
CDTA	Current Differencing Trans-conductance Amplifier

OTRA is a current mode active device with voltage as the output. It does not have any limitations on the slew rate and gain bandwidth product [30]-[35]. The parasitic effects are negligible as the internal terminals are grounded. Therefore OTRA can be easily and appropriately utilized for the design of filter with voltage output based on LC ladder network with Leapfrog simulation method.

The paper presented has been divided into five sections as described: Section 2 highlights leapfrog based simulation of LC-ladder, section 3 elaborates on the functioning of the proposed filter using OTRA block, section 4 describes the functioning of proposed filter considering non-idealities and section 5 presents simulation and results, which is finally followed by conclusion.

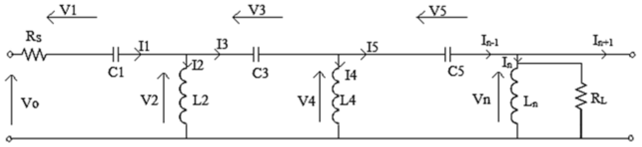

Fig.1. n^{th} order doubly terminated LC-Ladder

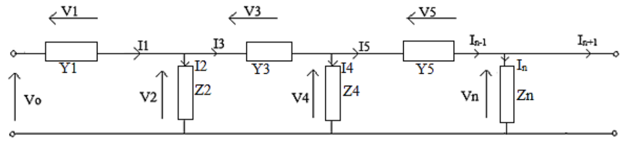

Fig.2. n^{th} order doubly terminated LC-Ladder with general immittances

2. LC HP LADDER FILTER USING LEAP FROG SIMULATION

This section illustrates and presents the realization of doubly terminated LC ladder with capacitors in series arm and inductors in the shunt arm to perform high pass operation. The currents and voltages in the shunt arm are given respectively as:

$$I_k = I_{k-1} - I_{k+1}, \text{ where } (k = 2,4,6,...,n-2) \quad (1)$$

and

$$V_k = V_{k-1} - V_{k+1}, \text{ where } (k = 1,2,3,...,n-1) \quad (2)$$

As the value of $I_n = 0$ and $I_n = I_{n-1}$

$$V_k = I_k\, sL_k \quad (3)$$

$$V_n = \frac{I_n}{\left[\dfrac{1}{sL_n} + G_L\right]} \text{ with } G_L = 1/R_L. \quad (4)$$

For the series arm, the currents are given as:

$$I_k = V_{k-1} - sC_{k+1}, \text{ where } (k = 4,6,8,...,n) \quad (5)$$

$$I_1 = \frac{V_n}{\left[\dfrac{1}{sL_1} + R_s\right]} \quad (6)$$

The elements in the series arms are rewritten as Admittances whereas those in the shunt arm as impedances. The Fig.2 shows modification over Fig.1.

The node voltages and the current in series arm are related as:

$$I_k = Y_k\,(V_{k-1} - V_{k+1}), \text{ where } (k = 1,3,5,...,n-1) \quad (7)$$

$$V_k = Z_k(I_{k-1} - I_{k+1}), \text{ where } (k=2,4,6,...,n-2) \quad (8)$$

$$V_n = Z_n\, I_{n-1} \quad (9)$$

OTRA is used for the active realization of above equations. OTRA is a block which provides voltage output by processing input current difference. Therefore, the necessary changes for performing the voltage differencing operation are discussed in the following section.

3. PROPOSED CIRCUIT

The proposed sixth order high pass filter uses OTRA block which is in active building block. The first section briefly describes the properties and characteristics of OTRA block. The design of the proposed filter is described in the subsequent section.

3.1 OTRA

OTRA is an active three terminal device that consist of two input terminals and an output terminal as represented in Fig.3. It is a current mode device where the input terminals are virtually grounded leading to low input and output impedance. Thus, parasitic effects of OTRA can be neglected rendering it suitable for high frequency applications. The port relationship of OTRA is represented in Eq.(10).

$$\begin{bmatrix} V_p \\ V_n \\ V_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ I_0 \end{bmatrix} \quad (10)$$

where, R_m represents the trans-resistance gain of OTRA, which approaches infinity for ideal operation. Due to the high value of $R_{m,}$ the two input currents are of same value. Therefore, OTRA is used in negative feedback configuration for linear circuit applications.

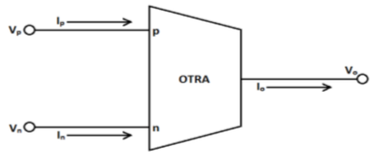

Fig.3. OTRA Circuit Symbol

3.2 OTRA BASED IMPLEMENTATION OF PROPOSED LC HIGH PASSED LADDER FILTER

Since OTRA provides current as output, for direct realization of Eq.(9) we multiply the equation by R_{sc}, the scaling resistance and Eq.(7) can be rewritten as:

$$R_{SC}I_k = R_{SC}Y_k(V_{k-1} - V_{k+1}), \text{ where } (k = 1,3,5,...,n-1) \quad (11)$$

$$V_{Ik} = t_{YK}[V_{k-1} - V_{k+1}], \text{ where } (k = 1,3,5,...,n-1) \quad (12)$$

where,

$$V_{Ik} = R_{SC}\, I_k$$

$$Y_1 = \frac{1}{\left[\dfrac{1}{sC_1} + R_s\right]},$$

$$Y_k = sC_k \text{ and } t_{Yk} = R_{SC}Y_k \quad (k = 1,3,5,...,n-1)$$

The node voltages in Eq.(8) and Eq.(9) are rewritten as Eq.(13), Eq.(14) and Eq.(15) with the help of Eq.(11) and Eq.(12).

$$V_k = \frac{Z_k}{R_{SC}}\left(R_{SC}I_{k-1} - R_{SC}I_{k+1}\right) (k = 2,4,6,...,n-2) \quad (13)$$

$$V_k = t_{Zk}\,[V_{I(k-1)} - V_{I(k+1)}](k = 2,4,6,....,n-2) \quad (14)$$

$$V_n = t_{Zn}\, V_{I(n-1)} \quad (15)$$

where,

$$Z_k = sL_k,$$

$$Z_n = \frac{1}{\left[\dfrac{1}{sL_n} + G_L\right]}$$

and

$$t_{Zk} = Z_k/R_{SC}(k = 2,4,6,...,n\text{-}2)$$

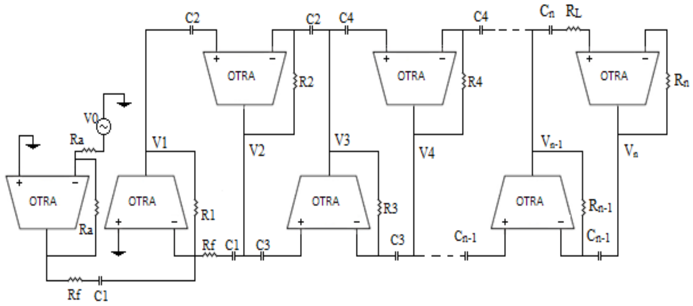

Fig.5. Proposed OTRA based n^{th} order doubly terminated HPF

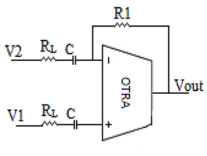

Fig.4. Non-Ideal Differentiator

OTRA block can be used to implement an ideal (lossless) and a non-ideal (lossy) differentiator. Using these two differentiators n^{th} order high pass filter has been proposed based on the leapfrog simulation.

The Eq.(11) to Eq.(15) are actively realized differencing lossy and lossless differentiators. A lossy differentiator as the first stage is followed by (n-2) lossless differentiator stages. The n^{th} stage, i.e. the output stage is again a lossy differentiator.

The circuit for the non-ideal differentiator is represented in Fig.4. The output voltage in terms of V_1 and V_2 is given as:

$$V_{out} = R_1[V_1(sC + G_L)\text{-}V_2(sC + G_L)] \quad (16)$$

For the first stage the non-ideal circuit is designed using an inverter stage followed by a summer stage as shown in Fig.5.

3.3 ELECTRONIC TUNABILITY

More attention is being given to electronically tunable components as traditional electronic components may have deviations in fine-tuning the tolerances of the electronic components [36]. Electronic tunability enhances the controllability of a microcomputer or microcontroller [37]. A tunable high pass OTRA filter could be simulated by using NMOS instead of the feedback resistances so as to change the value of resistances w.r.t. the input voltages at the gate of NMOS and hence change the cut-off frequency of the proposed filter. The Fig.6 represents a single stage tunable lossy differentiator with the value of resistance given by Eq.(17).

$$R_i = \frac{1}{\mu_n C_{ox}\left(\dfrac{W}{L}\right)(V_{ai} - V_{bi})} \quad (17)$$

Thus, electronic tunability can be embedded by implementing resistors R_1 to R_n with the help of MOS based realization using method. This makes the design flexible and the filter can be fine-tuned in case there is any deviation from desired response. The modified Fig.7 shows tunable filter implementations where the gate voltages V_{ai} and V_{bi} realize the required resistors using MOS. (i = 1,2,3,...,n).

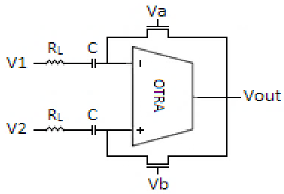

Fig.6. Single stage Tunable Differentiator

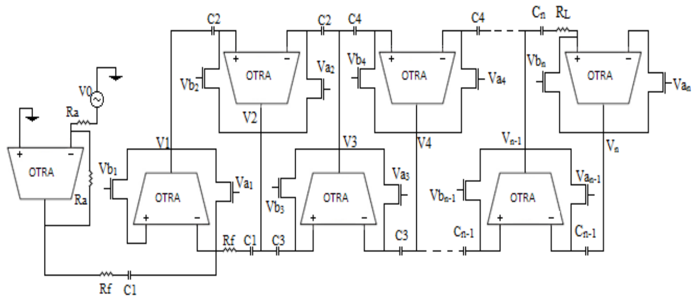

Fig.7. Electronically tunable Proposed OTRA based n^{th} order doubly terminated HPF

3.4 NON-IDEALITY ANALYSIS

The trans-resistance gain (g_m) of an ideal OTRA block is infinity causing the input currents to become equal. But in reality the gain is finite for small bandwidth and decreases further with increase in frequency. Therefore effects of this non-ideality should be included while deriving transfer functions.

The single pole model of the OTRA block will have trans-resistance gain of:

$$R_m(s) = R_0/(1+ (s/\omega_0)) \quad (18)$$

At high frequencies the Eq.(18) can be approximated to:

$$R_m(s) = 1/sC_P \quad (19)$$

where, the parasitic capacitance $C_p = 1/R_0\omega_0$, open loop DC trans-resistance gain is R_0 and trans-resistance cut-off frequency is ω_0.

The transfer function of single stage differentiator is modified to

$$V_{out} = R_1\{V_1[s(C + C_p) + G_L]\text{-}V_2\,[s(C + C_p) + G_L]\} \quad (20)$$

4. SIMULATIONS AND RESULTS

The proposed high-pass filter is realised using lossy and lossless differentiator implementations of OTRA on the lines of a sixth-order Chebyshev filter with a 0.1dB ripple width in passband. The passive elements used in the prototype Chebyshev filter has normalized values of C_1 = 0.8561, L_2 = 0.7122, C_3 = 0.4863, L_4 = 0.6592, C_5 = 0.5255, L_6 = 1.1604 and R_F = 0.7378. For a cut-off frequency of 455kHz, R_a = 1kΩ, R_f = 0.599kΩ and $C_a = C_b = C_c = C_d = C_e = C_f$ = 0.5nF the de-normalized values of the feedback path resistors are R_1 = 0.99kΩ, R_2 = 0.299kΩ, R_3 = 0.567kΩ, R_4 = 0.277kΩ, R_5 = 0.613kΩ, R_6 = 0.487kΩ and R_L = 1.1kΩ.

Table.2. Aspect ratios of transistors in Fig.8

Transistor	W(μm)/L(μm)
M_1 - M_3	100/2.5
M_4	10/2.5
M_5, M_6	30/2.5
M_7	10/2.5
M_8 - M_{11}	50/2.5
M_{12}, M_{13}	100/2.5
M_{14}	50/2.5

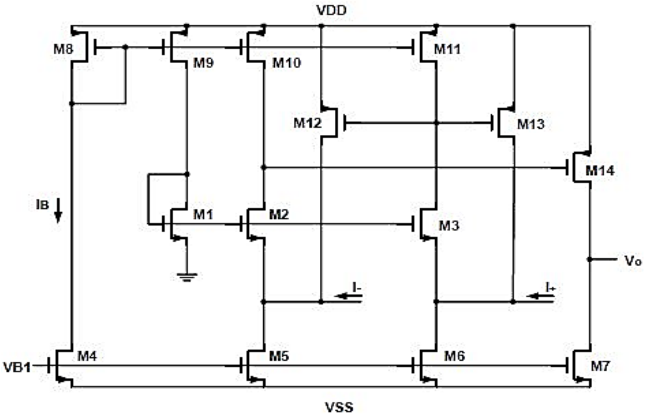

Fig.8. CMOS Implementation of OTRA [38]

The simulated frequency response of a high-pass LC-ladder filter is shown in Fig.9. Also the frequency response of OTRA based ladder filter in superimposed to know the deviations of the active realization. The simulated frequency response of a tunable OTRA based filter for cut-off frequencies of 455kHz and 1MHz are shown in Fig.10. Using Eq.(17) the aspect ratios (W/L) of the MOS transistors used to attain tunability are calculated as shown in Table.3. For achieving the cut-off frequency of 455kHz we have set the gate voltages of MOS resistors in feedback path to Va_i = 0.9V and Vb_i = 1.2V, while to achieve the cut-off frequency of 1MHz we have to set the gate voltages, Va_i and Vb_i to 0.75V and 1.4V respectively (i = 1,2,3…….6).

Table.3. Aspect Ratios of Transistors in Fig.8

Transistor	W(μm)/L(μm)
Ma_1 - Mb_1	2.7/2.5
Ma_2 - Mb_2	4.33/5
Ma_3 - Mb_3	5/2.73
Ma_4 - Mb_4	4.75/5
Ma_5 - Mb_5	5/2.96
Ma_6 - Mb_6	2.68/5

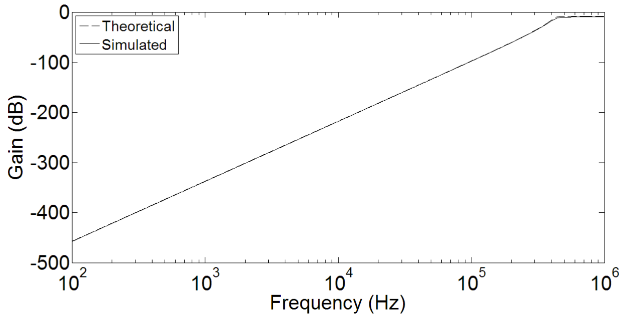

Fig.9. Simulated OTRA based vs Theoretical LC-ladder Filter Frequency Response

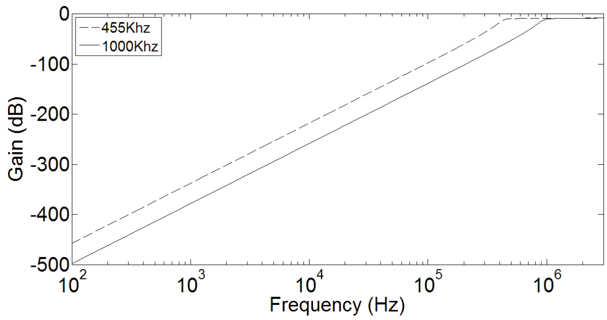

Fig.10. Simulated OTRA based Tunable Filter Frequency Response for 455kHz and 1MHz

5. CONCLUSION

OTRA based sixth order high-pass filter is presented and simulated in this paper. As compared to Current feedback operational amplifier (CFOA) based high pass ladder filter presented in [39], the proposed OTRA based sixth order high pass ladder filter is electronically tunable. The proposed topology also offers an advantage in terms of higher operating and cut-off frequencies as compared to existing high-pass ladder filter designs [39]. Simulation and results are presented for 455kHz and 1Mhz. Non-Ideality Analysis has been included along with electronic tunability specifications.

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