OTRA-Based Multi-Function Inverse Filter Configuration

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DOI: 10.15598/aeee.v15i5.2572

Abstract. *A new OTRA-based multifunction inverse filter configuration is presented which is capable of realizing low pass, high pass and band pass filters using only two OTRAs and five to six passive elements. To the best knowledge of the authors, any inverse filter configuration using OTRAs has not been reported in the literature earlier. The effect of the major parasitics of the OTRAs and their effect on the performance of the filter have been investigated and measured through simulation results and Monte-Carlo analysis. The workability of the proposed circuits has been confirmed by SPICE simulations using CMOS-based-OTRA realizable in 0.18 µm CMOS technology. The proposed circuits are the only ones, which provide simultaneously the following features: use of reasonable number of active elements (only 2), realizability of all the three basic filter functions, employment of all virtually grounded resistors and capacitors and tunability of all filter parameters (except gain factor, H_0 for inverse high pass). The centre/cut-off frequency of the various filter circuits lying in the vicinity of 1 MHz have been found to be realizable, which has been verified through SPICE simulation results and have been found to be in good agreement with the theoretical results.*

Keywords

Analogue signal processing, inverse active filters, Operational Transresistance Amplifier.

1. Introduction

Inverse filters are important from the view point of some applications in the areas of Communication, Control and Instrumentation Systems where the distortion of the signal, caused by the signal processor or transmission systems, can be corrected by inverse filters, the frequency response of which is the reciprocal of the frequency response of the signal processors or transmission systems which were responsible for creating the undesired distortion in the system.

In digital systems, there are well known methods for the realization of inverse filters, however, in the continuous-time case, only a few methods/circuits have so far been proposed for the realization of inverse filters such as those in [1], [2], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17] and [18]. It is, therefore, useful to take a stock of the existing works in this area so that the present proposals can be seen in the right perspective.

In [1], a general method for obtaining inverse transfer function for linear dynamic systems and the inverse transfer characteristics of nonlinear resistive systems using nullors as basic building block were presented. In [2], a procedure for transforming voltage-mode op-amp-based RC filter into a current mode, Four Terminal Floating Nullors (FTFN)-based inverse filter was given. In [3], another general procedure for the realization of FTFN-based inverse filter from the well-developed voltage-mode filters was presented. In [4], Abuelma'atti used a single FTFN to realize many filters including an inverse filter. In [5], Gupta, Bhaskar, Senani and Singh presented four new configurations which realize inverse low pass, band pass, high pass and band reject filters using AD844-type Current Feedback Operational Amplifiers (CFOA). In [6], Gupta, Bhaskar and Senani presented a number of new configurations that realize inverse LP, HP, and BR filters using CFOAs which offer the properties superior to the previously known inverse filters. In [7], a Current-Differencing Buffered Amplifier (CDBA)-based universal inverse filter which realizes five types of inverse filters was proposed. In [8], a general configuration, derived from the circuit of Fig. 1 of [5], was presented by Wang, Chang, Yang and Tsai from which low pass, band pass and high pass inverse filters were shown to be realizable by appropriate choices (resistive or capacitive) of the various circuit admittances. In [9] and [10] inverse all-pass filters using Current-Differencing Transconductance Amplifier (CDTA) and CCII were proposed. In [11] Herenscar, Lahiri, Koton and Vrba presented a configuration using three Differential Difference Current Conveyors (DDCCs), which realizes inverse low pass, band pass and high pass filter. In [12] Garg, Bhagat and Jain presented a novel multi-function inverse filter using three modified CFOAs, which normally required nine CFOAs. In [13], Leuciuc proposed a method for realization of inverse systems for circuits employing nullor for applications in chaos synchronization. In [14] Tsukutani, Sumi and Yabuki presented realization of inverse low pass, high pass and band pass filters using five/six Multiple Output Operational Transconductance Amplifiers (MOTAs) in operating both voltage and current-mode. In [15], Patil and Sharma have reported inverse filter realized using two CFOAs. In [17], Yuce, Tokat, Minaei and Cicekoglu reported low-component count insensitive current and voltage-mode PID using three current-conveyors, PI and PD controllers employing two current-conveyors. Nasir and Ahmed in [18] have presented multi function inverse filter realization using two CDBAs.

From the survey of the existing literature as detailed above, it has been found that so far, no universal inverse filters have been proposed using the Operational Transresistance Amplifiers (OTRAs) as an active element. Therefore, the main aim of this paper is to propose a generalized universal inverse filter configuration using OTRAs which can realize low pass, high pass and band pass filters from the same configuration as special cases.

2. A Brief Overview of OTRA and Its Applications

The OTRA which is a differential Current-Controlled Voltage-Source (CCVS), can be symbolically shown as in Fig. 1 and is characterized by the following terminal equation and matrix characterization:

$$V_O = R_m(s)(I_P - I_n). \tag{1}$$

$$\begin{bmatrix} V_p \\ V_n \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \cdot \begin{bmatrix} I_p \\ I_n \\ I_o \end{bmatrix}. \tag{2}$$

The OTRA has received prominent attention in analog circuit literature for more than two decades because of its important property of providing a virtual ground at both of its input terminals, which eliminates the effect of parasitics at both the input terminals. On the other hand, its low output impedance enables the OTRA-based circuits to be cascaded easily. As a consequence, the use of OTRA has been investigated in the realization of numerous functional circuits so far such as biquad filters [19] and [20], immittance simulators [23], [24], [25], [26], [39] and [42] oscillators [21], [22] and [23], square/triangular waveform generators [27] and [29], monostable/astable multivibrators [28], all pass filters [32] and [33], analog multiplier/divider [30], PID controller [40] and [41], etc.

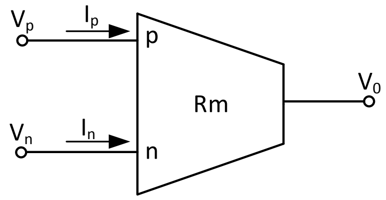

Fig. 1: Symbolic representation of an OTRA.

Several CMOS implementations of the OTRAs have also been advanced in the literature, for instance, see [34], [35], [36], [37] and [38] and the references cited therein. On the other hand, an implementation of the OTRA using two AD844-type CFOAs has also been popularly employed by several researchers.

3. The Proposed Configuration

The proposed new generalized structure for realizing inverse low-pass, inverse high-pass and band-pass filters as special cases, using two OTRAs and five admittances is shown in Fig. 2.

From a straightforward analysis, the transfer function of the circuit of Fig. 2 has been found to be:

$$\frac{V_0}{V_{in}} = \frac{Y_1Y_3 + Y_2Y_4}{Y_2Y_5}. \tag{3}$$

If we choose the various admittances as $Y_1 = sC_1$, $Y_2 = \dfrac{1}{R_2}$, $Y_3 = sC_2 + \dfrac{1}{R_3}$, $Y_4 = \dfrac{1}{R_4}$ and $Y_5 = \dfrac{1}{R_5}$ the

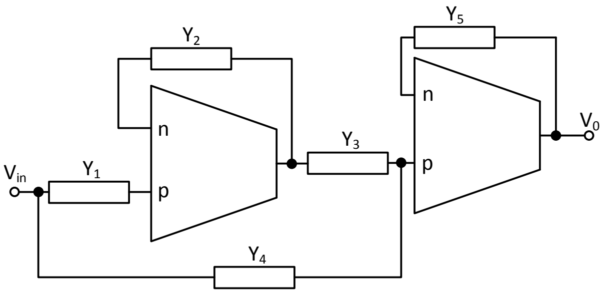

Fig. 2: The proposed generalized structure for realizing inverse filters.

resulting transfer function as given by:

$$\frac{V_0}{V_{in}} = \frac{1}{\dfrac{\frac{R_4}{R_5}\left(\frac{1}{C_1C_2R_2R_4}\right)}{s^2+s\left(\frac{1}{C_2R_3}\right)+\frac{1}{C_1C_2R_2R_4}}}, \tag{4}$$

which represents an inverse low pass filter with various parameters given by:

$$\begin{aligned} \omega_0 &= \sqrt{\frac{1}{C_1C_2R_2R_4}}, \\ Q &= R_3\sqrt{\frac{C_2}{C_1R_2R_4}}, \\ (H_O)_{ILP} &= \frac{R_4}{R_5}. \end{aligned} \tag{5}$$

If the admittances are chosen, such that $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$ and $Y_5 = \frac{1}{R_5}$, then we obtain the transfer function that represents an inverse band pass filter:

$$\frac{V_0}{V_{in}} = \frac{1}{\dfrac{\left(\frac{R_4}{R_5}\right)s\left(\frac{1}{C_4R_4}\right)}{s^2+s\left(\frac{1}{C_4R_4}\right)+\frac{1}{C_2C_4R_1R_3}}}. \tag{6}$$

The Inverse band pass filter parameters are given by:

$$\begin{aligned} \omega_0 &= \sqrt{\frac{1}{C_2C_4R_1R_3}}, \\ BW &= \frac{1}{C_4R_4}, \\ (H_O)_{IBP} &= \frac{R_4}{R_5}. \end{aligned} \tag{7}$$

Lastly, if the admittances are chosen as $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$ and $Y_5 = sC_5$ then the resulting transfer function represents the realization of an inverse high pass filter given by:

$$\frac{V_0}{V_{in}} = \frac{1}{\dfrac{s^2}{s^2+s\left(\frac{1}{C_4R_4}\right)+\frac{1}{C_2C_4R_1R_3}}}, \tag{8}$$

for $C_4 = C_5$.

The various parameter values in this case are given by:

$$\begin{aligned} \omega_0 &= \sqrt{\frac{1}{C_1C_2R_2R_4}}, \\ Q &= R_3\sqrt{\frac{C_2}{C_1R_2R_4}}, \\ (H_O)_{IHP} &= 1. \end{aligned} \tag{9}$$

From Eq. (5), Eq. (7) and Eq. (9), it can be seen that most of the relevant parameters of the frequency response of the inverse low pass, band pass and high pass filters, can be independently adjusted through various resistances. Since all the circuits resulting from the proposed structure employ virtual grounded resistors and capacitors, they are suitable from the view point of IC implementation.

4. Non-Ideal Analysis

Ideally, the transresistance gain $R_m(s)$ of an OTRA approaches infinity and forces the two input currents to be equal. However, practically, the transresistance gain $R_m(s)$ is finite and its effect therefore needs to be considered. The one-pole model of the OTRA is given by:

$$\begin{aligned} R_m(s) &= \frac{R_{mo}}{1+\frac{s}{\omega_o}} = \frac{R_{mo}\omega_o}{s+\omega_o} = \\ &= \frac{1}{\frac{s}{R_{mo}\omega_o}+\frac{1}{R_{mo}}}. \end{aligned} \tag{10}$$

For middle frequencies, the transresistance gain $R_m(s)$ can be approximated as:

$$R_{mo} \to \infty,\ R_m(s) \cong \frac{1}{sC_p}, \tag{11}$$

where, R_{mo} is the DC open-loop transresistance gain, ω_o is the transresistance cut-off frequency and C_p is the parasitic capacitance (the parasitic capacitance C_p appears at the high impedance node between the output of the Current Differencing Unit and the input of the voltage buffer of the OTRA architecture; for instance see node 'N' in the CMOS OTRA of Fig. 3). On the other hand, the more elaborate two-pole model of the OTRA is normally expressed as:

$$R_m(s) = \frac{R_o}{\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)}, \tag{12}$$

which can be can be modified and rewritten as:

$$R_m(s) = \frac{1}{C_p\left(s+\frac{1}{C_pR_o}\right)\left(\frac{s}{\omega_{p2}}+1\right)}. \tag{13}$$

In this case also, for frequencies lying in the range: $\omega_{p1} << \omega << \omega_{p2}$, Eq. (13) can be approximated as:

$$R_m(s) \cong \frac{1}{sC_p}, \text{ where } C_p = \frac{1}{R_o\omega_o}. \tag{14}$$

A straightforward analysis of the proposed generalized structure of Fig. 2, using Eq. (11) results in the non-ideal transfer function of the circuit given by the following expression:

$$\frac{V_o}{V_{in}} = \frac{sC_pY_4 + (Y_1Y_3 + Y_2Y_4)}{s^2C_p^2 + sC_p(Y_2+Y_5) + Y_2Y_5}. \tag{15}$$

If we choose the admittances as $Y_1 = sC_1$, $Y_2 = \frac{1}{R_2}$, $Y_3 = sC_2 + \frac{1}{R_3}$, $Y_4 = \frac{1}{R_4}$ and $Y_5 = \frac{1}{R_5}$, we obtain the non-ideal transfer function as:

$$\frac{V_0}{V_{in}} = \frac{1}{\dfrac{\frac{s^2C_p^2}{C_1C_2} + \frac{sC_p(R_2+R_5)}{C_1C_2R_2R_5} + \frac{R_4}{R_5}\left(\frac{1}{C_1C_2R_2R_4}\right)}{s^2 + s\left(\frac{C_1R_4+C_pR_3}{C_1C_2R_3R_4}\right) + \frac{1}{C_1C_2R_2R_4}}}. \tag{16}$$

Neglecting the terms involving s^2 and s (since in general, the product C_1 C_2 would be much larger than C_p^2 and C_p), we can approximate the transfer function of Eq. (16) as:

$$\frac{V_0}{V_{in}} \cong \frac{1}{\dfrac{\frac{R_4}{R_5}\left(\frac{1}{C_1C_2R_2R_4}\right)}{s^2 + \frac{s}{C_2R_3}\left(1+\frac{C_pR_3}{C_1R_4}\right) + \frac{1}{C_1C_2R_2R_4}}}. \tag{17}$$

The non-ideal inverse low pass filter parameters are given by:

$$\begin{aligned} \hat{\omega}_0 &= \sqrt{\frac{1}{C_1C_2R_2R_4}}, \\ \hat{Q}_0 &= Q_0\left(\frac{C_1R_4}{C_1R_4 + C_PR_3}\right), \\ \left(\hat{H}_o\right)_{ILP} &= \frac{R_4}{R_5}. \end{aligned} \tag{18}$$

From the above expressions, we conclude that the non-ideal cut-off frequency and the gain are not affected due to the non-ideal behavior of OTRA but the Q_0 is affected and the non-ideal Q_0 is given as:

$$\hat{Q}_0 = Q_0\left(\frac{C_1R_4}{C_1R_4 + C_PR_3}\right). \tag{19}$$

From the above, the percentage error in Q_0 is given by:

$$\begin{aligned} &\left(\frac{\hat{Q}_0 - Q_0}{Q_0}\right)\cdot 100 = \\ &= -\left(\frac{C_pR_3}{C_pR_3 + C_1R_4}\right)\cdot 100. \end{aligned} \tag{20}$$

Similarly, if the admittances are chosen, such that $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$ and $Y_5 = \frac{1}{R_5}$, then we obtain the non-ideal transfer function of the inverse band pass filter given by:

$$\frac{V_0}{V_{in}} \cong \frac{1}{\dfrac{\left(\frac{R_4}{R_5}\right)s\left(\frac{1}{C_4R_4}\right)}{s^2 + s\left(\frac{1}{C_4R_4}\right) + \frac{1}{C_2C_4R_1R_3\left(1+\frac{C_p}{C_2}\right)}}}. \tag{21}$$

From Eq. (21) the non-ideal inverse band pass filter parameters are given by:

$$\begin{aligned} \hat{\omega}_0 &= \sqrt{\frac{1}{C_2C_4R_1R_3\left(1+\frac{C_p}{C_2}\right)}}, \\ \hat{BW} &= \frac{1}{C_2R_4}, \\ \left(\hat{H}_o\right)_{IBP} &= \frac{R_4}{R_5}. \end{aligned} \tag{22}$$

Thus, in this case only centre frequency is affected by parasitics capacitance of the OTRA. The above parameters can be further expressed as:

$$\begin{aligned} \hat{\omega}_0 &= \frac{\omega_0}{\sqrt{\left(1+\frac{C_p}{C_2}\right)}}, \\ \hat{BW} &= BW, \\ \left(\hat{H}_o\right)_{IBP} &= (H_o)_{IBP}. \end{aligned} \tag{23}$$

Hence, the percentage errors in the radian frequency and Q factor are found to be as follows:

$$\left(\frac{\hat{\omega}_o - \omega_o}{\omega_o}\right)\cdot 100 = -\left(\frac{C_p}{2C_2}\right)\cdot 100. \tag{24}$$

Lastly, if the admittances are chosen such that $Y_1 = \frac{1}{R_1}$, $Y_2 = sC_2$, $Y_3 = \frac{1}{R_3}$, $Y_4 = sC_4 + \frac{1}{R_4}$ and $Y_5 = sC_5$, then we obtain the non-ideal transfer function of the inverse high pass filter which can be expressed as:

$$\frac{V_0}{V_{in}} = \frac{\dfrac{1}{s^2\left[C_2C_5 + C_p\left(C_2 + C_5\right) + C_p^2\right]}}{s^2 C_4\left(C_p + C_2\right) + \dfrac{sC_2}{R_4} + \dfrac{1}{R_1R_3}}. \tag{25}$$

Neglecting the term C_p^2 we obtain the resulting transfer function as:

$$\frac{V_0}{V_{in}} \cong \cong \frac{\dfrac{1}{s^2\dfrac{C_5}{C_4}\left[1 + \dfrac{\dfrac{C_p}{C_2}}{\left(1+\frac{C_p}{C_5}\right)}\right]}}{s^2 + s\dfrac{1}{C_4R_4\left(1+\dfrac{C_p}{C_2}\right)} + \dfrac{1}{C_2C_4R_1R_3\left(1+\dfrac{C_p}{C_2}\right)}}. \tag{26}$$

The non-ideal parameters of the inverse high pass filter are, therefore, given by:

$$\begin{aligned}
\hat{\omega}_0 &= \sqrt{\frac{1}{C_2C_4R_1R_3\left(1+\dfrac{C_p}{C_2}\right)}}, \\
\hat{Q}_0 &= R_4\sqrt{\frac{C_4\left(1+\dfrac{C_p}{C_2}\right)}{C_2R_1R_3}}, \\
\left(\hat{H}_o\right)_{IHP} &= \frac{C_5}{C_4}\left[1 + \frac{C_p/C_5}{\left(1+C_p/C_2\right)}\right].
\end{aligned} \tag{27}$$

Thus, the non-ideal parameters can be expressed in terms of ideal parameters, as follows:

$$\begin{aligned}
\hat{\omega}_0 &= \frac{\omega_0}{\sqrt{\left(1+\dfrac{C_p}{C_2}\right)}}, \\
\hat{Q}_0 &= Q_0\sqrt{\left(1+\dfrac{C_p}{C_2}\right)}, \\
\left(\hat{H}_o\right)_{IHP} &= \left(H_o\right)_{IHP}\left[1 + \frac{C_p/C_5}{\left(1+C_p/C_2\right)}\right].
\end{aligned} \tag{28}$$

Hence, percentage errors in the filter parameters are found to be: % error in radian frequency will be:

$$\left(\frac{\hat{\omega}_0 - \omega_o}{\omega_o}\cdot 100\right) = -\left(\frac{C_p}{2C_2}\right)\cdot 100. \tag{29}$$

% error in the Q factor would be:

$$\left(\frac{\hat{Q}_0 - Q_0}{Q_0}\right)\cdot 100 = \left(\frac{C_p}{2C_2}\right)\cdot 100. \tag{30}$$

Lastly, the % error in the gain will be:

$$\left(\frac{\hat{H}_0 - H_o}{H_o}\right)\cdot 100 = -\frac{C_2}{C_5}\left(\frac{C_p}{C_p + C_2}\right)\cdot 100. \tag{31}$$

5. Comparison With Previously Published Inverse Filters

A comparative study of all the inverse filters realized using various active elements is shown in Tab. 1. From the table, a comparison of the salient features of the proposed circuits with those previously known [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [14], [15], [16] and [18] reveals that the proposed circuit configuration is the only one which provides simultaneously the following features: use of reasonable number of active elements (only 2), realizability of all the three basic filter functions, employment of all virtually grounded resistors and capacitors and tunability of all filter parameters (except gain factor, H_0 for inverse high pass).

6. SPICE Simulation and Experimental Results

The workability of the all the three special cases of the proposed configuration has been verified through SPICE simulations using CMOS OTRA as presented by Mostafa-Soliman in 2006 [31] (reproduced here in Fig. 3 with the aspect ratios of MOSFETs as given in Tab. 1 and the model parameters using 0.18 μm CMOS technology provided by TSMC as given in Tab. 3.

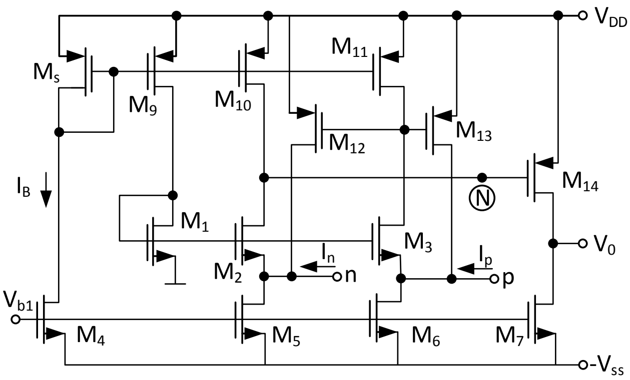

Fig. 3: An exemplary CMOS realization of the OTRA as presented by Mostafa-Soliman [31].

The SPICE simulation results of Fig. 5, Fig. 6 and Fig. 7 are seen to be consistent with the similar results obtained by other inverse filters using different devices known earlier [1], [2], [3], [4], [5], [6], [7], [8], [9], [10],

Tab. 1: Comparison with previously known circuits.

Reference	No. of Active device	Number of Passive Component	Type of Inverse Filters Realized (VM/CM)	Grounded /Floating Capacitors	Tunability
[1]	1	4R, 2C	IHP (VM)	2 FC	No
[2]	1	5R, 2C	ILP (VM)	1 GC, 1 FC	No
[3]	1	4R, 2C	IAP (CM)	1GC, 1 FC	No
[1]	1 (4 circuit)	2 – 4R, 2/3C	ILP, IHP, IBP, IBR, IAP (All CM)	1FC, 1/2GC	No
[5]	3	4R, 2C	ILP, IHP, IBP, IBR (VM)	2GC	Yes
[6]	3	3–5R, 2C	ILP, IHP, IBP, IBR (VM)	2GC	Yes, when $R_4 = R_0$
[7]	2	2–4R, 2–4C	ILP, IHP, IBP, IBR, IAP (VM)	2/4FC, 1/2 GC	No
[8]	3	3R, 3C	ILP, IHP, IBP (VM)	3GC	No
[9]	1	1R, 1C	First Order IAP (CM)	1GC	No
[10]	1	2R, 1C	First Order IAP (VM)	1GC	No
[11]	3	2R, 2C	ILP, IBP, IHP (All VM)	2GC	No
[12]	3	2–3R, 3–4C	ILP, IBP, IHP (VM)	3/4GC	Yes
[14]	10/12 OTAs	2C	ILP, IHP, IBP (VM&CM)	2GC	Yes
[15]	2	4–6R, 2C	ILP, IHP, IBP, IBR (All VM)	1FC, 1/2GC	No
[16]	3	2R. 2C	IHP (Trans conductance)	2GC	No
[18]	2	3R, 3C	ILP, IHP, IBPF (All CM)	2GC, 1FC	No
Proposed	2	4R, 2/3C	ILP, IHP, IBP (All VM)	Capacitor virtually grounded	Yes
R - Resistance, C - Capacitance, FC - Floating Capacitor, GC - Grounded Capacitor					

Tab. 2: Model parameters of NMOS and PMOS transistors.

Device Type	Model Parameters
NMOS	LEVEL = 7 VERSION=3.1 TNOM=27 TOX=4.1E-9 XJ=1E-7 NCH=2.3549E17 VTH0=0.3725327 K1=0.5933684 K2=2.050755E−3 K3=1E−3 K3B=4.5116437 W0=1E−7 NLX=1.870758E−7 DVT0W=0 DVT1W=0 DVT2W=0 DVT0=1.3621338 DVT1=0.3845146 DVT2=0.0577255 U0=259.5304169 UA=−1.413292E−9 UB=2.229959E-18 UC=4.525942E-11 VSAT=9.411671E4 A0=1.7572867 AGS=0.3740333 B0=−7.087476E−9 B1=−1E−7 KETA=−4.331915E−3 A1=0 A2=1 RDSW=111.886044 PRWG=0.5 PRWB=−0.2 WR=1 WINT=0 LINT=1.701524E-8 XL=0 XW=-1E-8 DWG=-1.365589E-8 DWB=1.045599E-8 VOFF=-0.0927546 NFACTOR=2.4494296 CIT=0 CDSC=2.4E-4 CDSCD=0 CDSCB=0 ETA0=3.175457E-3 ETAB=3.494694E-5 DSUB=0.0175288 PCLM=0.7273497 PDIBLC1=0.1886574 PDIBLC2=2.617136E-3 PDIBLCB=-0.1 DROUT=0.7779462 PSCBE1=3.488238E10 PSCBE2=6.841553E−10 PVAG=0.0162206 DELTA=0.01 RSH=6.5 MOBMOD=1 PRT=0 UTE=−1.5 KT1=−0.11 KT1L=0 KT2=0.022 UA1=4.31E−9 UB1=−7.61E−18 UC1=−5.6E−11 AT=3.3E4 WL=0 WLN=1 WW=0 WWN=1 WWL=0 LL=0 LLN=1 LW=0 LWN=1 LWL=0 CAPMOD=2 XPART=0.5 CGDO=8.53E-10 CGSO=8.53E−10 CGBO=1E−12 CJ=9.513993E−4 PB=0.8 MJ=0.3773625 CJSW=2.600853E-10 PBSW=0.8157101 MJSW=0.1004233 CJSWG=3.3E-10 PBSWG=0.8157101 MJSWG=0.1004233 CF=0 PVTH0=-8.863347E-4 PRDSW=-3.6877287 PK2=3.730349E-4 WKETA=6.284186E-3 LKETA=−0.0106193 PU0=16.6114107 PUA=6.572846E-11 PUB=0 PVSAT=1.112243E3 PETA0=1.002968E-4 PKETA=−2.906037E−3
PMOS	LEVEL=7 VERSION=3.1 TNOM=27 TOX=4.1E-9 XJ=1E−7 NCH=4.1589E17 VTH0=−0.3948389 K1=0.5763529 K2=0.0289236 K3=0 K3B=13.8420955W0=1E−6 NLX=1.337719E−7 DVT0W=0 DVT1W=0 DVT2 W=0 DVT0=0.5281977 DVT1=0.2185978 DVT2=0.1 U0=109.9762536 UA=1.325075E−9 UB=1.577494E−21 UC=−1E−10 VSAT=1.910164E5 A0=1.7233027 AGS=0.3631032 B0=2.336565E−7 B1=5.517259E−7 KETA=0.0217218 A1=0.3935816 A2=0.401311 RDSW=252.7123939 PRWG=0.5 PRWB=0.0158894 WR=1 WINT=0 LINT=2.718137E-8 XL=0 XW=−1E−8 DWG=−4.363993E−8 DWB=8.876273E-10 VOFF=−0.0942201 NFACTOR=2 CIT=0 CDSC=2.4E-4 CDSCD=0 CDSCB=0 ETA0=0.2091053 ETAB=−0.1097233 DSUB=1.2513945 PCLM=2.1999615 PDIBLC1=1.238047E−3 PDIBLC2=0.0402861 PDIBLCB=−1E−3 DROUT=0 PSCBE1=1.034924E10 PSCBE2=2.991339E−9 PVAG=15 DELTA=0.01 RSH=7.5 MOBMOD=1 PRT=0 UTE=−1.5 KT1=-0.11 KT1L=0 KT2=0.022 UA1=4.31E−9 UB1=−7.61E−18 UC1=−5.6E−11 AT=3.3E4 WL=0 WLN=1 WW=0 WWN=1 WWL=0 LL=0 LLN=1 LW=0 LWN=1 LWL=0 CAPMOD=2 XPART=0.5 CGDO=6.28E−10 CGSO=6.28E−10 CGBO=1E−12 CJ=1.160855E−3 PB=0.8484374 MJ=0.4079216 CJSW=2.306564E−10 PBSW=0.842712 MJSW=0.3673317 CJSWG=4.22E−10 PBSWG=0.842712 MJSWG=0.3673317CF=0 PVTH0=2.619929E−3 PRDSW=1.0634509 PK2=1.940657E−3 WKETA=0.0355444 LKETA=−3.037019E−3 PU0=−1.0227548 PUA=−4.36707E−11 PUB=1E−21 PVSAT=−50 PETA0=1E−4 PKETA=−5.167295E−3 AT=3.3E4 WL=0 WLN=1 WW=0 WWN=1 WWL=0 LL=0 LLN=1 LW=0 LWN=1 LWL=0 CAPMOD=2 XPART=0.5 CGDO=6.28E−10 CGSO=6.28E−10 CGBO=1E−12 CJ=1.160855E−3 PB=0.8484374 MJ=0.4079216 CJSW=2.306564E−10 PBSW=0.842712 MJSW=0.3673317 CJSWG=4.22E−10 PBSWG=0.842712 MJSWG=0.3673317 CF=0 PVTH0=2.619929E−3 PRDSW=1.0634509 PK2=1.940657E−3 WKETA=0.0355444 LKETA=−3.037019E−3 PU0=−1.0227548 PUA=-4.36707E−11 PUB=1E−21 PVSAT=−50 PETA0=1E−4 PKETA=−5.167295E−3

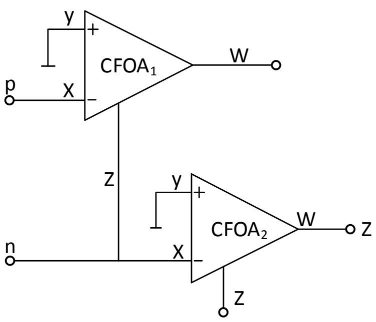

Fig. 4: OTRA implemented using two commercially available AD844 type CFOA ICs [22] and [27].

Tab. 3: Aspect ratios of the various MOSFETs for the circuit of Fig. 3 [39].

Transistor	W(μm)/L(μm)
M_1–M_3	36/0.9
M_4	3.6/0.9
M_5, M_6	10.8/0.9
M_7	3.6/0.9
M_8–M_{11}	18/0.9
M_{12}, M_{13}	36/0.9
M_{14}	18/0.36

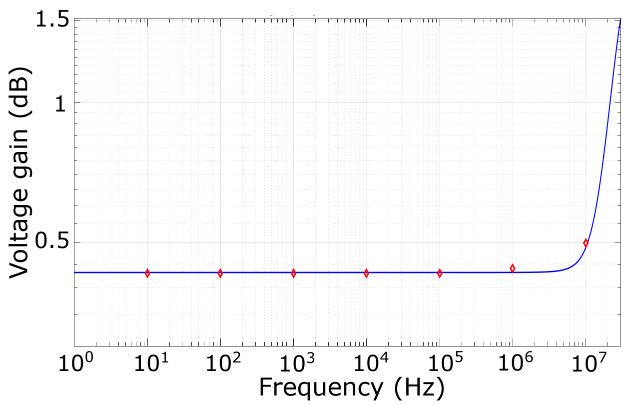

Fig. 5: Frequency Response of the Inverse Low Pass Filter.

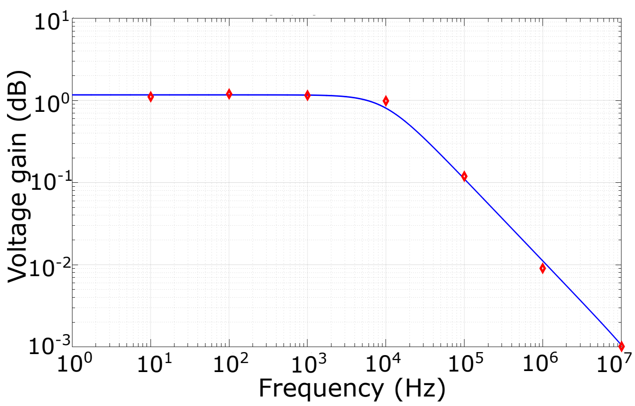

Fig. 6: Frequency Response of the Inverse High Pass Filter.

[11], [12], [13], [14], [15], [16], [17] and [18] and thus, establish the workability of the proposed configuration.

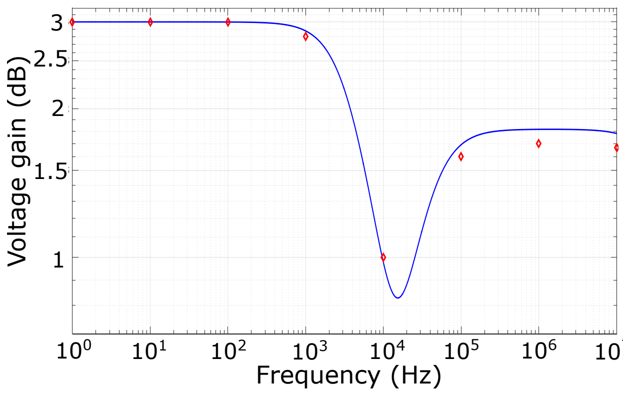

Fig. 7: Frequency Response of the Inverse Band Pass Filter.

The magnitude of percentage errors in the various filter parameters have been calculated for the component values as taken for SPICE simulations as $C_1 = C_2 = C_4 = C_5 = 100$ pF, $R_1 = R_2 = R_3 = R_4 = R_5 = 10$ kΩ and $C_p = 0.4$ pF. With the above choice of component values, the percentage errors in Q_0 due to the effect of parasitics, from the Eq. (20), Eq. (24), Eq. (29), Eq. (30) and Eq. (31) respectively, have been found to be not more than 1.5 %.

The percentage error between theoretical and the simulated results have been found to be nearly of the same order as those calculated.

The Monte-Carlo analysis of the three inverse filters has been carried out and the results have been included in Fig. 8, Fig. 9 and Fig. 10.

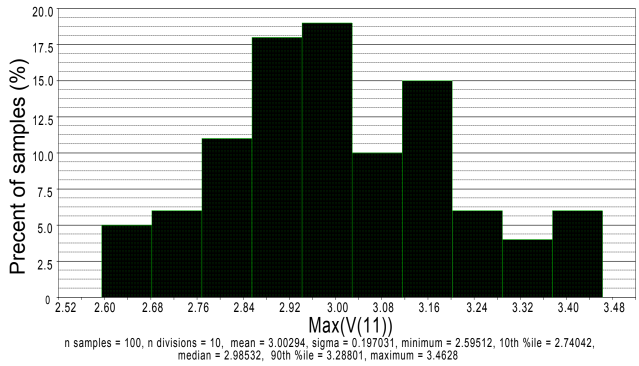

Fig. 8: Monte Carlo Analysis of ILPF showing variation of gain w.r.t. 5 % variation in resistance value.

The workability of all the proposed inverse filters has been also confirmed with hardware implementations using each OTRA being realized by two AD844 ICs (reproduced here in Fig. 4 as in [22] and [27]). The component values taken in hardware implementations were $R_1 = R_2 = R_3 = R_4 = R_5 = 1$ kΩ and $C_1 = C_2 = C_4 = C_5 = 1$ nF which results in the following value of filter parameters: cut-off frequency $f_0 = 159$ KHz, $Q_0 = 1$ and $H_0 = 1$.

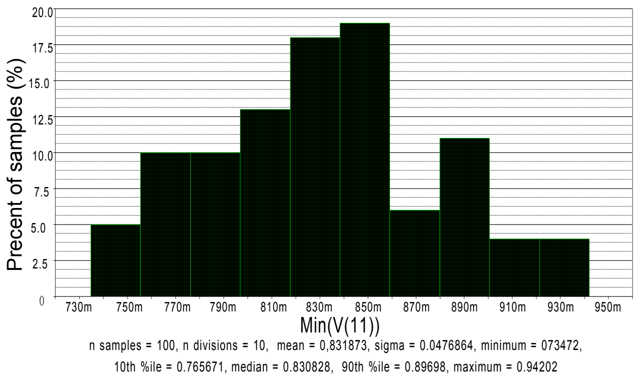

Fig. 9: Monte Carlo Analysis of IHPF showing variation of quality factor w.r.t. 5 % variation in resistance value.

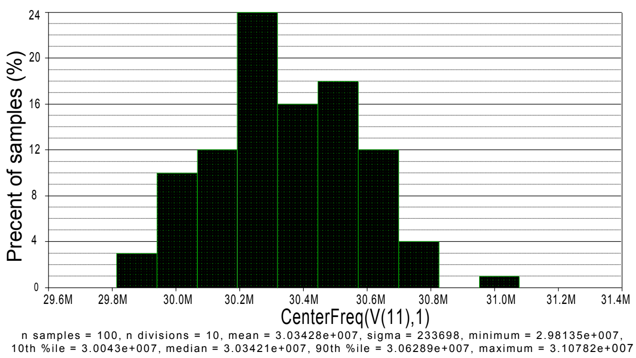

Fig. 10: Monte Carlo Analysis of IBPF showing variation of center frequency w.r.t. 5 % variation in resistance value.

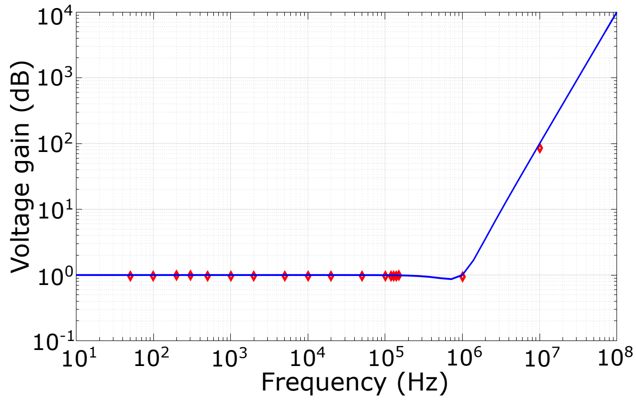

Fig. 11: Frequency Response of ILPF.

SPICE simulation results of Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9 and Fig. 10, and the hardware results of Fig. 11, Fig. 12 and Fig. 13, thus, establish the workability of the proposed circuits.

In conclusion, a good correspondence has been found between theoretical results and SPICE results as well as between theoretical results and experimental results.

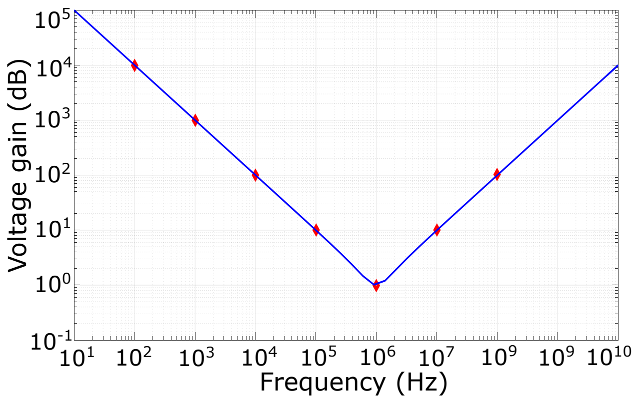

Fig. 12: Frequency Response of IBPF.

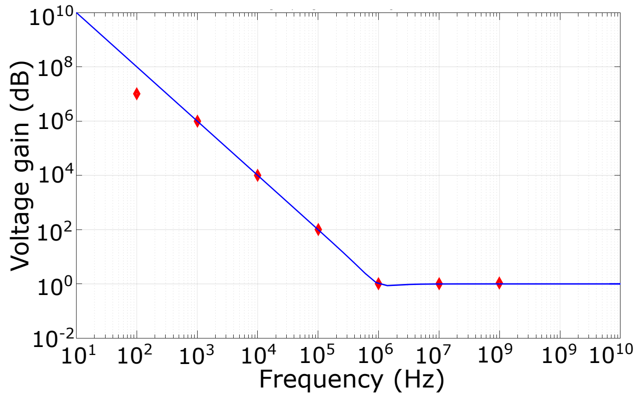

Fig. 13: Frequency Response of IHPF.

7. Conclusion

Among numerous alternative building blocks investigated in analog circuit literature over the last three decades, the OTRA has been prominently employed in the realization of numerous analog signal processing/signal generation applications in recent years. However, the use of OTRA in the realization of inverse filters had not been investigated earlier.

This paper fills this void by proposing a two-OTRA-based generalized configuration from which low-pass, band-pass and high-pass filters can be realized as special cases by judicious choices (resistive/capacitive) of various circuit admittances. The circuits have been analyzed in detail taking into account the various non-ideal parameters of the OTRA and the workability of the derived specific inverse filters has been confirmed by SPICE simulations using an exemplary CMOS OTRA architecture implemented in 0.18 μm CMOS technology, as well as by OTRAs implemented with AD844 ICs. Centre/cut-off frequencies of the order of 1.59 MHz in case of the former and of the order of 159 kHz in the case of latter have been found to be realisable.

The present paper, thus, adds a new application of the OTRA (namely, the realization of inverse filters) to the existing repertoire of its applications known earlier in [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40] and [41], and the references cited therein.

Acknowledgment

This work was performed at the Analog Signal Processing Research Lab of NSIT, New Delhi.

References

[1] LEUCIUC. A. Using nullors for realisation of inverse transfer functions and characteristics. *Electronics Letters*. 1997, vol. 33, iss. 11, pp. 949–951. ISSN 0013-5194. DOI: 10.1049/el:19970637.

[2] CHIPIPOP. B. and W. SURAKAMPONTORN. Realisation of current-mode FTFN-based inverse filter. *Electronics Letters*. 1999, vol. 35, iss. 9, pp. 690–692. ISSN 0013-5194. DOI: 10.1049/el:19990495.

[3] WANG, H. Y. and C. T. LEE. Using nullors for the realization of FTFN based Inverse filters. *Electronics Letters*. 1999, vol. 35, iss. 22, pp. 1889–1890. ISSN 0013-5194. DOI: 10.1049/el:19991336.

[4] ABUELMA'ATTI, M. T. Identification of Cascadable Current-Mode Filters and Inverse-Filters Using Single FTFN. *Frequenz*. 2000, vol. 54, iss. 11–12, pp. 284–289. ISSN 2191-6349. DOI: 10.1515/FREQ.2000.54.11-12.284.

[5] GUPTA, S. S., D. R. BHASKAR, R. SENANI and A. K. SINGH. Identification of Cascadable Current-Mode Filters and Inverse-Filters Using Single FTFN. *Frequenz*. 2000, vol. 54, iss. 11–12, pp. 284–289. ISSN 2191-6349. DOI: 10.1515/FREQ.2000.54.11-12.284.

[6] GUPTA, S. S., D. R. BHASKAR and R. SENANI. New analogue Inverse filters realized with current feedback op-amp. *International journal of Electronics*. 2011, vol. 98, iss. 8, pp. 1103–1113. ISSN 0020-7217. DOI: 10.1080/00207217.2010.547812.

[7] PANDEY, R., N. PANDEY, T. NEGI and V. GARG. CDBA based universal inverse filter. *ISRN Electronics*. 2013, vol. 2013, iss. 1, pp. 1–6. ISSN 2090-8679. DOI: 10.1155/2013/181869.

[8] WANG, H. Y., S. H. CHANG, T. Y. YANG and P. Y. TSAI. A Novel Multifunction CFOA-Based Inverse Filter. *Circuits and Systems*. 2011, vol. 2, no. 1, pp. 14–17. ISSN 2153-1293. DOI: 10.4236/cs.2011.21003.

[9] SHAH, N. A., M. QUADRI and S. Z. IQBAL. High output impedance current-mode allpass inverse filter using CDTA. *Indian Journal of pure and applied physics*. 2008, vol. 46, iss. 12, pp. 893–896. ISSN 0019-5596.

[10] SHAH, N. A. and M. F. RATHER. Realization of voltage-mode CCII-based all pass filter and its inversion version. *Indian Journal of Pure & Applied Physics*. 2006, vol. 44, iss. 3, pp. 269–271. ISSN 0975-1041.

[11] HERENCSAR, N., A. LAHIRI, J. KOTON and K. VRBA. Realizations of Second-Order Inverse Active Filters Using Minimum Passive Components and DDCCs. In: *33rd International Conference on Telecommunications and Signal Processing (TSP 2010)*. Baden near Vienna: Asszisztencia Szervezo Kft., 2010, pp. 38–41. ISBN 978-963-88981-0-4.

[12] GARG, K., R. BHAGAT and B. JAINT. A Novel Multifunction modified CFOA based Inverse filter. In: *IEEE 5th India International Conference on Power Electronics (IICPE)*. Delhi: IEEE, 2012, pp. 1–5. ISBN 978-1-4673-0934-9. DOI: 10.1109/IICPE.2012.6450471.

[13] LEUCIUC. A. The realization of inverse system for circuits containing nullors with applications in chaos synchronization. *International Journal of Circuit Theory and Applications*. 1998, vol. 26, iss. 1, pp. 1–12. ISSN 1097-007X. DOI: 10.1002/(SICI)1097-007X(199801/02)26:1<1::AID-CTA989>3.0.CO;2-B.

[14] TSUKUTANI, T., Y. SUMI and N. YABUKI. Electronically tunable inverse active filters employing OTAs and grounded capacitors. *International Journal of Electronics Letters*. 2016, vol. 4, iss. 2, pp. 166–176. ISSN 2168-1732. DOI: 10.1080/21681724.2014.984636.

[15] PATIL, V. N. and R. K. SHARMA. Novel Inverse Active Filters employing CFOAs. *International Journal for Scientific Research & Development*. 2015, vol. 3, iss. 7, pp. 359–360. ISSN 2321-0613.

[16] SHARMA, A., A. KUMAR and P. WHIG. On the performance of CDTA based novel analog Inverse Low Pass filter using 0.35 μm CMOS parameter. *International Journal of*

Science, Technology & Management. 2015, vol. 4, no. 1, pp. 594–601. ISSN 2394-1537. DOI: 10.13140/RG.2.1.1525.2002.

[17] YUCE, E., S. TOKAT, S. MINAEI and O. CICEKOGLU. Low-Component-Count Insensitive Current-Mode and Voltage-Mode PID, PI and PD Controllers. *Frequenz*. 2006, vol. 60, iss. 3–4, pp. 65–70. ISSN 2191-6349. DOI: 10.1515/FREQ.2006.60.3-4.65.

[18] NASIR, A. R. and S. N. AHMED. A New Current-Mode Multifunction Inverse Filter Using CDBAs. *International Journal of Computer Science and Information Security*. 2013, vol. 11, no. 12, pp. 50–52. ISSN 1947-5500.

[19] SALAMA, K. N. and A. M. SOLIMAN. Active RC Applications of the Operational Transresistance Amplifier. *Frequenz*. 2000, vol. 54, iss. 7–8, pp. 171–176. ISSN 2191-6349. DOI: 10.1515/FREQ.2000.54.7-8.171.

[20] SALAMA, K. N. and A. M. SOLIMAN. Third Order Universal Filter Using Single Operational Transresistance Amplifier. *AEU-Archiv fur Elektronik und Ubertragungstechnik*. 1999, vol. 53, iss. 1, pp. 49–52. ISSN 0001-1096.

[21] SALAMA, K. N. and A. M. SOLIMAN. Novel oscillators using the operational transresistance amplifier. *Microelectronics Journal*. 2000, vol. 31, iss. 1, pp. 39–47. ISSN 0026-2692. DOI: 10.1016/S0026-2692(99)00087-7.

[22] CAM, U. A Novel Single-Resistance-Controlled Sinusoidal Oscillator Employing Single Operational Transresistance Amplifier. *Analog Integrated Circuits and Signal Processing*. 2002, vol. 32, iss. 2, pp. 183–186. ISSN 1573-1979. DOI: 10.1023/A:1019586328253.

[23] GUPTA. A., R. SENANI, D. R. BHASKAR and A. K. SINGH. OTRA-based Grounded-FDNR and Grounded-Inductance Simulators and Their Applications. *Circuits, Systems, and Signal Processing*. 2012, vol. 31, iss. 2, pp. 489–499. ISSN 1531-5878. DOI: 10.1007/s00034-011-9345-2.

[24] KACAR, F., U. CAM, O. CICEKOGLU, H. KUNTMAN and A. KUNTMAN. New parallel Immittance simulator realizations employing a single OTRA. In: *45th Midwest Symposium on Circuits and Systems (MWSCAS-2002)*. Tulsa: IEEE, 2003, pp. 303–306. ISBN 0-7803-7523-8. DOI: 10.1109/MWSCAS.2002.1187217.

[25] CAM, U., F. KACAR, O. CICEKOGLU, H. KUNTMAN and A. KUNTMAN. New parallel Immittance simulator realizations employing a single OTRA. *AEU - International Journal of Electronics and Communications*. 2003, vol. 57, iss. 4, pp. 287–290. ISSN 1434-8411. DOI: 10.1078/1434-8411-54100173.

[26] HOU, C. L., H. C. CHIEN and Y. K. LO. Novel Two OTRA-Based Grounded Immitance Simulator Topologies. *Analog Integrated Circuits and Signal Processing*. 2004, vol. 39, iss. 2, pp. 169–175. ISSN 1573-1979. DOI: 10.1023/B:ALOG.0000024064.73784.58.

[27] CAM, U., F. KACAR, O. CICEKOGLU, H. KUNTMAN and A. KUNTMAN. Square-wave generators employing OTRAs. *IEEE Proceedings - Circuits, Devices and Systems*. 2005, vol. 152, iss. 6, pp. 718–722. ISSN 1350-2409. DOI: 10.1049/ip-cds:20045167.

[28] LO, Y. K. and H. C. CHIEN. Current-Mode monostable multivibrators using OTRAs. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2006, vol. 53, iss. 11, pp. 1274–1278. ISSN 1558-3791. DOI: 10.1109/TCSII.2006.882361.

[29] LO, Y. K. and H. C. CHIEN. Switch-controllable OTRA-based square/triangular waveform generator. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2007, vol. 54, iss. 12, pp. 1110–1114. ISSN 1558-3791. DOI: 10.1109/TCSII.2007.905879.

[30] PANDEY, R., N. PANDEY, B. SRIRAM and S. K. PAUL. Single OTRA based Analog Multiplier and its Applications. *International Scholarly Research Network Electronics*. 2012, vol. 2012, iss. 1, pp. 1–7. ISSN 2090-8679. DOI: 10.5402/2012/890615.

[31] MOSTAFA, H. and A. M. SOLIMAN. A Modified CMOS Realization of the Operational Transresistance Amplifier (OTRA). *Frequenz*. 2006, vol. 60, iss. 3–4, pp. 70–77. ISSN 2191-6349. DOI: 10.1515/FREQ.2006.60.3-4.70.

[32] CAM, U., C. CAKIR and O. CICEKOGLU. Noveltransimpedance Type First-Order All-Pass Filter Using Single Otra. *AEU - International Journal of Electronics and Communications*. 2004, vol. 58, iss. 1, pp. 296–298. ISSN 1434-8411. DOI: 10.1078/1434-8411-54100246.

[33] CAKIR, C., U. CAM and O. CICEKOGLU. Novel all pass filter configuration employing single OTRA. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 2005, vol. 52, iss. 3, pp. 122–125. ISSN 1558-3791. DOI: 10.1109/TCSII.2004.842055.

[34] CHEN, J. J., H. W. TSAO and C. C. CHEN. Operational transresistance amplifier using CMOS technology. *Electronics Letters*. 1992,

vol. 28, iss. 22, pp. 2087–2088. ISSN 0013-5194. DOI: 10.1049/el:19921338.

[35] RIEWRUJA, V., J. PARNKLANG and A. JULPRAPA. Current tunable CMOS operational transresistance amplifier. In: *IEEE International Symposium on Industrial Electronics Proceedings (ISIE 2001)*. Pusan: IEEE, 2001, pp. 1328–1332. ISBN 0-7803-7090-2. DOI: 10.1109/ISIE.2001.931674.

[36] DURUK, A. and H. KUNTMAN. A new CMOS Differential OTRA Design for the Low Voltage Power Supplies in the Sub-Micron Technologies. *Turkish Journal of Electrical Engineering and Computer Sciences*. 2005, vol. 13, no. 1, pp. 23–37. ISSN 1303-6203. DOI: 10.1049/el:19921338.

[37] DURUK, A., E. O. GUNES and H. KUNTMAN. A new low voltage CMOS differential OTRA for sub-micron technologies. *AEU - International Journal of Electronics and Communications*. 2007, vol. 61, iss. 5, pp. 291–299. ISSN 1434-8411. DOI: 10.1016/j.aeue.2006.05.009.

[38] KAFRAWY, A. K. and A. M. SOLIMAN. A modified CMOS differential operational transresistance amplifier (OTRA). *AEU - International Journal of Electronics and Communications*. 2009, vol. 63, iss. 12, pp. 1067–1071. ISSN 1434-8411. DOI: 10.1016/j.aeue.2008.08.003.

[39] NAGAR, B. C. and S. K. PAUL. Lossless grounded FDNR simulator and its application using OTRA. *Analog Integrated Circuits and Signal Processing*. 2017, vol. 92, iss. 3, pp. 507–517. ISSN 0925-1030. DOI: 10.1007/s10470-017-1021-4.

[40] PANDEY, R., N. PANDEY, S. CHITRANSHI and S. K. PAUL. Operational Transresistance Amplifier Based PID Controller. *Advances in Electrical and Electronic Engineering*. 2015, vol. 13, no. 2, pp. 171–181. ISSN 1804-3119. DOI: 10.15598/aeee.v13i2.1164.

[41] PANDEY, R., S. CHITRANSHI, N. PANDEY and C. SHEKHAR. Single OTRA based PD Controllers. *International Journal of Engineering Science and Technology*. 2012, vol. 4, iss. 4, pp. 1426–1437. ISSN 2215-0986. DOI: 10.15598/aeee.v13i2.1164.

[42] GUPTA. A., R. SENANI, D. R. BHASKAR and A. K. SINGH. Single OTRA based PD Controllers. *International Scholarly Research Network Electronics*. 2013, vol. 2013, iss. 1, pp. 1–10. ISSN 2090-8679. DOI: 10.1155/2013/907597.

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