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 OTAs and five to six passive elements. To the best knowledge of the authors, any inverse filter configuration using OTAs has not been reported in the literature earlier. The effect of the major parasitics of the OTAs 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], [3], [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 (CFOAs). 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 multifunction inverse filter using three modified CFOAs, which normally required nine CFOAs. In [13], Leucinc 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 Transconductance Amplifiers (MOTAs) in operating both voltage and current-mode. In [15], Patil and Sharma have reported inverse filter realized using two CFOAs. In [16], 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 [17] have presented multifunction 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:

\[
V_o = R_m (s) (I_p - I_n) .
\]  

(1)

\[
\begin{bmatrix}
V_p \\
V_n \\
V_o
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 \\
R_m & -R_m & 0 \\
0 & 0 & I_o
\end{bmatrix} \begin{bmatrix}
I_p \\
I_n \\
I_o
\end{bmatrix} .
\]  

(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.](image)

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:

\[
\frac{V_o}{V_{in}} = \frac{Y_1 Y_3 + Y_2 Y_4}{Y_2 Y_5} .
\]  

(3)

If we choose the various 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 \( Y_5 = \frac{1}{R_5} \), the
then the resulting transfer function represents the realization of an inverse high pass filter given by:

\[
\frac{V_0}{V_{in}} = \frac{1}{s^2 + s \left( \frac{1}{C_4 R_4} + \frac{1}{C_2 C_4 R_1 R_3} \right)},
\]

for \( C_4 = C_5 \).

The various parameter values in this case are given by:

\[
\omega_0 = \sqrt{\frac{C_1 C_2 R_2 R_4}{C_1 C_2 R_3 R_4}},
\]

\[
Q = R_3 \sqrt{\frac{C_2}{C_1 C_2 R_3 R_4}},
\]

\[
(H_{O})_{ILP} = \frac{R_4}{R_5}.
\]

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 viewpoint 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:

\[
R_m(s) = \frac{R_m}{1 + \frac{R_m}{\omega_0}} = \frac{R_m \omega_0}{s + \omega_0} = \frac{1}{s \omega_0 + \frac{1}{R_m}}.
\]

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

\[
R_m \to \infty, \quad R_m(s) \cong \frac{1}{s C_p},
\]

where, \( R_m \) is the DC open-loop transresistance gain, \( \omega_0 \) 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:

\[ R_m(s) = \frac{R_o}{\left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right)}, \quad (12) \]

which can be modified and rewritten as:

\[ R_m(s) = \frac{1}{C_p\left(s + \frac{1}{C_pR_o}\right)\left(s\omega_{p2} + 1\right)}. \quad (13) \]

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

\[ R_m(s) \approx \frac{1}{sC_p}, \quad \text{where} \quad C_p = \frac{1}{R_o\omega_o}. \quad (14) \]

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:

\[ \frac{V_o}{V_{in}} = \frac{sC_pY_4 + (Y_1Y_3 + Y_2Y_4)}{s^2C_p^2 + sC_p(Y_2 + Y_3) + Y_2Y_3}. \quad (15) \]

If we choose the admittances as \( Y_1 = sC_1, Y_2 = \frac{1}{R_2}, \)

\[ Y_3 = sC_2 + \frac{1}{R_3}, Y_4 = \frac{1}{R_4} \quad \text{and} \quad Y_5 = \frac{1}{R_5}, \]

we obtain the non-ideal transfer function as:

\[ \frac{V_o}{V_{in}} = \frac{1}{s^2C_p^2 + sC_p\left(\frac{R_3}{C_1C_2R_2R_3} + \frac{1}{R_4}\right)\left(\frac{1}{C_1C_2R_2R_3}\right) + \frac{1}{C_1C_2R_2R_4}}. \quad (16) \]

Neglecting the terms involving \( s^2 \) and \( s \) (since in general, the product \( C_1C_2 \) would be much larger than \( C_p^2 \) and \( C_p \)), we can approximate the transfer function of Eq. (16) as:

\[ \frac{V_o}{V_{in}} \approx \frac{1}{s^2C_pR_3\left(1 + \frac{C_pR_3}{C_1R_4}\right) + \frac{1}{C_1C_2R_2R_4}}. \quad (17) \]

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

\[ \hat{\omega}_0 = \sqrt{\frac{1}{C_1C_2R_2R_4}}, \quad \hat{Q}_0 = Q_0\left(\frac{C_1R_4}{C_1R_4 + C_pR_3}\right), \quad (18) \]

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:

\[ \hat{Q}_0 = Q_0\left(\frac{C_1R_4}{C_1R_4 + C_pR_3}\right). \quad (19) \]

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

\[ \left(\frac{\hat{Q}_0 - Q_0}{Q_0}\right)\cdot 100 = \left(-\frac{C_pR_3}{C_pR_3 + C_1R_4}\right)\cdot 100. \quad (20) \]

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:

\[ \frac{V_o}{V_{in}} = \frac{1}{s^2 + s\left(\frac{1}{C_1R_4}\right) + \frac{1}{C_2C_4R_4R_3\left(1 + \frac{C_p}{C_2}\right)}}. \quad (21) \]

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

\[ \hat{\omega}_0 = \sqrt{\frac{1}{C_2C_4R_1R_3\left(1 + \frac{C_p}{C_2}\right)}}, \quad (22) \]

\[ BW = \frac{R_4}{R_5}, \quad \left(\hat{H}_o\right)_{IBP} = \frac{R_4}{R_5}. \]

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

\[ \hat{\omega}_0 = \sqrt{\frac{\omega_0}{1 + \frac{C_p}{C_2}}}, \quad BW = \frac{R_4}{R_5}, \quad \left(\hat{H}_o\right)_{IBP} = \left(\hat{H}_o\right)_{BP}. \quad (23) \]

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

\[ \left(\frac{\hat{\omega}_0 - \omega_0}{\omega_0}\right)\cdot 100 = \left(-\frac{C_p}{2C_2}\right)\cdot 100. \quad (24) \]
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:

\[
\frac{V_0}{V_{in}} = \frac{1}{s^2 \left[ C_2 C_5 + C_p (C_2 + C_5) + C_p^2 \right]}.
\]

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

\[
\frac{V_0}{V_{in}} \approx \frac{1}{s^2 \frac{C_5}{C_4} \left[ 1 + \frac{C_p}{C_2} \left( \frac{1}{1 + \frac{C_p}{C_5}} \right) \right] + s \frac{C_4 R_4}{1 + \frac{C_p}{C_2}} + \frac{C_2 C_4 R_1 R_3}{1 + \frac{C_p}{C_2}}}. \tag{26}
\]

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

\[
\hat{\omega}_0 = \sqrt{\frac{1}{C_2 C_4 R_1 R_3 \left( 1 + \frac{C_p}{C_2} \right)}}.
\]

\[
Q_0 = R_4 \sqrt{\frac{C_4 \left( 1 + \frac{C_p}{C_2} \right)}{C_2 R_1 R_3}}.
\]

\[
\left( \hat{H}_0 \right)_{IHP} = \frac{C_5}{C_4} \left[ 1 + \frac{C_p}{C_5} \left( \frac{1}{1 + \frac{C_p}{C_2}} \right) \right].
\]

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

\[
\hat{\omega}_0 = \frac{\omega_0}{\sqrt{\left( 1 + \frac{C_p}{C_2} \right)}}.
\]

\[
Q_0 = Q_0 \sqrt{1 + \frac{C_p}{C_2}}.
\]

\[
\left( \hat{H}_0 \right)_{IHP} = \left( H_0 \right)_{IHP} \left[ 1 + \frac{C_p}{C_5} \left( \frac{1}{1 + \frac{C_p}{C_2}} \right) \right].
\]

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

\[
\left( \frac{\hat{\omega}_0 - \omega_0}{\omega_0} \right) \cdot 100 = \left( \frac{C_p}{2C_2} \right) \cdot 100. \tag{29}
\]

% 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:

\[
\left( \frac{\hat{H}_0 - H_0}{H_0} \right) \cdot 100 = - \frac{C_2}{C_5} \left( \frac{C_p}{C_p + C_2} \right) \cdot 100. \tag{31}
\]

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 \[1\], \[2\], \[3\], \[4\], \[5\], \[6\], \[7\], \[8\], \[9\], \[10\], \[11\], \[12\], \[13\], \[14\], \[15\], \[16\] 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.

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of Active device</th>
<th>Number of Passive Component</th>
<th>Type of Inverse Filters Realized (VM/CM)</th>
<th>Grounded /Floating Capacitors</th>
<th>Tunability</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>1</td>
<td>4R, 2C</td>
<td>ILP (VM)</td>
<td>2 FC</td>
<td>No</td>
</tr>
<tr>
<td>U1</td>
<td>1</td>
<td>5R, 2C</td>
<td>ILP (VM)</td>
<td>1 GC, 1 FC</td>
<td>No</td>
</tr>
<tr>
<td>U1</td>
<td>1</td>
<td>4R, 4C</td>
<td>ILP (CM)</td>
<td>1GC, 1 FC</td>
<td>No</td>
</tr>
<tr>
<td>U1 (4 circuit)</td>
<td>2 – 4R, 2/3C</td>
<td>ILP, IHP, IBP, IAP (All CM)</td>
<td>1FC, 1/2GC</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>U5</td>
<td>3</td>
<td>4R, 2C</td>
<td>ILP, IHP, IBP, IB (VM)</td>
<td>2GC</td>
<td>Yes</td>
</tr>
<tr>
<td>U5</td>
<td>3</td>
<td>3–5R, 2C</td>
<td>ILP, IHP, IBP, IB (VM)</td>
<td>2GC</td>
<td>Yes, when R4 = R0</td>
</tr>
<tr>
<td>U5</td>
<td>2</td>
<td>2–4R, 2-4C</td>
<td>ILP, IHP, IBP, IB, IAP (VM)</td>
<td>2/4FC, 1/2 GC</td>
<td>No</td>
</tr>
<tr>
<td>U5</td>
<td>2</td>
<td>3R, 7C</td>
<td>ILP, IHP, IBP, IB (VM)</td>
<td>1GC</td>
<td>No</td>
</tr>
<tr>
<td>B9</td>
<td>1</td>
<td>1R, 1C</td>
<td>First Order IAP (CM)</td>
<td>1GC</td>
<td>No</td>
</tr>
<tr>
<td>B9</td>
<td>1</td>
<td>2R, 1C</td>
<td>First Order IAP (VM)</td>
<td>1GC</td>
<td>No</td>
</tr>
<tr>
<td>B9</td>
<td>2</td>
<td>2R, 2C</td>
<td>ILP, IHP, IBP, (All VM)</td>
<td>2GC</td>
<td>No</td>
</tr>
<tr>
<td>B9</td>
<td>2</td>
<td>2–3R, 3-4C</td>
<td>ILP, IHP, IBP (VM)</td>
<td>3/4GC</td>
<td>Yes</td>
</tr>
<tr>
<td>H1</td>
<td>10/12 OTAs</td>
<td>2C</td>
<td>ILP, IHP, IBP (VM&amp;CM)</td>
<td>2GC</td>
<td>Yes</td>
</tr>
<tr>
<td>H5</td>
<td>2</td>
<td>4–6R, 2C</td>
<td>ILP, IHP, IBP, IB (All VM)</td>
<td>1GC</td>
<td>No</td>
</tr>
<tr>
<td>H5</td>
<td>2</td>
<td>2R, 2C</td>
<td>IHP (Trans conductance)</td>
<td>1GC</td>
<td>No</td>
</tr>
<tr>
<td>H5</td>
<td>2</td>
<td>3R, 3C</td>
<td>ILP, IHP, IBPF (All CM)</td>
<td>2GC, 1PC</td>
<td>Yes</td>
</tr>
<tr>
<td>Proposed</td>
<td>2</td>
<td>4R, 2/3C</td>
<td>ILP, IHP, IBP (All VM)</td>
<td>Capacitor virtually grounded</td>
<td>Yes</td>
</tr>
</tbody>
</table>

R - Resistance, C - Capacitance, FC - Floating Capacitor, GC - Grounded Capacitor

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

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>LEVEL = 7 VERSION=6.1 TONM=27 TOX=4.1E-9 XI=1E-7 NCH=2.3549E17 VTH=0.372532</td>
</tr>
<tr>
<td></td>
<td>K1=0.593684 K2=2.050755E-3 K3=1E–3 K3B=4.511643 W0=1E–7 NXL=1.870585E–7 DTVT00=0</td>
</tr>
<tr>
<td></td>
<td>DTVT1=0 DTVT2=0 DTVT=1.3621546 DTVT1=0.38454156 DTVT2=0.05772255 U0=259.5301469</td>
</tr>
<tr>
<td></td>
<td>UA=–1.413292E–9 UB=2.220966E-18 UC=–5.259942E-11 VSAT=9.411671E0 A0=7.372867 AGS=3.740333</td>
</tr>
<tr>
<td></td>
<td>PRWB=–0.2 Wr=–1 LINT=–0.701524E–8 XL=–0 XW=–1E–8 DWG=–1.365589E–8 DWB=–1.045599E–8</td>
</tr>
<tr>
<td></td>
<td>VOFF=–0.0275456 NFACCTOR=–2.4492496 CIT=–0.01754573 E=ETAB=3.494964E–5 DSUB=0.0175288 PCLM=0.7274971 PDIBLC1=0.1886574 PDIBLC2=2.617136E–3</td>
</tr>
<tr>
<td></td>
<td>PDIBLCB–0.1 DROUT=–0.779462 PSCB1=–3.882383E10 PSCBE2=–6.841553E–10 PVAG=0.0162298</td>
</tr>
<tr>
<td></td>
<td>DELTA=0.01 RSH=–6.5 MOBMOD=–1 PTR=–0 UTE=–1.5 KTI=–0.11 KTIL=–0.5 KTI2=–0.022 UA=–3.41E–9</td>
</tr>
<tr>
<td></td>
<td>UB=–7.61E–8 UC4=–5.6E–11 AT=–3.34E4 WL=–0 WLN=–1 WW=–0 WWN=–1 WWL=–0 LNN=–1</td>
</tr>
<tr>
<td></td>
<td>LW=–1 LWL=–1 CAPMOD=–2 XPAR1=–0.5 CGDO=–8.5E–10 CGSO=–8.5E–10 CGBO=–1E–12</td>
</tr>
<tr>
<td></td>
<td>CJ=3.513993E–3 PB=–0.8 MJ=–0.3773625 CJ=1.160855E5 PBSW=0.8157101 MJSW=0.1004233</td>
</tr>
<tr>
<td></td>
<td>CJWSW=3.3E–10 PBSSW=0.8157101 MSJW=0.1004233 CF=0 PVTTH=–8.863347E4 PRDSW=–3.6877287</td>
</tr>
<tr>
<td></td>
<td>PK2=–3.730349E–4 WKETA=–6.281486E–5 LKETA=–0.0166193 P0=16.6111407 PU=6.578464E–11</td>
</tr>
<tr>
<td></td>
<td>PUB=–0 PVSAT=–1.1122433E5 PETA0=–0.029864E–4 PKETA=–2.906037E–3</td>
</tr>
<tr>
<td>PMOS</td>
<td>LEVEL = 7 VERSION=6.1 TONM=27 TOX=4.1E-9 XI=1E-7 NCH=4.1589E17 VTH=–0.948389</td>
</tr>
<tr>
<td></td>
<td>K1=0.576352 K2=–0.028926 K3=–0 K3B=13.8429595 W=–1E–6 NXL=–1.373719E–7 DTVT00=–0</td>
</tr>
<tr>
<td></td>
<td>DTVT1=–0 DTVT2=–0 DTVT=–0.5281977 DTVT1=–0.2185978 DTVT2=–0.1 U0=109.9762536 UA=1.3250755E–9</td>
</tr>
<tr>
<td></td>
<td>UB=–1.757494E–21 UC=–1E–10 VSAT=0.19101645 A0=1.7233927 AGS=3.6310342 B0=–2.336556E–7</td>
</tr>
<tr>
<td></td>
<td>B1=–5.152759E–7 KETA=–0.0217218 A1=–0.3935816 A2=–0.403131 RDSW=–2.52123939 PRWB=–0.5</td>
</tr>
<tr>
<td></td>
<td>PRWB=–0.0158894 Wr=–1 WINT=–0 LINT=–2.718137E–8 XL=–0 XW=–1E–8 DWG=–4.4366399E–8</td>
</tr>
<tr>
<td></td>
<td>DWR=–8.876273E–10 VOFF=–0.0942201 NFACCTOR=–2 CIT=–0.01754573 E=ETAB=3.494964E–5</td>
</tr>
<tr>
<td></td>
<td>ETA0=–0.1909153 DSOUB=–1.2153945 PCLM=–2.1996615 PDIBCL1=–1.2380473 E=ETAB=3.494964E–5</td>
</tr>
<tr>
<td></td>
<td>PDIBLCB–0.1 DROUT=–0.80 PSCB1=–0.3735625 CJ=2.608653E10 PBSS=0.8157101 MJSW=0.1004233</td>
</tr>
<tr>
<td></td>
<td>CJWSW=3.3E–10 PBSSW=0.8157101 PVSAT=–0.1004233 CF=0 PVTTH=–8.863347E4 PRDSW=–3.6877287</td>
</tr>
<tr>
<td></td>
<td>PK2=–3.730349E–4 WKETA=–6.281486E–5 LKETA=–0.0166193 P0=16.6111407 PU=6.578464E–11</td>
</tr>
<tr>
<td></td>
<td>PUB=–0 PVSAT=–1.1122433E5 PETA0=–0.029864E–4 PKETA=–2.906037E–3</td>
</tr>
</tbody>
</table>
The magnitude of percentage errors in the various filter parameters have been calculated for the component values as taken for SPICE simulations as $C_1 = C_2 = C_4 = C_5 = 100 \, \text{pF}, R_1 = R_2 = R_3 = R_4 = R_5 = 10 \, \text{k}\Omega$ and $C_p = 0.4 \, \text{pF}$. 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.

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

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

7. Conclusion

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

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