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Voltage-mode high-Q band-pass filters and oscillators employing single CDBA and minimum number of components

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In this paper, voltage-mode second order high-Q band pass filters and oscillators which employ only single current differencing buffered amplifier (CDBA) as the active component are proposed. One of the four filter circuits and two of the four oscillators described have minimum passive component count properties, without using the internal pole of the active element. These BP filters can be easily cascaded without any recourse to impedance matching circuitry. The circuits have been analysed theoretically, simulated and experimentally tested in a laboratory. It is shown that the results of simulations and experimental work are in agreement with theoretical predictions.

Keywords: Voltage-mode circuits; Band pass filters; Oscillators; CDBA

1. Introduction

Current mode universal active elements have two distinct advantages; they provide wide bandwidths and high slew rates. On the other hand, many of today's analog signal processing applications require voltage mode operation. Therefore, it is advantageous to implement current mode active elements in voltage mode circuits.

Minimum passive component oscillators are receiving considerable attention in literature. Studies of this kind, using non-inverting second generation current conveyor (CCII+) (Abuelma'atti and Humood 1987), operational transconductance amplifier (OTA) (Senani and Banerjee 1989), operational transresistance amplifier, (OTRA) (Salama and Soliman 2000), current feedback amplifier (CFA) (Martinez *et al*. 1996, Soliman 1997), current and voltage followers (Soliman 1998) as active elements were reported.

On the other hand, the current differencing buffered amplifier (CDBA), is one of the current mode (CM) active elements that received much interest in recent years (Acar and Özoğuz 1999, Özcan *et al*. 2000, Tangsrirat *et al*. 2003, Acar and Sedef 2003). It is proven that the CDBA is a new, versatile, commercially implementable active building block for voltage (VM) and current mode (CM) signal processing applications.

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This paper presents single CDBA-based voltage mode band-pass filters (BPF) having minimum number of components, as well as high *Q*-factor. A catalogue of BPFs having second order voltage transfer functions (VTFs) using single CDBA as the active element is also given. Minimum component CDBA-based oscillator circuits are obtained by slight modification of the high-*Q* BPF circuit. Performance of the circuits are analysed using circuit simulation techniques and laboratory experiments.

2. CDBA

CDBA circuit symbol is shown in figure 1 and non-ideal terminal relationships can be described

$$\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & \alpha_p & -\alpha_n \\ \gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix}, \tag{1}$$

where α_p, α_n and γ are current and voltage gains, respectively, and $\alpha_p = 1 - \varepsilon_p$, $\alpha_n = 1 - \varepsilon_n$, $\gamma = 1 - \varepsilon_v$. Here, ε_p, ε_n are current tracking errors and ε_v is the voltage tracking error, absolute values of all last three terms being much less than unit value.

Here, current through *z*-terminal follows the difference of the currents through *p*-terminal and *n*-terminal. Input terminals *p* and *n* are internally grounded. The difference of the input currents are converted into the output voltage v_w through the impedance connected externally to terminal *z*.

3. Voltage mode, second order CDBA-based BPFs

Sedef and Acar (2000) proposed a configuration suitable for VM filters using a single CDBA in contrast to another circuit (Acar and Özoğuz 1999) that requires $(n+1)$ CDBAs for the realization of an *n*th order voltage transfer function (VTF). This single CDBA-based method uses the RC–RC decomposition technique (Lam 1979) resulting in a non-canonical realization of the VTF, and reducing the effects of current and voltage tracking errors on filter performances. Figure 2 shows the circuit

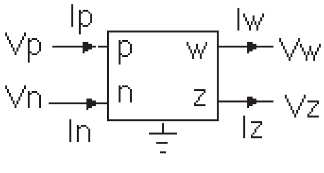


Figure 1. CDBA symbol.

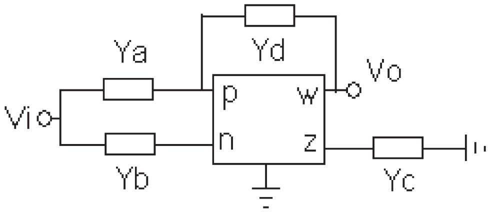


Figure 2. Realization of $H(s) = V_o(s)/V_i(s)$ using CDBA.

to realize the VTF

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{Y_a - Y_b}{Y_c - Y_d} = \frac{Y_b - Y_a}{Y_d - Y_c}, \tag{2}$$

where Y_a, Y_b, Y_c and Y_d are positive real admittance functions of passive two terminal elements; one of their terminals is either grounded or internally grounded.

Considering non-ideal CDBA, one can modify (2) as

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{\gamma(\alpha_p Y_a - \alpha_n Y_b)}{Y_c - \gamma\alpha_p Y_d}. \tag{3}$$

Since numerator and denumerator polynomials of the VTF are derived by cancellation of terms in RC–RC decomposition techniques, component sensitivities may be high with respect to the parameters of active elements, particularly for narrow band filters. Therefore, it is essential to keep the circuit component count at minimum.

Let the CDBA-based VM circuits be confined to biquadratic (second order) form

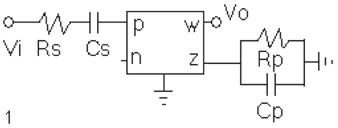
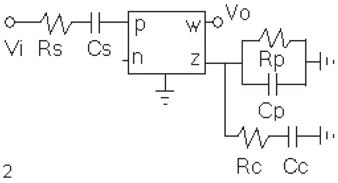
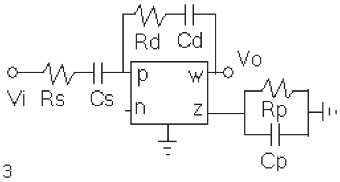
$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{a_2 s^2 + a_1 s + a_0}{b_2 s + b_1 s + b_0}. \tag{4}$$

Using only series and parallel RC admittances, Y_s and Y_p, a list of possible second order BPFs employing single CDBA are given in table 1. By changing the signal injection terminal from p to z terminal of the CDBA, a minimum component, VM, single CDBA-based BPF circuit can be obtained as shown in figure 3. The voltage transfer function of this new circuit is

$$H(s) = \frac{\gamma\alpha_p R_p C_s s}{R_p C_p R_s C_s s^2 + (R_p C_p + R_s C_s - \gamma\alpha_p R_p C_s)s + 1} \tag{5}$$

which shows that the circuit performs as a high-Q, BPF. It has canonic form with minimum component count. The pass band center frequency, quality factor and the

Table 1. Second order single CDBA-based BPF circuits and their voltage transfer functions (All voltages are referenced to ground).

BPF circuit	Voltage transfer function $= H(s) = V_o(s)/V_i(s)$
	$\dfrac{\gamma\alpha_p R_p C_s s}{R_p C_p R_s C_s s^2 + (R_p C_p + R_s C_s)s + 1}$
	$\dfrac{\gamma\alpha_p R_p C_s s}{R_p C_p R_s C_s s^2 + (R_p C_p + R_s C_s + R_p C_s)s + 1}$ $R_s = R_c, \quad C_s = C_c$
	$\dfrac{\gamma\alpha_p R_p C_s s}{R_p C_p R_s C_s s^2 + (R_p C_p + R_s C_s - \gamma\alpha_p R_p C_s)s + 1}$ $R_s = R_d, \quad C_s = C_d$

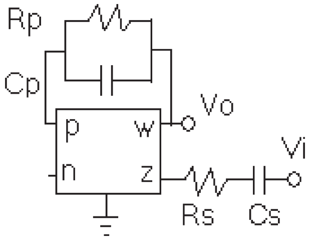


Figure 3. CDBA-based, High-Q, second order minimum component voltage mode BPF.

component sensitivities of the circuit are

$$\omega_o^2 = \frac{1}{R_p R_s C_p C_s} \tag{6}$$

$$Q = \frac{\sqrt{R_p C_p R_s C_s}}{R_p C_p + R_s C_s - \gamma\alpha_p R_p C_s} \tag{7}$$

$$S_{Cp}^{\omega_0} = S_{Cs}^{\omega_0} = S_{Rp}^{\omega_0} = S_{Rs}^{\omega_0} = -1/2 \tag{8}$$

$$S_{Rp}^{Q} = -S_{Rs}^{Q} = -\frac{1}{2} \cdot \frac{-R_p C_p + R_s C_s + \gamma\alpha_p R_p C_s}{-R_p C_p - R_s C_s + \gamma\alpha_p R_p C_s} \tag{9}$$

$$S_{Cp}^{Q} = -S_{Cs}^{Q} = \frac{1}{2} \cdot \frac{R_p C_p - R_s C_s + \gamma\alpha_p R_p C_s}{-R_p C_p - R_s C_s + \gamma\alpha_p R_p C_s}, \tag{10}$$

respectively.

4. Minimum component CDBA oscillators

Four oscillators can be designed using the circuits listed in table 1, and figure 3. The circuit 3 of table 1 can be converted to an oscillator by short circuiting its input signal terminal to ground. A second configuration can be obtained using the same circuit and by changing its series RC input branch into parallel RC circuit and then grounding its input. However, these two circuits are not of minimum component type.

Two minimum component oscillator circuits are obtained from the BPF configuration shown in figure 3. One of these oscillators results if the input terminal of the BPF in figure 3 is shorted to the ground, as shown in figure 4(a). An alternative minimum component oscillator structure is obtained if one swaps the series RC input branch connected to *z* terminal of the CDBA by the parallel RC branch, and then short it to the ground, as shown in 4(b).

The characteristic equation (CE) of the minimum component oscillator circuit of figure 4(a) is

$$(R_pC_pR_sC_s)s^2 + (R_pC_p + R_sC_s - R_pC_s)s + 1 = 0. \tag{11}$$

The frequency of oscillations (FO), condition of oscillations (CO), and the component sensitivities are

$$\omega_o^2 = \frac{1}{R_pR_sC_pC_s} \tag{12}$$

$$R_pC_p + R_sC_s = R_pC_s \tag{13}$$

$$S^{\omega_0}_{Cp} = S^{\omega_0}_{Cs} = S^{\omega_0}_{Rp} = S^{\omega_0}_{Rs} = -\tfrac{1}{2}, \tag{14}$$

respectively. Since CDBA tracking errors influence the CO in the non-ideal case, equation (11) is modified as

$$R_pC_p + R_sC_s = \gamma\alpha_pR_pC_s. \tag{15}$$

While equations for the frequency of oscillations and component sensitivities of the oscillator shown in figure 4(b) are the same as those given for the circuit of figure 4(a),

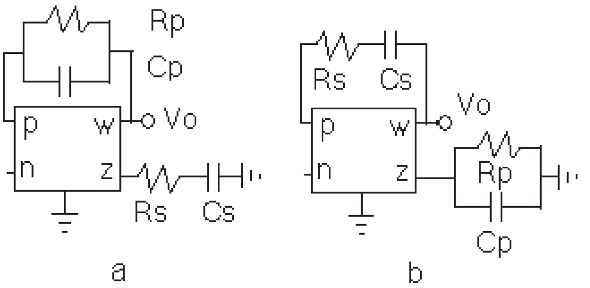


Figure 4. (a), (b) Minimum component oscillator configurations using the CDBA.

its ideal CO is

$$R_pC_p + R_sC_s = R_sC_p \tag{16}$$

which is modified in non-ideal case to

$$R_pC_p + R_sC_s = \gamma\alpha_p R_sC_p. \tag{17}$$

As is the case with all minimum component oscillators, FO and CO are not independently controlled. An advantage of CDBA–based oscillators compared to those based on most other current mode active counterparts arises from the fact that input parasitic capacitances do not exist in CDBA, since its input terminals are internally grounded.

5. Experimental results

In order to verify the above given theoretical analysis, all of the circuits introduced in this study have been tested experimentally in the laboratory, in addition to the SPICE circuit simulations.

The BPF and oscillator circuits were designed with an ideal center frequency of $f_o = 795.8$ Hz, by selecting $C_P = 0.01\,\mu\text{F}$, $C_S = 0.02\,\mu\text{F}$, $R_S = 10\,\text{k}\Omega$, $R_P = 20\,\text{k}\Omega$. In the first part of analysis, circuit simulations were performed using a CFA equivalent circuit of CDBA (Acar and Özoğuz 1999, 2000), as shown in figure 5. A SPICE macromodel of AD 844 IC CFA (supplied by Analog Devices Inc.) was employed during circuit simulations. The performances of the circuits have also been verified by using CDBA circuit models (Toker *et al.* 2000). In the second part, the circuits were set up and tested in the laboratory using the CDBA model given in figure 5. The simulated and experimental voltage gain and phase responses of the filter in figure 3 is displayed in figure 6. In the minimum component oscillator experiment, measured frequency of oscillation was 794 Hz, as shown in figure 7. This is the same value for the center frequency of BPF, the quality factor of which has been measured about $Q = 66$ at the resonance frequency gain of 43 dB. Deviations from theory mainly

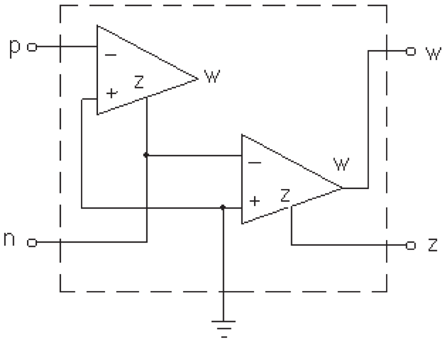


Figure 5. CFA-based CDBA equivalent circuit used during simulations and experiments in this study.

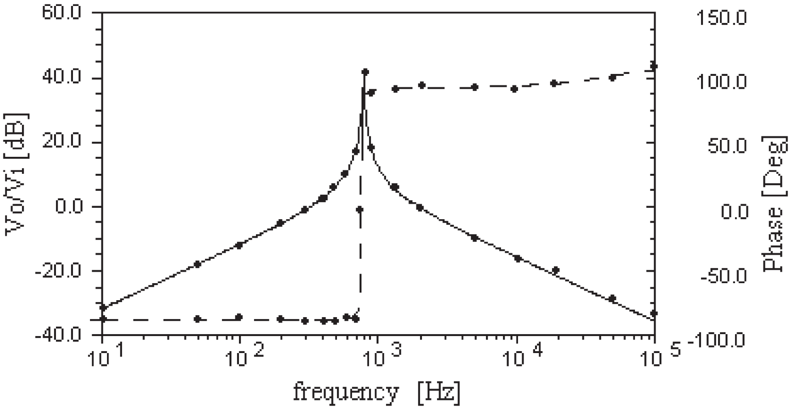
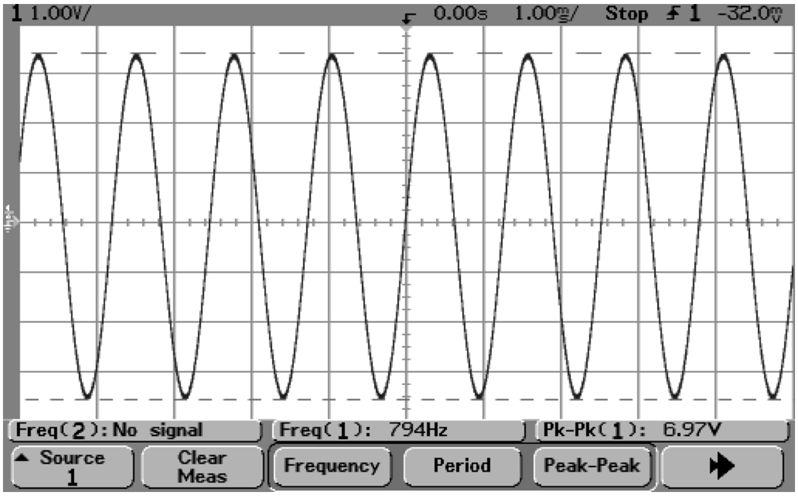


Figure 6. Magnitude and phase response curves for the minimum component BPF circuit in figure 3. The dots indicate the results obtained in laboratory measurements using CFA(=AD 844 IC) equivalent of the CDBA. Dashed line represents the phase response. Here, $C_s = 10\,\mathrm{nF}$, $C_p = 20\,\mathrm{nF}$, $R_p = 20\,\mathrm{k\Omega}$, $R_s = 10\,\mathrm{k\Omega}$, f_o (measured) $= 794\,\mathrm{Hz}$, f_o(theory) $= 795.8\,\mathrm{Hz}$. (Components with 1% tolerances are used).


1 1.00V/ 0.00s 1.00ms/ Stop 1 -32.0mV

Freq(2): No signal Freq(1): 794Hz Pk-Pk(1): 6.97V

Figure 7. Oscilloscope screen showing the sinusoidal signal produced at the output of minimum component CDBA oscillator shown in figure 4(b) Measured frequency is 794 Hz, with $C_s = 10\,\mathrm{nF}$, $C_p = 20\,\mathrm{nF}$, $R_p = 20\,\mathrm{k\Omega}$, $R_s = 10\,\mathrm{k\Omega}$.

originate from passive component tolerances (=1%) used throughout laboratory tests. Results are well in agreement with theoretical predictions.

6. Discussion and conclusion

An interesting observation is that, being a special case, *n* terminal of the CDBA is neither employed in second order band pass voltage transfer function realization nor in the minimum component oscillator configurations. This terminal is essential for all other types of voltage mode CDBA-based filter designs, as well as for higher order BPF realizations. It is also possible to design BPFs and oscillators described in this study in fully integrated MOS-C structure, using the CDBA and non-linearity cancellation methods in MOS transistors, since CDBA offers two virtually grounded terminals for the implementation of current subtraction operation required in MOS resistive circuits (Czarnul 1986, Tagaki *et al*. 1997).

In this study, a catalogue of single CDBA-based voltage mode second order high-Q BP filter configurations as shown in table 1 and figure 3, are given. Four oscillator circuits are described. The filter circuits displayed in table 1 are designed in accordance with the theory of Sedef and Acar (2000). Because it is based upon RC–RC decomposition technique which is prone to higher passive component sensitivities, a considerable improvement can be done by limiting filter design to minimum component type structures. Therefore, a BPF circuit shown in figure 3, and two minimum component type oscillators (shown in figure 4(a), 4(b)), without using the internal pole of the active element, are introduced in this study. Note that proposed minimum component BPF differs from those BPFs shown in table 1, as the input signal is injected into the circuit through z terminal of the CDBA and it is canonic in form. Moreover the BPFs are cascadable because of the very low output impedance of the (w) terminal associated with CDBA. Simulation and experimental results are in agreement with theoretical predictions.

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