New Advances and Possibilities in Active Circuit Design

H. Hakan KUNTMAN
Istanbul Technical University, Faculty of Electrical and Electronics Engineering,
34469, Maslak, Istanbul, TURKEY
kuntman@itu.edu.tr

***Abstract* —Operational amplifiers are important building blocks for analog circuit design. Unfortunately, their limited performance such as bandwidth, slew-rate etc. leads the analog designer to search other possibilites and other building blocks. As a result, new current-mode active building blocks such as operational transconductance amplifiers (OTA), second generation current conveyors (CCII), current-feedback op-amps (CFOA), four terminal floating nullors (FTFN), differential voltage current conveyor (DVCC), differential difference current conveyor (DDCC), third-generation current-conveyor (CCIII), dual X current conveyors (DXCCII), current controlled current conveyors (CCCII) etc. received considerable attention due to their larger dynamic range and wider bandwidth. Employing these new active elements for analog design and using CMOS technology for implementation the circuit designers obtained new possibilites to solve their problems. This work covers new advances and possibilities in the related research area including application on communication, measurement and RF systems.**

***Index Terms* — Analog integrated circuits, Analog processing circuits, Circuit simulation, Circuit synthesis, CMOS analog integrated circuits**

I. INTRODUCTION

Digital signal processing is becoming increasingly more powerful while advances in IC technology provides compact efficient implementation of these algorithms in silicon. Although many types of signal processing have indeed moved to digital domain, analog circuits are fundementally necessary in many of today's complex, high performance systems. This is caused by the reality that naturally occuring signals are analog. Therefore analog circuits act as a bridge between the real world and digital systems [1-4].

At the beginning, operational amplifiers were the unavoided building blocks for analog circuit design. Unfortunately, their limited performance such as bandwidth, slew-rate etc. leads the analog designer to search other possibilites and other building blocks. As a result, new current-mode active building blocks such as operational transconductance amplifiers (OTA), second generation current conveyors (CCII), current-feedback op-amps (CFOA), four terminal floating nullors (FTFN), differential voltage current conveyor (DVCC), differential difference current conveyor (DDCC), third-generation current-conveyor (CCIII), dual X current conveyors (DXCCII), current controlled current conveyors (CCCII) etc. received considerable attention due to their larger dynamic range and wider bandwidth. Employing these new active elements for analog design and using CMOS technology for implementation the circuit designers obtained new possibilites to solve their problems[5-56]. This work covers new advances and possibilities in the related research area including application on communication, measurement and RF systems.

II. OTHER TYPE ACTIVE ELEMENTS FOR ANALOG IC DESIGN

Basic amplifier types suitable for analog IC design are shown in TABLE I. Other type active elements are given with their symbols and definition equations in TABLE II.

TABLE I. BASIC ACTIVE ELEMENTS

Class	Gain Function	Operational Property	Name
V-V	$Vo = Av.(V_1-V_2)$	$Av\to\infty$	Operational Amplifier
V-I	$Io = Gm.(V_1-V_2)$	-	Operational Trans-conductance Amplifier
I-I	$Io = Ai.(I_1-I_2)$	$Ai\to\infty$	Current Operational Amplifier
I-V	$Vo = Rm.(I_1-I_2)$	-	Operational Trans-resistance Amplifier

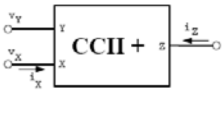
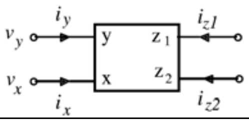
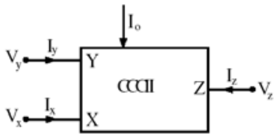
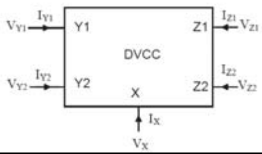
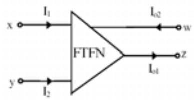
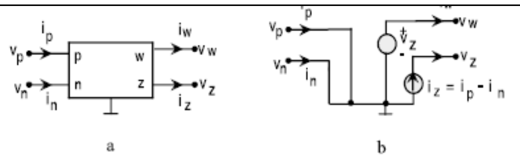
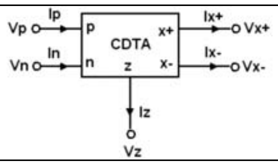
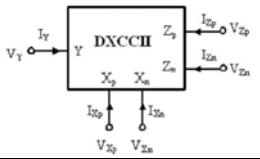
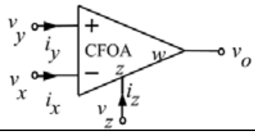
III. CURRENT-MODE OPERATION

Current mode circuits have received considerable attention due to their potential advantages, such as their inherently wide bandwidth, higher slew-rate, greater linearity, wider dynamic range, simple circuitry and low power consumption [57]. The active devices that have been used to realise current-mode circuits include current conveyors (CCIIs), current feedback op-amps (CFOAs), operational transconductance amplifiers (OTAs) and four-terminal floating nullors (FTFNs).

IV. OTA: OPERATIONAL TRANSCONDUCTANCE AMPLIFIER

OTA-C structures have attracted considerable attention in recent years because they offer several advantages over conventional op-amp based circuits as well as providing the evaluation of fully integrated circuits in VLSI design with CMOS technology. It is well-known that OTAs provide highly linear electronic tunability of their transconductance (gin) and require just a few or even no resistors for their

TABLE II. OTHER POPULAR ACTIVE ELEMENTS

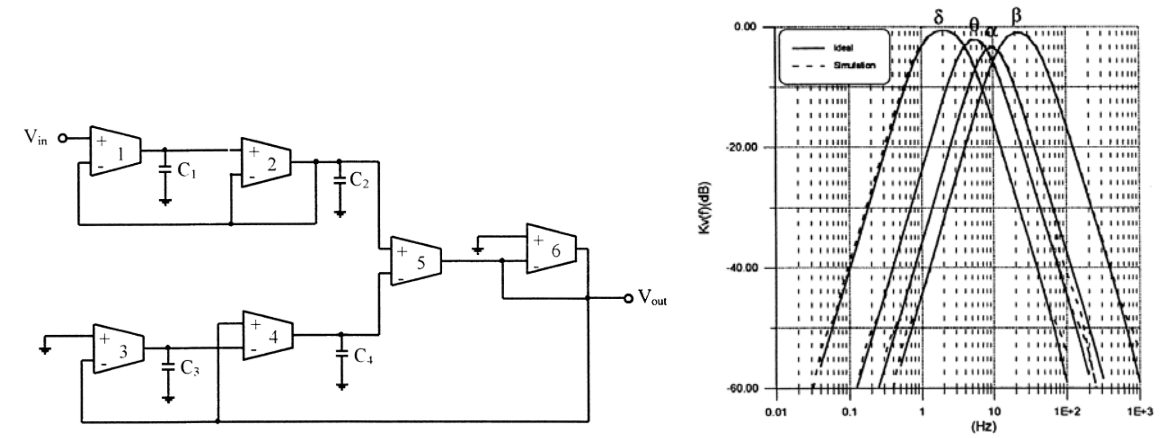
Name	Symbol	Definition Equations
CC Current Conveyor		$i_y = a \cdot i_x$ $V_x = V_y$ $i_z = \pm i_x$
DOCCII Dual Output Current Conveyor Second Generation		$\begin{bmatrix} v_x \\ i_y \\ i_{z1} \\ i_{z2} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ \pm1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_x \\ v_y \\ v_{z1} \\ v_{z2} \end{bmatrix}$
CCCII Current Controlled Current Conveyor		$\begin{bmatrix} I_y \\ V_x \\ I_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & R_x & 0 \\ 0 & \pm1 & 0 \end{bmatrix} \begin{bmatrix} V_y \\ I_x \\ V_z \end{bmatrix}, \quad R_x = \frac{V_T}{2I_o}$
DVCCII Differential Voltage Current Conveyor		$\begin{bmatrix} V_X \\ I_{Y1} \\ I_{Y2} \\ I_{Z1} \\ I_{Z2} \end{bmatrix} = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_X \\ V_{Y1} \\ V_{Y2} \\ V_{Z1} \\ V_{Z2} \end{bmatrix}.$
FTFN Four Terminal Nullor		$I_1 = I_2 = 0 \qquad I_{o1} = I_{o2} \qquad V_x = V_y$
CDBA Current differencing Buffered amplifier	 **Fig. 1.** a) Circuit symbol of CDBA. b) Equivalent circuit of CDBA.	$\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix} \quad (1)$
CDTA Current differencing Transconductance amplifier		$V_p = V_n = 0$ $I_z = \alpha_p I_p - \alpha_n I_n$ $I_{x+} = gV_z$ $I_{x-} = -gV_z$
DXCCII dual X second generation current conveyors		$V_{Xp} = \beta_1 V_Y, \quad V_{Xn} = -\beta_2 V_Y, \quad I_Y = 0,$ $I_{Zn} = \alpha_n I_{Xn}, \quad I_{Zp} = \alpha_p I_{Xp},$
CFOA Current feedback operational amplifier		$\begin{bmatrix} i_y \\ v_x \\ i_z \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}$

internal circuitry and have more reliable high frequency performance because of the current mode operation which has been established as art important topic in analogue signal processing owing to ils advantage over the voltage mode, particularly for higher frequency of operation. Because of these features, the OTAs are increasingly replacing operational amplifiers and in the past few years, a number of OTA-C based filters and oscillators have been reported [5,7,9,12,50,53].

The rapid increasing use of battery-operated portable equipment in application areas such as telecommunications and medical electronics imposes the use of low-power and small-sized circuits realized with VLSI (very large scale integrated) technologies. CMOS (complementary metal–oxide semiconductor) circuits operating in the subthrehold (weak inversion) region introduce a versatile solution for the realization of low-power VLSI building blocks [12]. Circuits needed for processing of biological signals are a typical and good example of low-power and small-sized building blocks. The main features of biological signals are their low amplitude and low frequency range.

The human electroencephalogram (EEG), which provides a rich picture of the electrical activities of the brain, is one of the most important biological signals [58]. The voltage amplitudes of EEG signals range from about 1–100 mV peak-to-peak at low frequencies (0.5–100 Hz) at the cranial surface.

It is possible to realize low-frequency OTA-C active filters with small capacitance values of the order of 25–400 pF. The circuit technique described is applied to the α (8–12 Hz), β (13–40 Hz), θ (4–8 Hz) and δ (1–4 Hz) band filters for EEG signals. Because of small capacitance values the filter circuit is suitable for realization on a single VLSI chip using the CMOS technology, and enables the user to implement the circuit on implantable biotelemetric applications.



Capacitance values for the α, β, θ and δ bands of the EEG signal

Band	f_{P1} (Hz)	f_{P2} (Hz)	C_1 (pF)	C_2 (pF)	C_3 (pF)	C_4 (pF)	I_B (nA)	G_{mi} (nA/V)
α	12	8	166	81	250	122	0.69	8.8
β	40	13	81	40	250	122	1.125	14.3
θ	8	4	125	61	250	122	0.347	4.4
δ	4	1	62.55	30.6	250	122	0.1	1.1

Figure 1. Fourth order OTA-C based EEG filter, frequency responses, capacitance values, biasing currents and OTA transconductance [12].

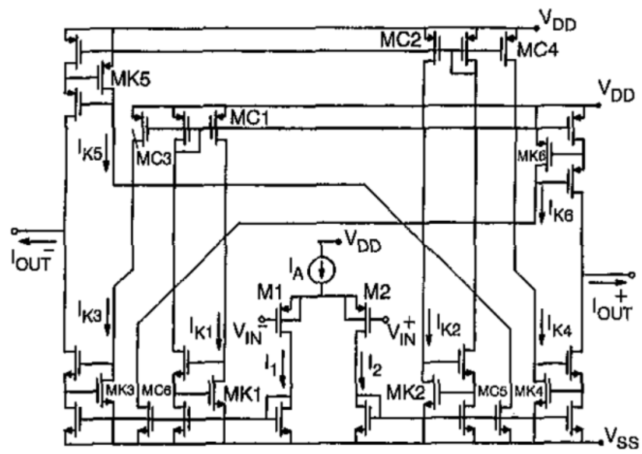


Figure 2. High-performance CMOS OTA realization [14].

The filter chip is fabricated in Turkish Scientific and Technological Council (TUBITAK) YITAL laboratory. Realized filter topology, filter frequency responses, capacitance values, biasing currents and OTA transconductances are shown in Fig.1.

A high performance CMOS dual output OTA realization providing high output impedance values is given in Fig.2.

V. FTFN: FOUR TERMINAL FLOATING NULLOR

It was demonstrated recently that the FTFN is a more general and flexible building block compared to the active elements mentioned above. This has led to a growing interest in the design of amplifiers, gyrators, inductance simulators, oscillators and current mode filters which use FTFN as the active element [16, 19-21, 24, 59–63, 81]. It is more suitable to exploit FTFN as an active element in current-mode circuit design since it has been shown that an FTFN is the most flexible and versatile building block in active network synthesis [16, 32, 38]. Examples of CMOS FTFN realization are shown in Fig.3. It is also possible to realize FTFN based nonlinear circuits to replace opamp-based nonlinear structures. A good example from chaotic communication is the following inductorless realization of Chua's circuit using a FTFN- based nonlinear resistor and a FTFN- based inductance simulator illustrated in Fig.4 [32,38].

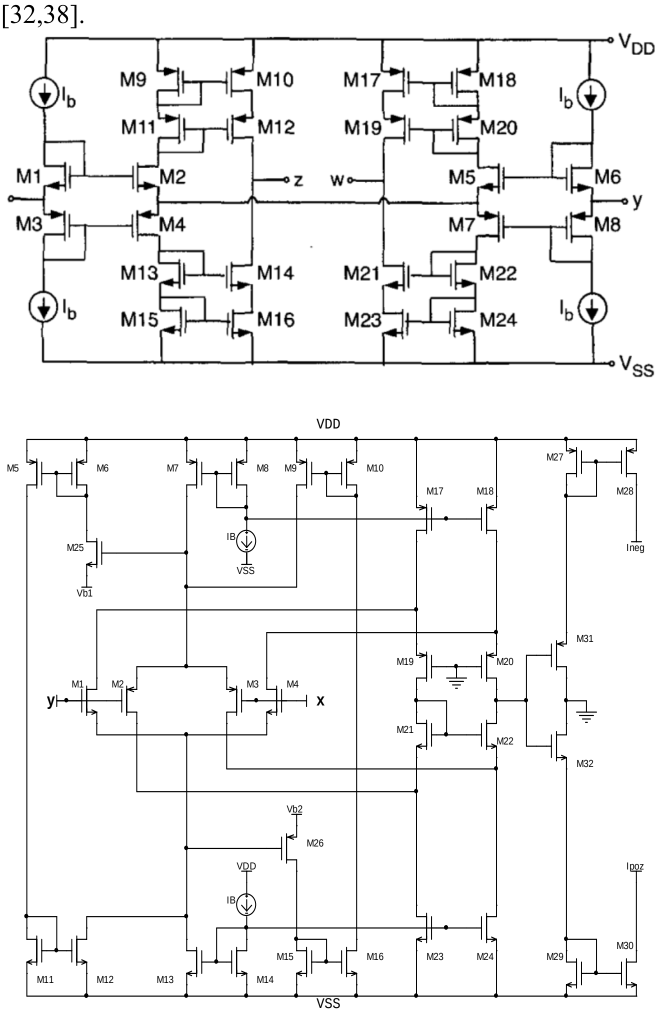


Figure 3. Examples of CMOS FTFN realization [16,32,38,81].

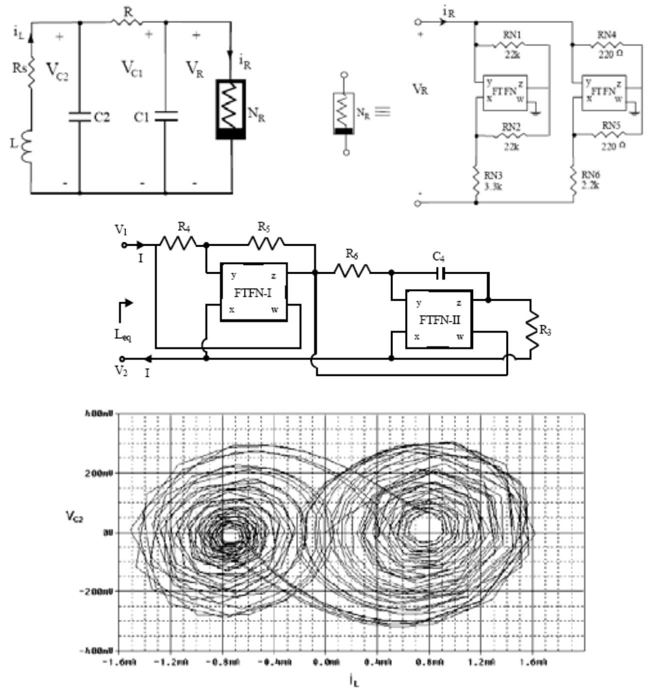


Figure 4. FTFN based realization of Chua's circuit. FTFN realization of nonlinear resistor and inductor, simulation result [38].

The CMOS implementation of Chua's circuit using FTFN based circuit topologies for inductance simulator and Chua's diode provides new possibilities to the designer for the integrated circuit realization of chaotic communication systems.

VI. OTRA: OPERATIONAL TRANSRESISTANCE AMPLIFIER

The growing demand for mobile communications has led to high level of chip integration and directed research towards the field of high frequency applications. In the new designed circuit topologies for high frequencies, current-mode approach is preferred rather than the traditional voltage-mode structures. OTRA (Operational Trans-resistance Amplifer), which is commercially available under the name of Norton amplifier has been attracted attention by its advantages in the current-mode circuit design [35,44,64]. Low input and output impedances, a bandwidth independent of the device gain can be considered the main advantageous properties of the OTRA. These commercial realizations don't provide a true virtual ground at the input terminals and they allow the input current to flow in one direction only. In order to remove these disadvantages of the OTRA, some topologies are proposed in the literature [3-8]. But these solutions are both complex structures and do not operate properly at low power supplies like 1.2V if they are realized with sub-micron technologies.

A CMOS realization example of the OTRA is illustrated in Fig. 5.

In todays technology, circuits which use power supplies as 1V, and fabricated in the CMOS 0.09 μm technology can be designed and the process improvement works on the CMOS 65 nm technology with a power supply of 0.9V are still going on. Also CMOS 45 nm technology is available with a power supply of 0.6V.

So for the future design concept the main interest is designing circuitries with low power supplies. This demand leads designing a high performance CMOS differential OTRA for the current-mode analog systems design. For these reasons, using the STMicroelectronics CMOS 0.13 μm technology, a differential OTRA is designed for 1.2V power supply. This new CMOS differential OTRA topology is characterized by the CADENCE simulation tool and the characteristic results showing its high performance are given. A filter design example is given in Fig.6.

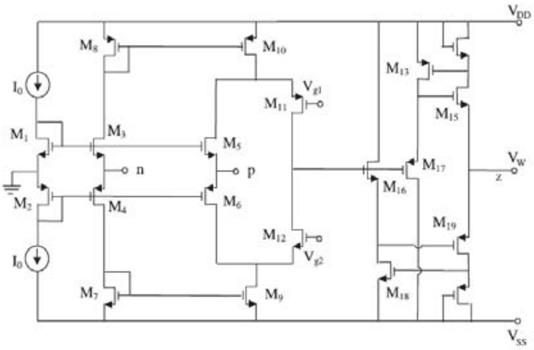


Figure 5. A CMOS implementation of the OTRA [36].

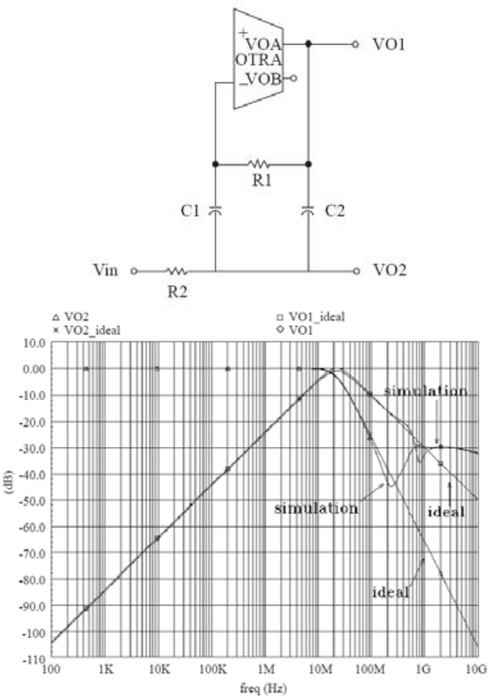


Figure 6. The band pass and low pass filters with OTRA and their frequency responses.

Low pass and band pass filters with single CMOS differential OTRA structures are tested with simulations to verify the theoretical results.

VII. CFOA: CURRENT-FEEDBACK AMPLIFIER

The conventional operational amplifiers were successfully used over the years for the design of analogue signal processing circuits. The maximum operation frequency of operational amplifier based circuits is determined primarily by the limited gain-bandwidth product and by the slew-rate of the operational amplifier. Since their introduction in 1985 the popularity of current feedback amplifiers has increased considerably as they were found to be able to overcome the limitations arising from conventional operational amplifiers [65–67]. A current feedback amplifier is equivalent to a plus-type second-generation current conveyor with a voltage buffer, as illustrated in Fig.7. The term current-feedback is used because the error signal entering at the feedback node of the op-amp is in the form of a current and this gives to the amplifier a constant closed loop bandwidth capability [68]. Ideally, the bandwidth of the current-feedback op-amp is independent of the closed loop gain. Therefore the closed loop gain-bandwidth product increases linearly with the closed loop gain. This is a major advantage over the voltage-feedback op-amp architecture, which exhibits a constant GBW [69].

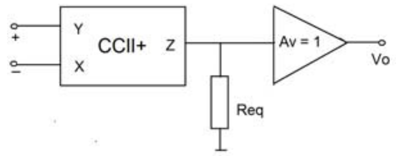


Figure 7. Realization of CFOA employing CCII+ and a voltage buffer.

Since the current feedback operational amplifier (CFOA) has a larger bandwidth and a higher slew-rate than the conventional operational amplifier, analogue signal processing circuits built around the CFOA are expected to operate at higher frequencies than the op-amp based circuits [68].

The current feedback amplifiers are gaining popularity as alternative building blocks for analogue signal processing because of offering the following advantages over the conventional opamps:

(i) wide bandwidth which is relatively independent of the closed-loop gain

(ii) very high slew-rate

(iii) simplicity of realization of various functions with the least possible number of external passive components.

Consequently, there is a growing interest employing CFOAs for the realization of active filters, immittance simulators, single frequency as well as single element controlled variable frequency sinusoidal oscillators and single/multiphase oscillators using CFOA pole.

Recently, several current conveyor based and CFOA based [33,70–72] oscillators are proposed in the literature. The CFOA based topologies offer the following advantage comparing to the current conveyor based circuits. As mentioned above the CFOA has an additional low impedance terminal, which buffers the z terminal of the current conveyor with a unity-gain, thus CFOA based oscillators exhibit low impedance voltage-mode output. CFOA based oscillator circuits are illustrated in Fig.8.

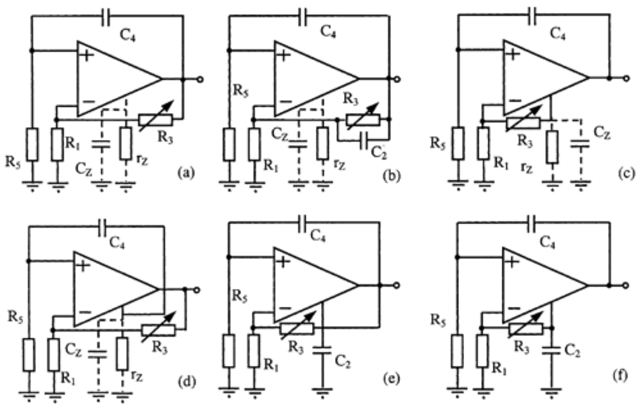


Figure 8. CFOA based oscillator circuits [33].

VIII. CURRENT CONVEYOR AND ITS DERIVATIVES, CCII, DO-CCII, DVCCII, CCCII, DXCCII

CCII, DO-CCII: The current conveyor is a versatile active element where the current is conveyed between ports at different impedance levels. As an active element it offers several advantages, such as greater linearity and wider bandwidth over the voltage mode counterparts, op-amps [73,74]. Current conveyors find application covering a broad area ranging from filter, oscillator and immittance simulator design to integrators and differentiators. there is growing interest in designing current-mode current conveyor (CC)-based active filters. A current-mode filter theoretically should exhibit high output impedance to enable easy cascadability and to enable additional filter responses by simply connecting the outputs. A current-mode second-order general filter topology employing dual output current conveyors is given in Fig. 9 [28].

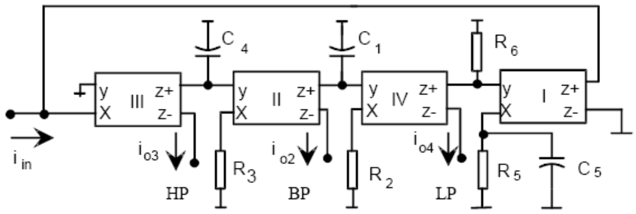


Figure 9. current-mode second-order general filter topology employing dual output current conveyors [28].

CCCII: By using the second generation current controlled conveyor (CCCII) introduced by Fabre *et al.* in 1995 [75], current conveyor applications can be extended to the domain of electronically adjustable functions. Electronic adjustability of the CCCII is attributed to the dependence of the parasitic resistance at port *x* on the bias current of the current conveyor. Therefore in the recent past, there has been great emphasis on the design of current-mode circuits using current controlled conveyors. A BP filter example and its frequency response are given in Fig.10 [23].

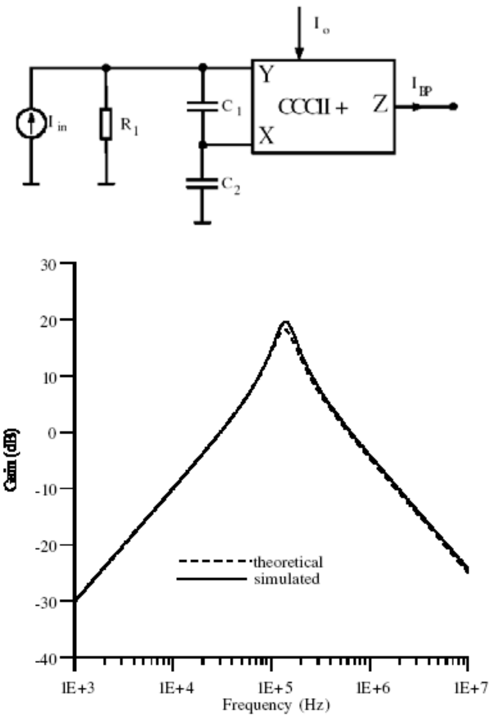


Figure 10. CCCII based filter and its frequency response [23].

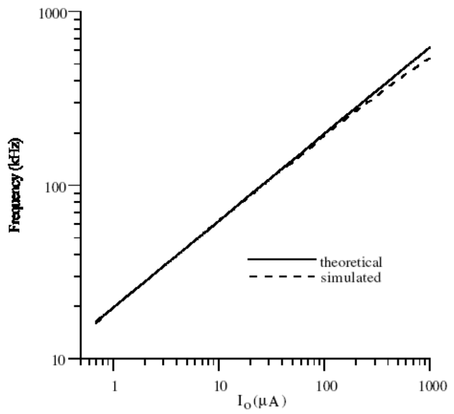


Figure 11. Tuning range of CCCII based filter [23].

DVCC: The differential voltage current conveyor DVCC was proposed first by Pal as a modified current conveyor [76] and then developed and realized in CMOS technology by Elwan and Soliman [77]. The DVCC has the advantages of both of the second generation current conveyor (CCII) (such as large signal bandwidth, great linearity, wide dynamic range) and the differential difference amplifier (DDA) (such as high input impedance and arithmetic operation capability) [77]. This element is a versatile building block for applications demanding floating inputs. A CMOS realization of the DVCC, filter design example and the filter response are shown in Fig.12 [40].

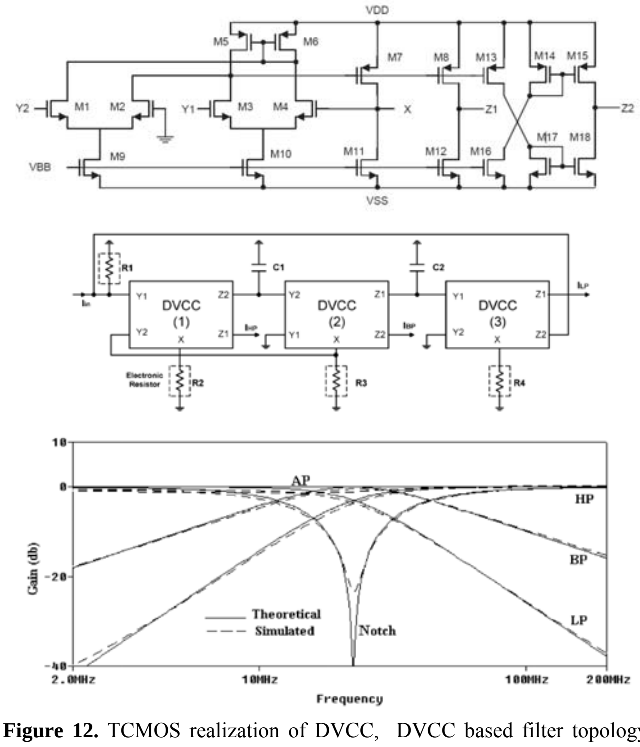


Figure 12. TCMOS realization of DVCC, DVCC based filter topology, frequency response [40].

DXCC: The dual X current conveyor DXCCII is conceptually a combination of the regular CCII and the inverting current conveyor (ICCII)[78]. It has two *X* terminals, namely *Xp* (non-inverting *X* terminal) and *Xn* (inverting *X* terminal). The *Xp* and *Xn* terminal currents are reflected to the respective Z terminals, namely *Zp* and *Zn*. It is worth emphasizing that, for this device, there is no direct relation between the *Zp* and *Zn* terminal currents. CMOS implementation examples of DXCC are illustrated in Fig.13 [47].

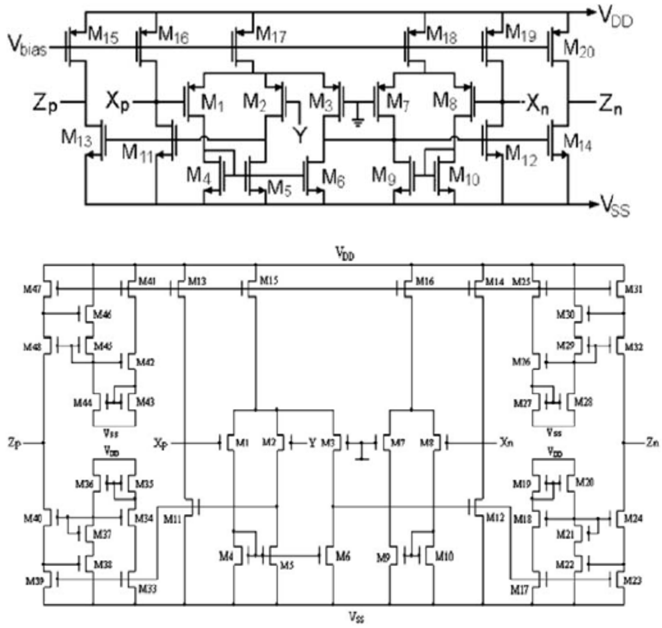


Figure 13. CMOS implementation examples for DXCC [47]

Figure 14 reflects an realization example of FDNR, frequency dependent negative resistor employing DXCC and an application example of ladder-filter constructed with DXCC based FDNRs [47].

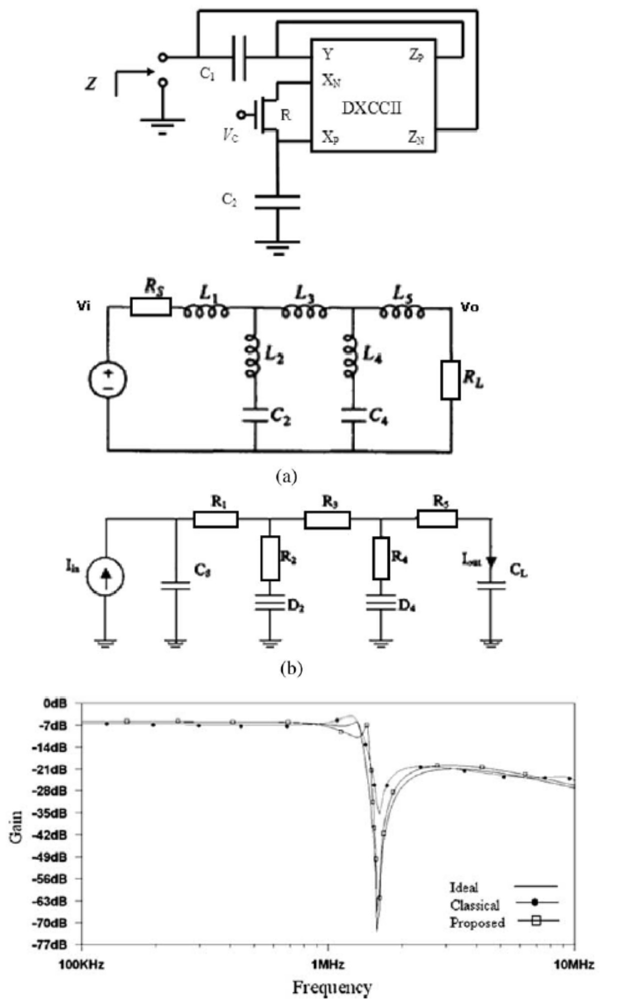


Figure 14. Realization example of FDNR employing DXCC and an application example of ladder-filter constructed with DXCC based FDNRs.

IX. CURRENT DIFFERENCING TRANSCONDUCTANCE AMPLIFIER (CDTA)

A recently reported five terminals active element, proposed by Biolek [79], namely current differencing transconductance amplifier (CDTA) seems to be a versatile component in the realization of a class of analog signal-processing circuits, especially in realization of analog frequency filters. Current differencing transconductance amplifier consists of an input current substractor and dual output transconductance stage. Improved CMOS realization is shown in Fig. 15. A design example of second-order transadmittance filter is illustrated in Fig.16. Frequency response of the notch filter is illustrated in Fig.17 [51].

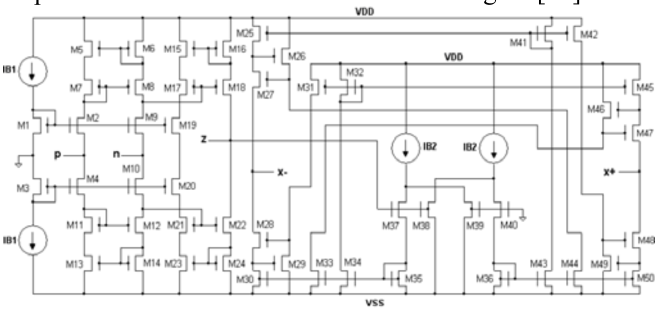


Figure 15. Improved CMOS realization of CDTA [51].

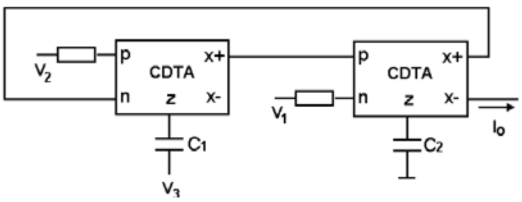


Figure 16. Second order filter realization employing CDTAs [51].

The filter topology realizes LP, BP, HP, BS and AP functions as follows:

1) V1= Vin and V2= V3= 0, LPF
2) V2= Vin and V1= V3 = 0, BPF.
3) V3= Vin and V1= V2= 0, HPF.
4) V1= V3= Vin and V2 = 0, BSF
5) V1 = -V2= V3= Vin, APF

Simulated BS frequency response is given in Fig.17.

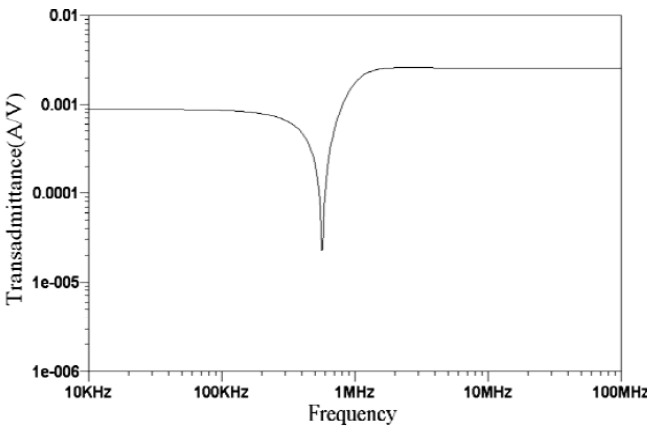


Figure 17. Simulated BS frequency response of CDTA based filter [51].

X. CDBA: CURRENT DIFFERENCING BUFFERED AMPLIFIER

The current differencing buffered amplifier CDBA is a new active element intended to simplify the design of analog signal processing filters [56]. *p* and *n* are input terminals and *w* and *z* are output terminals. This element is equivalent to the circuit in Fig. 18, which involves dependent current and voltage sources. current through *z*-terminal follows the difference of the currents through *p*-terminal and *n*-terminal. Moreover, voltage of *w*-terminal follows the voltage of *z*-terminal. Hence, we name *w*-terminal as voltage output. Finally, note that the input terminals *p* and *n* are internally grounded.

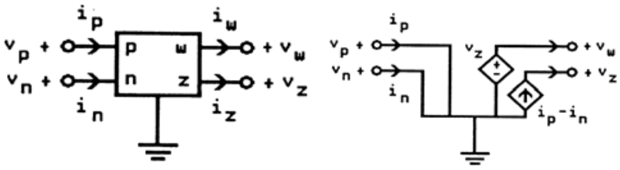


Figure 18. (a) Symbol of CDBA. and its equivalent circuit [56].

A second order general current mode filter topology example is illustrated in Fig. 19. Transfer functions of BP and LP filter functions can be obtained from i_{o1} and i_{o2} outputs, respectively. i_{o3} output yields the sum of HP and BP filter functions. To get the HP function an additional active element is necessary, as shown in Fig.20. Fig.21 and Fig. 22 illustrate the measured frequency responses and the output waveforms, respectively.

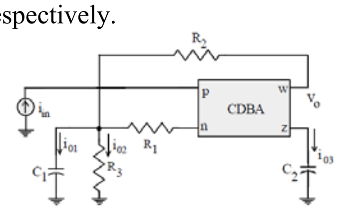


Figure 19. CDBA based general second-order filter topology [31].

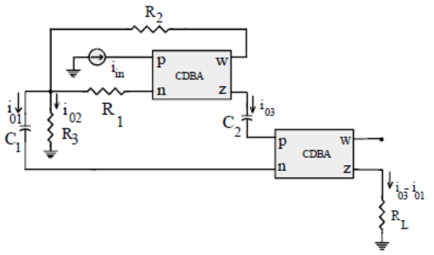


Figure 20. Realization of HP circuit [31].

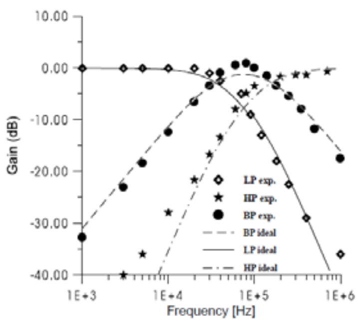


Figure 21. Frequency responses of the filters [31].

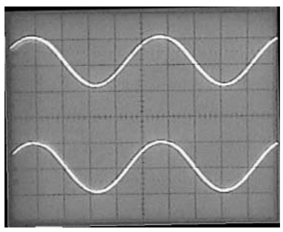


Figure 22. Output waveforms for a sinusoidal 100 kHz input signal of 1000μA and for a load resistance of R*L* = 10 kOhm. Lower trace w-output, upper trace z-output (voltages) of CDBA2. Vert.: 10 V/div, Hor.: 2 μs/div.

XI. COA: CURRENT OPERATIONAL AMPLIFLER

Current-mode operational amplifier (COA) is one of the useful current mode integrated building blocks. The main advantage of using COA is its ability to replace with the voltage operational amplifier (VOA) when applying the adjoint network theorem in voltage mode to current mode transformation [80]. A CMOS realization of COA, the step response of the amplifier, COA-based second order filter topologies and high-order BP response obtained by cascading LP and HP sections are given in Figs. 24, 25 and 26, respectively [45].

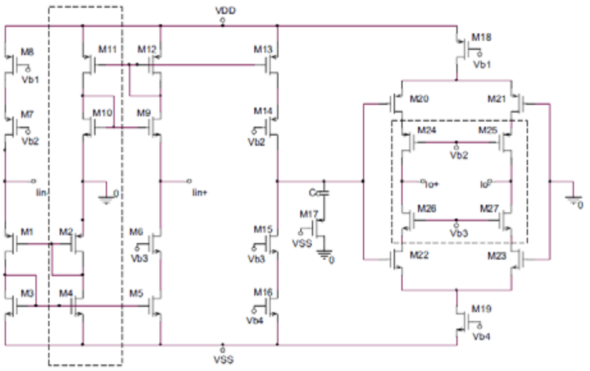


Figure 23. CMOS realization example of COA [45].

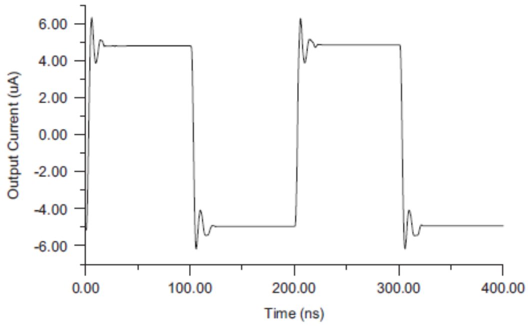


Figure 24. Response of the COA in unity-gain feedback to a ±5µA input step (*f* = 5MHz).

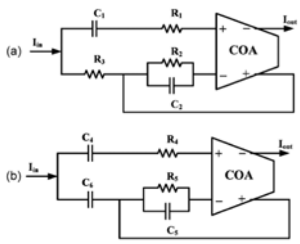


Figure 25. COA-based low-pass filter topology; (b) COA-based high-pass filter topology [45]

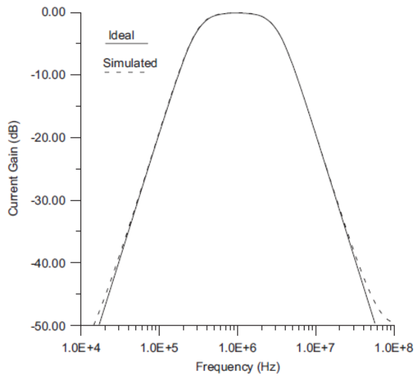


Figure 26. Simulated and ideal band-pass filter responses [45].

XII. CONCLUSION

This work covers new advances and possibilities in the related research area including application on communication, measurement and RF systems. Employing these new active elements for analog applications and using CMOS technology for implementation the circuit designers obtained new possibilities to replace the conventional operational amplifier in their design to solve the problems caused by the limited performance of OPAMPs.

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