Design Feature

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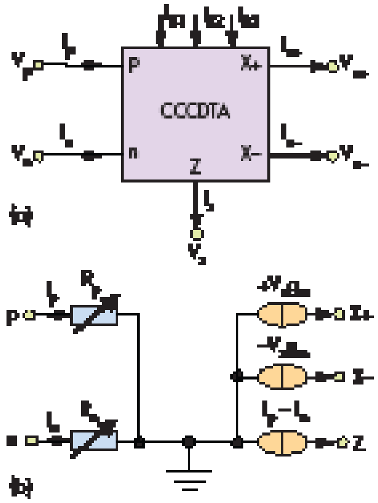
CCCDTAs Form Flexible Biquad Filter

Through the use of current-controlled, current-differencing transconductance amplifiers (CCCDTAs) and a pair of capacitors, this resistorless universal biquad filter can achieve all basic filtering functions.

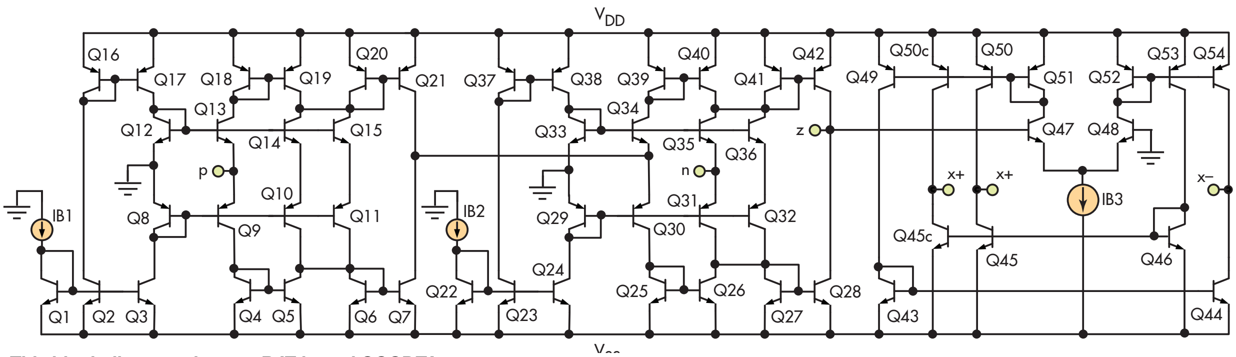
Filters have long been instrumental in cleaning and sorting signals. Likewise, the concept of a "universal" filter has long intrigued designers in search of flexible signal-processing solutions. In quest of that universal filter, which is a circuit that can realize all basic filtering functions, a transadmittance-mode (TA-M) universal biquad filter has been developed based on current-controlled, current-differencing transconductance amplifiers (CCCDTAs).

In a configuration with two CCCDTAs, two capacitors, and no resistors, this filter can realize all standard filtering functions. Among these are lowpass-filter (LPF), highpass-filter (HPF), bandpass-filter (BPF), bandstop-filter (BSF), and even all-pass filter (APF) responses using the same circuit structure. The design also offers great convenience, via electronic tuning of center frequency, quality factor (Q), and bandwidth. The TA gains of LPF, BPF, and HPF functions can be independently and electronically adjusted by means of bias currents to the CCDTAs. Since the CCCDTAs exhibit high input and output impedances, this flexible filter does not require impedance matching when cascaded with other circuits.

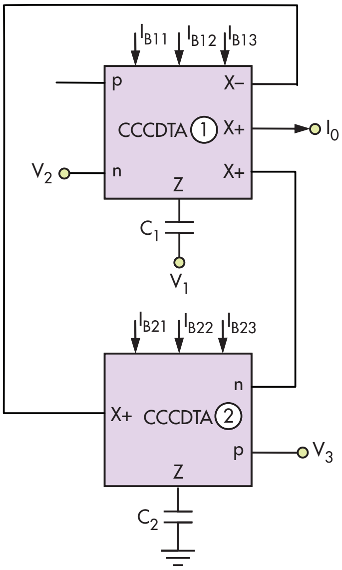


1. A current-controlled, current-differencing transconductance amplifier (CCCDTA) is represented by (a) this symbol and (b) this equivalent circuit.

Analog filters have long been essential building blocks for electronic design.[1,2] In recent years, a variety of current-mode (CM) and voltage-mode (VM) filter circuits have been developed with active devices, such as operational transconductance amplifiers (OTAs), current conveyors (CCs), and current differencing transconductance amplifiers (CDTAs). In many electronic systems, the use of voltage-to-current interface circuits is essential, since CM and VM circuits in these systems must be connected. In the process of making these voltage-to-current interfaces, it is also possible to realize signal processing, such as filtering, and the TA-M filter is a tremendous boost for these situations.[3]



2. This block diagram shows a BJT-based CCCDTA.



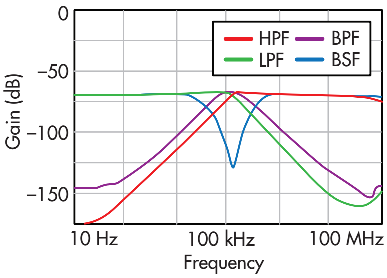
3. This block diagram shows a CCCDTA-based TA-M universal filter.

A number of TA-M filter studies have been published.[3-14] Unfortunately, all of these design efforts suffer from various shortcomings. Since a novel active-element design was first reported as a CCCDTA,[15] a wide range of CCCDTA-based applications have been realized.[15-24] The present design offers simplicity, electronic tenability, and high output impedance for versatility. Its parasitic resistance at two current input ports can be controlled by input bias current. As a result, in some circuit designs, there is no need for additional resistors to create an integrator circuit.

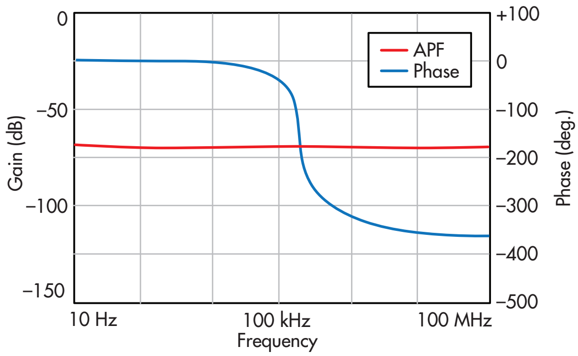
By exploring the capabilities of these CCCDTA designs, it was possible to create a novel TA-M universal biquad filter using CCCDTAs. The proposed circuit employs two CCCDTAs and two capacitors, one of which is permanently grounded. The circuit topology is suitable for integrated-circuit (IC) fabrication. With its three voltage input terminals and single current output terminal, the circuit can realize all standard filtering functions. Key parameters can be controlled by adjusting different bias currents for the CCCDTA.

The new CCCDTA design has been simulated with commercial software, and the simulations agree closely with theoretical analysis of the design. The *table* presents a comparison of the new design with previously published TA-M filters. This new design approach reduces the number of active and passive circuit elements required and overcomes some of the limitations of the earlier designs.

In general, a CCDTA can be represented by the diagram of *Fig. 1(a)* and the equivalent circuit of *Fig. 1(b)*. The matrix of Eq. 1 portrays the CCCDTA's terminal relationships:



4. These gain-frequency curves represent TA-M LPF, BPF, and BSF responses.



5. This plot shows the gain-phase simulation for a TA-M APF response.

THE COMPARISON RESULTS OF VARIOUS TA-M FILTERS

Topology	Number of active elements	Number of resistors	b	c	d	e	f
[3](CCII)	3	3	Yes	Yes	Yes	Yes	No
[5](CCIII)	3	0	No	Yes	Yes	Yes	No
[6](CCCII)	3	0	No	Yes	Yes	No	No
[7](PFTFN)	3	3	Yes	Yes	Yes	No	Yes
[8](CDTA)	2	2	No	No	Yes	Yes	No
[10](OTA)	4	0	Yes	No	Yes	No	No
[11](OTA)	7	0	No	No	Yes	No	No
[13](DVCC)	5	1	Yes	Yes	Yes	Yes	Yes
[14](VDTA)	2	0	No	No	Yes	Yes	No
Proposed (CCCDTA)	2	0	No	No	No	No	No

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_{x\pm} \end{bmatrix} = \begin{bmatrix} R_p & 0 & 0 & 0 \\ 0 & R_n & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_x \\ V_z \end{bmatrix} \quad (1)$$

where:

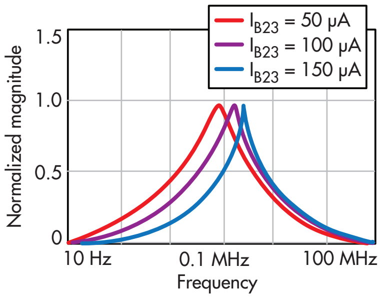
p and n = positive and negative current input terminals with finite resistances R_p and R_n, respectively, at those terminals;

z and x = current output terminals, which have high output impedance;

g_m = the transconductance gain, which can be tuned by using the external bias current of the CCCDTA;

V_Z = the voltage drop at terminal Z, which is turned into a current output by means of a transconductance stage.

Figure 2 presents a realization of a proposed CCCDTA universal filter.[24] The circuit is comprised of a current-controlled current differencer and a multiple-output operational transconductance amplifier (MO-OTA). The current-controlled current differencer consists of bipolar transistors Q_1 through Q_{42}. Bipolar transistors Q_{43} through Q_{54} form an MO-OTA, which



6. These plots show TA-M BPF responses for different values of I_{B23}.

is composed of transconductance circuits and multiple-output current mirror circuits. The transconductance gain and input resistance at two current input terminals (the p and n ports) can be directly controlled by the diverse bias currents of the CCCDTA, allowing for flexibility and versatility in many different applications.

In this CCCDTA design, resistances R_p and R_n and transconductance g_m can be expressed by means of Eqs. 2-4:

$$R_P = \frac{V_T}{2I_{B1}} \tag{2}$$

$$R_n = \frac{V_T}{2I_{B2}} \tag{3}$$

$$g_m = \frac{I_{B3}}{2V_T} \tag{4}$$

where:
V_T = the thermal voltage, and
I_{B1}, I_{B2}, and I_{B3} = the bias currents of the CCCDTA.

Figure 3 shows a circuit diagram of the designed transadmittance filter. From the diagram, it can be seen that a TA-M universal filter is relatively easy to realize by adopting minimum active and passive elements for the design. With its resistorless configuration, the filter design is also quite suitable for monolithic integration. Using Eqs. 1-4, the characteristic equations of *Fig. 3* are:

$$I_{out} = g_{m1}\frac{s^2V_1 - sV_2/C_1R_{1n} + V_3g_{m2}/C_1C_2R_{2p}}{\Delta(s)} \tag{5}$$

$$\Delta(s) = s^2 + sg_{m1}/C_1 + g_{m1}g_{m2}/C_1C_2 \tag{6}$$

where:
R_{in} = the finite negative input resistance of the CCCDTA, and
R_{ip} = the finite positive input resistance of the CCCDTA.

Through analysis of *Fig. 3* and Eqs. 5 and 6, the five current-transfer functions for the LPF, BPF, HPF, BSF, and APF responses can be obtained in the following ways. The LPF response can be achieved by means of Eq. 7 when $V_3 = V_{in}$ and $V_1 = V_2 = 0$:

$$T_{LP}(s) = \frac{I_o(s)}{V_{in}(s)} = \frac{g_{m1}g_{m2}/C_1C_2R_{2p}}{\Delta(s)} \tag{7}$$

The BPF response can be achieved by means of Eq. 8 when $V_2 = V_{in}$ and $V_1 = V_3 = 0$:

$$T_{BP}(s) = \frac{I_o(s)}{V_{in}(s)} = -\frac{sg_{m1}/C_1R_{1n}}{\Delta(s)} \tag{8}$$

The HPF function can be achieved with the aid of Eq. 9, when $V_1 = V_{in}$ and $V_2 = V_3 = 0$:

$$T_{HP}(s) = \frac{I_o(s)}{V_{in}(s)} = \frac{s^2g_{m1}}{\Delta(s)} \tag{9}$$

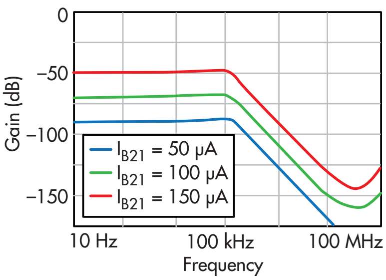
The BSF response can be gained with the help of Eq. 10 and when $I_{B12} = I_{B13}$ and $V_1 = V_3 = V_{in}$:

$$T_{BS}(s) = \frac{I_o(s)}{V_{in}(s)} = \frac{g_{m1}\left(s^2 + g_{m2}/C_1C_2R_{2p}\right)}{\Delta(s)} \tag{10}$$

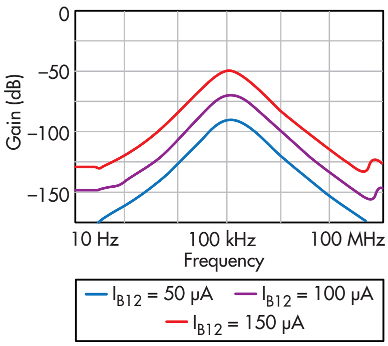
The APF response can be achieved with the help of Eq. 11 and when $I_{B12} = I_{B13} = I_{B21}$ and $V_1 = V_2 = V_3 = V_{in}$:

$$T_{AS}(s) = \frac{I_o(s)}{V_{in}(s)} = \frac{g_{m1}\left(s^2 - 1/C_1R_{1n} + g_{m2}/C_1C_2R_{2p}\right)}{\Delta(s)} \tag{11}$$

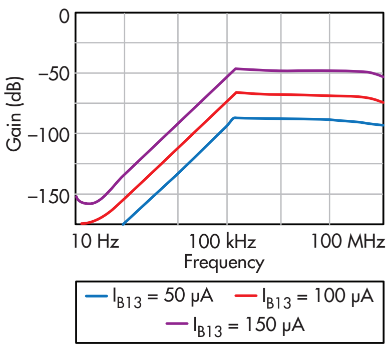
From Eqs. 7-11, it is evident that Fig. 3 provides second-order LPF, BPF, HPF, BSF, and APF responses from the same circuit design through the selection of different input signals. It is also



7. These plots show TA-M LPF responses for different values of I_{B21}.



8. These plots show TA-M BPF responses for different values of I_{B12}.



9. These plots show TA-M HPF responses for different values of I_{B13}.

apparent that there is no need for an external inverter and a matching element to realize BS and AP filters. The parameters of ω_0, Q, and ω_0/Q (bandwidth) for the proposed filter can be found from Eqs. 12-14:

$$\omega_o = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} = \frac{1}{2V_T}\sqrt{\frac{I_{B13}I_{B23}}{C_1C_2}} \quad (12)$$

$$Q = \sqrt{\frac{g_{m2}C_1}{g_{m1}C_2}} = \sqrt{\frac{I_{B23}C_1}{I_{B13}C_2}} \quad (13)$$

$$BW = \frac{\omega_o}{Q} = \frac{g_{m1}}{C_1} = \frac{I_{B13}}{2C_1V_T} \quad (14)$$

It is clear that all of the characteristic parameters of this filter can be electronically tuned by CCCDTA bias currents. Also, ω_0 and Q can be adjusted electronically and independently by means of I_{B23} without obstructing the value of ω_0/Q.

By using Eqs. 7-9, the transadmittance gain of the LPF, BPF, and HPF responses can be calculated by means of Eqs. 15, 16, and 17, respectively:

$$G_{LP} = \frac{1}{R_{2p}} = \frac{2I_{B21}}{V_T} \quad (15)$$

$$G_{BP} = \frac{1}{R_{1n}} = \frac{2I_{B12}}{V_T} \quad (16)$$

$$G_{HP} = g_{m1} = \frac{I_{B13}}{2V_T} \quad (17)$$

From these three expressions, it is easy to see that the transadmittance gains of the LP, BP, and HP filter functions can be independently and electronically modified by adjusting the different bias currents: I_{B21}, I_{B12}, and I_{B13}. The lowpass and bandpass gains—G_{LP} and G_{BP}, respectively—can be independently transformed by means of bias currents I_{B21} and I_{B12}, respectively, without the poly-frequency and bandwidth of the particular filter response.

Considering the CCCDTA's nonideal characteristics, its port relationship in *Fig. 3* can be rewritten as Eq. 18:

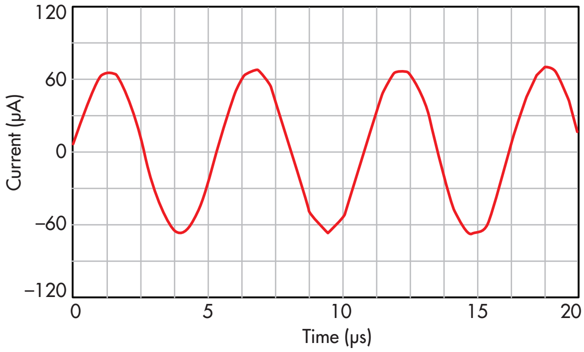
$$i_z = \alpha_p i_p - \alpha_n i_n, i_{x\pm} = \pm\beta g_m v_z \quad (18)$$

where:

α_{pi} ($\alpha_{pi} = 1 - \varepsilon_{pi}$, $|\varepsilon_{pi}| << 1$) and α_{ni}($\alpha_{ni} = 1 - \varepsilon_{ni}$, $|\varepsilon_{ni}| << 1$)

are parasitic current gains between p → z and n → z terminals of the ith CCCDTA, respectively, and

β_i ($\beta_i = 1 - \varepsilon_i$, $|\varepsilon_i| << 1$)



10. This is the TA-M APF response for a sinewave input signal.

is the parasitic transconductance tracking error from the z to the x terminals.

The circuit in *Fig. 3* was reanalyzed by using Eq. 18. The modified current transfer characteristic is approximated by Eq. 19:

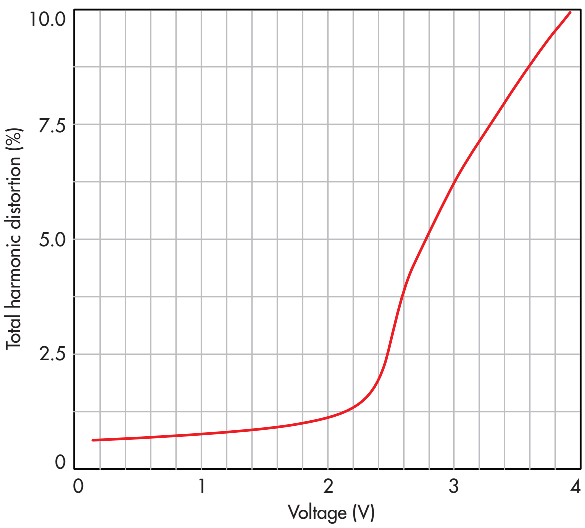
$$\Delta(s) = s^2 + s\beta_1\alpha_{p1}g_{m1}/C_1 + \alpha_{p1}\alpha_{n2}\beta_1\beta_2 g_{m1}g_{m2}/C_1C_2 \quad (19)$$

From Eq. 19, the nonideal values of ω_0 and Q for the universal filter can be expressed by means of Eqs. 20 and 21, respectively:

$$\omega_o = \sqrt{\frac{\alpha_{p1}\alpha_{n2}\beta_1\beta_2 g_{m1}g_{m2}}{C_1C_2}} \quad (20)$$

$$Q = \sqrt{\frac{\alpha_{n1}g_{m2}C_1}{\alpha_{p1}\beta_1 g_{m1}C_2}} \quad (21)$$

The sensitivities of the active and passive components to ω_0 can be found by means of Eqs. 22 and 23:



11. The linearity of the TA-M filter can be gauged by its low THD.

$$S^{\omega_o}_{\alpha_{p1},\alpha_{n2},\beta_1,\beta_2,g_{m1},g_{m2}} = 0.5,\quad S^{\omega_o}_{C_1,C_2} = -0.5 \qquad (22)$$

$$S^{Q}_{\alpha_{n1},g_{m2},C_1} = 0.5,\quad S^{Q}_{\alpha_{p1},\beta_1,g_{m1},C_2} = -0.5 \qquad (23)$$

It can be noted from Eqs. 22 and 23 that all sensitivities of the passive and active elements of the proposed TA-M filter do not exceed 50% in magnitude.

It was possible to simulate a TA-M filter as portrayed in *Fig. 3* by using the CCCDTA in *Fig. 2* simulated with the parameters of the PR200N and NR200N bipolar transistors of the ALA400 transistor array from AT&T in a PSPICE simulator.[25] The power supplies were set as $V_{DD} = -V_{SS} = 1.5$ V.

The universal filter was designed using passive component values of $C_1 = C_2 = 1$ nF. Bias currents for the CCCDTAs were chosen as $I_{B11} = I_{B22} = 500$ µA (for $R_{1p} = R_{2n} = 20\ \Omega$); $I_{B12} = I_{B21} = 100$ µA; and $I_{B13} = I_{B23} = 100$ µA (for $g_m = 1.2$ mS). Using Eq. 12, a polyfrequency of 190 kHz was achieved through these values. By selecting different input signals, it was possible to achieve simulated responses for LPF, BPF, HPF, and BSF functions *(Fig. 4)*. *Figure 5* offers simulated responses for the gain and phase of the APF function.

From *Figs. 4 and 5*, it is apparent that the proposed TA-M filter circuit can realize LP, HP, BP, BS, and AP functions depending upon input signal selection, without modifying the basic circuit framework. By setting different I_{B23} values, the different BPF magnitude responses of *Fig. 6* can be achieved. It is clear that the polyfrequency and Q of the filter can be adjusted electronically. The electronic tuning of gain for LPF, BPF, and HPF responses are achieved by changing bias currents from 50 to 150 µA while maintaining $C_1 = C_2 = 1$ nF, as shown in *Figs. 7 through 9*.

To test the large-signal behavior of the TA-M filter, a sinusoidal input at 190 kHz and 0.5 V was applied to the APF function with the circuit elements as established previously. *Figure 10* shows the results of the output transient response, while the total harmonic distortion (THD) is presented in *Fig. 11*.

In short, this is a single circuit that can be electronically tuned for different filter responses, and it can realize all standard filtering functions. Being completely without resistors, it is well suited for IC fabrication. **mw**

Note: For references, see the online version of this article at www.mwrf.com.

ACKNOWLEDGMENTS

The authors would like to thank the reviewers for their valuable comments and helpful suggestions. This work is supported by the foundation of outstanding youth science and technology innovation team of the Hubei Polytechnic University (No. 13xtx02) and the project planning of young teachers in enterprises of the Hubei Province (No. XD2014681), both of the People's Republic of China (PRC).

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