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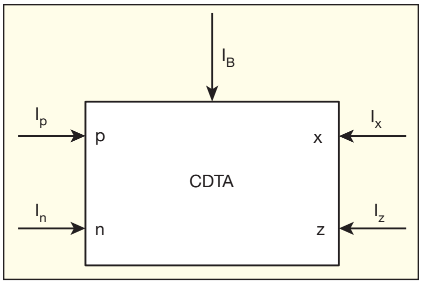
Single Filter Has Many Responses

This unique resistorless, current-mode filter design can realize a variety of filter responses, including lowpass, highpass, bandstop, and all-pass responses without changing topology.

FILTERS ARE crucial parts of RF/microwave systems—so much so that, often, many different types of filters and filter responses are needed within a single network. Fortunately, a new general synthesis method has been developed for designing resistorless nth-order current-mode universal filters capable of providing a number of different filter responses. These include lowpass, highpass, bandpass, bandstop, and all-pass responses, and do not necessitate changes to the basic filter topology.

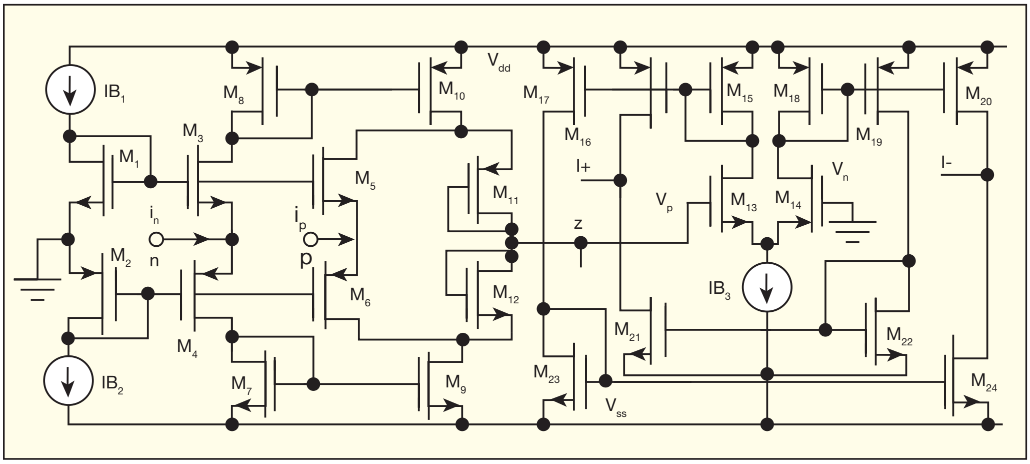


1. This simple diagram represents a basic symbol for a current differencing transconductance amplifier (CDTA).

Such a "universal" filter is based on a current differencing transconductance amplifier (CDTA) and features a current-mode, multiple-input, single-output structure. Different responses are achieved by changing how the external current signals are combined. Constructed without resistors, such a filter is assembled with n active components and n grounded capacitors, making it suitable for integrated-circuit (IC) fabrication processes. The values of the passive elements are found from the coefficients of the desired transfer function. As an example of how to realize such a filter, a simulation will be performed for a fourth-order Butterworth filter with the aid of the PSpice® simulation software from Cadence® (www.cadence.com).

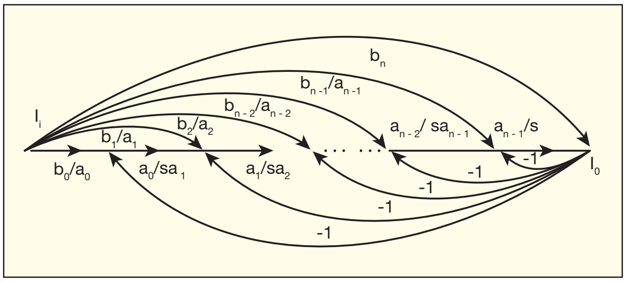
Filters are used for many purposes in communications systems, such as for image rejection at RF and microwave frequencies and for channel selection at intermediate frequencies (IFs). Filters fabricated on semiconductor chips mainly apply switched capacitors or a continuous-time structure, especially for continuous-time current-mode techniques. Recently, a new current-mode active element with two current inputs and two kinds of current output, called a current differencing transconductance amplifier (CDTA), was developed and shows good versatility.[1]

The CDTA represents a synthesis of the well-known advantages of a current-differencing buffered amplifier (CDBA)[2] and a multiple-output operation transconductance amplifier (OTA)[3] to facilitate the implementation of current-mode analog signal processing. It also exhibits capability for electronic tuning by means of its transconductance gain, g_m. As a result, CDTAs have been widely used in current-mode signal-processing circuits, such as inductance simulator circuits[4-6] and sinusoidal oscillator circuits,[7-9] and is a promising choice for current-mode filters.[10-19]



2. This circuit is a realization of a CMOS-based CDTA filter.

CDTA-based biquad universal filters have undergone considerable study. For example, refs. 20 and 21 detail work

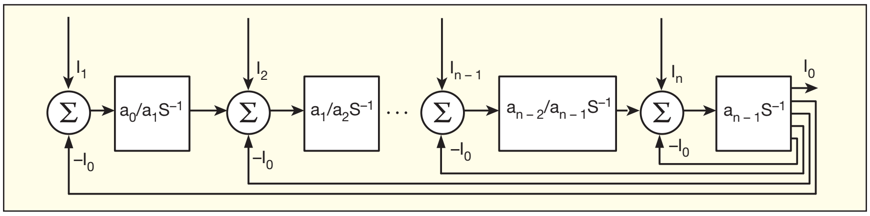


3. This is an nth-order equivalent signal flow graph for the universal filter.

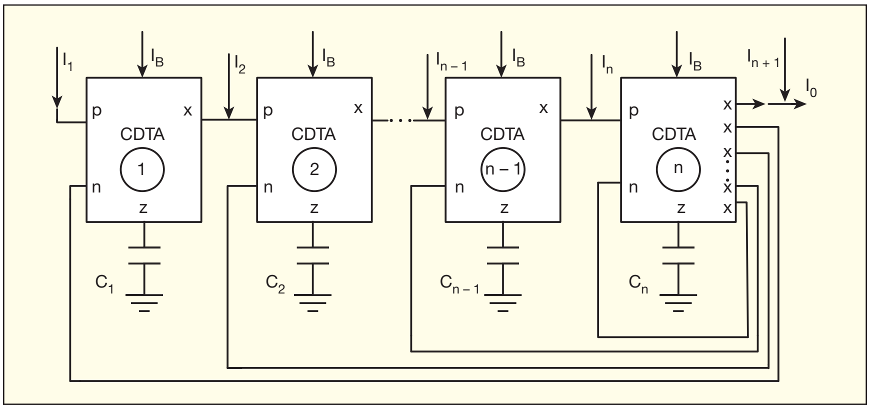
on a CDTA-based Kerwin-Huelsman-Newcomb (KHN) current-model filter and a multiple-input, single-output universal filter, respectively. Both filters incorporate two CDTAs, two grounded capacitors, and simple structures. Reference 22 also reports on a CDTA-based universal filter which can be cascaded while simultaneously providing all standard filter functions. However, in spite of these reported filter circuits, research on nth-order CDTA-based filters has been inadequate.[23-26]

References 23 and 24 proposed two kinds of nth-order current-mode filters using CDBAs. These filters are realized with the aid of a signal-flow graph and employ too many passive components. Reference 25 details a CDTA-based nth-order lowpass filter with a simple structure and n grounded capacitors. It is based on the analysis of a signal-flow diagram. Reference 26 proposes a method for creating an nth-order circuit, in which a fourth-order bandpass filter is designed.

These design approaches suffer drawbacks, however. They can only realize nth-order single filter functions, such as a lowpass filter,[25] and do not meet the requirements of a universal filter. These approaches employ circuit structures with single inputs to single outputs.[23-26] When needing to change the filter function, the circuit's topology must be changed simultaneously, not taking full advantage of the port characteristics and providing only limited filter flexibility. Another drawback is that these circuits are complicated and require many passive components; for example, the circuits in refs. 23 through 25 require external resistors and more CDTAs than the circuit of ref. 26.



4. This is an nth-order functional equivalent circuit block diagram for the universal filter.



5. This is a proposed CDTA-based nth-order current-mode universal filter.

Because of the shortcomings of these different universal filter design approaches, a new general synthesis method for CDTA-based resistorless nth-order current-mode universal filters was developed; it is based on mathematical analysis of transfer functions and signal-flow graphs. The circuit realization is obtained from a signal-flow graph, and the circuits developed from this approach feature a current-mode, multiple-input, single-output structure. By manipulating the amount and mode of joining the external current signals, a single circuit can provide lowpass, highpass, bandpass, bandstop, and all-pass filter functions without changing the topology.

The natural angular frequency of the filter, ω_0, can be adjusted properly by means of current I_B. The circuit configuration is simple: It contains n active components, n grounded capacitors, and no resistors, which is advantageous for IC fabrication. The required values of the passive elements can be found from the coefficients of the transfer function to be realized. Such a universal filter can be used in many applications, including in RF/microwave transmitters/receivers, in phase-locked-loop (PLL) frequency-modulation (FM) demodulators, in test instrumentation, and in wireless communications systems. It can also be used for an active filter in place of the surface-acoustic-wave (SAW) filters typically used in GSM systems.

The circuit symbol of the CDTA is shown in **Fig. 1**, where p and n are positive and negative current input terminals, z and x are current output terminals. Its current characteristics can be described by the matrix of Eq. 1:

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

where $V_z = I_z * Z_z$; g_m = the transconductance gain; and Z_z = an external impedance connected at terminal z.

According to Eq. 1, the currents through terminal z follow the difference of the currents through terminals p and n ($I_p - I_n$), and flows from terminal z into an impedance Z_z. The voltage drop at terminal z is transferred to a current at terminal x (I_x by means of transconductance g_m, which is electronically controllable by an external bias current, I_B.

Such a universal filter can be constructed using a number of techniques: a possible CMOS-based CDTA circuit suitable for IC fabrication is shown in **Fig. 2**.[20] The transconductance stage can be copied in a circuit, so the number of x ports for the CDTA can be chosen as needed.

For the design of an nth-order universal filter, the transfer function can be written as Eq. 2:

$$I_o = \frac{b_n s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + a_0} I_i \quad (2)$$

where:

$$\begin{aligned} I_o &= I_i \left(b_n + b_{n-1}s^{-1} + \cdots + b_1 s^{-n+1} + b_0 s^{-n}\right) \\ &\quad -(I_o a_{n-1}s^{-1} + \cdots + I_o a_1 s^{-n+1} + I_o a_0 s^{-n}) \end{aligned} \quad (3)$$

To present the feedback coefficient with units of gain and to simplify the design of the circuit, Eq. 3 can be modified, using the equivalent signal-flow graph shown in **Fig. 3**. According to the signal-flow graph, and using the Mason formula leading with the input variable, the output signal can be described by Eq. 4:

See Eq. 4 in box on p. 64.

where $I_1, I_2 \ldots I_{n+1}$ is the input variable with relationship to input signal I_i described by Eq. 5:

$$I_{j+1} = \frac{b_j}{a_j} I_i \quad (j = 0,1,2\cdots n) \quad (5)$$

The system block diagram for Eq. 4 is shown in **Fig. 4**. Using **Fig. 4**, the proposed CDTA-based nth-order current-mode universal filter can be obtained as shown in **Fig. 5**. By routine analysis, the single-output-current function realized by this circuit configuration is:

See Eq. 6 in box on p. 64.

where:

$\tau_0 = g_{mn}/C_n$,

$\tau_1 = g_{mn}g_{m(n-1)}/C_nC_{n-1}$,...

$$\tau_{n-2} = \frac{\prod_{i=0}^{n-2} g_{m(n-i)}}{\prod_{i=0}^{n-2} C_{n-i}} \qquad \tau_{n-1} = \frac{\prod_{i=0}^{n-1} g_{m(n-i)}}{\prod_{i=0}^{n-1} C_{n-i}} \quad (7)$$

That is:

$$\tau_k = \frac{\prod_{i=0}^{k} g_{m(n-i)}}{\prod_{i=0}^{k} C_{n-i}} \quad (0 \le k \le n-1) \quad (8)$$

and g_{mi} is the transconductance gain parameter of the ith CDTA.

From Eq. 6, through a rational chang-

$$I_o = \frac{a_0 I_1 s^{-n} + a_1 I_2 s^{-n+1} + \cdots + a_{n-2} I_{n-1} s^{-2} + a_{n-1} I_n s^{-1} + a_n I_{n+1}}{1 + a_{n-1} s^{-1} + \cdots + a_1 s^{-n+1} + a_0 s^{-n}} \quad (4)$$

$$I_o = \frac{I_1 \tau_{n-1} + s I_2 \tau_{n-2} + \cdots + s^{n-2} I_{n-1} \tau_1 + s^{n-1} I_n \tau_0}{s^n + s^{n-1}\tau_0 + s^{n-2}\tau_1 + \cdots + s\tau_{n-2} + \tau_{n-1}} + I_{n+1} \quad (6)$$

ing of the amount and mode of joining the external current signals, it is possible to derive the filter function in the following five ways:

1) If $I_1 = I_{in}$ and $I_2 = \ldots I_n = I_{n+1} = 0$, the lowpass filter response can be realized.

2) When n is an even number, if:
$I_{n/2} = I_{in}$, and the other input currents are zero, or when n is an odd number, if $I_{(n-1)/2} = I_{in}$ or:
$I_{(n+1)/2} = I_{in}$ and the other input currents are zero, a bandpass filter response can be realized.

3) If $I_{(n+1)} = I_{in}$ and $I_1 = \ldots = I_n = -I_{in}$, a highpass filter response can be realized.

4) If $I_{(n-1)/2} = I_{in}$ and $I_2 = \ldots = I_n = -I_{in}$, and $I_1 = 0$, a bandstop filter response can be realized.

5) When n is an even number, if I_{n+1} $= I_{in}$,
$I_n = -2I_{in}$,
$I_{n-1} = 0$,
$I_{n-2} = -2I_{in}$,
$I_{n-3} = 0, \ldots, I_2 = -2I_{in}$,
$I_{n-1} = 0$, or when n is an odd number, if:
$I_{n+1} = I_{in}$,
$I_n = -2I_{in}$,
$I_{n-1} = 0$,
$I_{n-2} = -2I_{in}$,
$I_{n-3} = 0, \ldots, I_2 = 0$, and
$I_1 = -2I_{in}$,
an all-pass filter response can be realized.

From Eqs. 6, 7, and 8, when calculating the required component parameters, if all g_{mi} values are known (according to the filter transfer function), the value of capacitance C_n can be found from τ_0 and then the value of C_{n-1} can be found from τ_0, τ_1. The other values can then be

The CDTA represents a synthesis of the well-known advantages of a CDBA and an OTA to facilitate the implementation of current-mode analog signal processing.

confirmed, and so forth, since it is fairly straightforward to find the required values of passive elements from the coefficients of the transfer function to be realized. It is also apparent that the angular frequency of the filter, ω_0, can be adjusted properly by adjusting current I_B.

To verify this theoretical analysis, a simulation was performed in PSpice, for a current-mode fourth-order Butterworth filter using the CMOS-based CDTA circuit of **Fig. 2**. The filter was modeled in PSPICE with 0.5-μm CMOS parameters, available upon request from the authors. The cutoff frequency of the fourth-order Butterworth filter is 13 MHz,[27]

The filter has a transfer function denominator polynomial of $D(s) = s^4 + 2.14 \times 10^7 + 2.292 \times 10^{12} s^2 + 1.437 \times 10^{17} s + 4.506 \times 10^{21}$. The CDTA element in this case has a bandwidth of approximately 420 MHz, and the circuit is supplied with symmetrical voltages of ±2.5 VDC. The external bias currents are $I_{B1} = I_{B2} = 85$ μA, $I_{B3} = 200$ μA, and the transconductance gain, g_{mi}, is 457.83 μS. One of these CDTAs is modified from the circuit in **Fig. 2** and is chosen with five x ports. It is easy to obtain the value C_i from the above parameters: $C_1 = 15$ pF, $C_2 = 7.3$ pF, $C_3 = 4.27$ pF, and $C_4 = 2.14$ pF. **Figure 6** shows the simulation results, with theoretical test and computer simulation results in good agreement. MWRF

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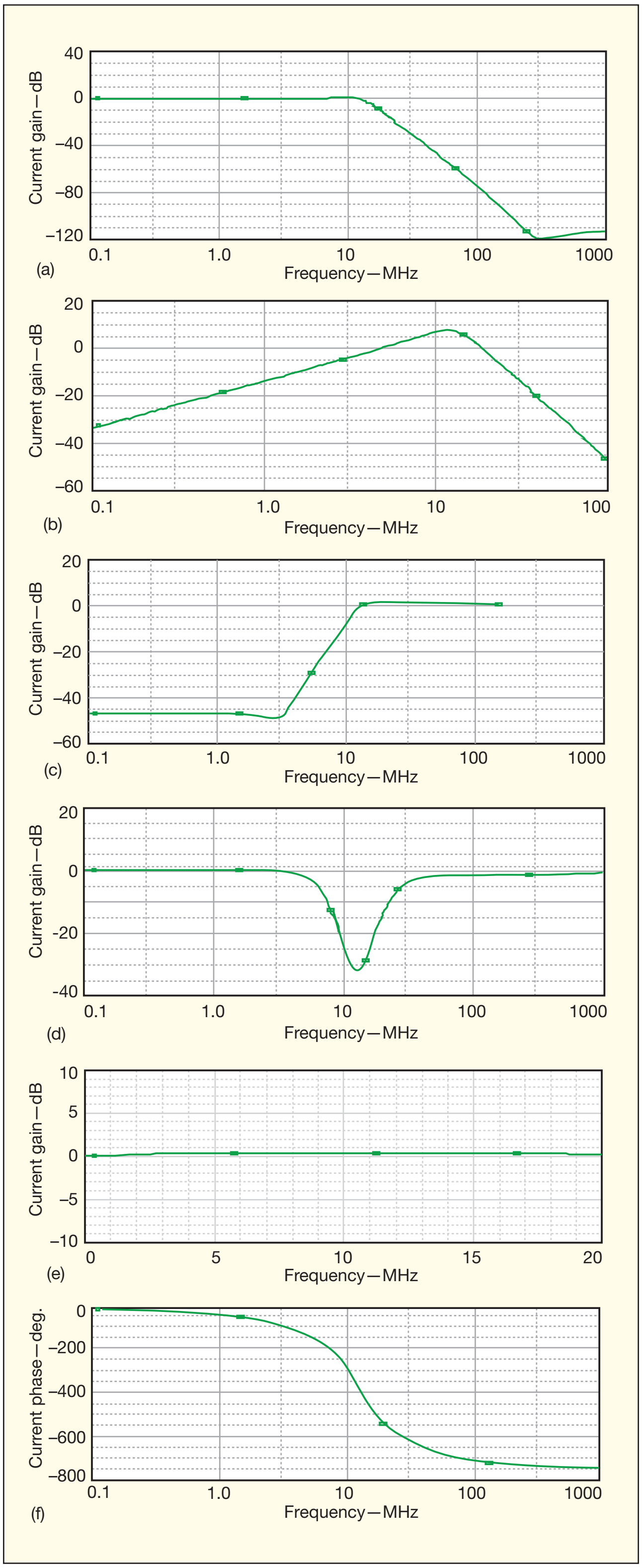

6. These frequency responses show the different proposed filter functions: (a) lowpass, (b) bandpass, (c) highpass, (d) bandstop, (e) all-pass frequency response, and (f) all-pass phase response.

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