Since an introduction of the current differencing transconductance amplifier (CDTA) in 2003, it has been acknowledged to be a versatile active building block for current-mode signal processing circuits\(^1\). Various analog signal processing/signal generation circuit solutions using this device have also been reported\(^2\-10\). However, all of the previous works need more than one CDTA. In point of view of the low power dissipation and manufacturing cost, it is important to keep the active component count at minimum. Moreover, the earlier reported configurations\(^6\-10\) do not exploit the full capacity of the used CDTAs, since one of the input terminals (\(p\) or \(n\) terminals) of the CDTA is not used. This may cause some noise injection into the monolithic circuit\(^11\). Thus, to avoid this problem, the modified version of the CDTA so-called current follower transconductance amplifier (CFTA) has recently been introduced\(^12\). This device can be thought of as a combination of the current follower and the multi-output transconductance amplifier. Its behaviour is quite similar to the CDTA element, in which the current differencing unit at the front-end is used instead of the current follower. Although, an application on building the current-mode universal filter using CFTAs as the major active building blocks is also reported\(^12\), it still requires a large number of active components, i.e., three CFTAs.

Therefore, the objective of this paper is to present novel current-mode and voltage-mode universal filters which employ a single CFTA as an active element. The first one of the presented filters with one input and three outputs employs one CFTA, one resistor and two grounded capacitors. It can simultaneously realize low-pass, band-pass and high-pass responses with no need to impose component choice. A new three-input single-output universal voltage-mode biquad using one CFTA, two resistors and two capacitors is also proposed as a second proposed circuit. The latter circuit can be configured to realize all the five standard biquadratic filter functions; low-pass, band-pass, high-pass, band-stop and all-pass, without changing the circuit configuration. Both two universal biquad filters also offer the advantage features of the use of minimum number of passive components, and independent electronic tuning of the important filter parameters (\(\omega_o\) and \(BW\)), as well as low active and passive sensitivities. To demonstrate the performances of the proposed filters and verify the theory, PSPICE simulations are accomplished.
conditions. PSPICE simulation results are obtained to demonstrate the characteristics of the proposed filters and to verify the theoretical analyses.

**Description of Current Follower Transconductance Amplifier (CFTA)**

The symbolic representation of the CFTA and its behaviour model are shown in Fig. 1. Assuming the standard notation, the terminal defining relations of this device can be characterized by the following set of equations

\[ v_f = 0, \quad i_z = i_f \quad \text{and} \quad i_x = g_m v_z = g_m Z z i_z \quad \ldots (1) \]

where \( g_m \) is the transconductance gain of the CFTA and \( Z_z \) is an external impedance connected to the \( z \)-terminal. The CFTA consists essentially of the current follower at the input part and the multi-output transconductance amplifier at the output part. According to Eq. (1), the \( f \)-terminal forms the current input terminal at ground potential \( (v_f = 0) \) and the output current at the \( z \)-terminal \( (i_z) \) follows the input current \( (i_f) \) through the \( f \)-terminal. The voltage drop at the \( z \)-terminal \( (v_z) \) is then converted to a current at the \( x \)-terminal \( (i_x) \) by a \( g_m \)-parameter. In general, the \( g_m \)-value is adjustable over several decades by a supplied bias current/voltage, which lends electronic controllability to design circuit parameters. It may also be emphasized that the electronic controllability becomes very important when the circuit is in a variety of design specifications and in the integrated circuit (IC) form.

**Proposed Single CFTA-Based Current-Mode Universal Biquad Filter**

The first proposed current-mode universal biquad filter using single CFTA is shown in Fig. 2. The circuit is constructed using canonic number of components, i.e., one CFTA, one virtually grounded resistor, and two grounded capacitors. The routine analysis of the circuit in Fig. 2 gives the current transfer functions as follows.

\[ \frac{I_{LP}(s)}{I_{in}(s)} = \left( \frac{g_m}{R C_1 C_2} \right) D(s) \quad \ldots (2) \]
\[ \frac{I_{BP}(s)}{I_{in}(s)} = \left( \frac{s}{R C_1} \right) D(s) \quad \ldots (3) \]
\[ \frac{I_{HP}(s)}{I_{in}(s)} = \frac{s^2}{D(s)} \quad \ldots (4) \]

where \( D(s) \) is found to be

\[ D(s) = s^2 + \left( \frac{s}{R C_1} \right) + \left( \frac{g_m}{R C_1 C_2} \right) \quad \ldots (5) \]

It can easily be observed from Eqs (2)-(5) that the first proposed filter simultaneously realizes LP, BP and HP current responses at \( I_{LP} \), \( I_{BP} \) and \( I_{HP} \), respectively, without requiring any passive component matching constrains. However, since the BP and HP output signals are available on the grounded passive capacitors \( C_1 \) and \( C_2 \), additional active elements are required to sense the currents \( I_{BP} \) and \( I_{HP} \).
and $I_{HP}$. On the other hand, only LP current response $I_{LP}$ has an advantage of high output impedance. In addition, the scheme can be classified as a current-mode single-input three-output universal filter.

All the above three filters possess the same natural angular frequency ($\omega_o$) and the bandwidth (BW), which can be given by:

$$\omega_o = \sqrt{\frac{g_m}{R_1 C_1 C_2}} \quad \ldots \quad (6)$$

and

$$BW = \frac{1}{R_1 C_1} \quad \ldots \quad (7)$$

From Eqs (6) and (7), one can see that the parameter $\omega_o$ can be adjusted electronically without affecting the parameter BW by tuning the $g_m$-value.

In case of the non-ideal CFTA, the relationship of the terminal voltages and currents given in Eq. (1) can be rewritten as:

$$v_f = 0, \quad i_z = \alpha i_f \quad \text{and} \quad i_x = g_m Z i_z \quad \ldots \quad (8)$$

where $\alpha = 1 - \varepsilon_i$ and $\varepsilon_i (|\varepsilon_i| << 1)$ is the current tracking error from the f-terminal to the z-terminal. Therefore, taking the non-idealities of the CFTA into account, the modified parameters $\omega_o$ and BW of the proposed filter shown in Fig. 2 are recalculated as:

$$\omega_o = \sqrt{\frac{\alpha g_m}{R_1 C_1 C_2}} \quad \ldots \quad (9)$$

and

$$BW = \frac{1}{R_1 C_1} \quad \ldots \quad (10)$$

Equation (9) indicates that the tracking error $\alpha$ of the CFTA slightly changes the $\omega_o$-value. However, this deviation should not be seen as a drawback, as we can compensate this effect as low as possible by re-adjusting the $g_m$-value properly. As a result, the desired $\omega_o$-value can always be satisfied. Note also from Eq. (10) that the tracking error $\alpha$ has no effect on the parameter BW. Therefore, an orthogonal control of $\omega_o$ and BW still exists.

The active and passive sensitivity analyses of the proposed filter in Fig. 2 show that:

$$S_{\omega_o}^{ai} = S_{g_m}^{ai} = \frac{1}{2} \quad \ldots \quad (11)$$

$$S_{\omega_o}^{ai} = S_{g_m}^{ai} = S_{C_1}^{ai} = -\frac{1}{2} \quad \ldots \quad (12)$$

$$S_{\omega_o}^{ai} = S_{g_m}^{ai} = S_{C_2}^{ai} = -1 \quad \ldots \quad (13)$$

and

$$S_{BW}^{ai} = S_{g_m}^{ai} = S_{C_1}^{ai} = 0 \quad \ldots \quad (14)$$

Consequently, all of the component sensitivities of $\omega_o$ and BW are very low and not more than unity in magnitude.

**Proposed Single CFTA-Based Voltage-Mode Universal Biquad Filter**

The second proposed voltage-mode universal biquad filter with three inputs and one output is shown in Fig. 3. The circuit comprises only one CFTA, two resistor and two capacitors. Applying the straightforward analysis to the proposed filter in Fig. 3 yields the following output voltage:

$$V_{out} = \frac{(s^2 R_1 C_1 C_2) V_1 - (s C_2)(g_m R_1) V_2 - \left(\frac{g_m R_1}{R_2}\right) V_3}{s^2 R_1 C_1 C_2 + s C_2 + g_m} \quad \ldots \quad (15)$$

The specialization of the numerator in Eq. (15) results in the following five standard biquadratic filter functions.

(i) If $V_1 = V_{in}$ (input voltage signal) and $V_2 = V_3 = 0$ (grounded), the HP response with a non-inverting unity pass-band gain can be obtained.

(ii) If $V_2 = V_{in}$ and $V_1 = V_3 = 0$, the BP response with a pass-band gain equal to $(-g_m R_1)$ can be obtained.
(iii) If $V_3 = V_\text{in}$ and $V_1 = V_2 = 0$, the LP response with a passband gain equal to $(-R_1/R_2)$ can be obtained.

(iv) If $V_1 = -V_3 = V_\text{in}$, $V_2 = V_3 = 0$, and $R_1 = R_2$, the BS response with a non-inverting unity pass-band gain can be obtained.

(v) If $V_1 = V_2 = -V_3 = V_\text{in}$ and $R_1 = R_2 = 1/g_m$, the AP response with a non-inverting unity pass-band gain can be obtained.

It is important to note that the proposed filter requires a minimum number of active and passive components with no need for critical component matching conditions, except for the BS and AP filter realizations. Moreover, in case of BS and AP realizations, an additional voltage inverter is needed to realize an inverting-type input voltage signal ($V_3 = -V_\text{in}$). From Eq. (15), the important parameters $\omega_0$ and $\text{BW}$ of the filter are still the same as those in Eqs (9) and (10), respectively. In addition, all of the active and passive sensitivities of $\omega_0$ and $\text{BW}$ are no different from Eqs (11)-(14), which are also very low values.

Results and Discussion

The characteristics of the proposed filters have been studied through simulation results using PSPICE program. The CFTA used in the simulations is obtained from the bipolar technology implementation given in Fig. 4. It is mainly composed of a current follower circuit formed by transistors $Q_1$-$Q_6$ and a multiple-output transconductance amplifier $Q_7$-$Q_{29}$. In

![Fig. 4–Bipolar technology implementation of the CFTA used for simulations](image)

![Fig. 5–Ideal and simulated LP, BP and HP current responses of the proposed filter in Fig. 2](image)
In this case, the transconductance gain $g_m$ of the CFTA is directly proportional to the external bias current $I_0$, which is equal to $(g_m = I_0/2V_T)$ and $V_T \approx 26$ mV at $27^\circ$C. The PNP and NPN transistors in CFTA implementation are simulated using the typical parameters of bipolar transistor model PR100N (PNP) and NP100N (NPN) from AT&T.$^{13}$ The DC power supply voltages and biasing currents are set to $+V = -V = 3$ V and $I_B = 50$ $\mu$A, respectively.

The following component values for both proposed filters in Figs 2 and 3 have been chosen as: $R_1 = R_2 = 1$ k$\Omega$, $C_1 = C_2 = 1$ nF and tuning current $I_0 = 50$ $\mu$A ($g_m = 1$ mA/V), which results in a natural angular frequency of $f_n = \omega_0/2\pi \approx 159$ kHz and a quality factor of $Q = 1$. The ideal and simulated LP, BP and HP frequency responses of the proposed filters in Figs 2 and 3 are depicted in Figs 5 and 6, respectively. As can be observed, there is a close agreement between ideal and simulation results. In the same way, the ideal and simulated gain and phase frequency-responses for the BS and AP characteristics of the presented filter in Fig. 3 are also shown in Figs 7 and 8, respectively.

**Conclusions**

This paper has been presented two configurations of universal biquadratic filter using a single recently reported active device, namely current follower transconductance amplifier (CFTA), as the active component. The proposed circuits employ canonic number of passive components, namely two capacitors and one or two resistors. The first proposed single-input three-output current-mode universal filter can realize LP, BP and HP current responses in the same time from the same circuit topology. The second proposed three-input single-output voltage-mode universal filter can realize all the five standard biquadratic functions with interconnection of the relevant input voltages. Both of the presented circuits provide the advantage of non-interactive electronic control of the parameters $\omega_0$ and BW through the transconductance of the CFTA, and also exhibit low active and passive component sensitivities. The characteristics of the
proposed filters are tested using PSPICE simulation program, and the simulation results agree well with the theoretical analysis.

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