Novel Resistorless First-Order Current-Mode Universal Filter Employing a Grounded Capacitor

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Abstract. *In this paper, a new bipolar junction transistor (BJT) based configuration for providing first-order resistorless current-mode (CM) all-pass, low-pass and high-pass filter responses from the same configuration is suggested. The proposed circuit called as a first-order universal filter possesses some important advantages such as consisting of a few BJTs and a grounded capacitor, consuming very low power and having electronic tunability property of its pole frequency. Additionally, types of filter response can be obtained only by changing the values of current sources. The suggested circuit does not suffer from disadvantages of use of the resistors in IC process. The presented first-order universal filter topology does not need any passive element matching constraints. Moreover, as an application example, a second-order band-pass filter is obtained by cascading two proposed filter structures which are operating as low-pass filter and high-pass one. Simulations by means of PSpice program are accomplished to demonstrate the performance and effectiveness of the developed first-order universal filter.*

Keywords

Current-mode, Universal filter, Resistorless, BJT.

1. Introduction

Since before now, great interest has been devoted to realization of analog circuits and basic building blocks employing bipolar junction transistors (BJTs) constructed of doped semiconductor materials which can be used in many applications [1]. Apart from these, since the use of grounded capacitors is beneficial in IC implementations, they are widely preferred by researchers [2], [3], [4].

At present, current-mode (CM) circuits are receiving much attention. As declared before in [5], [6], [7], the use of CM processes has some important advantages over that of voltage-mode (VM) ones, for instance wider bandwidth, bigger dynamic range, better linearity and more simple realizations.

Electronic tunability of a circuit in IC technology is one of the important issues [8]. In a tunable circuit, control can be achieved electronically via biasing currents in BJT technology. A number of first-order configurations were reported in the open literature [8] – [24]. Quite a large number of filters composed of basic building block(s) such as current conveyors and current controlled conveyors were also previously reported whereas each of the blocks uses tens of transistors [8] – [21]. Unfortunately, most of the presented circuits require floating capacitors [8] – [11], [20], [23], [24]. Also, most of reported circuits employ resistor [9] – [11], [13] – [18], [24] while some of them suggest resistorless design [8], [12], [19] – [23]. The topology of [22] contains tens of CMOS transistors. A bipolar technology based structure for realizing first-order VM filter response is suggested in [24] which employs several resistors, a floating capacitor, and has lack of electronic tunability. A new resistorless all-pass filter has been offered recently in [23]. The proposed circuit has all features of the all-pass filter of [23]; additionally, the proposed ones have a grounded capacitor and high output impedance resulting in easy cascadability with other CM circuits.

In the last decades, another current mode resistorless signal processing method named as log domain filtering was proposed by Frey [25] – [29]. Essentially, this class of circuits, based on the principles of translinear circuits, runs in nonlinear operation while keeping the transfer function to be linear. This type of filters offers large signal linearity [27]. Since the cut of frequency defined as inversely proportional with a term which is dependent on capacitor value, thermal voltage and dc control current, it can easily be electronically tunable in log domain circuits. On the other hand, proposed filter also can be electronically controllable with same terms scaled by $(\beta + 1)$. This yields that in order to obtain the same cut off frequency, less valued capacitor which is more suitable for IC process [2] – [4] is employed in the proposed design method.

The proposed universal circuit can produce first-order low-pass, high-pass and all-pass filter characteristics. It has other important features such as using only a grounded capacitor, fewer transistors when compared to previously published ones and providing electronic tunability through bias currents. Additionally, the filter can be switched between modes like low-pass, high-pass, and all-pass, by simply tuning the values of some current sources.

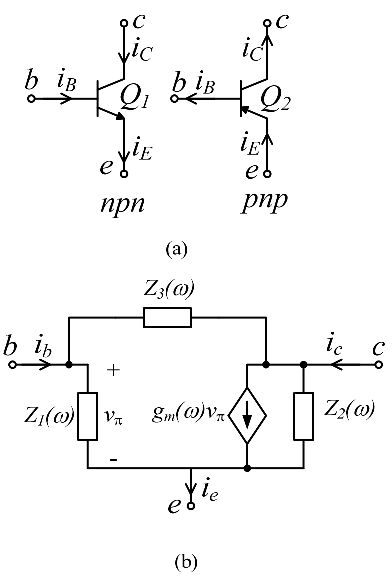


Fig. 1. (a) Electrical symbols of both of *npn*-type and *pnp*-type BJTs and (b) their small signal model.

The introduced circuit is free from critical passive component matching conditions and cancellation constraints and provides high output impedance current yielding easy cascadability. Second-order band-pass filter obtained by cascading a low-pass filter and a high-pass filter is also presented as an application example of the proposed first-order universal filter.

Parallel simulations based on the PSpice program are performed for the designed circuits in order to verify the theoretical results. It is well known that technologic devices especially communication's equipments make an endeavor to get some features such as small sizing, low power consumption. The proposed universal filter satisfies all these requirements.

2. Proposed First-Order Universal Filter

2.1 Fundamental Component Approximation

As an active device, both of *npn*-type and *pnp*-type BJTs shown in Fig. 1(a) are commonly preferred by researchers for general purpose, and can be used as voltage controlled current sources. A BJT has two ports which are dependent on themselves. A general small signal equivalent circuit is given in Fig. 1(b), in which parameters, impedances and transconductance gain, depend on frequency of the signal. Frequency dependent impedances of equivalent small signal model are composed of body resistors and junction parasitic capacitances [1]. Especially parasitic capacitances are very important for high frequency operations. Some parameters can be neglected for general purpose. In the basic concept, in the equivalent circuit, parameters of the small signal model are defined as transconductance $g_m = I_C / V_T$, base-emitter voltage v_π and input resistance seen from base $r_\pi = V_T / I_B = (\beta + 1)\, r_e$ where V_T is the thermal voltage approximately equal to 26 mV at room temperature and $r_e = V_T / I_E$ is the small signal resistance seen from emitter [1].

The terminal currents of an *npn*-type BJT can be defined as

$$i_E = i_C + i_B \,. \tag{1}$$

Here,

$$i_E = I_E + i_e \,, \tag{2.a}$$

$$i_C = I_C + i_c \,, \tag{2.b}$$

$$i_B = I_B + i_b \,. \tag{2.c}$$

In (2), I_E, I_C and I_B are dc currents while $i_e \ll I_E$, $i_c \ll I_C$ and $i_b \ll I_B$ are ac small currents.

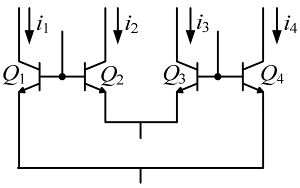
2.2 Static Translinear Principle and Design of Constant Multiplying Block

The well-known translinear principle introduced by Gilbert [30] based on exponential relation between voltage and current of bipolar transistor biased in active region is a very popular analysis and synthesis method for analog circuits. The static translinear circuits that are used for realizing static transfer functions can be classified as a restricted application of general translinear circuits [31]. It means that the gain and phase defined between output current and input current are not exposed to any attenuation and phase delay respectively for all frequency spectrum in the ideal condition. Two examples of translinear circuits, which are up-down translinear loop and stacked translinear loop are given in Fig. 2 [31].

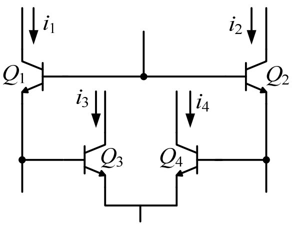
In this figure, it is assumed that all transistors are biased, they are operating in the active region. It is also supposed that the base currents of transistors are provided and all transistors operate at the same temperature. The following expression consists of transistor currents (i_m, m =1, 2, 3) and saturation currents (i_{Sm}, m =1, 2, 3) can be obtained by using closed loop Kirchhoff voltage equation. The saturation currents (I_S) can be expressed in terms of current densities. If all transistors have approximately equal emitter areas, saturation currents can be neglected

$$\frac{i_1}{I_{S1}}\frac{i_3}{I_{S3}} = \frac{i_2}{I_{S2}}\frac{i_4}{I_{S4}} \,. \tag{3}$$

This type of translinear circuits can be used for realizing a constant multiply block, which plays an essential role for synthesizing a system. Since the proposed circuit is considered as current mode circuit and it is processing input signal, the multiplier circuit has to amplify / attenuate the input current signal. Consider that i_1 and i_4 are the input current and the output current respectively. By choosing i_3 and i_2 as dc current, the output current is obtained as scaled input current by proportion of dc currents. An example of this type of circuit and its block are given in Fig. 3. As shown in this figure obviously, the output current is scaled by the factor of n, when forward current gain (β) is assumed as infinity and emitter nodes of Q_1 and Q_4 transistors are tied to the same potential.

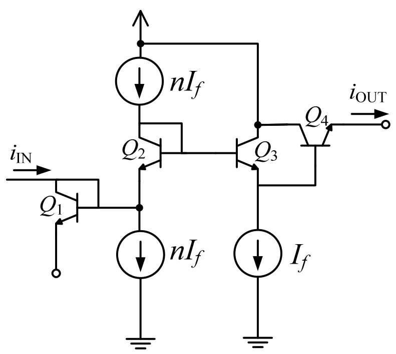


(a)



(b)

Fig. 2. (a) Up-down translinear loop and (b) stacked translinear loop.



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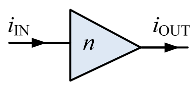
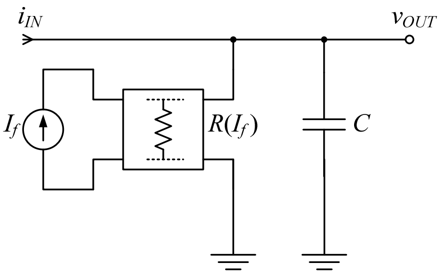


(b)

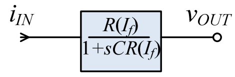
Fig. 3. (a) Constant multiplying circuit and (b) its block.

2.3 The Concept of Electronically Tunable Transresistance Lossy Integrator

Electronically tunable integrators are very useful building blocks in circuit design [32] – [33]. It offers important advantages such as easy controllability. In this paper, transresistance lossy integrator will be used to obtain the feature of frequency selectivity. This type of blocks integrates input signal while converting input current to output voltage. A basic example of electronically tunable lossy integrator concept and its block are shown in Fig. 4. In this circuit, the resistance value can be electronically tunable such as changing the control current.



(a)



(b)

Fig. 4. (a) Electronically tunable lossy integrator circuit and (b) its block.

2.4 State-Space Synthesis of First-Order Universal Filter

Since the state space synthesis method provides very general solutions for realizing a filter function, it is a very powerful and efficient approach in the synthesis filters [25], [26]. In order to obtain these advantages state space synthesis method is used in this work. Many researchers employed state-space modeling technique to design filter circuits [25], [26] , [34] – [36]. This method defines not only input and output signals but also internal state variables. This allows us to observe and control all internal variables. Therefore, we can obtain internal data simply by using dynamic state space equations. Moreover, the method can be applied for both nonlinear systems and time-variant systems.

Starting point of designing a first-order filter circuit is to determine the parameter of the transfer function, which constitutes the characteristic of the filter in frequency and time domain. The parameter of the desired filter circuits can be obtained in several ways such as by using design parameter table or by using mathematical programs. Let us consider a generalized first-order transfer function as follows:

$$H(s)=\frac{Y}{U}=\frac{n_1 s+n_2\omega_0}{s+\omega_0}\,. \tag{4}$$

It is observed from equation (4) that by setting $n_1 = 0$ and $n_2 = 1$, $n_1 = -1$ and $n_2 = 0$, $n_1 = -1$ and $n_2 = 1$ first-order low-pass filter, first-order high-pass filter and first-order all-pass filter are obtained respectively.

Many techniques are available to get state space representations of the given transfer function systems. One of them is known as companion form technique. In the time domain, according to this procedure, the obtained state space equations of generalized first-order transfer functions can be represented in the following equations

$$\dot{x}=-\omega_0 x+\left(n_2-n_1\right)\omega_0 u, \tag{5}$$

$$y=x+n_1 u \tag{6}$$

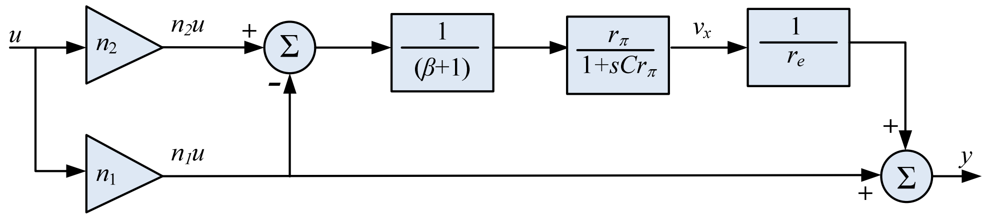


Fig. 5. Block diagram of state equations.

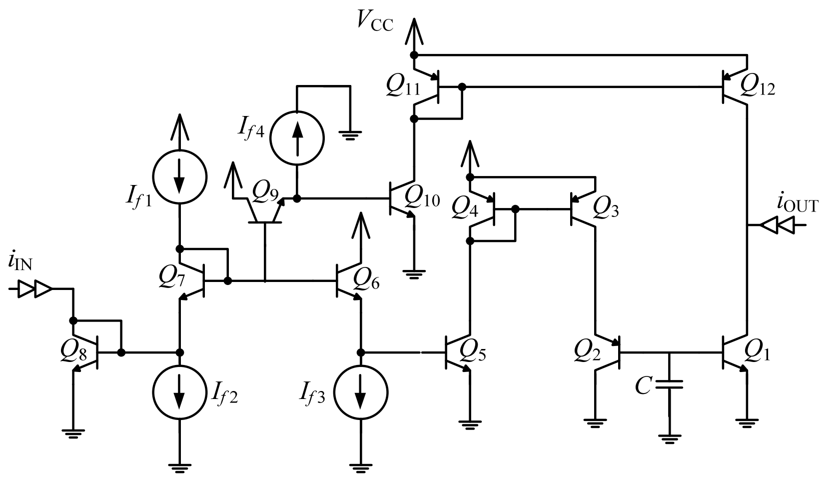


Fig. 6. Complete circuit of proposed universal filter.

where x is the state variable, u and y are the input and output variables respectively.

The key aspect of the synthesis of the proposed filter is mapping to state space variable. Due to this transformation, state equations become nodal equations. In the following equation, mapping function of the state variable is shown. The function of f depends on voltage of the corresponding node.

$$x(t) = f\left(v(t)\right). \tag{7}$$

After mapping by f function state space equations are yielded as follows,

$$\frac{df\left(v(t)\right)}{dt} = -\omega_0 f\left(v(t)\right) + \left(n_2 - n_1\right)\omega_0 u\,, \tag{8}$$

$$y = f\left(v(t)\right) + n_1 u\,. \tag{9}$$

Since in this paper we focus on resistorless first-order filter design, we choose linear mapping function as

$$x(t) = f\left(v(t)\right) = \frac{v_x}{r_e}\,. \tag{10}$$

Note that in this equation, function of f may be assigned to different transformations which yield distinct circuit topologies. Similar design procedure is used to obtain log domain filters by employing nonlinear exponential mapping which is a more suitable nature of BJT. However, circuits obtained using the proposed technique need less valued capacitor and low component count BJTs. For example first order log domain circuit employs four BJTs and in order to have 500 kHz pole frequency when dc current is equal to 10 μA it uses 123 pF capacitor value. On the other hand the proposed filter needs two BJTs and it uses 1.23 pF capacitor value when the forward current gain is equal to 100.

By substituting this transformed term in equation (8), the following expression is yielded

$$\frac{\dot{v}_x}{r_e} = -\omega_0\frac{v_x}{r_e} + \left(n_2 - n_1\right)\omega_0 u\,. \tag{11}$$

Let us multiply any term of the above equation with Cr_e where C is constant and r_e is the small signal resistance seen from emitter [1]. It yields the following:

$$C\dot{v}_x = -\omega_0 C v_x + \left(n_2 - n_1\right)\omega_0 C r_e u\,. \tag{12}$$

By appointing the cut off frequency of first-order filter as

$$\omega_0 = \frac{1}{Cr_e(\beta+1)}$$

and by applying the same transformation to equation (9), the nodal equations are obtained as follows

$$C\dot{v}_x = -\frac{v_x}{r_e\left(\beta+1\right)} + \frac{\left(n_2 - n_1\right)}{\left(\beta+1\right)}u\,, \tag{13}$$

$$y = \frac{v_x}{r_e} + n_1 u\,. \tag{14}$$

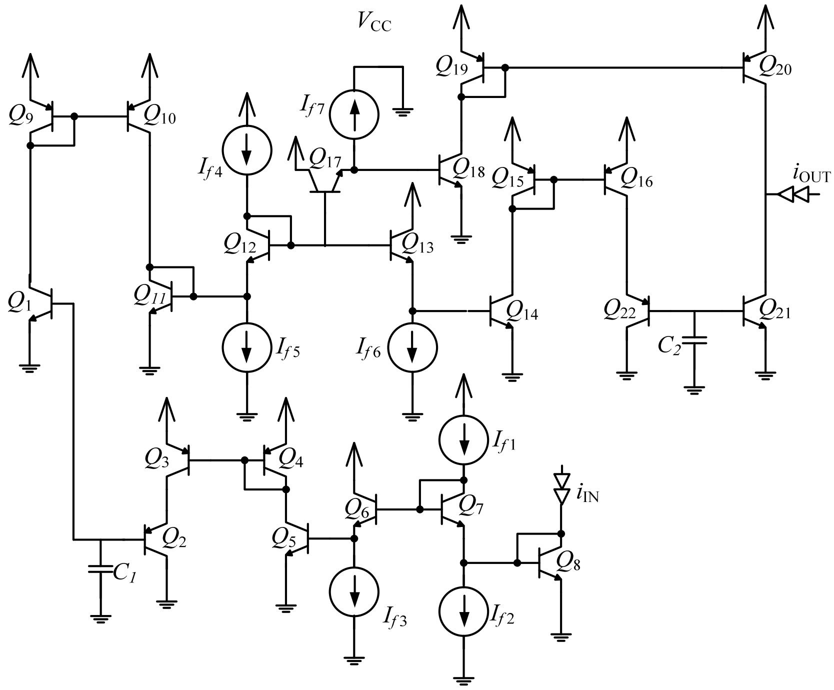


Fig. 7. Complete circuit of the second-order band-pass filter.

Each equation defines current law of corresponding node where v_x represents the node voltage. In this context, if we adopt C is a capacitor value, $C\dot{v}_x$ represents the current flowing through grounded capacitor tied to the node.

Block diagram of state equations is depicted in Fig. 5. Let us assume input signal (u) and output signal (y) is current. This block diagram consists of one scaling block, one transresistance lossy integrator block, one voltage to current convertor block, two constant multiplying blocks and two summing blocks.

All blocks of the proposed structure are designed using the mentioned synthesis method. This can be realized with bipolar transistors and current sources. The proposed complete circuit of universal filter is given in Fig. 6.

The proposed filter has single input and single output. The circuit in Fig. 6 consists of three parts, main circuit composed of Q_1, Q_2, capacitor, constant multiplying circuit employs $Q_5 - Q_{10}$ and current mirrors use Q_3, Q_4 & Q_{11}, Q_{12}. In this circuit the emitter area of Q_3 transistor is chosen 20 % less than of the other transistors. All of functional blocks such as scaling block, transresistance lossy integrator block given in Fig. 5 are realized in the proposed universal filter circuit. Note that the proposed circuit uses grounded capacitors which are particularly attractive for IC process [2] – [4].

In the proposed universal filter circuit, fundamental first-order filter characteristics which are high-pass, all-pass and low-pass are produced. The current sources are used for biasing transistors to ensure that they are operating in forward active region. The natural frequency of the filter can be tuned electronically only by varying the currents of these current sources. Moreover the proportion of current sources' values assign the multiplying constant term which determines the type of filter. It means that the proposed filter can be switched between modes, i.e., high-pass, all-pass and low-pass, by simply tuning the values of some current sources. The current sources should be set as depicted in the following equation

$$I_{f1} = I_{f2} = I_{f4} = kI_f, \quad I_{f3} = I_f \tag{15}$$

where $k = (n_2 - n_1)$.

One of the applications of the realized first-order universal filter is a second-order band-pass filter employing only grounded and canonical number of capacitors and BJTs, which is shown in Fig. 7. Essentially, this filter is obtained by cascading two proposed first-order universal filters as a low-pass filter and a high-pass filter.

2.5 High Frequency Analysis of Transfer Function of Proposed Filter

Using a single pole model for β [37], [38], it can be physically defined by

$$\beta(\omega) = \frac{\beta_0}{1 + \dfrac{j\omega}{\omega\beta}} \tag{16}$$

where ω_β and β_0 are expressed as pole frequency and dc gain of $\beta(\omega)$, respectively. Let us assume β is much bigger than unity, then it yields cut off frequency $\omega_0 = 1 / (Cr_e\beta)$. When the forward current gain of cut off frequency equation is replaced by (16), the following modified cut off frequency is obtained:

$$\hat{\omega}(\mathrm{j}\omega)=\frac{1+\dfrac{\mathrm{j}\omega}{\omega_\beta}}{Cr_e\beta_0}=\omega_0\left|T(\mathrm{j}\omega)\right|\exp\left(\varphi(\mathrm{j}\omega)\right) \tag{17}$$

where

$$\left|T(\mathrm{j}\omega)\right|=\sqrt{1+\left(\frac{\omega}{\omega_\beta}\right)^2}, \tag{18}$$

$$\varphi(\mathrm{j}\omega)=\arctan\left(\frac{\omega}{\omega_\beta}\right). \tag{19}$$

Let us consider the general transfer function of first-order filter given in (3). In (20) this function is re-written in frequency domain as

$$H(\mathrm{j}\omega)=\left|H(\mathrm{j}\omega)\right|\exp\left(\Psi(\mathrm{j}\omega)\right) \tag{20}$$

where

$$\left|H(\mathrm{j}\omega)\right|=\frac{\sqrt{\left(n_2\omega_0\right)^2+\left(n_1\omega\right)^2}}{\sqrt{\left(\omega_0\right)^2+\left(\omega\right)^2}}, \tag{21}$$

$$\Psi(\mathrm{j}\omega)=\arctan\left(\frac{n_1\omega}{n_2\omega_0}\right)-\arctan\left(\frac{\omega}{\omega_0}\right). \tag{22}$$

If the equation in equation (17) is replaced in equation (20), the following modified transfer function is obtained:

$$\hat{H}(\mathrm{j}\omega)=\left|\hat{H}(\mathrm{j}\omega)\right|\exp\left(\hat{\Psi}(\mathrm{j}\omega)\right) \tag{23}$$

where

$$\left|\hat{H}(\mathrm{j}\omega)\right|=\frac{\sqrt{\left(n_2\omega_0\right)^2+\omega^2\left(n_1+\dfrac{n_2\omega_0}{\omega\beta}\right)^2}}{\sqrt{\left(\omega_0\right)^2+\omega^2\left(1+\dfrac{\omega_0}{\omega_\beta}\right)^2}}, \tag{24}$$

$$\hat{\Psi}(\mathrm{j}\omega)=\arctan\left(\frac{\omega\left(n_1+\dfrac{n_2\omega_0}{\omega\beta}\right)}{n_2\omega_0}\right)-\arctan\left(\frac{\omega\left(1+\dfrac{\omega_0}{\omega_\beta}\right)}{\omega_0}\right). \tag{25}$$

If $\omega \ll \omega\beta$ is chosen, transfer function is to be $\hat{H}(\mathrm{j}\omega)=H(\mathrm{j}\omega)$. Otherwise, additional terms mentioned above modify the cut off frequency, ω_0 and transfer function, $H(\mathrm{j}\omega)$. This high frequency analysis yields that cut off frequency of the proposed filter should be set as $\omega_0 \leq 0.05\ \omega_\beta$. The value of pole frequency, ω_β is measured as approximately 48.2 Mrad/s.

It is important to note that the responses of the introduced filter in equation (17) have no stability problem as explained in [38].

3. Simulation Results and Discussions

In order to verify the theoretical synthesis, the proposed universal filter is simulated using PSpice with CBIC-R real transistor model [25] and default BJT model in which the values of *BF*s are set to be the same values of CBIC-R models. Since the default model of bipolar transistors do not suffer from non-ideal characteristics, obtained simulation results using this type of transistors are called as ideal. The results obtained after simulating the proposed universal filter for both of two transistors are in acceptable limits. The difference between them arises from non-idealities of the BJTs. Moreover, the simulation results including both transient and frequency domain analysis ones, agree quite well with the theoretical analysis.

The circuit supply voltage is selected to be 3 V. The total power dissipation is found as 834 μW, which is considerably low. The value of capacitance of lossy integrator is chosen to be $C = 50$ pF. The values of current sources are set to be around 40 μA. The measured cut off frequency for this operating point has approximately less than 3 % error due to calculated value of this parameter. Basically, by adjusting the values of current sources, this small difference can be tolerated. It should be noted that not only cut off frequency but also type of filter can be adjustable only by varying the values of the current sources of the circuit.

First simulation is performed for ac response of the circuit in which pole frequency is set to approximately $f_o = 39$ kHz. The frequency responses of all possible first-order filter characteristics are obtained. The gain characteristics of fundamental filter responses are given in Fig. 8.

Next simulation is performed for phase response of the all-pass circuit by tuning the pole frequency electronically. The value of capacitors remains unchanged. By varying the values of the dc current source, the pole frequency is tuned. It means that this advantage gives us a wide area of usage without modification of circuit architecture. The obtained phase response is plotted in Fig. 9 using CBIC-R transistors. It is shown that the cut off frequency f_o can be swept approximately two decades by only adjusting values of current sources.

All measured cut off frequencies of high-pass filter, all-pass filter and low-pass filter with respect to value of dc current source are given in Figs. 10, 11, 12 respectively . In these figures, the dc current sources are swept from 1 μA to 200 μA to tune the resonance frequencies of the filters where the value of capacitor remains unchanged. As seen from the figures, the simulated and ideal results are in accordance with each other.

A sinusoidal signal applied to the proposed circuit as input scaled from 0.1 times of dc current source to 0.8 times of one. The output signal's THD was measured for each case and all filter response. The THD% values are in increment behavior while input peak value is growing. Results of these simulations are given in Fig. 13.

Proposed universal filter circuit obeys grounded capacitor suitable for IC process. As it is well known, since parameters of electronic devices vary due to tolerances incurred from manufacturing processes, obtained results can be affected. To observe these variations and their affect, Monte Carlo (statistical) analysis is performed for

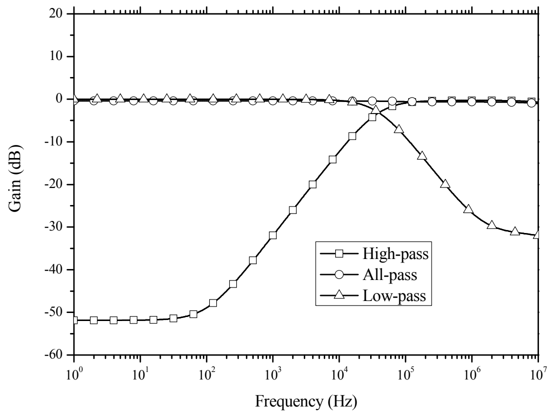


Fig. 8. Gain responses of proposed universal filter.

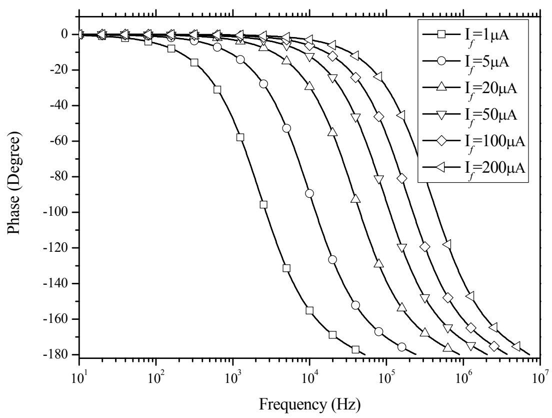


Fig. 9. Phase responses of first-order all-pass filter against frequency for various control currents I_f.

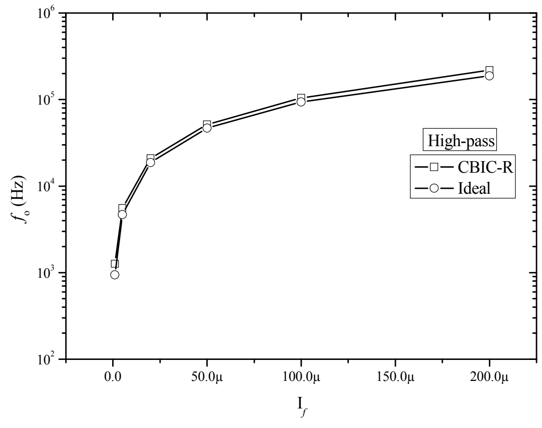


Fig. 10. Tunable f_o for high-pass filter with respect to control current.

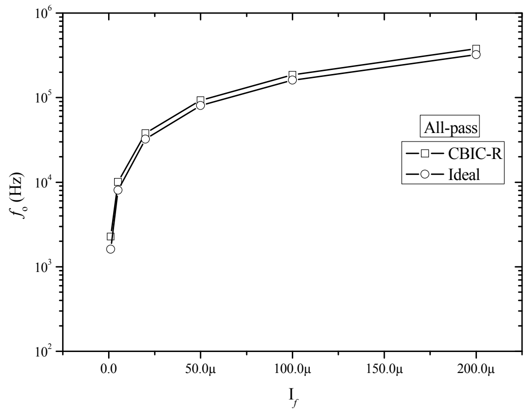


Fig. 11. Tunable f_o for all-pass filter with respect to control current.

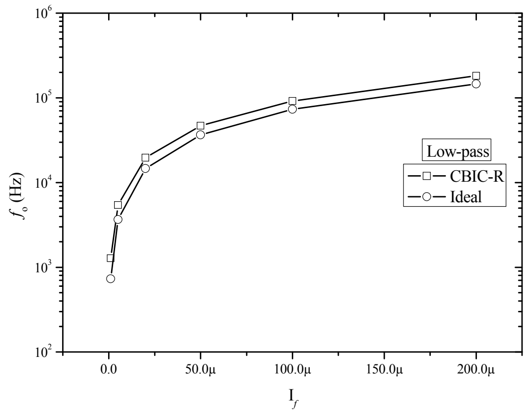


Fig. 12. Tunable f_o for low-pass filter with respect to control current.

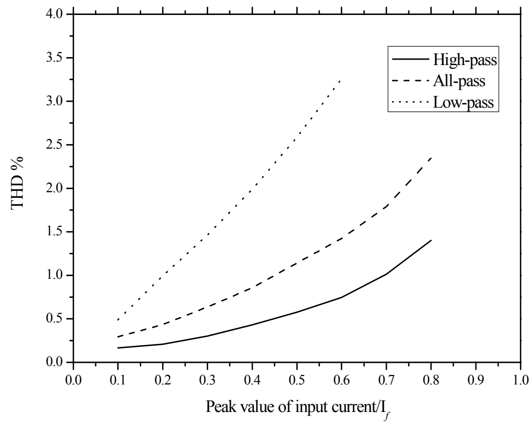


Fig. 13. THD values of low-pass, high-pass and all-pass filters versus ratio of peak sinusoidal input current to dc current.

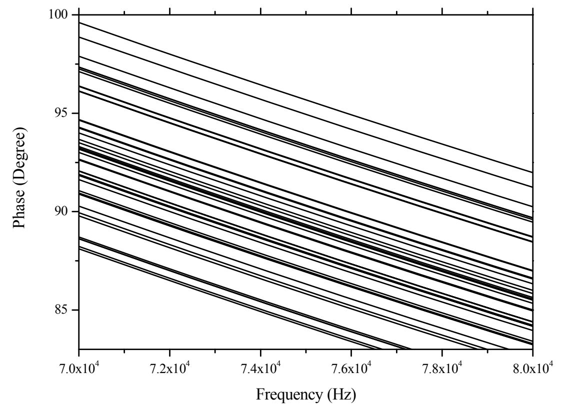


Fig. 14. Phase response changes due to variation of the value of capacitor.

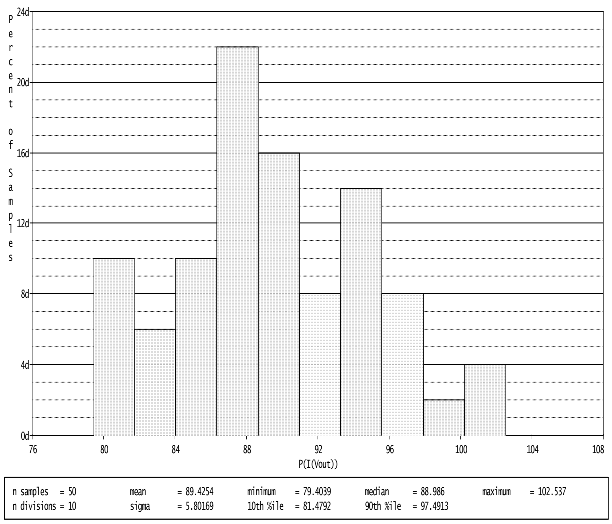


Fig. 15. The deviation in phase angle at resonance frequency of all-pass filter where the capacitor value is changed.

capacitor. By setting the value of capacitor with 5 % Gaussian deviation, all-pass filter is simulated. The dc current is $I_f = 40$ µA, capacitor value is 50 pF yielding resonance frequency of approximately 75 kHz. After 50 simulations in which the capacitor model parameter randomly varies for which we have defined tolerance, obtained simulation results are given in Figs. 14 and 15. In the first figure obtained from Monte Carlo analysis, the resonance frequency is affected in the range of −6.23 % +6.37 % which is acceptable. In the second figure a histogram graphic is given. As seen from these figures, the graphic is approximately suitable with Gaussian distribution.

The simulated second-order band-pass filter response is shown in Fig. 16 in which bias currents of both filters are selected as equal to each other. Gain response of each block, low-pass filter block and high-pass filter block is given in the figure as well. Additionally, by varying the values of the dc current source, the center frequency is tuned. The results are shown in Fig. 17. The values of capacitors remain unchanged.

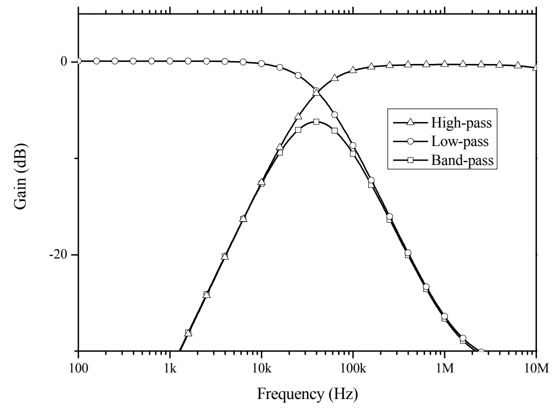


Fig. 16. Gain responses of the filter given in Fig. 7.

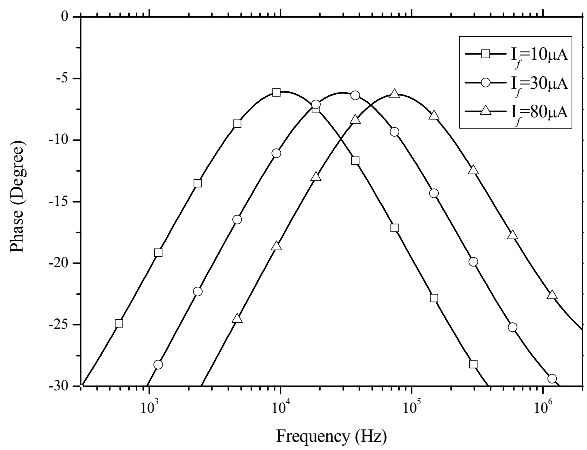


Fig. 17. Gain responses of the second-order band-pass filter against frequency for various control currents I_f.

Finally, noise analysis is performed for all filter approximations. The measured noises' values are presented in Tab. 1.

Filter Approximation	Noise
High-pass	$141.143\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$
All-pass	$152.144\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$
Low-pass	$141.016\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$

Tab. 1. Noise values of all filters.

4. Conclusion

BJT technology based novel circuit for realizing first-order CM, low-pass, high-pass, and all-pass filter responses from the same topology without requiring passive element matching conditions is presented. Characteristic parameter the resonance frequency, f_o, of the designed filter can be changed electronically by adjusting the values of dc current sources only. Moreover, the filter can be switched between modes like low-pass, high-pass, and all-pass, by simply tuning the values of some current sources. The designed filter circuit is simulated in PSpice by using both idealized and real modeled transistors. Parallel simulations evidence that the designed circuit is verified and the simulation results agree quite well with the theoretical analysis. In addition to this, both time domain and frequency domain results show that the designed filter takes advantages of current mode circuits. These advantages include electronic tunability and good stability. Additionally, second-order band-pass filter is presented as an application example which is obtained by cascading two first-order filters. In conclusion, it is expected that the developed simple structure will be useful as a first-order CM universal filter in analog communication systems and signal processing.

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