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Research Article

COMPARISON OF THIRD-ORDER ACTIVE-R FILTER WITH AND WITHOUT USING MULTIPLE FEEDFORWARD SIGNAL

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ABSTRACT
Comparison of Third-order Active-R Filter with and without using multiple feed forward Signal configurations is proposed. These circuits give three filter functions low-pass, high-pass and band-pass. This paper discusses a new configuration to realize third-order low pass, band pass and high pass. The presented circuits are using OP-AMP, passive components, multiple feedbacks and feed forward signals. The general range of this frequency response for these active-R filters is from 10 Hz to 1MHz. For higher and lower values of f_0, the proposed circuit filter can be used for wide bandwidth, whereas the previous reported circuit filter can be used for narrow bandwidth for all values of f_0. For high pass filter, circuit shows gain stabilization at 0 dB for higher values of f_0. The Ideal values of this filter which are closed to Ideal value of third-order active R filter are at f_0 <60 KHz, but in previous reported circuit, the gain doesn't get stabilized at 0dB for all values of Q and the overshoots appear for values of Q≥1. These filters circuits can be used for different cut-off frequencies f_0 and Merit Factor Q with high pass band gain. The advantages of these circuits are reduction in size and weight, increased circuit reliability, more economical and easy for manufacturing.

Keywords: *Third-Order Active-R Filter, Multiple Feed Forward Signals, Merit Factor Q, Cut-off Frequency*

INTRODUCTION
An electrical filter is a device designed to separate, pass or suppress a group of signals from a mixture of signals. It passes only the required signals and blocks the unwanted signals. Filters are basic electronic components used in the design of communication systems such as telephone, television, radio, radar and computer. Electrical filters permeate modern technology so much that it is difficult to find any electronic system that does not employ a filter in one form or another (Chen, 1986). These are frequency selective networks. Filters are also classified according to the functions they are to perform. The frequency ranges are defined as pass band and stop band. In ideal case, a pass band is the range of frequencies of the filter where signals are transmitted from input to output without attenuation of gain. In a stop band, transmission is blocked completely. The patterns of pass bands and stop bands give rise to most common filters as low pass, high pass; band pass and band stop (Kalsi, 2002). The operational amplifier (op. amp.) is now accepted as the basic active component for an inductor less filter. The circuit is realized using single pole (as "integrator") behavior of an internally compensated operational amplifier (Huelsman, 1971; Mohan and Patil, 1989; Shinde and Patil, 2002). The filter without the capacitor is called an active-R filter and has received much attention due to its potential advantages in term of miniaturization, ease of design and high frequency performance (Qasem and Shinde, 2013; Chavan and Shinde, 2013; Achole, 2006; Shinde and Achole, 2005; Jiang and Wang, 2006; Shinde *et al.*, 2002, 2003; Senani and Gupta, 2006; Shinde and Achole, 2003). It has been also pointed out in the literature that active-R networks offer substantially low sensitivity characteristics as compared to RC active structures (Soderstand and Mitra 1971). This paper proposes realization and design method for Third-order Active-R Filter with and without using multiple feed forward signal. These filters circuits give three filter functions low pass, high pass and band pass, with ideal gain roll-off and high pass band gain. These filters circuits are designed and studied for different values of Center Frequencies (f_0) and Merit Factor Q. The filters are extensively used in communication, instrumentation, control systems entertainment electronics, sonar systems etc.

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Proposed Circuit
Configuration

The proposed Comparison of Third-order Active-R Filter With and Without Using Multiple Feed forward Signal circuits diagram are shown in figures 1 and 2. With the advent of the high frequency roll-off in the response of the op.amp, the circuits are constructed with and without using multiple feed forward signal; three op. amplifiers (□A741) and four resistances. The op. amp can be used as an inverting or non-inverting grounded integration depending on connection with identical gain bandwidth product as an active element.

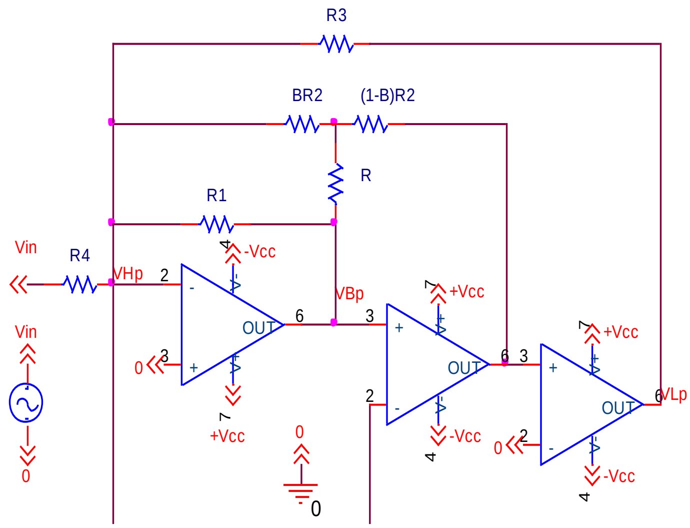

Figure 1: Previous Reported Circuit diagram for third-order active-R filter without multiple feed forward Signal

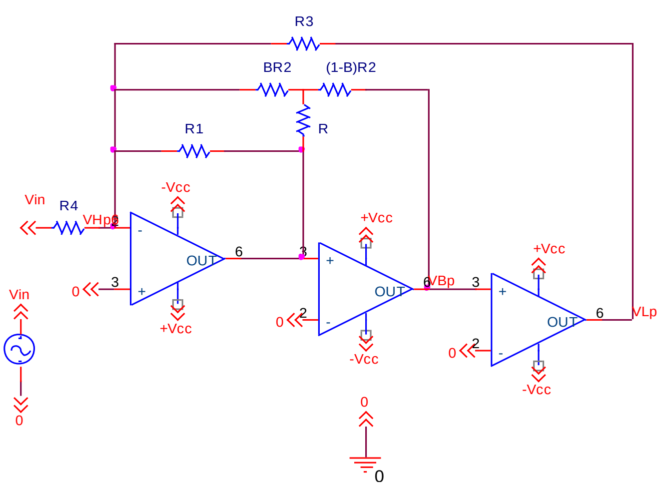

Figure 2: Proposed Circuit diagram for third-order active-R filter without multiple feed forward Signal

These filters give multiple outputs, which tend three filter functions, low pass, band pass and high pass. The negative feedback is introduced through resistances R_1; R_2 *and* R_3 from the output of three op. amplifiers to inverting input of the first op. amplifiers. The resistance R_2 is tapped at different points for variation in feedback. The op-amplifiers are coupled such that output of first op- amplifier is connected to non-inverting input of second op-amplifier and output of second op-amplifier is connected to non-inverting input of third op-amplifier. Non-inverting terminal of first op-amplifier, inverting terminal of second and third op-amplifiers are grounded in figure 2 whereas in figure1 inverting terminal of second op-amplifier is connected to Non-inverting terminal of first op-amplifier. The input is applied to inverting input of first op- amplifier through resistance R_4.

Circuit Analysis and Design Equations

The single-pole model of an op-amplifier leads to complex gain and the transfer function is given by (Chavan and Shinde, 2013).

$$A(s) = A_0\omega_0 / (S+\omega_0) \qquad (1)$$

Where,

A_0 = open loop d.c. gain, ω_0 = open loop (3dB) bandwidth, $GB = A_0\,\omega_0$ = gain bandwidth product of op-amplifier.

$$A(s) = A_0\omega_0 / S = GB/S, \qquad (2)$$

Where, $S >> \omega_0$

This shows that the op-amplifier is an "integrator", Thus Third-order Active-R Filter transfer function at three different terminals are given below. The voltage transfer functions for low pass filter.

$$T_{LP}(S) = \frac{-(1/R_4)GB_1GB_2GB_3}{X_1S^3 + X_2S^2 + X_3S + X_4} \qquad (3)$$

The voltage transfer function for band pass filter

$$T_{BP}(S) = \frac{-(1/R_4)GB_1GB_2S}{X_1S^3 + X_2S^2 + X_3S + X_4} \qquad (4)$$

The voltage transfer function for high pass filter

$$T_{HP}(S) = \frac{(1/R_4)S^3}{X_1S^3 + X_2S^2 + X_3S + X_4} \qquad (5)$$

Where (for figure1),

$$X_1 = \left\{\frac{1}{R_1} + \frac{1}{BR_2} + \frac{1}{R_3} + \frac{1}{R_4} - \frac{(1-B)RM}{B}\right\}$$

$$X_2 = GB_1\left\{\frac{1}{R_1} + (1-B)R_2M + GB_2RM\right\}$$

$$X_3 = GB_1GB_2RM + \frac{GB_2GB_3}{R3}$$

$$X_4 = \left\{\frac{GB_1\,GB_2GB_3}{R3}\right\}$$

Where (for figure 2),

$$X_1 = \left\{\frac{1}{R_1} + \frac{1}{BR_2} + \frac{1}{R_3} + \frac{1}{R_4} - \frac{(1-B)RM}{B}\right\}$$

$$X_2 = GB_1\left\{\frac{1}{R_1} + (1-B)R_2M\right\}$$

$$X_3 = GB_1GB_2RM$$

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$X_4=\left\{\frac{GB_1\, GB_2 GB_3}{R3}\right\}$

$M=1/(RR_2+B(1-B)R_2^2)$

The circuit was designed using coefficient matching technique with general third-order filter transfer function (Mohan and Patil, 1989; Shinde and Patil, 2002)

$$T(S)=\frac{H_3S^3+H_2S^2+HS+H_0}{S^3+S^2\omega_0\left[(1/Q)+1\right]+S\omega_0^2\left[(1/Q)+1\right]\omega_0^3} \quad (6)$$

By comparing (3), (4) and (5) with (6), we get the design equation for figure 1 as

$$\left\{\frac{1}{R_1}+\frac{1}{BR_2}+\frac{1}{R_3}+\frac{1}{R_4}-\frac{(1-B)RM}{B}\right\}=1 \quad (7)$$

$$GB_1\left\{\frac{1}{R_1}+(1-B)R_2M+GB_2RM\right\}=W_0\{1+1/Q\} \quad (8)$$

$$GB_1GB_2RM+\frac{GB_2GB_3}{R3}=W_0^2\{1+1/Q\} \quad (9)$$

$$\left\{\frac{GB_1\, GB_2GB_3}{R3}\right\}=W_0^3 \quad (10)$$

Also the design equation for figure 2 as

$$\left\{\frac{1}{R_1}+\frac{1}{BR_2}+\frac{1}{R_3}+\frac{1}{R_4}-\frac{(1-B)RM}{B}\right\}=1 \quad (11)$$

$$GB_1\left\{\frac{1}{R_1}+(1-B)R_2M\right\}=W_0\{1+1/Q\} \quad (12)$$

$$GB_1GB_2RM=W_0^2\{1+1/Q\} \quad (13)$$

$$\left\{\frac{GB_1\, GB_2GB_3}{R3}\right\}=W_0^3 \quad (14)$$

So that Values of R_1, R_2, R_3 and R_4 can be calculated using these equations for different values of f_0, Q, B and R.

Sensitivity

The sensitivities of ω_0 and Q in previous reported circuit are as follows.

$$S_R^{w0}=\frac{1}{3}\left[RM\left(\frac{1-B}{3B}\right)(1-RR_2M)\right]$$

$$S_{R1}^{w0}=\frac{1}{3}\left[\frac{1}{R_1}\right]$$

$$S_{R2}^{w0}=\frac{R_2}{3B}\left[\frac{1}{R_2}-RM^2(1-B)(R+2B(1-B)R_2)\right]$$

$$S_{R3}^{w0}=\frac{1}{3}\left[\frac{1}{R_3}-1\right]$$

$$S_{R4}^{w0} = \frac{1}{3}\left[\frac{1}{R_4}\right]$$

$$S_{GB1}^{w0} = S_{GB2}^{w0} = S_{GB3}^{w0} = \frac{1}{3}$$

$$S_{R}^{Q} = -(1+Q)RM(1-RR_2M)\left[\frac{GB1GB2}{Z} + (\frac{1-B}{3B}))\right]$$

$$S_{R1}^{Q} = -\frac{1}{3}(1+Q)\left[\frac{1}{R_1}\right]$$

$$S_{R2}^{Q} = -R_2(1+Q)\left[\frac{1}{3BR_2^2} - RM^2\,(R+2B(1-B)R_2)(\frac{GB1GB2}{Z} + (\frac{1-B}{3B}))\right]$$

$$S_{R3}^{Q} = -\frac{1}{3}(1+Q)\left[\frac{1}{R_3}\right]$$

$$S_{R4}^{Q} = -\frac{1}{3}(1+Q)\left[\frac{1}{R_4}\right]$$

$$S_{GB1}^{Q} = -(1+Q)\left[\frac{GB1GB2}{Z} - \frac{2}{3}\right]$$

$$S_{GB2}^{Q} = -\frac{1}{3}[(1+Q)]$$

$$S_{GB3}^{Q} = -(1+Q)\left[\frac{GB1GB2}{Z} - \frac{2}{3}\right]$$

And also the sensitivities of ω_0 and Q in Proposed circuit are as follows.

$$S_{R}^{w0} = \frac{1}{3}\left[\left(\frac{1-B}{B}\right)(1-RR_2M)\right]$$

$$S_{R1}^{w0} = \frac{1}{3}\left[\frac{1}{R_1}\right]$$

$$S_{R2}^{w0} = \frac{1}{3}\left[\frac{1}{BR_2} - RR_2\,M^2\,\left(\frac{1-B}{B}\right)(R_2 + 2B(1-\;B)R_2)\right]$$

$$S_{R3}^{w0} = -\;\frac{1}{3}\left[\;1+\frac{1}{R_3}\right]$$

$$S_{R4}^{w0} = \frac{1}{3}\left[\frac{1}{R_4}\right]$$

$$S_{GB1}^{w0} = S_{GB2}^{w0} = S_{GB3}^{w0} = \frac{1}{3}$$

$$S_{R}^{Q} = -(1+Q)\left[R(1-RR_2M)(\frac{1}{R} + \frac{1}{3}M(\frac{1-B}{B}))\right]$$

$$S_{R1}^{Q} = -\frac{1}{3}(1+Q)\left[\frac{1}{R_1}\right]$$

$$S_{R2}^{Q} = -R_2(1+Q)\left[\frac{1}{3}(\frac{1}{BR_2^2} - RM\left(\frac{1-B}{B}\right)(R_2+2B(1-B)R_2)) - R_2\,M(1+2B(1-B))\right]$$

$S_{R3}^{Q} =-\frac{1}{3}(1+Q)\left[1+\frac{1}{R_3}\right]$

$S_{R4}^{Q} =-\frac{1}{3}(1+Q)\left[\frac{1}{R_4}\right]$

$S_{GB1}^{Q} =-\frac{1}{3}[(1+Q)]$

$S_{GB2}^{Q} =-\frac{1}{3}[(1+Q)]$

$S_{GB3}^{Q} = -\frac{2}{3}[(1+Q)]$

Thus, passive and active sensitivities (except S_{R2}^{Q} *and* S_{GB3}^{Q} for previous reported circuit) are all less than unity. So for all practical purposes these circuits are stable as these sensitivities are very low.

Experimental

The circuits performance were studied with different values of f_0 (*10, 30, 60 and 100*) all in KHz with constant values B=0.5 and R=400 Ω for GB=$2\pi \times 5.6 \times 10^5\ rad/sec$. Same circuits were also studied for different values of design merit factor Q (0.1, 1, 6 and 10) with constant values of B=0.5 and R=400 Ω. The observed frequency response shows good agreement with theoretical results. The general range of this frequency response for these active-R filters is from 10 Hz to 1MHz as operating range of this op.amp is 10 Hz to 1.2 MHz following observations are noticed from experimental study at three different terminals low pass, band pass and high pass filter function for different values of f_0 and Q.

RESULT AND DISCUSSION

For Different Values of F_0

Low pass response

Table 1: Comparison of low pass (Lp) response for different values of f_0

f_0(KHz)	Max pass-band gain (dB)		Gain Roll-off in stop-band dB/octave		Overshoot in pass-band			
					P_{RC}		P_C	
	P_{RC}	P_C	P_{RC}	P_C	dB	f_{osh} (KHz)	dB	f_{osh} (KHz)
10	79.5	104.5	24	18.1	-	-	-	-
30	72	75	9	18	-	-	-	-
60	57	55.7	9	18	-	-	-	-
100	42.4	40	16	18	2.5	80	-	-

P_{RC} :Previous Reported circuit P_C :Proposed circuit

The maximum pass band gain varies from 104.5 dB for f_0=10KHz to 40 dB for f_0=100KHz, and the gain roll-off per octave in stop band varies between 18.1 to 18 dB/octave, which are closed to ideal value of 18 dB/octave for third order filter. But in previous reported circuit studies maximum pass band gain varies between 79.5 dB for f_0=10KHz to 42.4 dB for f_0=100KHz, and the gain roll-off per octave in stop band varies between 9 to 24 dB/octave (Achole, 2006). The response also shows no overshoot for all values of f_0 in proposed circuit. But it appears for f_0=100 KHz in previous reported circuit.

Band Pass Response

The maximum pass band gain varies between 66.6 dB for f_0=10 KHz to 22.2 dB for f_0=100 KHz, and bandwidth also varies between 35.2 KHz for f_0=10 KHz to 123 KHz for f_0=100 KHz. The gain roll-off per octave in the leading and trailing parts in the stop band are 6dB/octave and 12 dB/octave respectively for all values of f_0, which are closed to ideal value of third order filter. But in previous reported circuit studies

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the maximum pass band gain varies between 70 dB for f_0=10 KHz to 36.5 dB for f_0=100 KHz, and bandwidth also varies between 10.5 KHz for f_0=10 KHz to 38 KHz for f_0=100 KHz. The gain roll-off per octave in the leading and trailing parts in stop band isn't almost same for all values of f_0 (Achole, 2006). f_0 controls band width. For higher and lower values of f_0, proposed circuit filter can be used for wide bandwidth, whereas previous reported circuit filter can be used for narrow bandwidth for all values of f_0.

Table 2: Comparison of band pass (Bp) response for different values of f_0

f_0(KHz)	Max pass-band gain(dB)		Gain Roll-off in stop-band dB/octave				Bandwidth (KHz)	
	P_{RC}	P_C	P_{RC}		P_C		P_{RC}	P_C
			Leading part	Trailing part	Leading part	Trailing part		
10	70	66.6	0.5	13.5	6	12	10.5	35.2
30	54	46.7	12	16.5	6	12	22	73.7
60	43	33.5	14	14	6	12	50	109
100	36.5	22.2	12.5	17	6	12	38	123

P_{RC} :Previous Reported circuit P_C :Proposed circuit

High pass response

The gain gets stabilized at 0dB for all values of f_0 ≤60 KHz, and the gain roll-off per octave in stop band varies between17.5 to 18 dB/octave, which are closed to ideal value of 18 dB/octave for third order filter. But in previous reported circuit studies The gain doesn't get stabilized at 0dB for all values of f_0 ≥60 KHz, and the gain roll-off per octave in stop band varies between 3.5 to 18 dB/octave (Achole, 2006), which aren't closed to ideal value of 18 dB/octave for third order filter. The overshoot doesn't appear for all values of f_0 in proposed circuit, but it appears for all values of f_0 in previous reported circuit, and it increases as f_0 increases.

Table 3: Comparisons of High pass (Hp) response for different values of f_0

f_0(KHz)	Gain Roll-off in stop-band dB/octave		Gain stabilization at(KHz)				Overshoot in pass-band			
	P_{RC}	P_C	P_{RC}		P_C		P_{RC}		P_C	
			dB	F_s (KHz)	dB	F_s (KHz)	dB	f_{osh} (KHz)	dB	f_{osh} (KHz)
10	3.5	17.5	0	80	0	24	1.94	10	-	-
30	5.5	18	0	200	0	52	4.61	30	-	-
60	14	18	-0.2	800	0	150	4.5	60	-	-
100	18	18	-0.54	800	-0.5	200	6.98	100	-	-

P_{RC} :Previous Reported circuit P_C :Proposed circuit

For Different Values of Q

Low pass response

The maximum pass band gain varies from 91.2 dB for Q=0.1 to 94 dB for all other values of Q, and the gain roll-off per octave in stop band varies between 17.8 to 18 dB/octave, which are closed to ideal value of 18 dB/octave for third order filter. But in previous reported circuit studies maximum pass band gain varies between 34 dB for Q=.1 to 56.9 dB for all other vales of Q, and the gain roll-off per octave in stop band varies between 9 to 17 dB/octave (Achole, 2006). The response also shows no overshoot for all values of Q.

Table 4: Comparison of low pass (Lp) response for different values of Q

	Max pass-band	Gain Roll-off in stop-band	Overshoot in pass-band

Q	**gain(dB)**		**dB/octave**		**P_{RC}**		**P_C**	
	P_{RC}	**P_C**	**P_{RC}**	**P_C**	**dB**	**f_{osh} (KHz)**	**dB**	**f_{osh} (KHz)**
0.1	34	91.2	9	17.8	-	-	-	-
1	55.7	94	11	18	-	-	-	-
6	56.9	94	17	18	-	-	-	-
10	56.9	94	17	18	-	-	-	-
P_{RC} :Previous Reported circuit					P_C :Proposed circuit			

Band pass response

Table 5: Comparison of band pass (Bp) response for different values of Q

	Max pass-band gain(dB)		**Gain Roll-off in stop-band dB/octave**				**Bandwidth (KHz)**	
Q	**P_{RC}**	**P_C**	**P_{RC}**		**P_C**		**P_{RC}**	**P_C**
			Leading part	**Trailing part**	**Leading part**	**Trailing part**		
0.1	-3.9	39	3	3.5	6	12	107	55.6
1	33.5	58	8	13	6	12	77	48.7
6	42	62.4	11	14	6	12	52	43.2
10	43.1	62.4	12	14	6	12	50	43.2
P_{RC} :Previous Reported circuit					P_C :Proposed circuit			

The maximum pass band gain varies between 39 dB for Q=0.1 to 62.4 dB for all values of Q, and bandwidth also varies between 55.6 KHz for Q=0.1 to 43.2 KHz for all values of Q≥6. The gain roll-off per octave in the leading and trailing parts in the stop band are 6 dB/octave and 12 dB/octave respectively for all values of Q, which are closed to ideal value of third order filter. But in previous reported circuit studies the maximum pass band gain varies between -3.9 dB for Q=0.1 to 43.1 dB for Q=10, and bandwidth also varies between 107 KHz for Q=0.1 to 50 KHz for Q=10. The gain roll-off per octave in the leading and trailing parts in the stop band aren't almost same for all values of Q (Achole, 2006). Q controls the bandwidth. For higher and lower values of Q, the previous reported circuit filter can be used for wide bandwidth, whereas the proposed circuit can be used for narrow bandwidth for all values of Q.

High pass response

Table 6: Comparison of High pass (Hp) response for different values of Q

Q	**Gain Roll-off in stop-band dB/octave**		**Gain stabilization at(KHz)**				**Overshoot in pass-band**			
	P_{RC}	**P_C**	**P_{RC}**		**P_C**		**P_{RC}**		**P_C**	
			dB	***Fs* (KHz)**	**dB**	***Fs* (KHz)**	**dB**	**f_{osh} (KHz)**	**dB**	**f_{osh} (KHz)**
0.1	3.4	17.6	-	-	3.6	603	-	-	-	-
1	9.5	18	-0.7	500	0	55	0.46	60	-	-
6	14.7	18	-0.3	800	0	55	4.38	60	4.5	20
10	14	18	-0.2	800	0	55	4.5	60	4.6	20
P_{RC} :Previous Reported circuit							P_C :Proposed circuit			

The gain gets stabilized at 0dB for all values of Q≥1, and the gain roll-off per octave in stop band varies between 17.6 to 18 dB/octave, which are closed to ideal value of 18 dB/octave for third order filter. But in previous reported circuit studies The gain doesn't get stabilized at 0dB for all values of Q, and the gain roll-off per octave in stop band varies between 3.4 to 18 dB/octave (Achole, 2006), which aren't closed to ideal value of 18 dB/octave for third order filter. The overshoots appear for values of Q≥1, and it increases as Q increases. The response of proposed circuit shows excellent gain-roll off (18 dB/octave).

Conclusion

A realization of voltage-mode transfer function for Third-order Active-R Filter with and without using multiple feed forward Signal for different f_0 and Q has been presented. Also these filters circuits give three filter functions low pass, band pass and high pass. For higher and lower values of f_0, the proposed circuit filter can be used for wide bandwidth, whereas the previous reported circuit filter can be used for narrow bandwidth for all values of f_0. While For higher and lower values of Q, the previous reported circuit filter can be used for wide bandwidth, whereas the proposed circuit can be used for narrow bandwidth for all values of Q.

The low pass and band pass performance of the proposed circuit gives high pass band gain and excellent for lower value of f_0. For high pass filter, circuit shows gain stabilization at 0 dB for higher values of f_0. The Ideal values of this filter which are closed to Ideal value of third-order active R filter are at f_0 <60 KHz, but in previous reported circuit, the gain doesn't get stabilized at 0dB for all values of Q and the overshoots appear for values of Q≥1. The advantages of these circuits are reduction in size and weight, increased circuit reliability, more economical and easy for manufacturing.

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