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Feed Forward Third Order Switched Capacitor Filter for different circuit merit factor Q values

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Abstract

This paper proposes feed forward third order switched-capacitor filter. The circuit consists of only op-amps and switched capacitors. The circuit is designed for cut-off frequency 20 kHz. The proposed circuit implements three filter functions low pass, band pass and high pass simultaneously in single circuit. The circuit characteristics are studied for various values of circuit merit factors. In band pass operation pass band gain increases with increase in the value of Q. However pass band gain remains almost same for low pass filter. The gain-roll off for this circuit is close to the ideal value of 60dB as for third order filters. Thus, the circuit shows better response for Q > 10 and f_0 =20 kHz.

Keywords: Feed forward, third order filters, Switched capacitor (SC), pass band gain, Circuit merit factor, gain roll-off.

Introduction

Active filters with only resistors have many advantages in terms of miniaturization, ease of design and extension of response towards high frequencies [1,2]. The operational amplifier shows the high frequency roll off due to parasitic capacitances. Active-R circuits contain only op-amps and resistors, so that they are suitable for high frequency operation and integration with the bipolar monolithic technology [3, 4].

The need to have monolithic high-performance analog filters motivated circuit designers to investigate alternatives to conventional active-RC filters. A practical alternative appeared in the form of switched-capacitor (SC) filters. The original idea was to replace a resistor by an SC simulating the resistor. Thus, this equivalent resistor could be implemented with a capacitor and two switches operating with two-clock phases. SC filters consist of switches, capacitors, and op-amps. They are characterized by difference equations in contrast to differential equations for continuous-time filters [5].

SC approach overcomes some of the problems inherent in standard active filters while adding some interesting new capabilities. SC filters are low cost. They need a small chip area. They require low power. They are fully implementable in standard MOS processes [6]. They can be combined with digital circuits on one chip [7].

Switched-capacitor (SC) building blocks are often classified into two categories: *passive* and *active*. A passive SC building block (or element) is defined as a network composed of switches and capacitors only, whereas its active counterpart is not only built from switches and capacitors, but also active devices such as op-amps. Strictly speaking, a MOS switch is an active device, for it is composed of one or more transistors, which must be driven by the system clock or its derivatives [8].

Basic Switching operation:

The essence of the Switched-Capacitor is the use of Capacitors and analog Switches to perform the same function as resistors. This replacement of resistor, analog with op. amp based integrator, and then form an active filter [9]. Furthermore, the use of the Switched-Capacitor will be seen to give frequency tenability to active filters. Filter using Switched-Capacitor technique overcome a major obstacle of filter on a chip fabrication – the implementation of resistors by simulating resistors with high speed Switched-Capacitors using MOSFETs. The switching function of the MOSFET produces a discrete response rather than a continuous response from the filter.

The resistor is approximated by the Switched-Capacitor [10].

$$R = \frac{T_C}{C} = \frac{1}{f_C \cdot C}$$

Note that the switching frequency must be much larger than the input signal. Thus a Switched-Capacitor can be used to replace a resistor. Therefore, this equivalent resistor, in conjunction with other Capacitors and op amp integrators, can be used to synthesize in active filters.

Proposed Circuit Configuration

The proposed circuit configuration for Feed Forward Third order Switched-Capacitor (SC) filter is shown in fig (1). It uses three op –amps (μA 741 C) with wide identical gain bandwidth product (GB) and four Capacitors with MOSFET, which form Switched-Capacitor. Switched-Capacitor can replace resistors, which was proposed earlier [11]. The feed forward input is given to the second as well as third op-amp through SC. LP function is observed at the output of the third op-amp. The output of the second op-amp gives BP function. The HP function is seen at the output of the first op-amp.

Circuit analysis and design equations

Op-amp μA 741 is an internally compensated op-amp, which represented by "Single pole model" [12-14],

$$A(S) = \frac{A_0\omega_0}{S+\omega_0} \quad \text{............(1)}$$

Where A_0:- open loop D.C. gain of op-amp

ω_0 :- open loop – 3 dB bandwidth of the op-amp $= 2\pi f_0$

$A_0\,\omega_0$:- GB = gain-bandwidth product of op-amp

for $S >> \omega_0$

$$A(S) = \frac{A_0\omega_0}{S} = \frac{GB}{S} \quad \text{............(2)}$$

This shows Op-amp as integrator.

Transfer function of the proposed third order Switched-Capacitor filter for low pass $T_{LP}(S)$, for band pass $T_{BP}(S)$ and for high pass $T_{HP}(S)$ are given below.

$$T_{LP}(S) = \frac{-C_4\,GB_1GB_2GB_3}{X_1S^3+X_2S^2+X_3S+X_4} \quad \text{............(3)}$$

$$T_{BP}(S) = \frac{-C_4\,GB_1GB_2\,S}{X_1S^3+X_2S^2+X_3S+X_4} \quad \text{............(4)}$$

$$T_{HP}(S) = \frac{-C_4\,GB_1S^2}{X_1S^3+X_2S^2+X_3S+X_4} \quad \text{............(5)}$$

Where

$X_1 = C_1 + C_2 + C_3 + C_4$

$X_2 = GB_1C_1 + GB_2C_2 + GB_3C_3$

$X_3 = GB_1GB_2C_2 + GB_2GB_3C_3$

$X_4 = GB_1GB_2GB_3C_3$

The circuit was designed using coefficient matching technique i.e. by comparing these transfer functions with general second order transfer functions.

The general third order transfer function is given by

$$T(S) = \frac{\alpha_3\,S^3+\alpha_2\,S^2+\alpha_1\,S+\alpha_0}{S^3+\omega_0\left(1+\frac{1}{Q}\right)S^2+\omega_0^2\left(1+\frac{1}{Q}\right)S+\omega_0^3} \quad \text{............(6)}$$

Comparing equations (3), (4) and (5) with equation (6)

$$\frac{\omega_0^3}{GB^3} = GB_1GB_2GB_3C_3$$
$$\omega_0^2\left(1+\frac{1}{Q}\right) = GB_1GB_2C_2 + GB_2GB_3C_3$$
$$\omega_0\left(1+\frac{1}{Q}\right) = GB_1C_1 + GB_2C_2 + GB_3C_3$$
$$1 = C_1 + C_2 + C_3 + C_4$$

Using these equations, values of $C_{1,}$ C_2 and C_3 can be calculated for different values of merit factors Q.

Experimental

The circuit performance is studied for different values of circuit merit factors with cut-off frequency of 20 kHz. The general operating range of this filter is 10 Hz to 1·2 MHz. The value of GB $(GB_1 = GB_2 = GB_3)$ is $2\pi(5 \cdot 6)\times 10^5$ rad/sec for different values of Q (0·1, 0·5, 1, 5, 10, and 20).

Results and Discussion

Following observations are noticed for low pass, band pass and high pass at corresponding terminals.

(A) Low pass response

With the increase in the value of Q the maximum passband gain varies from 82 dB to 87 dB. Gain roll-off is 14 for Q = 0·1 which increases with the value of Q and is 19 dB/octave for Q = 20. These values are near about the ideal value of 18dB/octave for third order filter. The response also shows overshoot of 9 dB for Q = 5, which increases, to 19 dB for Q = 20.

(B) Band pass response

The maximum passband gain increases from 33 dB, which increases to 77 dB with the increase in the value of Q. The bandwidth decreases with the increase in Q. There is no shift in the central frequency for higher values of Q, but for lower values it shit leftward with decrease in Q. It is also observed that the passband distribution of frequency is asymmetric. In leading part of the response the gain roll-off/octave is 6dB/octave for all the values of Q. In trailing part of the response is it is 8 dB/octave for Q = 0·1 while it is 13 dB/octave for all the other values of Q.

(C) High pass response:

The gain-roll off is 11 dB/octave for Q = 0·1 while it is 12 dB/octave for all the other values of Q. These values are nowhere near the ideal value of 18 dB/octave. The overshoot of 38 dB appears for Q = 5 which increases with the value of Q and is 48 dB for Q = 20. The gain does not stabilize for any of the value of Q.

Conclusion

A realization of feed forward third order switched-capacitor filter has been proposed. Gain roll-off for low pass filter varies about the ideal value. The circuit can be used as wide band pass, while it acts as narrow band pass for higher values. However for high pass operation gain stabilisation does not take place. Thus the use of the Switched-Capacitor to replace resistor in active filter circuit will suited to overcome a major obstacle to filter on chip fabrication.

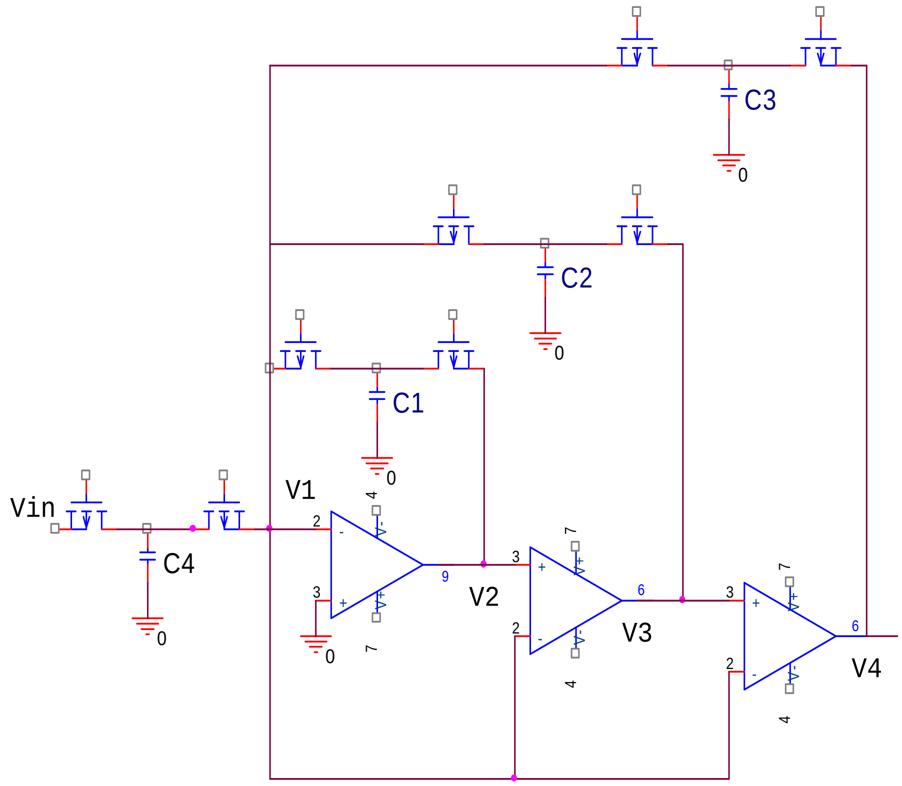

Figure 1: Circuit diagram of Universal Third order Switched-Capacitor filter

Table 1: Capacitor values for different Q

Q	C_1	C_2	C_3	C_4
0·1	33 µF	1µF	4·7 nF	56 µF
0·5	10 µF	0·33 µF	4·7 nF	82 µF
1	6·8 µF	0·22 µF	4·7 nF	100 µF
5	4·7 µF	0·1 µF	4·7 nF	100 µF
10	3·9 µF	0·1 µF	4·7 nF	100 µF
20	3·3 µF	0·1 µF	4·7 nF	100 µF

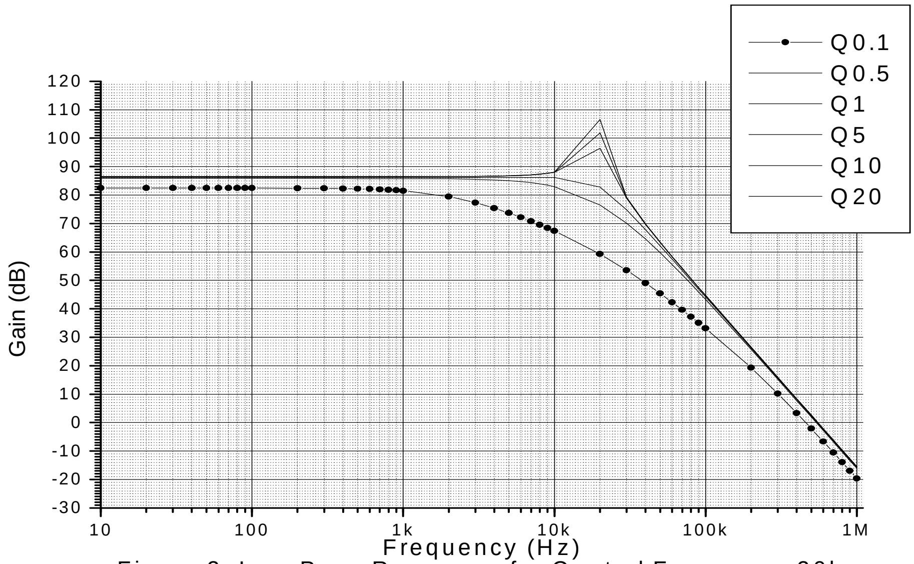

Figure 2: Low Pass Response for Central Frequency 20k

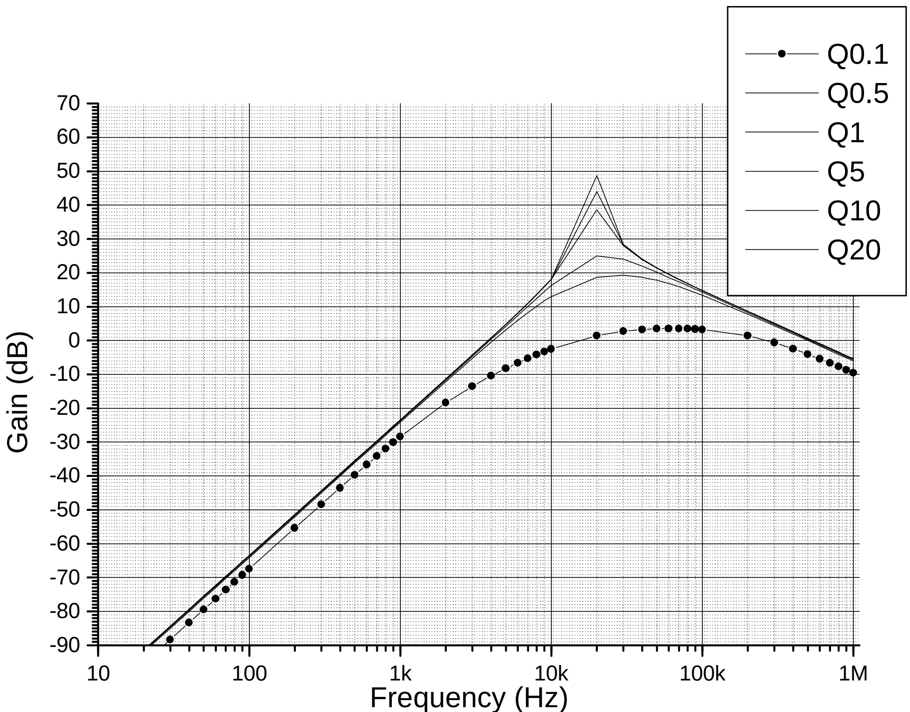

Figure 3: High Pass Response for Central Frequency 20k

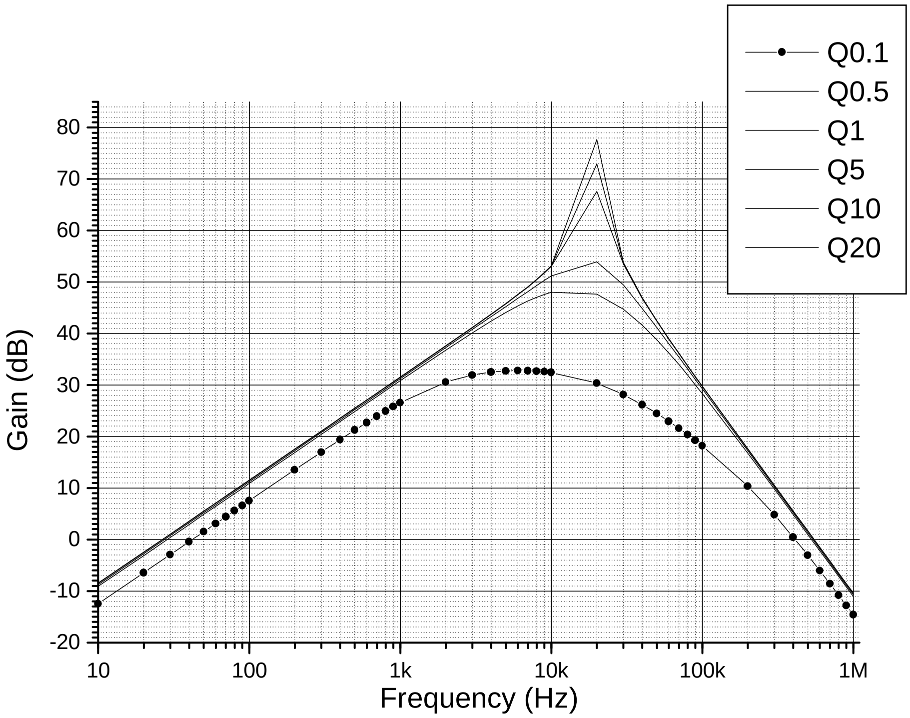

Figure 4: Band Pass Response for Central Frequency 20k

Table No.2: Data sheet for Low pass response

Q	Max. Pass Band Gain dB	F_{OL} kHz	$F_0 \sim F_{OH}$ kHz	% change in F_{OL}	Gain Roll-off in stop band	
					dB/Octave	Octave Starting at (kHz)
0.1	82	20	0	0	14	100
0.5	86	45	25	5	17	50
1	87	50	30	10	18	50
5	87	50	30	10	19	50
10	87	50	30	10	19	50
20	87	50	30	10	19	50

Table No.3: Data sheet for Band pass response

Q	Max. Pass Band Gain (dB)	f_1 (kHz)	f_2 (kHz)	Band-width (kHz)	Gain Roll-off in stop band			
					Leading Part		Trailing Part	
					dB/Octave	Octave Starting at (Hz)	dB/Octave	Octave Starting at (Hz)
0.1	33	0·6	60	59·4	6	200	8	100 k
0.5	48	13	70	57	6	800	13	50 k
1	54	21	60	39	6	2 k	13	40 k
5	67	5·3	40	34·7	6	2k	13	40 k
10	73	9	31	22	6	2k	13	40 k
20	77	10	30	20	6	2k	13	40 k

Table No.4: Data sheet for High pass response

Q	F_{OH} kHz	$F_0 \sim F_{OH}$ kHz	% change in F_{OH}	Gain Roll-off in stop band		Peak Gain of overshoot dB
				dB/Octave	Octave Starting at (kHz)	
0.1	14	6	42	11	400	
0.5	4	16	400	12	200	
1	3.9	16.1	412	12	200	
5	3.9	16.1	412	12	200	38
10	3.9	16.1	412	12	200	44
20	3.9	16.1	412	12	200	48
F_{OH}: 3-dB Frequency						

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