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Universal second order Switched-Capacitor filter for different Q values

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Abstract : This paper aims to show how the Switched-Capacitor (SC) concept can be used to realize a wide variety of universal filter that have the advantage of compactness and tunability. This paper also explains the basic idea behind the use of the Switched-Capacitor to replace resistor in active filter. Filter using Switched-Capacitor technique overcomes a major obstacle to filter on a chip fabrication. The implementation of resistors by simulating resistors with high speed Switched-Capacitors using MOSFET is also presented.

The proposed universal second order SC filter circuit implements three filter functions – low pass, band pass and high pass simultaneously in single circuit. The circuit works for narrow band to wide band filter responses with variation in Q value. The filter works better for values of $Q \geq 1$.

Keywords : Second order filter, Switched-Capacitor, pass band gain, circuit merit factor.

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1. Introduction

There have been several contributors for synthesis and realization of active-filters based on operational amplifier (op. amp.) [1–5], as well as for the synthesis of band pass or other Switched-Capacitor (SC) filters [6–10]. Universal active filters have several advantages such as integrability, programmability, design implementation simplicity, tunability and compactness. Moreover circuits realizing the finite and complex gain nature of an internally compensated operational amplifier are suitable for higher frequency operation such as audio frequency applications [5]. The principle drawback of the reported circuits is that filtering signals for some responses are required to be taken through passive grounded components involved in the circuits and only one filter function is studied in signal circuit [11–14].

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To overcome these critical problems, we proposed a universal second order Switched-Capacitor which implements low pass (LP), high pass (HP) and band pass (BP) signals simultaneously in single circuit. Also the proposed circuit circumvents the problems encountered in the earlier reported circuits. This circuit works for narrowband to wideband bandpass filter responses with variation of circuit merit factor Q.

2. 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 [6]. Furthermore, the use of the Switched-Capacitor will be seen to give frequency tunability 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 [6].

The resistor is approximated by the Switched-Capacitor [7].

$$R = \frac{T_C}{-} = \frac{1}{f_c \cdot C}$$

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.

3. Proposed circuit configuration

The proposed circuit configuration for second order Switched-Capacitor filter is shown in Figure 1. It uses two op.-amp.s (μA 741 C) with wide identical gain bandwidth product (GB) and three capacitors with MOSFET, which form Switched-Capacitor.

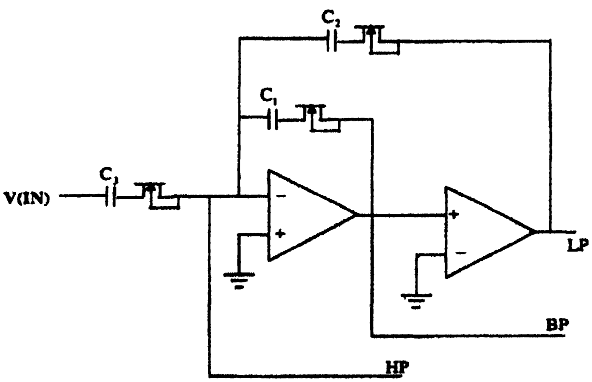

Figure 1. Circuit diagram of universal second order Switched-Capacitor filter.

Switched-Capacitor can replace resistors, which was proposed earlier [15]. The negative feedback is incorporated using C_1 and C_2. Three distinct terminals are used to measure three filter functions LP, HP and BP.

4. Circuit analysis and design equations

Op.-amp. μA 741 is an internally compensated op. amp. which represented by "single pole model" [5],

$$A(S) = \frac{A_0\omega_0}{S + \omega_0} \tag{1}$$

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 $S >> \omega_0$

$$A(S) = \frac{A_0\omega_0}{S} = \frac{GB}{S} \tag{2}$$

This shows op.-amp. as an "integrator".

Transfer function of the proposed second 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.

$$T_{LP}(S) = \frac{-C_3 GB_1 GB_2}{X_1 S^2 + X_2 S + X_3} \tag{3}$$

$$T_{BP}(S) = \frac{-C_3 GB_1 S}{X_1 S^2 + X_2 S + X_3} \tag{4}$$

$$T_{HP}(S) = \frac{-C_3 S^2}{X_1 S^2 + X_2 S + X_3} \tag{5}$$

where

$$X_1 = C_1 + C_2 + C_3$$

$$X_2 = GB_1 C_2$$

$$X_3 = GB_1 GB_2 C_1$$

The circuit was designed using coefficient matching technique *i.e.* by comparing these transfer functions with general second order transfer functions [15].

The general second order transfer function is given by

$$T(S) = \frac{\alpha_2 S^2 + \alpha_1 S + \alpha_0}{S^2 + \left(\frac{\omega_0}{Q}\right) S + \omega_0^2}. \tag{6}$$

Comparing eqs. (3), (4) and (5) with eq. (6)

$$\frac{\omega_0}{Q} = GB_1 C_2 \tag{7}$$

$$\omega_0^2 = GB_1 GB_2 C_1 \tag{8}$$

$$1 = C_1 + C_2 + C_3.$$

Using these equations, values of C_1, C_2 and C_3 can be calculated for different values of Q and central frequency f_0.

5. Experimental

The circuit performance is studied for different values of circuit merit factor Q with central frequency f_0 = 10 kHz. The general operating range of this filter is 10 Hz to 1.2 MHz. The value of GB ($GB_1 = GB_2$) is $2\pi(5.6) \times 10^5$ rad/sec for different Q (0.1, 0.5, 1, 5, 10, 20).

6. Results and discussion

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

(A) Low pass response :

The Figure 2 shows the low pass response for different values of Q. It gives high pass band gain (70 dB) and decreases with decrease in value of Q. It shows better gain roll-off (39 dB/decade) for higher values of Q. The response also shows overshoot for higher values of Q and the overshoot increases with increase in the value of Q.

(B) Band pass response :

The Figure 3 shows the band pass response for different values of Q. The band width is controlled by Q. For higher values of Q, this filter can be used for narrow band width and lower values of Q can be used for wide band width. There is no shift in the central frequency. It is also observed that the pass band distribution of frequency is symmetric for both sides. The gain roll-off/octave in leading and trailing part of the response is slightly differ. The circuit works better band pass response for $Q > 1$.

(C) High pass response :

Highpass response of the filter for different values of Q is shown in Figure 4 shows the band pass response. The response shows excellent gain-roll off (40 dB/decade).

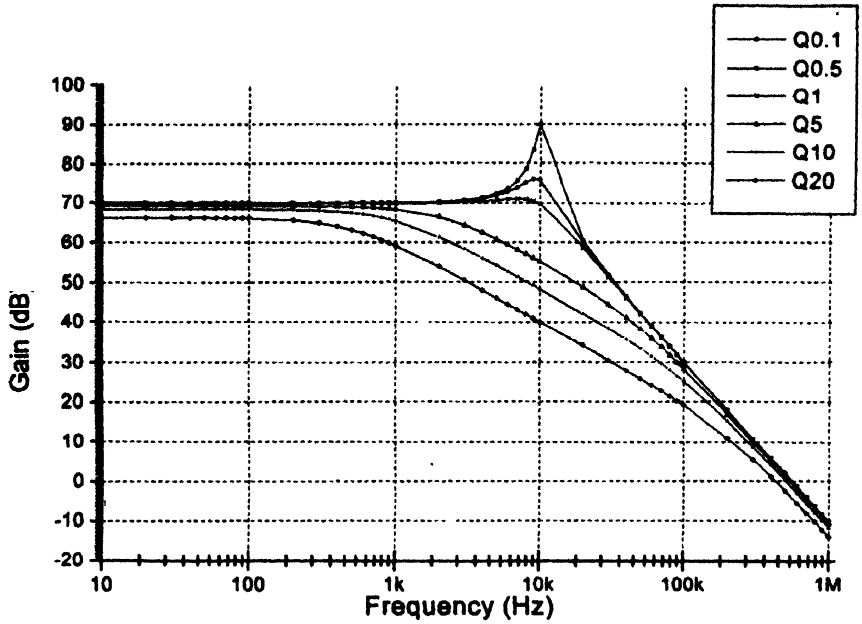

Figure 2. Low pass response for central frequency 10 k.

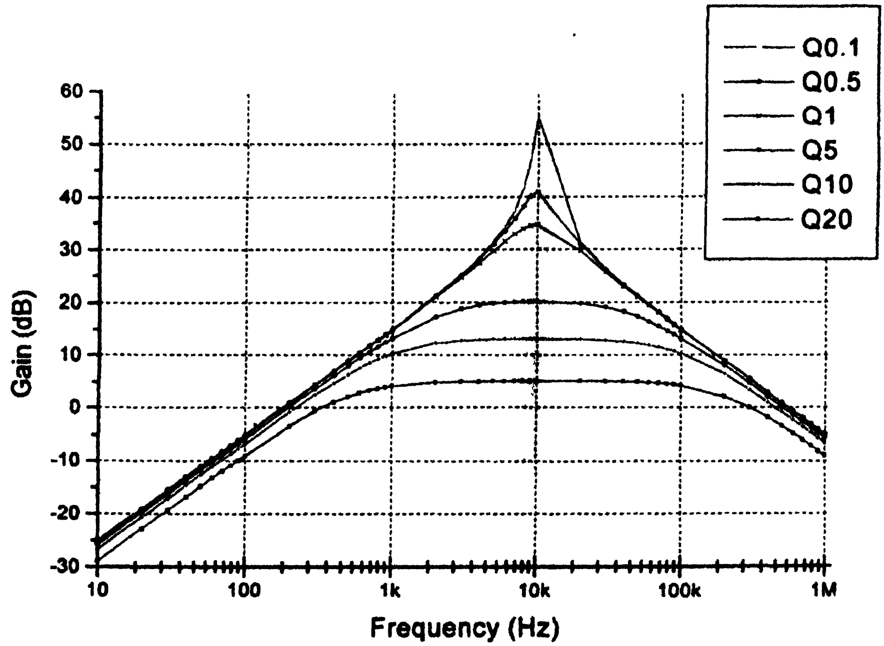

Figure 3. Band pass response for central frequency 10 k.

The passband increases with increase in *Q*. The overshoot appears for higher values of *Q* and it increases as *Q* increases. The gain gets stabilized almost at 0 dB for all values of $Q > 1$.

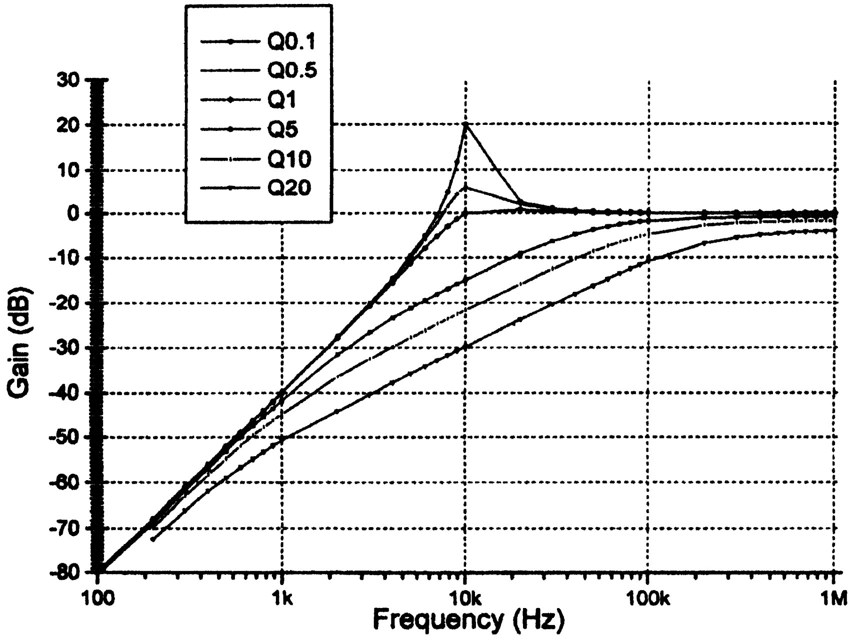

Figure 4. High pass response for central frequency 10 k.

The Tables 2, 3 and 4 show the analysis of graph for low pass; band pass and high pass respectively.

Table 1. Capacitor values for different *Q*.

Q	C_1 (μF)	C_2 (nF)	C_3 (μF)
0.1	0.22	33	100
0.5	82	33	100
1	2.2	33	100
5	8.2	33	100
10	22	33	82
20	33	47	56

Table 2. Analysis of graph for low pass response.

Q	Max. pass band gain (dB)	F_{OL} (kHz)	Fo ~ F_{OH} (kHz)	% change in F_{OL}	Gain roll-off in stop band	
					dB/Octave	Octave starting at (kHz)
20	70	13	3	7	16	20
10	70	13	3	7	15	20
5	70	13	3	7	13	20
1	69	11	1	9	7	20
0.5	68	10	0	0	6	20
0.1	66	6	4	66	6	20

Table 3. Analysis of graph for low 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)
20	54	9	12	3	18	8 k	6	20 k
10	41	8	15	7	6	6 k	6	20 k
5	35	6	21	15	4 5	4 k	6	30 k
1	20	2	50	48	4.5	1 k	4	60 k
0 5	13	1	100	99	3 5	800	4	200 k
0 1	5	350	215	214 65	2 5	200	4	300 k

Table 4. Analysis of graph for high pass response

Q	F_{OH} (kHz)	$F_O \sim F_{OH}$ (kHz)	% change in F_{OH}	Gain roll-off in stop band		Gain stabilization		Peak gain of overshoot (dB)
				dB/Octave	Octave starting at (kHz)	dB	Fs (kHz)	
20	6	4	66	13	6	0	70	20
10	6 5	3 5	53	12	6	0	50	6
5	8	2	25	40	10	0	50	
1	70	60	85	27	10	–1	120	
0 5	110	100	90 9	23	10	–2	140	
0 1	170	160	94	20	100	–6	90	

F_{OH} : 3-dB frequency FS : Frequency at width gain stabilizes

7. PSPICE simulation results

The responses are also obtained by PSPICE simulation. Electronic tunability of parameters was also checked and corresponding values were found to be correct. These PSPICE simulation results thus confirm the workability of the realizable from the new configuration.

The results of the circuit with resistances (active-*R* configuration) [5] are compared with replacement of resistances by Switched-Capacitor (active Switched-Capacitor configuration), shows better pass band gain such as

Configuration	Low pass	Band pass	High pass
Active-*R*	62 dB	54 dB	–2 dB
Switched-Capacitor	70 dB	34 dB	0 dB