

## A Novel High Stop Band All Complementary MOSFET Switched-Capacitor Filter

Moussa Abdallah and Ismail Nabhan

Department of Electronics Engineering, Princess Sumaya University for Technology,  
P.O. Box 1438, Amman, 11941 Jordan

**Abstract: Problem statement:** Filters are widely used in various applications including communications, electronics and biomedical engineering. The performance and size of the filter is of interest especially in chip implementation. A switched-capacitor low-pass filter was designed and simulated using a 0.18  $\mu\text{m}$  1P6M CMOS technology. **Approach:** This circuit design offered obvious advantages in increasing the stopband attenuation, reducing passband ripple and achieving accurate frequency response. **Results:** This circuit achieved 53 dB stop band attenuation, less than 0.1 dB passband ripple, a 5 KHz cut-off frequency, a 100 KHz stopband frequency and consumes 6 mW from a 2 V power supply. **Conclusion:** The proposed design is very suitable for the realization of analog signal processing blocks in complementary MOSFET integrated circuits.

**Key words:** Passband ripple, stopband attenuation, switched-capacitor filter

### INTRODUCTION

The most popular approach for realizing analog signal processing in MOS (or BICMOS) integrated circuits is through the use of switched-capacitor circuits<sup>[1-4]</sup>. A switched-capacitor circuit operates as a discrete-time signal processor. As a result, these circuits are most easily analyzed with the use of Z-transform techniques and typically require anti-aliasing and smoothing filters.

As a filtering technique, switched-capacitor circuits have become extremely popular due to their accurate frequency response as well as good linearity and dynamic range. Accurate discrete-time frequency responses are obtained since filter coefficients are determined by capacitance ratios which can be set quite precisely in an integrated circuit (on the order of 0.1%)<sup>[5]</sup>. Such an accuracy is orders of magnitude better than that which occurs for integrated RC time constants (which can vary by as much as 20%). Once the coefficients of a switched-capacitor discrete-time filter are accurately determined, its overall frequency response remains a function of the clock (or sampling) frequency. Fortunately, clock frequencies can also be set very precisely through the use of a crystal oscillator.

In this study, a switched-capacitor filter with a high stop band attenuation and low passband ripple is proposed and analyzed. The proposed fifth-order low-pass filter includes three cascaded stages. The first stage is the first order (linear) filter. The second stage is the high Q Biquad filter, while the third stage is the low

Q Biquad filter. The proposed circuit has a stop band attenuation of 53 dB, a passband ripple less than 0.1 dB and a cut-off frequency of 5 KHz.

### MATERIALS AND METHODS

**Architecture and circuit implementation:** The designed fifth-order switched-capacitor low-pass filter consists of three cascaded stages. The first stage is the first order (linear) filter. The output of this linear filter is connected to the input of the high Q Biquad filter which in turn is connected to the input of the low Q Biquad filter. Each of the three stages was realized using operational amplifiers, capacitors, switches and non-overlapping clocks. A brief description of the utilized circuits follows.

**First-order filter:** A general first-order active-RC filter is shown in Fig. 1. To obtain a switched-capacitor filter having the same low-frequency behavior, the resistors are replaced with delay-free switched capacitors, while the nonswitched capacitor feed in is left unchanged. The resulting first-order switched-capacitor filter is also shown in Fig. 1. The transfer function for this filter is found to be:

$$H_1(z) = \frac{V_o(z)}{V_i(z)} = \frac{\frac{C1 + Ca}{Ca} Z - \frac{C1}{Ca}}{\left(1 + \frac{C3}{Ca}\right) Z - 1} = \frac{0.15Z - 0.05}{1.1Z - 1} \quad (1)$$

**Corresponding Author:** Moussa Abdallah, Department of Electronics Engineering, Princess Sumaya University for Technology, P.O. Box 1438, Amman, 11941 Jordan

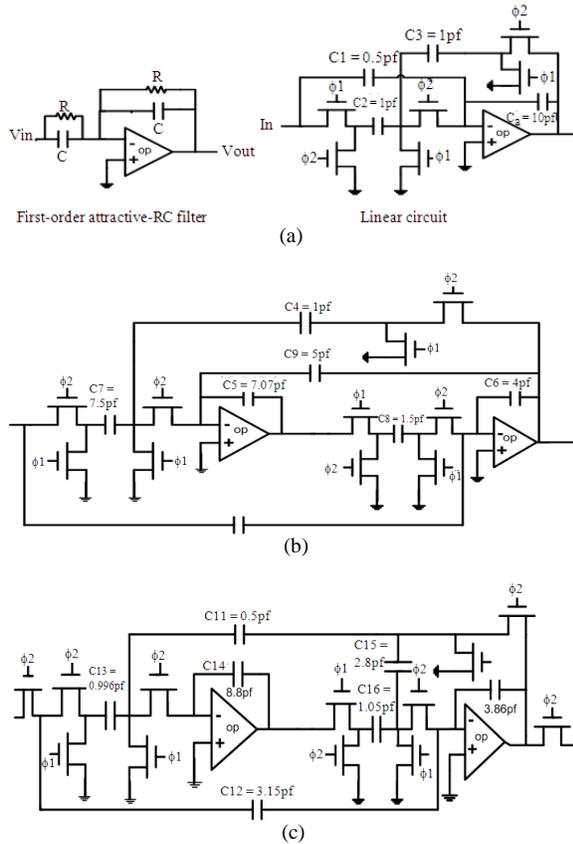


Fig. 1: Schematic of the switched-capacitor filter, (a): First order filter; (b): High Q biquad filter; (c): Low Q Biquad filter

**Biquad filters:** Similar to the first-order case, good switched-capacitor Biquad filter structures can be obtained by emulating well-known continuous-time filter structures. However, also as in the first-order case, once a filter structure is obtained, its precise frequency-response is determined through the use of discrete-time analysis using the signal-flow-graph technique. This exact transfer function is then used when determining capacitor ratios during the design phase.

Figure 1b shows the circuit diagram of the utilized high-Q switched-capacitor filter whose transfer function is found to be:

$$H_2(Z) = \frac{K_3 Z^2 + (K_1 K_5 + K_2 K_5 - 2K_3)Z + (K_3 - K_2 K_5)}{Z^2 + (K_4 K_5 + K_5 K_6 - 2)Z + (1 - K_5 K_6)} \quad (2)$$

Substituting  $K_1 = 0.07$ ,  $K_2 = 0$ ,  $K_3 = 0.114$ ,  $K_4 = 0.14$ ,  $K_5 = 0.34$ ,  $K_6 = 0.707$ , into (2) yields:

$$H_2(Z) = \frac{0.114Z^2 - 0.204Z + 0.114}{Z^2 - 1.73Z + 0.76} \quad (3)$$

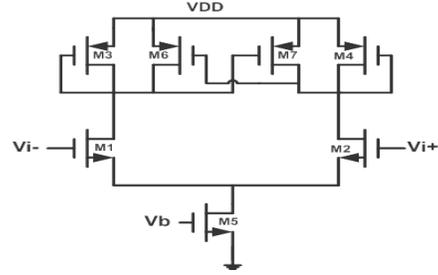


Fig. 2: Circuit diagram of the used op-amp

Figure 1c shows the circuit diagram of the utilized low-Q switched-capacitor filter whose transfer function is found to be:

$$H_3(Z) = \frac{(K_2 + K_3)Z^2 + (K_1 K_5 - K_2 - 2K_3)Z + K_3}{(1 + K_6)Z^2 + (K_4 K_5 - K_6 - 2)Z + 1} \quad (4)$$

Substituting  $K_1 = 0.113$ ,  $K_2 = 0$ ,  $K_3 = 0.86$ ,  $K_4 = 0.057$ ,  $K_5 = 0.272$ ,  $K_6 = 0.725$  into the above equation yields:

$$H_3(Z) = \frac{.816Z^2 - 1.6Z + .816}{1.725Z^2 - 2.71Z + 1} \quad (5)$$

**Operational amplifier:** Figure 2 shows the circuit diagram of the utilized operational amplifier. This single-stage op amp has high output impedance, a high dc gain despite the lack of an output buffer stage since the load of this op amp is purely capacitive. Moreover, this op amp has a high slew rate in order not to limit the clock rate since in this case the charge has to transfer quickly from one capacitor to another<sup>[6]</sup>.

## RESULTS

The Z-domain transfer function of the resultant fifth-order filter is the multiplication of the individual transfer functions of the three former filters:

$$H(Z) = H_1(Z).H_2(Z).H_3(Z) = \left( \frac{0.15Z - 0.05}{1.1Z - 1} \right) \left( \frac{0.114Z^2 - 0.204Z + 0.114}{Z^2 - 1.73Z + 0.76} \right) \left( \frac{0.816Z^2 - 1.6Z + 0.816}{1.725Z^2 - 2.71Z + 1} \right) \quad (6)$$

Where:

- $Z = \cos(WT) + j\sin(WT)$
- $Z^2 = \cos(2WT) + j\sin(2WT)$
- $W = \text{Angular frequency}$
- $T = \text{Sampling period}$

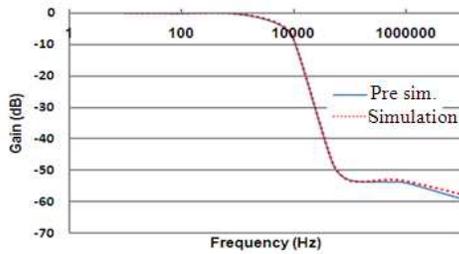
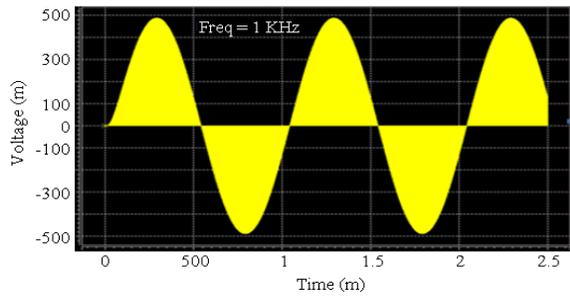
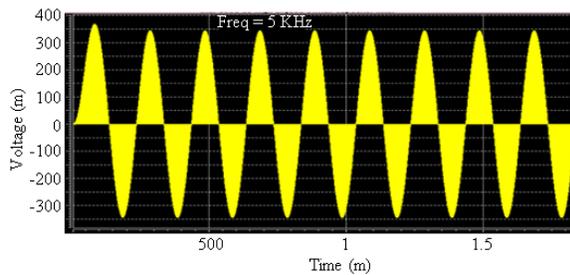


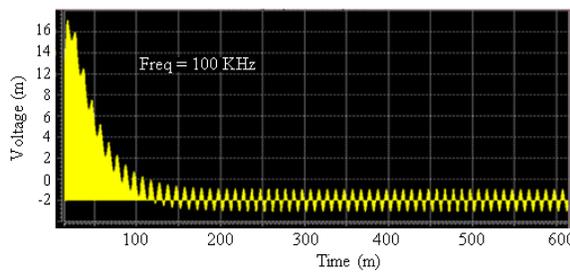
Fig. 3: Frequency response of the switched capacitor filter



(a)



(b)



(c)

Fig. 4: Transient response of the filter, (a): At 100 KHz; (b): At 5 KHz; (c): At 100 KHz

The Z-domain transfer function of (6) is plotted and compared with the output frequency response of the implemented switched capacitor filter as shown in Fig. 3 and Table 1. The obtained results show clearly that the two curves are almost identical and the cutoff frequency of the filter is 5 KHz.

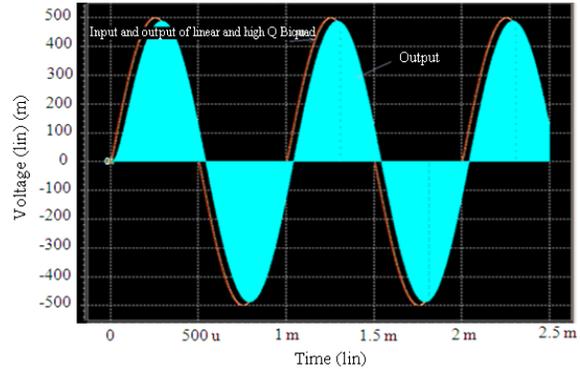


Fig. 5: Transient response of the filter at the outputs of the different circuits constituting the filter

Table 1: Variation of gain versus frequency for the filter

Frequency	Pre-simulation gain (dB)	Simulated gain (dB)
10 Hz	0.00	0.00
100 Hz	-0.06	-0.04
1 KHz	-0.25	-0.20
5 KHz	-3.25	-3.05
10 KHz	-8.50	-8.05
50 KHz	-48.00	-47.50
100 KHz	-53.00	-53.40
1 MHz	-53.90	-53.47
10 MHz	-59.00	-57.70

Table 2: Technical specifications the designed filter

Specification	Required	Achieved
Technology	0.18 $\mu$ m CMOS	0.18 $\mu$ m CMOS
Power supply	2 V	2 V
Sampling frequency	1536 KHz	1536 KHz
Cut-off frequency	5 KHz	5 KHz
Pass band gain	0 dB	0 dB
Pass band ripple	1 dB	Less than 0.1 dB
Stop band freq.	100 KHz	100 KHz
Stop band attenuation	50 dB	53 dB
Input, output swing	1 V	1 V

The transient response of this filter at 1, 5 and 100 KHz is shown in Fig. 4. As can be seen the stop band attenuation is 53 dB.

Figure 5 shows the transient response at the output of the three cascaded filters constituting the designed switched-capacitor filter.

In Table 2, the simulated results for the designed switched-capacitor filter are summarized.

## DISCUSSION

Table 2 shows the required specification of the designed stop band all CMOS switched-capacitor filter where it is based on 0.18  $\mu$ m technology. The achieved values are even better, for example, the passband ripple is less than 0.1 dB. Figure 3, shows the frequency response of the filter after implementation and the

results are very close to the simulated values. Figure 4 shows the time domain response at various frequencies. The low pass filter designed and implemented is small in size and compact.

### CONCLUSION

A 2 V CMOS switched-capacitor filter has been designed and simulated using 0.18  $\mu\text{m}$  CMOS technology. The simulation results indicate that the proposed Filter has a stop band attenuation of 53 dB, a passband ripple less than 0.1 dB and a cut-off frequency of 5 KHz.

This design is very suitable for the realization of analog signal processing blocks in MOS integrated circuits such as voltage-controlled oscillators and modulators.

### REFERENCES

1. Martin, K. and A.S. Sedra, 1981. Switched-capacitor building blocks for adaptive systems. *IEEE Trans. Circ. Syst.*, 6: 576-84. [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=1085017](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1085017)
2. Fried, D., 1972. Analog sample-data filters. *IEEE J. Solid-State Circ.*, 7: 302-304. [http://ieeexplore.ieee.org/xpl/freeabs\\_all.jsp?arnumber=1050305](http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=1050305)
3. Caves, J. and C. Rahim, 1977. Sampled-data filters using switched capacitors as resistors equivalents. *IEEE J. Solid-State Circ.*, 12: 592-600.
4. Hosticka, J., R.W. Broderson and P.R. Gray, 1977. MOS sampled data recursive filters using switched-capacitor integrators. *IEEE J. Solid-State Circ.*, 12: 600-608. [http://ieeexplore.ieee.org/xpl/freeabs\\_all.jsp?arnumber=1050967](http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=1050967)
5. Jones, D. and Ken Martin, 1997. *Analog Integrated Circuit Design*. John Wiley and Sons, Inc., ISBN: 0471144487, pp: 706
6. Brackett, P.O. and A.S. Sedra, 1978. *Filter Theory and Design: Active and Passive*. Matrix Publishers, Champaign, Illinois, ISBN: 0916460142, pp: 785.