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# MAXIM

## Dual Universal Switched Capacitor Filter

MF10

### General Description

The MF10 is a dual 2nd order, switched capacitor, state variable filter. Each of the two filter sections uses two switched capacitor integrators and an op amp to generate a second order function. The location of the poles (and thus the center frequency and Q) is determined by the frequency of an external clock and 2 to 4 external resistors. No external capacitors are used.

Each of the two filter sections of the MF10 can generate all standard 2nd order functions: bandpass, lowpass, highpass, notch (band-reject), complex zeroes and allpass functions. Three of these functions are simultaneously available. The frequency of the 2nd order poles is accurate to  $\pm 0.2\%$  and the Q is accurate to within 2%.

Fourth order filters can be made by cascading the two 2nd order filter sections of the MF10, and higher order filters can easily be made by cascading more MF10s. The excellent accuracy and stability of MF10 based filters eliminates the complex, costly tuning normally required in the production of high order (multipole) filters. Design equations for Butterworth, Bessel, Chebyshev, and Cauer (Elliptic) filters are provided.

### Applications

This versatile device is used for a wide range of filtering applications such as:

Tunable active filters	Adaptive Filtering
Multi-pole filters	Phase locked loops
Anti-aliasing filters	Signal Processing/ Conditioning

### Features

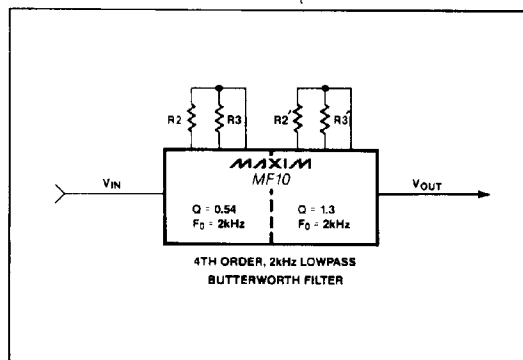
- ◆ No External Capacitors Required
- ◆ Low Sensitivity to External Component Variation
- ◆ Excellent Frequency and Q Stability
- ◆ Easily Cascaded for Multipole Filters
- ◆ Filter Frequency Set by External Clock Frequency
- ◆ 0.2% Clock to Center Frequency Ratio Accuracy
- ◆ Highpass, Lowpass, Bandpass, Notch, and Allpass Filter Functions.
- ◆ Up to 3 Simultaneous Filter Function Outputs
- ◆ Up to 30kHz Operation
- ◆ Easy to use—Design Directly from the Data Sheet
- ◆ Monolithic, Low Power CMOS Design

### Ordering Information

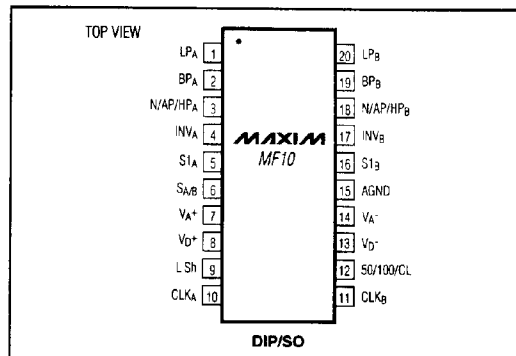
PART	TEMP. RANGE	PIN-PACKAGE
MF10BN	0°C to +70°C	20 Lead Plastic DIP
MF10CN	0°C to +70°C	20 Lead Plastic DIP
MF10BWP	0°C to +70°C	20 Lead Wide SO
MF10CWP	0°C to +70°C	20 Lead Wide SO
MF10BJ	0°C to +70°C	20 Lead CERDIP*
MF10CJ	0°C to +70°C	20 Lead CERDIP*
MF10CC/D	0°C to +70°C	Dice*

\* Contact Factory

### Typical Operating Circuit



### Pin Configuration



**MAXIM**

Maxim Integrated Products 1

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## Dual Universal Switched Capacitor Filter

### ABSOLUTE MAXIMUM RATINGS

Supply Voltage ( $V^+$  to  $V^-$ ) ..... 14V  
 Power Dissipation ..... 500mW  
 Operating Temperature ..... 0°C to +70°C

Storage Temperature ..... -65°C to +160°C  
 Lead Temperature (Soldering, 10 seconds) ..... +300°C

Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these or any other conditions above those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

### ELECTRICAL CHARACTERISTICS (Complete Filter)

( $V_S = \pm 5V$ ,  $T_A = +25^\circ C$ )

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Frequency Range	$f_0 \times Q \leq 200$ kHz	20	30		kHz
Clock to Center Frequency Ratio, $f_{CLK}/f_0$					
MF10B_	Pin 12 High, $Q = 10$		$49.94 \pm 0.2\%$	$\pm 0.6\%$	
MF10C_	$f_0 \times Q \leq 50$ kHz, Mode 1		$49.94 \pm 0.2\%$	$\pm 1.5\%$	
MF10B_	Pin 12 at Mid Supplies		$99.35 \pm 0.2\%$	$\pm 0.6\%$	
MF10C_	$Q = 10$ , $f_0 \times Q \leq 50$ kHz, Mode 1		$99.35 \pm 0.2\%$	$\pm 1.5\%$	
Q Accuracy (Q Deviation from an Ideal Continuous Filter)	$f_0 \times Q \leq 50$ kHz $f_0 \leq 5$ kHz, Mode 1		$\pm 2\%$	$\pm 6\%$	
$f_0$ Temperature Coefficient	Pin 12 High (~50:1) Pin 12 Mid Supplies (~100:1) $f_0 \times Q \leq 100$ kHz, Mode 1 External Clock Temperature Independent		$\pm 10$ $\pm 100$		ppm/°C ppm/°C
Q Temperature Coefficient	$f_0 \times Q \leq 100$ kHz, Q Setting Resistors Temperature Independent		$\pm 500$		ppm/°C
DC Low Pass Gain Accuracy	Mode 1, $R_1 = R_2 = 10$ k $\Omega$		$\pm 1$	$\pm 2$	%
Crosstalk			50		dB
Clock Feedthrough			10		mV
Maximum Clock Frequency		1	1.5		MHz
Power Supply Current			7	10	mA

### ELECTRICAL CHARACTERISTICS (Internal Op Amps)

( $V_S = \pm 5V$ ,  $T_A = +25^\circ C$ )

PARAMETER	CONDITIONS	MIN	Typ	MAX	UNITS
Supply Voltage		$\pm 4$	$\pm 5$		V
Voltage Swing (Pins 1, 2, 19, 20)	$R_L = 5$ k $\Omega$				
MF10B_		$\pm 4.0$	$\pm 4.1$		V
MF10C_		$\pm 3.8$	$\pm 3.9$		V
Voltage Swing (Pins 3 and 18)	$R_L = 3.5$ k $\Omega$				
MF10B_		$\pm 4.0$	$\pm 4.1$		V
MF10C_		$\pm 3.8$	$\pm 3.9$		V
Output short Circuit Current			3		mA
Source			1.5		mA
Sink					
Gain Bandwidth Product			2.5		MHz
Slew Rate			7		V/ $\mu$ S

# Dual Universal Switched Capacitor Filter

MF10

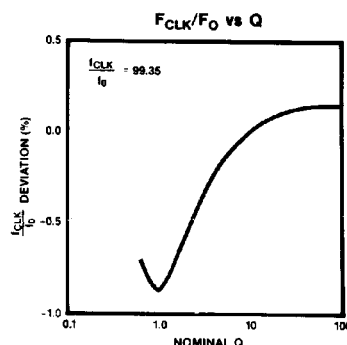
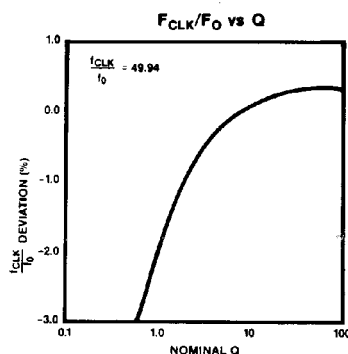


Table 1. PIN DESCRIPTION

PIN	PIN NUMBER		DESCRIPTION
NAME	Filter A	Section B	
LP	1	20	These are the lowpass, bandpass, and notch/allpass/highpass outputs of each 2nd order section. The LP and BP outputs can typically sink 1mA and source 3mA. The N/AP/HP output can typically sink 1.5mA and source 3mA.
BP	2	19	
N/AP/HP	3	18	
INV	4	17	INV is the inverting input of the summing op amp of each filter.
S1	5	16	This is an alternate signal input pin used in modes 1A, 4, 5 and 6B. This pin must be driven with a low source impedance.
SA/B	6		The SA/B input controls a switch connecting one of the inputs of the filter's 2nd summer — either to analog ground (SA/B low) or to the low pass output (SA/B high). The SA/B input controls the configuration of both sections of the MF10.
VA <sup>+</sup>	7	8	Analog and digital positive supply inputs.
VD <sup>+</sup>	8		These pins are internally connected through the MF10's substrate and therefore VA <sup>+</sup> and VD <sup>+</sup> should be derived from the same power supply source.
LSI	9		Level shift pin. This pin controls the digital input threshold level of the clock inputs, CLKA and CLKB. With the level shift pin at 0V and with ±5V power supplies, the clock inputs are TTL compatible. With the level shift pin connected to VD <sup>+</sup> the clock input thresholds are approximately 2V above VD <sup>+</sup> .

PIN NAME	PIN NUMBER		DESCRIPTION
	Filter A	Section B	
CLK	10	11	Clock inputs for each switched capacitor building block. The duty cycle should be close to 50% to allow the op amps the maximum time to settle, particularly when the clock frequency is above 200kHz.
50/100/CL	12		This three-level input pin selects one of three MF10 operating conditions. When the 50/100/CL pin is connected to $V_D^+$ the ratio between clock frequency and center frequency is 50:1. With this pin at mid supplies (i.e., analog ground with dual supplies) the clock frequency to center frequency ratio is 100:1. Tying the pin low activates a simple current limiting circuitry which halts normal filtering operation and reduces the supply current by 70%.
$V_D^-$ $V_A^-$	13 14		Analog and digital negative supply inputs. These pins are internally connected. $V_A^-$ and $V_D^-$ should be derived from the same power supply source.
AGND	15		Analog Ground. This pin should be connected to the system ground for dual supply operation or driven to mid supply for single supply operation. The non-inverting inputs of the filter op amps are internally connected to the AGND pin, therefore AGND should be well bypassed.

# Dual Universal Switched Capacitor Filter

## Definition of Terms

- $f_{CLK}$ : The frequency applied to the switched capacitor filter external clock input.
- $f_0$ : The center frequency of the second order complex pole pair,  $f_0$ , is determined by measuring the peak response frequency at the bandpass output.
- $Q$ : "Quality factor", or  $Q$ , is the ratio of  $f_0$  to the -3dB bandwidth of the second order bandpass filter.  $Q$  also determines the amount of amplitude peaking at the lowpass and highpass outputs, but is not measured at these outputs.
- $H_{OBP}$ : The gain in V/V of the bandpass output at  $f=f_0$ . See Figure 1.
- $H_{OLP}$ : The gain in V/V of the lowpass output as  $f \rightarrow 0$ Hz. See Figure 2.
- $H_{OHP}$ : The gain in V/V of the highpass output at  $f = f_{CLK}/2$ . See Figure 3.
- $Q_z$ : The quality factor of the 2nd order function complex zero pair, if any.
- $f_z$ : The center frequency of the 2nd order complex zero pair. If  $f_z$  is different from  $f_0$ , and  $Q_z$  is high,  $f_z$  can be observed as a notch frequency at the allpass output.
- $f_{notch}$ : The frequency of minimum amplitude response at the notch output.
- $H_{OCZ1}$ : The complex zero output gain as  $f \rightarrow 0$ Hz.
- $H_{OCZ2}$ : The complex zero output gain at  $f = f_{CLK}/2$ .
- $H_{ON1}$ : The notch output gain as  $f \rightarrow 0$ Hz.
- $H_{ON2}$ : The notch output gain at  $f = f_{CLK}/2$ .

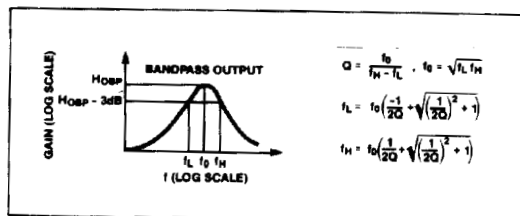


Figure 1. Bandpass Filter Terminology

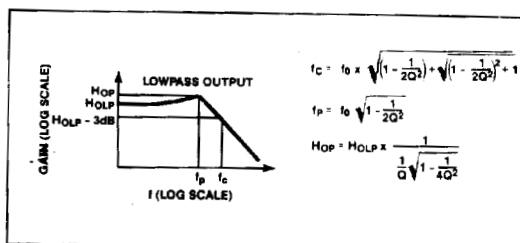


Figure 2. Lowpass Filter Terminology

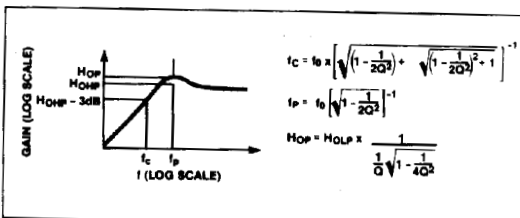


Figure 3. Highpass Filter Terminology

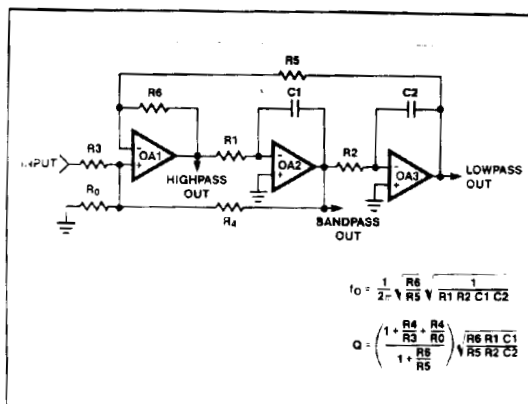


Figure 5. The Universal State Variable 2nd Order Active Filter Using RC Integrators

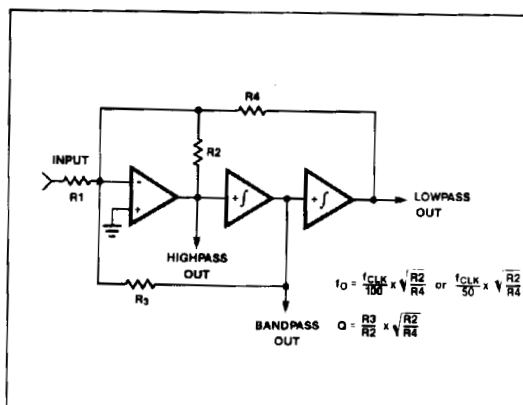


Figure 6. MF10 Universal State Variable 2nd Order Active Filter (Mode 3)

# Dual Universal Switched Capacitor Filter

MF10

## General Description

The MF10 is a switched capacitor (sampled data) filter. While the time domain approach most accurately describes the MF10's transfer functions, time domain calculations are cumbersome and most circuit designers are more familiar with the frequency domain approach used in designing RC active filters. Fortunately, the MF10 closely emulates RC active filters when the sampling frequency is much higher than the frequency band of interest. The operation of the MF10 can then be described in terms of the frequency domain with reasonable accuracy. Specifically, each of the two sections of an MF10 can be treated as a second order state variable filter. The similarity between the MF10 and the classic state variable filter allows the use of the extensive literature available on the design of 2nd order state variable filters.

The RC second order state variable filter (Figure 5) requires 3 op amps, 7 resistors, and 2 capacitors. This filter lacks the frequency stability and tunability of the MF10 switched capacitor filter. The MF10 excels in these areas because the center frequency of a switched capacitor filter is determined by the frequency of the clock, which, if crystal controlled, can achieve a stability of a few parts per million over the entire operating temperature range. Having the center frequency controlled by an external digital clock frequency also simplifies tuning of the filter since it is easier to accurately control a variable modulo divider than it is to precisely vary the time constant of an RC integrator.

The MF10's maximum guaranteed operating clock frequency is 1MHz, corresponding to a 20kHz maximum filter center frequency with a 50:1 clock to center frequency ratio, and a 10kHz maximum center frequency with a 100:1 clock to center frequency ratio.

## Filter Design

### Simple 2nd Order Bandpass Filter Design

All modes except mode 6 offer a 2nd order bandpass response. The simplest circuit, mode 1A uses only two external resistors, but is limited to low Q operation by output swing limitations. Mode 1 uses three resistors and is suitable for either low or high Q bandpass functions. The center frequency of modes 1 and 1A is determined solely by the external clock frequency. Modes 2 and 3 are also suitable for bandpass filters, and are easier to implement in some applications since the center frequency is controlled by both the external clock frequency and a resistor ratio. See Table 2.

Second order bandpass filter functions are characterized by Q, center frequency, and gain (or amplitude response). Resistor selection should follow these steps, using the design equations for the selected mode:

- 1) Pick a value for R2, typically 10 to 100 k $\Omega$ .

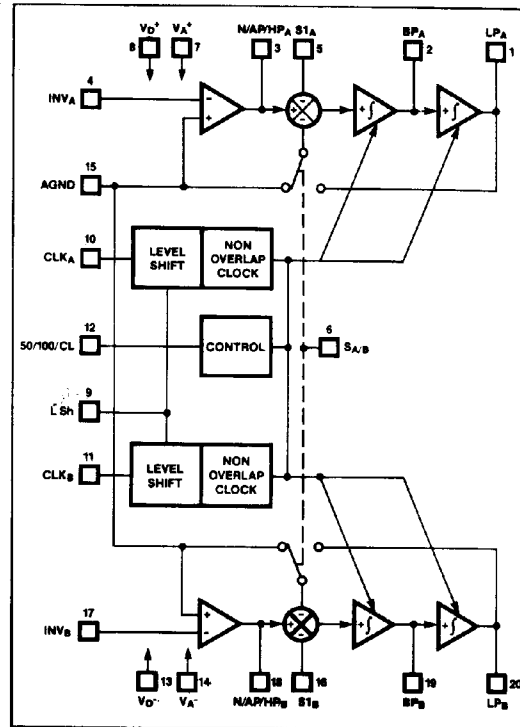


Figure 4. Block Diagram of the MF10

- 2) For modes 2 and 3 only, determine the value of R4 using the available external clock frequency and the selected value for R2. (The center frequency of mode 1 and 1A is determined solely by the external clock frequency.)

- 3) Determine the value of R3, using the desired Q and the previously determined values of R2 and R4.

- 4) Determine the value of R1 required to obtain the desired filter gain.

Table 2. MODE SELECTION

FILTER TYPE	MODE
Lowpass	1, 1A, 2, 3, 3A, 4, 5, 6A, 6B
Highpass	3, 3A, 6A
Bandpass	1, 1A, 2, 3, 3A, 4, 5
Notch	2, 3A, 5 (Complex Zero)
Allpass	4, 5

## Dual Universal Switched Capacitor Filter

Table 3A. NORMALIZED LOWPASS FILTER PARAMETERS

NUMBER OF POLES	BUTTERWORTH		BESSELL		CHEBYSHEV					
					0.1dB RIPPLE		0.5dB RIPPLE		2dB RIPPLE	
	f <sub>n</sub>	Q	f <sub>n</sub>	Q	f <sub>n</sub>	Q	f <sub>n</sub>	Q	f <sub>n</sub>	Q
2	1.0	0.707	1.274	0.577	1.820	0.767	1.231	0.864	0.907	1.129
3	1.0	Real Pole	1.325	Real Pole	0.969	Real Pole	0.625	Real Pole	0.369	Real Pole
	1.0	1.000	1.450	0.691	1.300	1.341	1.069	1.706	0.941	2.552
4	1.0	0.541	1.432	0.522	0.789	0.619	0.597	0.705	0.471	0.929
	1.0	1.307	1.606	0.806	1.153	2.183	1.031	2.941	0.964	4.594
5	1.0	Real Pole	1.505	Real Pole	0.539	Real Pole	0.362	Real Pole	0.218	Real Pole
	1.0	0.618	1.559	0.564	0.797	0.915	0.690	1.178	0.627	1.775
	1.0	1.618	1.758	0.917	1.093	3.282	1.018	4.545	0.976	7.232
6	1.0	0.518	1.607	0.510	0.513	0.599	0.396	0.684	0.316	0.902
	1.0	0.707	1.692	0.611	0.834	1.332	0.768	1.810	0.730	2.844
	1.0	1.933	1.908	1.023	1.063	4.633	1.011	6.513	0.983	10.462
7	1.0	Real Pole	1.687	Real Pole	0.377	Real Pole	0.256	Real Pole	0.155	Real Pole
	1.0	0.555	1.719	0.532	0.575	0.846	0.504	1.092	0.461	1.646
	1.0	0.802	1.82	0.661	0.868	1.847	0.823	2.575	0.797	4.115
	1.0	2.247	2.053	1.126	1.045	6.233	1.008	8.842	0.987	14.280
8	1.0	0.510	1.781	0.506	0.382	8.593	0.297	0.677	0.238	0.892
	1.0	0.601	1.835	0.560	0.645	1.183	0.599	1.611	0.572	2.533
	1.0	0.900	1.956	0.711	0.894	2.453	0.861	3.466	0.842	5.584
	1.0	2.563	2.192	1.226	1.034	8.082	1.006	11.530	0.990	18.687

The normalized frequencies for the Butterworth and Bessel filters are for a -3dB frequency of 1Hz. The Chebyshev and Elliptic normalized frequencies are for filters whose amplitude response passes from the ripple band to the stopband at 1Hz.

### Simple Lowpass Filter Design

Use mode 6 or 6A if a single pole lowpass filter is desired (such as the odd pole in an odd-ordered complex filter). Single pole resistor values are determined using the equations for modes 6 and 6A:

- 1) Select a value for R<sub>2</sub>, typically 10 to 100 kΩ.
- 2) Determine R<sub>3</sub>, using the selected value of R<sub>2</sub>, the available external clock frequency, and the desired cutoff frequency.
- 3) Determine the value of R<sub>1</sub> to obtain the desired gain.

Modes 1 and 1A, with a fixed clock to cutoff frequency, are the simplest 2nd order lowpass configurations. Modes 2 and 3 allow tuning of the cutoff frequency by either changing the clock frequency or adjusting resistor ratios.

Second order lowpass filter functions are characterized by Q, cutoff frequency, and gain (or amplitude response). Resistor selection should follow these steps, using the design equations for the selected mode:

- 1) Pick a value for R<sub>2</sub>, typically 10 to 100 kΩ.
- 2) For modes 2 and 3 only, determine the value of R<sub>4</sub> using the available external clock frequency and the selected value for R<sub>2</sub>. (The cutoff frequency of mode 1 and 1A is determined solely by the external clock frequency.)
- 3) Determine the value of R<sub>3</sub>, using the desired Q and the previously determined values of R<sub>2</sub> and R<sub>4</sub>.
- 4) Determine the value of R<sub>1</sub> required to obtain the desired filter gain.

### Simple Highpass Filter Design

Use mode 3 or 3A to implement 2nd order highpass filters and mode 6 for a single pole highpass filter.

Second order highpass filter functions are characterized by Q, cutoff frequency, and gain (or amplitude response). Resistor selection should follow these steps, using the design equations for the selected mode:

- 1) Pick a value for R<sub>2</sub>, typically 10 to 100 kΩ.
- 2) For modes 3 and 3A, determine the value of R<sub>4</sub> using the available external clock frequency and the selected value for R<sub>2</sub>.
- 3) Determine the value of R<sub>3</sub>, using the desired Q and the previously determined values of R<sub>2</sub> and R<sub>4</sub>.
- 4) Determine the value of R<sub>1</sub> required to obtain the desired filter gain.

### Multi-pole Filter Design

The two 2nd order filter sections of the MF10 can be cascaded to obtain a 4th order (4 pole) filter response. Several MF10s can be cascaded to get very high order filter responses. Unlike filters based on RC time constants, MF10-based filters usually do not require tuning of each section since the Q and center frequencies are precisely controlled by the external clock frequency and the ratio of external resistors.

The information included here is for the most common types of multi-pole filters: Butterworth, Bessel, Chebyshev, and Elliptic or Cauer. The design information given is for a 1Hz lowpass filter. However this filter can be transformed to any desired filter type and frequency using the following steps:

## Dual Universal Switched Capacitor Filter

MF10

**Table 3B. CAUER OR ELLIPTICAL FILTER PARAMETERS**

NUMBER OF POLES	STOPBAND EDGE FREQUENCY = 1.5 PASSBAND EDGE FREQUENCY PASSBAND RIPPLE = 0.5dB				STOPBAND EDGE FREQUENCY = 2.0 PASSBAND EDGE FREQUENCY PASSBAND RIPPLE = 0.5db				STOPBAND EDGE FREQUENCY = 3.0 PASSBAND EDGE FREQUENCY PASSBAND RIPPLE = 0.5dB			
	F <sub>n</sub>	Q	F <sub>z</sub>	A <sub>min</sub> (dB)	F <sub>n</sub>	Q	F <sub>z</sub>	A <sub>min</sub> (dB)	F <sub>n</sub>	Q	F <sub>z</sub>	A <sub>min</sub> (dB)
2	1.266	0.969	1.982	8.3	1.262	0.803	2.732	13.9	1.247	0.737	4.182	21.5
3	0.707 1.072	Real Pole 2.208	1.675	21.9	0.693 1.072	Real Pole 1.859	2.27	31.2	0.653 1.070	Real Pole 1.697	3.439	42.8
4	1.03 0.687	3.922 1.087	1.592 3.478	36.2	1.031 0.641	3.32 1.13	2.143 4.992	48.6	1.031 0.615	3.032 1.159	3.3233 7.647	64.2
5	0.426 1.016 0.759	Real Pole 6.118 1.754	1.557 2.332	50.6	0.393 1.017 0.725	Real Pole 5.193 1.723	2.089 3.251	66.1	0.375 1.017 0.705	Real Pole 4.747 1.711	3.146 5.008	85.5

1) Identify the type of transfer function (lowpass, highpass, bandpass, etc.); the type of response (Butterworth, Bessel, Chebyshev, etc.); the number of poles, and the cutoff frequency.

2) Determine the normalized lowpass filter frequency and Q of each filter section, using Table 3A or 3B.

3) If a multi-pole transfer function other than lowpass is desired, perform the filter type transformation, as described below.

4) Denormalize each filter section frequency, f<sub>n</sub>, by multiplying the f<sub>n</sub> by the actual desired cutoff or center frequency.

5) Select a mode of operation for each filter section. Mode 3 is suitable for most filters, including Bessel and Chebyshev. Butterworth filters can be implemented using either mode 3 or mode 1. Elliptical filters can be implemented using modes 2 and 3A. Modes 6 and 6A provide a single, real pole needed for odd-ordered transfer functions. Allpass and complex zeroes can be generated in modes 4 and 5.

6) Select a clock frequency. The ratio of clock frequency to center frequency can be adjusted with resistor ratios in modes 2,3,5 and 6; allowing the use of any conveniently available clock frequency that is approximately 20 to 200 times the desired cutoff or center frequency.

7) Determine the resistor values for each filter section, using the design procedures given in the sections above for simple 2nd order bandpass, lowpass and highpass filters.

Tables 3A and 3B gives the normalized filter frequency and Q for each second order section of a multi-pole filter. Filters with an odd number of poles have one entry with "real pole" in the Q column. This denotes a

real pole that should be implemented using mode 6 or a simple RC section.

### Lowpass to Highpass Transformation.

The cutoff frequency and Q of each lowpass section is transformed using these equations:

$$f_n(\text{highpass}) = \frac{1}{f_n(\text{lowpass})}$$

$$Q(\text{highpass}) = Q(\text{lowpass})$$

### Lowpass to Bandpass Transformation.

If the ratio between the upper and lower -3dB cutoff frequencies is greater than 1.5, the best way to make the desired bandpass filter is to cascade a lowpass filter and a highpass filter. The lowpass filter's cutoff frequency should be set to the desired bandpass upper cutoff frequency, and the highpass filter's cutoff frequency should be set to the desired bandpass filter lower cutoff frequency.

For very narrowband filters, several sections with identical center frequencies can be cascaded. When identical bandpass filters are cascaded, the Q of the resultant filter is

$$Q = \frac{Q}{\sqrt{2^n - 1}}$$

where Q is the Q of each individual filter section, B is the bandwidth of each individual filter section, and n is the number of identical sections cascaded. See table 4.

**Table 4. CASCADING IDENTICAL BANDPASS FILTER SECTIONS**

NUMBER OF IDENTICAL BANDPASS SECTIONS	BANDWIDTH	Q
1	1.000 B	1.00 Q
2	0.644 B	1.55 Q
3	0.510 B	1.96 Q
4	0.435 B	2.30 Q
5	0.386 B	2.60 Q



## Dual Universal Switched Capacitor Filter

### Application Hints

- 1) The maximum output swing is typically to within 1V of either supply rail. Check the peak amplitude response gains,  $H_{OBP}$ ,  $H_{OLP}$ ,  $H_{OHP}$ , and the input signal level to ensure that the outputs will not be driven beyond their maximum output swing range. This caution particularly applies to mode 1A when used with high Q values. The section labeled "Circuit Dynamics" is included in the description of each mode to clarify the relationship between the various filter parameters and the output amplitude peaking at the filter outputs. The lower Q sections of cascaded filters should precede the sections with high Q. This reduces the possibility of output clipping.
- 2) The absolute values of resistors are not critical, only the ratios between resistors directly affect filter operation. The absolute values must be high enough so that the output drive currents do not approach the limits of 3mA source current and 1mA sink current. At the other extreme, resistor values should not be so high that stray leakage currents and stray capacitances have a significant effect on circuit operation.
- 3) Selecting 100:1 operation doubles the number of samples per output cycle, and halves the number of output steps compared to 50:1 operation. On the other hand, 50:1 allows higher frequency operation (20kHz max vs. 10kHz max), and also offers better center frequency stability ( $\pm 10\text{ppm}/^\circ\text{C}$  vs.  $\pm 100\text{ppm}/^\circ\text{C}$ ).
- 4) The minimum frequency of operation is limited by the rate of discharge of the internal switched capacitors. The droop rate at the output of the integrators will be approximately 0.1mV/ms. This limits the lower value of clock frequency to about 100Hz for reasonable accuracy, corresponding to a center frequency of 1Hz using the 100:1 mode.
- 5) For the best accuracy in setting the center frequency, use the corrections shown in the Typical Operating Characteristic graphs. These graphs aid in the correction for the slight interaction between clock frequency, Q, and center frequency.
- 6) As with all sampled data systems, high frequency components of the input signal above half the clock rate will be aliased. In particular, input signal components with frequencies near the clock rate will generate difference frequencies that may fall within the passband of the lowpass and bandpass filters. Since the ratio of clock frequency to center frequency is approximately 50:1 or 100:1, a simple one pole passive RC filter will be sufficient filtering in many cases. In many other cases the input signal will itself be band-limited and will not require additional filtering.
- 7) The  $S_{A/B}$  input controls the source of feedback into the three input summer of both sections of the MF10. If your design requires that the input of one

section's summer be grounded and the input to the other section's summer be connected to the low-pass output, check to see if  $S_{A/B}$  can be connected to  $V_D^-$  and the lowpass output connection made via the  $S1_A$  (or  $S1_B$ ) input.

- 8) If large input voltage signals are applied to the filter, the DC offset voltages of the MF10 may cause output clipping. For a more detailed discussion see the section on DC Offsets.
- 9) For best results, the positive and negative supplies should be bypassed to AGND with a 10 $\mu\text{F}$  tantalum and 0.1 $\mu\text{F}$  ceramic capacitors.

### Mode 1A

#### Non-Inverting Bandpass, Inverting Bandpass, Lowpass.

This minimum component count configuration uses only two external resistors. The peak gain at the inverting bandpass output is equal to the Q times the input voltage, so this circuit should only be used for low Q applications. The ratio of bandpass center frequency to clock frequency is fixed at either 50:1 or 100:1, as selected by the 50/100/CL input.

#### Design Equations

$$f_0 = \frac{f_{\text{CLK}}}{100} \text{ or } \frac{f_{\text{CLK}}}{50}$$

$$Q = \frac{R_3}{R_2}$$

$$H_{OLP} = -1$$

$$H_{OBP1} = -\frac{R_3}{R_2}$$

$$H_{OBP2} = 1 \text{ (non-inverting)}$$

#### Circuit Dynamics

$H_{OBP1} = Q$  (this is the reason for the low Q recommendation)

$H_{OLP}(\text{peak}) = Q \times H_{OLP}$  (for high Qs)

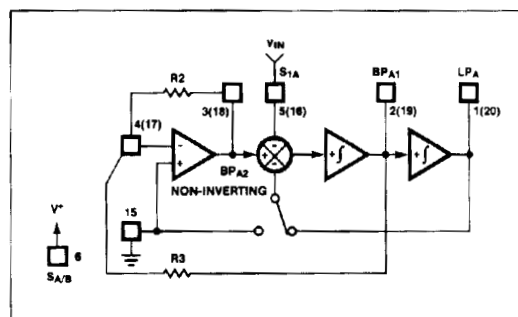


Figure 7. Mode 1A

## MF 70

### Mode 2 Notch, Bandpass, and Lowpass

The circuit of mode 2 is created by adding resistor R4 to the circuit of mode 1. This fourth resistor causes the ratio of the bandpass center frequency to clock frequency to be less than the fixed 50:1 or 100:1 ratio of mode 1. Stated another way, R4 allows the center frequency of the bandpass filter to be tuned to a higher frequency while maintaining a constant clock frequency. The notch frequency remains at  $f_{CLK}/50$  or  $f_{CLK}/100$ , making mode 2 suitable for elliptic highpass filters, where the complex zero pair ( $f_{notch}$ ) must be lower than the complex pole ( $f_0$ ).

### Design Equations

$$f_0 = \frac{f_{CLK}}{100} \times \sqrt{1 + \frac{R2}{R4}} \quad \text{or} \quad \frac{f_{CLK}}{50} \times \sqrt{1 + \frac{R2}{R4}}$$

$$f_n = \frac{f_{CLK}}{100} \text{ or } \frac{f_{CLK}}{50} ; Q = \frac{R3}{R2} \times \sqrt{1 + \frac{R2}{R4}}$$

$$H_{OLP} = \frac{-\frac{R_2}{R_1}}{1 + \frac{R_2}{R_4}} \quad ; \quad H_{OBP} = -\frac{R_3}{R_1}$$

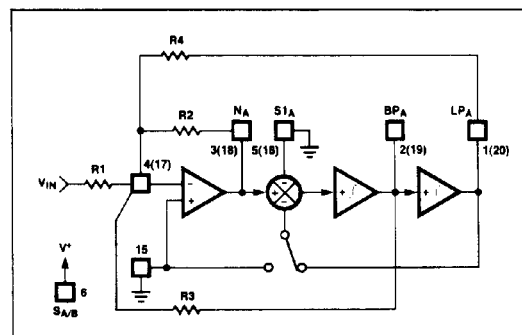
$$H_{ON1} \text{ (as } f \rightarrow 0) = \frac{-\frac{R_2}{R_1}}{1 + \frac{R_2}{R_4}}$$

$$H_{ON2} \left( \text{at } f = \frac{f_{CLK}}{2} \right) = \frac{R_G}{R_H} \times H_{OHP}$$

### Circuit Dynamics

$$H_{OBP} = Q \sqrt{H_{OLP} \times H_{ON_2}} = Q \sqrt{H_{ON_1} \times H_{ON_2}}$$

### Circuit Dynamics

$$H_{OBP} = Q \sqrt{H_{OLP} \times H_{ON_2}} = Q \sqrt{H_{ON_1} \times H_{ON_2}}$$


**Figure 9. Mode 2**

**MF10**

### Mode 3

## Design Equations

$$Q = \frac{R_3}{R_2} \times \sqrt{\frac{R_2}{R_4}}$$

$$H_{OHP} = -\frac{R_2}{R_1}$$

$$H_{OBP} = -\frac{R_3}{R_1}$$

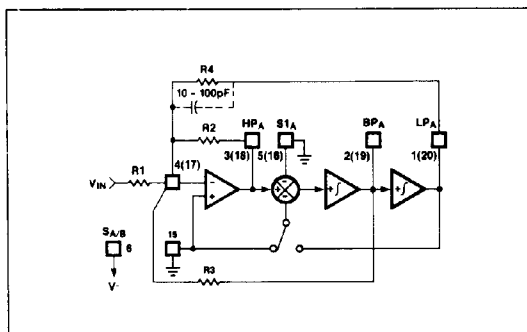
$$H_{OLP} = -\frac{R_4}{R_1}$$

$$H_{OHP} = H_{OLP} \left( \frac{R_2}{R_4} \right)$$

$$H_{OLP(\text{peak})} = Q \times H_{OLP}$$

$$H_{OBP} = Q \sqrt{H_{OHP} \times H_{OLP}}$$

$$H_{OHP(peak)} = Q \times H_{OHP}$$



**Figure 10. Mode 3**

### Mode 3A

## Design Equations

$$Q = \frac{R_3}{R_2} \times \sqrt{\frac{R_2}{R_4}}$$

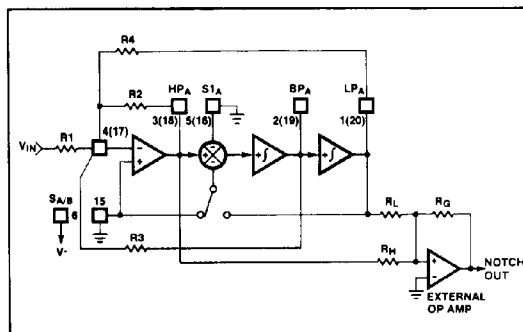
$$f_{\text{notch}} = \frac{f_{\text{CLK}}}{100} \times \sqrt{\frac{R_H}{R_L}} \text{ or } \frac{f_{\text{CLK}}}{50} \times \sqrt{\frac{R_H}{R_L}}$$

$$H_{OHP} = -\frac{R_2}{R_1} \quad H_{OLP} = -\frac{R_4}{R_1} \quad H_{OBP} = -\frac{R_3}{R_1}$$

$$H_{ON} \text{ (at } f = f_0) = \left| Q \left( \frac{R_G}{R_I} H_{OLP} - \frac{R_G}{R_H} H_{OLP} \right) \right|$$

$$H_{ON1} \text{ (as } f \rightarrow 0) = \frac{R_G}{R_L} \times H_{OLP}$$

$$H_{ON2} \left( \text{at } f = \frac{f_{CLK}}{2} \right) = \frac{R_G}{R_H} \times H_{OHP}$$



**Figure 11. Mode 3A**

# Dual Universal Switched Capacitor Filter

MF10

## Mode 4 Allpass, Bandpass, and Lowpass

Mode 4 provides an allpass output which has a nearly flat amplitude response with a phase shift that changes linearly with frequency (a constant time delay). For a flat amplitude response R2 must equal R1, fixing the allpass gain at -1.

### Design Equations

$$f_0 = \frac{f_{CLK}}{100} \text{ or } \frac{f_{CLK}}{50}$$

$$f_z \text{ (frequency of complex zero pair)} = f_0$$

$$Q = \frac{R_3}{R_2}$$

$$Q_z \text{ (Q of complex zero pair)} = \frac{R_3}{R_1}$$

$$H_{OAP} = -\frac{R_2}{R_1} = -1$$

$$H_{OLP} = -\left(\frac{R_2}{R_1} + 1\right) = -2$$

$$H_{OBP} = -\left(1 + \frac{R_2}{R_1}\right) \times \frac{R_3}{R_2} = -2\frac{R_3}{R_2}$$

### Circuit Dynamics

$$H_{OBP} = H_{OLP} \times Q = (H_{OAP} + 1)Q$$

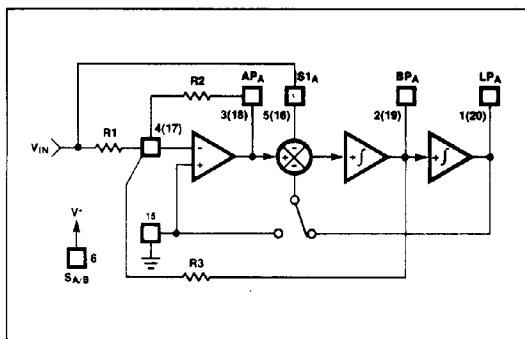


Figure 12. Mode 4

## Mode 5 Complex Zero, Bandpass, and Lowpass

The addition of R4 to the circuit of mode 4 allows the independent tuning of the complex zero frequency,  $f_z$ , and the complex pole frequency,  $f_0$ . Mode 5 can achieve a more constant allpass amplitude vs. frequency response than can be achieved with mode 4.

### Design Equations

$$f_0 = \frac{f_{CLK}}{100} \times \sqrt{1 + \frac{R_2}{R_4}} \text{ or } \frac{f_{CLK}}{50} \times \sqrt{1 + \frac{R_2}{R_4}}$$

$$f_z = \frac{f_{CLK}}{100} \times \sqrt{1 - \frac{R_1}{R_4}} \text{ or } \frac{f_{CLK}}{50} \times \sqrt{1 - \frac{R_1}{R_4}}$$

$$Q = \frac{R_3}{R_2} \times \sqrt{1 + \frac{R_2}{R_4}}$$

$$Q_z = \frac{R_3}{R_1} \times \sqrt{1 - \frac{R_1}{R_4}}$$

$$H_{OCZ1} \text{ (as } f \rightarrow 0) = \frac{R_2(R_4 - R_1)}{R_1(R_2 + R_4)}$$

$$H_{OCZ2} \left( \text{at } f = \frac{f_{CLK}}{2} \right) = \frac{R_2}{R_1}$$

$$H_{OBP} = \frac{R_3}{R_2} \times \left( 1 + \frac{R_2}{R_1} \right)$$

$$H_{OLP} = \frac{R_4}{R_1} \times \left( \frac{R_2 + R_1}{R_2 + R_4} \right)$$

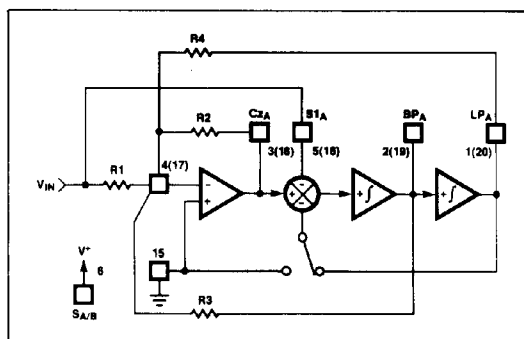


Figure 13. Mode 5

# Dual Universal Switched Capacitor Filter

## Mode 6A Single Pole; Highpass and Lowpass

This circuit provides a single real pole for use in odd-ordered cascaded filters. Unlike the simple RC pole used in continuous filters, the MF10 single pole filter can be tuned by simply changing the clock frequency. The cutoff frequency is also resistor tunable.

### Design Equations

$$f_c \text{ (cutoff frequency)} = \frac{f_{CLK}}{100} \times \left(\frac{R2}{R3}\right) \text{ or } \frac{f_{CLK}}{50} \times \left(\frac{R2}{R3}\right)$$

$$H_{OLP} = -\frac{R3}{R1}$$

$$H_{OHP} = -\frac{R2}{R1}$$

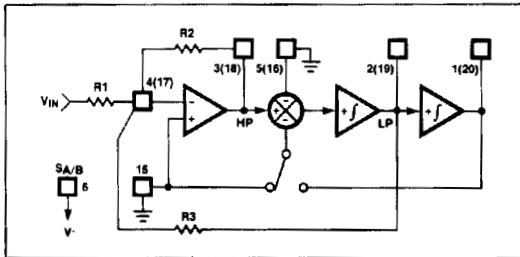


Figure 14. Mode 6A

## Mode 6B Single Lowpass Pole; Inverting and Non-Inverting

As with mode 6A, this mode is useful in implementing filters with an odd number of poles.

### Design Equations

$$f_c \text{ (cutoff frequency)} = \frac{f_{CLK}}{100} \times \left(\frac{R2}{R3}\right) \text{ or } \frac{f_{CLK}}{50} \times \left(\frac{R2}{R3}\right)$$

$$H_{OLP} \text{ (inverting output)} = -\frac{R3}{R2}$$

$$H_{OLP} \text{ (non-inverting output)} = +1$$

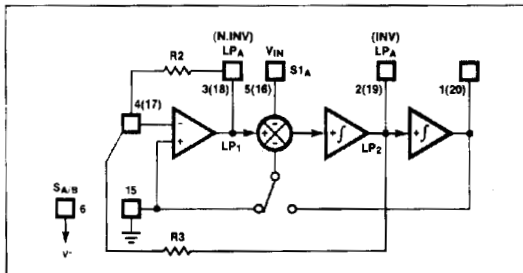


Figure 15. Mode 6B

## MF10 Offsets

The MF10's switched capacitor integrators have higher equivalent input offsets than the typical RC integrator in a continuous active filter. The MF10 offsets are produced by parasitic charge injection from the switches into the integrating capacitors. These offsets are relatively independent of clock frequency and temperature. The input offset of the CMOS op amps also contribute to the overall offset error, but these offsets are small in comparison to the offsets caused by charge injection. Figure 16 shows the equivalent circuit for calculating output DC offsets.

$$V_{OS1} = 0 \text{ mV to } \pm 10 \text{ mV}$$

$$V_{OS2} = \text{charge injected offset plus op amp offset} \\ \approx -60 \text{ mV to } -80 \text{ mV (50:1)}$$

$$V_{OS3} = \text{charge injected offset plus op amp offset} \\ \approx +100 \text{ mV to } +150 \text{ mV (at 50:1)}$$

(At 100:1 the  $V_{OS2}$  and  $V_{OS3}$  are approximately doubled.)

Using the same designation for resistors as are used in Figures 7 to 15, the output offsets can be calculated as shown below.

### Mode 1 and Mode 4 Output Offsets

$$V_{OS(N)} = V_{OS1} \left( \frac{1}{Q} + 1 + |H_{OLP}| \right) - \frac{V_{OS3}}{Q}$$

$$V_{OS(BP)} = V_{OS3}$$

$$V_{OS(LP)} = V_{OS(N)} - V_{OS2}$$

### Mode 2 and Mode 5 Output Offsets

$$V_{OS(N)} = \left( \frac{R2}{R_p} \pm 1 \right) V_{OS1} \times \frac{1}{1 + R2/R4} \\ + V_{OS2} \frac{1}{1 + R4/R2} - \frac{V_{OS3}}{Q \sqrt{1 + R2/R4}}$$

$$R_p = R1 // R2 // R4$$

$$V_{OS(BP)} = V_{OS3}$$

$$V_{OS(LP)} = V_{OS(N)} - V_{OS2}$$

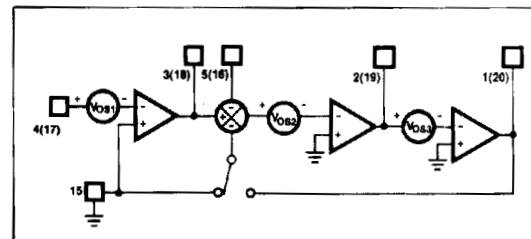


Figure 16. MF10 Offset Model

## Dual Universal Switched Capacitor Filter

MF10

### Mode 3 Output Offsets

$$\begin{aligned} V_{OS(HP)} &= V_{OS2} \\ V_{OS(BP)} &= V_{OS3} \\ V_{OS(LP)} &= -\frac{R_4}{R_2} \times \left( \frac{R_2}{R_3} V_{OS3} + V_{OS2} \right) + \\ &\quad \frac{R_4}{R_2} \times \left( 1 + \frac{R_2}{R_p} \right) V_{OS1} \end{aligned}$$

$$R_p = R_1 // R_3 // R_4$$

### Mode 1A Output Offsets

$$V_{OS(N.INV.BP)} = \left( 1 + \frac{1}{Q} \right) V_{OS1} - \frac{V_{OS3}}{Q}$$

$$V_{OS(INV.BP)} = V_{OS3}$$

$$V_{OS(LP)} = V_{OS(N.INV.BP)} - V_{OS2}$$

In most applications the outputs are AC coupled and the DC offsets present no problem unless large input voltages are applied to the filter.

For Mode 3 operation it should be noted that the use of small  $R_2/R_4$  ratios and high  $Q$  will produce an LP output with a couple of volts DC offset and an offset adjustment should be made. Make the offset adjustment by injecting a small amount of current into the first op amp's inverting input (see Figure 17). This changes  $V_{OS1}$  but leaves the output DC offset of the integrators unchanged.

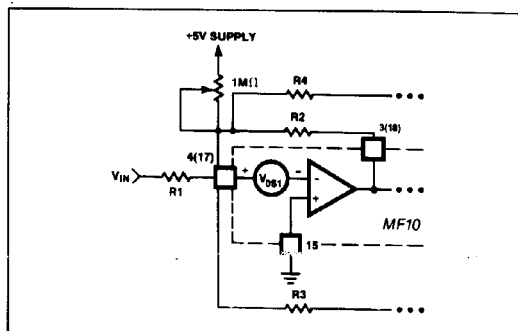


Figure 17.  $V_{OS}$  Adjustment

### Application Examples

#### 4th Order, 2kHz Lowpass Butterworth Filter

A 4th order lowpass filter can be made by cascading the two second order filter sections of the MF10 (See Figure 18). Table 3 shows that the two sections of a Butterworth 4th order filter will have the same cutoff frequency, with one stage having a  $Q$  of 0.541 and the other stage having a  $Q$  of 1.307. Any of the modes may be used, but mode 1A uses only 2 resistors per section, and should therefore be used. The  $Q$  of both sections is low, so output clipping will not be a problem.

Using the 2nd order lowpass filter design steps shown in the Filter Design section, the resistor values for the first filter section can be calculated as follows:

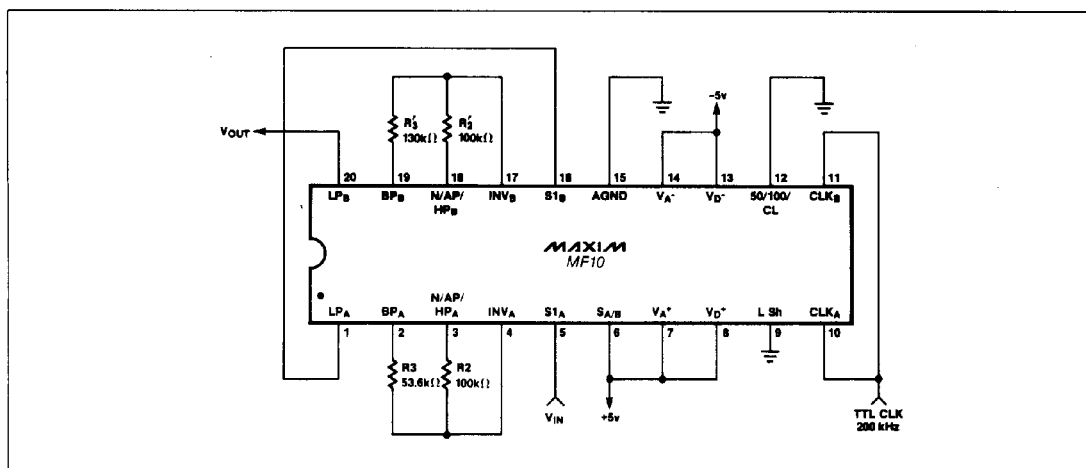


Figure 18. 4th Order, 2kHz Lowpass Butterworth Filter

## Dual Universal Switched Capacitor Filter

Mode = 1A

$$f_0 = 2\text{kHz}$$

$$Q = 0.541$$

- 1) Let  $R_2$  be  $100\text{k}\Omega$ .

2)  $f_0 = 2\text{kHz} = \frac{f_{\text{CLK}}}{100}$  (pin 12 mid-supply)

so  $f_{\text{CLK}} = 200\text{kHz}$  (pin 12 mid-supply)

$f_{\text{CLK}} = 100\text{kHz}$  with pin 12 high.

3)  $Q = \frac{R_3}{R_2}$ ;

so  $R_3 = Q \times R_2 = 0.541 \times 100\text{k}\Omega = 54.1\text{k}\Omega$ .

Picking the nearest 1% resistor value,  $R_3 = 53.6\text{k}\Omega$

Using similar calculations for the second filter section,  $R_2 = 100\text{k}\Omega$  and  $R_3 = 130\text{k}\Omega$ .

The output of the first section,  $LP_A$  (pin 1), is the input for the second stage, at  $SI_B$  (pin 16). The filter output is at  $LP_B$  (pin 20). With  $\pm 5\text{V}$  supplies and the Level Shift pin connected to ground, the digital input threshold of the CLK inputs is about 1.6V. The CLK inputs can therefore be driven by either TTL or CMOS logic levels. The 50/100/CL pin is grounded, which selects a 100:1 ratio between the clock frequency and the lowpass cutoff frequency.

### 4th Order Chebyshev Lowpass Filter

Figure 19 shows a 4th order Chebyshev lowpass filter with the following specifications:

Passband Ripple = 2dB (nominal)

Cutoff Frequency = 5kHz

The filter uses a 200kHz clock for both sections.

Table 3 shows that for a 2dB ripple, 4th order Chebyshev filter the parameters of the two sections are:

$$f_n = 0.471, Q = 0.929$$

and

$$f_n = 0.964, Q = 4.594$$

Either mode 3 or mode 2 is suitable for this filter. The resistors for mode 2 can be calculated as follows:

- 1) Let  $R_2 = 10\text{k}\Omega$ .

- 2) For the first section  $f_n = 0.471$ , so for a 5kHz cutoff  $f_0 = 0.471 \times 5\text{kHz} = 2.355\text{kHz}$

Using the mode 2 equation for  $f_0$ ,

$$f_0 = \frac{f_{\text{CLK}}}{100} \times \sqrt{1 + \frac{R_2}{R_4}}$$

and using 200kHz for  $f_{\text{CLK}}$ ,  $R_4$  is calculated as 25.87k $\Omega$ . The closest 1% resistor value of 26.1k $\Omega$  is chosen.

- 3) The mode 2 formula for  $Q$  is

$$Q = \frac{R_3}{R_2} \times \sqrt{1 + \frac{R_2}{R_4}}$$

Using  $Q = 0.929$  and the previously determined values for  $R_2$  and  $R_4$ ,  $R_3$  is calculated as 7.9k $\Omega$ . The closest 1% value, 7.87k $\Omega$  is used.

- 4) Choose  $R_1$  for the desired filter gain. In this example  $R_1$  is 10k $\Omega$ .

Repeat the above steps for the second section, with  $f_n = 0.964$  and  $Q = 4.594$ . If  $R_2$  is chosen to be 10k $\Omega$ , the value of  $R_4$  will be 2.1k $\Omega$  and the value of  $R_3$  will be 19.1k $\Omega$ .

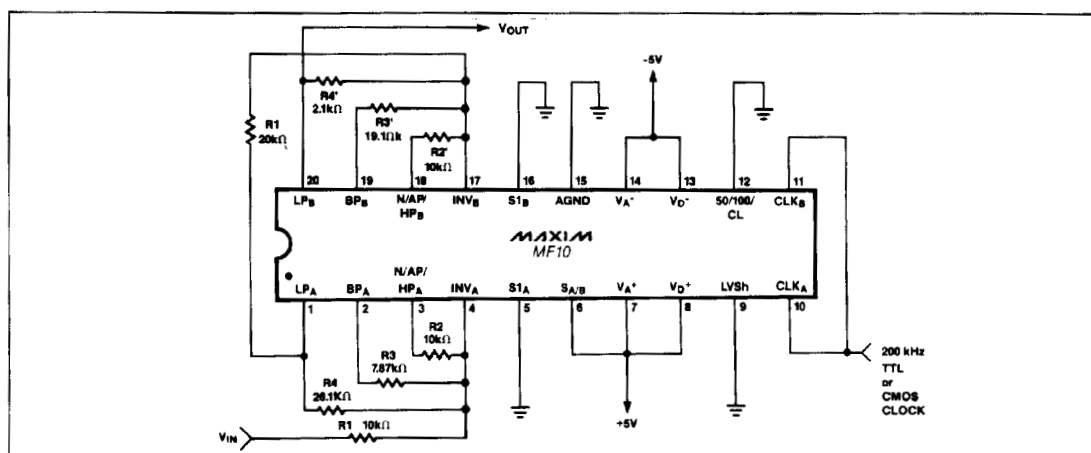


Figure 19. 4th Order Chebyshev 5kHz Lowpass Filter

# Dual Universal Switched Capacitor Filter

MF10

## Switched Capacitor Filter Fundamentals

While it is not necessary to understand the internal operation of the MF10 in order to use it, a basic understanding of switched capacitor operation may help in optimizing designs.

Figure 20 shows a standard integrator using an op amp. The time constant is determined by the passive components, R and C. When a positive input voltage is applied, the integrator output will ramp downward at a rate determined by the input voltage and the time constant, RC. This ramp has a slope of

$$\frac{\Delta V}{\Delta T} = - \frac{V_{IN}}{RC}$$

Figure 21 is a simple inverting switched capacitor integrator, where the R of the standard integrator has been replaced by a capacitor and two analog switches, S1 and S2. As S1 and S2 alternately open and close at the rate set by the clock input, first C1 is charged to the input voltage, then C1 transfers its charge into the capacitor C2. This creates a series of voltage steps on the integrator output, with each voltage step having a value of  $-V_{IN} \times C1/C2$ . If the value of C1 is small compared to C2, the series of steps at the integrator output approximates a ramp with the slope

$$\frac{\Delta V}{\Delta T} = - \frac{V_{IN} \times f_{CLK} \times C1}{C2}$$

where  $f_{CLK}$  is the frequency of the clock input.

This equation is similar to that of the standard integrator, but with the sampled capacitors time constant of

$$\frac{C2}{C1 \times f_{CLK}}$$

replacing the standard integrators time constant of RC. The center frequency of an RC based 2nd order state variable filter is

$$f_0 = \frac{1}{2\pi RC}$$

The center frequency of a switched capacitor 2nd order state variable filter is approximately

$$f_0 = \frac{f_{CLK} \times C1}{2\pi C2}$$

The ratio of C2/C1 in the MF10 is approximately 8 when the 50/100/CL input selects a 50:1 clock to center frequency ratio, and the ratio of C2/C1 is approxi-

mately 16 when the 50/100/CL input selects a 100:1 clock to center frequency ratio. Substituting these C2/C1 ratios in the above formula, the MF10  $f_0$  equation (for modes 1 and 6) results:

$$f_0 = \frac{f_{CLK}}{50} \text{ (50/100/CL Input High)}$$

or

$$f_0 = \frac{f_{CLK}}{100} \text{ (50/100/CL Input Mid-supply)}$$

The integrators used in the MF10 are non-inverting, and use the basic switching scheme of Figure 22. The switches ground one side of the input capacitor C1 when it is connected to the input; and connect the other side to ground while it is connected to the op amp's input. By changing the polarity of C1 in this manner, an additional inversion is added, and overall operation is non-inverting. This means the direction of the voltage ramp at the output of the integrator has the same polarity as  $V_{IN}$ .

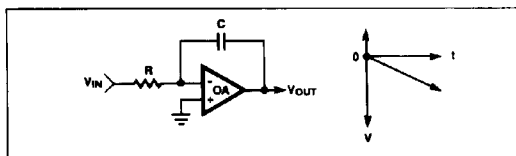


Figure 20. Typical RC integrator

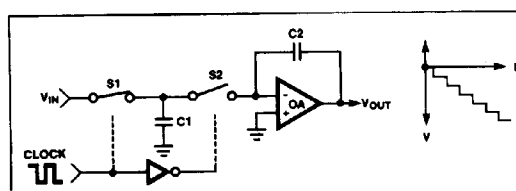


Figure 21. Simple Inverting Switched Capacitor Integrator

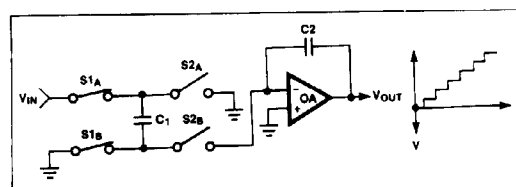
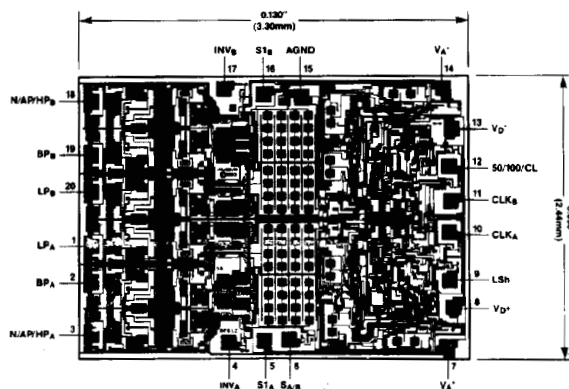


Figure 22. The Non-Inverting Integrator Used in the MF10

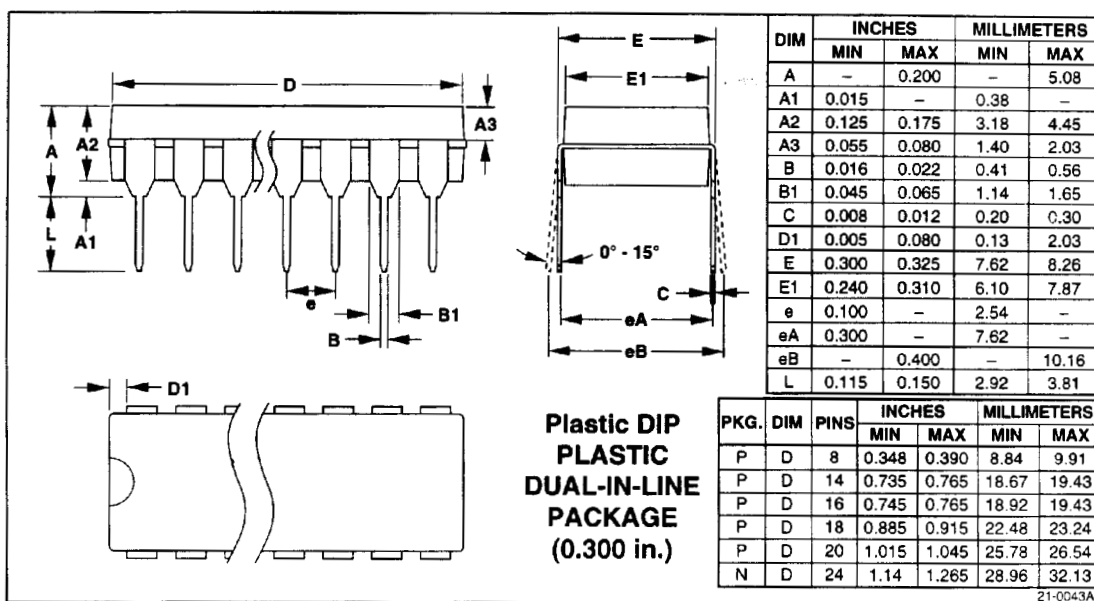


# Dual Universal Switched Capacitor Filter

## Chip Topography



## Package Information



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