University of California
Berkeley

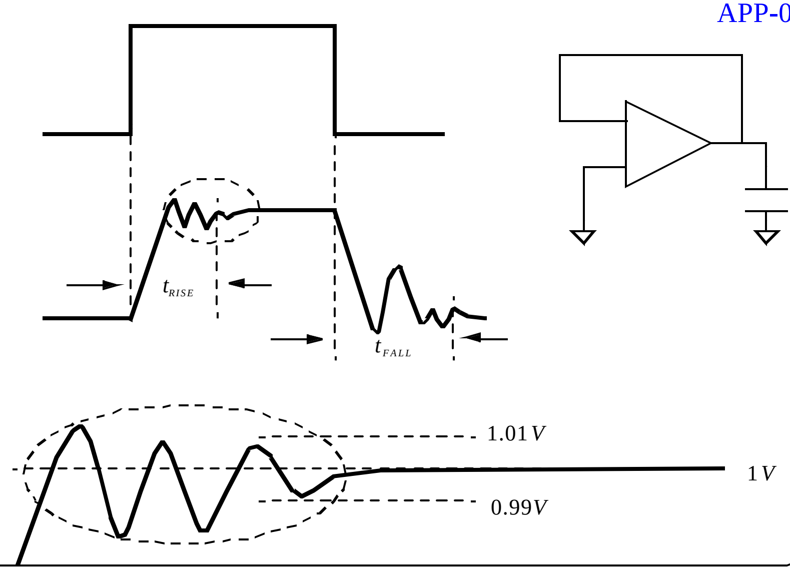
College of Engineering
Department of Electrical Engineering
and Computer Science

Robert W. Brodersen
EECS140

Analog Circuit Design

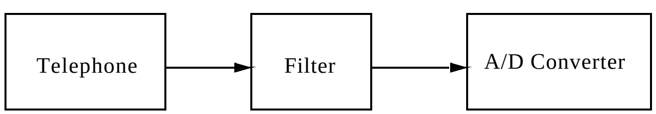
Lectures on APPLICATIONS

APP-01



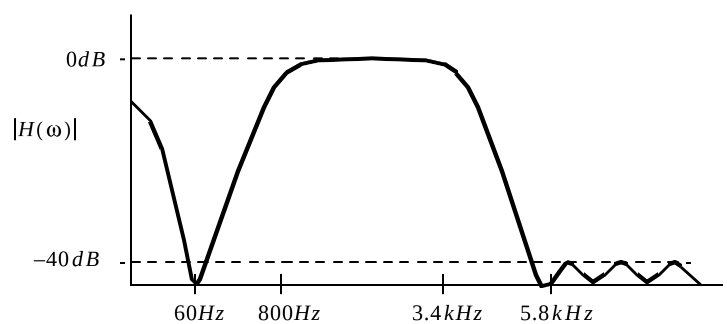
APP-02

15-20 Years Ago



PCM Codec

APP-03

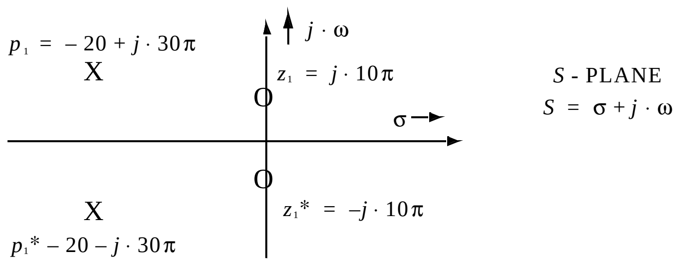


Pole - Zero Diagrams

APP-04

A convenient way of visualizing transfer functions, the Laplace Transform :

$$H_{(S)} = \frac{v_{OUT}(s)}{v_{IN}(s)} = \frac{(s - z_1) \cdot (s - z_1^*)}{(s - p_1) \cdot (s - p_1^*)}$$



Poles - Zero Diagrams (Cont.)

APP-05

Often what we are really interested in is $|H(\omega)|$,i.e. the magnitude and phase at frequency, ω.

$$H(\omega) = H(s)|_{S = j \cdot \omega}$$

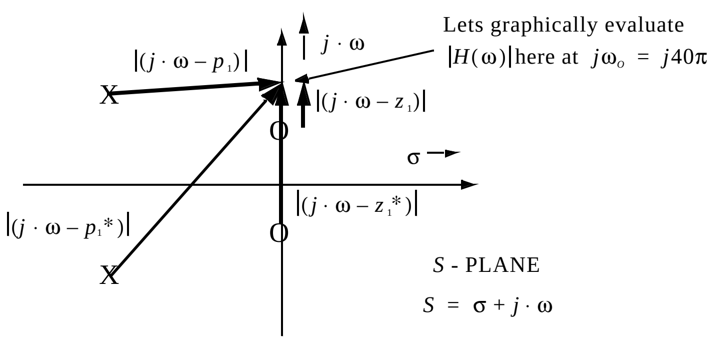
$$H(\omega) = \frac{(j \cdot \omega - z_1) \cdot (j \cdot \omega - z_1^*)}{(j \cdot \omega - p_1) \cdot (j \cdot \omega - p_1^*)}$$

To find the magnitude use the fact that magnitude of the products equals the product of the magnitudes , so that :

$$|H(\omega)| = \left|\frac{(j \cdot \omega - z_1) \cdot (j \cdot \omega - z_1^*)}{(j \cdot \omega - p_1) \cdot (j \cdot \omega - p_1^*)}\right| = \frac{|(j \cdot \omega - z_1)| \cdot |(j \cdot \omega - z_1^*)|}{|(j \cdot \omega - p_1)| \cdot |(j \cdot \omega - p_1^*)|}$$

Poles - Zero Diagrams (Cont.)

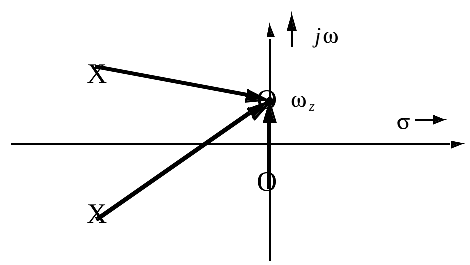
APP-06

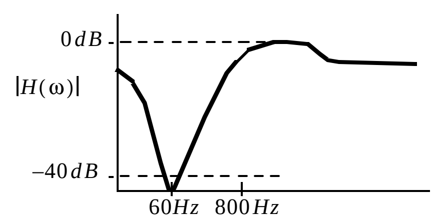


The magnitude $|H(\omega)|$ is the product of the lengths of vectors 3 & 4 divided by the product of the lengths of vectors 1 & 2.

Poles - Zero Diagrams (Cont.)

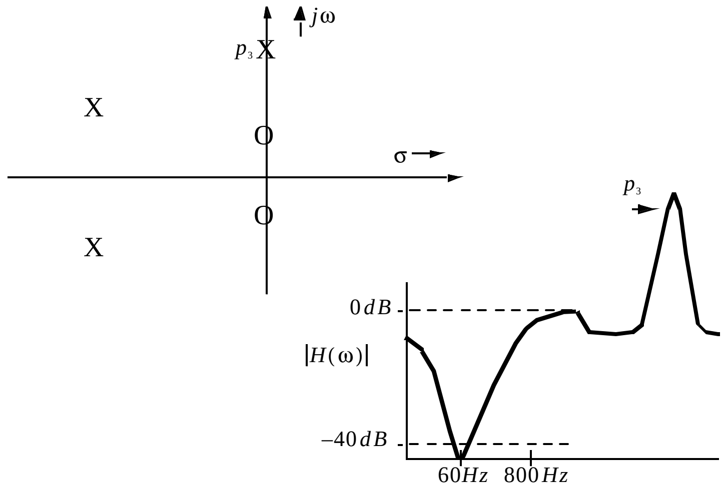
APP-07





Poles - Zero Diagrams (Cont.)

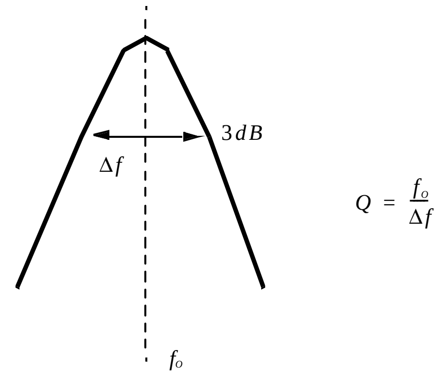
APP-08



EECS140 ANALOG CIRCUIT DESIGN LECTURES ON APPLICATIONS

Poles - Zero Diagrams (Cont.)

APP-09



$$Q = \frac{f_o}{\Delta f}$$

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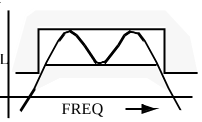
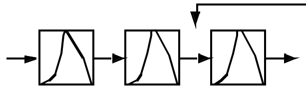
Filter Design

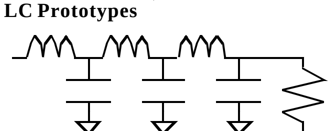
APP-10

Specification



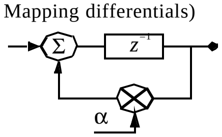


LC Prototypes



Continuous Time Factorization into
2-Pole,2-Zero sections
(Biquadratic)

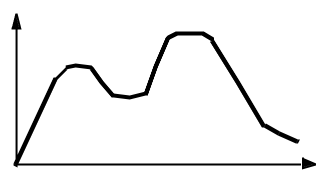
Chose an "Equivalent" discrete time structure.
Use appropriate cont. → Discrete Transformation
(i.e. Bilinear, Mapping differentials)



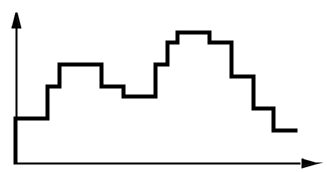
→ Simulate Disirete Time inplementation and compare with original spec.(DINAP)

EECS140 ANALOG CIRCUIT DESIGN LECTURES ON APPLICATIONS

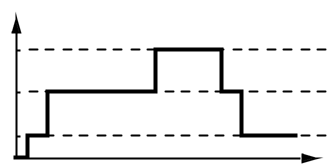
APP-11



Active RC Filter
(Continuous Time)

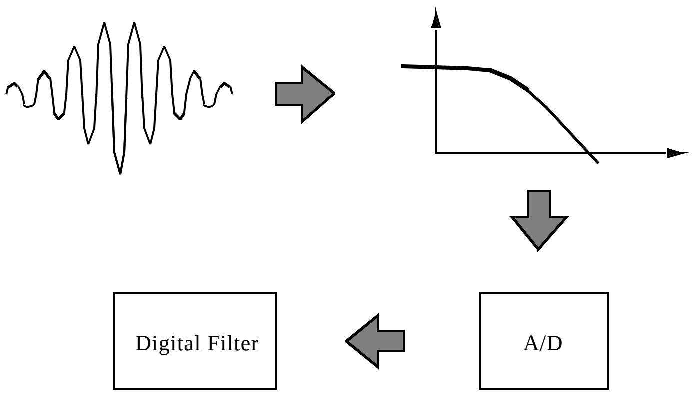


Switched Capacitor Circuits
(Sampled Data any Amplitude)



Digital Filter
(Sampled Data, Quantized Amplitude)

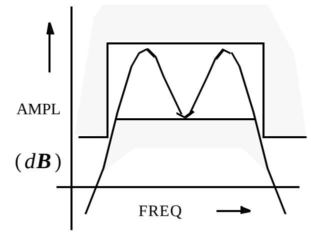
APP-12



Typical Filter Specifications

APP-13

Continuous time specifications of transfer function $|H(\omega)|$

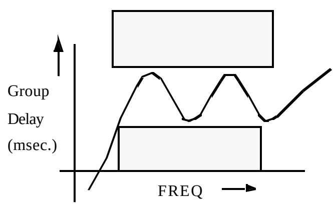


$$\frac{v_{OUT}(\omega)}{v_{IN}(\omega)} = H(\omega) = |H(\omega)| \cdot e^{j \cdot \theta(\omega)}$$

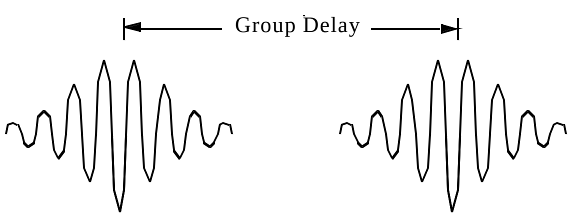
Amplitude (Magnitude in dB) $= 10 \log[\underbrace{H(\omega) \cdot H^*(\omega)}_{|H(\omega)|^2}]$

Typical Filter Specifications (Cont.)

APP-14



Group Delay $= \frac{\partial}{\partial \omega} \theta(\omega)$

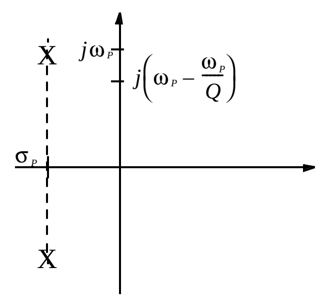


Types of 2-Pole Transfer Functions

APP-15

Lowpass :

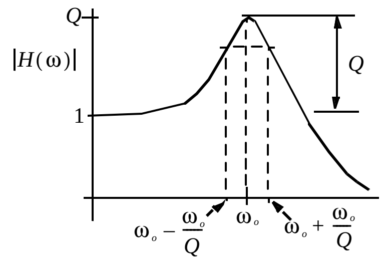
$$H(s) = \frac{\omega_o^2}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}$$



$$s_1, s_1^* = -\frac{\omega_o}{Q} \mp \sqrt{\left(\frac{\omega_o}{Q}\right)^2 - 4 \cdot \omega_o^2}$$

Types of 2-Pole Transfer Functions (Cont.) APP-16

(Lowpass)



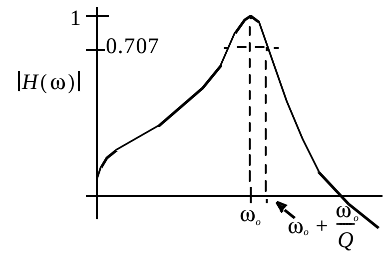
$$\omega_o \equiv |s_P| = \sqrt{s_P^2 + \omega_P^2}$$

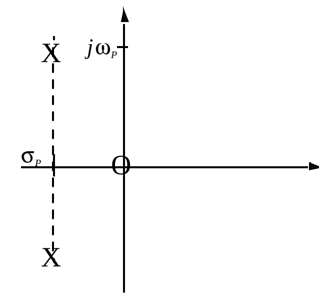
$$Q \equiv \frac{|s_P|}{2 \cdot |s_P|} = \frac{1}{2} \cdot \sqrt{1 + \left(\frac{\omega_P}{s_P}\right)^2}$$

Types of 2-Pole Transfer Functions (Cont.) APP-17

Bandpass :

$$H(s) = \frac{\frac{\omega_o}{Q} \cdot s}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}$$



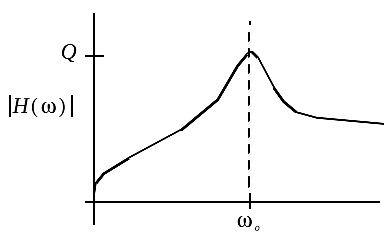


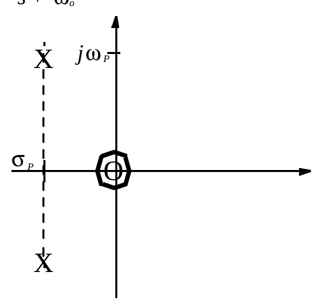
Types of 2-Pole Transfer Functions (Cont.) APP-18

Highpass :

$$Highpass = 1 - (Lowpass) - (Bandpass)$$

$$= 1 - \left(\frac{\frac{1}{\omega_o^2} + \frac{\omega_o}{Q} \cdot s}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}\right) = \frac{s^2}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}$$

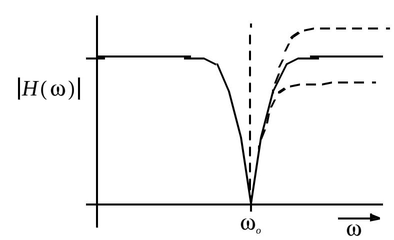


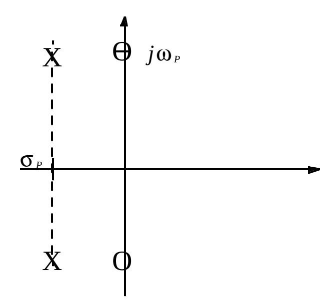


Types of 2-Pole Transfer Functions (Cont.) APP-19

Bandstop (or Notch) :

$$Bandstop = 1 - \frac{s \cdot \left(\frac{\omega_o}{Q}\right)}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2} = \frac{s^2 + \omega_o^2}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}$$



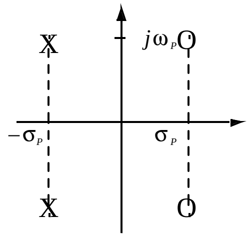


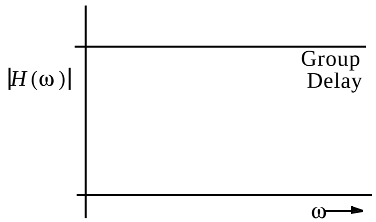
Types of 2-Pole Transfer Functions (Cont.) APP-20

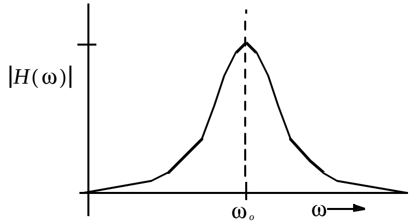
All Pass (Delay Equalizer) :

$$= 1 - 2 - (Bandpass)$$

$$H(s) = 1 - \frac{2 \cdot s \cdot \frac{\omega_o}{Q}}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2} = \frac{s^2 - \frac{\omega_o}{Q} \cdot s + \omega_o^2}{s^2 + \frac{\omega_o}{Q} \cdot s + \omega_o^2}$$

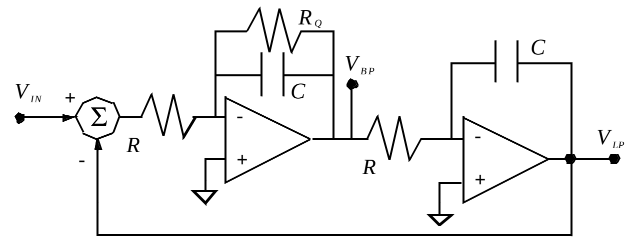




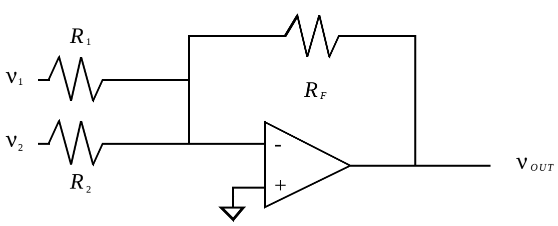


State Variable Active RC Filter APP-21

Lowpass & Bandpass :

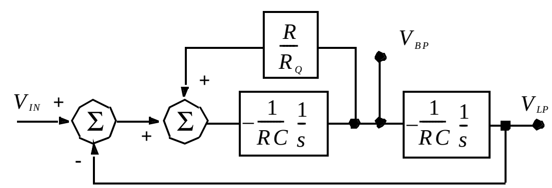


State Variable Active RC Filter (Cont.) APP-22



$$\nu_{OUT} = \nu_1 \frac{R_F}{R_1} + \nu_2 \frac{R_F}{R_2}$$

State Variable Active RC Filter (Cont.) APP-23



$$\frac{V_{LP}}{V_{IN}} = \frac{\left(\frac{1}{RC}\right)^2}{s^2 + \left(\frac{1}{R_C \cdot C} \cdot s\right) + \frac{1}{R_C}} = \frac{\omega_o^2}{s^2 + \frac{\omega_o}{Q} s + \omega_o^2}$$

$$\therefore \omega_o = \frac{1}{RC} \qquad Q = \frac{R_Q}{R}$$

State Variable Active RC Filter (Cont.)

$$\frac{V_{BP}}{V_{IN}} = \frac{-\frac{1}{RC} \cdot S}{S + \frac{1}{R_C \cdot C} \cdot S + \left(\frac{1}{R_C}\right)^2} = \frac{-\omega_o \cdot S}{S + \frac{\omega_o}{Q} \cdot S + \omega_o^2}$$

(Note GAIN is $-Q$ at ω_o instead of 1
as required for a canonical bandpass.)

Highpass :

$$Highpass = 1 - (Lowpass) - (Bandpass)$$

Using a 3RD OP AMP we form the sum,

$$V_{HIGHPASS} = V_{IN} - V_{LP} + \frac{1}{Q} \cdot V_{BP}$$

State Variable Active RC Filter (Cont.)

Bandstop :

$$Bandstop = 1 - (Bandpass)$$

$$V_{BANDSTOP} = V_{IN} + \frac{1}{Q} \cdot V_{BP}$$

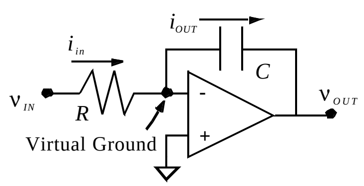
All Pass :

$$Allpass = 1 - 2(Bandpass)$$

$$V_{ALLPASS} = V_{IN} + \frac{2}{Q} \cdot V_{BP}$$

Active RC Filters - Integrator or State Variable Configurations

Basic Element is the OP AMP Integrator :



Active RC Filters - Integrator or State Variable Configurations (Cont.)

$$i_{OUT} = i_{in}$$

$$i_{in} = \frac{v_{in} - 0}{R} = \frac{v_{in}}{R}$$

$$-SC \cdot v_{OUT} = \frac{v_{in}}{R}$$

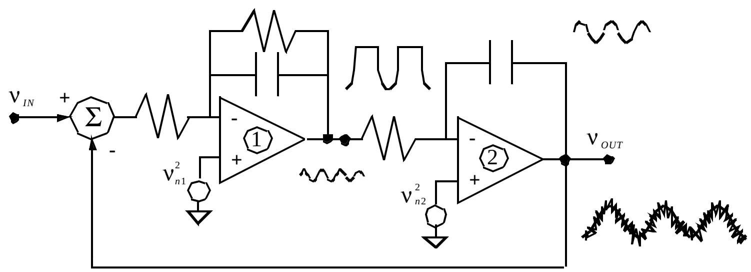
$$i_{OUT} = \frac{0 - v_{OUT}}{1/SC} = -SC \cdot v_{OUT}$$

$$\frac{v_{OUT}}{v_{in}} = -\frac{1}{RC} \cdot \frac{1}{S} = H(s)$$

$$H(s)|_{s=j\omega} = -\frac{1/RC}{j\omega}$$

Active RC Filters - Integrator or State Variable Configurations (Cont.)

Scaling of the internal node voltages for maximum dynamic range.



Active RC Filters - Integrator or State Variable Configurations (Cont.)

For maximum dynamic range. (Signal / Noise Ratio) the outputs of both op amps should have the same peak values.
If this is not true;

- If op amp #1 has a peak signal larger than #2, then #1 will saturate early limiting the maximum signal.
- If #1 has a peak amplitude less than #2, then there must be gain from #1 to #2 and the noise of #1 will be amplified.

$$f_o = 3kHz$$

$$\omega_o = \frac{20krad}{\sec} = \frac{1}{RC}$$

$$C = 10pF$$

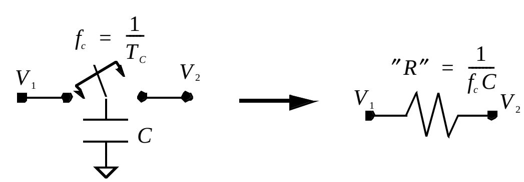
$$R = \frac{1}{10pF \cdot 20 \cdot 10^3} = \frac{1}{2 \cdot 10^{-7}}$$

$$R = 5M\Omega$$

$R \pm 10\%$ $\qquad$ $C \pm 10\%$

$RC \pm 20\%$

Basic Element of Switched - Capacitor Filters

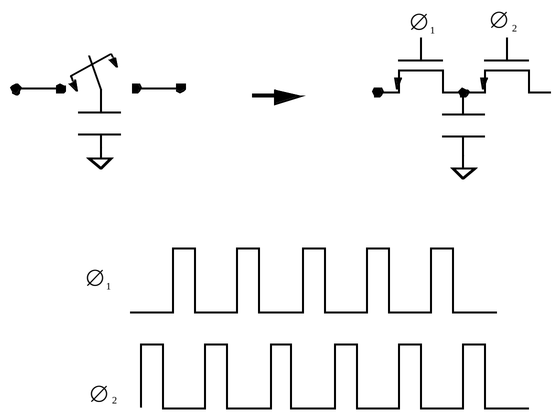


$$\Delta Q = C \cdot (V_2 - V_1)$$

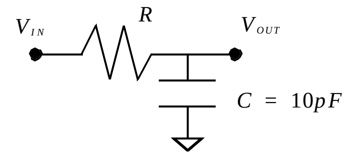
$$"I" = \frac{\Delta Q}{T_C} = f_c \cdot C \cdot (V_2 - V_1)$$

$$"R" = \frac{V_2 - V_1}{I} = \frac{1}{f_c C}$$

Basic Element of Switched - Capacitor Filters (Cont.) APP-32



Size of Switched - Capacitor, Resistors APP-33



$f_{3dB} = 10kHz$

$$R = \frac{1}{2\pi \cdot f_{3dB} \cdot C} = \frac{1}{(6.28)\cdot(10^4)\cdot(10^{-11})}$$

$= 1.6M\Omega$

Area of S-C Resistor

$(f_c = 100kHz)$

$$C_R = \frac{1}{f_c \cdot R} = \frac{1}{10^5 \times 1.6 \times 10^6}$$

$= 6.28pF$

$\approx 31mil^2s(@5mil^2/pF)$

Area of Poly Resistor

$(50\Omega/\square)$

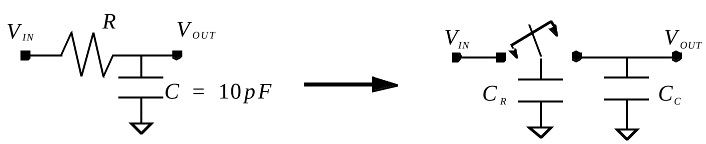
$= 32 \times 10^3 \ \square$

$\approx 3.2 \times 10^3 mil^2s(@1mil^2/\square)$

Equivalent S-C resistor about

2 orders of magnitude smaller in area.

Simple Filter APP-34



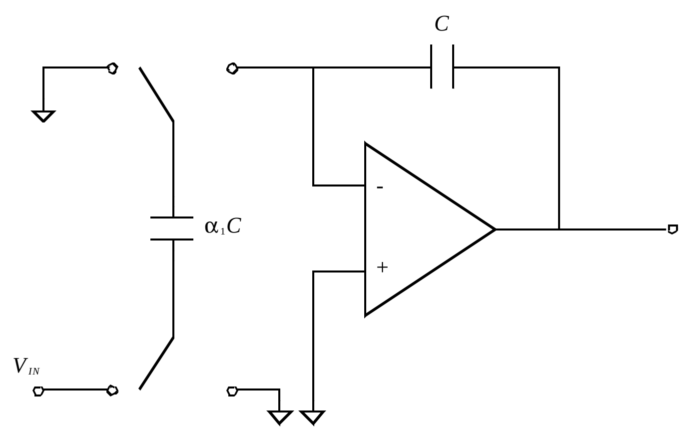
$$\omega_{3dB} = \frac{1}{RC}$$

$$\omega_{3dB} \approx \frac{1}{\left(\frac{1}{f_c \cdot C_R}\right)\cdot C_C} = f_c \cdot \left(\frac{C_R}{C_C}\right)$$

Requires absolute control of R and C

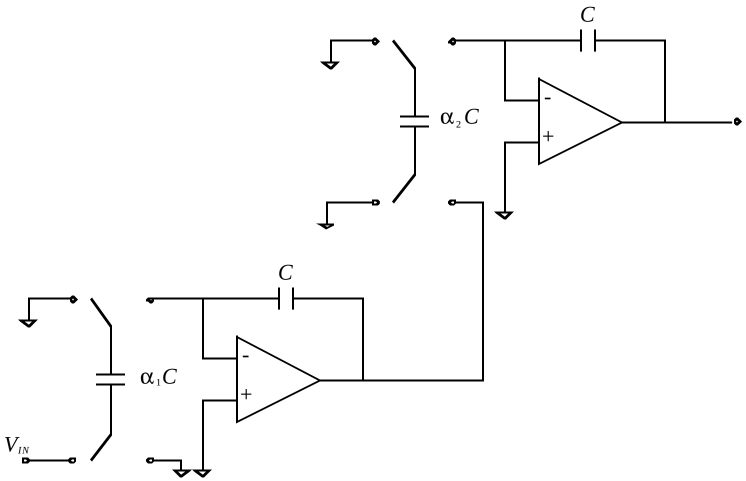
Requires control of Ratios of C

S-C Integrator APP-35



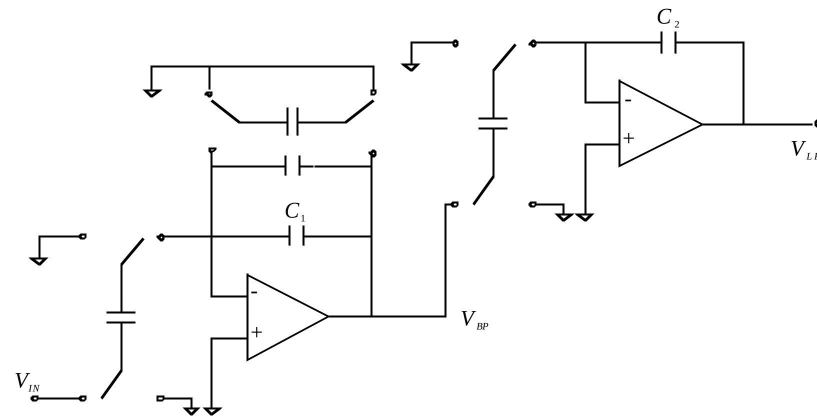
APP-36

Two Integrators Together



APP-37

Time Switched Equivalent Circuit

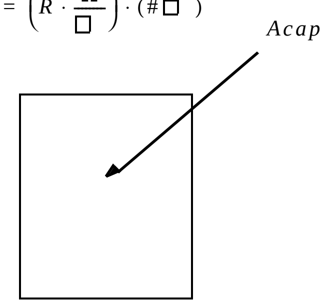


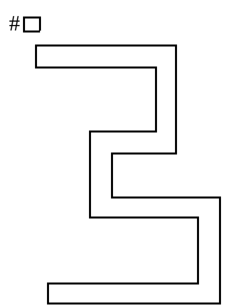
APP-38

$$C_{ox} = \frac{\varepsilon_{SiO_2}}{t_{ox}}$$

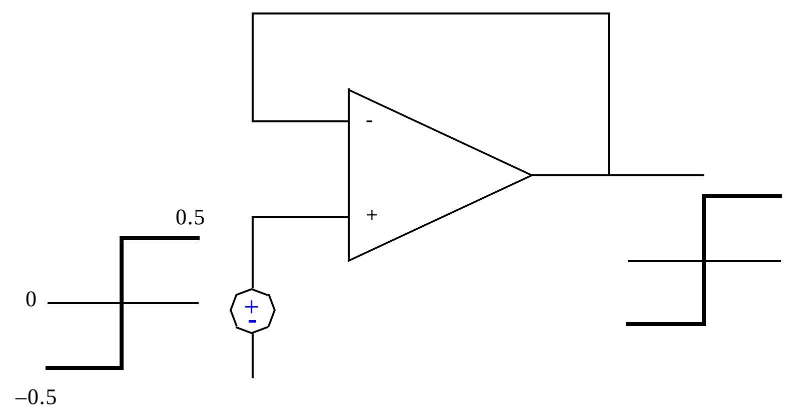
$$C_C = Acap \cdot C_{ox}$$

$$R = \left(R \cdot \frac{\Omega}{\square}\right) \cdot (\#\square)$$

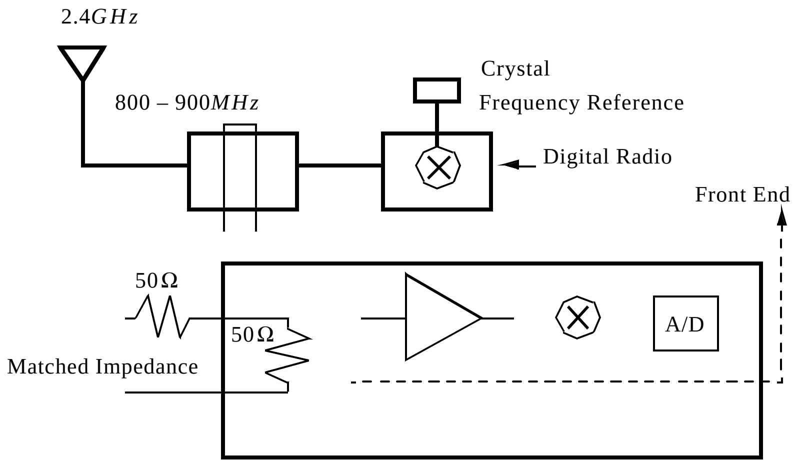




APP-39



RF Front End


2.4GHz
800 – 900MHz
Crystal
Frequency Reference
Digital Radio
Front End
50Ω
50Ω
Matched Impedance
A/D