

EE247

Lecture 6

- Summary last lecture
- Continuous-time filters (continued)
 - Opamp MOSFET-RC filters
 - Gm-C filters
- Frequency tuning for continuous-time filters
 - Trimming via fuses or laser
 - Automatic on-chip filter tuning
 - Continuous tuning
 - Master-slave tuning
 - Periodic off-line tuning
 - Systems where filter is followed by ADC & DSP, existing hardware can be used to periodically update filter freq. response

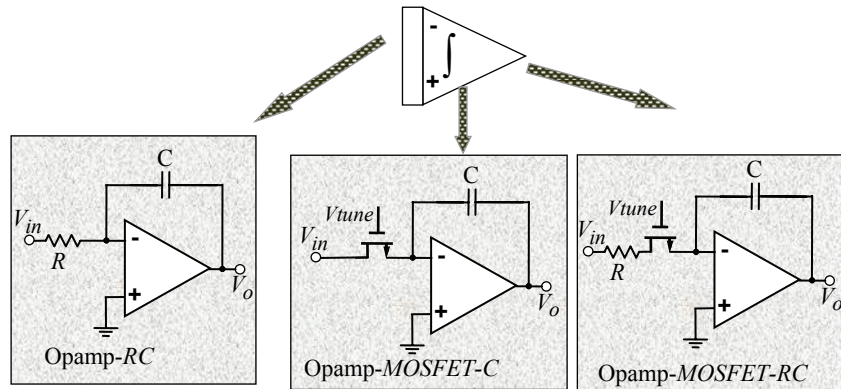
Summary

Lecture 5

- Continuous-time filters
 - Effect of integrator non-idealities on integrated continuous-time filter behavior
 - Effect of integrator finite DC gain & non-dominant poles on filter frequency response
 - Integrator non-linearities affecting filter maximum signal handling capability (harmonic distortion and intermodulation distortion)
 - Effect of integrator component variations and mismatch on filter response & need for frequency tuning
- Frequency tuning for continuous-time filters
 - Frequency adjustment by making provisions to have variable R or C
- Various integrator topologies used in filters
 - Opamp MOSFET-C filters
 - Opamp MOSFET-RC filters

Integrator Implementation

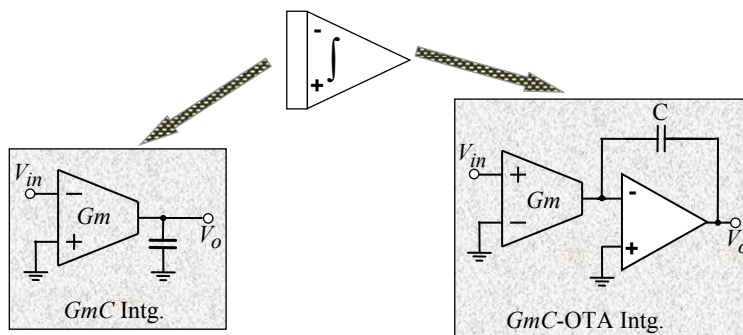
Opamp-RC & Opamp-MOSFET-C & Opamp-MOSFET-RC



$$\frac{V_o}{V_{in}} = \frac{-a_b}{s} \text{ where } a_b = \frac{1}{R_{eq}C}$$

Integrator Implementation

Transconductance-C & Opamp-Transconductance-C



$$\frac{V_o}{V_{in}} = \frac{-a_b}{s} \text{ where } a_b = \frac{G_m}{C}$$

Gm-C Filters

Simplest Form of CMOS Gm-C Integrator

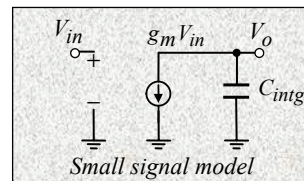
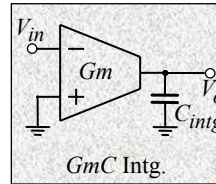
- Use ac half circuit & small signal model to derive transfer function:

$$V_o = -g_m \times V_{in} \times C_{int} g^s$$

$$\frac{V_o}{V_{in}} = -\frac{g_m}{C_{int} g^s}$$

$$\frac{V_o}{V_{in}} = \frac{-\omega_o}{s}$$

$$\rightarrow \omega_o = \frac{g_m}{C_{int} g^s}$$

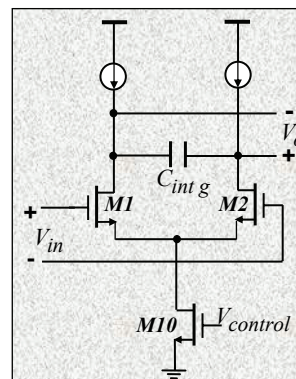


- Issue: Design is parasitic sensitive

Gm-C Filters

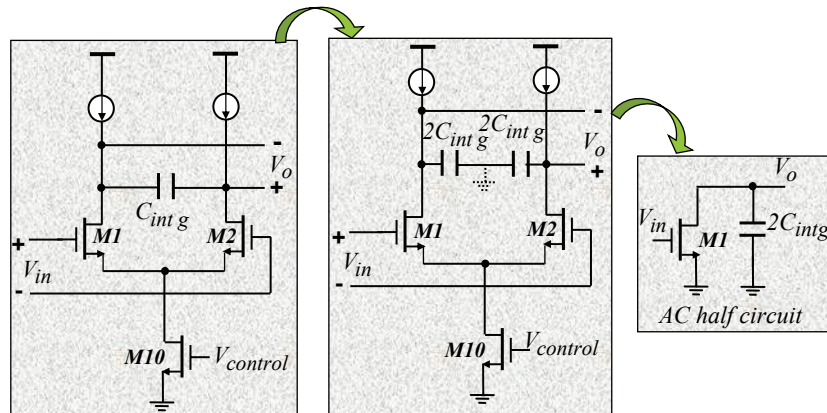
Simplest Form of CMOS Gm-C Integrator

- Transconductance element formed by the source-coupled pair *M1* & *M2*
- All MOSFETs operating in saturation region
- Current in *M1* & *M2* can be varied by changing $V_{control}$
- Find transfer function by drawing ac half circuit



Ref: H. Khorramabadi and P.R. Gray, "High Frequency CMOS continuous-time filters," IEEE Journal of Solid-State Circuits, Vol.-SC-19, No. 6, pp.939-948, Dec. 1984.

Simplest Form of CMOS Gm-C Integrator AC Half Circuit



Gm-C Filters Simplest Form of CMOS Gm-C Integrator

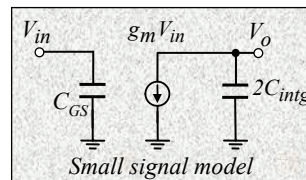
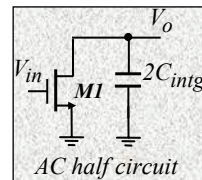
- Use ac half circuit & small signal model to derive transfer function:

$$V_o = -g_m^{M1,2} \times V_{in} \times 2C_{intg} s$$

$$\frac{V_o}{V_{in}} = -\frac{g_m^{M1,2}}{2C_{intg} s}$$

$$\frac{V_o}{V_{in}} = \frac{-\omega_o}{s}$$

$$\rightarrow \omega_o = \frac{g_m^{M1,2}}{2 \times C_{intg}}$$



Gm-C Filters

Simplest Form of CMOS Gm-C Integrator

- MOSFET in saturation region:

$$I_d = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{gs} - V_{th})^2$$

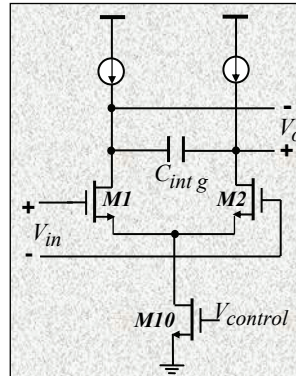
- Gm is given by:

$$g_m^{M1 \& M2} = \frac{\partial I_d}{\partial V_{gs}} = \mu C_{ox} \frac{W}{L} (V_{gs} - V_{th})$$

$$= 2 \frac{I_d}{(V_{gs} - V_{th})}$$

$$= 2 \left(\frac{1}{2} \mu C_{ox} \frac{W}{L} I_d \right)^{1/2}$$

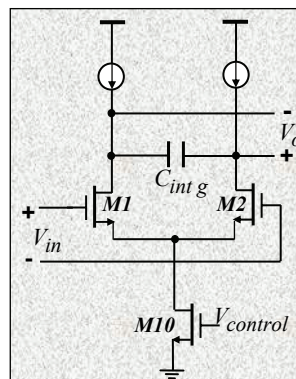
*I_d varied via $V_{control}$
 $\rightarrow g_m$ tunable via $V_{control}$*



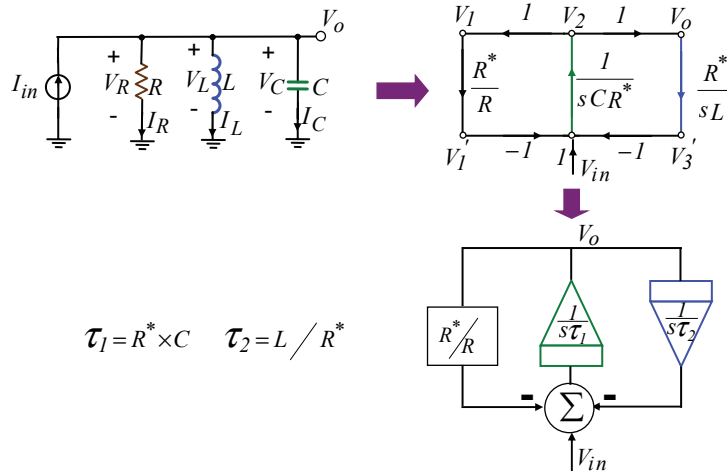
Gm-C Filters

2nd Order Gm-C Filter

- Use the Gm-cell to build a 2nd order bandpass filter



2nd Order Bandpass Filter



$$\tau_1 = R^* \times C \quad \tau_2 = L / R^*$$

2nd Order Integrator-Based Bandpass Filter

$$\frac{V_{BP}}{V_{in}} = \frac{\tau_2 s}{\tau_1 \tau_2 s^2 + \beta \tau_2 s + 1}$$

$$\tau_1 = R^* \times C \quad \tau_2 = L / R^*$$

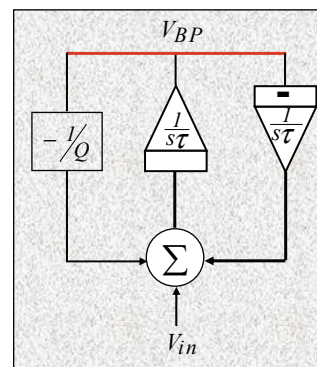
$$\beta = R^* / R$$

$$\omega_0 = 1 / \sqrt{\tau_1 \tau_2} = 1 / \sqrt{L C}$$

$$Q = 1 / \beta \times \sqrt{\tau_1 / \tau_2}$$

From matching point of view desirable:

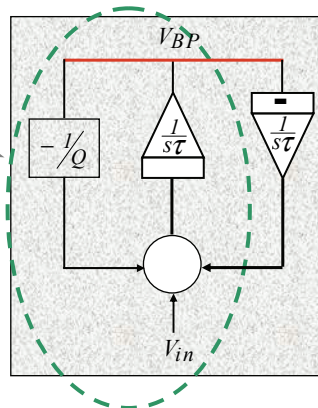
$$\tau_1 = \tau_2 = \tau = \frac{1}{\omega_0} \rightarrow Q = R / R^*$$



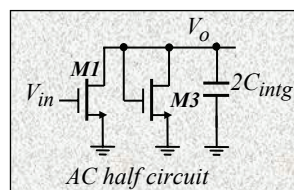
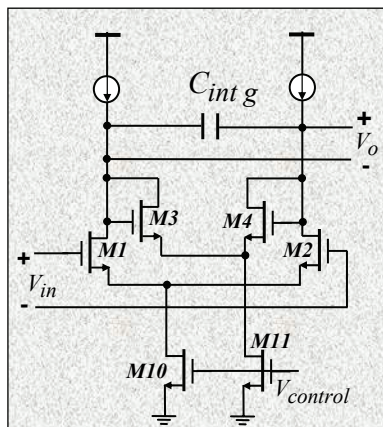
2nd Order Integrator-Based Bandpass Filter

First implement this part
With transfer function:

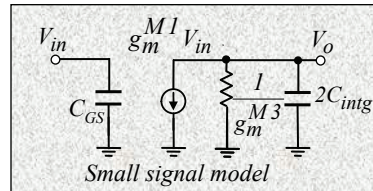
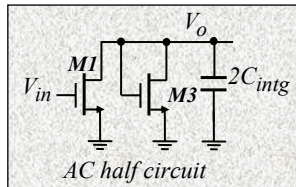
$$\frac{V_0}{V_{in}} = \frac{-1}{\frac{s}{\omega_0} + \frac{1}{Q}}$$



Terminated Gm-C Integrator



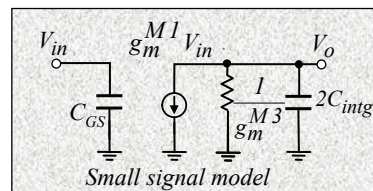
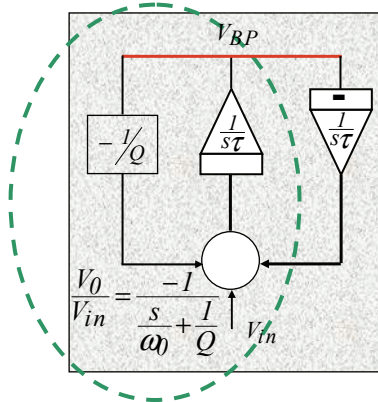
Terminated Gm-C Integrator



$$\frac{V_o}{V_{in}} = \frac{-1}{s \frac{2C_{intg} g}{g_m M1} + \frac{g_m M3}{g_m M1}}$$

Compare to: $\frac{V_o}{V_{in}} = \frac{-1}{\frac{s}{\omega_0} + \frac{1}{Q}}$

Terminated Gm-C Integrator



$$\frac{V_o}{V_{in}} = \frac{-1}{s \times 2C_{intg} g + \frac{g_m M3}{g_m M1}}$$

$$\rightarrow \omega_0 = \frac{g_m M1}{2C_{intg} g} \quad \& \quad Q = \frac{g_m M1}{g_m M3}$$

Question: How to define Q accurately?

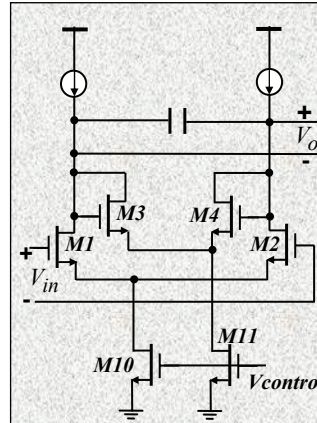
Terminated Gm-C Integrator

$$g_m^{M1} = 2 \left(\frac{1}{2} \mu C_{ox} \frac{W_{M1}}{L_{M1}} I_d^{M1} \right)^{1/2}$$

$$g_m^{M3} = 2 \left(\frac{1}{2} \mu C_{ox} \frac{W_{M3}}{L_{M3}} I_d^{M3} \right)^{1/2}$$

Let us assume equal channel lengths for M1, M3 then:

$$\frac{g_m^{M1}}{g_m^{M3}} = \left(\frac{I_d^{M1}}{I_d^{M3}} \times \frac{W_{M1}}{W_{M3}} \right)^{1/2}$$



Terminated Gm-C Integrator

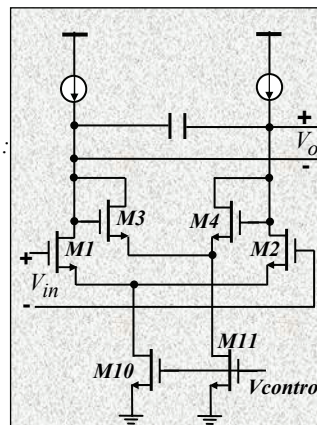
Note that:

$$\frac{I_d^{M1}}{I_d^{M3}} = \frac{I_d^{M10}}{I_d^{M11}}$$

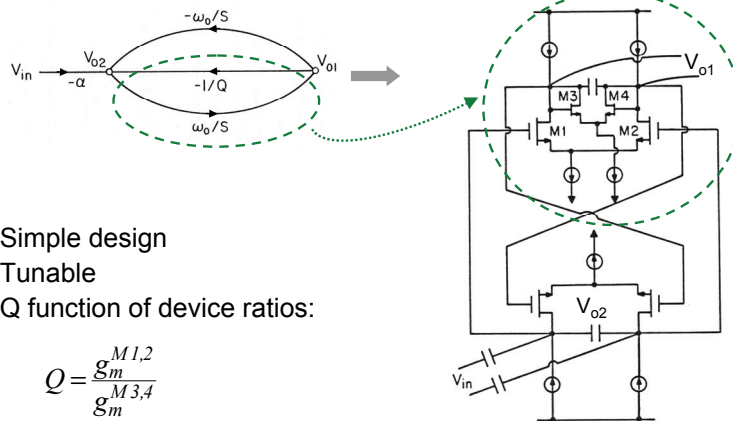
Assuming equal channel lengths for M10, M11:

$$\frac{I_d^{M10}}{I_d^{M11}} = \frac{W_{M10}}{W_{M11}}$$

$$\rightarrow \frac{g_m^{M1}}{g_m^{M3}} = \left(\frac{W_{M10}}{W_{M11}} \times \frac{W_{M1}}{W_{M3}} \right)^{1/2}$$



2nd Order Gm-C Filter



- Simple design
- Tunable
- Q function of device ratios:

$$Q = \frac{g_m^{M1,2}}{g_m^{M3,4}}$$

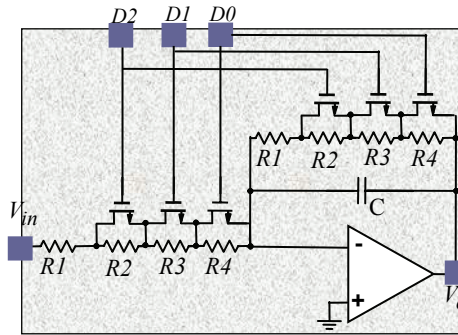
Continuous-Time Filter Frequency Tuning Techniques

- Component trimming
- Automatic on-chip filter tuning
 - Continuous tuning
 - Master-slave tuning
 - Periodic off-line tuning
 - Systems where filter is followed by ADC & DSP, existing hardware can be used to periodically update filter freq. response

Example: Tunable Opamp-RC Filter

Post manufacturing:

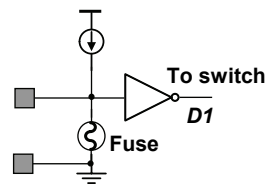
- Usually at wafer-sort tuning performed
- Measure -3dB frequency
 - If frequency too high decrement D to D-1
 - If frequency too low increment D to D+1
 - If frequency within 10% of the desired corner freq. stop



Not practical to require end-user to tune the filter
 → Need to fix the adjustment at the factory

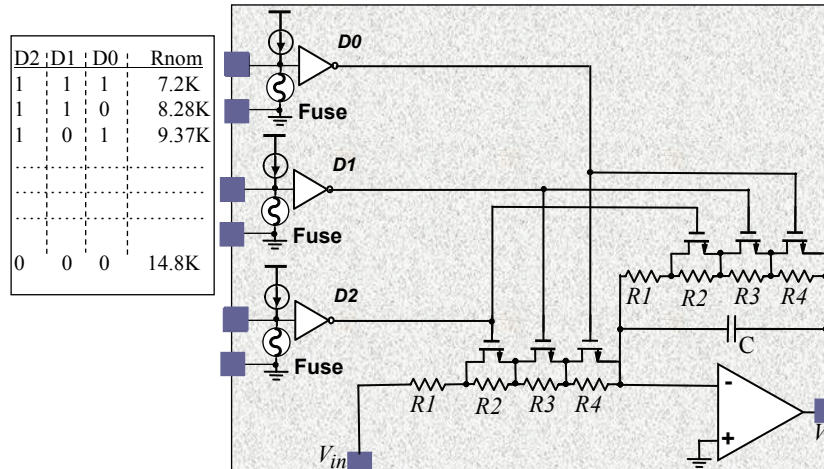
Factory Trimming

- Factory component trimming
 - Build fuses on-chip
 - Based on measurements @ wafer-sort blow fuses selectively by applying high current to the fuse
 - Expensive
 - Fuse regrowth problems!
 - Does not account for temp. variations & aging
 - Laser trimming
 - Trim components or cut fuses by laser
 - Even more expensive
 - Does not account for temp. variations & aging



Fuse not blown → D1=1
 Fuse blown → D1=0

Example: Tunable/Trimmable Opamp-RC Filter



Automatic Frequency Tuning

- By adding additional circuitry to the main filter circuit
 - Have the filter critical frequency automatically tuned
 - ☺ Expensive trimming avoided
 - ☺ Accounts for critical frequency variations due to temperature, supply voltage, and effect of aging
 - ☺ Additional hardware, increased Si area & power & reference signal feed-thru

Master-Slave Automatic Frequency Tuning

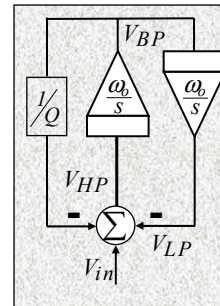
- Following facts used in this scheme:
 - Use a replica of the main filter or its main building block in the tuning circuitry
 - The replica is called the master and the main filter is named the slave
 - Place the replica in close proximity of the main filter to ensure good matching between master & slave
 - Use the tuning signal generated to tune the replica, to also tune the main filter
 - In the literature, this scheme is called *master-slave* tuning!

Master-Slave Frequency Tuning 1-Reference Filter (VCF)

- Use a biquad built with replica of main filter integrator for master filter (VCF)
- Utilize the fact that @ the frequency f_o , the lowpass (or highpass) outputs signal should be 90 degree out of phase wrt to input

$$\frac{V_{LP}}{V_{in}} = \frac{I}{\frac{s^2}{\omega_o^2} + \frac{s}{Q\omega_o} + 1} \bigg|_{\omega = \omega_o} = -jQ \rightarrow \phi = -90^\circ$$

- Apply a sinusoid at the desired f_o^{desired}
- Compare the phase of LP output versus input
- Based on the phase difference:
 - Increase or decrease filter critical freq.



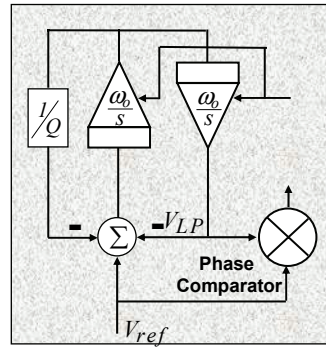
Master-Slave Frequency Tuning 1-Reference Filter (VCF)

$$V_{ref} = A \sin(\omega t)$$

$$V_{LP} = A \sin(\omega t + \phi)$$

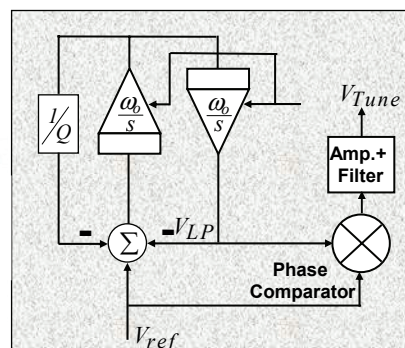
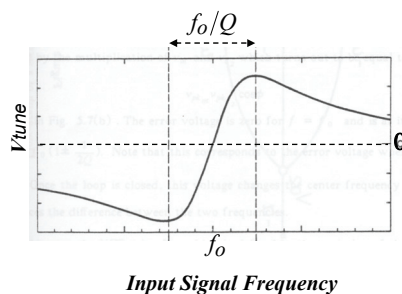
$$V_{ref} \times V_{LP} = A^2 \sin(\omega t) \sin(\omega t + \phi)$$

$$V_{ref} \times V_{LP} = \underbrace{\frac{A^2}{2} \cos \phi}_{\text{Note that this term is 0 only when the incoming signal is at exactly the filter -3dB frequency}} - \underbrace{\frac{A^2}{2} \cos(2\omega t + \phi)}_{\text{Filter Out}}$$



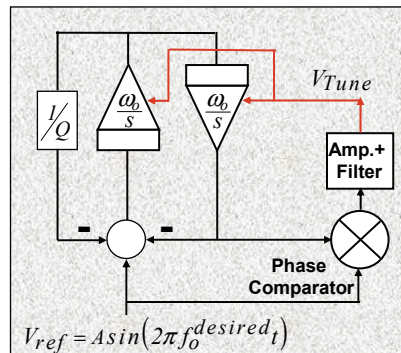
Master-Slave Frequency Tuning 1-Reference Filter (VCF)

$$V_{tune} \approx -K \times V_{ref}^{rms} \times V_{LP}^{rms} \times \cos \phi$$

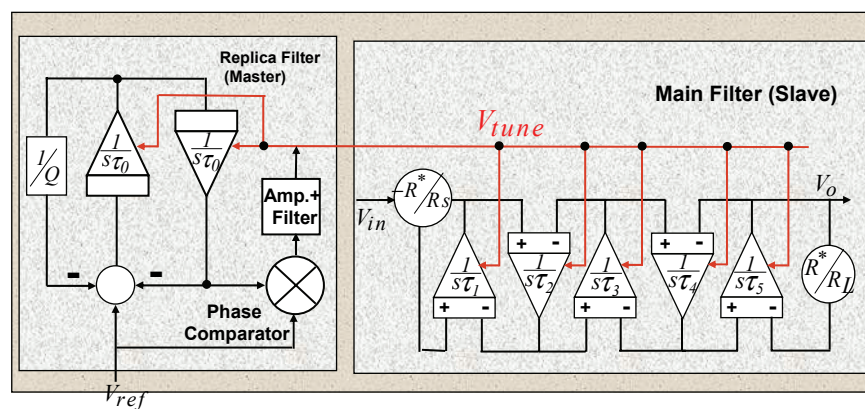


Master-Slave Frequency Tuning 1-Reference Filter (VCF)

- By closing the loop, feedback tends to drive the error voltage (V_{Tune}) to zero.
 → Locks f_o to $f_o^{desired}$, the critical frequency of the filter to the accurate reference frequency
- Typically the reference frequency is provided by a crystal oscillator with accuracies in the order of few ppm



Master-Slave Frequency Tuning 1-Reference Filter (VCF)



Ref: H. Khorramabadi and P.R. Gray, "High Frequency CMOS continuous-time filters," IEEE Journal of Solid-State Circuits, Vol.-SC-19, No. 6, pp.939-948, Dec. 1984.

Master-Slave Frequency Tuning

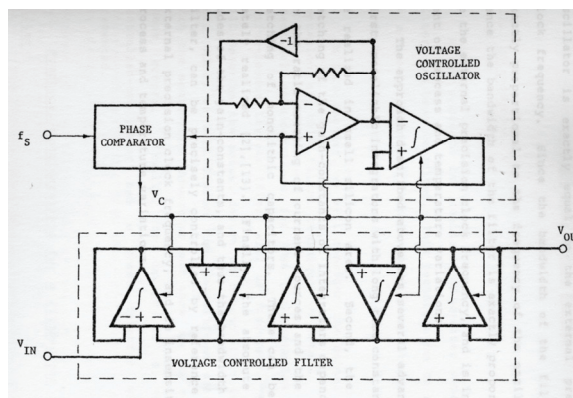
1- Reference Filter (VCF)

- Issues to be aware of:
 - Input reference tuning signal needs to be sinusoid → Disadvantage since clocks are usually available as square waveform
 - Reference signal feed-through to the output of the filter can limit filter dynamic range (reported levels of about $100\mu V_{rms}$)
 - Ref. signal feed-through is a function of:
 - Reference signal frequency with respect to filter passband
 - Filter topology
 - Care in the layout
 - Fully differential topologies beneficial

Master-Slave Frequency Tuning

2- Reference Voltage-Controlled-Oscillator (VCO)

- Instead of VCF a voltage-controlled-oscillator (VCO) is used
- VCO made of replica integrator used in main filter
- Tuning circuit operates exactly as a conventional phase-locked loop (PLL)
- Tuning signal used to tune main filter



Ref: K.S. Tan and P.R. Gray, "Fully integrated analog filters using bipolar FET technology," IEEE, J. Solid-State Circuits, vol. SC-13, no.6, pp. 814-821, December 1978..

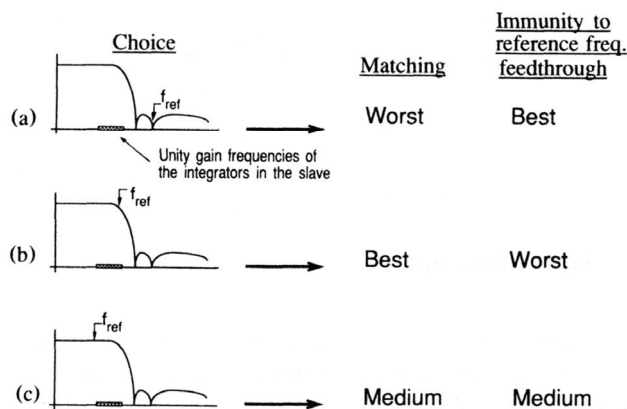
Master-Slave Frequency Tuning

2- Reference Voltage-Controlled-Oscillator (VCO)

- Issues to be aware of:
 - Design of stable & repeatable oscillator challenging
 - VCO operation should be limited to the linear region of the integrator or else the operation loses accuracy (e.g. large signal transconductance versus small signal in a gm-C filter)
 - Limiting the VCO signal range to the linear region not a trivial design issue
 - In the case of VCF based tuning ckt, there was only ref. signal feedthrough. In this case, there is also the feedthrough of the VCO signal!!
 - Advantage over VCF based tuning → Reference input signal square wave (not sin.)

Master-Slave Frequency Tuning

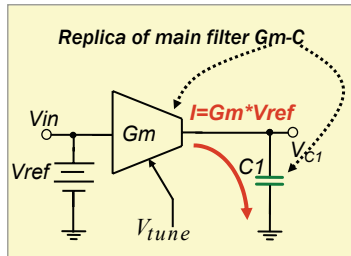
Choice of Ref. Frequency wrt Feedthrough Immunity



Ref: V. Gopinathan, et. al, "Design Considerations for High-Frequency Continuous-Time Filters and Implementation of an Antialiasing Filter for Digital Video," *IEEE JSSC*, Vol. SC-25, no. 6 pp. 1368-1378, Dec. 1990.

Master-Slave Frequency Tuning

3-Reference Integrator Locked to Reference Frequency



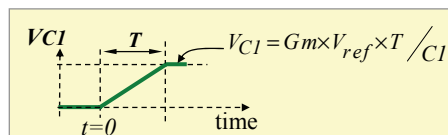
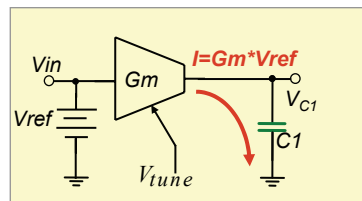
- Replica of main filter integrator e.g. Gm-C building block used
- Utilizes the fact that a DC voltage source connected to the input of the Gm cell generates a constant current at the output proportional to the transconductance and the voltage reference

$$I = G_m \cdot V_{ref}$$

Reference Integrator Locked to Reference Frequency

- Consider the following sequence:

- Integrating capacitor is fully discharged @ $t = 0$
- At $t = 0$ the capacitor is connected to the output of the Gm cell then:



$$Q_{C1} = V_{C1} \times C1 = G_m \times V_{ref} \times T$$

$$\rightarrow V_{C1} = G_m \times V_{ref} \times T / C1$$

Reference Integrator Locked to Reference Frequency

Since at the end of the period T:

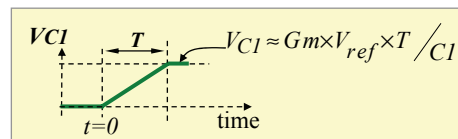
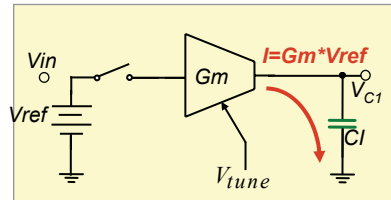
$$V_{CI} \approx Gm \times V_{ref} \times T / CI$$

If V_{CI} is forced to be equal to V_{ref} then:

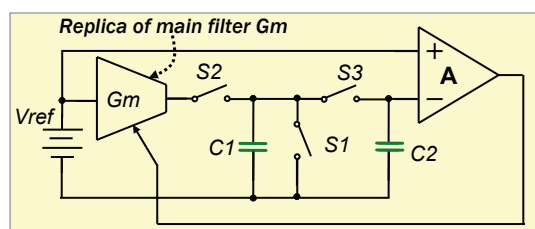
$$\frac{CI}{Gm} = T = \frac{N}{f_{clk}}$$

How do we manage to force $V_{CI} = V_{ref}$?

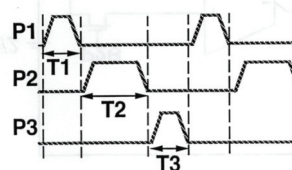
→ Use feedback!!



Reference Integrator Locked to Reference Frequency

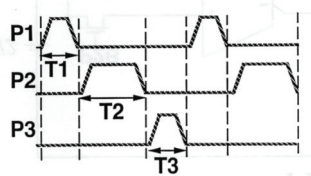
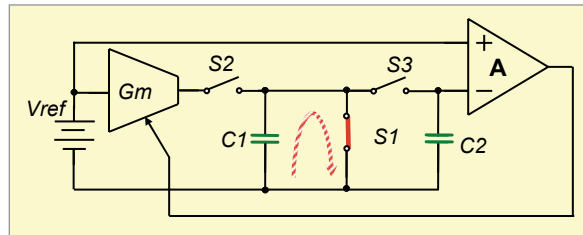


- Three clock phase operation
- To analyze → study one phase at a time



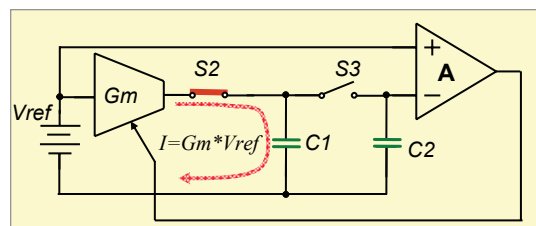
Ref: A. Durham, J. Hughes, and W. Redman-White, "Circuit Architectures for High Linearity Monolithic Continuous-Time Filtering," *IEEE Transactions on Circuits and Systems*, pp. 651-657, Sept. 1992.

Reference Integrator Locked to Reference Frequency P1 high \rightarrow S1 closed

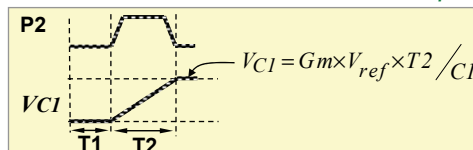


$C1 \rightarrow$ discharged $\rightarrow V_{C1}=0$
 $C2 \rightarrow$ retains its previous charge

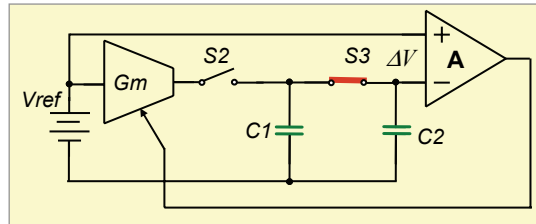
Reference Integrator Locked to Reference Frequency P2 high \rightarrow S2 closed



$C1 \rightarrow$ charged with constant current: $I=Gm*V_{ref}$
 $C2 \rightarrow$ retains its previous charge



Reference Integrator Locked to Reference Frequency
P3 high \rightarrow S3 closed



C1 charge shares with C2

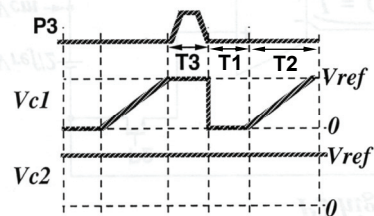
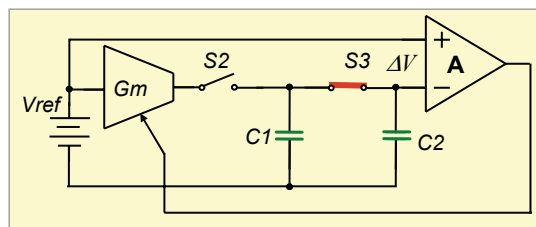
$$V_{C1}^{T2} C1 + V_{C2}^{T2} C2 = (C1 + C2) V_{C1,2}^{T3}$$

$$V_{C1,2}^{T3} = V_{C1}^{T2} \frac{C1}{C1 + C2} + V_{C2}^{T2} \frac{C2}{C1 + C2}$$

Few cycles following startup

$$V_{C1,2}^{T3} = V_{C1}^{T2} = V_{C2}^{T2}$$

Reference Integrator Locked to Reference Frequency
P3 high \rightarrow S3 closed



C1 charge shares with C2

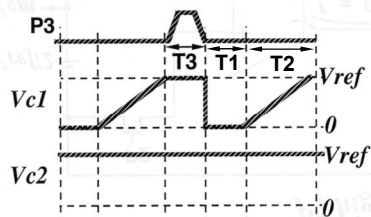
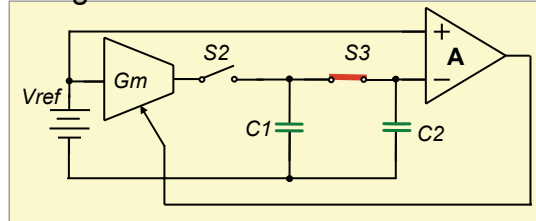
Few cycles following startup

Assuming A is large, feedback forces:

$$\Delta V \rightarrow 0$$

$$\rightarrow V_{C2} = V_{ref}$$

Reference Integrator Locked to Reference Frequency P3 high → S3 closed



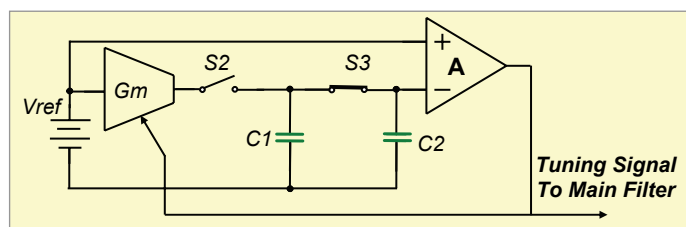
$$V_{C1} = V_{C2} = V_{ref}$$

since: $V_{C1} = G_m \times V_{ref} \times T2 / C1$

then: $V_{ref} = G_m \times V_{ref} \times T2 / C1$

or: $C1 / G_m = T2 = N / f_{clk}$

Summary Replica Integrator Locked to Reference Frequency



Feedback forces G_m to assume a value so that :

- Integrator time constant locked to an accurate frequency
- Tuning signal used to adjust the time constant of the main filter integrators

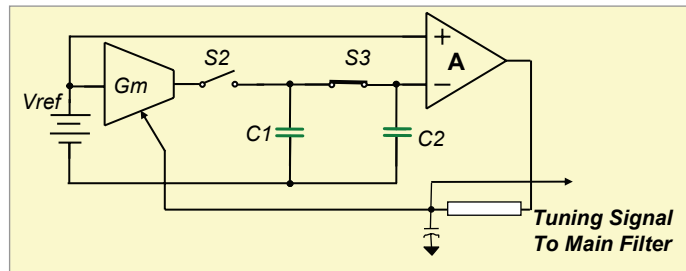
$$\tau_{intg} = C1 / G_m = N / f_{clk}$$

or

$$\omega_0^{intg} = G_m / C1 = f_{clk} / N$$

Issues

1- Loop Stability

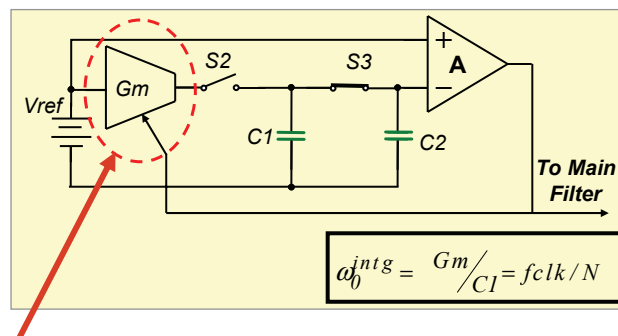


- Note: Need to pay attention to loop stability
 - ✓ C1 chosen to be smaller than C2 – tradeoff between stability and speed of lock acquisition
 - ✓ Lowpass filter at the output of amplifier (A) helps stabilize the loop

Issues

2- GM-Cell DC Offset Induced Error

Problems to be aware of:



→ Tuning error due to master integrator DC offset

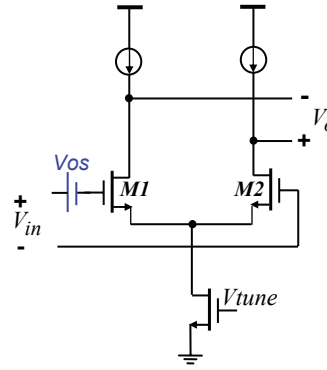
Issues Gm Cell DC Offset

What is DC offset?

Simple example:

For the differential pair shown here, mismatch in input device or load characteristics would cause DC offset:
 $\rightarrow V_o = 0$ requires a non-zero input voltage

Offset could be modeled as a small DC voltage source at the input for which with shorted inputs $\rightarrow V_o = 0$



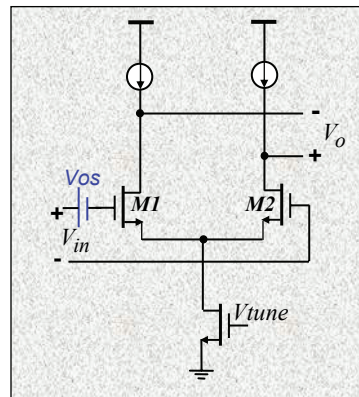
Example: Differential Pair

Simple Gm-Cell DC Offset

Mismatch associated with M1 & M2
 \rightarrow DC offset

$$V_{os} = (V_{th1} - V_{th2}) - \frac{1}{2} V_{ov1,2} \frac{\Delta(W/L)_{M1,2}}{(W/L)_{M1,2}}$$

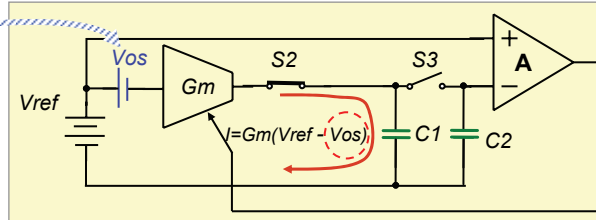
Assuming offset due to load device mismatch is negligible



Ref: Gray, Hurst, Lewis, Meyer, *Analysis & Design of Analog Integrated Circuits*, Wiley 2001, page 335

Gm-Cell Offset Induced Error

Voltage source
representing
DC offset



- Effect of Gm-cell DC offset:

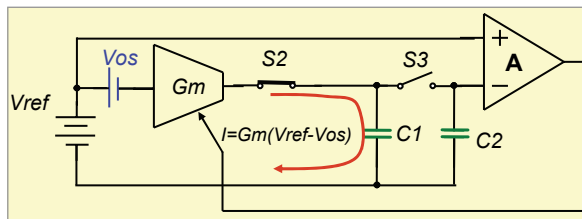
$$V_{C1} = V_{C2} = V_{ref}$$

$$\text{Ideal: } V_{C1} = Gm \times V_{ref} \times T2 / C1$$

$$\text{with offset: } V_{C1} = Gm \times (V_{ref} - V_{os}) \times T2 / C1$$

$$\text{or: } C1 / Gm = T2 \left(1 - \frac{V_{os}}{V_{ref}} \right)$$

Gm-Cell Offset Induced Error



- Example:

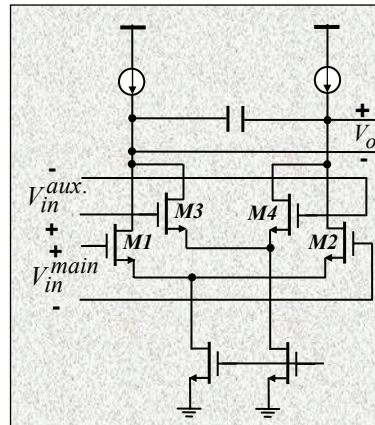
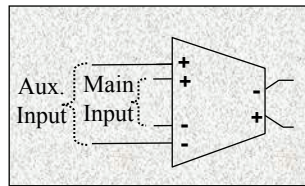
$$C1 / Gm = T2 \left(1 - \frac{V_{os}}{V_{ref}} \right) \quad f_{critical} \propto Gm / C1$$

$$\text{for } \frac{V_{os}}{V_{ref}} = 1/10$$

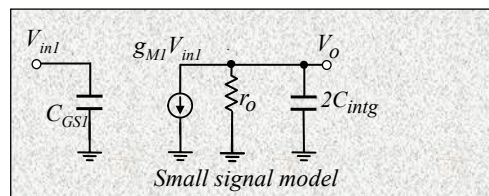
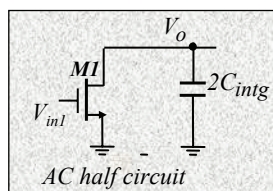
10% error in tuning!

Gm-Cell Offset Induced Error Solution

- Assume differential integrator
- Add a pair of auxiliary inputs to the input stage of the master Gm-cell for offset cancellation purposes



Simple Gm-Cell AC Small Signal Model

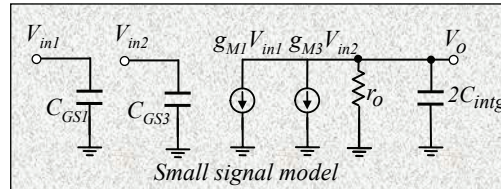
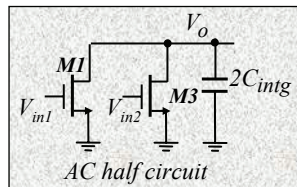


$$V_o = (g_{m1}^M V_{inl}) \left(r_o \parallel \frac{1}{s \times 2C_{intg}} \right) \quad r_o \text{ is parallel combination of } r_o \text{ of } M1 \text{ \& load}$$

$$V_o = \frac{-g_{m1}^M r_o}{1 + s \times 2C_{intg} g r_o} V_{inl} \quad \& \quad g_{m1}^M r_o = a1 \rightarrow \text{Integrator finite DC gain}$$

$$V_o = \frac{-a1}{1 + \frac{a1 \times s \times 2C_{intg} g}{g_{m1}^M}} V_{inl} \quad \text{Note: } a1 \rightarrow \infty, \quad V_o = \frac{-g_{m1}^M}{s \times 2C_{intg}} V_{inl}$$

Simple Gm-Cell + Auxiliary Inputs AC Small Signal Model

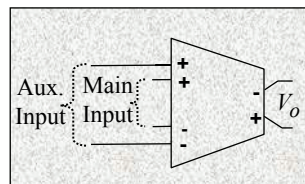


$$V_o = (g_m^{M1} V_{in1} + g_m^{M3} V_{in2}) \left(r_o \parallel \frac{1}{s \times 2C_{intg}} \right) \quad r_o \text{ parallel combination of } r_o \text{ of } M1, M3, \text{ \& current source}$$

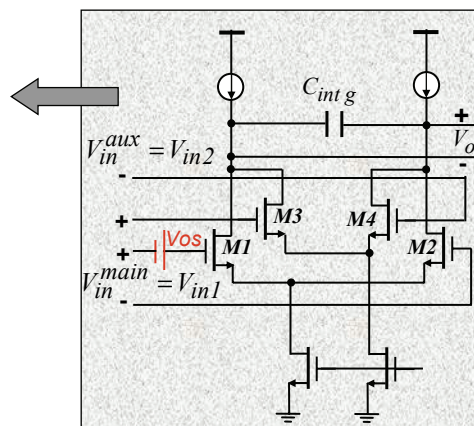
$$V_o = \frac{-g_m^{M1} r_o}{1 + s \times 2C_{intg} g r_o} V_{in1} - \frac{g_m^{M3} r_o}{1 + s \times 2C_{intg} g r_o} V_{in2}$$

$$V_o = - \frac{a1}{1 + \frac{a1 \times s \times 2C_{intg}}{g_m^{M1}}} V_{in1} - \frac{a3}{1 + \frac{a3 \times s \times 2C_{intg}}{g_m^{M3}}} V_{in2}$$

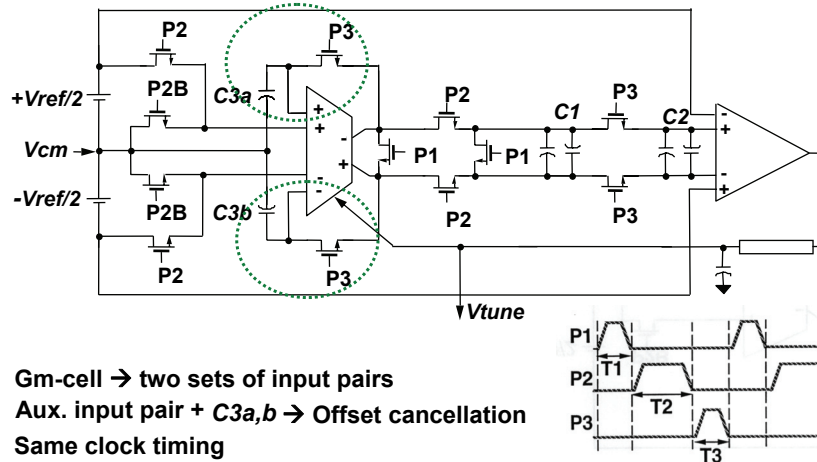
Gm-Cell DC Model



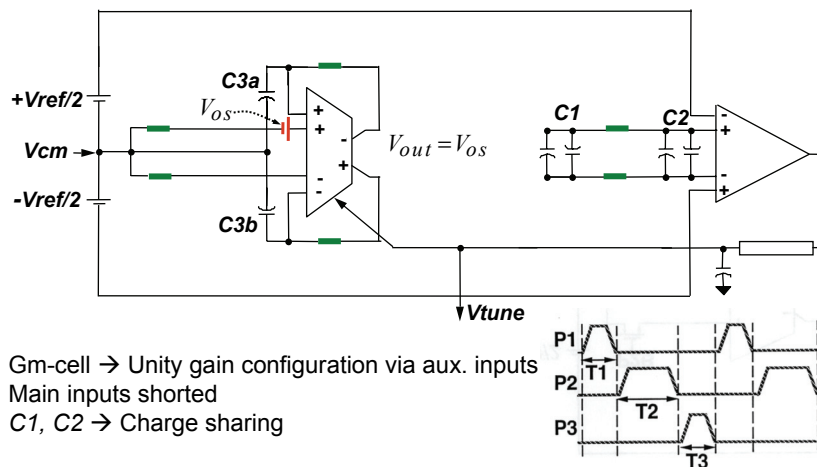
$$V_o = a1(V_{in1} + V_{os}) + a3 V_{in2}$$



Reference Integrator Locked to Reference Frequency Offset Cancellation Incorporated



Reference Integrator Locked to Reference Frequency P3 High (Update & Store offset)



Reference Integrator During Offset Cancellation Phase

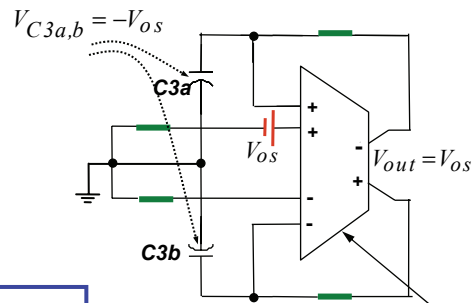
$$V_o = a1(V_{in1} + V_{os}) + a3 V_{in2}$$

$$V_{in2} = -V_o$$

$$V_o = a1 \times V_{os} - a3 \times V_o$$

$$\rightarrow V_o = \frac{a1}{1 + a3} \times V_{os}$$

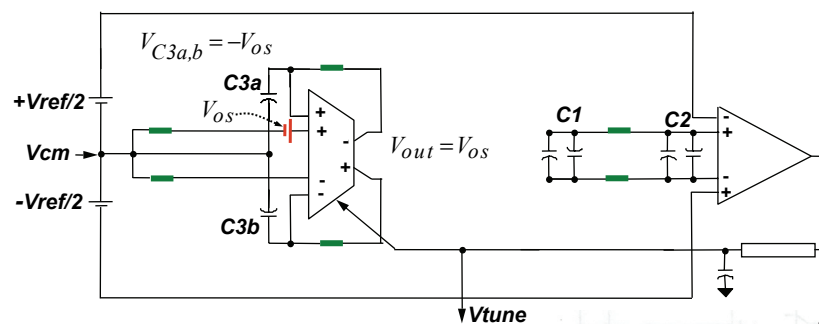
$$\text{Assuming } a1 = a3 \gg 1$$



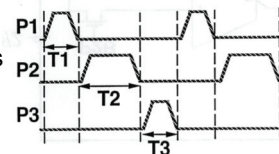
$$V_o = V_{os} \quad \& \quad V_{in2} = -V_{os}$$

$C3a, b \rightarrow$ Store main Gm-cell offset

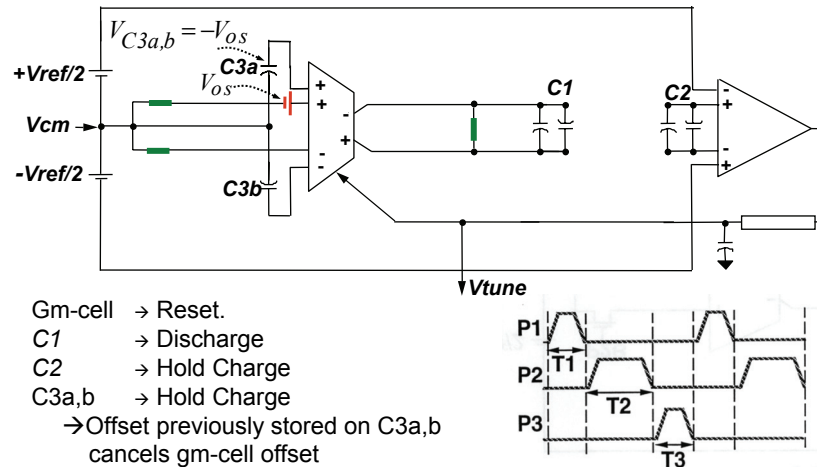
Reference Integrator Locked to Reference Frequency P3 High (Update & Store offset)



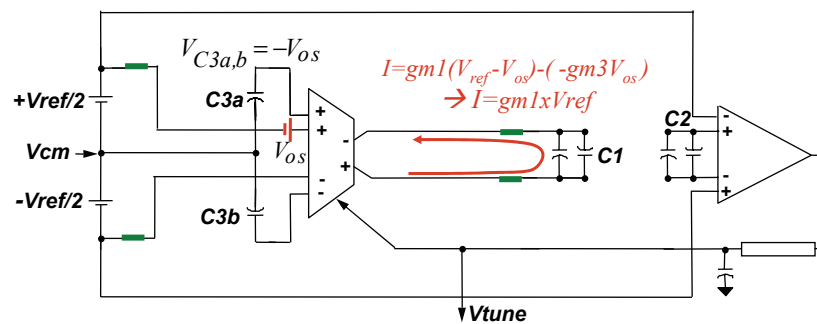
Gm-cell \rightarrow Unity gain configuration via aux. inputs
Main input shorted
 $C3a, b \rightarrow$ Store Gm-cell offset
 $C1, C2 \rightarrow$ Charge sharing



Reference Integrator Locked to Reference Frequency P1 High (Reset)



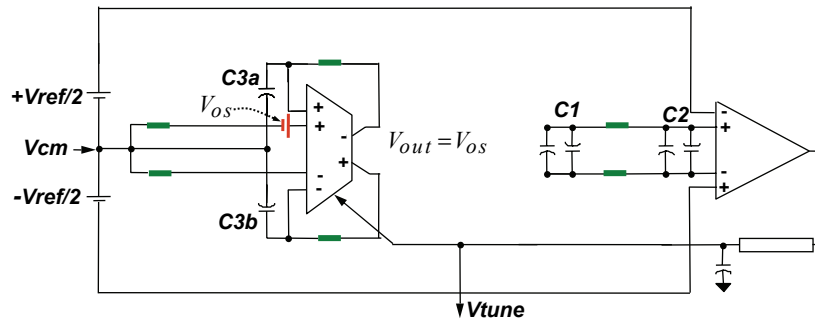
Reference Integrator Locked to Reference Frequency P2 High (Charge)



Gm-cell → Charging C1
 C3a,b → Store/hold Gm-cell offset
 C2 → Hold charge

Summary

Reference Integrator Locked to Reference Frequency



Key point: Tuning error due to Gm-cell offset cancelled

*Note: Same offset compensation technique can be used in many other applications

Summary

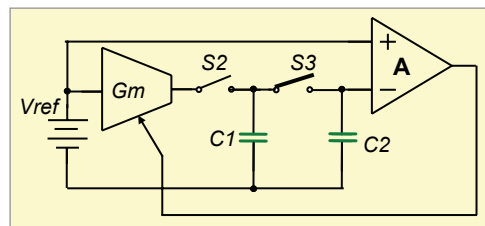
Reference Integrator Locked to Reference Frequency

Tuning error due to gm-cell offset voltage resolved

Advantage over previous schemes:

→ f_{clk} can be chosen to be at much higher frequencies compared to filter bandwidth ($N > 1$)

→ Feedthrough of clock falls out of band and thus attenuated by filter



Feedback forces Gm to vary so that :

$$\tau_{intg} = \frac{C1}{Gm} = N / f_{clk}$$

or

$$\omega_0^{intg} = \frac{Gm}{C1} = f_{clk} / N$$

DC Tuning of Resistive Timing Element

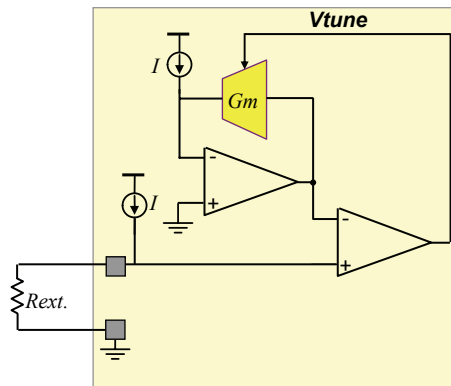
Tuning circuit $G_m \rightarrow$ replica of G_m used in filter

R_{ext} used to lock G_m to accurate off-chip R

Feedback forces:
 $G_m = 1/R_{ext}$

Issues with DC offset

Account for capacitor variations in this gm-C implementation by trimming in the factory



Ref: C. Laber and P.R. Gray, "A 20MHz 6th Order BiCMOS Parasitic Insensitive Continuous-time Filter and Second Order Equalizer Optimized for Disk Drive Read Channels," *IEEE Journal of Solid State Circuits*, Vol. 28, pp. 462-470, April 1993