EE247
Lecture 6

- Summary last lecture
- 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

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Summary Last Lecture

- Continuous-time filters
  – Facts about monolithic Rs & Cs and its effect on integrated filter characteristics
  – Opamp MOSFET-C filters
  – Opamp MOSFET-RC filters
  – Gm-C filters
- Frequency tuning for continuous-time filters
  – Trimming

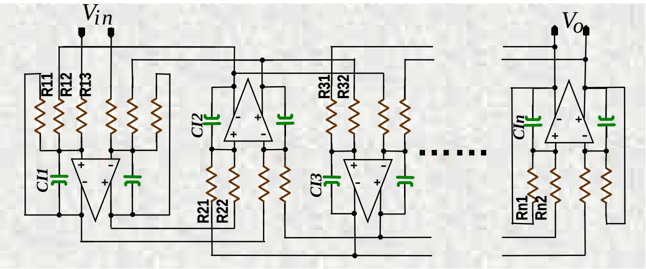
Summary Last Lecture
Effect of Monolithic R & C Variations on Filter Characteristics

- Filter shape (whether Elliptic with 0.1dB Rpass or Butterworth..etc) is a function of *ratio* of normalized *Ls & Cs* in RLC filters
- Critical frequency (e.g. w_{-3dB}) function of absolute value of *Ls & Cs* in RLC filters and *Rs & Cs & Gms* for integrator based filters

- Absolute value of integrated *Rs & Cs & Gms* are quite variable
- *Ratios* very accurate and stable over time and temperature

→ What is the effect of on-chip component variations on monolithic filter frequency characteristics?

Summary Last Lecture
Impact of Process Variations on Filter Characteristics



$$t_1^{int\,g} = C_{I1}.R_1 = \frac{C_1^{Norm}}{w_{-3dB}}$$

$$t_2^{int\,g} = C_{I2}.R_2 = \frac{L_2^{Norm}}{w_{-3dB}}$$

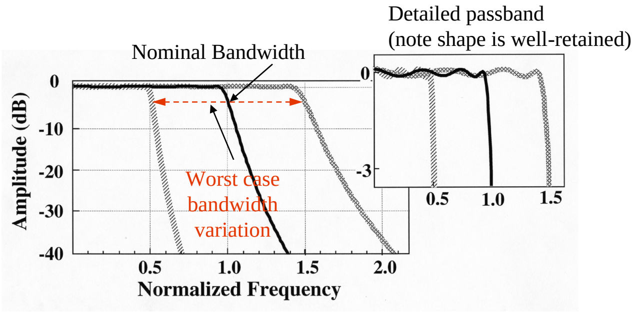
⇨ Variation in absolute value of integrated *Rs & Cs* causes change in critical freq. (w_{-3dB})

$$\frac{t_1^{int\,g}}{t_2^{int\,g}} = \frac{C_{I1}.R_1}{C_{I2}.R_2} = \frac{C_1^{Norm}}{L_2^{Norm}}$$

⇨ Since *Ratios* of Rs & Cs very accurate

→ Continuous time monolithic filters fully retain their shape

Summary Last Lecture
LPF Worst Case Corner Frequency Variations



•While absolute value of on-chip RC (gm-C) time-constants vary by as much as 100% (process & temp.)

•With proper precautions, excellent matching can be achieved:

→ Well-preserved relative amplitude & phase vs freq. charactersitics

→ Need to adjust (tune) continuous-time filter critical frequencies only

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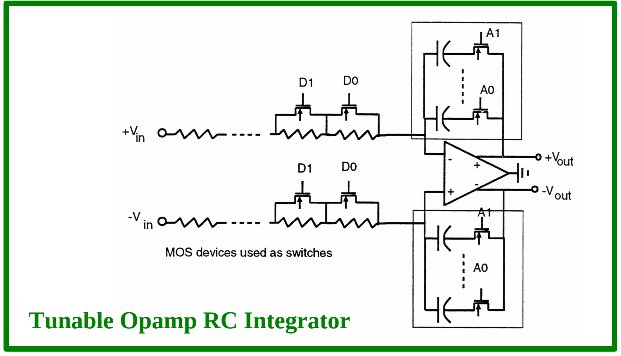
Summary Last Lecture
Tunable Opamp-RC Integrator



- Program Cs and/or Rs to freq. tune the filter
- All filter integrators tuned simultaneously
- Tuning in discrete steps & not continuous
- Tuning resolution limited
- Switch parasitic C & series R can affect the freq. response of the filter

Review Last Lecture
MOSFET-C Integrator

$$I_D = mC_{ox}\frac{W}{L}\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds}$$

$$I_{D1} = mC_{ox}\frac{W}{L}\left(V_{gs1} - V_{th} - \frac{V_i}{4}\right)\frac{V_i}{2}$$

$$I_{D3} = -mC_{ox}\frac{W}{L}\left(V_{gs2} - V_{th} + \frac{V_i}{4}\right)\frac{V_i}{2}$$

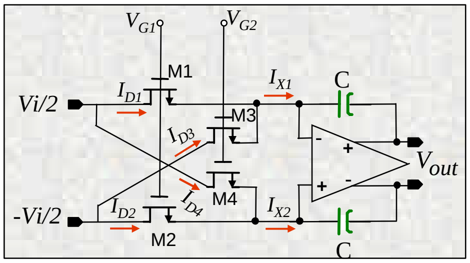
$$I_{X1} = I_{D1} + I_{D3}$$

$$= mC_{ox}\frac{W}{L}\left(V_{gs1} - V_{gs2} - \frac{V_i}{2}\right)\frac{V_i}{2}$$

$$I_{X2} = mC_{ox}\frac{W}{L}\left(V_{gs2} - V_{gs1} - \frac{V_i}{2}\right)\frac{V_i}{2}$$

$$I_{X1} - I_{X2} = mC_{ox}\frac{W}{L}\left(V_{gs1} - V_{gs2}\right)V_i$$

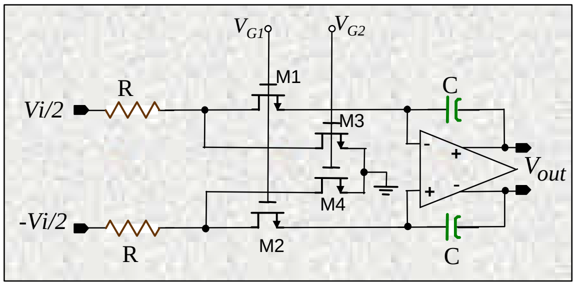
$$G = \frac{\partial\left(I_{D1} - I_{D2}\right)}{\partial V_i} = mC_{ox}\frac{W}{L}\left(V_{gs1} - V_{gs2}\right)$$



No threshold dependence
First order Common-mode non-linearity cancelled
Linearity achieved in the order of 60-70dB

Ref: Z. Czarnul, "Modification of the Banu-Tsividis Continuous-Time Integrator Structure," *IEEE Transactions on Circuits and Systems*, Vol. CAS-33, No. 7, pp. 714-716, July 1986.

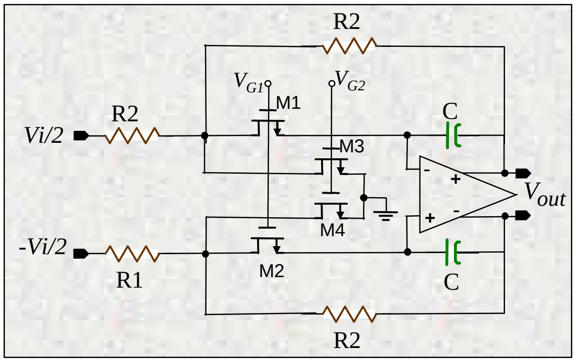
R-MOSFET-C Integrator



Improvement over MOSFET-C by adding resistor in series with MOSFET
Voltage drop primarily across resistor → small MOSFET Vds → improved linearity
Linearity in the order of 90dB possible
Generally low frequency applications

Ref: U-K Moon, and B-S Song, "Design of a Low-Distortion 22-kHz Fifth Order Bessel Filter," *IEEE Journal of Solid State Circuits*, Vol. 28, No. 12, pp. 1254-1264, Dec. 1993.

R-MOSFET-C Lossy Integrator



Negative feedback around the non-linear MOSFETs improves linearity
Reduced frequency response accuracy

Ref: U-K Moon, and B-S Song, "Design of a Low-Distortion 22-kHz Fifth Order Bessel Filter," *IEEE Journal of Solid State Circuits*, Vol. 28, No. 12, pp. 1254-1264, Dec. 1993.

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

- MOSFET in saturation region Gm is given by

:

$$g_m = \frac{\partial I_d}{\partial V_{gs}} = 2\left(\frac{1}{2} m C_{ox} \frac{W}{L} I_d\right)^{1/2}$$

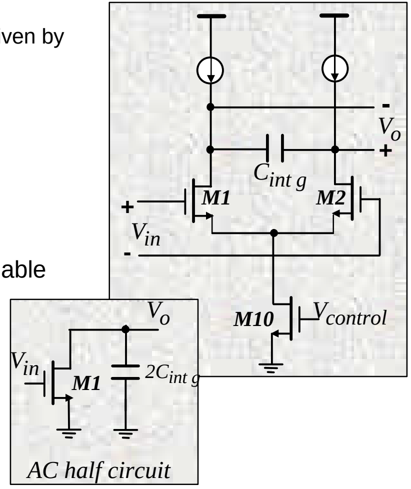
Id varied via Vcontrol

→ *gm* tunable via *Vcontrol*

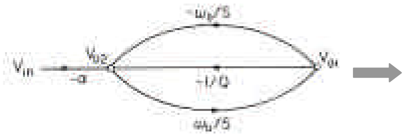
- Critical frequency continuously tunable via V_{control}

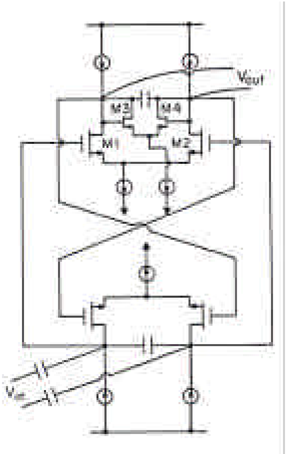
$$\frac{V_o}{V_{in}} = \frac{-w_o}{s}$$

$$\text{where} \quad w_o = \frac{g_m^{M1,2}}{2 \times C_{int\,g}}$$



Second Order Gm-C Filter





- Simple design- high frequency potential
- Tunable
- Q function of device ratios:

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

Filter Frequency Tuning Techniques

- Component trimming

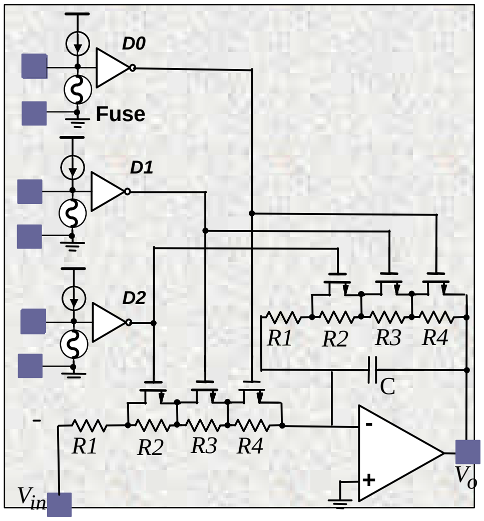
- Automatic on-chip filter tuning
  - Continuous tuning
    - Master-slave tuning

  - 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/Trimmable Opamp-RC Filter

Component trimming

- Build fuses on-chip,
  - Based on measurements @ wafer-sort blow fuses 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



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 temp. and voltage changes

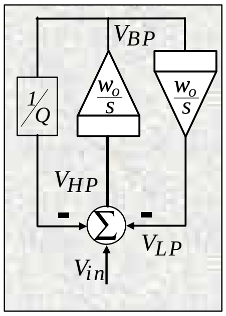
Master-Slave Automatic Frequency Tuning

- Following facts used in this scheme:
  - Use a replica (master) of the main filter (called the slave) in the tuning circuitry
  - Place the replica in close proximity of the main filter
  - 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 Reference Filter (VCF)

- Use a biquad for master filter (VCF)
- Utilize the fact that @ the frequency *fo* the lowpass (or highpass) outputs are 90 degree out of phase wrt to input

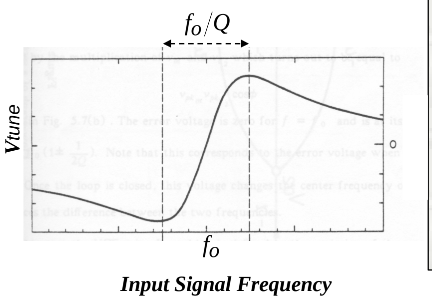
$$\frac{V_{LP}}{V_{in}} = \frac{1}{\frac{s^2}{w_o^2} + \frac{s}{Qw_o} + 1} \qquad @\ w = w_o \quad f = -90^o$$

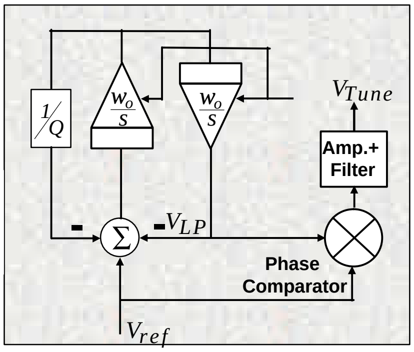


- Apply a sinusoid at the desired *fo*
- Compare the LP output phase to the input
- Based on the phase difference
  - Increase or decrease filter critical freq.

Master-Slave Frequency Tuning
Reference Filter (VCF)

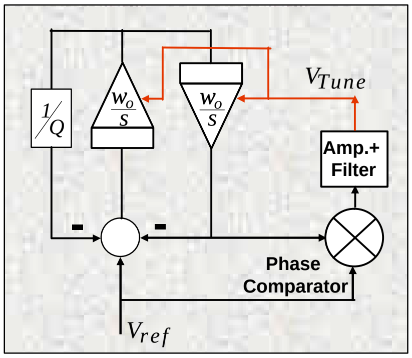
$$V_{tune} \approx -K \times V_{ref}^{rms} \times V_{LP}^{rms} \times \cos\phi$$



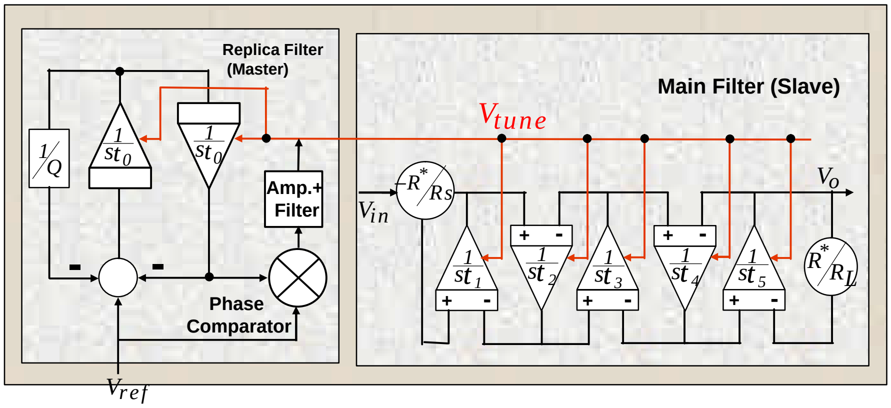


Master-Slave Frequency Tuning
Reference Filter (VCF)

- By closing the loop, feedback tends to drive the error voltage to zero.
  → Locks *fo*, 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
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.

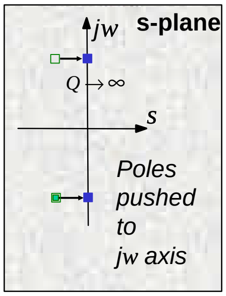
Master-Slave Frequency Tuning
Reference Filter (VCF)

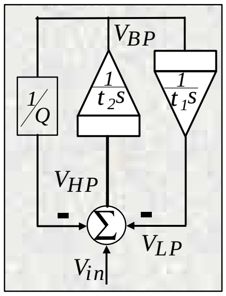
- Issues to be aware of:
  - Input reference tuning signal needs to be sinusoid → disadvantage since clocks are usually available as square waveform
  - Reference signal feed-through to the output of the filter can limit filter dynamic range (reported levels or about 100uVrms)
  - Ref. signal feed-through is a function of:
    - Reference signal frequency wrt filter passband
    - Filter topology
    - Care in the layout
    - Fully differential topologies beneficial

Master-Slave Frequency Tuning
Reference Voltage-Controlled Oscillator (VCO)

- Possible to build voltage-controlled oscillator (VCO) using replica integrators
  - In the biquad structure, if Q→inf. Complex conjugate poles moves to jω axis.
    - → Oscillation @ frequency

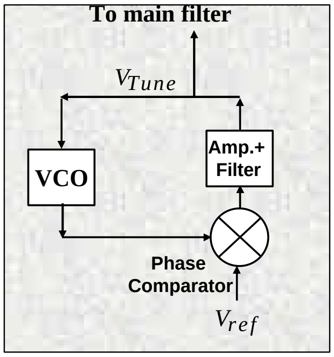
$$f_{osc} = 1 \Big/ 2p\sqrt{t_1 t_2} =$$





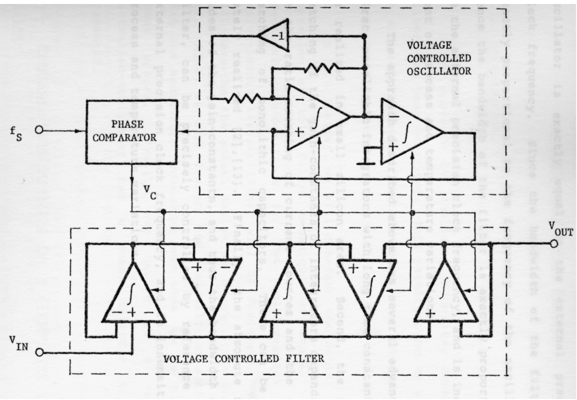
Master-Slave Frequency Tuning
Reference Filter (VCO)

- Utilizes classical phase-locked loop techniques to lock the frequency of the VCO to an incoming reference signal
- Typically the reference frequency is provided by a crystal oscillator with accuracies in the order of few ppm
- Since the VCO uses a replica of the main filter integrator, the same tuning voltage can be used to tune the main filter:
  - → Locks *fo*, the critical frequency of the filter to the accurate reference frequency



Master-Slave Frequency Tuning
Reference Voltage-Controlled-Oscillator (VCO)

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

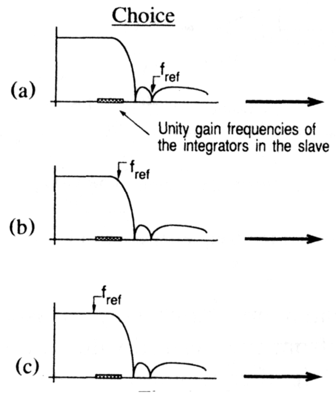


Ref: K.S. Tan and P.R. Gray, “Fully integrated analog filters using bipolar FET technology,” IEEE, J. Solid-State Circuits, vol. SC-13, no.6, pp. 814-821, December 1978..

Master-Slave Frequency Tuning
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 or else the operation loses accuracy
  - 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



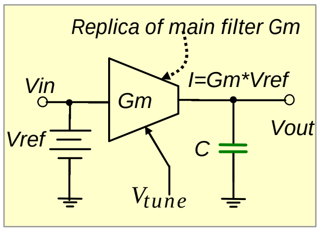
Choice	Matching	Immunity to reference freq. feedthrough
(a)	Worst	Best
(b)	Best	Worst
(c)	Medium	Medium

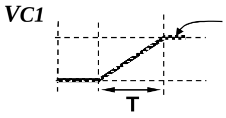
Ref: V. Gopinathan, et. al, "Design Considerations for High-Frequency Continuous-Time Filters and Implementation of an Antialiasing Filter for Digital Video," *IEEE JSSC*, Vol. SC-25, no. 6 pp. 1368-1378, Dec. 1990.

Master-Slave Frequency Tuning
Reference C/Gm Locked to Ref. Frequency

- Replica of main filter 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

  $I=Gm.Vref$
- If the integrating capacitor is fully discharged and at t=0 is connected to the output of the Gm cell then:





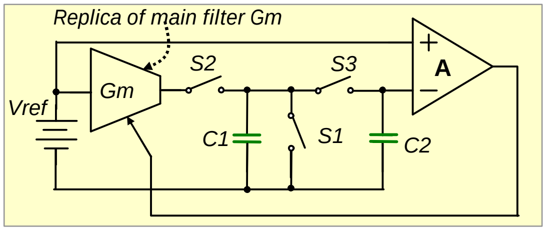
$$V_{C1} \approx Gm \times V_{ref} \times T \big/ C1$$

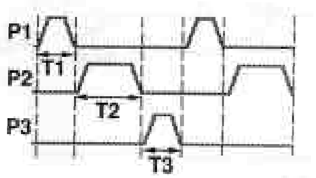
- If $VC1$ is forced to be equal to $Vref$ then: $\frac{C}{Gm} = T = \frac{N}{f_{clk}}$

Master-Slave Frequency Tuning
Reference C/Gm Locked to Ref. Frequency

- Three phase operation
- Feedback loop forces:

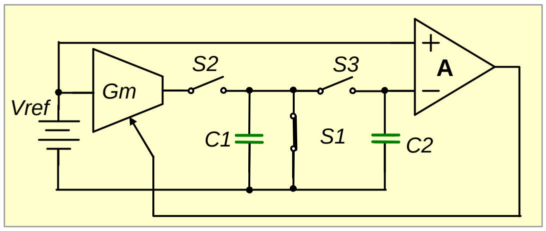
$$\frac{C}{Gm} \approx \frac{N}{f_{clk}}$$

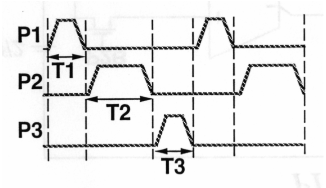




Ref: A. Durham, J. Hughes, and W. Redman- White, “Circuit Architectures for High Linearity Monolithic Continuous-Time Filtering,” *IEEE Transactions on Circuits and Systems*, pp. 651-657, Sept. 1992.

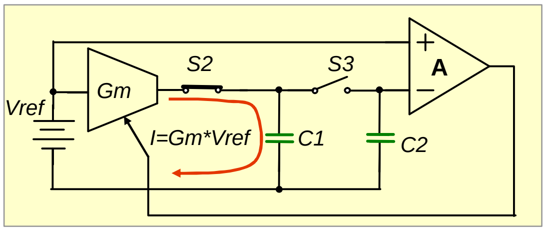
Reference C/Gm Locked to Ref. Frequency
P1 high→ S1 closed



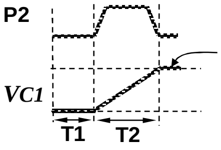


→ Discharge *C1*

Reference C/Gm Locked to Ref. Frequency
P2 high → S2 closed

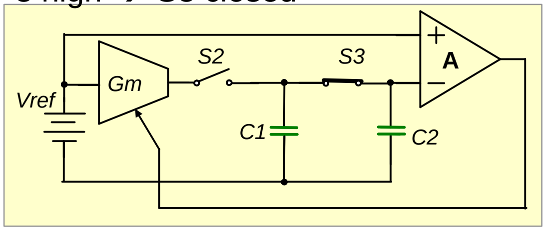


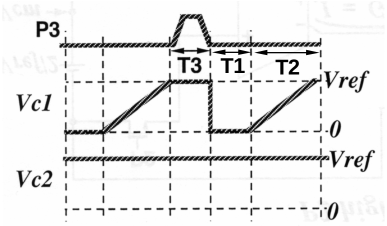
Charge *C1 with I=Gm*Vref*



$V_{C1} \approx Gm \times V_{ref} \times T2 \big/ C1$

Reference C/Gm Locked to Ref. Frequency
P3 high → S3 closed





Charge on *C1 shared with C2*
Feedback forces Gm to assume a value:

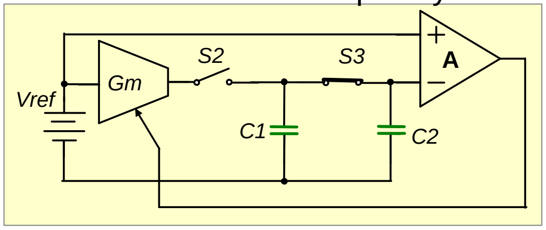
$V_{C1} = V_{C2} = Vref$

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

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

or: $\boxed{C1 \big/ Gm = T2 = N / fclk}$

Summary
Reference C/Gm Locked to Ref. Frequency



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

Feedback forces Gm to vary so that :

$$\boxed{\begin{array}{l} t_{intg} = C1/Gm = N/fclk \\ or \\ w_0^{intg} = Gm/C1 = fclk/N \end{array}}$$

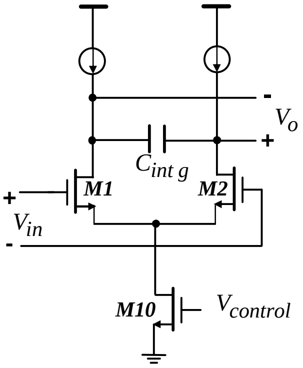
Problems to be aware of:
→ Tuning error due to Gm-cell DC offset

Issues
Reference C/Gm Locked to Ref. Frequency

What is DC offset?

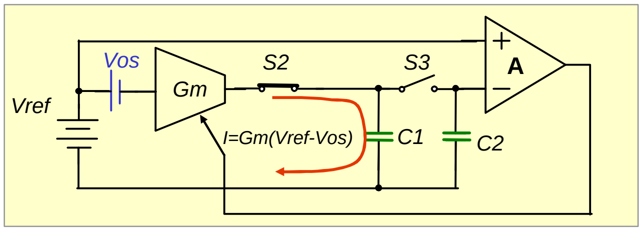
Simple example:

For the gm-cell shown here, difference between the threshold voltage of the input devices (*M1 & M2*) would cause DC offset.
→ A non-zero voltage should be applied to input to have ***Vo=0***
Offset is usually models as a small DC voltage source at the input



Example: Gm-cell

Gm-Cell Offset Induced Error



- Effect of Gm-cell DC offset:

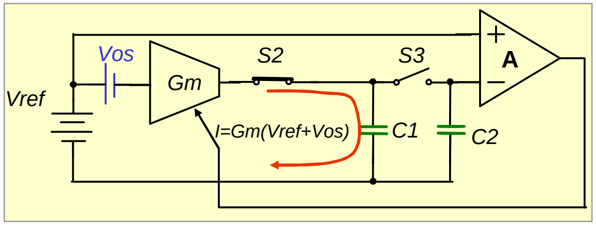
$$V_{C1}=V_{C2}=Vref$$

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

$$with\ offset:\ V_{C1}=Gm\times\left(V_{ref}-V_{os}\right)\times T2\,\big/\,C1$$

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

Reference C/Gm Locked to Ref. Frequency
Gm-Cell Offset Induced Error



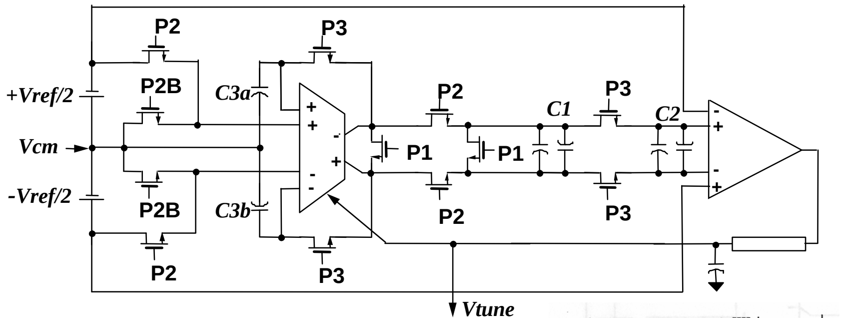
- Example:

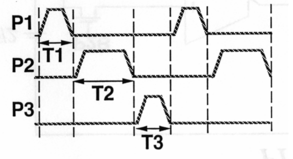
$$C1\big/Gm=T2\left(1-\frac{V_{os}}{V_{ref}}\right)$$

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

$$10\%\ \ error\ in\ tuning!$$

Reference C/Gm Locked to Ref. Frequency Incorporating Offset Cancellation



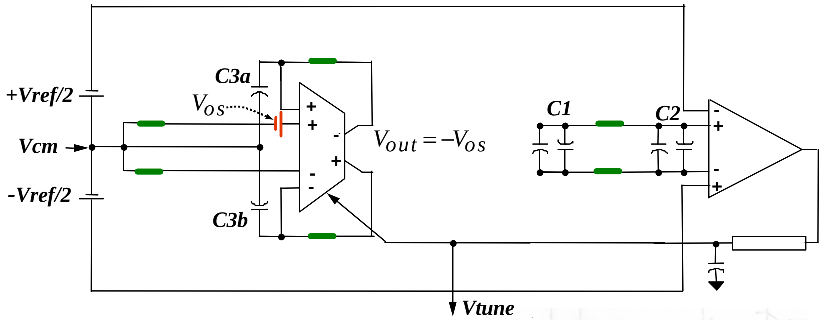


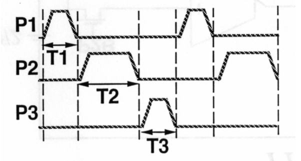
Gm-cell -> two sets of input pairs

Aux. input pair + *C3a,b* → Offset cancellation

Same clock timing

Reference C/Gm Locked to Ref. Frequency P3 High (Update & Store Vos)



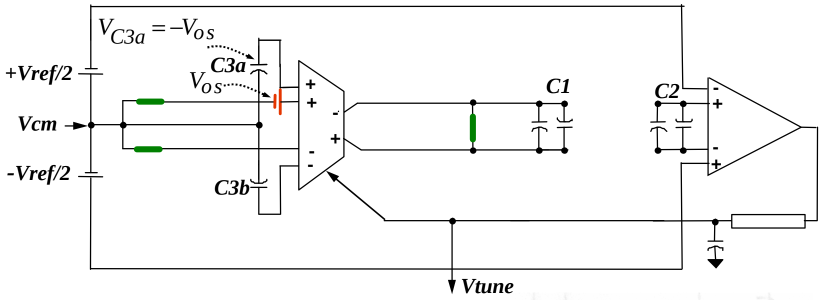


Gm-cell → Unity gain config.

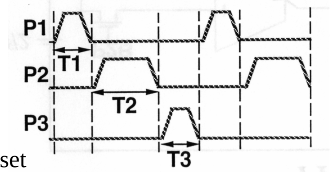
C3a,b → Store Gm-cell offset

C1, C2 → Charge sharing

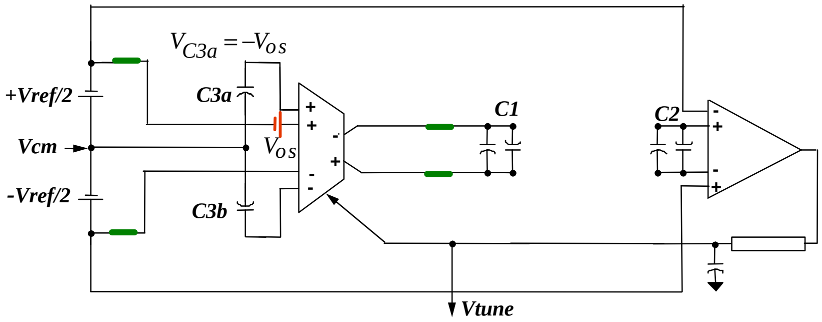
Reference C/Gm Locked to Ref. Frequency
P1 High (Reset)



Gm-cell → Reset.
C1 → Discharge
C2 → Hold Charge
C3a,b → Hold Charge
→ Offset stored on C3a,b cancels gm-cell offset



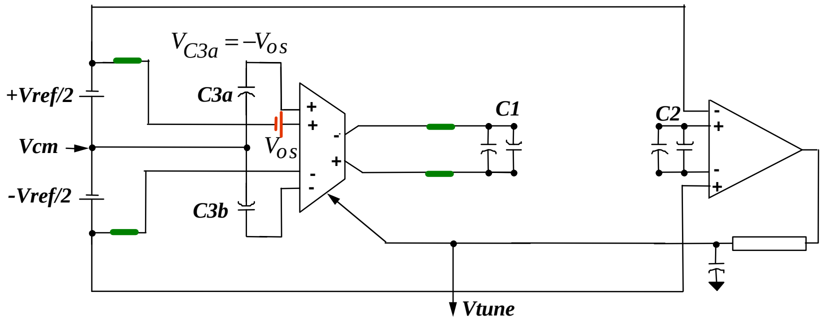
Reference C/Gm Locked to Ref. Frequency
P2 High (Charge)



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

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

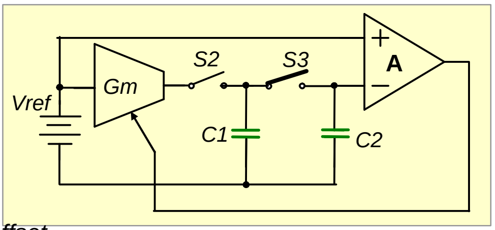
Summary
Reference C/Gm Locked to Ref. Frequency



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

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

Summary
Reference C/Gm Locked to Ref. Frequency



Tuning error due to gm-cell offset voltage resolved
Has the advantage over previous scheme that fclk can be chosen to be at much higher frequencies compared to filter bandwidth (N>1)
→ Feedthrough of Vref attenuated by filter

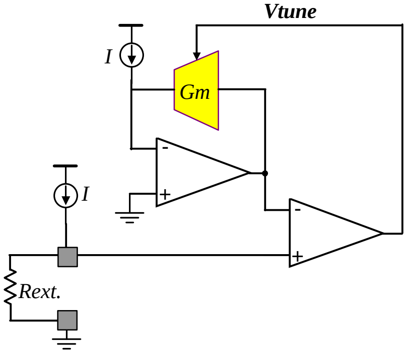
Feedback forces Gm to vary so that :

$$t_{intg} = C1/Gm = N/fclk$$

or

$$w_0^{intg} = Gm/C1 = fclk/N$$

DC Tuning of Resistive Timing Element



Rext used to lock Gm or on-chip R

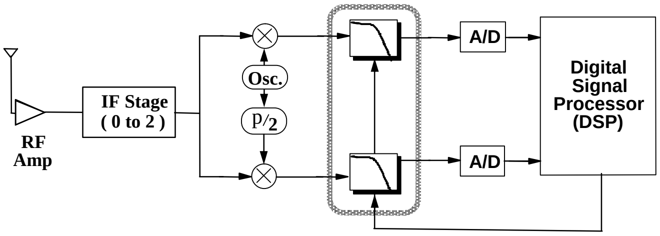
Feedback forces *Gm=1/Rext*

Account for Cap. variations in the gm-C implementation by trimming

Ref: C. Laber and Gray, “A 20MHz 6th Order BiCOM 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

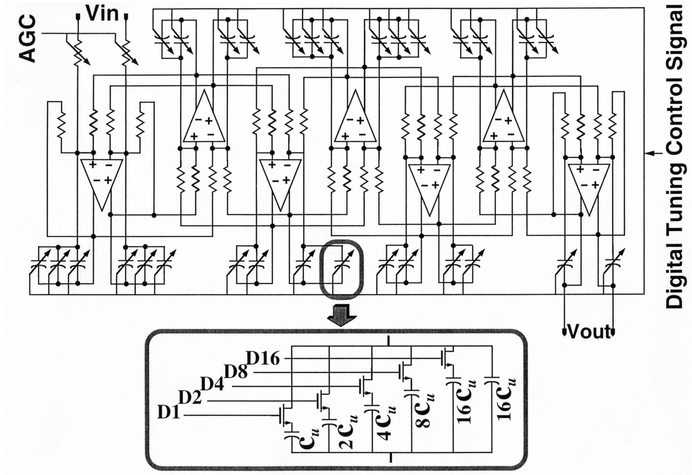
Off-line Frequency Tuning

Example:Wireless Receiver Baseband Filters

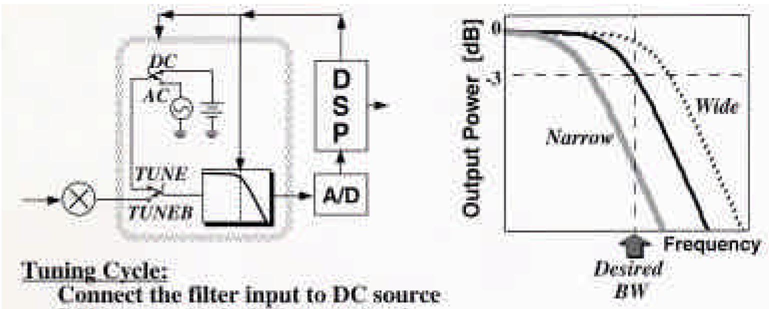


- Systems where filter is followed by ADC & DSP
  - Take advantage of existing digital signal processor to periodically update the filter critical frequency
  - Filter tuned only at the outset of each data transmission session (off-line tuning)

Seventh Order Tunable Low-Pass OpAmp-RC Filter

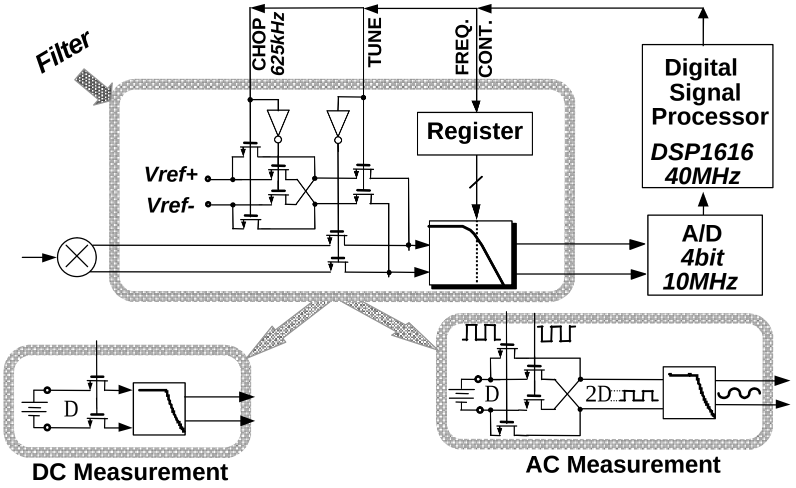


Offline Filter Tuning Concept

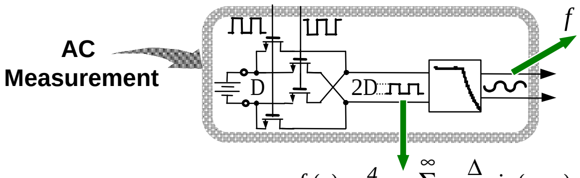


```
Tuning Cycle:
    Connect the filter input to DC source
    DSP measures the DC power level
    Connect the filter input to AC souce (freq. -> desired -3dB freq.)
    DSP measures the AC signal power level
    If DC = 4*AC
            Then filter is tuned
            Else If DC > 4*AC
                Then widen the filter bandwidth & repeat
                Else narrow the filter bandwidth & repeat
```

Practical Implementation of Frequency Tuning



Practical Implementation of Frequency Tuning



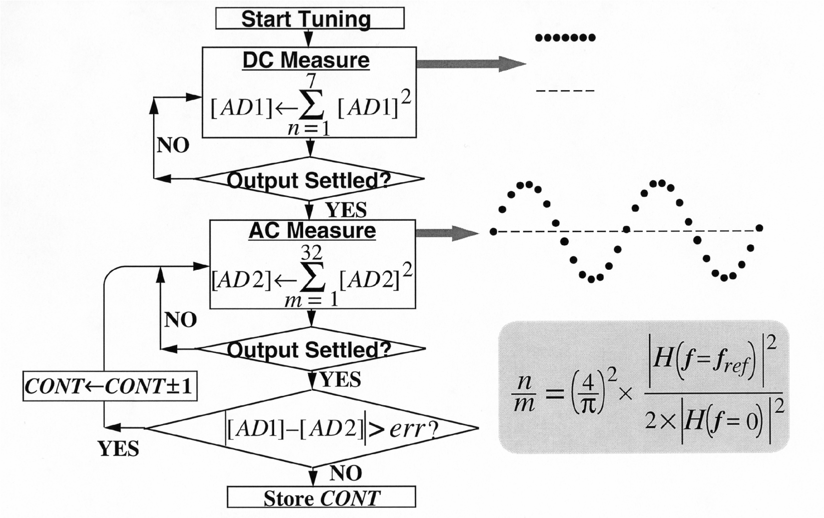
$$f(t) = \frac{4\Delta}{p} sin(wt)$$

$$f(t) = \frac{4}{p} \sum_{n=1,3,5,..}^{\infty} \frac{\Delta}{n} sin(nwt)$$

- Input signal chosen to be a square wave due to ease of generation
- Filter input signal comprises a sinusoidal waveform @ the fundamental freq. + its odd harmonics:

Key Point: The filter itself attenuates the unwanted odd harmonics -> Inaccuracy incurred by the harmonics negligible

Simplified Frequency Tuning Flowchart

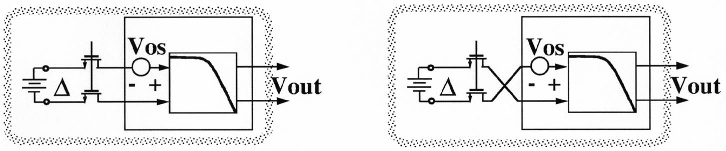


$$\frac{n}{m} = \left(\frac{4}{\pi}\right)^2 \times \frac{\left|H(f=f_{ref})\right|^2}{2 \times \left|H(f=0)\right|^2}$$

Offset Compensation

In cases where the filter DC offset cause significant error in tuning (i.e. high passband gain)

- **Offset compensation needed:**
  - ➪**DC measurement performed in two steps:**



Vout1 = A (Δ + Vos) **Vout2 = A (- Δ + Vos)**

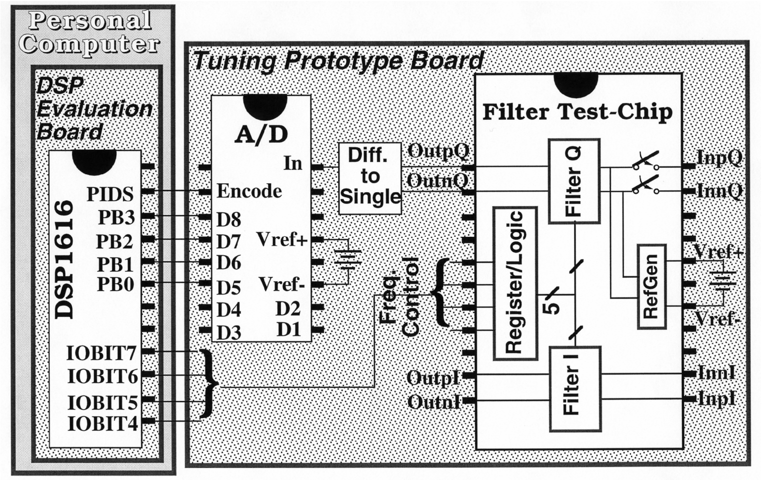
Passband Gain

➪**DSP extracts: Offset component ➡ 1/2(Vout1 + Vout2) = A . Vos**

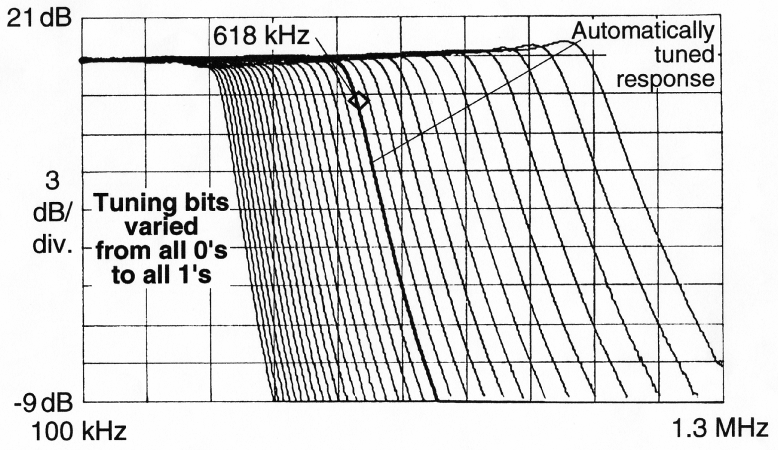
DC component ➡ 1/2(Vout1 - Vout2) = A . Δ

➪**DSP substracts Vos from all subsequent AC measurement**

Filter Tuning Prototype Diagram

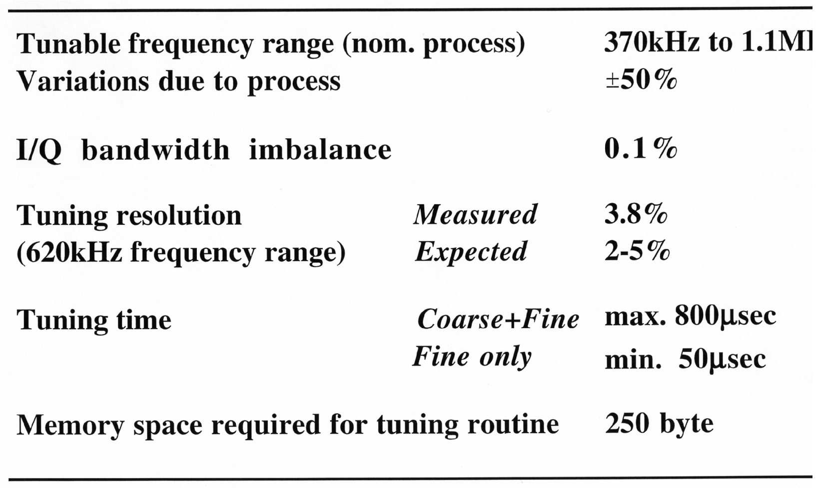


Measured Frequency Response



Chip Photo

Measured Tuning Characteristics



Tunable frequency range (nom. process) Variations due to process		370kHz to 1.1M ±50%
I/Q bandwidth imbalance		0.1%
Tuning resolution (620kHz frequency range)	*Measured* *Expected*	3.8% 2-5%
Tuning time	*Coarse+Fine* *Fine only*	max. 800µsec min. 50µsec
Memory space required for tuning routine		250 byte

Off-line Tuning

- Advantages:
  - No reference signal feedthrough since tuning does not take place during data transmission (off-line)
  - Minimal additional hardware
  - Small amount of programming
- Disadvantages:
  - If acute temp. change during data transmission, filter may slip out of tune!
    - Can add fine tuning cycles during dead periods of data transmission

Ref: H. Khorramabadi, M. Tarsia and N.Woo, "Baseband Filters for IS-95 CDMA Receiver Applications Featuring Digital Automatic Frequency Tuning," *1996 International Solid State Circuits Conference*, pp. 172-173.