ECEN689: Special Topics in High-Speed Links Circuits and Systems Spring 2010

Lecture 28: VCOs

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Announcements

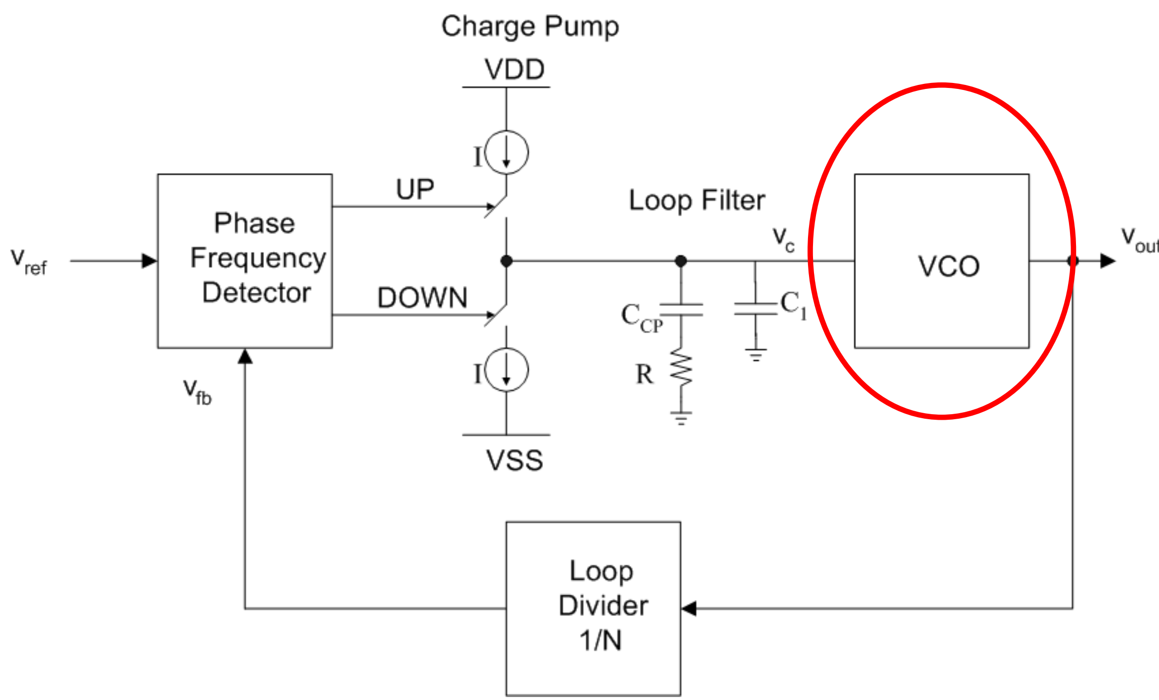
- Project Preliminary Report #2 now due Monday April 26 in class
- Exam 2 is April 30
- Project feedback meetings
  - Today 3:30-5
  - Wednesday 10:30-12

Agenda

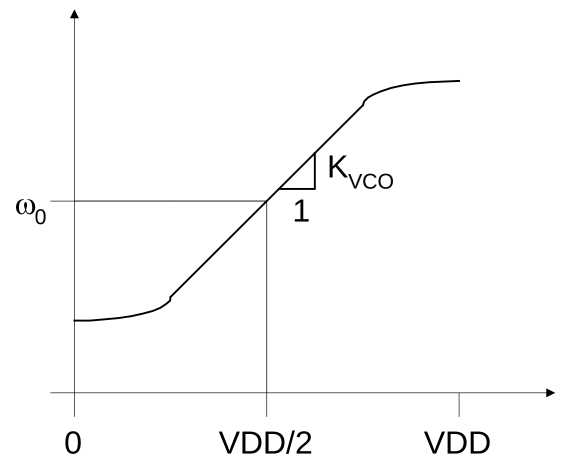
- VCOs

Charge-Pump PLL Circuits

- Phase Detector
- Charge-Pump
- Loop Filter
- VCO
- Divider



Voltage-Controlled Oscillator

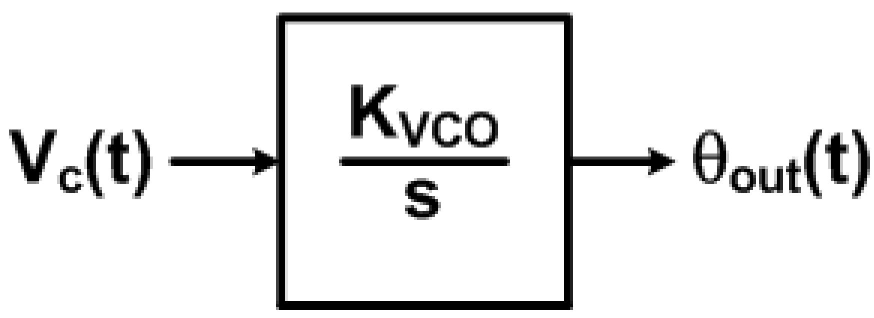


$$\omega_{out}(t) = \omega_0 + \Delta\omega_{out}(t) = \omega_0 + K_{VCO} v_c(t)$$

- Time-domain phase relationship

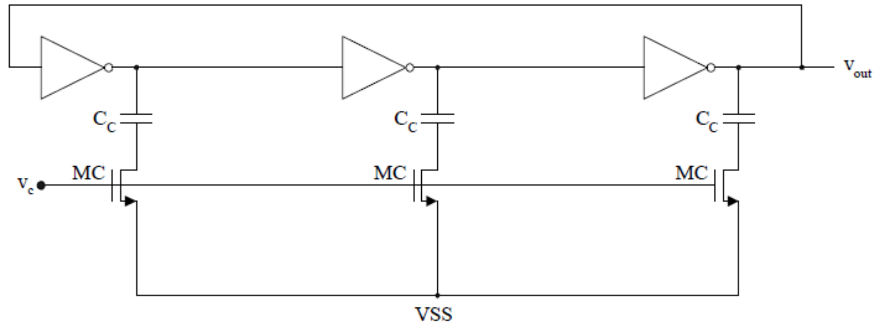
$$\theta_{out}(t) = \int \Delta\omega_{out}(t)\mathrm{dt} = K_{VCO}\int v_c(t)\mathrm{dt}$$

Laplace Domain Model

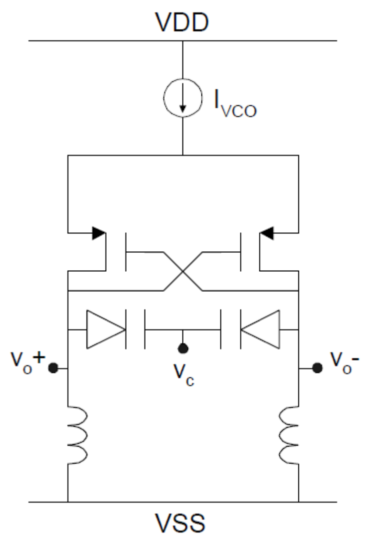


Voltage-Controlled Oscillators (VCO)

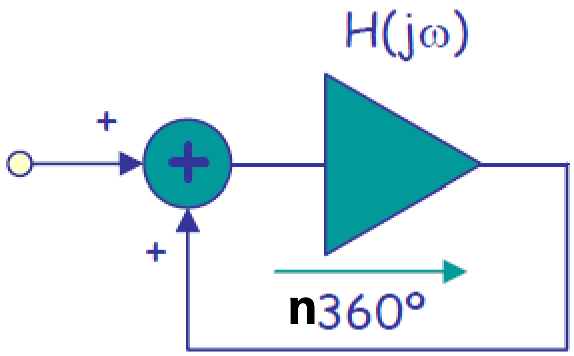
- Ring Oscillator
  - Easy to integrate
  - Wide tuning range (5x)
  - Higher phase noise



- LC Oscillator
  - Large area
  - Narrow tuning range (20-30%)
  - Lower phase noise



Barkhausen's Oscillation Criteria



[Sanchez]

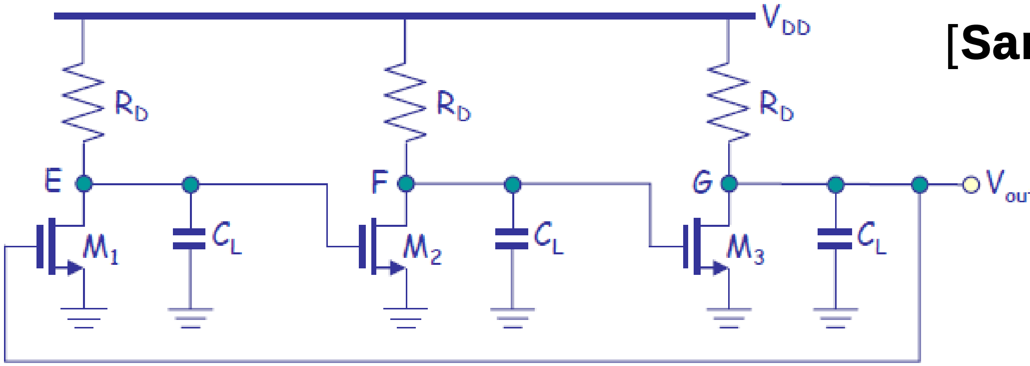
Closed-loop transfer function: $$\frac{H(j\omega)}{1-H(j\omega)}$$

- Sustained oscillation occurs if $H(j\omega)=1$

- 2 conditions:
  - Gain = 1 at oscillation frequency ω_0
  - Total phase shift around loop is n360° at oscillation frequency ω_0

Ring Oscillator Example

[**Sanchez**]



Three-stage ring oscillator

$$H(s) = -\frac{A_0^3}{\left(1+\frac{s}{\omega_0}\right)^3}$$

$$\omega_{osc} = \sqrt{3}\omega_0$$

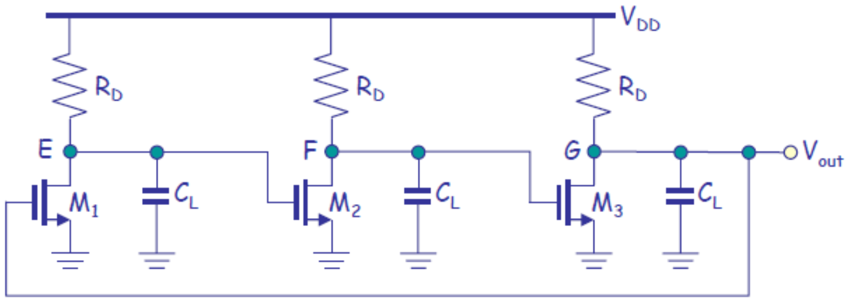
$$\tan^{-1}\frac{\omega_{osc}}{\omega_o} = 60^\circ$$

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\frac{-A_0^3}{(1+s/\omega_0)^3}}{1+\frac{A_0^3}{(1+s/\omega_0)^3}} = \frac{-A_0^3}{(1+s/\omega_0)^3 + A_0^3}$$

$$\frac{A_0^3}{\left[\sqrt{1+\left(\frac{\omega_{osc}}{\omega_0}\right)^2}\right]^3} = 1$$

$$A_0 = 2$$

Ring Oscillator Example



Three-stage ring oscillator

- 4-stage oscillator
  - A0 = sqrt(2)
  - Phase shift = 45
- Easier to make a larger-stage oscillator oscillate, as it requires less gain and phase shift per stage

$$H(s) = -\frac{A_0^3}{\left(1+\frac{s}{\omega_0}\right)^3}$$

$$\omega_{osc} = \sqrt{3}\omega_0$$

$$\tan^{-1}\frac{\omega_{osc}}{\omega_o} = 60^\circ$$

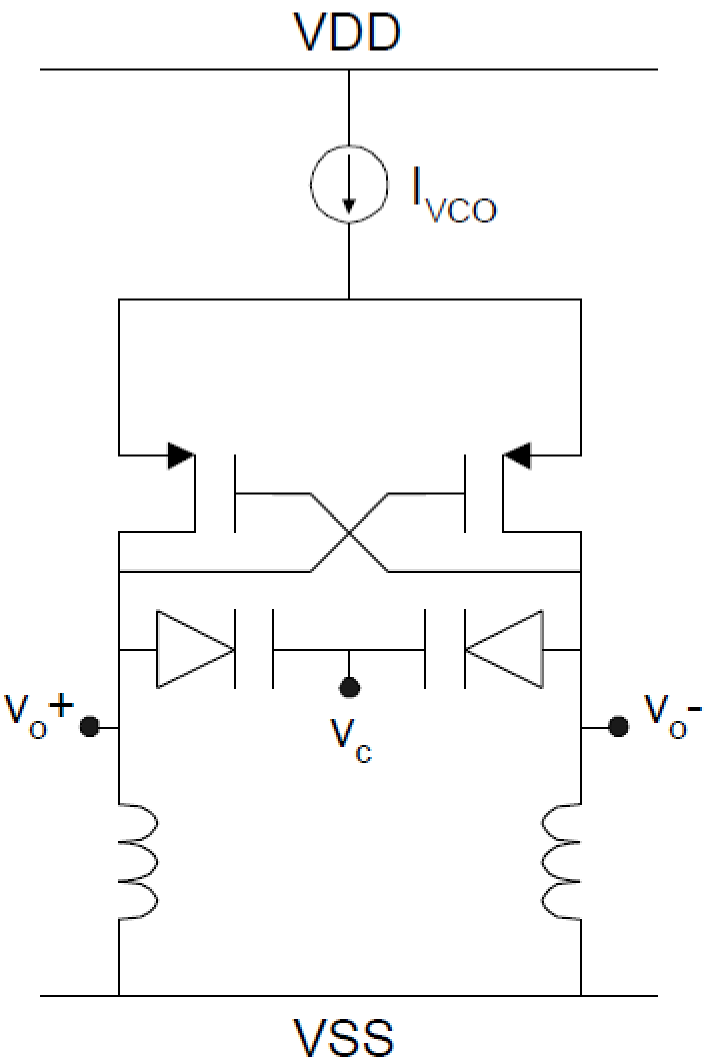
$$\frac{A_0^3}{\left[\sqrt{1+\left(\frac{\omega_{osc}}{\omega_0}\right)^2}\right]^3} = 1$$

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{\frac{-A_0^3}{(1+s/\omega_0)^3}}{1+\frac{A_0^3}{(1+s/\omega_0)^3}} = \frac{-A_0^3}{(1+s/\omega_0)^3 + A_0^3}$$

[Sanchez]

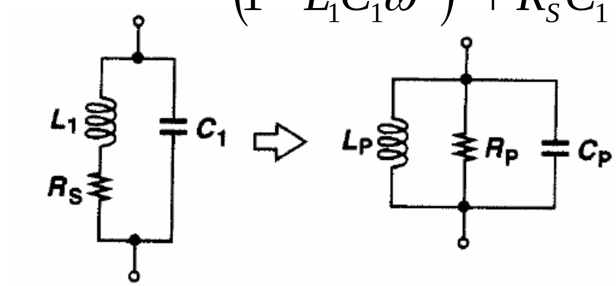
$$A_0 = 2$$

LC Oscillator Example

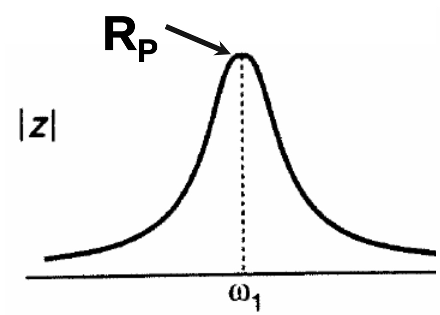


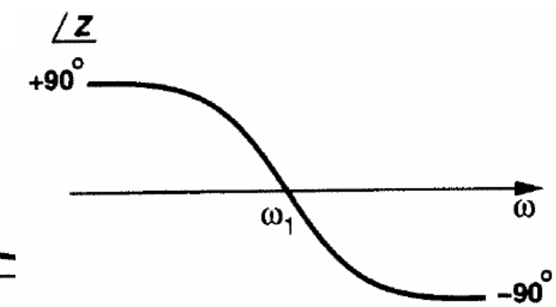
LC tank impedance

$$\left|Z_{eq}(s=j\omega)\right|^2 = \frac{R_S^2 + L_1^2\omega^2}{\left(1 - L_1C_1\omega^2\right)^2 + R_S^2C_1^2\omega^2}$$



$$L_P = L_1\left(1 + \frac{R_S^2}{L_1^2\omega^2}\right), \quad C_P = C_1, \quad R_P \approx \frac{L_1^2\omega^2}{R_S}$$

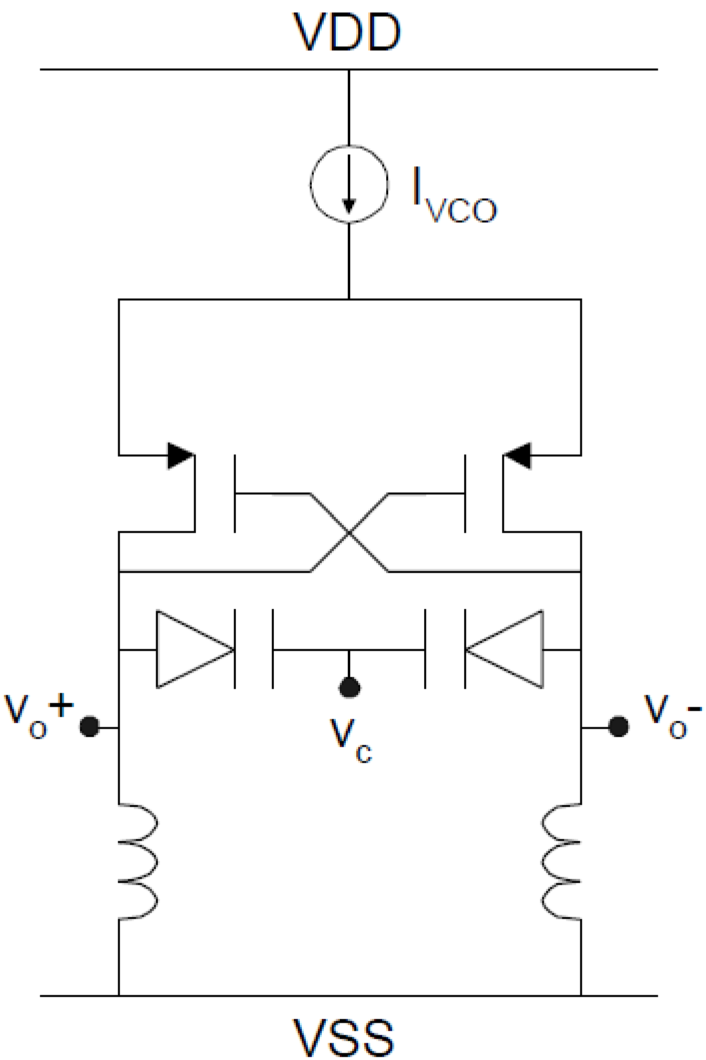




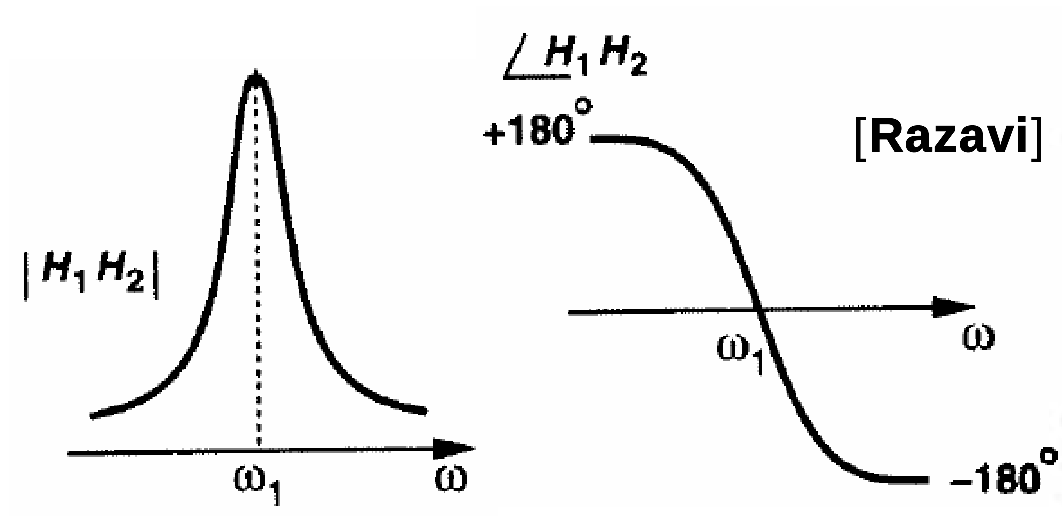
$$\omega_1 = \frac{1}{\sqrt{L_P C_P}}$$

[Razavi]

LC Oscillator Example



Loop Gain



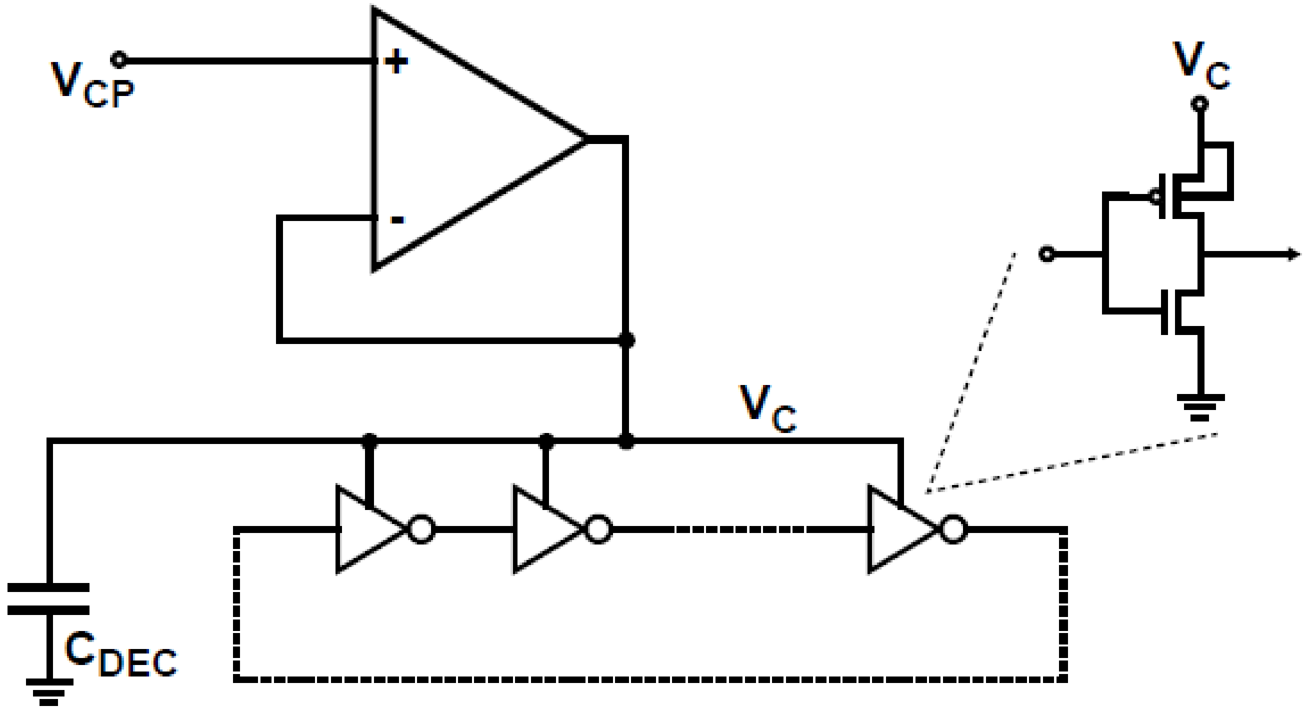
- Phase condition satisfied at

$$\omega_1 = \frac{1}{\sqrt{L_P C_P}}$$

- Gain condition satisfied when

$$(g_m R_P)^2 \geq 1$$

Supply-Tuned Ring Oscillator

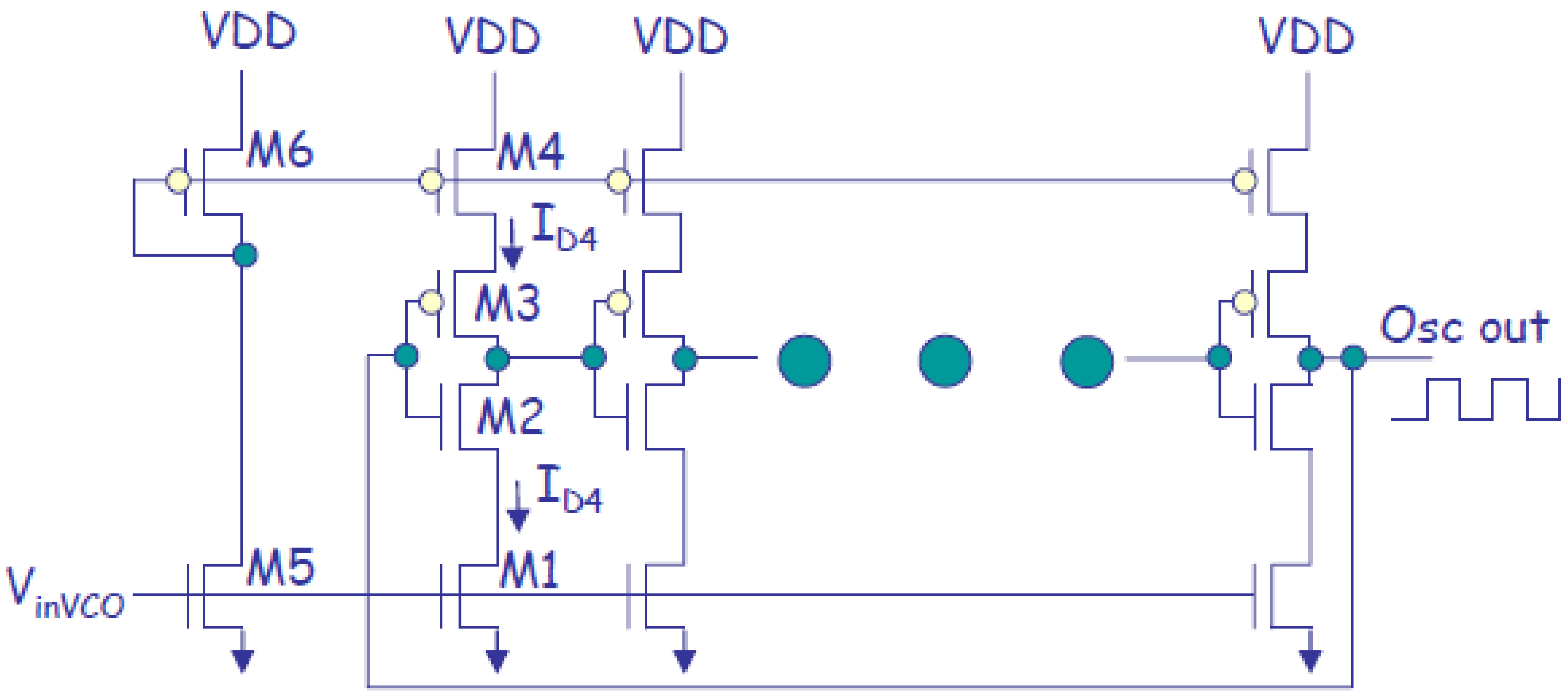


[**Sidiropoulos VLSI 2000**]

$$T_{VCO} = 2nT_D \approx \frac{2nC_{stage}}{\beta(V_c - V_{th})}$$

$$K_{VCO} = \frac{\partial f_{VCO}}{\partial V_c} = \frac{\beta}{2nC_{stage}}$$

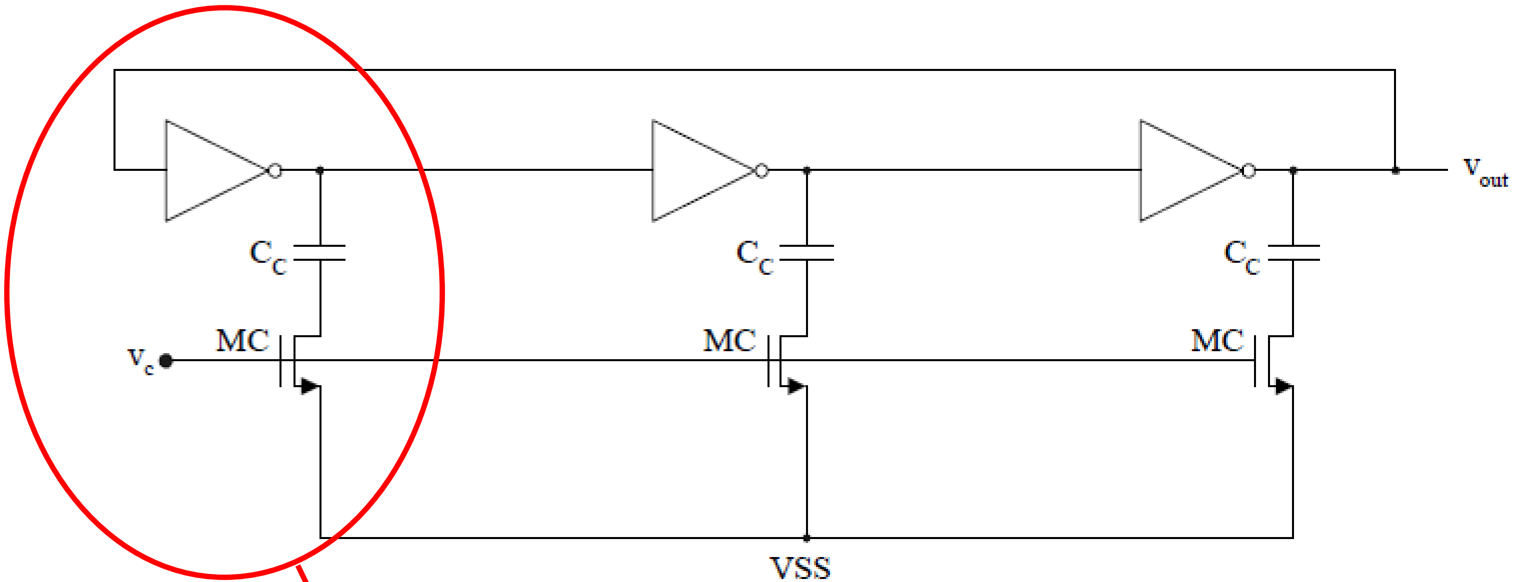
Current-Starved Ring Oscillator

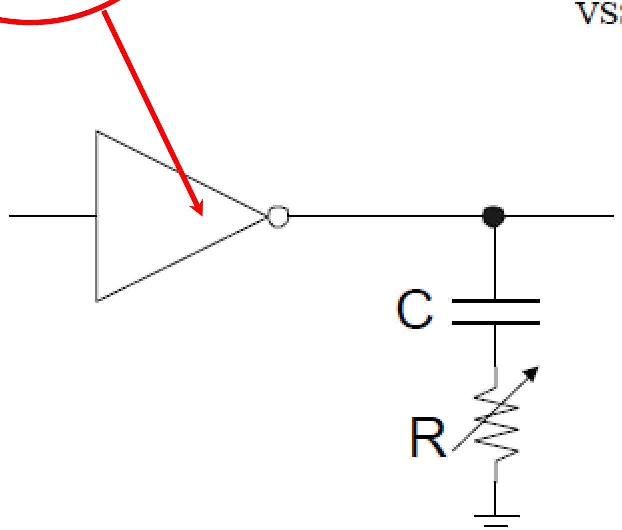


[Sanchez]

Current - starved VCO.

Capacitive-Tuned Ring Oscillator

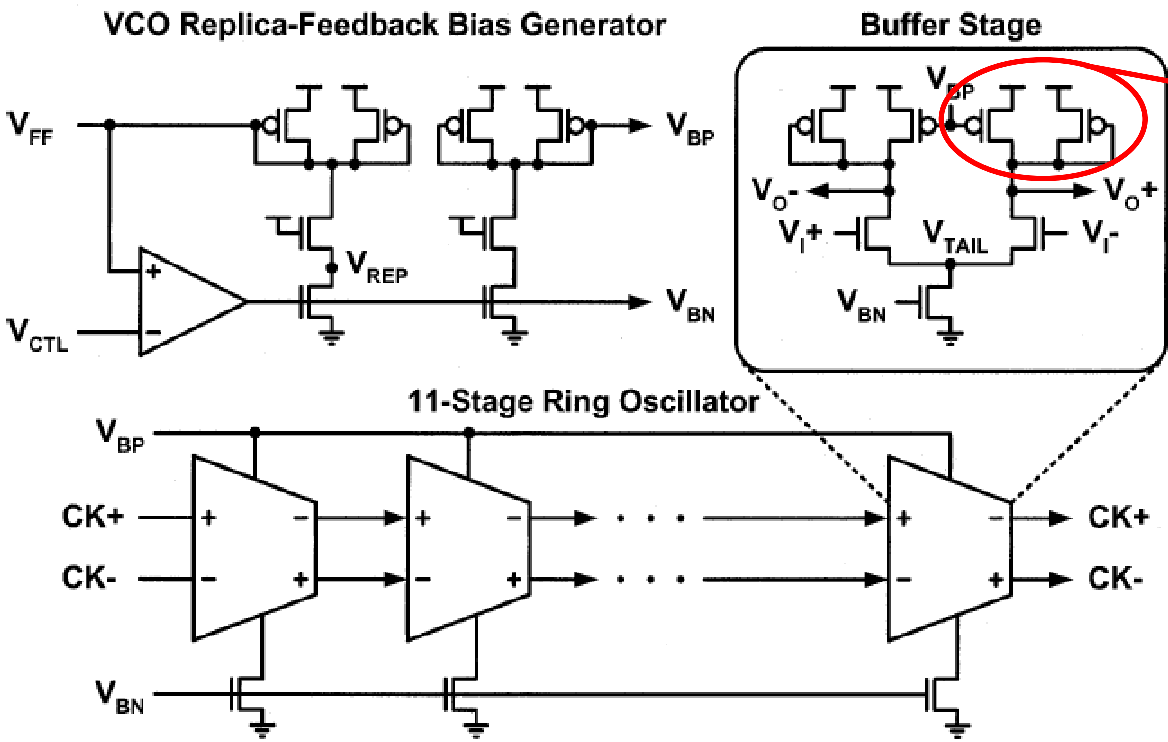


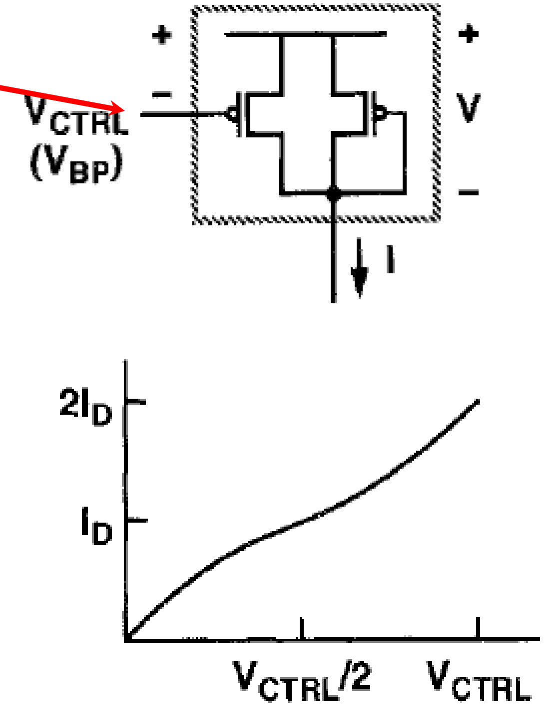


$$C_{eff} = \frac{C}{1 + sCR}$$

Symmetric Load Ring Oscillator

[Maneatis JSSC 1996 & 2003]



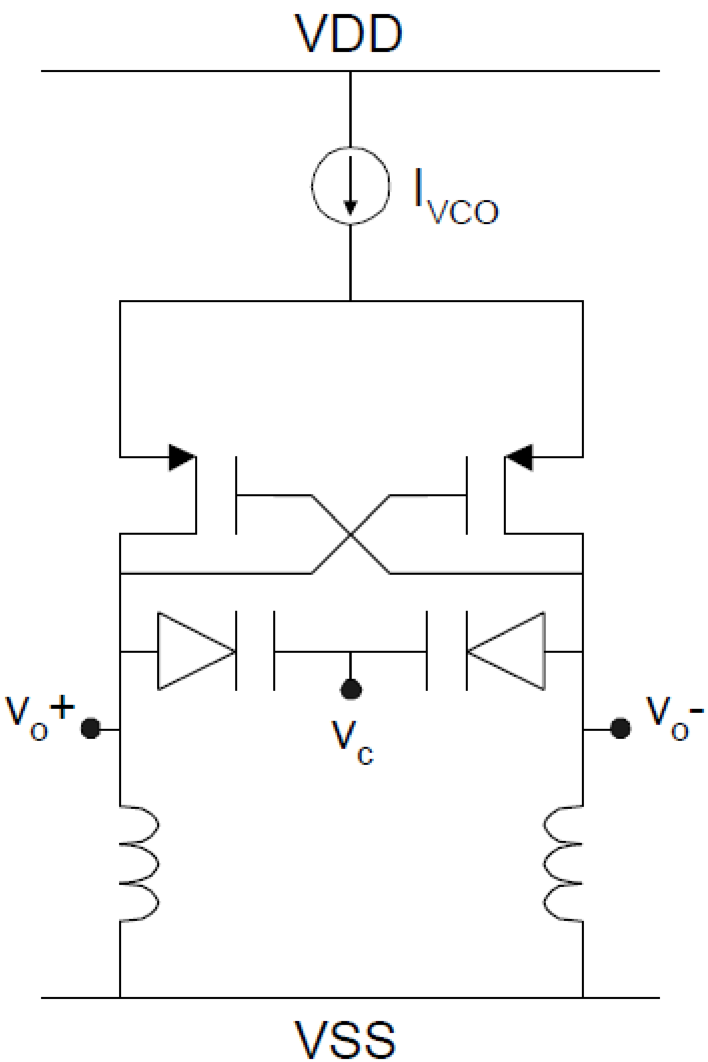


- Symmetric load provides frequency tuning at excellent supply noise rejection
- See Maneatis papers for self-biased techniques to obtain constant damping factor and loop bandwidth (% of ref clk)

LC Oscillator

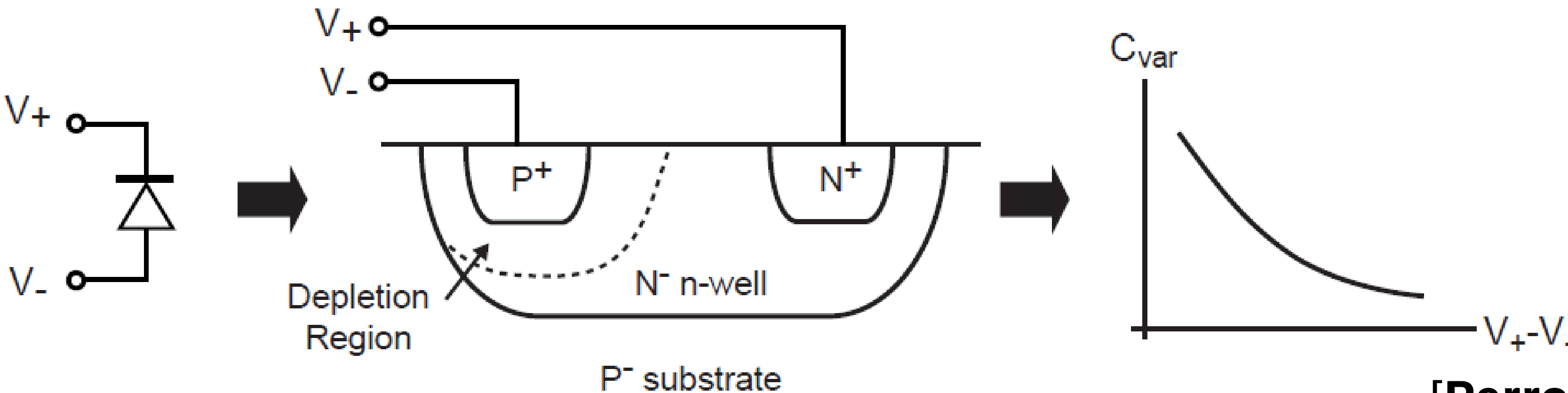
- A variable capacitor (varactor) is often used to adjust oscillation frequency
- Total capacitance includes both tuning capacitance and fixed capacitances which reduce the tuning range

$$\omega_{osc} = \frac{1}{\sqrt{L_P C_P}} = \frac{1}{\sqrt{L_P \left(C_{tune} + C_{fixed}\right)}}$$



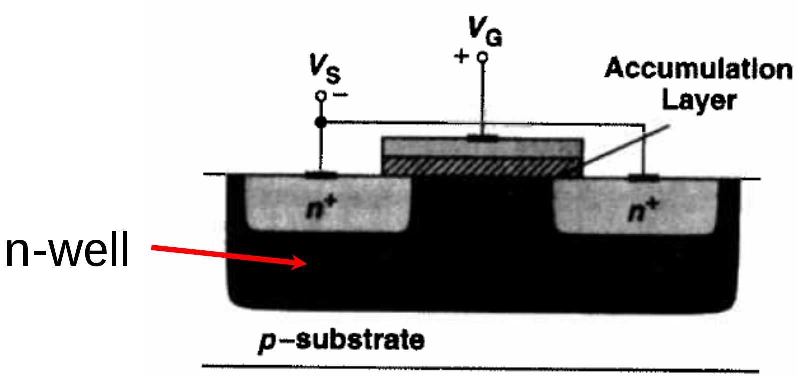
Varactors

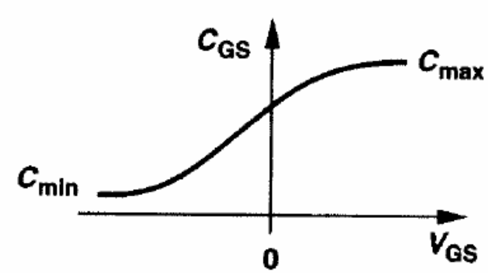
- pn junction varactor
  - Avoid forward bias region to prevent oscillator nonlinearity



[Perrott]

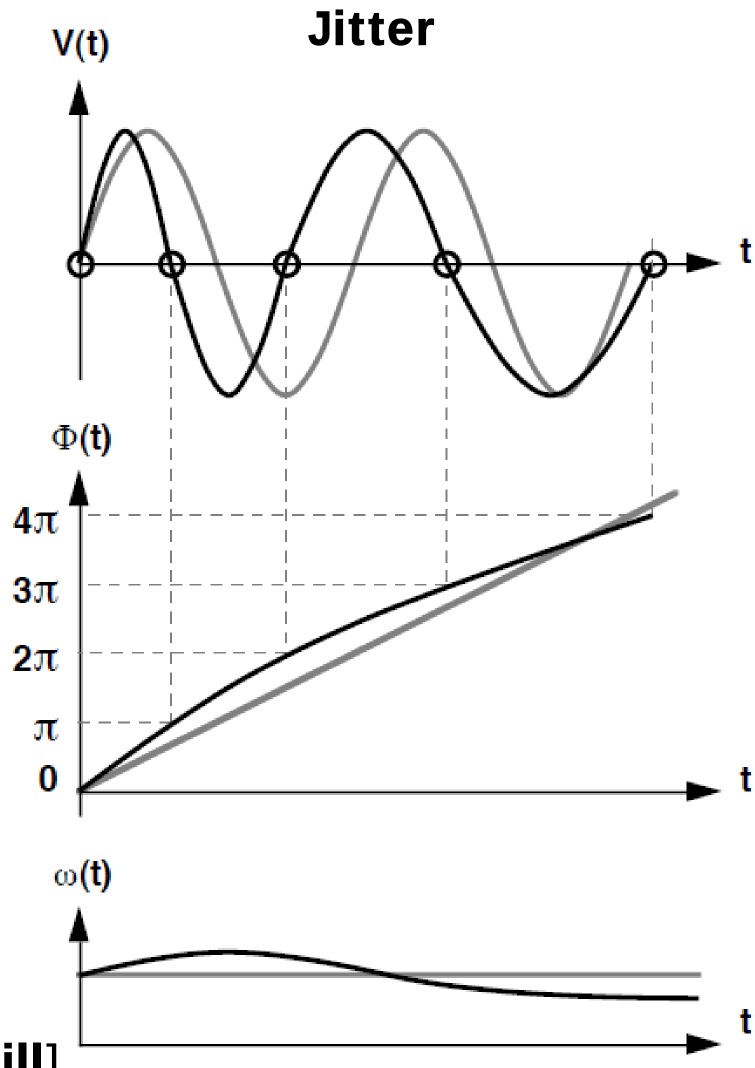
- MOS varactor
  - Accumulation-mode devices have better Q

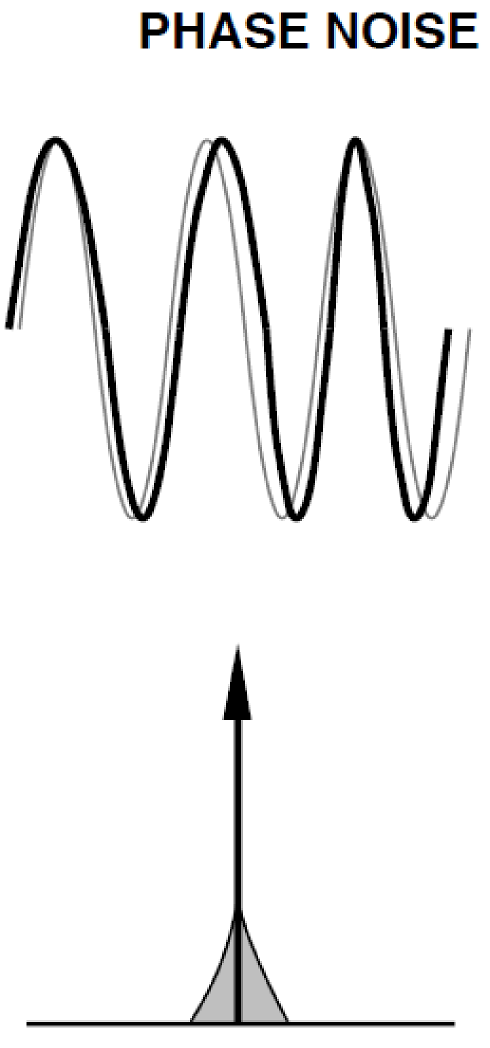




[Razavi]

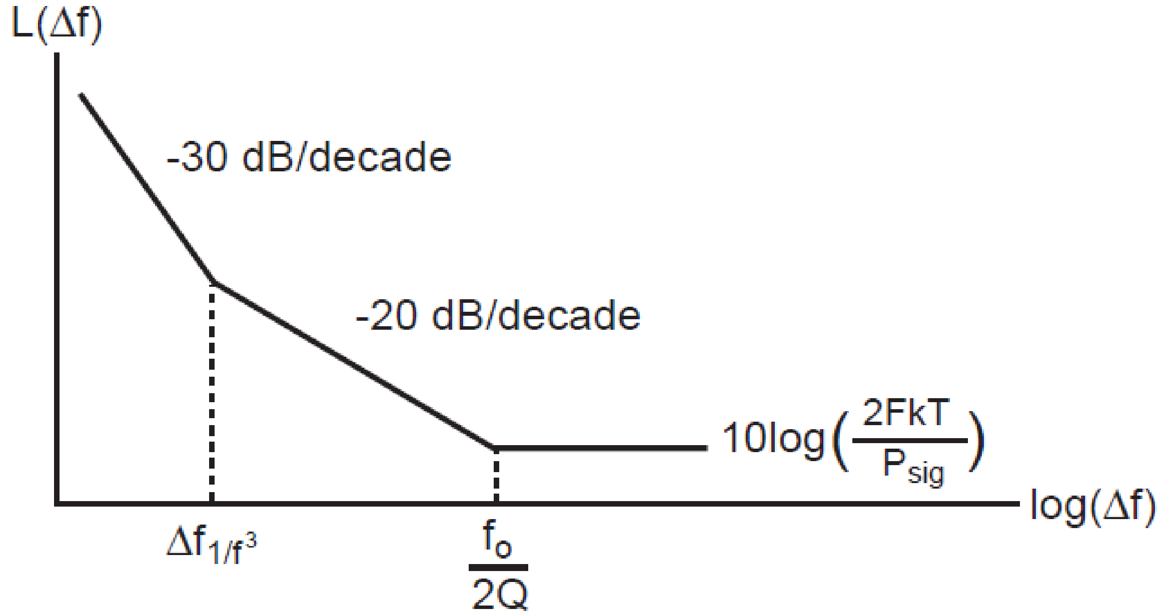
Oscillator Noise





[McNeill]

Oscillator Phase Noise Model



[Perrott]

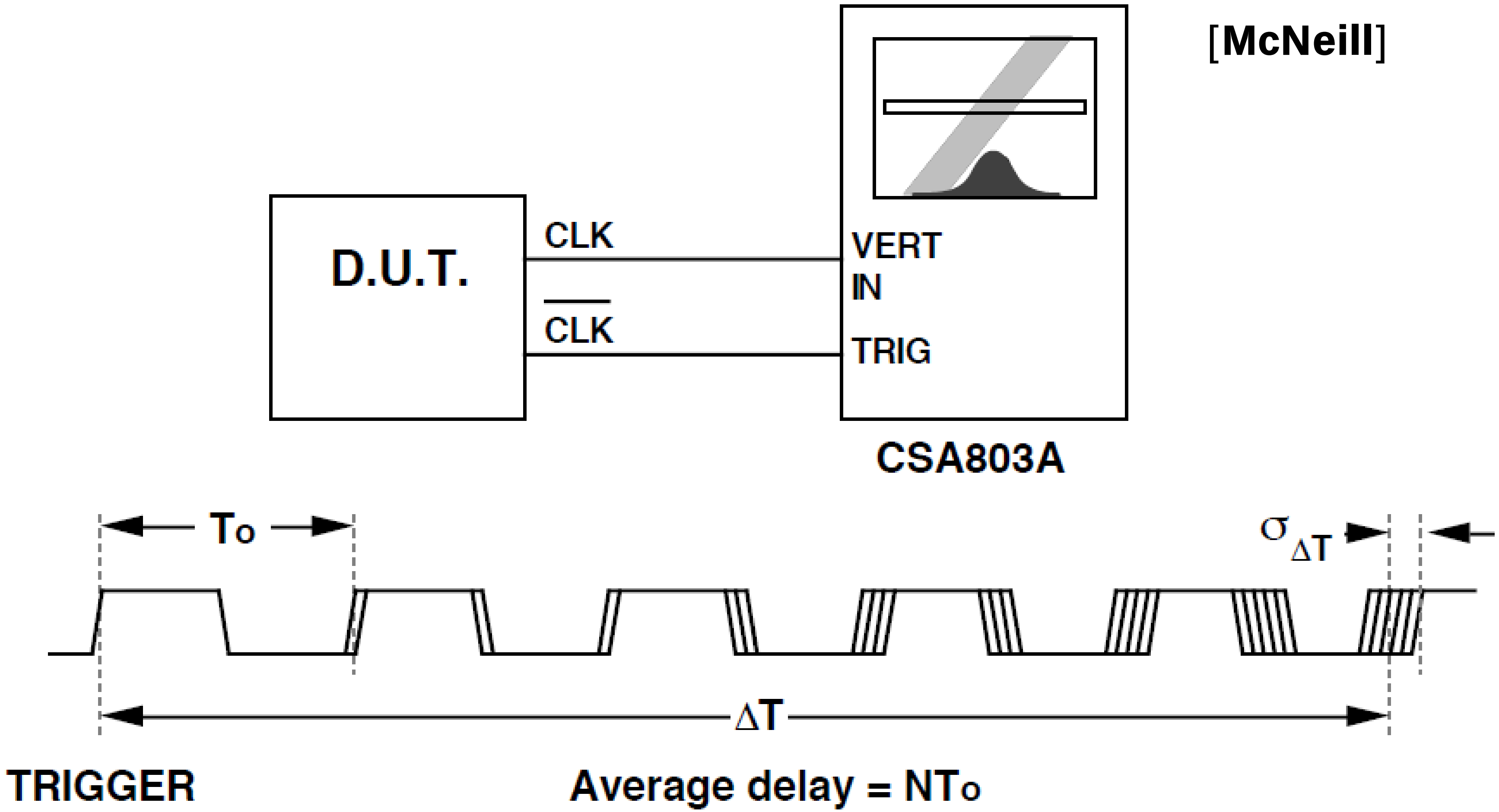
$$L(f) = 10\log\left(\frac{\textbf{Noise Spectral Density}}{\textbf{Carrier Power}}\right)\ (\textbf{dBc/Hz})$$

Leeson's Model: $$L(\Delta f) = 10\log\left(\frac{2FkT}{P_{sig}}\left(1+\left(\frac{1}{2Q}\frac{f_o}{\Delta f}\right)^2\right)\left(1+\frac{\Delta f_{1/f^3}}{|\Delta f|}\right)\right)$$

- For improved model see Hajimiri papers

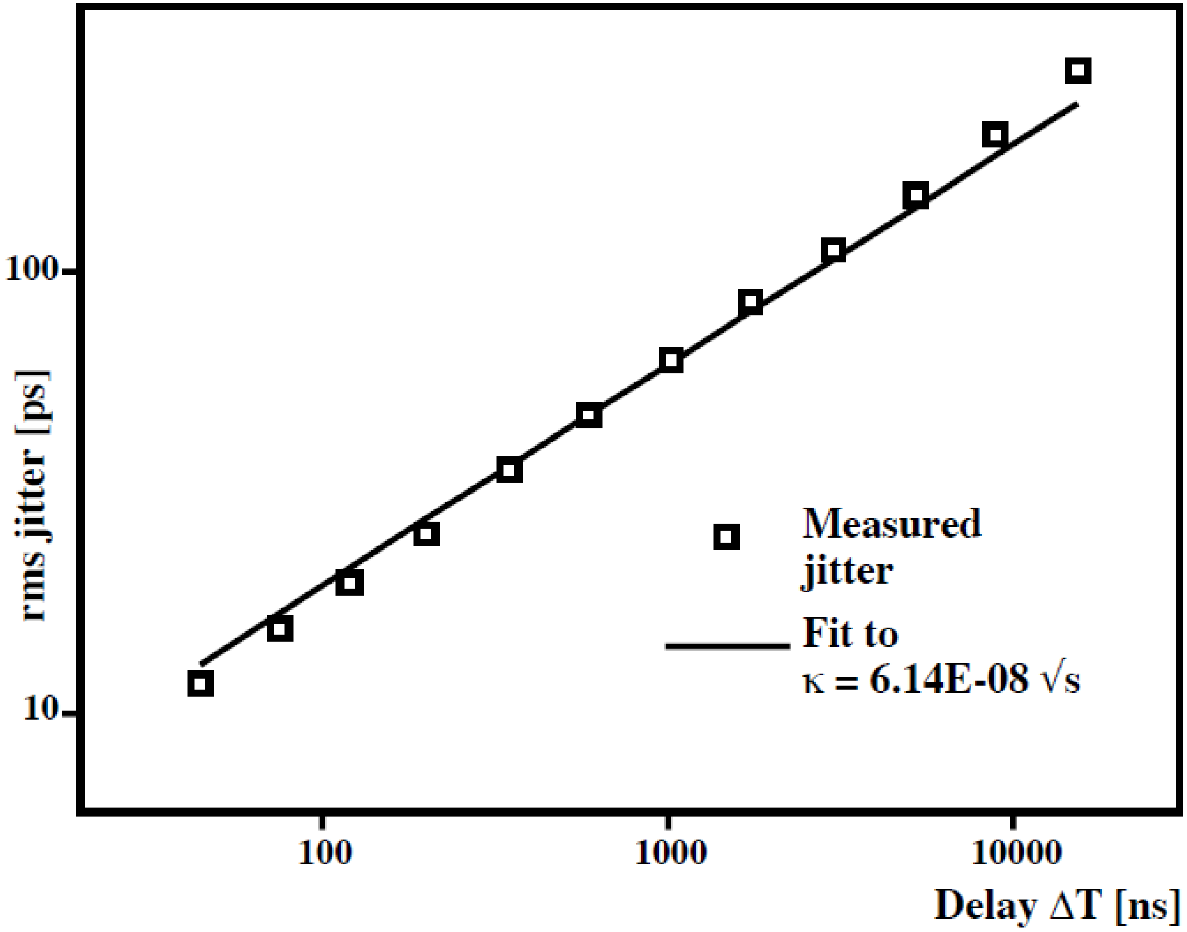
Open-Loop VCO Jitter

[**McNeill**]



- Measure distribution of clock threshold crossings
- Plot σ as a function of delay ΔT

Open-Loop VCO Jitter

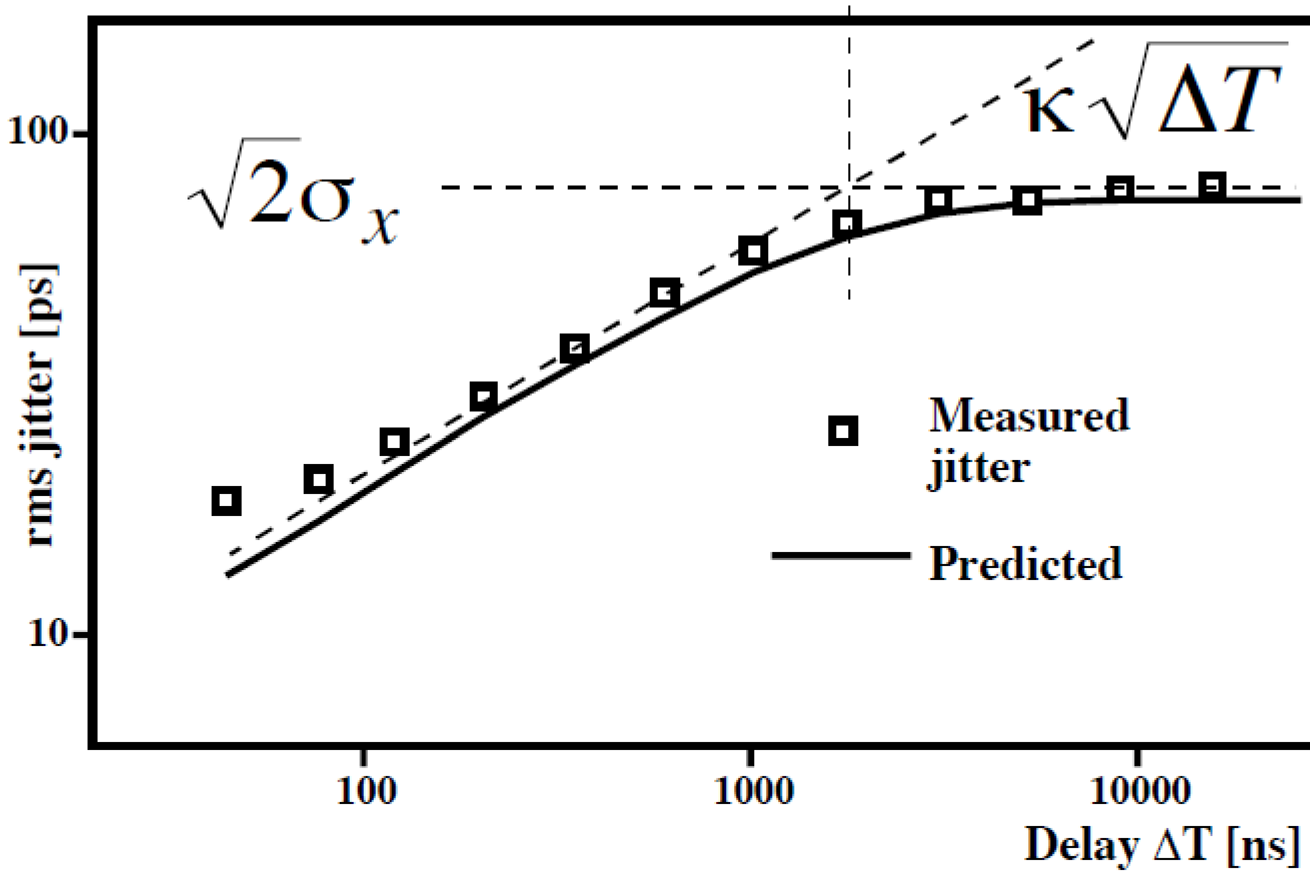


[McNeill]

$$\sigma_{\Delta T(OL)}(\Delta T) \approx \kappa\sqrt{\Delta T}$$

- Jitter σ is proportional to sqrt(ΔT)
- K is VCO time domain figure of merit

VCO in Closed-Loop PLL Jitter



[**McNeill**]

- PLL limits σ for delays longer than loop bandwidth τ_L

$$\tau_L = 1/2\pi f_L$$

Converting Phase Noise to Jitter

- RMS Phase Jitter

$$J_{phase} = \frac{1}{2\pi f_{vco}} \sqrt{\int S_{\phi}(f)\,df}$$

- Integration range depends on application
  - f_{min} set by standard
    - Ex. Assumed CDR tracking bandwidth
  - Usually stop integration at $f_o/2$ to avoid capturing carrier and harmonics

Next Time

- PLL wrap-up
- CDRs