Wireline Transceiver Circuits

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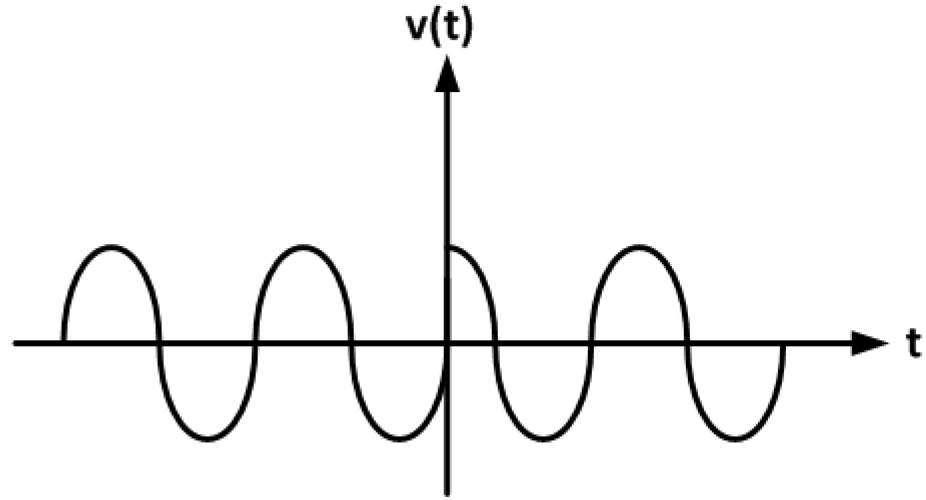
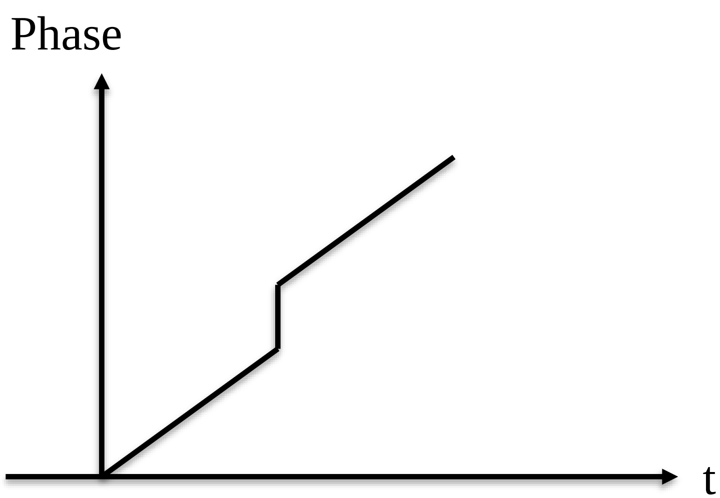
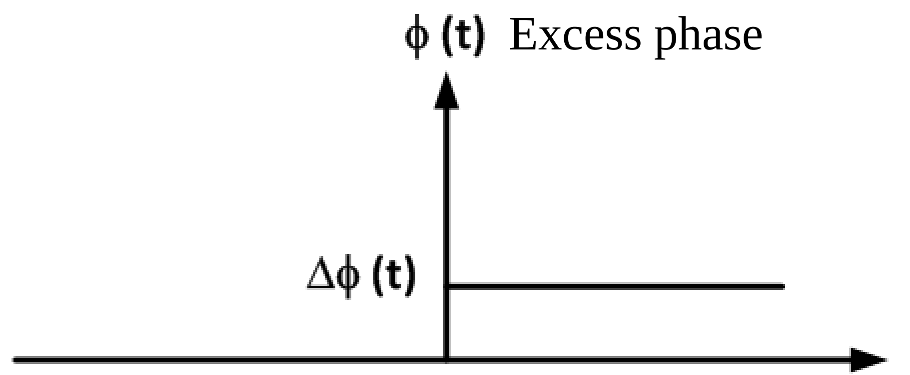
Introduction to Phase Noise

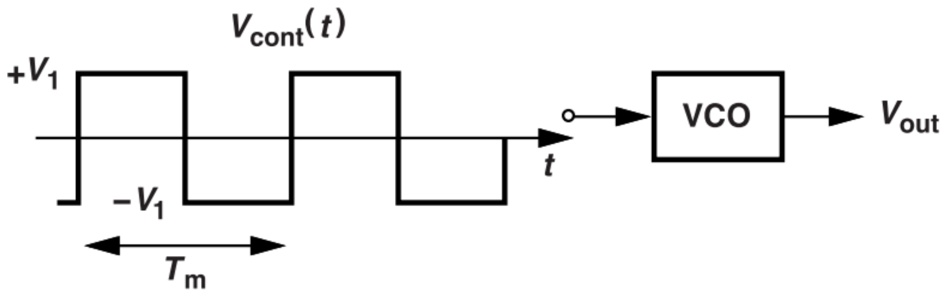
- Phase step
- $v(t) = \sin(\omega t + \Delta\emptyset\, u(t))$

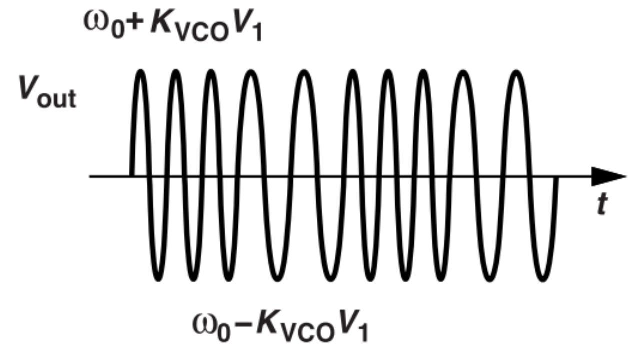


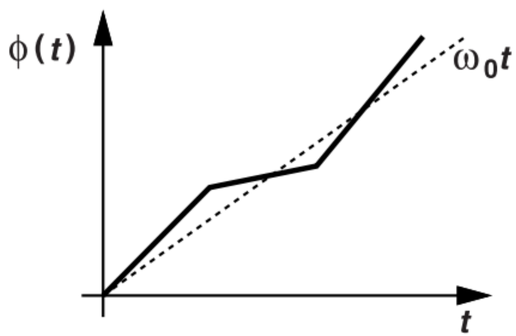


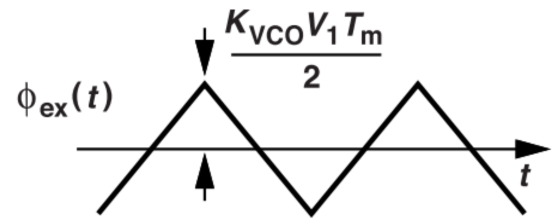


Introduction to Phase Noise

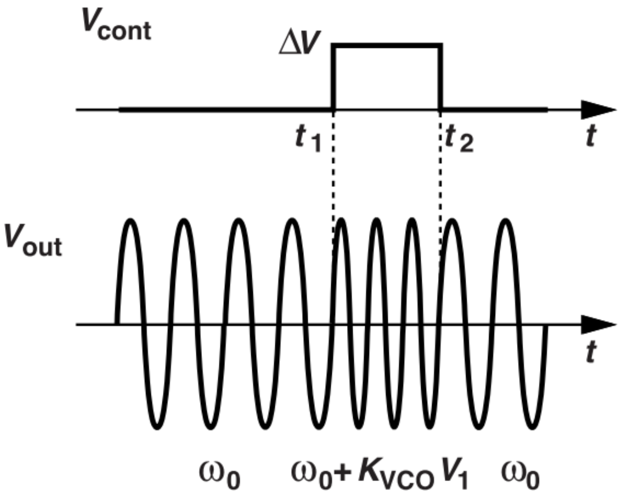


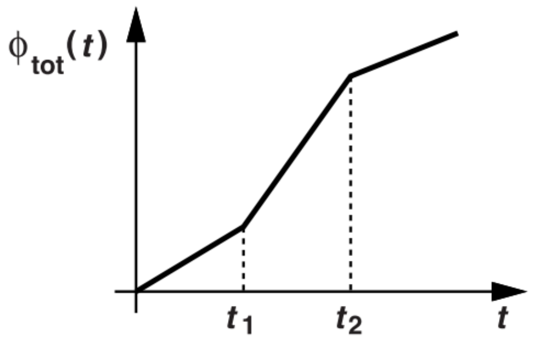


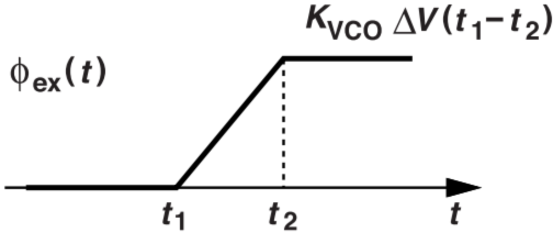




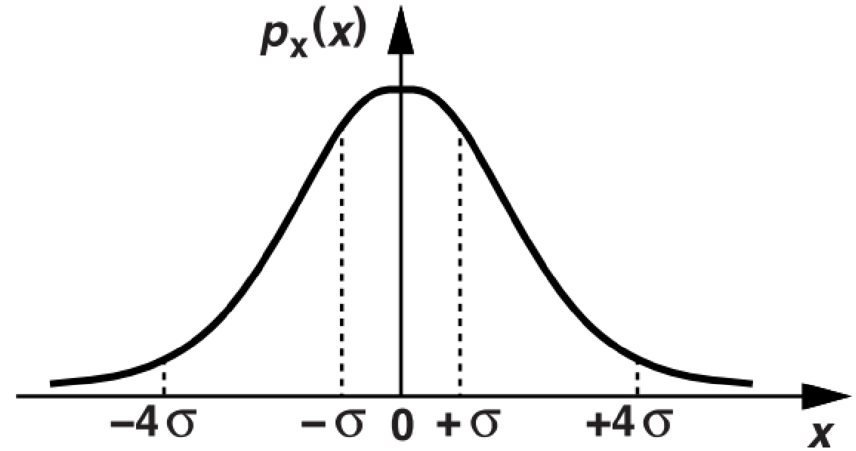
Introduction to Phase Noise







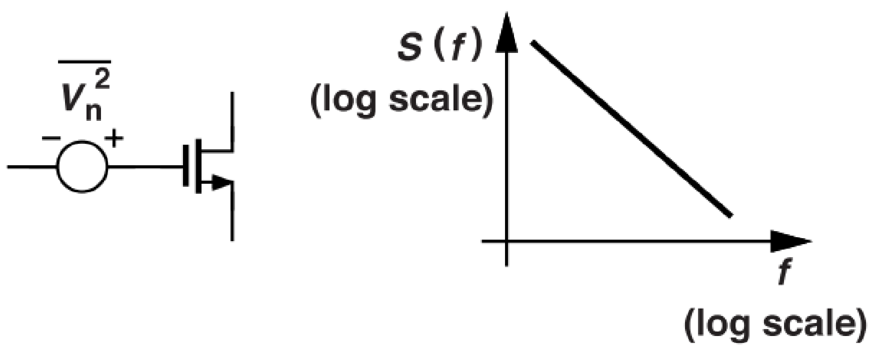
Voltage Noise

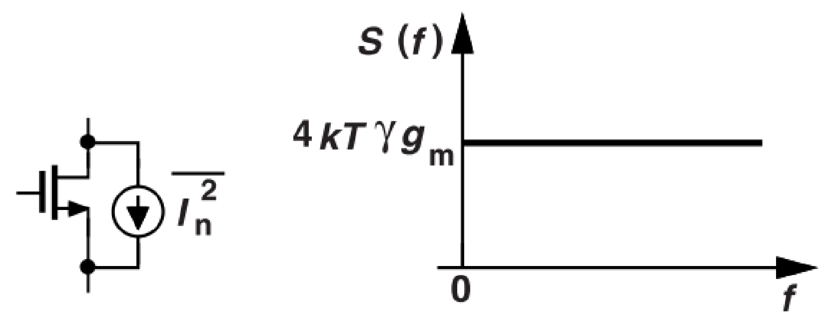


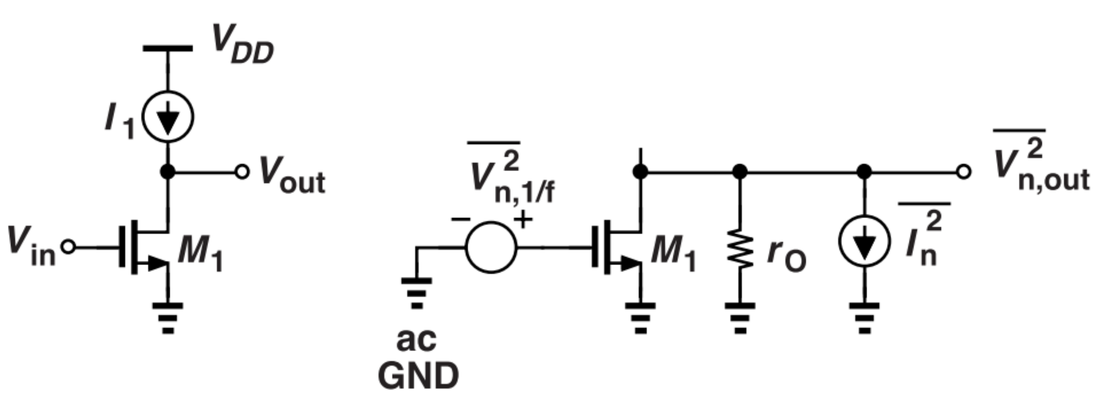
- Noise is a time varying random signal
  - Frequency domain representation of noise is Fourier transform of autocorrelation function of noise
  - Autocorrelation of white noise is delta function
  - What is the definition of SNR

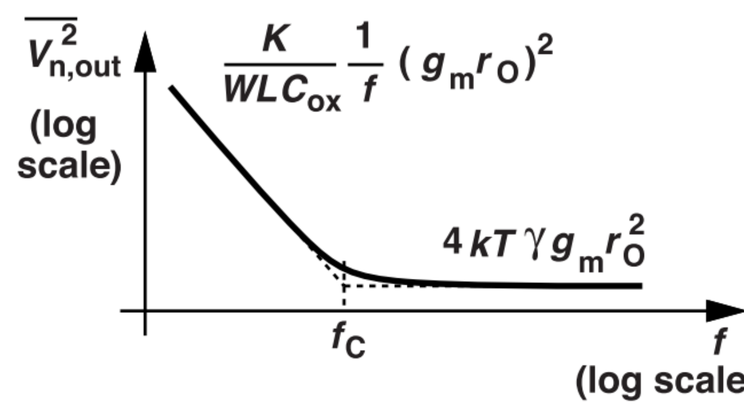
White Noise and Flicker Noise

- Transistor noise consists of two parts
  - White noise modeled as current $\mathrm{i}_n^2 = 4KT\gamma g_m$
  - Flicker noise modeled as voltage at gate $v_n^2 = \frac{K}{WLC_{ox}f}$



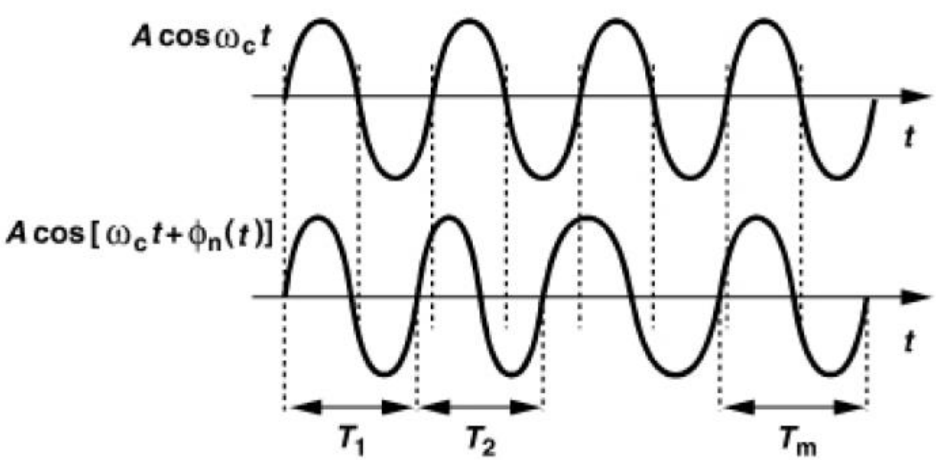


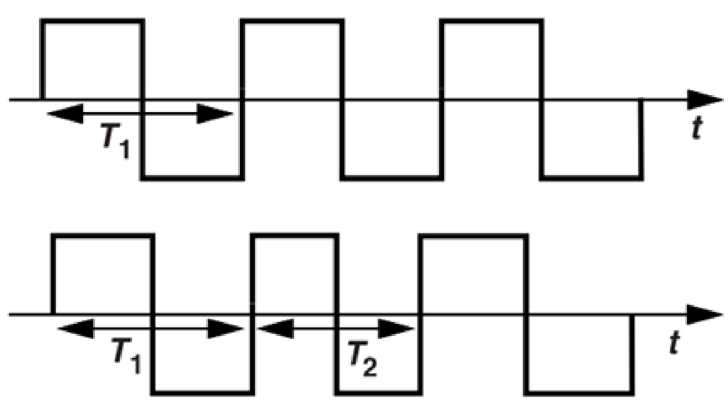




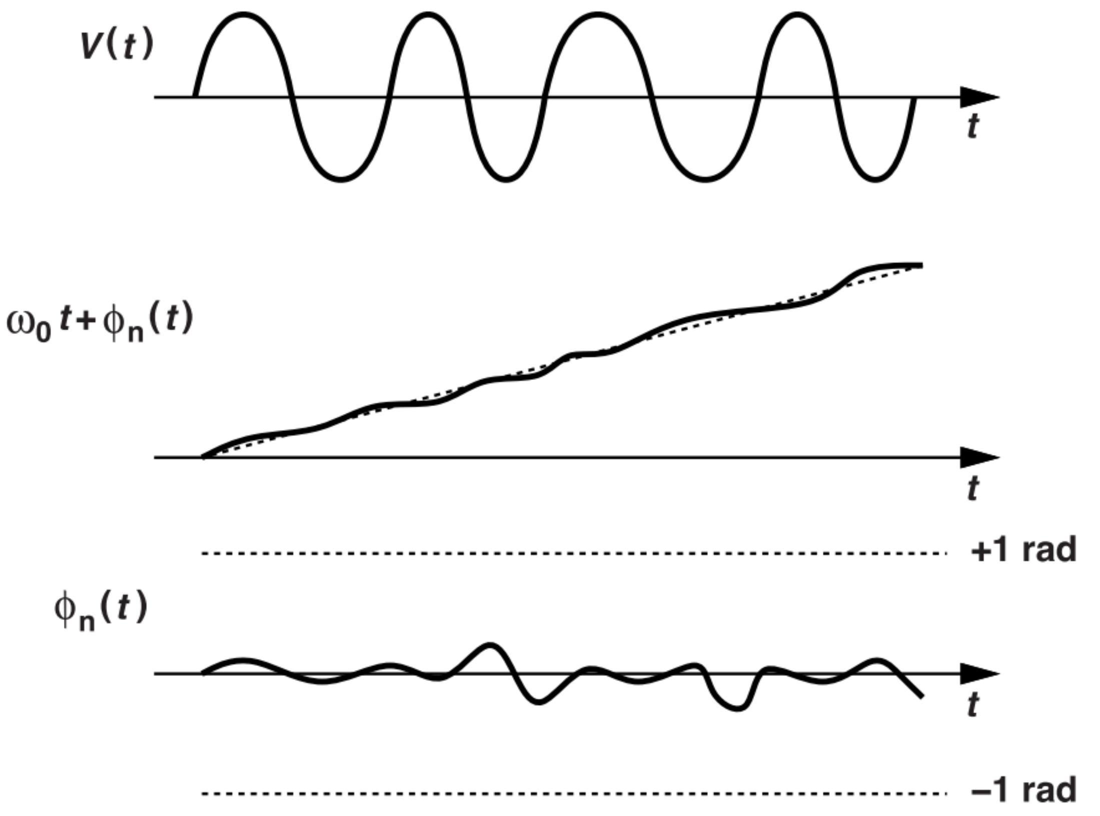
Phase Noise

- Oscillator ideal output signal is given by $V_{out} = ACos(\omega t)$
- Real output signal contains noise and hence zero crossing changes randomly
- $V_{out} = ACos(\omega t + \phi_n)$
  - Frequency of real oscillator is not constant
  - Amplitude noise is not important in oscillator since it is removed when it is converted to digital signal





Phase Noise



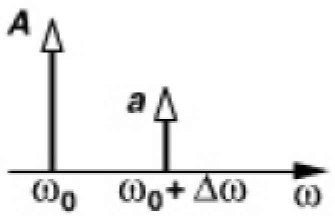
- Phase noise is varying with time
  - Frequency spectrum of phase noise is Fourier transform of phase noise autocorrelation function

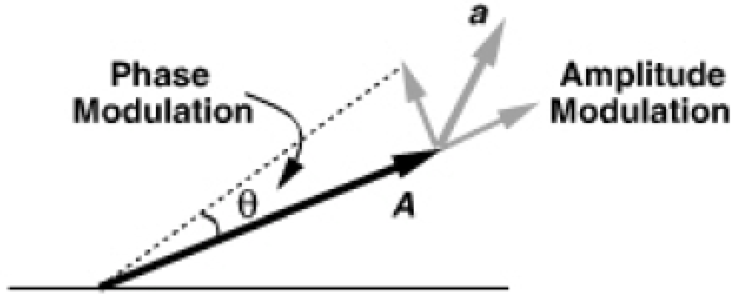
Relationship Between Phase Noise and Jitter

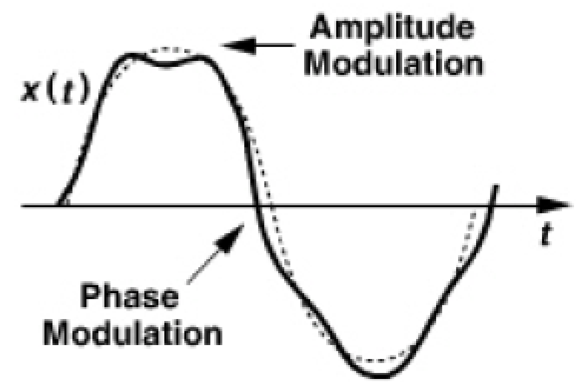
- Jitter is the time domain representation of phase noise
- For a periodic signal, period time T is equivalent to 2π
- A signal with frequency f_0 and phase noise ϕ_n, the jitter is simply given by
  - $\frac{t_n}{T_0} = t_n f_0 = \frac{\phi_n}{2\pi}$
  - Jitter=$t_n = \phi_n / 2\pi f_0$
- Jitter is typically used for square waves
- Integral of jitter is called rms jitter

Phase Noise

- Noise added to sinusoidal signal will cause phase noise



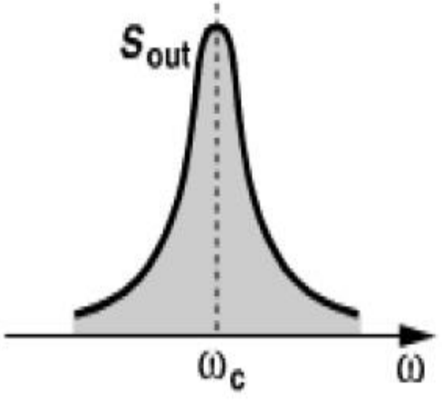




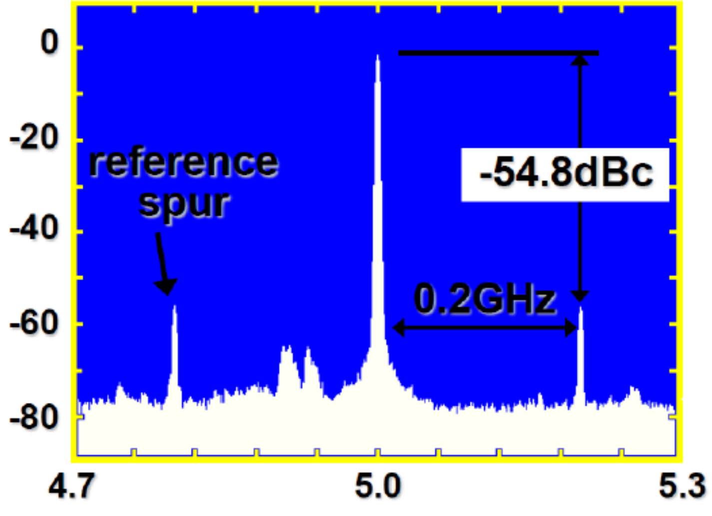
Phase Noise

- Spectrum of real oscillator is broadened
- Note that the spectrum of PLL output will contain spurs in addition to phase noise

VCO Spectrum

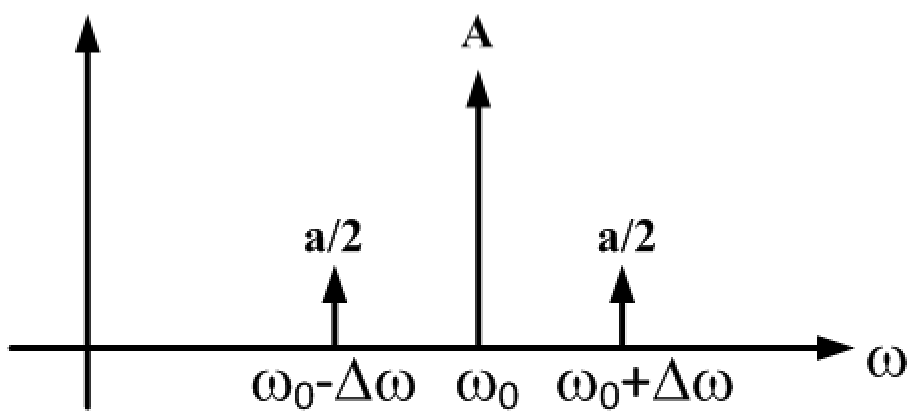


PLL Spectrum



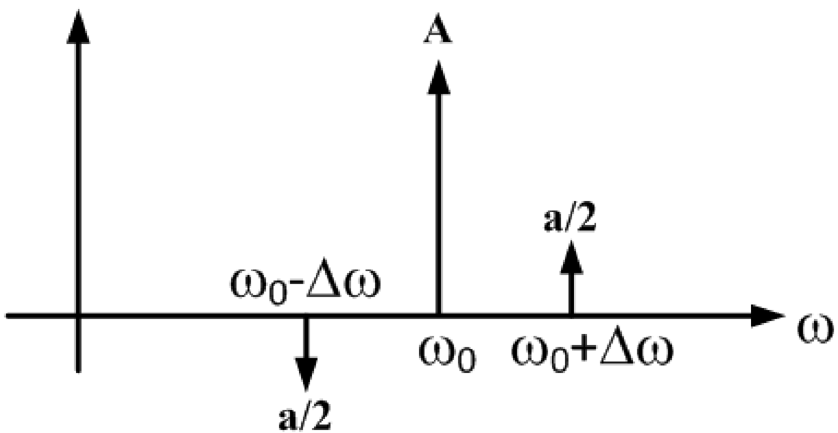
Amplitude and Phase Noise

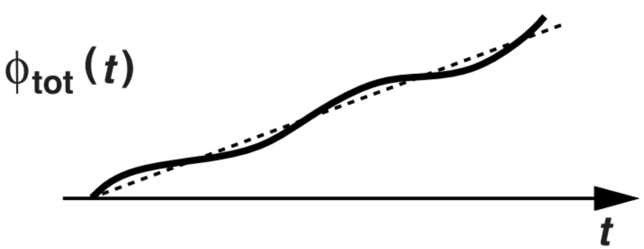
- Amplitude noise is most common form of noise
- $V_{out} = (A + aCos(\Delta\omega t))Cos(\omega t)$
- $V_{out} = ACos(\omega t) + \frac{a}{2}Cos((\omega + \Delta\omega)t) \ + \frac{a}{2}Cos((\omega - \Delta\omega)t)$

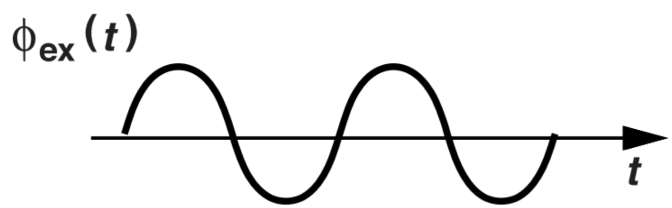


Amplitude and Phase Noise

- $V_{out} = ACos\left(\omega t - \frac{a}{A}Sin(\Delta\omega t)\right)$
- $V_{out} = ACos(\omega t)Cos\left(-\frac{a}{A}Cos(\Delta\omega t)\right) + ASin(\omega t)Sin\left(-\frac{a}{A}Sin(\Delta\omega t)\right)$
- $V_{out} \approx ACos(\omega t) - aSin(\omega t)Sin(\Delta\omega t)$
- $V_{out} = ACos(\omega t) + \frac{a}{2}Cos\big((\omega + \Delta\omega)t\big) - \frac{a}{2}Cos((\omega - \Delta\omega)t)$

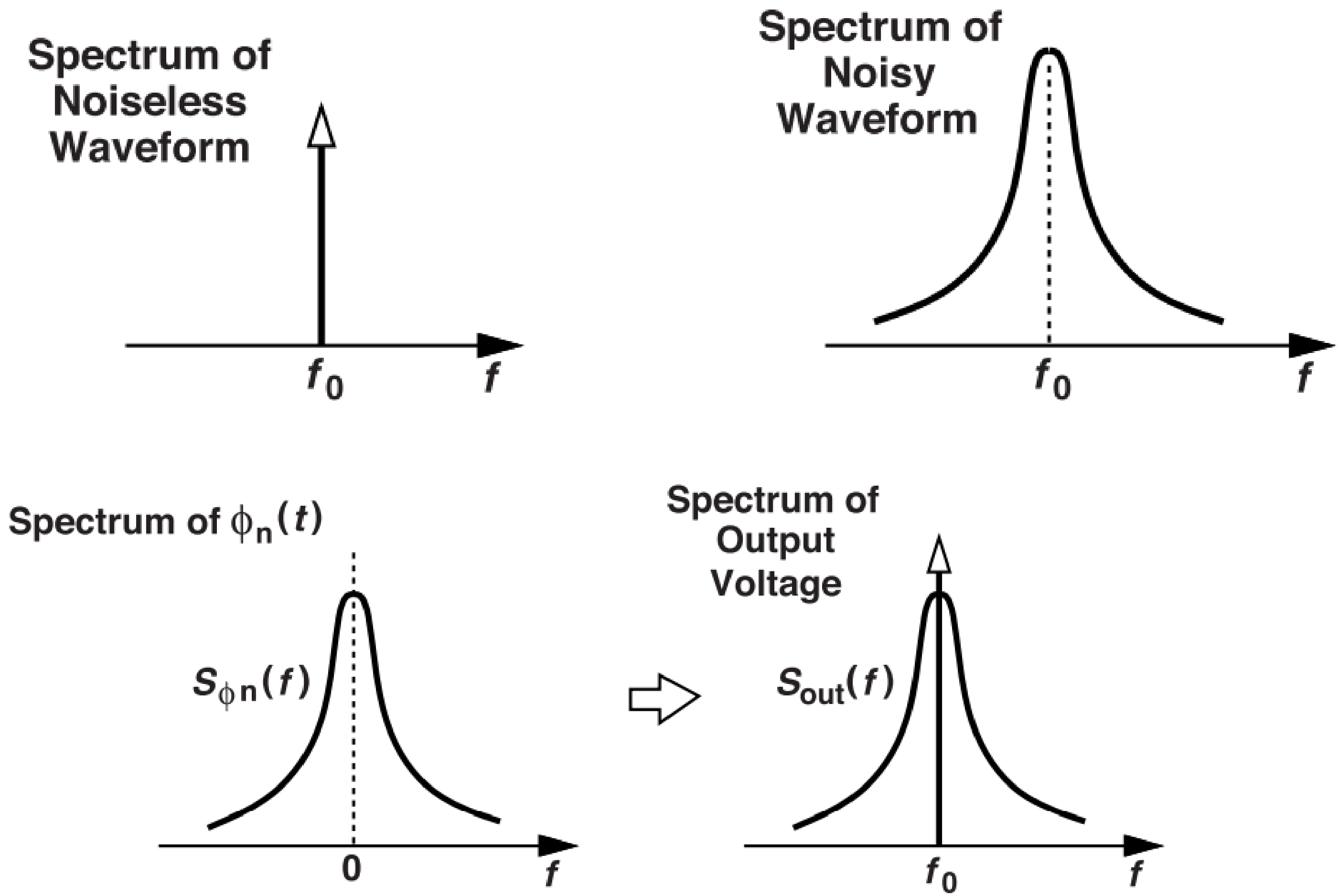






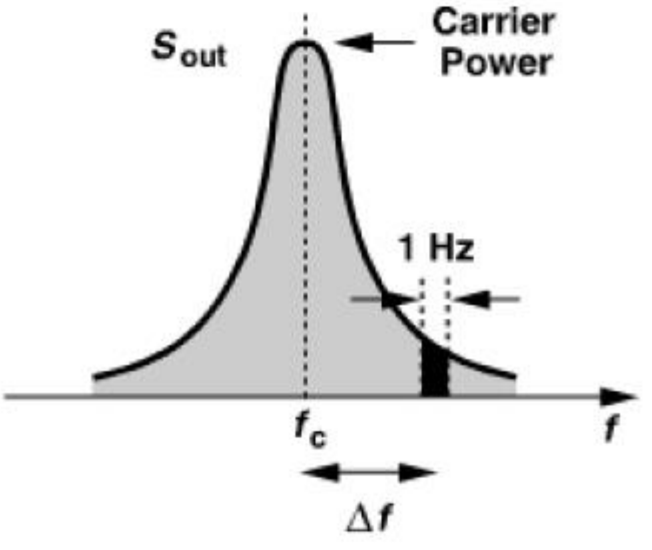
Phase Noise Spectrum

- $V_{out} = V_0 Cos(\omega_0 t + \phi_n(t)) \approx V_0 Cos(\omega_0 t) - V_0 \phi_n(t) Sin(\omega_0 t)$



Phase Noise

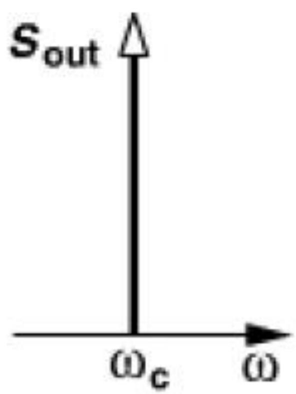
- Phase noise is measured in dBc/Hz
  - ➢Total noise is integrated in 1Hz BW at a certain offset and then divided by the carrier power



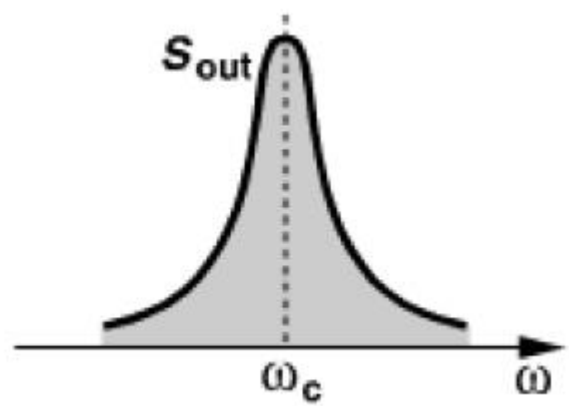
Phase Noise

- At small frequency offset, phase noise is large and previous approximation doesn't hold
- Spectrum of real oscillator is broadened

$$S_{out}(f) = \frac{V_0^2(\eta/4)}{(\omega_0 - \omega)^2 + \eta^2/16}.$$



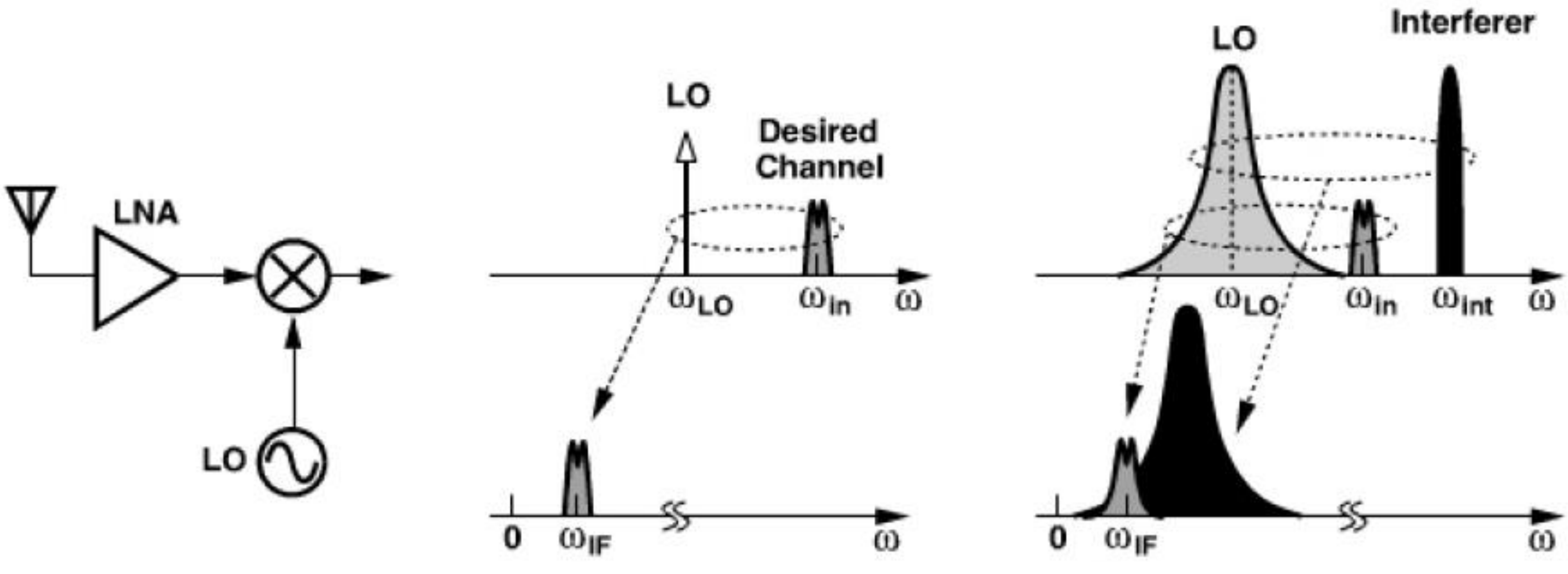
Ideal Oscillator



Real Oscillator

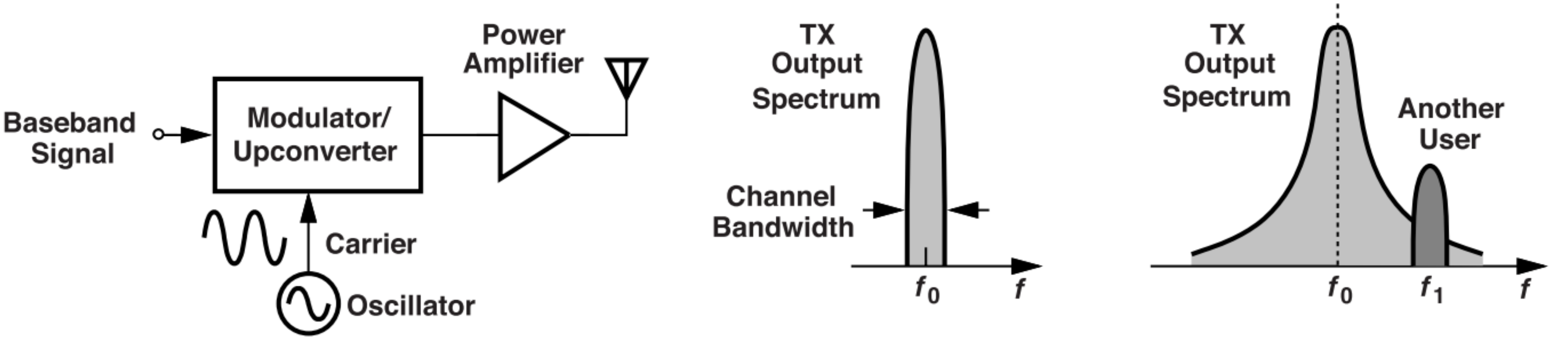
Effect of Phase Noise

- Oscillator phase noise may cause interferer to distort desired channel

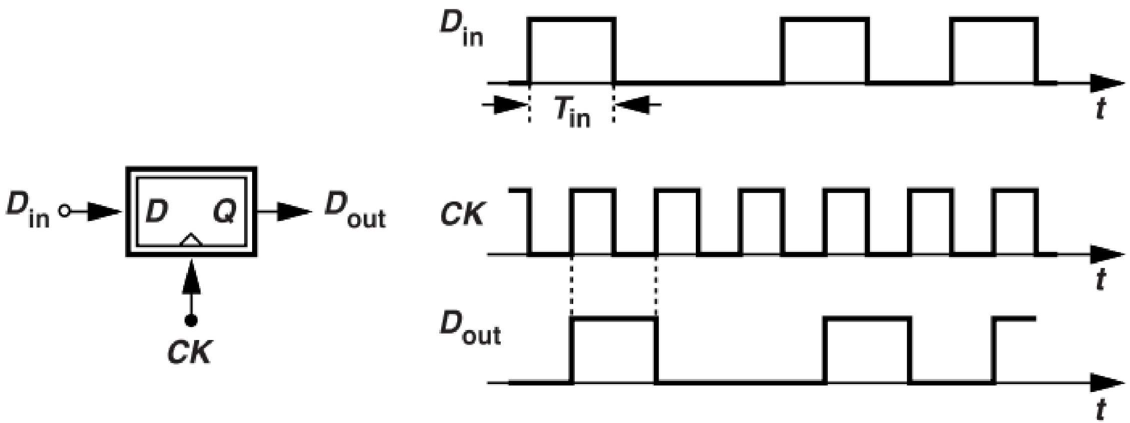


Effect of Phase Noise

- Also transmitting outside the allocated band might distort signals to nearby receivers



Effect of Jitter



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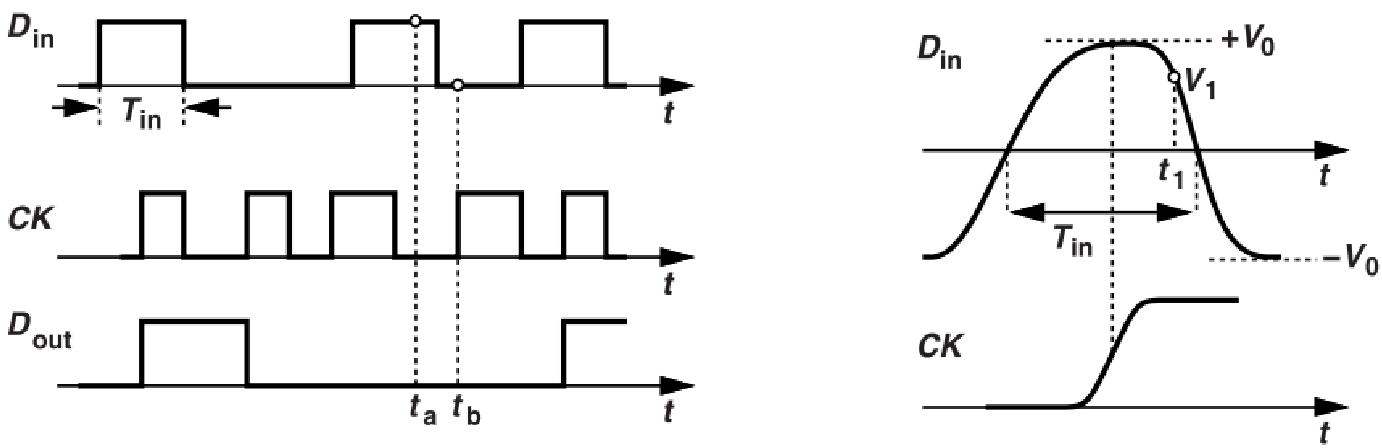


Noise at Control Line

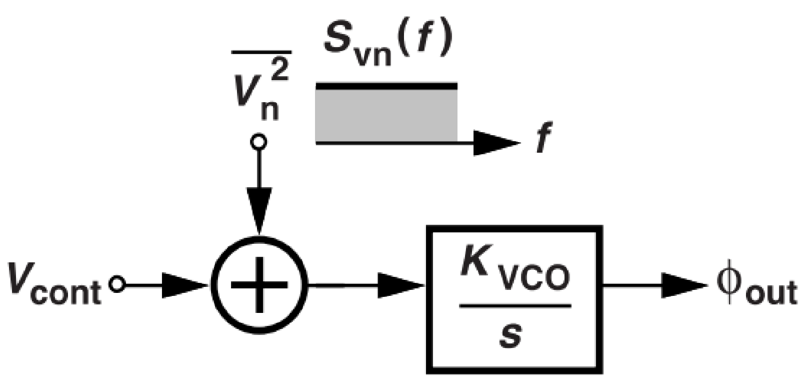
- $\omega_{VCO}=\omega_0+KV_C$
- Any noise at control line affect the frequency and cause phase noise
- $\omega_{VCO}=\omega_0+K(V_C+V_n)$
- Higher VCO gain means higher phase noise
  - ➢VCO gain should be selected to be lowest possible value

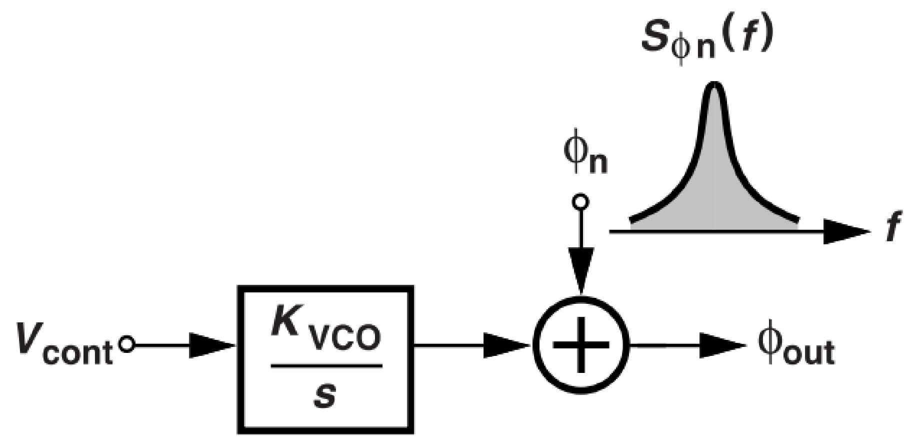
Noise at Control Line

- $\omega_{VCO}=\omega_0+K(V_C+V_n)$
- $V_{out} = ACos\left(\int \omega dt\right) = ACos((\omega_0+KVC)t+\int V_n dt))$
- Assume $V_n = -aCos(\Delta\omega t)$
- $V_{out} = ACos((\omega_0+KV_C)t-\frac{a}{\Delta\omega}Sin(\Delta\omega t)))$
- $V_{out} = ACos(\omega_{vco}t) + \frac{aA}{2\Delta\omega}Cos\left((\omega_{vco} + \Delta\omega)t\right) - \frac{aA}{2\Delta\omega}Cos((\omega_{vco} - \Delta\omega)t)$
- Noise power is inversely proportional to $(1/\Delta\omega)^2$

Effect of VCO Noise

- Noise can be modeled as a separate source added at control line or output of VCO



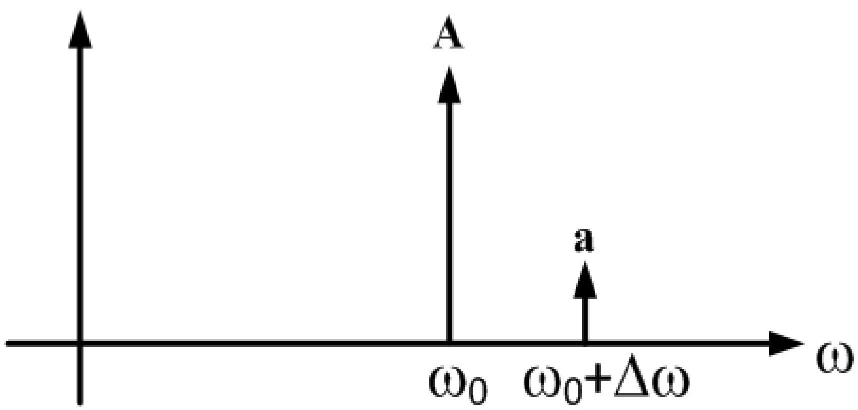


Phase Noise

- How does normal noise convert to phase noise
    - Noise at control line directly affect frequency of oscillator
    - Thermal noise affect both amplitude and phase of oscillator

Phase Noise

- Noise component at $\omega_0+\Delta\omega$ will affect amplitude and phase



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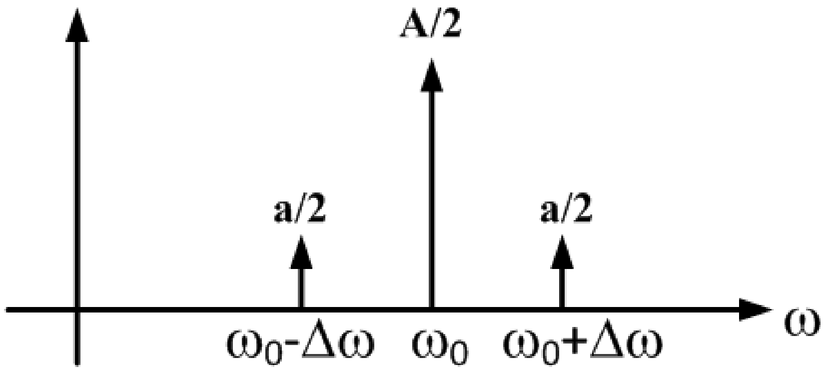

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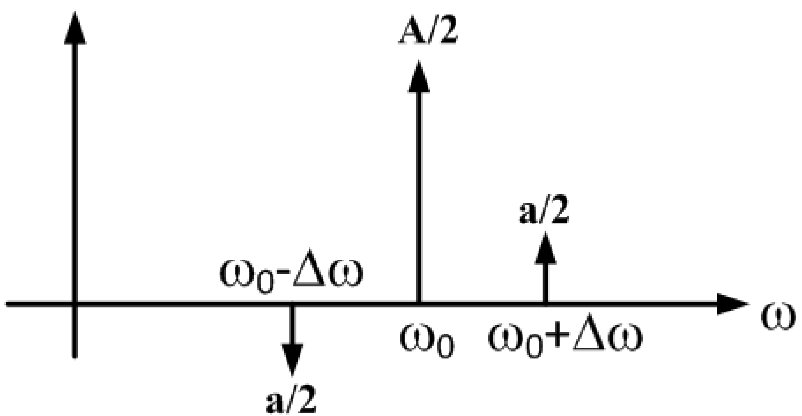
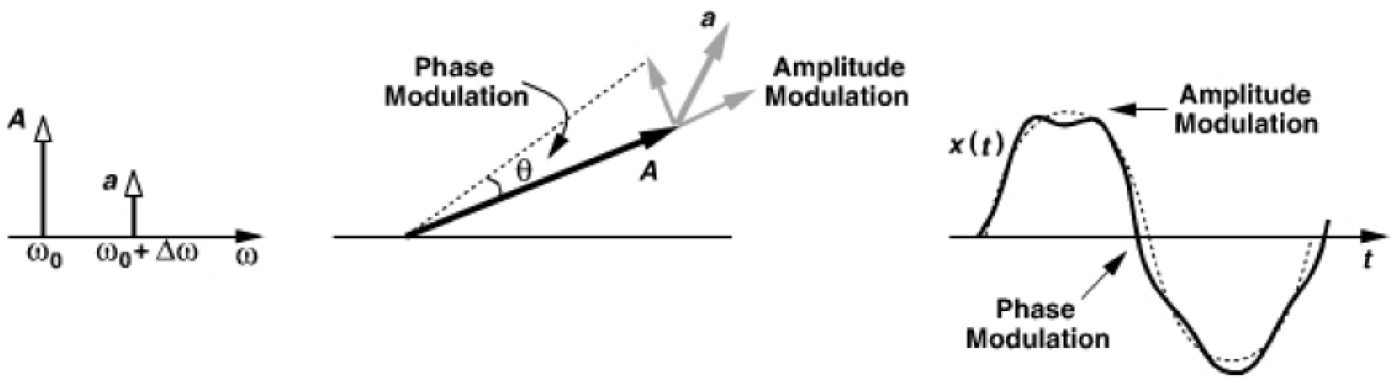


Phase Noise



- $V_{out} = ACos(\omega t) + \phi_n Cos((\omega + \Delta\omega)t)$
- $V_{out} = (A + (\phi_n)Cos(\Delta\omega t))Cos(\omega t) - (\phi_n)Sin(\omega t)Sin(\Delta\omega t)$
- $V_{out} \approx (A + (\phi_n)\ Cos(\Delta\omega t))\mathrm{Cos}(\omega t + (\phi_n/A)Sin(\Delta\omega t))$

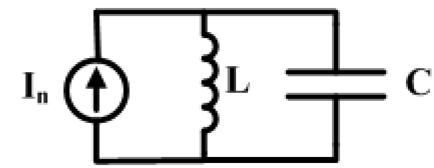
Phase Noise

- Actual noise around ω_0 can be represented by
- $n(t) = n_I \cos(\omega_0 t) - n_Q \sin(\omega_0 t)$
- Half of noise component near ω_0 will be converted to phase noise and other half will be converted to amplitude noise

$$\begin{aligned} V_{out}(t) &= V_0 \cos \omega_0 t + n(t) \\ &= [V_0 + n_I(t)] \cos \omega_0 t - n_Q(t) \sin \omega_0 t \\ &= \sqrt{[V_0 + n_I(t)]^2 + n_Q^2(t)} \cos \left[\omega_0 t + \tan^{-1} \frac{n_Q(t)}{V_0 + n_I(t)} \right] . \end{aligned}$$

Phase Noise in LC VCO

- Any noise current is converted to noise voltage when multiplied by tank Impedance
- ½ of the noise will be phase noise and ½ will be amplitude noise
- $Z(\omega) = \frac{j\omega L}{1-\omega^2 LC}$



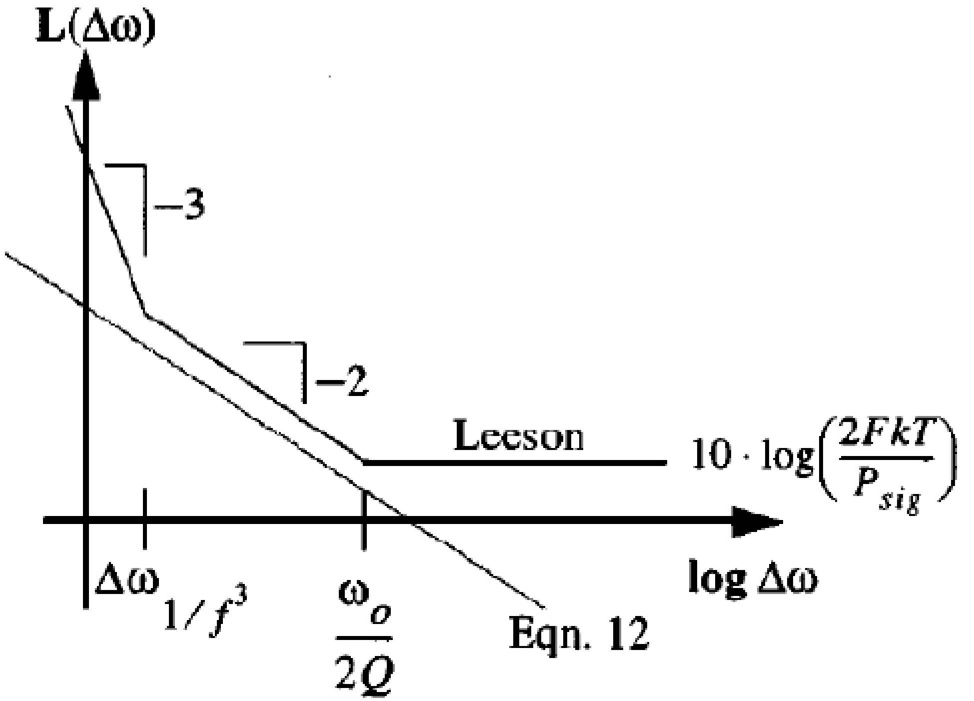
- $Z(\omega_0 + \Delta\omega) = \frac{j(\omega_0+\Delta\omega)L}{1-\omega_0^2 LC-2\omega_0\Delta\omega LC-\Delta\omega^2 LC}$
- $Z(\omega_0 + \Delta\omega) \approx -\frac{j}{2\omega_0 C}\frac{\omega_0}{\Delta\omega} = -\frac{jR}{2Q}\frac{\omega_0}{\Delta\omega}$

Phase Noise in LC VCO

- Resistor noise can be represented by current
- $i_n^2 = 4KT/R$
- $v_n^2 = i_n^2 * |Z_{tank}|^2 = \frac{4KT}{R} * \left|\frac{R}{2Q}\frac{\omega_0}{\Delta\omega}\right|^2$
- half of this noise will be amplitude noise and the other half will be phase noise
- Phase noise in dBc is given by
- $L(\Delta\omega) = \frac{2KTR}{V_{sig}^2} * \left|\frac{\omega_0}{2Q\Delta\omega}\right|^2 = \frac{2KT}{P_{sig}} * \left|\frac{\omega_0}{2Q\Delta\omega}\right|^2$ dBc/Hz

Leeson Model

- Takes into account flicker noise
- $L(\Delta\omega) = \frac{2KTF}{P_{sig}}\left(1+\left(\frac{\omega_0}{2Q\Delta\omega}\right)^2\right)\left(1+\frac{\Delta\omega_{1/f}}{\Delta\omega}\right)$ dBc/Hz
- Where F is an empirical fitting factor and $\Delta\omega_{1/f}$ is the flicker noise corner

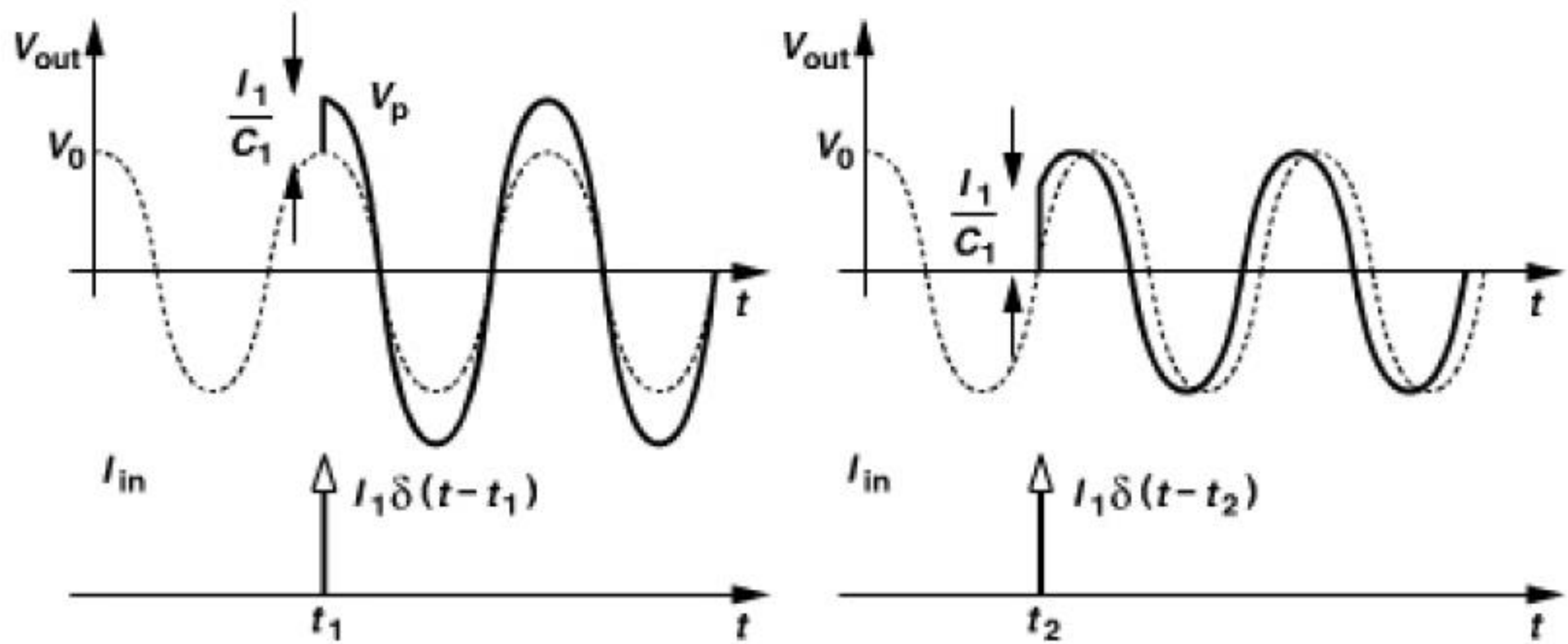


Cyclo-stationary Noise

- Transistor flicker noise and thermal noise are function of current
- Current through VCO transistor are periodic
  - $I = I_0 + I_1 \sin(\omega t)$
  - $g_m = g_{m0} + g_{m1} \sin(\omega t)$
- Hence noise is also periodic, thus noise is up-converted by the periodic nature of current
- $i_n^2 = \frac{8}{3} KT g_m = \frac{8}{3} KT(g_{m0} + g_{m1} \sin(\omega t))$
- $i_n^2 = \frac{8}{3} KT g_m = \frac{8}{3} KT(g_{m0} + g_{m1} \sin(\omega t))$
- $i_f^2 = \frac{K_f I}{f} = \frac{K_f (I_0 + I_1 \sin(\omega t)\ )}{f}$

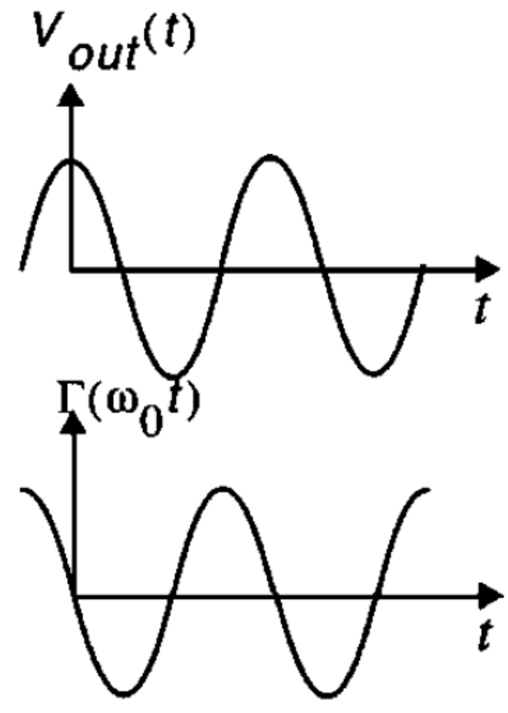
Time Varying Noise Nature

- Noise injected at oscillation peak has effect on amplitude only, while noise injected at zero crossing affect phase of signal



Time Varying Noise Nature

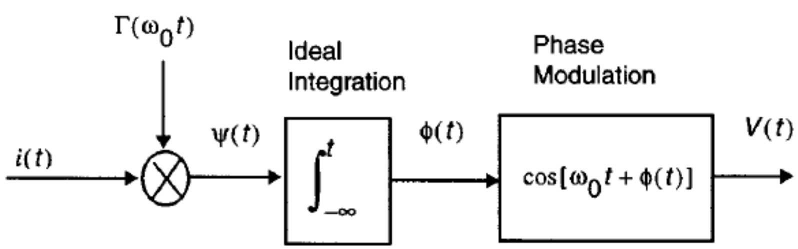
- Convolution still valid for time varying systems
- $\phi(t) = \int h(t,\tau) i(\tau) d\tau$
- $h(t,\tau) = \Gamma(\omega_0 \tau) u(t-\tau)$
- Where Γ is the impulse sensitivity function (ISF)
- $\Gamma(\omega_0 \tau) = C_0 + \sum C_n Cos(n\omega_0 t + \theta_n)$
- If noise is time varying and effectively multiplied by $\alpha(\omega_{0t})$, then $\Gamma_{eff}(\omega_0 t) = \alpha(\omega_0 t) * \Gamma(\omega_0 t)$

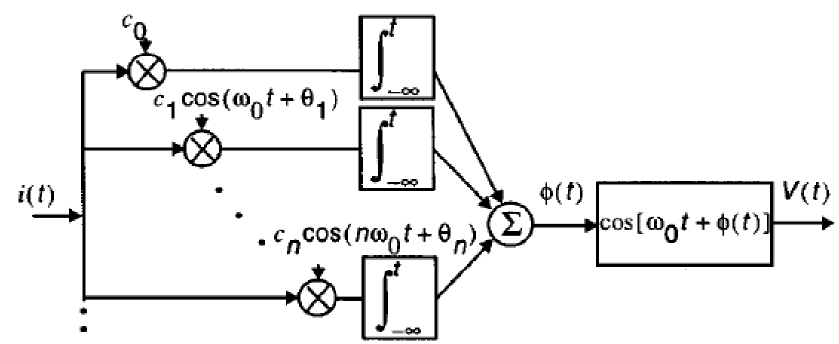


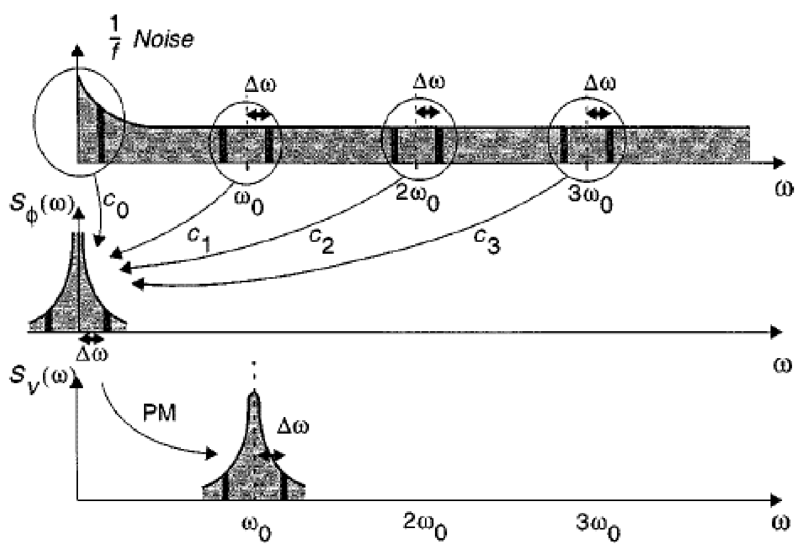
ISF of LC oscillator

Time Varying Noise Nature

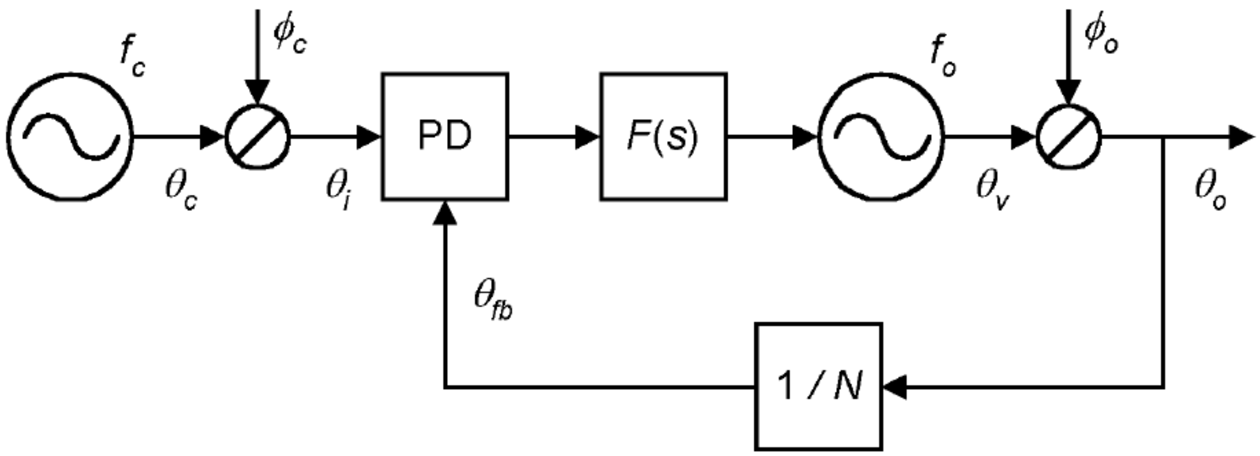
- Noise is multiplied by ISF and then converted to phase noise
- C0 is small for LC oscillator, hence flicker noise is minimized
    - ➢ Improve Symmetry of VCO





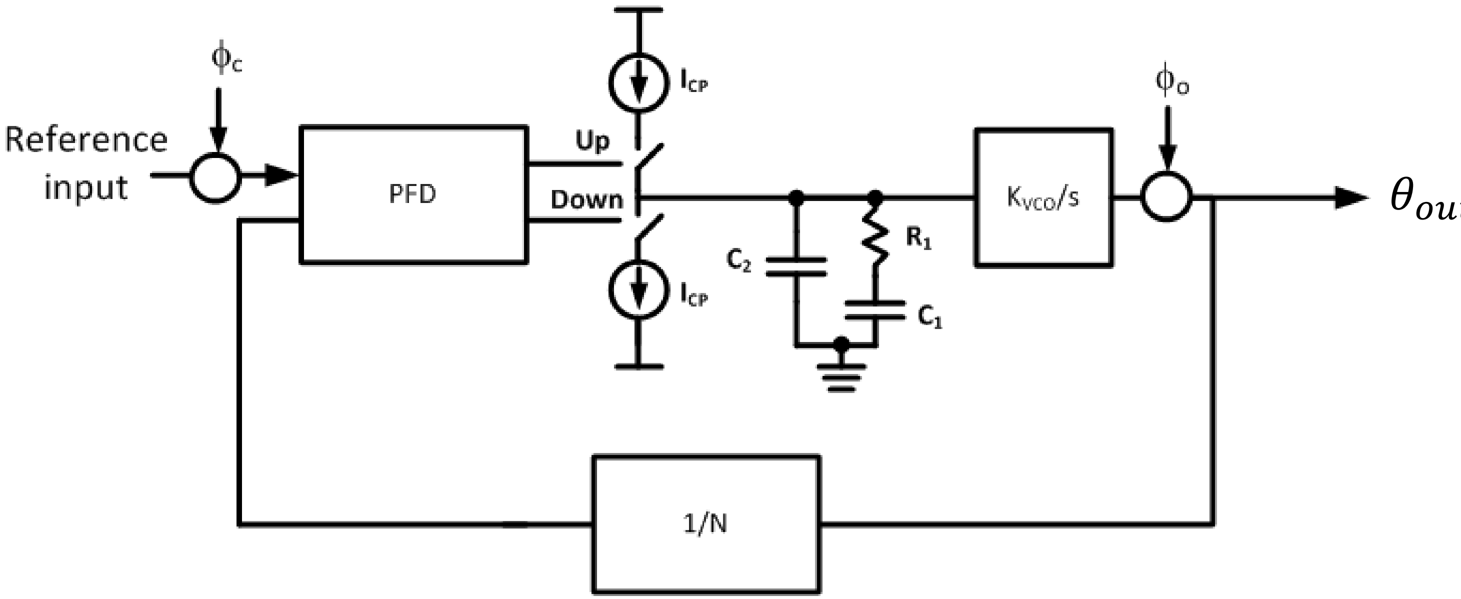


Noise Transfer Function



- $\frac{\theta_{out}}{\phi_o} = \frac{1}{1+K_D K_{VCO} F(s)/s}$
- $\frac{\theta_{out}}{\phi_c} = N \frac{K_D K_{VCO} F(s)/s}{1+K_D K_{VCO} F(s)/s}$

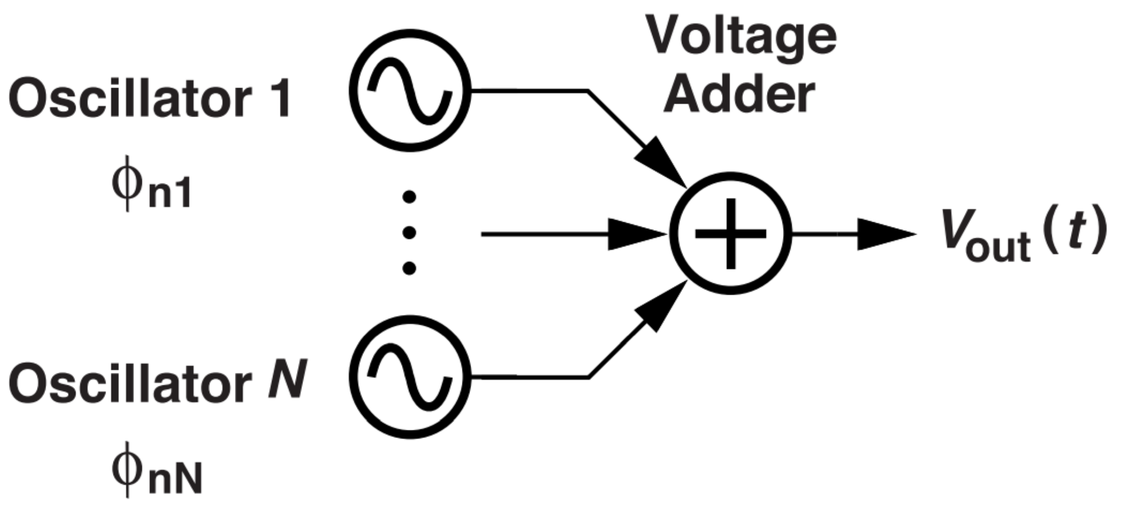
Noise Transfer Function



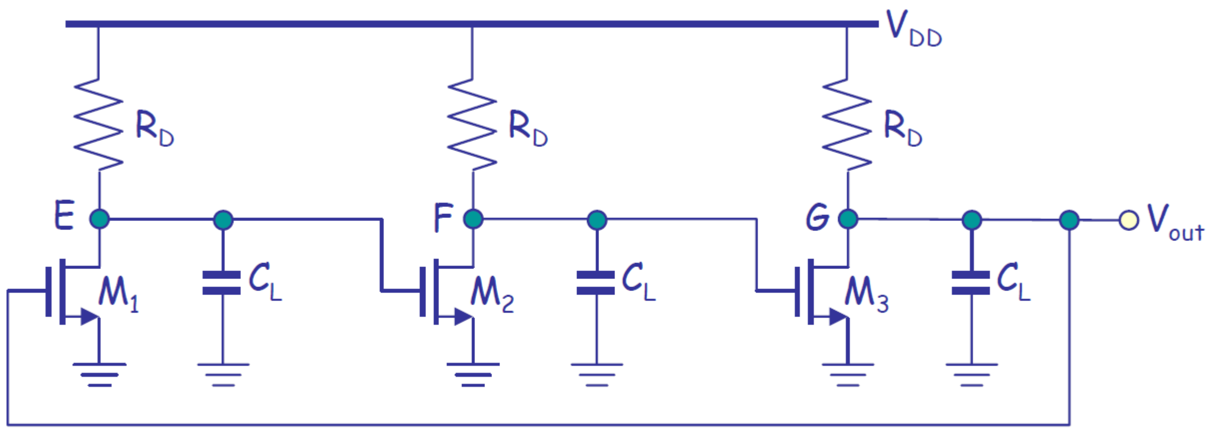
- $K_D = I_{CP}/2\pi N$
- $F(s) = \frac{1+s/\omega_z}{s(1+s/\omega_p)}$
- $\frac{\theta_{out}}{\phi_o} = \frac{s^2}{s^2+sK_DK_{VCO}/\omega_z+K_DK_{VCO}}$
- $\frac{\theta_{out}}{\phi_c} = N\frac{K_DK_{VCO}(1+s/\omega_z)}{s^2+sK_DK_{VCO}/\omega_z+K_DK_{VCO}}$

Tradeoff Between Noise and Power Consumption

- Adding output of 2 oscillators results 6dB higher signal and 3 dB higher noise, hence 3 dB SNR enhancement
  - For N oscillators, signal is improved by 20log(N), while noise is multiplied by 10log(N)



Three stage ring oscillator

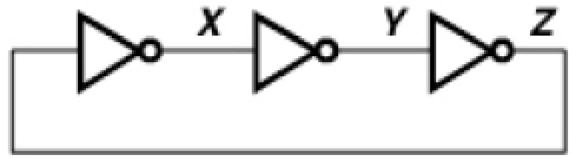


Three-stage ring oscillator

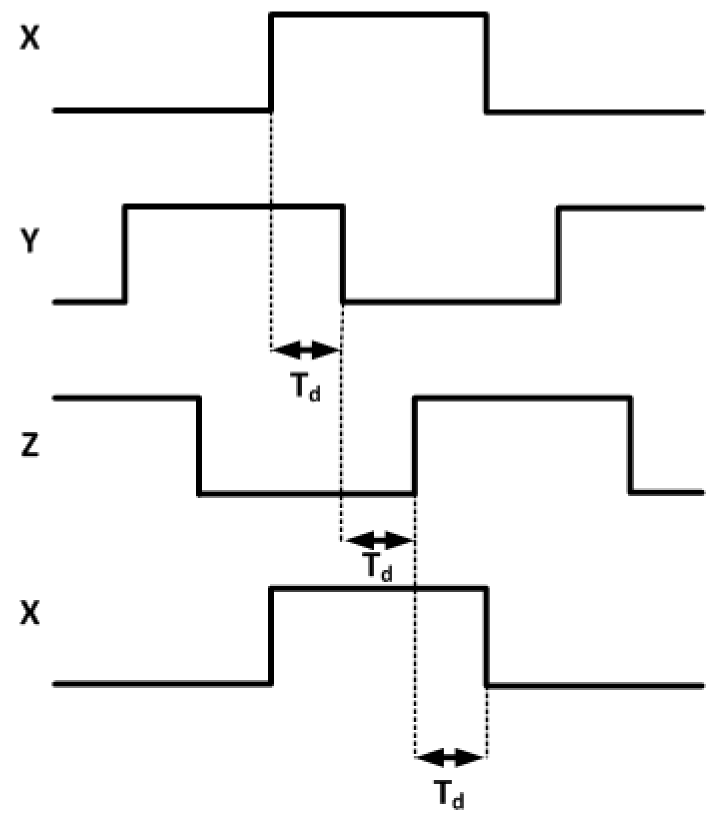
$$H(s) = -\frac{A_0^3}{\left(1+\frac{j\omega}{\omega_0}\right)^3}$$

$$\omega_{osc} = \sqrt{3}\omega_0$$
$$A_0 = 2$$

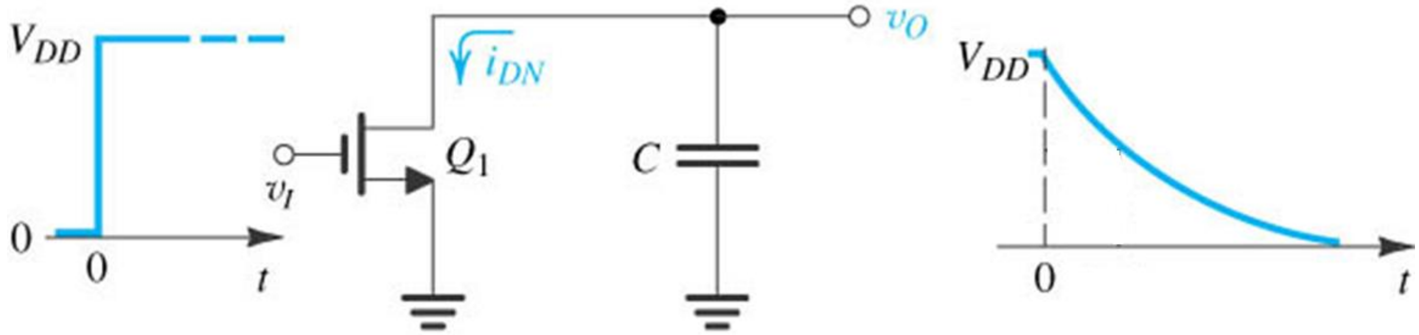
Ring Oscillator



- Ring oscillator consists of odd number of inverters
- Each inverter should provide a phase shift = 180/N (N is the number of inverters)
- $f_{osc}=1/2Nt_d$



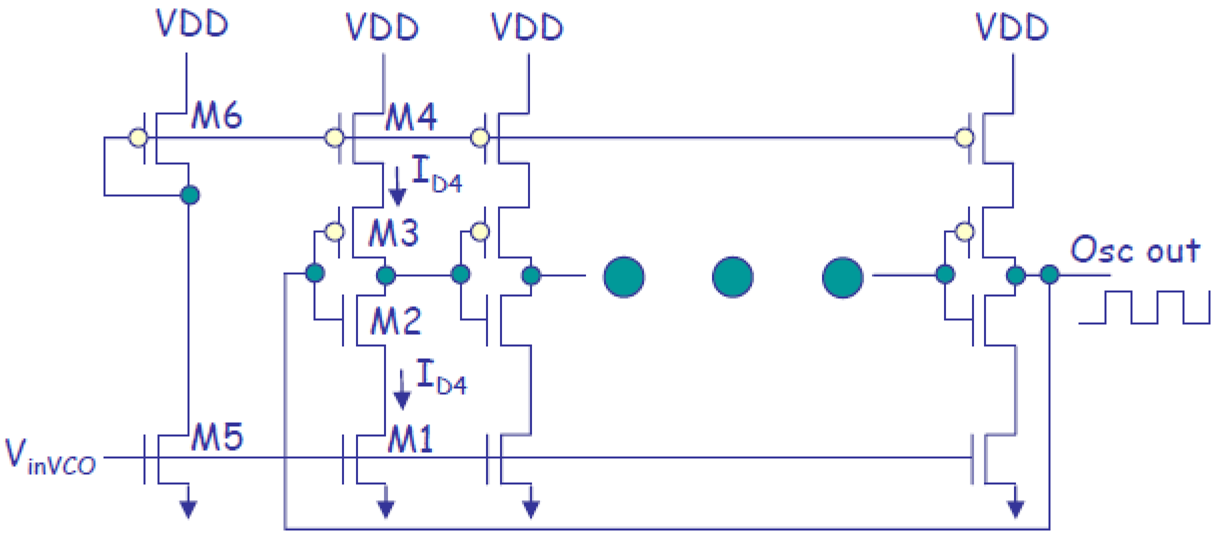
Propagation Delay of Inverter



(a)

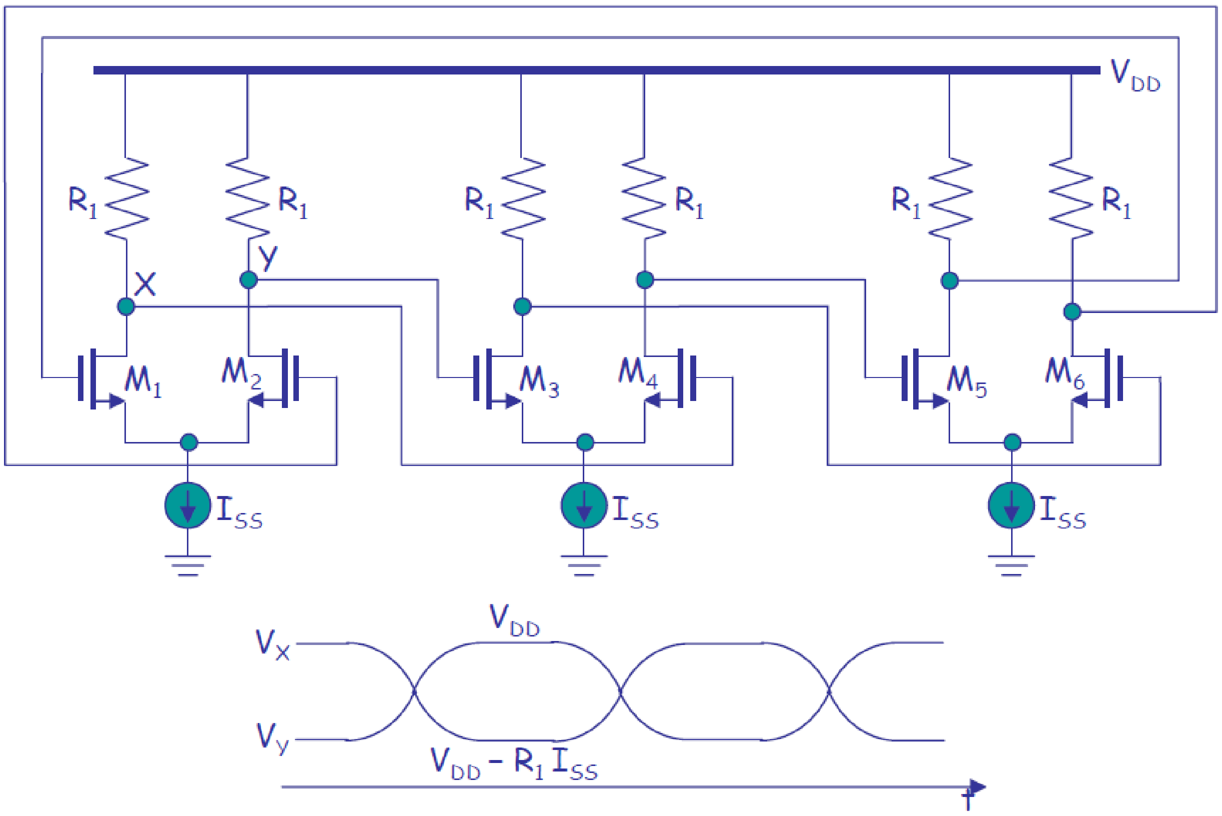
- $i(0) = \frac{1}{2} k_n (V_{DD} - V_t)^2$
- $i(t_{pHL}) = k_n \left((V_{DD} - V_t) V_{DD}/2 - (V_{DD}/2)^2/2 \right)$
- $i_{av} = \left(i(0) + i(t_{pHL}) \right)/2$
- $t_{pHL} = \frac{C\Delta V}{i_{av}} = \frac{CV_{DD}/2}{i_{av}}$
- $t_p = 0.5 \left(t_{pHL} + t_{pLH} \right)$

Current Starved Ring Oscillator



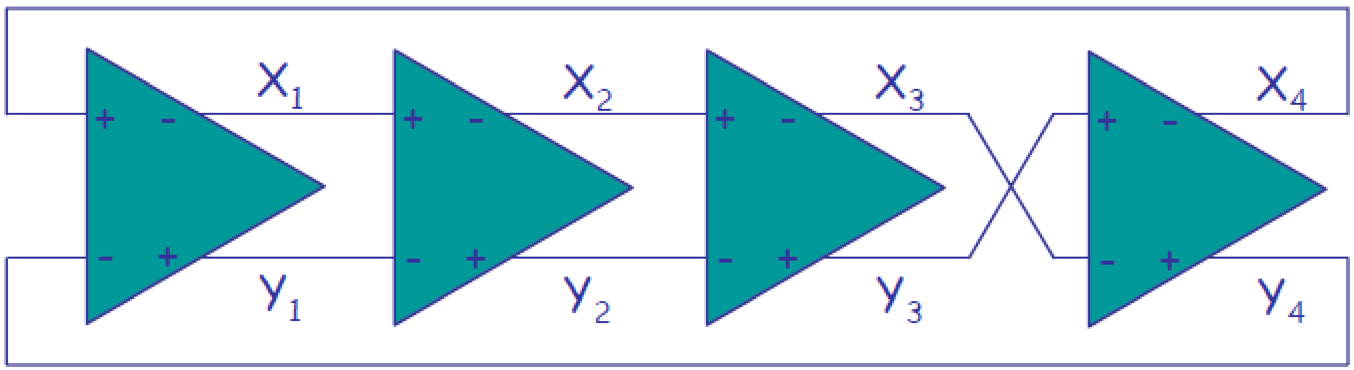
- Current control the delay and hence the frequency
- $t_d \approx CV_{DD}/2I$

Differential Ring Oscillator



- Differential pair can be used as a differential inverter
- Very fast since the voltage variation is $I_{ss}R_1$

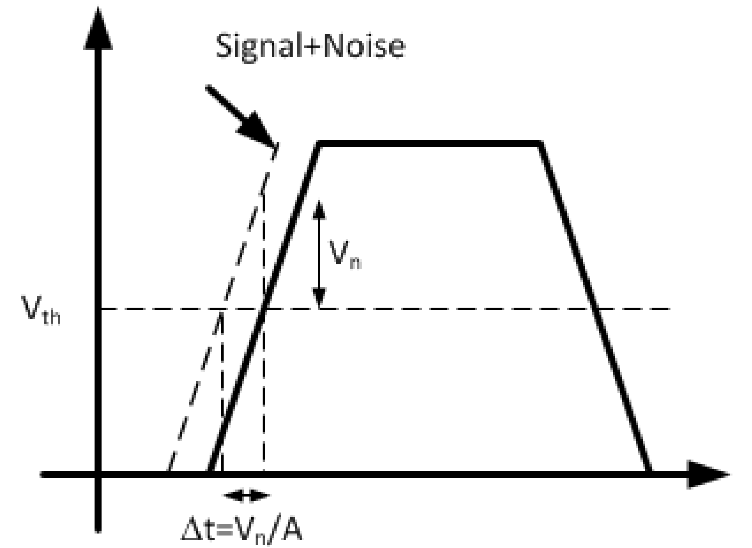
Differential Ring Oscillator



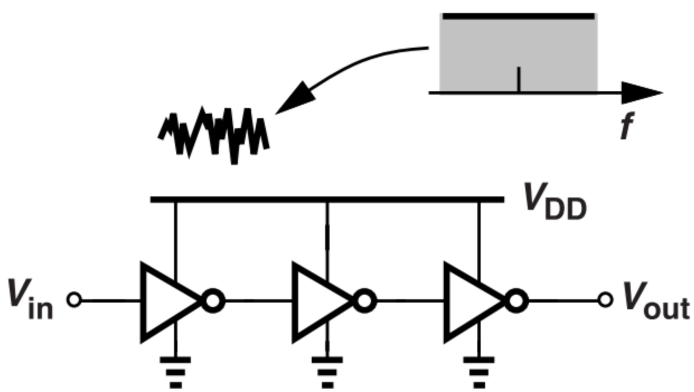
- Even number of inverter stages can be used

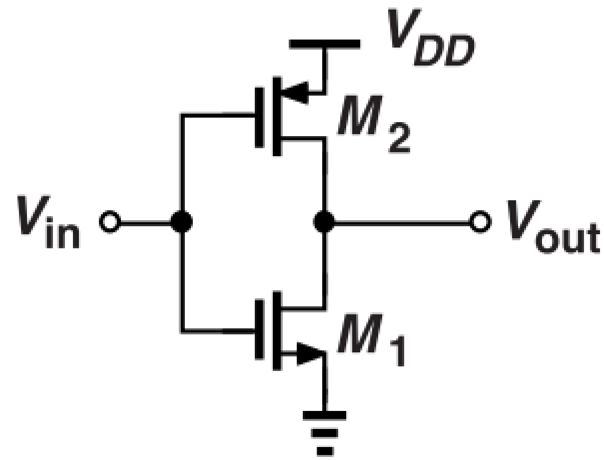
Noise Analysis of Ring Oscillator

- Divider output is a square signal
  - Signal consists of multiple harmonics
- Zero crossing is a function of all signal harmonics
  - Noise at All harmonic matters
- Voltage noise will result in a time shift given by
  - $t_n = v_n / A$, where A is the slope of the voltage with respect to time
  - Equivalent phase noise is $\phi_n = 2\pi f_0 t_n$



Effect of Supply Noise





- For simple inverter, the noise on supply is translated to noise at input as follows
  - $v_{noise\_in} = v_{noise\_sup}/2$ (assuming symmetrical inverter)
  - $t_n = v_{noise\_in}/A$, where A is the slope of the signal