Wireline Transceiver Circuits

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Oscillators

Oscillation: an effect that repeatedly and regularly fluctuates about the mean value

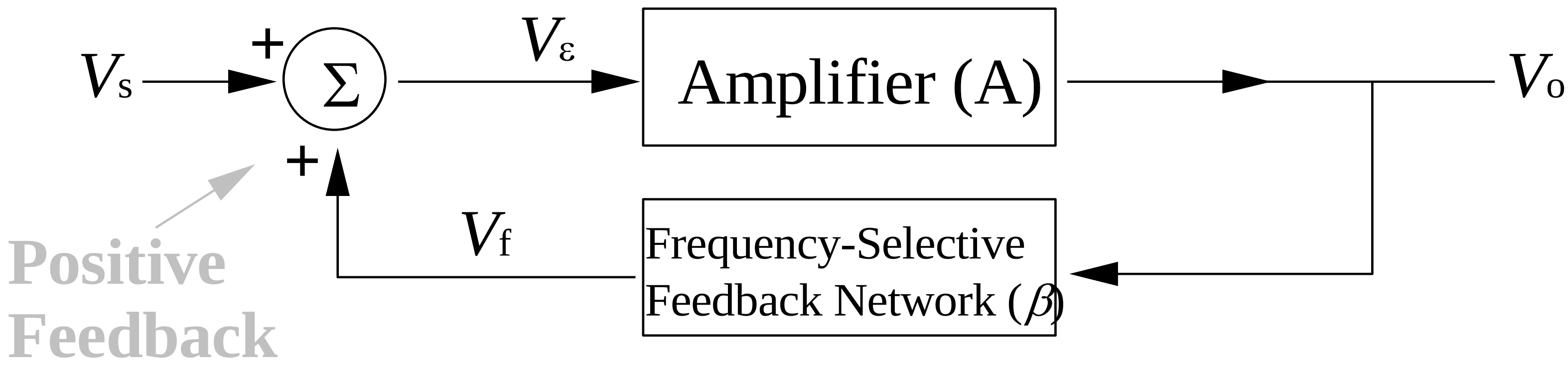
Oscillator: circuit that produces oscillation

Characteristics: wave-shape, frequency, amplitude, distortion, stability

Application of Oscillators

- Oscillator applications:
  - Used to generate clocks in digital systems
  - Used as a local oscillator in receiver and transmitter systems
  - Used in test equipment

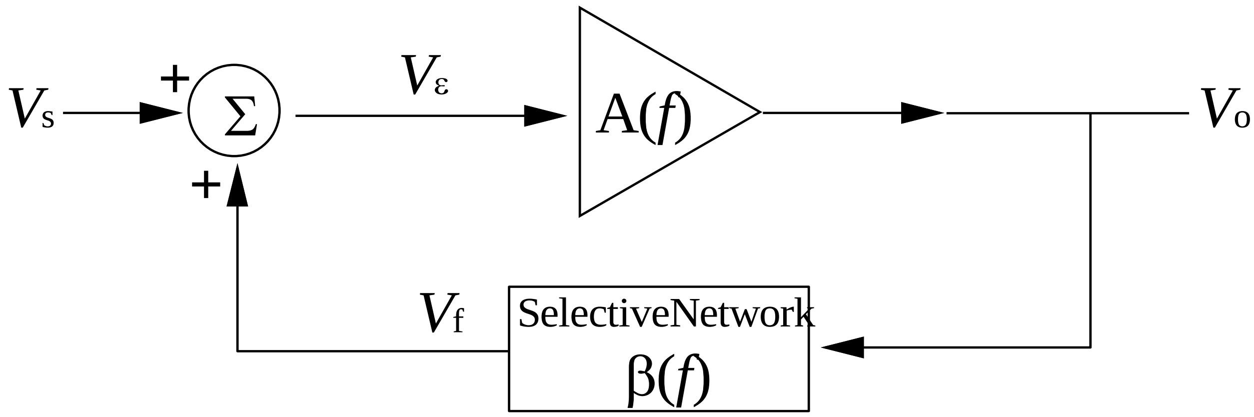
Oscillator feedback loop



<u>A linear oscillator contains:</u>

- a frequency selection feedback network
- an amplifier to maintain the loop gain at **unity**

Basic Linear Oscillator



$V_o = AV_\varepsilon = A(V_s + V_f)$ and $V_f = \beta V_o$

$$\Rightarrow \frac{V_o}{V_s} = \frac{A}{1 - A\beta}$$

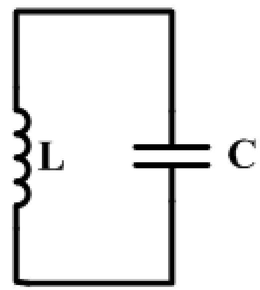
If $V_s = 0$, the only way that V_o can be nonzero is that loop gain $A\beta=1$ which implies that

$$|A\beta| = 1$$

(Barkhausen Criterion)

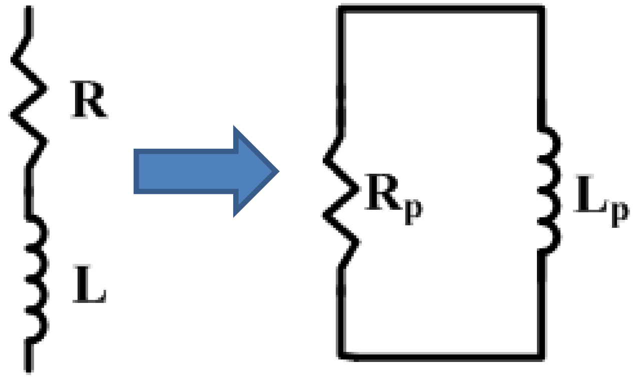
$$\angle A\beta = 0$$

LC Oscillators



- Voltage swing in ideal LC tank is sustained
- $Z = \frac{\mathrm{V}}{\mathrm{I}} = j\omega L - \frac{j}{\omega C}$
- At ω_0 Z=∞
- Output voltage is finite even if the current is zero

LC Oscillators



- Real inductor has loss that can be represented by series resistant

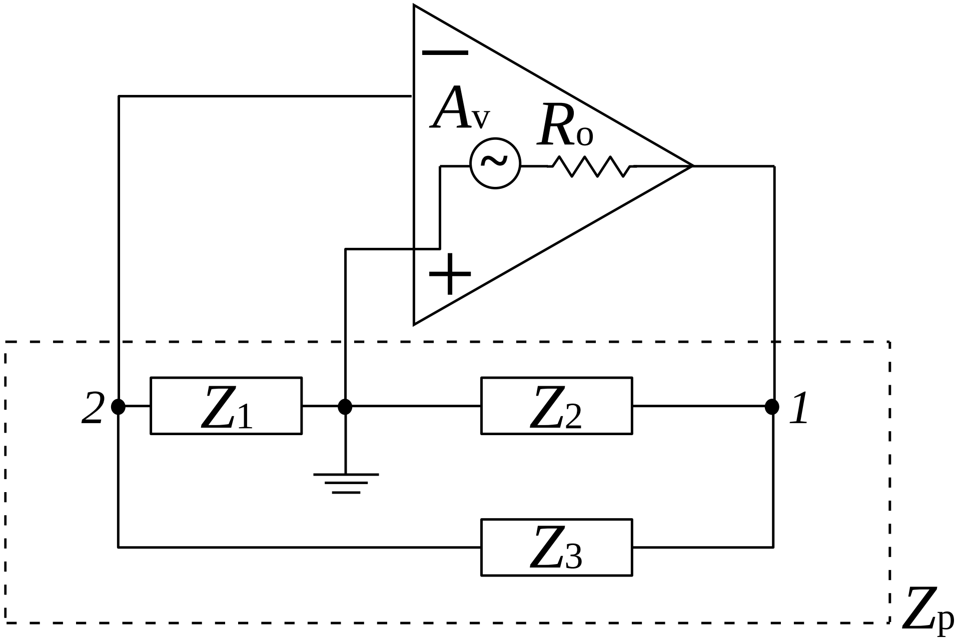
$$R + j\omega L = \frac{1}{1/R_p + 1/j\omega L_p}, \, hence \, \frac{1}{R_p} + \frac{1}{j\omega L_p} = \frac{1}{R + j\omega L} = \frac{R - j\omega L}{R^2 + (\omega L)^2} = \frac{1}{R(1+Q^2)} + \frac{1}{j\omega L(1+1/Q^2)}$$

$$R_p = R(1+Q^2), L_p = L\left(1 + \frac{1}{Q^2}\right), Q = \omega_0 L$$

- IF R = 0, oscillation is sustained

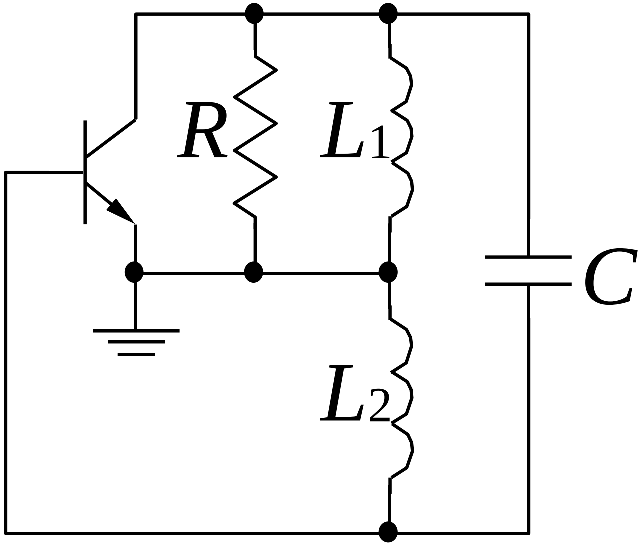
LC Oscillators

- The frequency selection network (Z_1, Z_2 and Z_3) provides a phase shift of 180^o
- The amplifier provides an addition shift of 180^o



Two well-known Oscillators:
Colpitts Oscillator
Hartley Oscillator

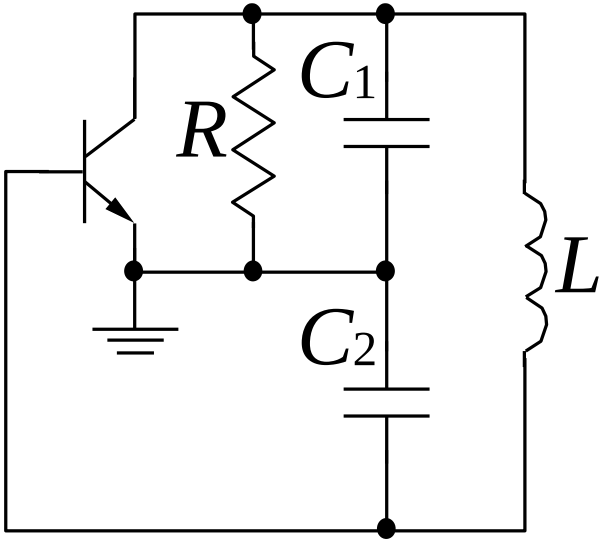
Hartley Oscillator



$$\omega_o = \frac{1}{\sqrt{(L_1 + L_2)C}}$$

$$g_m = \frac{L_1}{RL_2}$$

Colpitts Oscillator

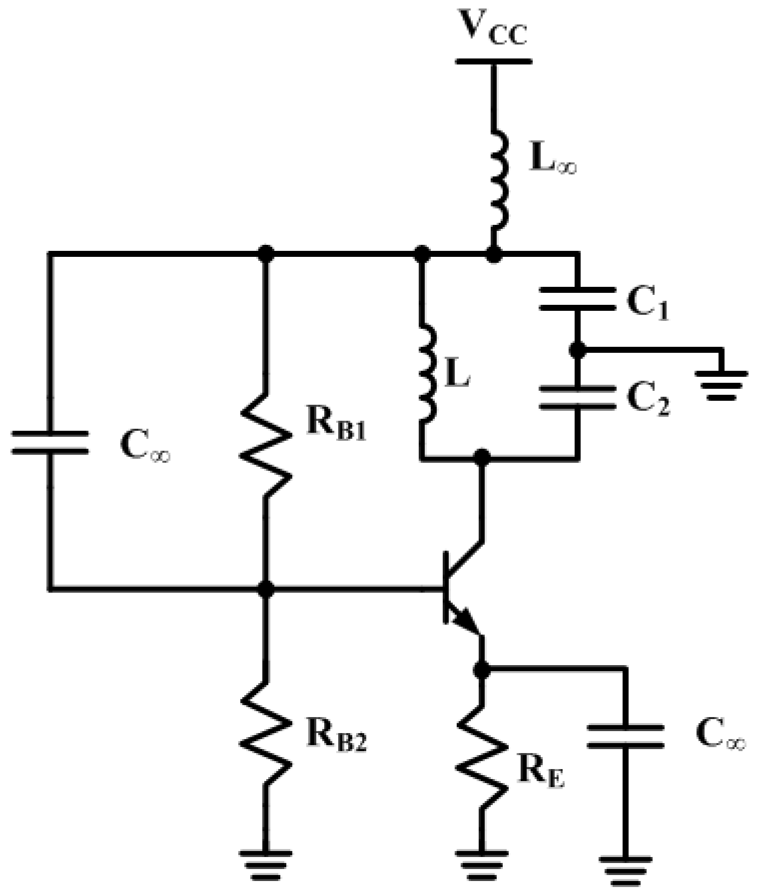


$$\omega_o = \frac{1}{\sqrt{LC_T}} \qquad C_T = \frac{C_1 C_2}{C_1 + C_2}$$

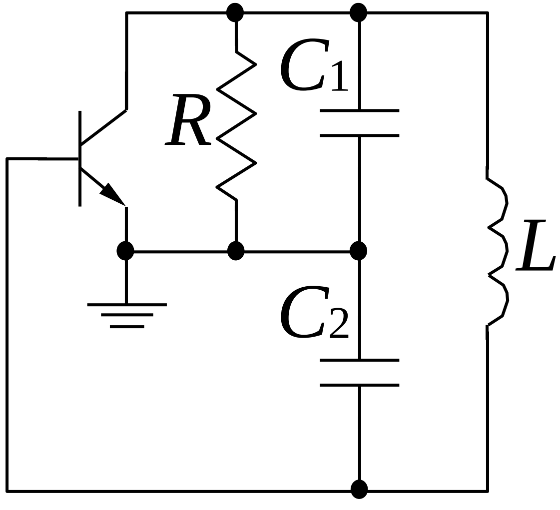
$$g_m = \frac{C_2}{RC_1}$$

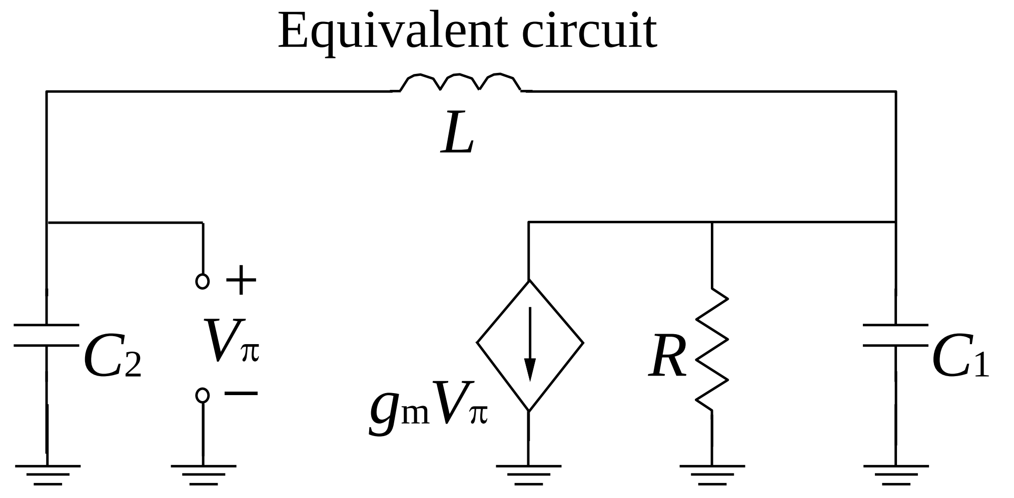
Colpitts oscillator circuit

- L_∞ and C_∞ are used for biasing



Colpitts Oscillator





In the equivalent circuit, it is assumed that:

- Linear small signal model of transistor is used
- The transistor capacitances are neglected
- Input resistance of the transistor is large enough

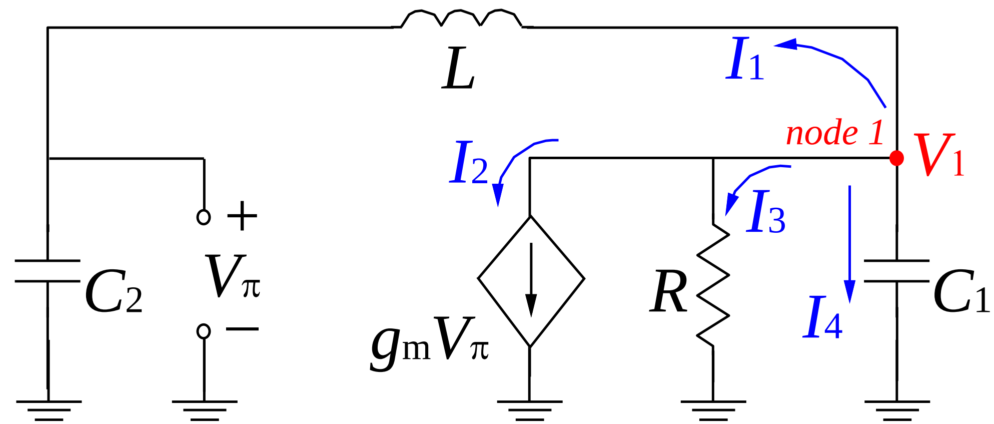
At node 1,

$$V_1 = V_\pi + i_1 (j\omega L)$$

where,

$$i_1 = j\omega C_2 V_\pi$$

$$\Rightarrow \quad V_1 = V_\pi (1 - \omega^2 L C_2)$$



Apply KCL at node 1, we have

$$j\omega C_2 V_\pi + g_m V_\pi + \frac{V_1}{R} + j\omega C_1 V_1 = 0$$

$$j\omega C_2 V_\pi + g_m V_\pi + V_\pi (1 - \omega^2 L C_2)\left(\frac{1}{R} + j\omega C_1\right) = 0$$

For Oscillator V_π must not be zero, therefore it enforces,

$$\left(g_m + \frac{1}{R} - \frac{\omega^2 L C_2}{R}\right) + j\left[\omega(C_1 + C_2) - \omega^3 L C_1 C_2\right] = 0$$

$$\left(g_m + \frac{1}{R} - \frac{\omega^2 LC_2}{R}\right) + j\left[\omega(C_1 + C_2) - \omega^3 LC_1C_2\right] = 0$$

Imaginary part = 0, we have

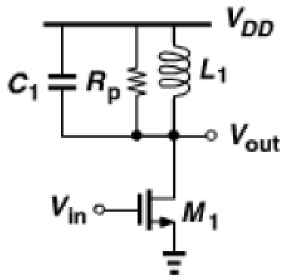
$$\omega_o = \frac{1}{\sqrt{LC_T}} \qquad C_T = \frac{C_1C_2}{C_1 + C_2}$$

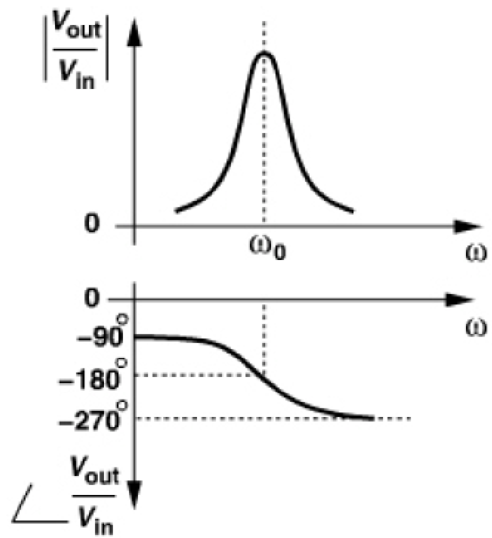
Real part = 0, yields

$$g_m = \frac{C_2}{RC_1}$$

Frequency can be tuned by changing capacitor value (use of varactor)

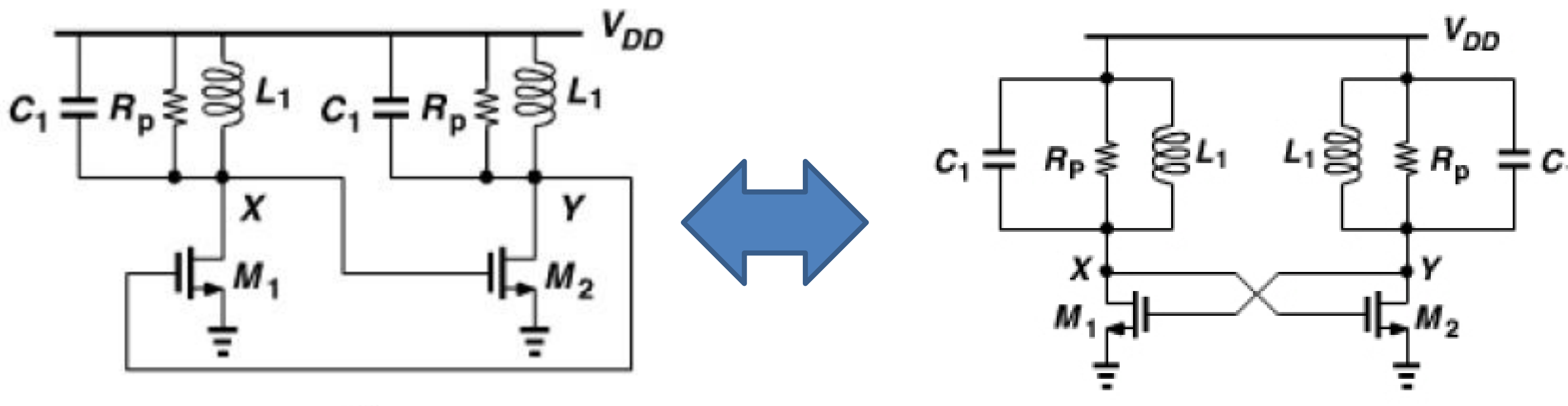
Cross Coupled Oscillator





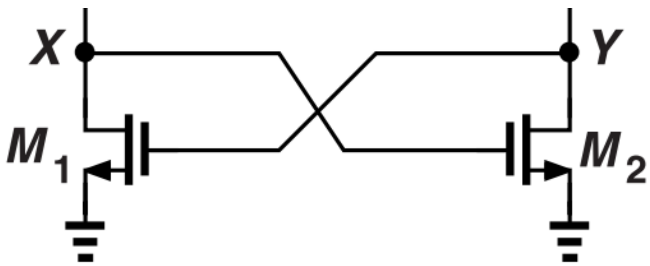
- $V_{out}=-g_m Z_L V_{in}$
- Using single stage oscillator phase shift cannot reach 360^o
- Use of multiple stages is required to achieve the oscillation

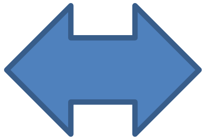
Cross Coupled Oscillator

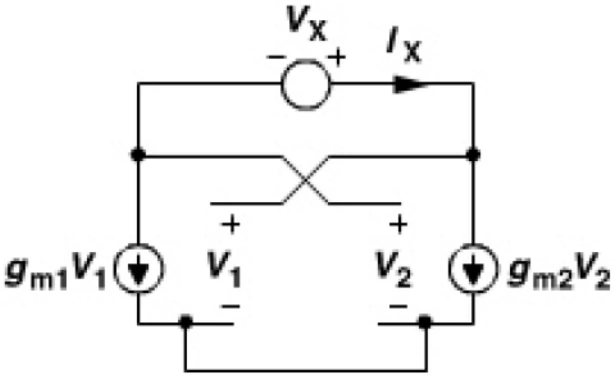


- Loop Gain=$(g_m Z_L)^2$
- Loop Gain =1, imaginary part of Z_L=0, real part = R_p
- $g_m R_p$>1 for oscillation to start

Cross Coupled Oscillator

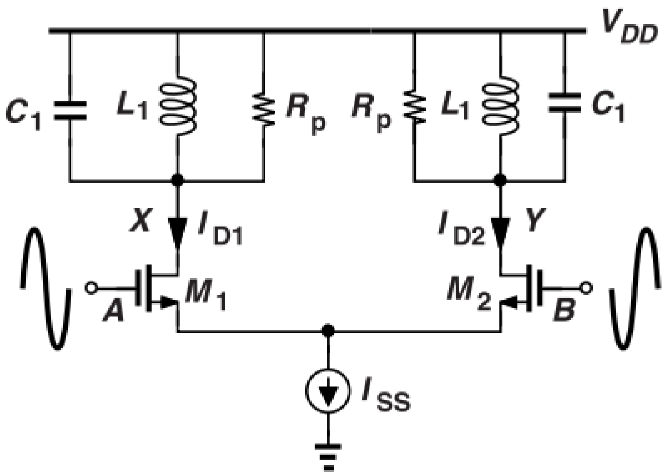


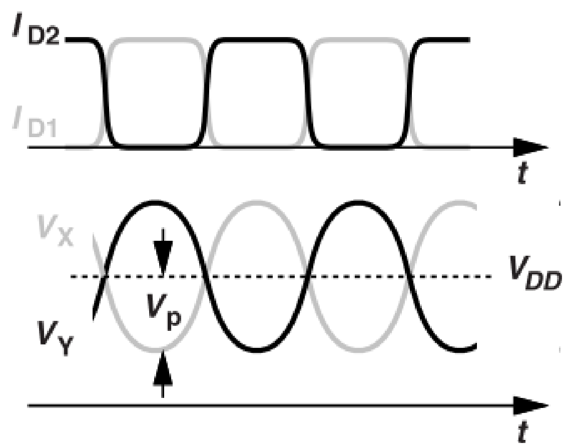


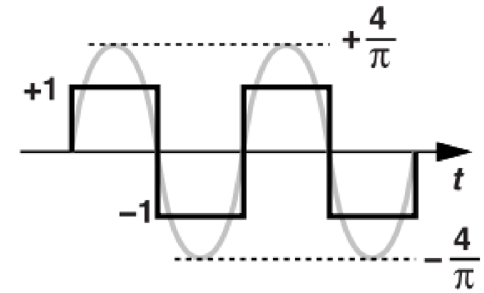


- $I_x = -g_{m1}v_1 = g_{m2}v_2 \Rightarrow v_1 = -I_x/g_{m1}, v_2 = I_x/g_{m2}$
- $v_x = v_1 - v_2 = -\left(\frac{I_x}{g_{m1}} + \frac{I_x}{g_{m2}}\right)$
- $\frac{V_x}{I_x} = -\left(\frac{1}{g_{m1}} + \frac{1}{g_{m2}}\right) = -\frac{2}{g_m}\ for\ g_{m1} = g_{m2}$

Differential Oscillator







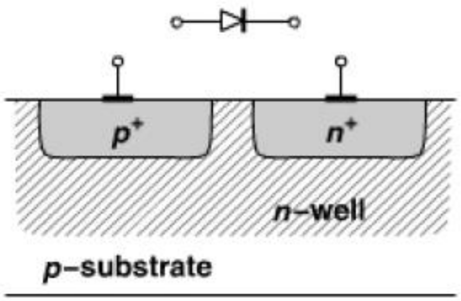
- Maximum voltage amplitude is given by
  - $V_p = \frac{2}{\pi} I_{ss} R_p$

Varactor design

- Varactors have two important properties
  - Capacitor range, or ratio between max and min capacitance values that can be achieved
  - The quality factor which depends on series resistor
- Reverse bias diodes and MOSFET transistors can be used as varactors

PN junction Varactor

- $C_j = \frac{C_{j0}}{\left(1+\frac{V_D}{V_0}\right)^m}$
  - $V_0 \approx 0.7$, $m \approx 0.3$
  - Since supply is limited, tuning range is limited
  - At $V_D=0$ $C_j=C_{j0}$
  - At $V_D=1.5$ V $C_j=0.7C_{j0}$

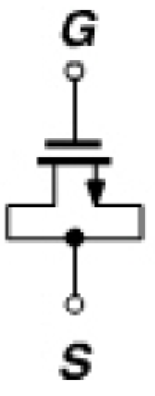


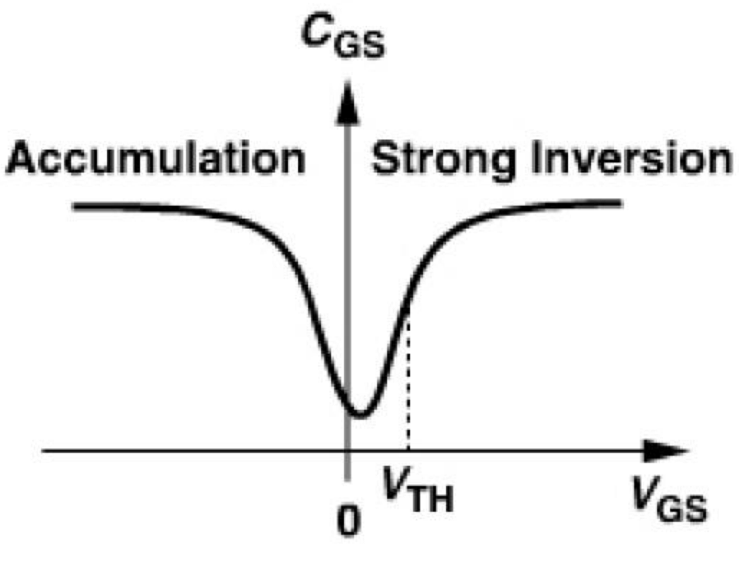
CMOS Varactor

- Behavior of MOS capacitance is divided into three regions
  - Accumulation mode, for $V_{GS}<0$
  - Depletion mode

    $0<V_{GS}<V_{TH}$
  - Inversion mode

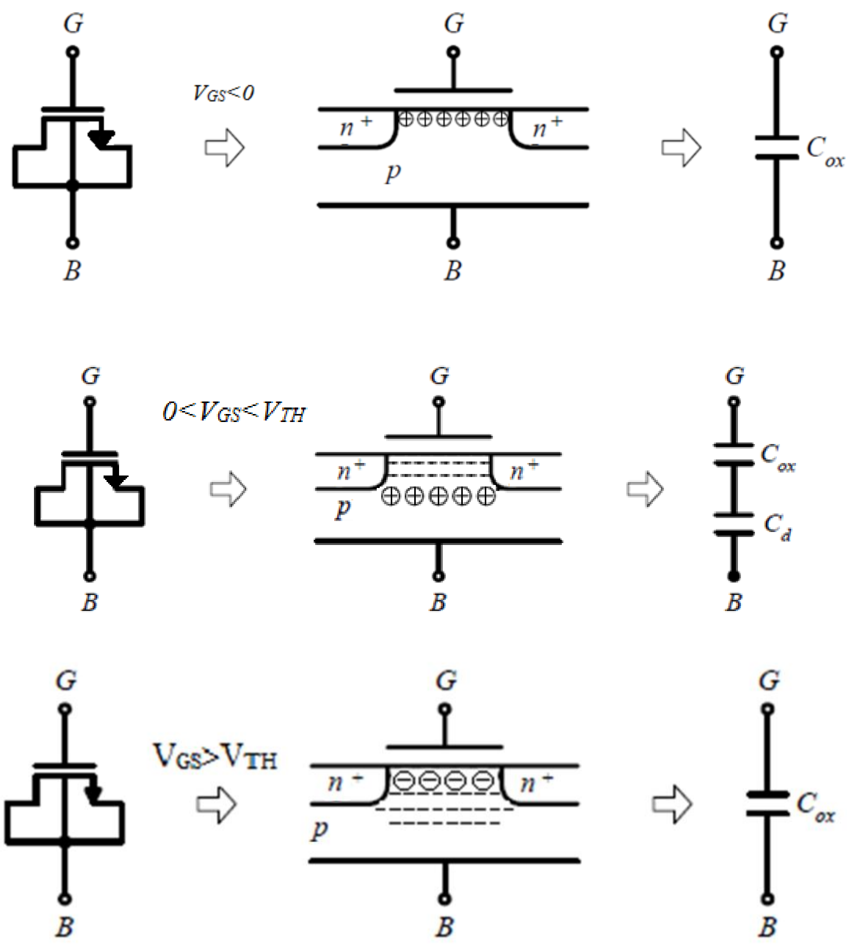
    $V_{GS}>V_{TH}$





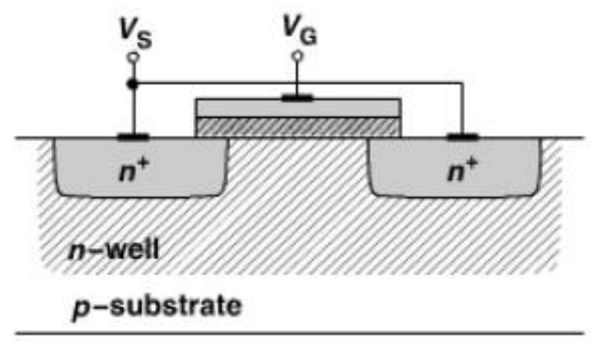
CMOS Varactor

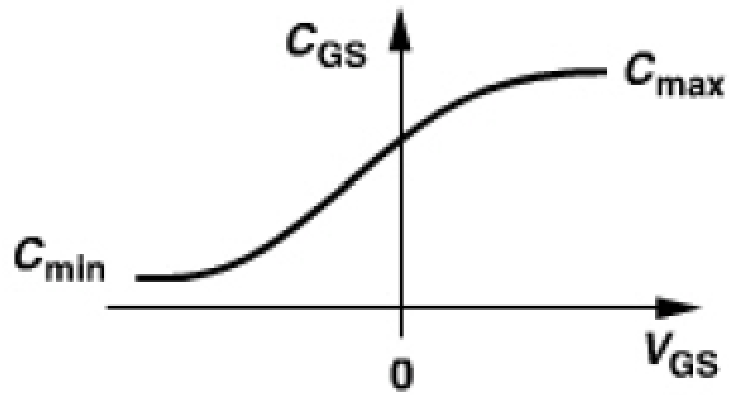
- Accumulation mode
  - Holes form other side of varactor
- Depletion mode
  - Total capacitance is the series equivalent of two caps
- Inversion mode
  - Electrons form the other side of varactor



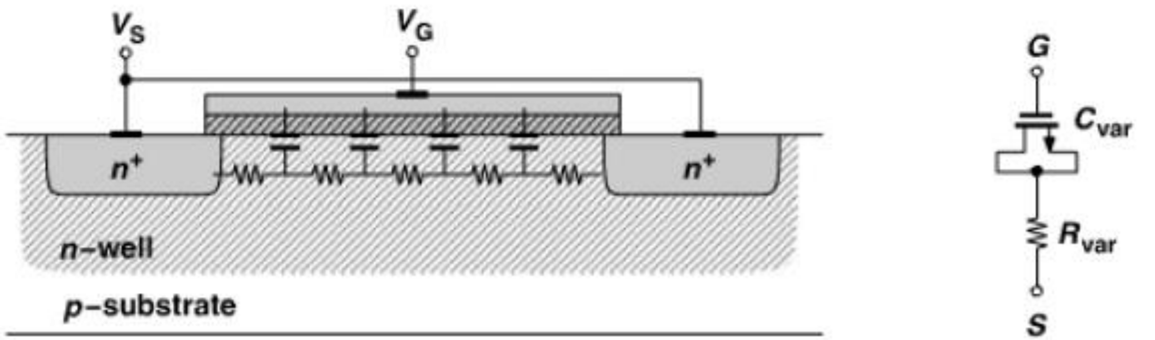
MOS Varactor

- NMOS in nwell
  - ➢Accumulation mode and depletion mode only
  - ➢No sign inversion in the varactor gain





Quality Factor of MOS Varactor



- Maximum resistance that any electron will see when it is in the middle of the channel ($R_{ch}/2 \| R_{ch}/2 = R_{ch}/4$)
- $R_{ch} \approx \dfrac{L}{\mu C_{ox} W (V_{GS} - V_t)}$

Quality Factor of MOS Varactor

- Consider the input impedance from half the structure

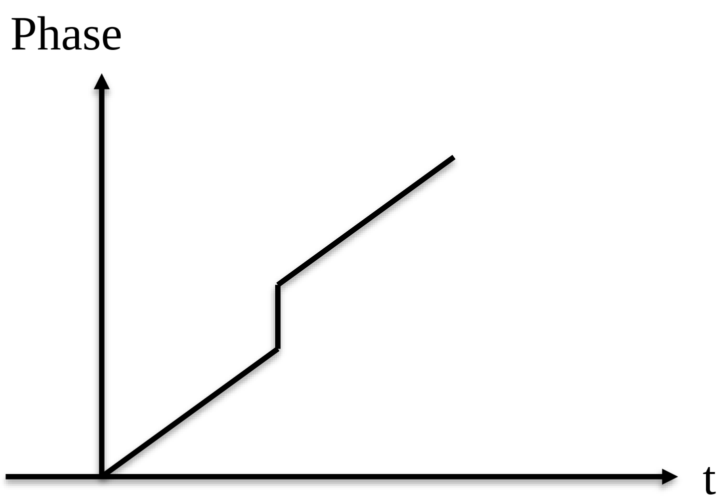
- Consider the input impedance from half the structure
- $Z_{in} = \frac{Z_0}{\tanh(\gamma l)} = \frac{\sqrt{Z_1/Y_1}}{\tanh\left(\sqrt{Z_1 Y_1 d^2}\right)}$, where Z_1 and Y_1 are the impedance and admittance per unit length ($Z_1=R_{tot}/2d$, $Y_1=sC_{tot}/2d$)
- $\tanh(\varepsilon) \approx \frac{\varepsilon}{1+\varepsilon^2/3}$, then $Z_{in} = \frac{1}{sC_{tot}/2} + \frac{R_{tot}}{6}$ (half structure)
- $Z_{in,tot} = \frac{1}{sC_{tot}} + \frac{R_{tot}}{12}$ (of the whole structure)

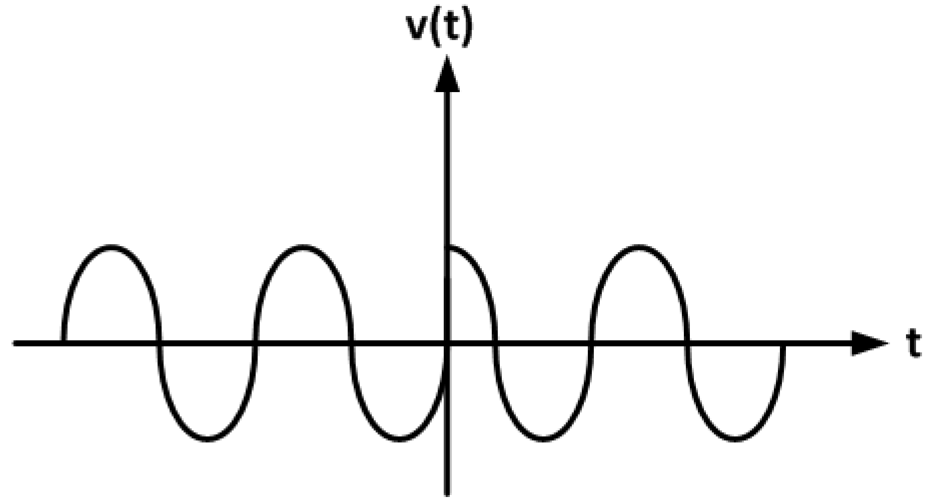
VCO Gain

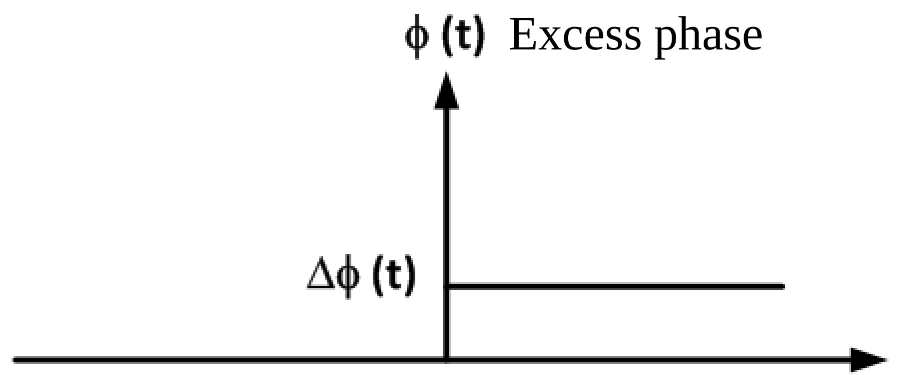
- $\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{L(C_0+C(v))}} = \frac{1}{\sqrt{LC_0}\sqrt{1+C(v)/C_0}}$
- $\omega = \frac{1}{\sqrt{LC_0}}\left(1 - \frac{C(v)}{2C_0}\right)$
- $\omega = \omega_0 + K_{vco}V_c$

Introduction to Phase Noise

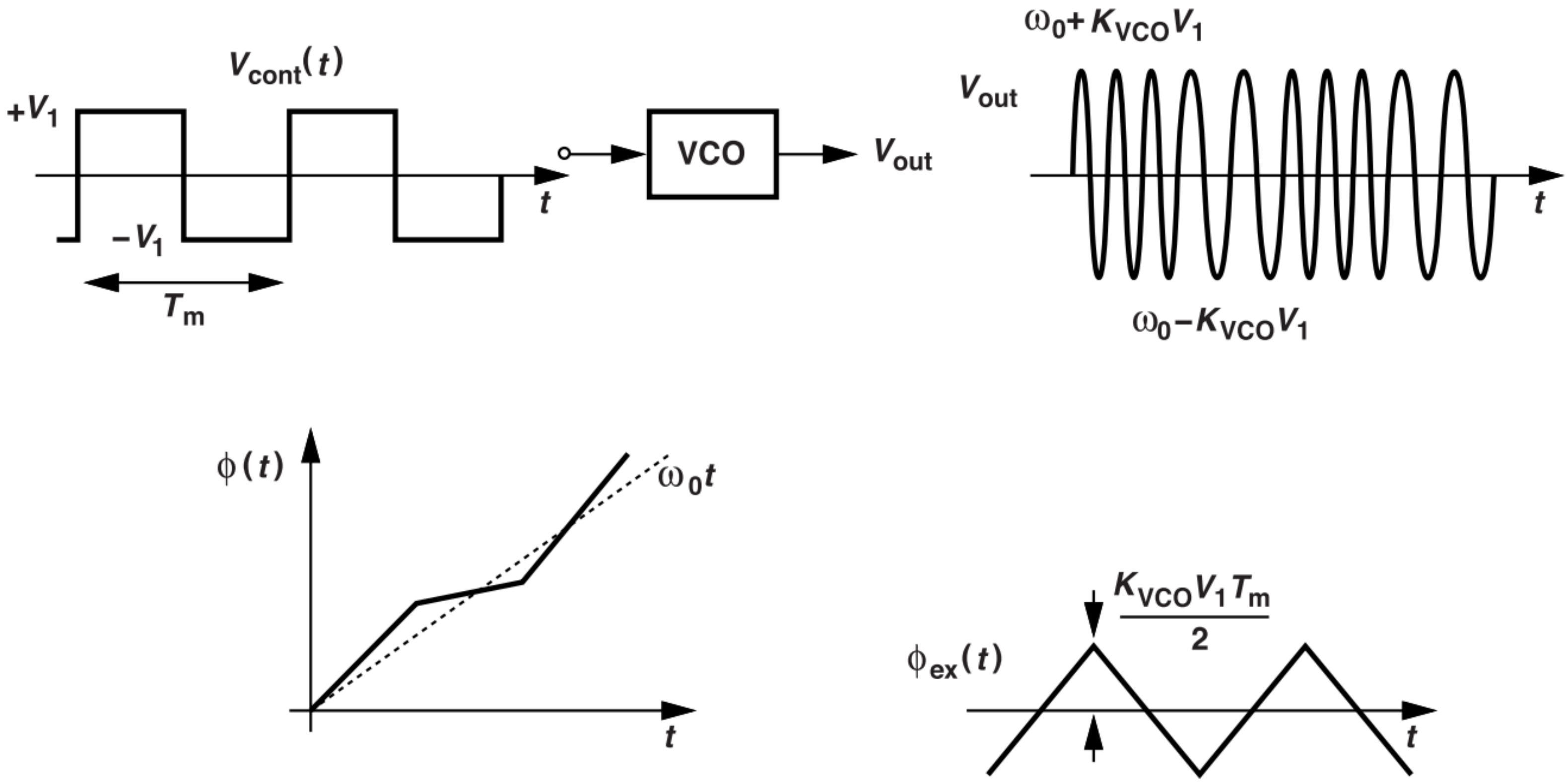
- Phase step
- $v(t) = \sin(\omega t + \Delta\emptyset\, u(t))$



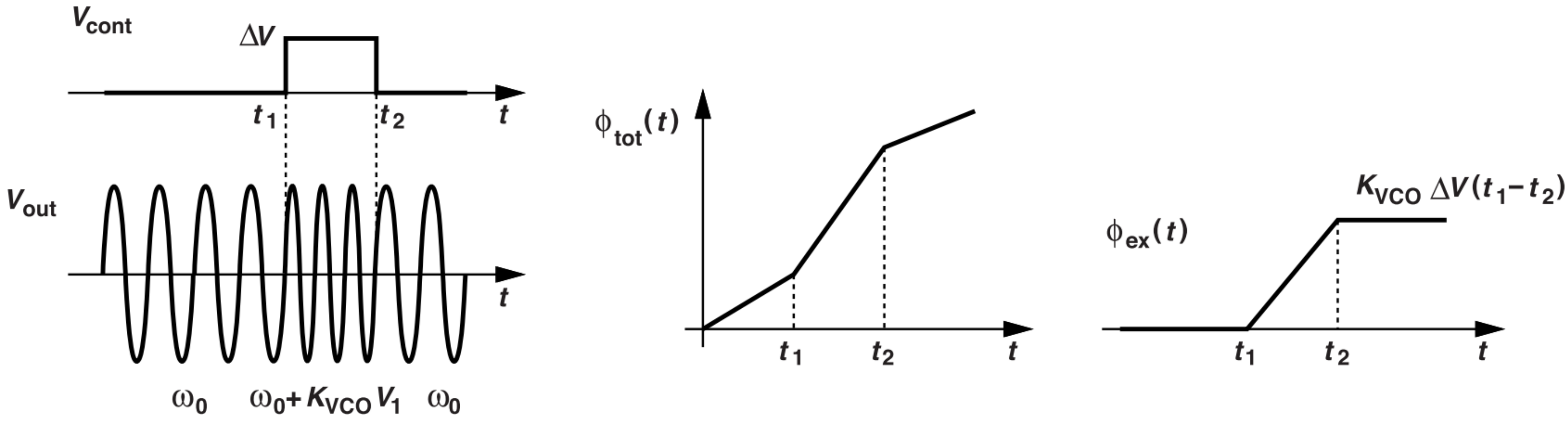




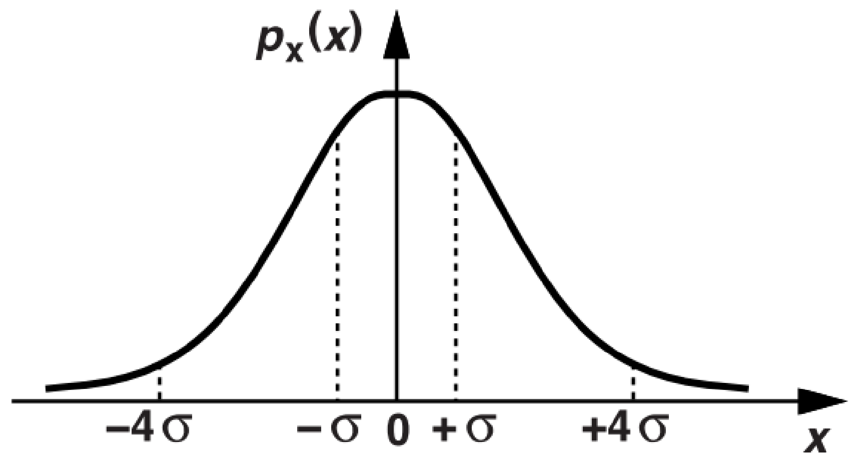
Introduction to Phase Noise



Introduction to Phase Noise



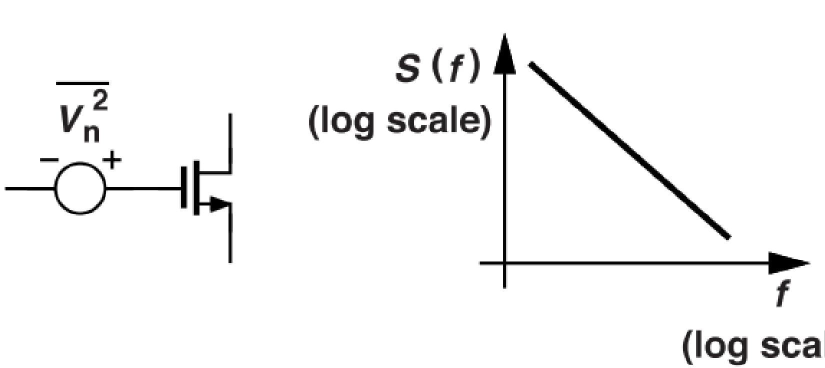
Voltage Noise

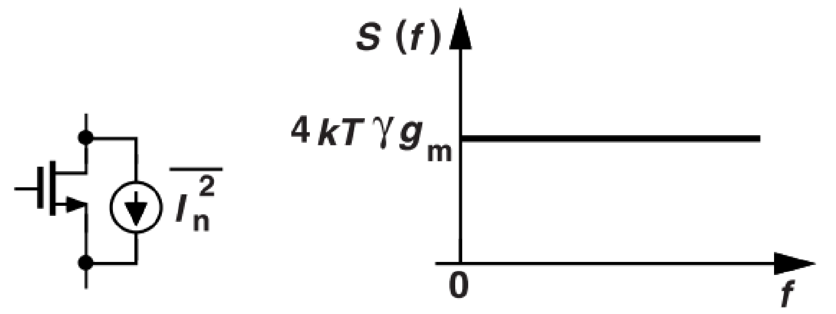


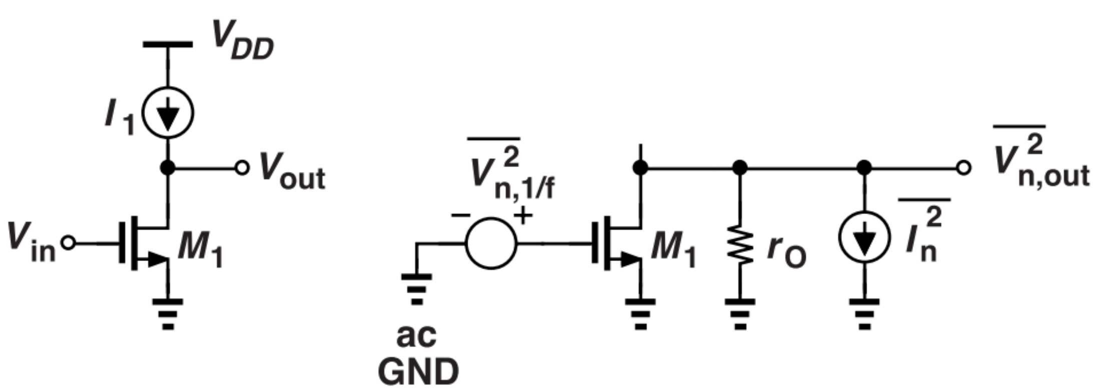
- Noise is a time varying random signal
  - Frequency domain representation of noise is Fourier transform of autocorrelation function of noise
  - Autocorrelation of white noise is delta function
  - What is the definition of SNR

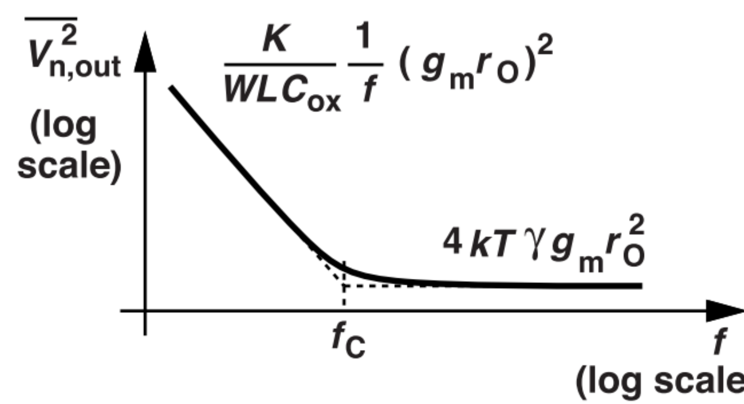
White Noise and Flicker Noise

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



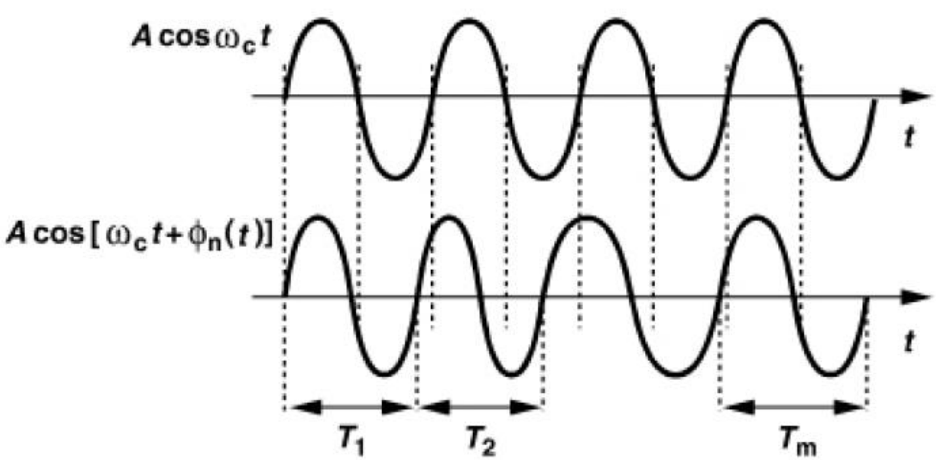


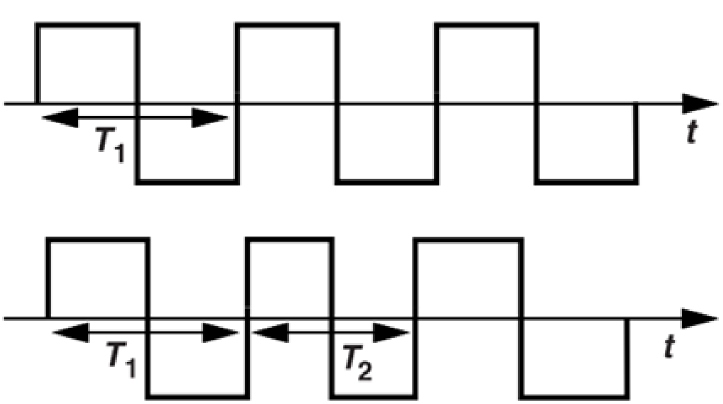




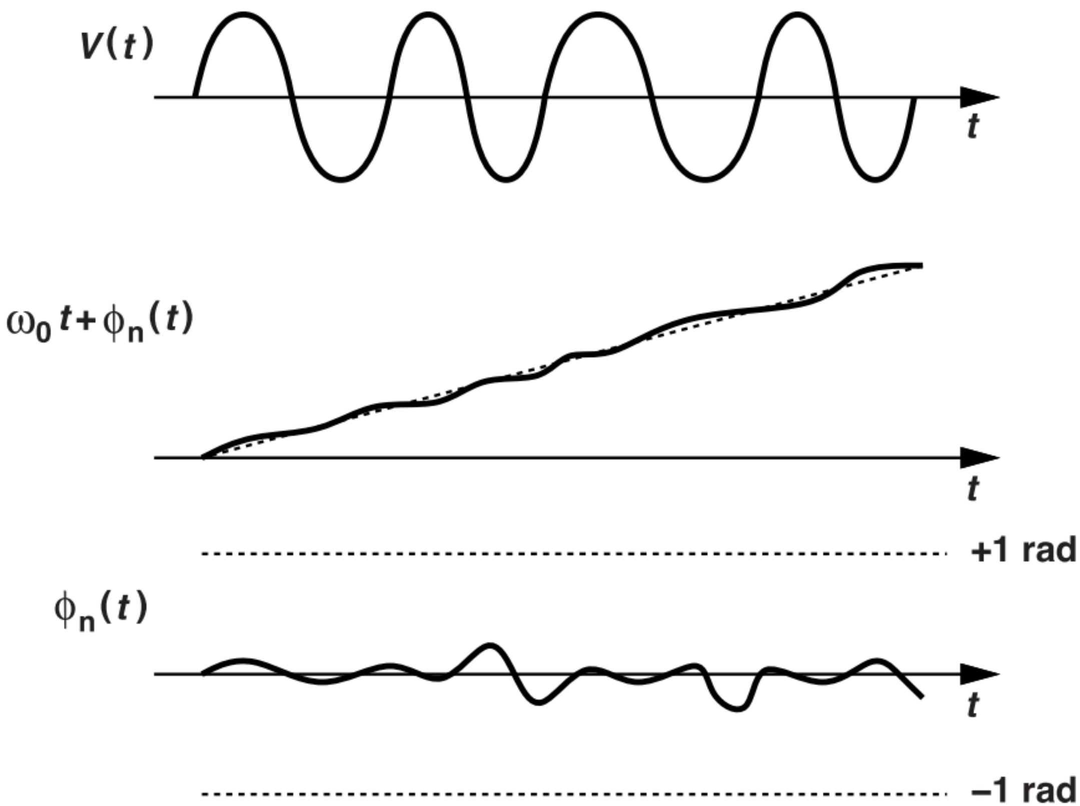
Phase Noise

- 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



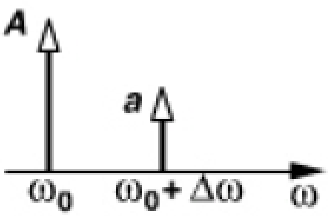
- Phase noise is varying with time
  - Frequency spectrum of phase noise is Fourier transform of phase noise autocorrelation function

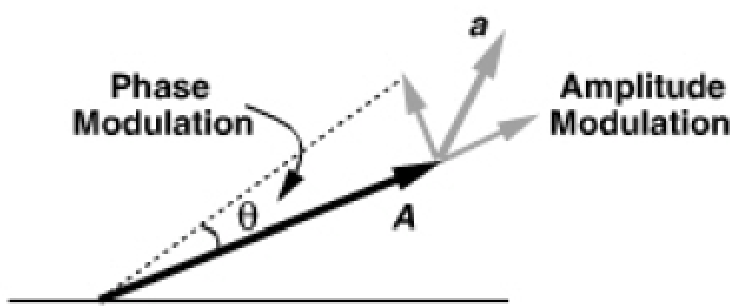
Relationship Between Phase Noise and Jitter

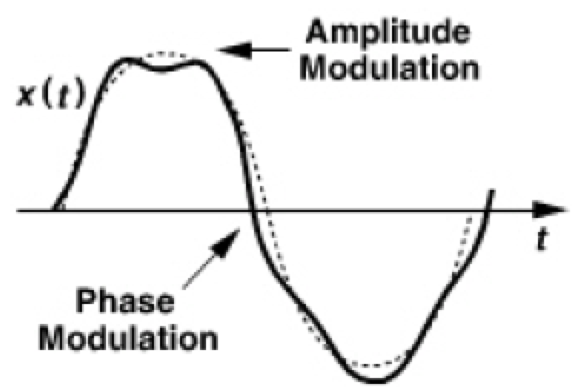
- Jitter is the time domain representation of phase noise
- For a periodic signal, period time T is equivalent to 2π
- A signal with frequency f_0 and phase noise ϕ_n, the jitter is simply given by
  - $\frac{t_n}{T_0} = t_n f_0 = \frac{\phi_n}{2\pi}$
  - Jitter=t_n= $\phi_n/2\pi f_0$
- Jitter is typically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

Phase Noise

- Noise added to sinusoidal signal will cause phase noise



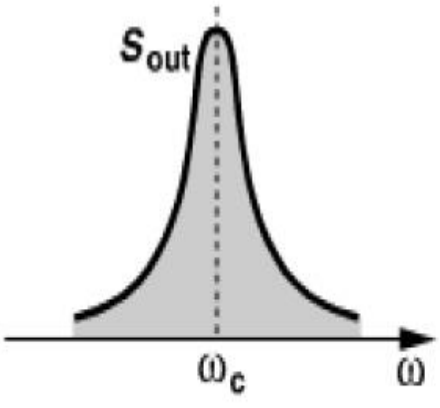




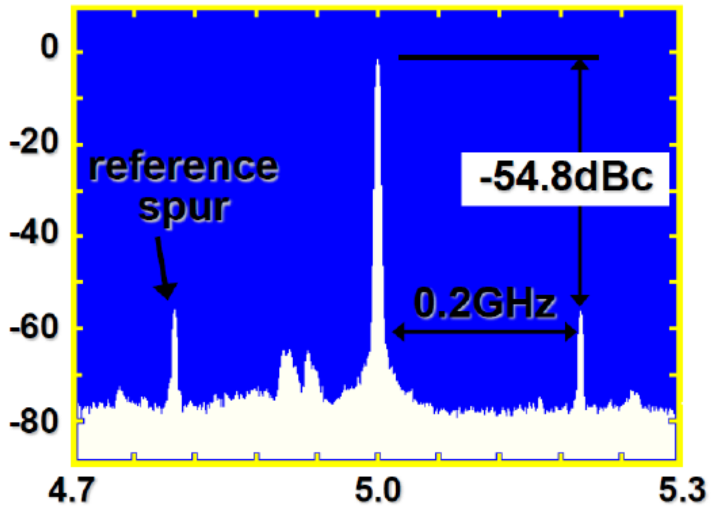
Phase Noise

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

VCO Spectrum

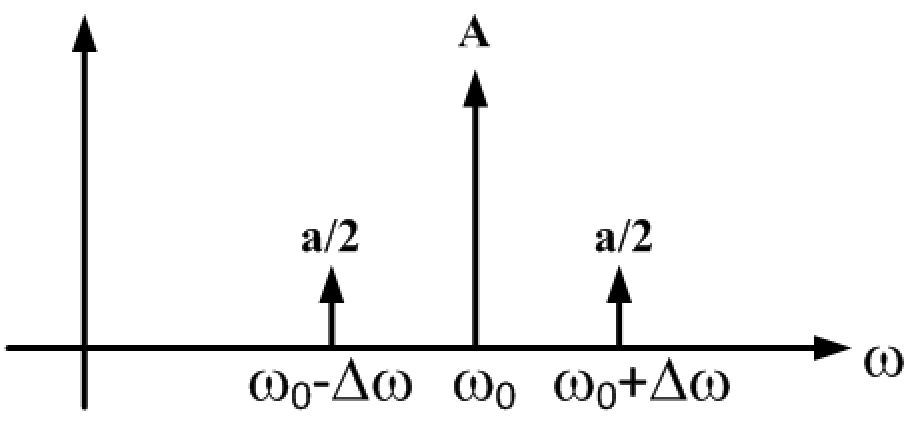


PLL Spectrum



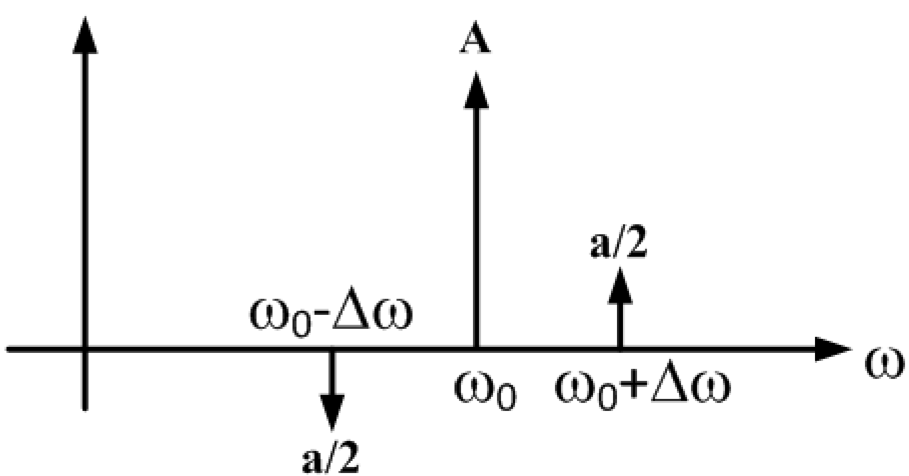
Amplitude and Phase Noise

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



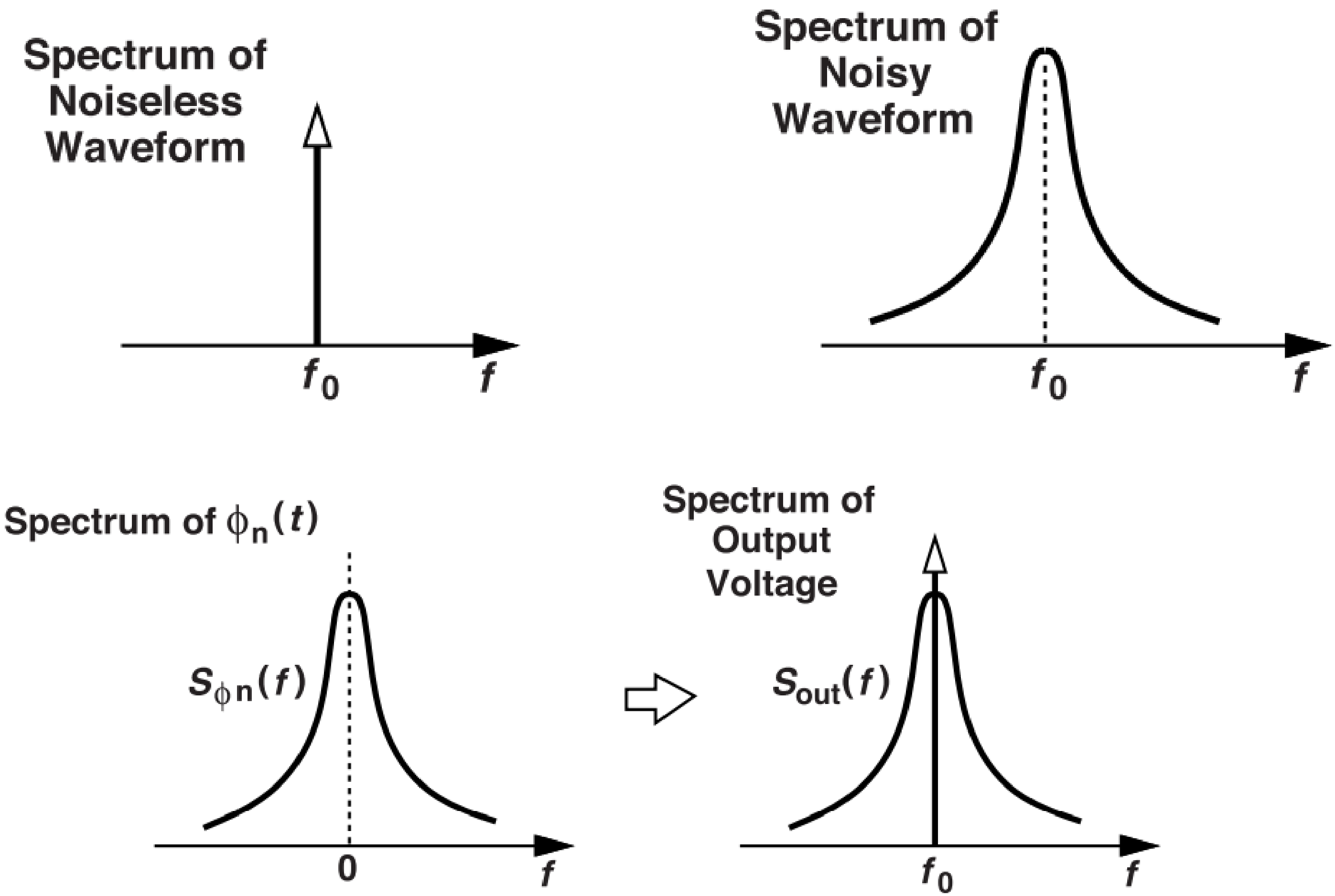
Amplitude and Phase Noise

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



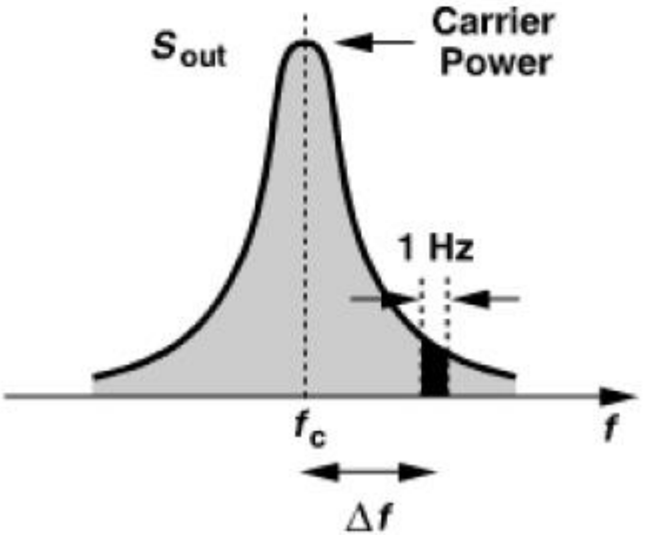
Phase Noise Spectrum

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



Phase Noise

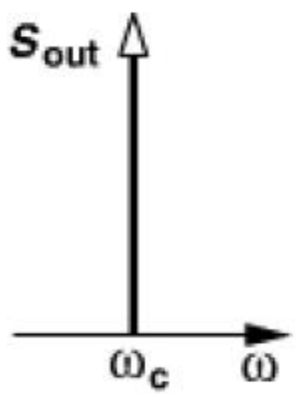
- Phase noise is measured in dBc/Hz
  - Total noise is integrated in 1Hz BW at a certain offset and then divided by the carrier power



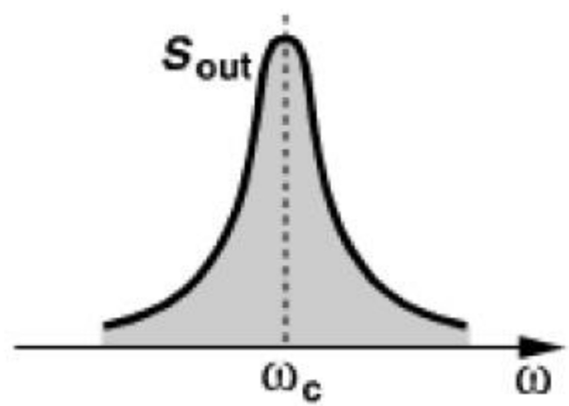
Phase Noise

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

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



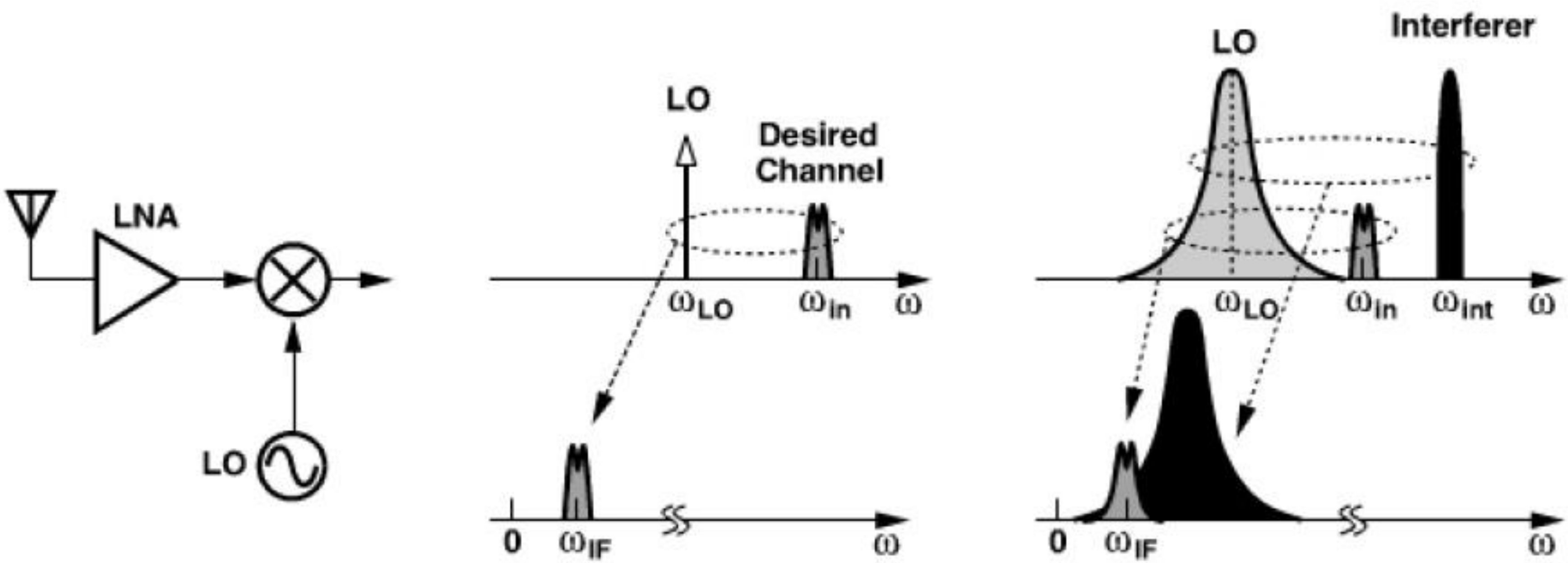
Ideal Oscillator



Real Oscillator

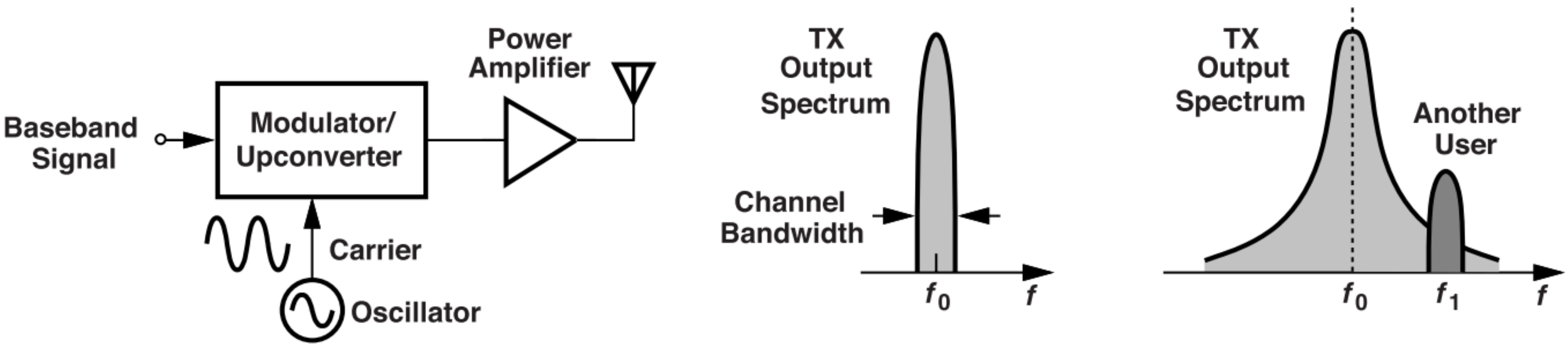
Effect of Phase Noise

- Oscillator phase noise may cause interferer to distort desired channel

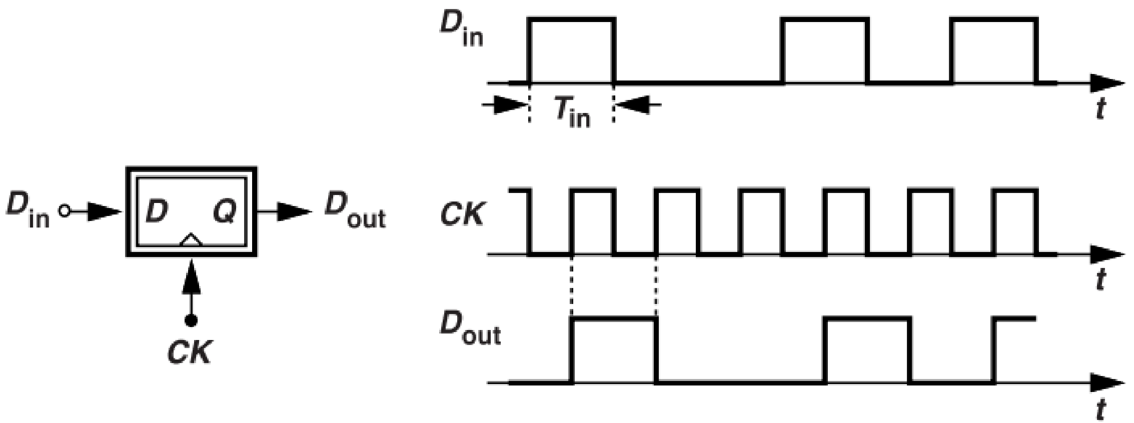


Effect of Phase Noise

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



Effect of Jitter



(a)