Oscillators

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Job Advertisement

- RF/analog circuits design experience
  - LNA, mixer, VCO, PLL, filter, A/D, PA
- CAD proficiency
  - Cadence, ADS, Spice
- Packaging, measurement, and PCB design skills are strongly encouraged
- Programming in C is an asset

- Salary experience based, 80.000 – 120.000

UMTS VCO Requirements

VCO design parameters	***Design requirement***
Oscillating frequency	2.1GHz
Tuning range	400MHz
Voltage swing	0.7V
Phase noise	-110dBc@1MHz
Supply voltage	3V
Power consumption	10mW

Technology parameters	***Values***
Technology	BiCMOS
Number of metals	4
Transit frequency	50GHz
MIM capacitors	available
Varactors	available

Outline

- Oscillator Classification, Oscillation Condition and Frequency
- LC Oscillators
- Oscillation Signal Steady-State Amplitude
- Interpretation of Noise in Oscillators
- Linear Phase-Noise Model
- Spectral Analysis of Phase Noise
- Design Procedure for LC-Oscillator
- Simulations/Layout/Measurements

Oscillator Definition

- An oscillator is a tunable circuit that generates a stable periodical signal, which is in the limit independent of the initial conditions.

$$\frac{d^2}{dt^2}x(t) + f(x(t))\frac{d}{dt}x(t) + \omega^2 x(t) = 0$$

oscillation signal non-linear function angular frequency

- A non-linear system that should be of a second order (with two time constants).

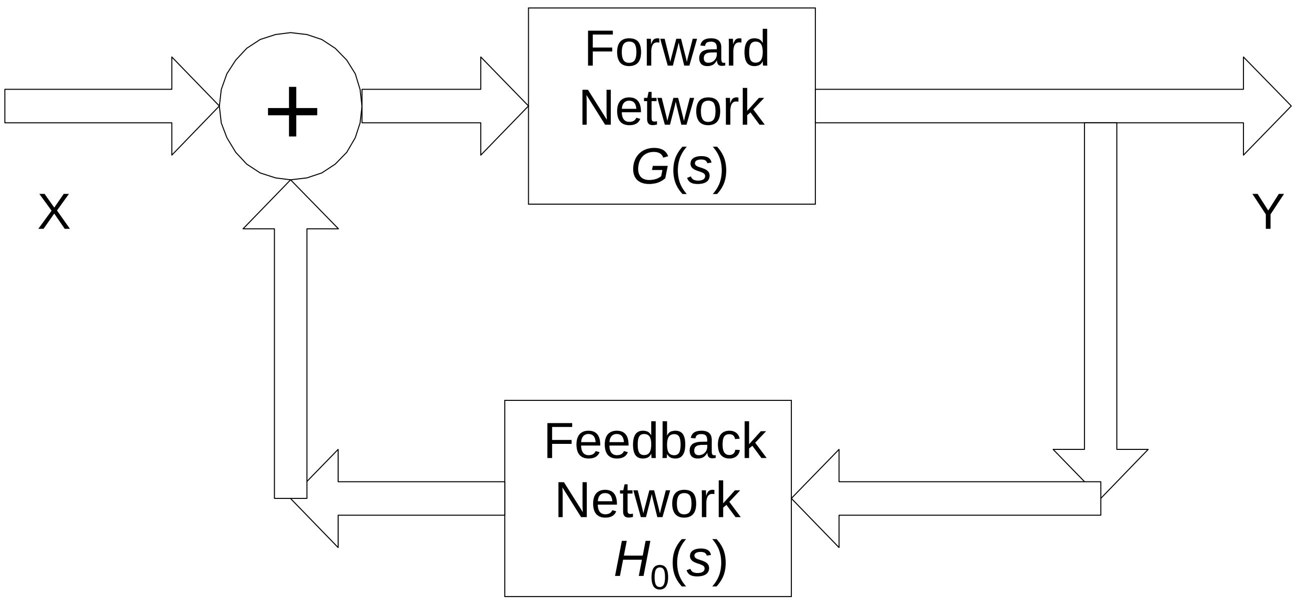
Oscillator Classification –Time Constants Based

frequency dominated by	oscillator order
1 time constant	1st-order oscillator
2 time constants	2nd-order oscillator
…	…

Oscillator Classification – Resonator Based

- Resonator oscillators
  - LC oscillators, negative resistance oscillators
    - good phase noise properties
    - poor quadrature accuracy
- Resonatorless oscillators
  - Ring oscillators
    - poor phase noise properties
    - good quadrature accuracy
  - Relaxation oscillators
    - poor phase noise properties
    - good quadrature accuracy

Oscillator Positive Feedback Model



$$H(s) = \frac{Y(s)}{X(s)} = \frac{G(s)}{1 - G(s)H_0(s)}$$

Oscillation Condition

- Barkhausen's criteria
  - Loop-gain module > 1 (start up)

    $$\left|T(j\omega)\right| = \left|G(j\omega)\cdot H_0(j\omega)\right| > 1$$

  - Loop-gain module equals 1 (steady state)

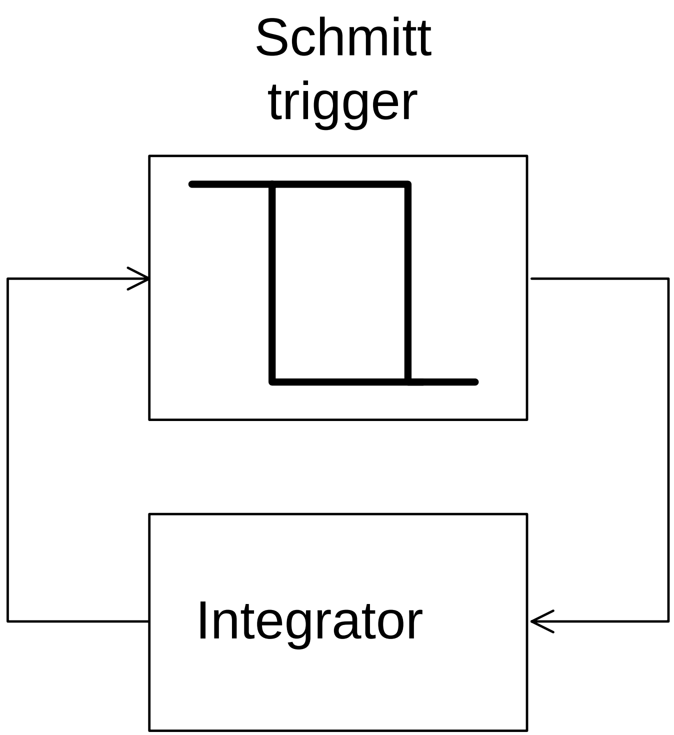
    $$\left|T(j\omega)\right| = \left|G(j\omega)\cdot H_0(j\omega)\right| = 1$$

  - Phase shift around the loop equals 360º

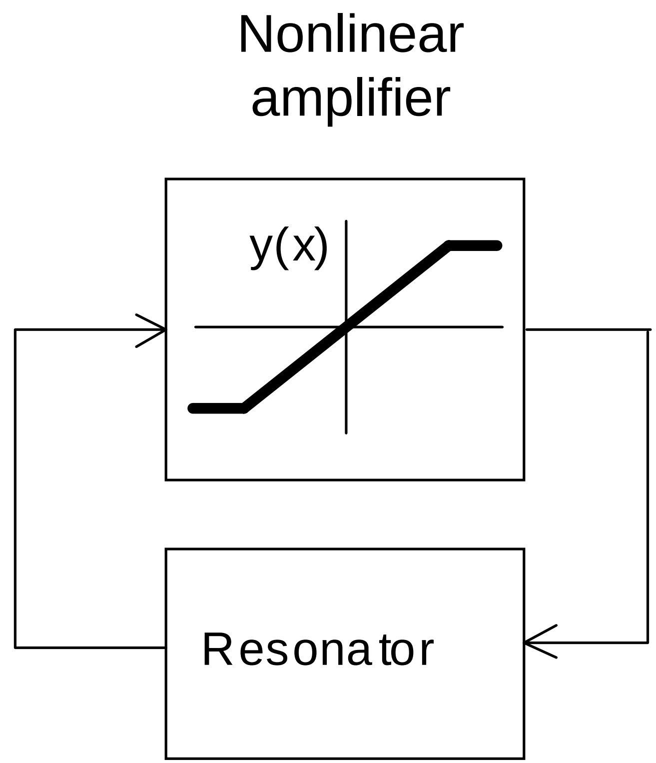
    $$\angle\left(T(j\omega)\right) = 2\pi$$

Oscillator Models

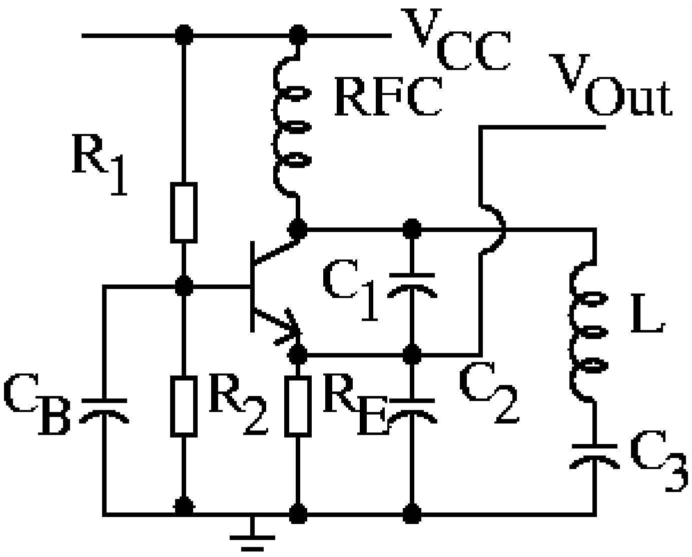
- 1st-order oscillator
  - 1st-order timing constant
  - Schmitt trigger



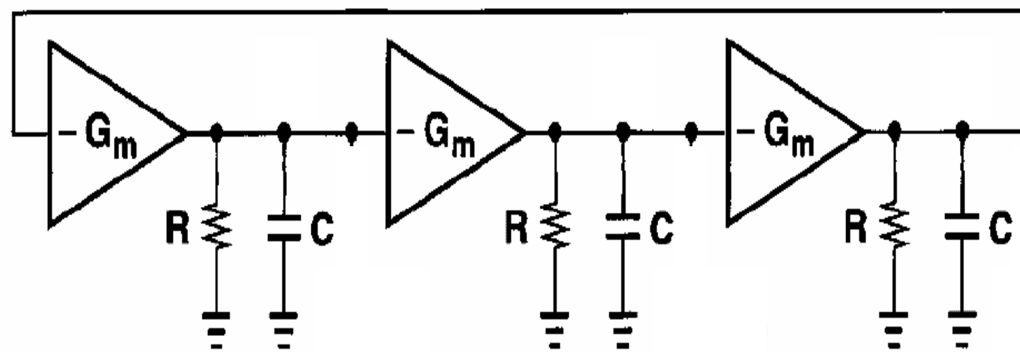
- 2nd-order oscillator
  - 2nd-order timing constant
  - amplitude limiter



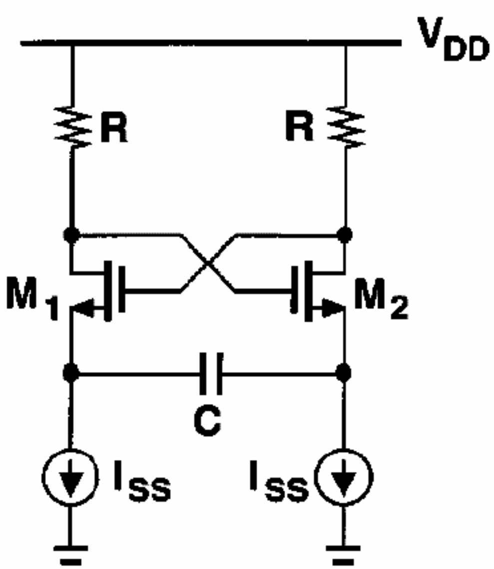
LC oscillator



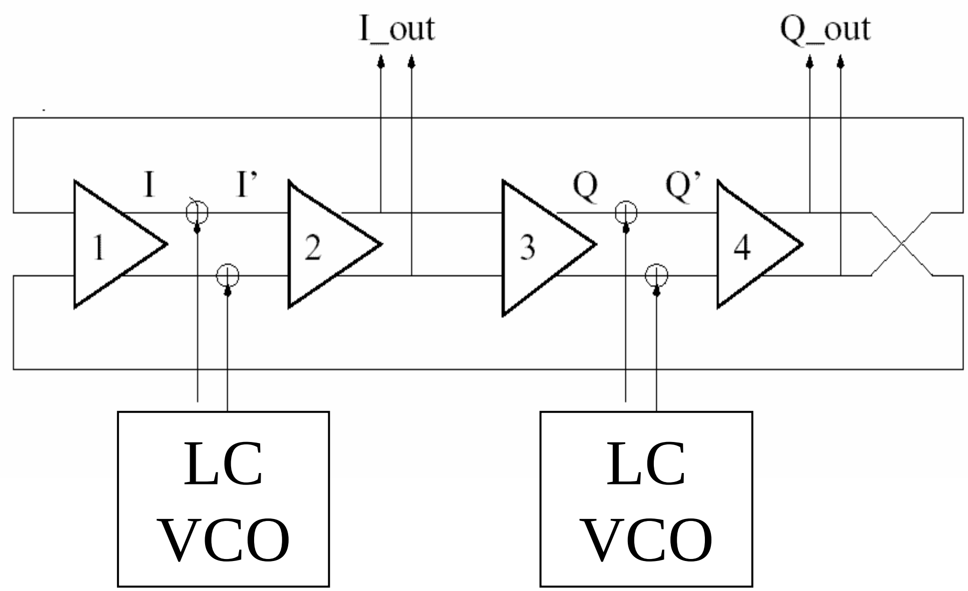
RC ring oscillator



1st–order oscillator



injection-lock ring oscillator



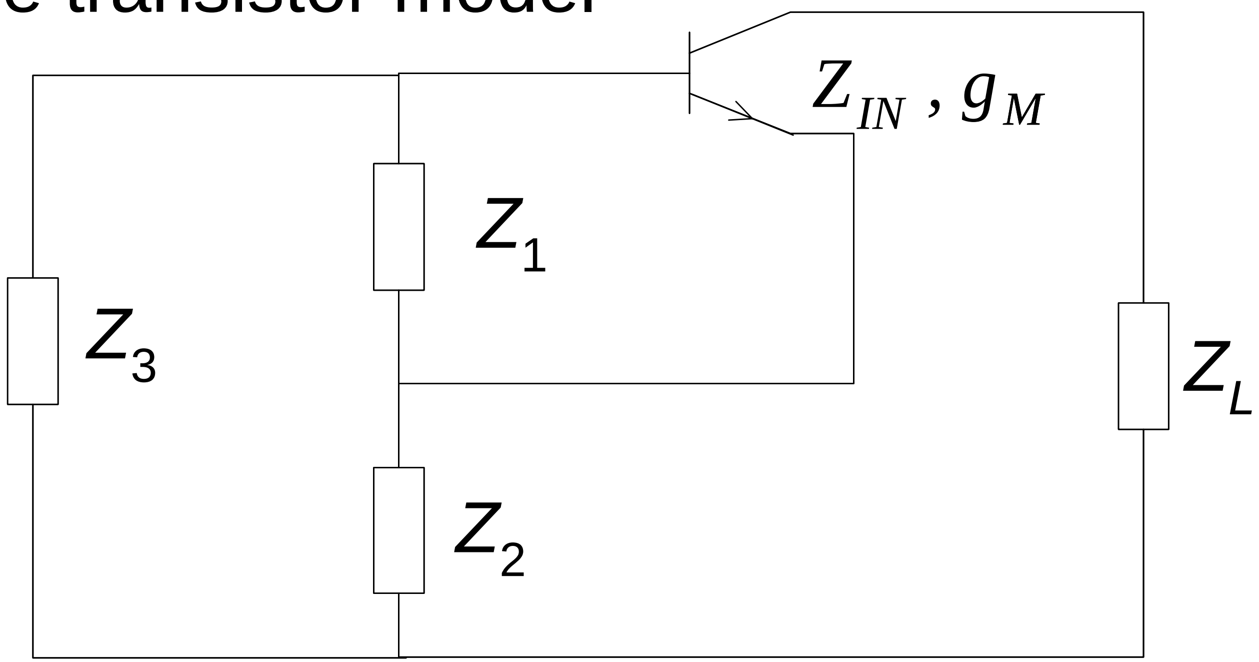
Oscillator Application

- Frequency conversion
  - Downconversion in receivers
  - Upconversion in transmitters
- Clock generation
- Channel selection
- Modulation/demodulation

LC Oscillators

Generalized LC Oscillator Circuit

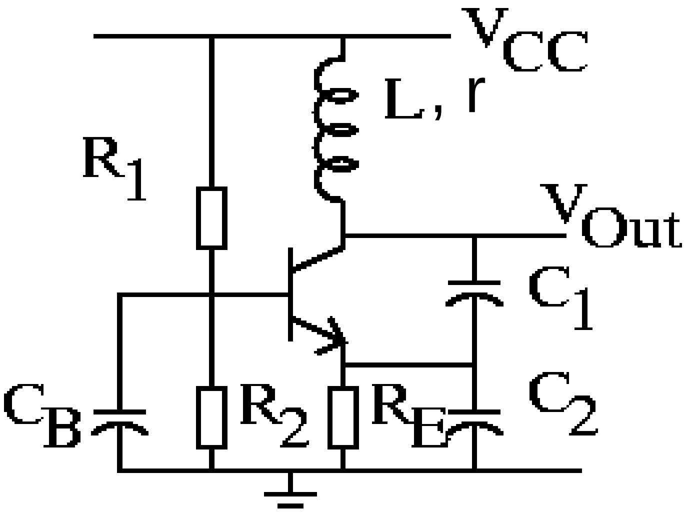
- Single transistor model



- Loop-gain approach: $T(j\omega)=1$
- Impedance matrix approach: $det(Z)=0$ (or $det(Y)=0$)

$$\left(Z_1+Z_3\right)\left(Z_{IN}+Z_1\right)+Z_1Z_{IN}\left(1+g_MZ_2\right)=0$$

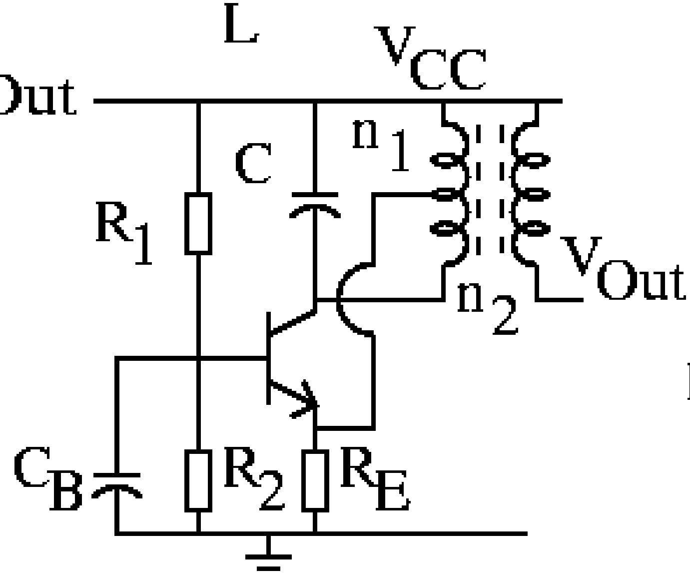
Examples of LC Oscillator



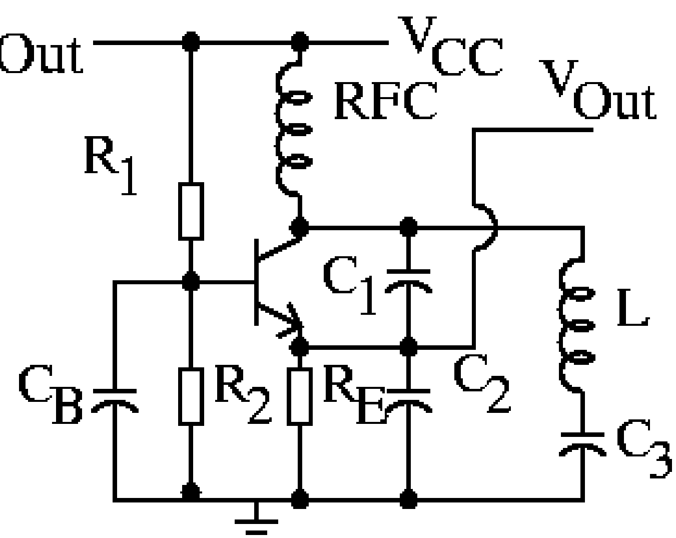
Colpitts

$$\omega_0 = \frac{1}{\sqrt{LC_1C_2/(C_1+C_2)}}$$

$$(1-n)\omega_0^2 C_1 C_2 r < g_m$$

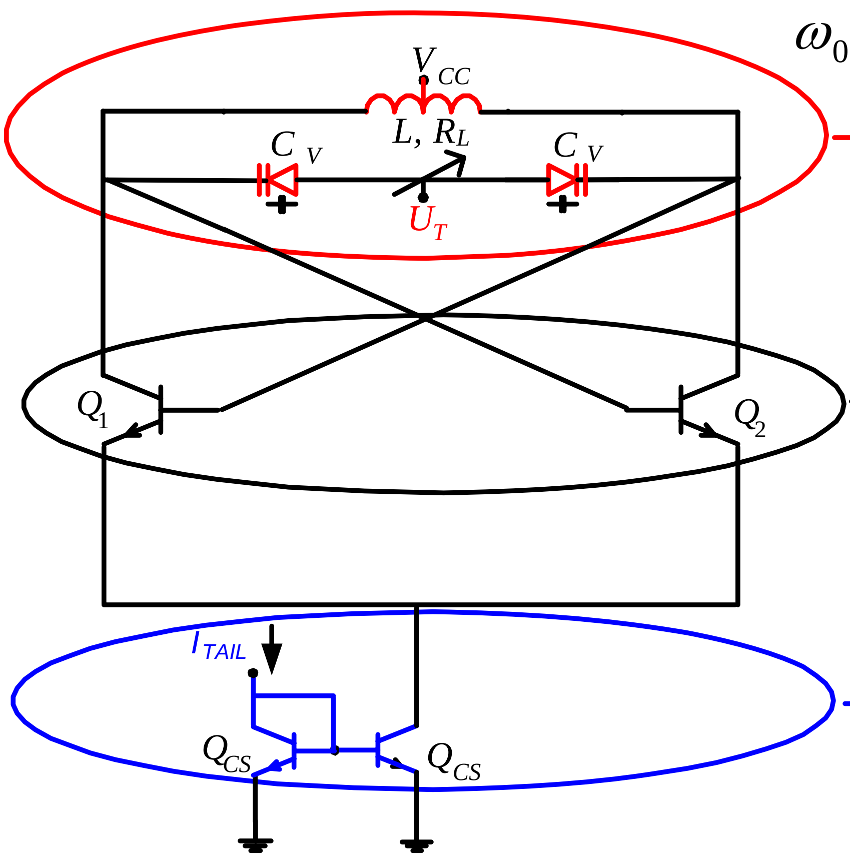


Hartley



Clapp

Negative Resistance Oscillator



$$\omega_0 = \frac{1}{\sqrt{LC_V/2}}$$

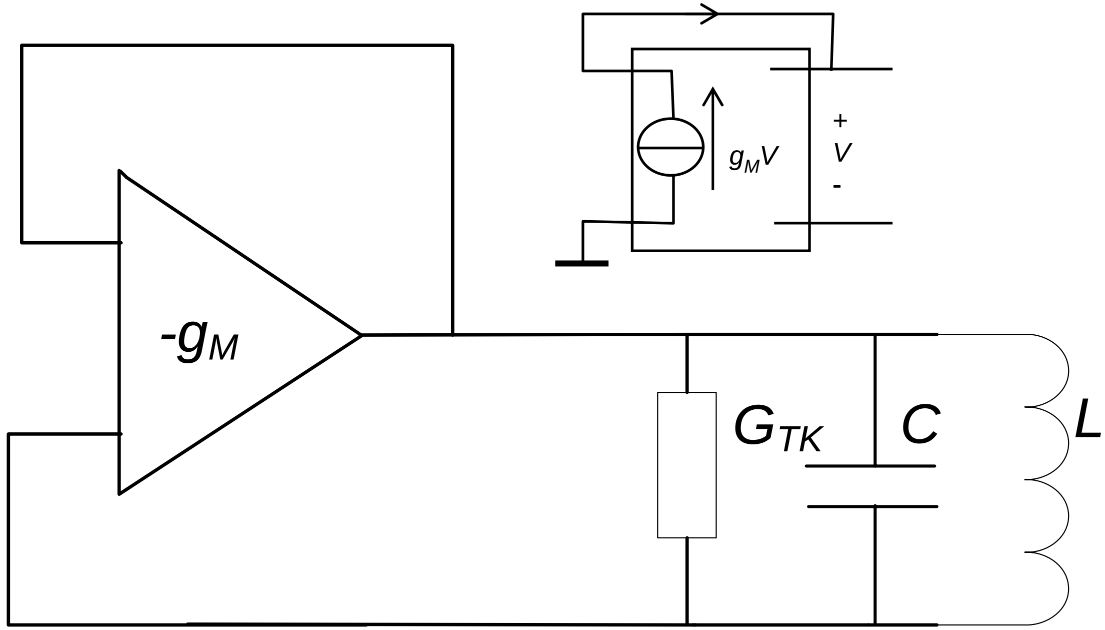
resonating LC tank

$-g_M$

active pair

biasing current source

Negative Resistance Oscillator - Simplified Model



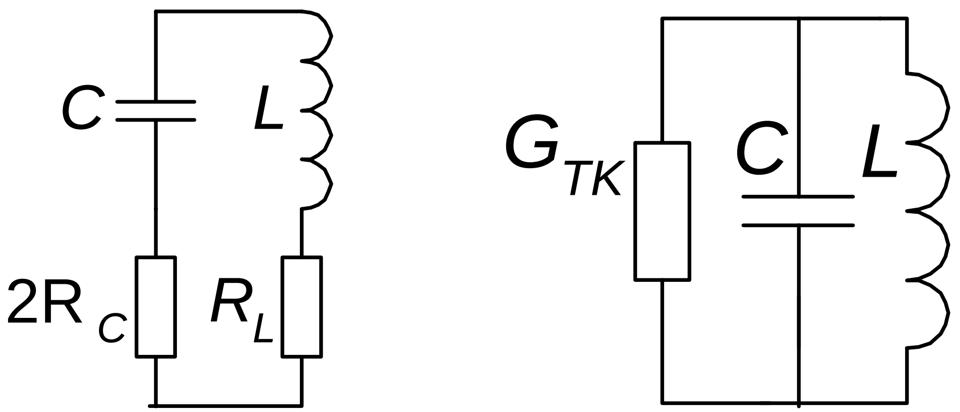
- oscillation condition

$$g_M > G_{TK} \qquad g_M = g_m / 2$$

- oscillation frequency

$$\omega = \omega_0 = 1/\sqrt{LC} \qquad C = C_V / 2$$

LC Tank



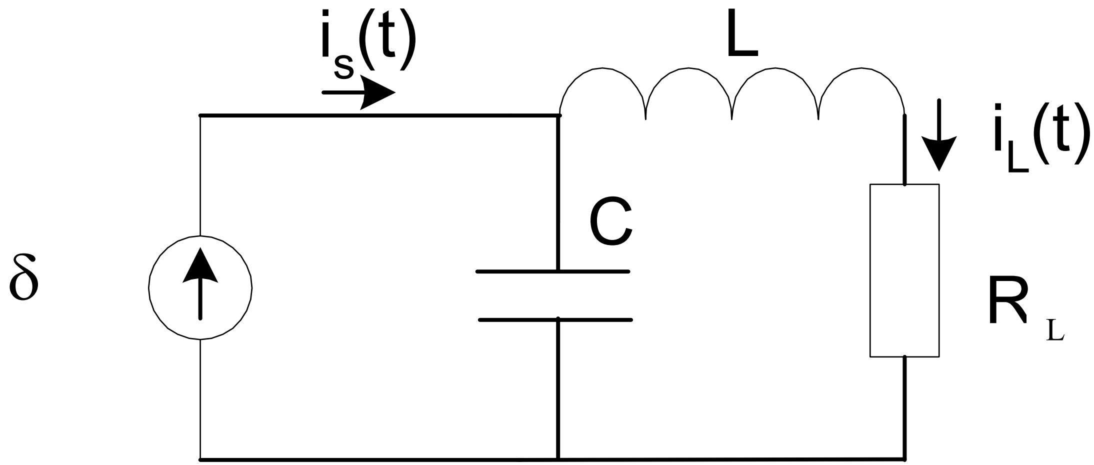
- tank conductance

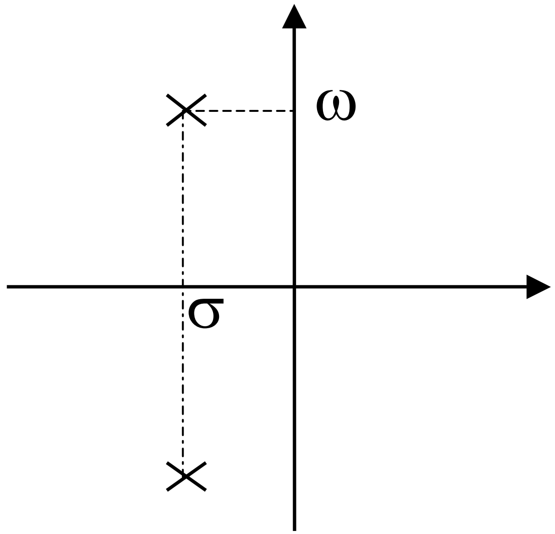
$$G_{TK} = \frac{R_L}{(\omega_0 L)^2} + 2R_C(\omega_0 C)^2 \qquad G_{TK} = \frac{1}{\omega_0 L}\left(\frac{1}{Q_L} + \frac{1}{Q_C}\right)$$

- quality factors

$$Q_L = \frac{\omega_0 L}{R_L} \qquad Q_C = \frac{1}{\omega_0 C_V R_C}$$

Resonator Impulse Response





$$s_i = \sigma \pm j\omega$$

resonator pole pattern

$$H(s) = \frac{I_L(s)}{I_S(s)} = \frac{1}{LC}\frac{1}{s^2 + sR_L/L + 1/LC}$$

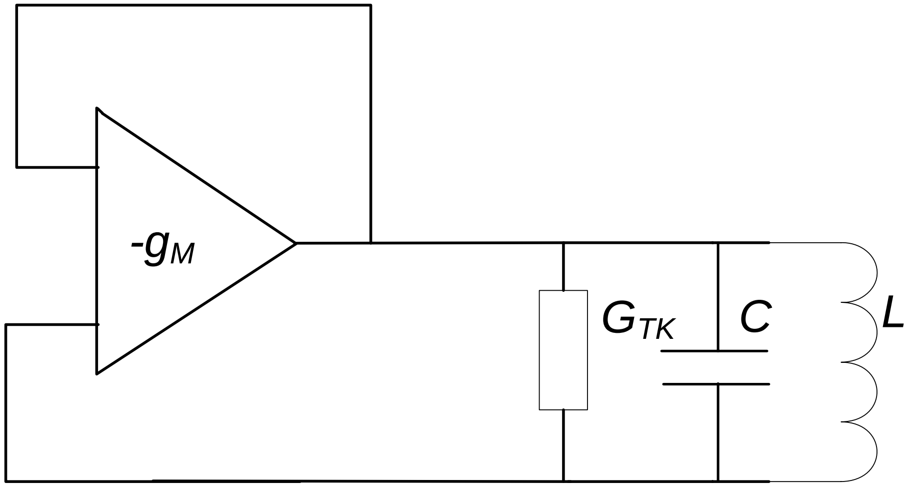
$$i_L(t) = \left(\frac{I_L(s)}{I_S(s)}\right)^{-1} = \sum_{i=0}^{n}\frac{P(s_i)}{Q(s_i)'}e^{s_i t}$$

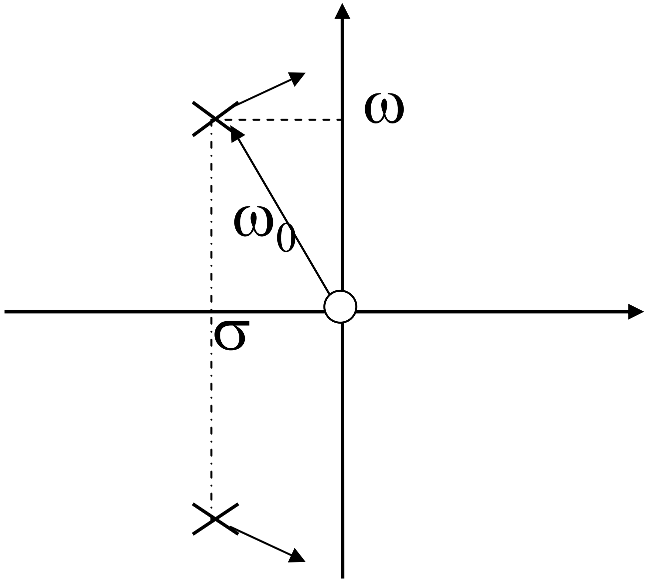
$$i_L(t) = \frac{\omega_0 e^{\sigma t}}{\sqrt{1-(\sigma/\omega_0)^2}}\sin\omega t \qquad \omega = \omega_0\sqrt{1-(\sigma/\omega_0)^2}$$

$$\omega_0 = 1/\sqrt{LC}$$

$$\sigma = -R_L/2L$$

Oscillator System Transfer Function





$$H(s) = \frac{Z(s)}{1 - g_M Z(s)}$$

system pole pattern

$$H(s) = \frac{1}{C} \frac{s}{s^2 + s(G_{TK}/C - g_M/C) + 1/LC}$$

- oscillation condition and frequency

$g_M > G_{TK}$ $\omega = \omega_0 = 1/\sqrt{LC}$

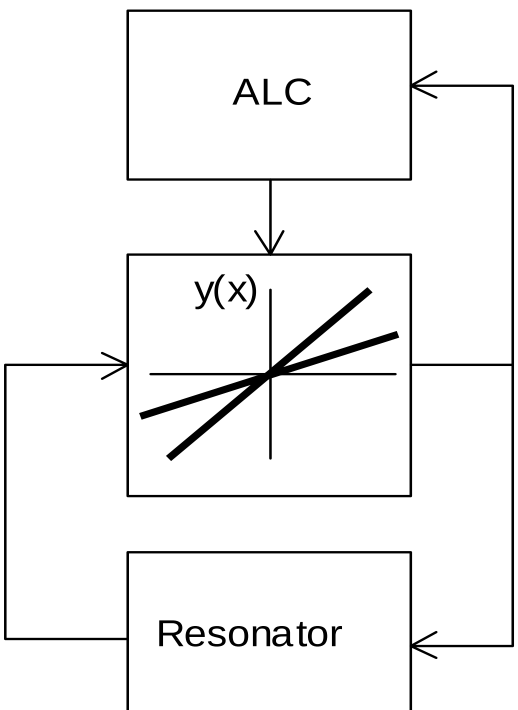
Steady-State Oscillation Signal Amplitude

Sub-Outline

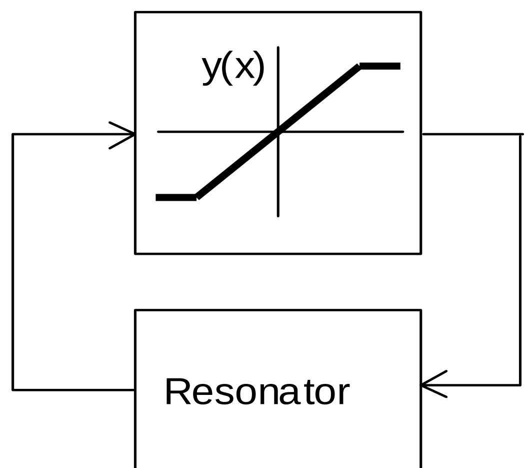
- Differential Pair Characteristic
- Large-Signal Conductance
- Steady-State Oscillation Signal Amplitude

Amplitude Stabilization

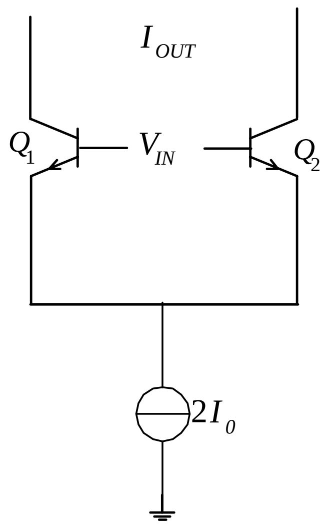
- Amplitude regulator
  - amplitude control mechanism

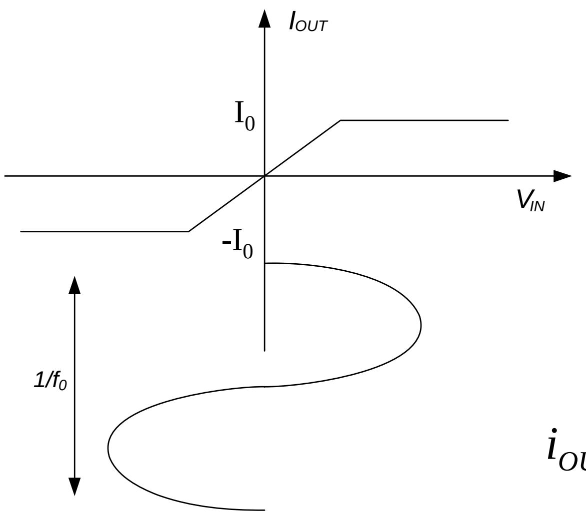


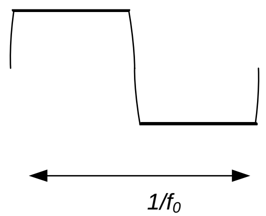
- Nonlinear amplifier
  - well defined nonlinearity
  - timing reference loss compensation
  - loop-gain control



Differential Characteristic







$$i_{OUT}(t) = I_0 \tanh\left(\frac{x}{2}\cos\omega t\right)$$

$$v_{IN}(t) = V_1 \cos\omega t$$

$$x = V_1 / V_T \qquad V_1 >> V_T$$

- current harmonic content

$$i_{OUT}(t) = I_1 \cos\omega t + I_3 \cos 3\omega t + I_5 \cos 5\omega t + \ldots = I_0 \sum_n a_{2n-1} \cos(2n-1)\omega t$$

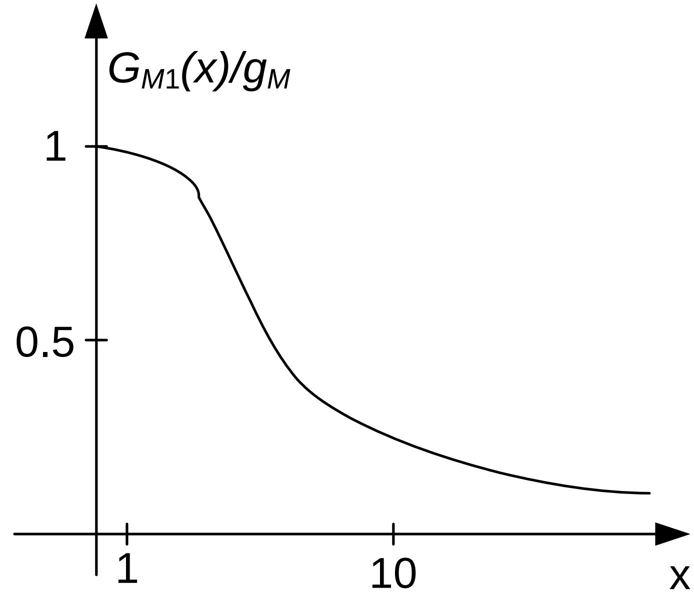
$$I_n(x) = I_0 a_n(x) \qquad a_n(x) = \frac{1}{\pi}\int_{-\pi}^{\pi} \tanh\left(\frac{x}{2}\cos\theta\right)\cos(n\theta)d\theta$$

Large Signal (Trans)Conductance

$$G_{M1}(x) = \frac{I_1}{V_1} = \frac{I_0}{V_T}\frac{V_T}{V_1}\frac{I_1}{I_0}$$

$$G_{M1}(x) = g_m \frac{1}{x}\frac{I_1}{I_0} = 2g_M \frac{a_1(x)}{x}$$

$$G_{M1}(x)/g_M = 2\frac{a_1(x)}{x}$$



- steady state oscillation condition

$$\left|G_{M1}(V_1)\cdot H_0(j\omega)\right| = 1$$

$$\left|\frac{G_{M1}(V_1)}{g_M}\cdot g_M H_0(j\omega)\right| = 1$$

$$\frac{\text{large signal fundamental (trans)conductance}}{\text{small signal trans(conductance)}} = \frac{1}{\text{small signal loop gain}}$$

Large Signal Components

- output current

$$i_{OUT}(t) = I_1 \cos \omega t + I_3 \cos 3\omega t + I_5 \cos 5\omega t + \ldots = I_0 \sum_{n=0}^{\infty} a_{2n-1} \cos(2n-1)\omega t$$

- close to square wave if $V_1 >> V_T$
- harmonics of the square-wave signal current

$$I_n = \frac{4I_0}{n\pi} = \frac{2I_{TAIL}}{n\pi}$$

Steady State Signal Amplitude

- large signal conductance and steady state oscillation condition

$$G_{M1}(V_1) = \frac{I_1}{V_1} = \frac{I_1}{I_{TAIL}} \frac{I_{TAIL}}{V_1} = \frac{2}{\pi} \frac{I_{TAIL}}{V_1} \qquad \frac{G_{M1}(V_1)}{g_M} = \frac{1}{k}$$

- small signal loop gain (*k*)

$$k = R_{TK} g_M$$

- steady state fundamental amplitude

$$V_1 = \frac{2}{\pi} I_{TAIL} R_{TK}$$

$$\text{voltage fundamental} = \text{tank resistance} \times \text{current fundamental}$$

So Far

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Interpretation of Noise in Oscillators

Sub-Outline

- Signal Phasor Description
- Signal Spectral Description
- Phase-Noise Definition
- Phase-Noise Specification

Bennett Noise Interpretation

- White noise spectrum (power spectral density)

$$N(f) = A$$

- One noise component (time domain)

$$n(t) = a_k \cos\left(\omega_k t + \theta_k\right)$$

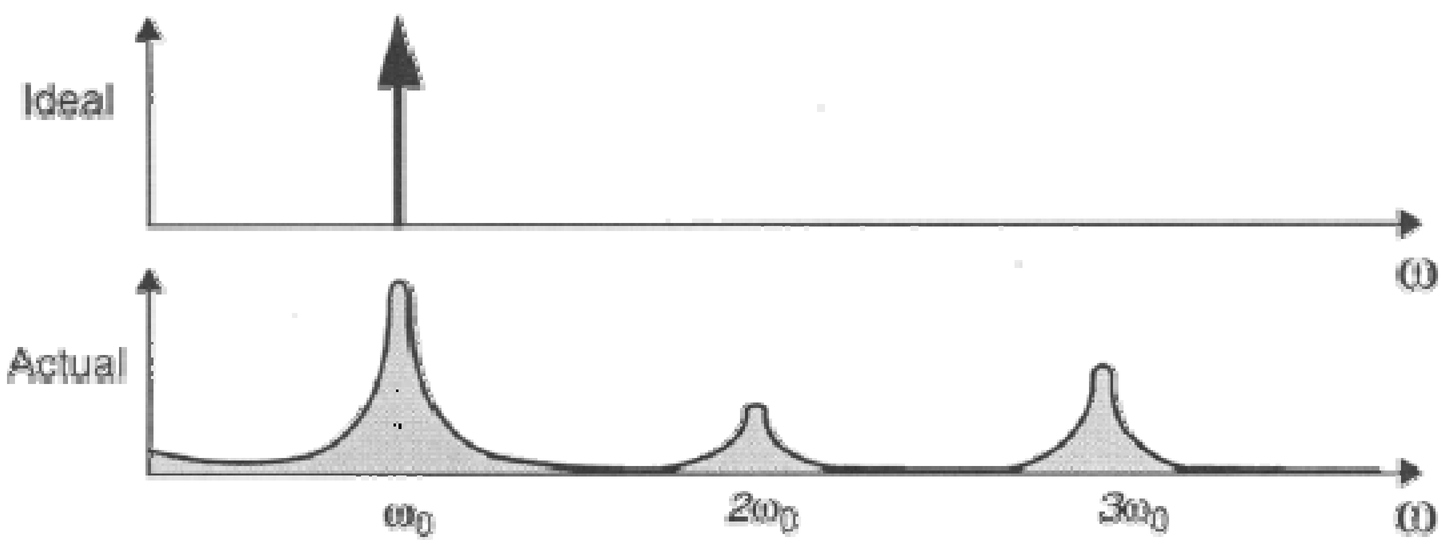
  - a_k – known amplitude $(= \sqrt{2A})$
  - ω_k – known angular frequency
  - θ_k – random phase (constant and uniform)

Oscillation Signal Description

- Ideal vs. actual oscillation signal

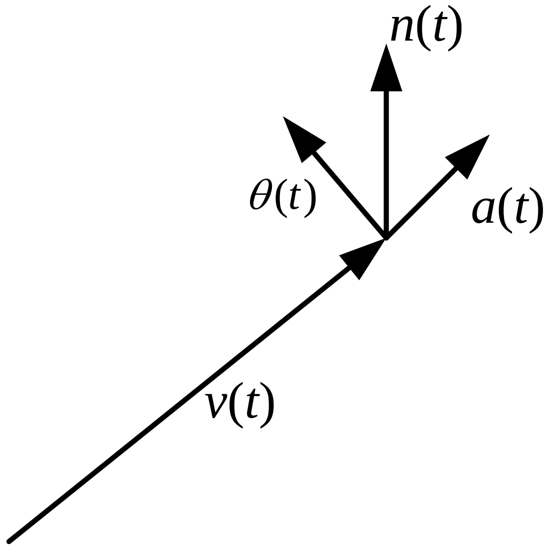
$V_0 cos\omega_0 t$ *vs.* $V_0[1+a(t)]cos[\omega_0 t+\theta(t)]$

  - a(t) amplitude modulated component
  - $\theta(t)$ phase modulated component



Oscillation Signal Phasor Description

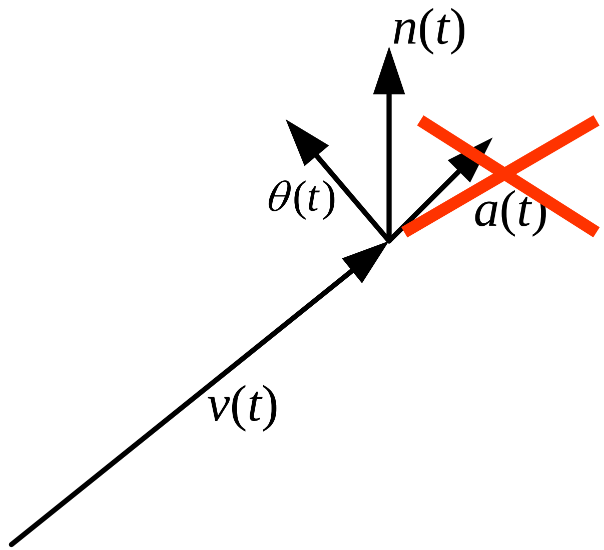
$$v(t)\Big|_{+n(t)} = [1 + a(t)]\cos\big(\omega_0 t + \theta(t)\big) \approx \cos\big(\omega_0 t\big) + a(t)\cos\big(\omega_0 t\big) - \theta(t)\sin\big(\omega_0 t\big)$$



- $a(t)$ in-phase component (AM) can be removed
- $\theta(t)$ quadrature-phase component (PM) is unavoidable

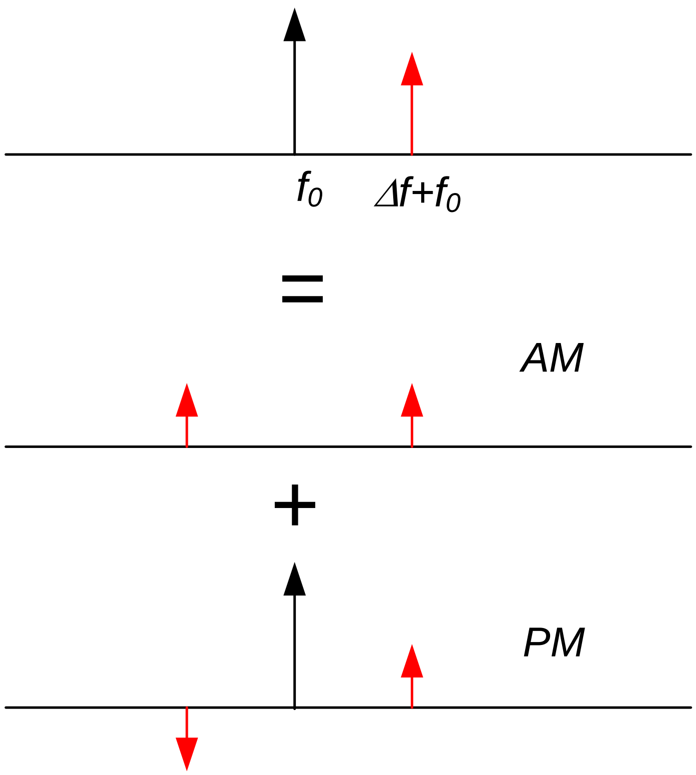
Oscillation Signal Phasor Description

$$v(t)\Big|_{+n(t)} = [1+a(t)]\cos\big(\omega_0 t + \theta(t)\big) \approx \cos\big(\omega_0 t\big) + a(t)\cos\big(\omega_0 t\big) - \theta(t)\sin\big(\omega_0 t\big)$$



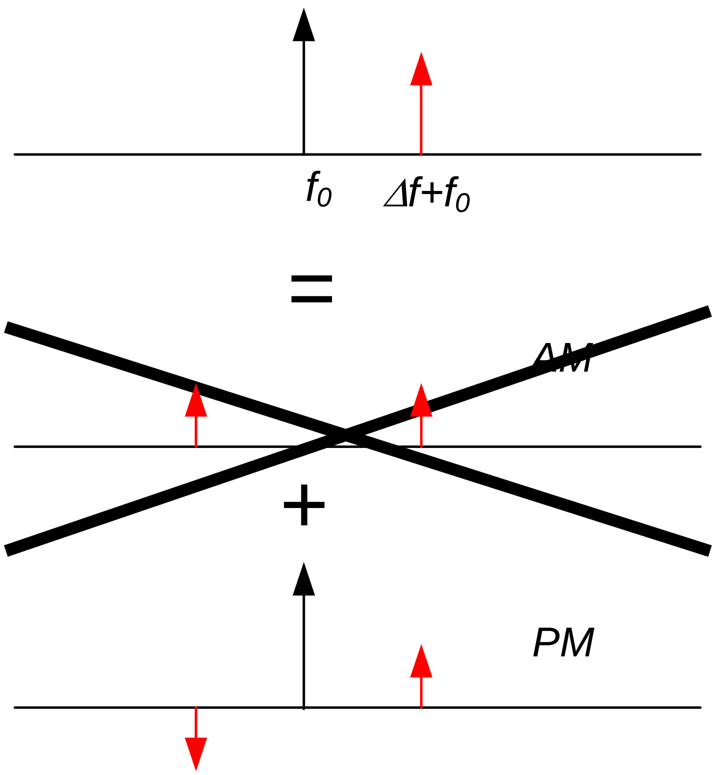
- amplitude control mechanism

Oscillation Signal Spectral Description



- oscillating signal and noise component
- amplitude modulated component
- phase modulated component

Oscillation Signal Spectral Description



• oscillating signal and noise component

• amplitude control mechanism

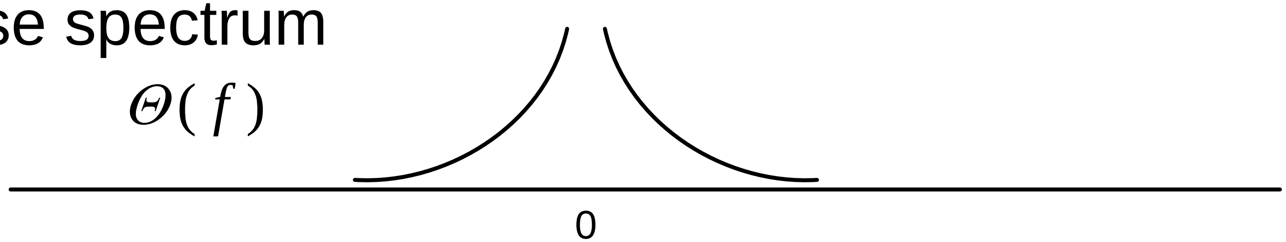
• phase modulated component

Phase Spectrum vs. Oscillation Signal Spectrum

$$v(t) = A\cos\left(\omega_0 t + \theta(t)\right) = A\cos\left(\omega_0 t + \theta_k \sin\left(\omega_k t + \phi_k\right)\right) \approx$$
$$\approx A\cos\left(\omega_0 t\right) - A\theta_k \sin\left(\omega_k t + \phi_k\right)\sin\left(\omega_0 t\right)$$

- phase spectrum

$\Theta(f)$



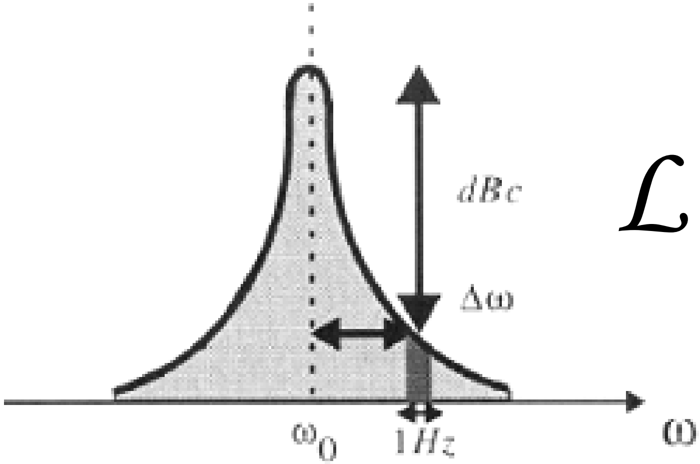
- oscillation signal spectrum

$$V(f) \approx \delta(f - f_0) + \delta(f + f_0) + \Theta(f - f_0) + \Theta(f + f_0)$$

Phase Noise Definition

• ratio of the noise power in a 1Hz bandwidth at frequency $f_0 + \Delta f$ and the carrier power

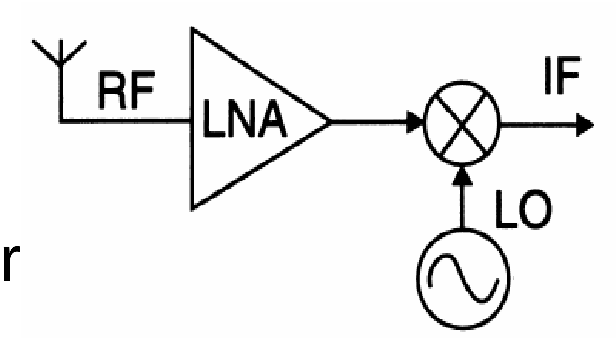
$$\mathcal{L}(\Delta\omega) = 10 log[P_{side\text{-}band}(\omega_0 + \Delta\omega)/P_{carrier}(\omega_0)] \quad [dBc/Hz]$$

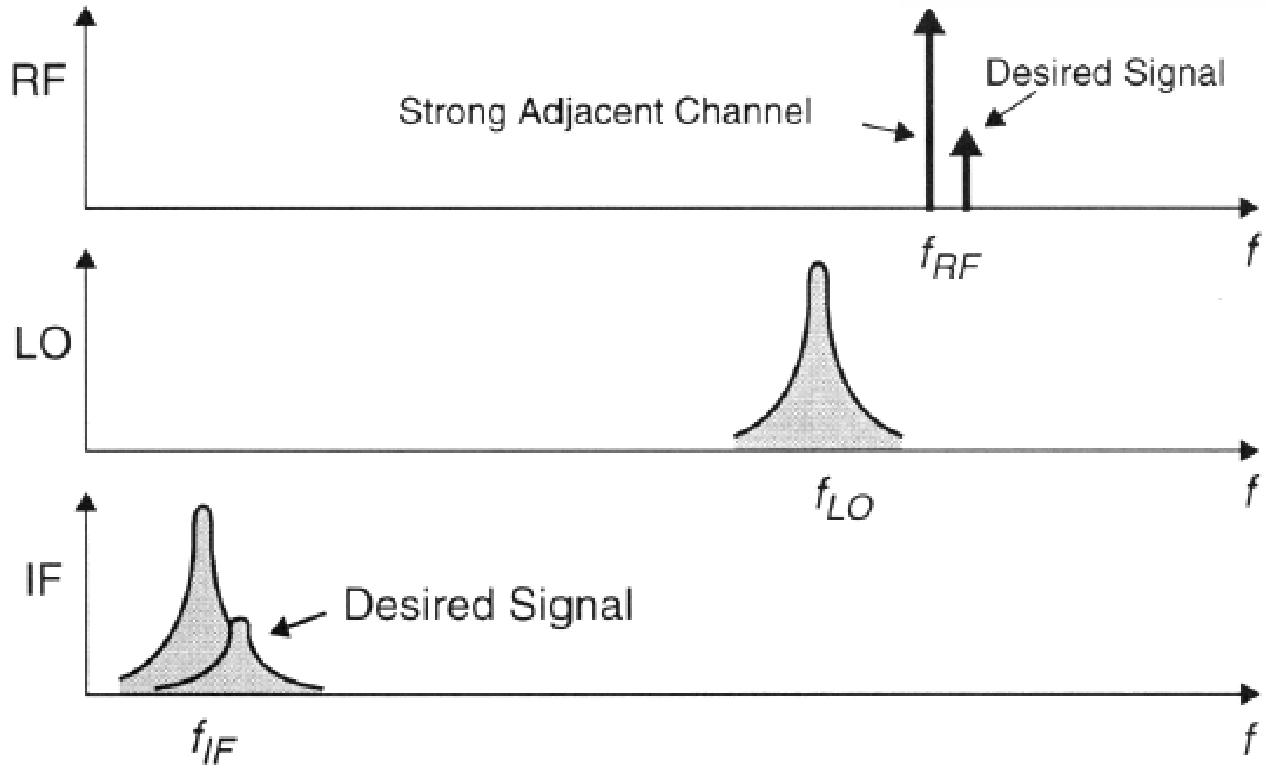


$\mathcal{L}$

Why is Phase Noise Important?

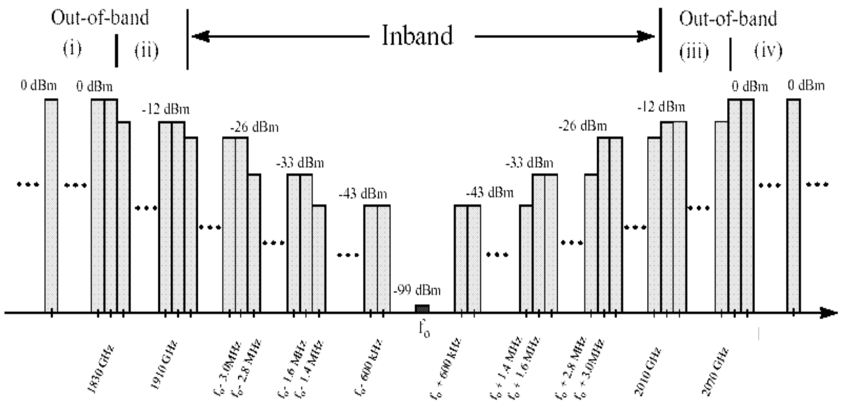
- *Reciprocal mixing*
  - desired signal covered by the phase-noise skirt of the interferer



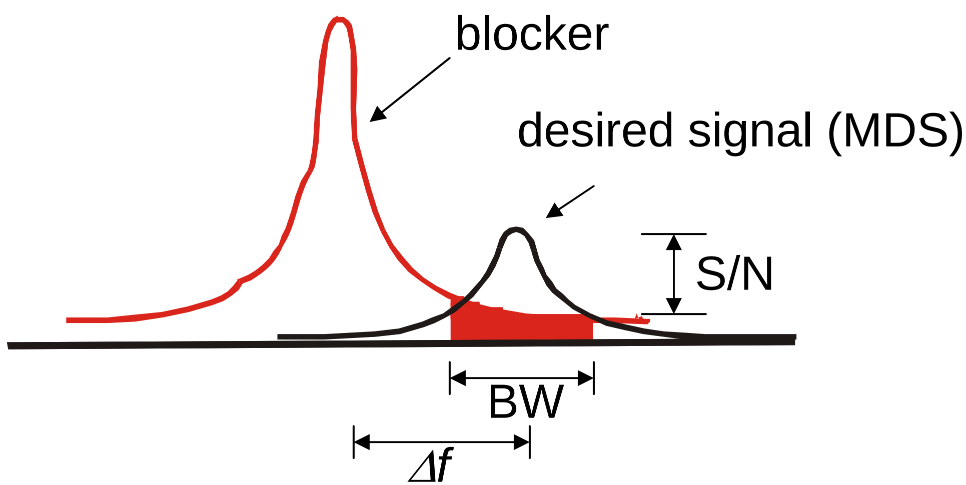


Phase Noise Specification

- Typical blocking profile



- Specra of downconverted signals



$S/N = S_{MDS} - N x BW$

$\mathcal{L} = N/S_{BLOCK}$

$\mathcal{L}(\Delta f) = S_{MDS} - S_{BLOCK} - 10 log BW - S/N$ [dBc/Hz]