MOS AK

Noise in RF Circuits and RF Noise Device Characterization

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Never stop thinking

RF Circuit Noise Characterization : Outline

- Overview:
  - Typical wireless architectures
  - Importance of noise for wireless communication
  - Semiconductor Noise Sources
- Noise in Linear Amplifiers
  - Noise Figure, Noise Temperature, Noise Measure
  - NF Measurement
  - Noise of Two-Ports
  - Characterization of 4 Noise Parameters
  - MOS model/characterization examples
  - LNA Example
- Noise in Mixer Circuits
  - Mixer Introduction
  - Cyclostationary Noise
  - Gilbert Mixer
- Noise in Oscillators
  - Basics and Requirements
  - Hajimiri and Leeson Theory
  - Typical VCO Circuit
  - Characterization

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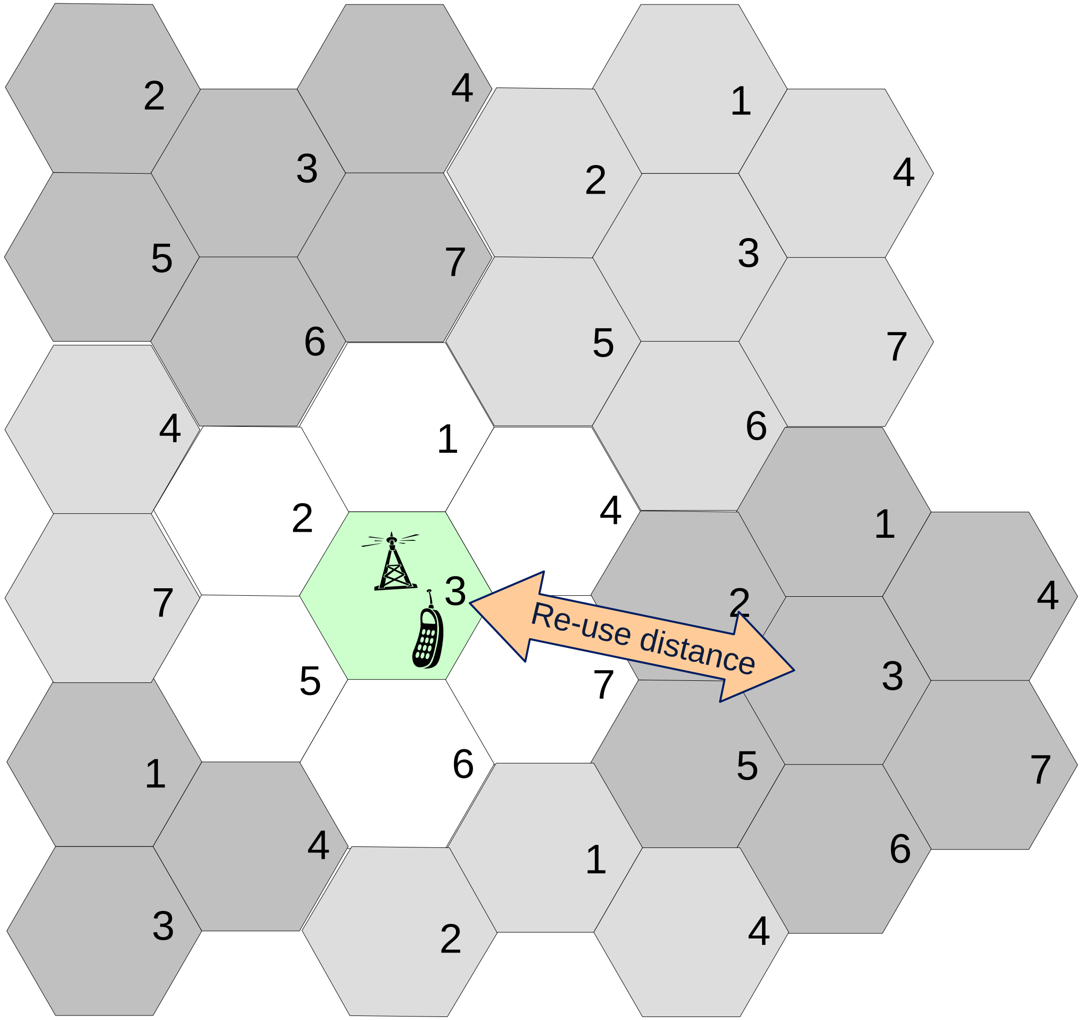
Cellular System



Cellular Structure

$$B_{Cell} = B \ / \ N_C$$

$$B_{UserChannel} = B_{Cell} \ / (N_{User} \ / \ N_{User\_per\_Channel})$$

B: Bandwidth of standard
(e.g. 2X35MHz for GSM-900)

Channel Capacity in the Presence of Noise

Shannon (Communication in the Presence of Noise 1948):

$$C = B \cdot \log_2 (1 + S / N)$$

$$C = B \cdot \log_2 \left(1 + \frac{P_0 B}{S_N B} \right)$$

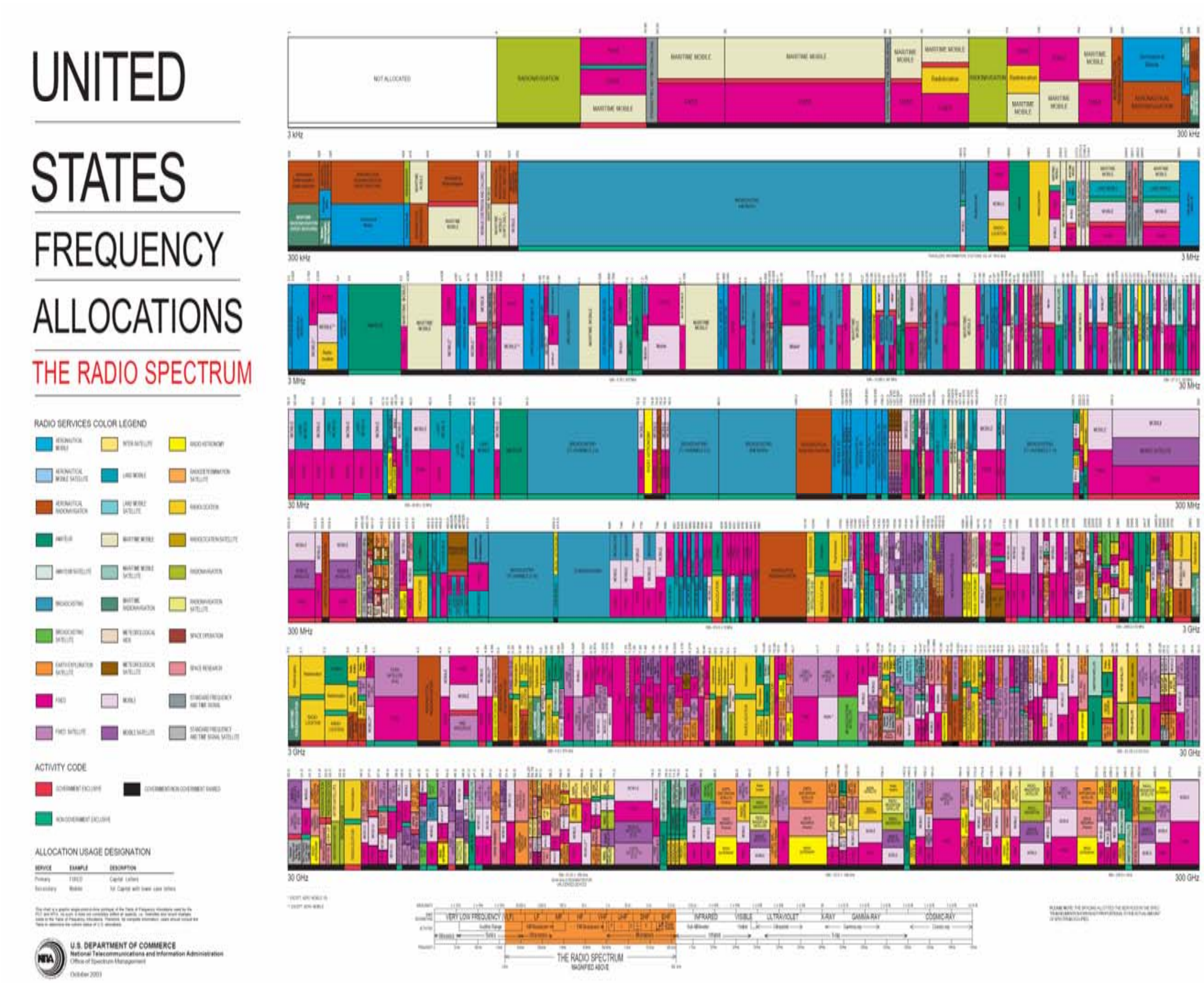
C: Channel Capacity (bit/s)
B: Bandwidth of channel
S/N: Signal to Noise
P_0: Signal Spectral Density
S_N: Noise Spectral Density

⇒Noise has direct impact on:

Channel capacity
Transmit Power (battery power)
Channel Bandwidth
Number of users per Bandwidth
Number of necessary Basestations
Maximum cell size

Increased Noise
=> Increased Cost

The Radio Frequency Spectrum



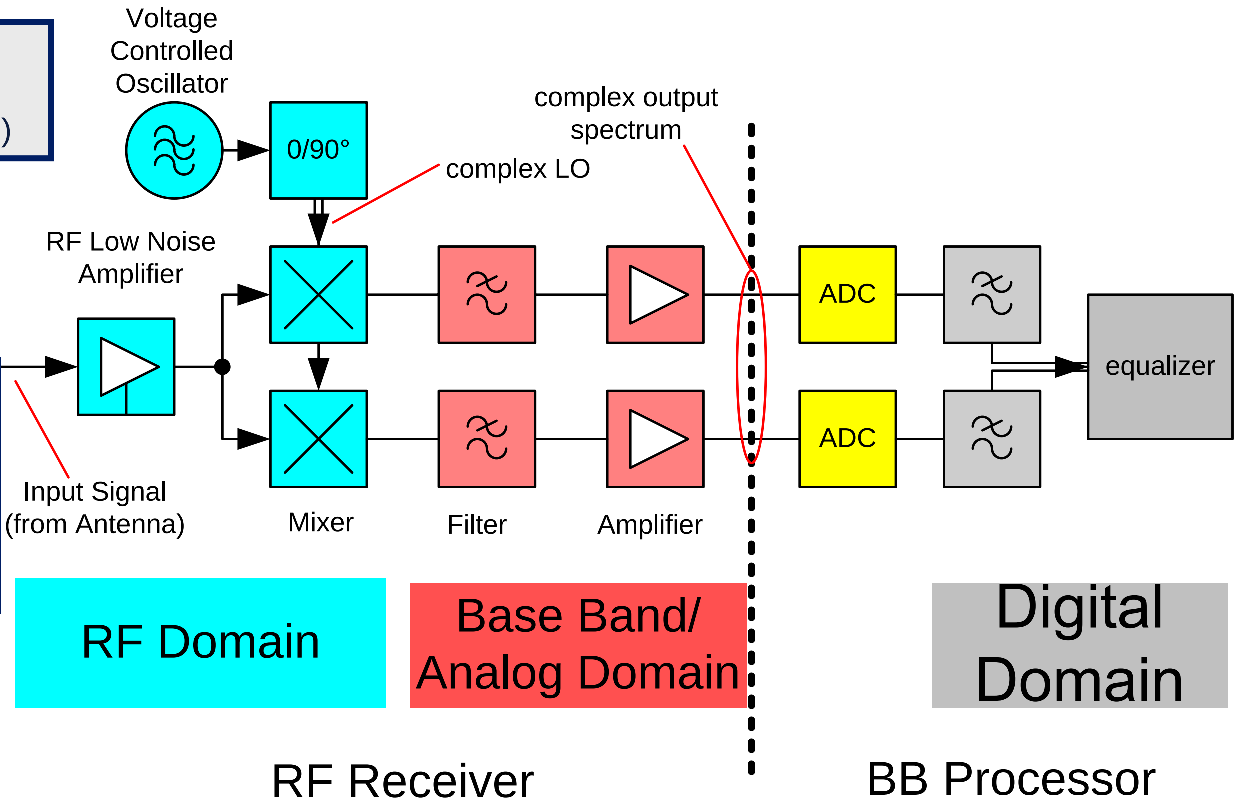
Complete Radio Spectrum 3kHz-30GHz is essentially used and occupied

Ultra Wide Band (UWB) to reuse frequency in short range applications:
Very wide bandwidth, but signal power below background noise.

Typical RF Receiver Architecture and some Requirements

GSM Channels:
200kHz seperation
(@0.9 and 1.8 GHz)

Input Signal:
~ µV
~ fW
~ 1E9 dynamic range
(power)
Strong interferers



Voltage Controlled Oscillator

0/90°

complex LO

complex output spectrum

RF Low Noise Amplifier

Input Signal (from Antenna)

Mixer

Filter

Amplifier

ADC

ADC

equalizer

RF Domain

Base Band/ Analog Domain

Digital Domain

RF Receiver

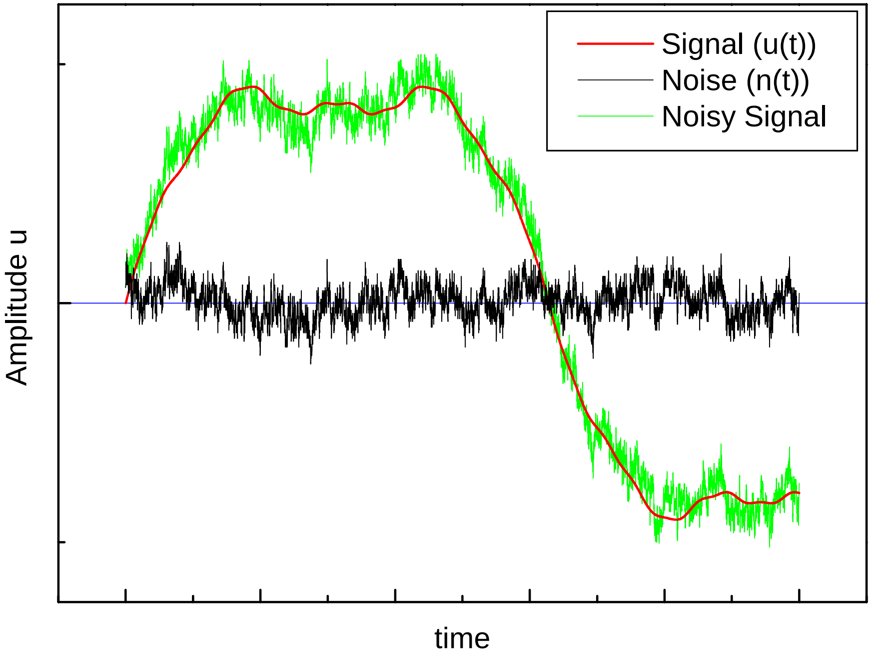
BB Processor

⇒RF Requirements:
High Speed Analog
Low Noise
High Linearity
Low Power

Some Noise Basics

Noisy Signal is composed of ideal signal and additive noise

$$u_n(t) = u(t) + n(t)$$



Time average of noise is zero

$$< n(t) >= \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} n(t)dt = 0$$

Mean square of noise

$$< n(t)^2 >= \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} n(t)^2 dt$$

Noise is assumed to be small perturbation of signal

⇒ Noise propagation in circuit can be described by linear small signal analysis

But Signal can be large

⇒ Time varying noise sources or noise propagation (Cyclostationary Noise)

Some Noise Basics

Correlation function between different noise sources

$$\rho_{12}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} n_1(t) \cdot n_2(t+\tau) dt$$

Autocorrelation of one noise source

$$\rho(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} n(t) \cdot n(t+\tau) dt$$

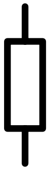
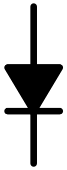
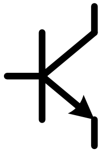
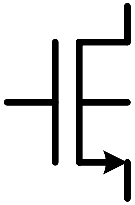
Fourier Transform of Autocorrelation
=> Spectral Power Density of Noise (Wiener-Khinchin Theorem)

$$S(f) = \int_{-\infty}^{\infty} \rho(\tau) \cdot \exp(-2\pi i f \tau) d\tau$$

Mean square is equivalent to total noise power

$$\int_0^\infty S(f) df = < n^2 >$$

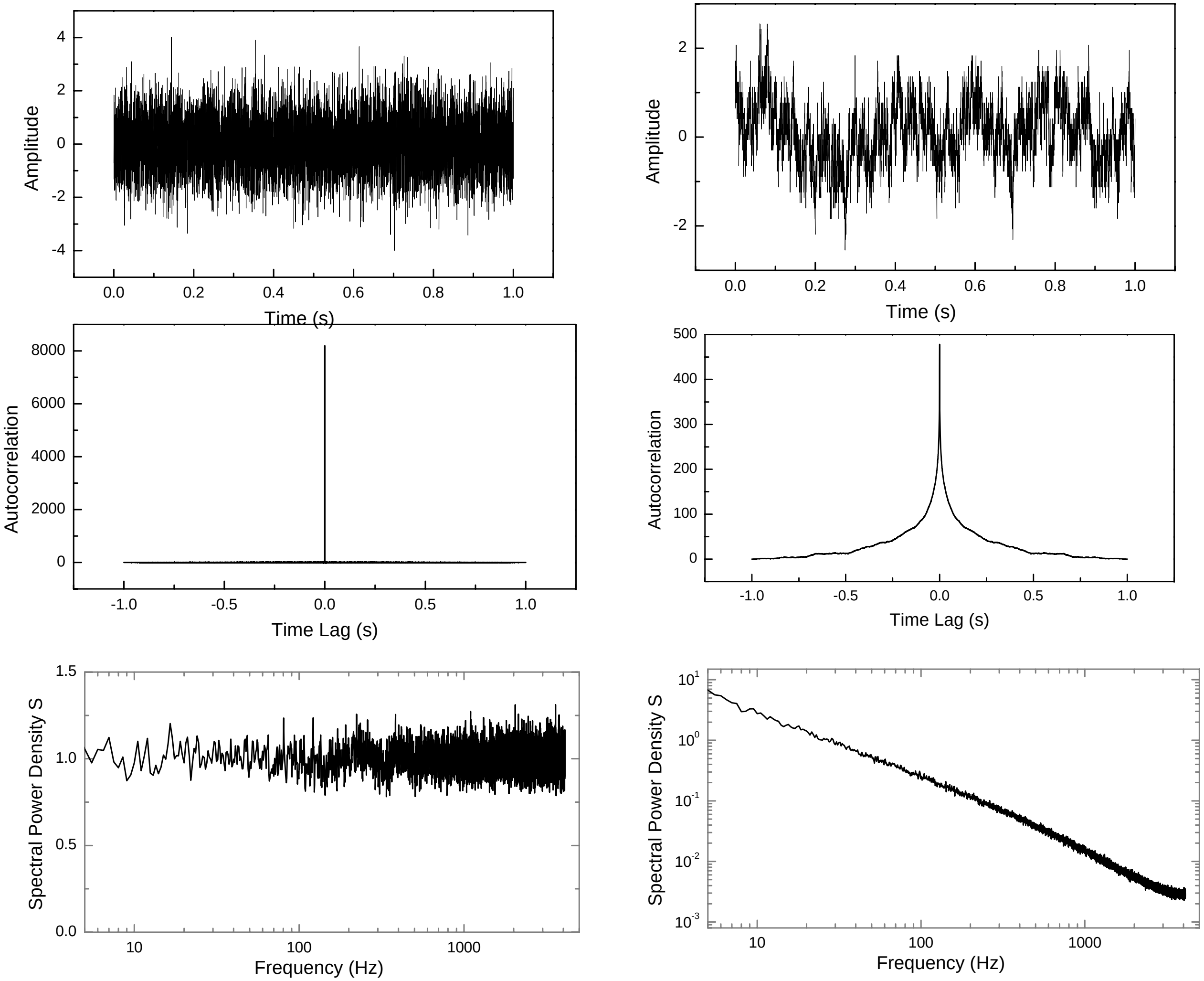
Typical Noise Sources in Devices

				
Thermal Noise $S(f)=kT$	√	√	√	√
Shot Noise $S(f)=2e\cdot I$		√	√	√
Flicker Noise $S(f)\propto\frac{I^{\alpha}}{f^{\beta}}$	√	√	√	√

Noise, Autocorrelation, Frequency and Time Domain

White Noise

Flicker Noise



Transient

Autocorrelation

Spectral Power Density

= Fourier Transform of Autocorrelation (Wiener Khinchin theorem)

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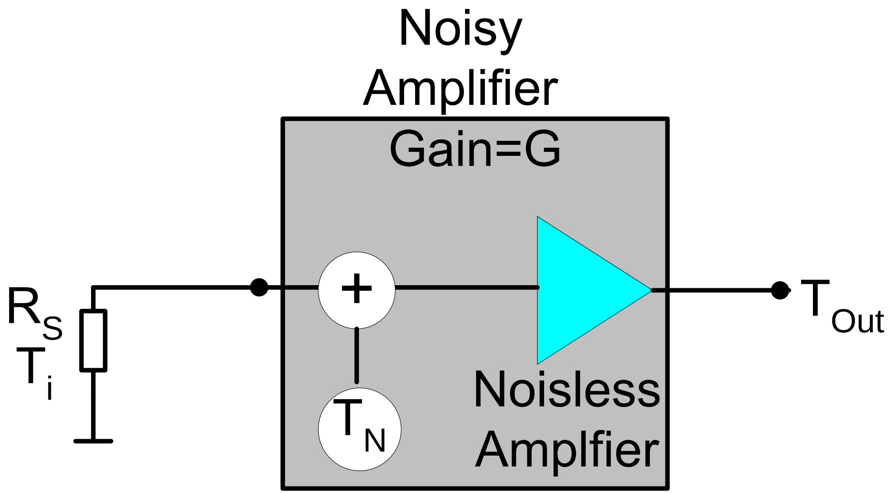
Matched Amplifiers (e.g.50Ohm): Noise Temperature



Thermal Noise:

$$N = k \cdot T \cdot B$$

Standard for T_i

$$T_i = 290K \Rightarrow kT = 4 \cdot 10^{-21} J/s$$

Output Noise Temperature

$$T_{Out} = G \cdot (T_i + T_N)$$

Matched Amplifiers (e.g.50Ohm): Noise Figure

$$F = \frac{(S/N)_i}{(S/N)_O} = \frac{N_O}{(S_O/S_i)N_i} = \frac{N_O}{G \cdot N_i}$$

$$N = k \cdot T \cdot B$$

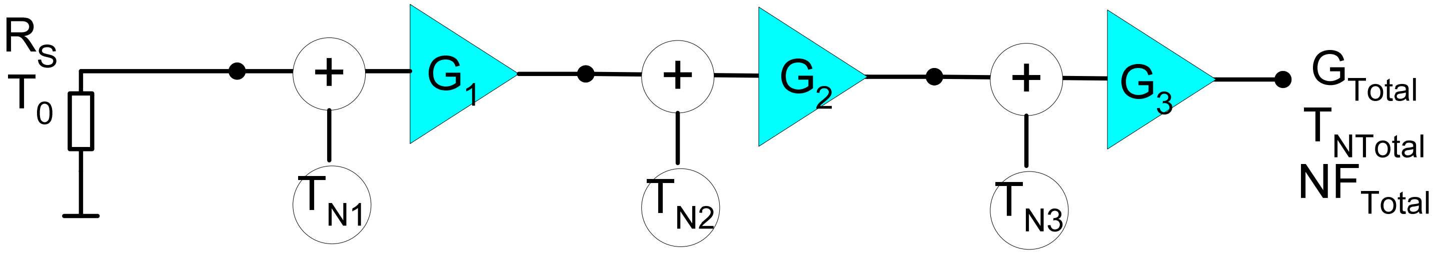
$$F = \frac{N_o}{G \cdot N_i} = \frac{T_o}{G \cdot T_i} = \frac{G \cdot (T_i + T_N)}{G \cdot T_i} = 1 + \frac{T_N}{T_i}$$

F	NF
1.0	0.0
1.1	0.4
1.3	1.0
2.0	3.0
10.0	10.0

$$T_i = 290K$$

$$NF = 10 \cdot \log_{10}(F)$$

Cascade of Amplifiers



$$G_{Tot} = G_1 \cdot G_2 \cdot G_3 \ldots$$

$$F = 1 + T_N / T_i$$

$$T_{NTotal} = T_{N1} + T_{N2} / G_1 + T_{N3} / (G_1 \cdot G_2) \ldots$$

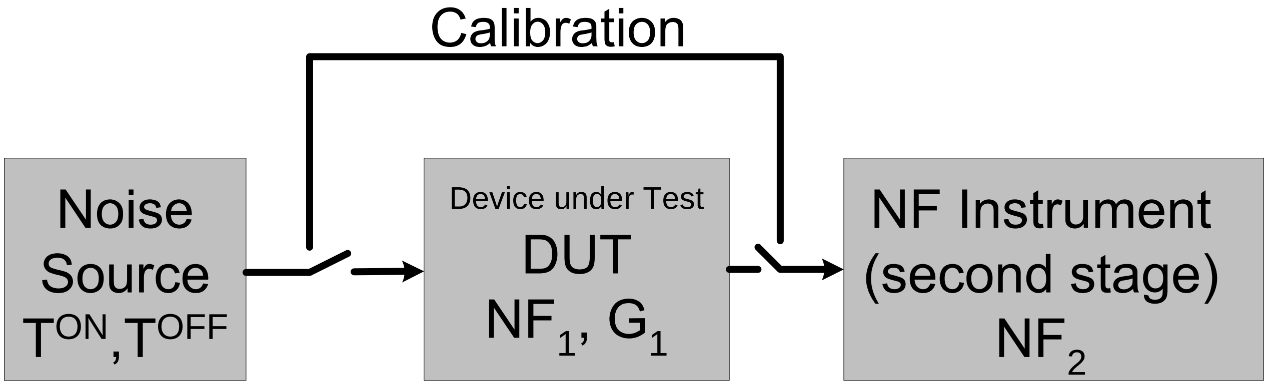
$$T_N = (F - 1) \cdot T_i$$

$$F_{Total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G2} \ldots$$

Formula of Friis

First Amplifier: Low noise figure
& high gain preferred

Noise Characterization: Y-Factor Method



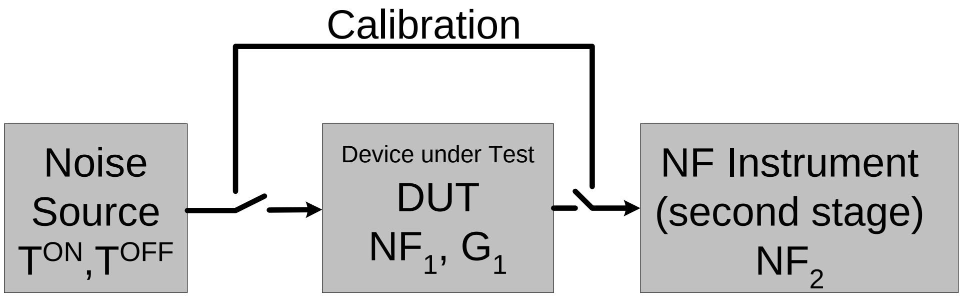
Noise Source: Two Noise Levels T_S^{OFF} T_S^{ON}

Excess Noise Ratio $ENR = (T_S^{ON} - T_S^{OFF}) / T_0$

Y-Factor $Y = N^{ON} / N^{OFF} = (T_S^{ON} + T_{Meas}) / (T_S^{OFF} + T_{Meas})$

Measured Noise $T_{Meas} = (T_S^{ON} - Y \cdot T_S^{OFF}) / (Y - 1)$

Noise Characterization: Y-Factor Method



Calibration

Noise Source T^{ON}, T^{OFF}

Device under Test

DUT

NF_1, G_1

NF Instrument (second stage)

NF_2

Calibration:

$$Y_2 = N_2^{ON} / N_2^{OFF}$$

$$T_2 = (T_S^{ON} - Y_2 \cdot T_S^{OFF}) / (Y_2 - 1)$$

Measurement with DUT:

$$Y_{12} = N_{12}^{ON} / N_{12}^{OFF}$$

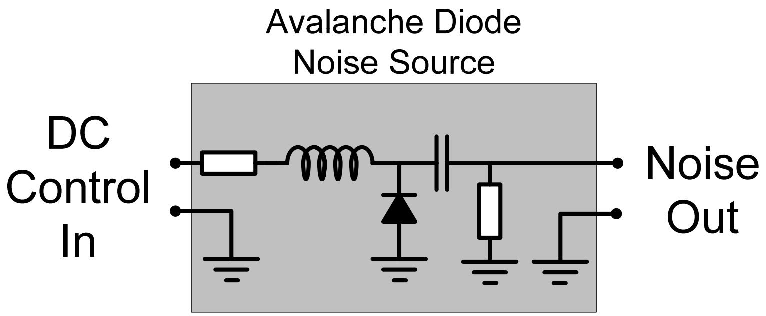
$$T_{12} = (T_S^{ON} - Y_{12} \cdot T_S^{OFF}) / (Y_{12} - 1)$$

second stage correction

$$G_1 = (N_{12}^{ON} - N_{12}^{OFF}) / (N_2^{ON} - N_2^{OFF})$$

$$T_1 = T_{12} - T_2 / G_1$$

Avalanche Diode Noise Source



$$ENR = (T_S^{ON} - T_S^{OFF}) / T_0$$

Standard ENR values:
5.2dB, 15.2dB

Diode in avalanche break down for high noise temperature

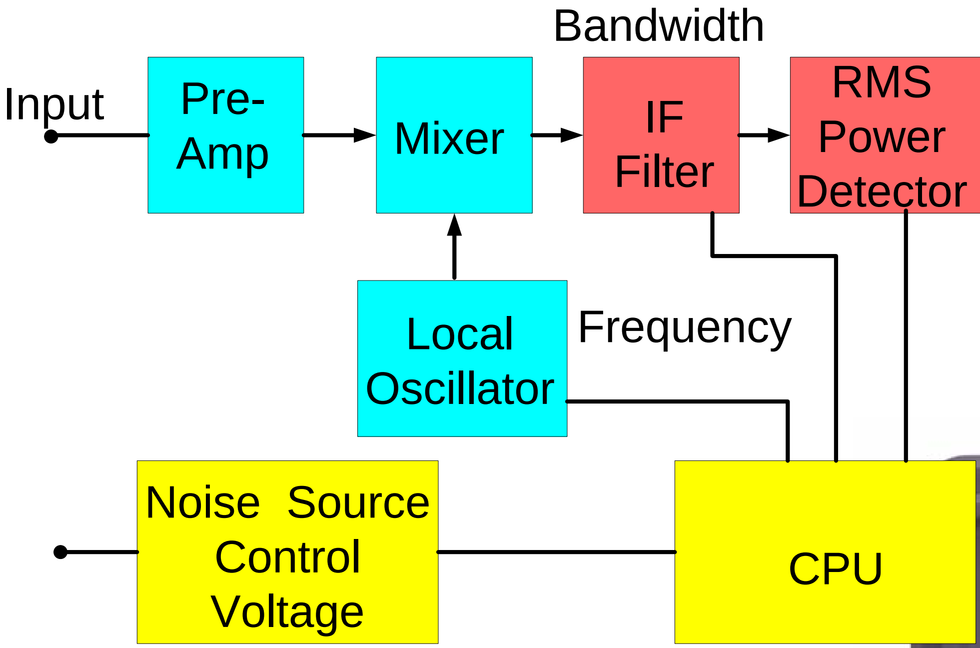
$\Rightarrow$ High noise temperature of Diode (e.g. 300kK)

$\Rightarrow$ Attenuator to reduce impedance difference T^{ON} vs. T^{OFF}

$\Rightarrow$ Fast switch between on/off

$\Rightarrow$ Calibration with thermal noise source

Noise Figure Analyzer


Bandwidth

Input

Pre-Amp

Mixer

IF Filter

RMS Power Detector

Local Oscillator

Frequency

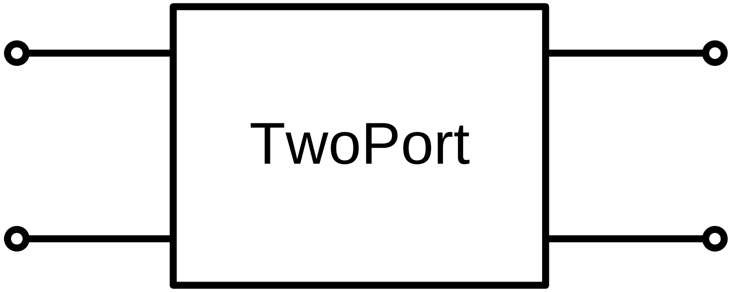
Noise Source Control Voltage

CPU

Tuned Superhet Receiver:
Oscillator sets measurement frequency
IF Filter sets measurement bandwidth


Input   Noise Source Ctrl.

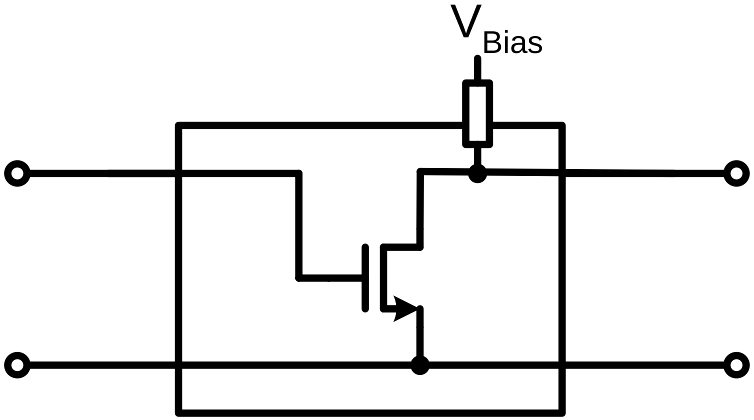
General Impedance: Linear Two Ports



Two-port:“Black box“ with 2 RF ports
(= 4 Terminals)

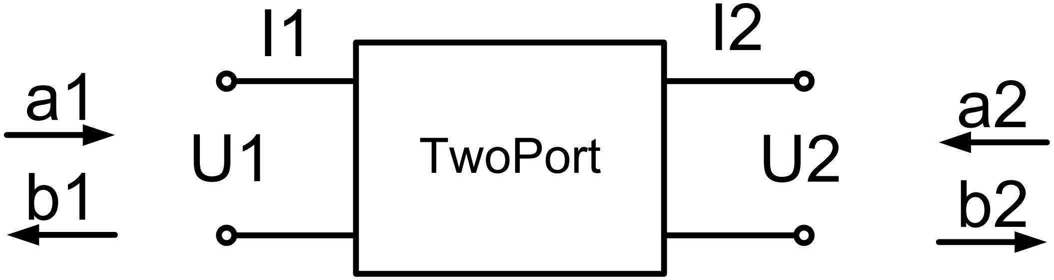
Noise=small signal => linear 2-ports

Non RF connections (e.g. biasing, supply) are not considered



Example for In and Out ports of a transistor amplifier

Two Port Basics


I1

I2

a1

b1

U1

TwoPort

U2

a2

b2

a,b: Amplitudes
of incoming
and refl. waves

$$b = \frac{U_{\mathrm{Re}\,fl}}{\sqrt{Z_0}}$$

$$a = \frac{U_{In}}{\sqrt{Z_0}}$$

Common Y,Z,A,S – Parameter representation of two-ports

Y $$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix}$$

Z $$\begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

S $$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

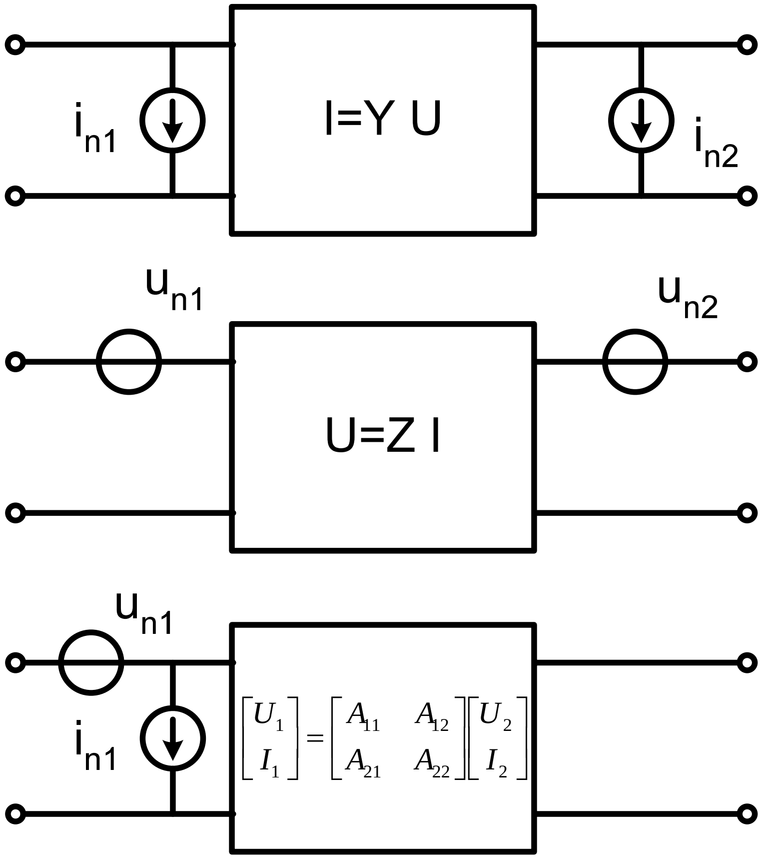
A $$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix}$$

Transistor: Two-port parameters are a function of bias and frequency

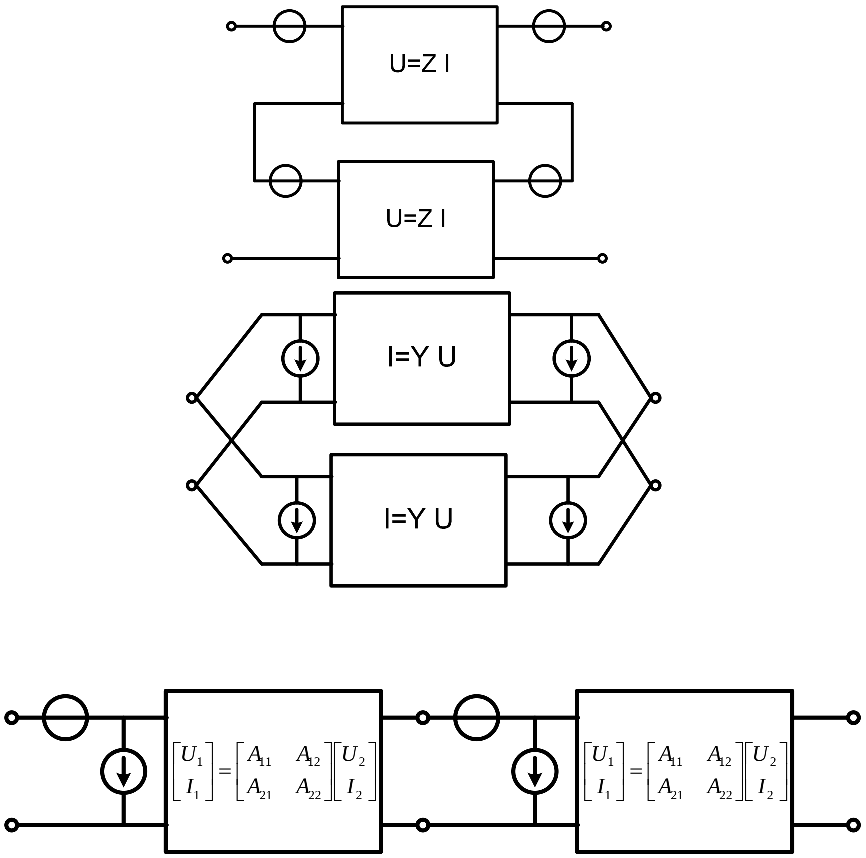
Two Port Basics

Two noise sources are necessary

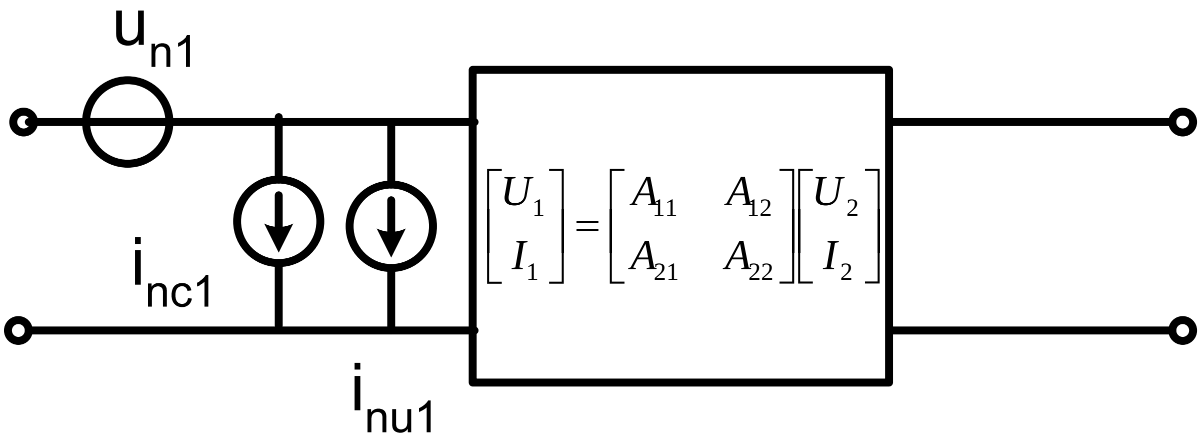
Convenient: Add noise sources for dependent quantities



Combination of two-ports



Noise in Two Ports: Correlation of Noise Sources



Noise sources can be partially correlated

$i_{nc1} = Y_C \cdot u_{n1}$ ⇒ Two-port has 4 Noise Parameters

Uncorrelated part u_{n1} i_{nu1}

Noise in Two Ports: Correlation Matrices

General approach with correlation matrices:

$$C_Z = \frac{1}{2B} \begin{bmatrix} \overline{u_{n1} \cdot u_{n1}^*} & \overline{u_{n1} \cdot u_{n2}^*} \\ \overline{u_{n2} \cdot u_{n1}^*} & \overline{u_{n2} \cdot u_{n2}^*} \end{bmatrix}$$

$$C_Y = \frac{1}{2B} \begin{bmatrix} \overline{i_{n1} \cdot i_{n1}^*} & \overline{i_{n1} \cdot i_{n2}^*} \\ \overline{i_{n2} \cdot i_{n1}^*} & \overline{i_{n2} \cdot i_{n2}^*} \end{bmatrix}$$

$$C_A = \frac{1}{2B} \begin{bmatrix} \overline{u_{n1} \cdot u_{n1}^*} & \overline{u_{n1} \cdot i_{n1}^*} \\ \overline{i_{n1} \cdot u_{n1}^*} & \overline{i_{n1} \cdot i_{n2}^*} \end{bmatrix}$$

Hermitian 2X2 Matrix:

4 Parameters:

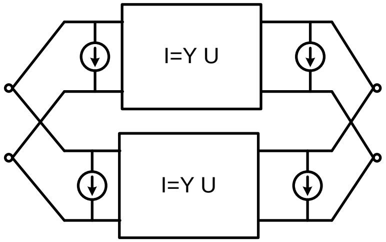
-2 real diagonal elements
  => Strength of noise source
-1 complex off diagonal element
  => Correlation of noise sources

Passive two-ports:

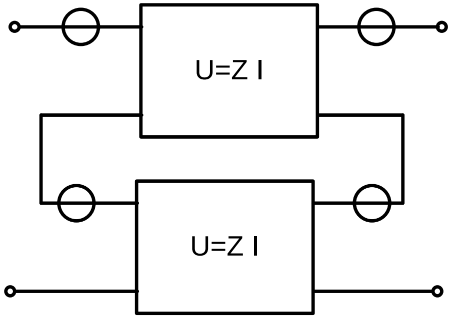
$$C_Z = 2 \cdot k \cdot T \cdot \mathrm{Re}\{Z\}$$
$$C_Y = 2 \cdot k \cdot T \cdot \mathrm{Re}\{Y\}$$

Noise in Two Ports: Combining Two Ports and Correlation Matrices

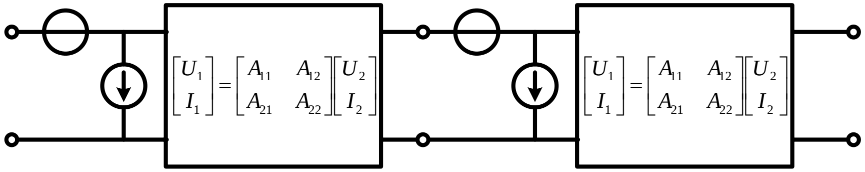
Combination of two-ports



$$C_Y = C_{Y1} + C_{Y2}$$



$$C_Z = C_{Z1} + C_{Z2}$$



$$C_A = C_{A1} + A_1 \cdot C_{Z2} \cdot A_1^t$$

Noise in Two Ports: Transforming Correlation Matrices

Correlation matrices can be transformed between different representations by matrix transforms

$$C' = T \cdot C \cdot T^{+}$$

Transformation
Matrices T:

From (C)

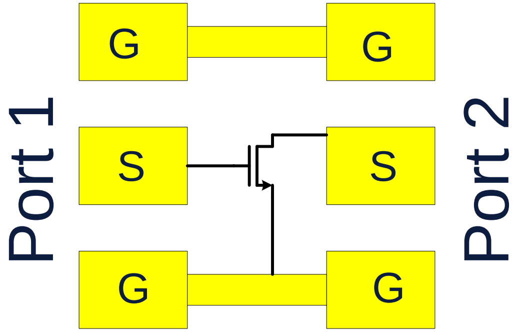
To (C‘)

	Y	Z	A
Y	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$	$\begin{bmatrix} -Y_{11} & 1 \\ -Y_{21} & 0 \end{bmatrix}$
Z	$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & -Z_{11} \\ 0 & -Z_{21} \end{bmatrix}$
A	$\begin{bmatrix} 0 & A_{12} \\ 1 & A_{22} \end{bmatrix}$	$\begin{bmatrix} 1 & -A_{11} \\ 0 & -A_{21} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

Noise Deembedding with Correlation Matrices

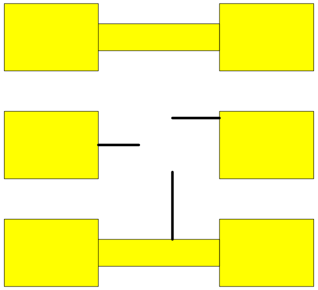
Measurement

Device Teststructure



S-Param.
C Noiseparam.

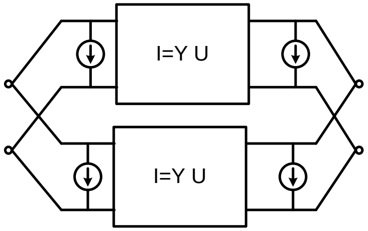
Open Deemb.



S-Param.

Deembedding Steps

Device



Pad-Cap.

$$S \Rightarrow Y$$

$$C \Rightarrow C_Y$$

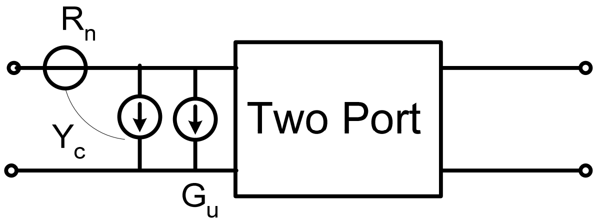
$$S_{Open} \Rightarrow Y_{Open}$$

$$C_{Y-Open} = 2kT \cdot \mathrm{Re}\{Y_{Open}\}$$

$$Y_{Deemb} = Y - Y_{Open}$$

$$C_{Y-Deemb} = C_Y - C_{Y-Open}$$

How to Measure the Noise Correlation Matrix?



4 Noise Par.

$$\overline{u_n}^2 = 4\cdot kT\cdot R_n\cdot B$$
$$\overline{i_n}^2 = 4\cdot kT\cdot G_u\cdot B$$
$$i_{nc} = Y_c\cdot u_n$$

⇔

Equivalent

Correlation Matrix

$$C$$

Noise figure F is a function of source impedance Y_s

$$Y_s = G_s + j\cdot B_s \qquad \overline{i_s}^2 = 4\cdot kT\cdot G_s\cdot B$$

$$F = 1 + \frac{\overline{i_n}^2 + \left|Y_C + Y_S\right|\cdot\overline{u_n}^2}{\overline{i_s}^2} \Longrightarrow F = F_{\min} + \frac{R_n}{G_s}\left[\left(G_s - G_{Opt}\right)^2 + \left(B_s - B_{Opt}\right)^2\right]$$

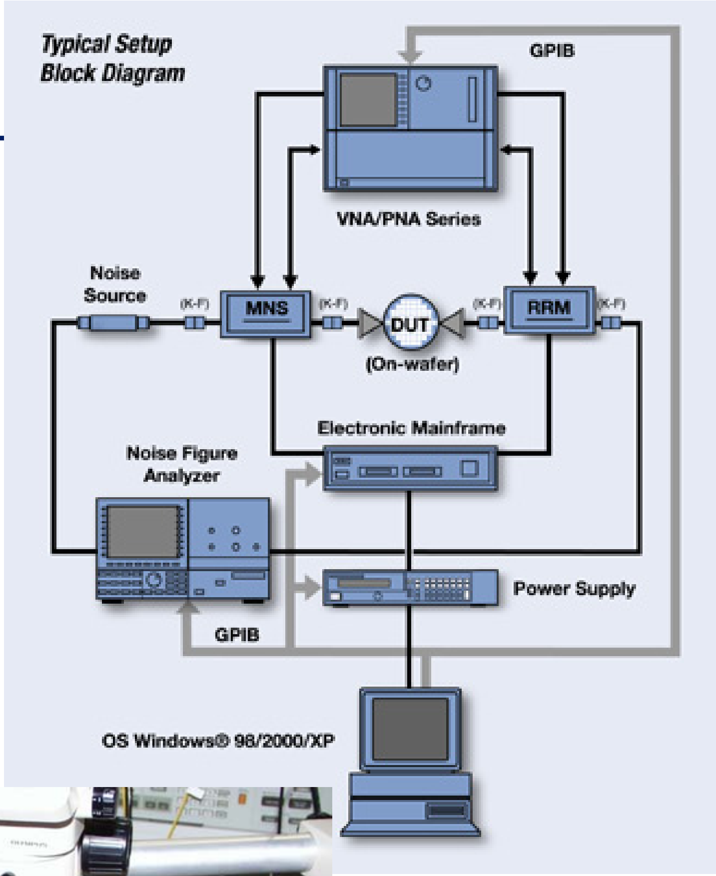
Again 4 equivalent noise parameters:

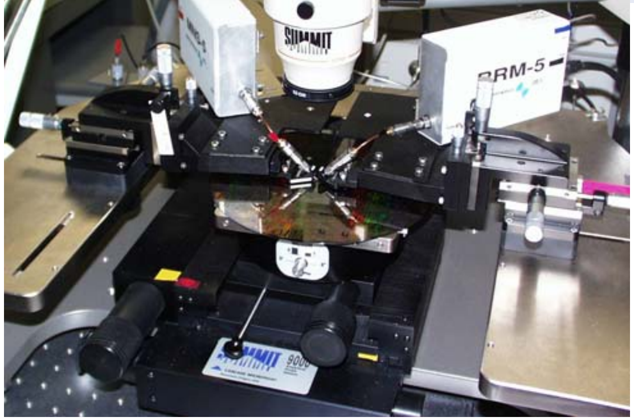
$$F_{\min} \qquad R_n \qquad Y_{S-Opt} = G_{Opt} + j\cdot B_{Opt}$$

Noise Parameter Test System

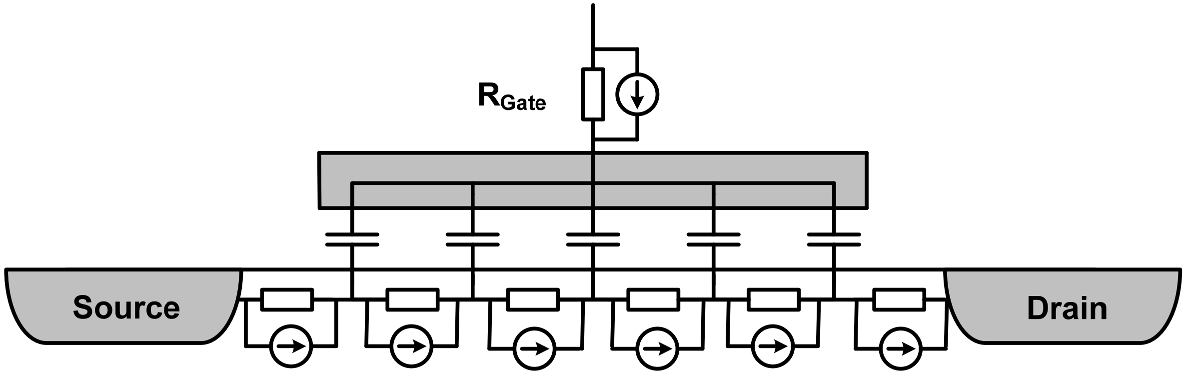
$$F = F_{\min} + \frac{R_n}{G_s}\left[\left(G_s - G_{Opt}\right)^2 + \left(B_s - B_{Opt}\right)^2\right]$$

- MNS (mismatch noise source): Tuner for source impedance variation
- Basic procedure:
  Measure F@$Y_{1,2,3,4}$
  Fit F(Y) to esitmate
  Fmin,Rn,Gop,Bopt





Noise Sources in the MOS Transistor



- Local noise sources related to channel resistance
- Additional noise sources: parasitic resistances (e.g. RGate)

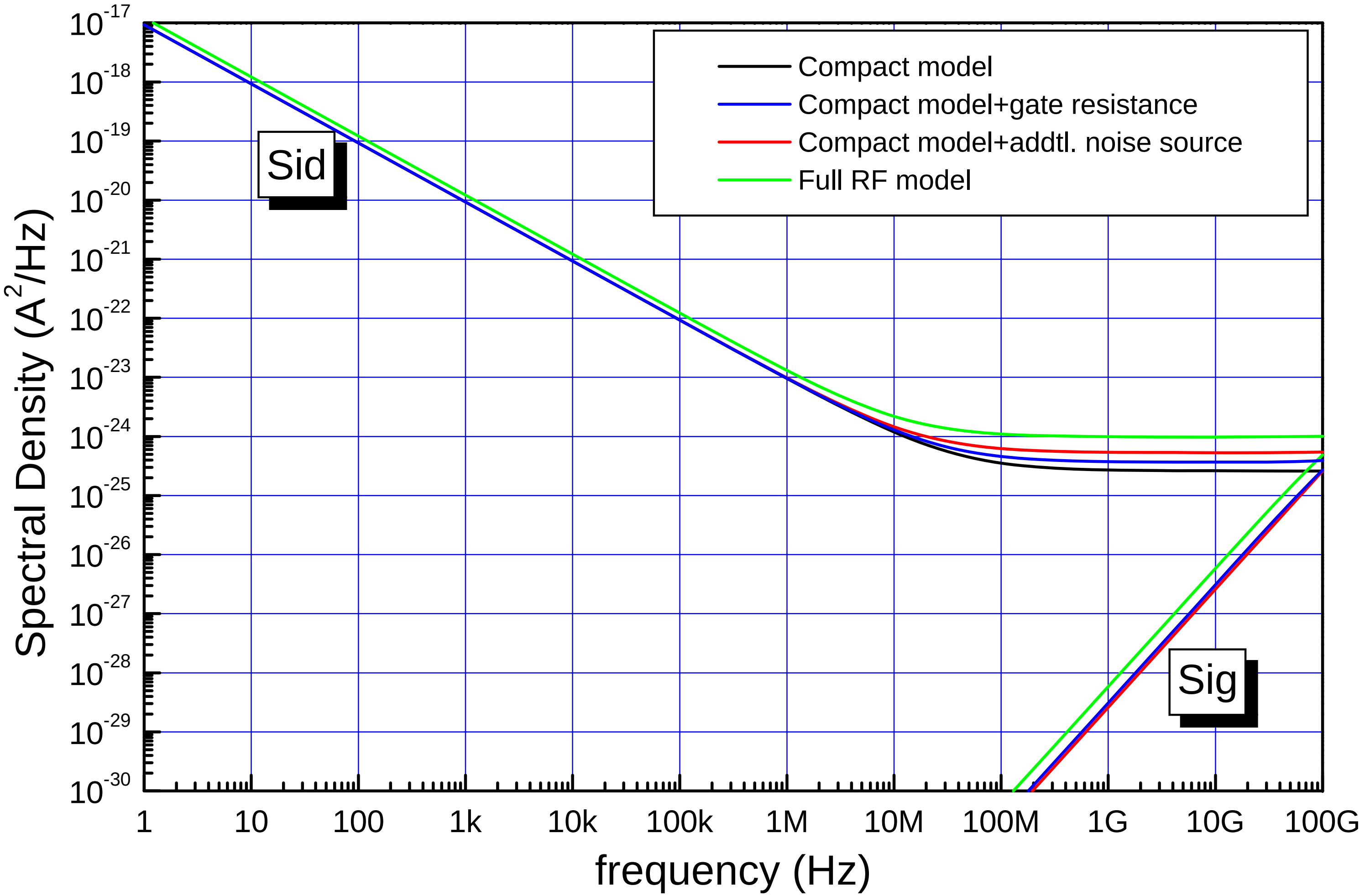
- Transfer of local channel noise sources to terminal noise: Klaassen-Prins equation

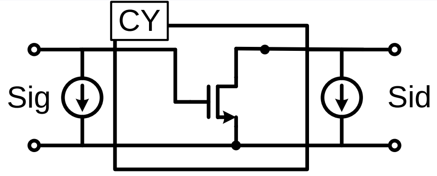
Thermal Channel Noise: $$S_{id} = i_d^2 = \quad 4 \cdot k_B \cdot T \cdot g_m \cdot \gamma \quad \sim \frac{W}{L}$$

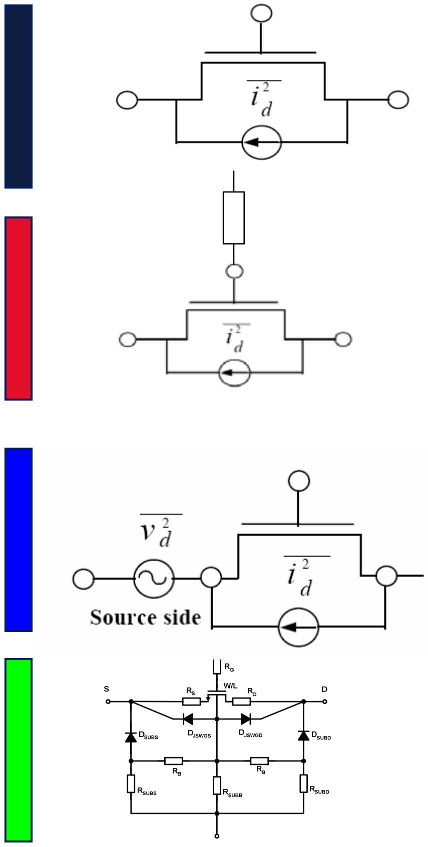
Induced Gate Noise: $$S_{ig} = i_g^2 = \quad 4 \cdot k_B \cdot T \cdot \frac{\omega^2 \cdot C_{gs}^2}{5 \cdot g_m} \cdot \delta \quad \sim \quad W \cdot L^3$$

Correlation Coefficient: $$c = \frac{i_g \cdot i_d^*}{\sqrt{i_g^2 \cdot i_d^2}} = \quad i \cdot 0.395$$

Gate and Drain Noise Spectral Density for different model topologies (130nm Technology) in BSIM4.3

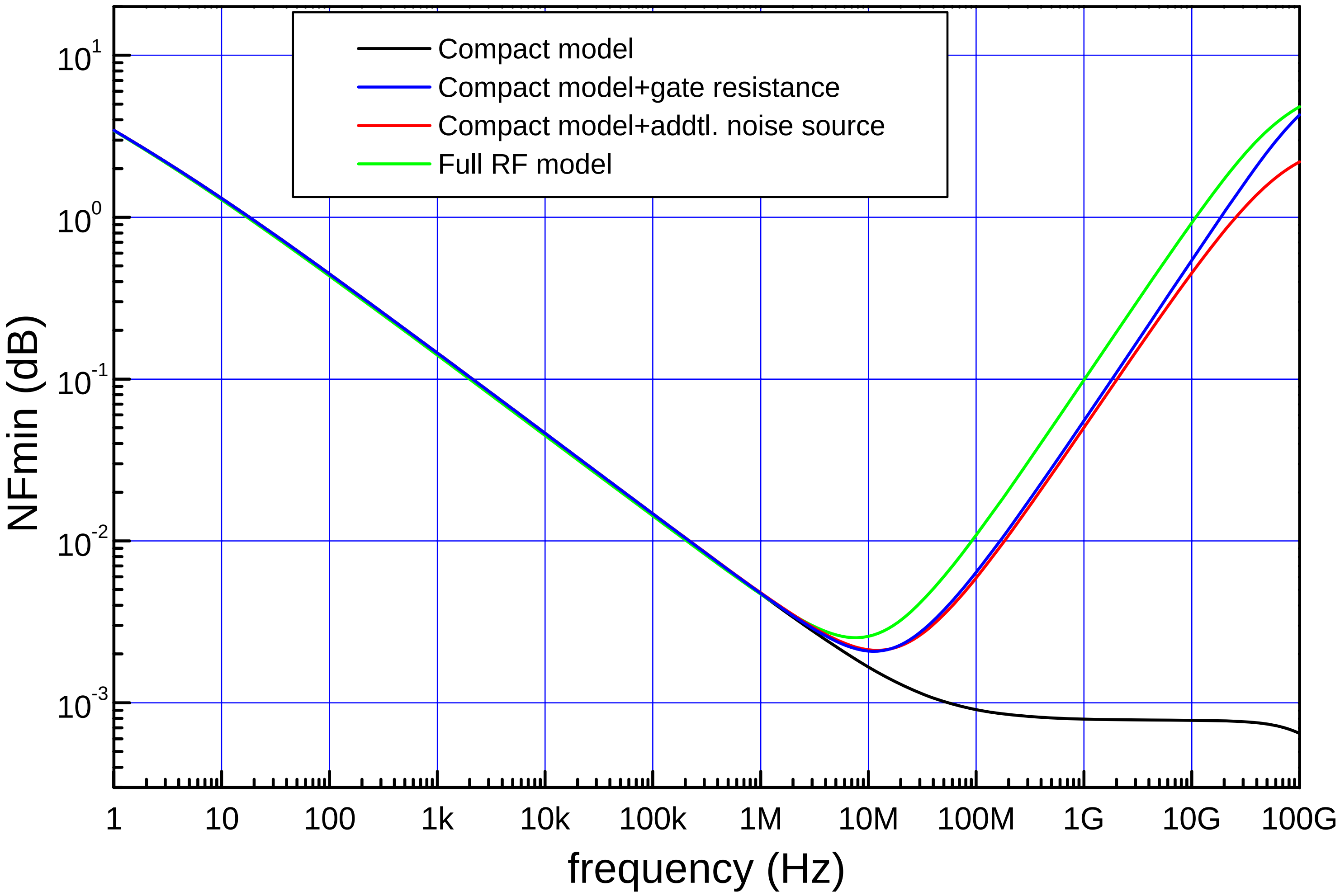


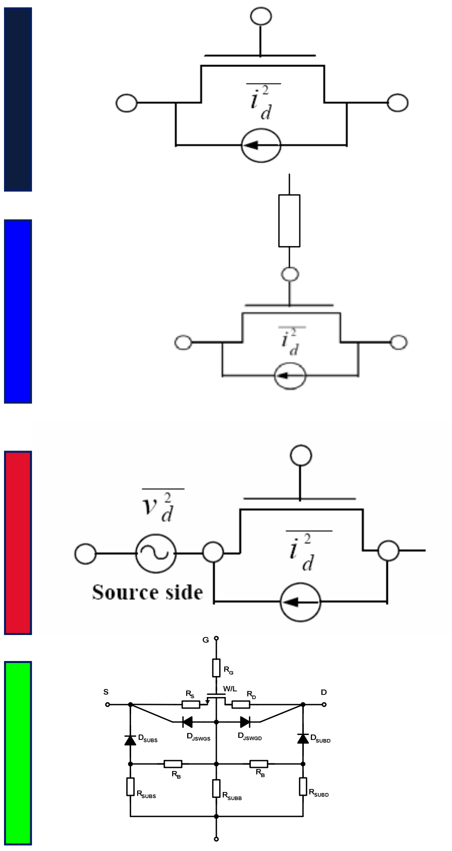




Full RF model (shown subcircuit is only an example)

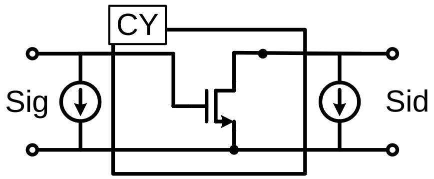
Noise Figure for different model topologies (130nm Technology)



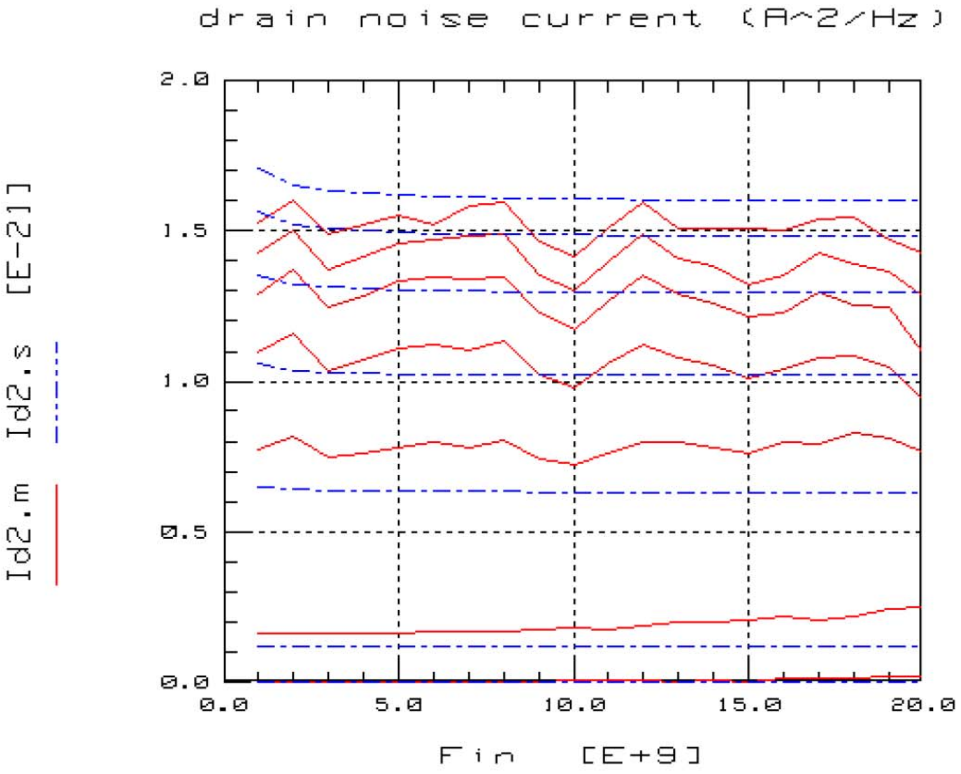


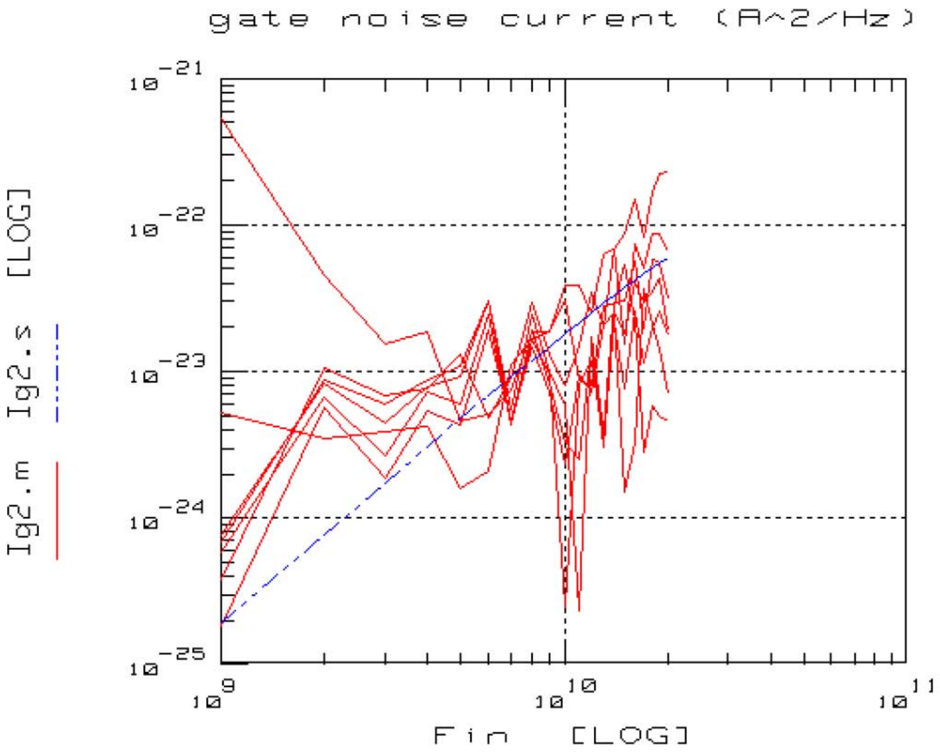
Full RF model (shown subcircuit is only an example)

RF Transistor Characterization / Model Examples (400nm IO Device)

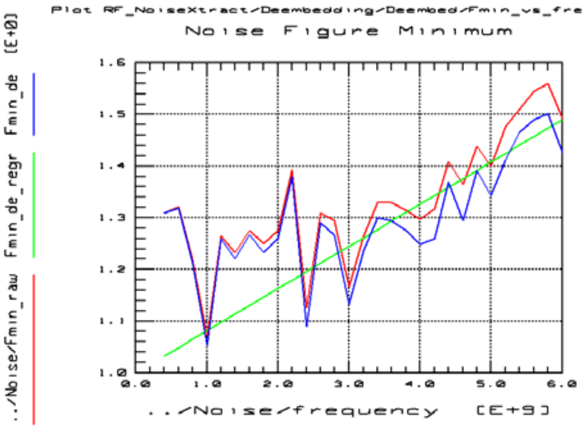


Characterization vs.
Model

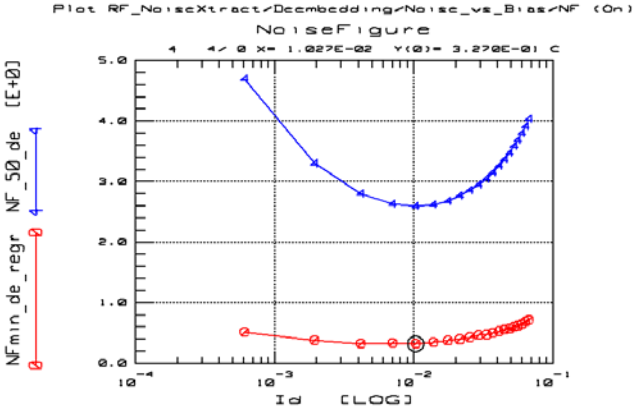




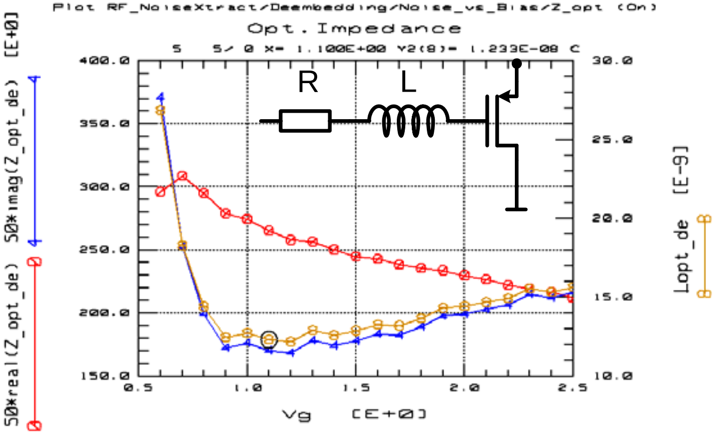
RF Transistor Characterization / Model Examples (250nm Node)



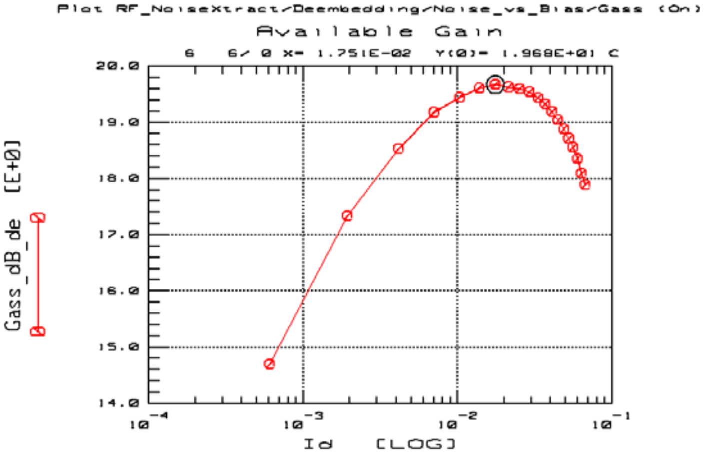
F_{min} vs. frequency
red: raw data, blue: deembeded data



NF_{50} & NF_{min} vs. drain current

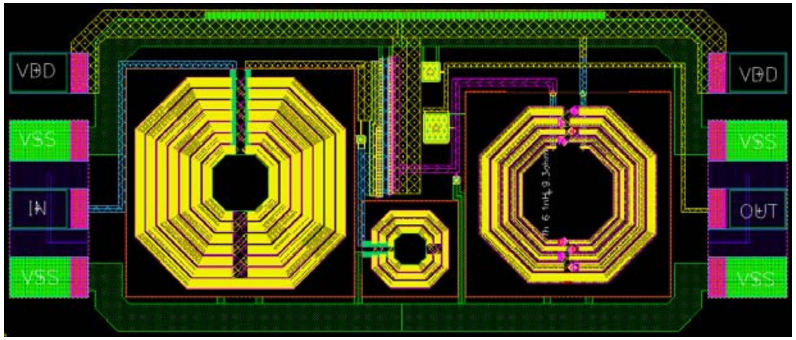


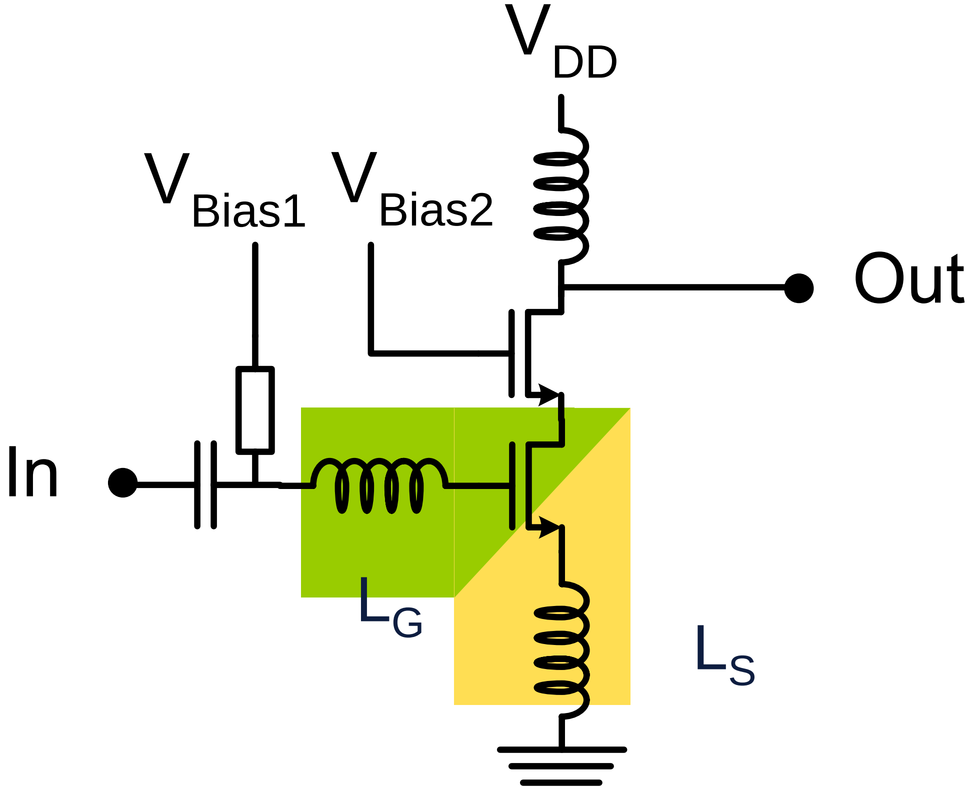
Optimum Impedance vs. gate voltage



Associated Gain Gas vs. drain current

Design Example: Narrowband LNA with Inductors





Mos Transistor:

$$I_D / I_G = \omega_T / (j\omega)$$

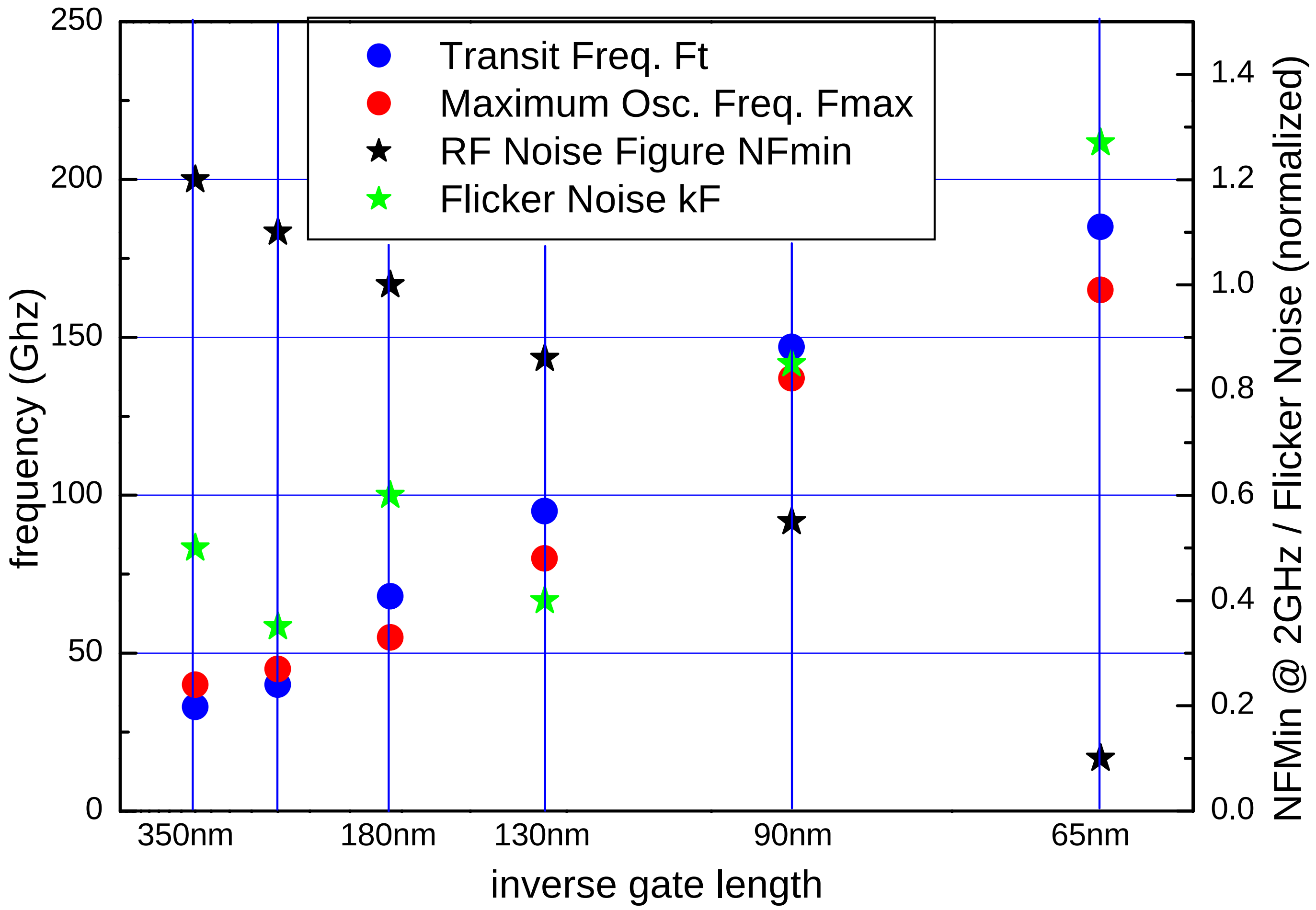
Transit frequency: ω_T

$$V_{In} = I_{In} \cdot \frac{\omega_T}{j\omega} \cdot j\omega L_s + I_{In} \cdot \frac{1}{j\omega C_{gs}} + I_{In} \cdot j\omega L_G$$

$$Z_{In} = \underbrace{\omega_T \cdot L_S}_{\text{real part}} + \underbrace{\frac{1}{j\omega C_{gs}} + j\omega L_G}_{\text{img. part}}$$

Problem: Resistance of inductors (especially for on chip conductors)

Technology Trend: RF Performance and Flicker Noise



Summary Noise in Linear Amplifiers

- Noise measurement is a narrowband power measurement.
- Test system is basically a tunable low noise receiver.
- Four noise parameters are necessary to model noise sources of a two port, many representations are used (and are equivalent).
- Tuning of source impedance is necessary to characterize all noise parameters.

RF Circuit Noise Characterization : Outline

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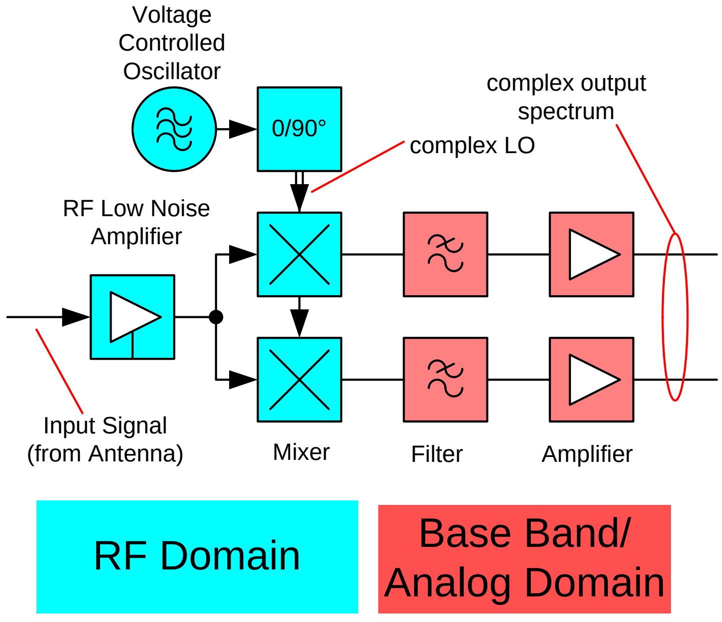
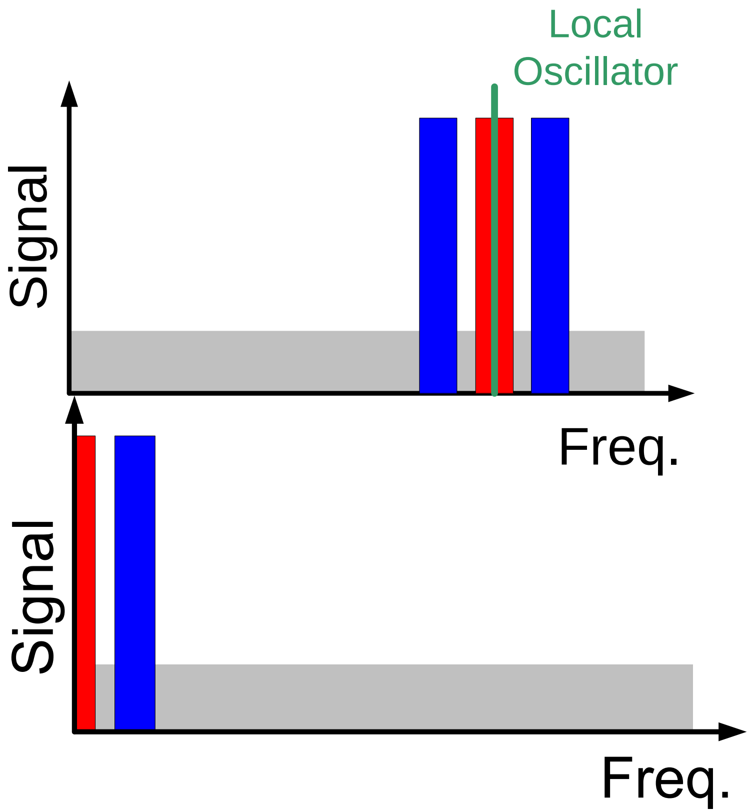
  - Hajimiri and Leeson Theory
  - Typical VCO Circuit
  - Characterization

Mixer Basics: Why is Frequency Conversion Necessary

Homodyne (Zero IF) receiver: Direct down conversion to Base Band frequency

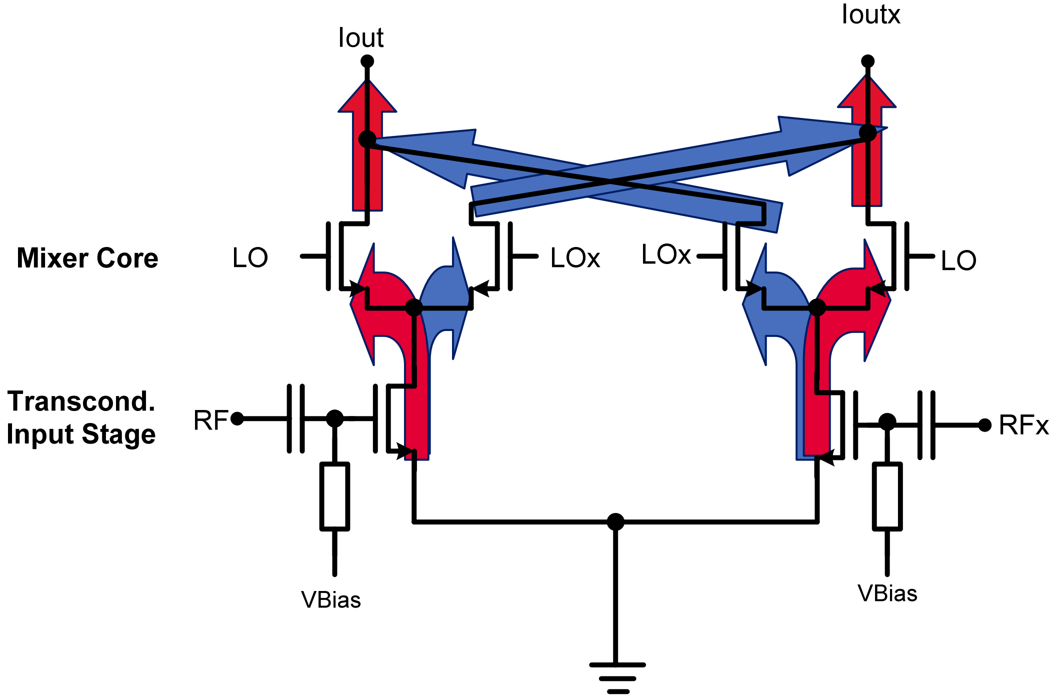


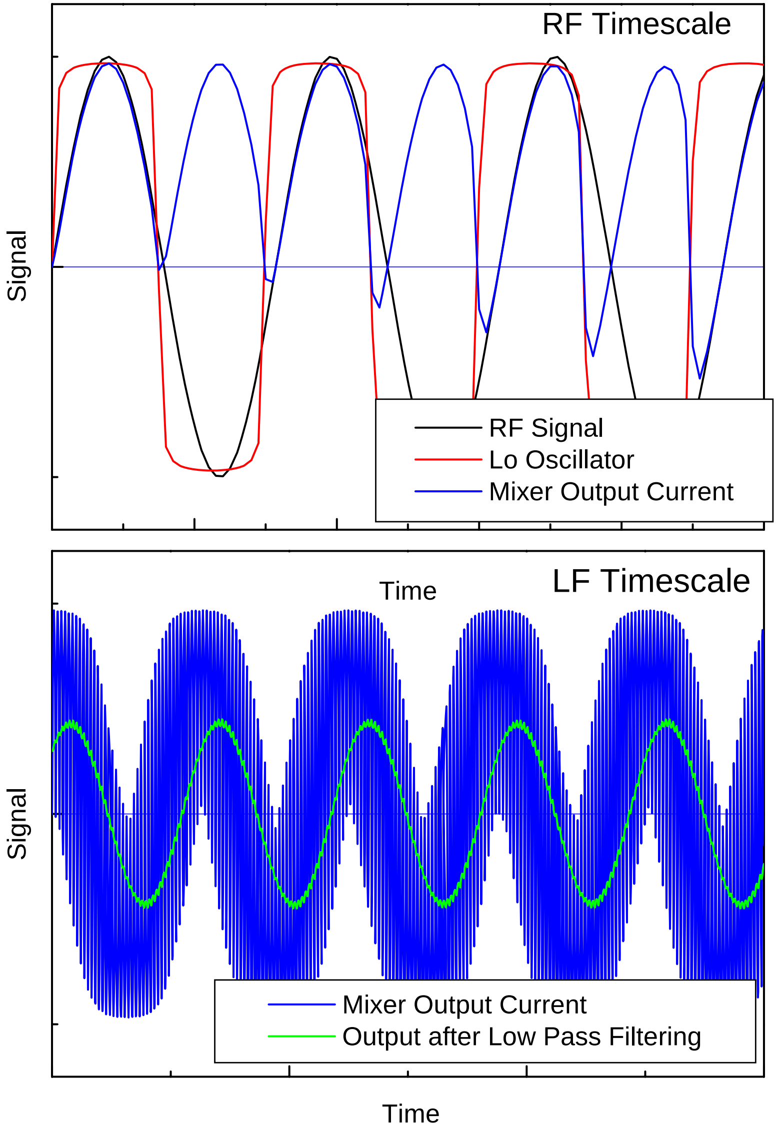


- Filtering signal in RF domain difficult: $Q = F / \Delta F$
- Changing LO-Freq. easier than changing filter freq.
- AD/DA at RF difficult (high power)

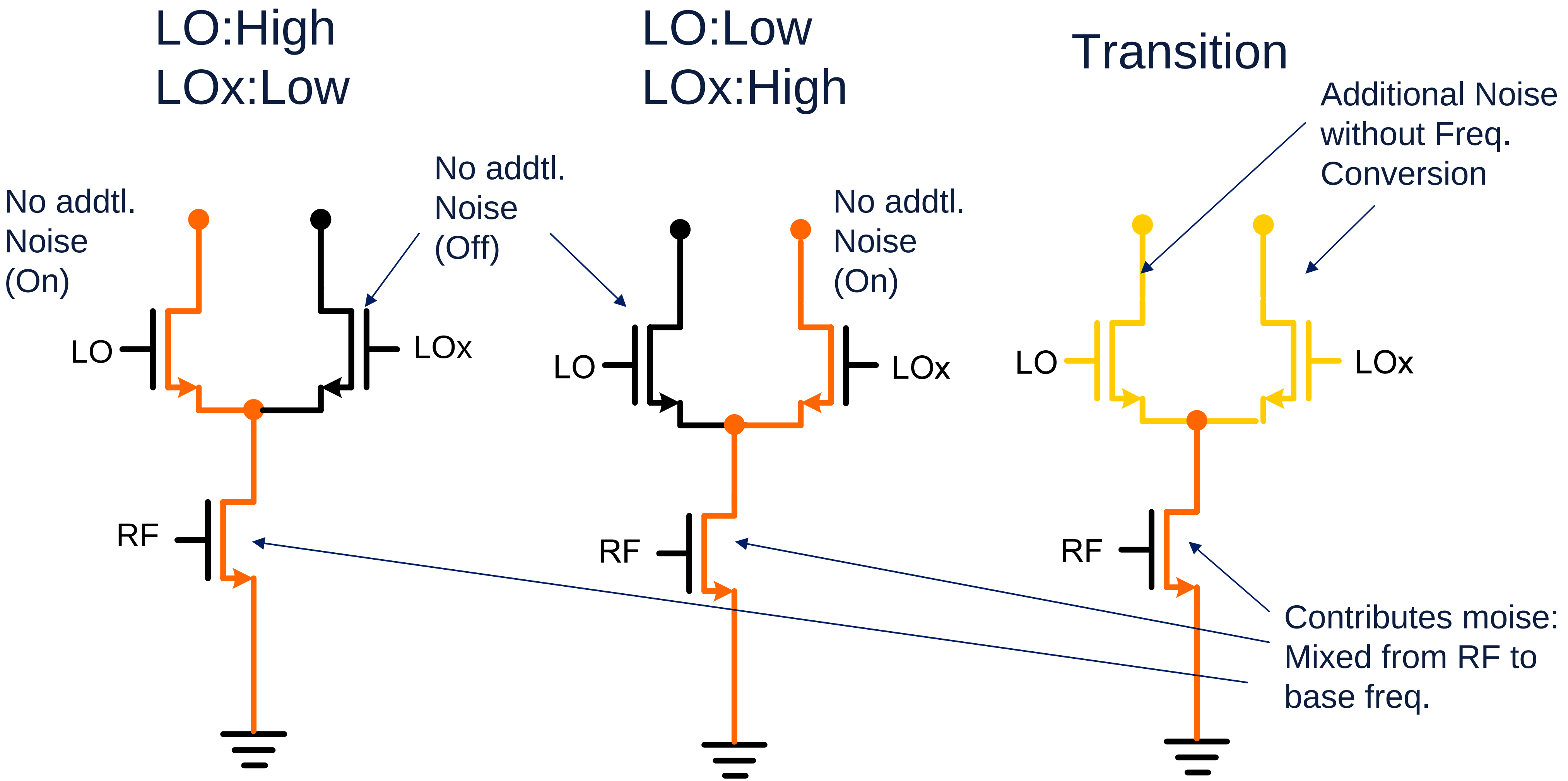
Typical Mixer Circuit

Double Balanced Gilbert Mixer





Noise Contributors in Gilbert Mixer



LO:High
LOx:Low

LO:Low
LOx:High

Transition

No addtl.
Noise
(On)

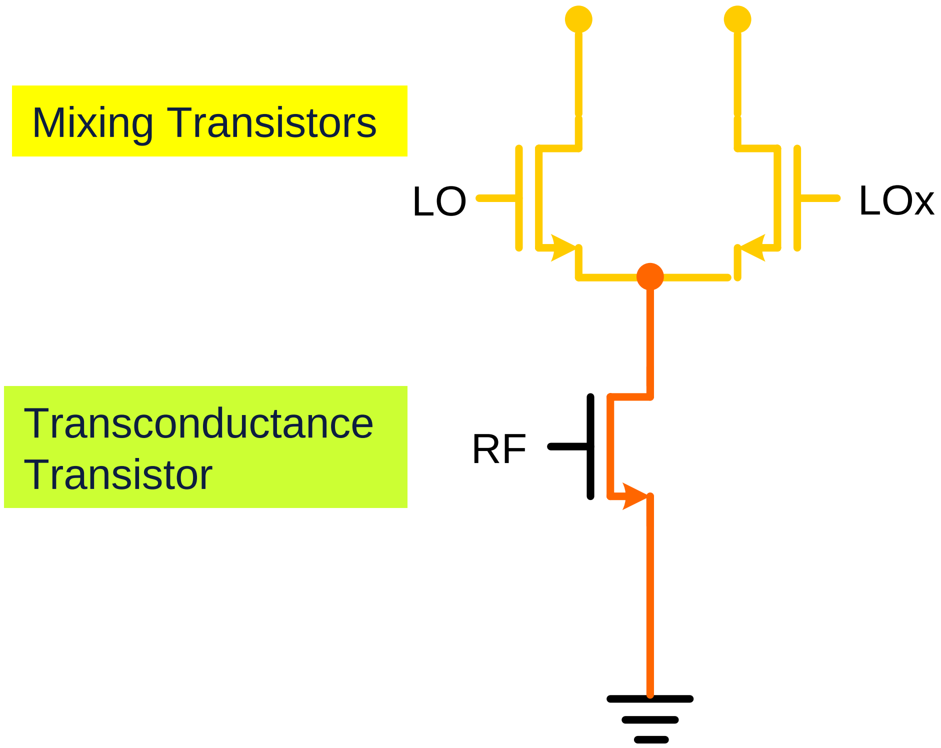
No addtl.
Noise
(Off)

No addtl.
Noise
(On)

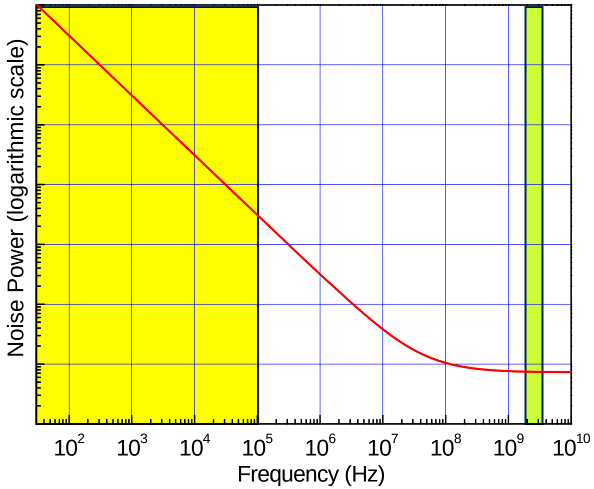
Additional Noise
without Freq.
Conversion

Contributes moise:
Mixed from RF to
base freq.

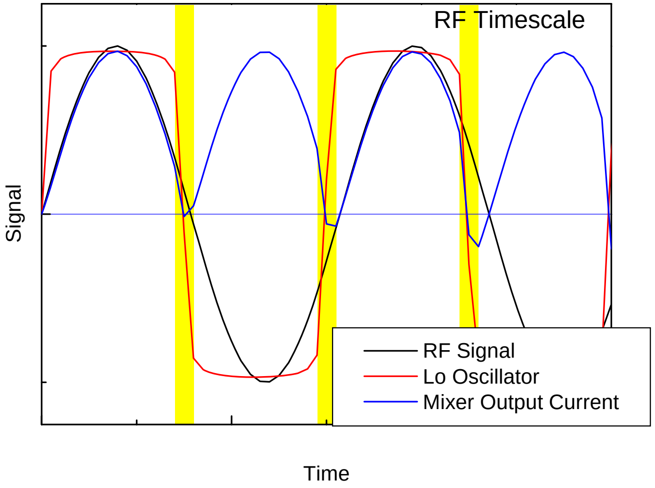
Noise Contributors in Gilbert Mixer: Frequency and Time



Noise Spectrum of CMOS Transistor



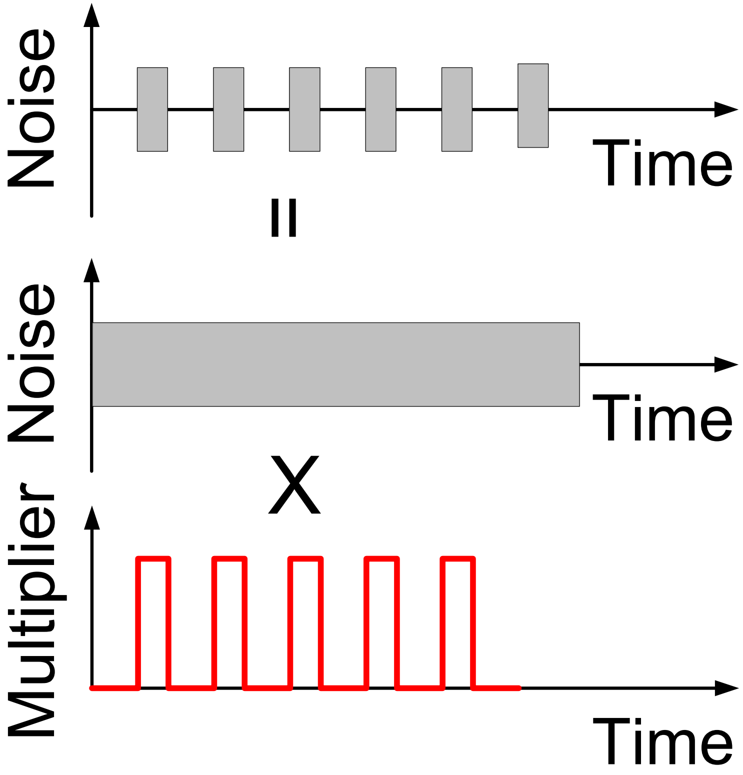
Transient Signals of Mixer

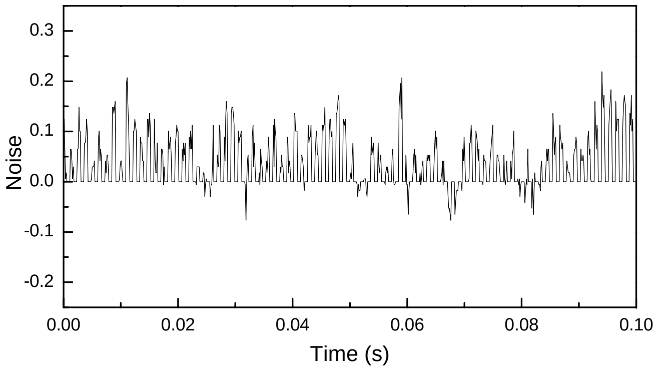


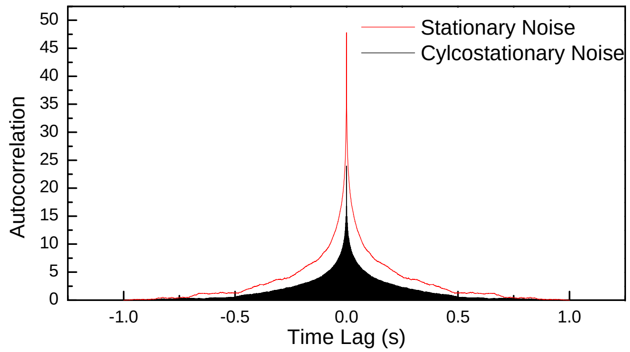
Mixing Transistors:
- Large noise levels (flicker noise)
- Short noise duration (transition time)

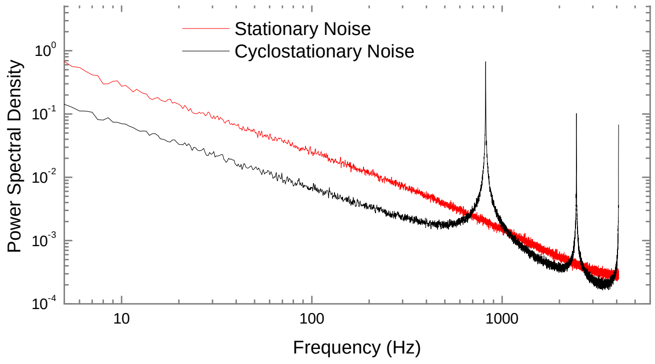
⇒Cyclostationary noise!

Cyclostationary Noise



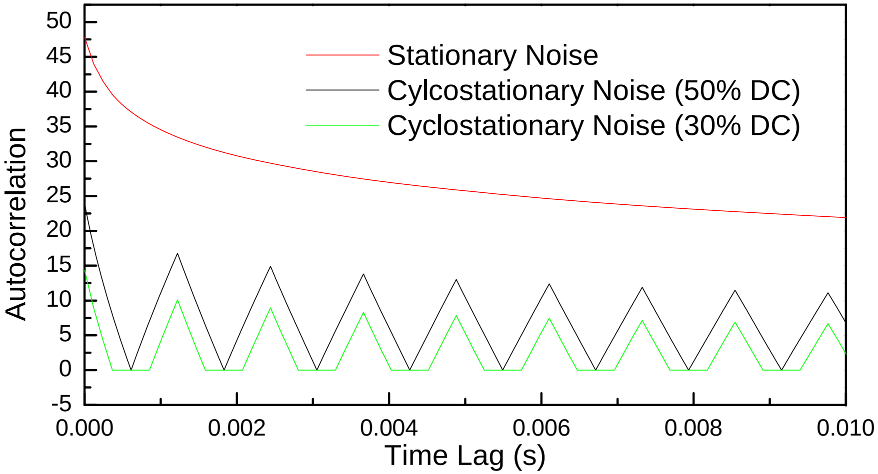


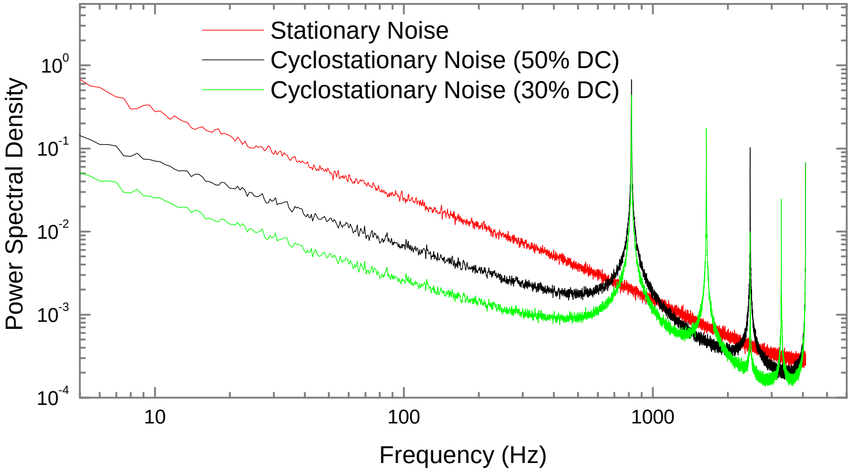




Convolution in frequency domain
Part of noise power is shifted to multiples of switch frequency

Cyclostationary Noise: On/Off Dutycycle





Reduced duty cycle
(=faster switching of mixer)

⇒Overall noise power decreases

⇒Larger percentage is mixed to higher frequencies

But: small devices, which are necessary for fast switching have higher flicker noise!

How to Optimizer Noise of Gilbert Mixer: Darabi/Abidi Model

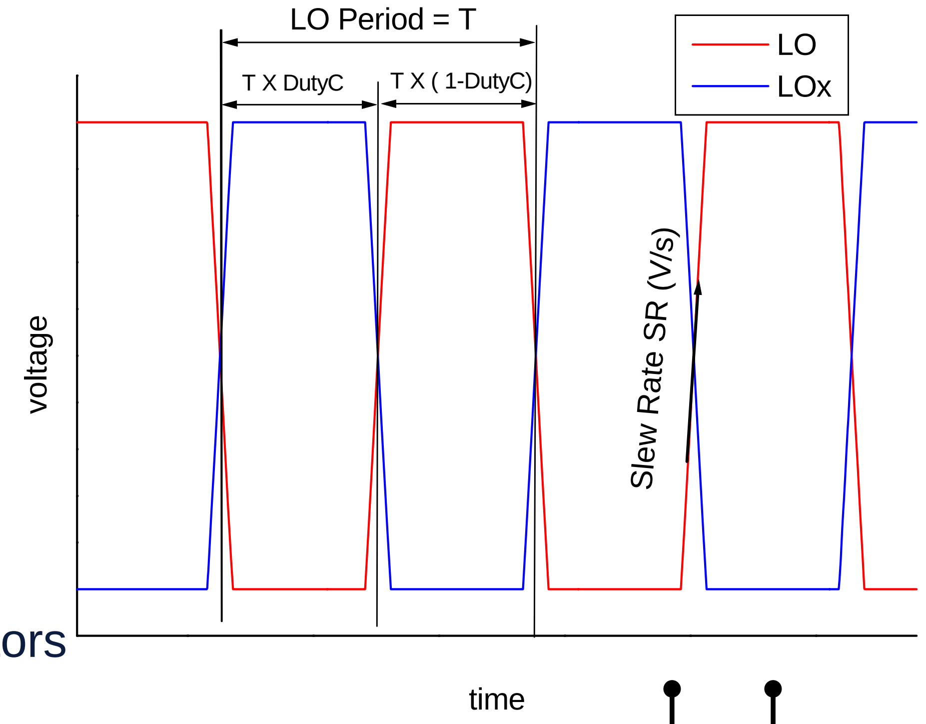
Model:

Variation of Duty cycle is responsible for output noise:

$$\left\langle I_{Out}^{2}\right\rangle \propto I_{tail}^{2}\cdot\left\langle DutyCNoise^{2}\right\rangle$$

Duty cycle variation depends on LO slew rate

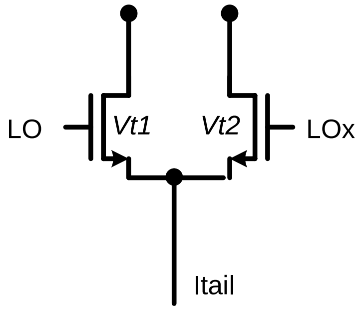
$$SR=\frac{Ibuffer}{Cox\times W\times L+CPar}$$



And threshold voltage variation of switch transistors

$$DutyCNoise=\frac{VDiffNoise}{SR\times T}$$

KF: Flicker Noise Parameter

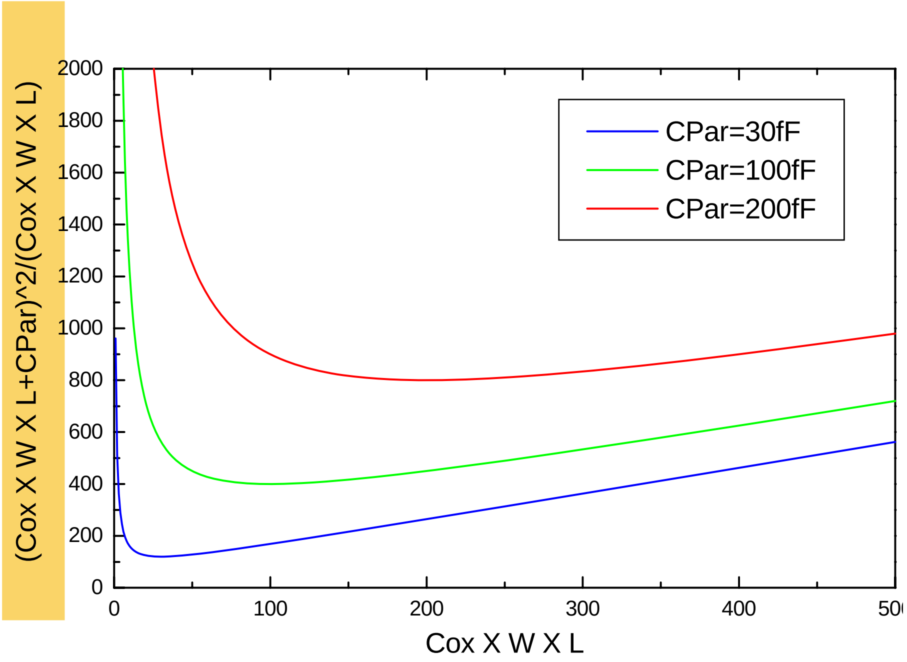


$$<VDiffNoise^{2}>=<Vt1^{2}>+<Vt2^{2}>=\frac{KF}{\mu eff\cdot Cox^{2}\cdot W\cdot L\cdot F}$$

$$\Rightarrow\quad \left\langle I_{Out}^{2}\right\rangle \propto \frac{(C_{Ox}\cdot W\cdot L+C_{Par})^{2}}{C_{Ox}\cdot W\cdot L\cdot I_{Buffer}^{2}\cdot T^{2}}$$

How to Optimize Noise of Gilbert Mixer:Darabi/ Abidi Model

$$\left\langle I_{Out}{}^{2}\right\rangle \propto \frac{(C_{Ox}\cdot W\cdot L+C_{Par})^{2}}{C_{Ox}\cdot W\cdot L\cdot I_{Buffer}{}^{2}\cdot T^{2}}$$



Some results:

- To optimize stationary noise:
  Increase transistor size

- To optimize cyclostationary mixer noise:
  Reduce transistor size (till parasitics appear)

- Minimize parasitics

- Noise scales with $F^{2}=1/T^{2}$
  => Advantage for superhet:
  First mixer to intermediate frequency (IF)
  Second mixer to baseband frequency
  Tradeoff: Complexity, power consumption, size

- Maximize gate drive current
  Tradeoff: power consumption

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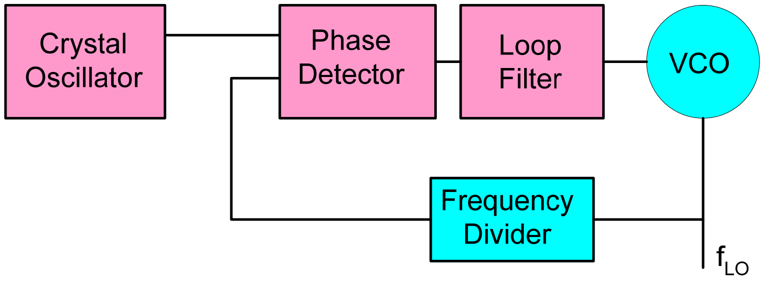
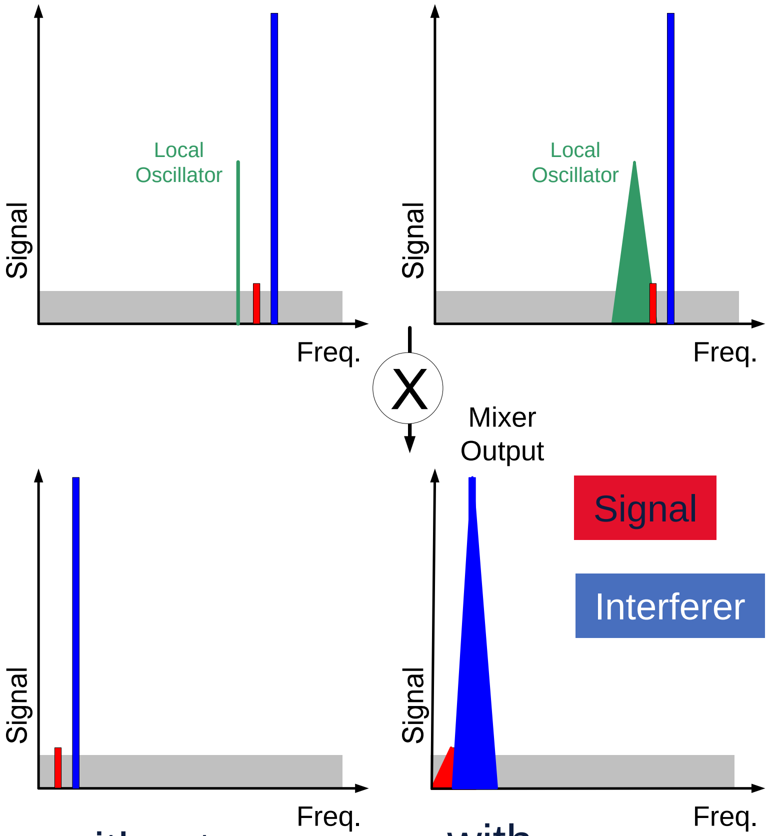
Frequency Generation for Local Oscillator



Requirements:

- Frequency Stability:
    Crystal Oscillator
- Low Phase Noise:
    VCO (far off carrier)
    Loop Filter, Divider, Phase Detector
    (near carrier)

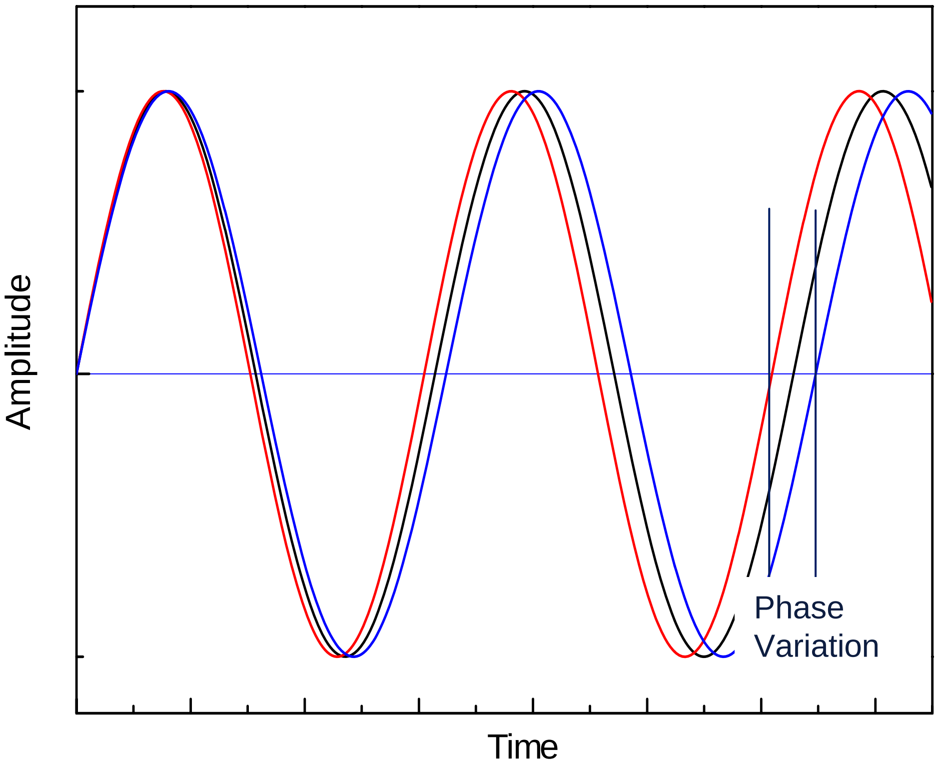
Reciprocal Mixing



without
LO Phase Noise

with
LO Phase Noise

Phase Noise Basics



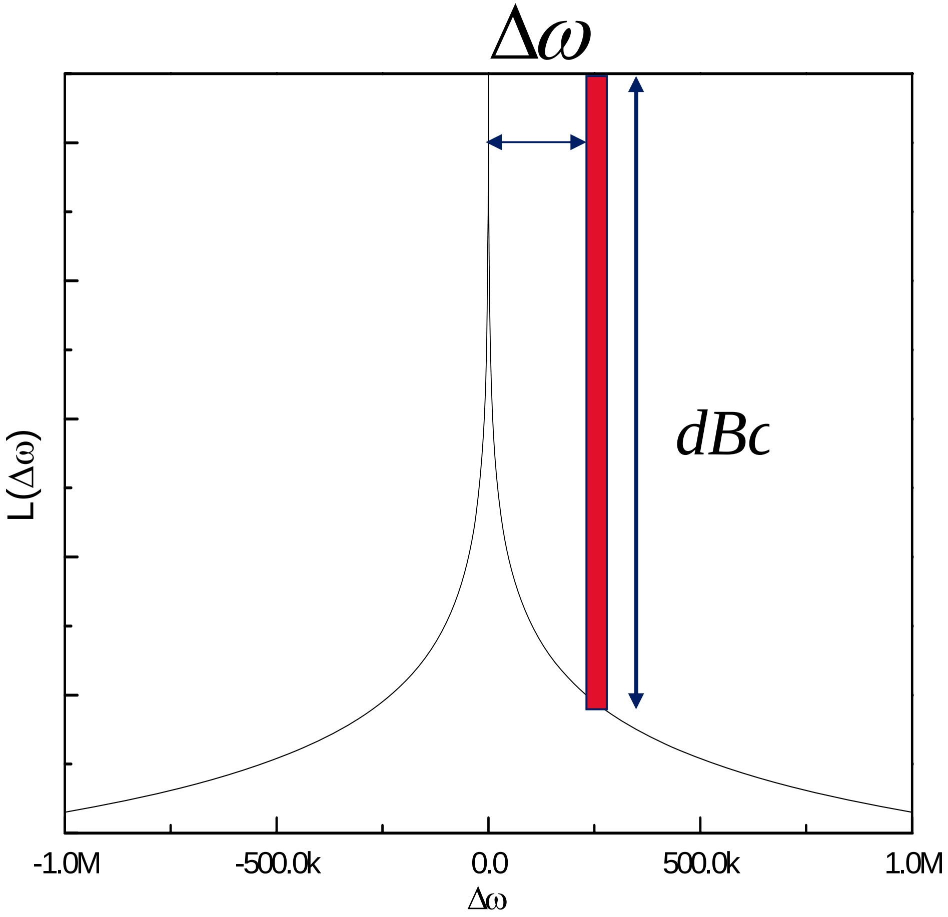
$$A(t) = A_0 \cdot \left(1 + \underbrace{\Delta A(t)}_{\text{AM Noise}}\right) \cdot f\left(\omega_0 \cdot t + \underbrace{\varphi(t)}_{\text{Phase Noise}}\right)$$

Phase Noise is equivalent to frequency Noise

$$\Delta\omega(t) = \frac{\partial \varphi(t)}{\partial t}$$

AM-Noise typically unimportant (e.g. Gilbert Mixer works at LO=LOx) and can be reduced with an amplitude regulation

Phase Noise Basics

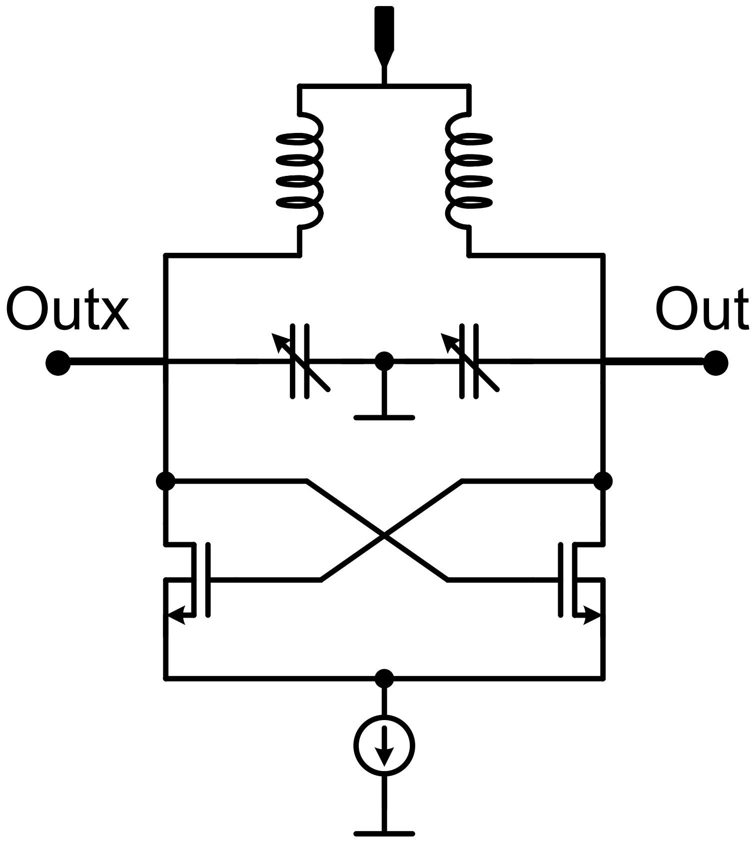


Phase noise is characterized by spectral power density:

$$L(\Delta\omega) = \frac{P_{SingleSideband(\omega_0 + \Delta\omega, 1Hz)}}{P_{Carrier}}$$

Unit used for phase noise: dBc/Hz (dB relativ to carrier)

LC Oscillators for Good Phase Noise Performance

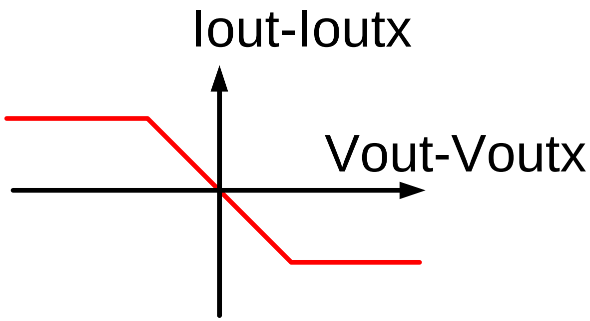


Typical VCO Circuit:

- LC tank

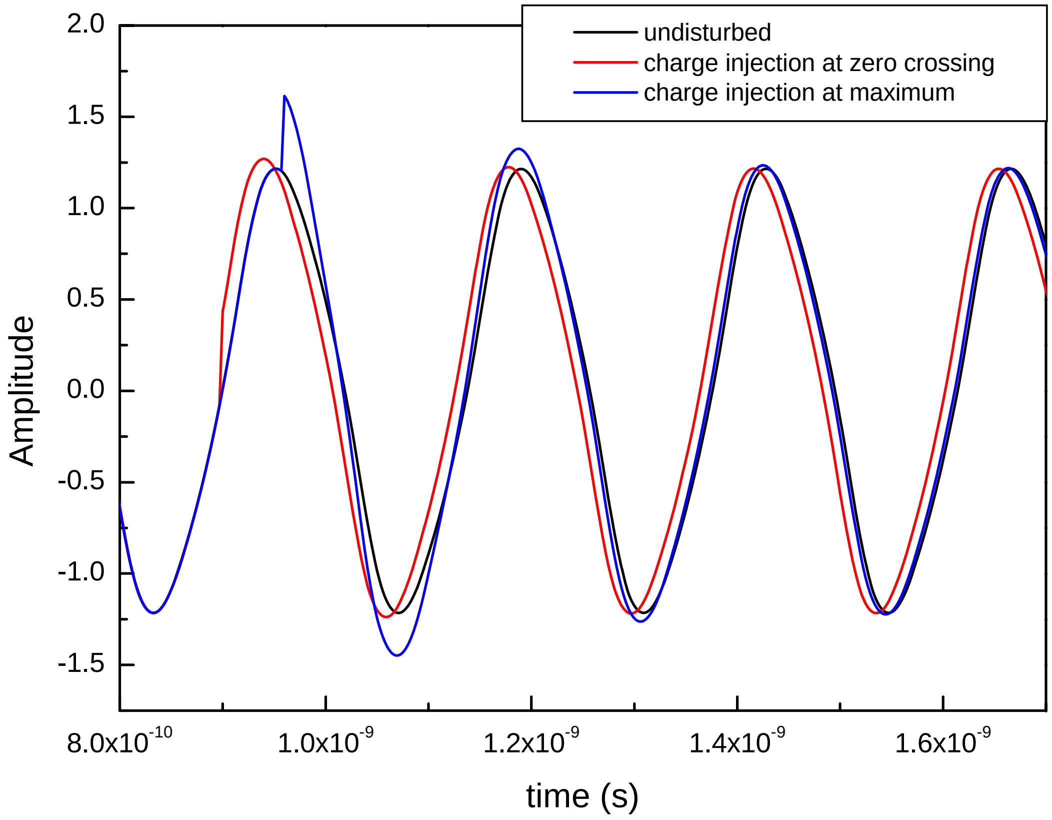
$$\omega = \frac{1}{\sqrt{LC}}$$

- Tuning with varactor
- Differential circuit
- Cross coupled transistors:
  Negative resistance around Vout=Voutx
  to compensate LC tank losses



Phase Noise: Hajimiri Model

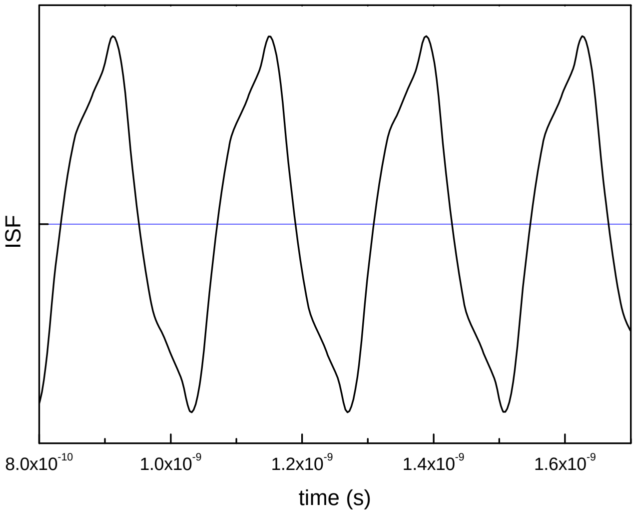
Phase Noise Response to Noise Current depends on Injection Time



Impulse Sensitivity Function:

$$\varphi(t) = \frac{1}{q\max}\int_{-\infty}^{t} ISF(\tau)\cdot i_n(\tau)\cdot d\tau$$

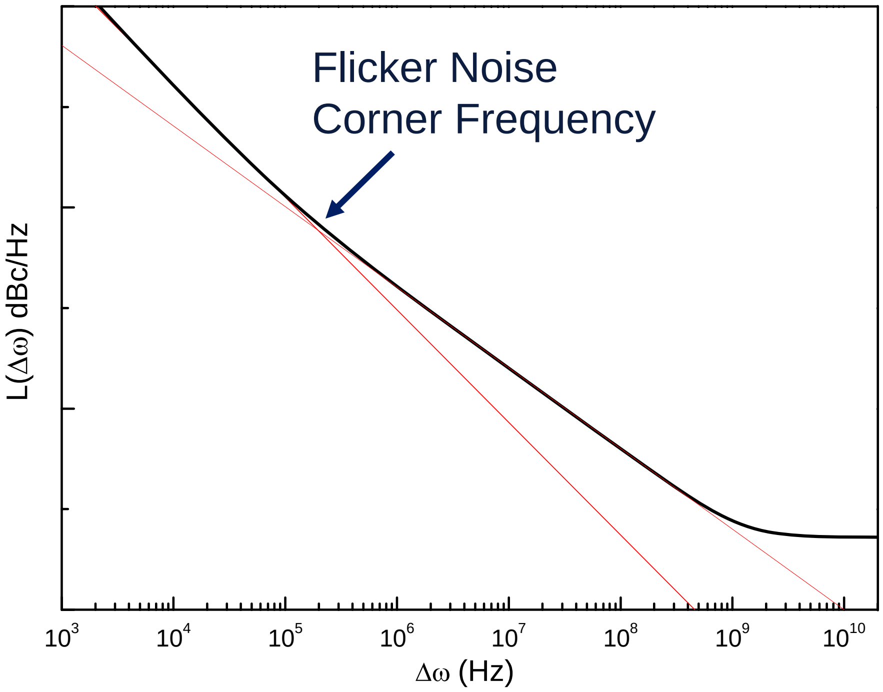
qmax: maximum charge on capacitor



Phase Noise: Leesons Heuristic Model

Leeson‘s Heuristic Formula (1966)

$$L(\Delta\omega)=10\cdot\log\left[\frac{2\cdot F\cdot k\cdot T}{P_{Carrier}}\cdot\left(1+\left(\frac{\omega_0}{2\cdot Q\cdot\Delta\omega}\right)^2\right)\cdot\left(1+\frac{\Delta\omega_{1/f^3}}{|\Delta\omega|}\right)\right]$$



Flicker Noise
Corner Frequency

Oscillator Optimization:

Q ↑

PCarrier ↑

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