ECE 5990

Note 8
Circuit Components in UHF Readers

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Outline

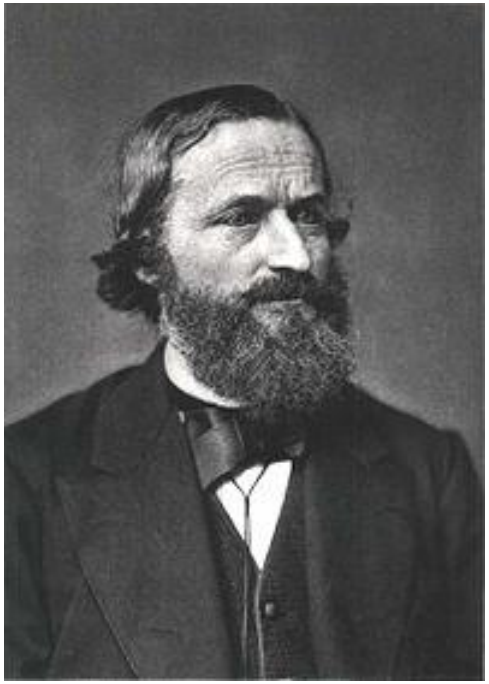
- Reader architecture
- Tag-to-reader encoding and modulation
- Signal path components:
  - Quadrature mixer
  - Low-noise amplifier (LNA)
  - Power amplifier
  - Filters and attenuators
- Frequency synthesizer: oscillator and PLL
- Transmitter-Receiver isolation

Quotable Quotes

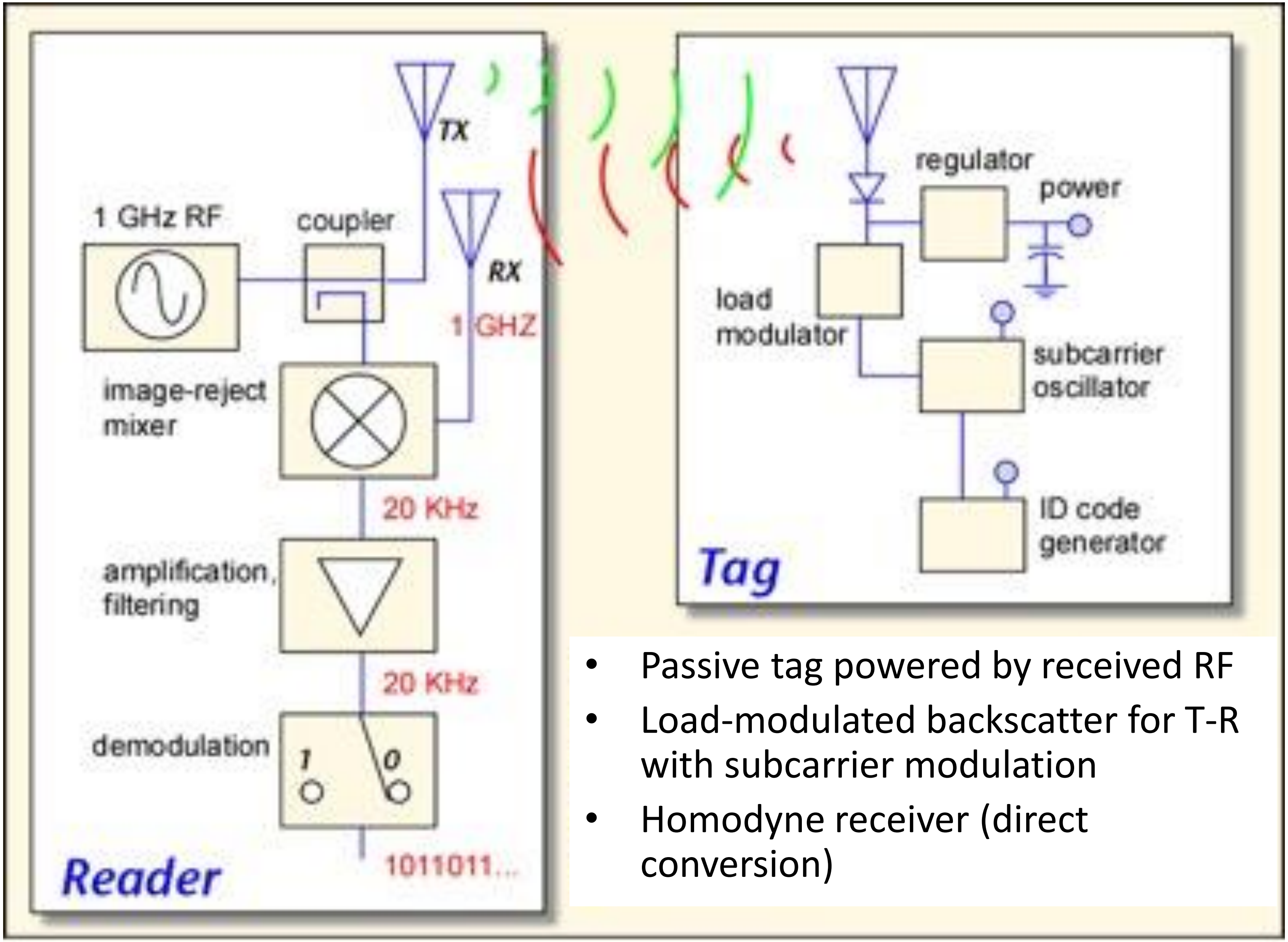
“Look here, I have succeeded at last in fetching some gold from the sun.”

(After his banker questioned the value of investigating gold in the Fraunhofer lines of the sun and Kirchhoff handing him over a medal he was awarded for his investigations.)

— Gustav Kirchhoff (1824 – 1887)

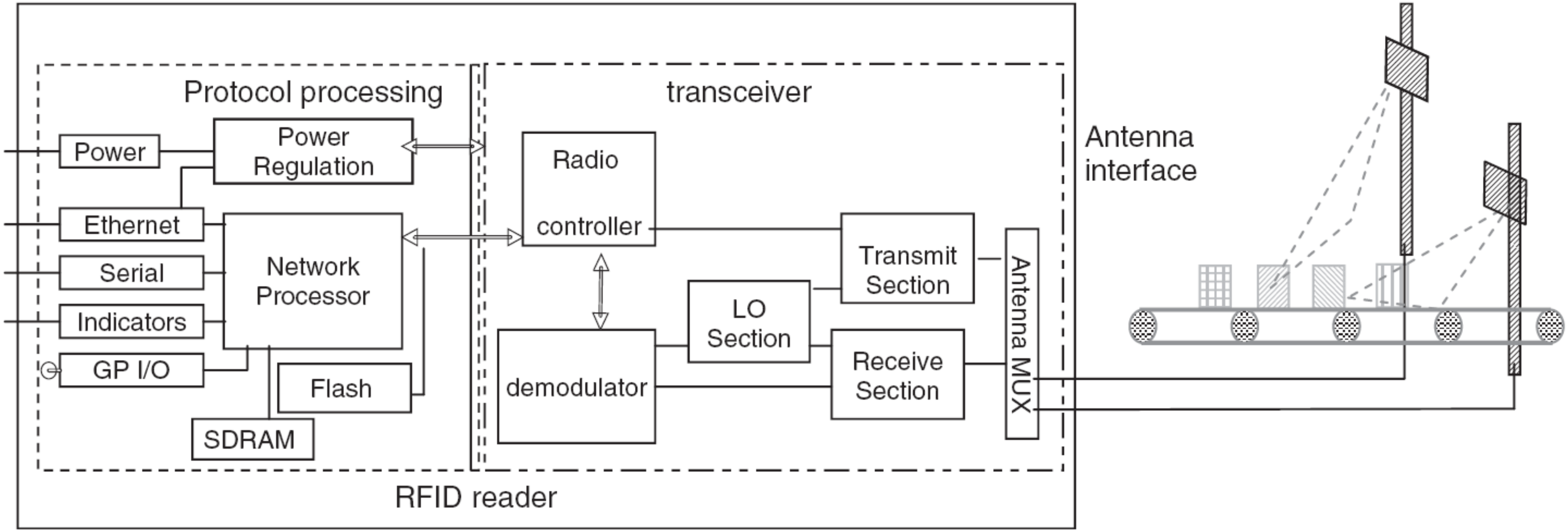


UHF RFID R-T and T-R Review



- Passive tag powered by received RF
- Load-modulated backscatter for T-R with subcarrier modulation
- Homodyne receiver (direct conversion)

UHF RFID Reader Architecture

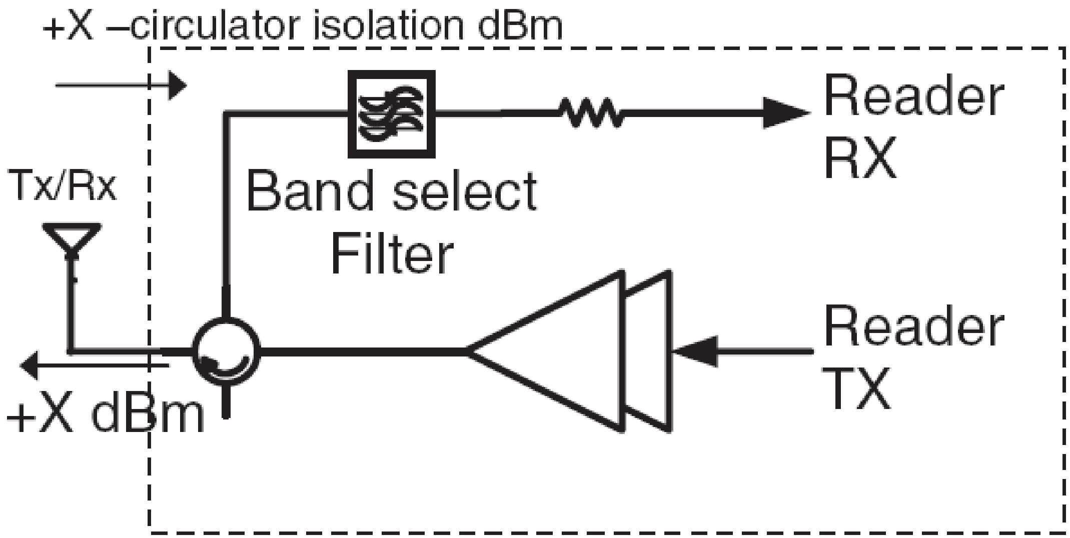


- Antenna interface
- RF transceiver
- Digital processing (protocol and applications)

UHF RFID Reader Examples

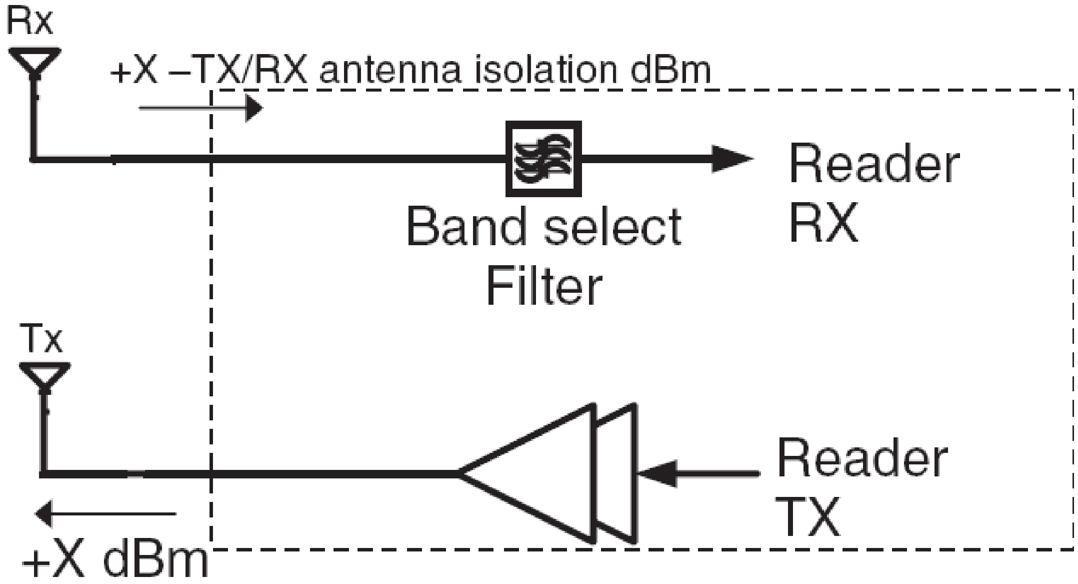
- Impinj
- Alien
- Speedata
- …

Monostatic and Bistatic RFID Readers



Monostatic

- Single antenna with selector
- Isolation of transmitter and receiver



Bi-static

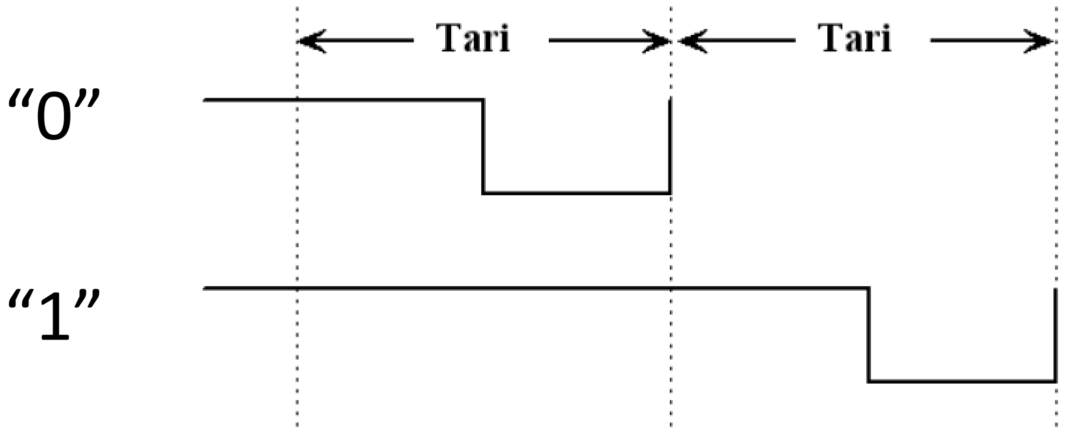
- Two antennas
- Good channel isolation, but still self jamming

Data Encoding

- Encoding is the process of converting a digital bit into symbols
- What changes corresponding to “0” and “1”
- Symbol rate (baud) is the rate the symbols change per unit of time
- Data rate (bits per second, bps) is the rate the binary information is transferred
- Each symbol may contain more than one bit

EPC G2 R-T Modulation and Encoding

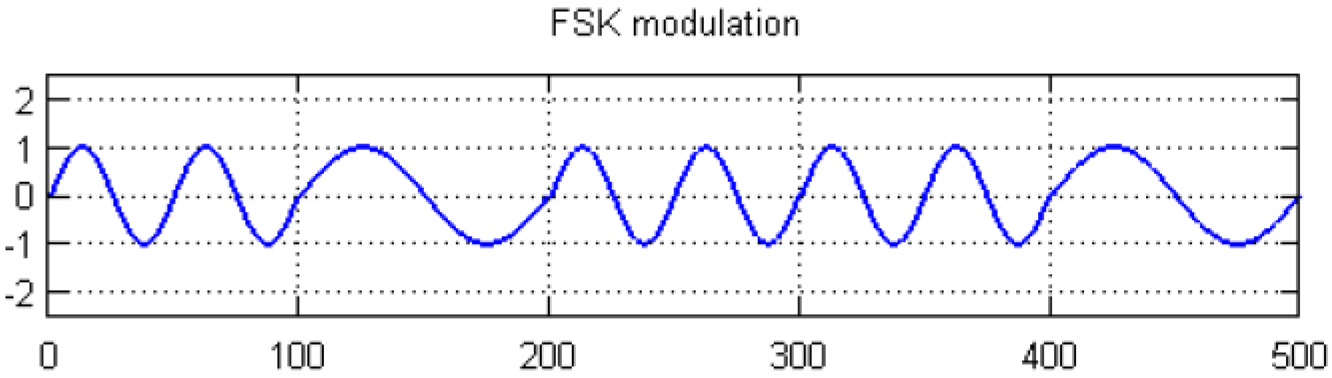
- Modulation
  - Double sideband ASK (DSB-ASK)
  - Single sideband ASK (SSB-ASK)
  - Phase reversal ASK (PR-ASK)
- Encoding: pulse interval encoding (PIE)
- Data rate based on Tari (Type A reference interval)
  - Tari 25 µs: 40 Kbps maximum; 27 Kbps average
  - Tari 12.5 µs: 80 Kbps maximum; 53 Kbps average



- High level: full carrier wave
- Low level: attenuated carrier wave

EPC G2 T-R Modulation and Encoding

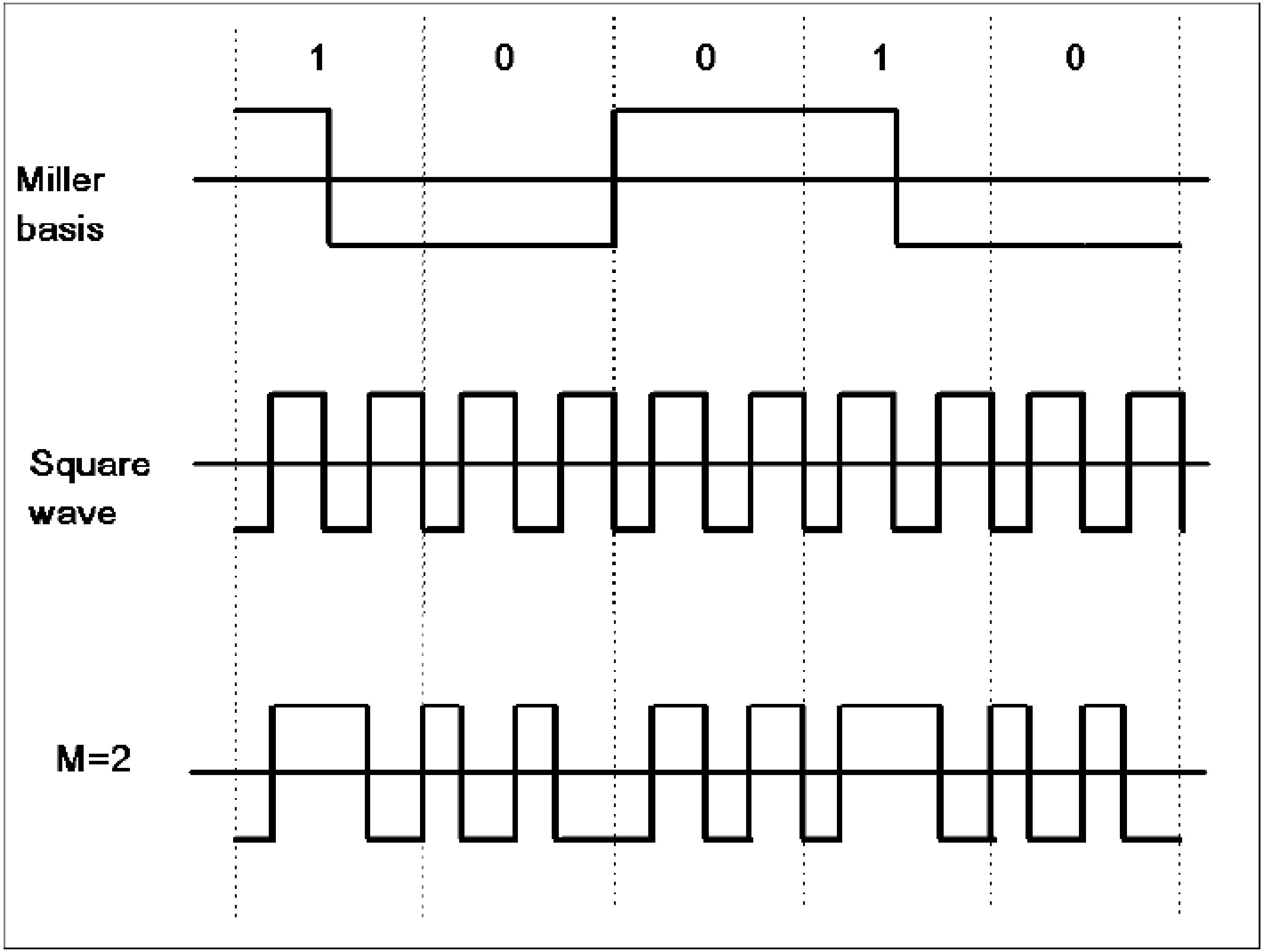
- T-R modulation and encoding
  - FM0 (Frequency modulation)
  - “1”: two transitions per symbol
  - “0”: three transition per symbol
- Change in the baseband frequency is also called “subcarrier modulation”



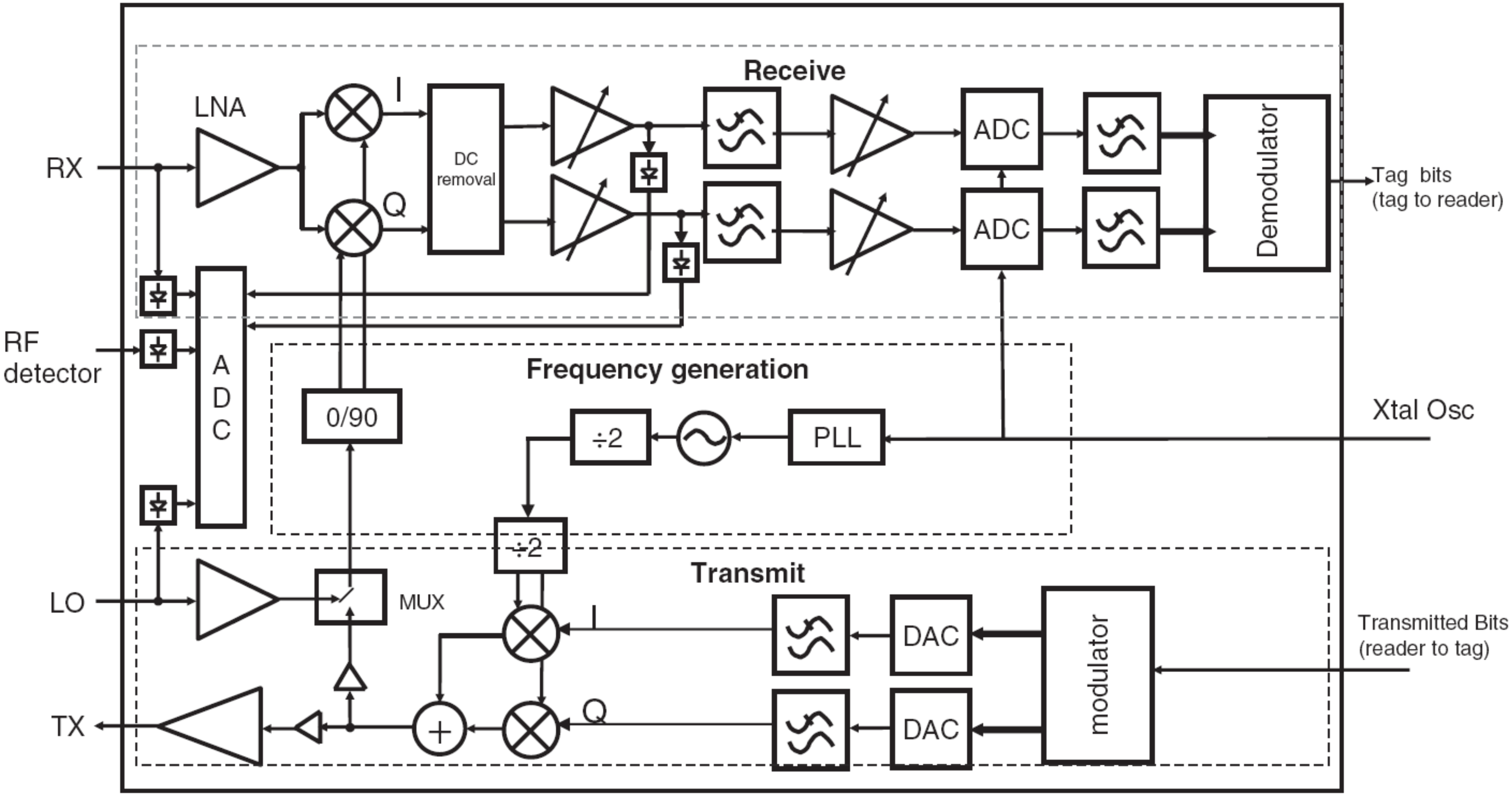
Miller Subcarrier Modulation

- Miller subcarrier modulation: T-R transmitted waveform is the baseband waveform multiplied by a square wave at M times the symbol rate
- M = 2, 4, 8 (to increase the number of transitions for easier detection at the penalty of data rate)
- M specified by reader in Query

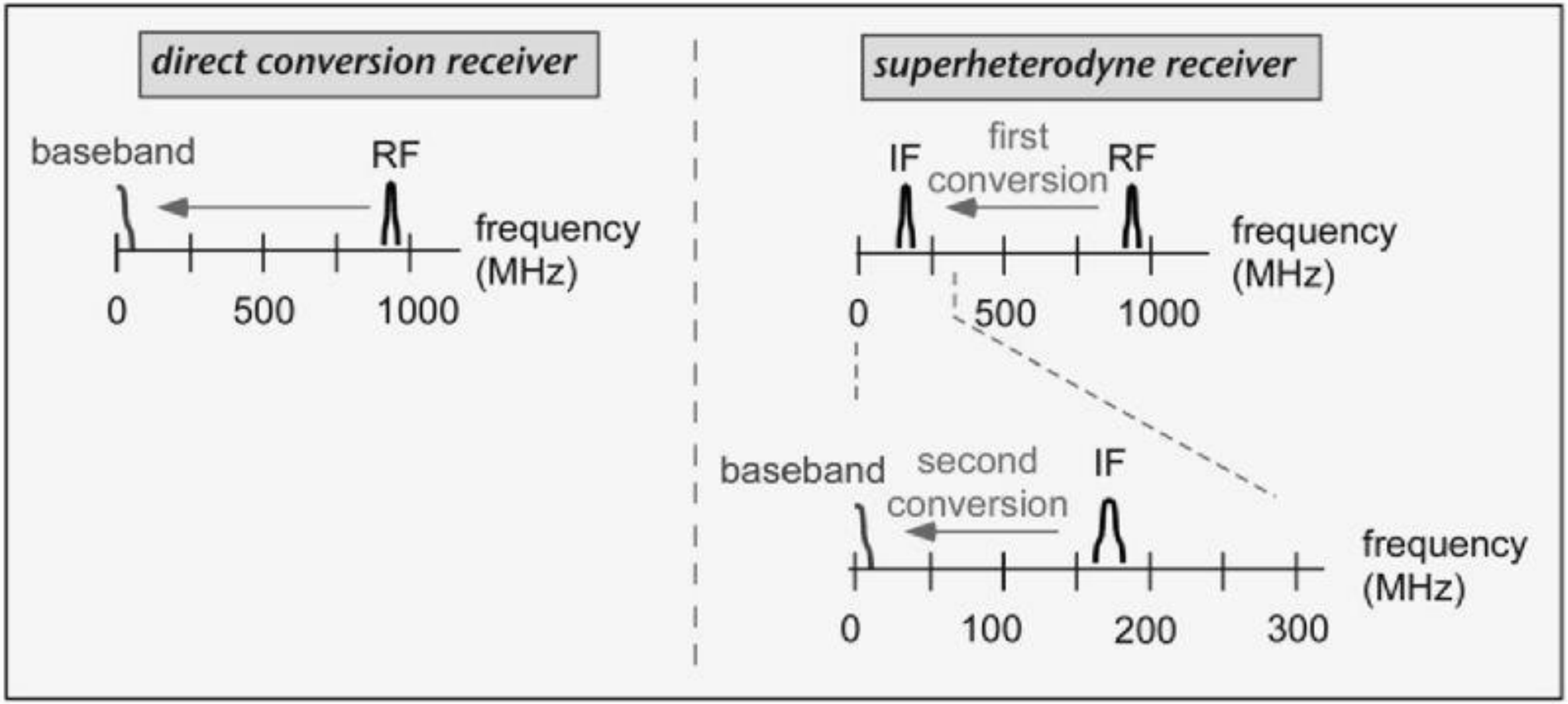
Miller Subcarrier Modulation Example (M=2)



RFID Transceiver

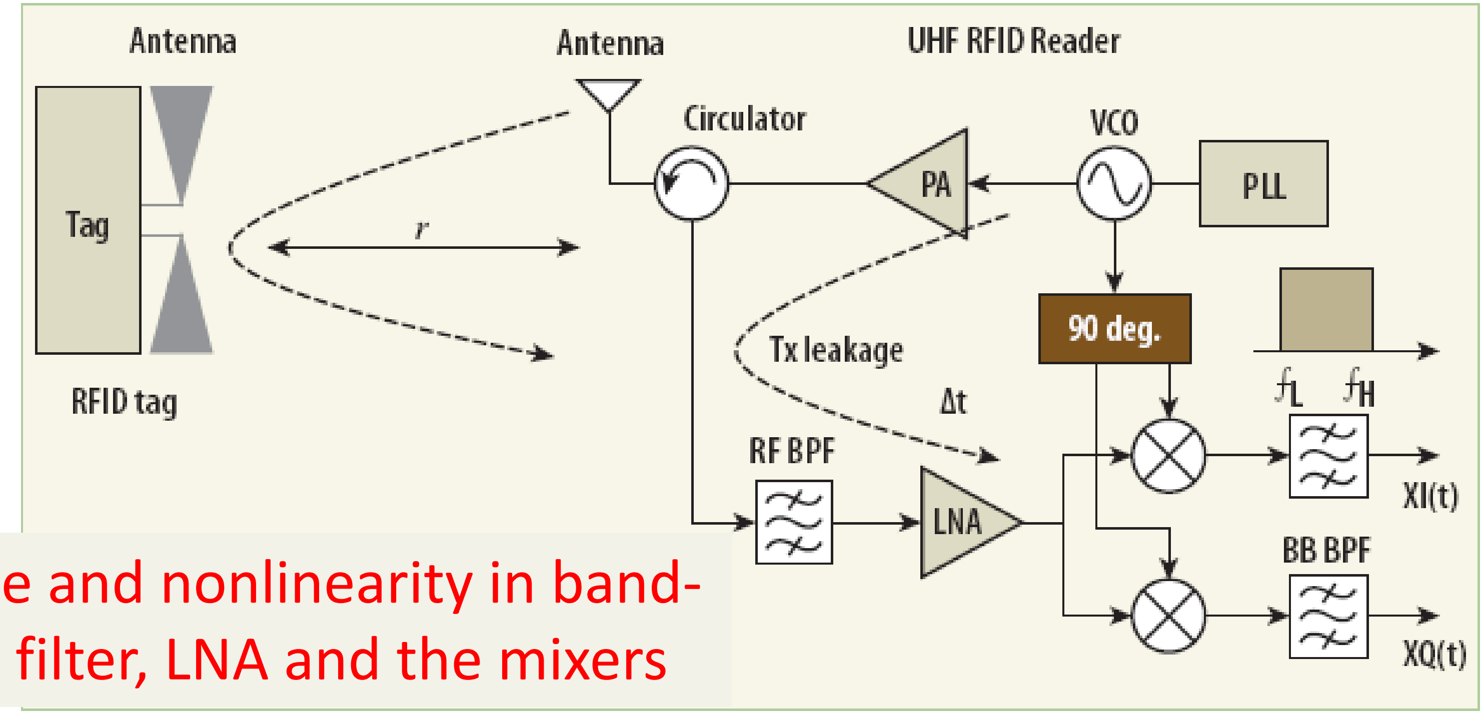


Direct Conversion vs. Superheterodyne



Fundamental Limits of Receivers

- Dynamic range (dB): The range of signal power when a receiver can decode the intended signal correctly.
- The lowest signal power that can be decoded is limited by **NOISE** (SNR).
- The highest signal power that can be decoded is limited by receiver **NONLINEARITY** (jamming)



Noise and nonlinearity in band-pass filter, LNA and the mixers

Nonlinearity and Jamming

- A dynamic range of 100dB of a receiver means: if the sensitivity is –90 dBm (1pW, 7μV), then when the input power is higher than 10dBm (10mW, 0.7V), it would cause jamming.
- Signal itself can be distorted after amplifier
- Signal can be buried with a strong in-band jamming
- Very similar to the **precision** of a number when the receiver is just a calculator.

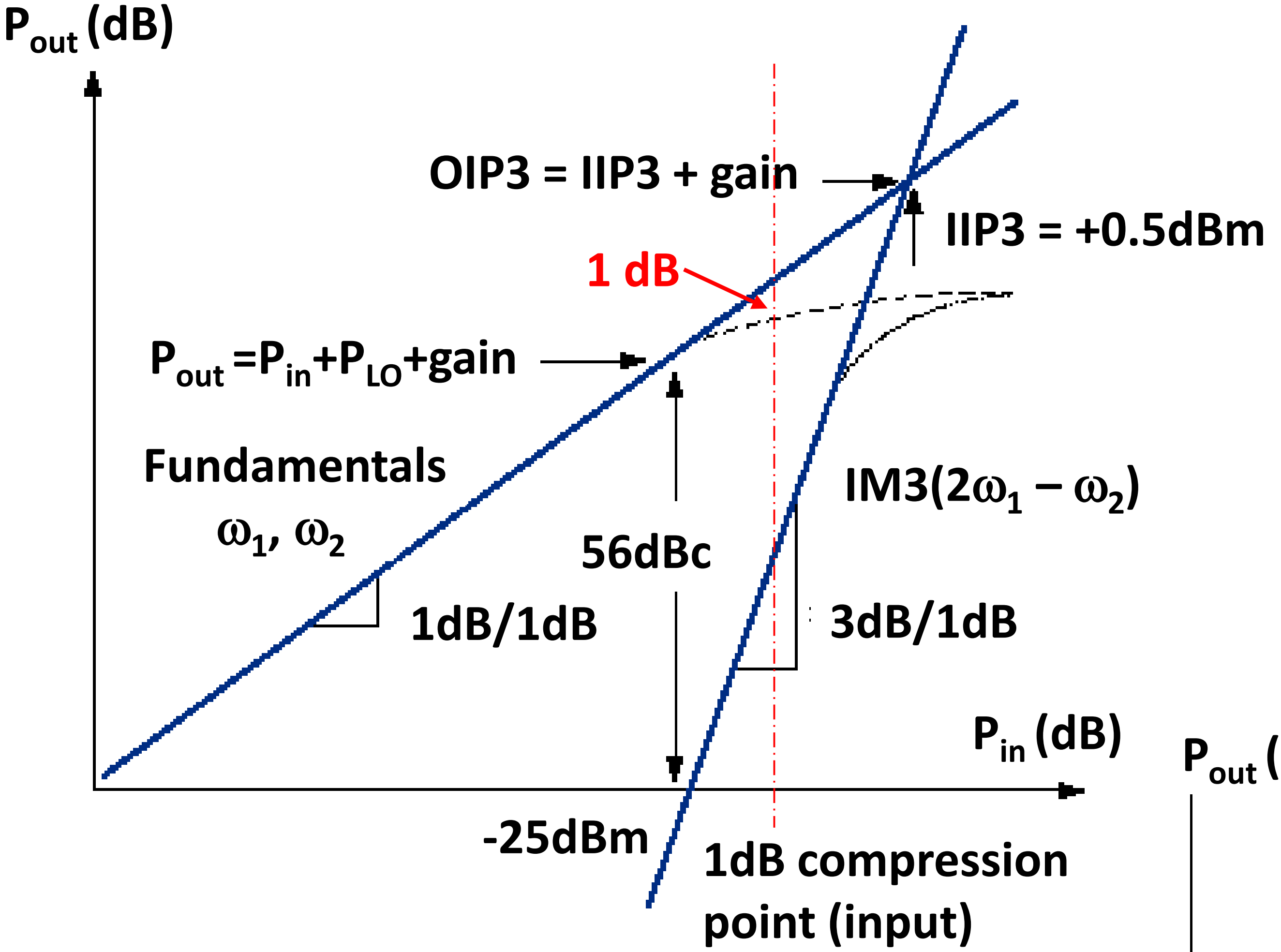
Weakly Nonlinear Receivers

- Practical amplifiers ALWAYS have nonlinearity when the input signal is sufficiently large.
- In a transfer function point of view:

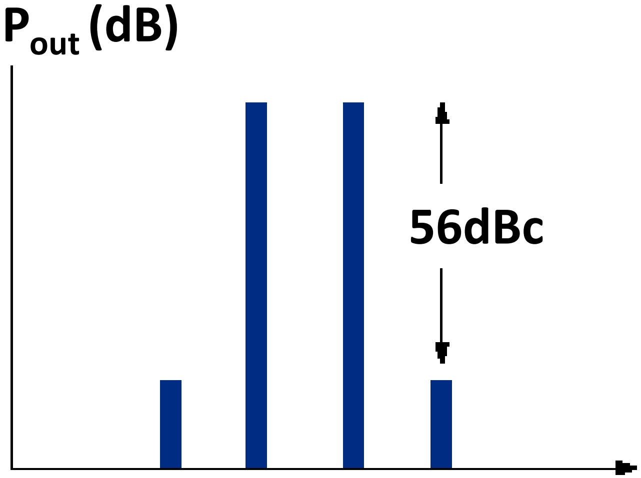
$$P_{out} = \alpha_1 P_{in} + \alpha_2 P_{in}^2 + \alpha_3 P_{in}^3 + \ldots$$

- Harmonics from single-tone input
- Intermodulation products from two-tone input (f_1 and f_2 are fairly close): $A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)$
- Rule-of-thumb use for "IIP$_3$" (input interception point 3)
  - IIP3 = 10 dBm; at Pin = -5dBm, the nonlinear product will be: (3 – 1)×(10 – (-5)) = 30 dB below test signal

IP3 or TOI



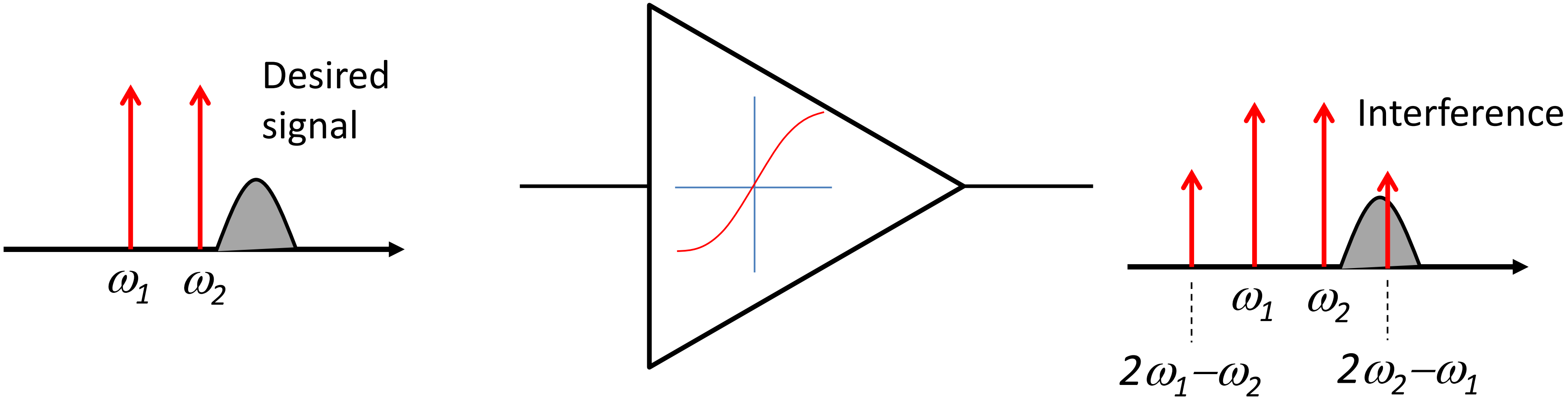
- IIP3: Input third-order intermodulation point
- OIP3: Output third-order intermodulation point
- IM3: Third-order intermodulation
- dBc: decibels relatice to carrier



TOI: Third-order interception

Maxim SiGe BJT Mixer

Third-Order Nonlinearity Effect



Nonlinear amplifier:

$$V_{out} = GV_{in} - D_3 V_{in}^{\ 3} + \ \ldots$$

$$\cos^3(x) = \frac{3}{4}\cos(x) + \frac{1}{4}\cos(3x)$$

“1dB compression point” is about **10dB** lower than IIP_3

Proof: http://en.wikipedia.org/wiki/Third-order_intercept_point

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- Reader architecture
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- Signal path components:
  - Quadrature mixer
  - Low-noise amplifier (LNA)
  - Power amplifier
  - Filters and attenuators
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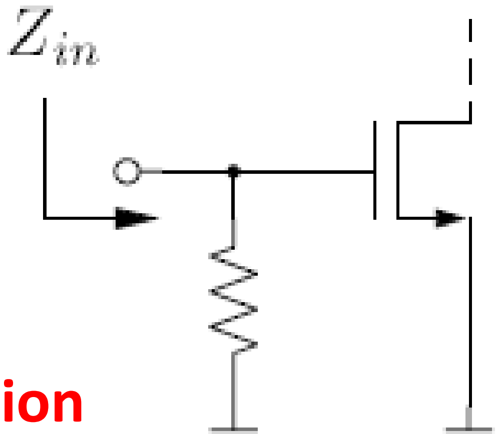
LNA Design Goals

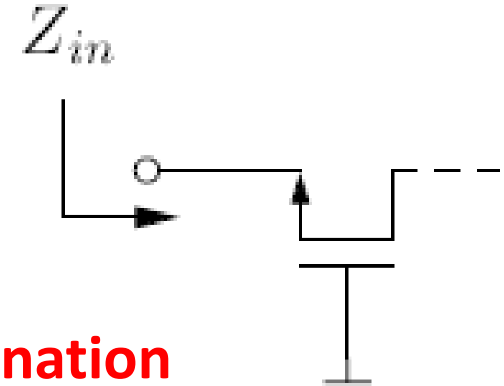
- Provide enough gain to overcome the noise of subsequent stages (mixer, etc.)
- Adding as little noise as possible (small NF)
- Impedance match to the input source (antenna or filter); filter $H(\omega)$ often depends on load.
- Narrow band is often acceptable

- Figure of merits: gain, NF, input impedance, power consumption, band and bandwidth.

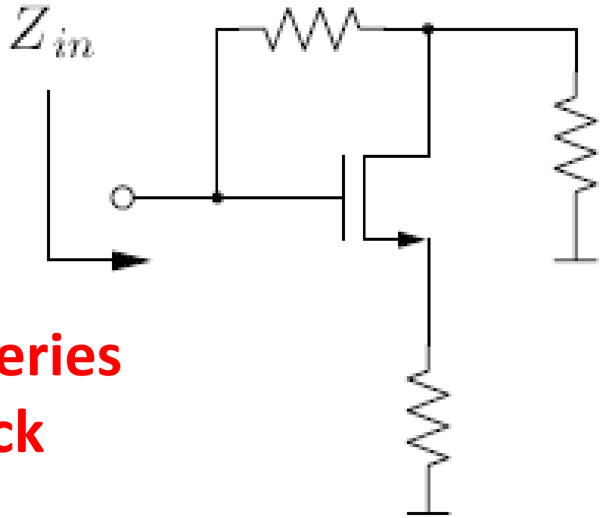
Common LNA Circuits



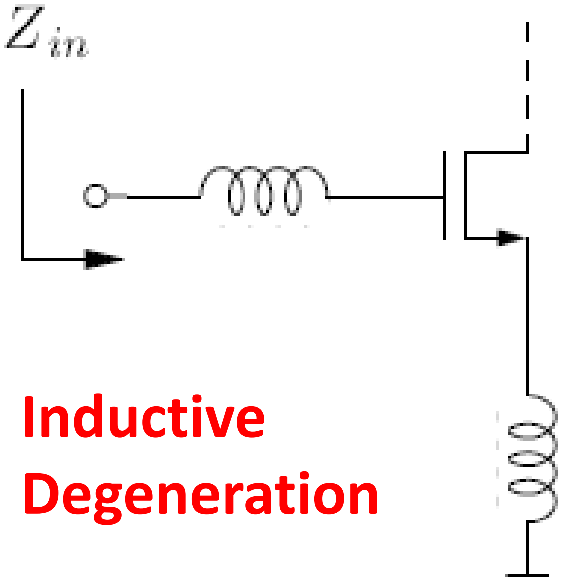
Resistive Termination



$1/g_m$ Termination



Shunt-series Feedback



Inductive Degeneration

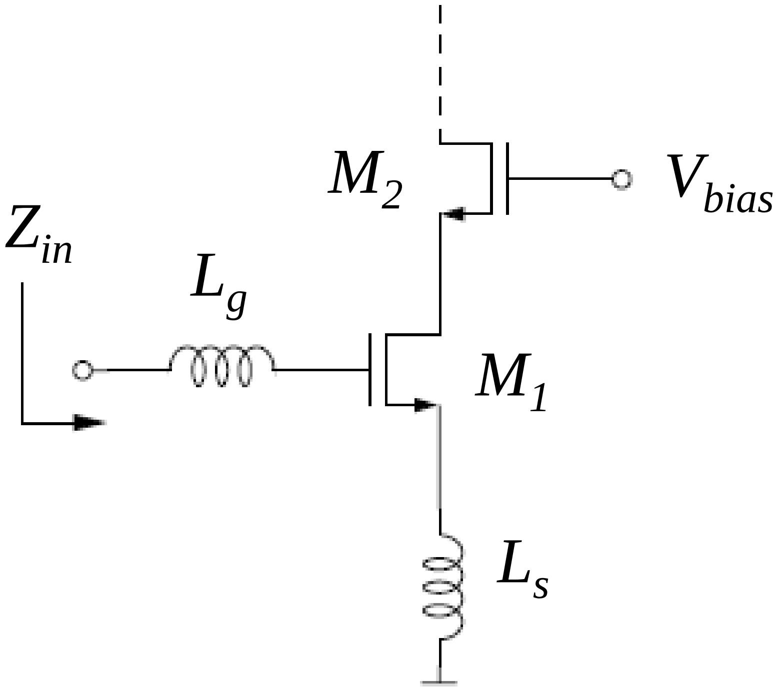
Typical LNA Performance

Architecture	NF (dB)	Gain (dB)	IP3/1dB (dBm)	Power (mW)	f_0 (GHz)	Technology
R. Term.	6.0	14	?/?	7	0.75	2μM CMOS
L. Degen.	2.2	15.6	12.4/?	20	0.9	0.5μM CMOS
Shunt-Ser. FB	7.5	11.0	?/?	36	0.9	1μM CMOS
1/g_m Term.	3.5	22	?/?	27	0.9	1μM CMOS
L. Degen.	2.2	19.6	6/-3	10	1.0	1μM GaAs
L. Degen. Double Stage	**3.5**	**22**	**12.7/0**	**30**	**1.5**	**0.6μM CMOS**

$$F \equiv \frac{Total \quad output \quad noise}{noise \quad by \quad source} \cong 1 + \frac{P_{na,i}}{4kT \cdot BW \cdot G_a}$$

- $P_{na,i}$: available noise power at output
- BW: bandwidth; G_a: gain

Typical Inductive Degenerate CMOS LNA



$$Z_{in} = \cancel{s\left(L_S + L_g\right) + \frac{1}{sC_{gs}}} + \left(\frac{g_{m1}}{C_{gs}}\right) L_s$$

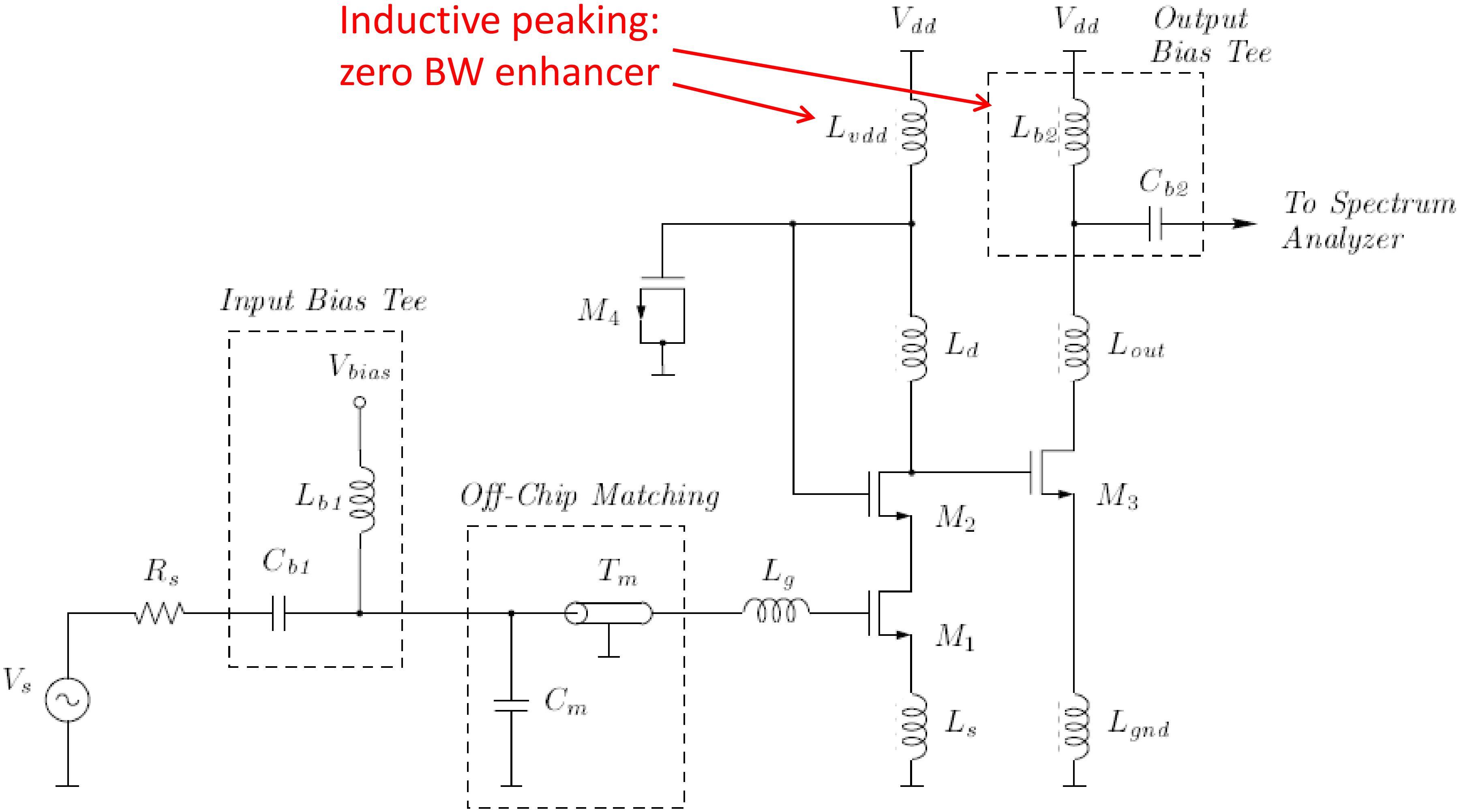
$$\cong \omega_T L_s$$

$$F = 1 + \frac{R_l}{R_s} + \frac{R_g}{R_s} + \gamma g_{d0} R_s \left(\frac{\omega_0}{\omega_T}\right)^2$$

$$\omega_0 = \frac{2\pi}{\sqrt{C_{gs}(L_g + L_s)}}$$

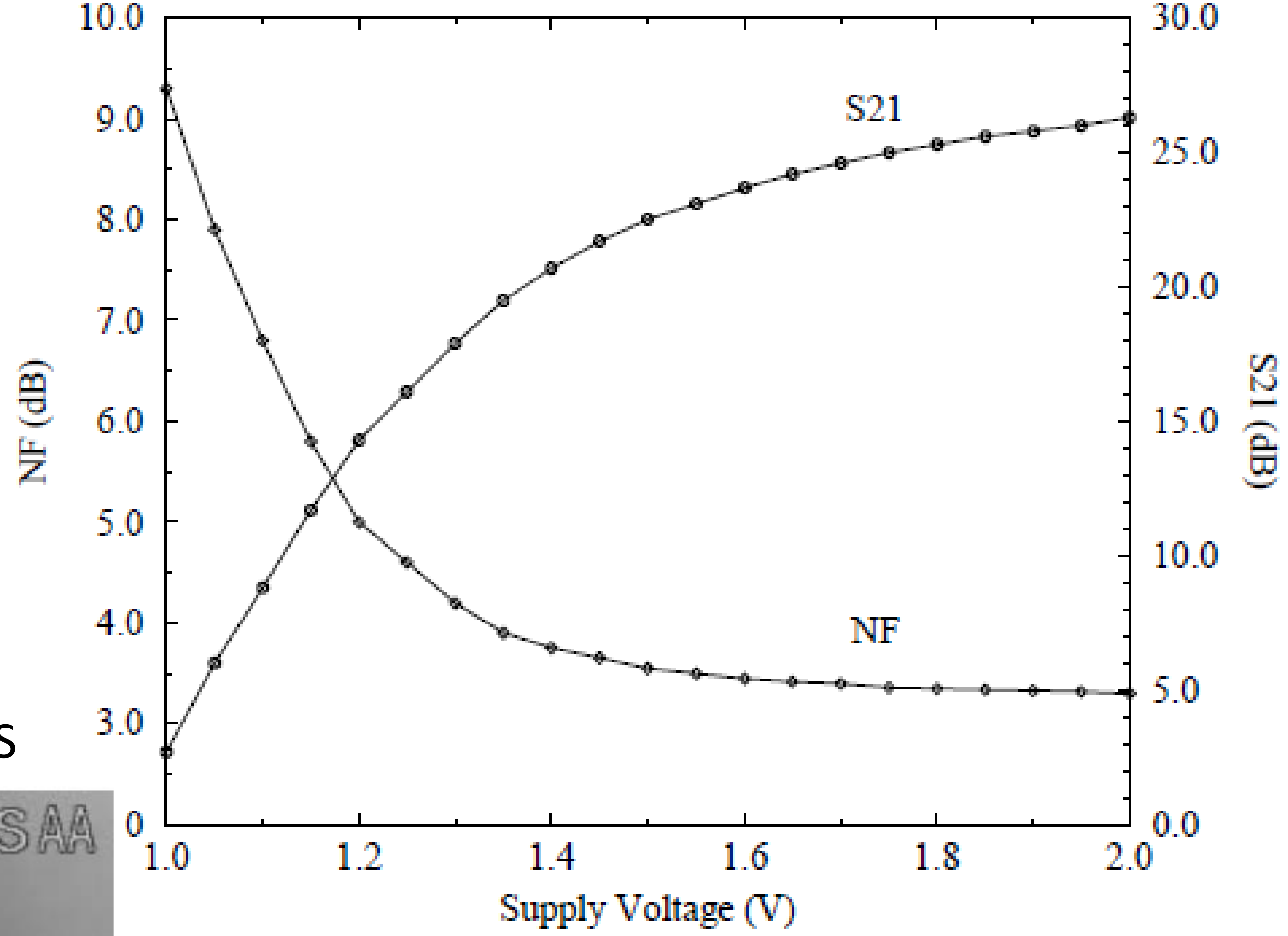
- R_s: source resistance
- R_l: line resistance
- R_g: gate resistance
- g_{d0}: drain conductance at $V_{ds} = 0$
- ω_T: cutoff freq. = g_m/C_{gs}
- g_m: transconductance
- C_{gs}: gate-source input C
- γ: MOS channel noise factor

Two-Stage LNA

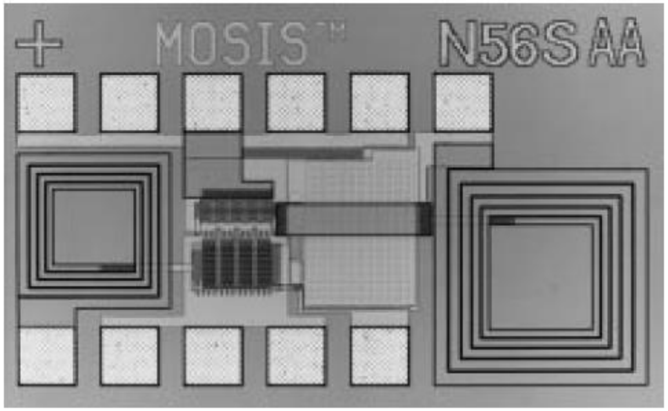


Inductive peaking:
zero BW enhancer

Two-Stage LNA Performance



0.12 cm^2 in 0.6μm CMOS

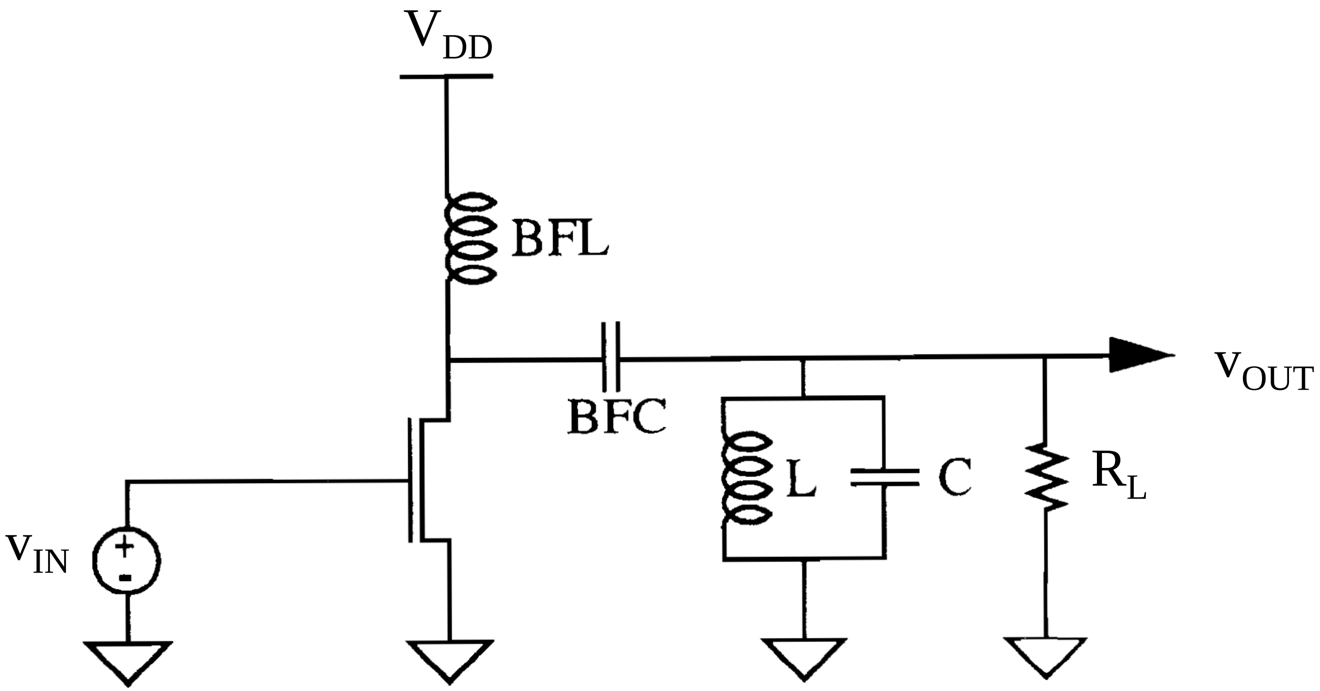


CMOS RF Power Amplifier

- Delivering RF power “efficiently” to a load.
- Small-signal analysis, by default, almost useless.
- Not limited by 50% power delivery from source impedance point of view: much higher efficiency is needed simply due to amplifier thermal management
- May carry additional amplitude/phase modulation.
- As the inductor *Q* so critical, usually not IC for high power output.
- RFID reader of 36dBm (4W), lower efficiency is tolerable

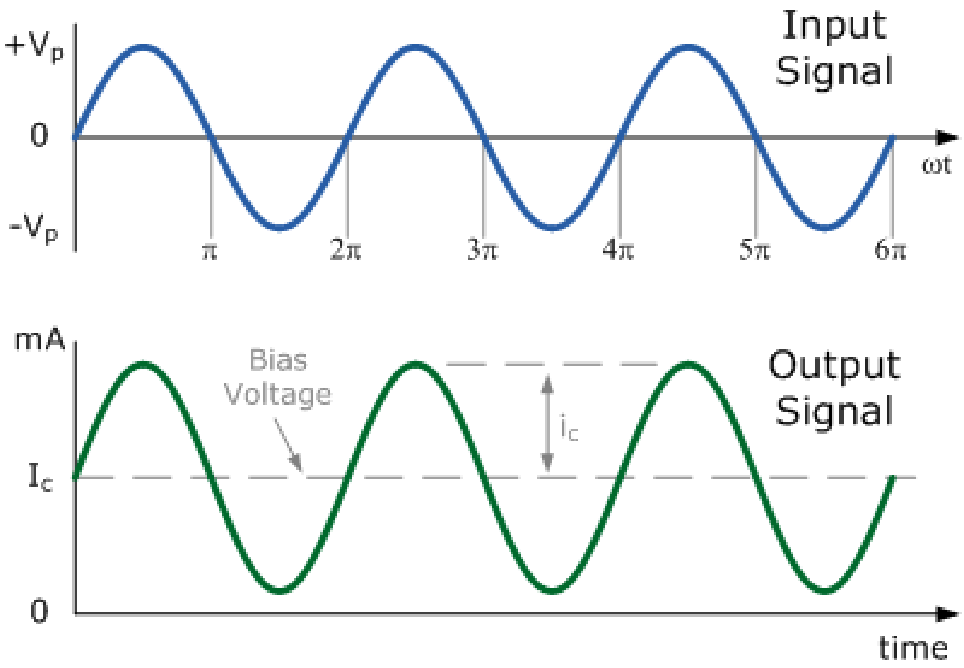
- Figure of merits: power gain, output power, linearity (distortion and radiation interference), efficiency

Generic RF Power Amplifier (PA)



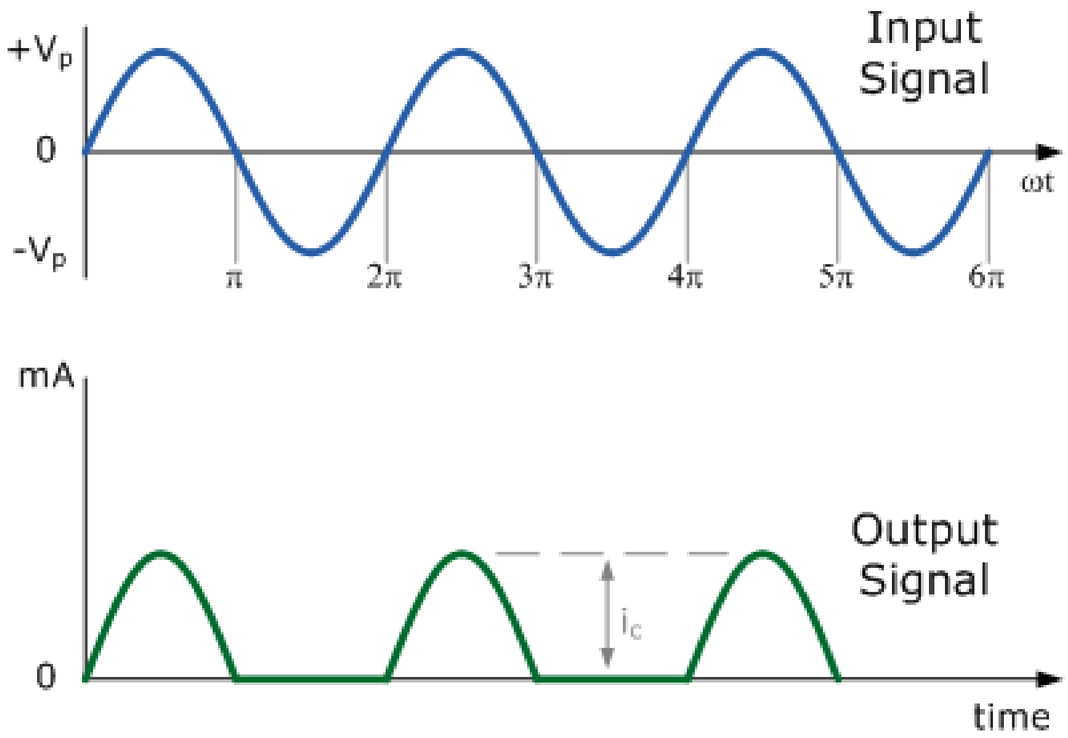
- BFL: big, fat inductor to keep current constant
- BFC: big, fat capacitor to block all DC leakage but pass all RF power
- R_L: load (most often, antenna or another PA)

Class A Power Amplifier



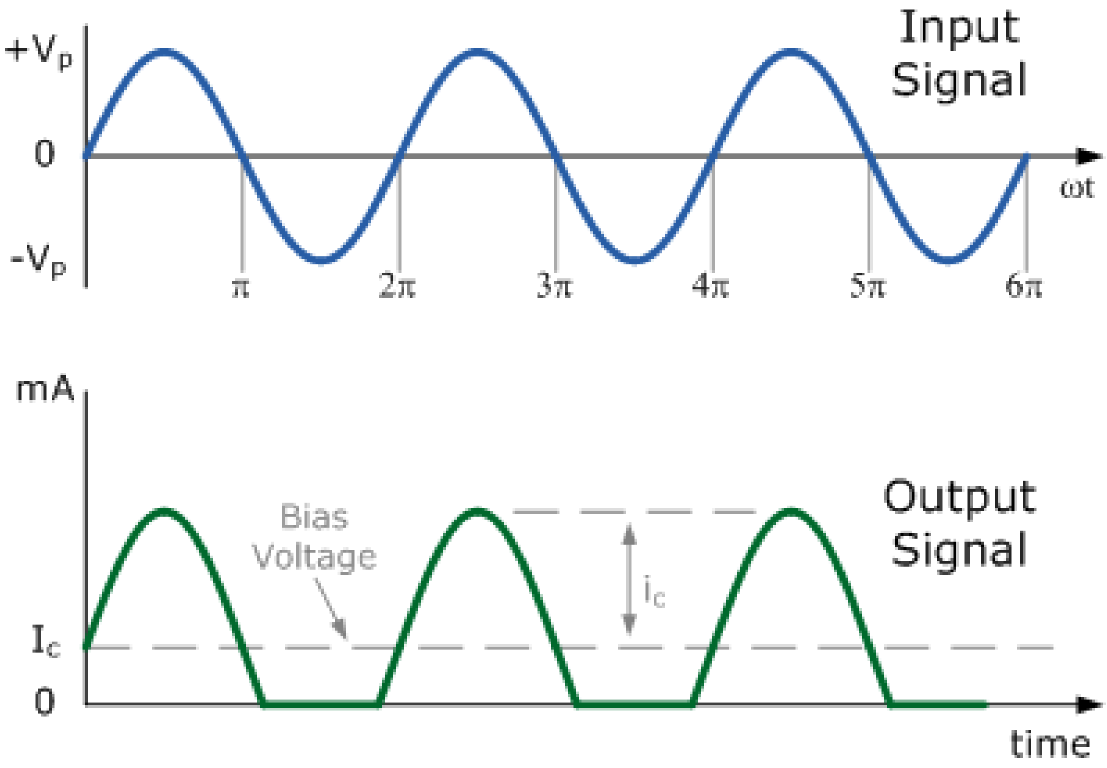
- A blow-up version of small-signal amplifier
- Bias levels are chosen so that the transistors are always on in the saturation region
- Narrow-band tank circuits to give linearity
- Efficiency very low, as the active device is on 100%.

Class B Power Amplifier



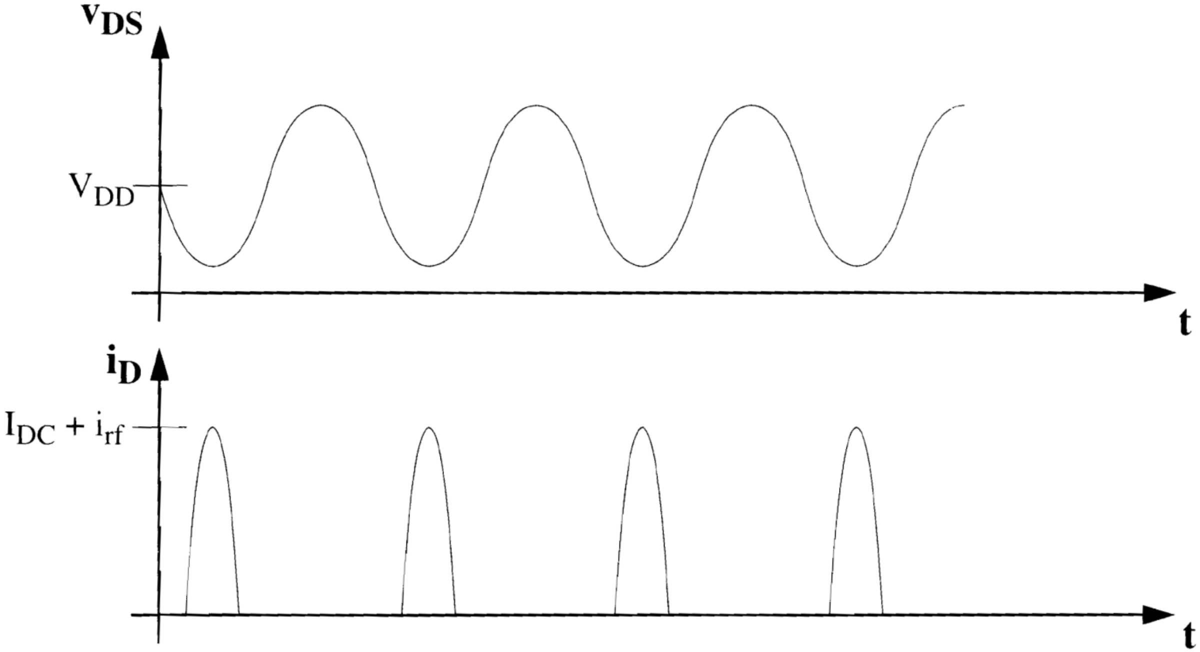
- Class B PA has the transistor turn on 50% of time, but keeps linearity (full sine wave output is maintained by high Q tank).
- Class B PA can use two switches (transistors) so that each turn on 50% of time and disable DC current
- When switch is OFF, there is cross-over distortion.

Class AB Power Amplifier



- Class B PA has the transistor turn between 50% and 100% of time, but keeps linearity still (full sine wave output is maintained by high Q tank).
- Compromise between efficiency of Class B and linearity of Class A

Class C Power Amplifier



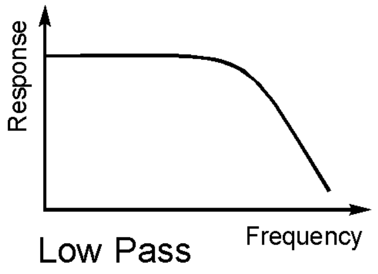
- Class C PA has the transistor turn on < 50% of time, and linearity degrades.
- Efficiency can be larger than 80% power wise, but only for a narrow bandwidth.

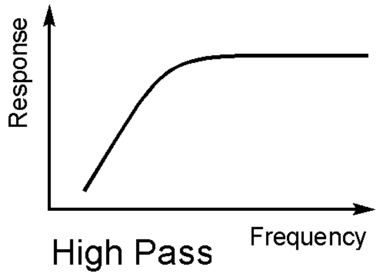
Power Amplifier Comparison

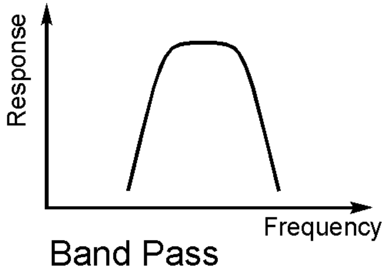
Class	A	B	C	AB
Conduction Angle	360^o	180^o	Less than 90^o	180 to 360^o
Position of the Q-point	Centre Point of the Load Line	Exactly on the X-axis	Below the X-axis	In between the X-axis and the Centre Load Line
Overall Efficiency	Poor, **25 to 30%**	Better, **70 to 80%**	Higher than **80%**	Better than A but less than B **50 to 70%**
Signal Distortion	None if Correctly Biased	At the X-axis Crossover Point	Large Amounts	Small Amounts

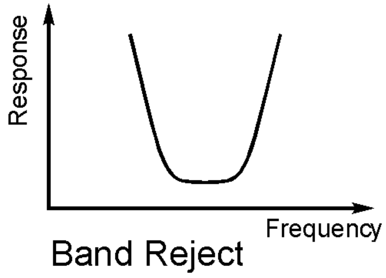
Filters and Attenuators

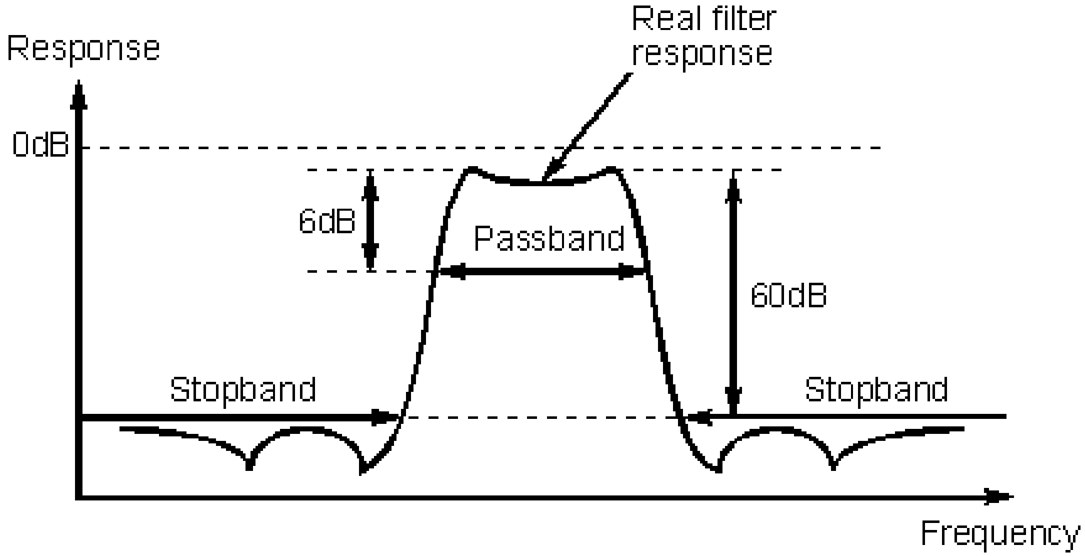
- Also called resonant circuits
- Type: low-pass, high-pass, bandpass and band reject
- Figure of merits: center frequency, bandwidth, Q, insertion loss, input/output impedance, shape factor (or order), ripples



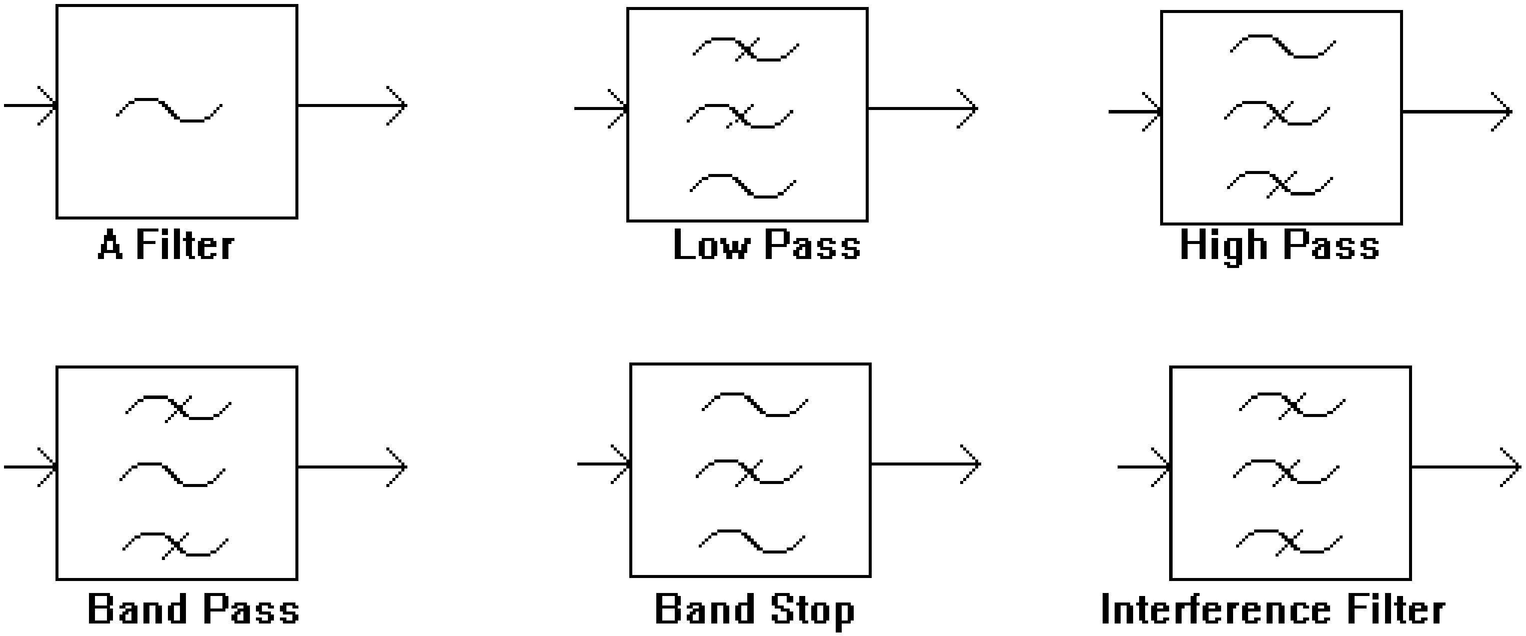






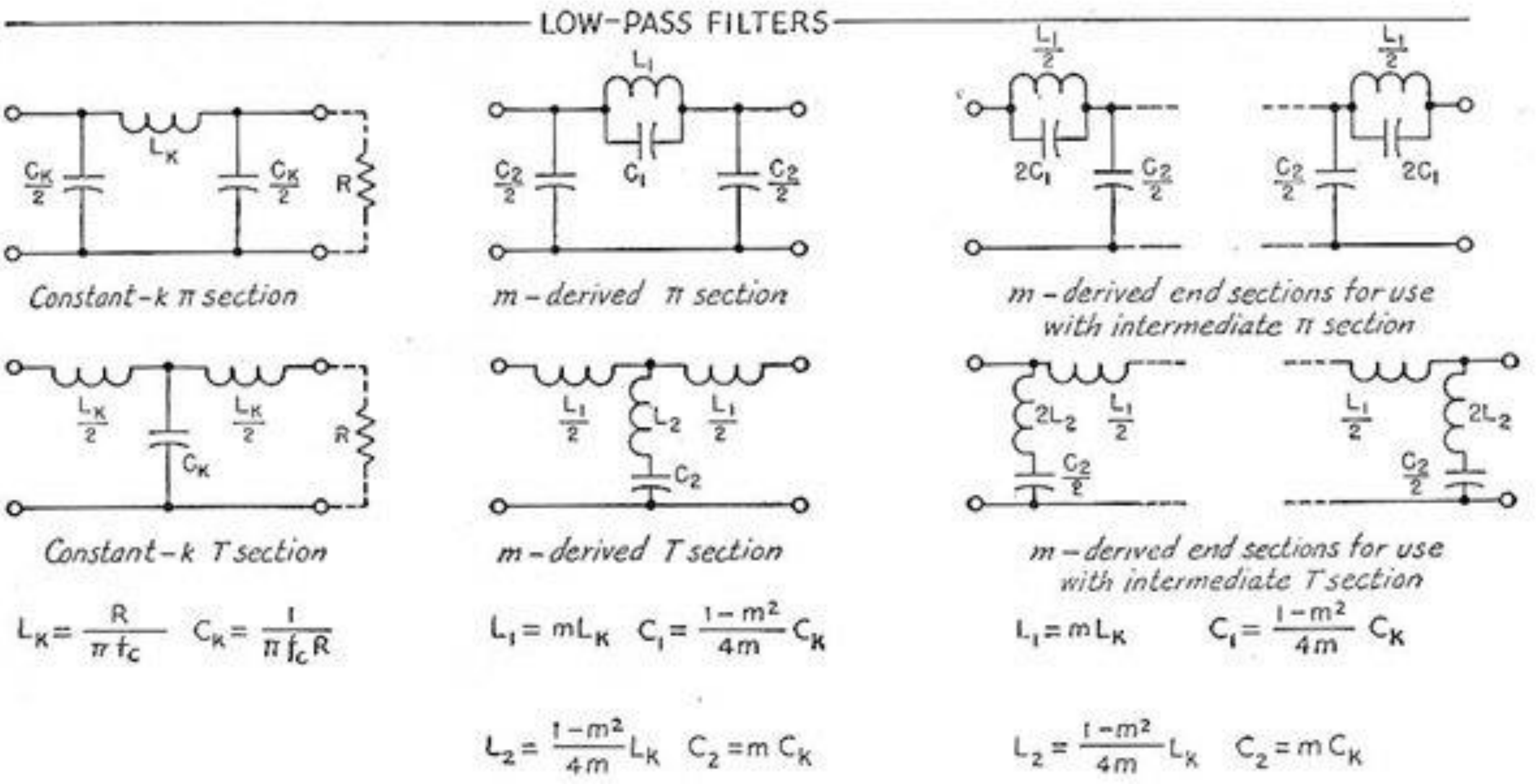


Filter Symbols



BLOCK DIAGRAM SYMBOLS FOR FILTERS

Low-Pass Filter



LOW-PASS FILTERS

Constant-k π section

m-derived π section

m-derived end sections for use with intermediate π section

Constant-k T section

m-derived T section

m-derived end sections for use with intermediate T section

$L_K = \frac{R}{\pi f_c}$ $C_K = \frac{1}{\pi f_c R}$

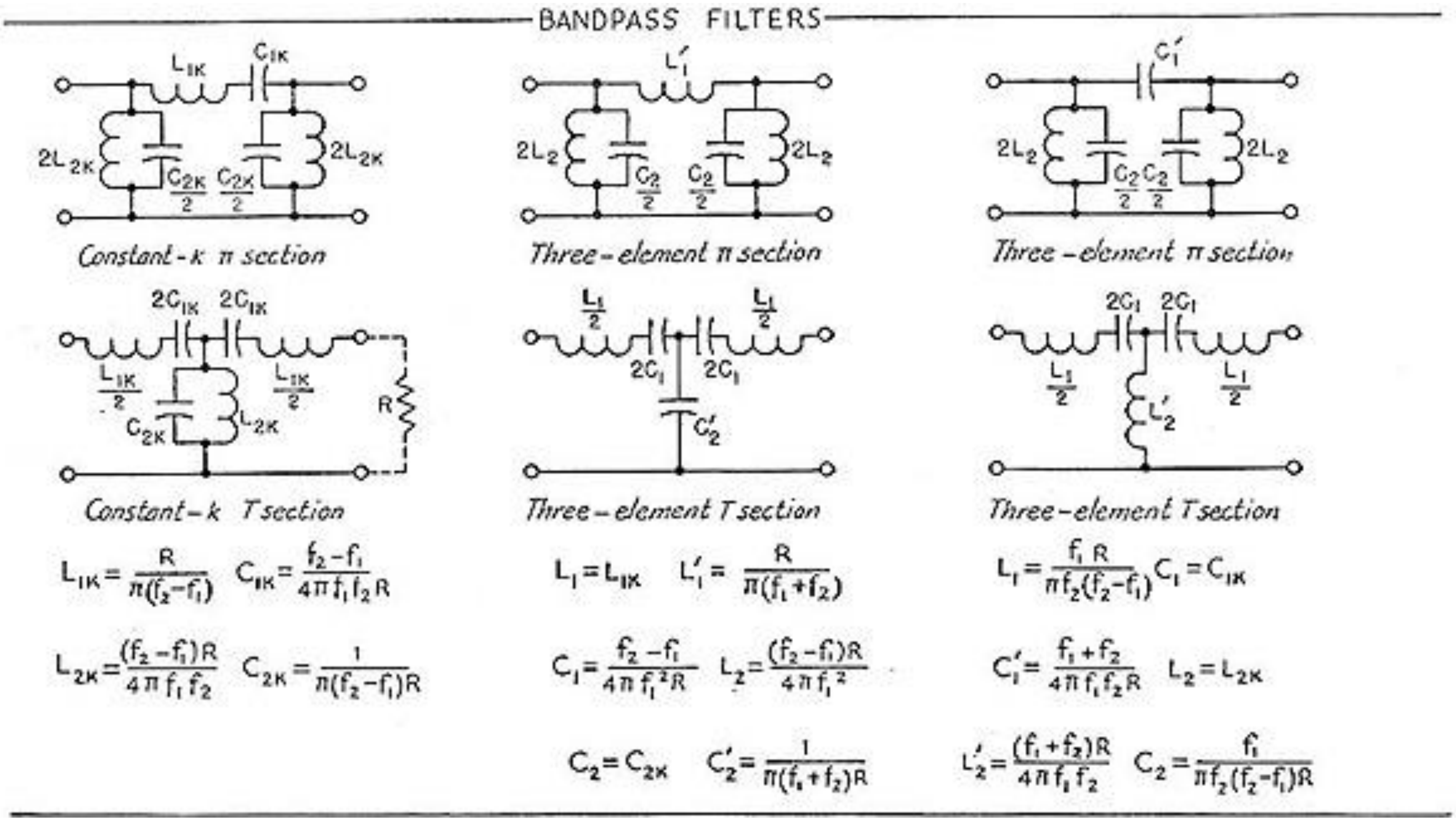
$L_1 = mL_K$ $C_1 = \frac{1-m^2}{4m} C_K$

$L_2 = \frac{1-m^2}{4m} L_K$ $C_2 = mC_K$

$L_1 = mL_K$ $C_1 = \frac{1-m^2}{4m} C_K$

$L_2 = \frac{1-m^2}{4m} L_K$ $C_2 = mC_K$

Bandpass Filter



BANDPASS FILTERS

Constant-k π section

Three-element π section

Three-element π section

Constant-k T section

Three-element T section

Three-element T section

$L_{1K} = \frac{R}{\pi(f_2-f_1)}$ $C_{1K} = \frac{f_2-f_1}{4\pi f_1 f_2 R}$

$L_{2K} = \frac{(f_2-f_1)R}{4\pi f_1 f_2}$ $C_{2K} = \frac{1}{\pi(f_2-f_1)R}$

$L_1 = L_{1K}$ $L_1' = \frac{R}{\pi(f_1+f_2)}$

$C_1 = \frac{f_2-f_1}{4\pi f_1^2 R}$ $L_2 = \frac{(f_2-f_1)R}{4\pi f_1^2}$

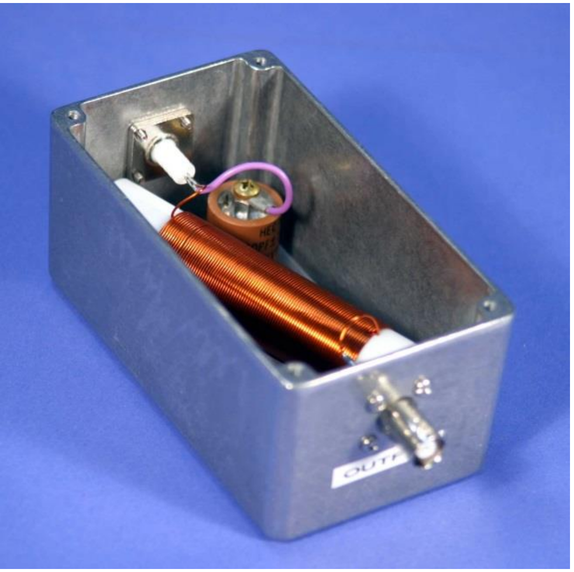
$C_2 = C_{2K}$ $C_2' = \frac{1}{\pi(f_1+f_2)R}$

$L_1 = \frac{f_1 R}{\pi f_2(f_2-f_1)}$ $C_1 = C_{1K}$

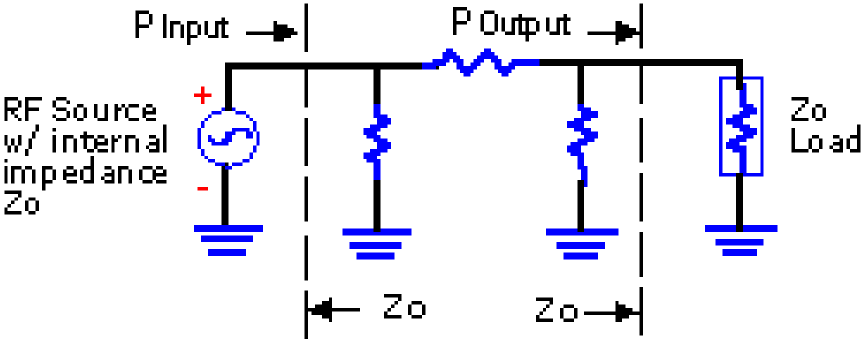
$C_1' = \frac{f_1+f_2}{4\pi f_1 f_2 R}$ $L_2 = L_{2K}$

$L_2' = \frac{(f_1+f_2)R}{4\pi f_1 f_2}$ $C_2 = \frac{f_1}{\pi f_2(f_2-f_1)R}$

RF Filter Examples



RF Attenuators



Input/Output impedance!!!

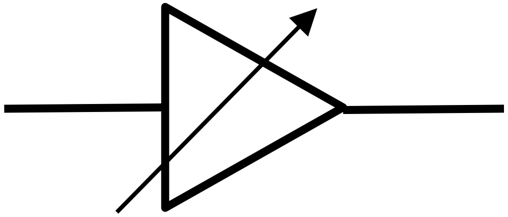
$$Attenuation(dB) = 10\log\left(\frac{P_{in}}{P_{out}}\right)$$

Passive RF attenuator

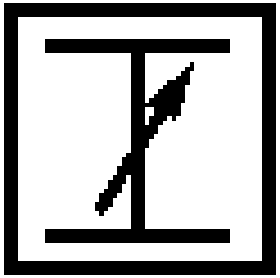
Variable RF attenuator

Power RF attenuator

Attenuator Symbols



Baseband attenuators



RF attenuators with I/O impedance match

Group Activities: Fundamental Trade-off

- Power amplifier: linearity, efficiency and bandwidth
- LNA:
- Generic signal amplifier:
- Filter:
- Inductor:
- Digital logic:
- Engineering design:
- Your happiness:
- This class:

Fundamental trade-offs are often used to define figure of merits (FoM)

Group Activities: My View

- Power amplifier: linearity, efficiency and bandwidth
- LNA: gain, noise figure, power consumption
- Generic signal amplifier: sensitivity and dynamic range
- Filter: tunability and orders
- Inductor: inductance, Q and operating frequency
- Digital logic: power and performance
- Engineering design: performance and cost
- Your happiness: short-term vs. long-term
- This class: time investment and grade

Outline

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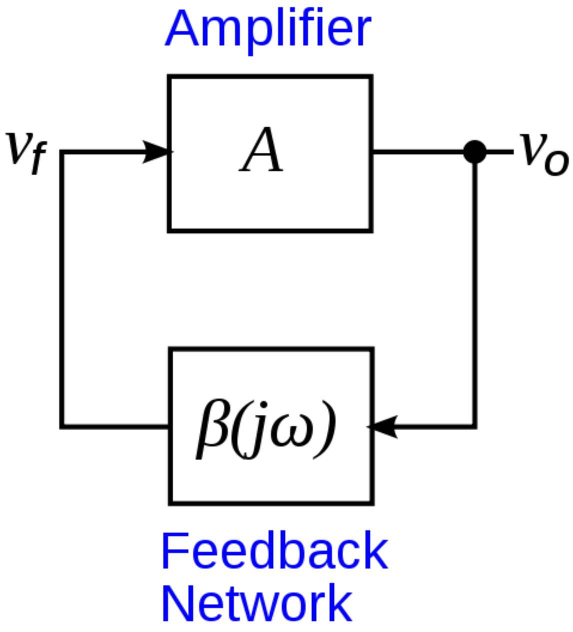
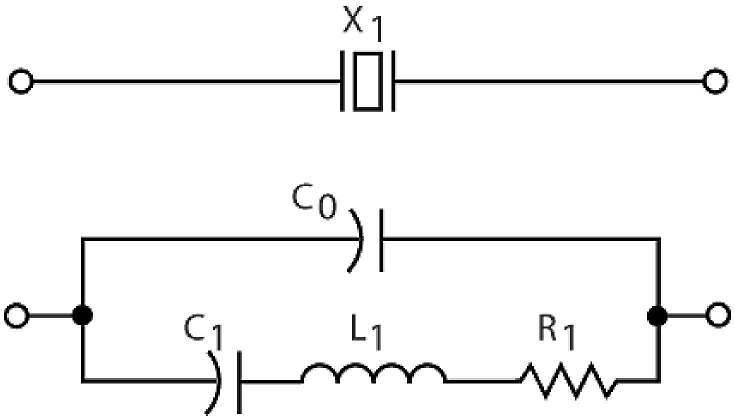
Oscillators

- Periodic output is not sufficient as free-running oscillators
  - Spectral purity
  - Amplitude stability
  - Phase consistency
- Barkhausen stability criteria
  - $|\beta A| = 1$
  - $\angle \beta A = 2\pi n$
- Practical oscillator usually contains a transistor gain unit and a resonator (quarter-wave, LC tank, bulk acoustic, surface acoustic, etc.)



Quartz "Oscillators"

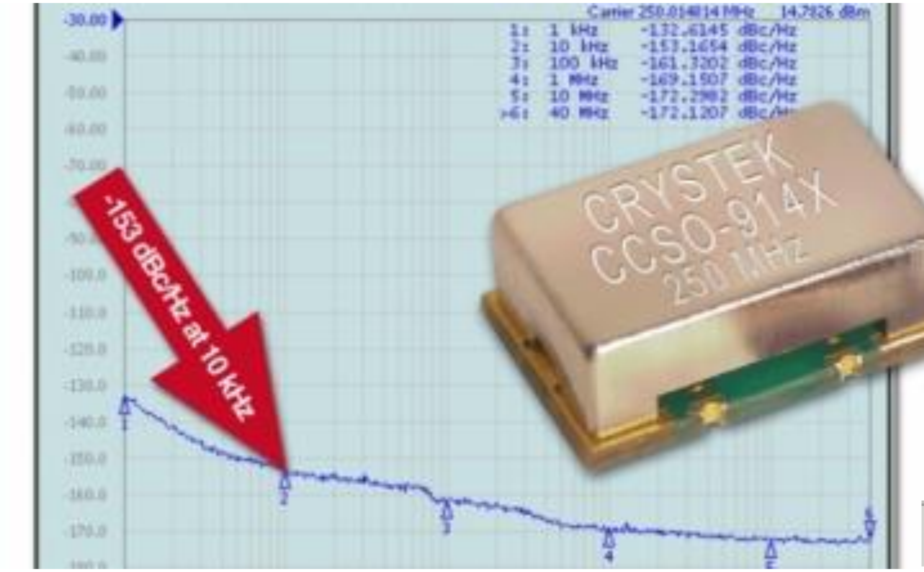
- The bulk shear mode of the piezoelectric quartz is used most often as the RF resonator:
  - Spectral purity
  - Electrical and mechanical stability
  - Very low temperature coefficients
  - Almost lossless electrical/mechanical transduction
  - Q of 10^4 to 10^6.



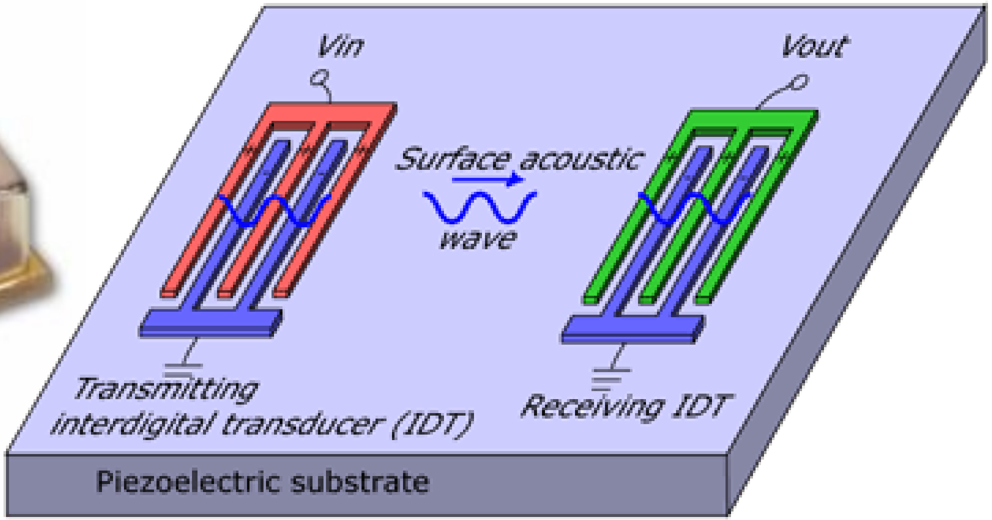
Limited to few MHz for reasonable physical dimensions (unless Prof. Bhave tells you otherwise)

Surface Acoustic Wave (SAW) “Oscillators”

- Piezoelectric crystals that support surface acoustic waves (most often by lithium niobate (LiNbO3)
  - Higher frequency at 250 MHz – 1 GHz.
  - Almost as good as crystal oscillators (in comparable price)

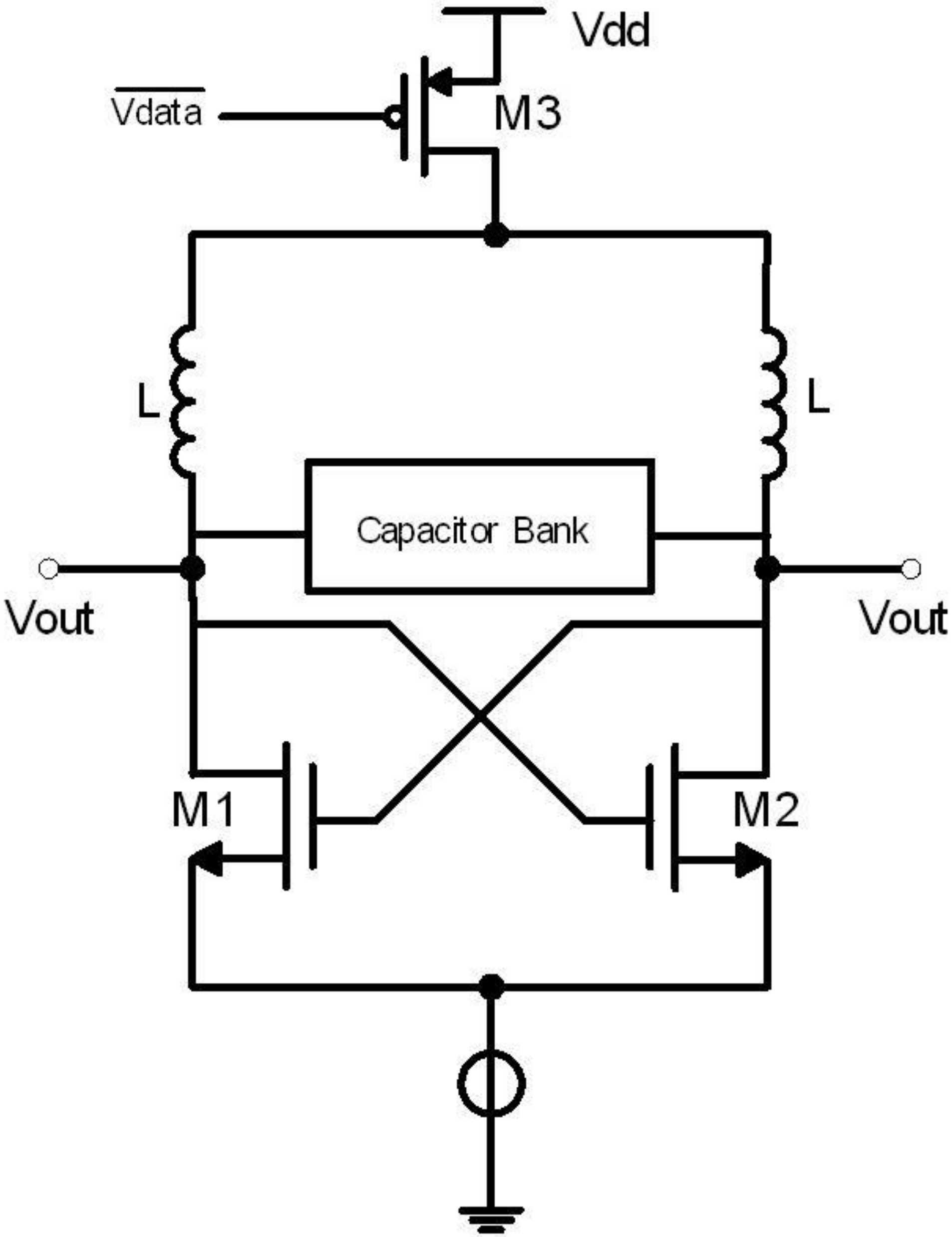


SAW resonator



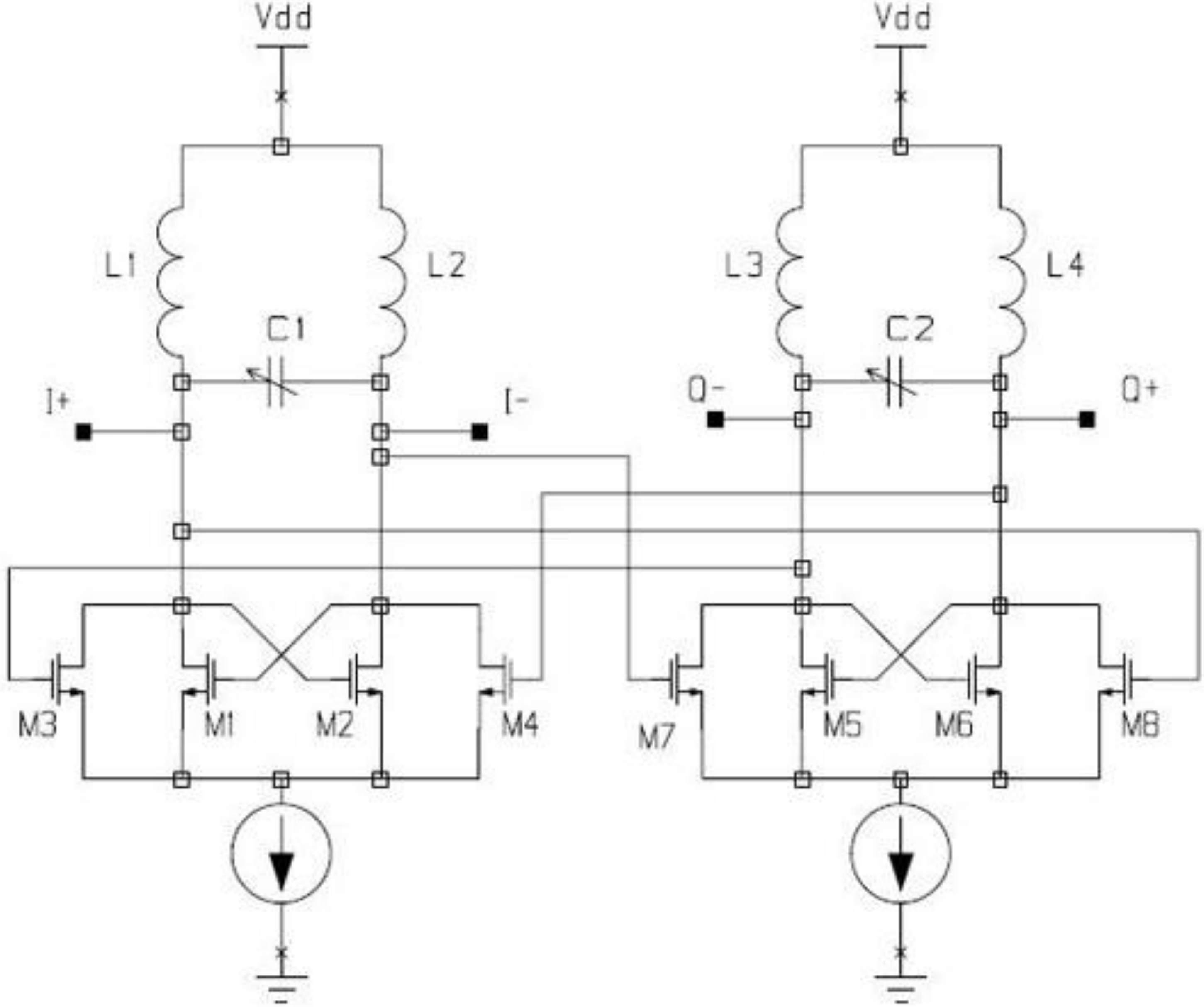
SAW sensor/transponder

Cross-Coupled LC Oscillators



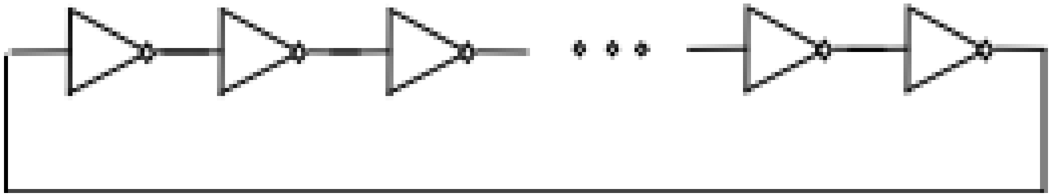
- Capacitor bank and the bias current determines the oscillating frequency
- Modulation from Vdata
- Cross-coupled LC oscillators provides reasonable phase noise but small tuning range
- Temperature coefficients determined mostly by LC values, not transistors

Quadrature Cross-Coupled Oscillators

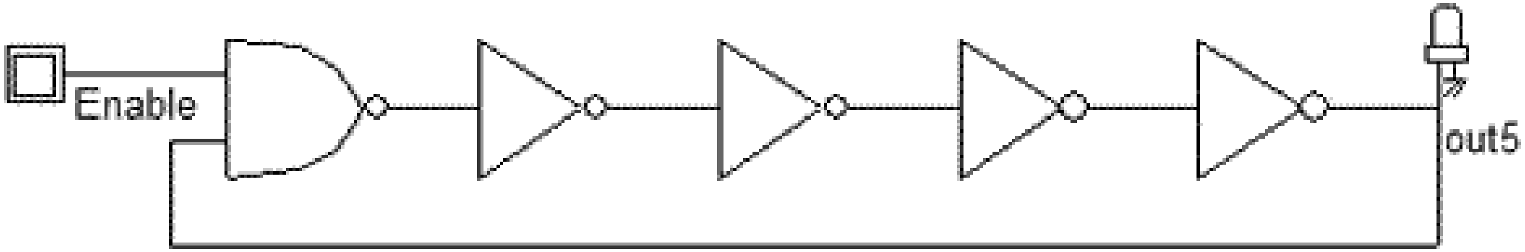


Ring Oscillators

Odd-number (N) of stages in feedback loop



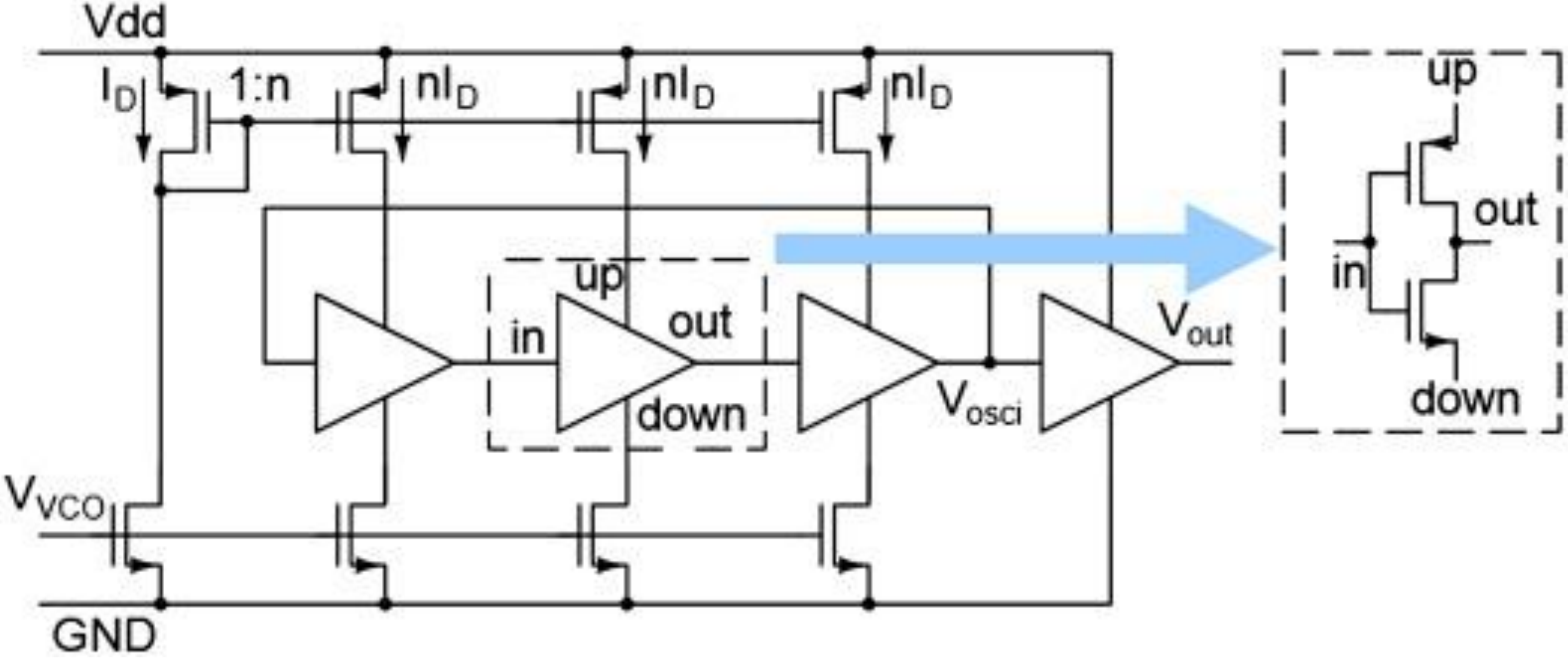
Loop delay =
N × (Inverter delay)



Five-stage ring oscillator with enable

- Bad phase noise and inaccurate duty cycle
- Can have large tuning range
- Bad temperature coefficients

Current-Starved Voltage-Controlled Ring Oscillators (VCO)



- Large tuning range by V_{VCO}
- Stable duty cycle

Phase Noise in Oscillators

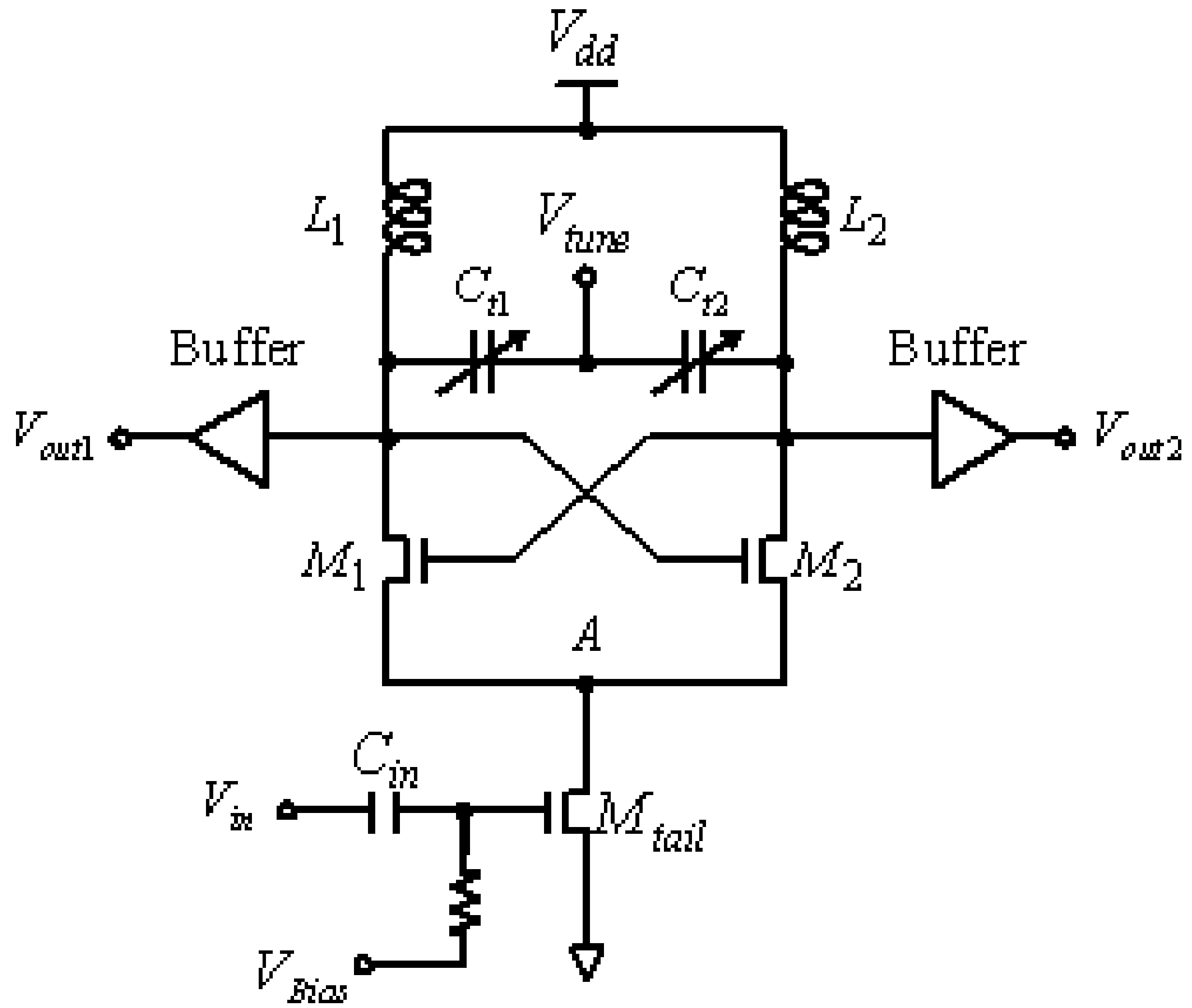
- Small deviation from the Barkhausen phase criterion $\angle \beta A = 2\pi n + \theta$ will cause timing issues
- Most oscillators do not provide sufficiently small phase noise (uncertainty in zero-crossing points in a waveform), except by crystal or SAW.
- RF channel selection means we need to pin point frequency (and phase) accurately
- Can we “lock” the zero-crossing point of two similar frequencies???

- Figure of merits: phase noise, settling time, bandwidth, power consumption

Ubiquitous Phase Lock Loop

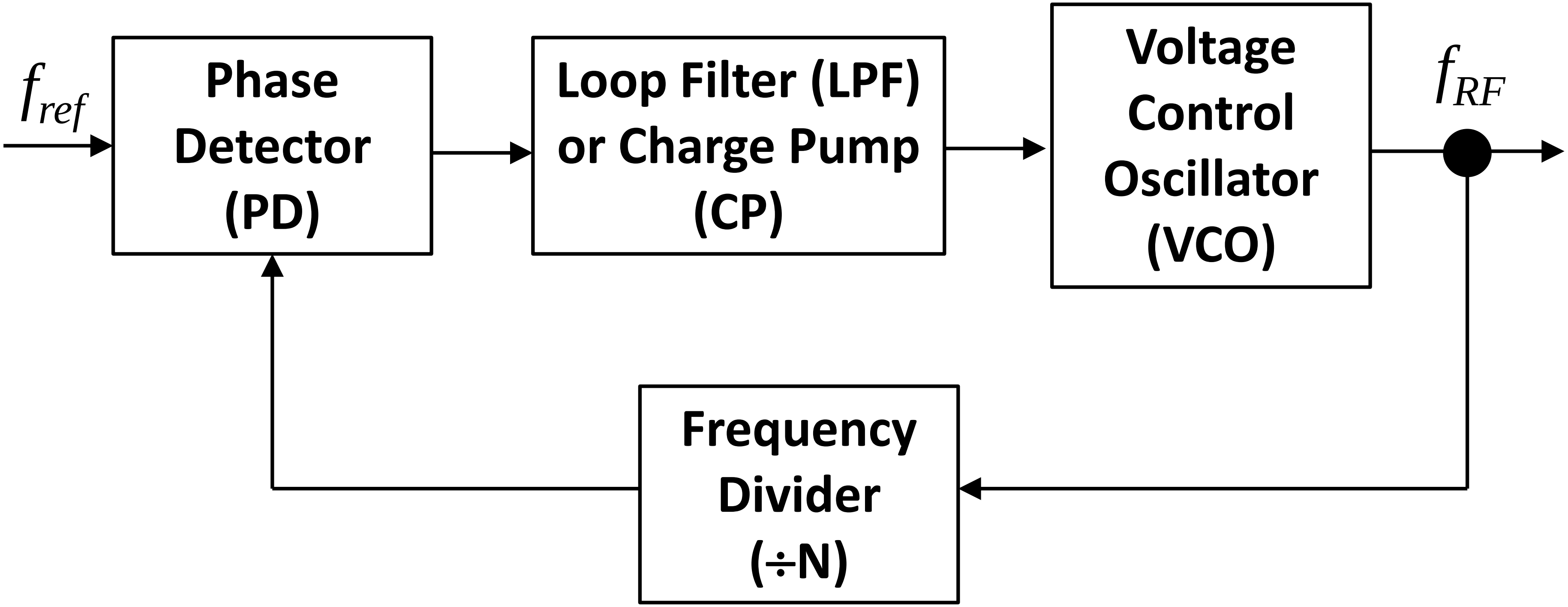
- Phase lock loops (PLL) have been ubiquitous in modern computing and communication systems.
- In RF, PLL can generate programmable frequency (rational multiple) that inherits the phase noise of crystal oscillators.
- Can be used in frequency modulation and demodulation
- Regenerate carriers
- In Digital circuits, PLL can perform skew compensation, clock recovery and generation of clocks

Concept of Injection Locking



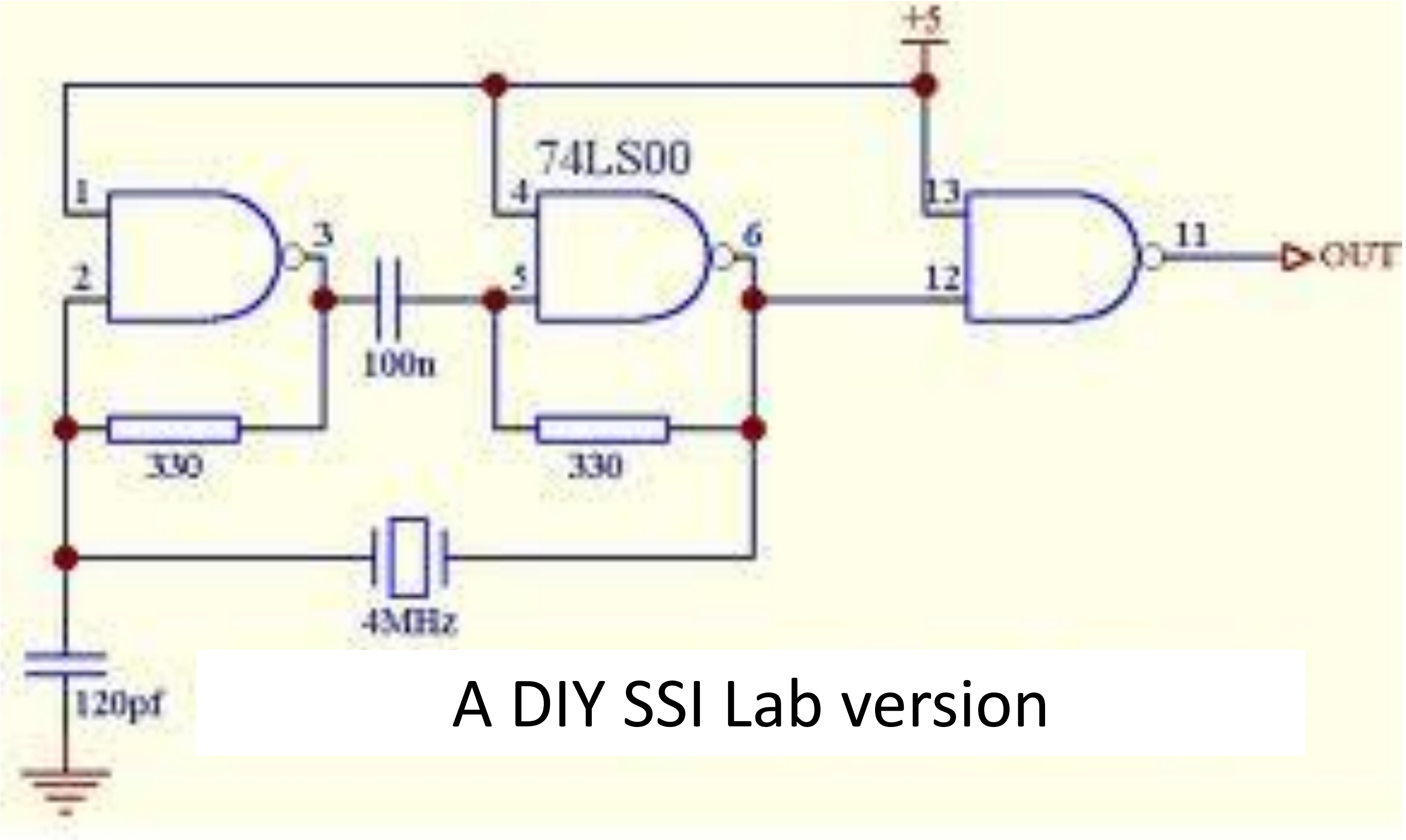
Injection lock frequency divider (ILFD, even number)

General PLL Architecture



DIY Oscillator Circuits with Phase Locking

- Use crystal oscillator to provide stable oscillations in a ring-oscillator configuration

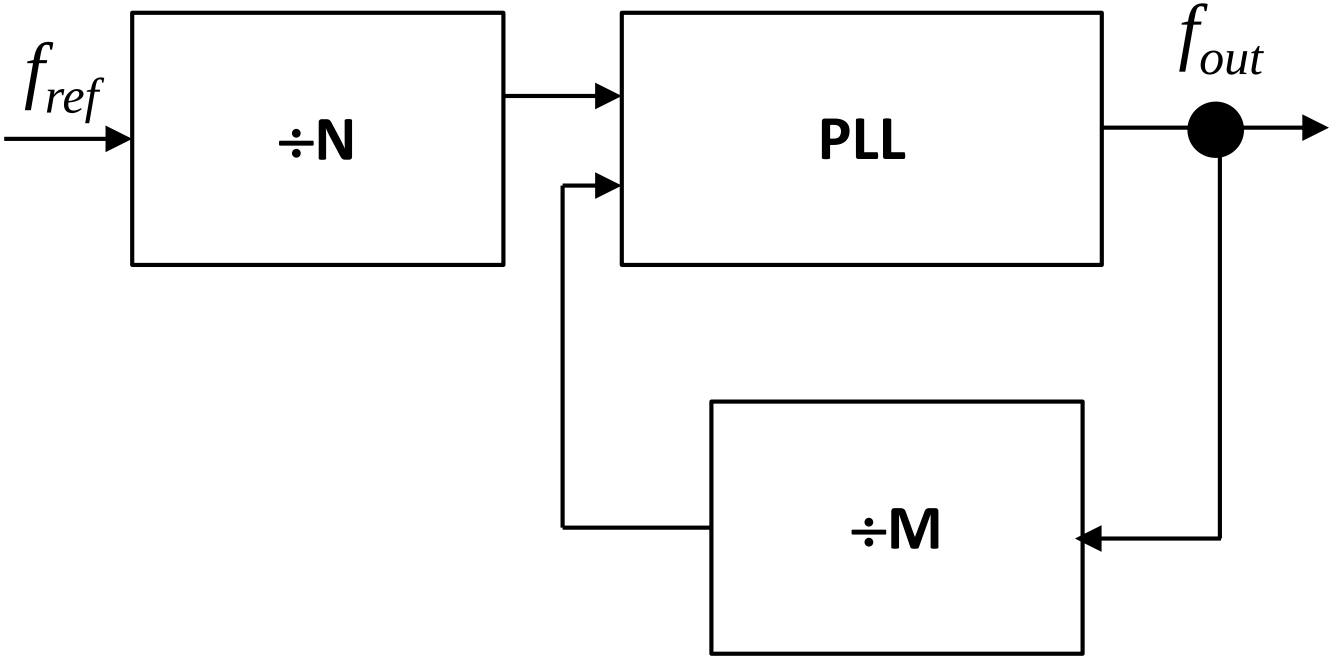


A DIY SSI Lab version

Frequency Synthesizer

- Use an accurate f_{ref} with good spectral purity and phase noise to create multiple RF frequencies with similar quality by PLL
- Figure of merits: Frequency range, frequency precision, power consumption, output power, settling time

Classic Rational Frequency Synthesizer



$$\frac{f_{ref}}{N} = \frac{f_{out}}{M}$$

$$f_{out} = \frac{M}{N} \cdot f_{ref}$$

Frequency Synthesizer Examples

TI TRF 3765

- A broadband Integer-N/Fractional-N frequency synthesizer
- Integrated broadband VCO.
- Programmable output dividers enable continuous frequency coverage from 300 MHz to 4.8 GHz.
- Four separate differential, open-collector RF outputs allow multiple devices to be driven in parallel without the need of external splitters.

Outline

- Reader architecture
- Tag-to-reader encoding and modulation
- Signal path components:
  - Quadrature mixer
  - Low-noise amplifier (LNA)
  - Power amplifier
  - Filters and attenuators
- Frequency synthesizer: oscillator and PLL
- Transmitter-Receiver isolation

Transmitter/Receiver Isolation

- In mono-static configuration, the circulator between the TX and RX mode often only have around –20dB to – 30dB isolation.
- A 36dBm carrier (to continuously supply tag power) will leak to have 6dBm, much stronger than the expected –90dBm backscattered signal. Often the dynamic range is achieved by subcarrier modulation and GREAT filters.
- Bi-static configuration can have additional antenna isolation.
- However, for RFID, this self jamming is known, and cancellation can be applied.

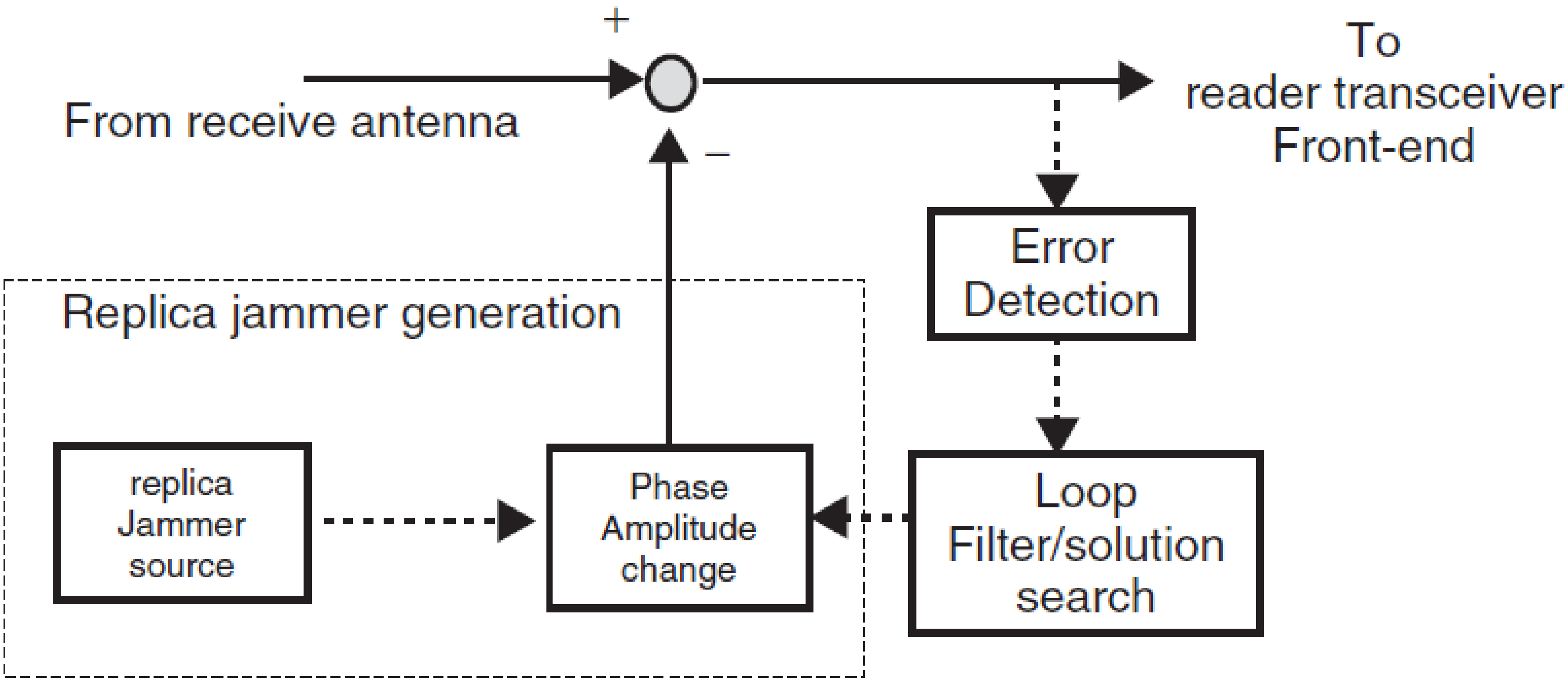
Self-Jamming Cancellation

- Picking the replica jamming source
- Devising a method to vary the phase and amplitude of the replica
  - Ex., generation in the quadrature scheme

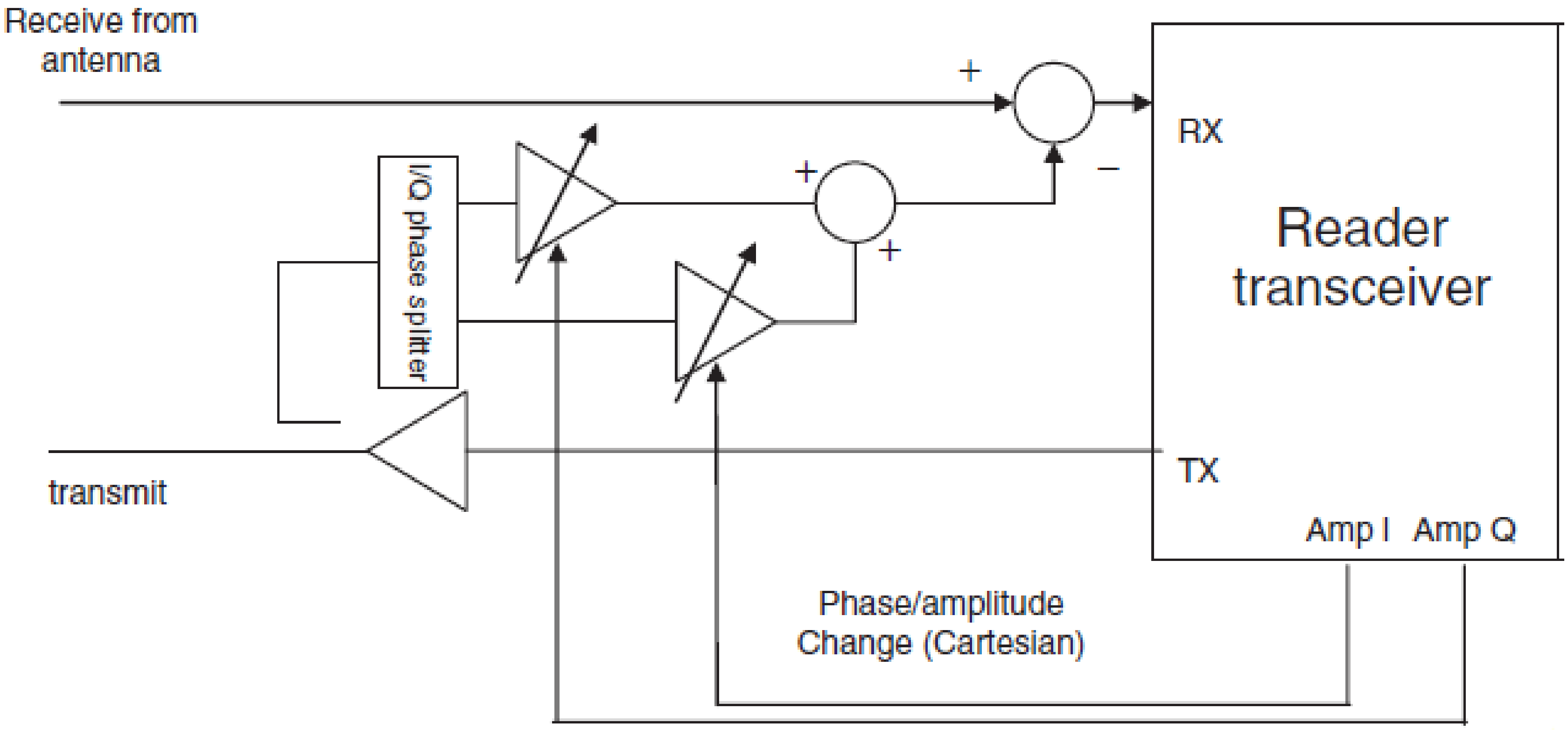
$$\cos(\omega t-\omega_0)=\cos(\omega t)\cos(\omega_0)+\sin(\omega t)\sin(\omega_0)$$

- Deriving the error detection scheme
- Finding the search mechanism for an optimal cancellation

Software-Defined Feedback Cancellation



Self-Jamming Quadrature Cancellation



- Jammer replica from transmitter output by coupler
- IQ phase splitter gives orthogonal vector signals
- Attenuators give the amplitude and phase change
- Error: DC amplitude from the receiver I and Q mixer output
- Software-defined optimization scheme.

What Do You Learn

- RFID reader architecture in UHF backscattering
- Different encoding for reader-to-tag and tag-to-reader
- Reader RF circuit components: mixer, LNA, PA, filters, frequency synthesizer (oscillator and PLL)
- TX/RX Isolation to avoid/cancel self jamming