An introduction to RF receivers for radio astronomy

2026 DARA February Training School

Tinus Stander
Carl and Emily Fuchs Institute for Microelectronics
Dept. EEC Engineering, University of Pretoria

tinus.stander@up.ac.za

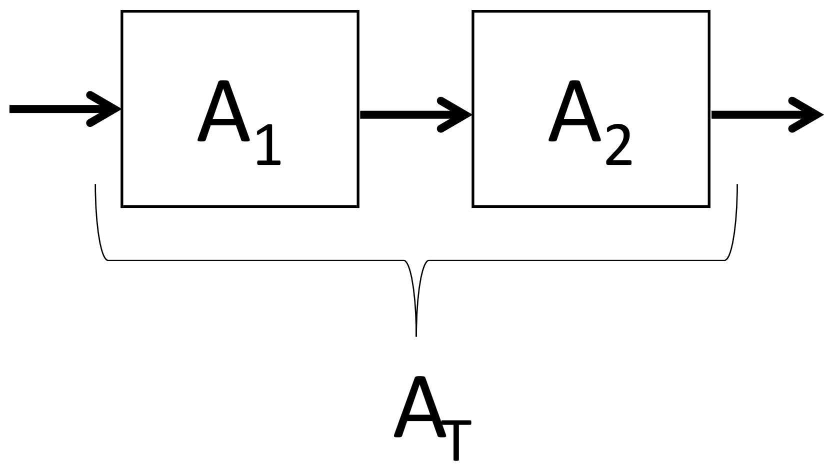
Agenda

- RF Basics
- Noise & Distortion
- Components and Connections
- Important RF circuits
- Receiver architectures
- RF measurement equipment

RF Basics

The Decibel (dB)

- Used wherever we have a ratio
  - Usually loss or gain
- $A_T = A_1 \times A_2$
- Power: A_X (dB) = $10\log(A_X)$
- Voltage / Current / S-parameters:
  A_X (dB) = $20\log(A_X)$
- A_T (dB) = A_1 (dB) + A_2 (dB)
- A > 0 dB : gain
- A < 0 dB : loss



The S-parameter (Scattering Matrix)

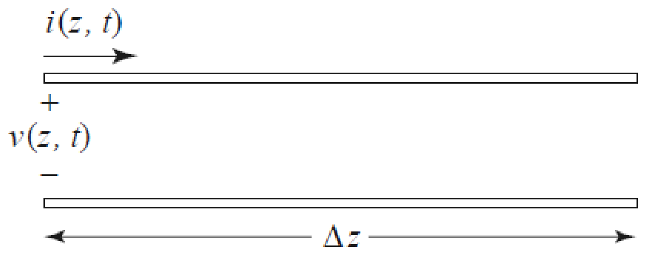
- Incident and reflected voltage wave relationships
  - Frequency variant
  - Complex
- All ports terminated Z_0
  - Characteristic impedance of system
- Important ones for N = 2:
  - S_{21}: Forward transmission
  - S_{11}: Input reflection
  - S_{22}: Output reflection
  - S_{12}: Reverse transmission
- Reciprocal: $S_{21} = S_{12}$

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & & & \vdots \\ S_{N1} & \cdots & & S_{NN} \\ \vdots & & & \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{V_k^+=0 \text{ for } k \neq j}$$

$$[S] = \begin{bmatrix} 0.15\angle 0^\circ & 0.85\angle -45^\circ \\ 0.85\angle 45^\circ & 0.2\angle 0^\circ \end{bmatrix}$$

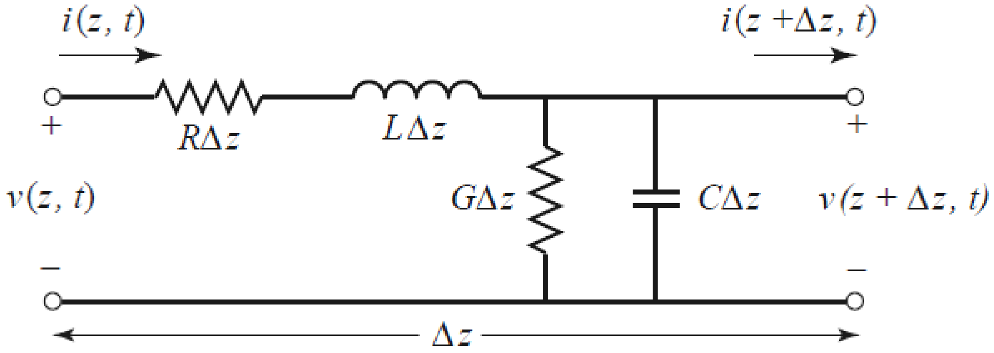
Wires and Interconnects



- DC approximation: $i(z=0) = i(z = z_x)$, $v(z=0)=v(z=z_x)$
- Non-negligible other effects:
  - Inductance
  - Resistance
  - Stray capacitance (get to that with TX lines)
- Lumped Element approximation: $z_x << \lambda/10 \rightarrow \lambda/20$

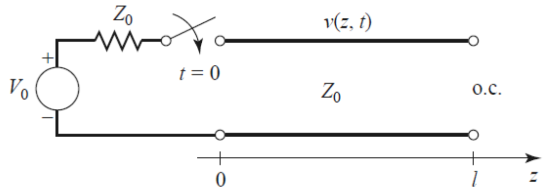
Transmission Lines

- Wave propagating along medium
    - v(z,t), i(z,t)
    - Finite phase shift
- Medium characteristics
    - Z, β, α
    - Reflection
- TEM modes
    - Nondispersive, 2+ conductors
- TE, TM modes
    - Dispersive, 1+ conductor

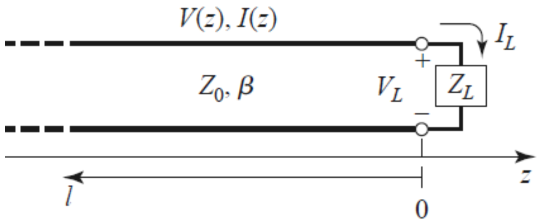


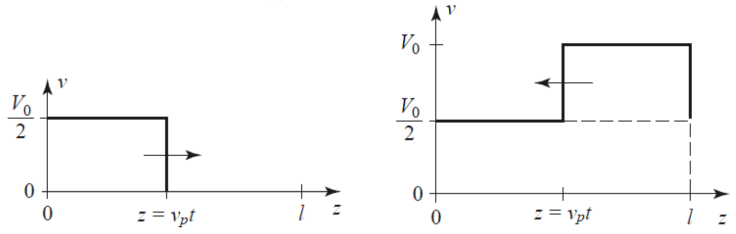
$$v_p = \frac{\omega}{\beta} = \lambda f. \quad Z_0 = \sqrt{\frac{L}{C}} \quad \lambda = \frac{2\pi}{\beta} = \frac{2\pi}{\omega\sqrt{LC}}$$

$$\alpha \simeq \frac{1}{2}\left(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}}\right) = \frac{1}{2}\left(\frac{R}{Z_0} + GZ_0\right)$$



(a)

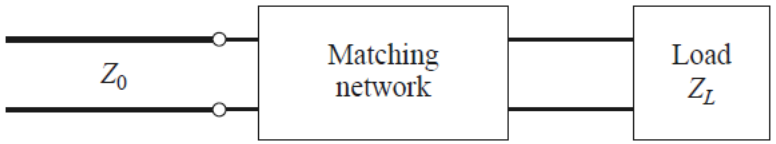




Impedance matching

- Maximum power delivery between matched source and load
- Sometimes a specific source impedance is sought
  - We'll get to that later
- In cases of mismatch: impedance matching network

$$Z_{\text{in}} = Z_0 \frac{1 + \Gamma_\ell e^{-2j\beta\ell}}{1 - \Gamma_\ell e^{-2j\beta\ell}} = Z_0 \frac{Z_\ell + jZ_0 \tan\beta\ell}{Z_0 + jZ_\ell \tan\beta\ell},$$

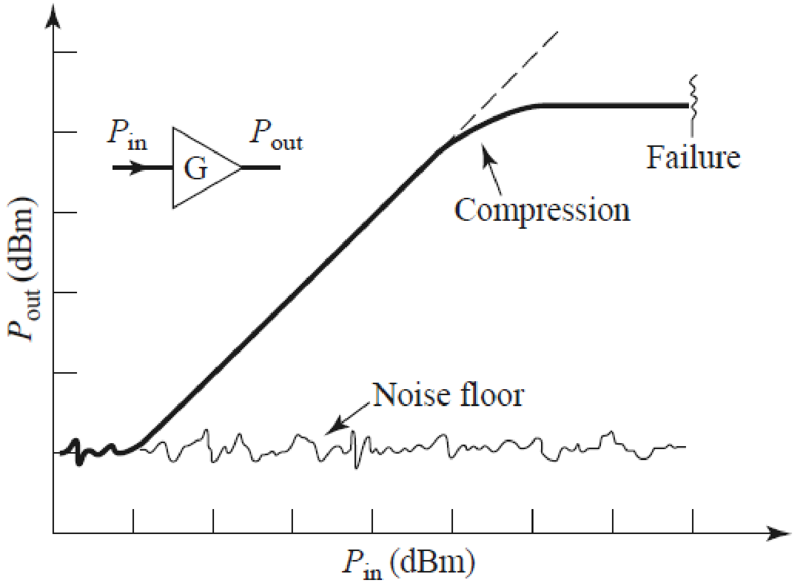


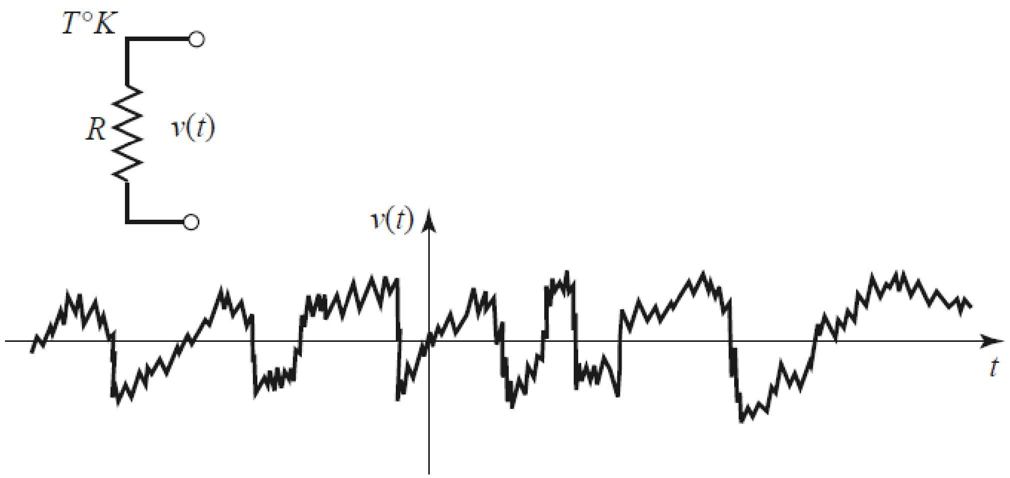
$$\Gamma_\ell = \frac{Z_\ell - Z_0}{Z_\ell + Z_0}.$$

Noise

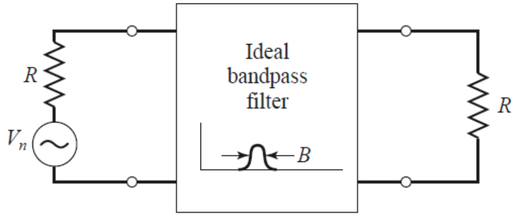
General principles (1)

- Random variation
  - Internal: charge carriers
    - Thermal noise (Johnson / Nyquist)
    - Shot noise
    - Flicker (1/f) noise
  - External: physical phenomenon
    - Thermal emissions, cosmic background
    - Sources = interferers, not noise
  - Flat spectrum = “white noise”
    - Zero average, nonzero RMS
- Limits dynamic range
  - Other end: compression / distortion



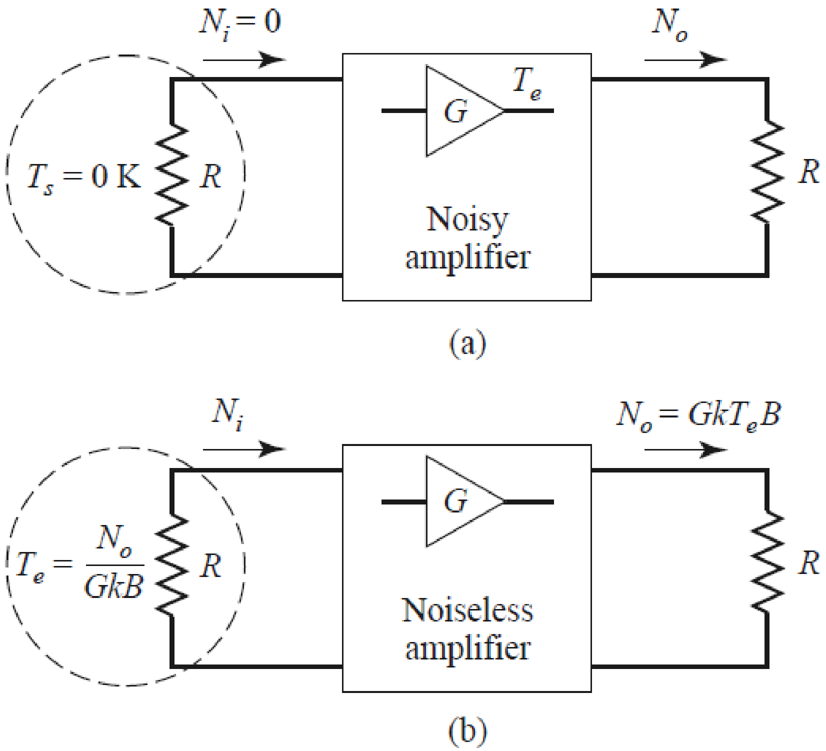


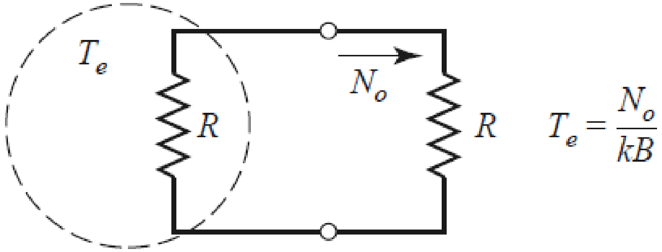
General principles (2)



$$V_n = \sqrt{4kTBR}.$$

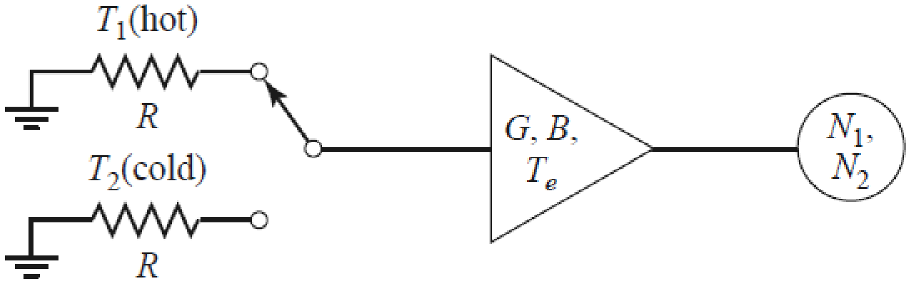
- Link between noise and temperature
- Planck blackbody
    - Rayleigh-Jeans approx. okay, except
        - f > 1 THz, K << 300K
- Equivalent noise temperature
- Used for noise-generating components
- Used for antennas





Noise Measurement

- Y-factor method
- Switch between "hot" and "cold" loads
- Need Y >> 1
  - T1 >> T2
  - T1, T2 >> Te
- Re-write i.t.o. ENR: T1/T2
  - ENR tables provided in noise sources



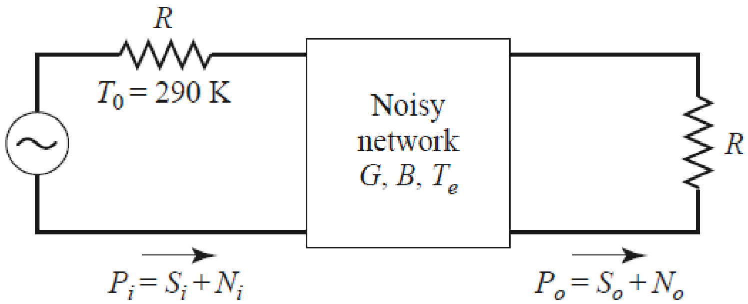
$$N_1 = GkT_1B + GkT_eB,$$
$$N_2 = GkT_2B + GkT_eB,$$

$$Y = \frac{N_1}{N_2} = \frac{T_1 + T_e}{T_2 + T_e} > 1,$$

$$T_e = \frac{T_1 - YT_2}{Y - 1},$$

Noise Figure

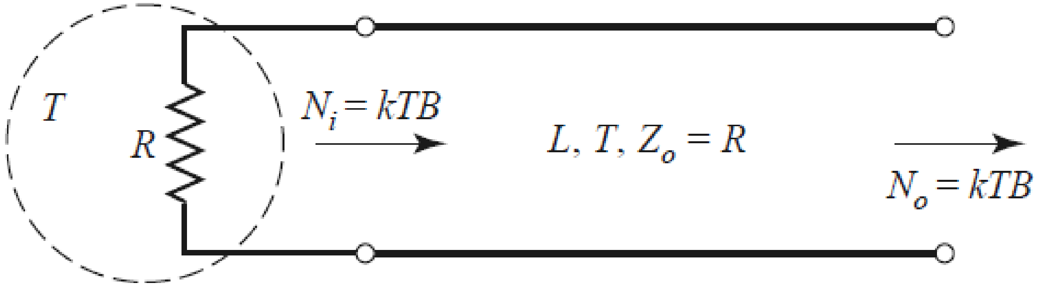
- Measure of SNR_i/SNR_o, > 1
- Nomenclature:
  - F = Noise Factor, linear
  - NF = Noise Figure, dB
- Defined for:
  - Matched load input
  - Reference T_0
    - Else: stick to T_e
    - Or: T_A, for antenna front-end.
- Passive, lossy components:
  - IL = F
  - Can apply to mismatch too: gain lower



$$F = \frac{S_i/N_i}{S_o/N_o} \geq 1,$$

$$F = \frac{S_i}{kT_0B}\frac{kGB(T_0 + T_e)}{GS_i} = 1 + \frac{T_e}{T_0} \geq 1.$$

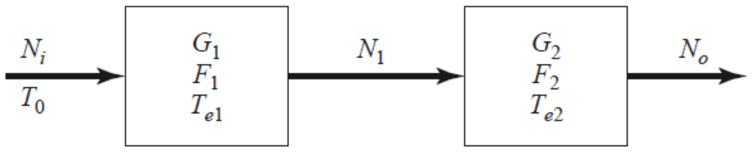
$$T_e = (F - 1)T_0.$$



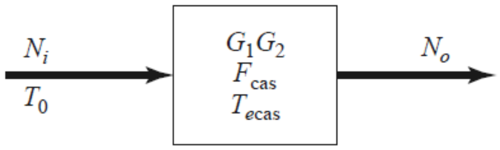
NF in Cascaded Systems

- Amplifiers amplify gain AND noise!
  - SNR_i/SNR_o increases down the chain
  - F increases
- Subsequent noise contribution mitigated by prior gain stages…
- First stage NF dominant in system!
  - Want T_A low as well.
- Use T, not NF, to avoid $T \neq T_0$

$$N_1 = G_1 k T_0 B + G_1 k T_{e1} B,$$



(a)



(b)

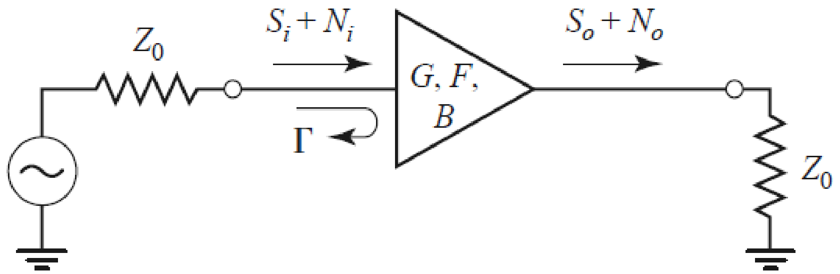
$$\begin{aligned} N_o &= G_2 N_1 + G_2 k T_{e2} B \\ &= G_1 G_2 k B \left(T_0 + T_{e1} + \frac{1}{G_1} T_{e2} \right). \end{aligned}$$

$$T_{cas} = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots,$$

$$F_{cas} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots.$$

NF of mismatched amplifiers

- F increases with mismatch

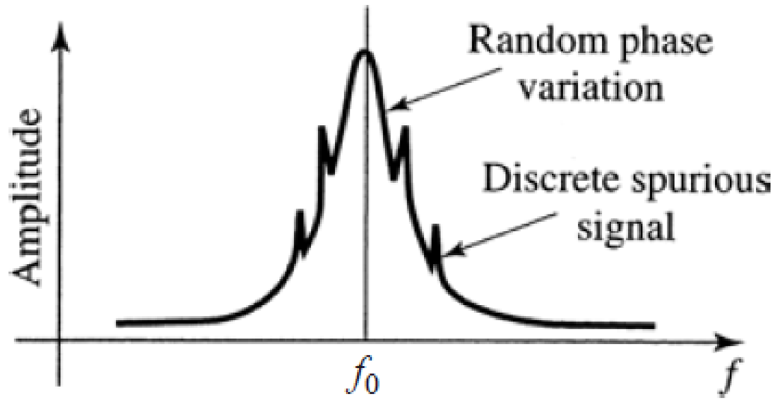


$$N_o = kT_0 GB\left(1 - |\Gamma|^2\right) + kT_0\left(F - 1\right) GB$$

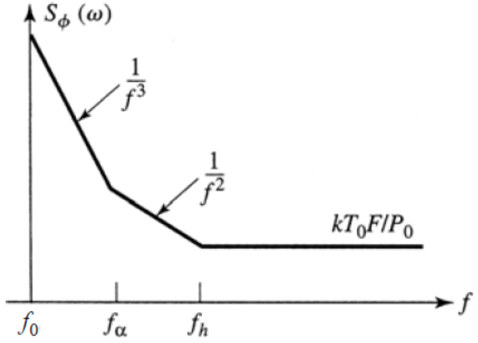
$$F_m = \frac{S_i N_o}{S_o N_i} = 1 + \frac{F - 1}{1 - |\Gamma|^2}.$$

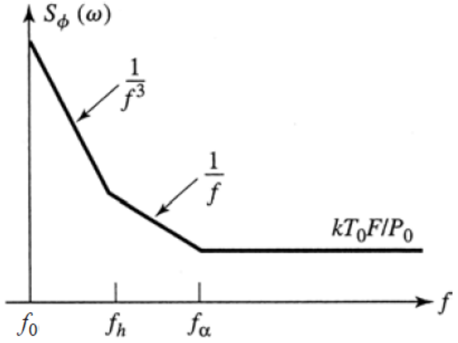
Phase noise

- Random variation of tone f_0
  - Frequency or phase variation
  - Increase noise power
  - Error in downconversion
- Expressed in dBc/Hz @ offset f_m
- Spectrum described by Leeson's model
  - For oscillators with resonators of Q.
    - High Q reduces L
- f_α corner frequency of 1/f
  - Transistor dependent
- Far out: amplifier NF



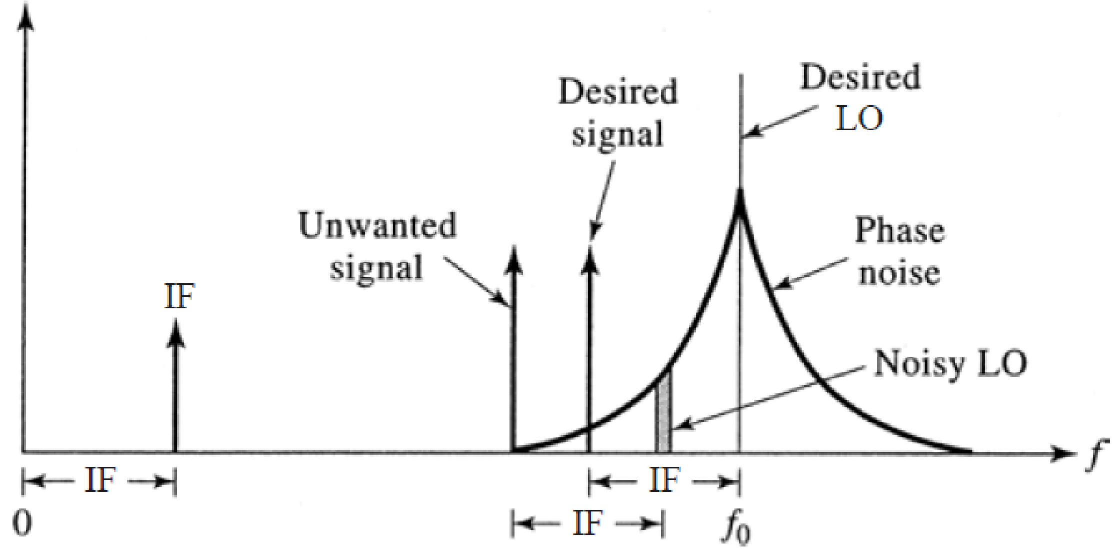
$$S_\phi(\omega) = \frac{kT_0F}{P_0}\left(\frac{K\omega_0^2\omega_\alpha}{4Q_0^2\Delta\omega^3} + \frac{\omega_0^2}{4Q_0^2\Delta\omega^2} + \frac{K\omega_\alpha}{\Delta\omega} + 1\right)$$





Phase noise (2)

- Downconversion error
- Maximum interferer tolerable -> choice of L spec.

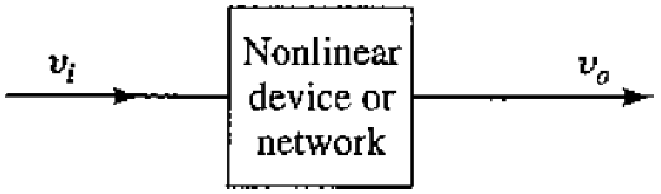


$$\mathscr{L}(f_m) = C\ (\text{dBm}) - S\ (\text{dB}) - I\ (\text{dBm}) - 10\log(B), \quad (\text{dBc/Hz}),$$

Distortion

Nonlinear effects & distortion

- Harmonic generation
- Saturation (gain reduction, AM-AM distortion)
- Intermodulation (two tones mix)
- AM-PM conversion (amplitude -> phase shift)
- N order of terms
  - DC, linear, quadratic, etc.

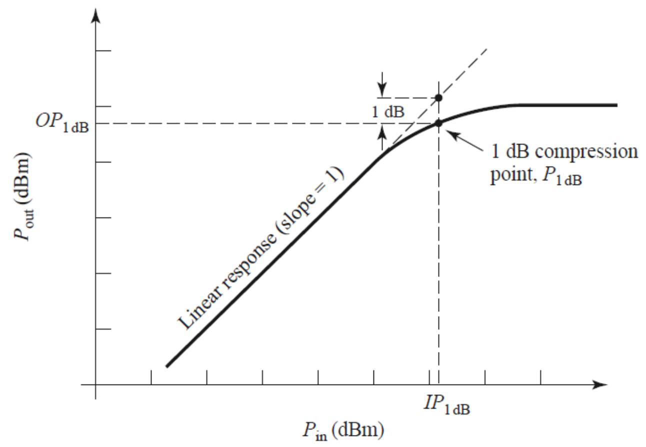


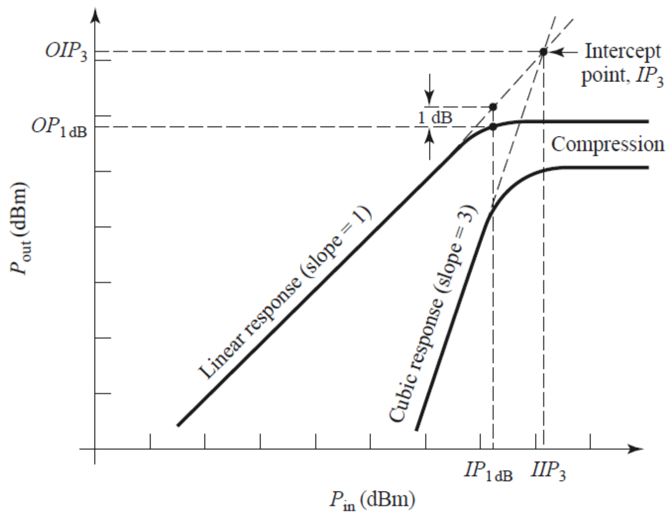
$$v_o = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \cdots,$$

$$\begin{aligned} v_o &= a_0 + a_1 V_0 \cos\omega_0 t + a_2 V_0^2 \cos^2\omega_0 t + a_3 V_0^3 \cos^3\omega_0 t + \cdots \\ &= \left(a_0 + \frac{1}{2}a_2 V_0^2\right) + \left(a_1 V_0 + \frac{3}{4}a_3 V_0^3\right)\cos\omega_0 t + \frac{1}{2}a_2 V_0^2 \cos 2\omega_0 t \\ &\quad + \frac{1}{4}a_3 V_0^3 \cos 3\omega_0 t + \cdots. \end{aligned}$$

Different kinds of distortion

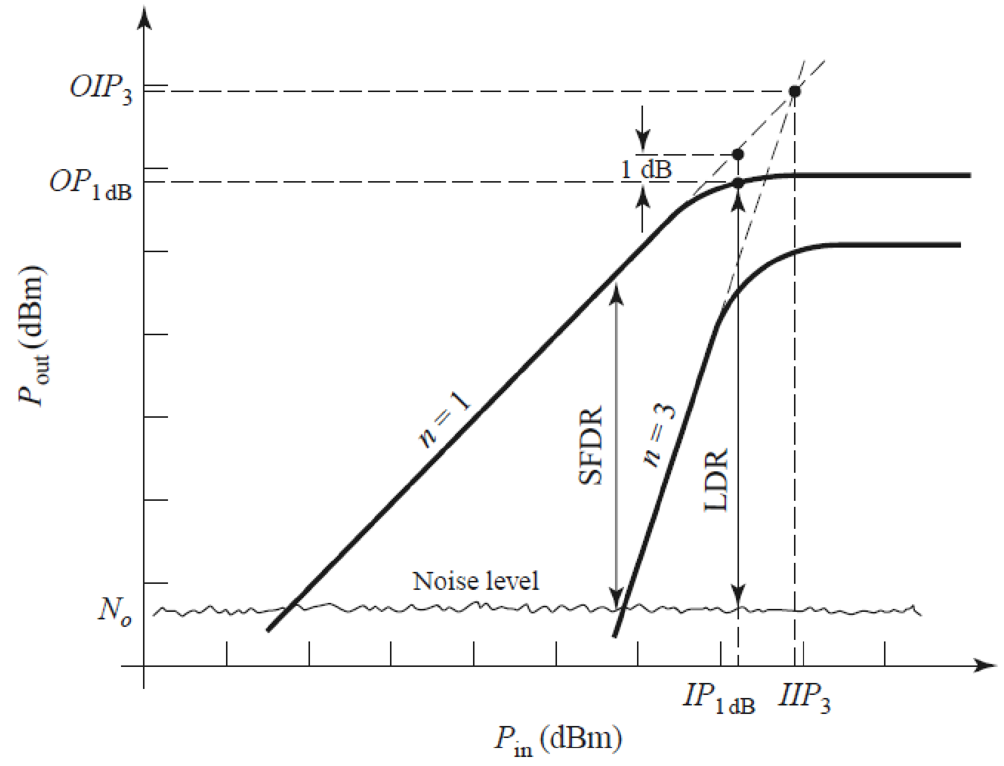
- Gain compression (P1db)
  - Lower than expected output
- Third order intercept (IIP3/OIP3)
  - Mixing term of two-tone input
- Passive intermodulation (PIM)
  - Parasitic diodes from oxidation on metal
  - Only a consideration at high power





Dynamic Ranges

- Power range over which performance is desirable
- Limited by which undesired effect we want to avoid!
- Linear dynamic range (LDR)
  - Range over which operation is “linear”
  - Noise floor -> P1db
- Spurious free dynamic range (SFDR)
  - Range over which spurs below noise floor
    - Typ. 3rd order ($2f_2$-f_1, $2f_1$-f_2)
  - SFDR typ. << LDR



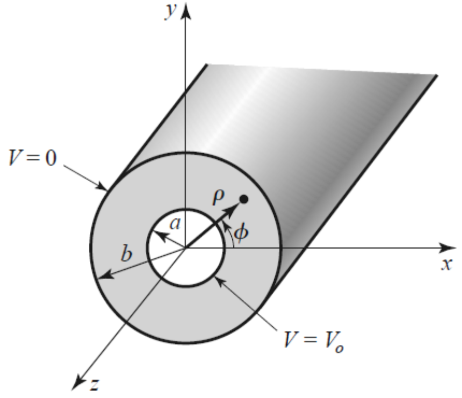
Sensitivity

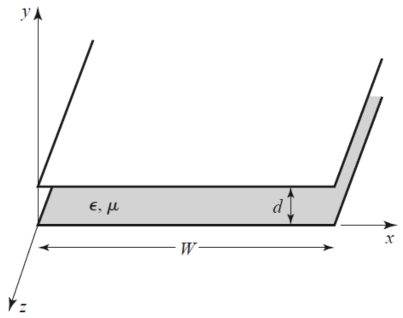
- Definition specific to receiver
- Smallest detectable signal
- Sensitivity (dBm) for comms = -174 + NF + 10logB + SNR
- For antenna temperature NOT 290K
  - More generally: $Si(min) = kB(T_A + (F-1)T_0)SNR_{min}$

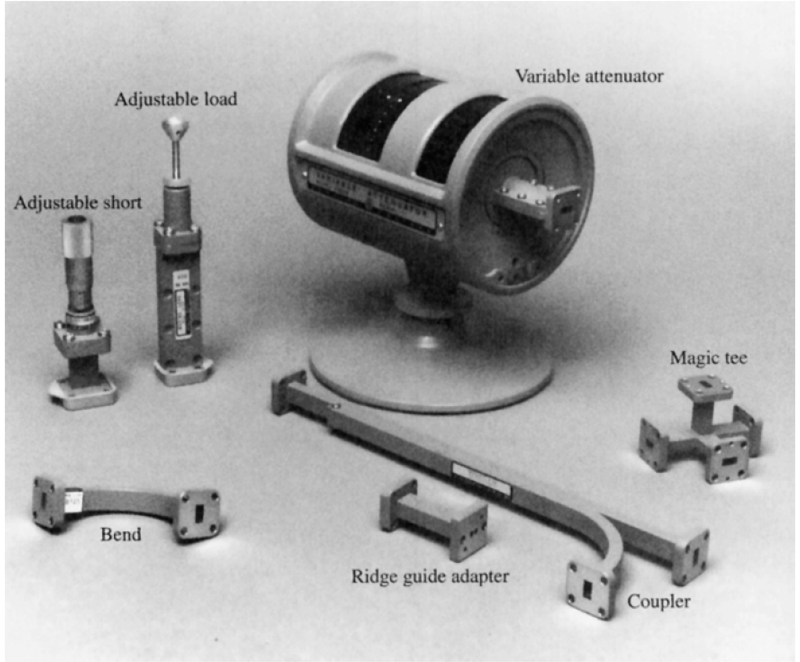
Components and Connections

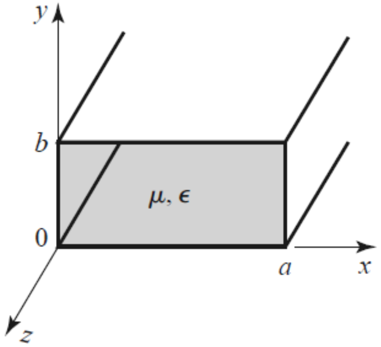
Transmission media (1)

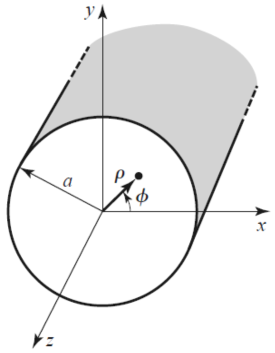
- Waveguide
  - Coax
    - Modes!
  - Parallel Plate
    - Parasitic!
  - Surface Waves
    - Parasitic!
  - Rectangular, Circular

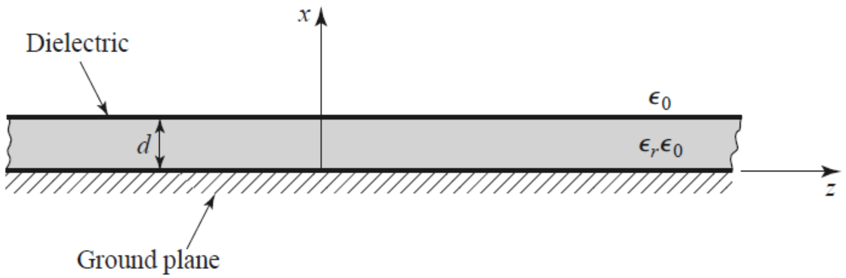






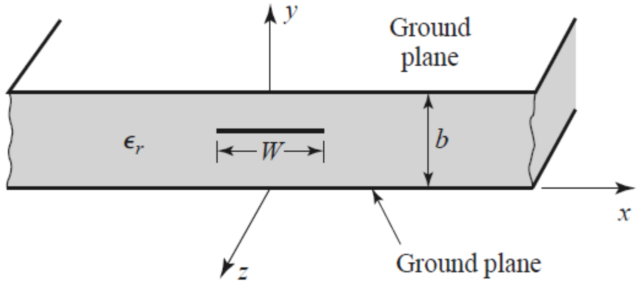


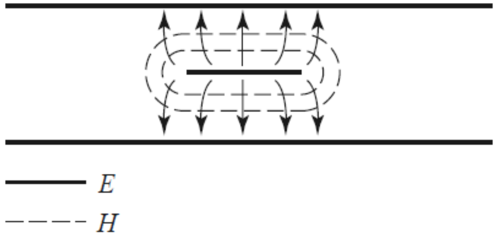


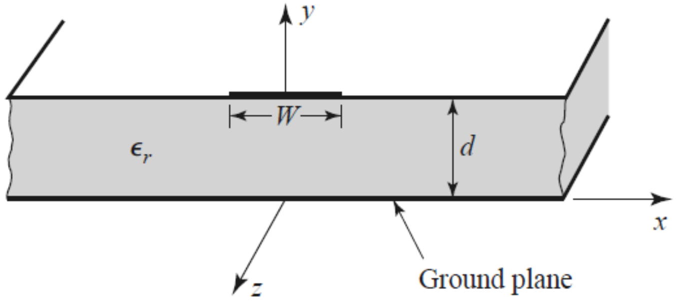


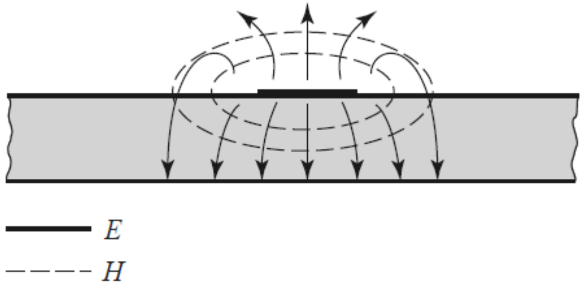
Transmission media (2)

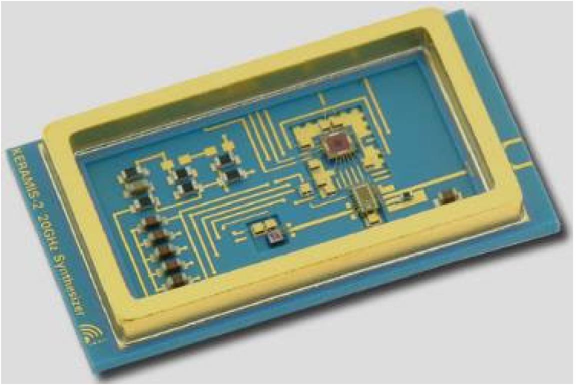
- Planar
  - Stripline
  - Microstrip
  - CPW, GCPW
  - And others…
- Integrate with SMD components

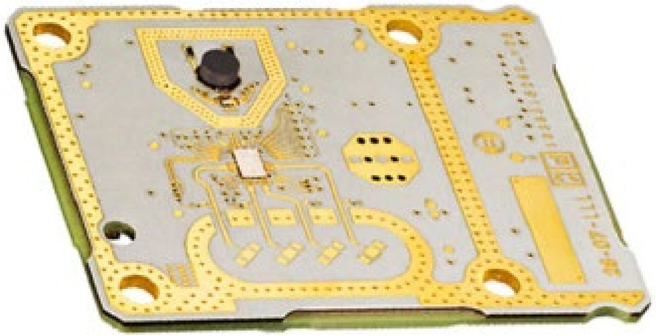


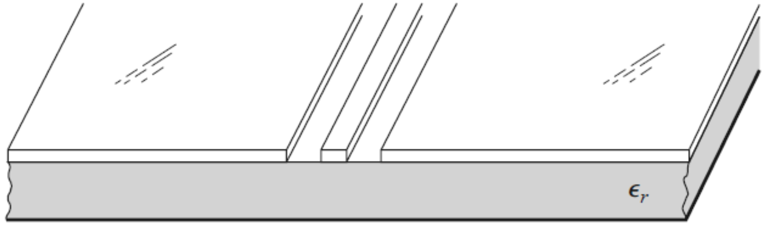






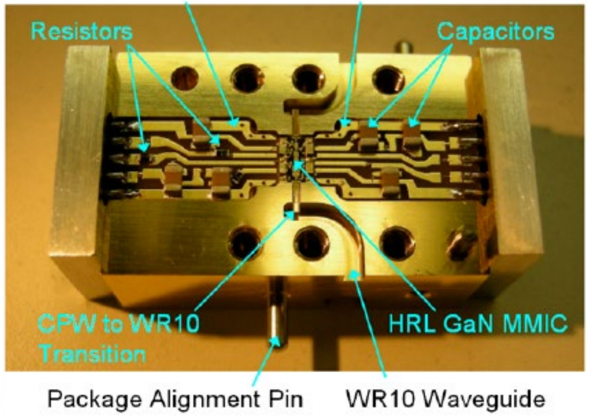


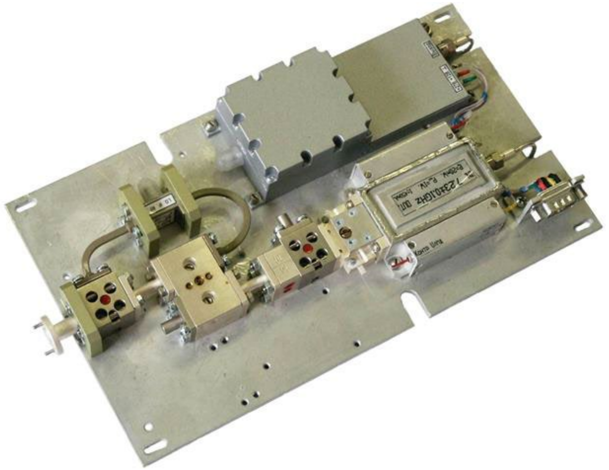




Non-planar system integration

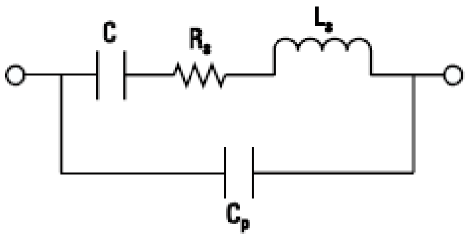
- Waveguide
  - Split block / finline
  - WR standards
- Microwave coax connectors
  - Different standards for different frequencies
    - SMA most common
- Mixed modules
  - WG RF, coax IF
- Cables
  - Limited by overmoding, connectors

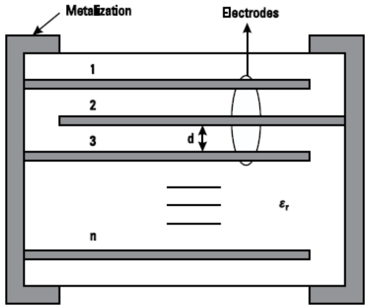


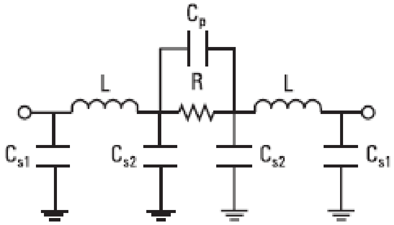


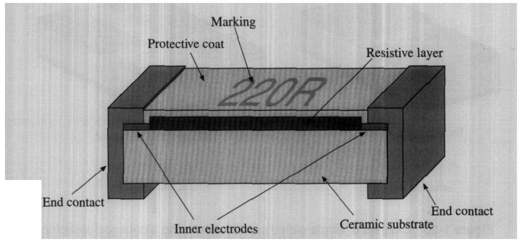
Passive components

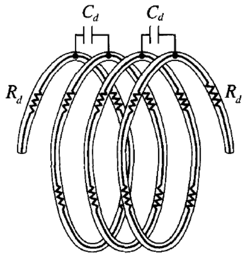
- Resistors, capacitors, inductors
  - Complex responses
- Resonators
  - Used for e.g. filters, oscillators
  - Temporary storage of energy at a specific frequency

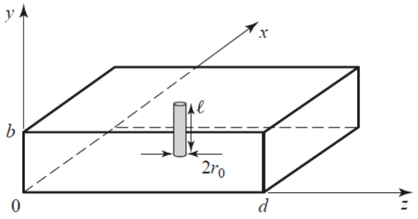


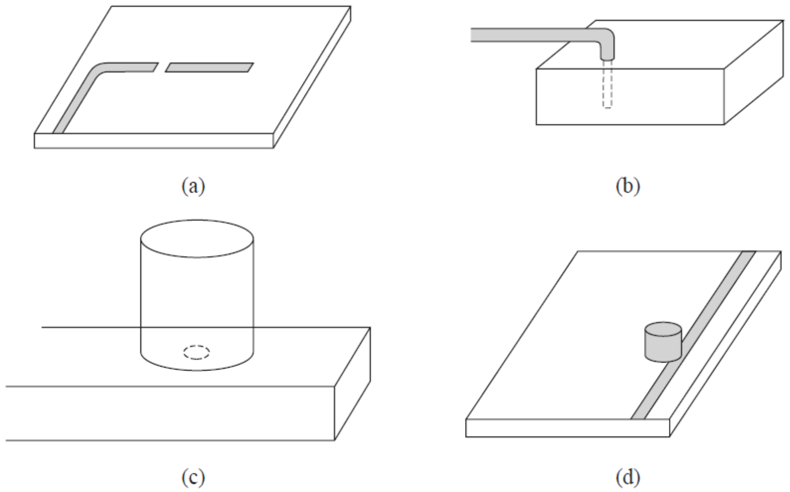






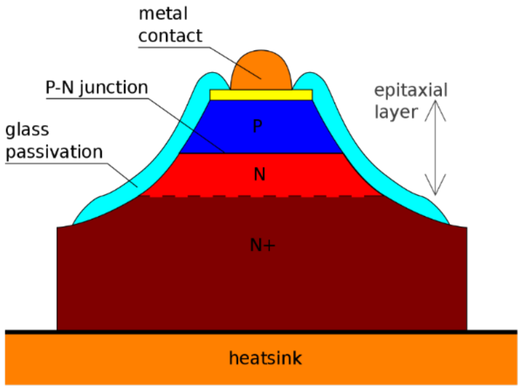


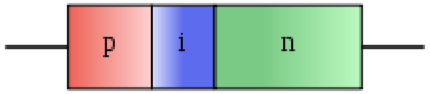


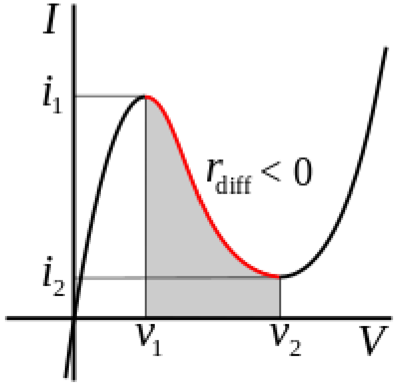


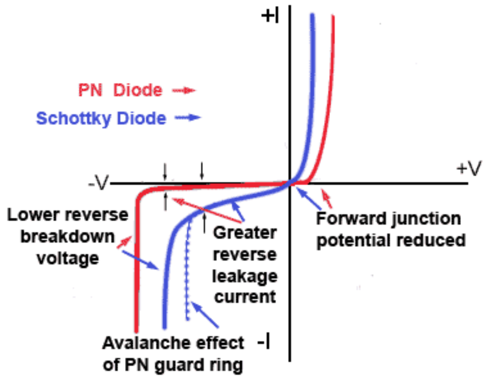
Diodes

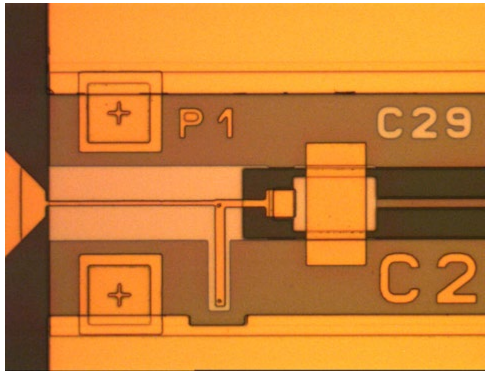
- PN: low frequency
  - Varactor: Vary C with DC (depletion layer)
- PIN
  - DC biasing -> very linear R at RF
  - Switches, variable attenuators
- Schottky
  - Metal-semi contact
  - Fast switching; no recovery time
  - Detectors
- Tunnel Diode
  - Negative I-V region
    - Quantum well
  - Detectors, switches
- SIS mixers
  - Photon-assisted tunnelling, superconducting T's
  - Used for detecting sub-THz and THz frequencies

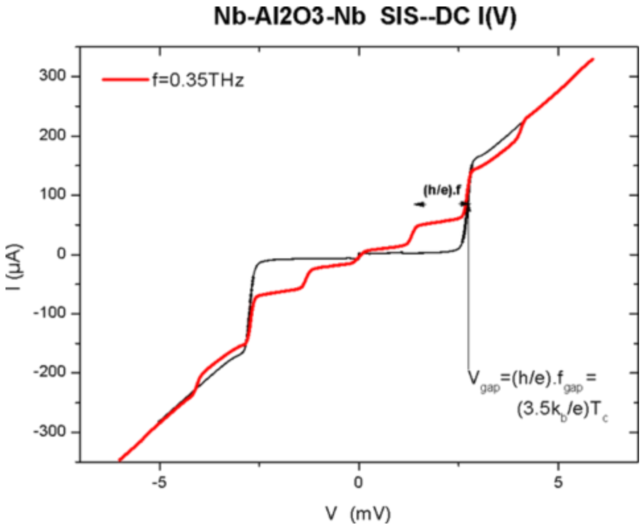






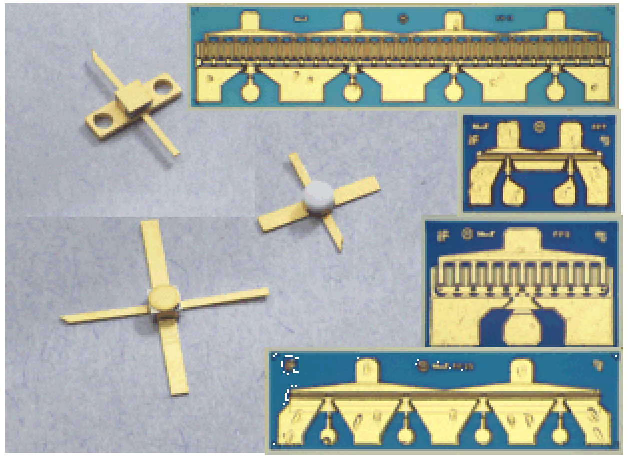


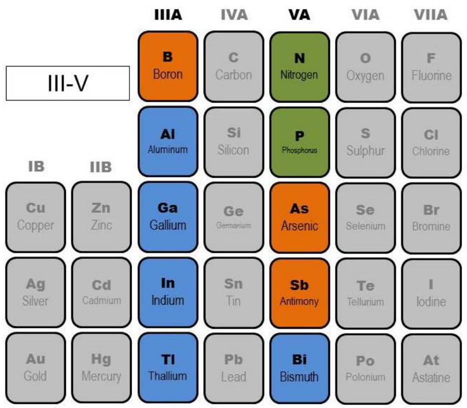


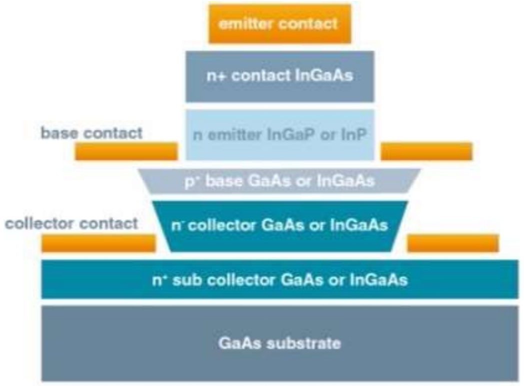


Transistors

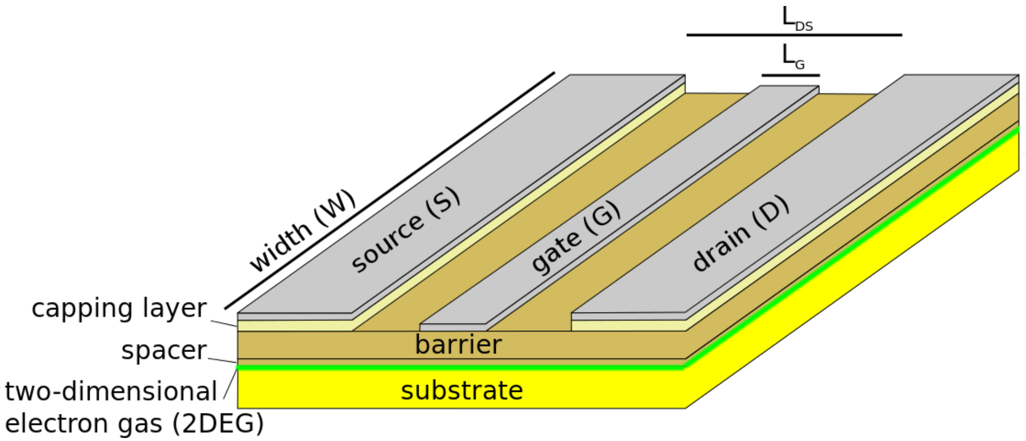
- Different semiconductors
  - Si: Cheap, moderate performance
  - SiGe: More expensive, faster III-V
    - GaAs: Common in Radio Astronomy
    - InP: The best, most expensive choice
- Types
  - Bipolar: BJT / HBT
  - MOSFET, MESFET
  - HEMT





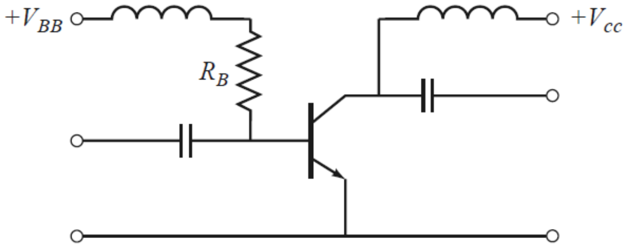


HBT Structure

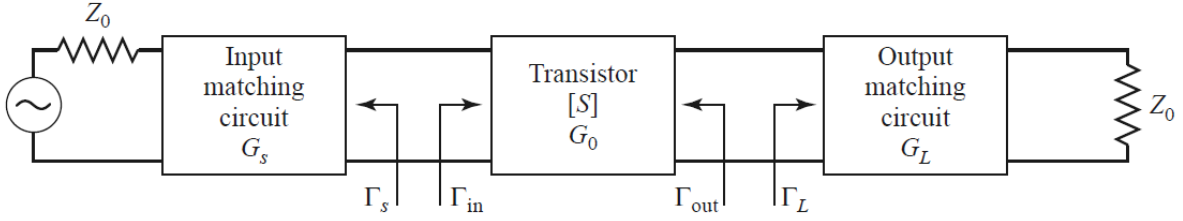


Important RF circuits

Low noise amplifiers



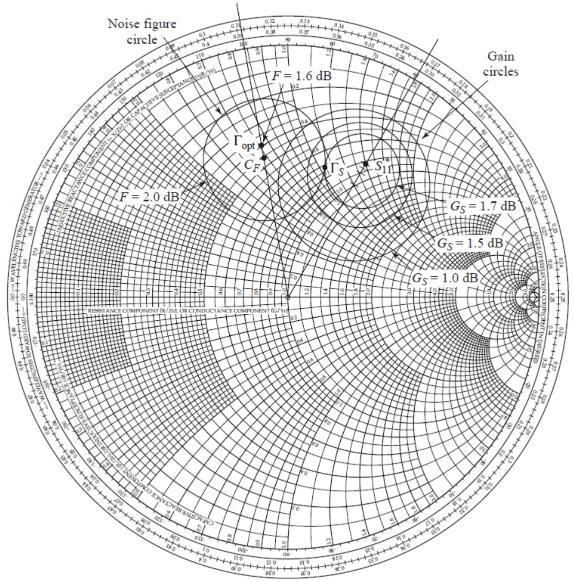
- Transistor, biasing, matching
- Match for
  - Gain
    - Complex conjugate power match
  - Noise
    - NF_{min}, R_N, Γ_{opt} in datasheet
  - Stability
  - … It's a trade-off.
- Usually multiple stages



$$G_S = \frac{1 - |\Gamma_S|^2}{|1 - \Gamma_{in}\Gamma_S|^2},$$

$$G_0 = |S_{21}|^2,$$

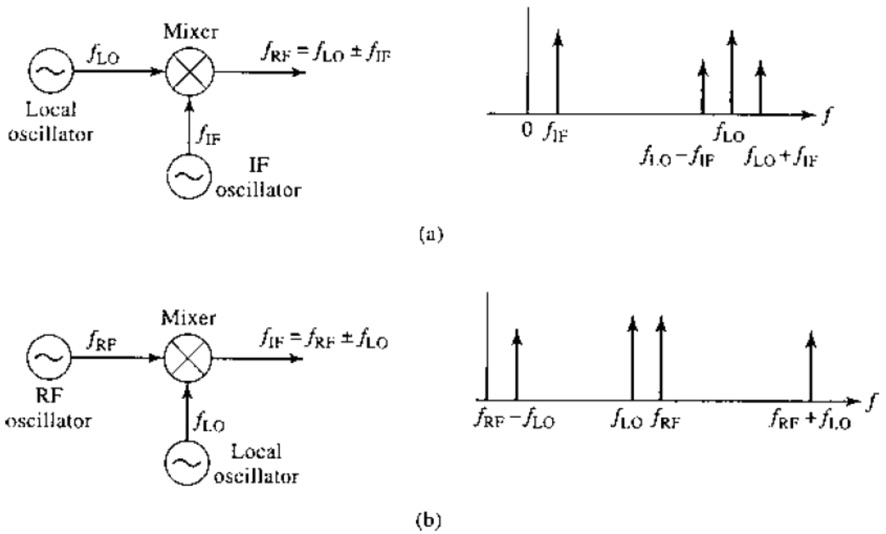
$$G_L = \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}.$$

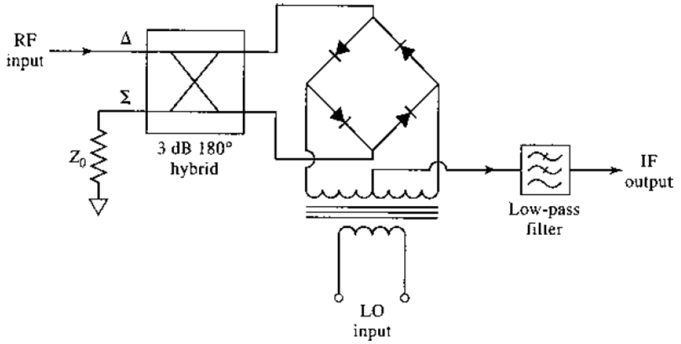


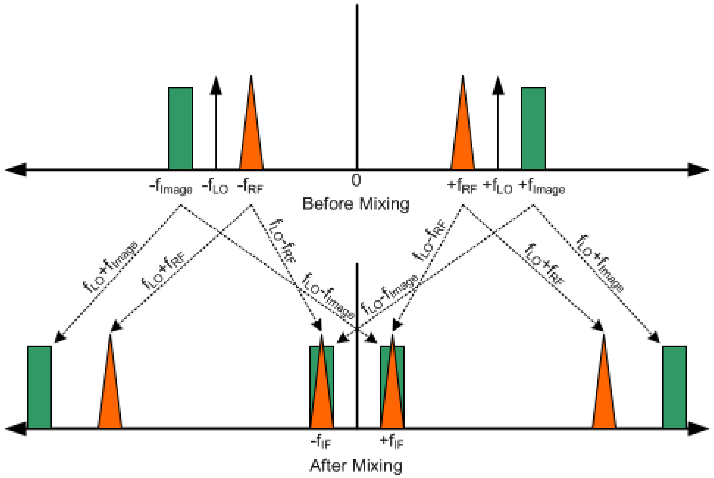
$$N = \frac{|\Gamma_S - \Gamma_{opt}|^2}{1 - |\Gamma_S|^2} = \frac{F - F_{min}}{4R_N/Z_0}|1 + \Gamma_{opt}|^2$$

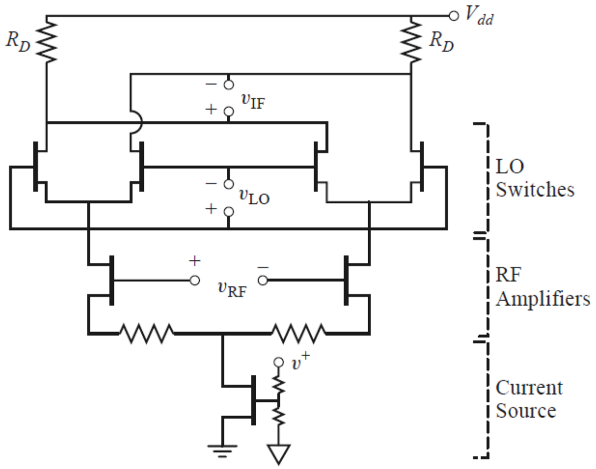
Mixers

- 3-port device for frequency translation
- Image frequencies!
- Diode circuits
- Transistor circuits
    - Gilbert cell
- Harmonic versions



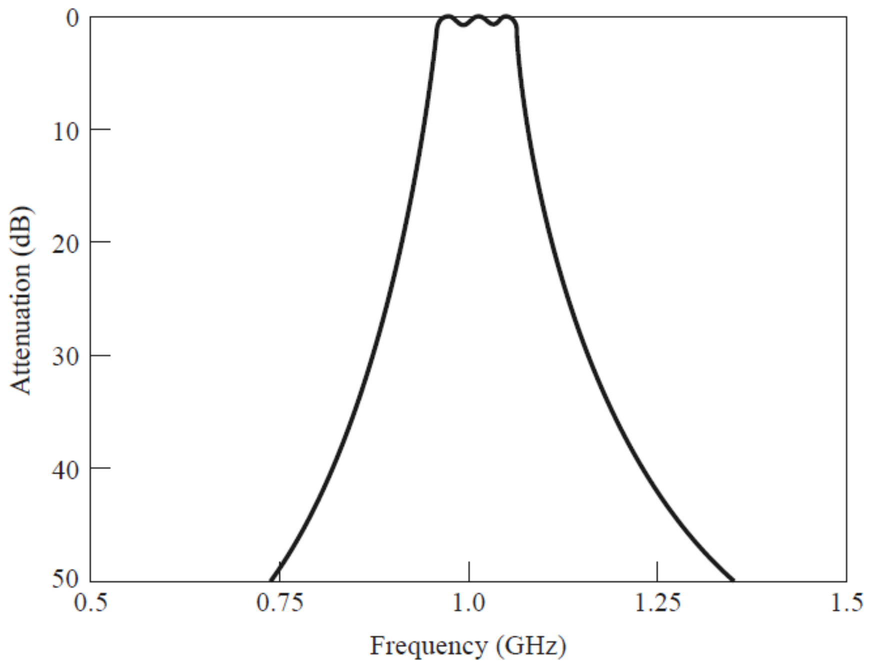


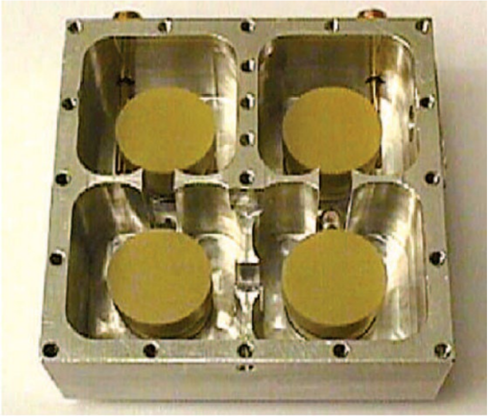


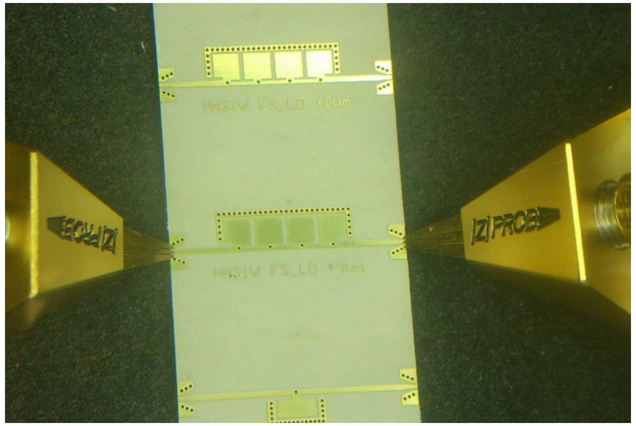


Filters

- Low-pass, high-pass, band-pass, band-stop
- Frequency selective transmission
- Limits received noise band
- Suppresses mixing products
- Reject interferers
- More elements:
    - More selective
    - More loss

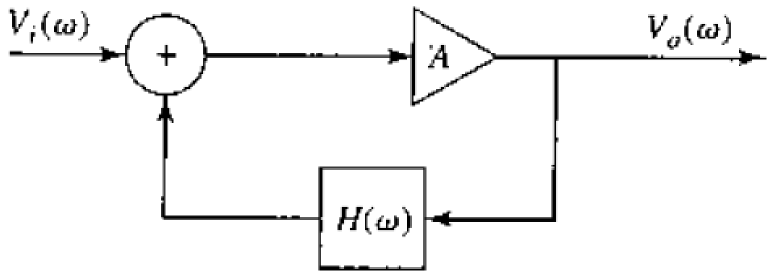


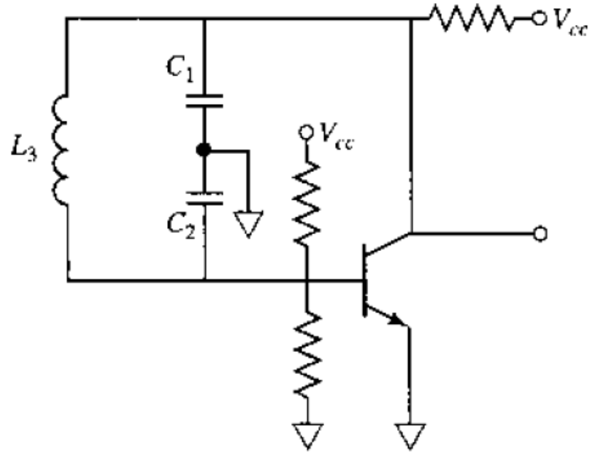


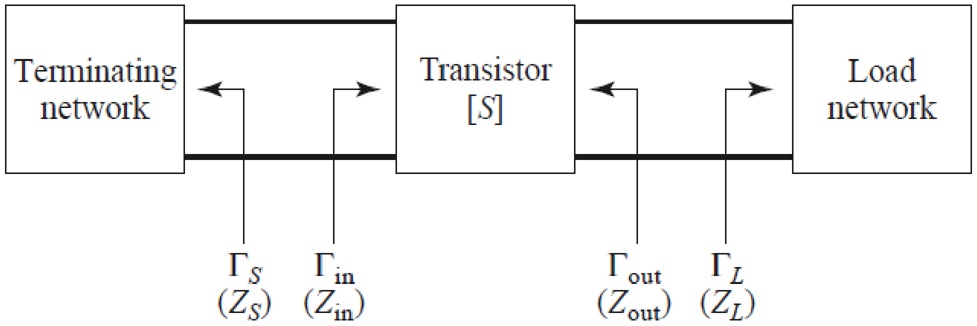


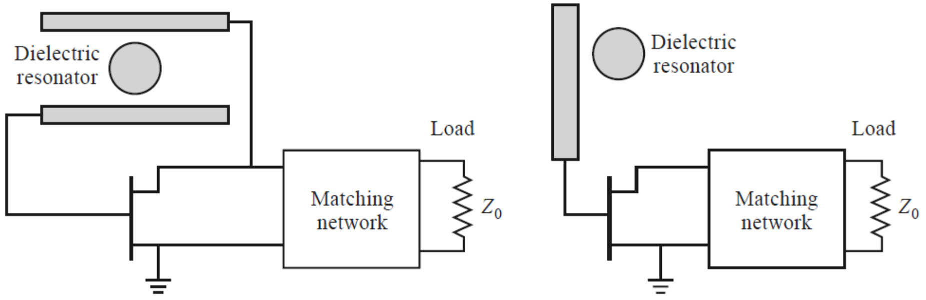
Oscillators

- Generate a steady sinusoid
- Characterized by
  - Power
  - Phase noise
  - Tunability
- Gain + astable feedback
  - Can use astable reflection as well



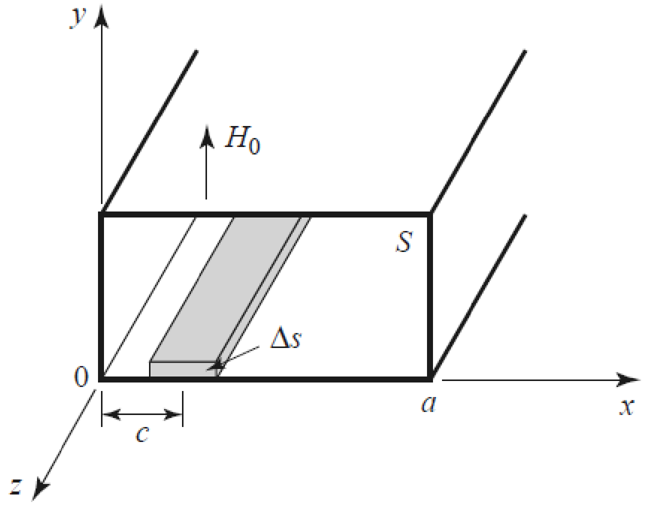


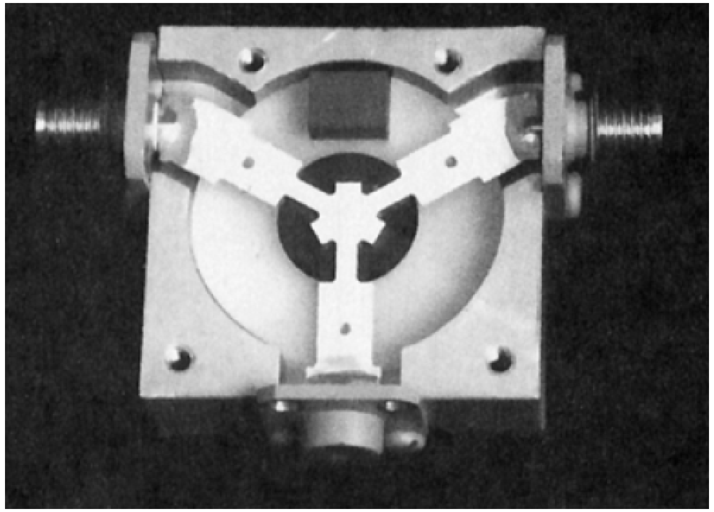




Isolators

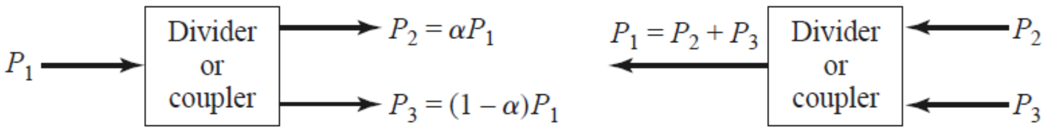
- RF transmission in one direction, but not the other
  - $S_{21} \approx 0$ dB, $S_{12} < -40$ dB
  - Usually ferromagnetic
- Used to
  - Control noise and leakage propagation
    - Eg. LO reflection from antenna
  - Improve impedance matching
- Three-port: Circulator
  - Signal Merry-go-round

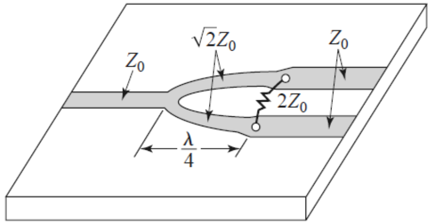


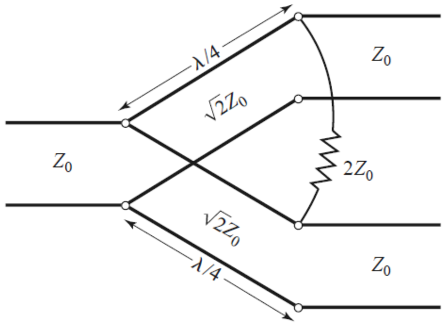


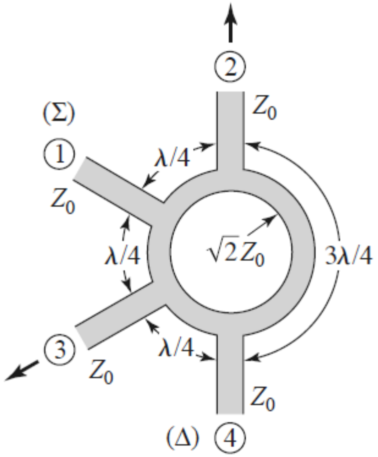
Couplers

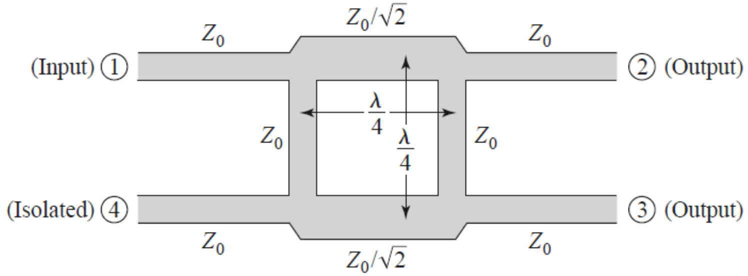
- Split energy from source to outputs
- T-junction
  - 3-port
  - Wilkinson
- Quadrature Hybrid
- Directional
  - 4-port
- Rat Race

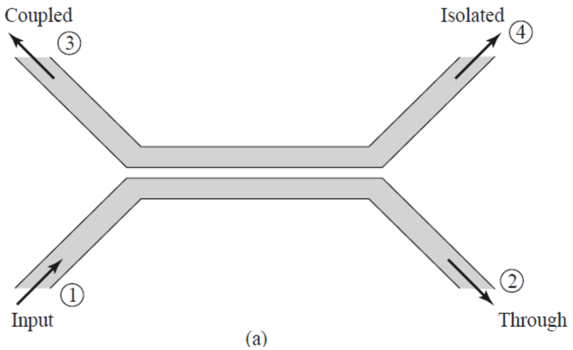




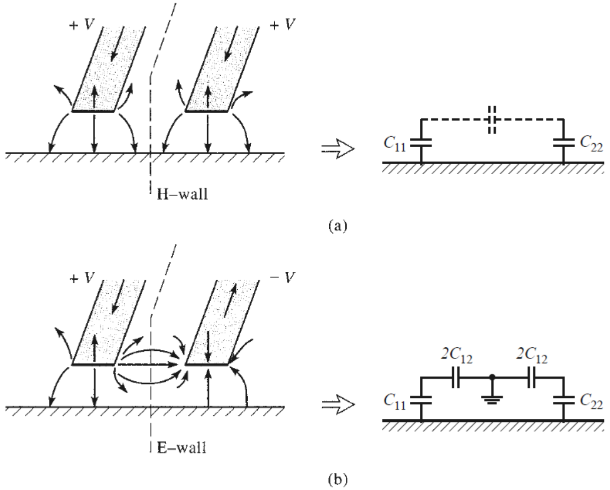


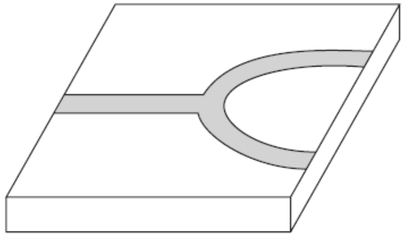






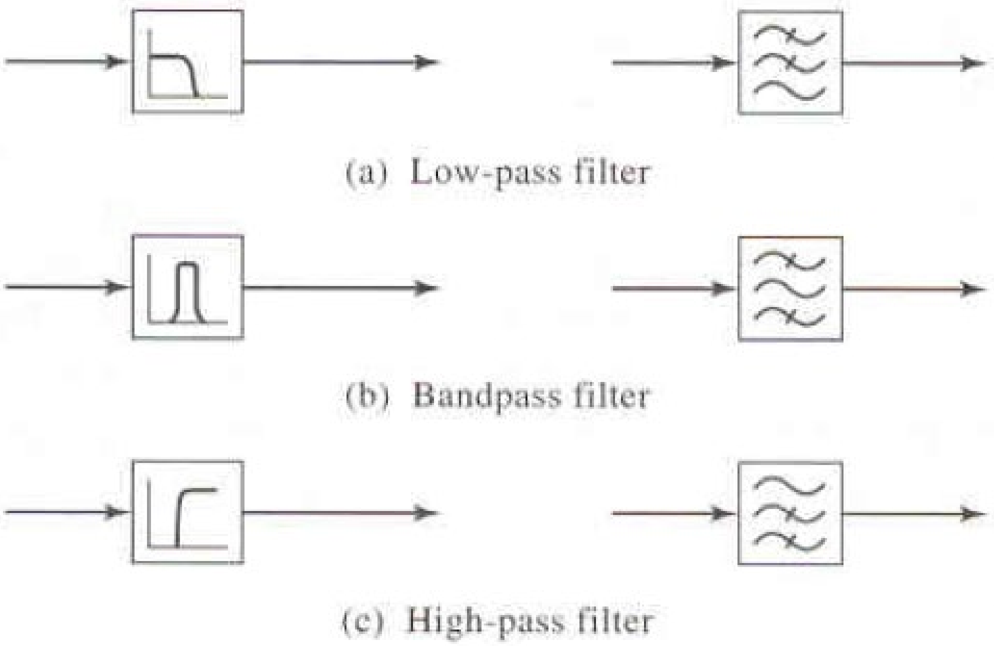
(a)





Receiver Architectures

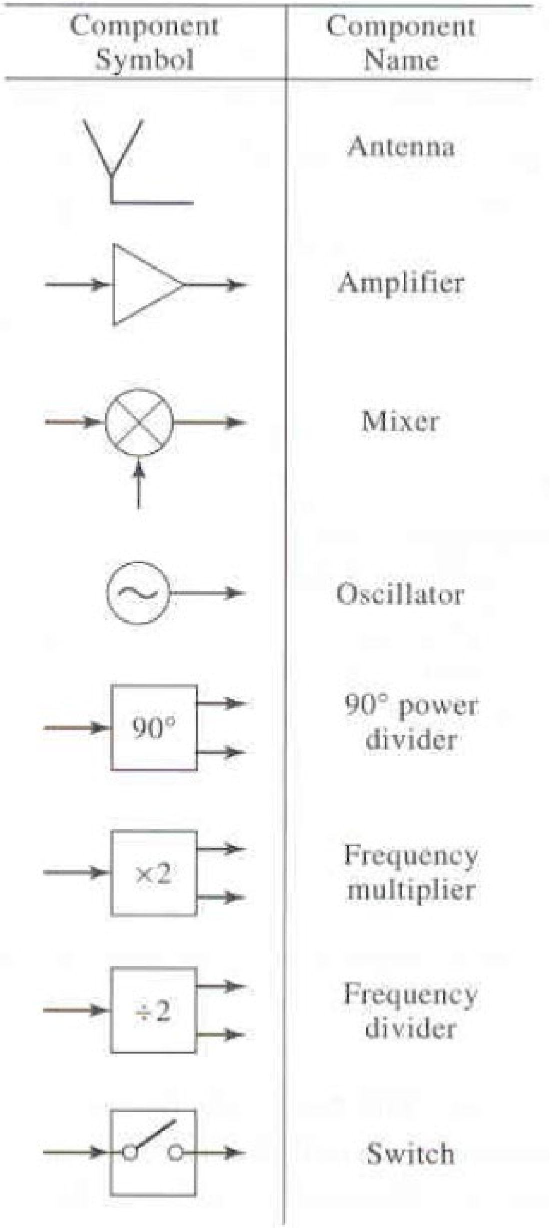
Common components



(a) Low-pass filter

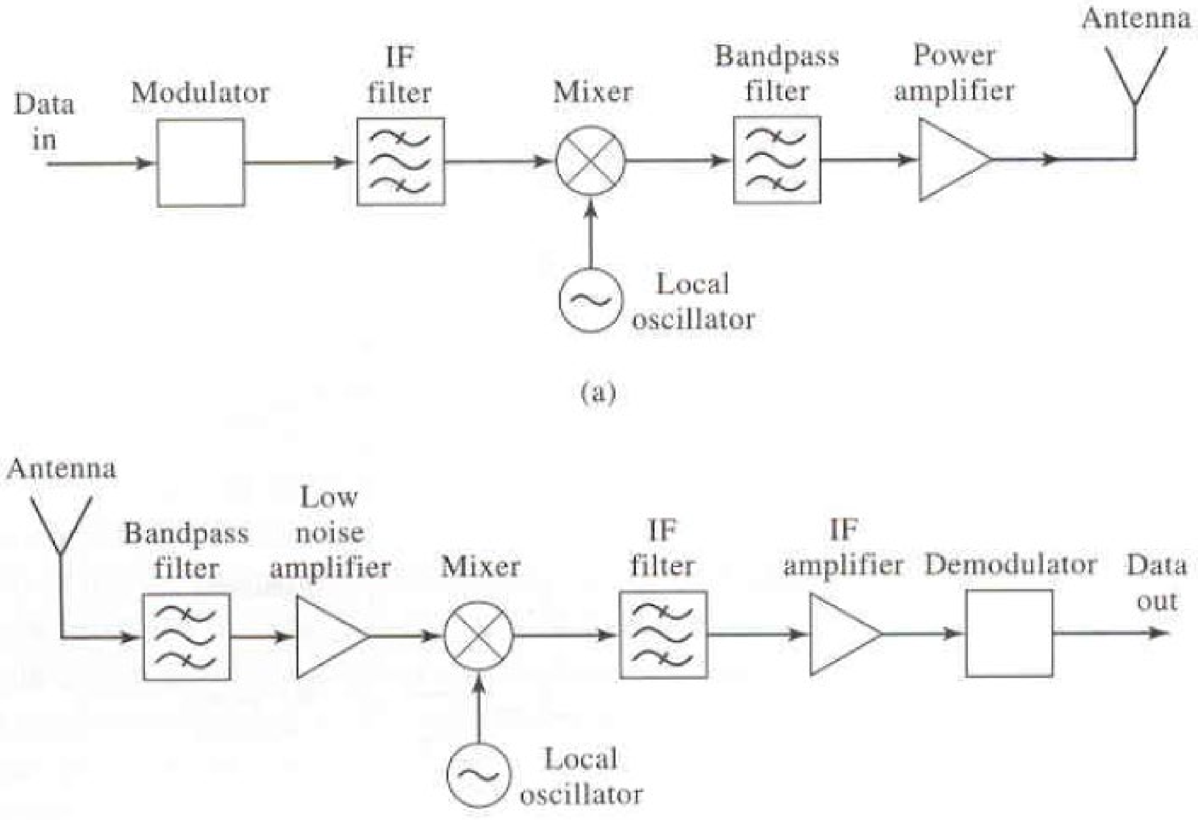
(b) Bandpass filter

(c) High-pass filter



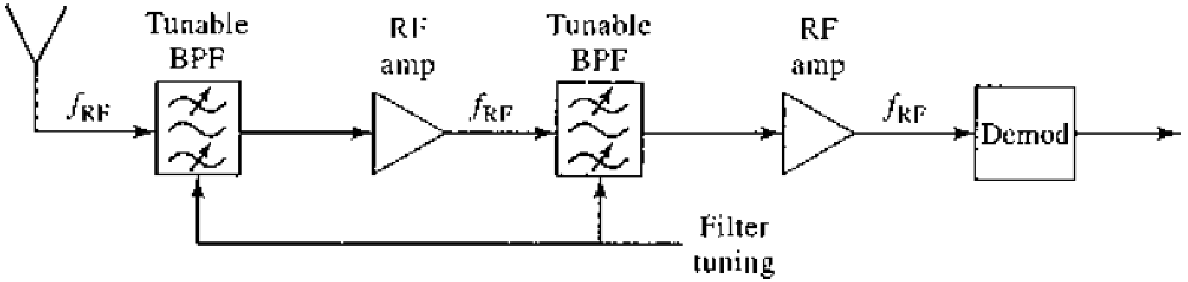
Basic TX and RX blocks

- Digitization
- Filtering
- Mixing
- Generation
- Amplification

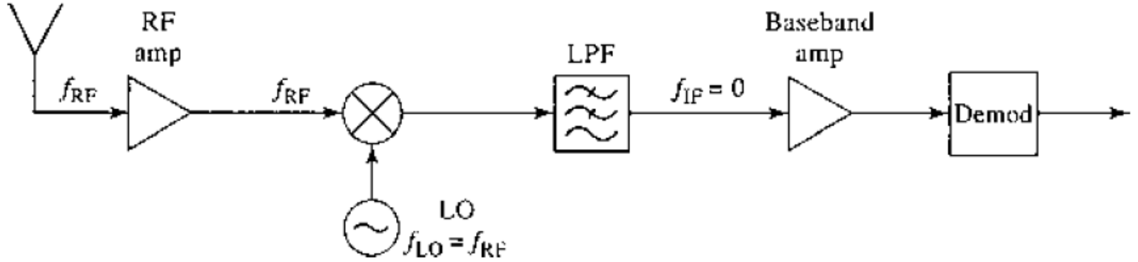


Downconversion Architectures (1)

- Tuned receivers
  - Modern: direct digitization receivers

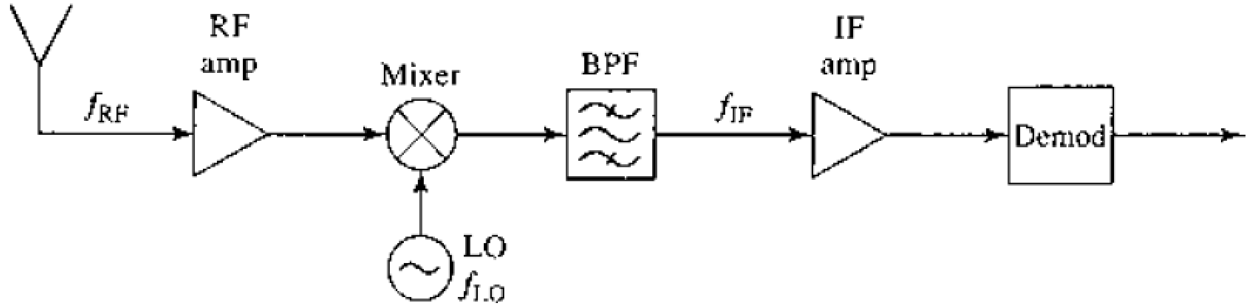


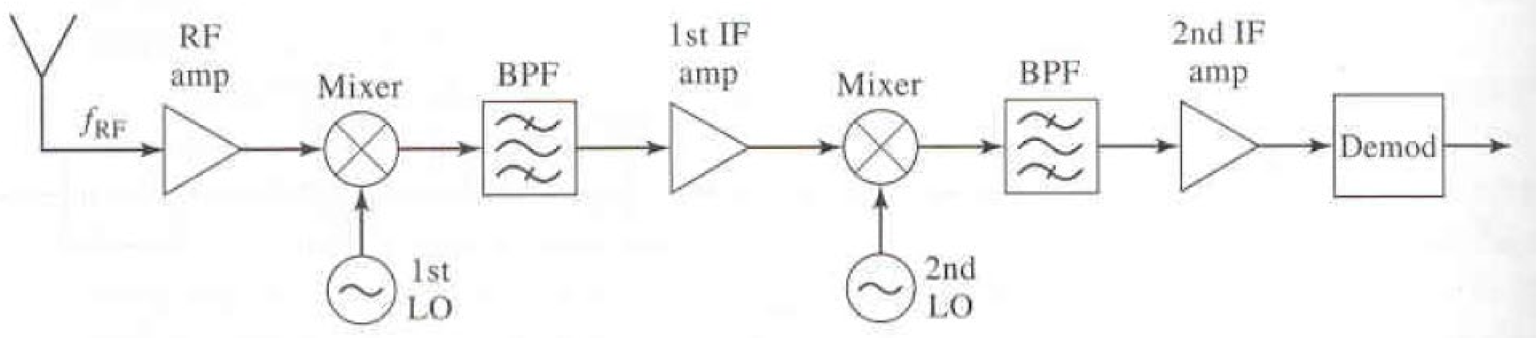
- Direct conversion receivers
  - Zero IF, homodyne
  - No image frequency
  - Stability, precision!
    - Doppler RADAR
  - Sensitive to DC offsets



Downconversion Architectures (2)

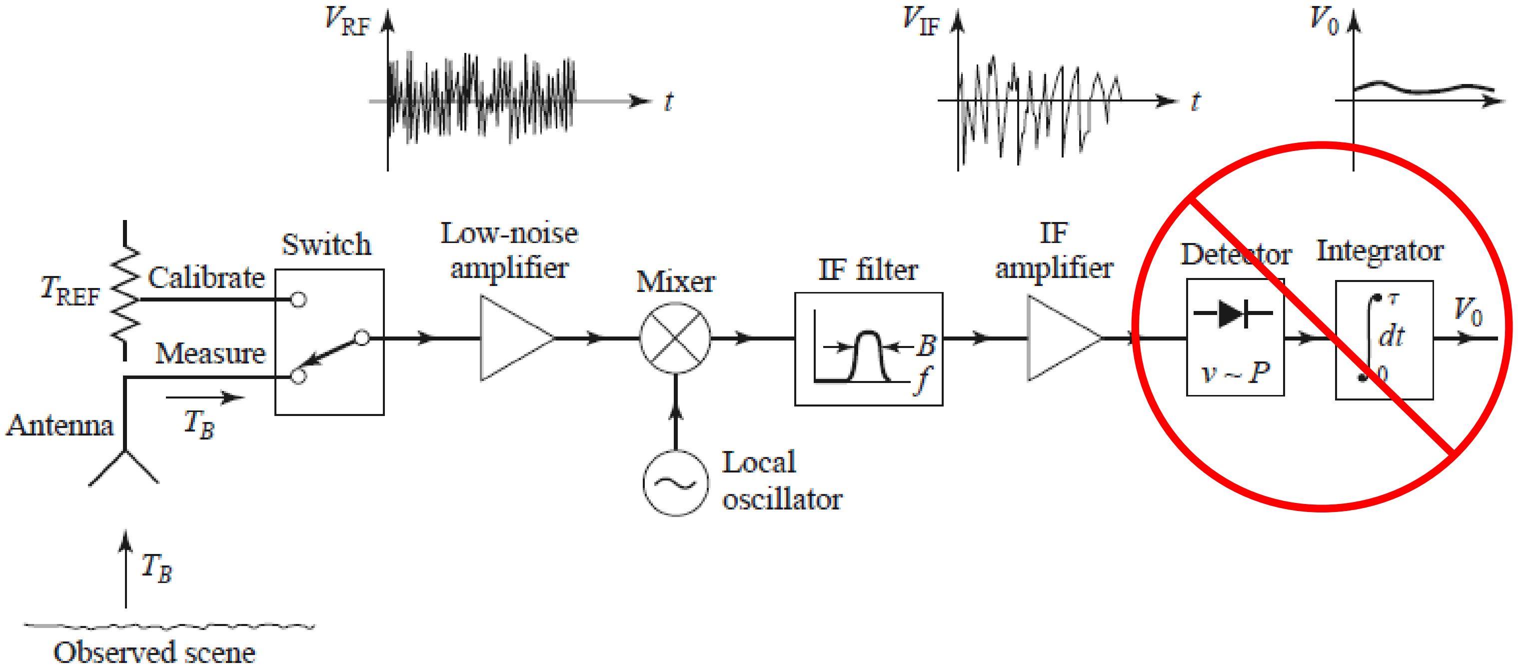
- Superheterodyne
  - Non-zero IF (filters)
  - More stages sometimes used
    - More LOs, IFs



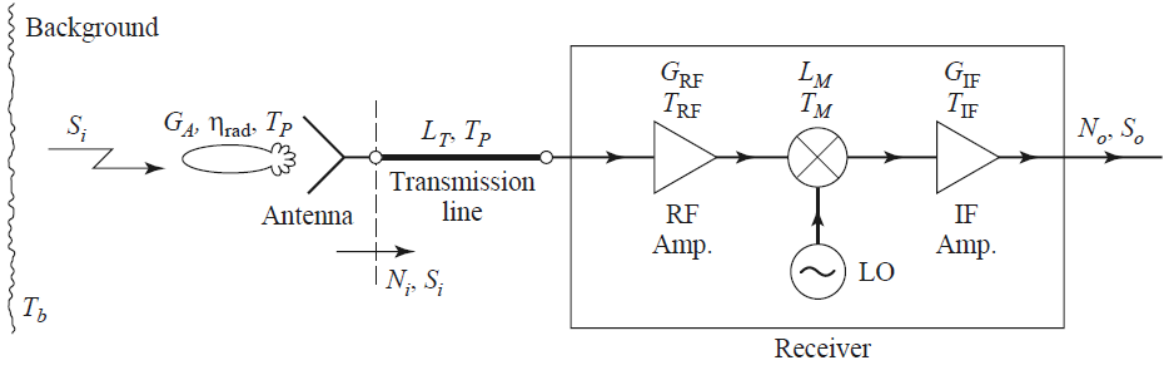


Radiometer receivers

- Total power radiometer
  - Simple
  - Gain variation
  - Can't distinguish between system and observed T
  - Regular calibration!
- Analog diode detection less common today
  - Analog-to-digital conversion + digital signal processing



Noise in receivers



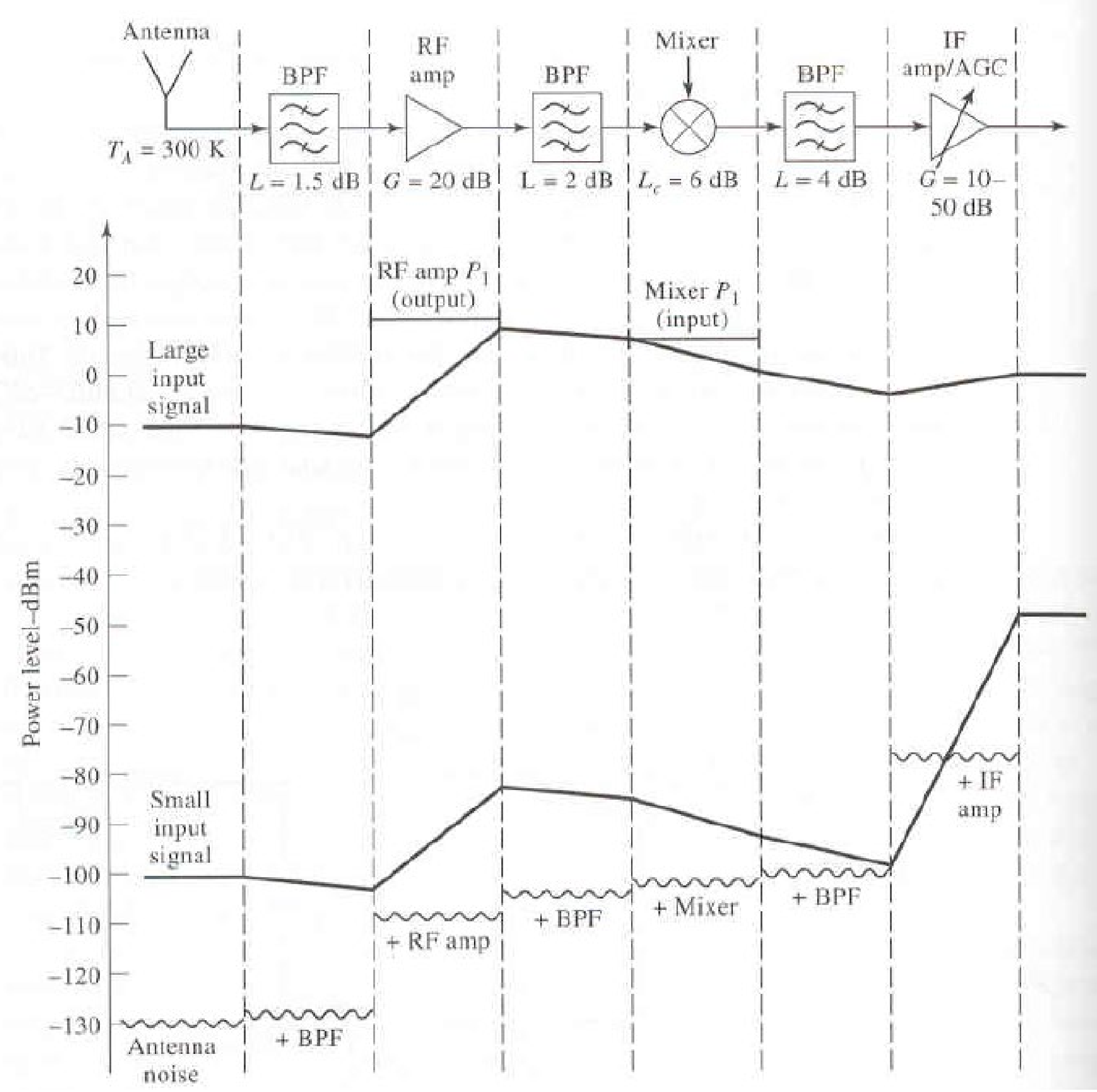
- Everything generates noise
  - Loss == noise
- Noise floor increases down the chain
- Need SNR_{min} for demod

$$\frac{S_o}{N_o} = \frac{S_i}{kBT_{SYS}} = \frac{S_i}{kB[\eta_{rad}T_b + (1-\eta_{rad})T_p + (L_T - 1)T_p + L_T T_{REC}]}.$$

System	SNR (dB)
Analog voice	5–10
Analog telephone	25–30
Analog television	45–55
AMPS cellular	18
AM-PCM	30–40
QPSK ($P_e = 10^{-5}$)	10

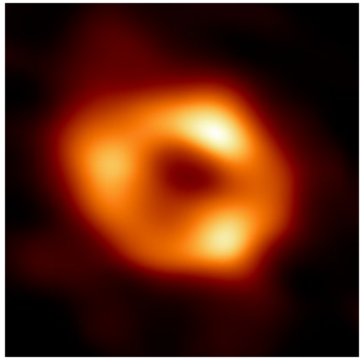
Dynamic Range

- “Ceiling” limited by compression
- “Floor” limited by noise

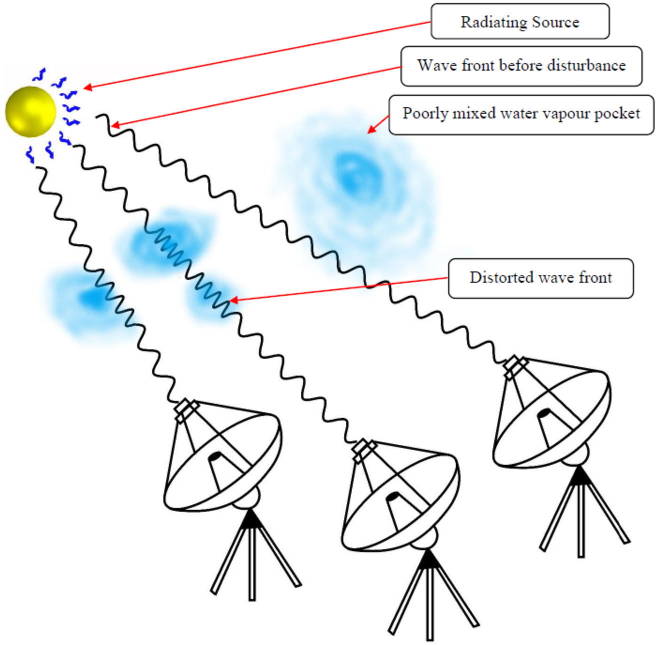


New receiver trends

- Wideband, multi-band
  - Frequency Phase Transfer (FPT)
  - Establish coherence with longer wavelength observation, transfer to higher band
  - Need concurrent observations over wide separated bands.

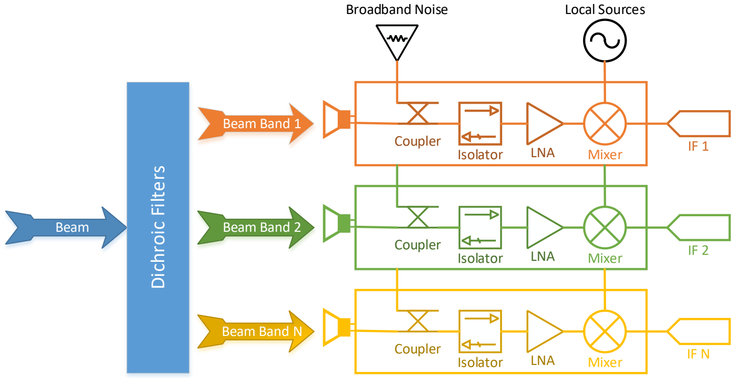


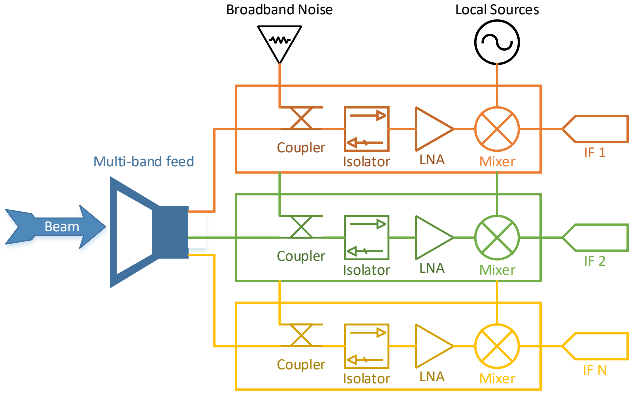
Sgr A. Image courtesy of EHT Collaboration, www.eventhorizontelescope.org*

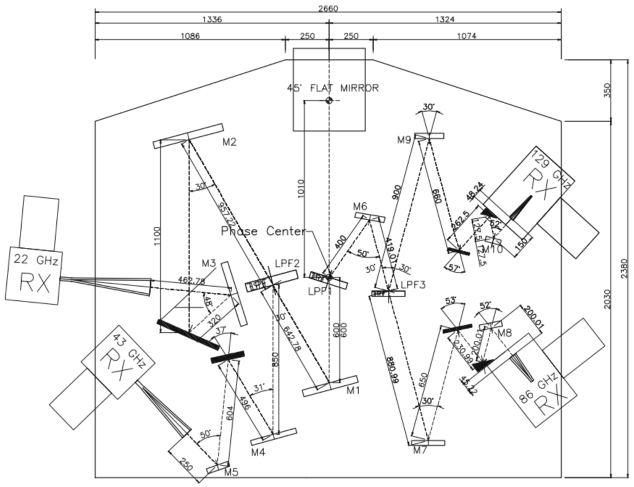


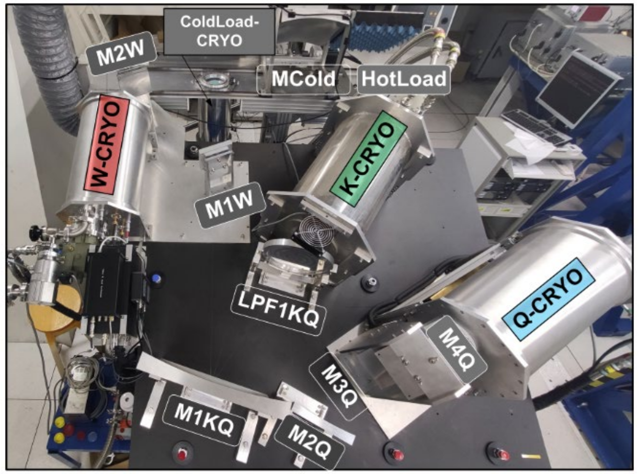
Multi-band observation with multiple receivers

- Typically: multiple independent receivers, optical beam splitting.
- Some multi-band feeds
- Examples:
  - KVN, Yebes 40m, TNRT 22, 43, 86, 129 GHz
  - Sardinia (L-P), RAEGE (2.4, 8, 30 GHz).





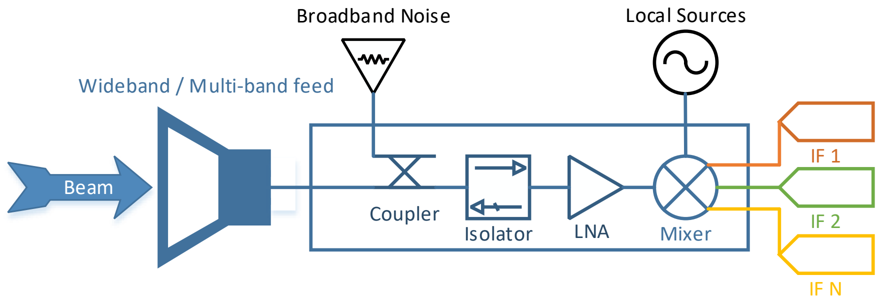


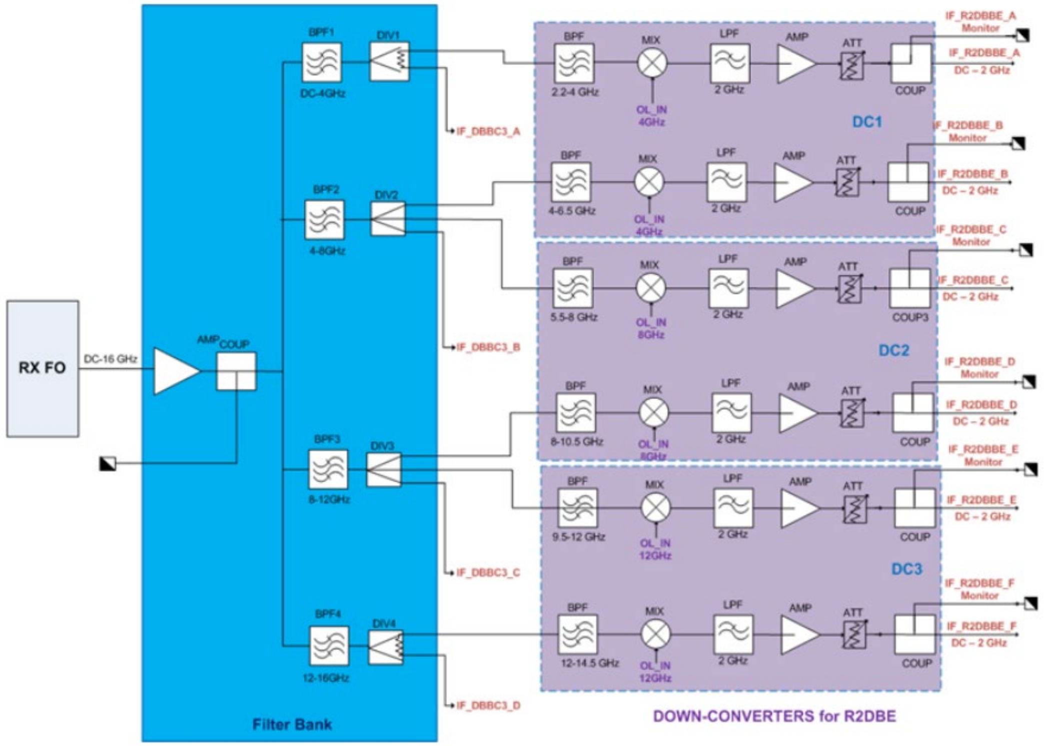


S.-T. Han et al., "Millimeter-wave Receiver Optics for Korean VLBI Network," Int. J. Infrared Millimeter Waves, vol. 29, no. 1, pp. 69–78, Jan. 2008; F. Tercero et al., "Yebes 40 m radio telescope and the broad band Nanocosmos receivers at 7 mm and 3 mm for line surveys," Astron. Astrophys., vol. 645, p. A37, Jan. 2021; Stander et al, ICEAA 2024

Wideband receivers

- All-in-one-go
  - Observation bands selected by downconversion / IF
- Examples:
  - VGOS





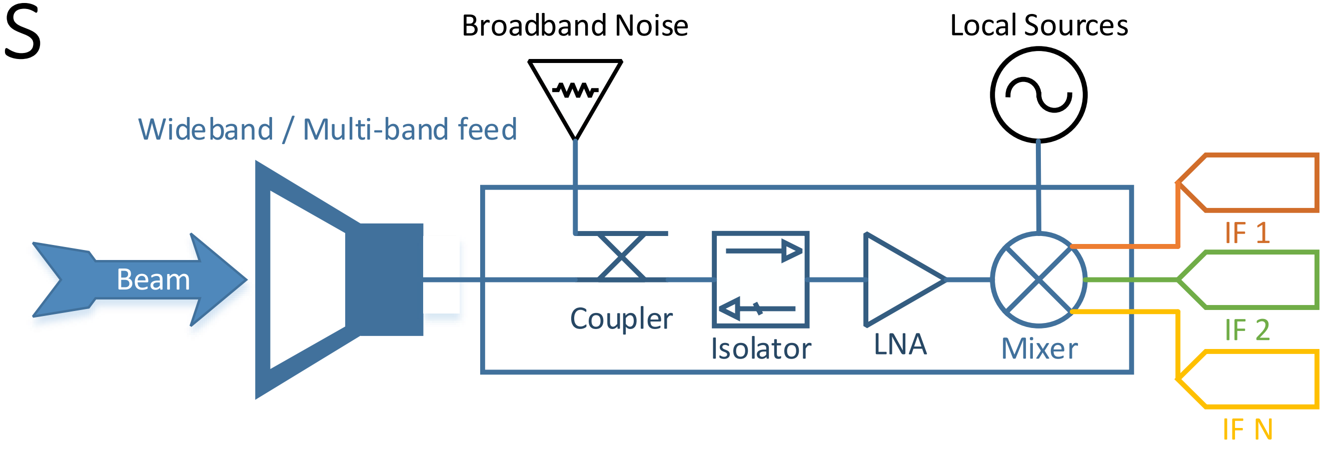
J. A. Lopez-Perez et al., "Description of RAEGE Yebes VGOS Receiver Upgrades," in IVS 2022 General Meeting Proceedings, 2022, pp. 47–51; Stander et al, ICEAA 2024.

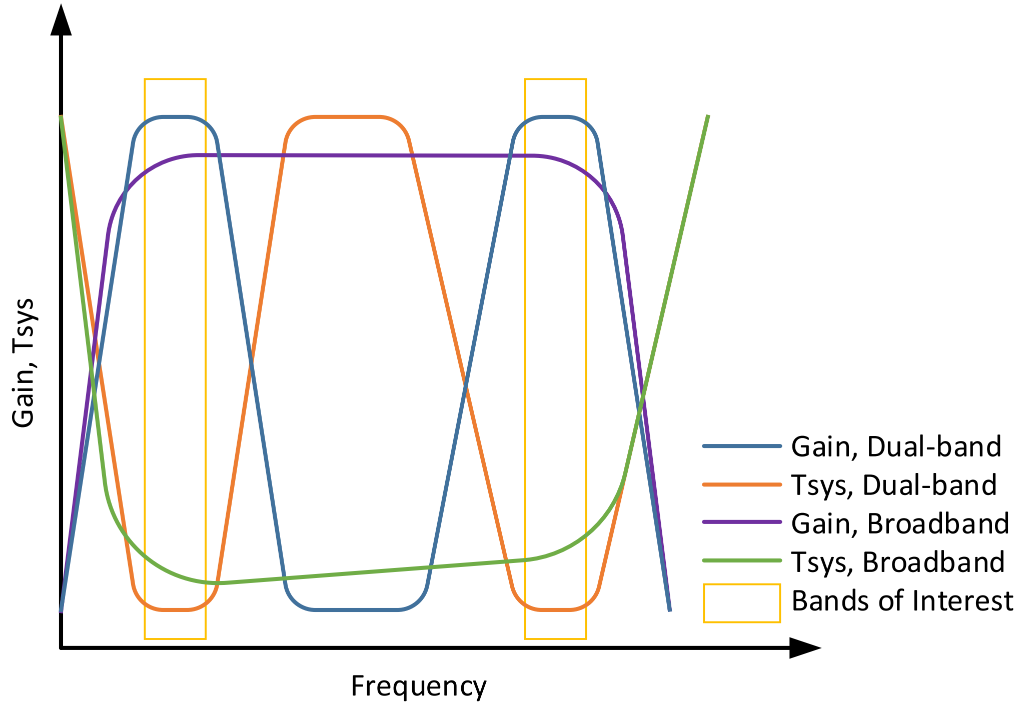
Multi-band receivers

- Multiple concurrent bands
- 4:1 → 6:1 separation
- Individual FBWs of 3% → 9%

- Wideband = optimized for unused spectrum

- *What is the appropriate wideband / multi-band mix?*
- *Look at components first!*





And the winners are…

For receiver 4:1 → 6:1 band spacing, FBWs of 3% → 9%...

Component	Wideband	Multi-band
Feed	Designs available	Needs work: Single feed point, N > 2 bands
LNA	Exists, but with severe performance trade-offs	No N > 2, but worth exploring!
Isolator	Custom designs, but proven feasible.	Would need N > 2 improvement, no apparent multi-band benefit?
Couplers	Exist as ICs; fairly high loss	Exist, with independent band control, but N > 2?
Downconversion	Wideband poses little difficulty	Cascaded SSB / multi-LO
OMT	Needs investigation!	Needs investigation!

RF measurement equipment

Vector Network Analyser (VNA)

- Two or more ports
- Single frequency tone in
  - Monitors outputs at all other ports
- Linear S-parameters
  - Complex values
  - Can do power sweep
- Calibrated every time before use!

Spectrum Analyser

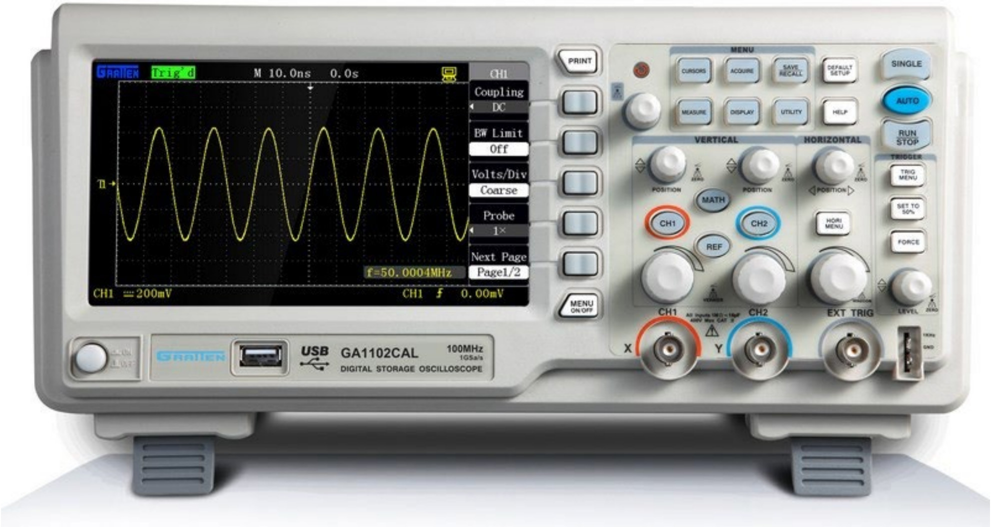
- Single input port
- Provides a view of the RF spectrum
  - Multiple tones / harmonics
  - Only P over frequency

Signal generator

- Generates an output signal for testing
- Sinusoid of controlled
  - Frequency
  - Power
- Can produce modulated output
  - Digital modulation
  - Pulsed RF

Oscilloscope

- Voltage over time
- Modern versions go to RF frequencies
- Built-in processing available
- Need special probes
- Usually for frequencies < 1 – 2 GHz



Power meter

- Total power over the sensitivity spectrum
- Usually thermal sensor
- Used to verify power levels

Torque wrench

- Used to connect RF connectors and cables
  - SMA, 3.5mm and up
  - Not for BNC
- Prohibits over-torque
- Always use this!
- NEVER USE AN ORDINARY WRENCH!

References

- D. M. Pozar, Microwave engineering, 4th ed. Hoboken, NJ: Wiley, 2012.
- D. M. Pozar, Microwave and RF Design of Wireless Systems. John Wiley & Sons, Inc., 2001.
- R. Ludwig and G. Bogdanov, RF Circuit Design. Pearson Education, 2009.
- I. J. Bahl, Lumped Elements for RF and Microwave Circuits. Artech House, 2013.
- N. Honingh, SIS Mixers, https://astro.uni-koeln.de/honingh/sis-mixers