RF and microwave integrated circuits & devices – an introduction

Microwave Electronics

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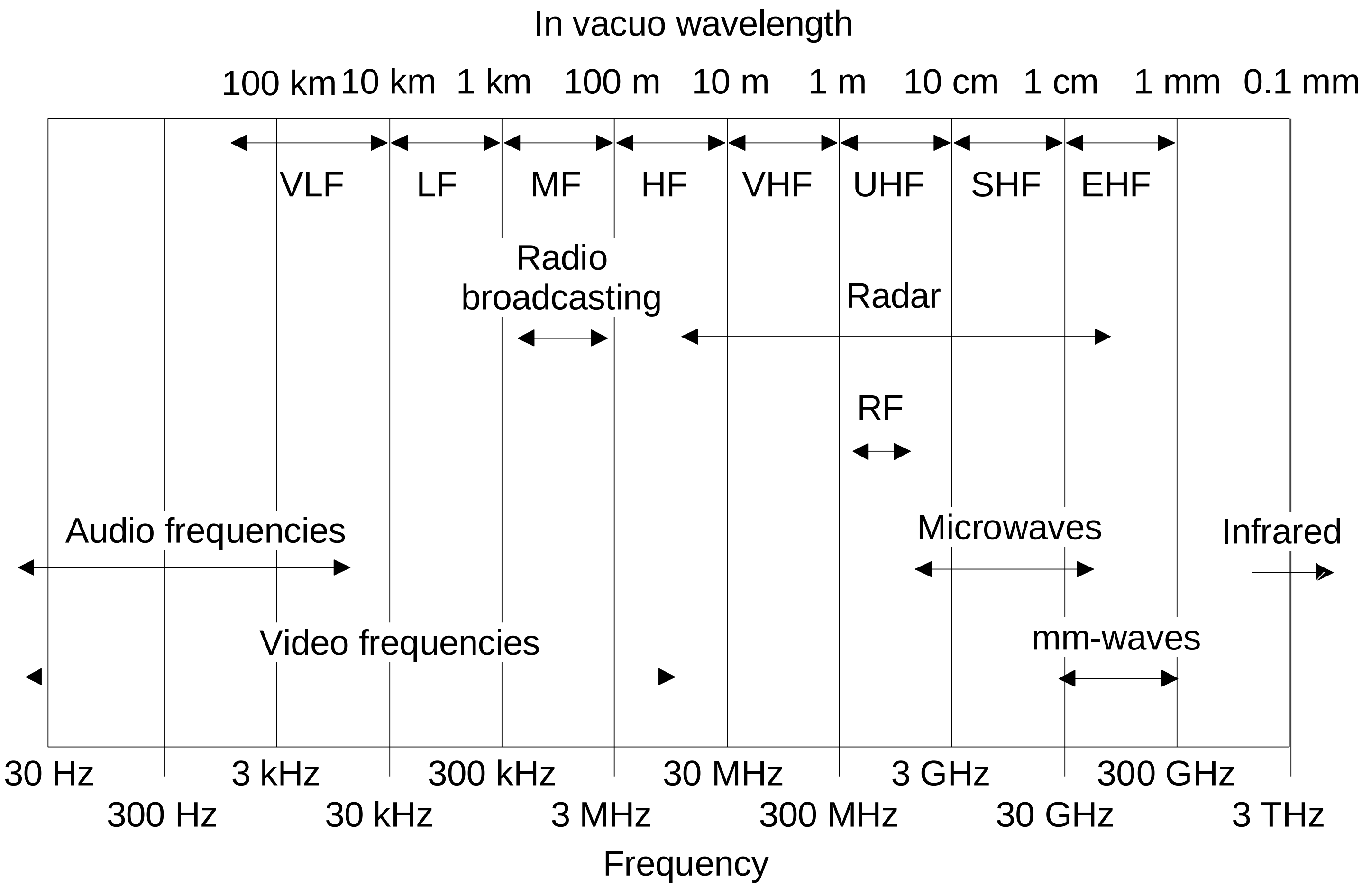
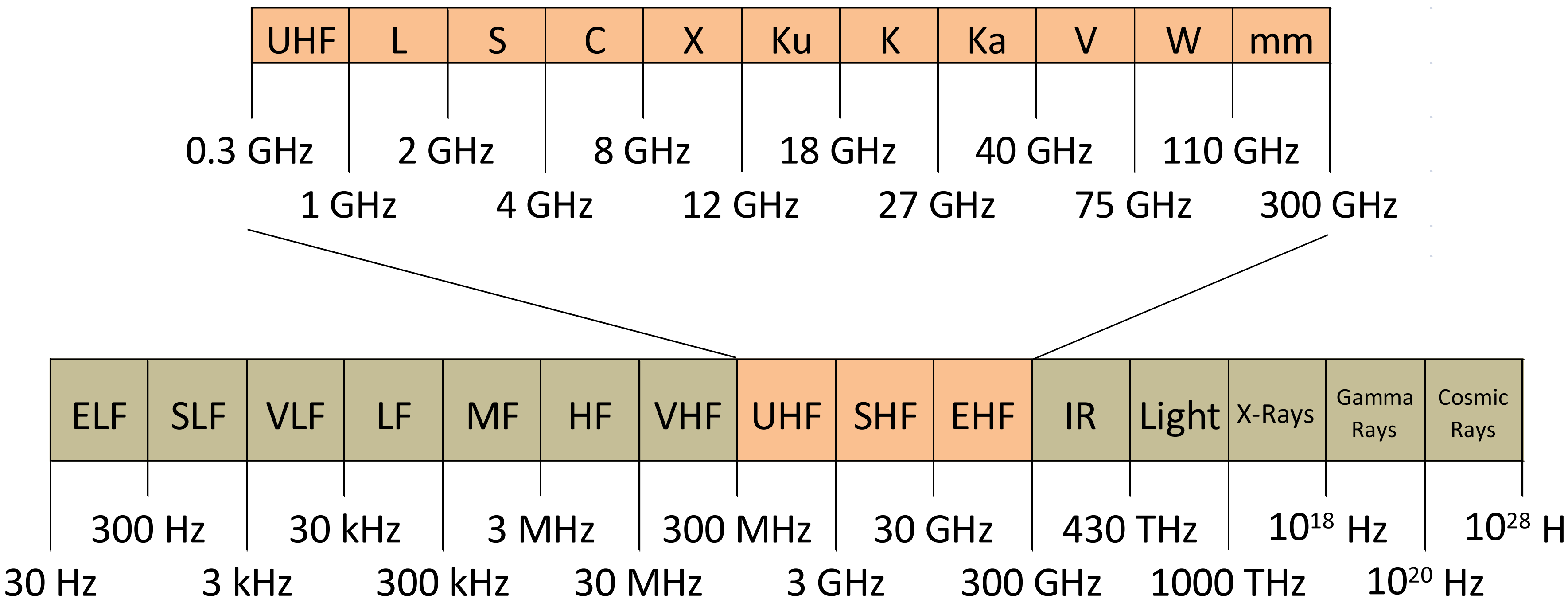
RF, microwaves, millimeter waves

- Radiofrequencies (RF):
  - frequency between a few MHz and 1 GHz, free space wavelengths of the order of 1 m (remember $\lambda f = c_0$)
  - Applications: broadcasting, point-to-point communications, radar, industrial
- Microwaves:
  - frequencies between 1 GHz and 30 GHz, free space wavelengths between 30 cm and 1 cm
  - Applications: wireless systems, WLAN, radio links (terrestrial, satellite), radar systems, electronic part of optical communication systems
- Millimeter waves:
  - frequencies between 30 GHz and 100 (300) GHz, free space wavelengths below 1 cm
  - Applications: radio links, radar systems (e.g. automotive)

Frequency bands



Frequency spectrum & standard bands (IEEE)



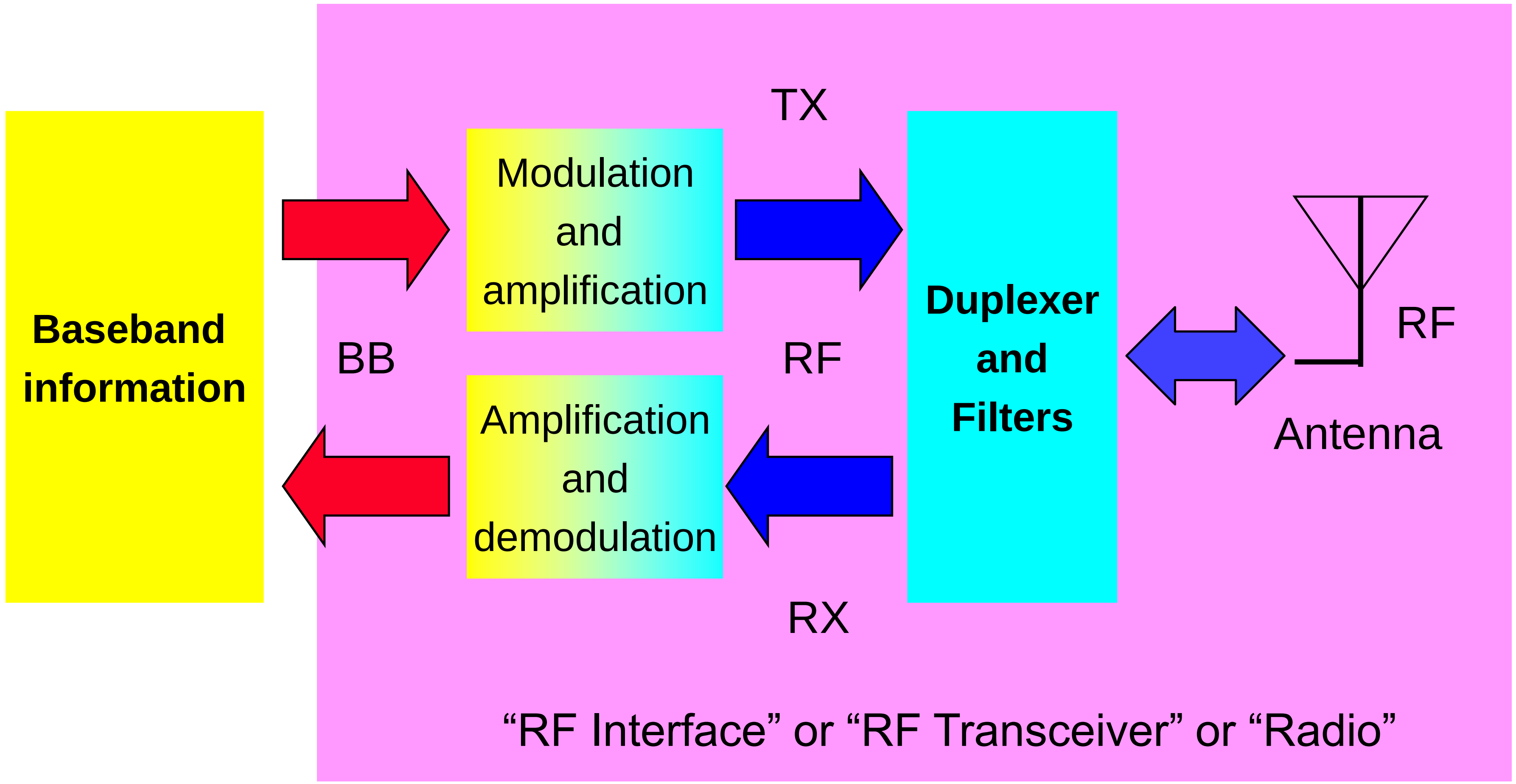
Sending information through RF & microwaves

- Analog or digital signals carry information in *baseband*, e.g. voice occupies 0-10 KHz approximately or a corresponding data rate after sampling (e.g. 100 Kbps)
- Baseband signals cannot be directly transmitted through the Herzian channel by means of an antenna (why?)
- Thus, *modulation* is needed to upconvert the baseband signal around a *carrier frequency*, thus making it suitable for transmission through an antenna; usually the upconverted signal is **narrowband**
- For example, a GSM wireless channel is a few kHz around ~0.9 or ~1.8 GHz; a digital modulation scheme is exploited to encode the baseband information (called Gaussian Minimum Shift Keying, GMSK); the receiver and transmitter band are separated in frequency and signals are received and transmitted in different time slots

The Hertzian channel

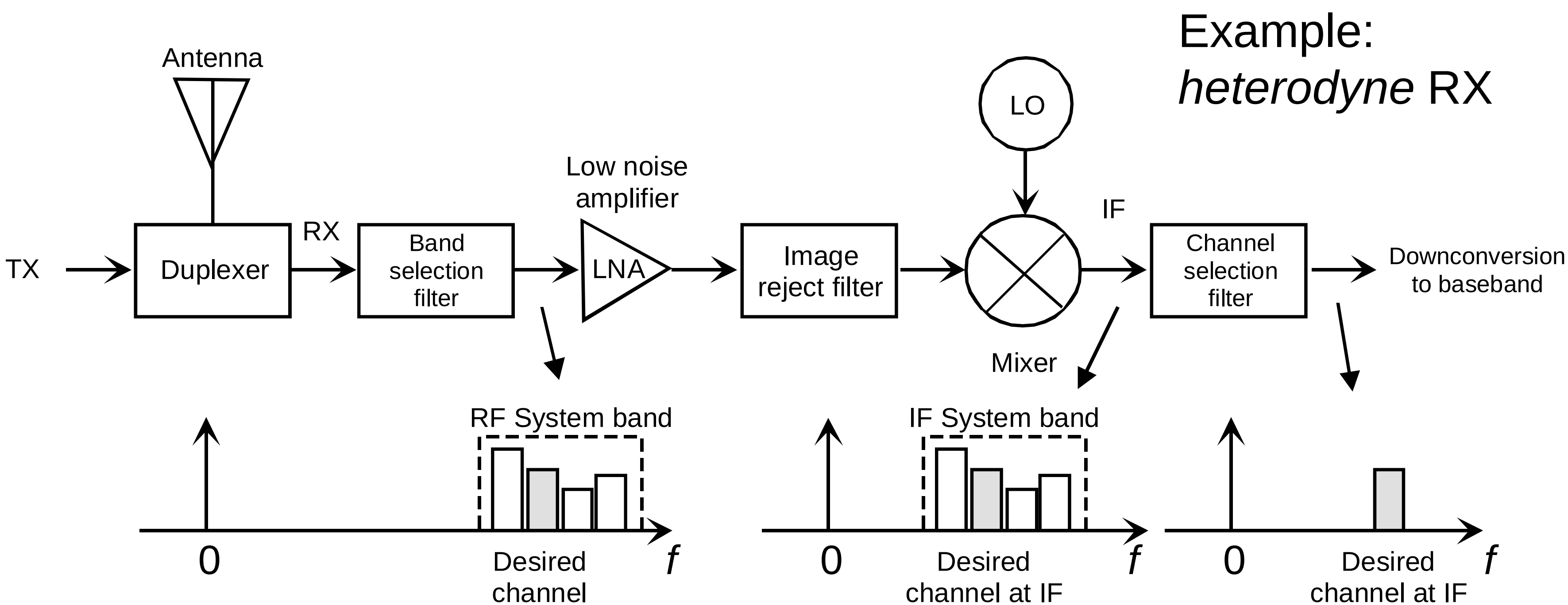
- At RF > 1 GHz and microwaves the channel provides enough attenuation to allow for **frequency reuse** (e.g. in cellular systems)
- At millimeter waves the attenuation can be so strong to allow for **spatial diversity** → also antennas tend to be more directive
- The Hertzian channel in the atmosphere presents attenuation peaks due to molecular resonances, e.g. at sea level:
  - 0.2 dB/km at 22 GHz (water)
  - 15 dB/km at 60 GHz (oxygen)
  - 2 dB/km at 118 GHz (oxygen)
  - 30 dB/km at 183 GHz (water)
- Outside resonance, the average attenuation at sea level increases from ~0.02 dB/km at 10 GHz to ~10 dB/km at 300 GHz.
- See e.g. http://propagation.ece.gatech.edu/ECE6390/project/Fall2012/Team06/Webpage%20Folder/Webpage%20Folder/img/atmosphereatten.png

Block scheme of a RX/TX



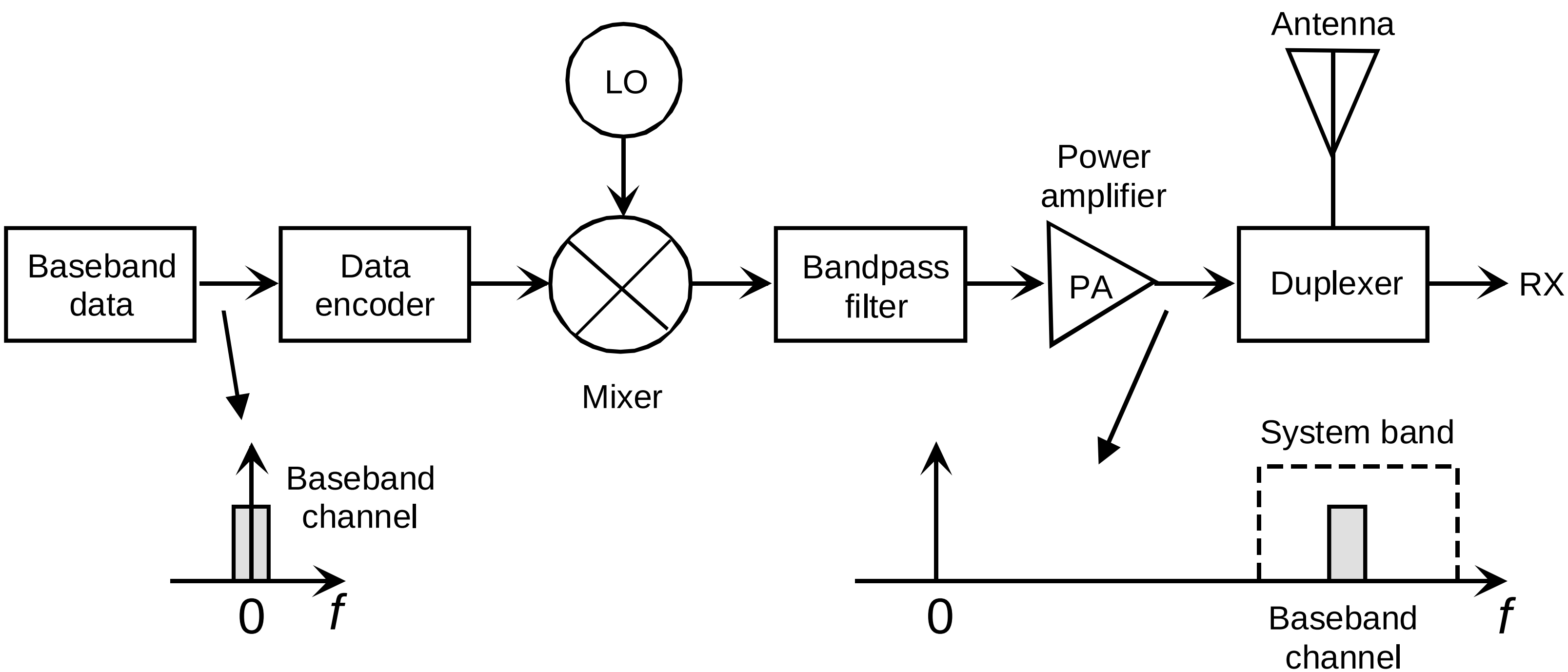
Transceiver building blocks - I

- Antennas – Duplexers
- Receiver:
  - Low-noise amplification → LNAs
  - Signal downconversion to IF or baseband → mixers, local oscillators (LO)
  - Passive elements → filters

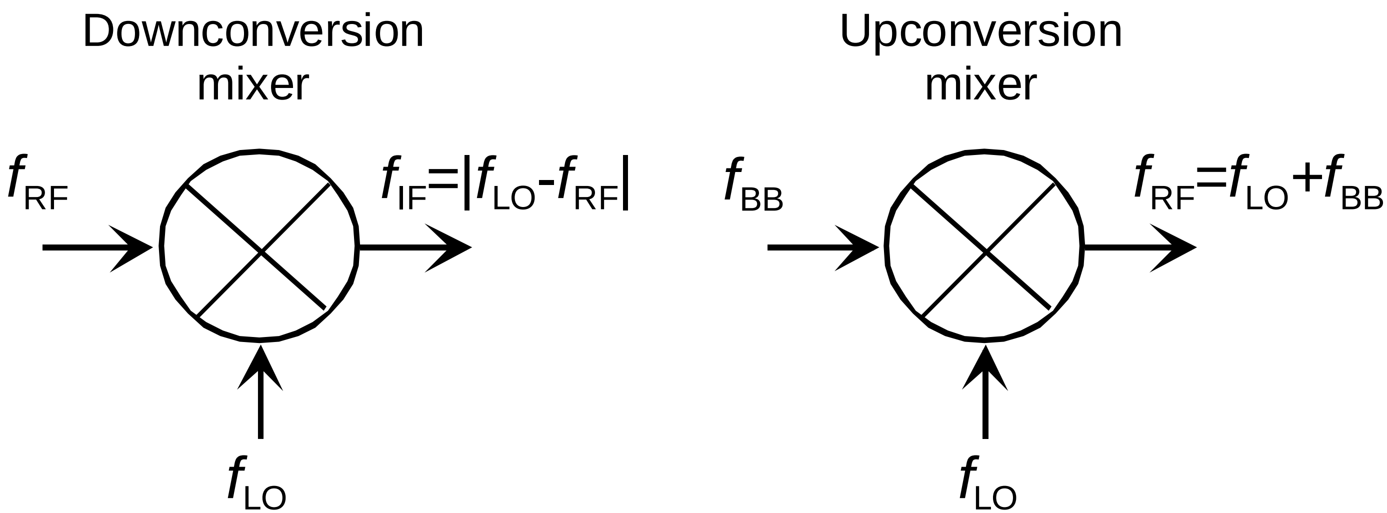


Transceiver building blocks – II

- Transmitter:
  - RF carrier generation → oscillators and frequency synthesizers (LO)
  - Baseband signal upconversion → modulation → mixers
  - Power amplification → PAs

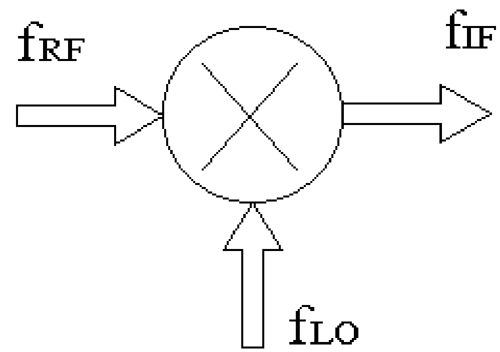


Up- and down-conversion mixer



Downconversion mixer I

- Mixing = RF multiplication by LO signal (Local Oscillator)



$$\cos(\omega_{RF}t) \times \cos(\omega_{LO}t) =$$

$$= \frac{1}{2}\cos\Big[\underbrace{(\omega_{RF}+\omega_{LO})}_{\text{LP filtered}}\ t\Big] + \frac{1}{2}\cos\Big[\underbrace{(\omega_{RF}-\omega_{LO})}_{\text{Int. Freq. } \omega_{IF}}\ t\Big]$$

$\omega_{IF} = \omega_{RF} - \omega_{LO}$ low-side injection

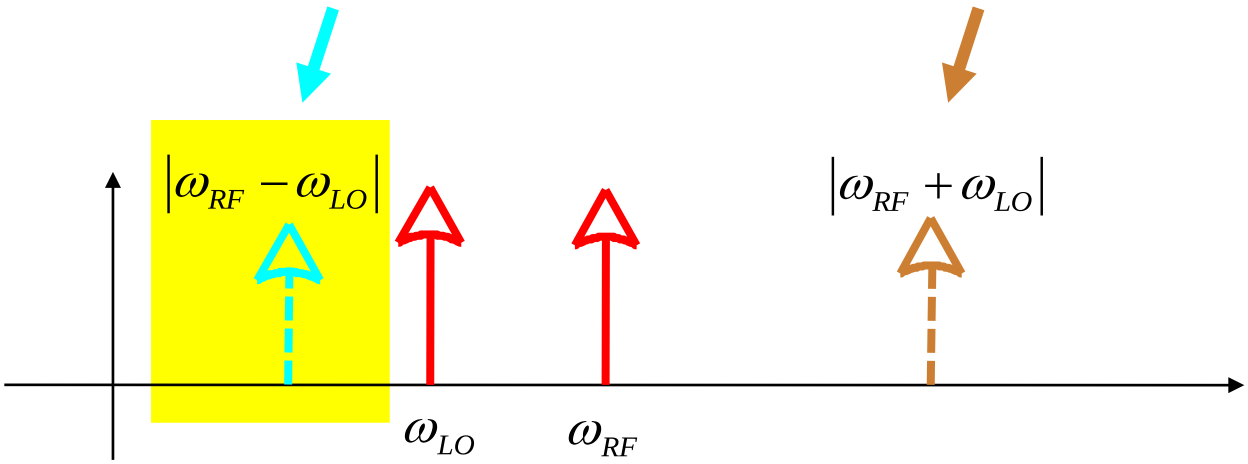
$\omega_{IF} = \omega_{LO} - \omega_{RF}$ high-side injection

Downconversion mixer II

- Conversion (e.g. downconversion) is followed by filtering to select only the desired frequency component

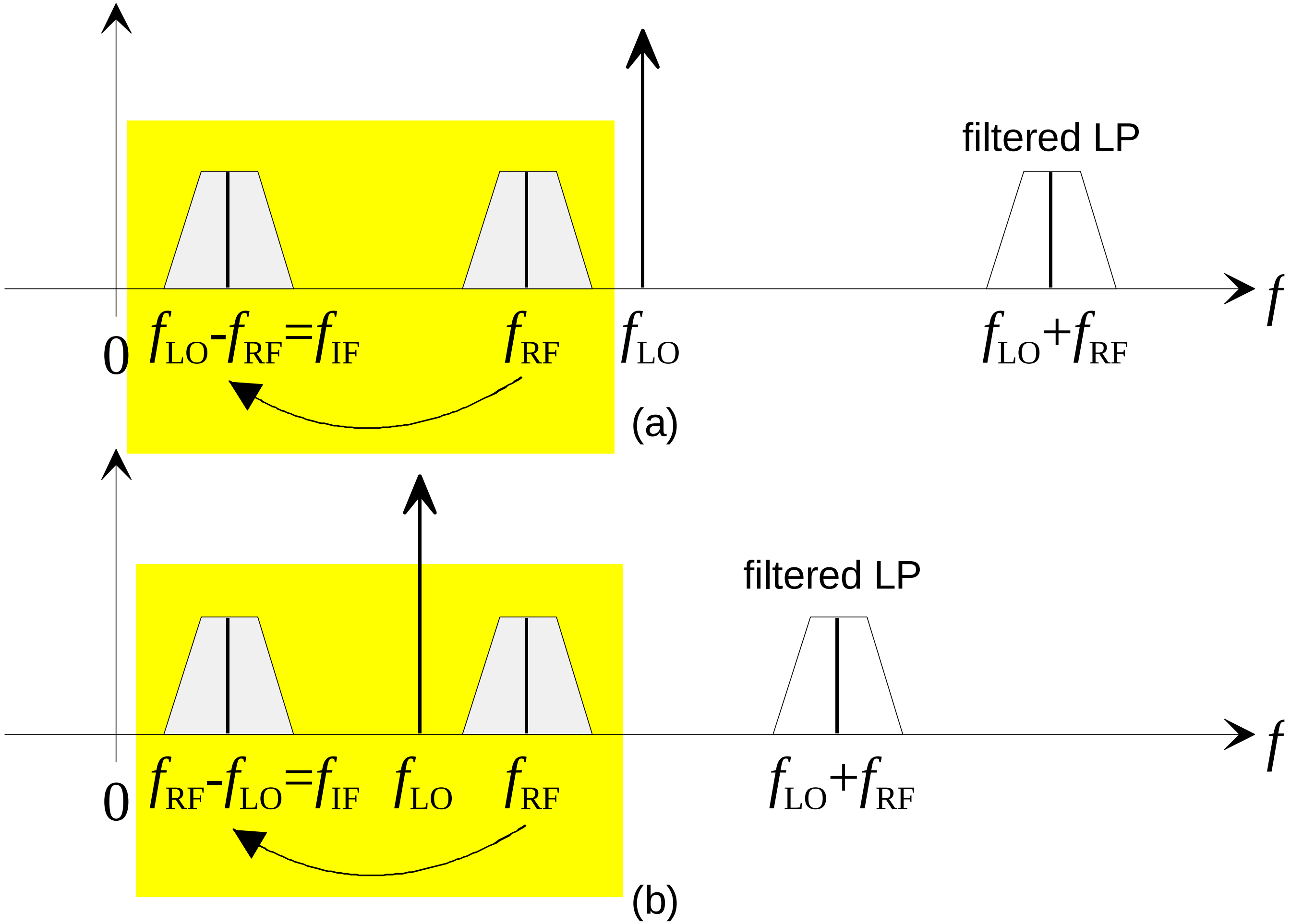
$$y_{IF} = x_{RF} \cdot x_{LO} = A_{RF} A_{LO} \cos(\omega_{RF} t + \varphi_{RF}) \cos(\omega_{LO} t + \varphi_{LO}) =$$

$$= \frac{A_{RF} A_{LO}}{2} \left\{ \cos\left[(\omega_{RF} - \omega_{LO}) t + \varphi_{RF} - \varphi_{LO} \right] + \cos\left[(\omega_{RF} + \omega_{LO}) t + \varphi_{RF} + \varphi_{LO} \right] \right\}$$



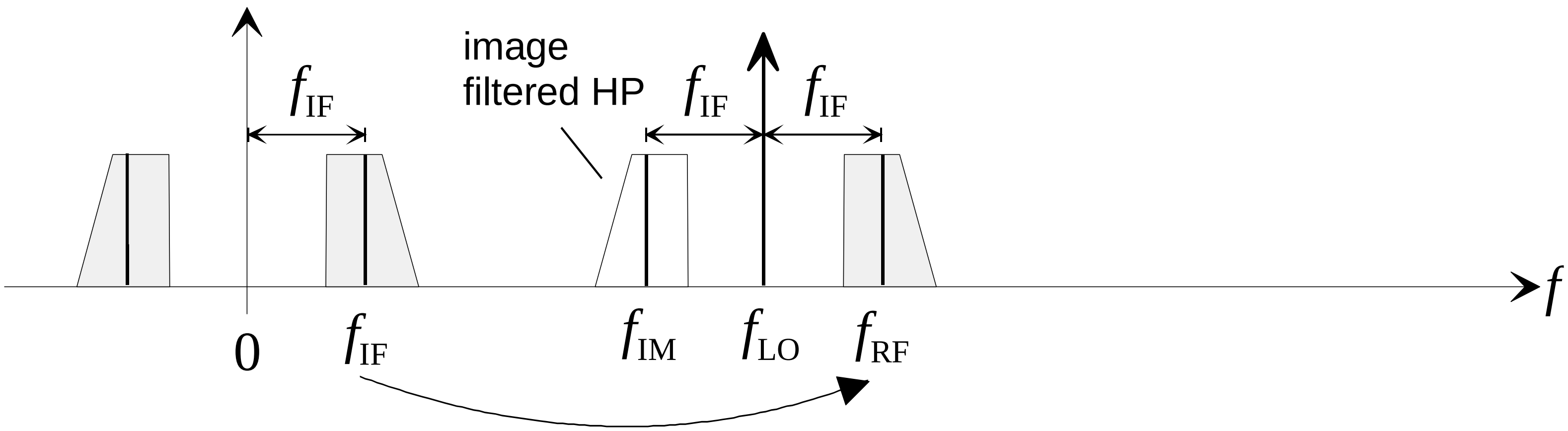
- Mixing can be carried out by a passive, time-varying device (typically a switch) or by an active device → possibility of gain

High- and low-side injection

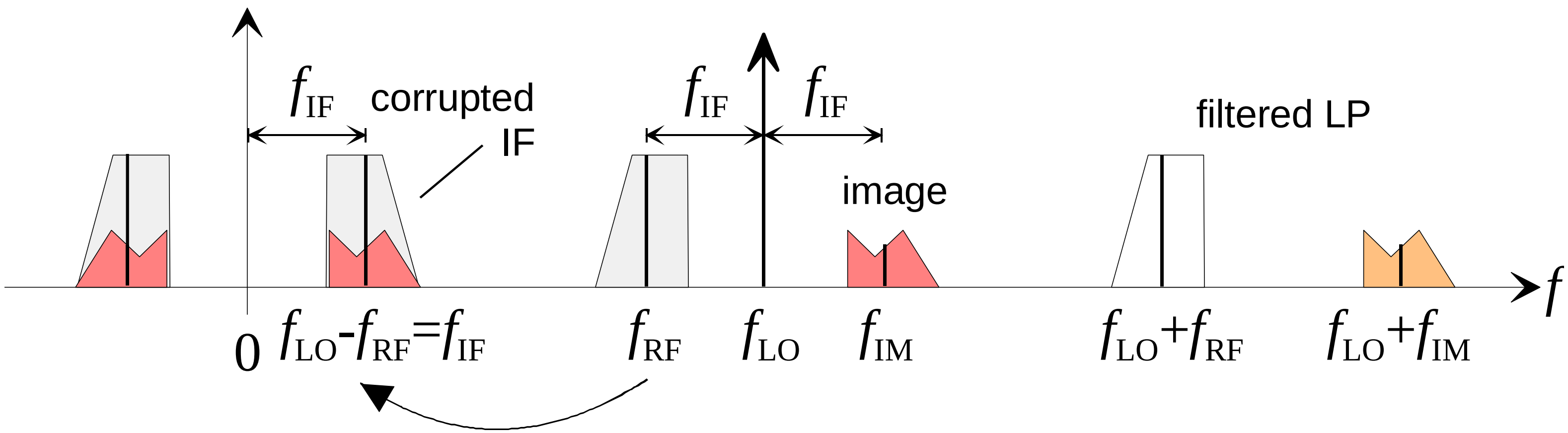


The image frequency issue

- Upconversion mixer – no problem:



- Downconversion mixer – image aliasing:

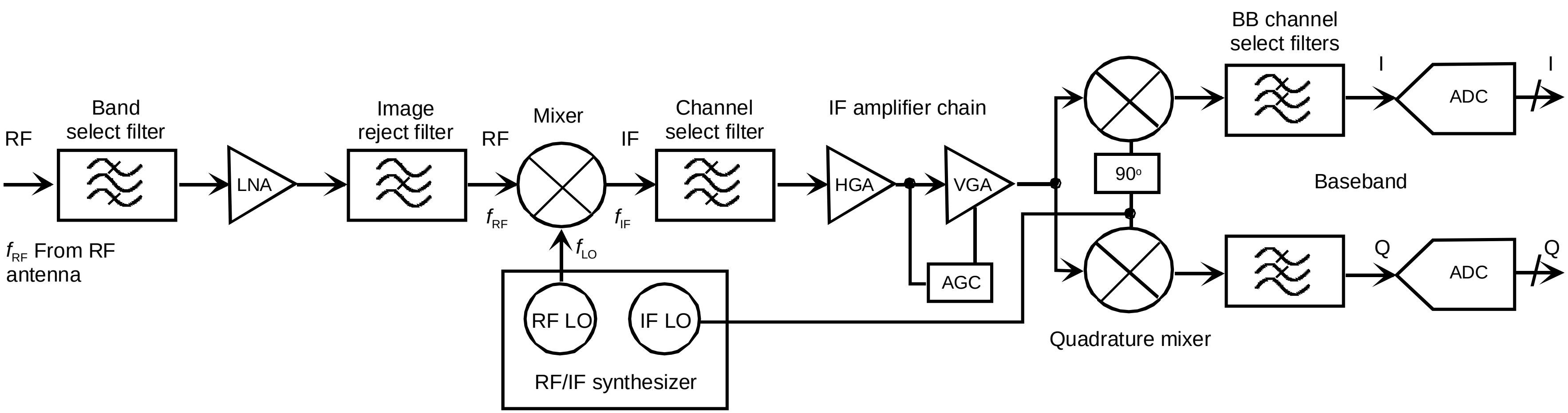


More on the image frequency

- The image frequency problem only exists in receivers exploiting an intermediate frequency → heterodyne, see later
- Direct conversion receivers have zero IF and no image frequency problem
- The image frequency can be cancelled through filtering (image rejection filters) or through proper receiver architectures (image rejection receivers)

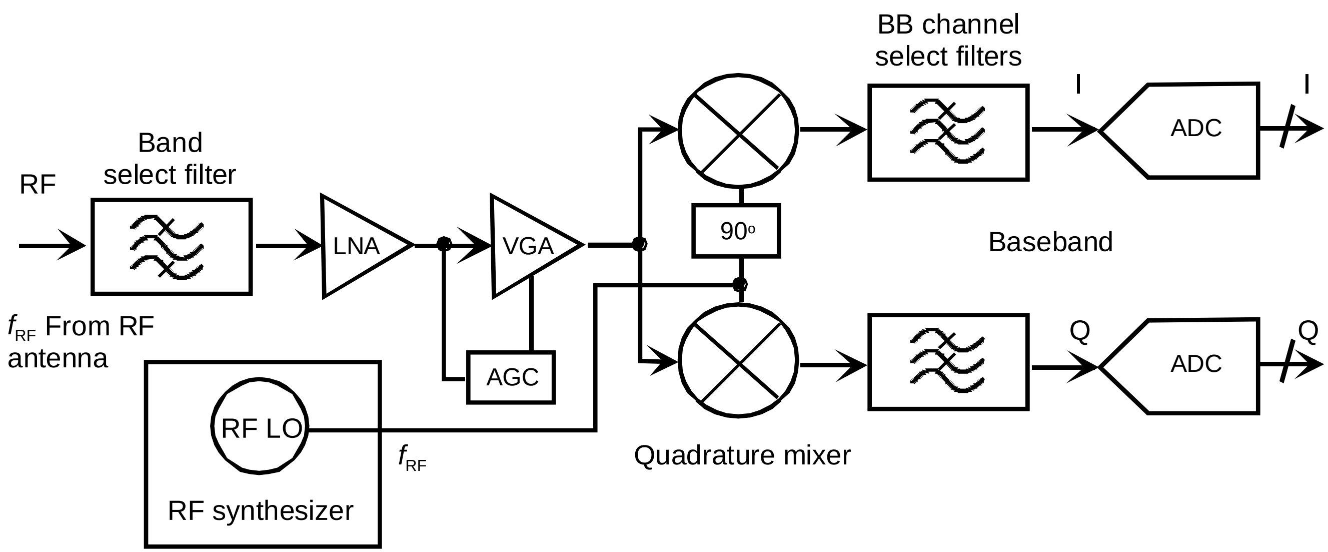
Receiver architectures - I

- Heterodyne receivers:
  - the RX band is downconverted into Intermediate Frequency (IF) → relax the filter Q for channel selection
  - further downconversion to Baseband follows



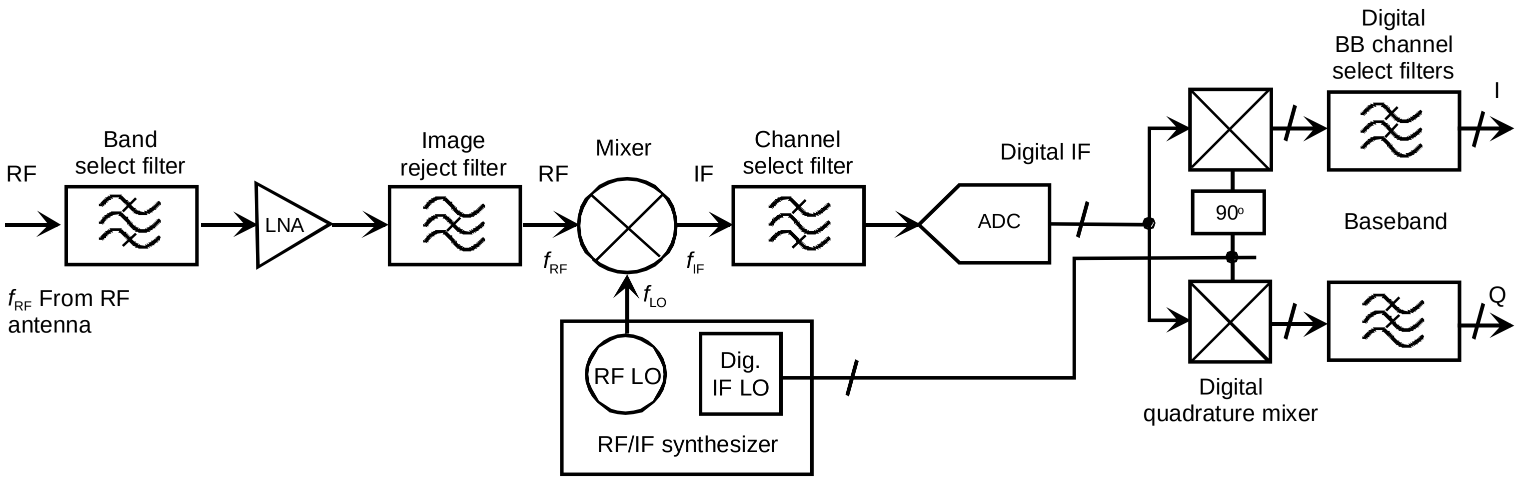
Receiver architectures - II

- Homodyne receivers:
  - the RX band is directly downconverted into Baseband
  - also called Direct Conversion receivers

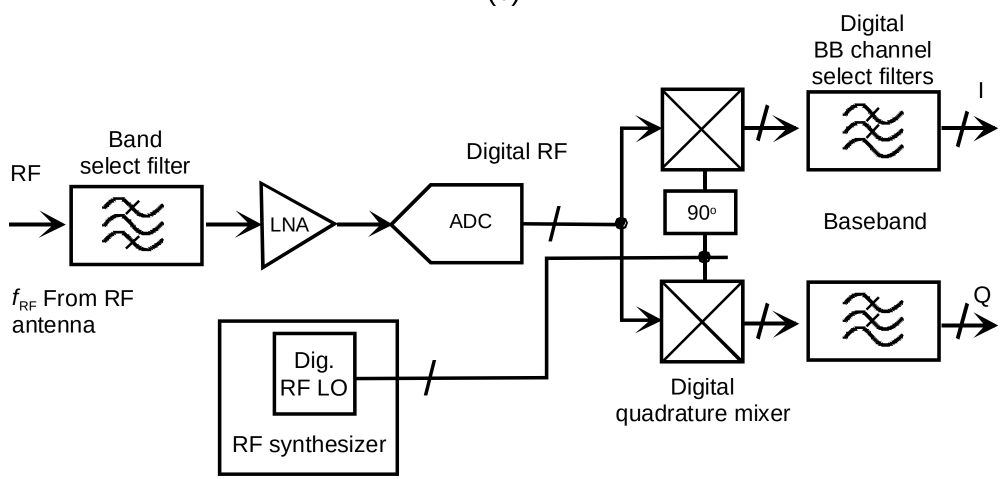


(b)

Digital IF and Software radio



(c)



(d)

In short…

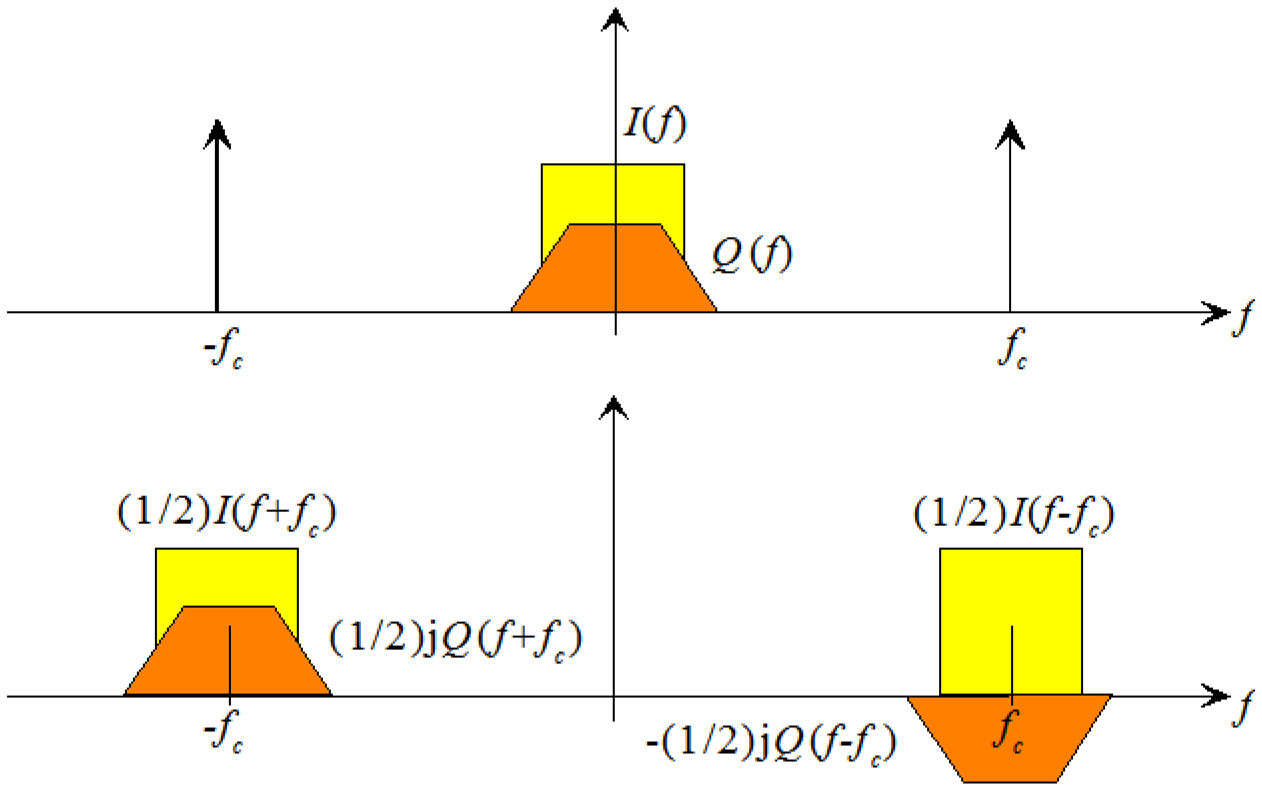
- In heterodyne transceivers the RF is downconverted to Intermediate Frequency (~video, 1-100 MHz) and then to baseband
- Motivation: channel selection issue; cons: need for external bandpass filters
- In homodyne or direct conversion the RF is directly converted to baseband; more critical design, no bandpass filters needed → can be (almost) completely integrated
- In all architectures a few building blocks appear systematically

I and Q signal components

- A phase and amplitude modulated signal can be expressed as:

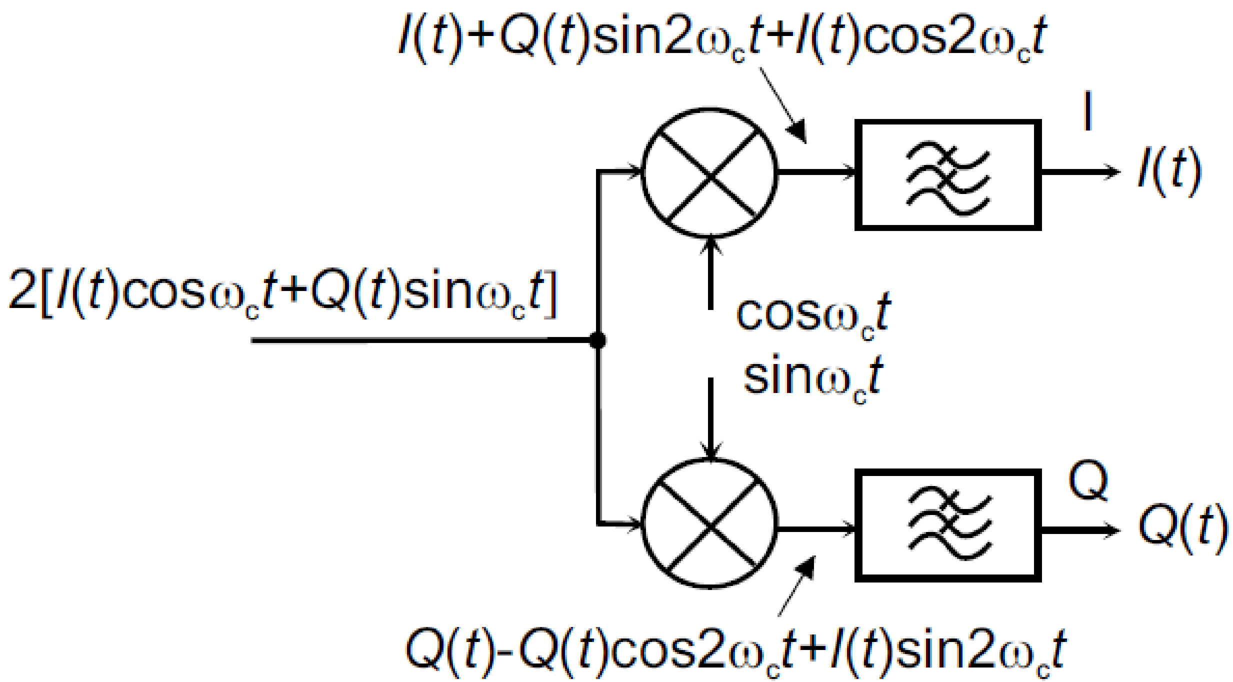
$$x(t) = A(t)\cos(\omega_c t + \phi(t)) = I(t)\cos\omega_c t + Q(t)\sin\omega_c t$$

- *I* and *Q* are the in-phase and quadrature components of the modulated signals, the spectrum of the modulated signal will be:



Quadrature demodulation

- Mixing with a sine / cosine will downconvert only the in **quadrature** $Q(t)$ / **in phase** $I(t)$ component
- To convert both we need **quadrature demodulation**



RF interface building blocks

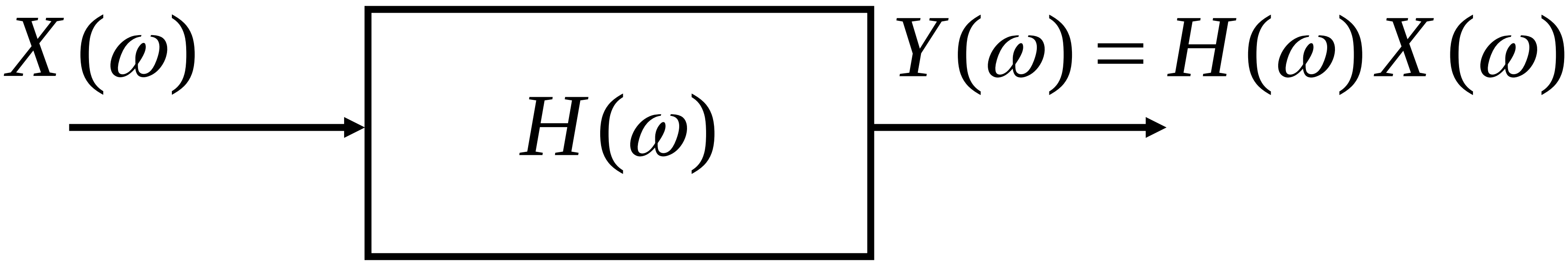
- **Amplifiers**
  - **Low noise** (LNA)
  - **High gain**
  - **Power** (PA)
- Mixers → modulators, demodulators
- Local Oscillators → Frequency Synthesizers
- **Filters** → bandpass, lowpass
- **Couplers**
- Duplexers, RF switches

RF building blocks – system wise

- Some analog subsystems are approximately linear (low-noise amplifier, high-gain amplifiers, filters, duplexers…)
- Some others are quasi-linear (power amplifiers): nonlinear effects are becoming important
- Others heavily rely on nonlinearity or on its consequences: mixers, frequency multipliers
- Others yet could not operate without nonlinearity: oscillators

Linear blocks

- At a system level they are described by a linear input-output relationship in the time or frequency domain:



- Same policy for circuit level: e.g. scattering parameters of a two-port $\underline{\boldsymbol{b}} = S\underline{\mathbf{a}}$

Linear block features

- In linear blocks the output is proportional to the input
- In linear blocks frequencies do not mix → sinusoidal input @*f* leads to sinusoidal output @*f* → no harmonic generation
- Linear blocks can be
  - memoriless (nondispersive) → H is constant,
  - with memory (dispersive) → H depends on frequency

Quasi-linear blocks

- Quasi-linear blocks (e.g. power amplifiers) are nonlinear systems operating at low enough input and output signal to make nonlinearity “not dominant”
- The behaviour is roughly speaking (at least in some cases) linear, but some nonlinear features appear, such as:
  - Harmonic generation
  - Generation of intermodulation products
  - Saturation of the output when increasing input → nonlinear input-output relationship

Describing nonlinear blocks

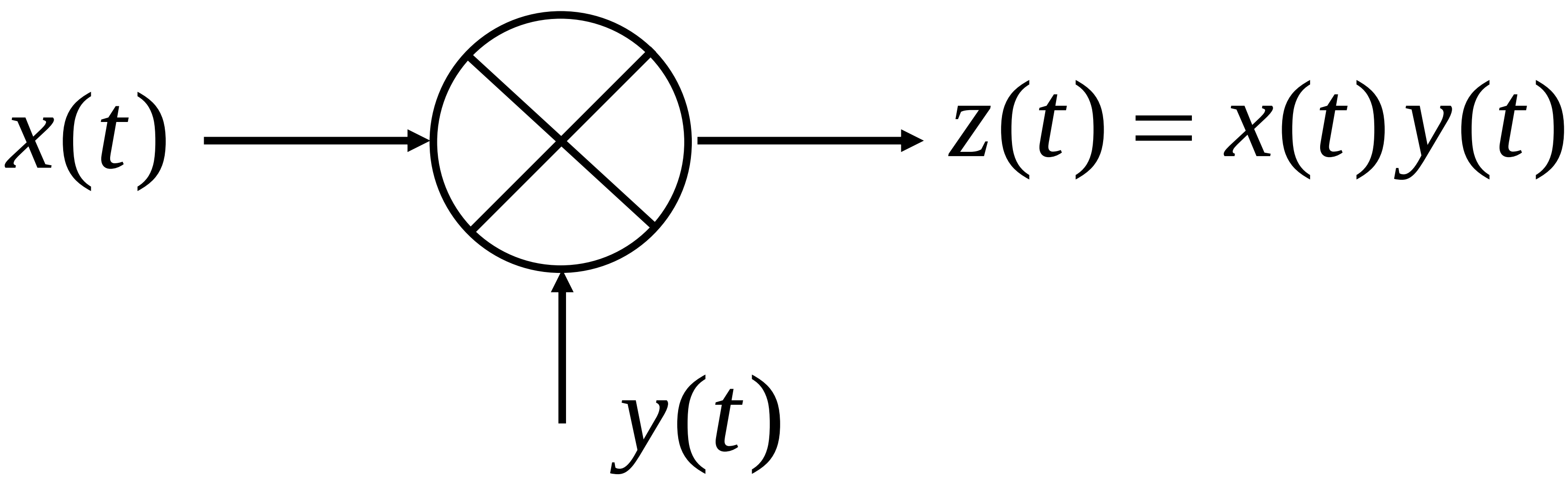
- For nonlinear blocks simple models exist if the block is memoriless (nondispersive):

$$y(t) = f(x(t))$$

but for nonlinear dispersive systems the situation is complex: the exact model (Volterra series) is unpractical, and simplified models can be devised by combining linear dispersive and nonlinear memoriless blocks.

Nonlinear and bilinear blocks

- Some subsystems entirely rely on nonlinear effects: e.g. frequency multipliers rely on the harmonic generation
- Other subsystems are ideally **bilinear** (but in fact often create this behaviour from nonlinear components) → mixers:



Microwave technology implementations: IC vs. waveguide

- Planar circuits: low cost, small size, same approach as low-frequency ICs or hybrid circuits
- Waveguide circuits → large size and cost
- In what follows we mainly deal with planar circuits, even though waveguide circuits still are used for certain applications (e.g. high power)

Hybrid and monolithic implementations

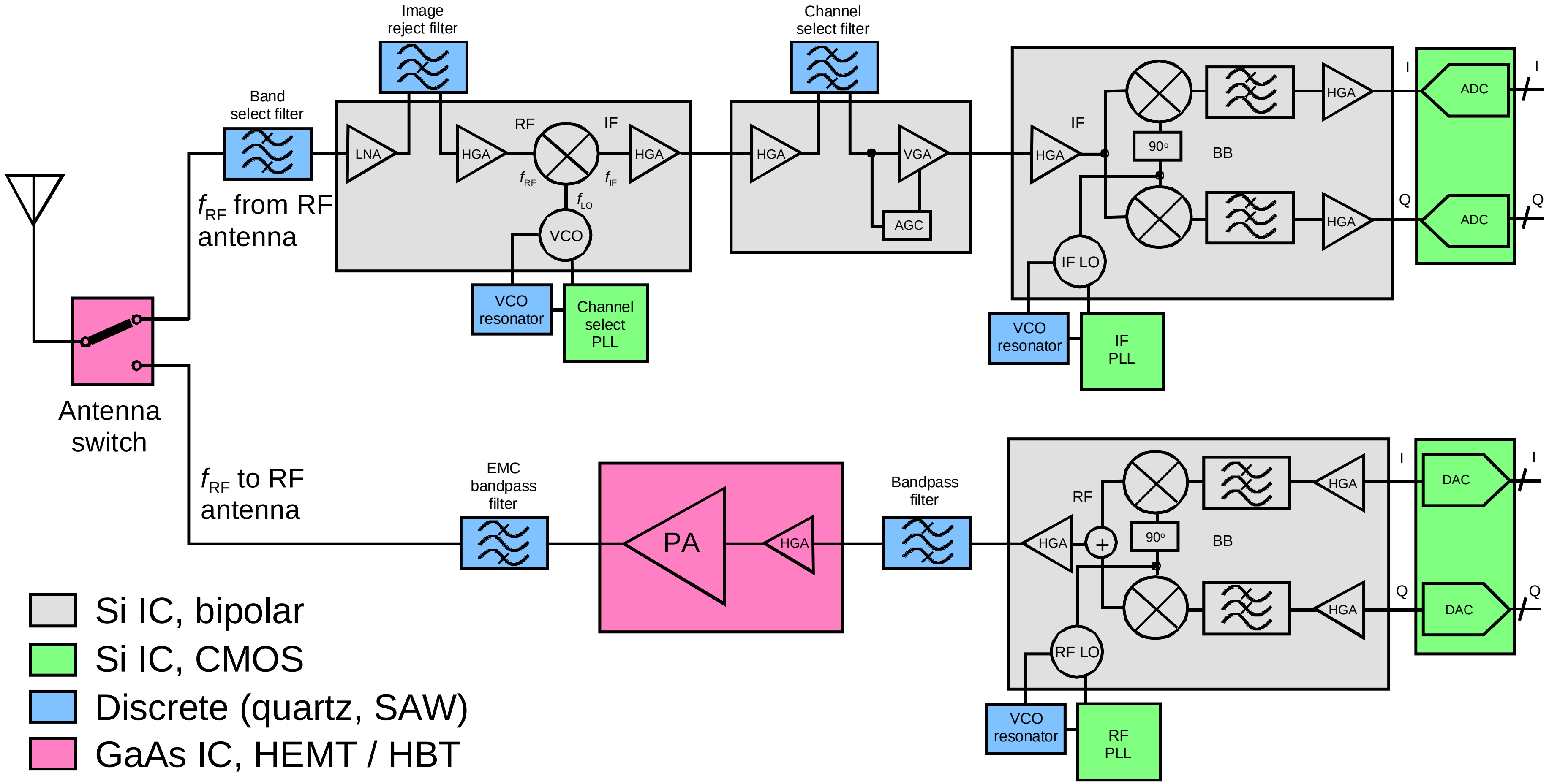
- MMICs (monolithic)
  - Cheap for large scale production
  - Good reproducibility
  - Small size, low weight, more reliable
  - Less parasitics, more BW and higher frequency
  - Long turn-around time (a few months) ☹
- HICs (hybrid)
  - Cheaper for simple circuits
  - Larger, heavier, less reproducible, less reliable ☹
  - Circuit design can be pushed to the limits and the circuit can be tuned
  - Fast turn-around time (1 week) and redesign

Materials and devices in RF and microwave electronics

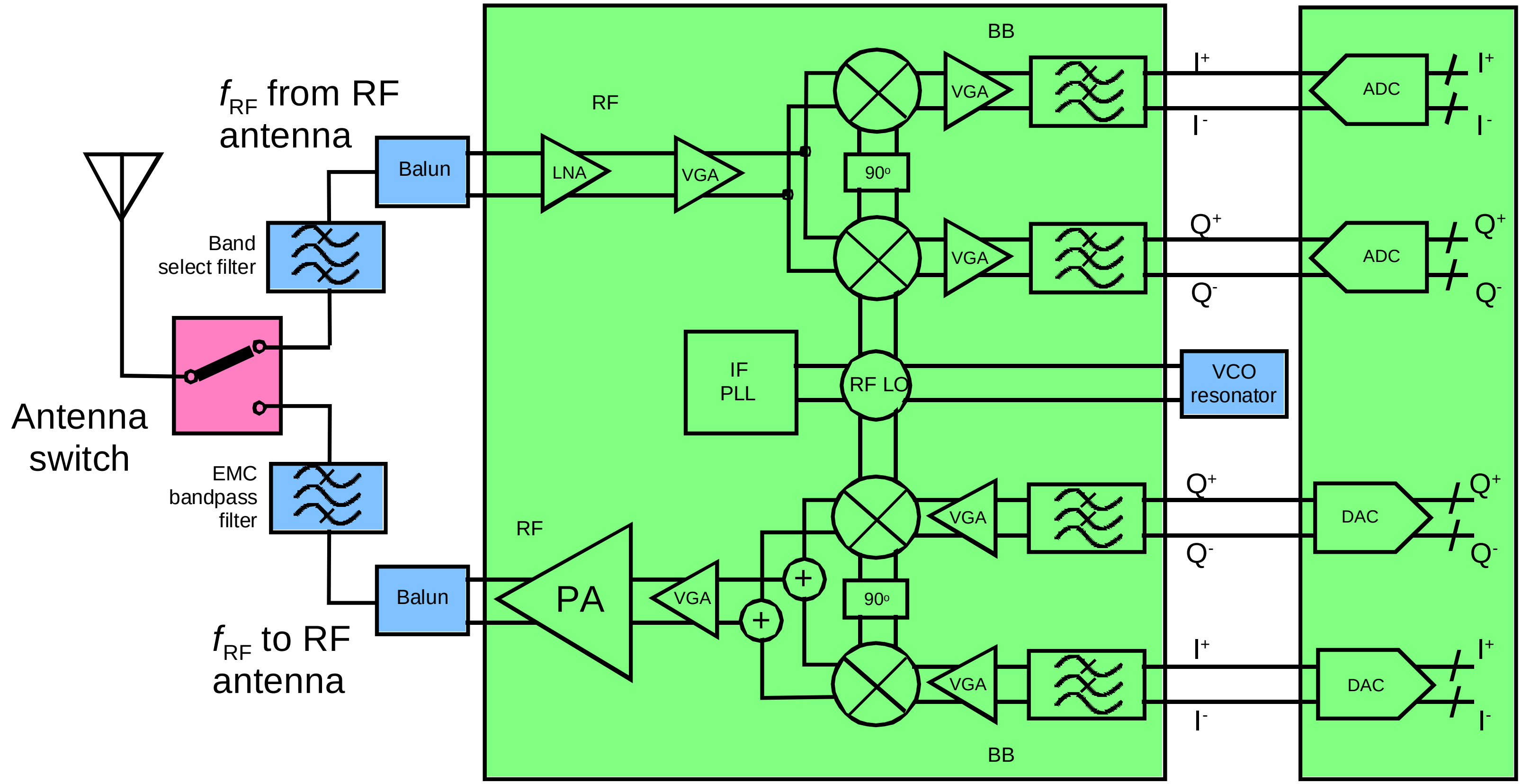
- **Silicon IC's** (MOSFET and bipolars) → OK up to 5-10 GHz, but not for power (yet?)
- **Silicon-Germanium** (SiGe) Heterojunction Bipolar Transistors (HBT) → low noise and low power up to 40 GHz
- **GaAs (Gallium Arsenide)** IC's (MESFETs and HEMTs) → up to 50 GHz, also for high power
- **InP (Indium Phosphide)** IC's (HEMTs) → up to mm waves, low market

- **GaN, Gallium Nitride** (HEMTs) → high power up to 30 GHz, not yet mature
- **GaSb, Gallium Antimonide** (HEMTs) → low noise up to mm waves, not yet mature

Technologies in a GSM wireless handset - 2000



Single-chip WLAN CMOS transceiver (2012)



Si IC, CMOS

Discrete (quartz, SAW)

GaAs IC, HEMT / HBT

Lumped and distributed microwave circuits

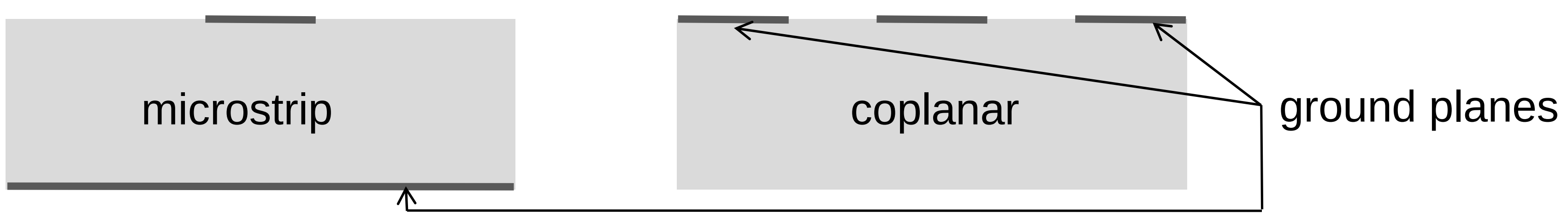
- Lumped parameter circuit
  - Elements small versus wavelength (<λ/8)
  - Typically **integrated** on Si (un to a few GHz), gallium arsenide (GaAs → 50 GHz), indium phosphide (InP→100 GHz).
- Distributed parameter circuit
  - Elements based on transmission line approaches (e.g. microstrip), typically same order of magnitude as wavelength (>λ/8)
  - Typically **hybrid** (with discrete active elements, passive integrated with the substrate or sometimes in discrete from if lumped); the circuit is made on a dielectric substrate (e.g. allumina) with thin-film technique
  - High-frequency integrated circuits also often have distributed elements

Lumped and distributed passive elements

- Lumped elements:
  - Resistors
  - Capacitors
  - Inductors
  - Filters, Couplers, Lumped power dividers, Matching stages
- Distributed elements:
  - Transmission lines, simple and coupled (multiconductor)
  - Filters, Couplers, Power dividers, Matching stages made with transmission lines
- At low frequency distributed components have a large layout → monolithic integration unfeasible below 10-20 GHz

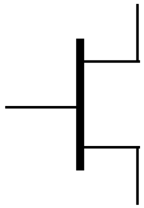
Microstrip anc coplanar waveguide circuits

- In RF and microwave circuits often we must exploit distributed components:
  - **Planar transmission lines** (no hollow waveguides)
  - **Coupled transmission lines** (couplers, power dividers, certain filters)
- Two possible choices:
  - Most common, **microstrip circuits**, active conductors on top, bottom ground plane
  - At mm waves or for specific reason**, coplanar waveguide circuits**, some pros and cons will be reivewed afterwards

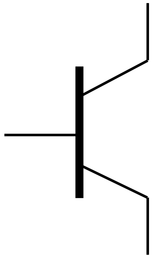


Active elements

- **Field-effect transistors**
  - Si-based MOSFETs
  - Special MOSFETs: LDMOS
  - GaAs-based MESFETs (old), HEMTs
  - InP-based HEMTs

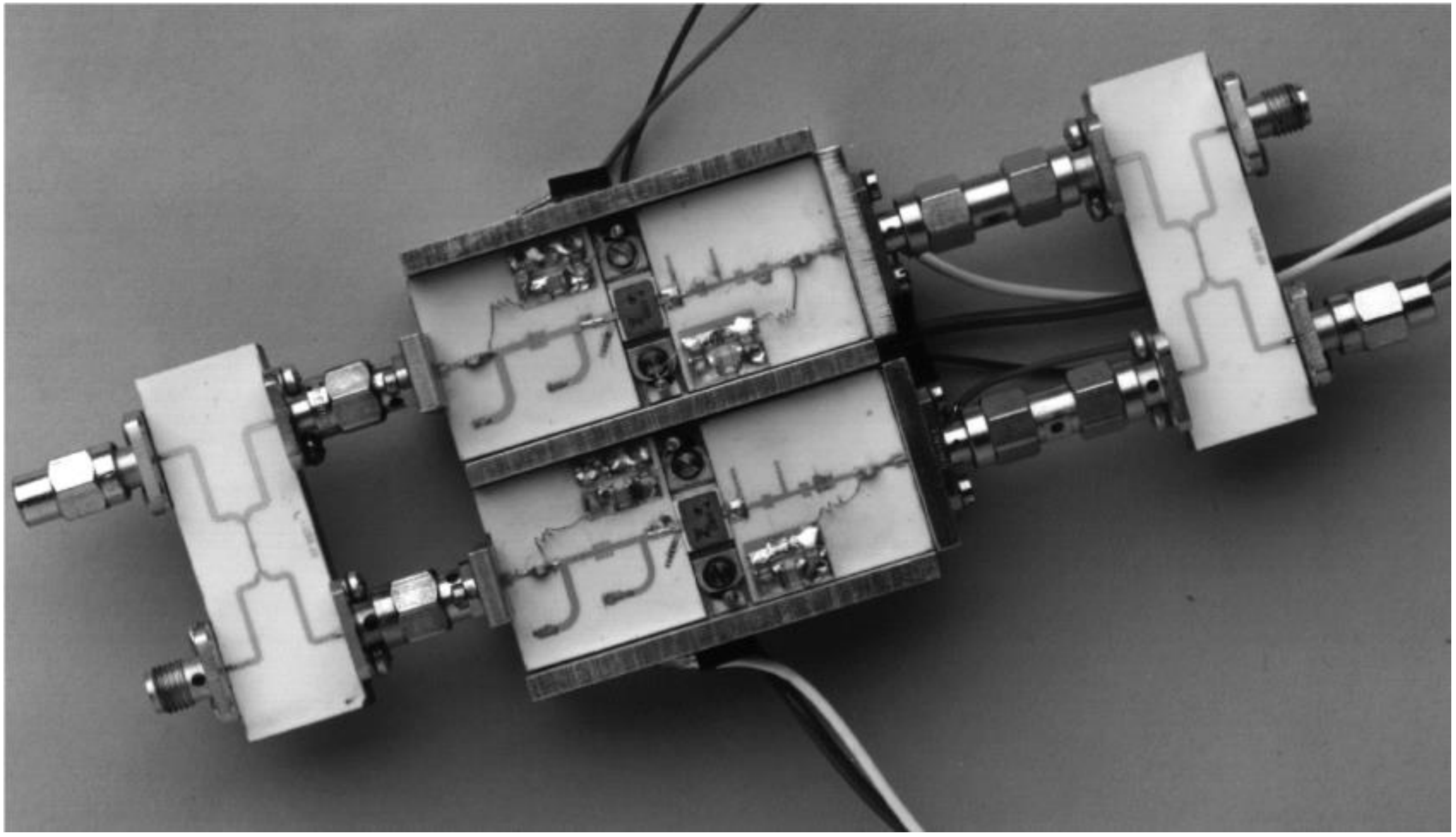


- **Bipolar transistors**
  - Si-based BJTs
  - SiGe HBTs
  - GaAs-based and InP-based HBTs

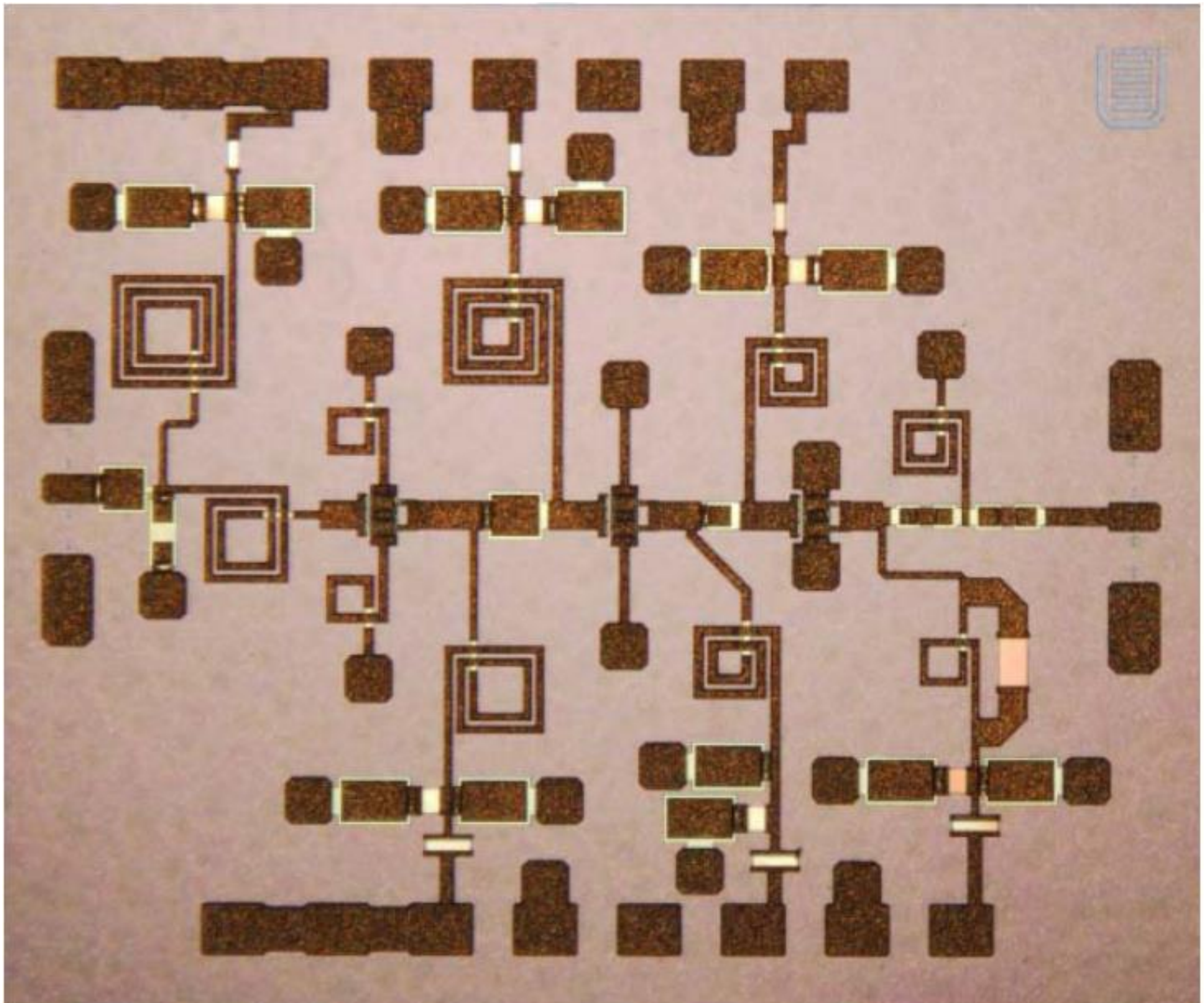


- **Vacuum tubes**
  - Traveling Wave Tubes (TWTs), still exploited for high-power applications

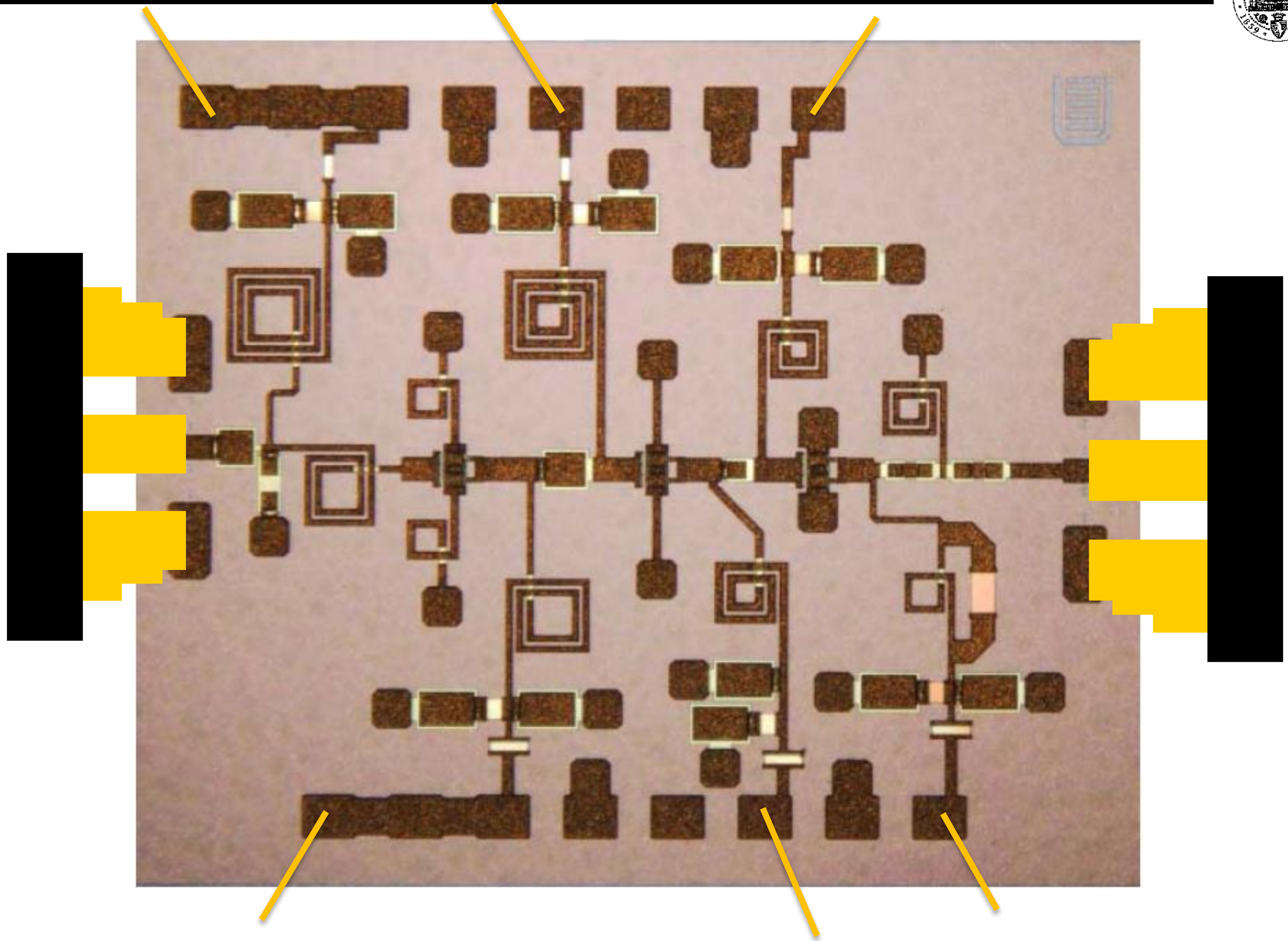
Example: hybrid balanced amplifier



GaN low-noise amplifier (LNA)



Coplanar RF probing + DC



GaAs integrated core-chip

A GaAs integrated core chip; in the left inset a scheme of the internal functional blocks is shown: (1) TX stage amplifier; (2) RX stage amplifier; (3) switch between the TX and RX stages; (4) 6-bit variable attenuator; (5) serial to parallel converter; (6) 6-bit phase shifter.