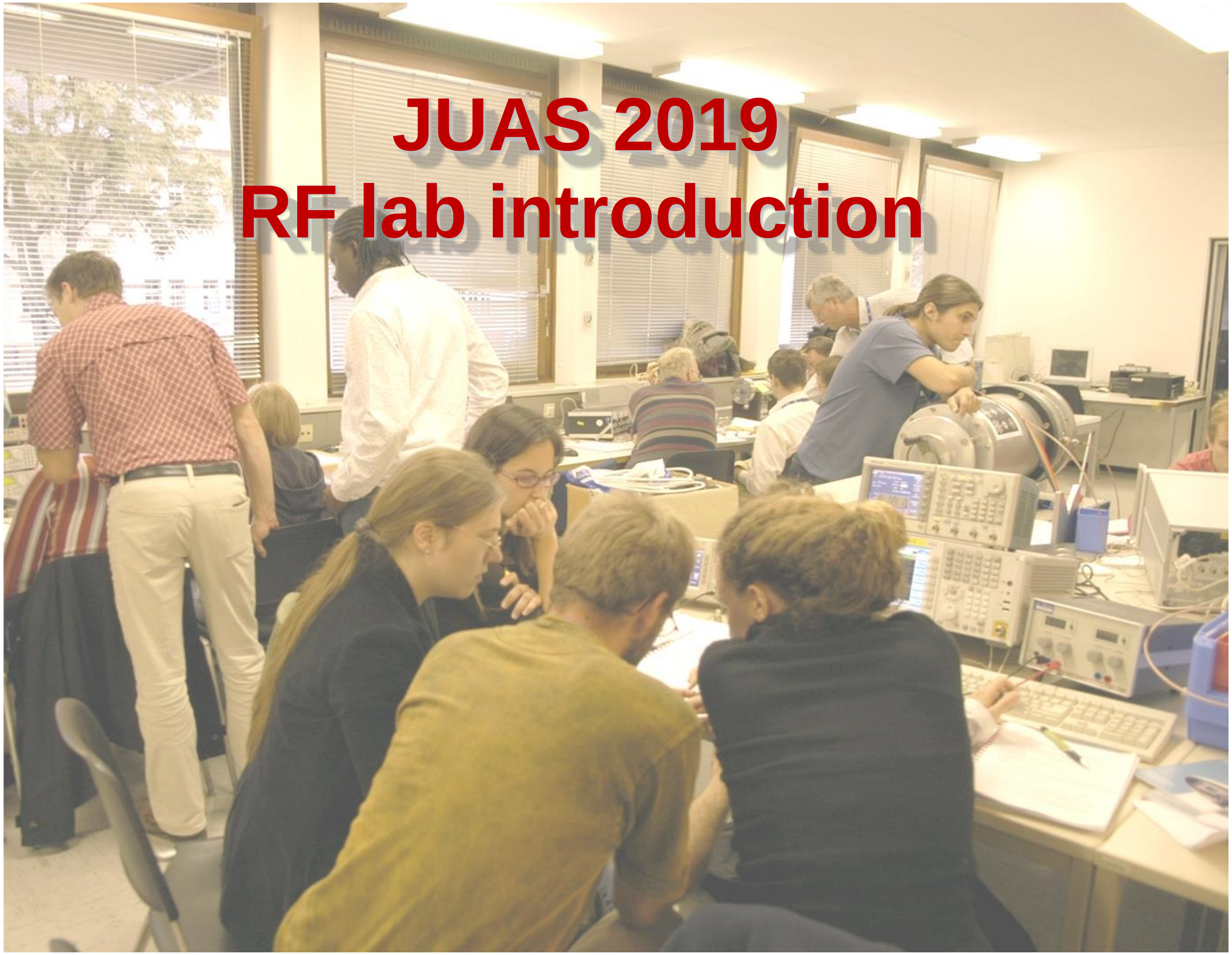

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RF lab introduction

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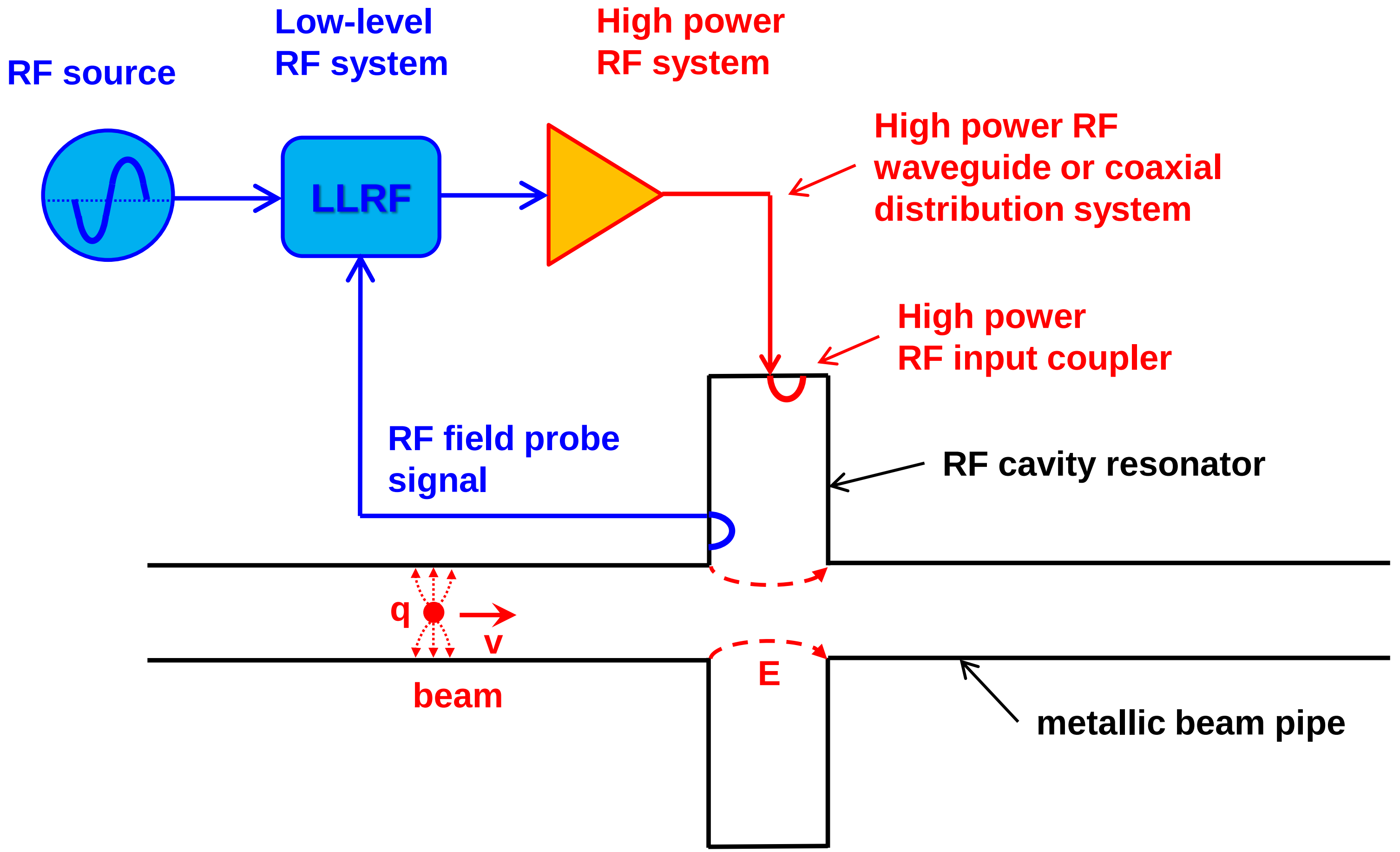
Contents

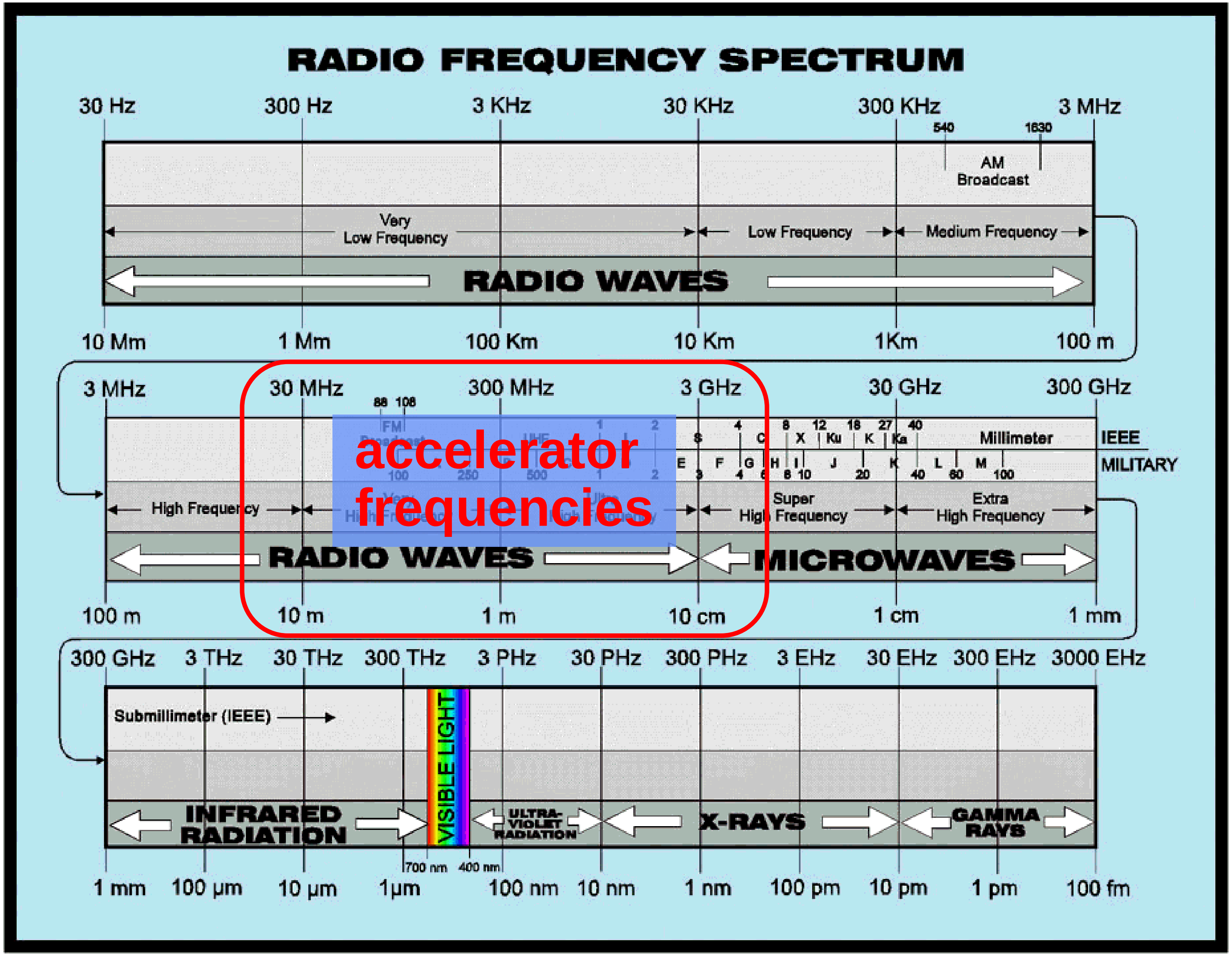
- RF measurement methods – overview
- The super-heterodyne concept
- Characteristic impedance
- Voltage Standing Wave Ratio (VSWR)
- Introduction to Scattering-parameters (S-parameters)
- The Smith chart
- What awaits you?!

Introduction – Simple RF System



Things get a bit more complicated in the real world: pulsed power RF, multi-cell resonators or traveling wave structures, non-relativistic beams, HOM’s, etc.

What are Radio Frequencies?



Free space wavelength:

$$\boxed{\lambda = \frac{c_0}{f}}$$

We care about RF concepts if the physical dimensions of an apparatus is $> \lambda/10$

Measurement methods - overview (1)

There are many ways to observe RF signals. Here we give a brief overview of the five main tools we have at hand

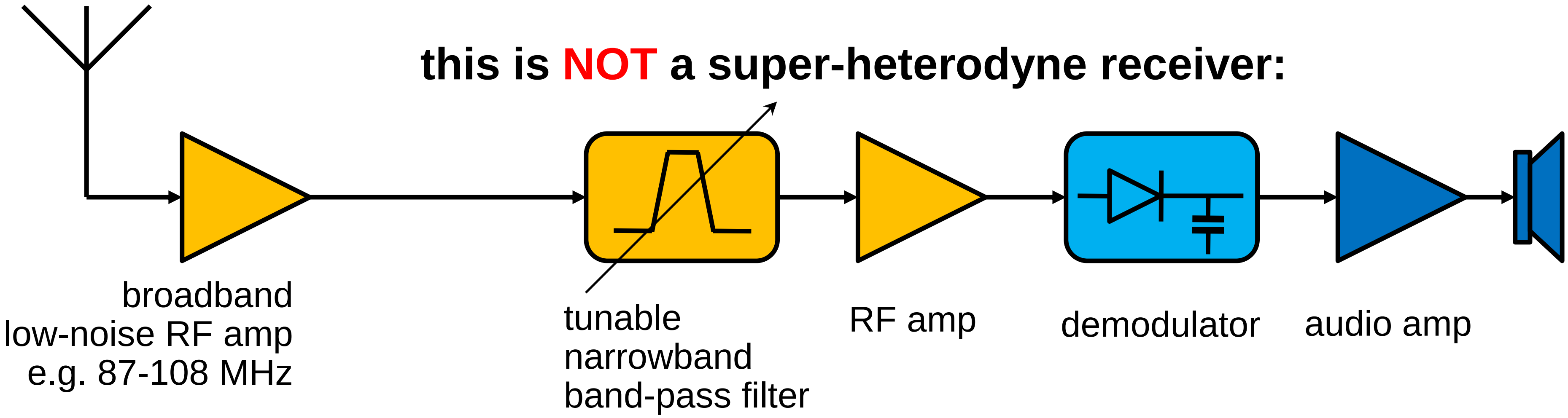
- Oscilloscope: to observe signals in time domain
  - periodic signals
  - burst signal
  - application: direct observation of signal from a pick-up, shape of common 230 V mains supply voltage, etc.

- Spectrum analyser: to observe signals in frequency domain
  - sweeps through a given frequency range point by point
  - application: observation of spectrum from the beam or of the spectrum emitted from an antenna, etc.

Measurement methods - overview (2)

- Dynamic signal analyzer (FFT analyzer)
  - Acquires signal in time domain by fast sampling
  - Further numerical treatment in digital signal processors (DSPs)
  - Spectrum calculated using Fast Fourier Transform (FFT)
  - Combines features of a scope and a spectrum analyzer: signals can be looked at directly in time domain or in frequency domain
  - Contrary to the SPA, also the spectrum of non-repetitive signals and transients can be observed
  - Application: Observation of tune sidebands, transient behavior of a phase locked loop, etc.
- Coaxial measurement line
  - old fashion method – no more in use but good for understanding of concept
- Network analyzer
  - Excites a network (circuit, antenna, amplifier or similar) at a given CW frequency and measures response in magnitude and phase => determines S-parameters
  - Covers a frequency range by measuring step-by-step at subsequent frequency points
  - Application: characterization of passive and active components, time domain reflectometry by Fourier transforming reflection response, etc.

The Super-Heterodyne Receiver (1)



this is NOT a super-heterodyne receiver:

broadband
low-noise RF amp
e.g. 87-108 MHz

tunable
narrowband
band-pass filter

RF amp

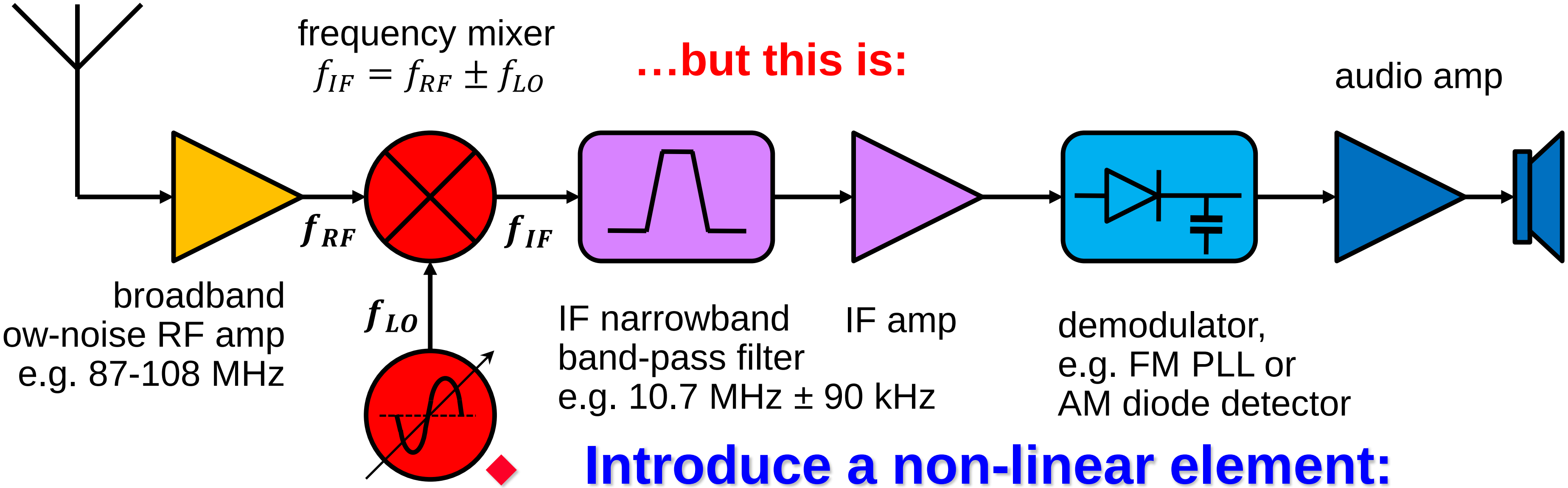
demodulator

audio amp

- …or: ’How does a ”traditional” analog radio works?
  - It was, and still is, difficult to make precisely tunable narrowband, band-pass filters for high frequencies (~100 MHz)!!
  - high frequency low-noise amplifiers are expensive!
  - high frequency demodulators are not trivial.

  - direct detection of radio and RF signals is challenging!

The Super-Heterodyne Receiver (2)



frequency mixer
$f_{IF} = f_{RF} \pm f_{LO}$

…but this is:

audio amp

f_{RF}

f_{IF}

f_{LO}

broadband
low-noise RF amp
e.g. 87-108 MHz

IF narrowband
band-pass filter
e.g. 10.7 MHz ± 90 kHz

IF amp

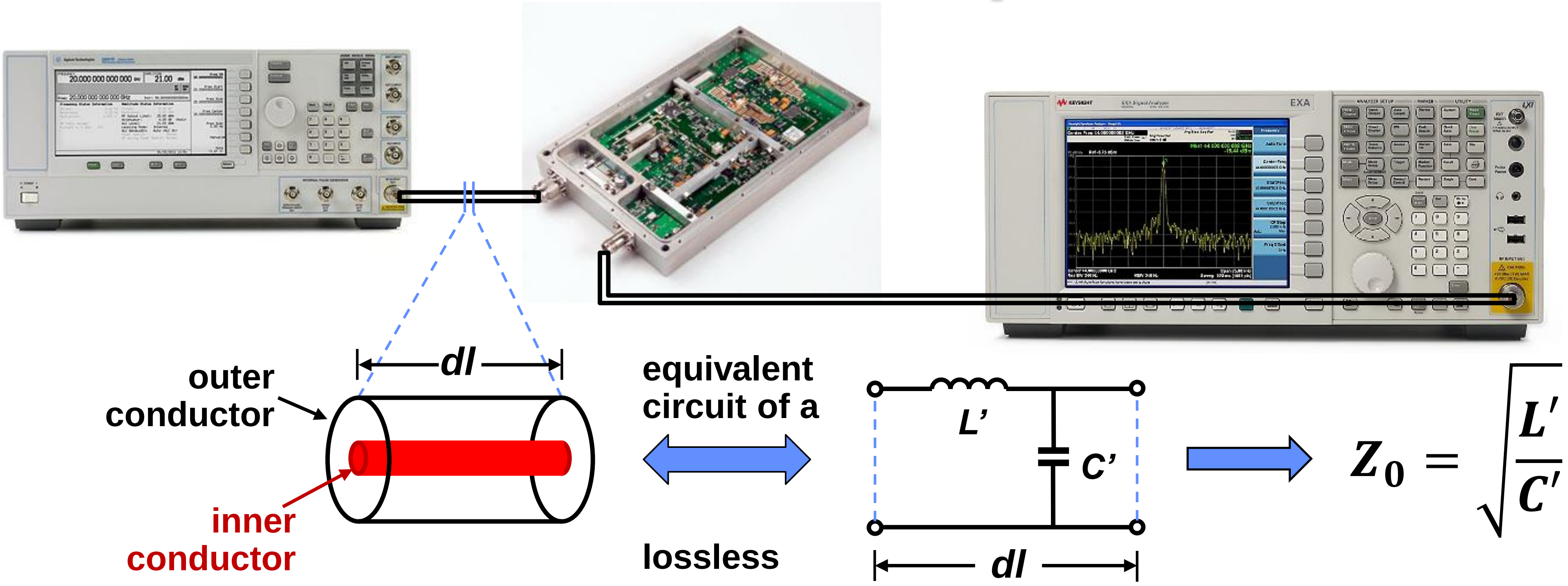
demodulator,
e.g. FM PLL or
AM diode detector

tunable
local oscillator (LO)
e.g. 97.7-118.7 MHz

Introduce a non-linear element: the (frequency) mixer!

- **”down-convert” the RF band to a fixed ”intermediate” frequency (IF)** $f_{IF} = f_{RF} \pm f_{LO}$
- **requires a tunable local oscillator (LO)**
- **well manageable IF section:**
  - **narrowband band-pass filter(s) (BPF) and amplifier(s)**
- **RF telecommunication standard**
- **Often multiple mixing stages are used in modern RF instruments, line spectrum analyzers**

Characteristic Impedance



outer conductor

dl

inner conductor

equivalent circuit of a lossless TEM transmission-line

L'

C'

dl

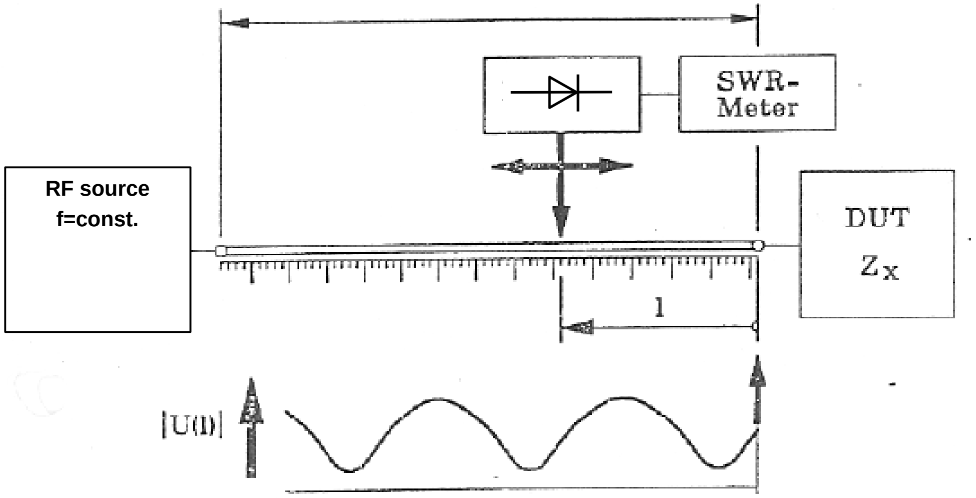
$$Z_0 = \sqrt{\frac{L'}{C'}}$$

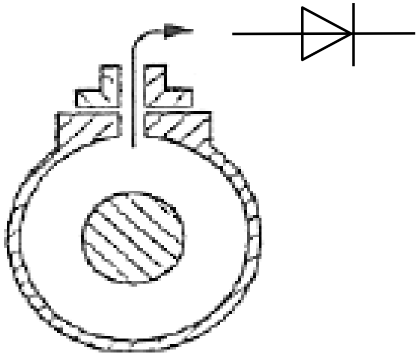
- **The reference impedance Z_0 in a RF system is defined by the characteristic impedance of the interconnect cables**
  - often coaxial cables of Z_0=50Ω (compromise: high voltage / high power handling)
- **The characteristic impedance of a TEM transmission-line is defined by the cross-section geometry**
  - Ratio of H- and E-field, represented by *L'* [H/m] and *C'* [F/m] in the equivalent circuit of a line segment *dl*
  - The characteristic impedance Z_0 has the unit Ohm [Ω]

Voltage Standing Wave Ratio VSWR

- **On a transmission-line (single frequency, CW):**
  - Superposition of forward *a* (E^{inc}) and backward *b* (E^{refl}) traveling waves
    ⇒ standing waves
- **Slotted coaxial air-line is used as standing wave detector**
  - Probes the radial electric field along the slotted line.
  - Measurement of E-field minima's E_{min} and maxima's E_{max} with a diode detector, thus detect $|V_{min}|$ and $|V_{max}|$ along the line.
  - Evaluate the reflection coefficient Γ
    of a DUT of unknown Z_L at the end of the line

$$\Gamma = \frac{E^{\mathrm{refl}}}{E^{\mathrm{inc}}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

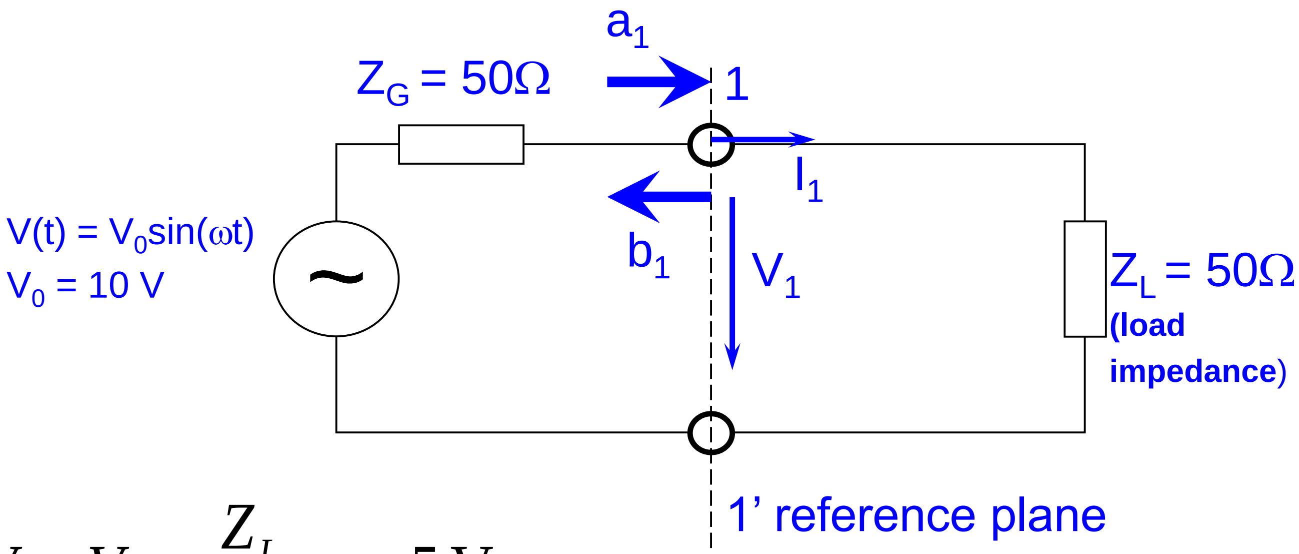




S-Parameters – Introduction

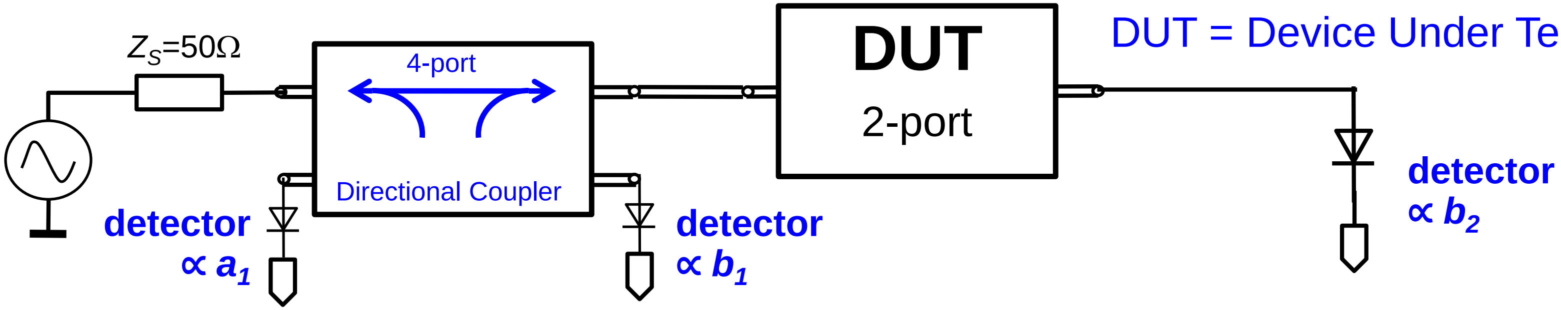
- **Light falling on a car window:**
  - Some parts of the incident light is reflected (you see the mirror image)
  - Another part of the light is transmitted through the window (you can still see inside the car)
- **Optical reflection and transmission coefficients of the window glass define the ratio of reflected and transmitted light**
- **Similar:**
  Scattering (S-) parameters of an *n*-port electrical network (DUT) characterize reflected and transmitted (power) waves

Simple example: a generator with a load



- Voltage divider: $V_1 = V_0 \dfrac{Z_L}{Z_L + Z_G} = 5\,\mathrm{V}$
- This is the matched case i.e. $Z_G = Z_L$.
  -> forward traveling wave only, no reflected wave.
- Amplitude of the forward traveling wave in this case is V_1=5V;
  forward power = $25V^2/50\Omega = 0.5W$
- Matching means maximum power transfer from a generator with given source impedance to an external load

How to measure S-Parameters?



Performed in the frequency domain

- Single or swept frequency generator, stand-alone or as part of a VNA or SA
- Requires a directional coupler and RF detector(s) or receiver(s)

Evaluate S_{11} and S_{21} of a 2-port DUT

- Ensure $a_2=0$, i.e. the detector at port 2 offers a well matched impedance
- Measure incident wave a1 and reflected wave b1 at the directional coupler ports and compute for each frequency
- Measure transmitted wave b_2 at DUT port 2 and compute

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

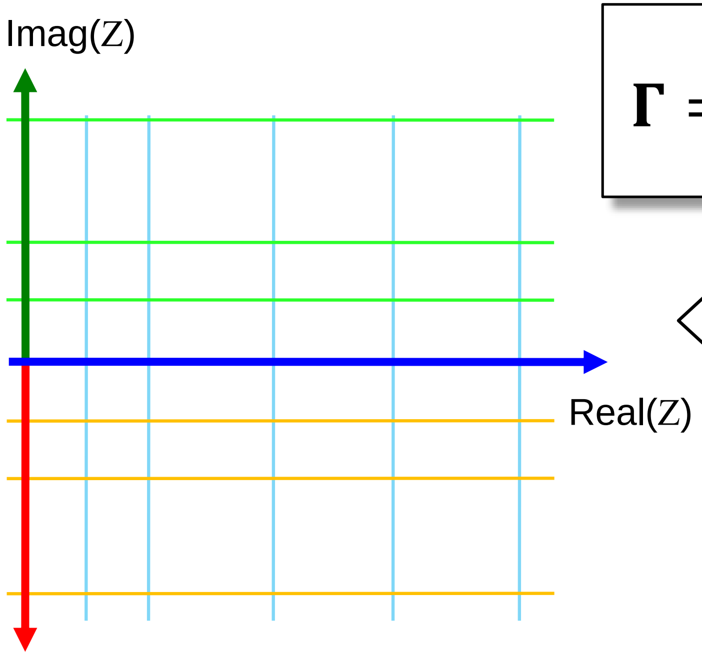
Evaluate S_{22} and S_{12} of the 2-port DUT

- Perform the same methodology as above by exchanging the measurement equipment on the DUT ports

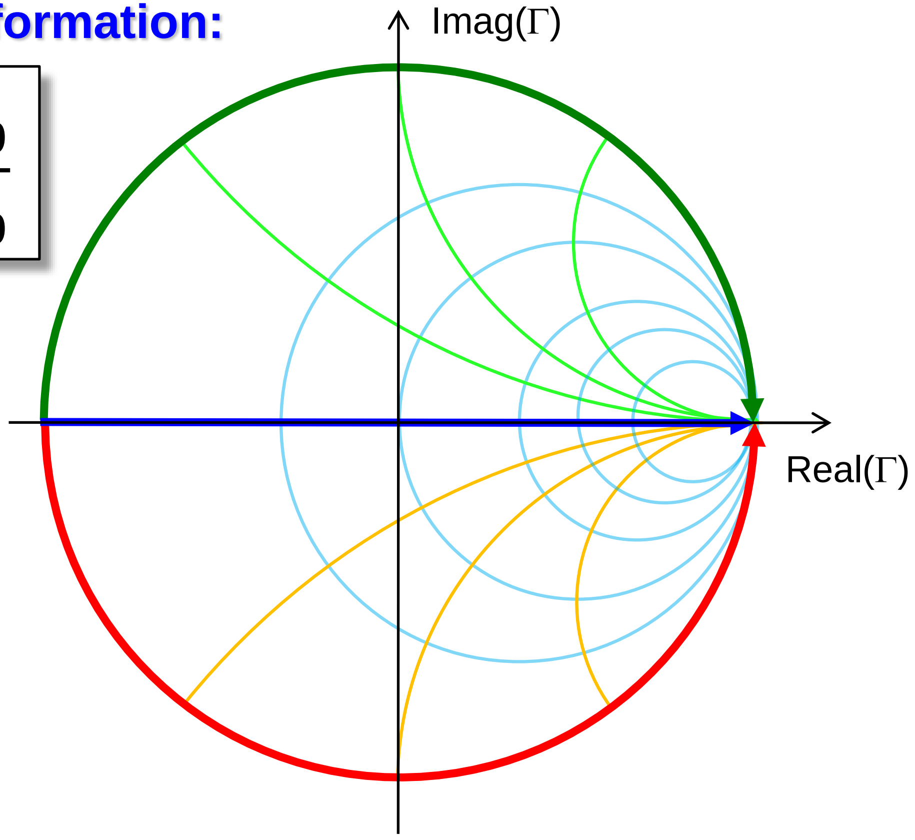
The *Smith* Chart (1)

- The *Smith* Chart (in impedance coordinates) represents the complex Γ-plane within the unit circle.
- It is a conformal mapping of the complex *Z*-plane on the Γ-plane by applying the transformation:

$$\boxed{\Gamma = \frac{Z - Z_0}{Z + Z_0}}$$

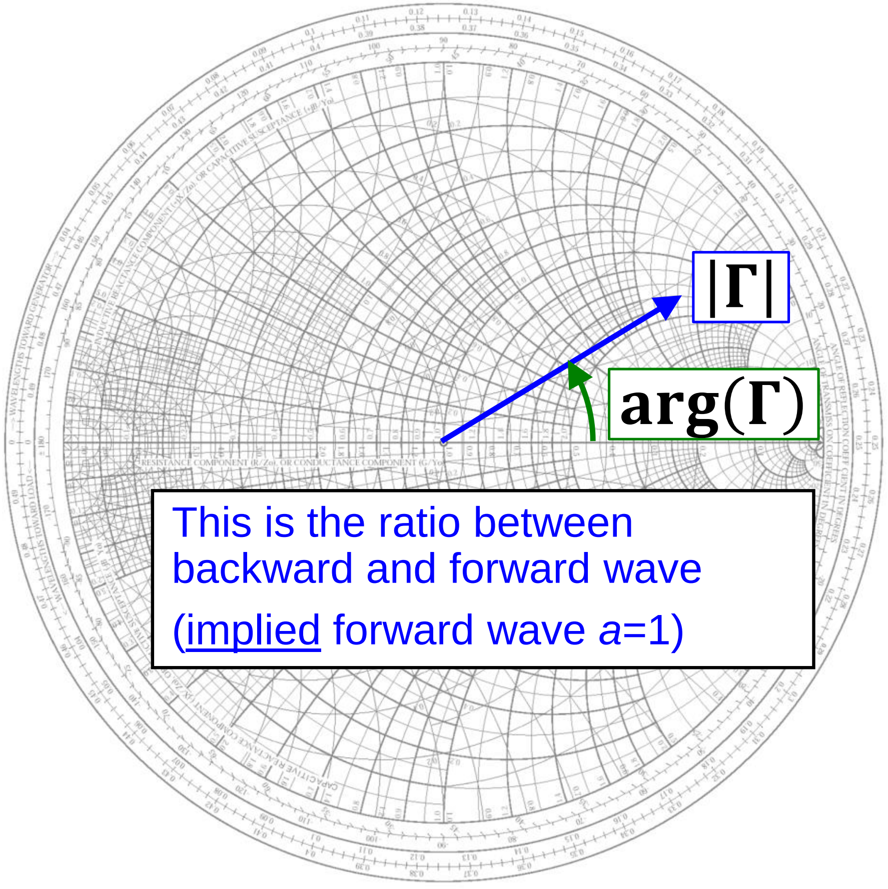


$\Leftrightarrow$



- ⇒ the real positive half plane of *Z* is thus transformed (*Möbius*) into the interior of the unit circle!

The *Smith* Chart (2)



This is the ratio between backward and forward wave

(implied forward wave *a*=1)

- **In the *Smith* chart, the complex reflection factor**

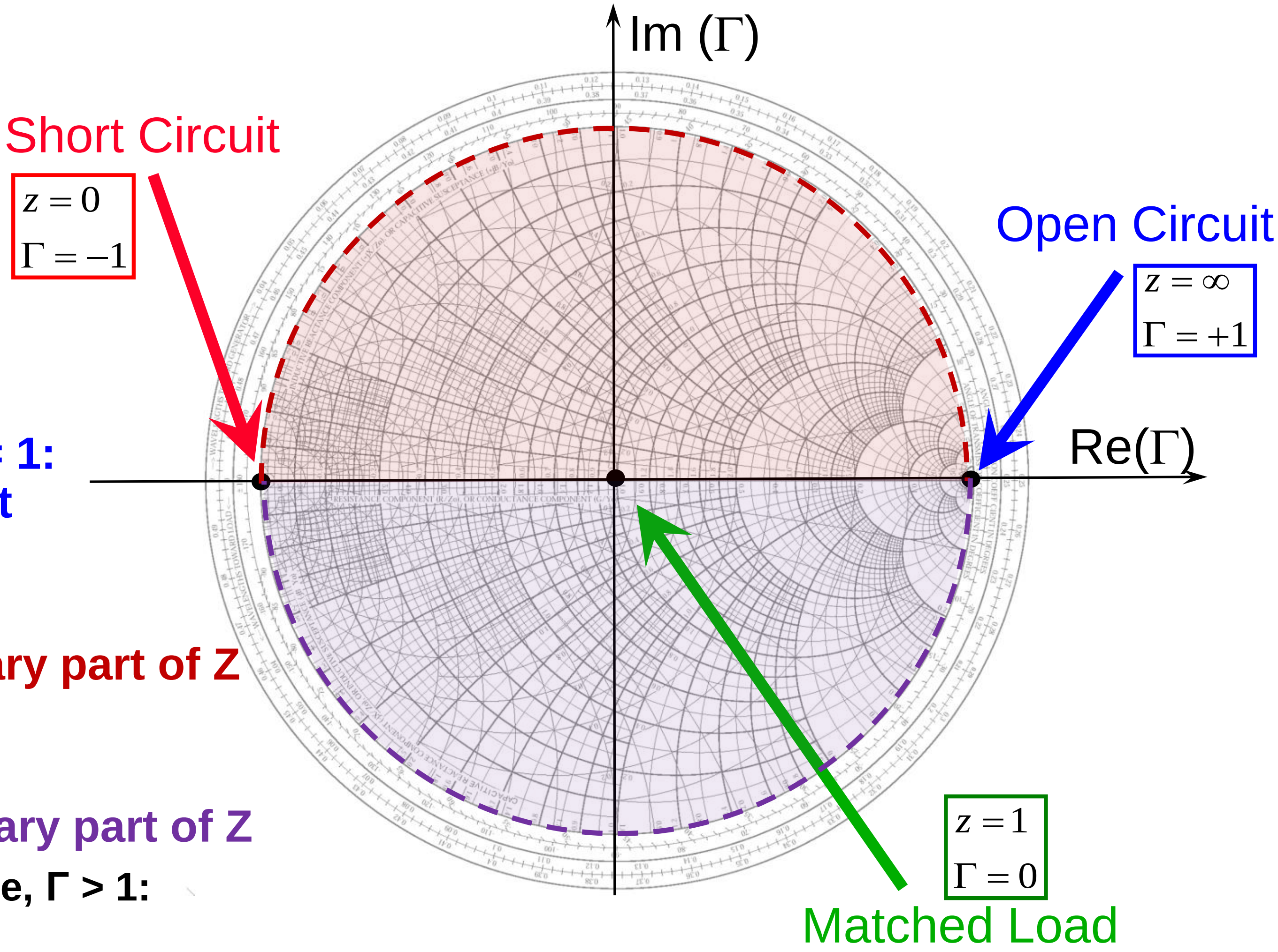
$$\Gamma = |\Gamma| e^{j\varphi} = \frac{b}{a}$$

is expressed in linear cylindrical coordinates, representing the ratio of backward vs. forward traveling waves.

The *Smith* Chart – “Important Points”

Important Points:

- **Short Circuit**
  $\Gamma = -1$, $z = 0$
- **Open Circuit**
  $\Gamma = +1$, $z \to \infty$
- **Matched Load**
  $\Gamma = 0$, $z = 1$
- **On the circle $\Gamma = 1$:**
  lossless element
- **Upper half:**
  ”inductive” =
  positive imaginary part of Z
- **Lower half:**
  ”capacitive” =
  negative imaginary part of Z
  - **Outside the circle, $\Gamma > 1$:**
    active element,
    for instance tunnel diode reflection amplifier



What awaits you?

Photos from RF-Lab
CAS 2009,
Darmstadt

Measurements using Spectrum Analyzer and oscilloscope (1)

- Measurements of several types of modulation (AM, FM, PM) in the time-domain and frequency-domain.
- Superposition of AM and FM spectrum (unequal height side bands).
- Concept of a spectrum analyzer: the superheterodyne method. Practice all the different settings (video bandwidth, resolution bandwidth etc.). Advantage of FFT spectrum analyzers.
- Measurement of the RF characteristic of a microwave detector diode (output voltage versus input power... transition between regime output voltage proportional input power and output voltage proportional input voltage); i.e. transition between square low and linear region.
- Concept of noise figure and noise temperature measurements, testing a noise diode, the basics of thermal noise.
- Noise figure measurements on amplifiers and also attenuators.
- The concept and meaning of ENR (excess noise ratio) numbers.

Measurements using Spectrum Analyzer and oscilloscope (2)

- EMC measurements (e.g.: analyze your cell phone spectrum).
- Noise temperature of the fluorescent tubes in the RF-lab using a satellite receiver.
- Measurement of the IP3 (intermodulation point of third order) on some amplifiers (intermodulation tests).
- Nonlinear distortion in general; Concept and application of vector spectrum analyzers, spectrogram mode (if available).
- Invent and design your own experiment !

Measurements using Vector Network Analyzer (1)

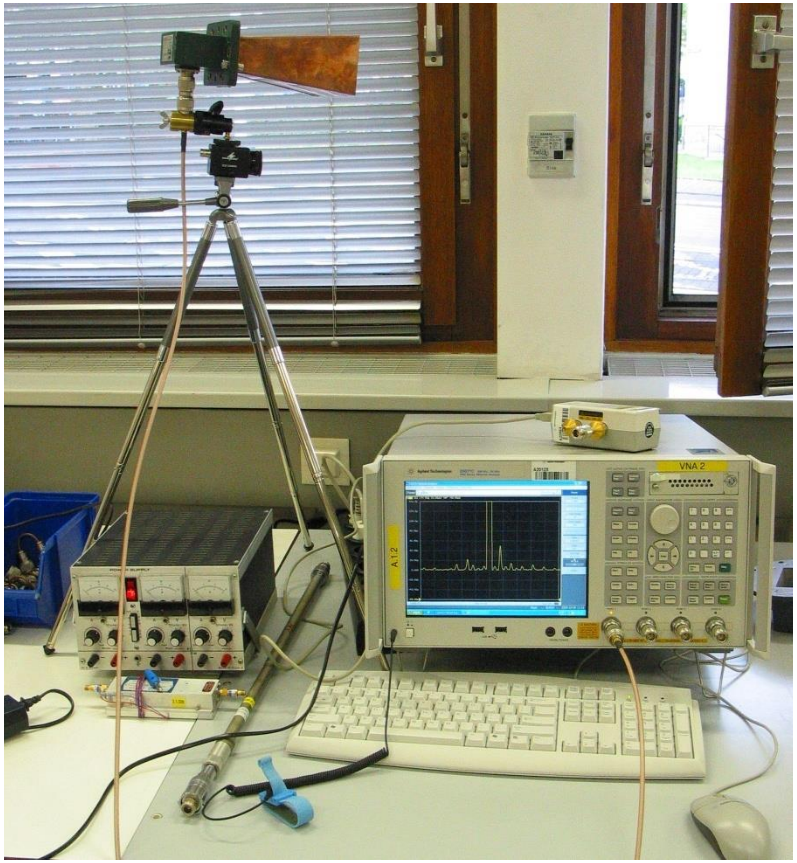
- N-port (N=1…4) S-parameter measurements on different reciprocal and non-reciprocal RF-components.
- Calibration of the Vector Network Analyzer.
- Navigation in The Smith Chart.
- Application of the triple stub tuner for matching.
- Time Domain Reflectometry using synthetic pulse →direct measurement of coaxial line characteristic impedance.
- Measurements of the light velocity using a trombone (constant impedance adjustable coax line).
- 2-port measurements for active RF-components (amplifiers):
  1 dB compression point (power sweep).
- Concept of EMC measurements and some examples.

Measurements using Vector Network Analyzer (2)

- Measurements of the characteristic cavity properties (Smith Chart analysis).
- Cavity perturbation measurements (bead pull).
- Beam coupling impedance measurements with the wire method (some examples).
- Beam transfer impedance measurements with the wire (button PU, stripline PU.)
- Self made RF-components: Calculate build and test your own attenuator in a SUCO box (and take it back home then).
- Invent and design your own experiment!
  (as time allows…)

Invent your own experiment!

Build e.g. Doppler traffic radar
(this really worked in practice during
CAS 2009 RF-lab)



or „Tabacco-box” cavity

or test a resonator of any other type.

You will have enough time to think

and have a contact with hardware and your colleges.

We hope you will have a lot of fun…