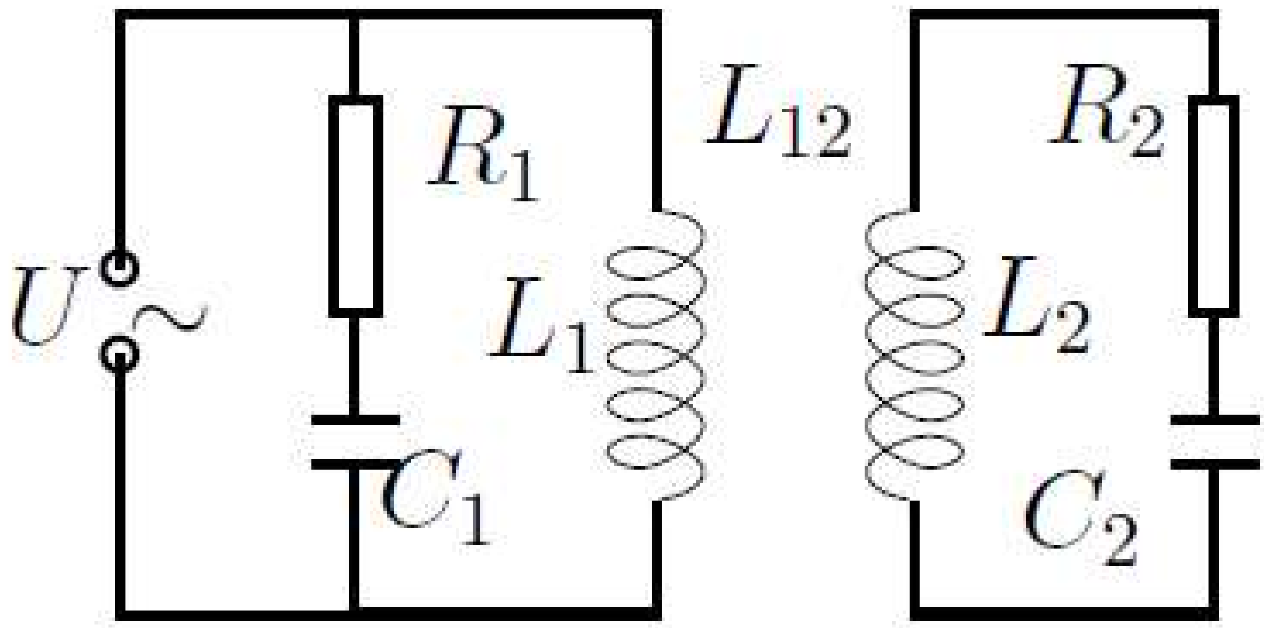
Basics of radio astronomy III

Assistent Professor for Astronomy
Dr. Jürgen Kerp
Bonn University

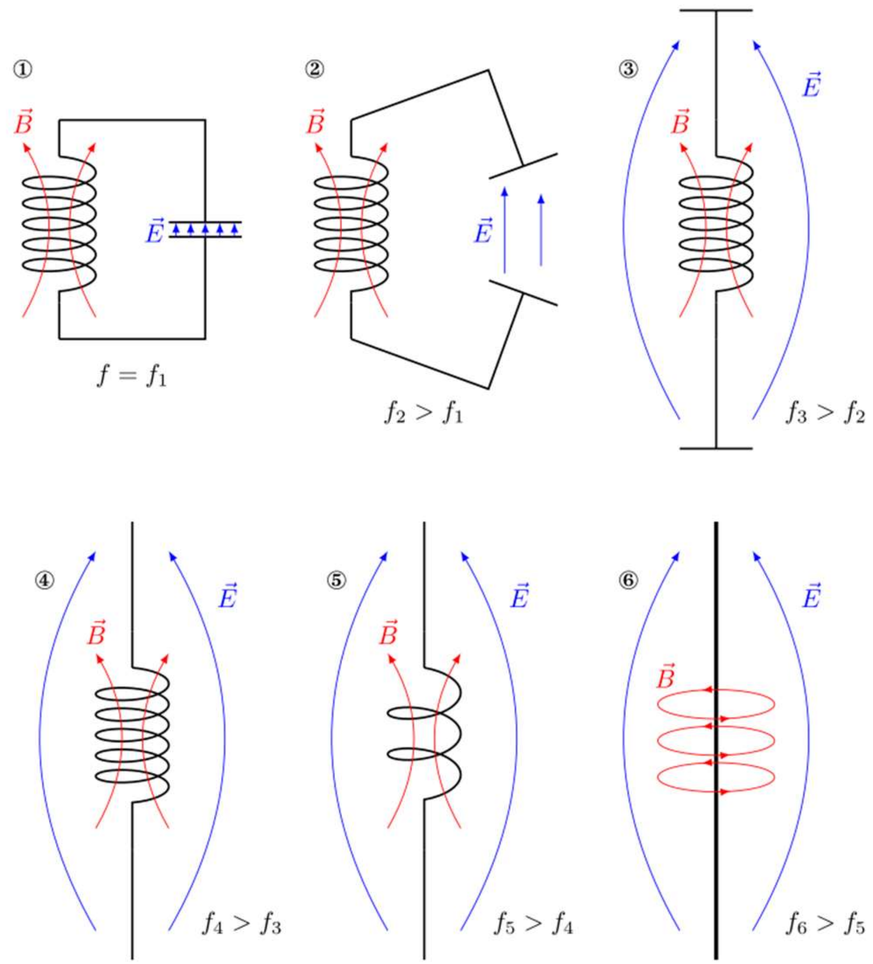
UNIVERSITÄT BONN

Forces oscillation



Astronomical source Telescope

Oscillating circuit



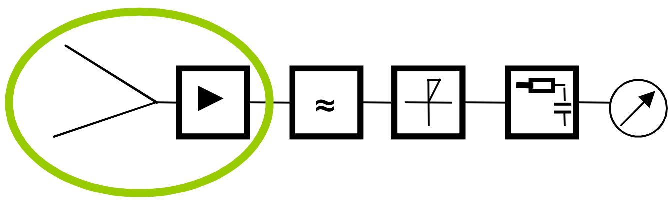
If we physically bend a resonant circuit apart, i.e. we increase the distance of the capacitor plates and decrease the inductance of the coil, we get from the resonant circuit to the Hertzian dipole.

$$\omega_0{}^2 = \frac{1}{LC} \qquad \delta = \frac{R}{2L}$$

Radiometer

http://www.cv.nrao.edu/course/astr534/Brightness.html
http://www.cv.nrao.edu/course/astr534/AntennaTheory.html

Radiometer



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

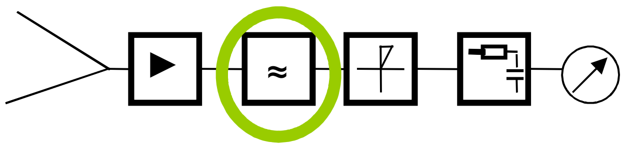
The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

Radiometer



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

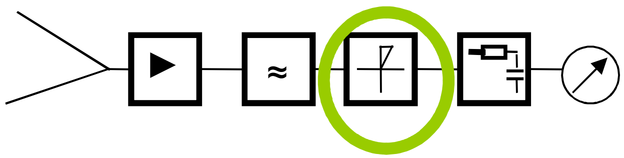
The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

UNIVERSITÄT BONN

Radiometer



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

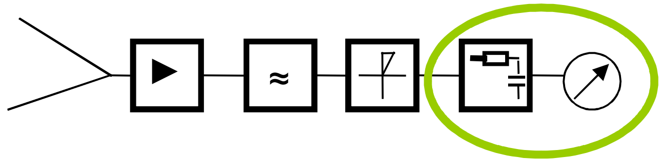
The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

Radiometer



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

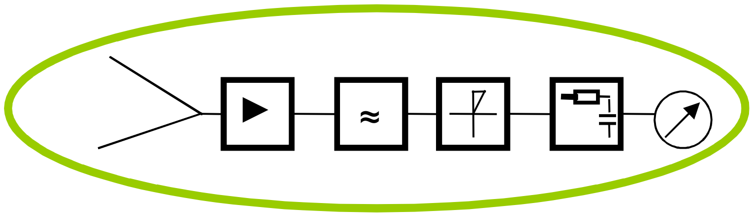
The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

UNIVERSITÄT BONN

Radiometer



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

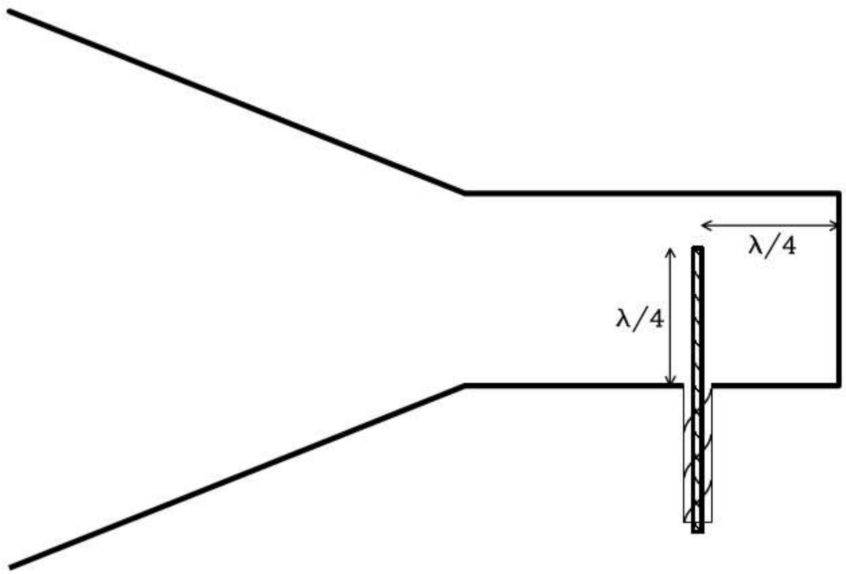
We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

UNIVERSITÄT BONN

Individual components of the radiometer

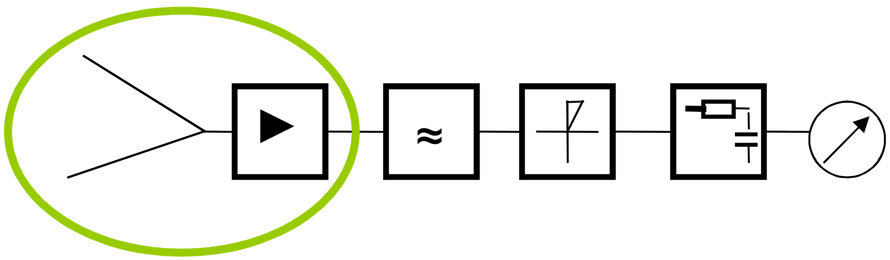
UNIVERSITÄT BONN

Feed



Most high-frequency feeds are quarter-wave ground-plane verticals inside waveguide horns. The only true antenna in this figure is the $\lambda/4$ ground-plane vertical, which converts electromagnetic waves in the waveguide to currents in the coaxial cable extending down from the waveguide.

Radiometer: Feed und Verstärker



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

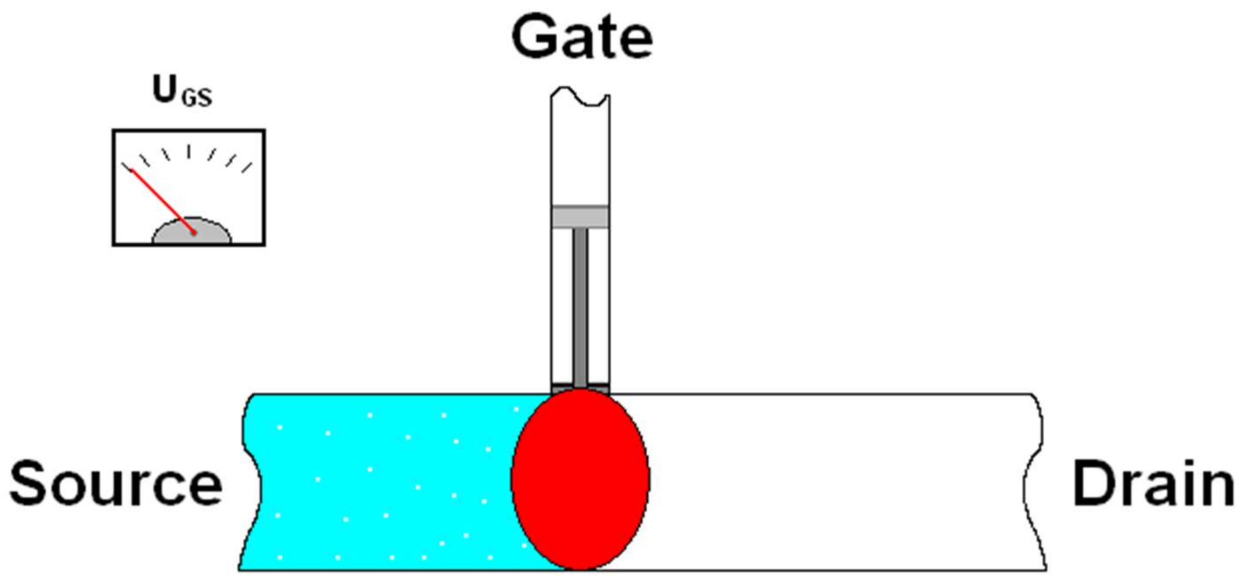
The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

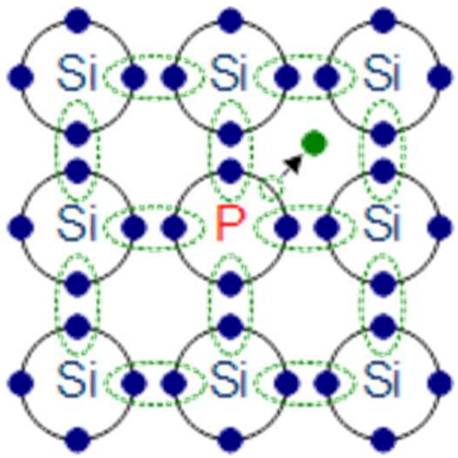
Amplifier: HEMT-Transistor



UNIVERSITÄT BONN

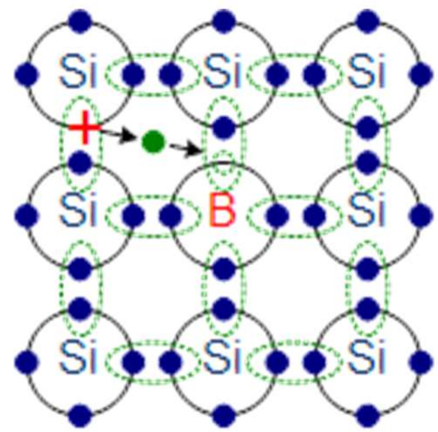
Semiconductors

Semiconductors



n-type doping

The phosphor sets its fiftth unbound electron free into the semiconductors structure. This electron has a high mobility in the crystal.



p-type doping

The free position in the boron atom attatracts electrons from its environment. Equivalent to a positive charge the free position can move freely in the crystal structure of the semiconductor.

Semicondutor

Main group

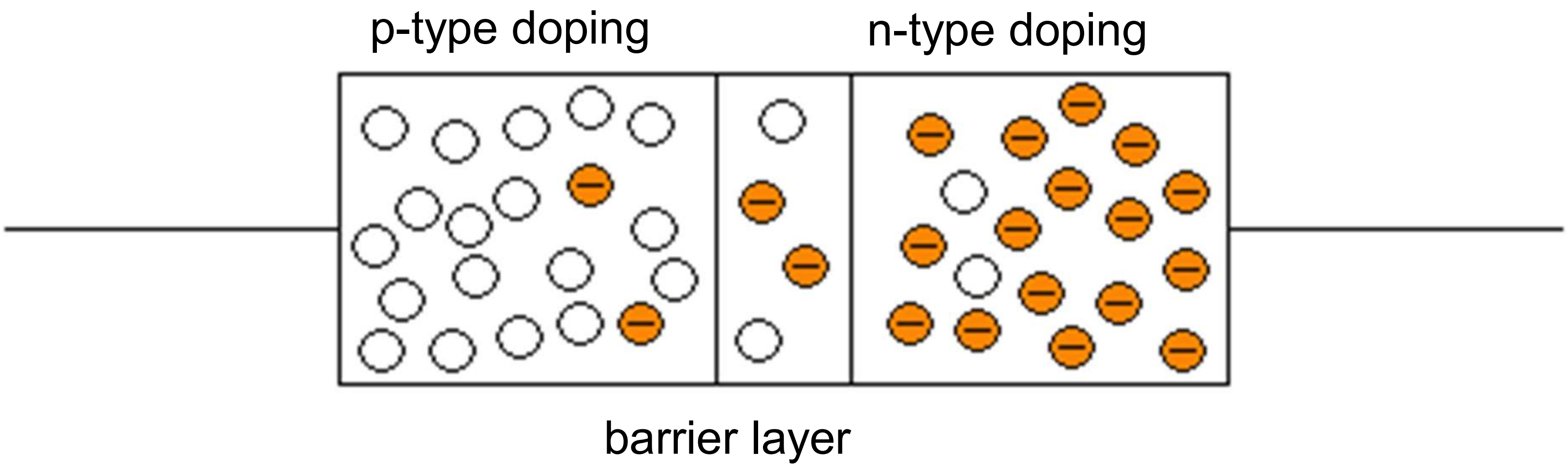
Periode	II	III	IV	V	VI
2	9,0 Be 4	10,8 B 5	12,0 C 6	14,0 N 7	16,0 O 8
3	24,3 Mg 12	27,0 Al 13	28,1 Si 14	31,0 P 15	32,1 S 16
4	40,1 Ca 20	69,7 Ga 31	72,6 Ge 32	74,9 As 33	79,0 Se 34
5	87,6 Sr 38	114,8 In 49	118,7 Sn 50	121,8 Sb 51	127,6 Te 52
6	137,3 Ba 56	204,4 Tl 81	207,2 Pb 82	209,0 Bi 83	209 Po 84

p-type doping →

← n-type doping

UNIVERSITÄT BONN

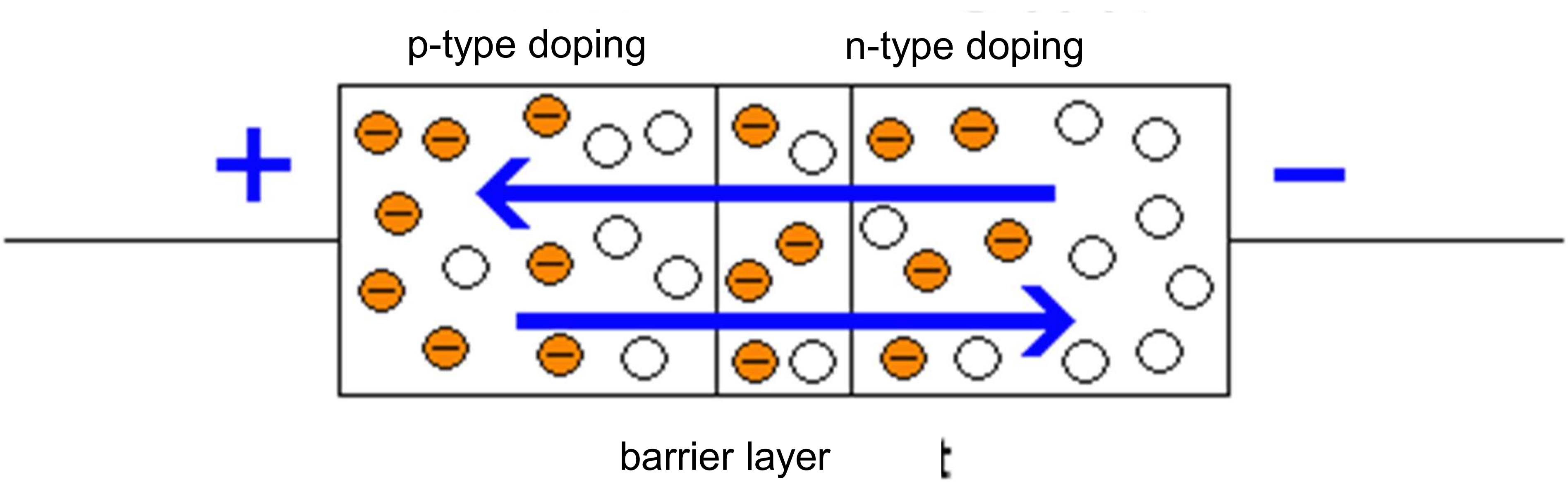
Semiconductor: Diode



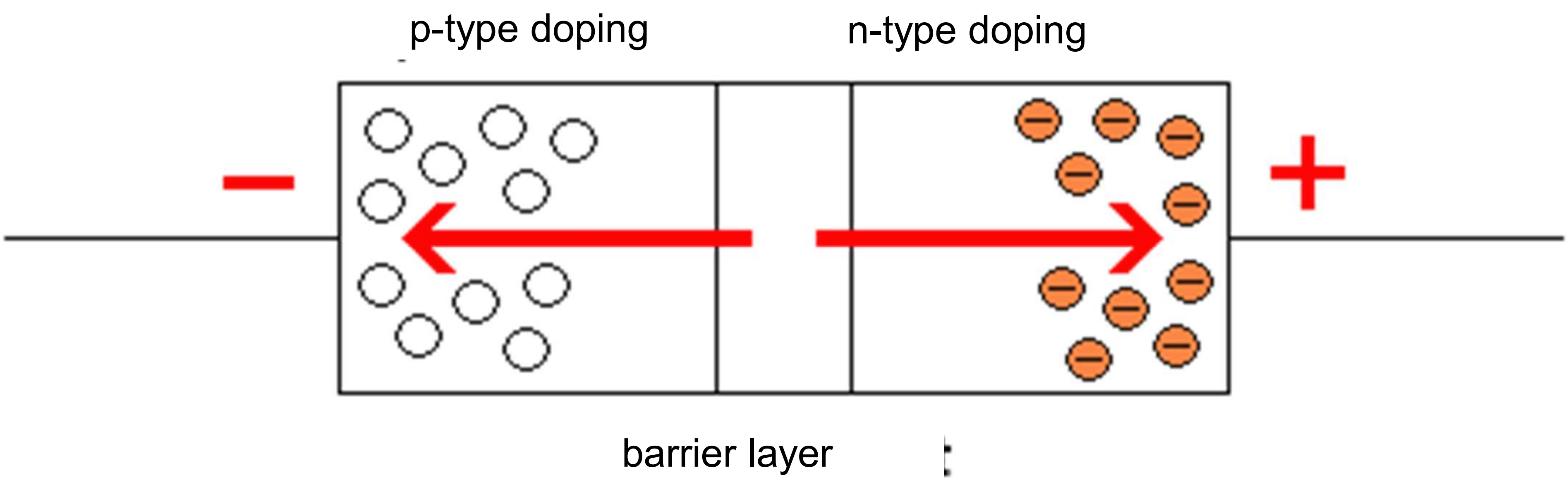
 p-type doping, positive charges can move freely

 n-type doping, free electrons

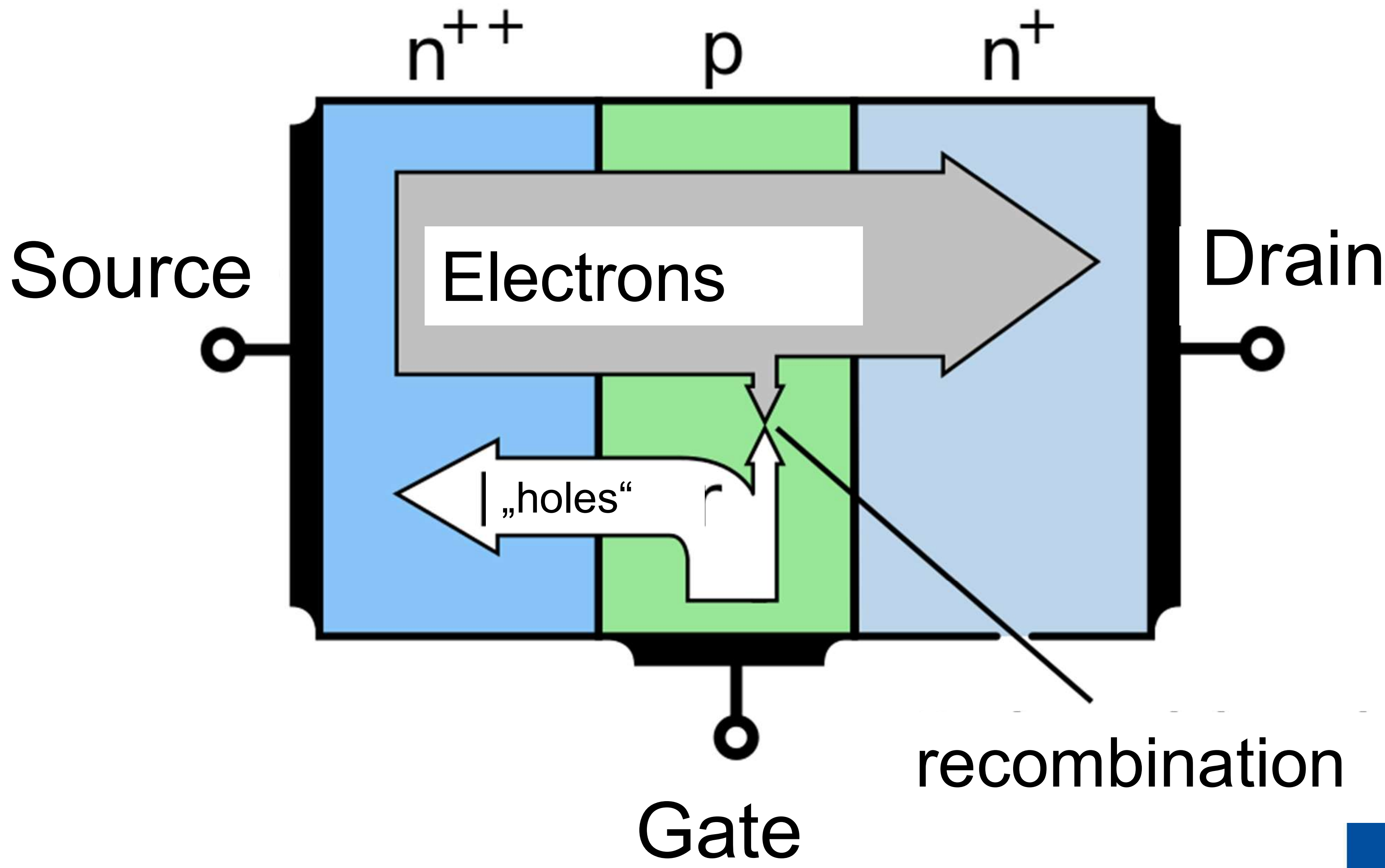
Diode: forward direction



Diode: reverse direction

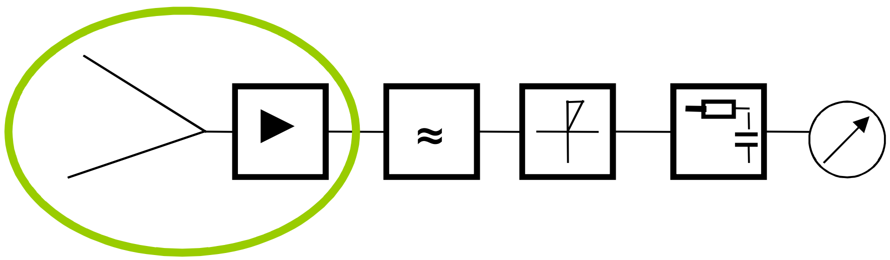


Transistor



UNIVERSITÄT BONN

Radiometer: Feed and amplifier



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

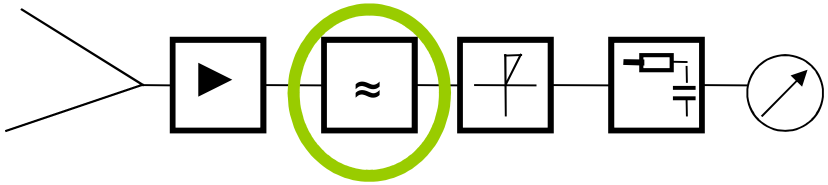
The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

Radiometer: bandpass



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

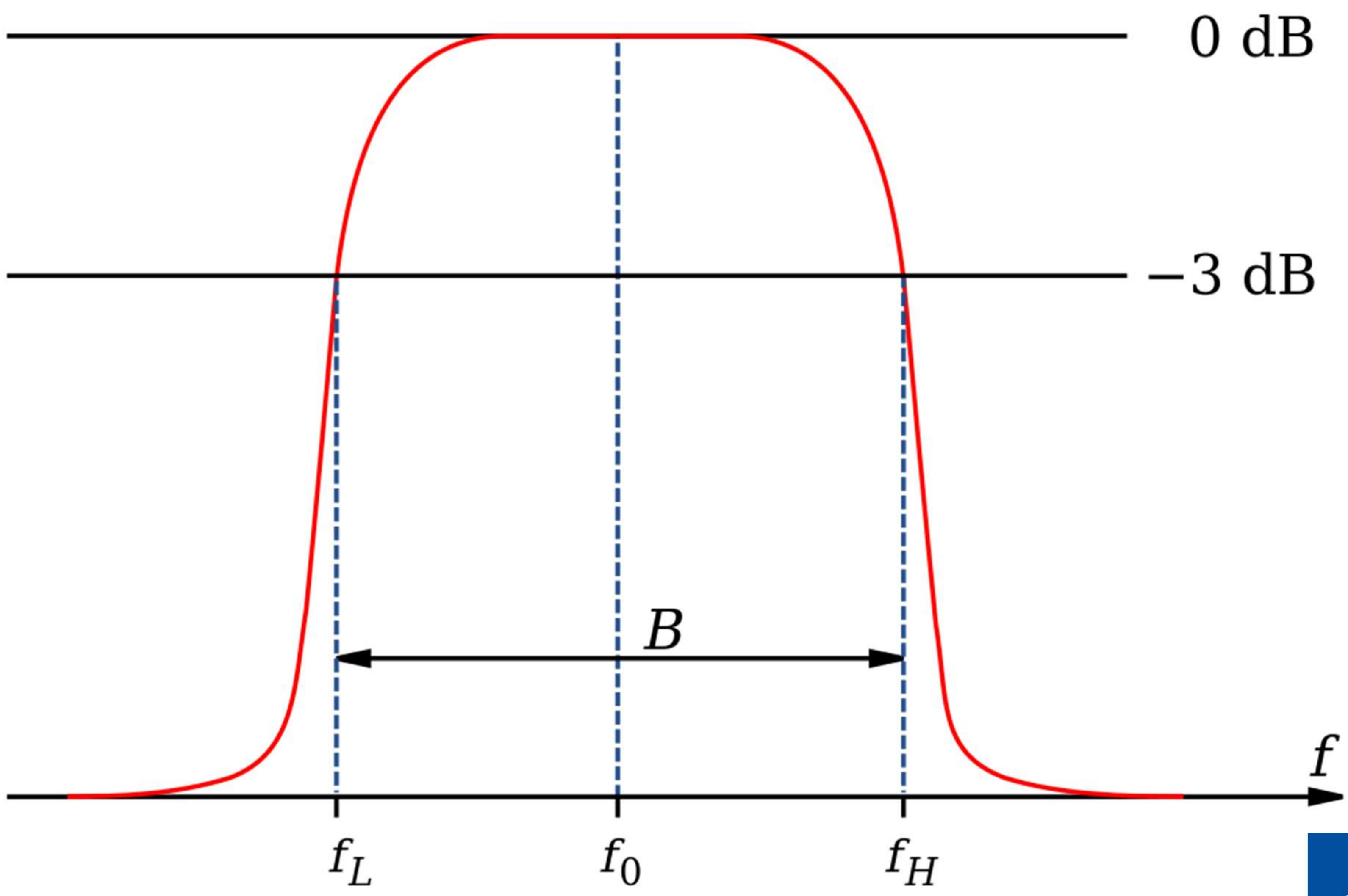
The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

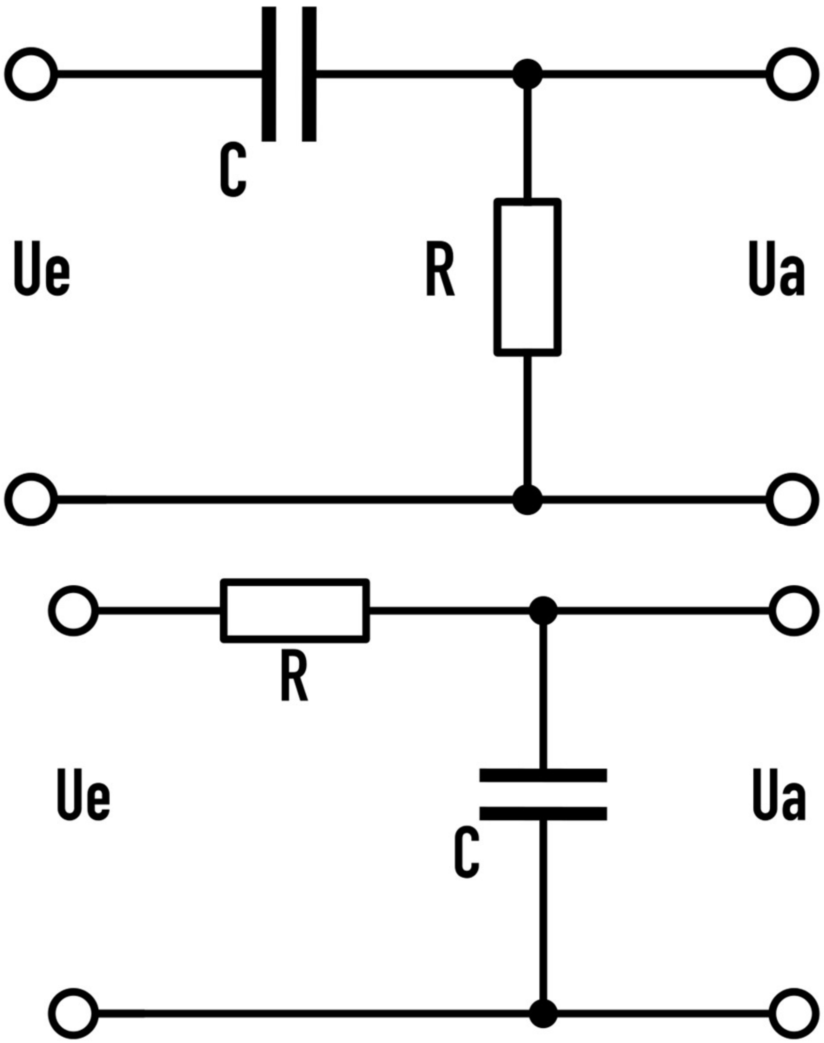
We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

Bandpass



UNIVERSITÄT BONN

Bandpass



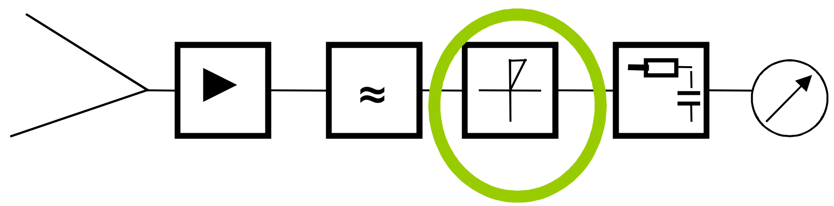
Top: High pass filter, this only allows frequencies above a frequency threshold to pass.

Bottom: Low pass filter, this one lets frequencies pass only below a frequency threshold.

The combination of both filter types is a bandpass filter.

UNIVERSITÄT BONN

Radiometer: Diode



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

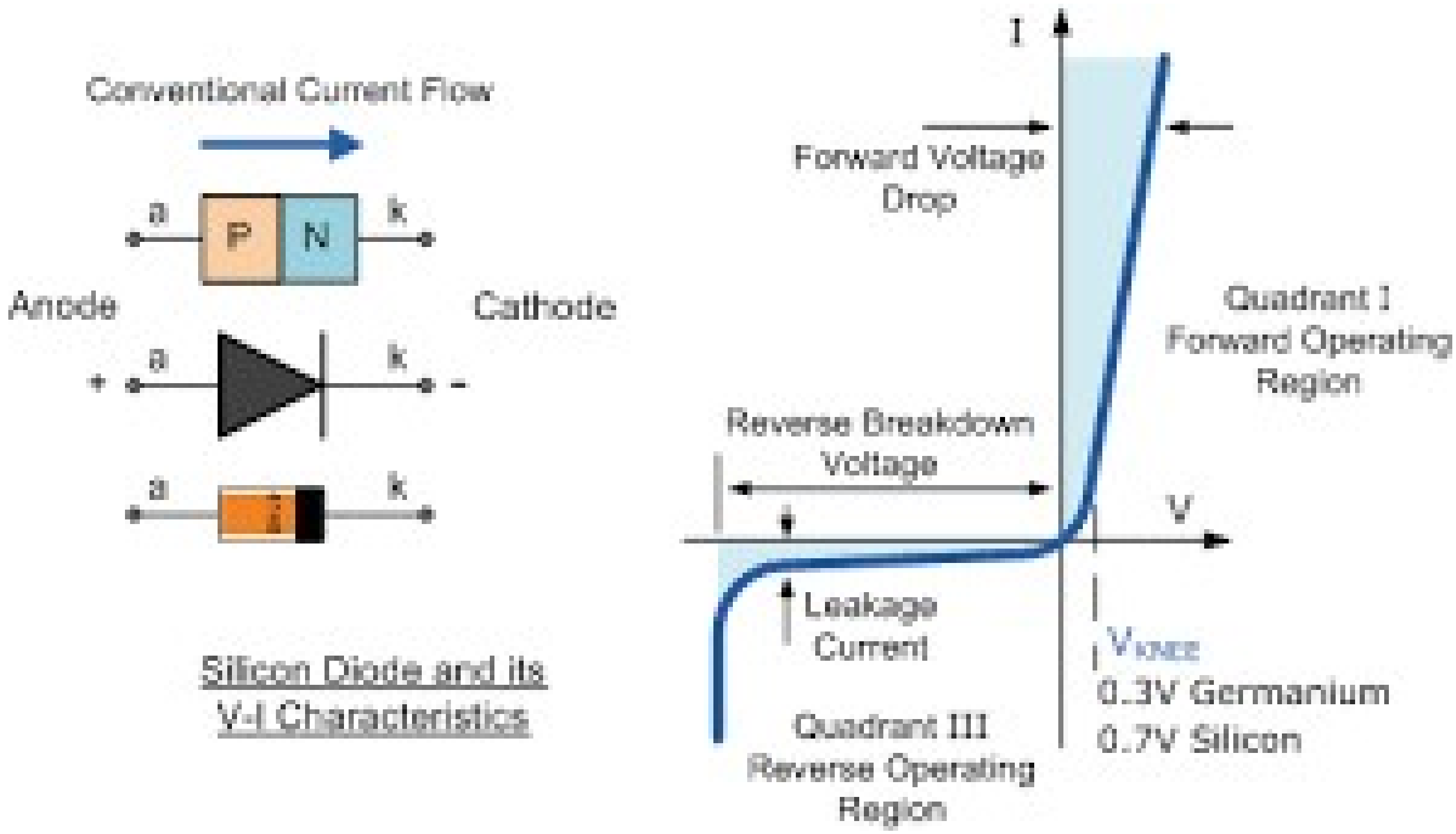
The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

UNIVERSITÄT BONN

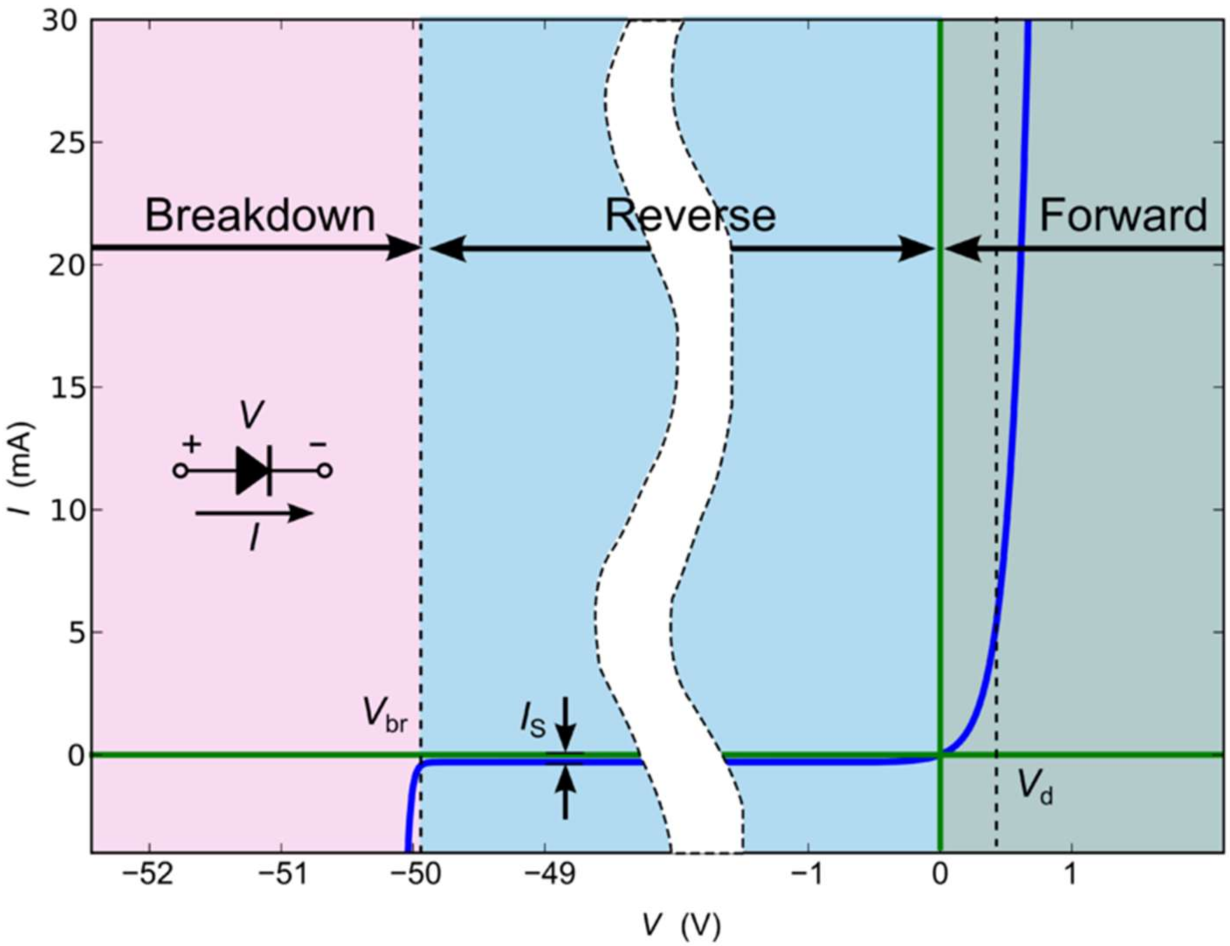
Diode



UNIVERSITÄT BONN

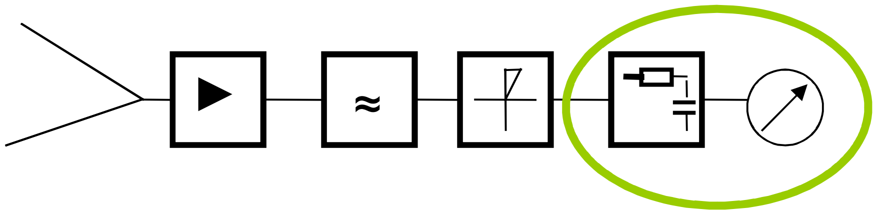
Diode

http://www.wikipedia.org



UNIVERSITÄT BONN

Radiometer: Integrator



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

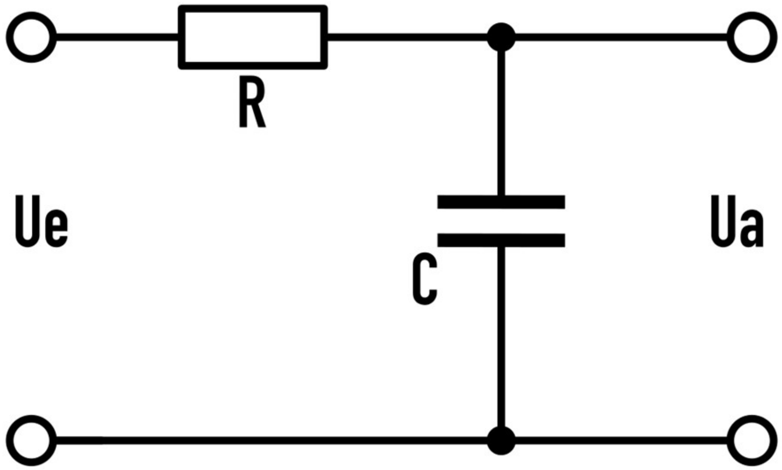
The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

UNIVERSITÄT BONN

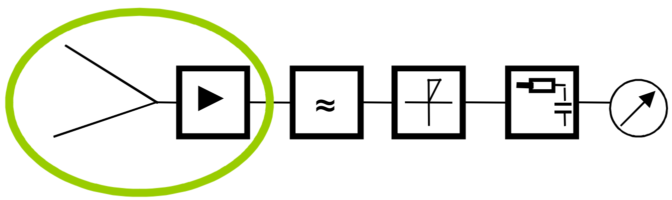
Integrator

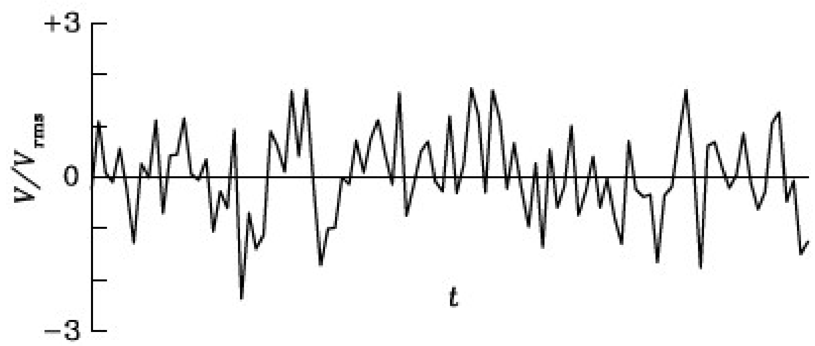


The integrator is a low pass filter with a very large time constant. In practice, the charges transferred from the diode to the integrator are stored on the capacitor. Then the amount of charge collected in the integration time is read out.

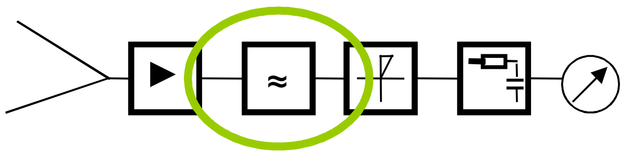
Radiometer graphically

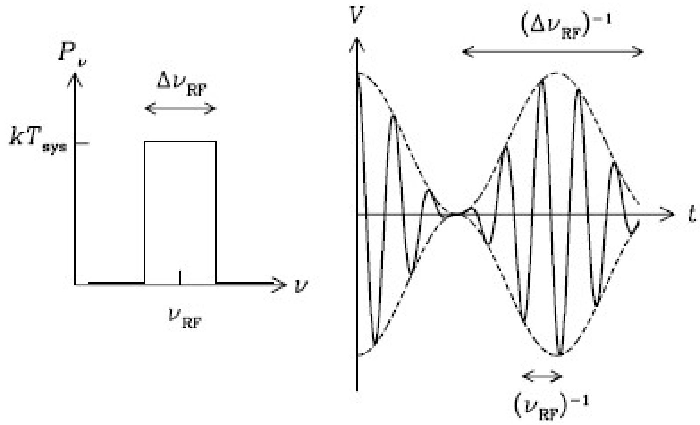
Radiometer - Amplifier



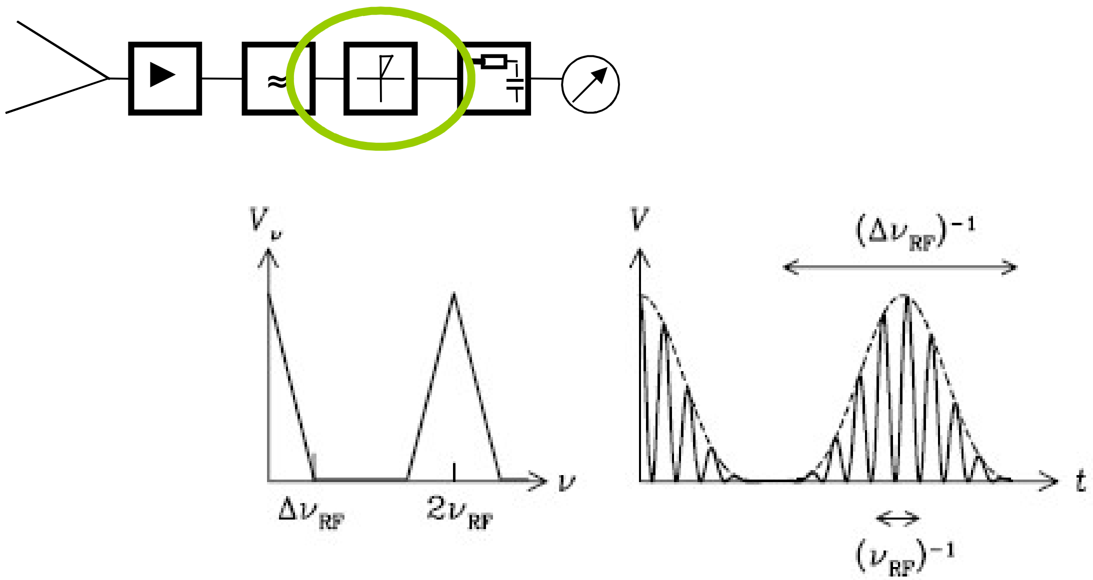


Radiometer – bandpass filter

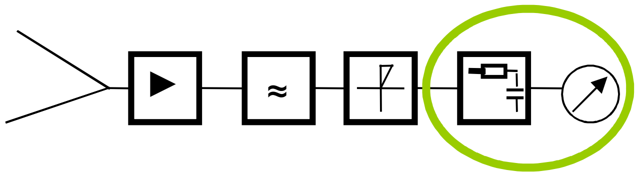




Radiometer - Diode



Radiometer - Integrator



Quadratik characteristic curve

$$S(\nu) = \lim_{T \to \infty} \frac{1}{T} E_T \left\{ |X(\nu)|^2 \right\}$$

$$S(\nu) = \int_{-\infty}^{\infty} R(\tau)\, e^{-2\pi i \nu \tau}\, d\tau$$

UNIVERSITÄT BONN

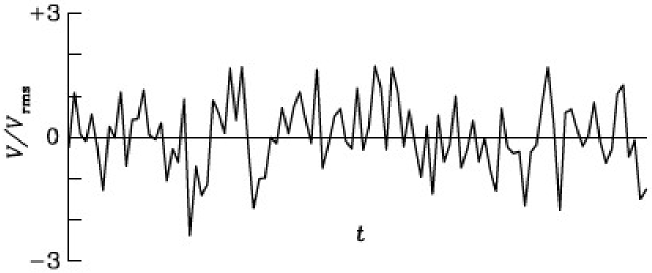
Signal at the integrator

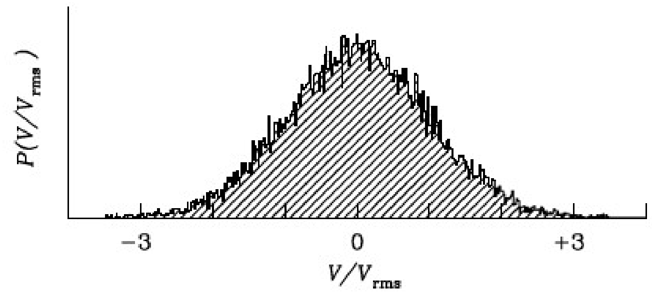
- Temporal sequence of voltage values corresponding to a sequence of 100 measuring points.

- Gaussian probability distribution with zero as mean and v_{rms} as standard variation

- With $\Delta\nu * \tau = N/2 = 50$ this corresponds to a bandwidth of

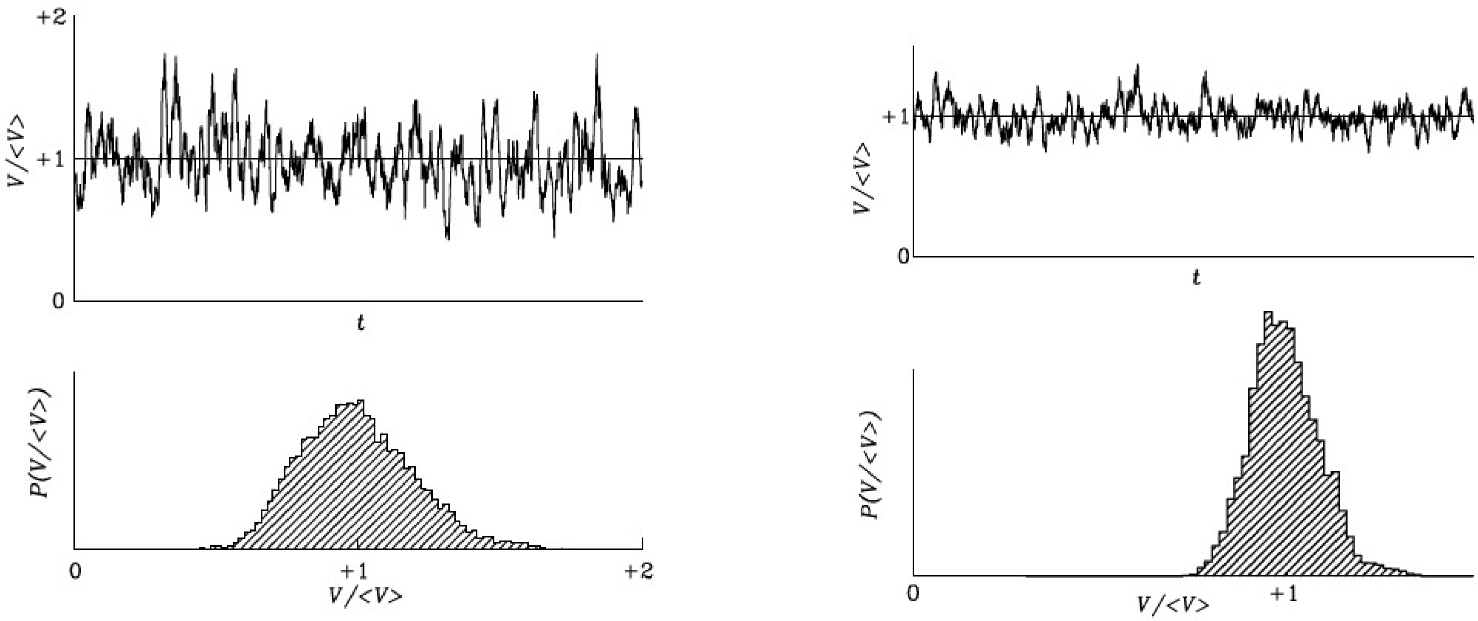
  $\Delta\nu$ = 1 MHz a sampling rate of τ = 50µs.





UNIVERSITÄT BONN

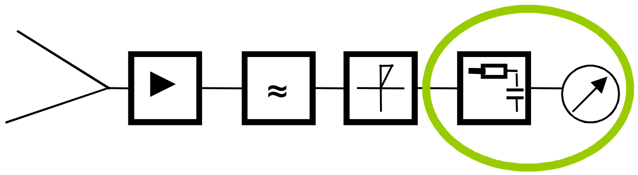
Effect of integration time



- **Left:** 50 independent wave trains were recorded in one integration. The voltage distribution can already be described by a Gaussian distribution.
- **Right:** 100 independent wave trains were recorded during the integration. The mean value of the voltage is as on the left at 1V, but the dispersion of the noise distribution is much smaller and thus the expected value is better determined.

UNIVERSITÄT BONN

Radiometer - Integrator



quadratic characteristic curve!

$$S(\nu) = \lim_{T \to \infty} \frac{1}{T} E_T \left\{ |X(\nu)|^2 \right\}$$

Statistical noise: Theory

Expectation value *E*:

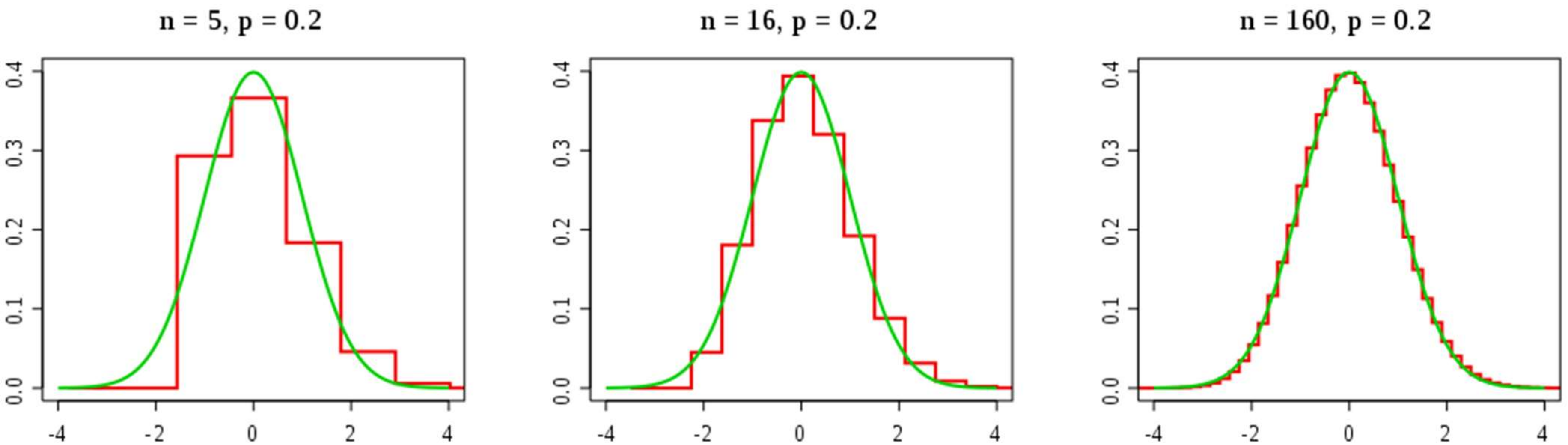
$$E\{x\} = \int_{-\infty}^{\infty} x \cdot p(x)\, dx$$

$$E\{f(x)\} = \int_{-\infty}^{\infty} f(x) \cdot p(x)\, dx$$

Mean value $\mu = E\{x\}$

dispersion $\sigma = E\{x^2\} - E^2\{x\}$

Central limit theorem



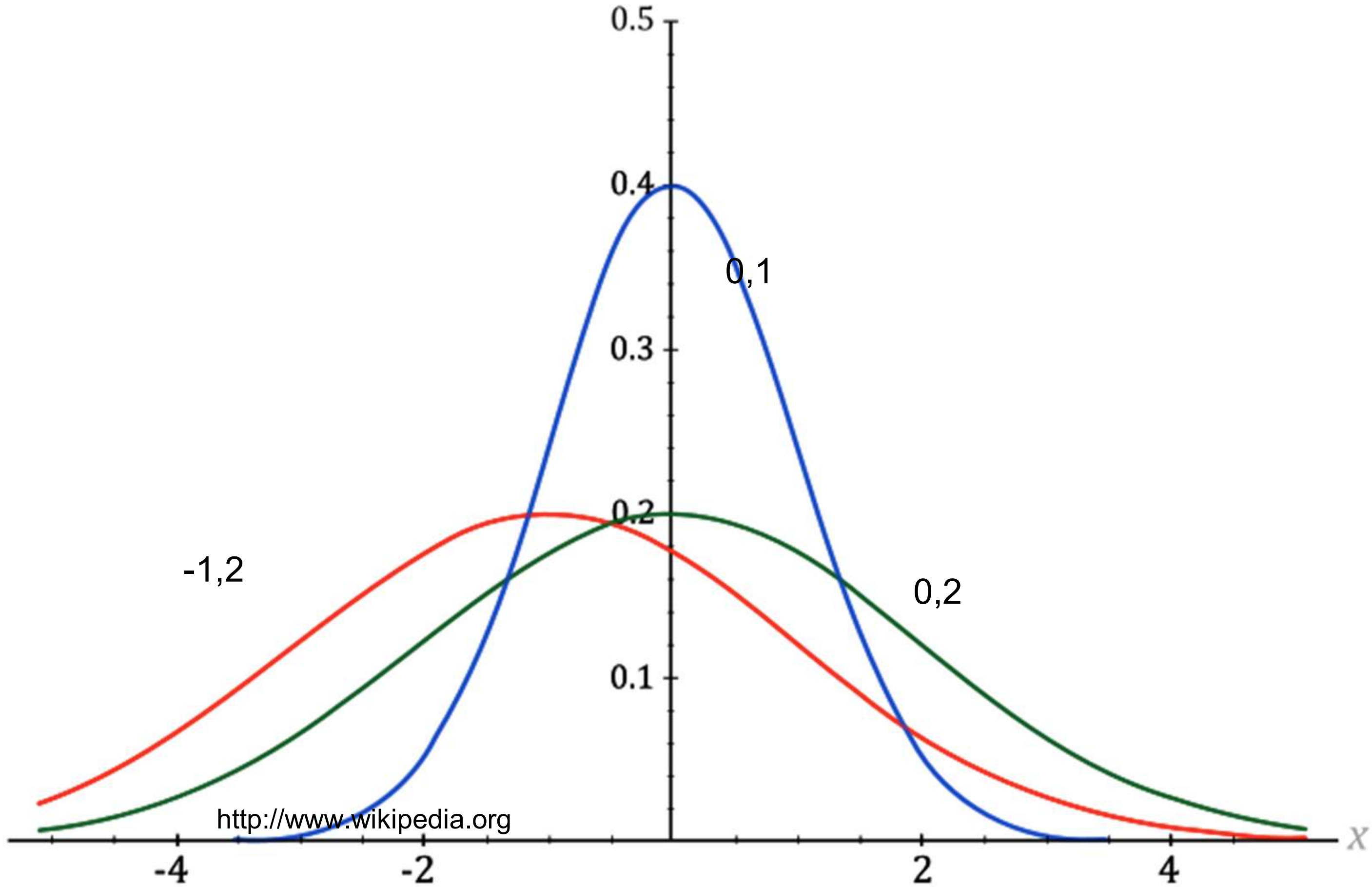
Radiometer

- Our goal is to derive the expected value of a quantity (e.g. energy density) as accurately as possible from the statistical variation of the measurand (voltage).
- We therefore observe different expected values x of our measurand as a function of time t.
- If the distribution of the expected values x(t) can be described by a normal distribution, we speak of a Gaussian noise

$$p(x)=\frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{x^2}{2\sigma^2}}$$

UNIVERSITÄT BONN

Normal distribution



UNIVERSITÄT BONN

Radiometer equation

- The limiting sensitivity of a receiver is described by the so-called radiometer equation.

- Example: We integrate 30 seconds at a bandwidth of 100 MHz. Thus we sample the signal $30s*100\cdot10^6$ Hz $=3\cdot10^9$ times. This means that we can detect source temperatures of $1.8\cdot10^{-5}*T_{sys}$.

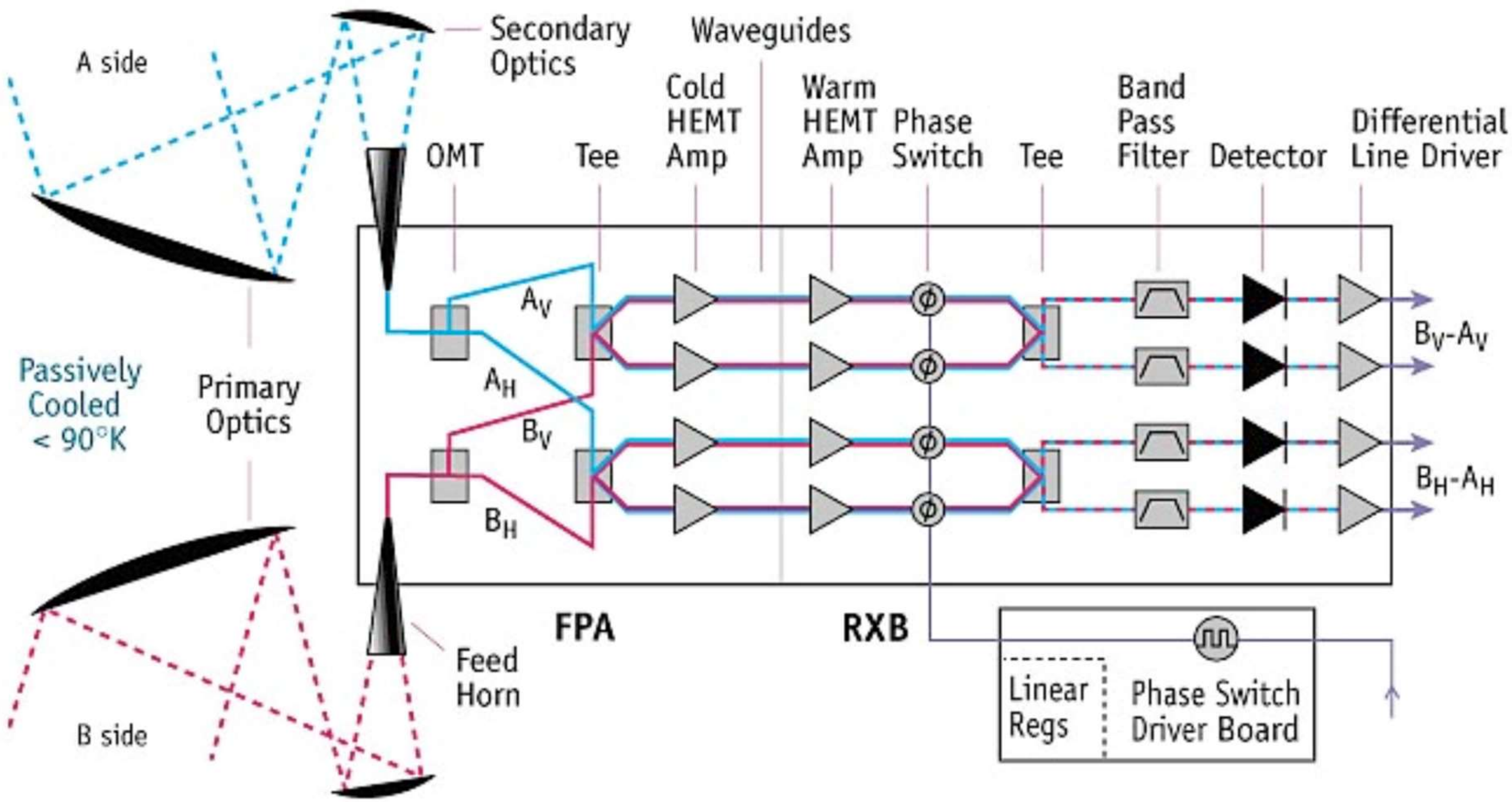
- If we integrate 30 seconds at a bandwidth of 6 kHz, we find $30s*6\cdot10^3$Hz -> $2.3\cdot10^{-3}*T_{sys}$,
- with T_{sys} = 40 K follows 92 mK.

UNIVERSITÄT BONN

Radiometer equation

$$\sigma_T \approx \frac{T_{sys}}{\sqrt{\Delta\nu \cdot \tau}}$$

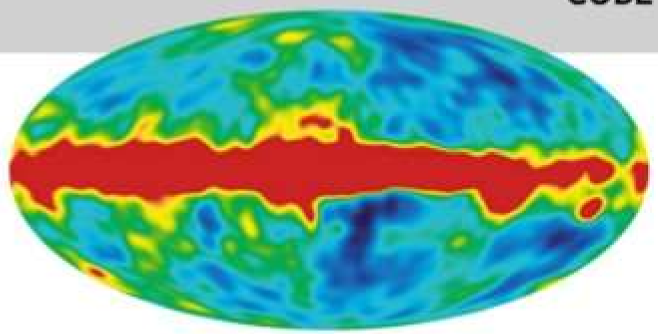
Wilkinson Microwave Anisotropy Probe (WMAP)



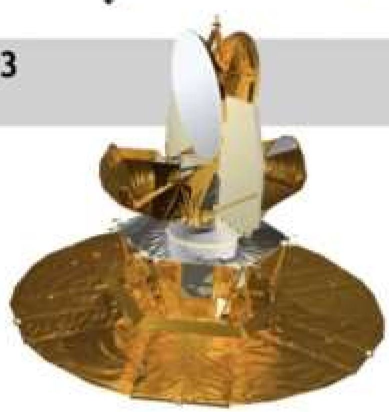
UNIVERSITÄT BONN

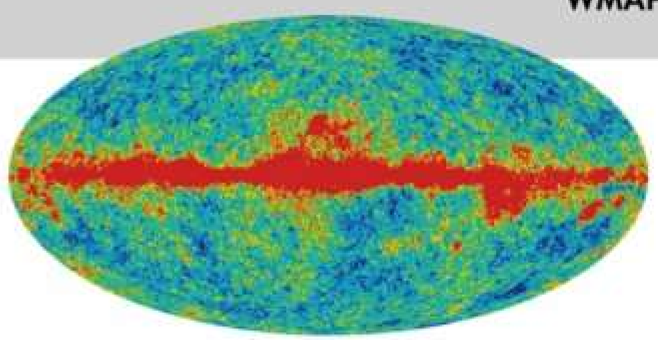
1965 Penzias and Wilson

1992 COBE



2003 WMAP





System temperture

- The system temperature can be determined via a "hot-cold" calibration

$$T_{Sys} = T_{Empfänger} + T_{Antenne} = const. * P$$

- Messen wir eine hot-load P_H (Wand) und danach eine cold-

UNIVERSITÄT BONN

System temperature: hot-cold-calibration

- The system temperature can be determined via a "hot-cold" calibration:

$$T_{Sys} = T_{\text{Receiver}} + T_{\text{Antenna}} = const. * P$$

- If we measure a hot-load P_H (wall) and then a cold-load P_C (nitrogen bath), we find:

$$P_H = (T_H + T_{\text{Receiver}}) * const.$$

$$P_C = (T_C + T_{\text{Receiver}}) * const.$$

mit

$$y = \frac{P_H}{P_C}$$

$$\Rightarrow T_{\text{Receiver}} = \frac{T_H - y * T_C}{y - 1}$$

UNIVERSITÄT BONN

Robert H. Dicke 1945 in action

Plate 1.7 Preparing to make measurements with the Dicke radiometer in 1945. Left to right: R. L. Kyhl, E. R. Beringer, A. B. Vane, R. H. Dicke (*by courtesy of R. H. Dicke, Princeton University*)

UNIVERSITÄT BONN

System and source temperature

- Via Rayleigh Jeans law, the received power corresponds to a noise temperature T_{noise}.
- This noise temperature is composed of several components. The most comprehensive measure is the system temperature T_{sys}, which is the addition of all contributions that the receiver measures as integrated voltage.
- The sources that can be detected without problems have mK levels, while typically Tsys is ~ 30 K (at 1.4 GHz).

$$T_{\text{noise}} = \frac{P_\nu}{k}$$

$$T_{sys} = T_{CMB} + T_{\text{source}} + T_{\text{Amplifier}} + \dots$$

$$T_{\text{source}} << T_{sys}$$