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Analog Signal Processing for Particle Detectors

PSI, LTP-Seminar, 12.06.2017

Intro

Citation of a slightly dispirited assistant I met during the early days of my studies:

"If you need an amplifier then try to build an oscillator, I am sure it will never oscillate, but if you need an oscillator then try to build an amplifier…"

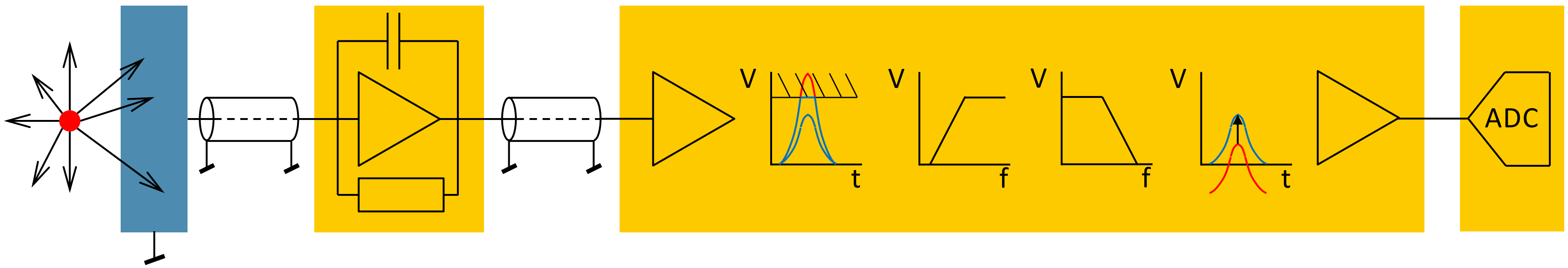
Of course this statement is not true, but there are a couple of reasons why an oscillator may not oscillate whereas an amplifier does.

Topics

- analog signal processing
- charge and current preamplifier
- pulse shaping
- examples

Analog Signal Processing

Analog Signal Processing for Particle Detectors

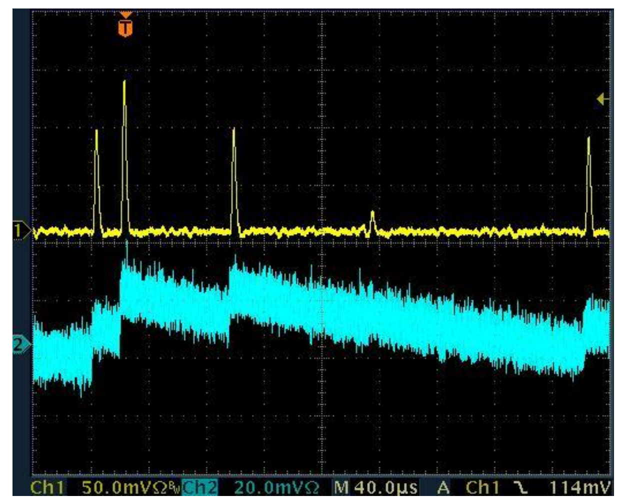


Mostly linear treatment of weak currents caused by small charges deposited or generated within a detector

Its goal is the extraction of information out of the weak generally noisy signals with the best possible S/N-ratio and/or the lowest possible timing jitter

It includes at lest three steps:

- signal capturing and (pre-)amplification
- pulse shaping by bandwidth manipulations
- signal conditioning for the following stage



Ch1(yellow): signal after pulse shaping

Ch2(blue): signal e.g. after a charge sensitive preamplifier

Analog Signal Processing

Keywords in Analog Signal Processing are:

- Gain
- Bandwidth
- Dynamic input/output range
- Stability
- Linearity
- Pulse shaping/Filtering
- Noise
- Distortion
- Drive strength
- Powering and grounding scheme
- Power consumption and cooling
- Mechanical considerations (housing, size, integration)

Not covered in the above list are topics specific for **non-linear analog processing** (e.g. frequency mixing as it is usual done in RF-communication, …)

Analog Signal Processing

What has to be known to be able to develop a signal processing chain

from the experiment:

- parameters to be measured (energy, position, intensity, time of arrival, counts, …)
- expected hit rate and their time distribution (poisson, bunch,…)
- other particles giving signals which has to be suppressed (e.g. by energy evaluation)
- environment conditions(magnetic fields, vacuum, ….)

from the detector:

- amount of charge deposited
- charge collection time
- detector recovery time
- detector capacitance and resistivity
- part of signal containing information
- readout scheme (e.g. charge division, time delay, …)
- number of channels
- operating voltage

Analog Signal Processing

What has to be known to develop a signal processing chain

- **from the next DAQ stage:**
- type of stage (discriminator, counter, TDC, ADC, …)
- input type (single ended, differential)
- input voltage or current range
- bias point
- input impedance
- input bandwidth or sampling frequency (for analog signals)
- minimum pulse width (for digital signals)

Preamplifier for Charge Measurements

Applicable for Measurements of Energy deposited on detector

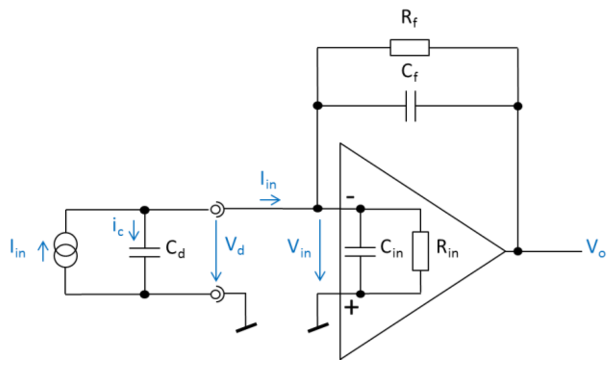
$$E_{particle} \propto Q_s = \int^{\tau} i_s(t)dt \qquad \text{with } \tau >> T_{charge\_collection}$$

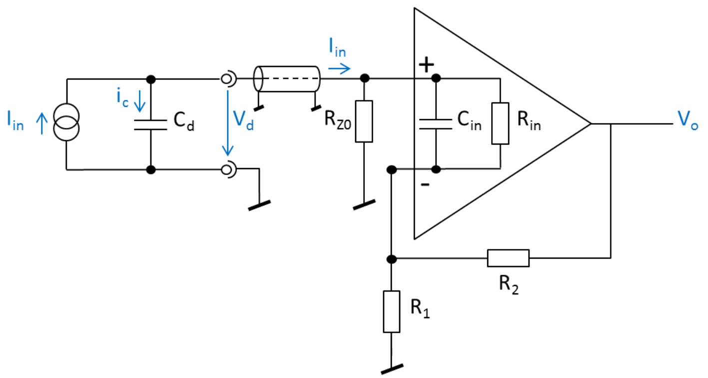
typical dynamic range: $\frac{Q_{s\_max}}{Q_{s\_min}} = 10^3 \ldots 10^5$ (= 60 … 100 dB or = 10…17 bits)

Energy information is a charge => Integration of current is needed

Charge sensitive preamplifier:

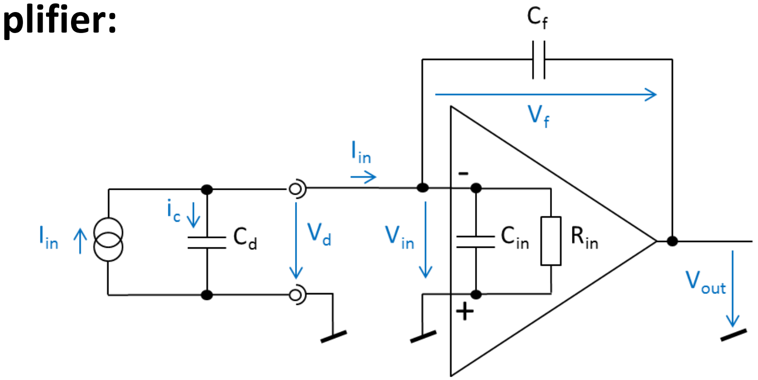
The most common ways are either to use a charge sensitive preamplifier based on a operational amplifier or especially when there is a cable in between detector and preamplifier a resistor with the cable impedance followed by a voltage amplifier:





Preamplifier for Charge Measurements

Attention: this circuit will not really work, see next slide



Charge Sensitive amplifier using an operational amplifier:

Operational Amplifier:

Open loop gain dV_{out}/dV_{in} = -A (|A|≈ 1E3-1E4 >> 1)

Input resistance R_{in} ≈ 10 – 100 MΩ (or even higher)

Negative feedback forces V_{in} ≈ 0 (but not = 0)

=> partial charge transfers from C_d to C_f

Reason for the only partial transfer:

Amplifier transforms the feedback capacitor C_f into a dynamic input capacitance

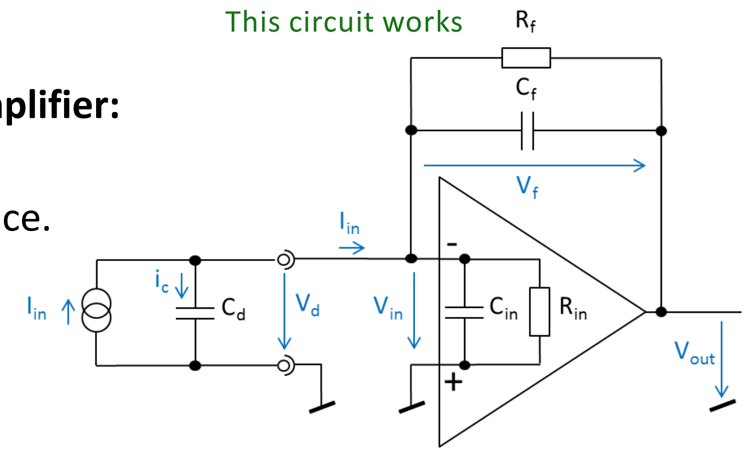
$$C_{in} = \frac{Q_{in}}{V_{in}} = \frac{C_f \cdot V_f}{V_{in}} = \frac{C_f \cdot V_{in} \cdot (A+1)}{V_{in}} = C_f(A+1)$$

=> Free charges from the detector are divided on both capacitances (C_d and C_{in}) with the ratio: $v_{in} = Q_d/C_d = Q_{in}/C_{in}$ => $Q_d = Q_{in} \cdot C_d/C_{in}$ and $Q_{tot} = Q_d + Q_{in} = Q_{in}(C_d/C_{in} + 1)$

$$\Rightarrow \quad \frac{Q_{in}}{Q_{tot}} = \frac{1}{\left(\frac{C_d}{C_{in}} + 1\right)}$$

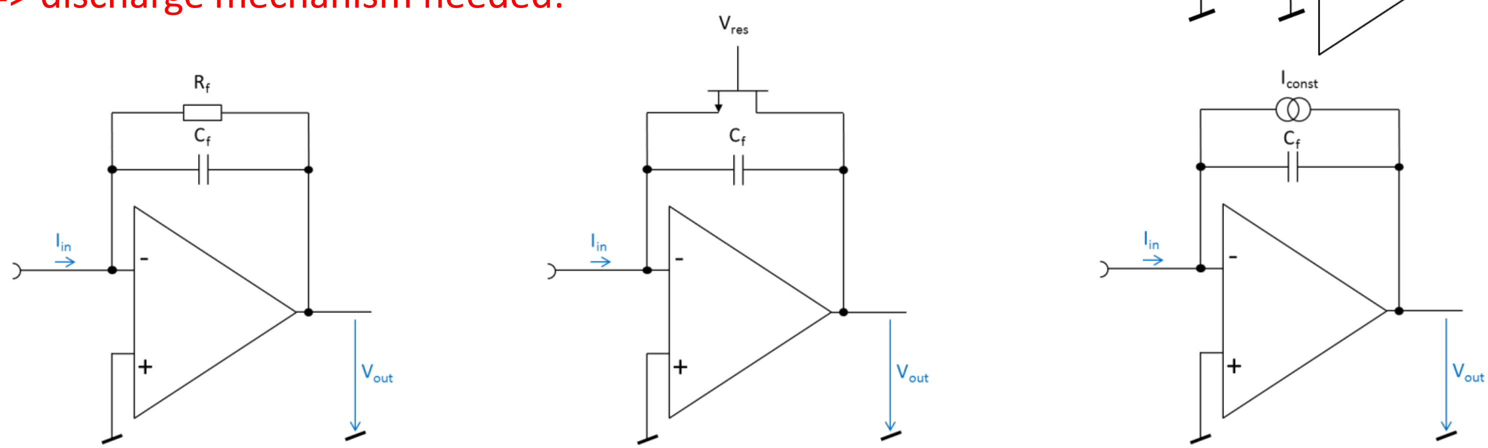
Charge sensitivity of the amplifier: $A_{VQ} = \frac{V_o}{Q_{in}} = \frac{-A}{A+1} \cdot \frac{1}{C_f} \approx -\frac{1}{C_f} \quad \left[\frac{V}{C}\right]$

Preamplifier for Charge Measurements



Charge Sensitive amplifier using an operational amplifier:
The previously shown circuit will not work, as there is no significant discharge of the feedback capacitance. The amplifier would integrate up until it saturates.

=> discharge mechanism needed:



$\tau = R_f \cdot C_f$ > charge collection time
larger τ : - increases linearity but
- reduces gain
has an exponential slope ($dU \sim e^{-t/\tau}$)

reset by a transistor (normally not after each event)
voltage V_{res} may be generated by a comparator with hysteresis switching the transistor on after V_{out} reaches a certain level
generates unpredictable dead-times

$I_{const} << I_{in}$
reduces gain
has a linear slope ($dU/dt = I_{const}/C_f$)
may be harder affected by temperature variations than resistor

Dynamic Range of Amplifiers

Dynamic Range of Amplifiers:

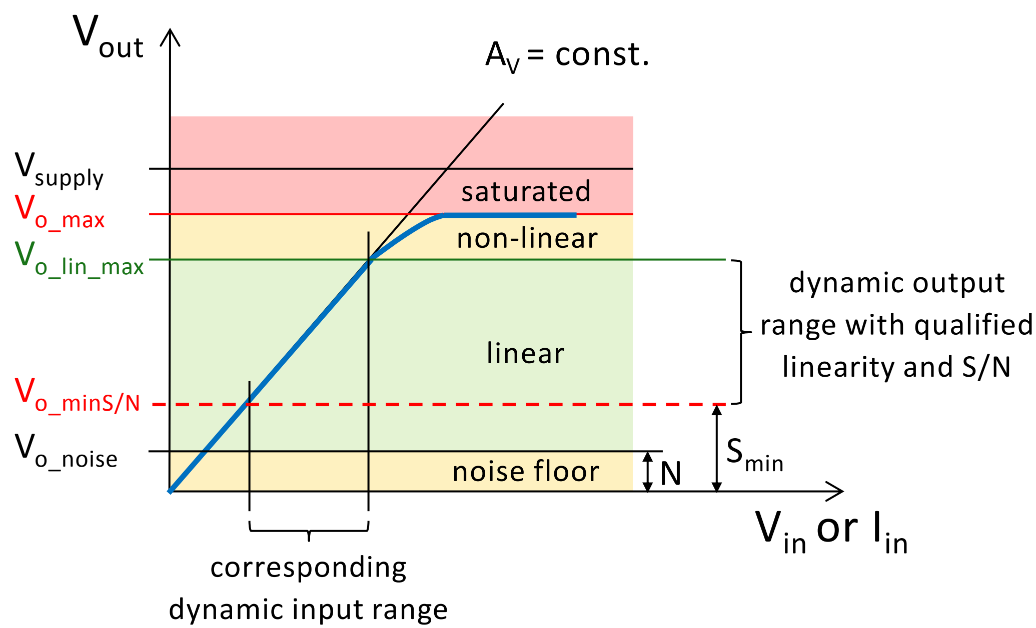
Ratio between largest (S_{max}) and smallest (S_{min}) signal for which the amplifier works within its specifications

It is typically expressed in [dB]: $DR = 20 \cdot log_{10}\left(\frac{S_{max}}{S_{min}}\right)$ [dB]

Rem: The dynamic range can be expressed for output or input signals. In a perfect linear system it would be the same.

For precision measurement systems:

The specification of a minimum S/N-ratio and enhanced linearity requirements reduce the available dynamic range of the system.



Preamplifier for Current Measurements

Applicable for event counting at high counting rates

Remark: Current preamplifier (also called transimpedance amplifier) are not faster but they have almost no tail what makes their signals shorter

Characteristics:

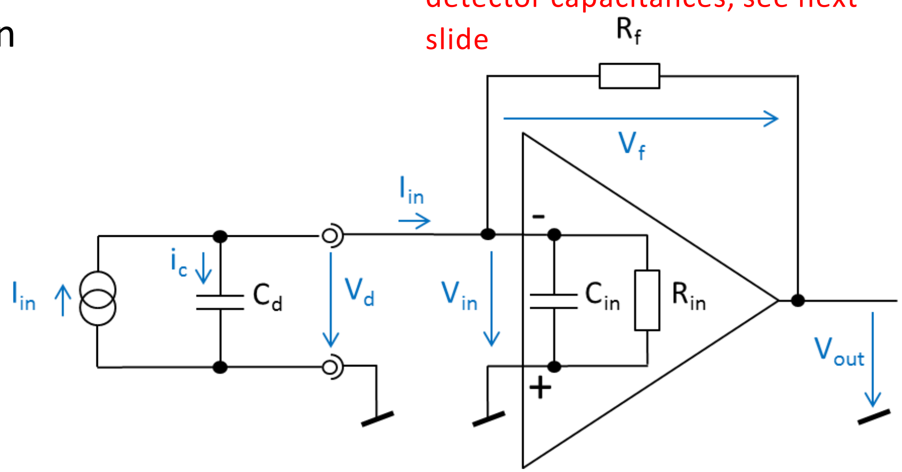
- Best for high counting rates
- poorer noise performance compared to charge sensitive preamplifiers
- more affected by stability issues especially for detectors with high detector capacitance

Transimpedance preamplifier (TIA):

the working principle is quit similar than for the charge amplifier except that the the feedback resister can not store charges

=> the main topic here is stability

Attention: this circuit works only stable for detectors with small detector capacitances, see next slide



Preamplifier for Current Measurements

Stability is afected by detector capacitance

Amplifier
OPA657 **f_GBW** 1,6E+9 Hz

DC Performance: Open Loop Voltage Gain:

	OL Gain [dB]	Frequency [Hz]
OL Gain	70	1,0E+0
	70	350,0E+3
	0	1,6E+9

AC Performance: Small Signal Voltage Gain

Gain [V/V]	Gain dB	Bandwidth [Hz]
7	16,90	350,0E+6
10	20,00	275,0E+6
20	26,02	90,0E+6
20	26,02	90,0E+6

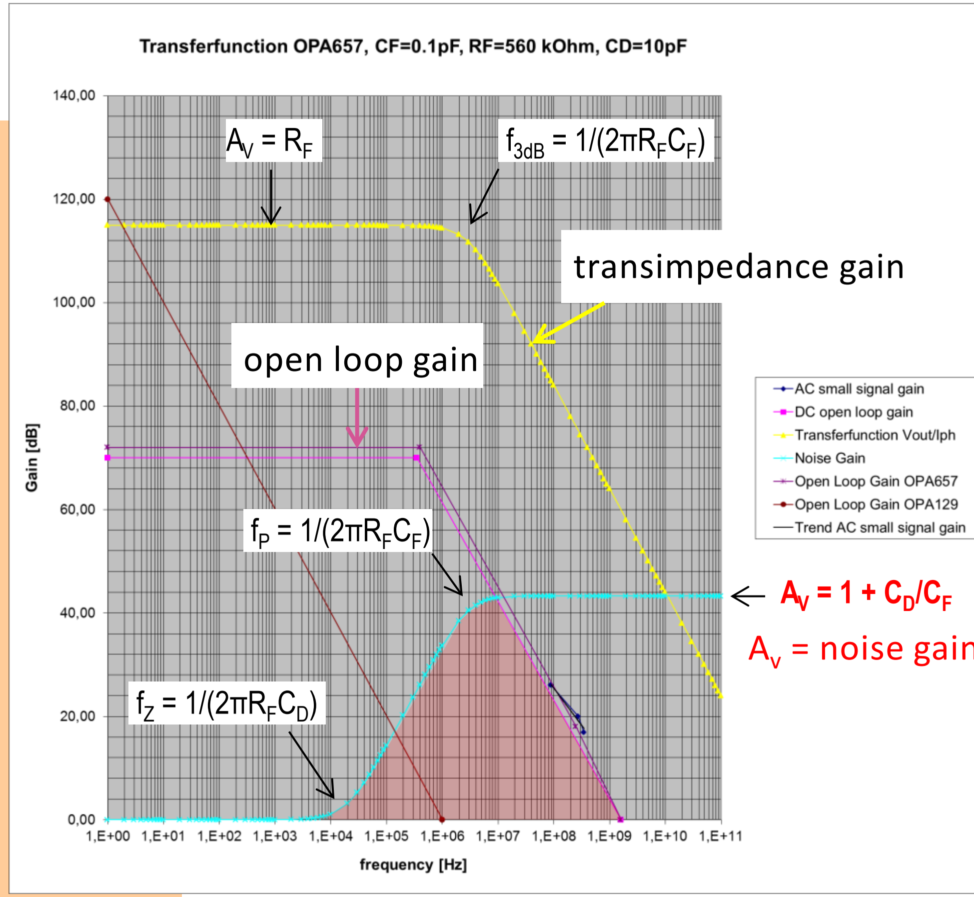
Input Common Mode Capacitance
C_CM 4,5E-12 F

Detector Capacitance
Capacitance
C_J 10,0E-12 F

Amplifier

choose	RF	560,0E+3	Ohm
calculated	CF min.	42,7E-15	F
added safety		57,3E-15	F
calculated:	CF	100,0E-15	F
calculated	3dB point of TF	2,84E+06	Hz

Annahme: C_CM + C_J >> CF



detector capacitance adds noise gain and bandwidth not available to the signal

optimum gain-bandwidth and noise performance when f_P close to open loop gain curve

becomes unstable when f_P outside the open loop gain curve

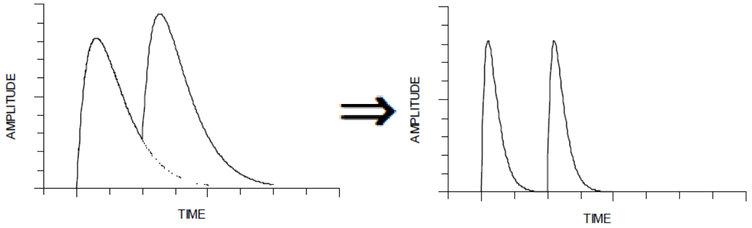
Pulse Shaping - Objectives

Reasons for pulse shaping:

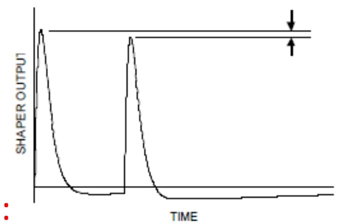
- **Shaping towards increased pulse width:**
  => Bandwidth-reduction
  - Improve of Signal-to-Noise Ratio
  - Pulse conditioning to match next stage requirements
    (e.g. stretching & rounding of sharp peaks for amplitude measurement with an ADC at a given $f_{sampling}$)

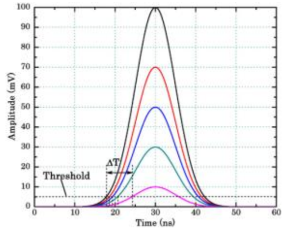
Detector Pulse | Shaper Output

- **Shaping towards reduced pulse width**
  => Improve of Pulse Pair Resolution (pile-up reduction):
  - Increase of maximum count-rate
  - Minimization of energy-measuring errors
  - Dead-time or dead time variation reduction



- **Other, sometimes included objectives:**
  - Reduction of baseline problems
  - Minimization of timing errors





Conflicting objectives (e.g. best S/N-Ratio at max. count-rate):
=> "Optimum shaping" is usually an application dependent compromise and has to be specified!

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Pulse Shaping - Methodes

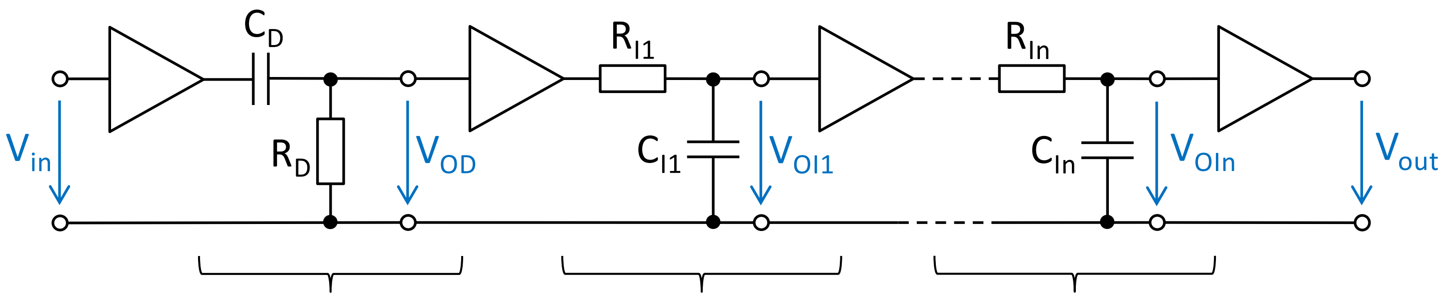
Most common pulse shaping methods:

1. CR-RC Pulse Shaping
2. Pole-Zero Cancellation
3. Delay-Line Pulse Shaping
4. Gaussian Filter
5. Raised-cosine Filter
6. Sinc Filter
7. Constant Fraction Discriminator
8. Baseline Restorer

Blue = subjects in tis talk

Pulse Shaping Methods

1. CR-(RC)^n Pulse Shaping:



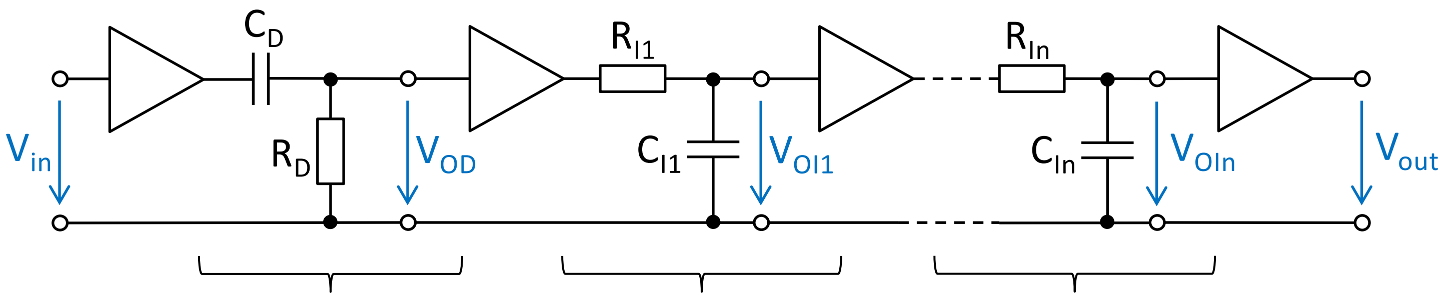
high pass filter ("differentiator") $\tau_D = R_D \cdot C_D$

low pass filter 1 ("integrator") $\tau_{I1} = R_{I1} \cdot C_{I1}$

optional: low pass filter n ("integrator") $\tau_{In} = R_{In} \cdot C_{In}$

Pulse Shaping Methods

1. CR-(RC)ⁿ Pulse Shaping:

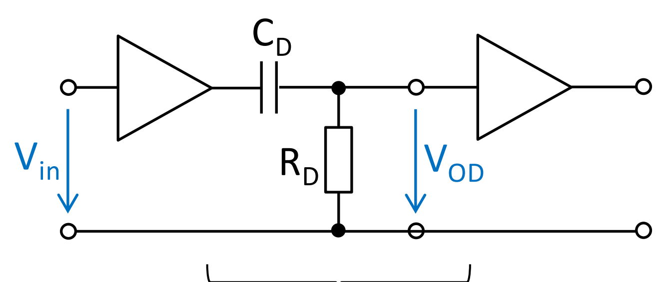


high pass filter ("differentiator") $\tau_D = R_D \cdot C_D$

low pass filter 1 ("integrator") $\tau_{I1} = R_{I1} \cdot C_{I1}$

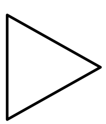
optional: low pass filter n ("integrator") $\tau_{In} = R_{In} \cdot C_{In}$

may have as well further "differentiators" in between



high pass filter ("differentiator")
$\tau_D = R_D \cdot C_D$

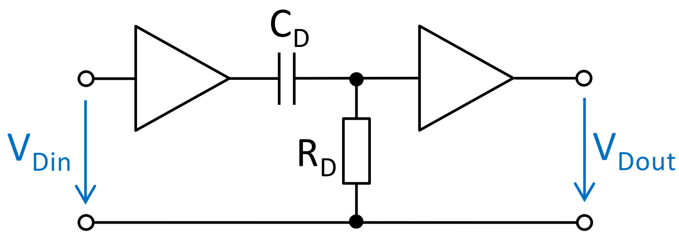
Symbol:



= voltage amplifier with high input impedance

Pulse Shaping Methods

CR - Pulse Shaping ("differentiator"):



high pass filter ("differentiator")

$\tau_D = R_D \cdot C_D$

step response:

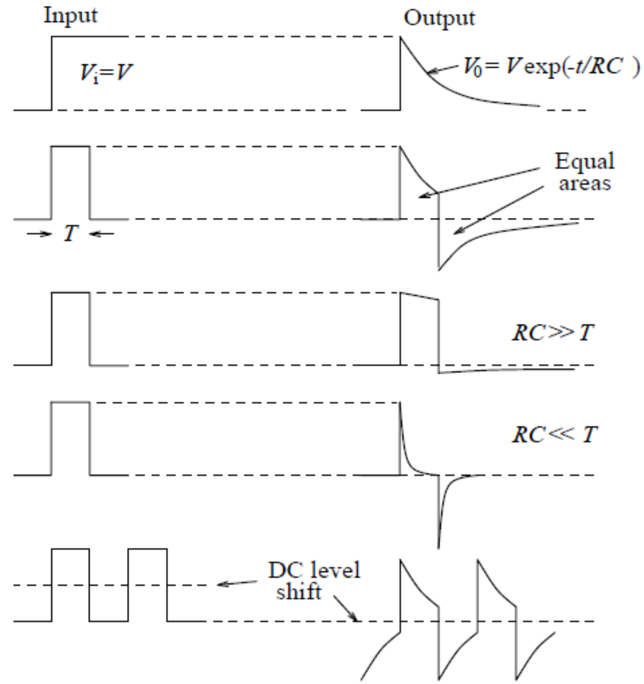
$$h(t) = \frac{V_{Dout}(t)}{V_{step}(t)} = e^{-\frac{t}{R_D C_D}}$$

Design limits for R_D :

- a lower limit for R_D is given by the max. output drive current of the previous amplifier stage and their maximum peak to peak output voltage

- to be dominant, R_D should be big compared to the output impedance of the previous amplifier

Time domain characteristics



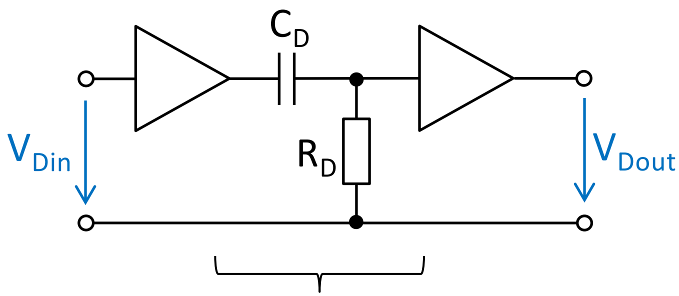
reduces pulse width if RC << T, but has inconveniences:

- Generates bipolar output pulses (positive on rising edges and negative on falling edges) => only applicable if falling edge has a much longer time constant

- Peak at maximum amplitude is very short in time (bad e.g. for ADC-sampling)

Pulse Shaping Methods

CR - Pulse Shaping ("differentiator"):



high pass filter ("differentiator")

$\tau_D = R_D \cdot C_D$

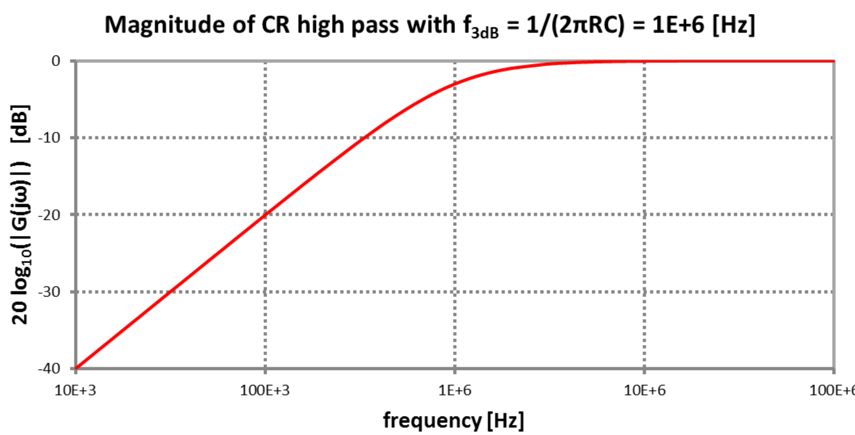
step response:

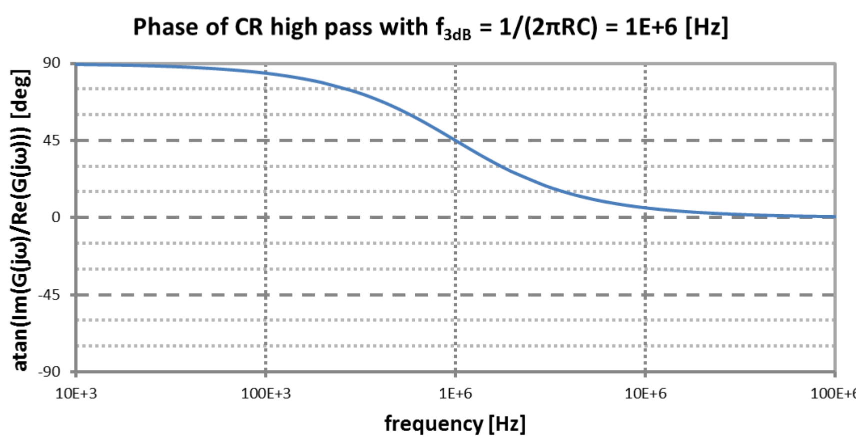
$$h(t) = \frac{V_{Dout}(t)}{V_{step}(t)} = e^{-\frac{t}{R_D C_D}}$$

transfer function:

$$G_D(s) = \frac{V_{Dout}(s)}{V_{Din}(s)} = \frac{sC_D R_D}{1 + sC_D R_D}$$

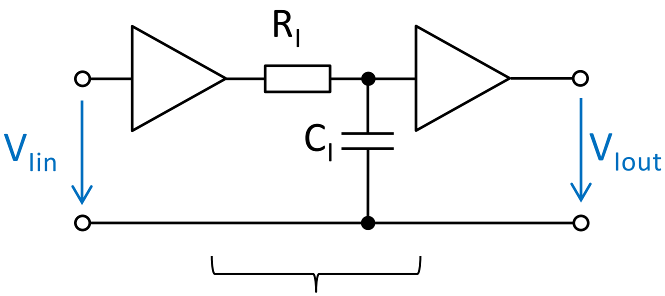
Frequency domain characteristics





Pulse Shaping Methods

RC - Pulse Shaping ("integrator"):



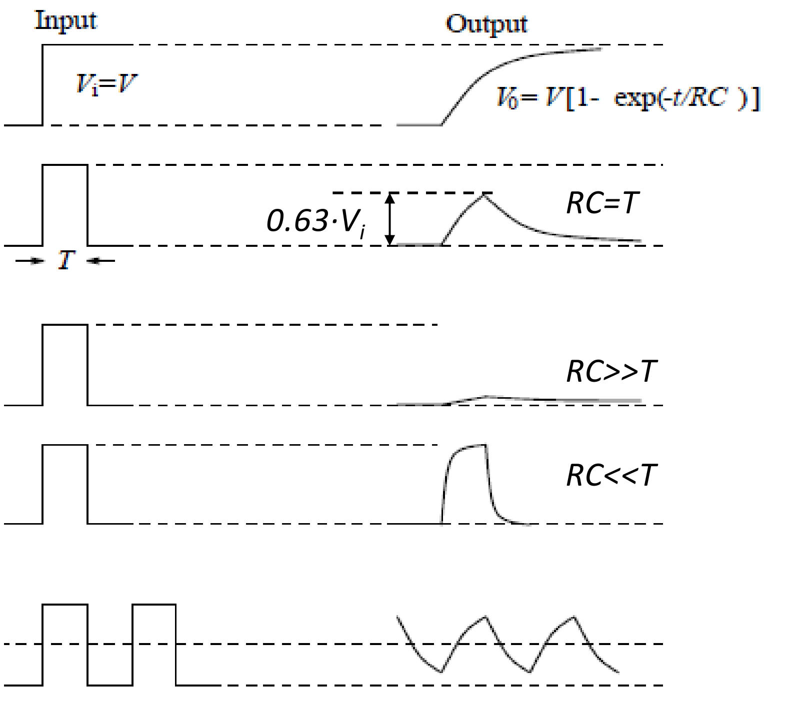
low pass filter ("integrator")

$\tau_I = R_I \cdot C_I$

step response:

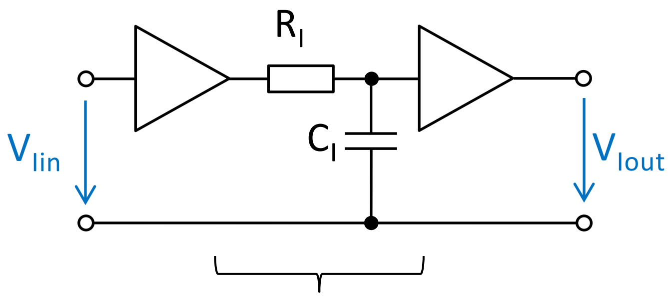
$$h(t) = \frac{V_{Iout}(t)}{V_{step}(t)} = (1 - e^{-\frac{t}{R_I C_I}})$$

Time domain characteristics



Pulse Shaping Methods

RC - Pulse Shaping ("integrator"):



low pass filter ("integrator")

$\tau_I = R_I \cdot C_I$

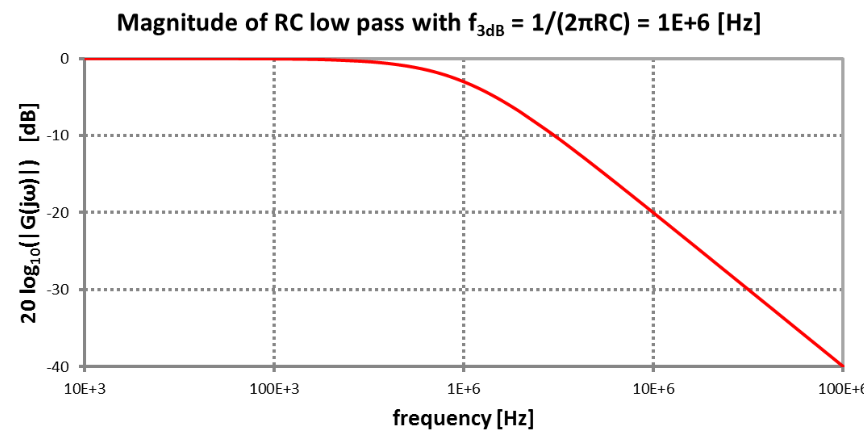
step response:

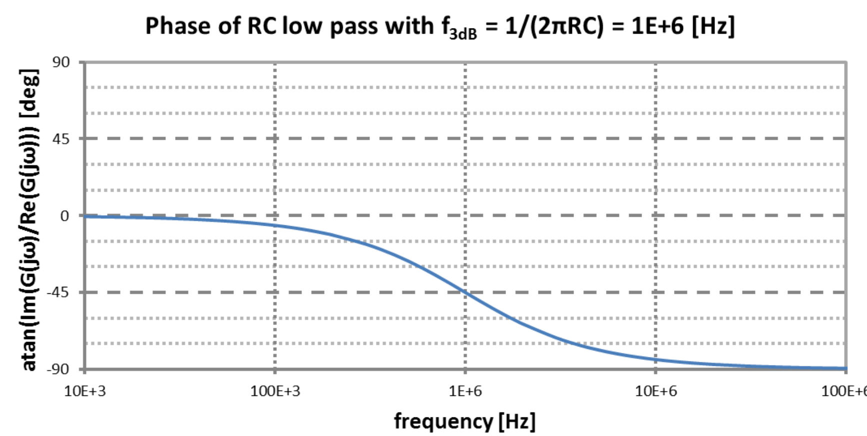
$$h(t) = \frac{V_{Iout}(t)}{V_{step}(t)} = (1 - e^{-\frac{t}{R_I C_I}})$$

transfer function:

$$G_I(s) = \frac{V_{Iout}(s)}{V_{Iin}(s)} = \frac{1}{1 + sC_I R_I}$$

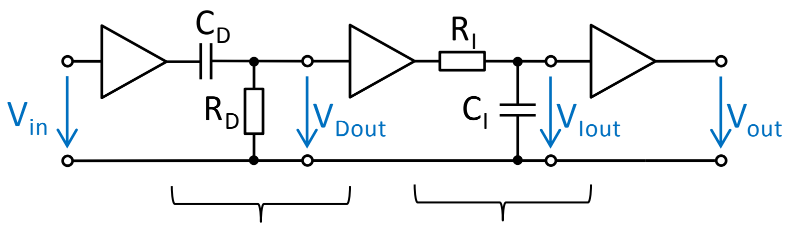
Frequency domain characteristics





Pulse Shaping Methods

CR-RC Pulse Shaping (combination of a "differentiator" and an "integrator"):



high pass filter ("differentiator") $\tau_D = R_D \cdot C_D$

low pass filter ("integrator") $\tau_I = R_I \cdot C_I$

a good starting point is to set $\tau_D = \tau_I$

transfer function:

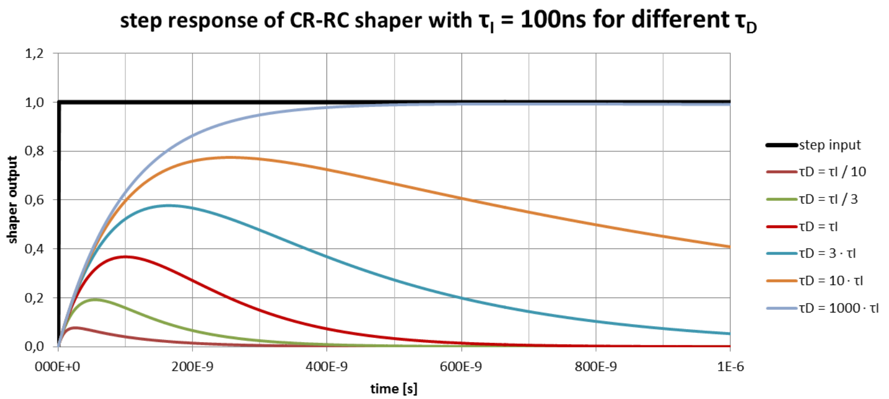
$$G_{DI}(s) = \frac{V_{out}(s)}{V_{in}(s)} = G_D(s) \cdot G_I(s) =$$

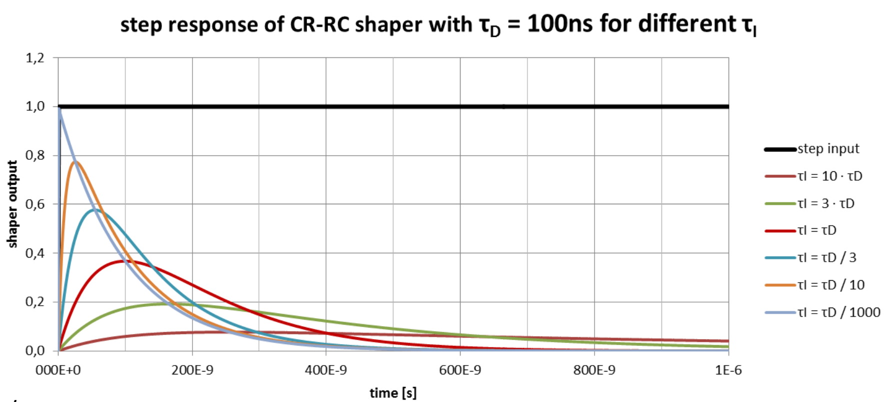
$$= \frac{sC_DR_D}{(1 + sC_DR_D) \cdot (1 + sC_IR_I)}$$

step response:

$$h(t) = \frac{v_{out}(t)}{v_{step}(t)} = \mathcal{L}^{-1}\left\{\frac{G_{DI}(s)}{s}\right\} = \frac{\tau_D}{\tau_D - \tau_I} \cdot \left(e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_I}}\right)$$

and for the most common case with $\tau_D = \tau_I = \tau$: $h(t) = \frac{t}{\tau} \cdot e^{-\frac{t}{\tau}}$





Pulse Shaping Methods

CR-RC Pulse Shaping-mathematical intermezzo: Derivation of h(t) for the case where $\tau_D = \tau_I$:

Starting point is the previous general formula for the CR-RC step response:

$$h(t) = \mathcal{L}^{-1}\left\{\frac{G_{DI}(s)}{s}\right\} = \frac{v_{out}(t)}{v_{step}(t)} = \frac{\tau_D}{\tau_D - \tau_I} \cdot \left(e^{-\frac{t}{\tau_D}} - e^{-\frac{t}{\tau_I}}\right)$$

As the above formula for $\tau_D = \tau_I$ apparently results in a zero divided by zero division, a limes calculation with $\Delta\tau = \tau_D - \tau_I \rightarrow 0$ may help:

$$h(t) = \lim_{\Delta\tau\to 0}\left(\frac{\tau_D}{\tau_D - \tau_I} \cdot e^{-\frac{t}{\tau_D}} \cdot \left(1 - e^{-t\left(\frac{1}{\tau_I} - \frac{1}{\tau_D}\right)}\right)\right)$$

factored out $e^{-\frac{t}{\tau_D}}$

$$= \tau_D \cdot e^{-\frac{t}{\tau_D}} \cdot \lim_{\Delta\tau\to 0}\left(\frac{1 - e^{-t\left(\frac{\tau_D - \tau_I}{\tau_I \tau_D}\right)}}{\tau_D - \tau_I}\right)$$

some minor cosmetics

$$= \tau_D \cdot e^{-\frac{t}{\tau_D}} \cdot \lim_{\Delta\tau\to 0}\left(\frac{\frac{d}{d\Delta\tau}\left(1 - e^{-t\left(\frac{\Delta\tau}{\tau_I \tau_D}\right)}\right)}{\frac{d}{d\Delta\tau}(\Delta\tau)}\right)$$

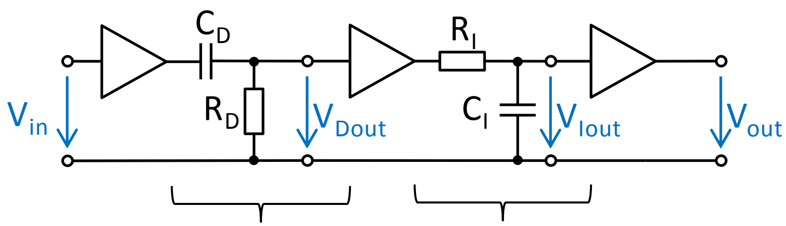
l'Hospital's rule

$$= \tau_D \cdot e^{-\frac{t}{\tau_D}} \cdot \lim_{\Delta\tau\to 0}\left(\frac{t}{\tau_I \tau_D} \cdot e^{-t\left(\frac{\Delta\tau}{\tau_I \tau_D}\right)}\right) = \frac{t}{\tau_I} \cdot e^{-\frac{t}{\tau_D}} = \frac{t}{\tau} \cdot e^{-\frac{t}{\tau}}$$

limes, then $\tau_I = \tau_D = \tau$

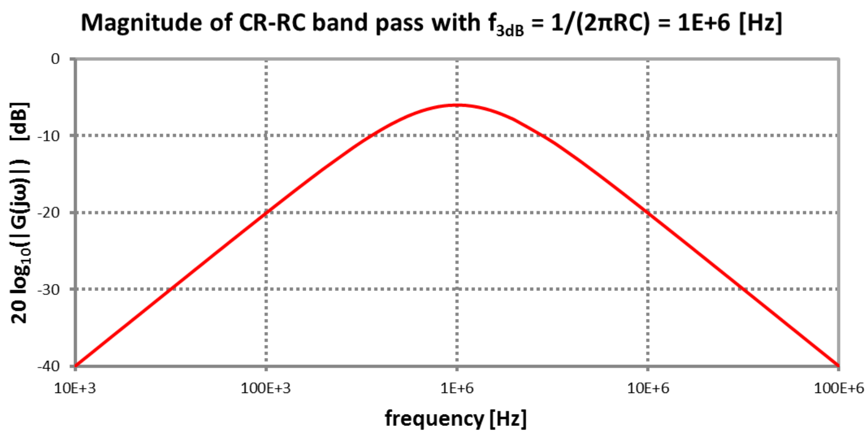
Pulse Shaping Methods

CR-RC Pulse Shaping (combination of a "differentiator" and an "integrator"):

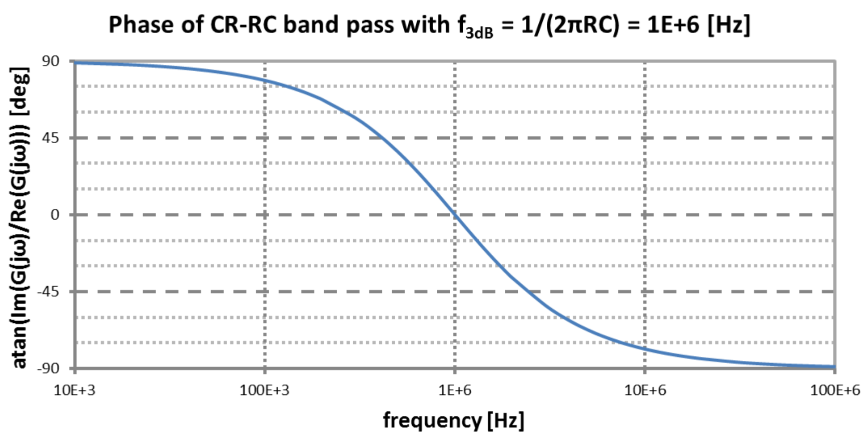


high pass filter ("differentiator") $\tau_D = R_D \cdot C_D$

low pass filter ("integrator") $\tau_{I1} = R_I \cdot C_I$



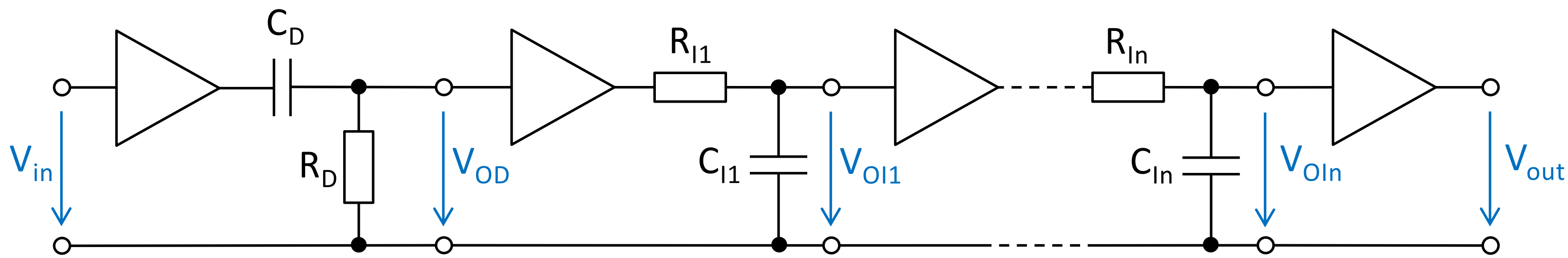
$$G_{DI}(s) = \frac{V_{out}(s)}{V_{in}(s)} = G_D(s) \cdot G_I(s) = $$
$$= \frac{sC_DR_D}{(1 + sCDRD) \cdot (1 + sCIRI)}$$



Effect of a simple CR-RC Pulse shaping:

Signal reduced (bad), but much higher reduction of noise => enhancement of S/N-Ratio

1. CR-(RC)^n Pulse Shaping:

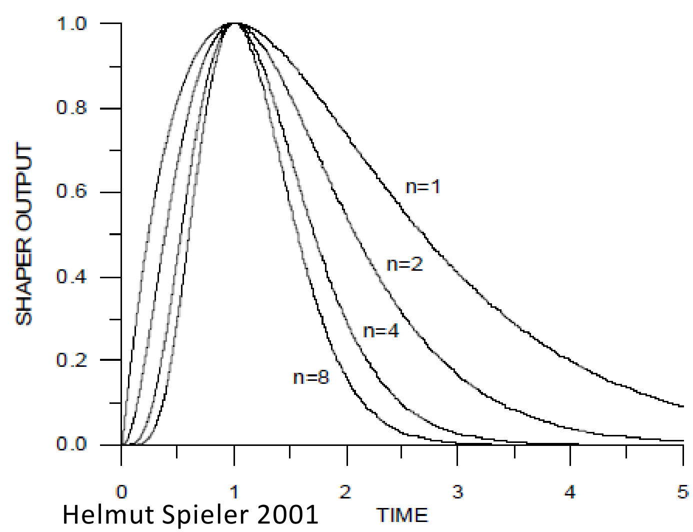


high pass filter
("differentiator")
$\tau = R_D \cdot C_D$

low pass filter 1
("integrator")
$\tau = R_{I1} \cdot C_{I1}$

optionally: low pass filter n
("integrator")
$\tau = R_{In} \cdot C_{In}$

Increasing number of integrators make the output Pulse more symmetrical wit a faster return to base-Line.
To preserve the peaking time the time constant of the original integrator (for n=1) has to be divided by the number n: $\tau_n = \tau_1 / n$

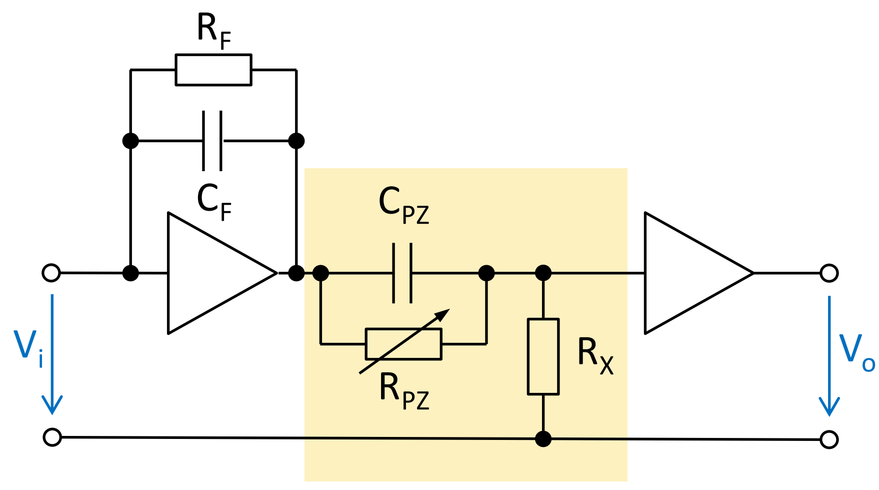


Helmut Spieler 2001

Pulse Shaping Methods

2. Pole-Zero Cancellation:

- Controls the lower cutoff frequency
- No impact on the upper cutoff freq.
- Can be used for pulse shape and baseline recovery adjustments
- It is not the most efficient but an easy to integrate shaper



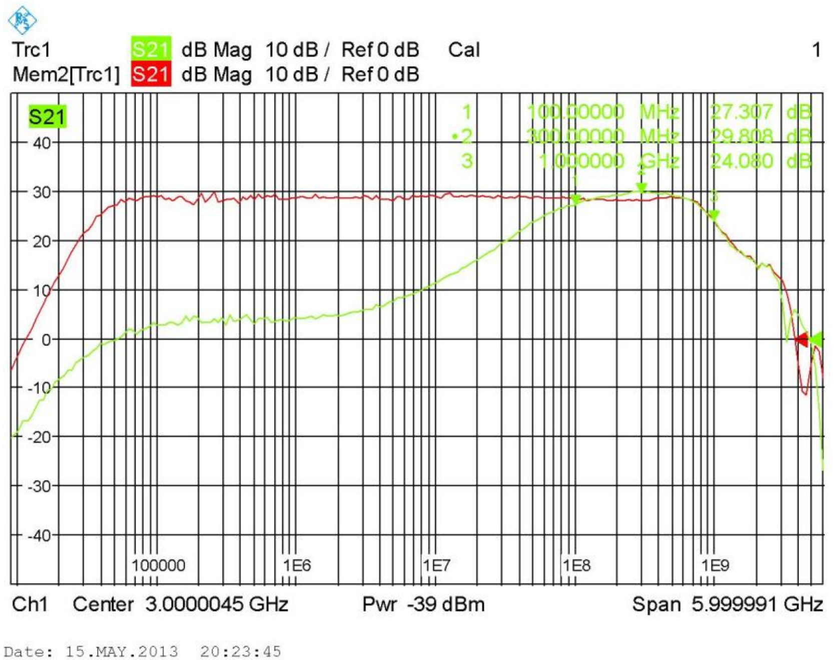
Application:
Charge sensitive amplifiers and stabilized transimpedance amplifiers (with a capacitance in their feedback) have a pole at $s=1/C_F R_F$ in their transfer function.
This pole can be compensated with the above circuit (yellow part) which creates a zero.
To compensate the pole one has to choose: $C_{PZ} \cdot R_{PZ} = C_F \cdot R_F$
The value of the Resistor R_X has no effect on the zero except it would be zero or infinite.

=> pole zero cancellation can be applied as well in other networks for pulse shape and baseline optimization (e.g. for AC-coupled signal paths)

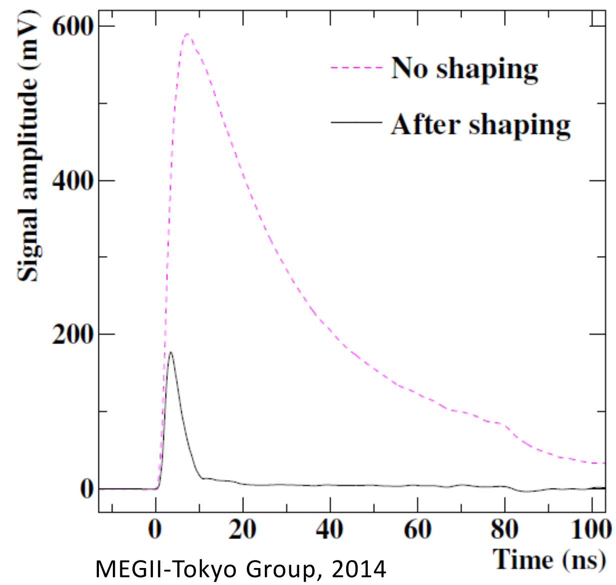
Pulse Shaping Methods

2. Pole-Zero Cancellation:

In frequency domain:



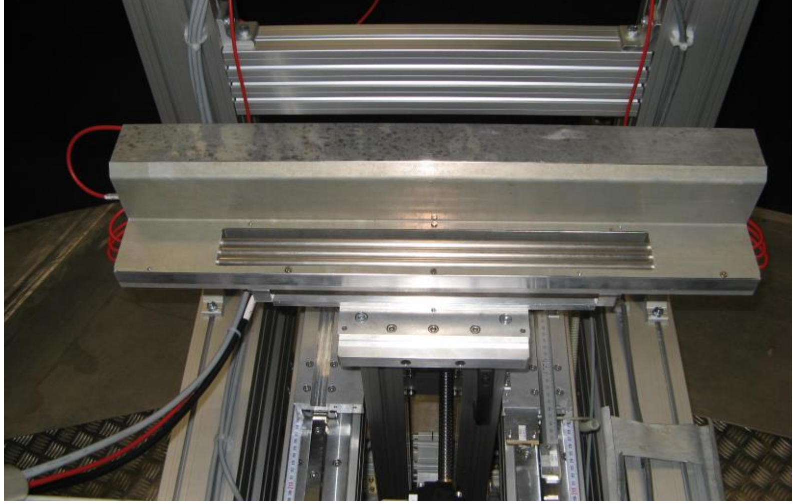
in time domain:

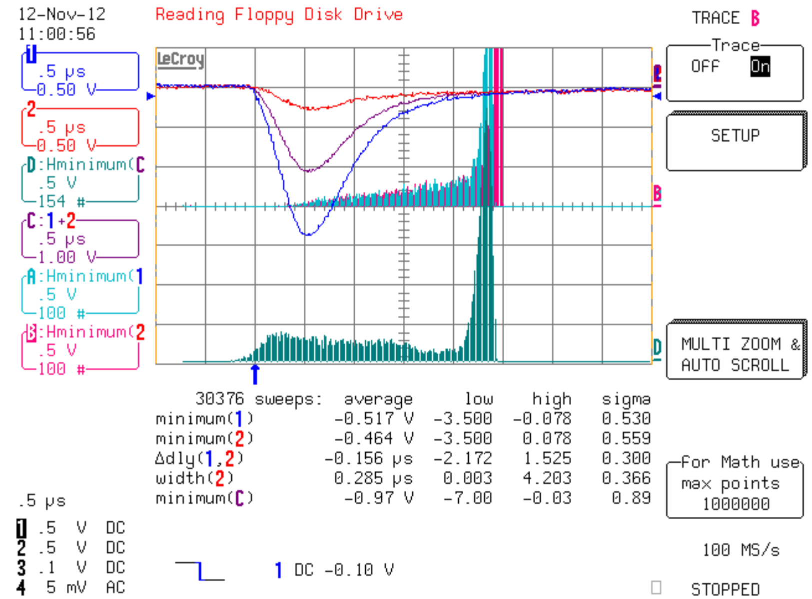


MEGII-Tokyo Group, 2014

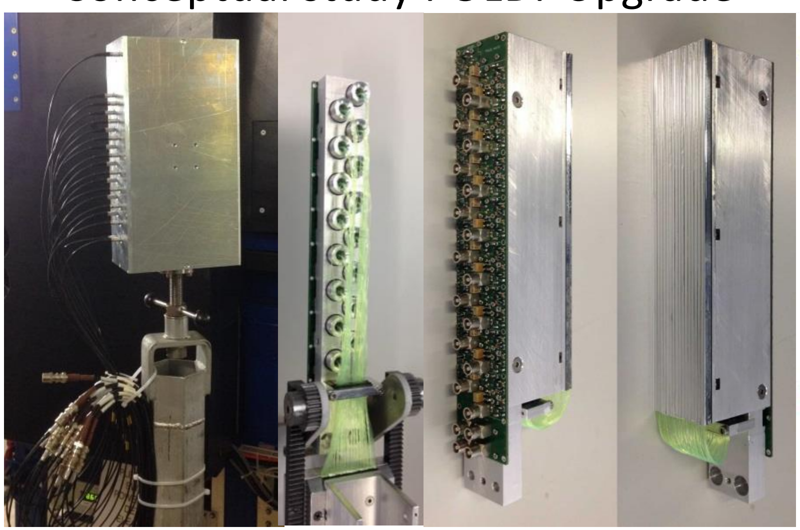
Some Examples

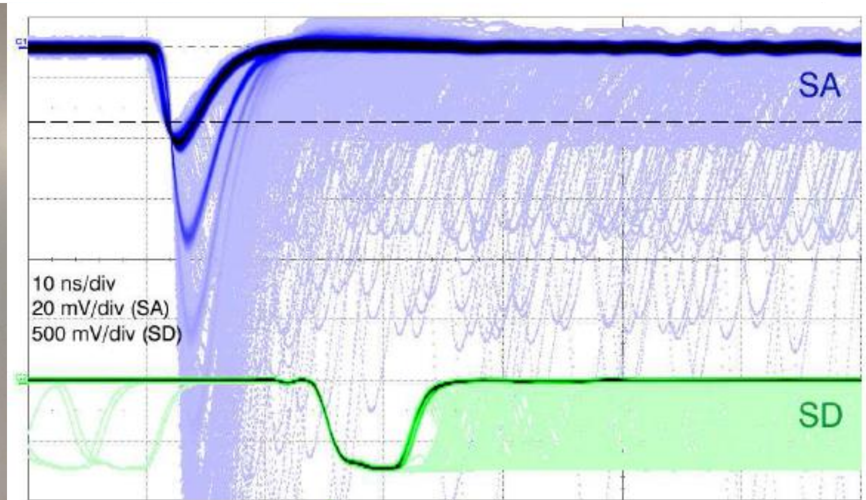
Conceptual study TOFTAS (ESS-WP1)





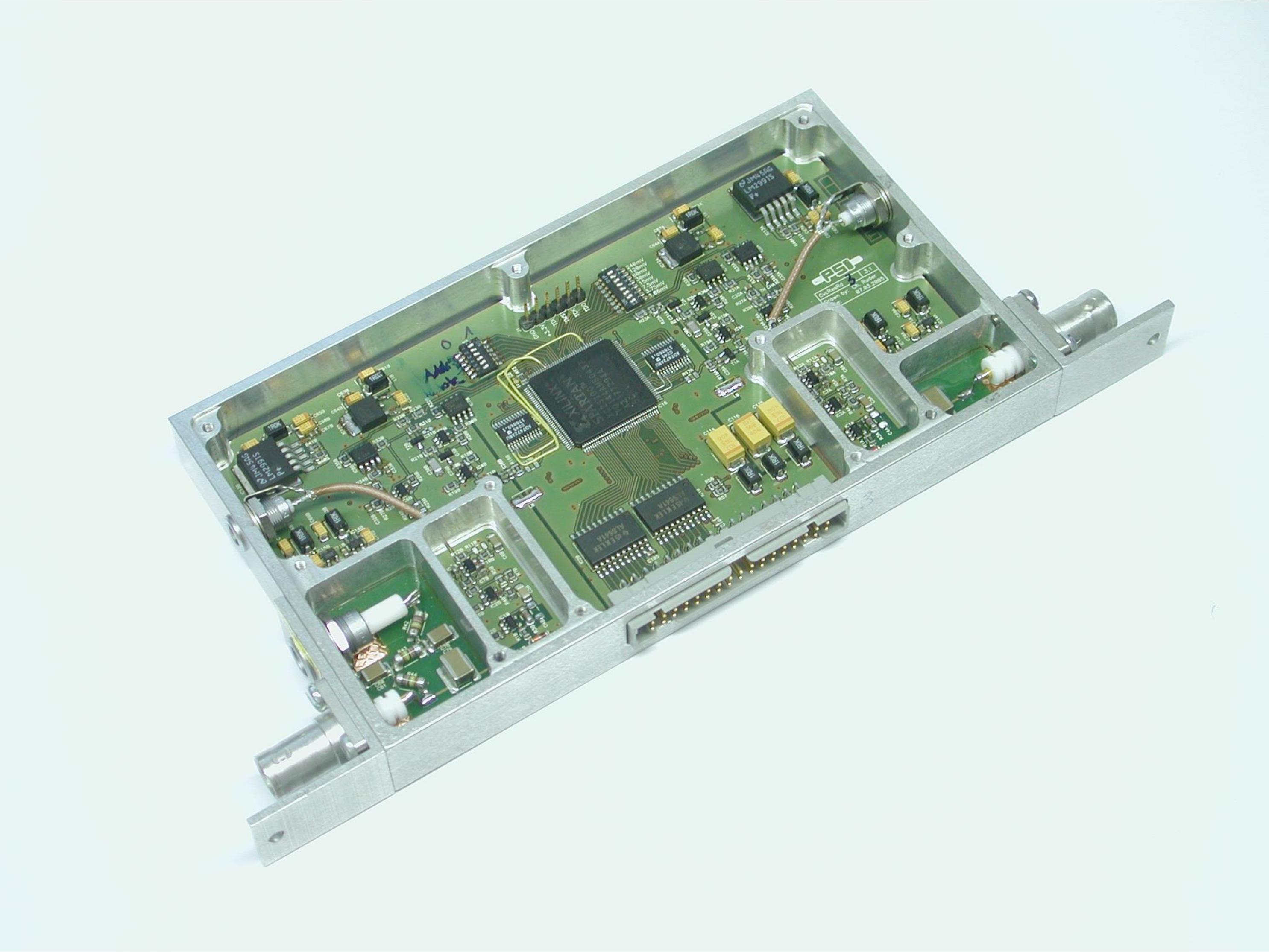
Conceptual study POLDI-Upgrade





Pictures below: Hildebrand, Stoykov, Mosset

Example: Charge Division Readout



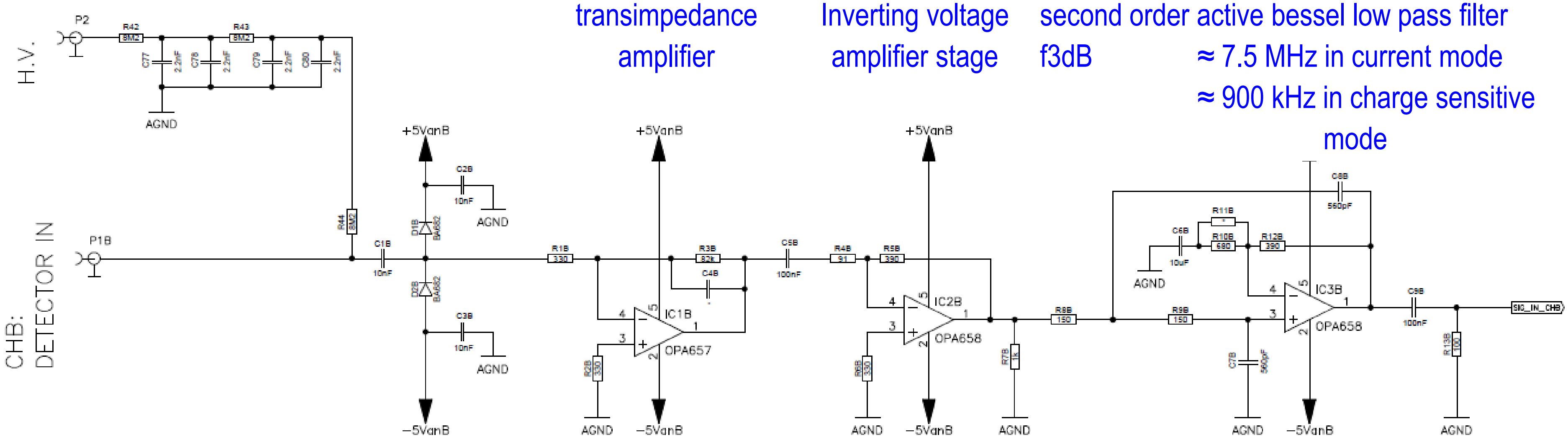
Charge Division Readout - Preamplifier

Schematics of the Input Amplifier:

transimpedance amplifier

Inverting voltage amplifier stage

second order active bessel low pass filter
f3dB ≈ 7.5 MHz in current mode
≈ 900 kHz in charge sensitive mode



OPA657: FET-input

GBP = 1.6 GHz

$T_{rise\&fall}$ = 1 ns (0.2 V Step)

$T_{settling}$ = 20 ns (2 V Step)

Z_{inDiff} = 10 TΩ || 0.7 pF

Z_{inCM} = 10 TΩ || 4.5 pF

A_{OL} = 70 dB

$V_{in\text{-}noise}$ = 4.8 nV/√Hz

$I_{in\text{-}noise}$ = 1.3 fA/√Hz

OPA658: Current Feedback

BW = 900 MHz (unity gain stable)

SR = 1700V/us

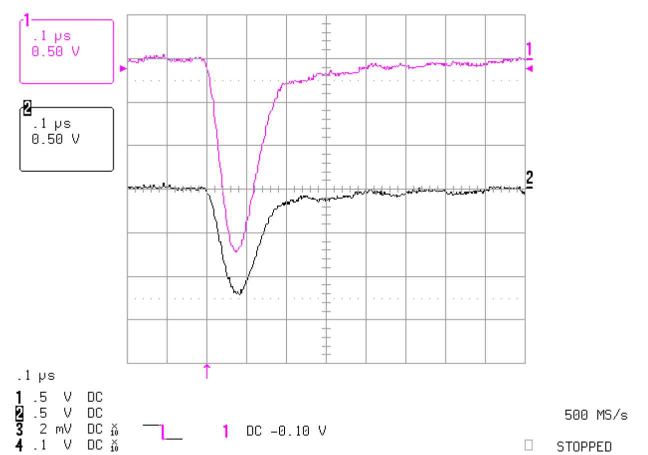
G/ϕ $_{error}$ = 0.025%/0.02°

$G_{flatness}$ = 0.1 dB to 135MHz

I_{out} = 80 mA

$V_{in\text{-}noise}$ = 45.3 µVrms (to 200 MHz)

$I_{in\text{-}noise}$ = 32 pA/√Hz



Charge Division Readout – Track and Hold Stage

Schematics of the Track and Hold Stage:

track and hold stage

inverting amplifier adding an offset to original signal

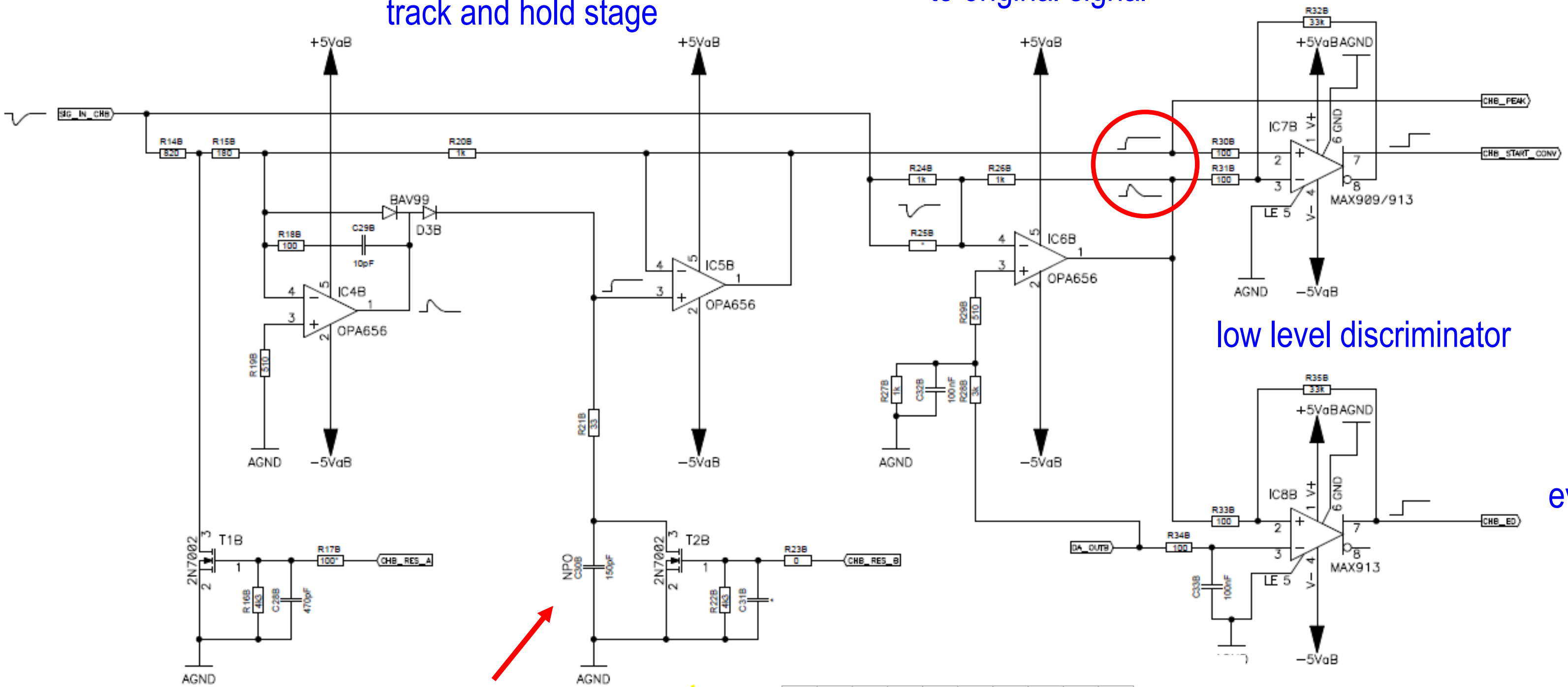
peak-detector

peak signal to ADC

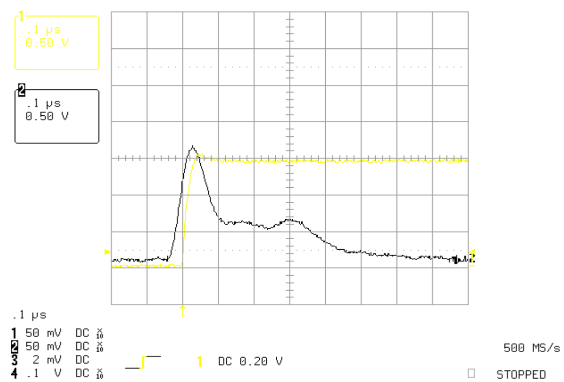
peak detected to FPGA

low level discriminator

event detected to FPGA

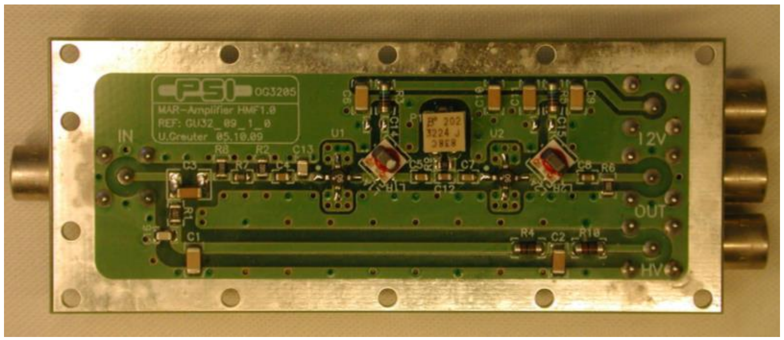


analog storage
Happens here



Example: MAR-Amplifier

MAR-Amplifier for Photon-Detectors



Functional description:

The "MAR"-Amplifier was designed for fast photo-diode (e.g. APD) applications where due to limited space at the detector-side the photo-diodes has to be off-board and where coax cables are needed to connect them to the amplifiers.

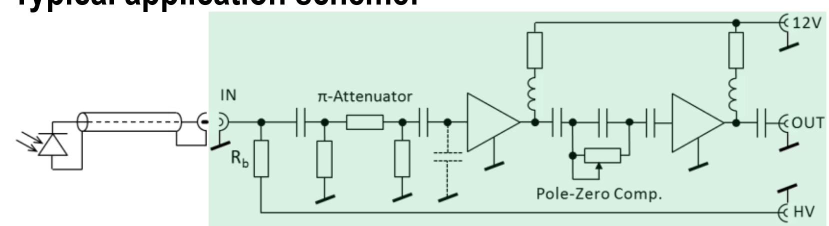
The board layout allows for the assembly of two RF gain blocks which can be chosen from a wide palette of monolithic amplifiers in .085 micro-x or SOT-89 case styles.

Within 50 Ω systems the amplifier can be used either as transimpedence or voltage amplifier. It is cascadable.

The two gain stage amplifier design includes:

- π-attenuator for gain setting
- adjustable pole-zero cancellation for pulse shaping
- integrating capacitor for upper bandwidth limitation
- lower bandwidth adjustment by of AC-coupling capacitor
- filtered high voltage path for reverse bias voltage

Typical application scheme:



Specifications (with MAR-6SM on both stages):

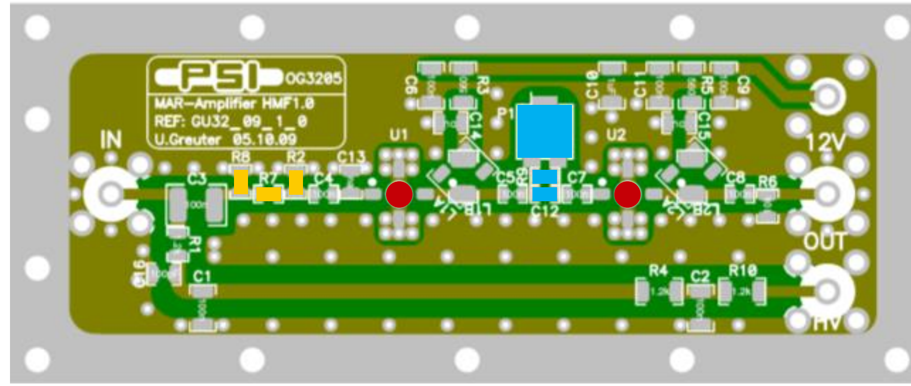
- Input impedance 50 Ω
- primary transimpedance gain 50 V/A
- voltage gain (with no π- attenuation):

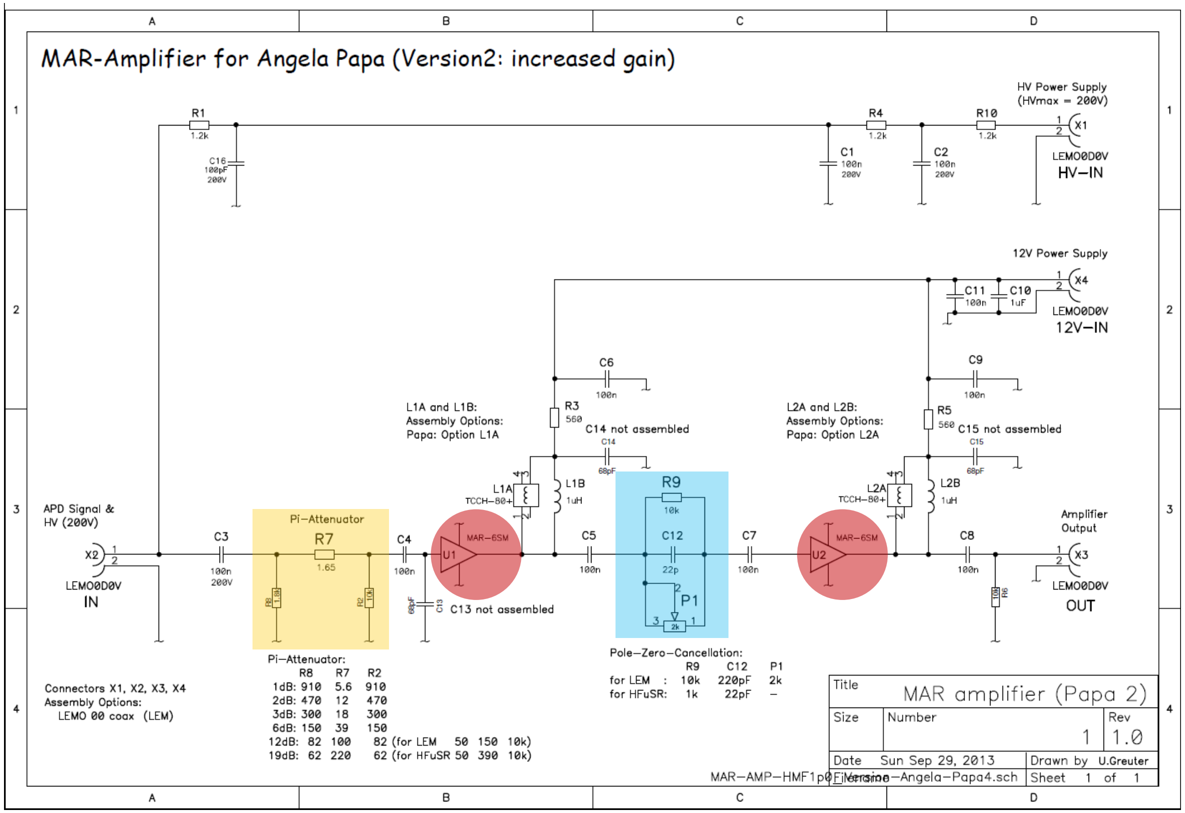
Frequency	100 kHz	750 MHz	1 GHz	2 GHz
Gain	40 dB	37 dB	32 dB	22 dB

- linear output range (1dB compression) 342 mV_{rms} @ 50Ω
- max. reverse bias voltage 200 V
- power-consumption amplifier +12 V, 32 mA

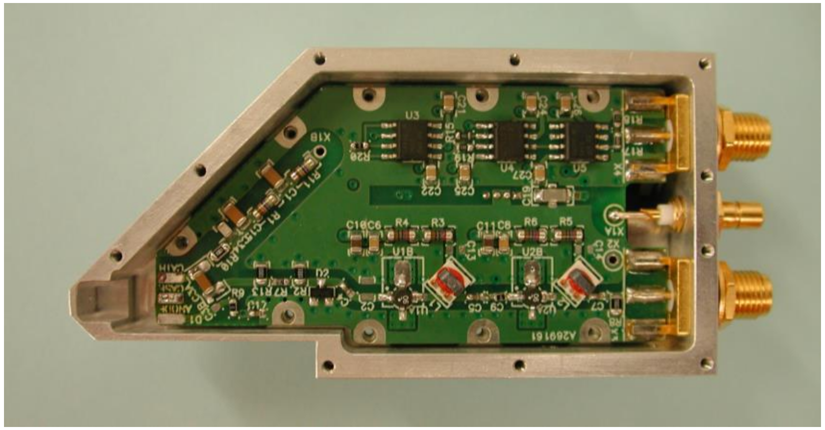
Example: MAR-Amplifier

The MAR-Amplifier





MAR-Amplifier for STXM @ PolLux-Beamline



Brief description:

Amplifier for fast avalanche photo diodes (e.g. Silicon Sensor, AD230-8, 180 ps rise time) with integrated low and high voltage filters, a current monitor output for the APD bias current and pulse-shaping options like a π-attenuator, an integrating capacitor and a pole-zero cancellation stage.

The board layout allows to read out the APD-signal either on the cathode or anode side. The two RF amplifier stages can be assembled with a wide palette of monolithic amplifiers in .085 micro-x or SOT-89 case styles.

Specifications (MAR-6SM on both stages):

RF-Amplifier Output:
- current to voltage conversion 50 V/A
- voltage gain at frequency

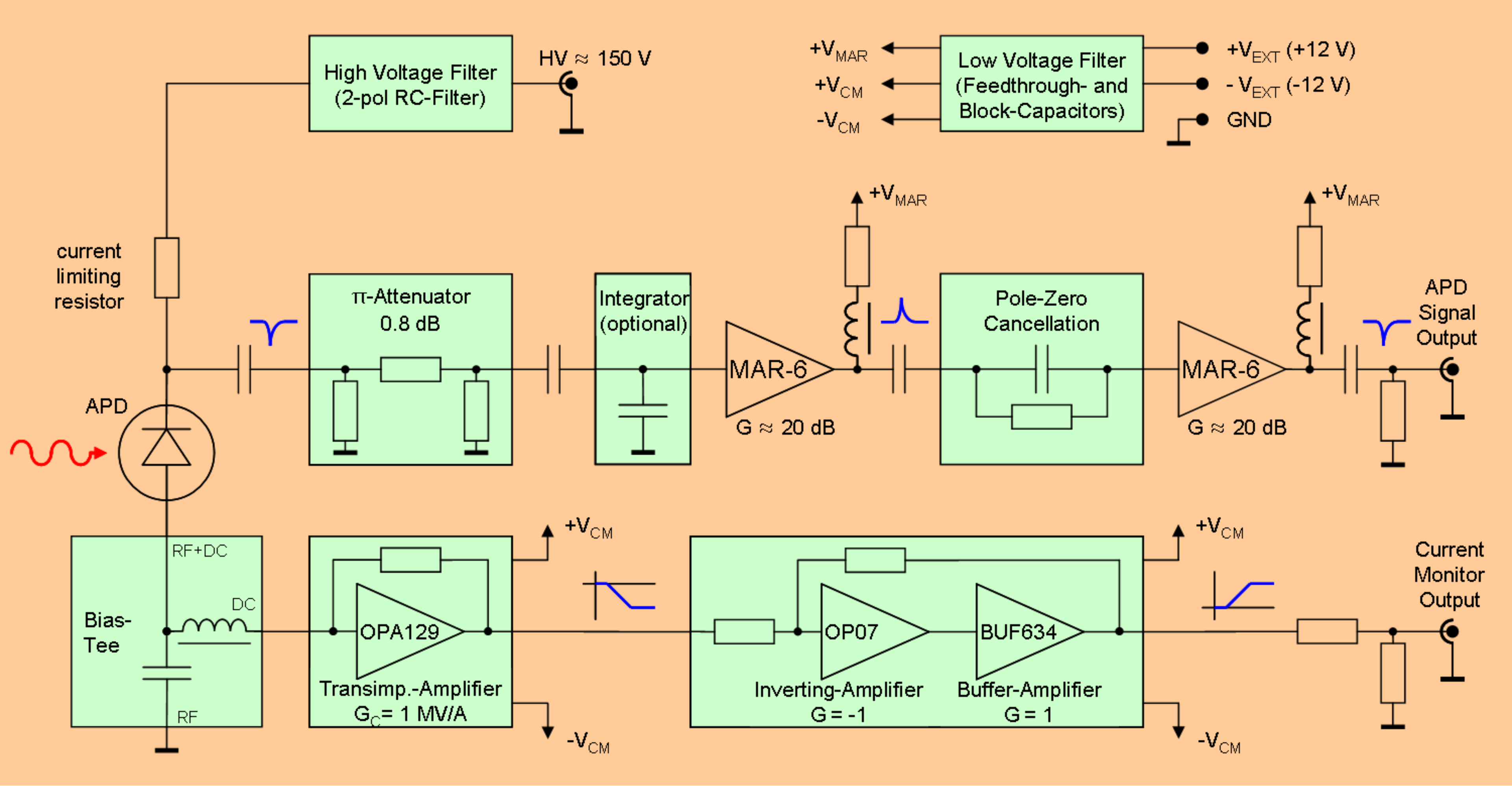
Frequency	100 kHz	750 MHz	1 GHz	2 GHz
Gain	40 dB	37 dB	32 dB	22 dB

- max. output voltage (1dB Comp): 282 mV @ 50Ω

Current Monitor Output:
- input current range 0 … 500 nA
- accuracy < 0.1% full scale
- current to voltage conversion 1 V/µA
- bandwidth 1 kHz

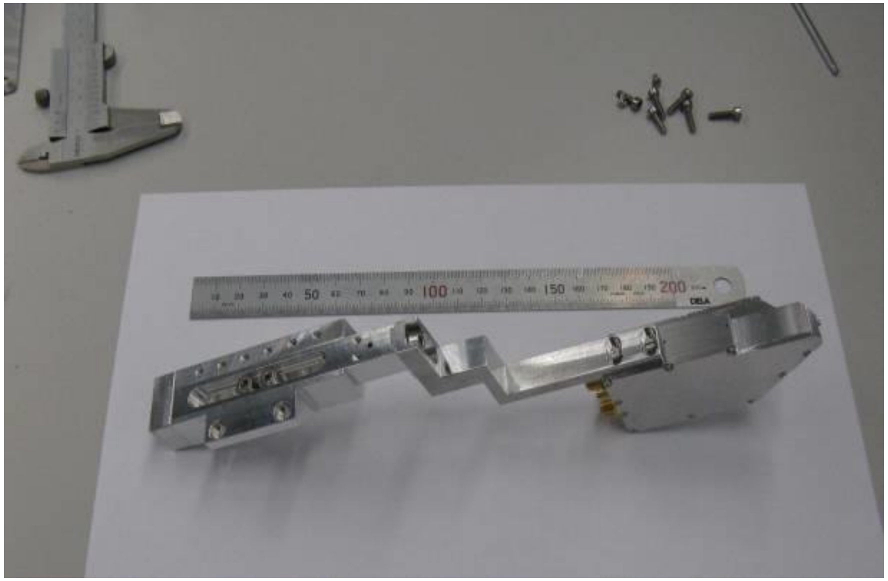
Power-Supply:
- Amplifier +/-12V, 300mA
- max. APD - voltage 200 V

MAR-Amplifier for STXM @ PolLux-Beamline



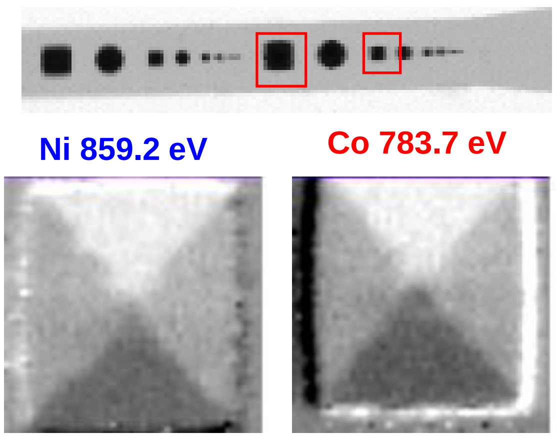
Static imaging and 1st movie of magnetization dynamics taken with the new APD-Detector at the PolLux-STXM

PAUL SCHERRER INSTITUT PSI

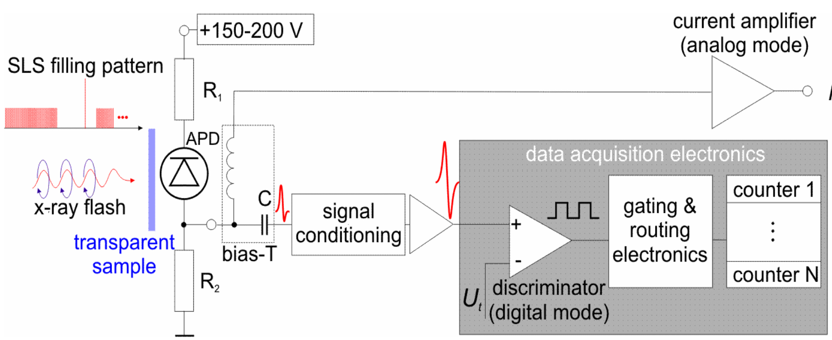


APD-Detector : Urs Greuter, Blagoj Sarafimov, Jörg Raabe, Aleksandar Puzic

Sample: Co (50 nm) / Rh (0.75) / NiFe (50 nm)
FM coupling due to Ne ion irradiation



static magnetic imaging:
square 2000 nm x 2000 nm, P+/P-



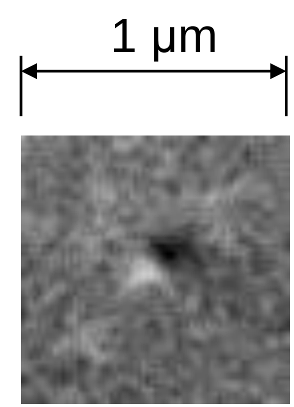
Principle of detection and data acquisition

movie: square 1000 nm x 1000 nm

image size: 1000 nm x 1000 nm
resolution: 15 nm
dwell time: 20ms
2 phases (0 deg & 45 deg) with 4 channels

measured magnetization component:
out-of-plane (vortex core)
Ni (859.2 eV), P-

Excitation:
f = 625 MHz, B_0 = 2.25 mT (in plane) field



Slide received on 24.06.2010 from Jörg Raabe

Sample preparation: Sebastian Wintz, Thomas Strache

Forschungszentrum Dresden Rossendorf