*Advanced course on*

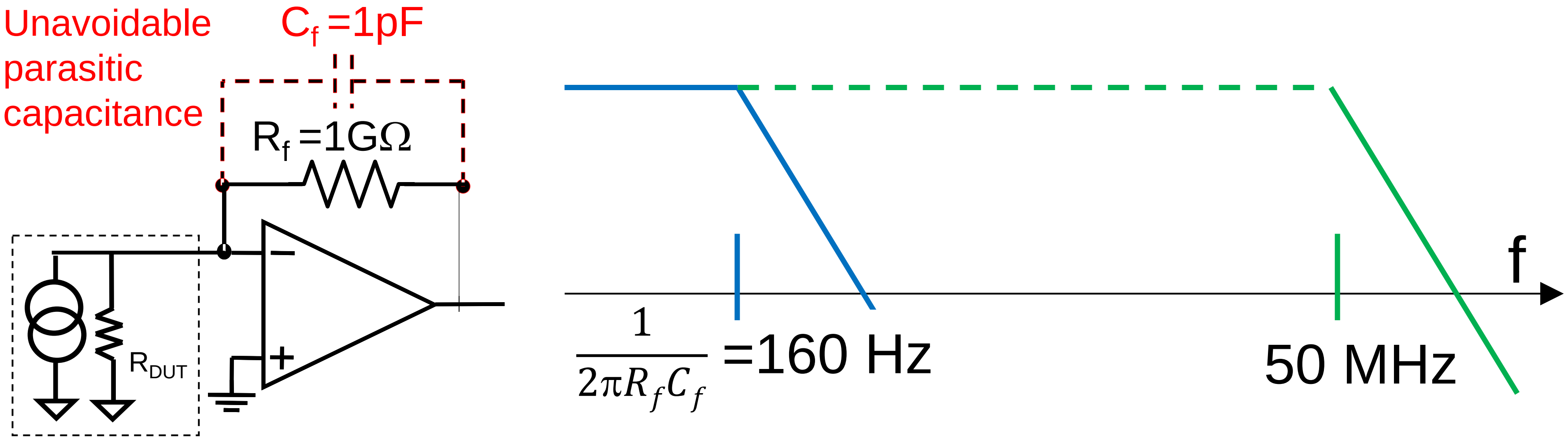
HIGH RESOLUTION ELECTRONIC MEASUREMENTS
IN NANO-BIO SCIENCE

# ADVANCED TIAs
# Reaching aA resolution

Marco Sampietro

# How to :

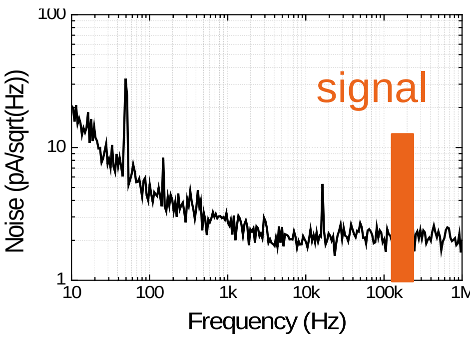
1 - Extend Bandwidth → reach MHZ



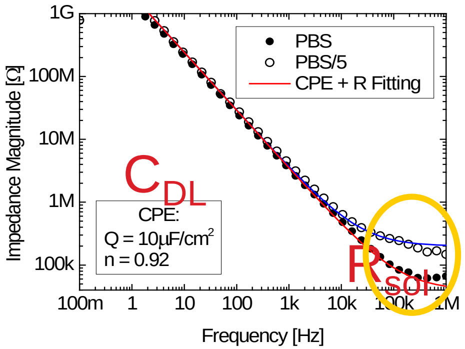

2 - Extend Sensitivity → reach attoAmpère ($10^{-18}$A)

# Why working at higher frequencies ?

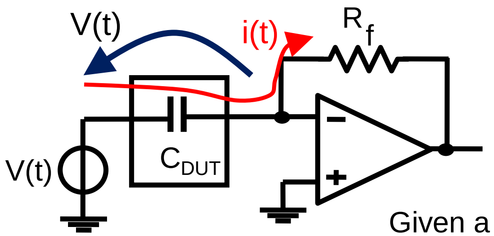
Go away from 1/f noise of many sensors/devices




Track interesting physics that may be there




Investigate capacitive behaviour in nanodevices




$$i(\omega) = \frac{v(\omega)}{1/j\omega C} = v(\omega) \cdot j\omega C$$

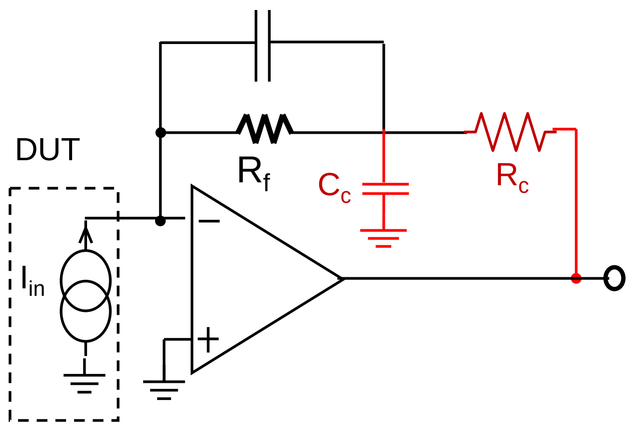
Given a current resolution…

at higher frequency ...

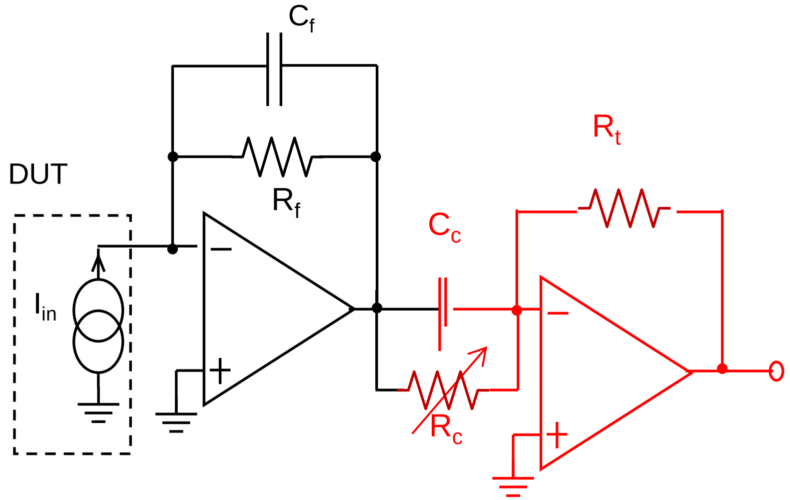
smaller C can be measured

# **How to extend BW ?** A guide for circuit designer

## T – network

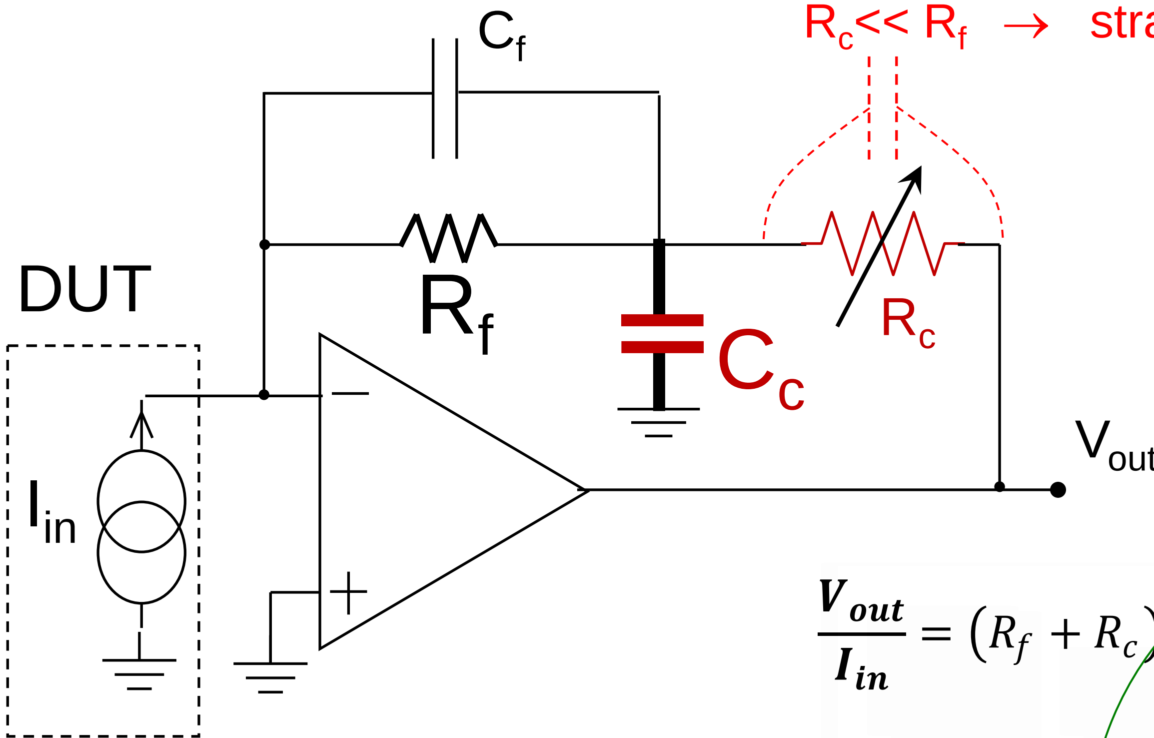



## Compensated Transimpedance Amplifier



# T – network: transfer function

$R_c << R_f$ → strays are not important




$$\frac{V_{out}}{I_{in}} = (R_f + R_c)\frac{1 + s(C_c + C_f)R_c||R_f}{1 + sC_f R_f}$$

$R_c$ calibrated to obtain

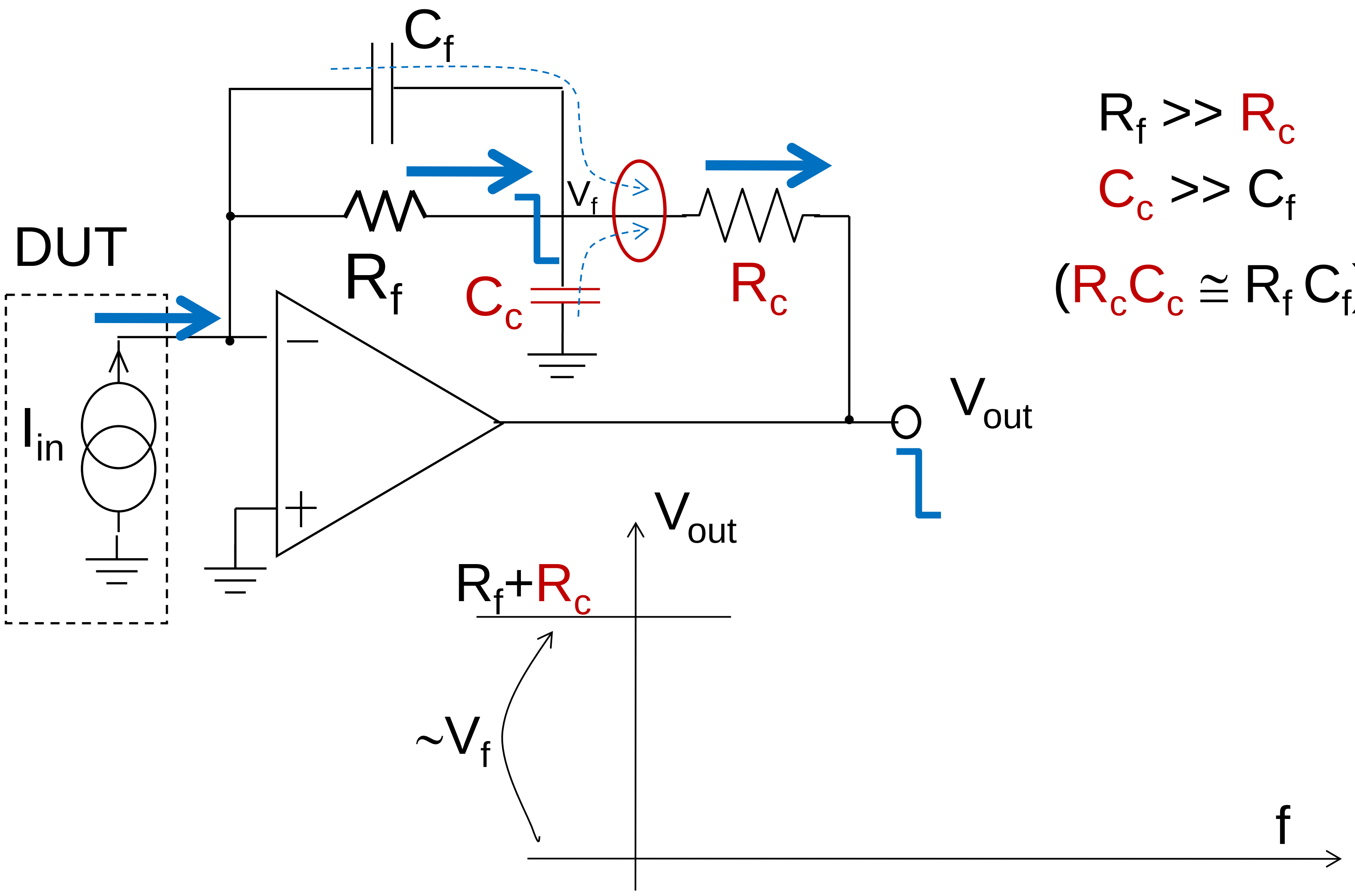
$(C_c+C_f)\, R_c||R_f = R_f\, C_f$

$C_c\, R_c \approx R_f\, C_f$

$$\frac{V_{out}}{I_{in}} = (R_f + R_c)$$

Bandwidth limited by OpAmp !

# T network – low frequencies

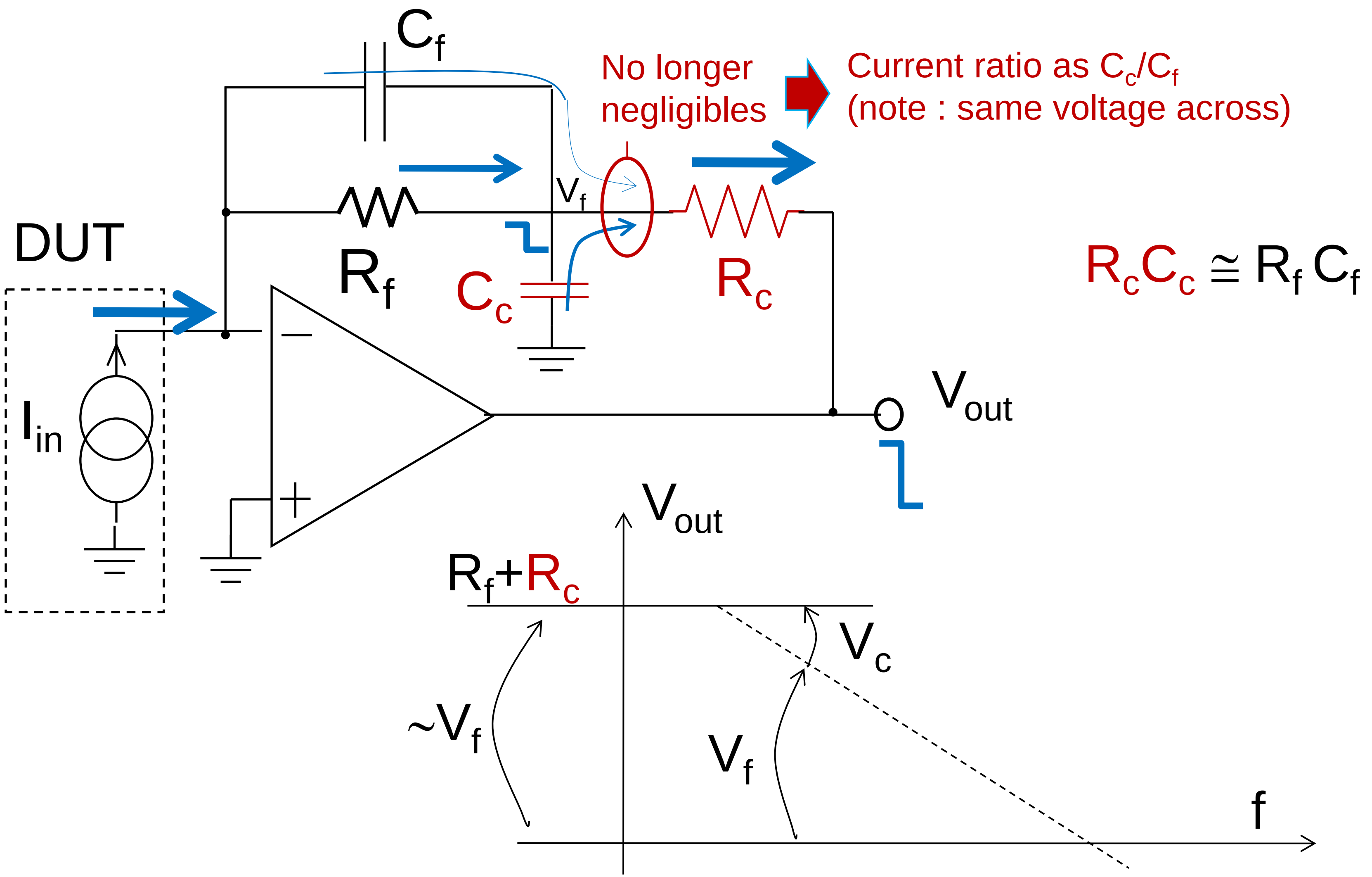



$R_f >> R_c$

$C_c >> C_f$

$(R_c C_c \cong R_f C_f)$

# T network - medium frequencies

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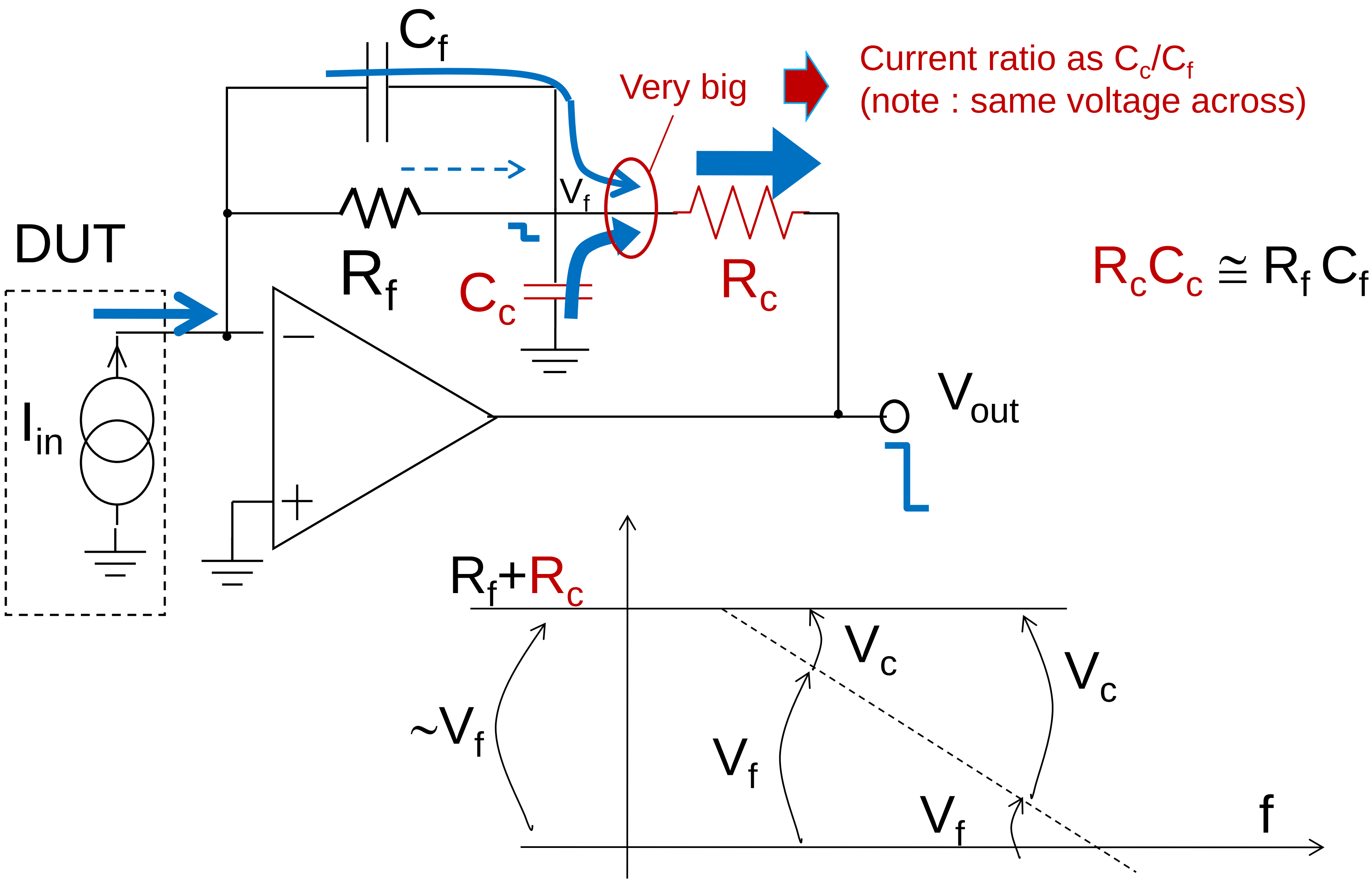
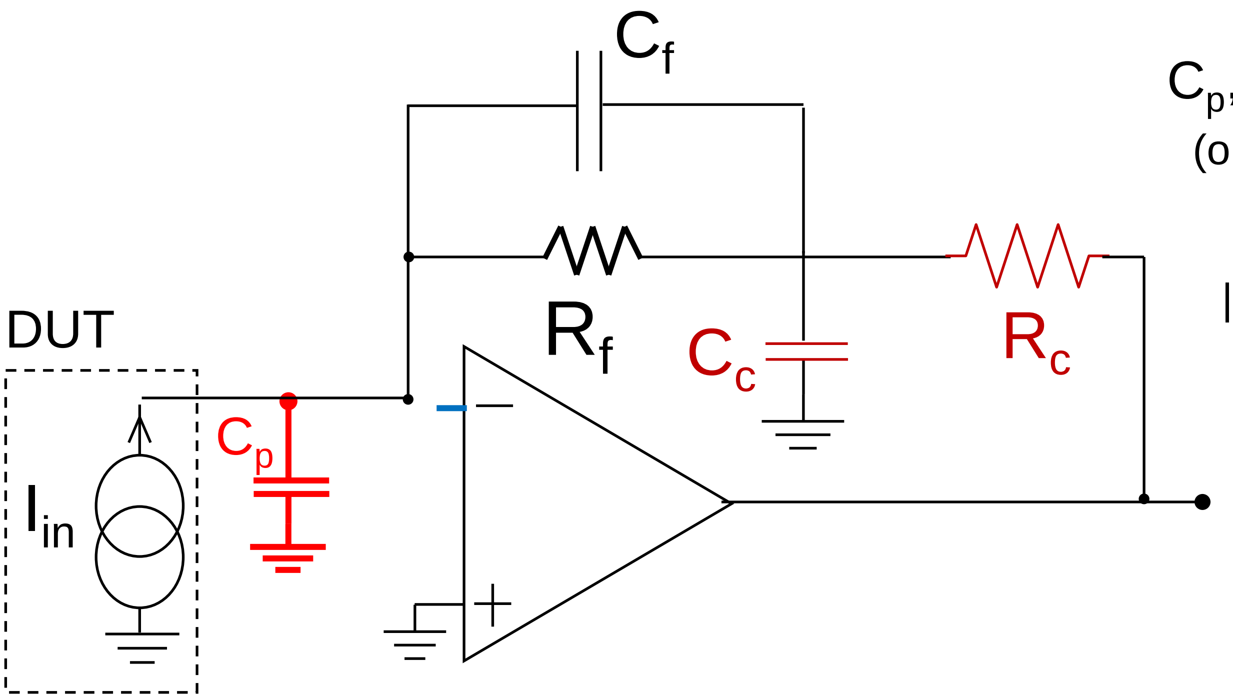
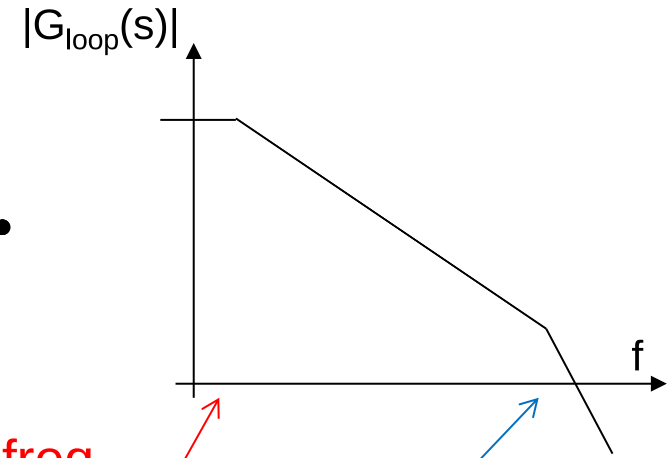
# T network - high frequencies



# T – network: stability




$C_p$,$C_f$,$C_c$ are GND to GND
(only 2 poles, and 1 zero)



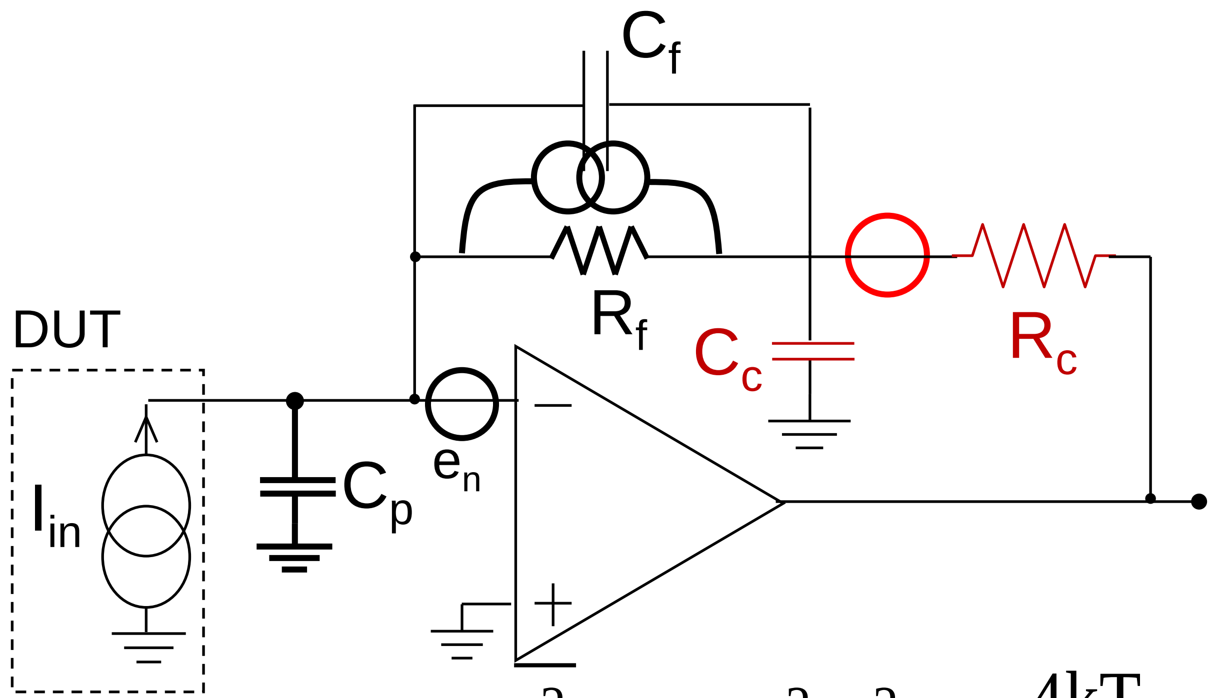

Hyp.: $C_c R_c \approx R_f C_f$
$C_f << C_c, C_p$

low freq. (<100Hz)

$$\boldsymbol{G_{loop}(s)} \cong -A(s)\frac{1+sC_fR_f}{(1+sC_pR_f)(1+sC_cR_c)} \cong \frac{A(s)}{1+sC_pR_f}$$

Design A(s) with a pole at high frequency !

# T – network: noise of the added section

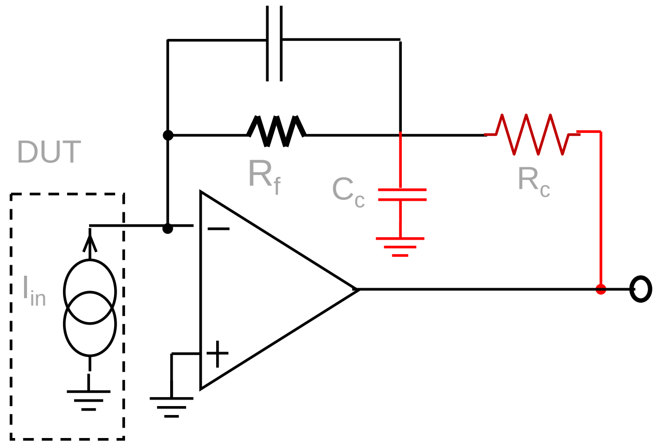



$$i_n^2 = e_n \omega^2 C_p^2 + \frac{4kT}{R_f} + \frac{4kT \cdot R_C}{(R_f + R_C)^2}$$

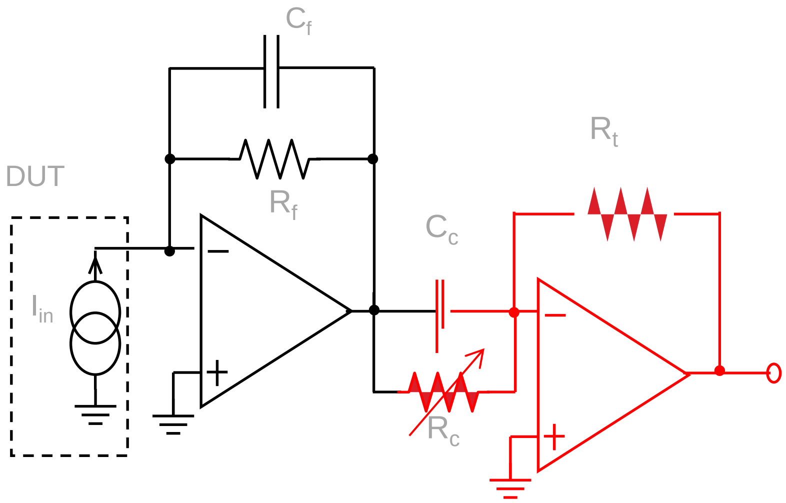
LIKE A STANDARD AMP. NEGLIGIBLE

Howard, RSI, 70, p.1860 (1999): BW=17kHz, $i_{eq} \approx 1.3fA/\sqrt{Hz}$ up to 100Hz

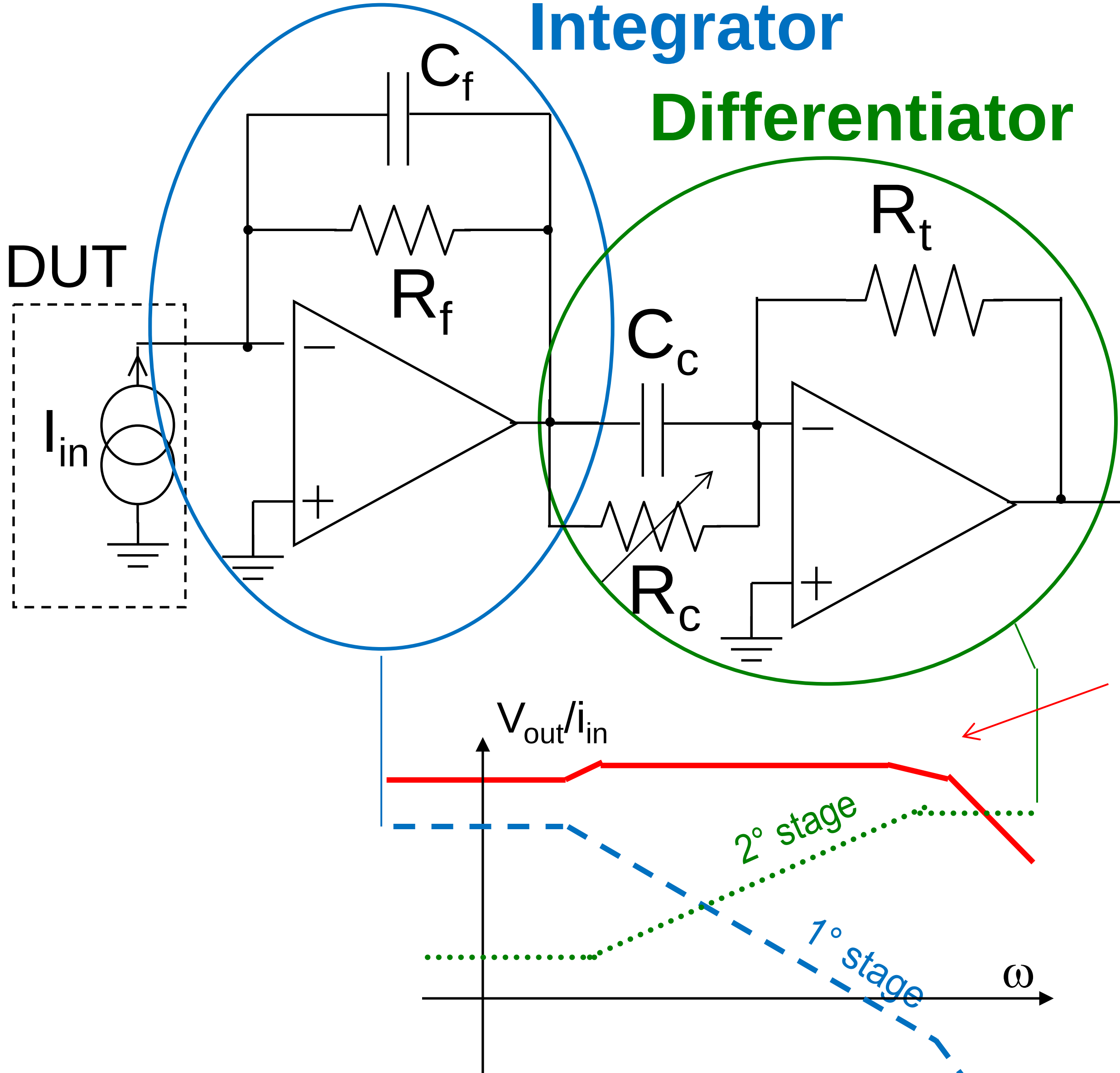
## T – network




## Compensated Transimpedance Amplifier



# Compensated Transimpedance Ampl.




$$\frac{V_{out}}{I_{in}} = R_t \frac{R_f}{R_c} \frac{1 + sC_cR_c}{1 + sC_fR_f}$$

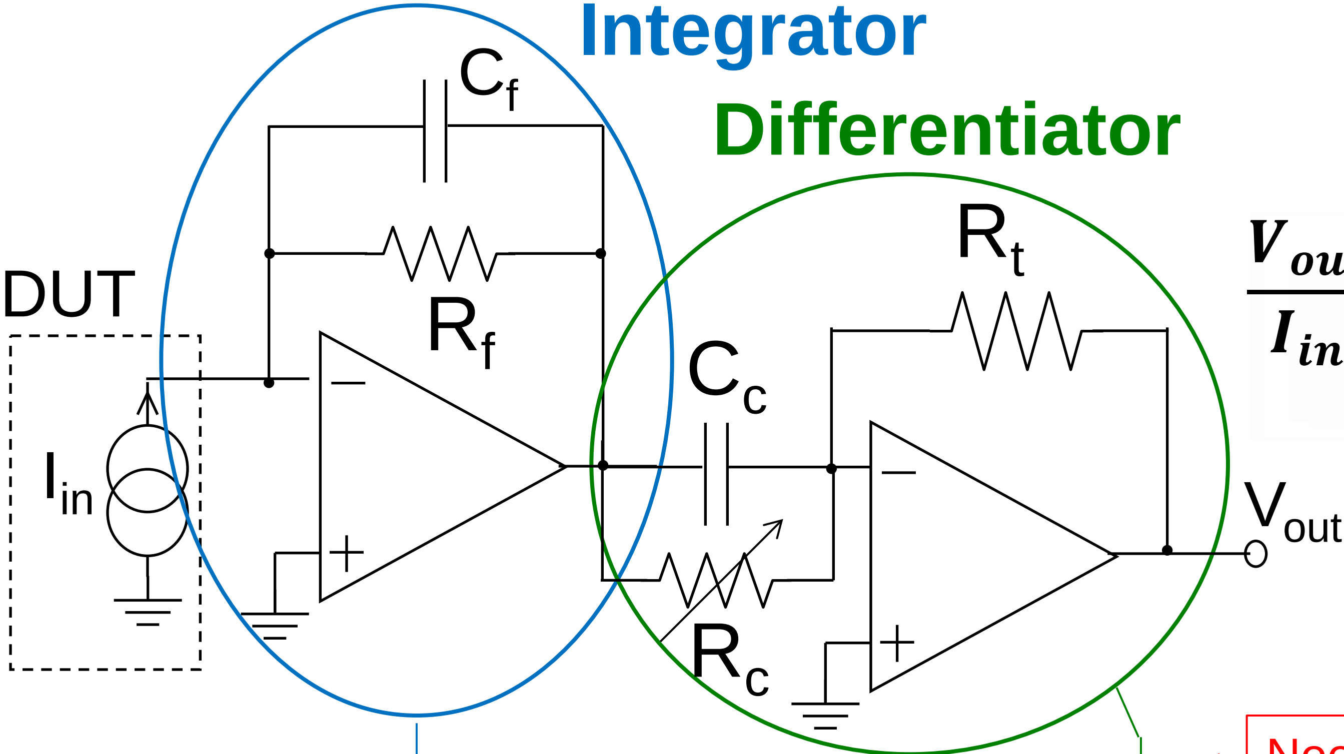
$$C_cR_c = C_fR_f$$

Needs carefull tuning of $R_c$

$$\frac{V_{out}}{I_{in}} = R_t \frac{R_f}{R_c}$$

Carlà, RSI, 75, p.497 (2004),
Ciofi, IEEE Instr.&Meas. 55, p.814 (2006)
Carminati, Analog IC Sig. Process (2013)

# Compensated Transimpedance Ampl.

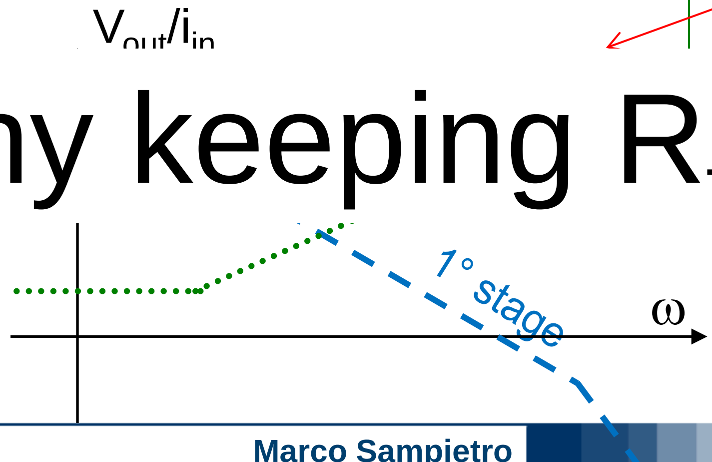



$$\frac{V_{out}}{I_{in}} = R_t \frac{R_f}{R_c} \frac{1 + sC_cR_c}{1 + sC_fR_f}$$

$$C_cR_c = C_fR_f$$

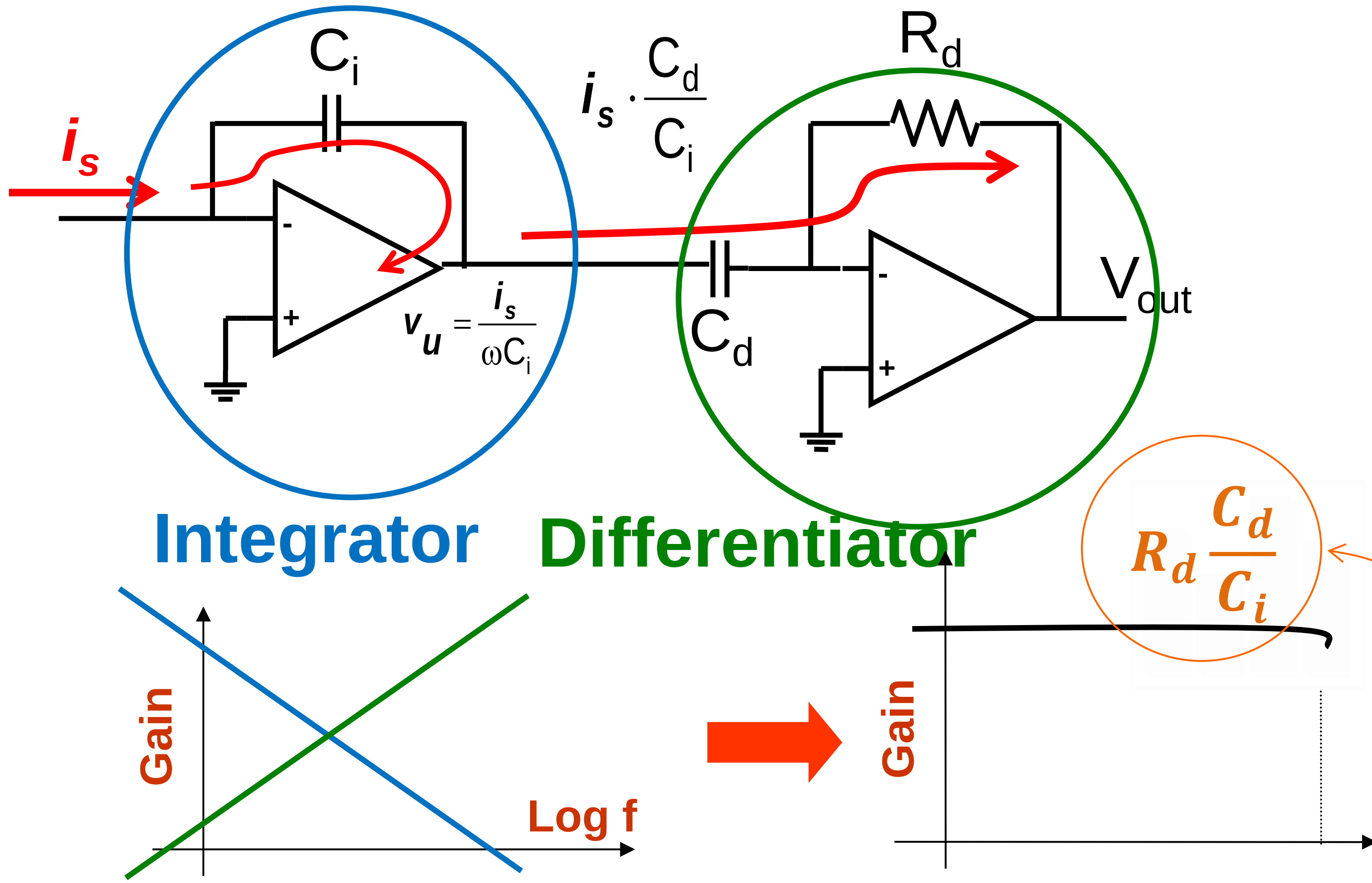
Needs carefull tuning of $R_c$

Why keeping $R_f$ and $R_C$ ?



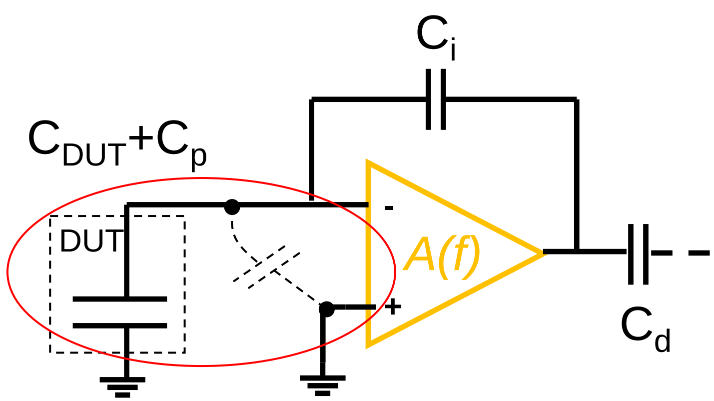

Carlà, RSI, 75, p.497 (2004),
Ciofi, IEEE Instr.&Meas. 55, p.814 (2006)
Carminati, Analog IC Sig. Process (2013)

# NO $R_f$ and $R_C$ - SIGNAL OK

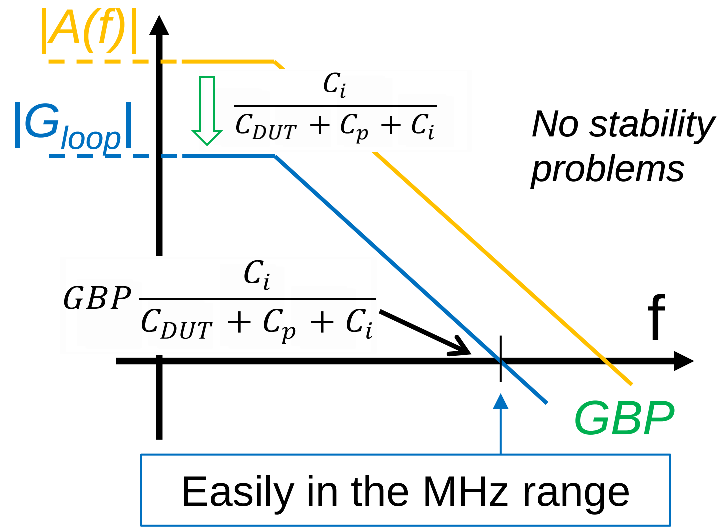


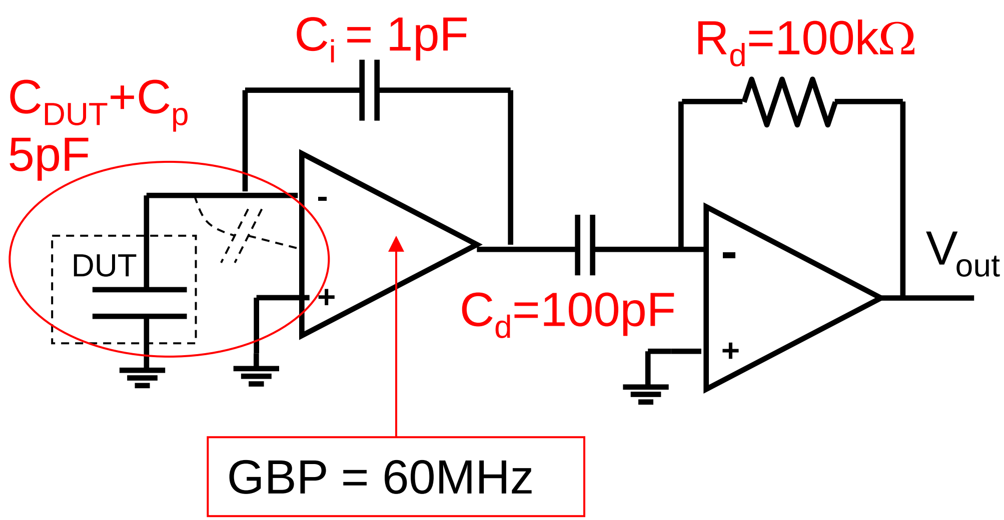

Stable, easy to be set, linear, no calibration

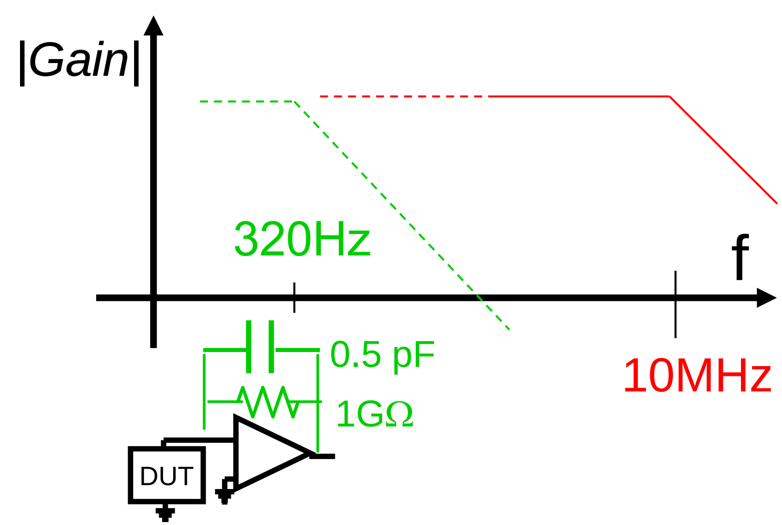
# NO $R_f$ and $R_C$ - BANDWIDTH OK




$$G_{loop}(s) \cong -A(s)\frac{C_i}{C_{DUT}+C_p+C_i}$$





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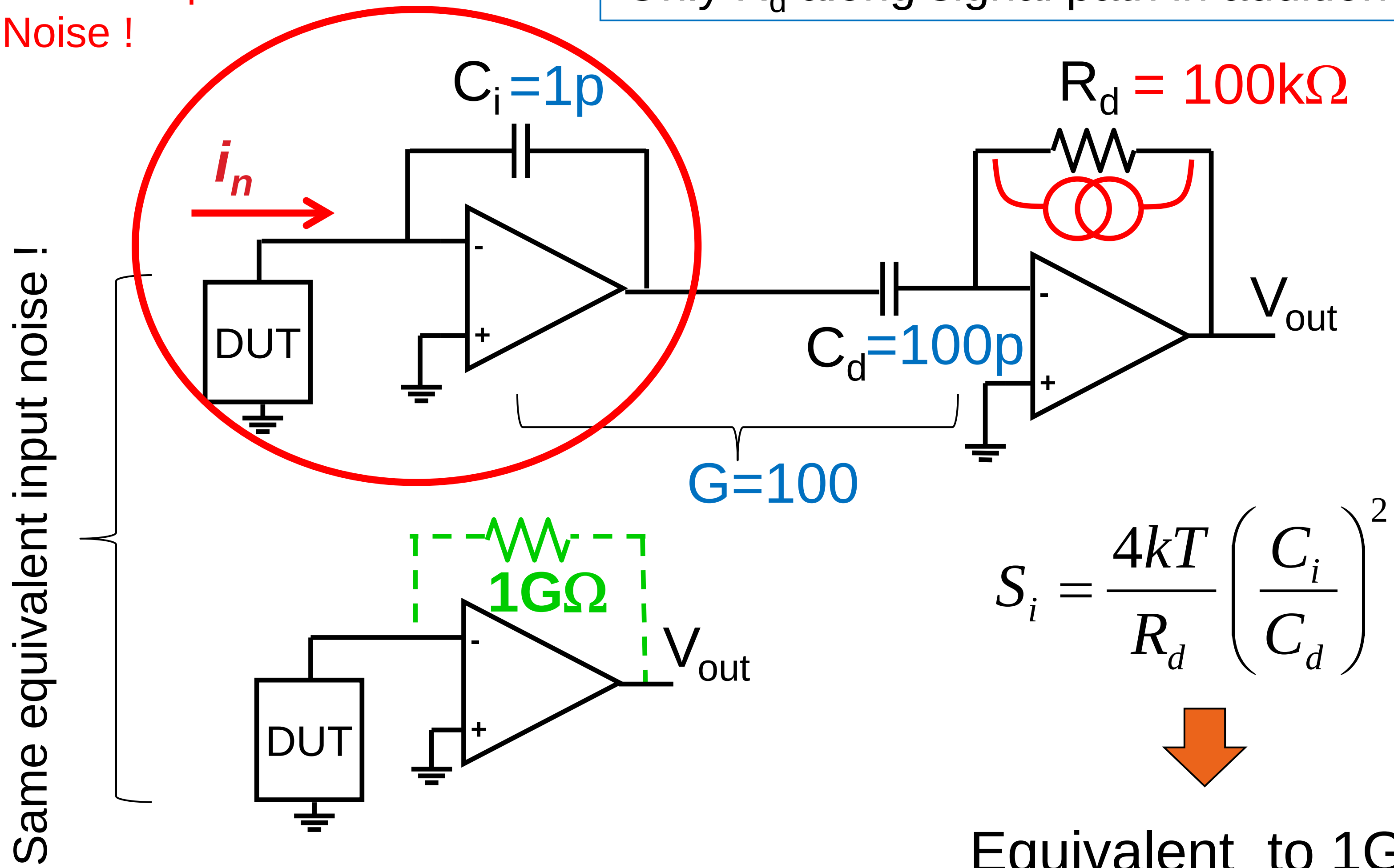
# NO $R_f$ and $R_C$ - NOISE OK

Minimum possible Noise !

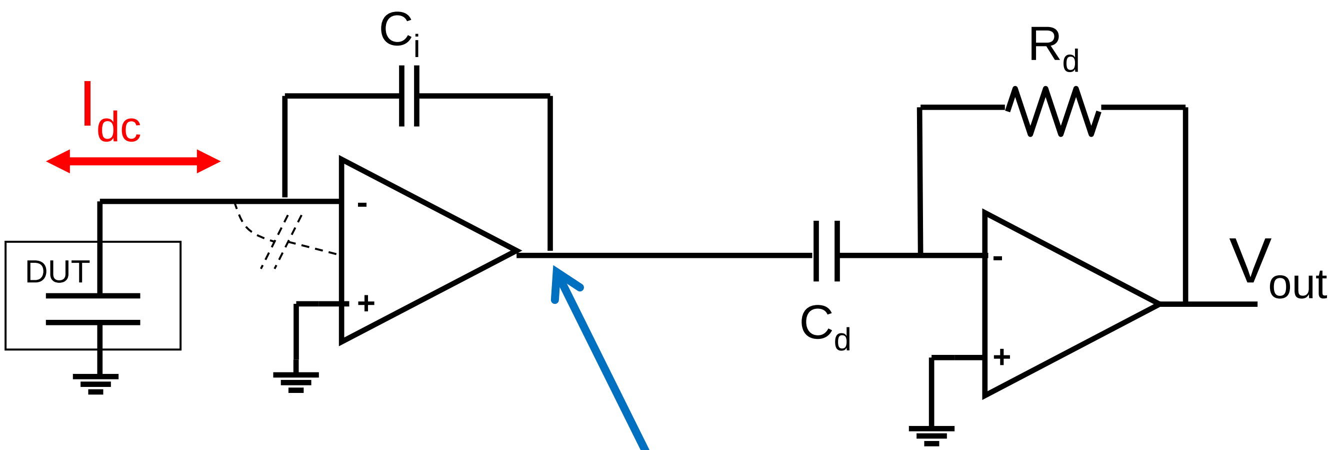
Only $R_d$ along signal path in addition to OpAmps




$$S_i = \frac{4kT}{R_d}\left(\frac{C_i}{C_d}\right)^2$$

Equivalent to 1GΩ

# NO $R_f$ and $R_C$ - OpAmp SATURATION

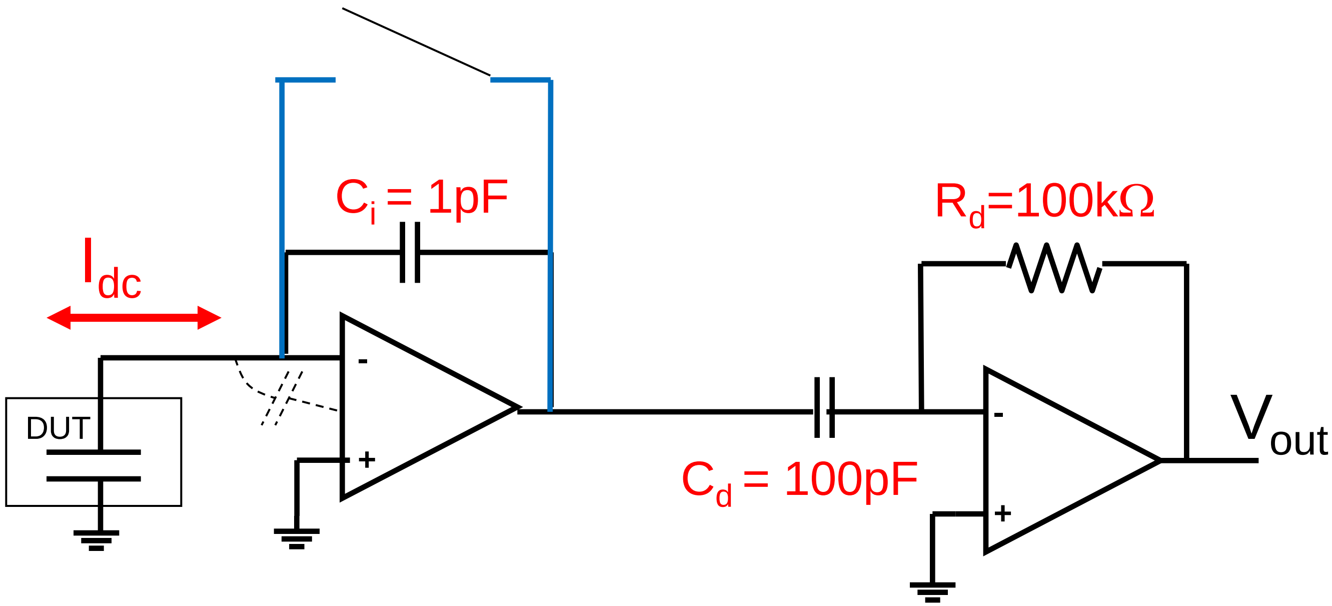



$$V_{out}(t) = \frac{1}{C_i}\int I_{\mathrm{dc}}\mathrm{d}t = \frac{I_{dc}}{C_i}t$$

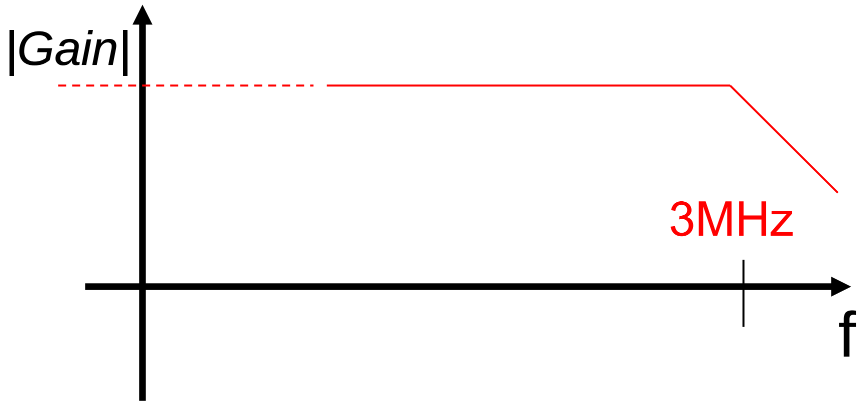
We need to reset !

Unavoidable OpAmp saturation !

# Pulsed reset




Limited time for measurement :

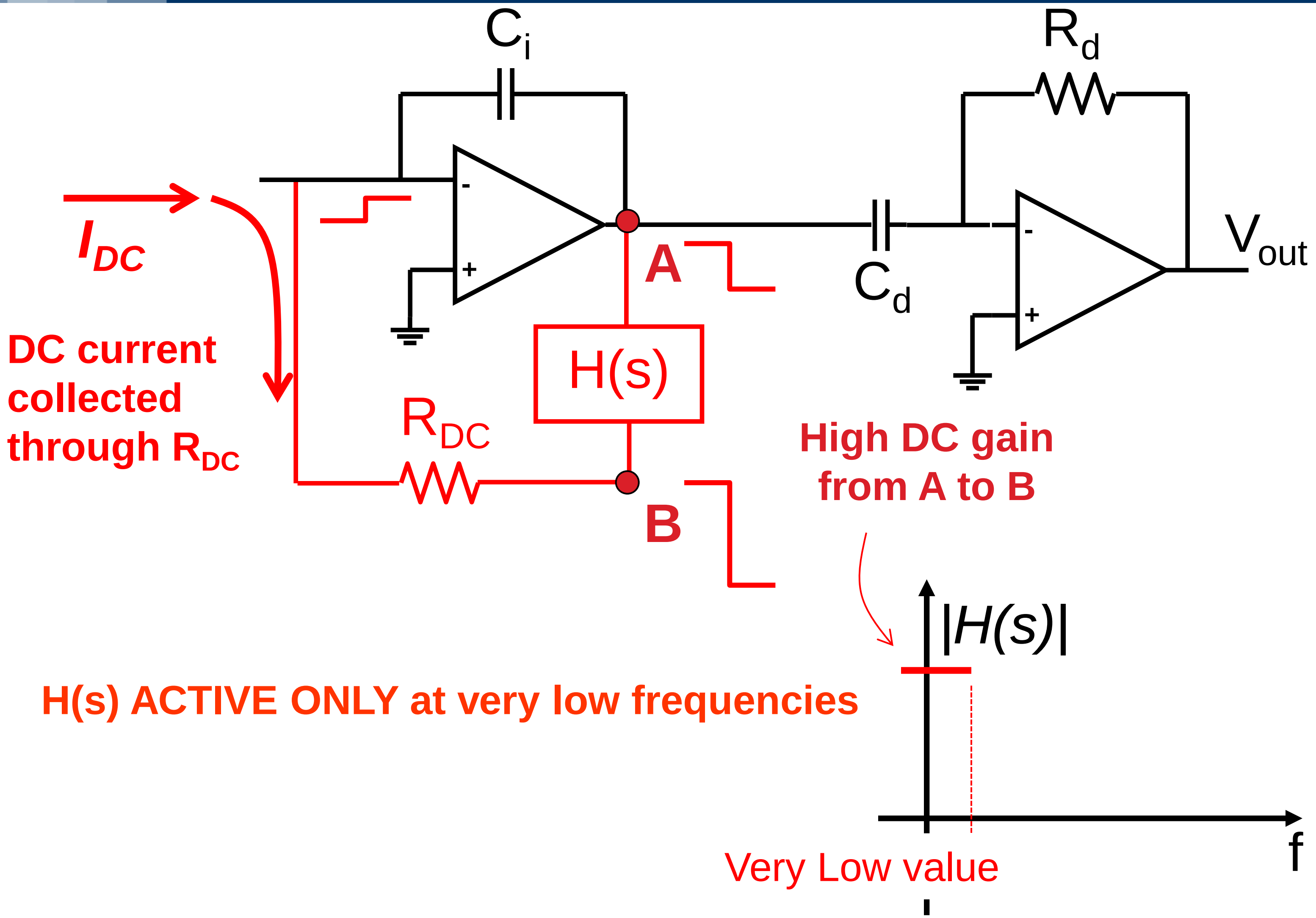



If $I_{dc}$=10nA, $V_{max}$=10V

$T_m$ = 1ms

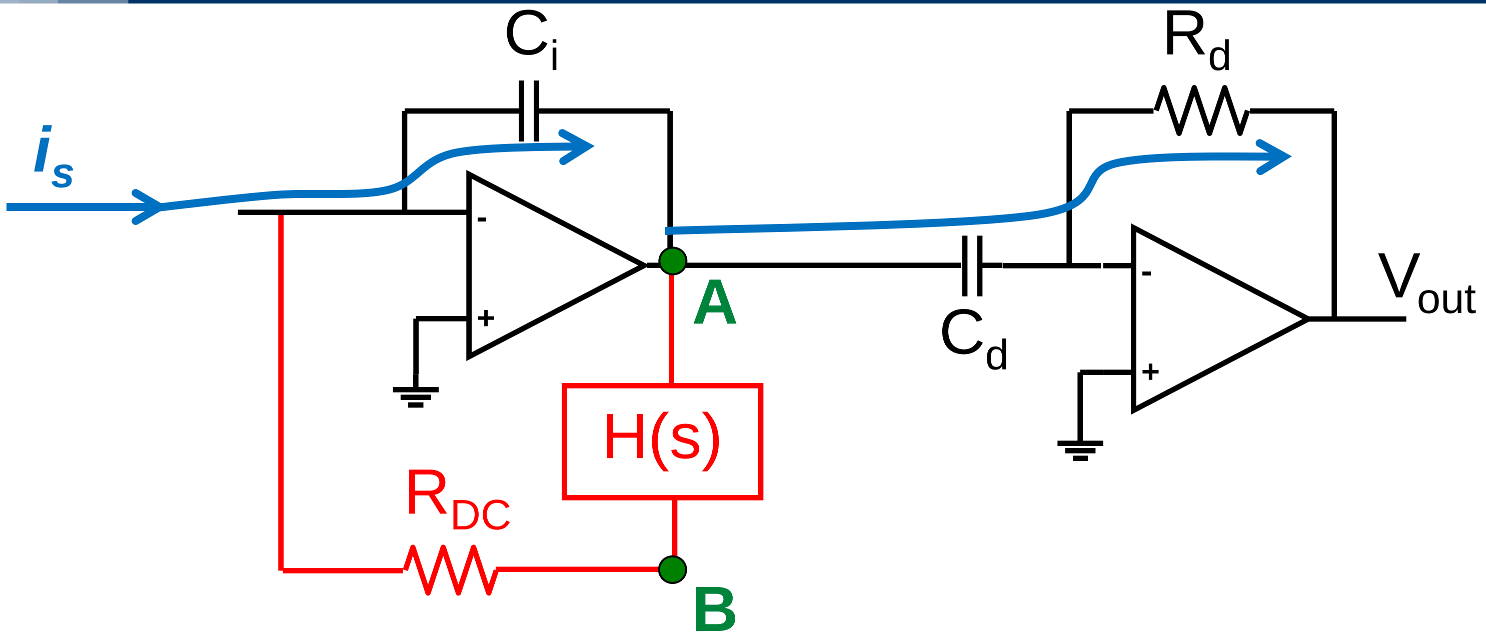
Axopatch 200B

# DC current reset

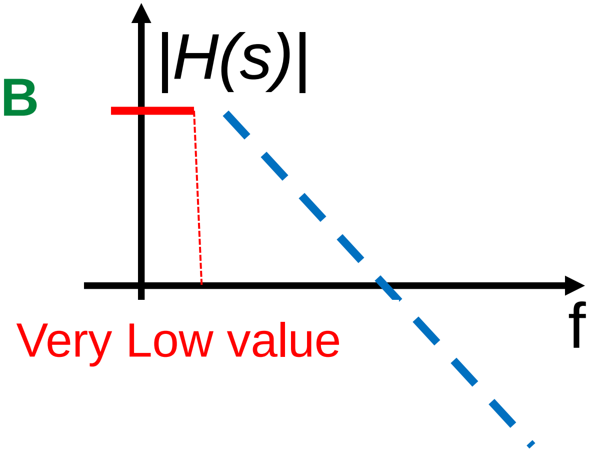



G.Ferrari et al., Rev.Sci.Instr., 78, p. 094703 (2007)

# DC current reset : signal path

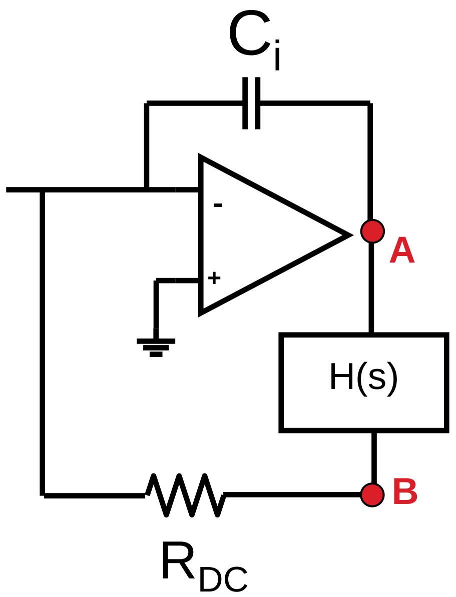



**Zero gain of H(s) from A to B at signal frequencies**

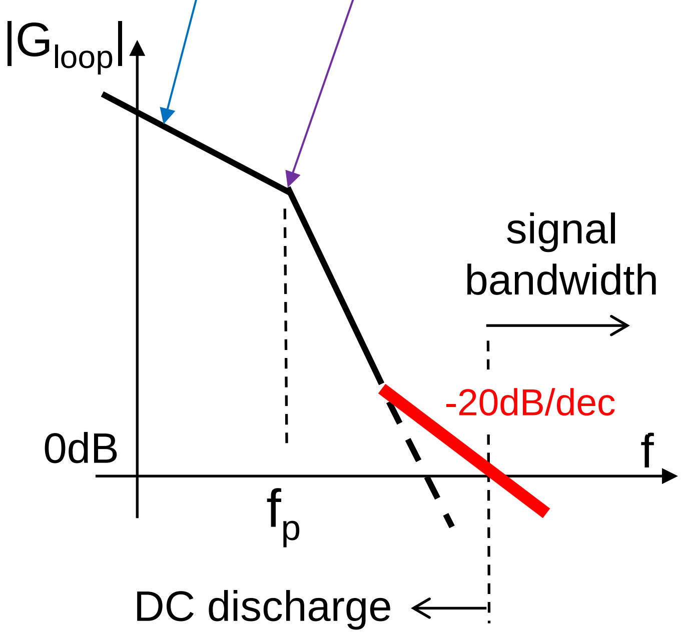


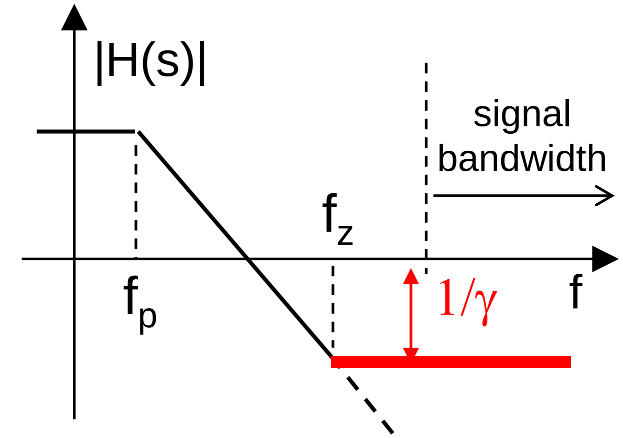

**H(S)** NOT active when signal is present

# DC current reset : stability remarks

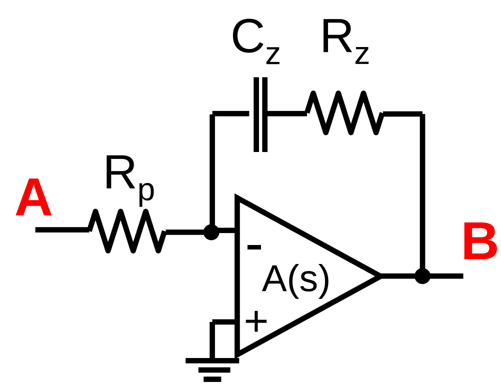



$$G_{loop} = \frac{1}{sC_i} \cdot H(s) \cdot \frac{1}{R_{DC}}$$



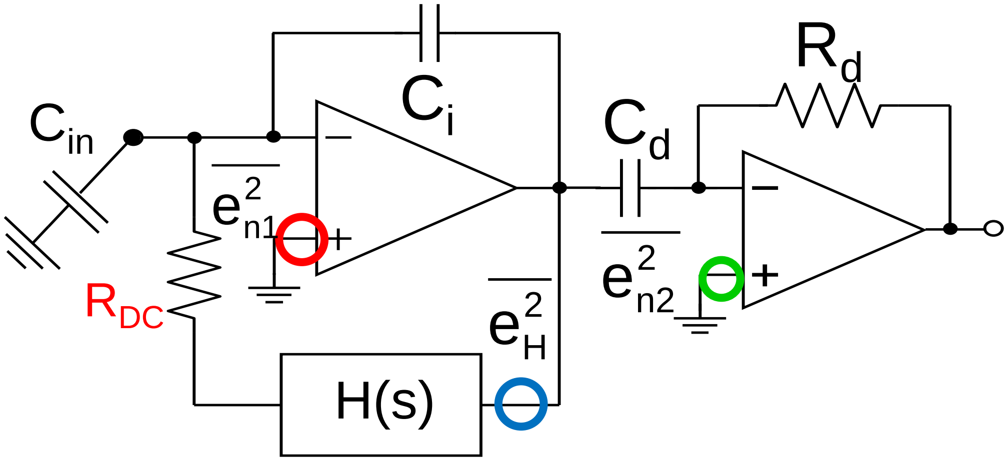



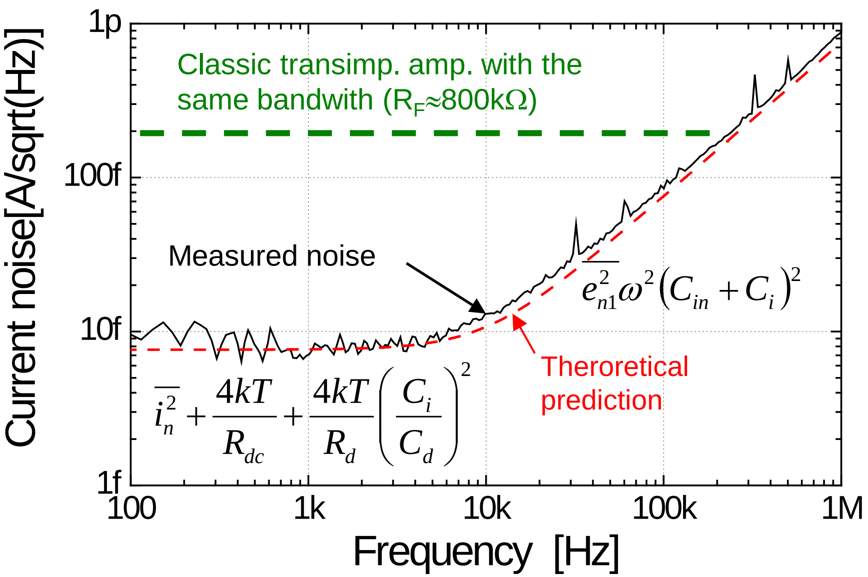

STABILITY imposes the same number of poles and zeros in H(s)




G.Ferrari et al., Rev.Sci.Instr., 78, p. 094703 (2007)

# DC current reset : noise




Input equivalent noise: $R_{DC}$ big

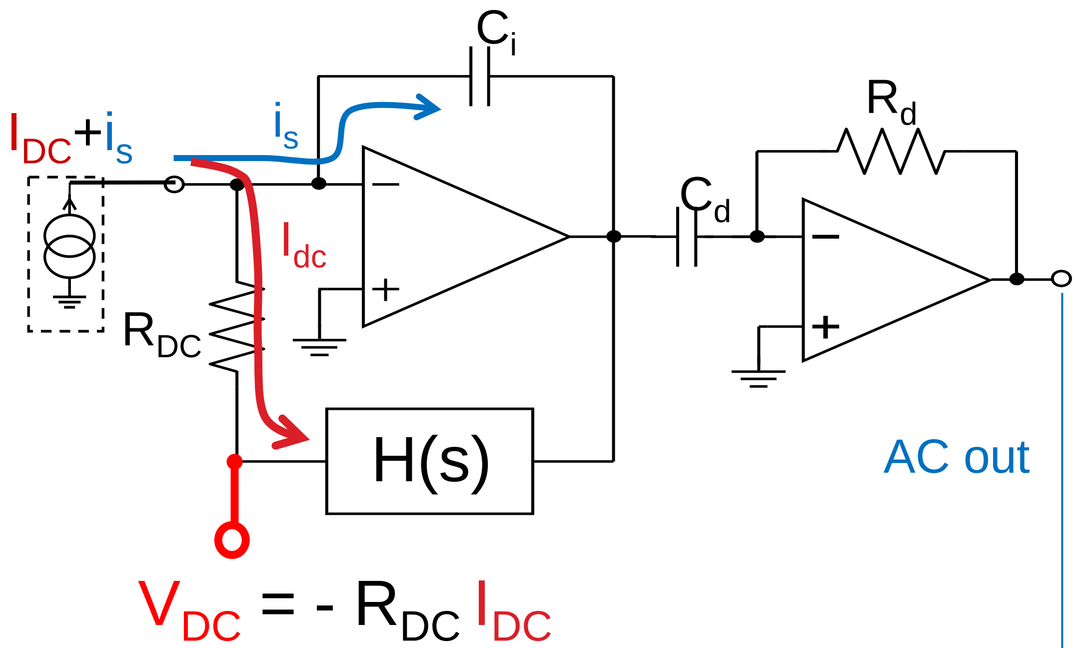
$$\overline{i_{eq}^2} \approx \overline{i_n^2} + \overline{e_{n1}^2}\omega^2(C_{in}+C_i)^2 + \frac{4kT}{R_{dc}} + \frac{\overline{e_H^2}}{R_{dc}^2} + \overline{e_{n2}^2}\omega^2 C_i^2 + \frac{\overline{e_{n2}^2}}{R_d^2}\left(\frac{C_i}{C_d}\right)^2 + \frac{4kT}{R_d}\left(\frac{C_i}{C_d}\right)^2$$

Same as a classical TIA

negligible for $R_{dc}$>100kΩ

Reduced by the gain $C_d/C_i$

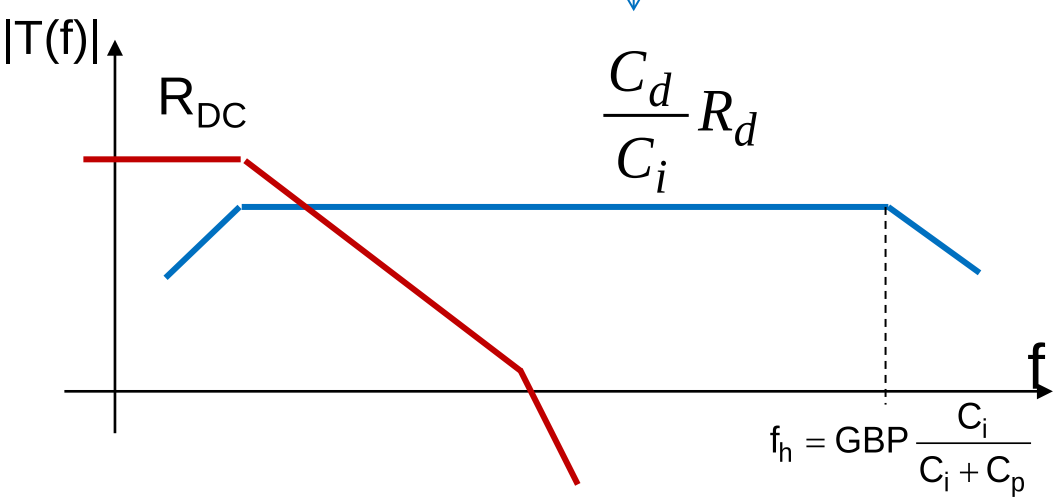
# DC current reset : $I_{leak}$ monitor




$R_{DC}$ as BIG as possible
$\Rightarrow$ low noise

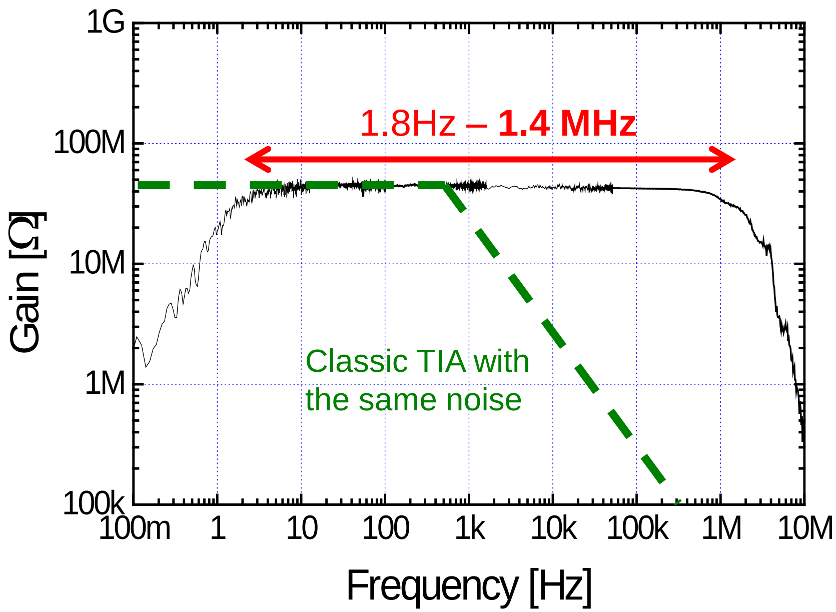
$R_{DC}$ not too big
$\Rightarrow$ large dynamic of $I_{DC}$

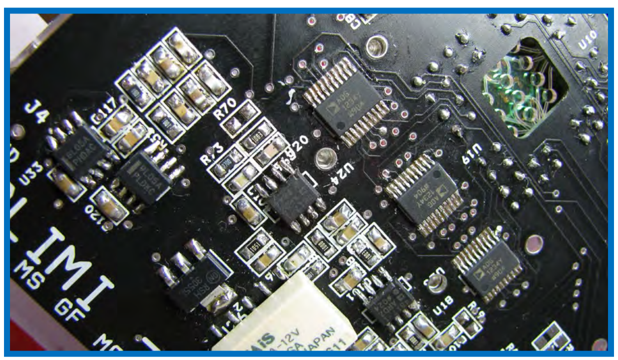
**$R_{DC}$ doesn't affect BW**
***Very good !***



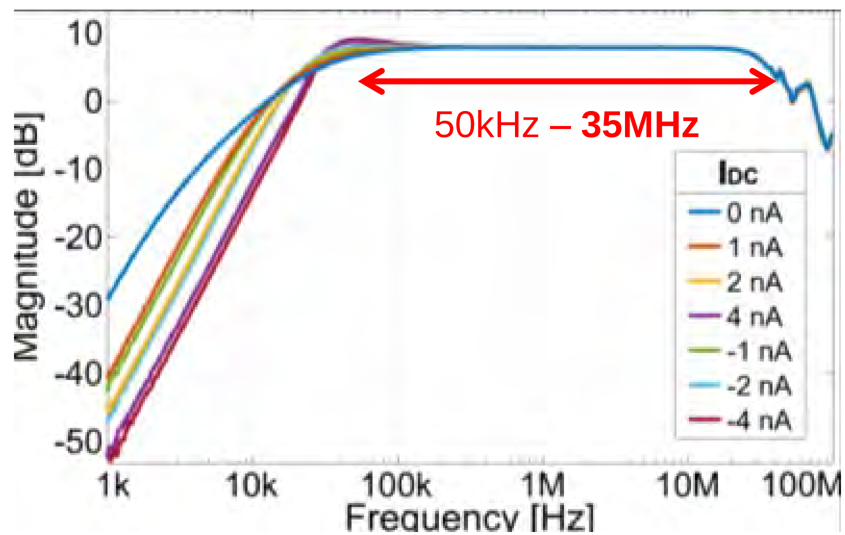
# DC current reset : examples

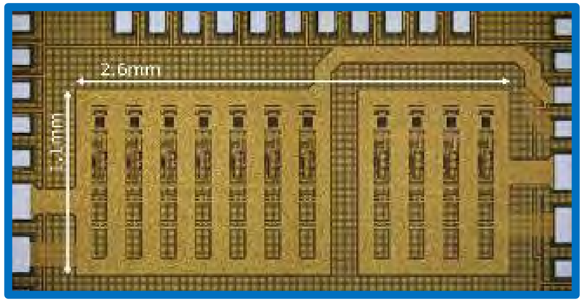
*Components on a board*



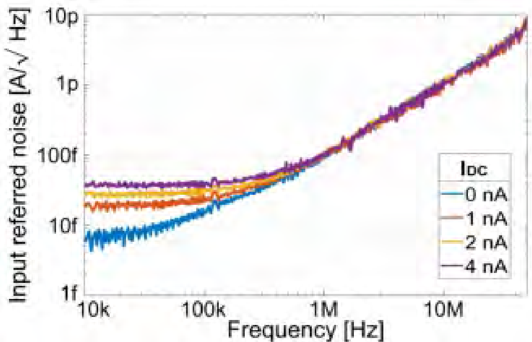



*Integrated Circuit (ASIC)*

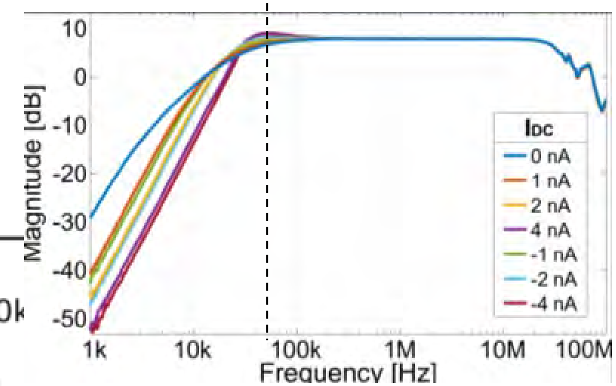


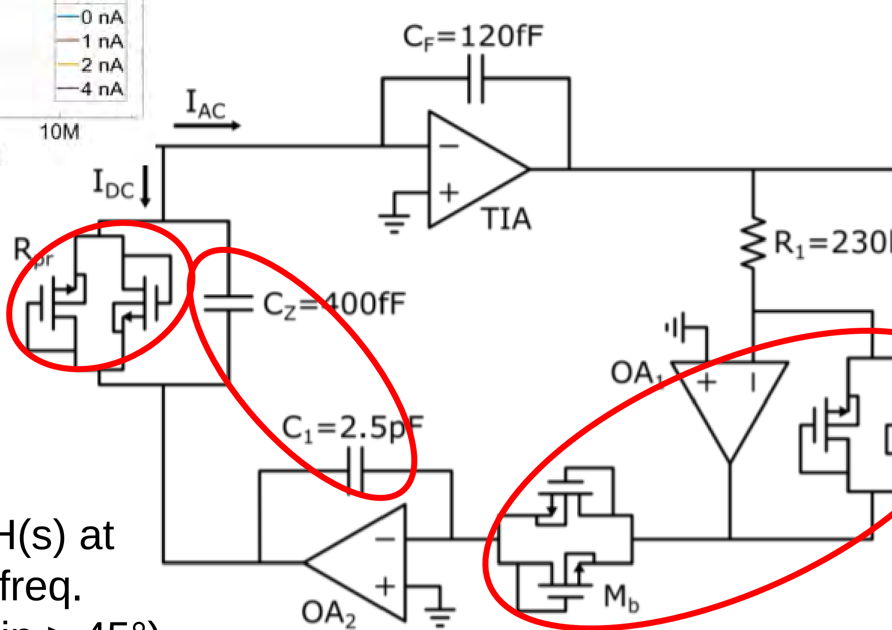



# DC current reset : Integrated circuit




Signal 50kHz – 35MHz



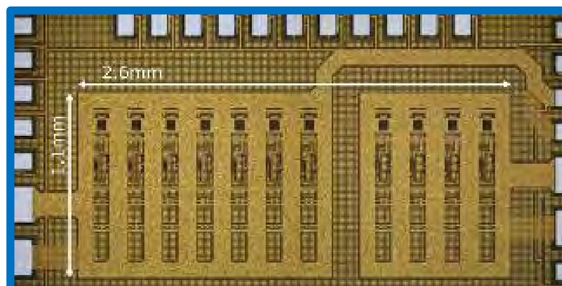




Adaptive Pseudo-resistor $R_{pr} \cong 25mV/I_{DC}$

Constant H(s) at medium freq. (Phase margin > 45°)

Current reducer (x24) to obtain a large resistor (6MΩ)

STm BCD8sP 0.18-μm
Supply voltage : 1.8 V
11 parallel channels
Current cons. : 5 mA/ch



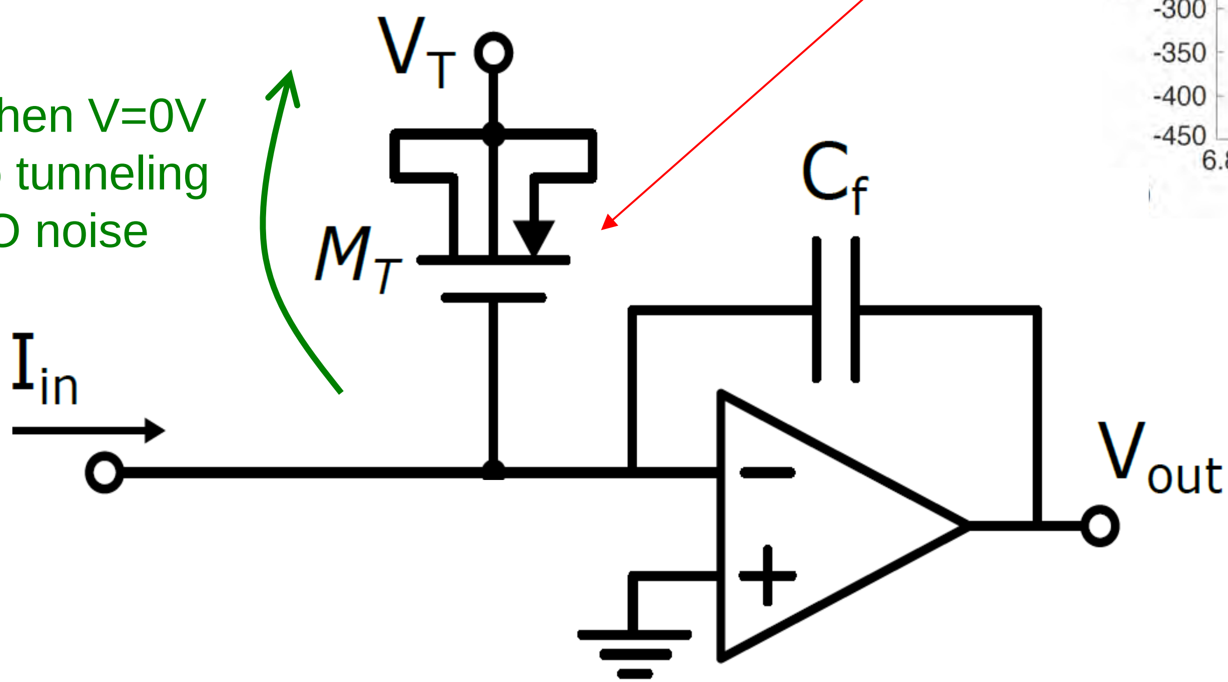

E. Guglielmi et al., "High-Value Tunable Pseudo-Resistors Design," in IEEE Journal of Solid-State Circuits, vol. 55, no. 8, pp. 2094-2105, 2020

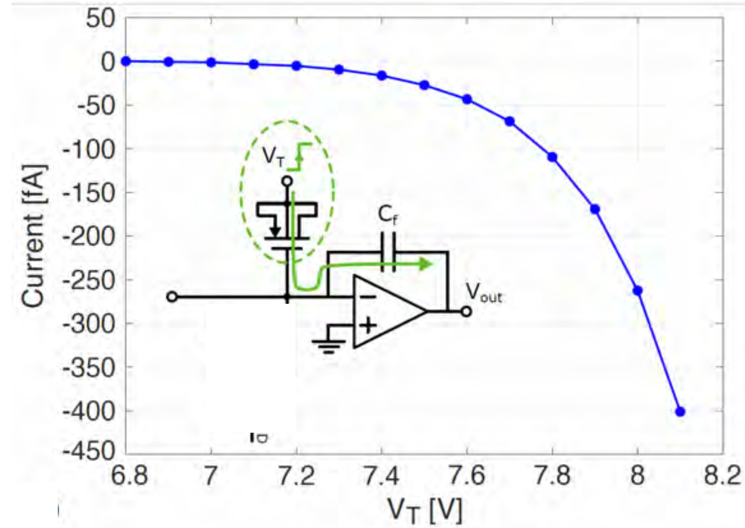
F.Zanetto et al. “Wide Dynamic Range Multichannel Lock-In Amplifier …”, IEEE SOLID-STATE CIRCUITS LETTERS, VOL. 3, 246-249, 2020

# Tunneling current reset

Use tunneling through the MOSFET oxide to reset

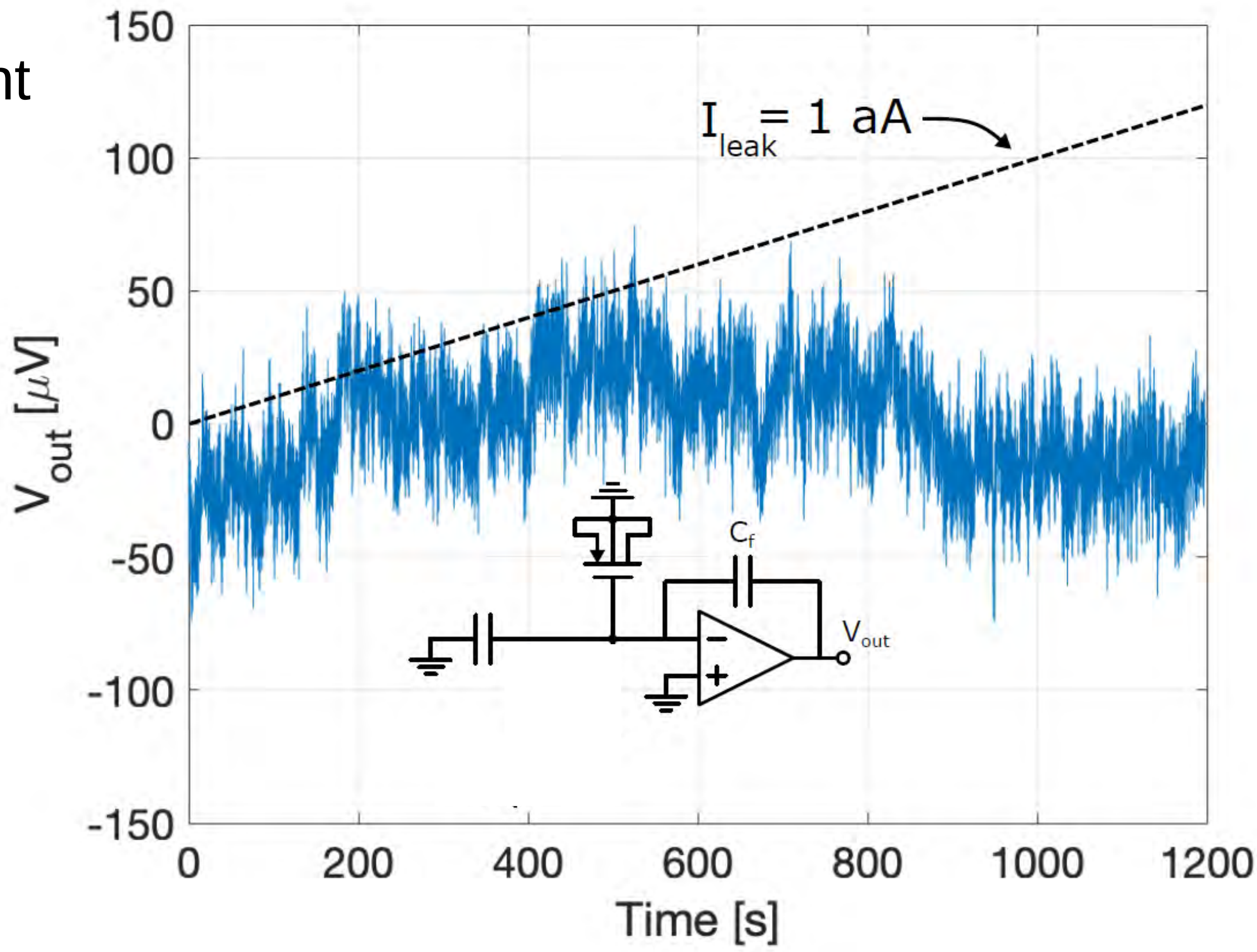
When V=0V
no tunneling
NO noise



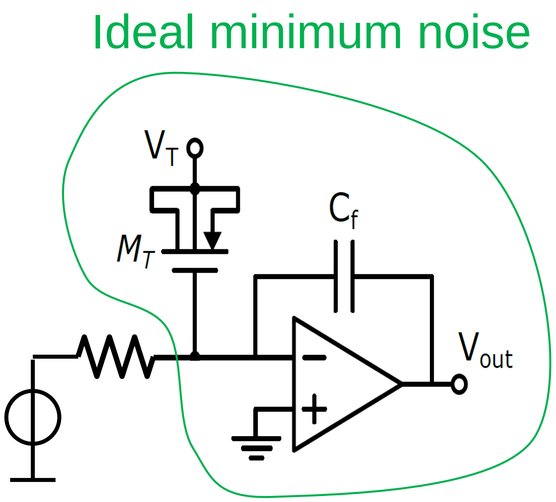



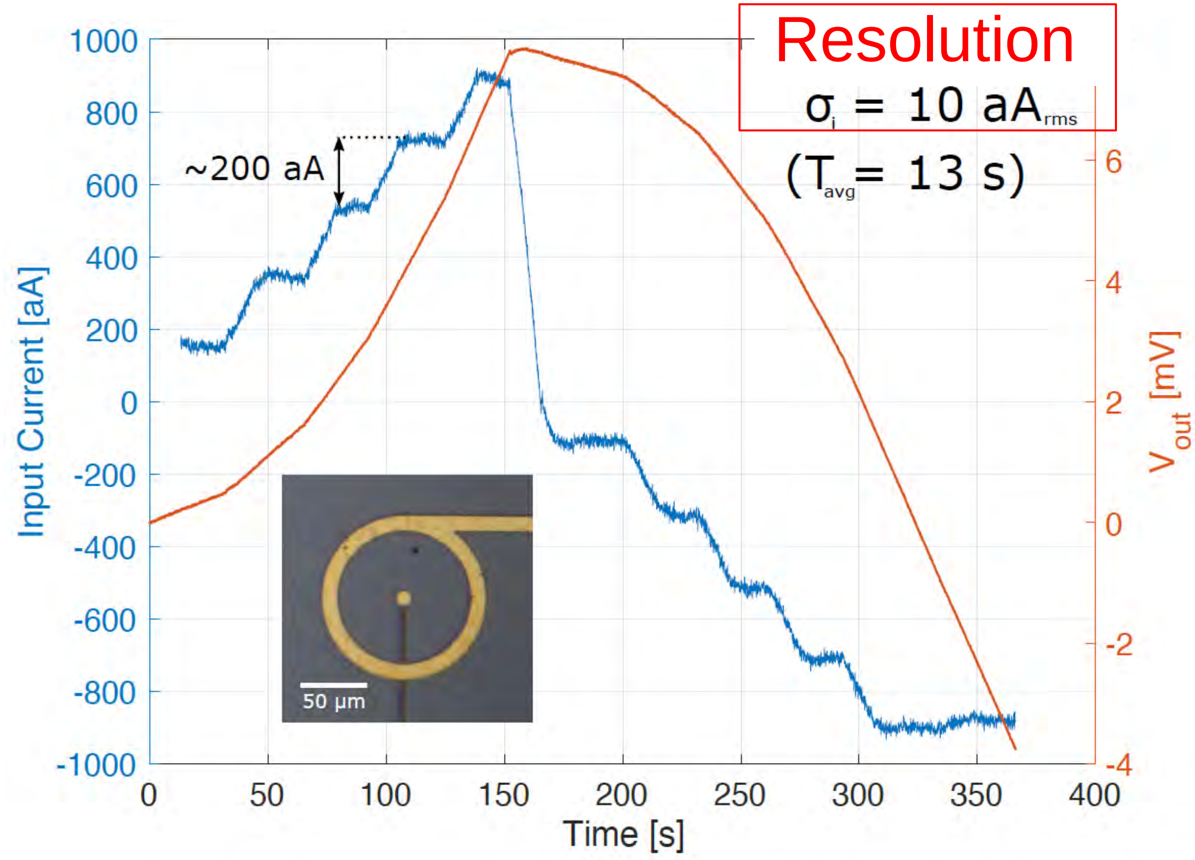
# Tunneling current reset : sensitivity OK

Leakage current in a IC is much less than 1aA



# Tunneling current reset : sensitivity OK



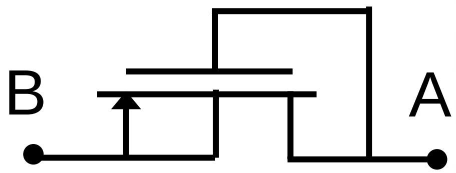



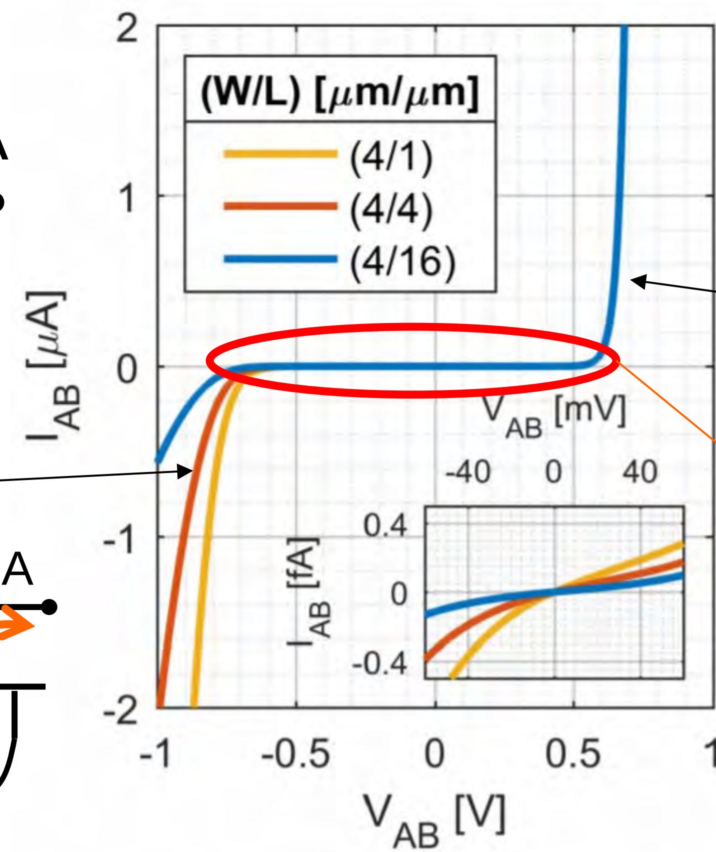

Response is obtained by applying a voltage between metal ring and input electrode (see inset figure). Voltage is decreased from −0.1V to −0.5V and then increased from 0.1V to 0.5V in steps of 0.1V, producing current steps of approximately 200 aA.

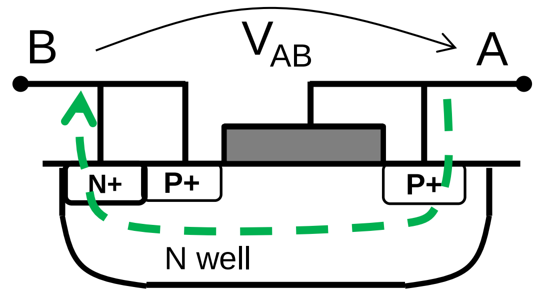
# Additional material

# The challenge of high value resistors

single MOSFET connected in transdiode configuration

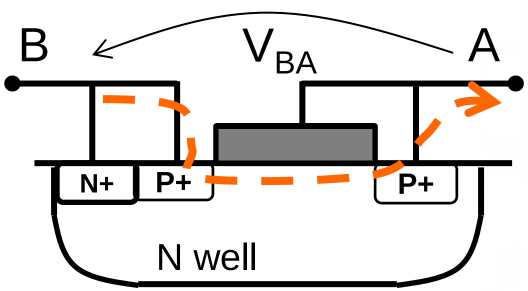



Exponential of *PN* junction

Parabola of MOSFET



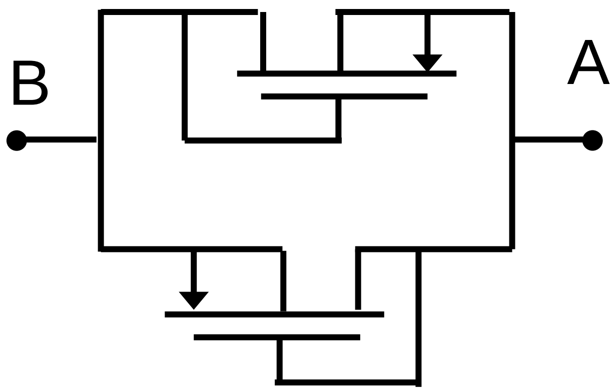

High equivalent resistance

$r_{eq} \cong 25\text{mV} / I_{DC}$

E. Guglielmi et al., "High-Value Tunable Pseudo-Resistors Design," in IEEE Journal of Solid-State Circuits, vol. 55, no. 8, pp. 2094-2105, 2020

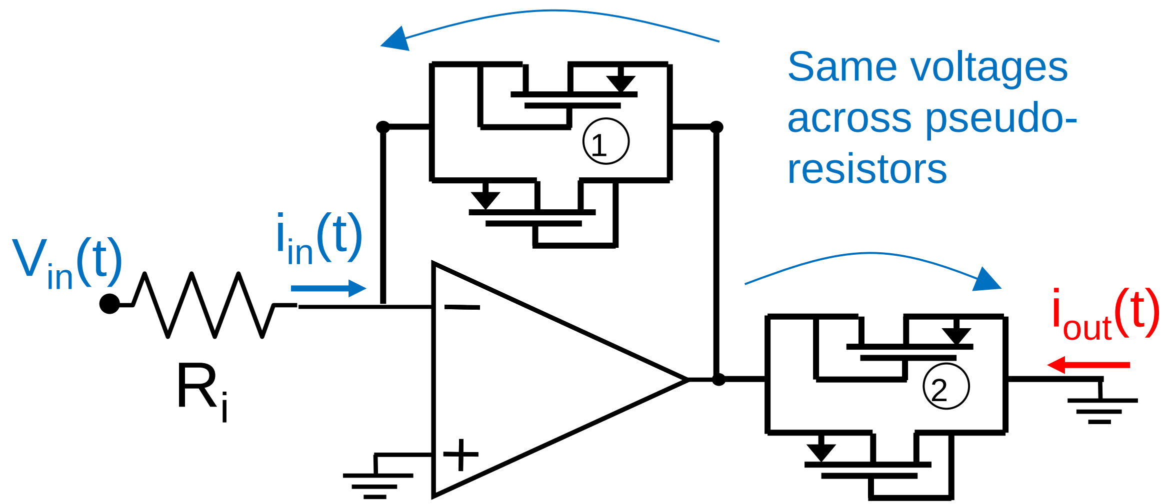
## Parallel back-to-back

to obtain symmetric response




## Ratiometric topology

to compensate for non-linearities



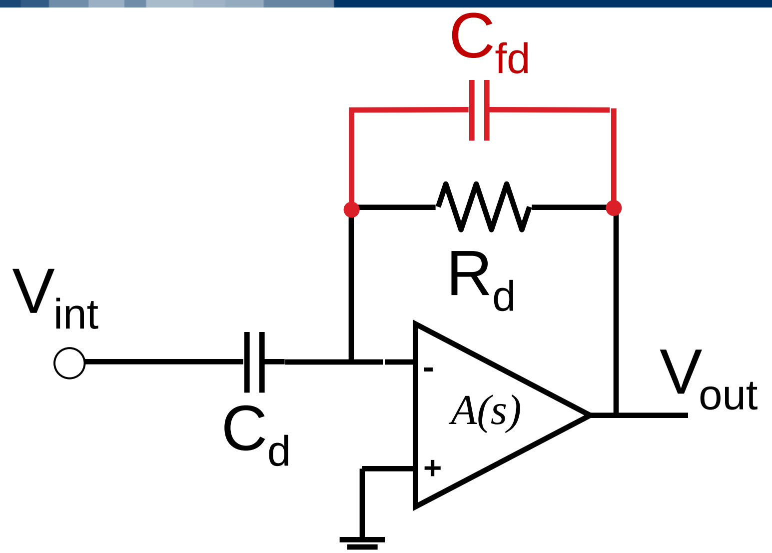

If $W_1 = 100 \times W_2$ ➡ $i_{out}(t) = \dfrac{i_{in}(t)}{100}$

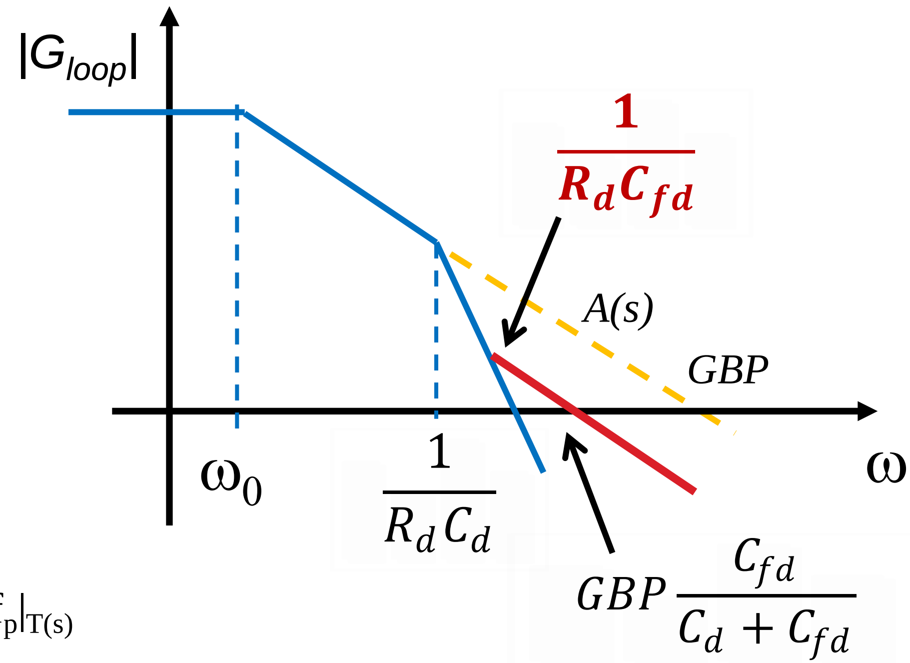
$$R_{TOT} = \frac{V_{in}(t)}{i_{out}(t)} = 100 \times R_i$$

High value resistor : small current $i_{out}(t)$ with large voltage $V_{in}(t)$

F. Gozzini et al., Electronics Letters 42, 1069-1070 (2006)

# How to make the Differentiator




**Constraints:**

$$\begin{cases} \dfrac{1}{2\pi R_d C_{fd}} = BW \quad \cong f_z|_{Gloop} \cong f_p|_{T(s)} \\ R_d \left(\dfrac{C_d}{C_i}\right)^2 = R_{eq\ noise} \\ GBP \dfrac{C_{fd}}{C_{df} + C_d} > \dfrac{1}{2\pi R_d C_{fd}} \end{cases} \Rightarrow GBP > 2\pi B^2 C_i \sqrt{R_{eq\ noise} R_d}$$

**Example:**

Chose : $C_i$=1.5pF
$C_d$=220pF

Request : $R_{eq}|_{noise}$ = 1GΩ
**BW = 2MHz**

→

$R_d$=47kΩ
$C_{fd}$=2pF
**$GBP|_{OpAmp}$>260MHz**