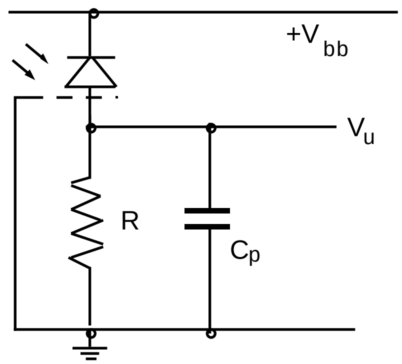
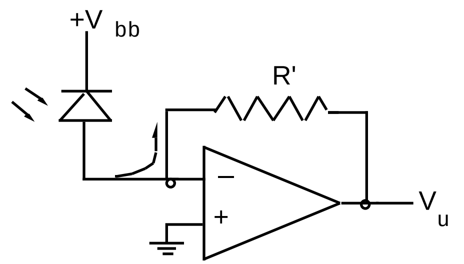
Overview



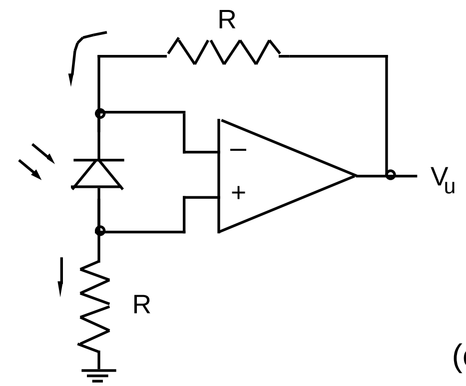
(a)

basic circuit



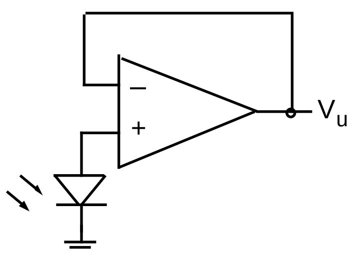
(b)

transimpedance



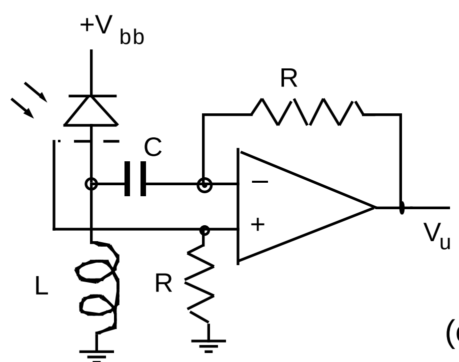
(c)

dark current cancellation



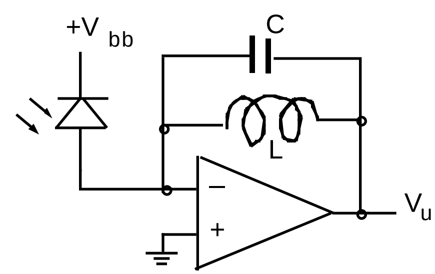
(d)

logarithmic



(e)

dc cancellation

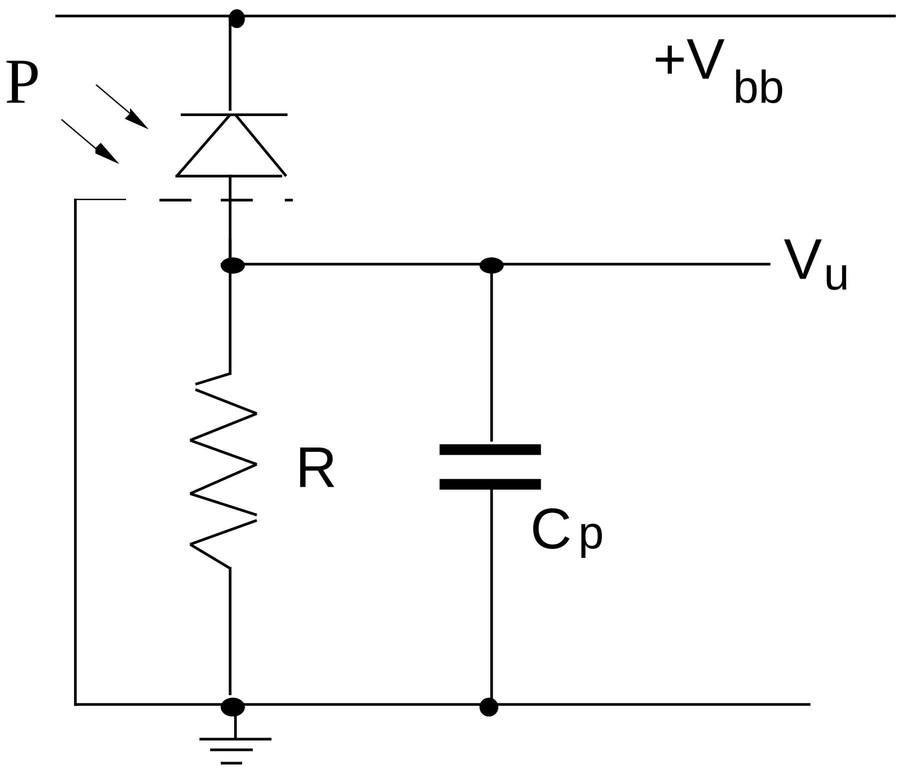


(f)

narrow- band

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Basic Scheme



$V_u = V_{u0} + v_u,$

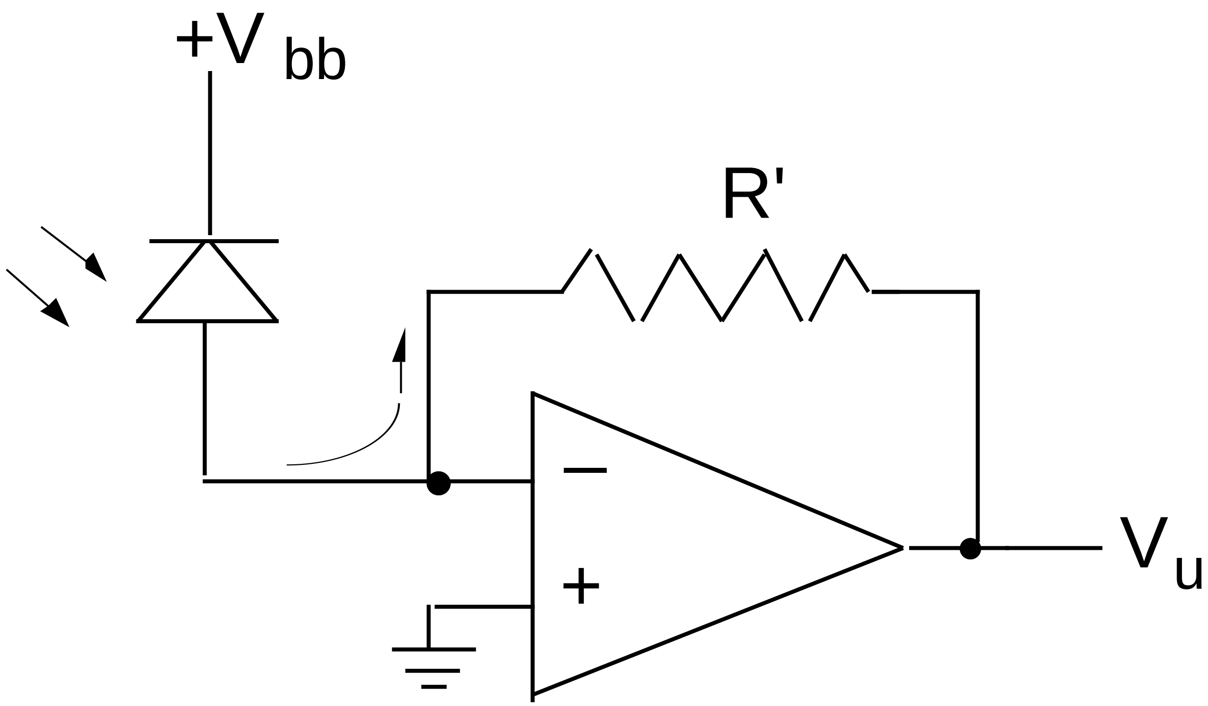
$V_{u0} = I_o R \quad v_u = \sigma P R,$

$v^2_{nu} = 4kTBR + 2e(\sigma P + I_o)R^2B$

$f_2 = 1/2\pi RC_p, \quad C_p = C_b + C_{ext}$

from:"Photodetectors", by S.Donati, Prentice Hall 2000

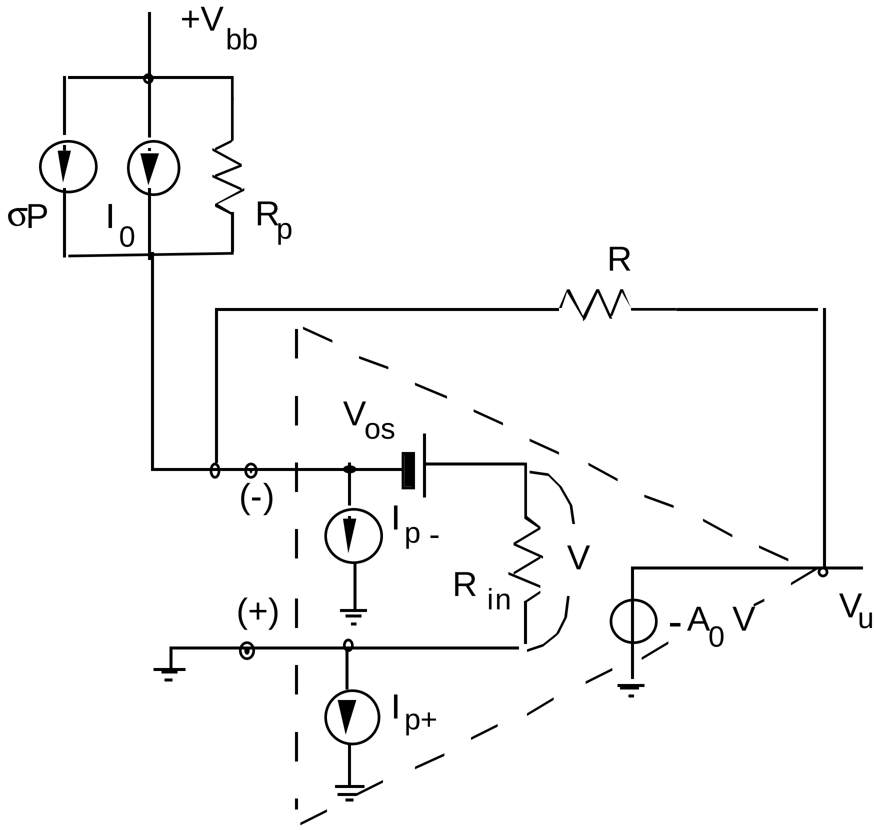
Cold-resistance (or Transimpedence) Scheme



As PD sees a much smaller R= R'/(1+A), this *cold resistance* preamplifier has the same noise and a much larger bandwidth than the basic circuit

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Transimpedence in dc



$V_u = -\sigma P R \gamma + V_{u0}$

$V_{u0} = -(I_o - I_{p-}) R \gamma + V_{os} (1+R/R_p) \gamma$

where $\gamma = [1+(1+R/R_i)/A_o]^{-1}$

and $R_i = R_p // R_{in}$

for $\gamma \approx 1$ (or, $A_o >> R/R_i$):

$V_{u0} = -(I_o - I_{p-}) R + V_{os} (1+R/R_p)$ V_{u0} $\approx V_{os}$ for small R, and is dominated by term $I_o - I_{p-}$ at large R; break-point value is: $R = V_{os}/(I_o - I_{p-})$

in typ. Op-Amps:

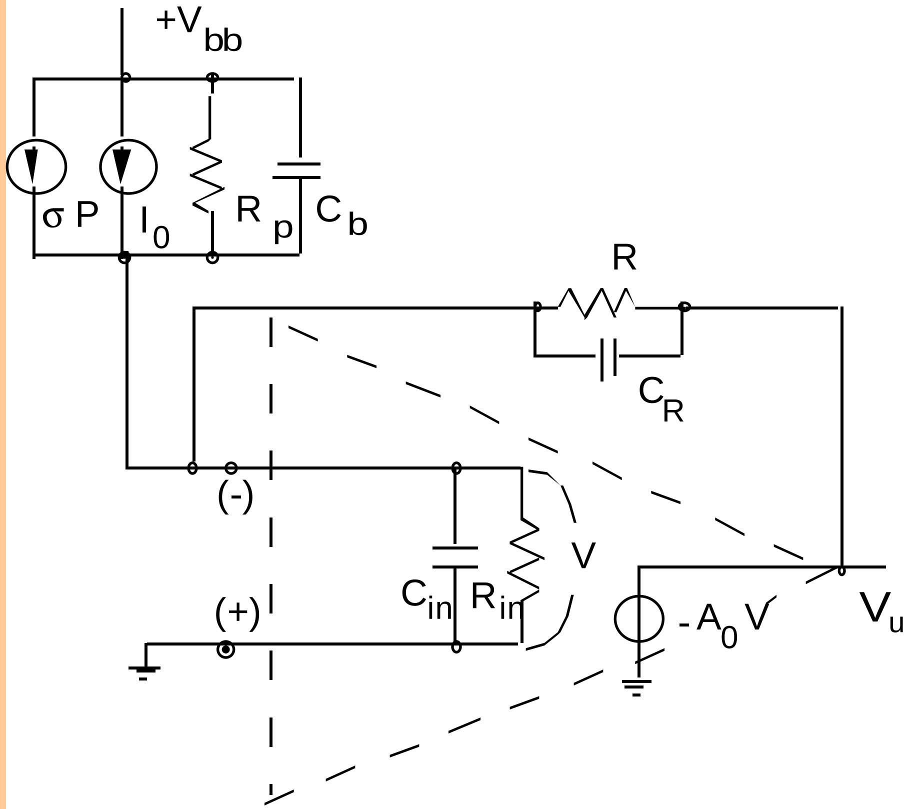
V_{os}/I_p = 0.5mV/0.2μA =2.5 kΩ

with a bipolar input stage, and :

V_{os}/I_p = 3mV/200pA=1.5 MΩ

with a FET input stage

Transimpedence in ac



$(C_i = C_{in}+C_b)$

$v_u(0) = -\sigma P R \gamma \approx -\sigma P R$

$v_u(s) = -\sigma P Z/[1+(1+Z/Z_i)/A]$

transfer function is:

$v_u(s)/v_u(0) = \{1+s[RC_R+$
$+(1+R/R_i)/\omega_o A_o+R(C_i+C_R)/A_o]+$
$+s^2 R(C_i+C_R)/\omega_o A_o\}^{-1}$

or, is of the type: $\{1+s\chi/\omega_2+s^2/\omega_2^2\}^{-1}$,

a 2nd-order response, with cutoff frequency:

$f_2 = [2\pi R(C_i+C_R)/\omega_o A_o]^{-1/2}$
$= [f_R \, GB_A]^{1/2}$,

(the geometrical mean of f_R and GB_A)

and damping:

$\chi = {}^1/_2 \, f_2 \, (1/f_R + 1/GB_A)$
$= {}^1/_2\{[C_R/(C_i+C_R)] \, [GB_A/f_R]^{1/2} + [f_R/GB_A]^{1/2}\}$

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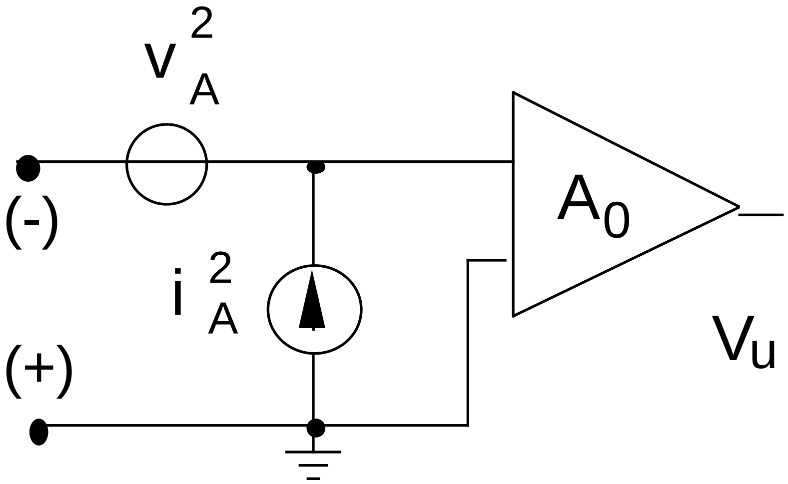
Transimpedence noise



typ FET Op-Amp (356):
$[dv_A^2/df]^{1/2}$=15 nV/√Hz
$[di_A^2/df]^{1/2}$=0.01 pA/√Hz

output noise spectral density:

$$dv_{nu}^2/df = [4kT/(R_i//R) + 2e(\sigma P+I_o) + di_A^2/df]\,(Z\gamma)^2 + dv_A^2/df\,(1+\gamma Z/Z_i)^2$$

in the passband and for $\gamma \approx 1$, $R<<R_i$, this becomes:

$$dv_{nu}^2/df = [4kT/R + 2e(\sigma P+I_o) + di_A^2/df]\,R^2 + dv_A^2/df$$

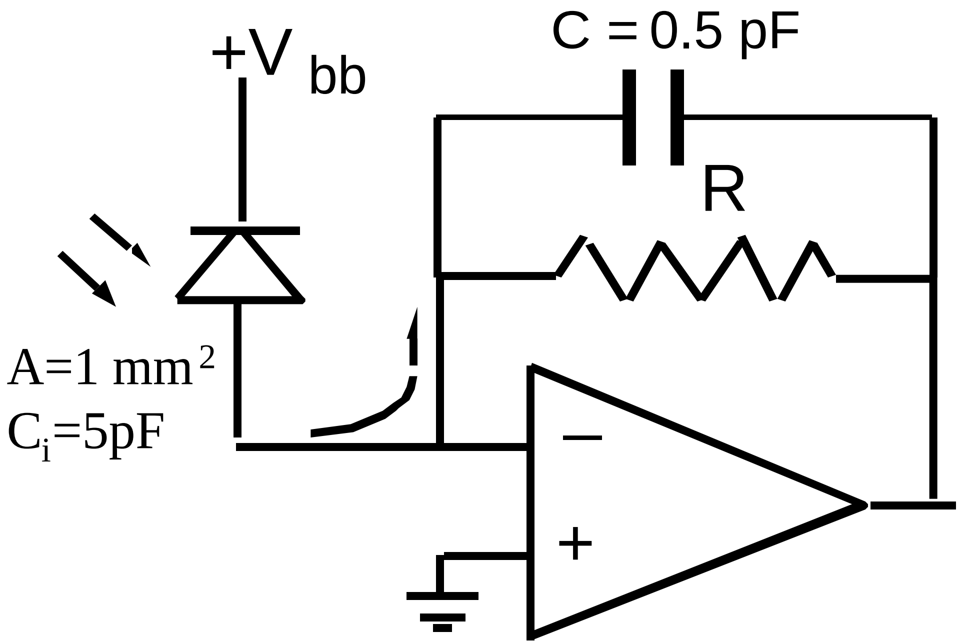
integrating on f in 0–B, total output noise for a measurement bandwidth B is:

$$v_{nu}^2 = 4kTBR + [2e(\sigma P+I_o)B + i_A^2]\,R^2 + v_A^2$$

$$= 4kTBR + 2e[\sigma P+I_o+I_A(1+R_A^2/R^2)]\,BR^2$$

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Example: transimpedence with an IC Op-Amp



op-amp 741:

GB_A=10 MHz, R_i>10MΩ

Example: transimpedence with an IC Op-Amp

for feedback resistances:

R=10k, 100k, 1M, 10MΩ giving

f_R= 2.9M, 290k, 29k, 2.9kHz

high frequency cutoff $\sqrt{GB_A f_R}$ is: f_2 = 5.4M, 1.7M, 540k, 170kHz

and damping factor is: χ= 0.35, 0.46, 0.87, 2.6

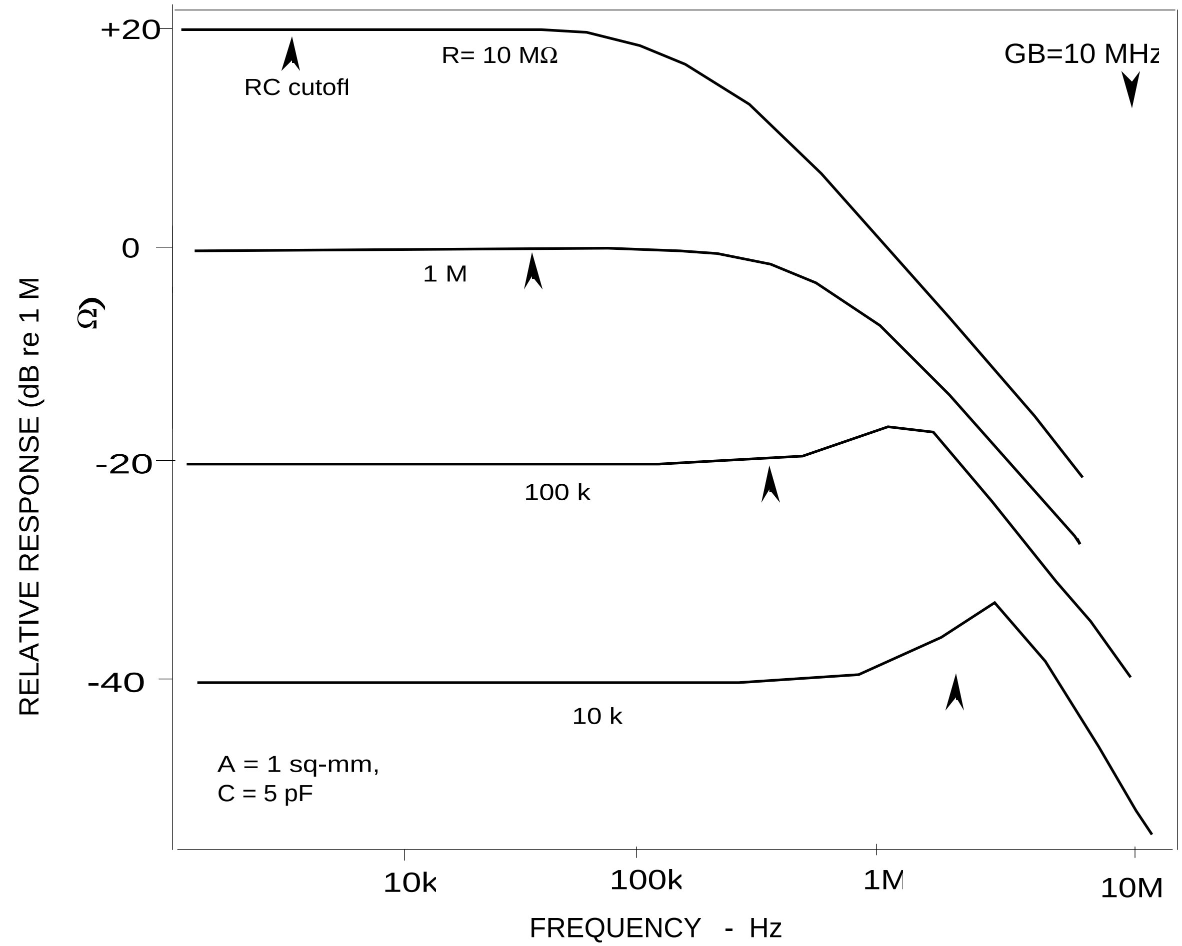
(overshoot) 5 3 0 0 dB

noise: $i_{nu} = \sqrt{[4kTB/R + 2e(\sigma P+I_o)B + i_A^2+v_A^2/R^2]} = 2eI_{pho}B$

(FET-input) I_{pho}=12μA, 0.57μA, 51nA, 5.3nA

(bipolar-input) = 12μA, 0.6μA, 2 10nA, 200nA

IC Op-Amp transimpedance: performance



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noise definitions and parameters

(i) input equivalent *current noise density*

$$di_{neq}^2/df = (dv_{nu}^2/df) / [Z\gamma]^2,$$

$$di_{neq}^2/df = 4kT/(R_i //R) + 2e(\sigma P+I_o) + di_A^2/df + dv_A^2/df(1/\gamma Z + 1/Z_i)^2$$

$$= 4kT/(R_i //R) + 2e(\sigma P+I_o) + 2eI_A[1+(R_A/\gamma Z//Z_i)^2]$$

(ii) input equivalent *total noise current*, (by integration of di_{neq}^2/df)

(iii) the *noise figure* F_A ratio of the total input noise to that already contained in detected signal and dark current $[2e(\sigma P+I_o)B$:

$$F_A^2 = 1+\{4kTB/R + i_A^2+v_A^2/R^2\}/ 2e(\sigma P+I_o)B$$

$$= 1+[(2kT/e)/R + I_A(1+R_A^2/R^2)]/(\sigma P+I_o)$$

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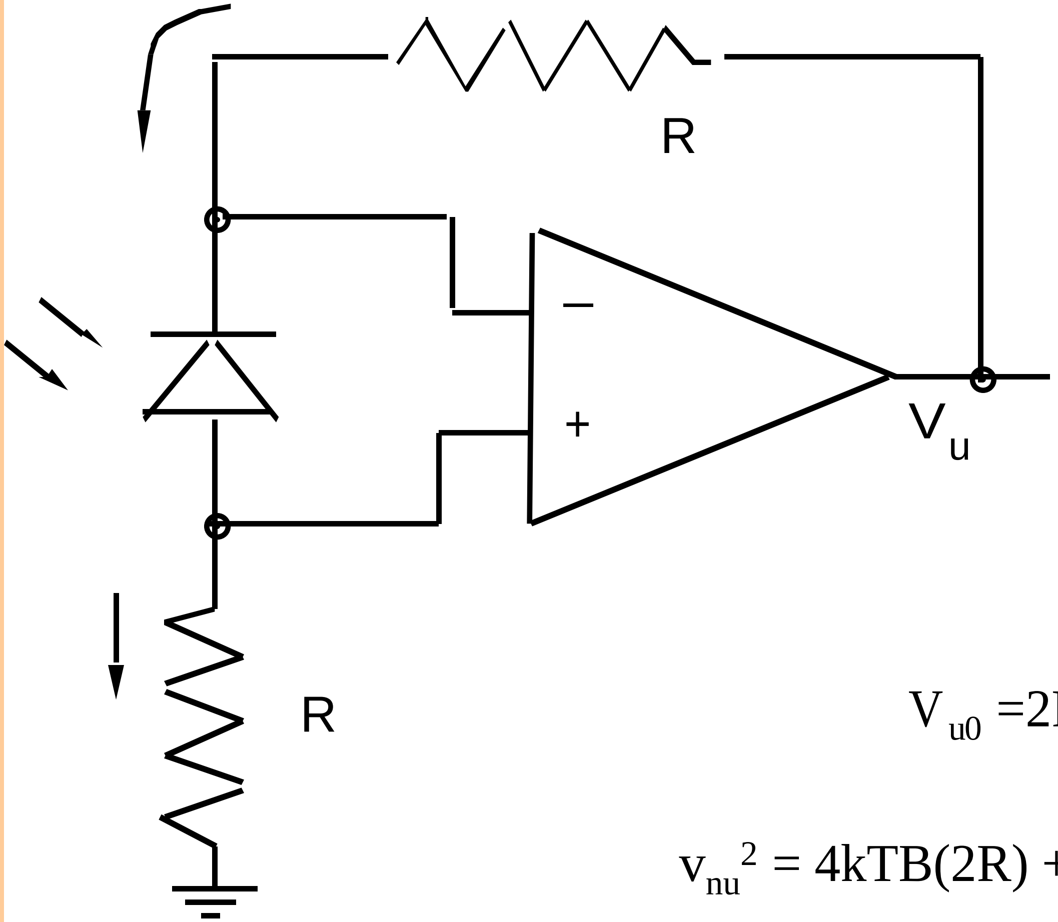
Dark-cancellation Op-Amp circuit



$I = I_0[\exp V/(kT/e) - 1] - I_{ph}$

for $V = V_{os} << (kT/e)$

$I = I_0 V_{os}/(kT/e) - I_{ph}$

$V_u = V_{u0} + v_u$

$v_u = 2\sigma P R$

$V_{u0} = 2R\, I_o[V_{os}/(kT/e)] - R\Delta I_p + V_{os}$

$v_{nu}^2 = 4kTB(2R) + [2e(\sigma P + 2I_o)B + i_A^2](2R)^2 + v_A^2$

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Dark-cancellation: an example

$$v_u = 2\sigma P R \qquad V_{u0} = 2R\, I_o[V_{os}/(kT/e)] - R\Delta I_p + V_{os}$$

$$v_{nu}^2 = 4kTB(2R) + [2e(\sigma P+2I_o)B+i_A^2](2R)^2 + v_A^2$$

Example: using a FET op-amp (356): • V_{os}=3mV, I_p=200pA, ΔI_p=5pA

- after trimming offset to zero, residual error may be V_{os}=25μV
- dark current term is reduced to (25μV/25mV)1nA=1pA
- second term [..] dominates for R>25μV/5pA =5MΩ
- using R= 500MΩ, output offset is V_{u0}= 500MΩ·(2·1pA+ 5pA)=3.5 mV.
- minimum detectable power in dc follows:

$$P = 3.5\ mV/(2\sigma 500M\Omega) = 3.5pW \quad (\text{at } \sigma=1A/W)$$

- circuit responsivity is v_u/P=1V/pW
- noise voltage is v_{nu}=13μV (B=1Hz), whence p_{ni}=13 fW (or ≈ -110 dBm equivalent noise power)

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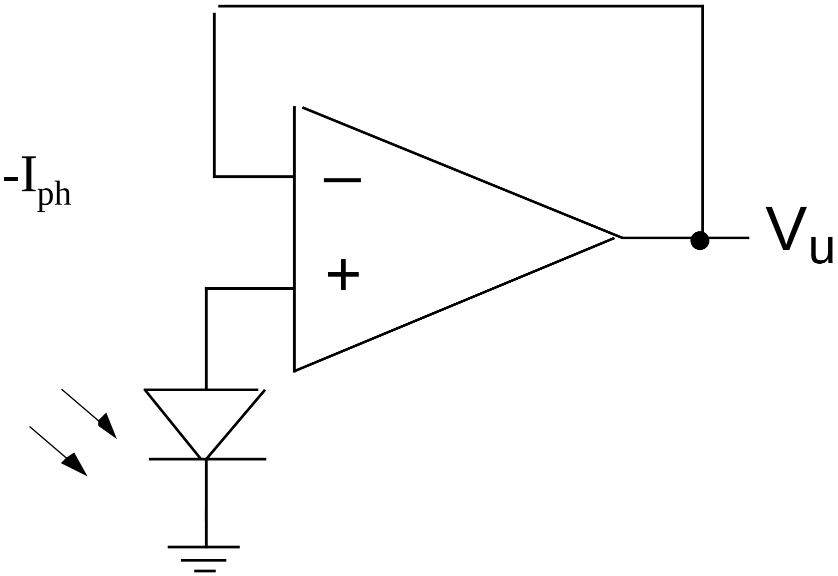
Logarithmic conversion circuit

$I = I_o\,[\exp(eV/nkT) - 1] - I_{ph}$



$$V_{u0} = V_{os} + (nkT/e)\ \ln\,[(I_{ph} - I_p + I_o)/I_o]$$

at T=300K, n=1, and for a signal $I_{ph} >> I_o, I_p$:

$$V_{u0} = V_{os} + [59.6\ \mathrm{mV}]\ \ Log_{10}(I_{ph}/I_o)$$

both scale factor and added constant vary with T

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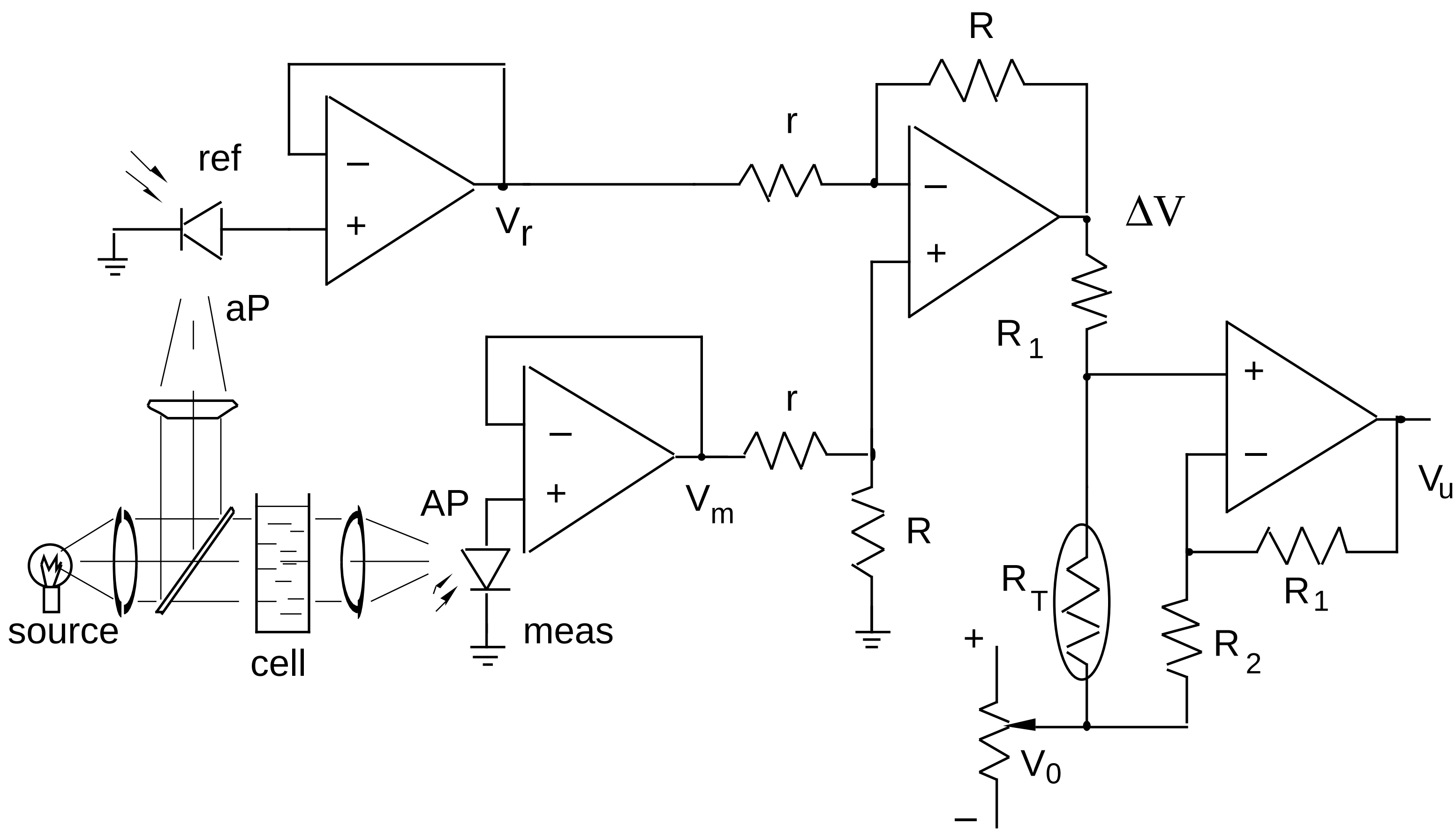
Log-scheme for 2-Ch attenuation measurements



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Log-scheme for 2-Ch attenuation measurements (cont'n)

Signals from (meas) and (ref) channels:

$$V_m = V_{osm} + (nkT/e)\ \ln [(\sigma_m AP - I_{pm} + I_{om})/I_{om}]$$

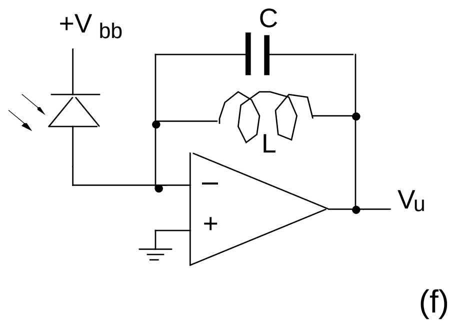
$$V_r = V_{osr} + (nkT/e)\ \ln [(\sigma_r aP - I_{pr} + I_{or})/I_{or}]$$

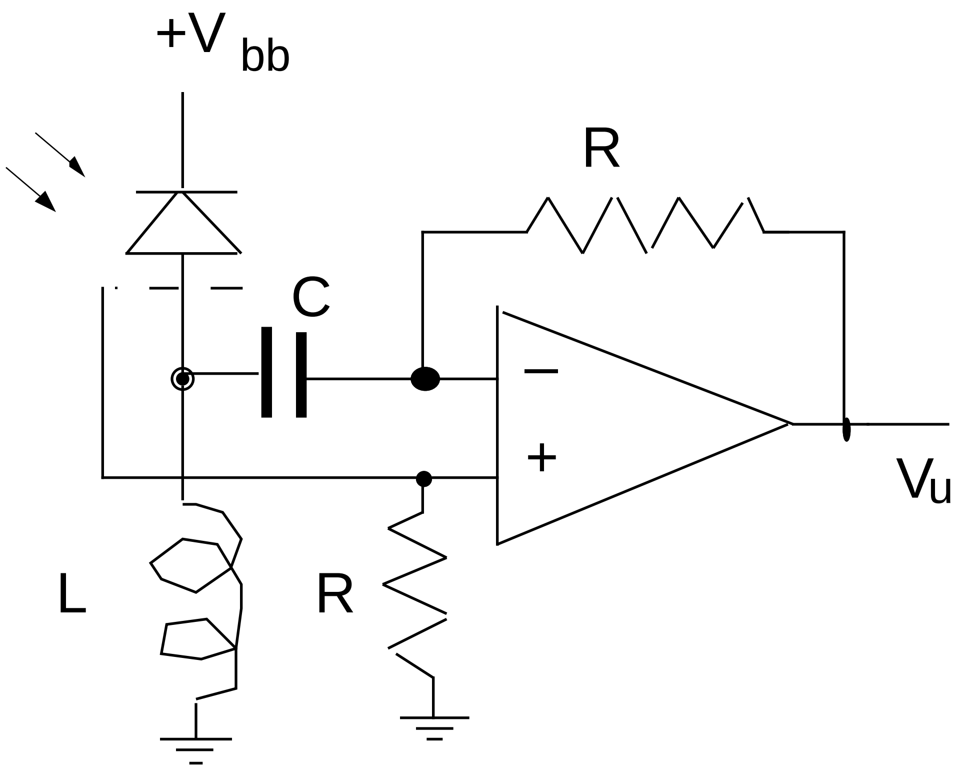
Subtracting in 2nd stage, for $\sigma_m AP$, $\sigma_m aP >> I_{pm}, I_{om}, I_{pr}, I_{or}$, n=1:

$$\Delta V = (kT/e)\ \ln A + V_{osm} - V_{osr} + (kT/e)\ \ln(\sigma_m I_{or} / a\sigma_r I_{om})$$
$$= [59.6\text{mV}]\ \text{Log}_{10} A + \text{const}$$

Scale factor drifts with T. NTC thermistor bridge corrects this tempco $\alpha_A = -\alpha_T R_1/(R_1+R_2)$ to residual error of ±0.005%/°C, and also zero dc level $V_{u(dc)} = \text{const} = [(e/kT)(V_{osm} - V_{osr}) + \ln(\sigma_m I_{or} / a\sigma_r I_{om})] \cdot 1V$ against all tempcos [typ.: α_{Vos} =- 4mV/°C, α_σ = ±5mV/°C, α_{Io}= +140mV/°C] to: $v_{nu} = A_2 \cdot 10\mu V/\sqrt{Hz}$ at $I_{ph}=1\mu A$ or $10\mu AU/\sqrt{Hz}$

dc cancellation scheme





$f_{pass}=1/2\pi\sqrt{LC}$,

$\chi={}^{1}/_{2}(\sqrt{C/L})R/(1+A)$

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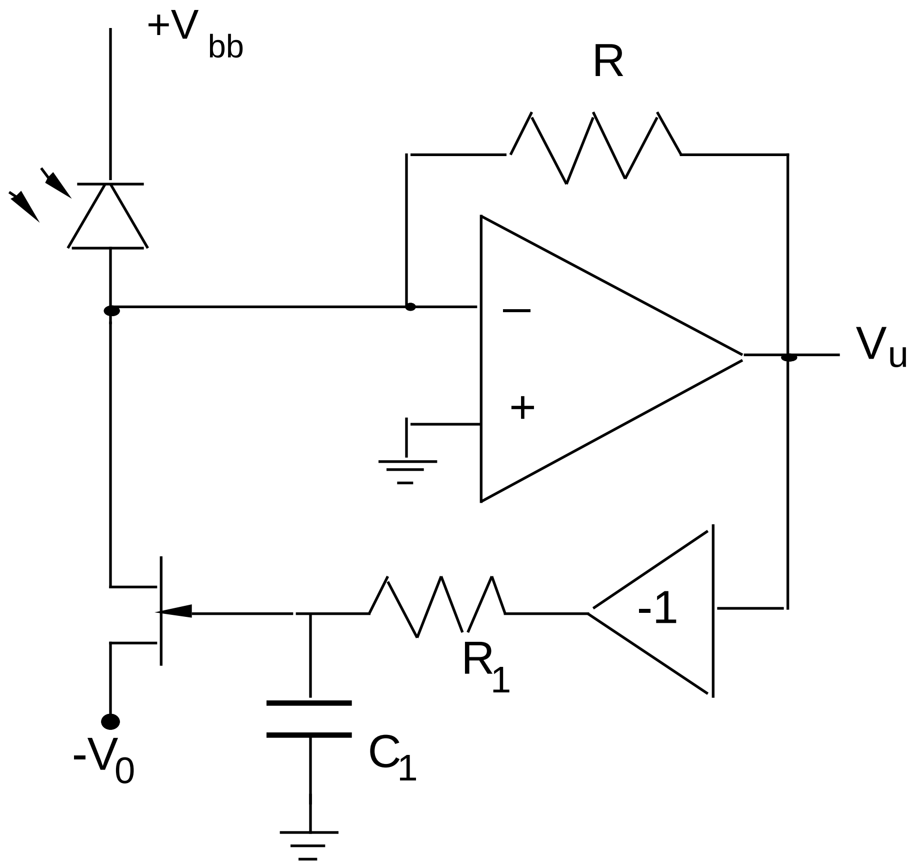
dc cancellation scheme (2)



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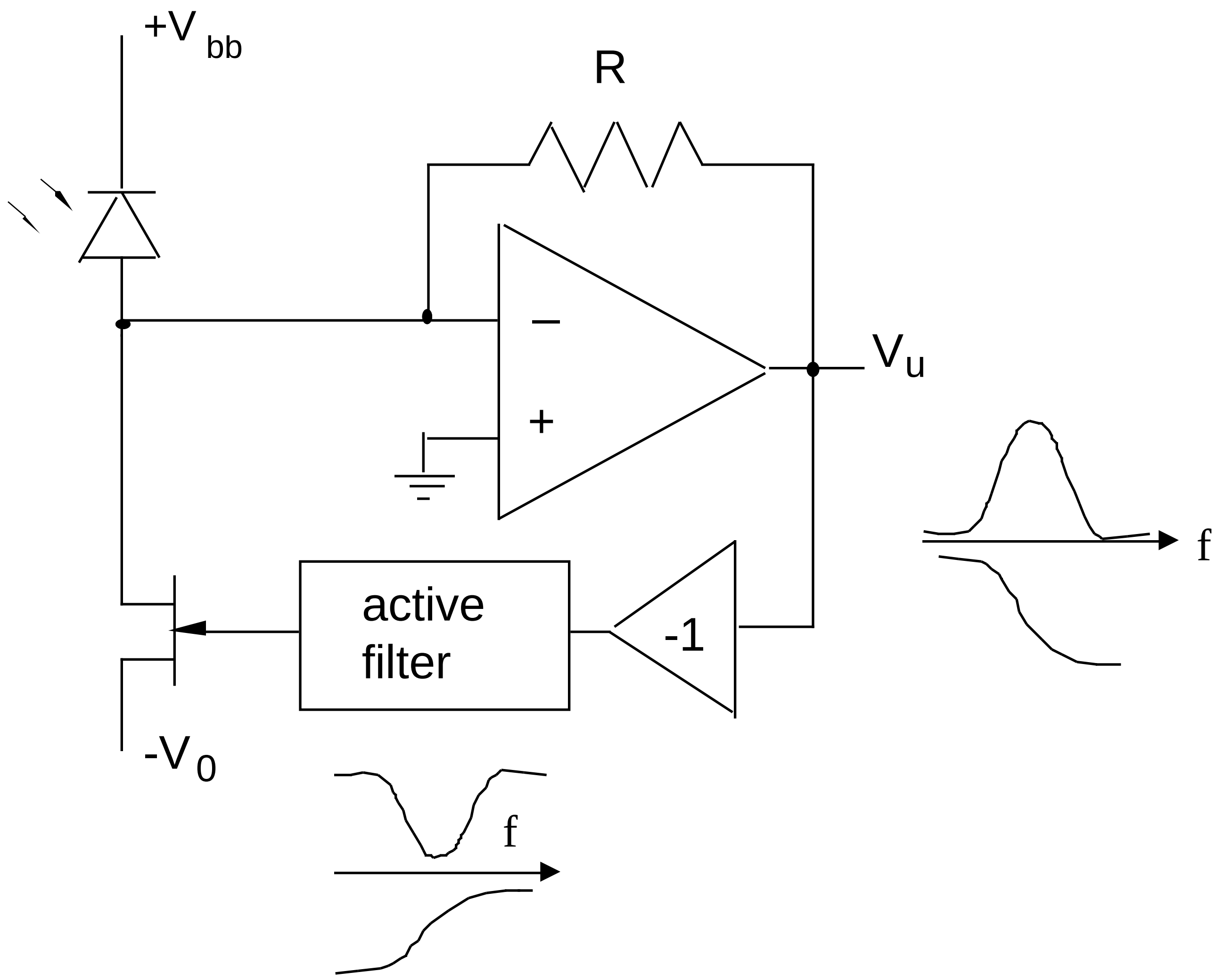
Selective (or synthetic response) scheme



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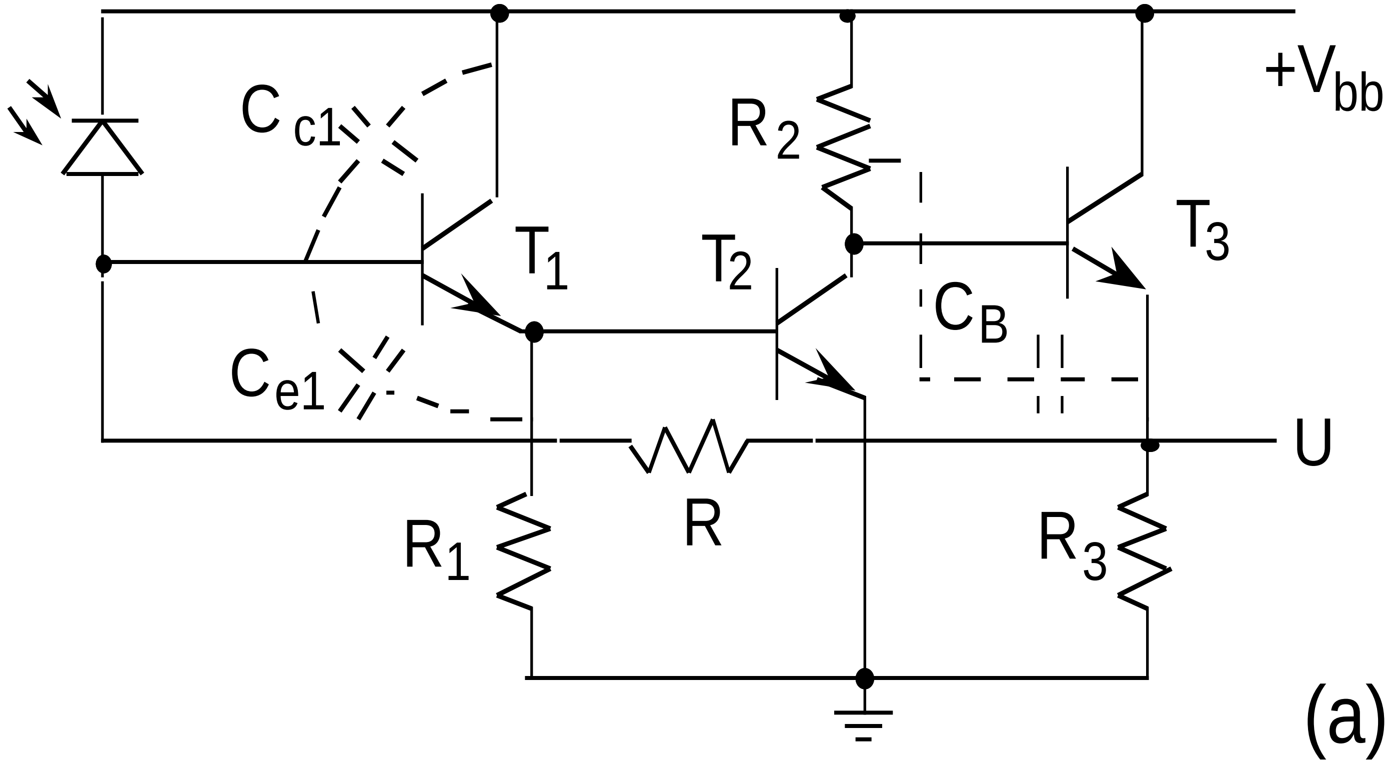
Fast-pulses and High-frequency Transimpedence



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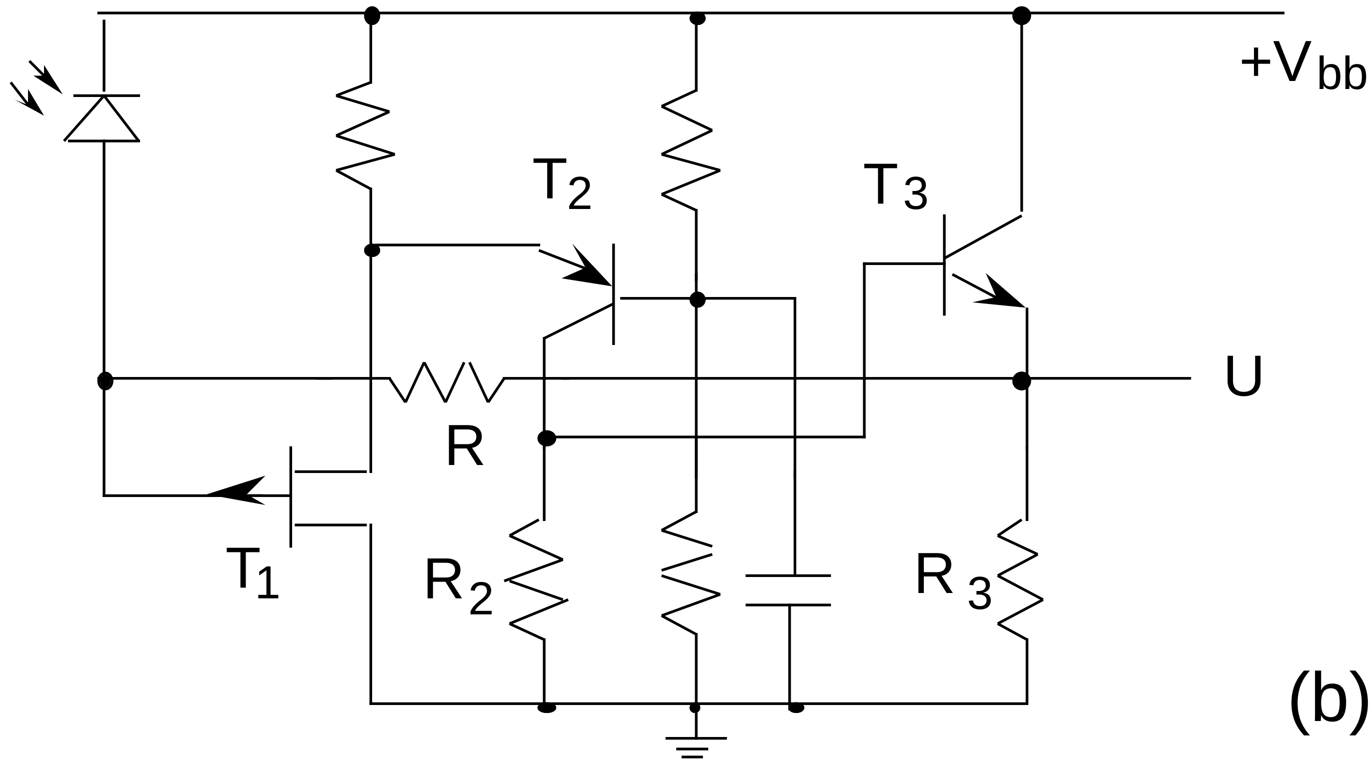
Fast-pulses and High-frequency Transimpedence (2)



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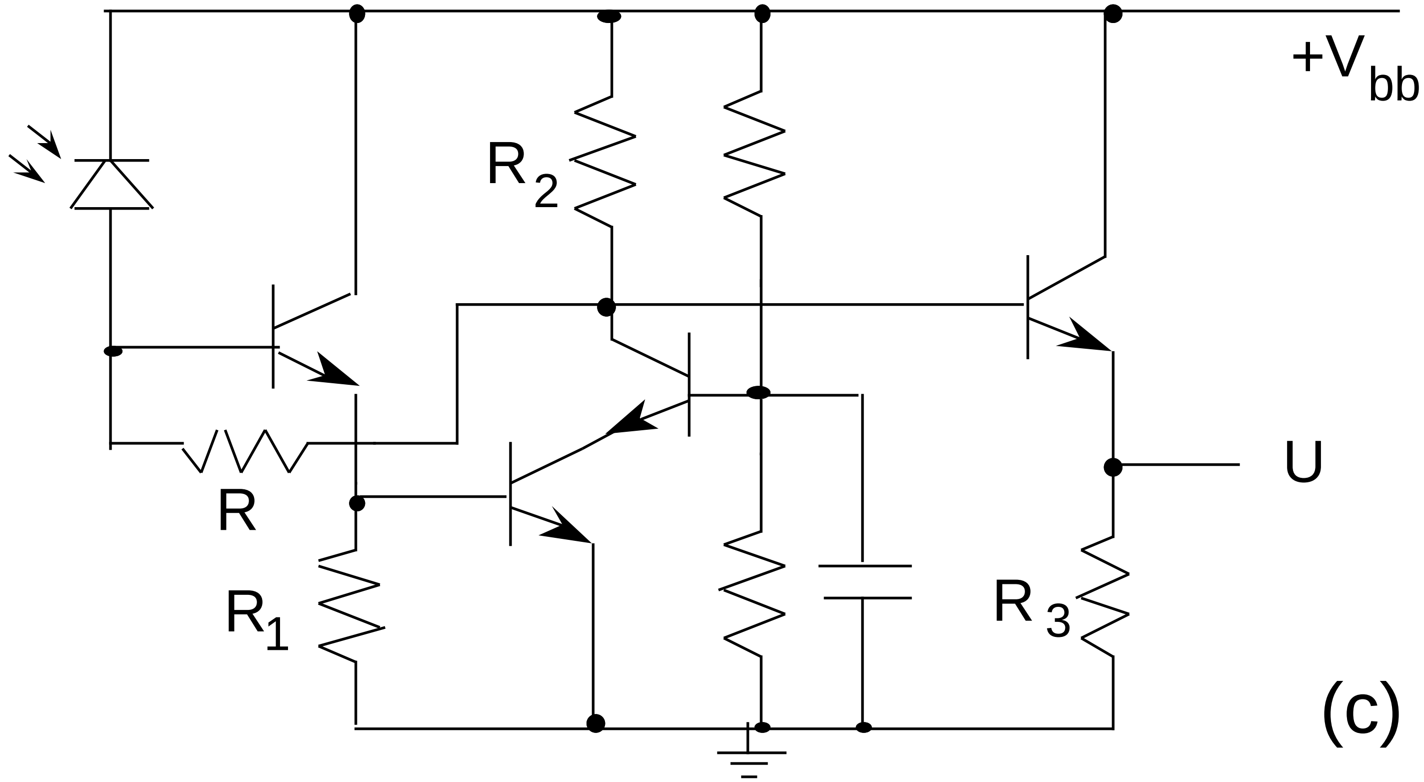
Fast-pulses and High-frequency Transimpedence (3)



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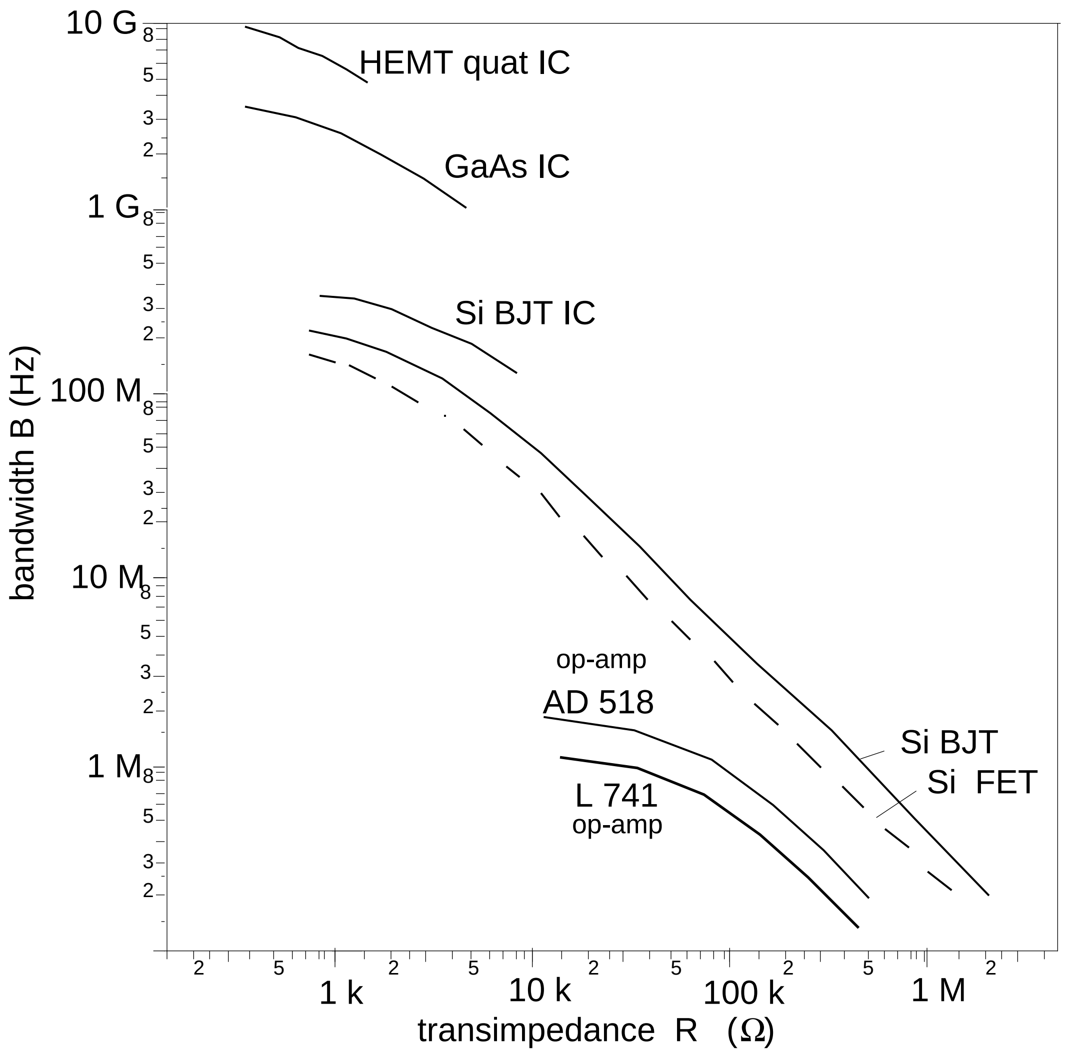
High-frequency Transimpedence performance (bandwidth)



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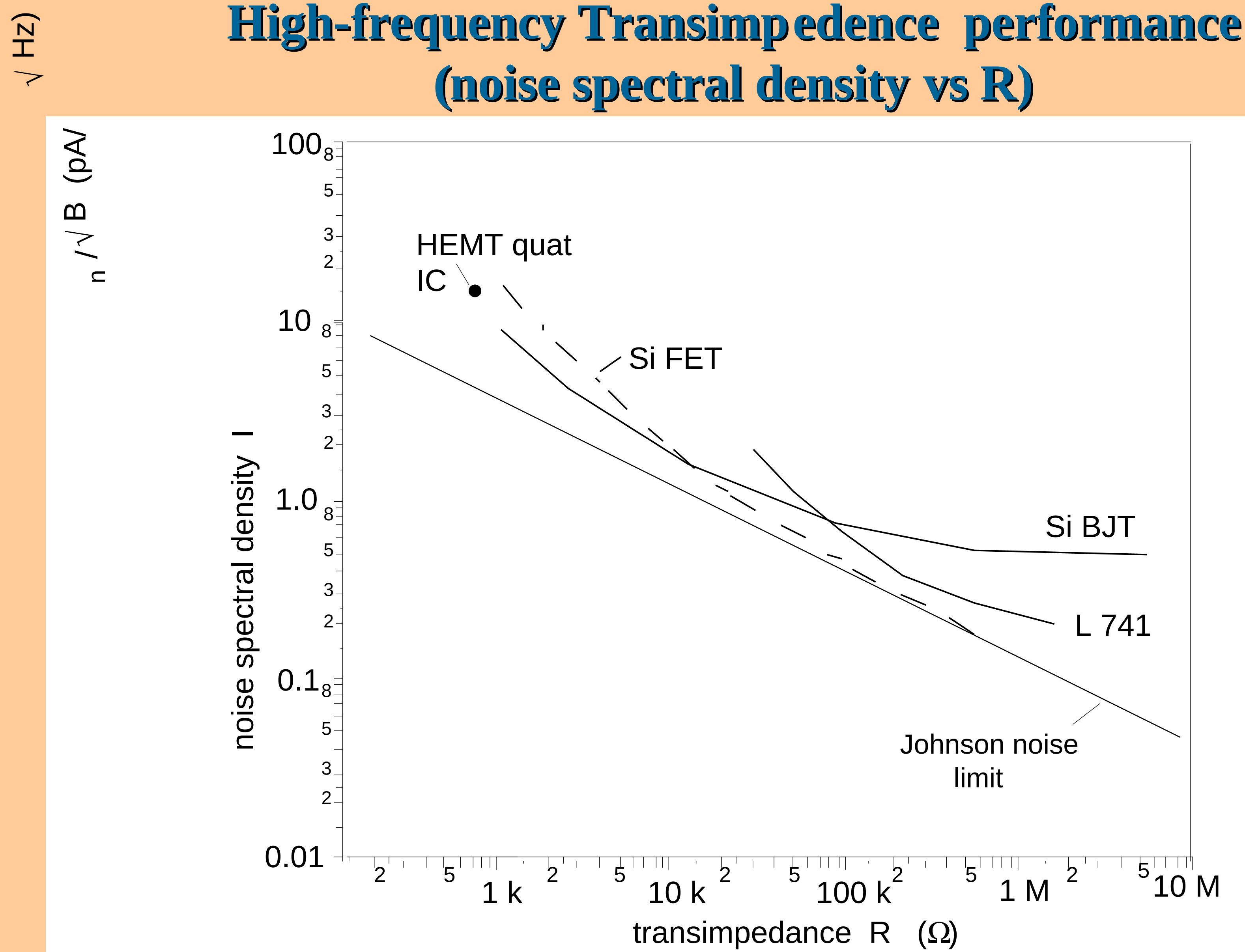
High-frequency Transimpedence performance (noise spectral density vs R)



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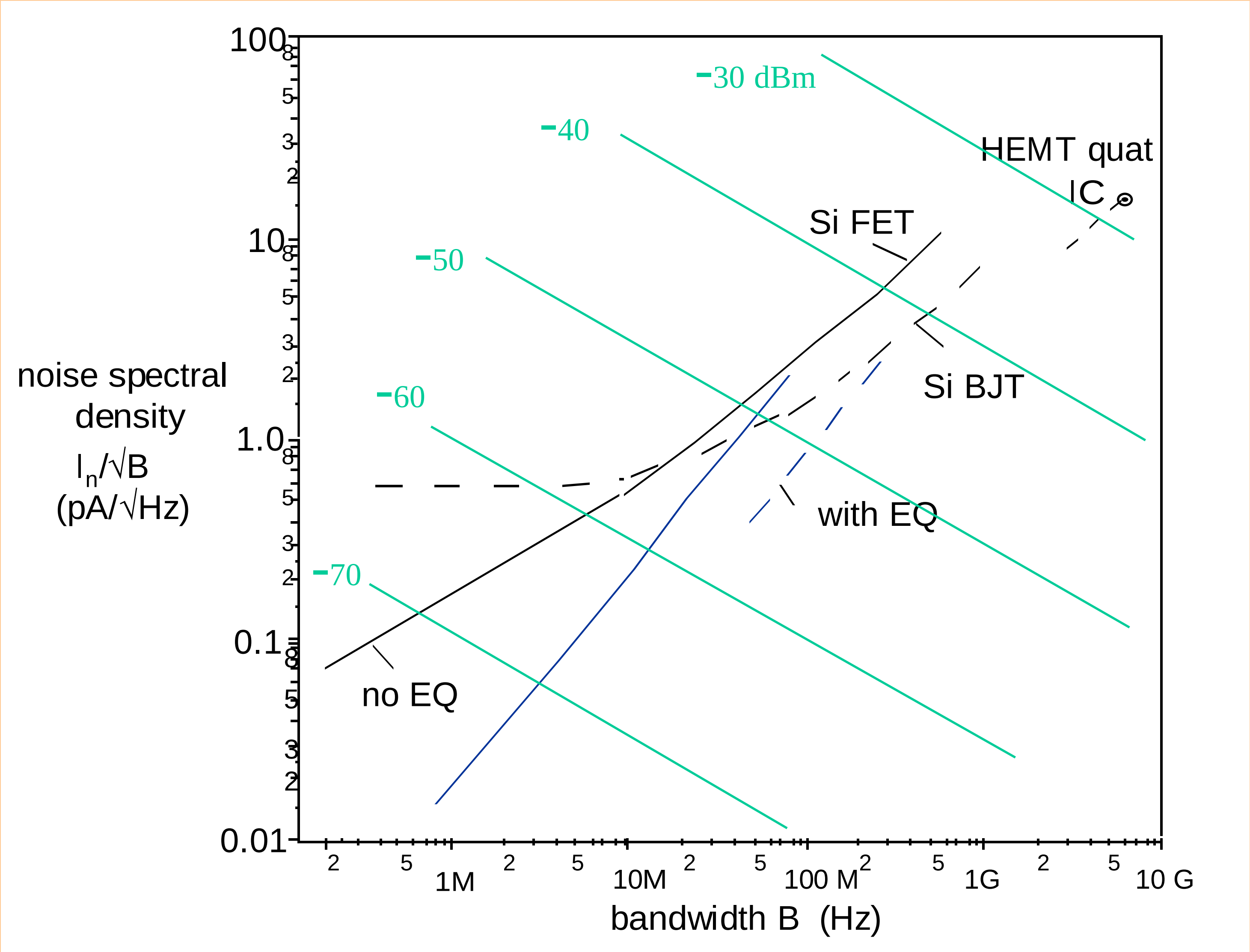
High-frequency Transimpedence performance (noise spectral density vs B)



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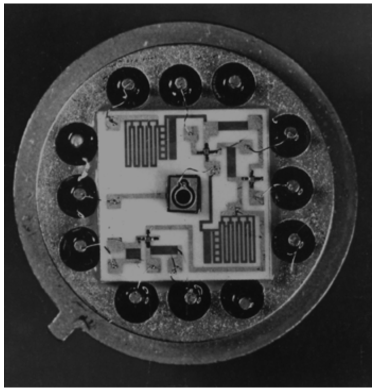
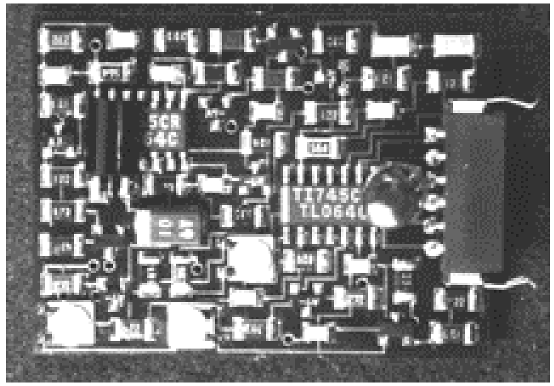
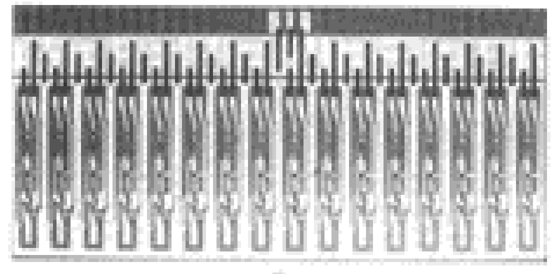
Transimpedence integration technologies



HTF
hybrid-thick-film
(100MHz)



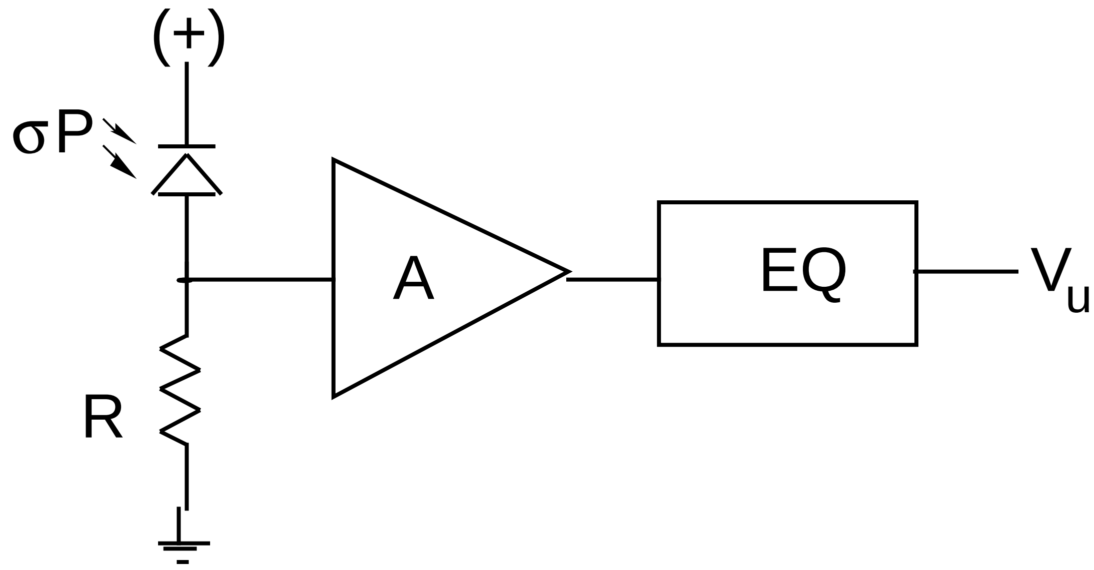
SMD
surface-mont-device
(200 MHz)



16-channel
In P IC
(11GHz)

from:"Photodetectors", by S.Donati, Prentice Hall 2000

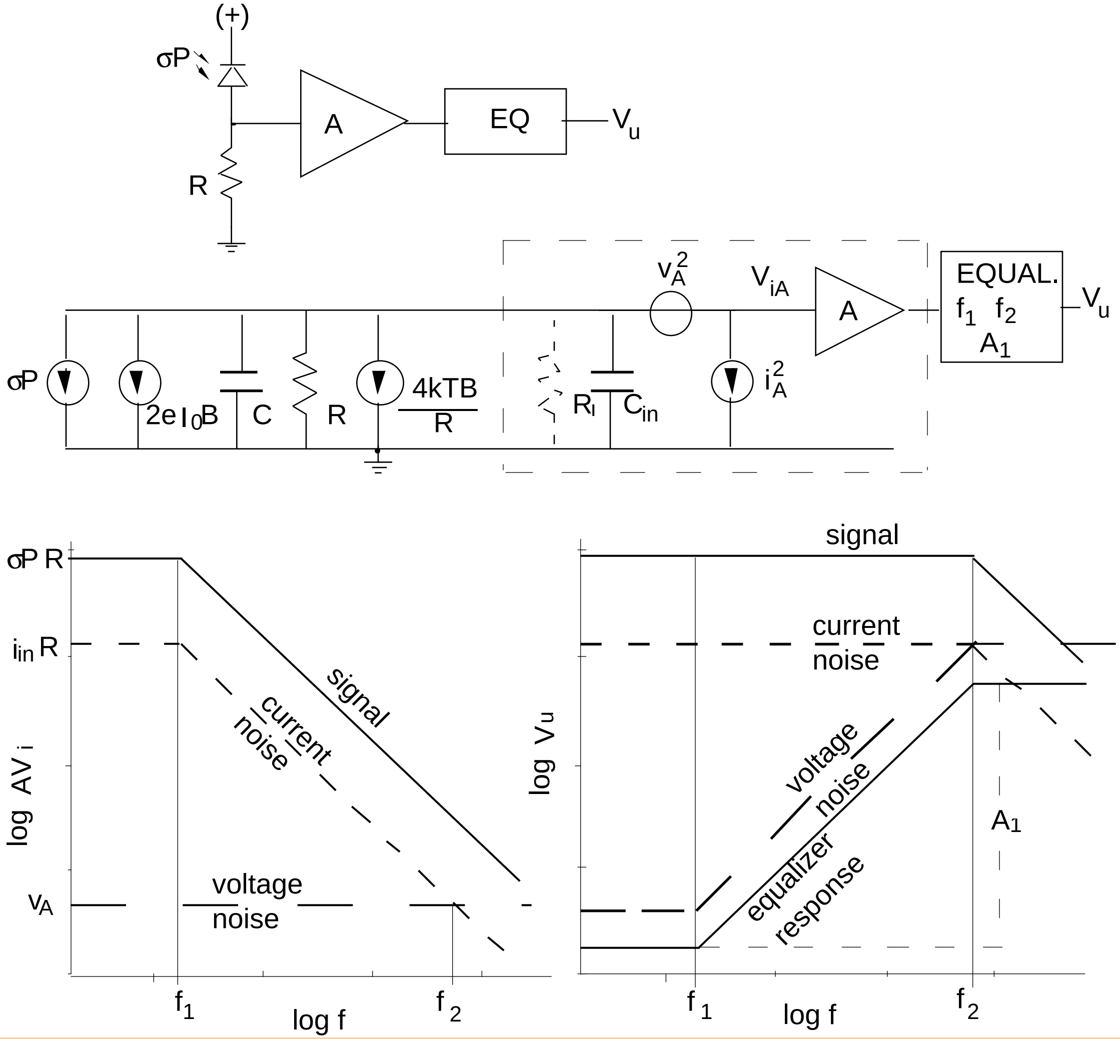
Equalization



$$4kTB/R \leq 2eI_0B + i_A^2 \quad \text{or}$$
$$\leq 2e(I_0+\sigma P)B.$$

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Frequency response



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Analysis

We ask that $4kTB/R \leq 2eI_0B + i_A^2$ [or $\leq 2e(I_0+\sigma P)B$].

In a good amplifier, noise $i_A^2 <<$ shot noise $2eI_0B$:

let $i_A^2 = \kappa\, 2eI_0B$ with $\kappa<1$,

With the = sign above, $R=(2kT/e)/I_0(1+\kappa)$ so that

$i_{in}^2 = 4kTB/R + 2eI_0B + i_A^2 = i_A^2\, 2\,(1+\kappa)$, and $f_1=1/2\pi RC_i$.

Max. frequency f_2 with no S/N degradation is when the amplified v_A equals current noise i_{in}:

$$i_{in} R = v_A(f_2/f_1) = v_A\,(f_2\, 2\pi RC_i)$$

whence $f_2 = 1/\,2\pi RC_i\,(v_A/i_{in}) = [2(1+\kappa)]^{1/2}/2\pi C_i\,(v_A/i_A)$

new cutoff is that of a resistance $R_A = v_A/i_A$ (typ. 50)

bandwidth improvement is $f_2/f_1 = [2(1+\kappa)]^{1/2} R/R_A$

yet noise remains: $i_{in}^2 = 2eI_0B\;\; 2\kappa\,(1+\kappa)$

Equalization: an example

For a PD with I_0=500pA, and κ=0.5, the required load is:

$$R = 50mV/300pA \cdot 1.5 = 110\ M\Omega$$

In a FET-input op-amp (LF356), typical noises are:

$$i_A/\sqrt{B} = 10\ fA/\sqrt{Hz}, \quad v_A/\sqrt{B} = 15\ nV/\sqrt{Hz}$$

so that: R_A=15nV/10fA =1.5 MΩ

Bandwidth improvement obtained with equalization is

$$\sqrt{[2(1+1/\kappa)]}\ R/R_A = \sqrt{6} \cdot 110/1.5 = 180$$

Noise spectral density corresponding to the dark current I_0 is $\sqrt{(2eI_0)}$ = 14 fA/√Hz, whence the correctness of $\kappa \approx 0.5$.

With C_i=5pF, input cutoff frequency is: f_1= 21kHz

and equalized cutoff frequency is f_2= 3.8 MHz;

current noise (0-f_2 frequency band): $i_{in}/\sqrt{B}$=25 fA/√Hz

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Equalization beyond f_2

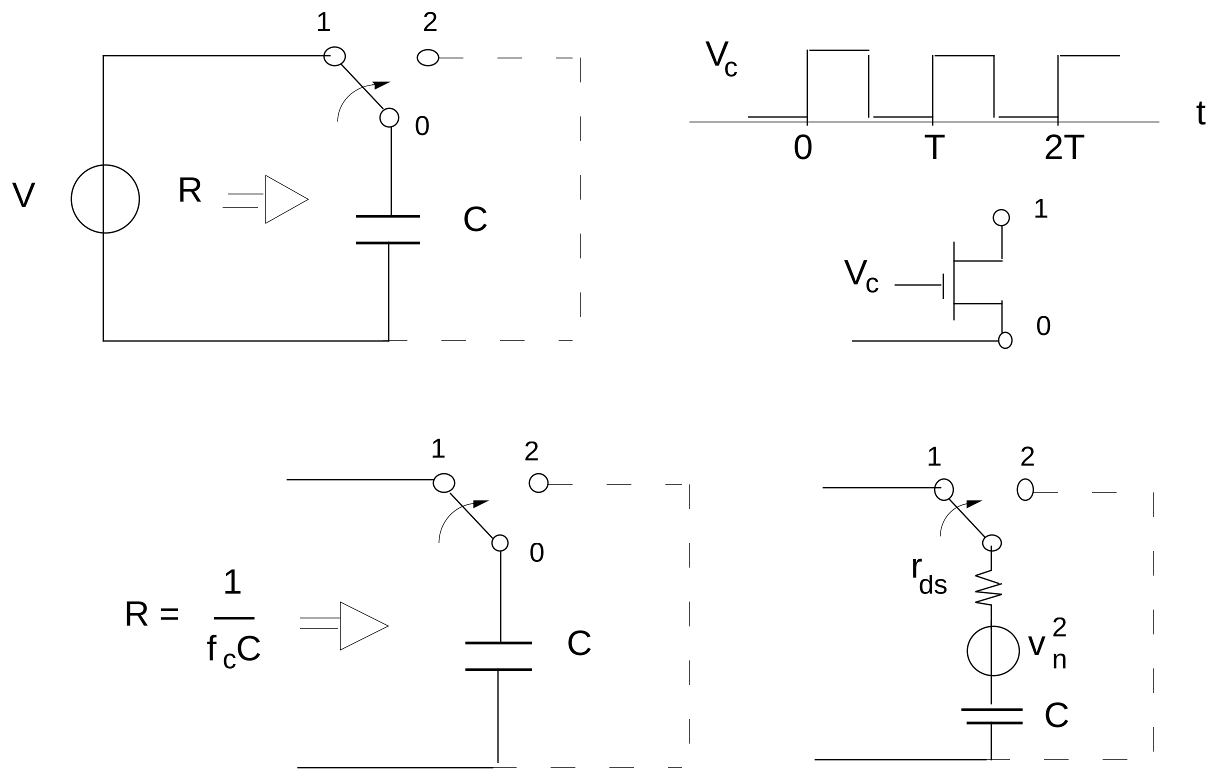
We may also go beyond f_2 with the equalization, but then noise worsens because v_A dominantes at $f > f_2$. If $f_3 > f_2$ is the desired new cutoff, noise is increased by $1+(f_3/3f_2)^2$ respect to optimum value, or, it becomes

$$i_{in}^2 = 2eI_0B \; 2\kappa(1+\kappa)[1+(f_3/3f_2)^2]$$

Limitation of equalization: the equalizer stage requires a gain $A=f_2/f_1$ at the equalized frequency f_2, thus the active device shall have f_T at least equal to Af_2. When f_2 approaches f_T no reserve of gain is available for equalization.

Thus, the technique is good (and widely applied) for $f_2 << f_T$, but at the highest frequencies $f_2 \approx f_T$ where it would be most challenging, its improvement becomes marginal.

Switched capacitor (basics)



$$R = VT/Q = 1/f_c C, \qquad I_{ph0} = (50\ mV)\, f_c\, C$$

from:"Photodetectors", by S.Donati, Prentice Hall 2000

Example on SC

In a 5 × 5 (μm)^2 MOS-switch, it is typ. $r_{ds} \approx$ 2-3kΩ/sq, and the strays are ≈ 0.05 pF. Choose C =2pF (>>C_{stray}) and make the switch short (L/W=0.3) to lower r_{ds}, so as r_{ds}=0.8 kΩ (typ). Then, the min. clock period is τ=(3÷5) Cr_{ds} = 5÷8 ns.

At the clock frequency f_c= 1, 10, 100, 1000 kHz

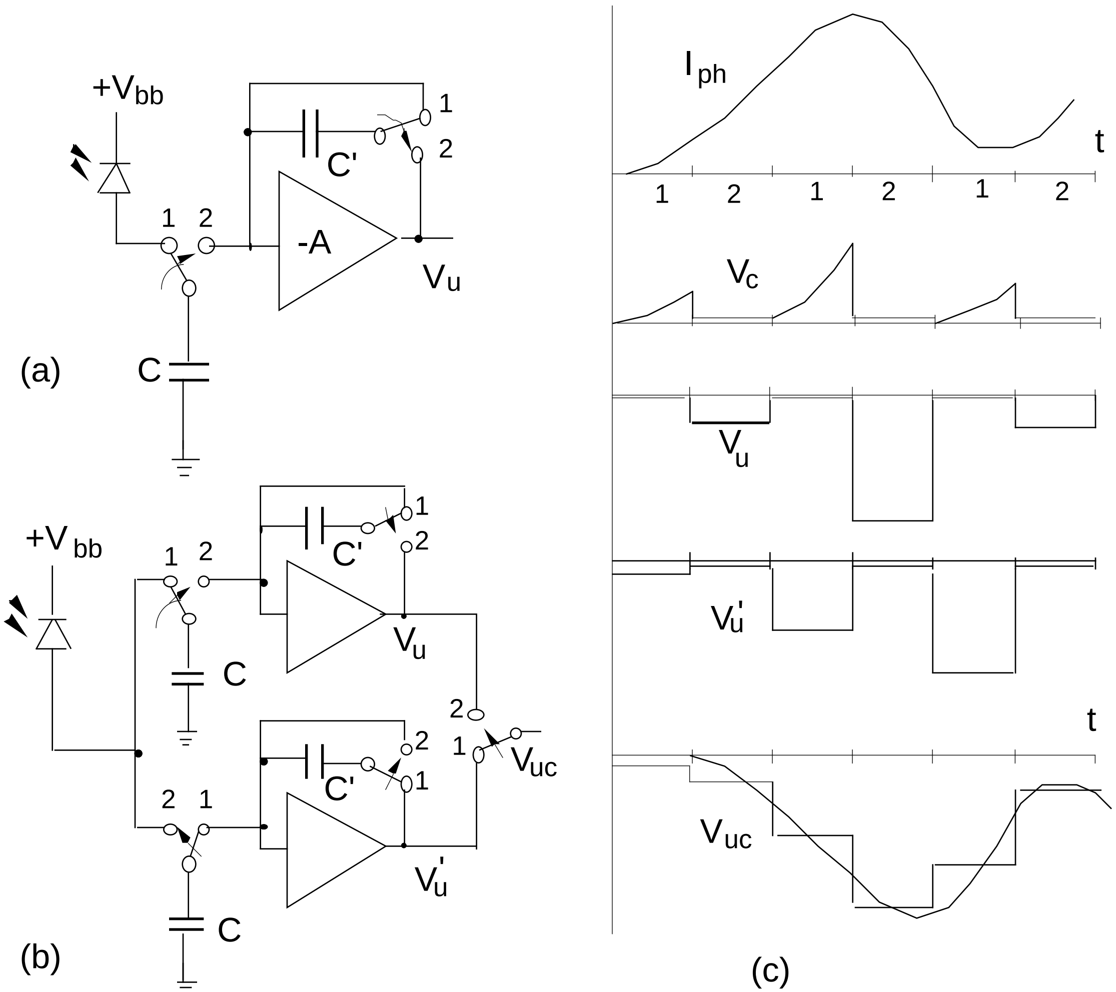
the SC resistance is R = 500, 50, 5, 0.5 MΩ

and quantum regime current is I_{ph0} = 0.1, 1, 10, 100 nA.

Performance is good at low f, but worsens approaching the MHz range.

Values above are typ. of IC-switches in SSI MOS (CD4066). With JFETs SSI (LF13333), r_{ds} is smaller (100 Ω) but parasitic is higher (2 pF). Taking C=50pF, one can have, at the above freq. an SC R = 20, 2, 0.2, 0.02 MΩ, still adequate up to the MHz range.

SC Transimpedence



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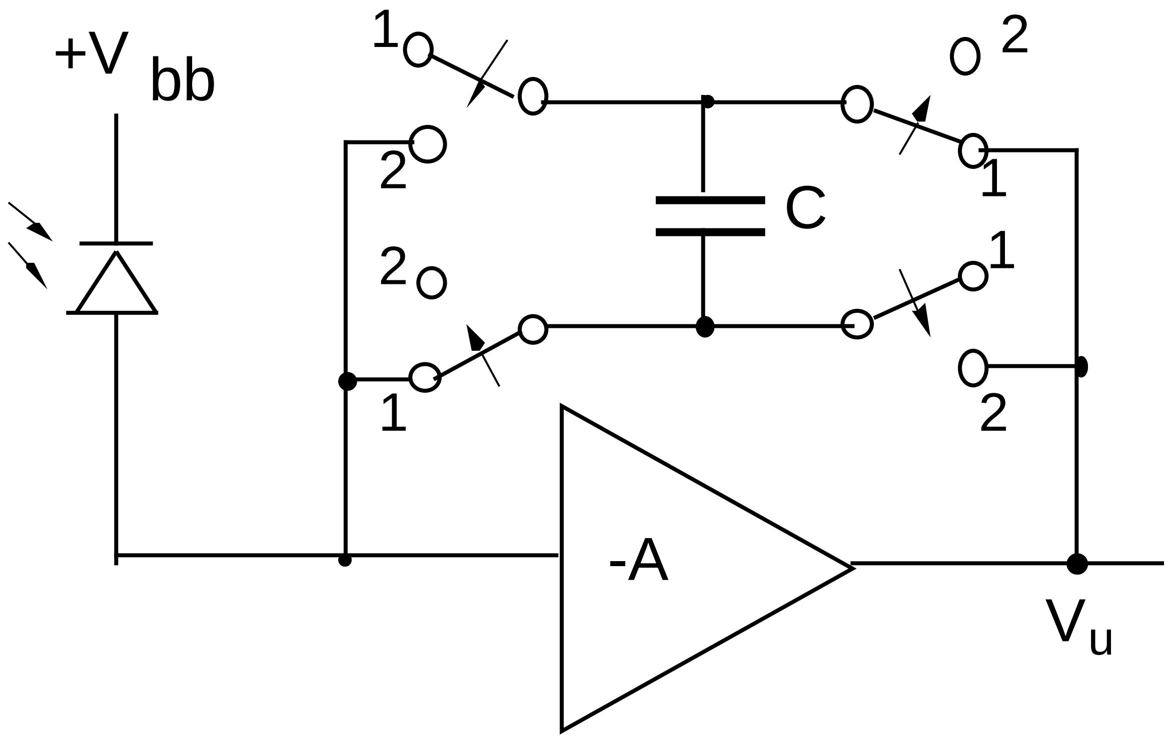
SC transimpedence with chopped output



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