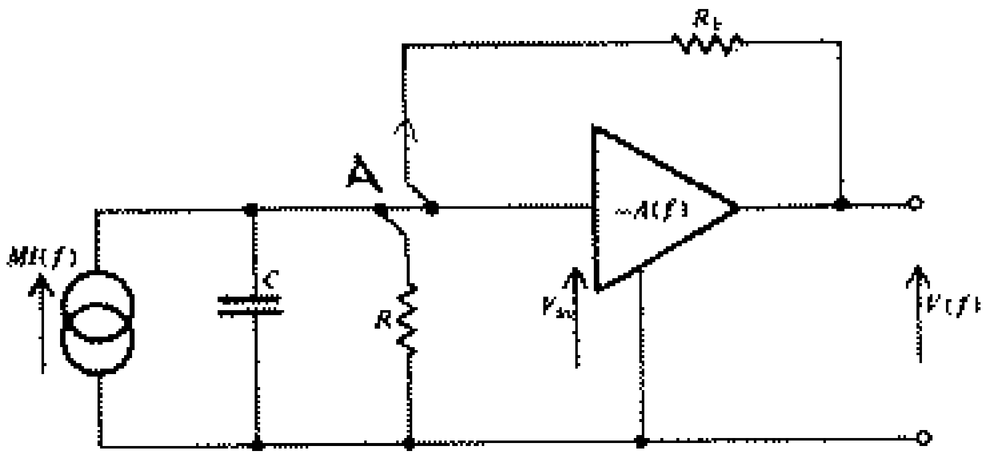
The Transimpedance Amplifier

R and R_f can be large (-A(f)) cancels and good reproducibility results



$$V_{in} = -V/A$$

$$MI + \frac{V - V_{in}}{R_f} = V_{in}\left(\frac{1}{R} + j2\pi f C\right)$$

Node Equation at A

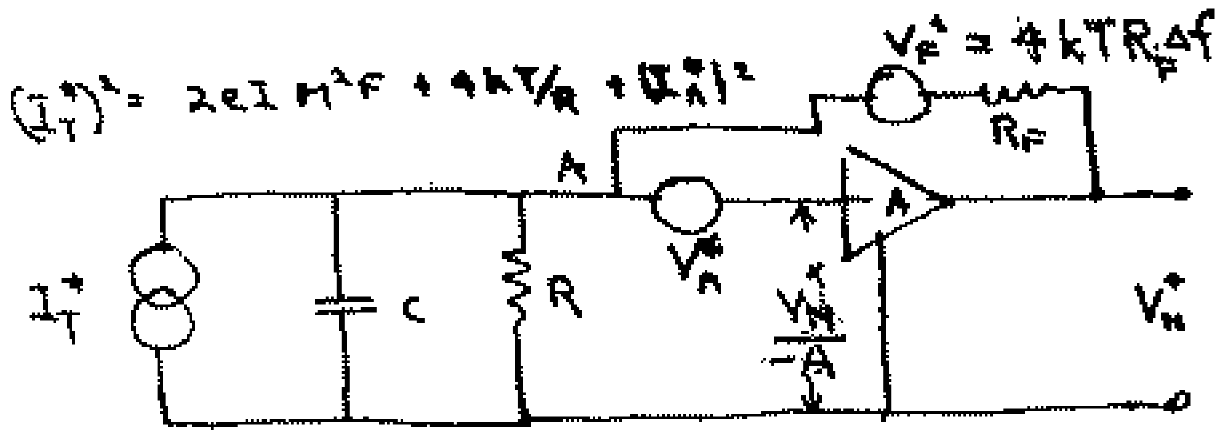
$$MI = -V\left(\frac{1}{R_F} + \frac{1}{AR_f} + \frac{1}{AR} + j\frac{2\pi f C}{A}\right)$$

$$V = \frac{-R_F M I}{\left(1 + \frac{1}{A} + \frac{R_F}{AR} + j\frac{2\pi f C R_F}{A}\right)}$$

$$= \frac{-R_F M I / \left(1 + \frac{1}{A} + \frac{R_F}{AR} + j\frac{2\pi f C R_F}{A}\right)}{\left[1 + j\frac{2\pi f C R_F}{(1 + R_F/R + A)}\right]}$$

$$V \approx \frac{-R_F M I}{1 + j\frac{(2\pi f C R_F)}{A}} \approx -R_F M I$$

Noise Terms



Use Superposition and Node Equation at A

① V_A^* $(I_T^* = V_F^* = 0)$

$$\left(V_A^* + \underbrace{\frac{V_N^*}{-A}}_{A \text{ large} \to 0}\right)\left(\frac{1}{R} + j2\pi fC\right) = \left(V_N^* - \left(V_A^* + \underbrace{\frac{V_N^*}{-A}}_{A \text{ large} \to 0}\right)\right)\frac{1}{R_F}$$

$$V_N^* = V_A^* R_F\left(\frac{1}{R_F} + \frac{1}{R} + j2\pi fC\right) \Big/ \left(1 + \frac{1}{A} + \frac{R_F}{AR} + j\frac{2\pi fC}{A}R_F\right)$$

For A large

$$V_N^* = V_A^*\left(1 + \frac{R_F}{R} + j2\pi fCR_F\right)$$

② I_T^* $(V_F^* = V_A^* = 0)$

$$\left(V_N^* - \frac{V_N^*}{-A}\right)\frac{1}{R_F} + I_T^* = \frac{V_N^*}{(-A)}\left(\frac{1}{R} + j2\pi fC\right) \qquad \text{Eq. (2)}$$

$$V_N^*\left(\frac{1}{R_F} + \frac{1}{AR_F} + \frac{1}{AR} + j\frac{2\pi fC}{A}\right) = -I_T^*$$

For A large from Eq. (2)

$$V_N^* = -R_F I_T^*$$

③ V_F^* $(V_A^* = I_T^* = 0)$ $\quad V_N^* = V_F^* + V_N/(-A) \simeq V_F^*$

Total Noise

$$(V_N^*)^2 = \int (V_A^*)^2 \left(\left(1 + \frac{R_F}{R}\right)^2 + 4\pi^2 f^2 C^2 R_F^2 \right) + R_F^2 (I_T^*)^2 + (V_F^*)^2 \, df$$

$$(V_N^*)^2 = \int_0^{\Delta f} (V_N^*)^2 \, df$$

$$V_N = \left[(V_A^*)^2 \left\{ \left(1 + \frac{R_F}{R}\right)^2 + \frac{4\pi^2}{3} (\Delta f)^2 C^2 R_F^2 \right\} + R_F^2 (I_T^*)^2 + 4kTR_F \right]^{1/2} (\Delta f)^{1/2}$$

$(V_F^*)^2 \rightarrow 4kTR_F$

$(I_T^*)^2 \rightarrow 2eIM^2F + \frac{4kT}{R} + (I_A^*)^2$

$$K = \left| \frac{V}{V_N} \right| = \frac{I}{\left[\frac{(V_A^*)^2}{M^2} \left\{ \left(\frac{1}{R} + \frac{1}{R_F} \right)^2 + \frac{4\pi^2}{3} C^2 (\Delta f)^2 \right\} + 2eIF + \frac{4kT}{M^2} \left(\frac{1}{R} + \frac{1}{R_F} \right) + \frac{(I_A^*)^2}{M^2} \right]^{1/2} (\Delta f)^{1/2}}$$

(a) (b) (c) (d) (e)

Same as previously with $1/R$ replaced by $1/R + 1/R_F$

Note: No equalization

Example APD $C = 3\,pF$, $R = 4\,k\Omega$, $R_F = 10\,k\Omega$

Si Bipolar Transistor Input $\quad V_A^* = 2\,nV/\sqrt{Hz}$

$\lambda = 1.3\,\mu m$ $\quad I_A^* = 2\,pA/\sqrt{Hz}$

	p–i–n $M = 1, F = 1$	APD $M = 20, F = 10$
Term (a)	6.25×10^{-26} [A²/Hz]	1.6×10^{-28} [A²/Hz]
Term (b)	2.3×10^{-24} [A²/Hz]	5.8×10^{-27} [A²/Hz]
Term (d)	2.1×10^{-24} [A²/Hz]	5.2×10^{-27} [A²/Hz]
Term (e)	4.0×10^{-24} [A²/Hz]	1.0×10^{-26} [A²/Hz]
Total, (a) + (b) + (d) + (e) = (A)	8.5×10^{-24} [A²/Hz]	2.1×10^{-26} [A²/Hz]
$\frac{1}{2}(I_{SH}^*)^2_{UL} = (KeF)^2\Delta f = (B)$	7.2×10^{-28} [A²/Hz]	7.2×10^{-26} [A²/Hz] Shot Noise Dominates
$q/p^2 = (A)/(B)$	11800	0.3
$I_{min} = p\{1 + (1 + q/p^2)^{1/2}\}$	490 nA	96 nA
$(\Phi_P)_{min}$ (with $\eta = 0.5$)	1 μW	200 nW