Comparison of parameters of simple current-to-voltage converters

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Abstract

Current-to-voltage converters are widely used in spectrophotometry, fast and long-distance data transfer, etc., when coupled with photodiodes. This work presents a comparative analysis of two basic I–V converters: sensing resistor and operational-amplifier-based converter. To somehow classify each circuit, a Figure of Merit (FoM) was chosen, which takes into account current-to-voltage gain, noise performance, and bandwidth. The analysis was performed by the author, with reference to relevant literature for guidance.

Photodiode model

Semiconductor-junction photodiode is a device which converts photon energy into electron-hole pairs, generating a current. A photodiode can be modeled as a light-controlled current source along with its parasitic elements. For TIA the most important parasitic element is the photodiode's junction capacitance, and thus the model gets simplified to:

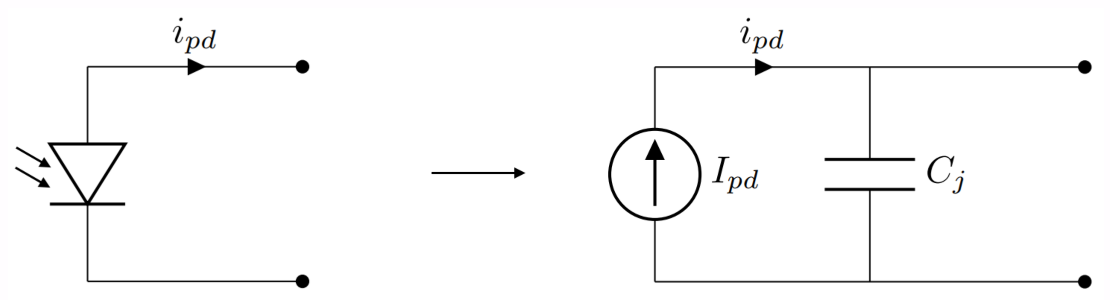

Figure 1: Practical photodiode model

Sensing resistor

Ohm's law provides us with the simplest I-V converter: a resistor.

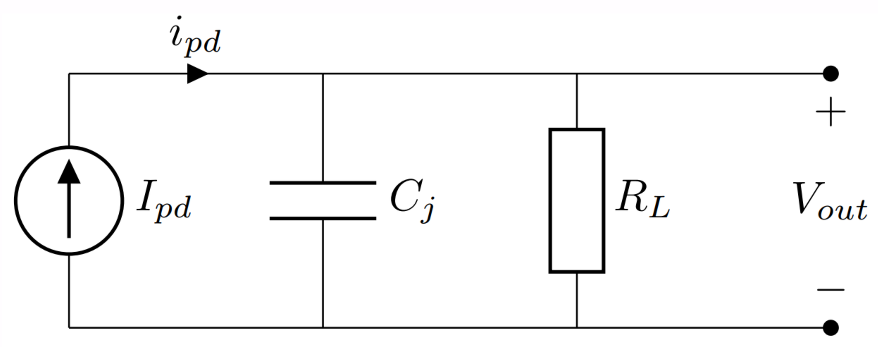

Figure 2: Usage of resistor as an I-V converter

Unfortunately this topology does not give us promising results when it comes to performance.

$$\frac{V_{out}}{I_{in}}(s) = -(R_L \| C_j) = \frac{-R_L}{1 + sR_LC_j}$$

$$BW = \frac{1}{2\pi R_L C_j}$$

Sensing resistor - Noise analysis

Current noise from the added resistor is seen in the same way as current from the photodiode. We can transfer this current noise source to output node (as a voltage noise source) simply by multiplying it by the I-V gain of the circuit.

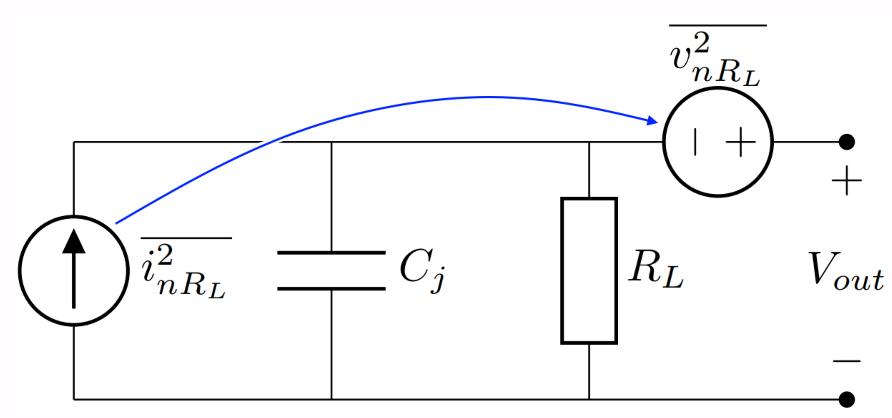

Figure 3: Transferring current noise source to output node

$$\overline{v^2_{nR_L}} = \overline{i^2_{nR_L}} * H^2(s) = \frac{4kT}{R_L} * \frac{R_L^2}{(1 + sR_LC_j)^2} = \frac{4kTR}{(1 + sR_LC_j)^2}$$

After integrating the noise over the whole bandwidth we can come to the following conclusion:

$$v_{nRMS} = \sqrt{\int_0^\infty \frac{4kTRf}{(1 + sR_LC_j)^2} df} = \sqrt{\frac{kT}{C_j}}$$

Sensing resistor - Summary

I-V Gain $[\frac{V}{A}]$	Bandwidth [Hz]	RMS noise [Vrms]
$\frac{R_L}{1+sR_LC_j}$	$\frac{1}{2\pi R_L C_j}$	$\sqrt{\frac{kT}{C_j}}$

Operational Amplifier TIA

Better parameters can be achieved by using operational amplifier's virtual ground at inverting-input. C_s is the sum of junction capacitance and all parasitic capacitances involved with adding an op amp ($C_s = C_j + C_{OAin} + C_p$).

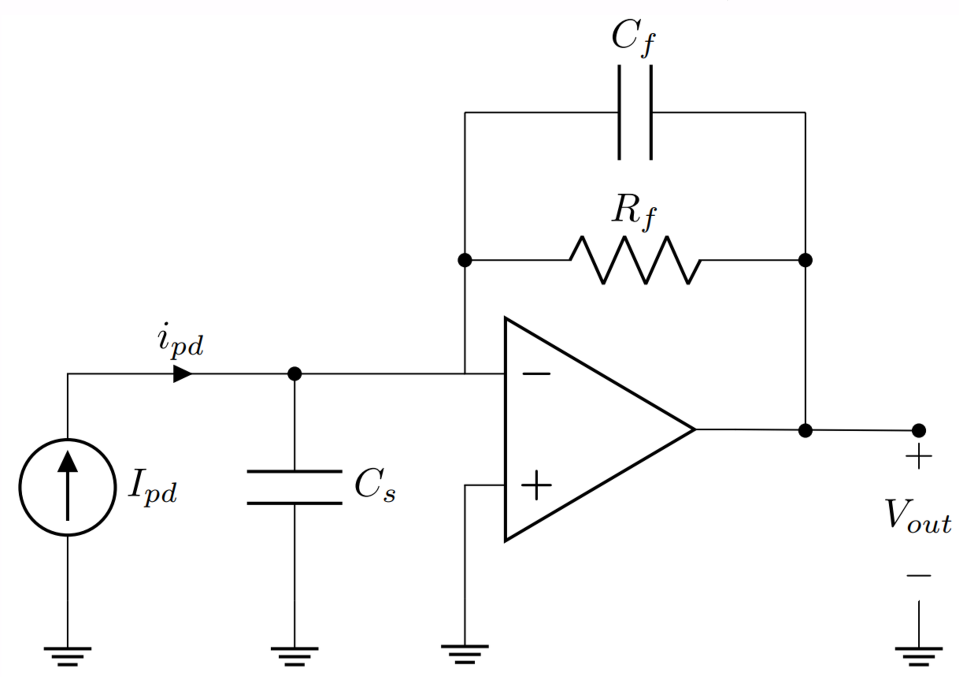

Figure 4: Operational amplifier based I-V converter

$$\frac{V_{out}}{I_{in}}(s) \approx \frac{-R_f}{1 + s\frac{R_fC_s}{A_{ol}}}$$

$$BW = \frac{A_{OL}}{2\pi R_f C_s}$$

Preliminary analysis shows that OA based circuit is a major improvement to the simple resistor. Pole's location is multiplied by the open loop gain of the used amplifier, while maintaining gain equal to the feedback resistor value in low frequencies.

Operational Amplifier TIA - Stability and bandwidth

Unfortunately without a feedback capacitor this circuit is unstable. When analyzing the stability of an op-amp TIA, it is important to examine the loop gain Bode plots and poles/zeros locations.

$$A_{OL}(s)\beta(s) = \frac{A_o}{(1 + s\frac{A_o}{GBW2\pi})} * \frac{(1 + sR_fC_f)}{1 + sR_f(C_s + C_f)}$$

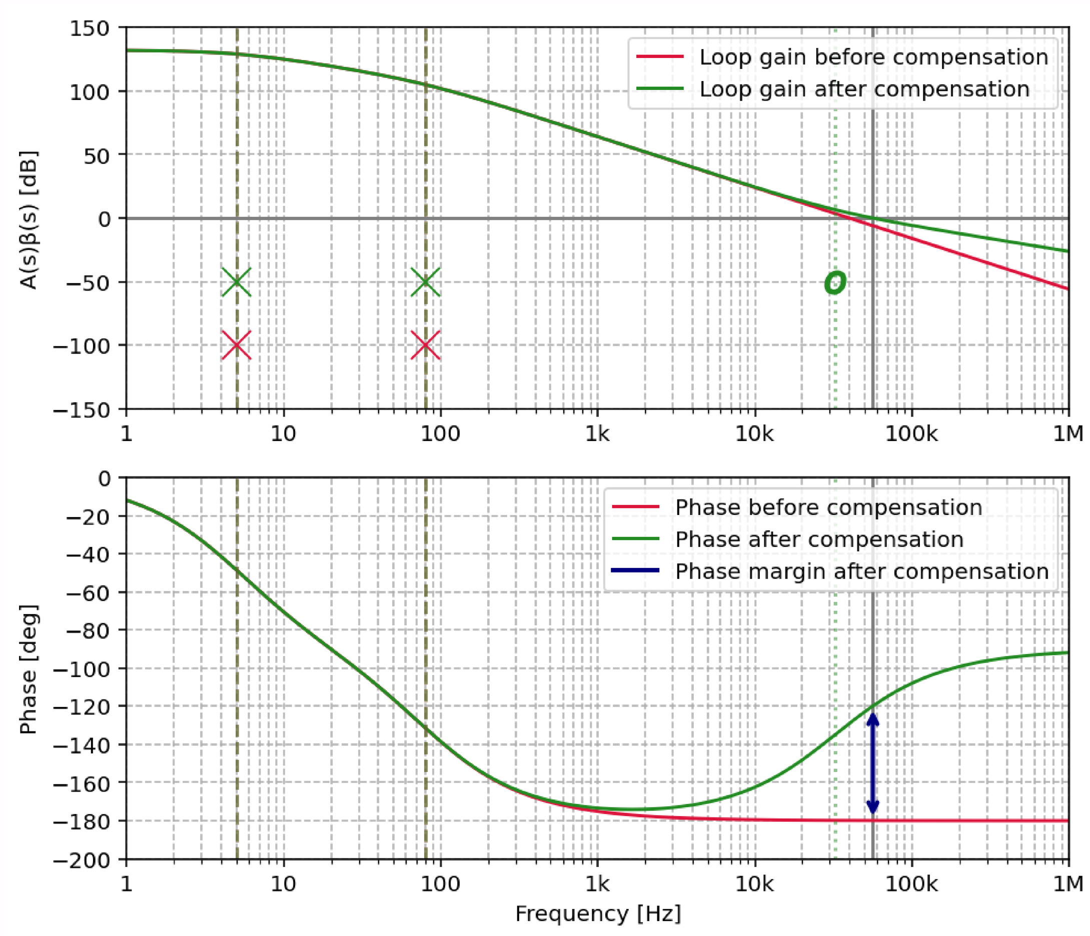

Figure 5: Loop gain Bode plots showing PM and poles/zeros locations before and after compensation.

For phase margin of 60° the formula for feedback capacitance[2] is:

$$C_f \approx \sqrt{\frac{C_s}{\pi GBWR_f}}$$

Operational Amplifier TIA - Noise analysis

In this noise analysis only noise from the resistor and op amp were taken into account.

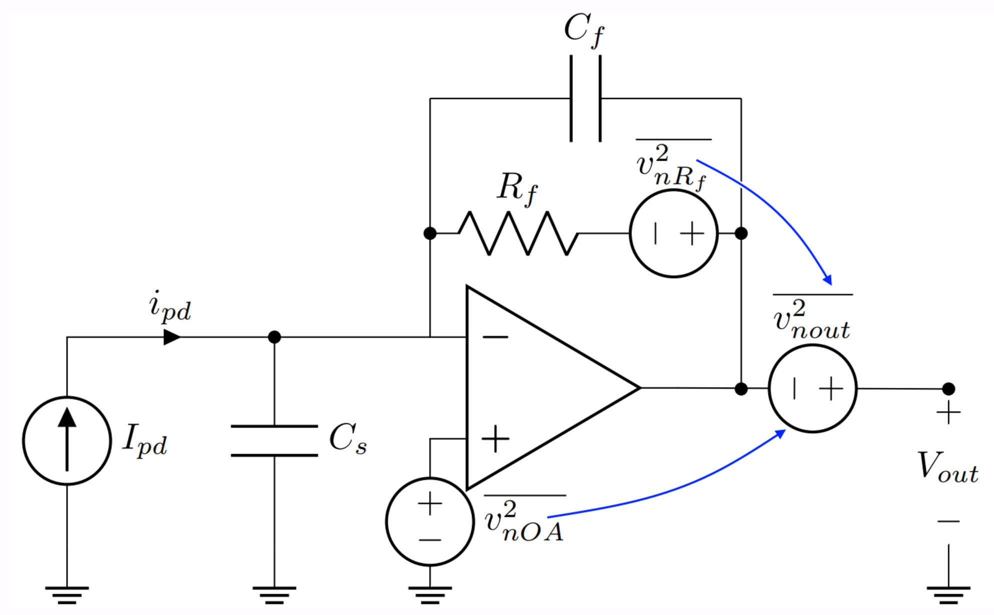

Figure 6: Noise sources in an op amp-based TIA

When performing noise analysis for the OA's input voltage noise it is important to examine noise gain of a circuit. It acts like a bandpass amplifier with a gain of $1 + \frac{C_s}{C_f}$. [2]

$$\overline{v^2_{n,out}} = \overline{v^2_{n,OA}}\left(\left(1 + \frac{C_s}{C_f}\right)\frac{1 + s \cdot 2\pi R_f(C_s + C_f)}{(1 + s \cdot 2\pi R_fC_f)\left(1 + s \cdot \frac{C_s + C_f}{GBW \cdot C_f}\right)}\right)^2 + \overline{v^2_{n,R_f}}\left(\frac{1}{1 + sR_fC_f}\right)^2$$

Operational Amplifier TIA - Summary

I-V Gain $[\frac{V}{A}]$	Bandwidth [Hz]	RMS noise [Vrms]
$\frac{-R_L}{1+sR_fC_f}$	$\frac{1}{2\pi R_L\sqrt{C_s/(\pi GBWR_f)}}$	$\sqrt{\int_0^\infty \overline{v^2_{n,out}}(f)\, df}$

Figure of Merit (Fom)

To somehow classify each circuit, a Figure of Merit (FoM) was chosen, which takes into account current-to-voltage gain, noise performance, and bandwidth.

$$FoM[\frac{(V * Hz)/A}{V_{rms}}] = \frac{GAIN * BW}{ORN}$$

FoM for sensing resistor is given by this formula:

$$FoM_R = \frac{1}{\sqrt{4\pi^2 C_j}}$$

Sensing resistor's figure of merit is defined only by the photodiode's capacitance. FoM for operational amplifier-based TIA is given by a more complicated formula.

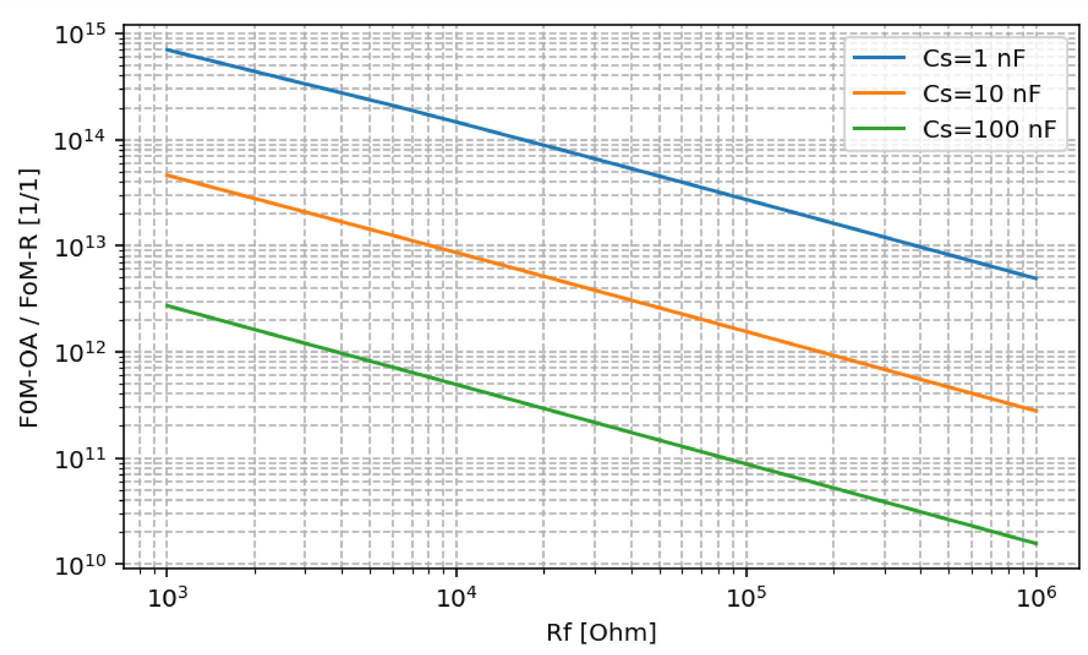

Figure 7: FoM-OA/FOM-R values computed numerically for GBW OF 20MHz and different C_s values

References

[1] W. Sansen, *Analog Design Esentials*

[2] J. Graeme, *Photodiode Amplifiers - Op Amp Solutions*