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COMPENSATE TRANSIMPEDANCE AMPLIFIERS INTUITIVELY

By Tony Wang and Barry Ehrman

Transimpedance amplifiers are used to convert low-level photodiode currents to usable voltage signals. All too often the amplifiers have to be empirically compensated to operate properly. The problem can be easily understood if one looks at all the elements involved. Figure 1 shows the typical photodiode application.

The ideal transimpedance transfer function is, by inspection:

$$V_{OUT} = -I_S \cdot Z_F = -I_S \cdot \frac{R_F}{1 + j\,2\,\pi\,f\,R_F C_F}$$

This equation suggests that the frequency response is strictly due to the feedback network. This does not explain why transimpedance amplifiers are prone to oscillate. Figure 2 provides more insight into the stability problem. The photodiode is replaced with an ideal current source in parallel with its equivalent resistance, R_D, and capacitance, C_D. The op amp input capacitance cannot be considered insignificant and should be included as part of C_D.

The noise gain (i.e., the noninverting closed-loop gain) of this configuration determines the stability of the circuit. The reason for this is that any noise signal, no matter how small, can trigger an unstable circuit into oscillation. From inspection, the transfer function can be determined to be:

$$A_{CL}(f) = \frac{R_F + R_D}{R_D} \cdot \frac{1 + j\,2\,\pi\,f\left(\frac{R_F R_D}{R_F + R_D}\right)(C_F + C_D)}{1 + j\,2\,\pi\,f\,R_F C_F}$$

$$= \frac{R_F + R_D}{R_D} \cdot \frac{1 + j\,\frac{f}{f_Z}}{1 + j\,\frac{f}{f_p}}$$

The dc gain is set solely by the resistors. The pole frequency, f_P, is set by the feedback network, just as in the transimpedance function. The zero frequency, f_Z, is determined by (a) the sum of the feedback and the diode capacitances and (b) the parallel combination of the feedback and the diode resistances.

Typically, the feedback resistor is much smaller than the photodiode's equivalent resistance. This makes the dc resistive gain unity. The value of the parallel combination is essentially equal to the feedback resistor alone. Therefor, f_Z will always be lower than f_P, as shown in Figure 3.

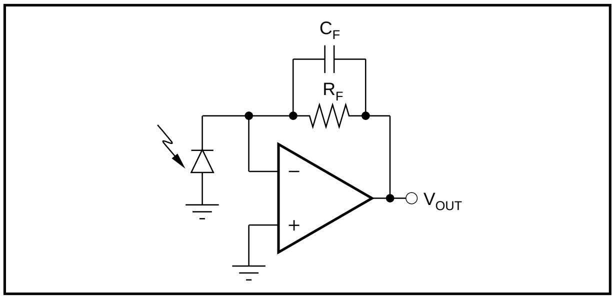

FIGURE 1. Typical Photodiode Transimpedance Amplifier.

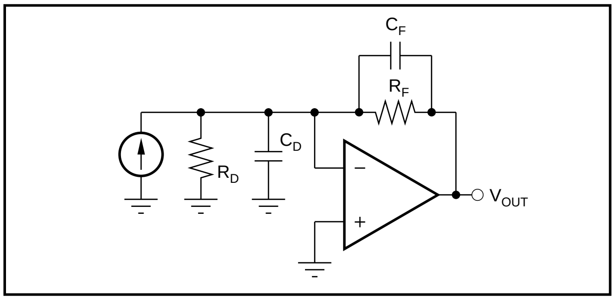

FIGURE 2. Photodiode Modelled with Ideal Elements.

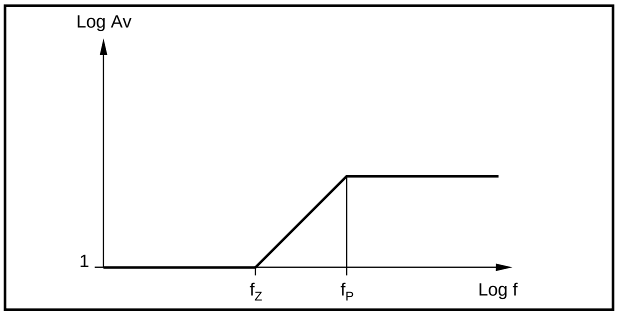

FIGURE 3. Bode Plot of Noise Gain.

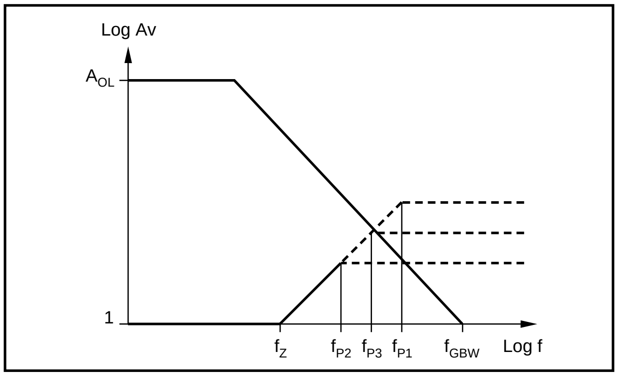

FIGURE 4. Various Feedback Responses Intersecting Op Amp Open-loop Gain.

Figure 4 depicts three different scenarios for the intersection of the closed-loop response curve with the open-loop gain curve. Stability degradation will occur when f_P falls outside the open-loop gain curve. For f_{P1} the circuit will oscillate. If f_P lies inside the open-loop gain curve, the transimpedance circuit will be unconditionally stable. This is the case for f_{P2} but stability is traded off for transimpedance bandwidth. The optimum solution paces f_P on the open-loop gain curve as shown for f_{P3}.

Since f_P is determined by the feedback network, judicious selection of C_F is all that is necessary. This process can be greatly simplified by noting that the high frequency asymptote for the noise gain is determined by capacitance values alone:

$$A_{CL}(f >> f_P) = \frac{C_F + C_D}{C_F}$$

This value should be equal to the op amp's open-loop gain at f_P. The open-loop gain is found by dividing the op amp's gain-bandwidth product (GBW) by f_P. Setting these two expressions equal yields:

$$\frac{GBW}{f_P} = \frac{C_F + C_D}{C_F}$$

Simple substitution yields a quadratic equation whose only real, positive solution is:

$$C_F = \frac{1}{4\pi R_F GBW} \sqrt{(1 + \quad 1 + 8\pi R_F C_D GBW)}$$

This simple equation selects the appropriate feedback capacitor for guaranteed stability once the op amp's minimum gain-bandwidth and the photodiode's maximum capacitance are determined.

Further insight can be gained with some simplifying assumptions and a little algebra:

$$f_P \approx \sqrt{\frac{GBW}{2\pi R_F C_D}}$$

This result indicates that, for a given op amp and photodiode, transimpedance bandwidth is inversely related to the square root of the feedback resistor. Thus, if bandwidth is a critical requirement, the best approach may be to opt for a moderate transimpedance gain stage followed by a broadband voltage gain stage.

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