Simplify Transimpedance Applications with High-bandwidth, Precision JFET Op Amps

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Modern JFET-input operational amplifiers (op amps) offer a combination of high input impedance, excellent DC and AC performance, low noise, high bandwidth, and wide voltage supply range, making them a natural choice for transimpedance op amp (TIA) applications. A TIA is a current-to-voltage converter, typically used as a front-end for optical sensors such as photodiodes, commonly found in Optical Line Cards, Light Level Sensors, PM 2.5 Detectors, and many more. Silicon photodiodes produce a current output that changes linearly with incident light, where the typical photo current ranges from a few pico-amps to a few milliamps. The combination of high input impedance, with low input bias currents of a few pico-amps at room temperature, and very low current and voltage noise, allow JFET op amps to be used in precision, high-resolution photodiode applications. Furthermore, JFET op amps operate over a wide voltage range and are able to cover a broad spectrum of photodiode output current, which is beneficial in TIA applications as this increases the overall resolution and accuracy of the system. Figure 1 shows a typical photodiode transimpedance application.

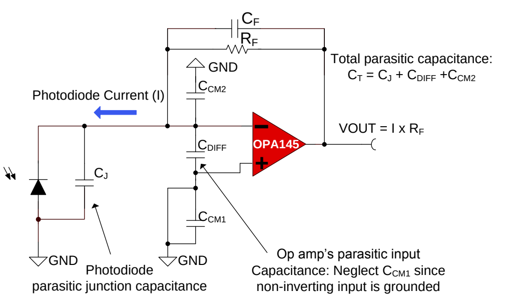

Figure 1. Photodiode Transimpedance Amplifier

The feedback resistor (RF) across the op amp converts the photodiode current (I) to a voltage (VOUT) using Ohm's law, shown in Equation 1:

$$V_{OUT} = I \times R_F \quad (1)$$

The feedback resistor (R_F) determines the gain of the transimpedance op amp, and the feedback capacitor (C_F) defines the closed-loop bandwidth of the circuit. In addition, the feedback capacitor (C_F) is required for stability and is used to compensate for the total parasitic capacitance (C_T) at the inverting input of the op amp: the photodiode junction capacitance (C_J) and the input capacitance of the op amp (C_{DIFF} + C_{CM2}).

Transimpedance Op Amp Gain, Bandwidth, and Stability

When selecting an op amp for a photodiode TIA application, it is important to carefully consider the three factors that dictate the minimum gain bandwidth product of the op amp (f_{GBW}) necessary for circuit stability: the TIA required V/I gain, the required closed-loop TIA bandwidth, and the parasitic junction capacitance of the photodiode (C_J).

The stability of an op amp is related to its closed-loop gain and phase response over frequency. The closed-loop gain is defined as the product of the open-loop gain of the op amp (AOL) and the feedback factor of the op amp (β), defined as AOL × β. Figure 2 shows the bode plots of the open loop gain (AOL) and 1/β plot of a typical TIA. See the TI Precision Labs - Op Amps: Stability – Lab Video Series for more information about stability analysis and simulation.

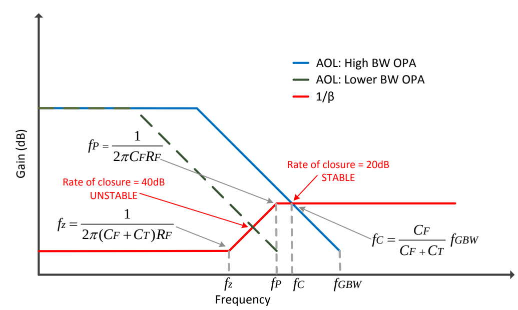

Figure 2. AOL and 1/β Plot for Transimpedance Op Amp Circuit

The 1/β curve of the Figure 2 presents a zero (f_Z) and a pole (f_P) on its frequency response. Above the zero (f_Z), the 1/β curve increases a rate of +20 dB per decade. At frequencies above the pole (f_P), the 1/β curve remains flat. The 1/β curve intersects the AOL curve at frequency f_C is shown in Equation 2:

$$f_C = \frac{C_F}{C_F + C_T} f_{GBW} \quad (2)$$

In Equation 2, f_{GBW} is the unity gain bandwidth of the op amp. By analyzing the rate of closure of AOL and 1/β when the curves intersect, you can determine the stability of the circuit. A handy rule of thumb for this method is that the rate of closure must equal 20-dB for optimal stability. Therefore, to maintain stability, the AOL curve must intersect the 1/β curve when the 1/β curve is flat (assuming a unity gain stable op amp). If the AOL curve intersects the 1/β curve when the 1/β curve is rising, as shown by the lower bandwidth op amp AOL curve in Figure 2, the circuit may be unstable, leading to many unfavorable circuit behaviors. Equation 3 gives us the necessary condition to avoid these problems:

$$f_C > f_P \quad (3)$$

Substituting the equations for f_C and f_P into the inequality provided on equation 3, and solving for the amplifiers unity gain bandwidth (f_{GBW}), provides a useful equation.

Equation 4 determines the minimum required bandwidth of the amplifier to guarantee stability for a TIA design. Therefore, higher bandwidth amplifiers support higher gain and bandwidth TIA circuits, and tolerate a higher parasitic photodiode capacitance while remaining stable. Consider the case of a photodiode application with the following specifications: Transimpedance Amplifier Gain (50-K V/A), Transimpedance Amplifier Bandwidth, 1-MHz, and Photodiode Junction Capacitance (Cj) (100 pF).

$$f_{GBW} > \frac{C_T + C_F}{2\pi R_F C_F 2} \quad (4)$$

For comparison, consider two implementations with op amps with different bandwidths: the OPA140 offers 11-MHz of gain bandwidth product, while the OPA828 offers 45-MHz. Using the previously derived equation for minimum bandwidth, the minimum fGBW for the transimpedance op amp is ~37-MHz. Using a single stage, the OPA140 is unstable as shown on Figure 3.

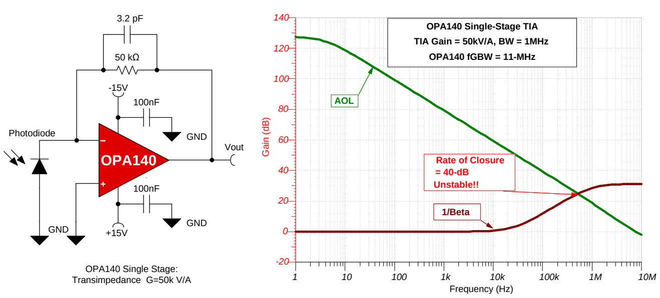

Figure 3. Single-stage OPA140 (f_{GBW} = 11-MHz) Stability Analysis (Unstable)

To meet the TIA requirements, two cascaded stages of the OPA140 are required. A transimpedance stage with a lower gain of 10-kΩ cascaded a with a non-inverting gain stage of 5 V/V as shown on Figure 4.

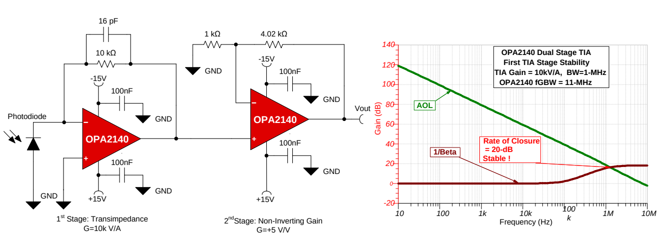

Figure 4. Alternate Two-stage OPA140 TIA Amplifier (Stable)

In contrast, the higher f_{GBW} OPA828 is able to support the TIA gain of 50 k V/A with 1-MHz bandwidth while offering 55 degrees of phase margin using a single-stage as shown on Figure 5. A single stage TIA implemented with a precision, high bandwidth op amp offers better noise performance and accuracy than a dual stage version built with two lower bandwidth amplifiers of similar accuracy, since only one amplifier contributes to noise, offset, and drift errors in the system. This greatly simplifies your design while offering lower component count, simpler routing and a smaller solution size.

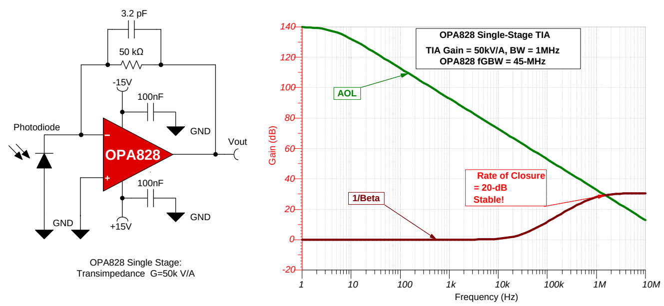

Figure 5. Single-stage OPA828 (f_{GBW} = 45-MHz) TIA Stability Analysis (Stable)

Summary

Modern JFET op amps combine high input impedance, excellent noise performance, high bandwidth, and wide output voltage range, making JFET amplifiers an optimal choice in the use of high gain, and high resolution transimpedance photodiode circuits.

Table 1. TIA Op Amps

DESCRIPTION	OP AMP
36-Volt, High-speed (45 MHz GBW and 150 V/µs SR), low-noise (4 nV/√Hz) RRO JFET Op Amplifier	OPA828
5.5 MHz, High Slew Rate, Low-Noise, Low-power, RRO Precision JFET Op Amplifier	OPA145
Low-Offset, Low-Drift, Low-Noise, 11-MHz, 36-V JFET-Input, RRO Op Amplifier	OPA140

Table 2. Related Documentation

TYPE	TITLE
Application Brief	*Green-Williams-Lis: Improved Op Amp Spice Model*
Application Report	*Cookbook Circuit: Transimpedance Amplifier*