Optimizing Precision Photodiode Sensor Circuit Design

by Luis Orozco, system applications engineer, Analog Devices, Inc.

Photodiodes are one of the most popular sensor types for many light-based measurements. Applications such as absorption and emission spectroscopy, color measurement, turbidity, gas detection, and more, all rely on photodiodes for precision light measurement.

Photodiodes generate a current proportional to the light that strikes their active area. Most measurement applications involve using a transimpedance amplifier to convert the photodiode current into an output voltage. Figure 1 shows a simplified schematic of what the circuit could look like.
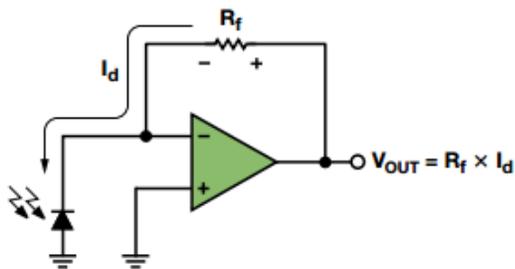

Figure 1. Simple Transimpedance Amplifier Circuit

This circuit operates the photodiode in photovoltaic mode, where the op amp keeps the voltage across the photodiode at 0 V. This is the most common configuration for precision applications. The photodiode's voltage vs. current curve is very similar to that of a regular diode, with the exception that the entire curve will shift up or down as the light level changes. Figure 2a shows a typical photodiode transfer function. Figure 2b is a zoomed-in view of the transfer function, and it shows how a photodiode outputs a small current even if there is no light present. This "dark current" grows with increasing reverse voltage across the photodiode. Most manufacturers specify photodiode dark current with a reverse voltage of 10 mV.
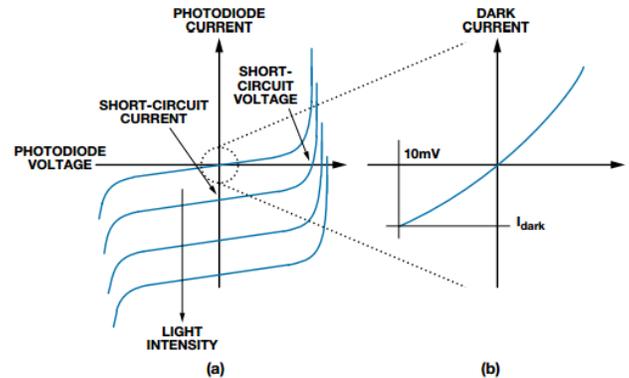

Figure 2. Typical Photodiode Transfer Function

Current flows from cathode to anode when light strikes the photodiode's active area. Ideally, all of the photodiode current flows through the feedback resistor of Figure 1, generating an output voltage equal to the photodiode current multiplied by the feedback resistor. The circuit is conceptually simple, but there are a few challenges you must address to get the best possible performance from your system.

DC CONSIDERATIONS

The first challenge is to select an op amp with dc specifications that match your application's requirements. Most precision applications will have low input offset voltage at the top of the list. The input offset voltage appears at the output of the amplifier, contributing to the overall system error, but in a photodiode amplifier, it generates additional error. The input offset voltage appears across the photodiode and causes increased dark current, which further increases the system offset error. You can remove the initial dc offset through software calibration, ac coupling, or a combination of both, but having large offset errors decreases the system's dynamic range. Fortunately, there is a wide selection of op amps with input offset voltage in the hundreds or even tens of microvolts.

The next important dc specification is the op amp's input-leakage current. Any current that goes into the input of the op amp, or anywhere else other than through the feedback resistor, results in measurement errors. There are no op amps with zero input bias current, but some CMOS or JFET input op amps get close. For example, the AD8615 has a maximum input bias current of 1 pA at room temperature. The classic AD549 has a maximum input bias current of 60 fA that is guaranteed and production tested. The input bias current of FET input amplifiers increases exponentially

as temperature rises. Many op amps include specifications at 85°C or 125°C, but for those that do not, a good approximation is that the current will double for every 10 degrees of temperature increase.

Another challenge is designing a circuit and layout to minimize external leakage paths that could ruin the performance of your low input bias current op amp. The most common external leakage path is through the printed circuit board itself. For example, Figure 3 shows one possible layout of the photodiode amplifier schematic of Figure 1. The pink trace is the +5 V rail that powers the amplifier and goes off to other parts of the board. If the resistance through the board between the +5 V trace and the trace carrying the photodiode current is 5 GΩ (shown as R_L in Figure 3), 1 nA of current will flow from the +5 V trace into the amplifier. This would obviously defeat the purpose of carefully selecting a 1 pA op amp for the application. One way to minimize this external leakage path is to increase the resistance between the trace carrying the photodiode current and any other traces. This can be as simple as adding a large routing keep-out around the trace to increase the distance to other traces. For some extreme applications, some engineers will eliminate PCB routing altogether and run the photodiode lead through air directly into the op amp's input pin.
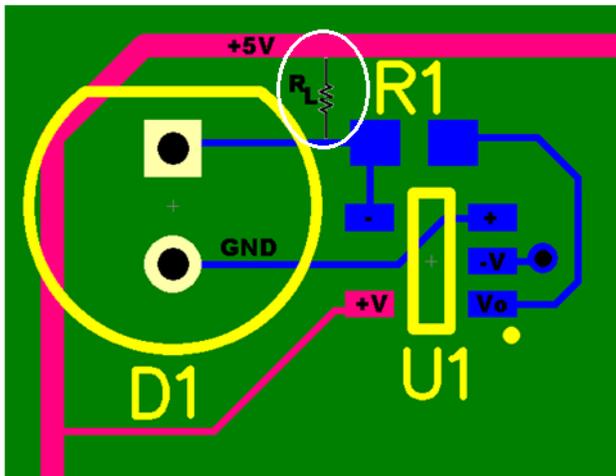

Figure 3. Photodiode Layout with Leakage Path

Another way to prevent external leakage is to run a guard trace adjacent to the trace carrying photodiode current, making sure both are driven to same voltage. Figure 4 shows a guard trace around the net carrying the photodiode current. The leakage current caused by the +5 V trace now flows through R_L into the guard trace rather than into the amplifier. In this circuit, the voltage difference between the guard trace and the input trace is only due to the op amp's input offset voltage, which is another reason to select an amplifier with low input offset voltage.
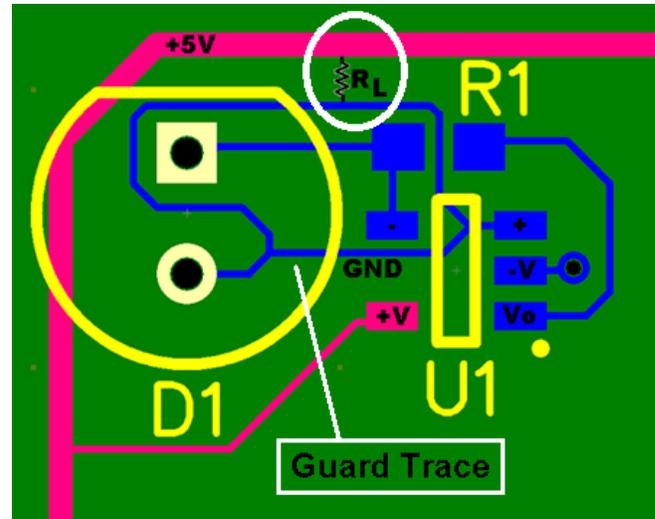

Figure 4. Using a Guard Trace to Reduce External Leakage

AC CONSIDERATIONS

Although most precision photodiode applications tend to be low speed, we still need to make sure the system's ac performance is adequate for the application. The two main concerns here are the signal bandwidth (or closed-loop bandwidth) and the noise bandwidth.

The closed-loop bandwidth depends on the open-loop bandwidth of the amplifier, the gain resistor, and the total input capacitance. Photodiode input capacitance can vary widely from a few picofarads for high speed photodiodes, to a few thousand picofarads for very large area precision photodiodes. However, adding capacitance on the input of an op amp causes it to become unstable unless you compensate it by adding capacitance across the feedback resistor. The feedback capacitance limits the closed-loop bandwidth of the system. You can use Equation 1 to calculate the maximum possible closed-loop bandwidth that will result in a phase margin of 45 degrees.

$$f_{45} = \sqrt{\frac{f_u}{2\pi \cdot R_F \cdot (C_{IN} + C_M + C_D)}}$$ Equation 1

Where:

f_U is the amplifier's unity gain frequency.

R_F is the feedback resistor.

C_{IN} is the input capacitance, which includes diode capacitance and any other parasitic capacitance on the board, etc.

C_M is the common mode capacitance of the op amp.

C_D is the differential capacitance of the op amp.

For example, if you have an application with 15 pF of photodiode capacitance and 1 MΩ of transimpedance gain, Equation 1 predicts you would need an amplifier with unity gain bandwidth of about 95 MHz to achieve a 1 MHz signal bandwidth. This is with a 45° phase margin, which will cause peaking during step changes in signal. You may want to reduce the peaking by designing for a 60° phase margin or higher, which would require a faster amplifier. This is why parts like the ADA4817-1, with 20 pA of maximum input bias current and a unity gain frequency of around 400 MHz are a good fit for high gain photodiode applications, even for moderate bandwidths.

The photodiode capacitance will dominate the total input capacitance in most systems, but some applications may require extra care in selecting an op amp with very low input capacitance. To address this issue, some op amps are available with special pinouts designed to reduce input capacitance. For example, Figure 5 shows the ADA4817-1's pinout, which routes the op amp output to a pin adjacent to the inverting input.
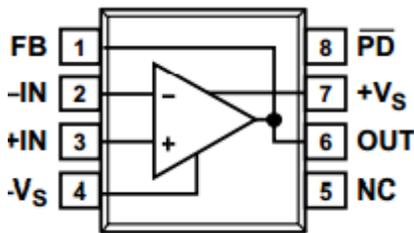

Figure 5. ADA4817-1 Pinout is Optimized for Low Parasitic Capacitance

System noise is typically another challenge when designing with photodiodes. The main contributors to output noise are the amplifier's input voltage noise and the feedback resistor's Johnson noise. The noise from the feedback resistor appears at the output without additional amplification. If you increase the size of the resistor to amplify the photodiode current, the increase in noise due to the gain resistor will only increase by the square root of the resistor value increase. In practical terms, this means it is beneficial to have as much gain as possible in the photodiode amplifier rather than adding a second amplifier stage, where the noise will increase linearly with gain.

The output noise of the amplifier is the input voltage noise multiplied by the amplifier's noise gain. The noise gain is determined not just by the feedback resistor, but also by the feedback and input capacitors, so it is not constant over frequency. Figure 6 shows a typical plot of amplifier noise gain vs. frequency, with the closed-loop gain superimposed for reference. The two things you can learn from this plot are that the output noise increases at some frequencies and the

frequency range where the noise peaks can be beyond the amplifier's closed-loop cutoff bandwidth.
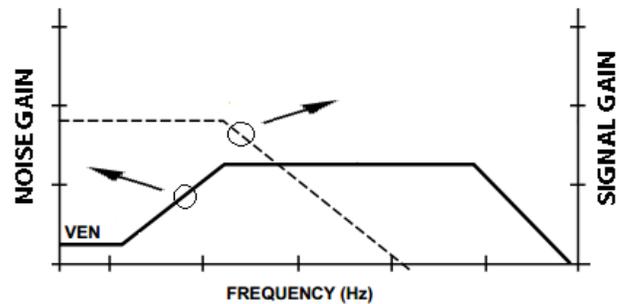

Figure 6. The Noise Gain of a Photodiode Amplifier Increases at Higher Frequencies

Because you can't take advantage of this bandwidth, use a low-pass filter set to the signal bandwidth of the amplifier to reduce the noise.

USING PROGRAMMABLE GAINS TO EXTEND DYNAMIC RANGE

Because the Johnson noise of the feedback resistor increases with the square root of the resistance, it makes sense to have as much gain as possible in the photodiode amplifier, rather than in a second stage. You can take this one step further by adding programmable gain to your photodiode amplifier as in the circuit of Figure 7.
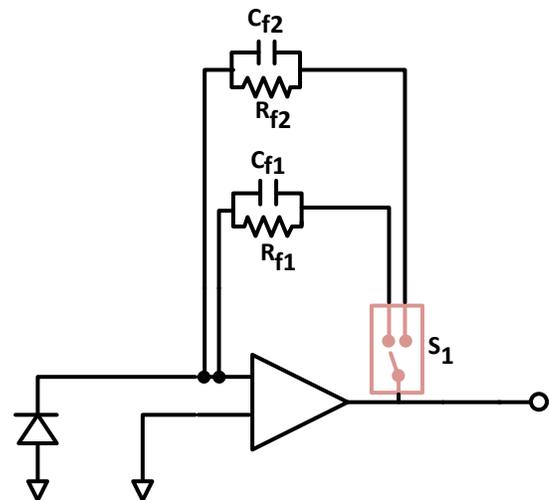

Figure 7. The Concept of a Programmable Gain Photodiode Amplifier

Switch S_1 selects the desired feedback path so that you can select the optimal gain for different signals. Unfortunately, analog switches have on resistance that will introduce gain errors to our circuit. This on resistance will change with applied voltage, temperature, and other factors, so you must find a way to eliminate it from the circuit. Figure 8 shows how you can use two sets of switches to remove the error due to the on resistance in the feedback loop. With this circuit,

you have one switch inside the feedback loop just like Figure 7, but instead of looking at the voltage on the output of the amplifier, switch S_2 connects the output of the circuit directly to the gain resistor. This eliminates any gain errors due to current flowing through switch S_1. One of the trade-offs when using this circuit is that the output no longer has the very low impedance associated with amplifier outputs, since it includes the on resistance of multiplexer S_2. This is usually not a big problem if the next stage has a high impedance input, such as with an ADC driver.
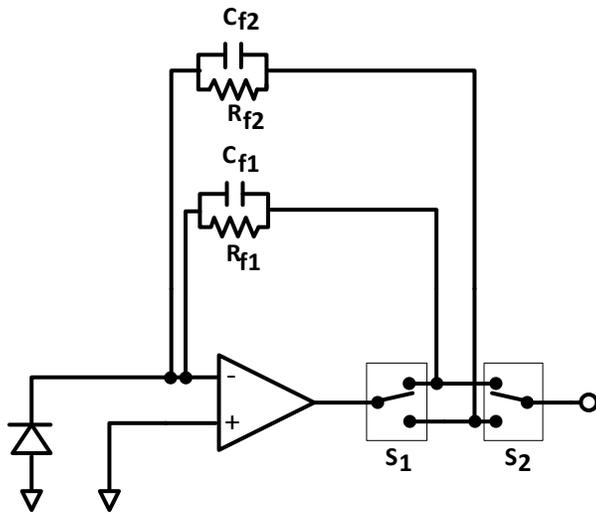

Figure 8. Using Two Sets of Switches Reduces Errors Due to Additional Resistance Inside the Loop

USING MODULATION AND SYNCHRONOUS DETECTION TO REDUCE NOISE

Many precision applications involve measuring a dc light level absorbed or reflected through a sample.

While some applications allow shielding from all ambient light, many other systems, mainly in industrial environments, have to operate exposed to ambient light. In this case, you can modulate the light source and use synchronous detection to move your signal away from the low frequency spectrum where electrical and optical interference is the highest. The simplest form of modulation is to rapidly turn the light source on and off. Depending on the light source, you can electronically modulate it, or as is the case in some older instruments, you can use a mechanical chopper to block the light at a given rate.

For example, if you are interested in measuring light absorption through a substance to determine concentration, you can chop the light source at a few kHz. Figure 9 shows how this results in moving the measurement away from most of the low frequency light pollution typically present in most environments, such as changes in the ambient light level due to time of day, 50 Hz/60 Hz fluorescent lights, and the like.
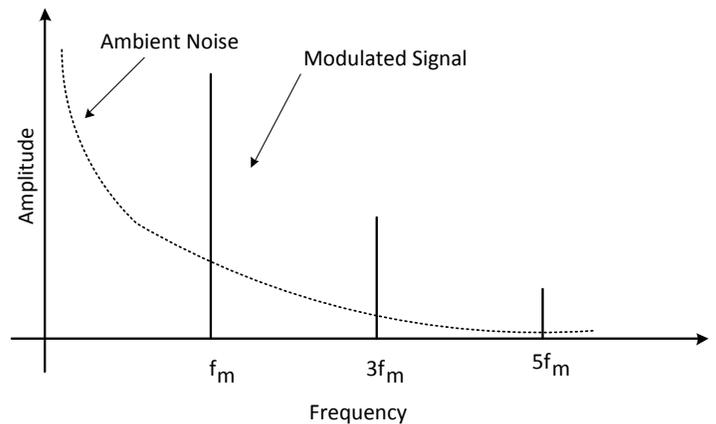

Figure 9. Chopping the Input Signal Moves the Information to the Chopping Frequency and Away from Ambient Noise

Because you control the frequency of the modulation signal, you can use the same clock to synchronously demodulate the received light. The circuit of Figure 10 is a very simple synchronous demodulator. The voltage at the output of the photodiode amplifier is ac-coupled and then passed through an amplifier with programmable gain of +1 and −1. The gain switch is synchronized to set the gain to +1 exactly when the light is expected to be on, and to −1 when the light is expected to be off. Ideally, the output would then be a dc voltage corresponding to the amplitude of the light pulses. The low-pass filter rejects any other signals that are not synchronous to the modulation clock. The cutoff frequency of the low-pass filter is equivalent to the width of a band-pass filter around the modulation frequency. For example, if the modulation frequency is 5 kHz and you use a low-pass filter with bandwidth of 10 Hz, the output of the circuit would pass signals from 4.99 kHz to 5.01 kHz. Lowering the low-pass filter bandwidth results in stronger rejection at the expense of slower settling time.

Figure 9 also shows an additional caveat when using chopping. The resulting waveform is not a single line in the frequency domain (which would require a sine wave), but rather a line at the chopping frequency and its odd harmonics. Any noise present at the odd harmonics of the chopping frequency will appear at the output with minimal attenuation. You can completely eliminate this by using sine wave modulation, but that requires more complex or expensive circuitry. Another solution is to pick an oddball fundamental frequency whose harmonics do not coincide with any known sources of interference. You can also implement the same functionality of Figure 10 in firmware. You can sample the chopped light signal synchronously with the modulation clock and use digital signal processing

techniques to extract the amplitude information at the frequency of interest.
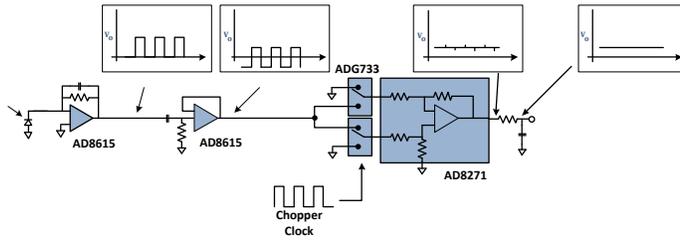

Figure 10. Synchronous Detection Circuit

CONCLUSION

Photodiode amplifiers are an important building block of most precision optical measurement systems. Selecting the right op amp is an important first step in obtaining the best possible system performance, and using other performance enhancing techniques such as using programmable gains and synchronous detection can help boost dynamic range and reject noise. If you are interested in learning more about precision photodiode circuits, please visit http://instrumentation.analog.com/en/chemical-analysis/segment/im.html.

AUTHOR

Luis Orozco [luis.orozco@analog.com] is a system applications engineer in ADI's industrial and instrumentation segment. Before joining ADI in 2011, he designed precision measurement equipment for 11 years. He currently focuses on test and measurement, chemical analysis, and environmental monitoring applications.

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