Noise and Stability in PIN Detectors

by Nick Bertone and Paul Webb

Abstract

In almost every area of measurement, the ultimate limit to the detectability of weak signals is set by noise - unwanted signals that obscure the desired signal. This article will examine the main contributions to noise in photometric systems using PIN photodectors and the effects which cooling the detectors will have on noise and stability.

Noise in Photometric Systems Using PIN Detectors

To quantify detector noise, a good figure of merit to use is NEP, Noise Equivalent Power. NEP is defined as the minimum incident power required to generate a photocurrent equal to the noise current (i_{nD}) of the photodetector ata specified frequency (f), and within a specific bandwidth (Df). The NEP for a PIN detector is calculated by the following formula:

$$NEP(\lambda, f, \Delta f) - \frac{i_{n(D)}}{R(\lambda)} \quad \frac{Watts}{\sqrt{Hz}} \qquad (1)$$

Where:

i_{nD} = noise current of the detector

R(l) = responsivity of the detector at wavelength.

The noise of the photodector-amplifier combination as shown in Figure 1, will have the following components of noise:

1. Detector Noise $i_{n(D)}$
2. Thermal noise from R_F, $i_{n(feedback)}$
3. Amplifier noise, $i_{n(amp)}$

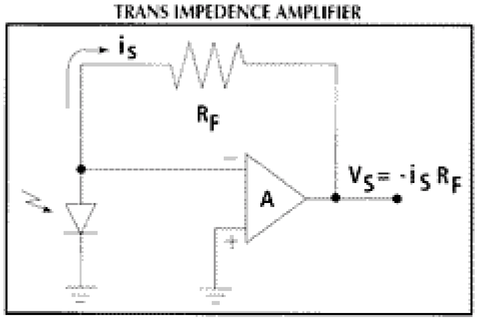

Figure 1. Photodetector-amplifier combination

Detector noise generated by a planar diffused photodiode operating in the reverse bias mode is a combination of shot noise and thermal noise. Shot noise is generated by random fluctuations of current flowing through the device. This current may be either dark current or photocurrent. The shot noise produced by the dark current (leakage current generated by bias voltage applied to the PIN detector) and by photocurrent is given by:

$$i_{n(shot)} = \sqrt{2\,q(I_d + I_{ph})\,\Delta f} \qquad \frac{Amps}{\sqrt{Hz}} \qquad (2)$$

Where:

q = Electron charge (1.6 x 10^{-19} coulombs)

I_d = Dark Current (amperes)

I_{ph} = Photocurrent (amperes)

Df = Noise bandwidth (Hertz)

The thermal noise of the detector is a function of the shunt resistance and, in the case of a guard ring device, the channel resistance. The thermal noise current for a PIN detector of feedback resistor is given by the following formula:

$$i_{n(shunt/feedback)} = \sqrt{\frac{4\,k\,T\,\Delta f}{R_{shunt/feedback}}} \qquad \frac{Amps}{\sqrt{Hz}} \qquad (3)$$

Where:

k = Boltzmann's constant, 1.38 x 10^{-23} J K^{-1}

T = Temperature in degree Kelvin (K)

Df = Noise bandwidth (Hertz)

$R_{shunt/feedback}$ = shunt or feedback resistance

Shunt resistance is also a function of temperature. Figure 2 shows shunt resistance as a function of temperature for Silicon, InGaAs and Germanium PIN detectors. The total detector noise ($i_{n(D)}$), is the quadratic sum of the shot noise and the thermal noise generated by the detector. However, in most cases, shot noise will be the main contributor to detector noise when a bias voltage is applied to the detector.

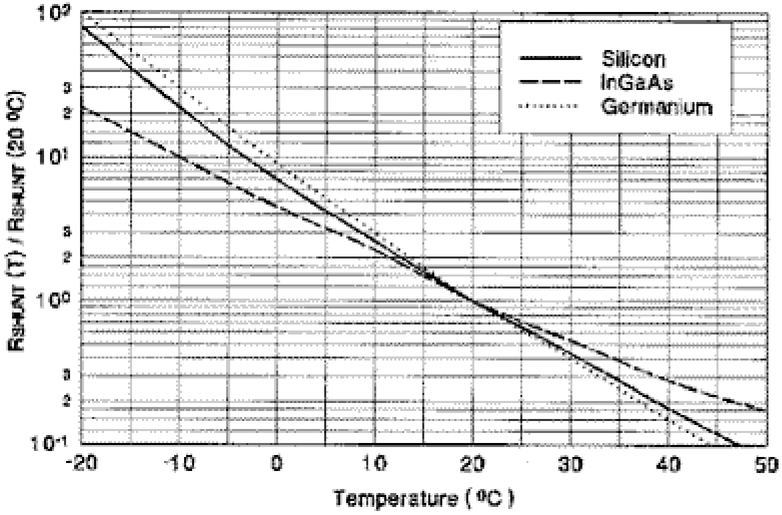

Figure 2. Shunt resistance vs. temperature for Silicon, InGaAs and Germanium PIN detectors.

From Figure 2 and equation 3, it is seen that as temperature decreases and shunt or feedback resistance increases, the detector noise or feedback resistor noise both decrease.

The final contribution to total noise is the amplifier noise. This noise depends on the type of amplifier used and is a function of frequency. The total amplifier noise current ($i_{n(amplifier)}$) is given by:

$$i_{n(amplifier)} = \sqrt{<i_{amp}>^2 + <V_{amp}\,\omega C_T>^2} \quad \frac{Amps}{\sqrt{Hz}} \quad (4)$$

Where:

i_{amp} = Amplifier input leakage current

V_{amp} = Amplifier input noise voltage

w = 2pf, where f is the frequency

C_T = Total input capacitance seen by the amplifier

Both i_{amp} and V_{amp} depend on the type of operational amplifier used, these values are provided by the manufacturer. For example, the AD549 is a low-noise, low-bandwidth precision pre-amplifier from Analog Devices with i_{amp} = 0.22fA/Hz$^{1/2}$ and V_{amp} = 90nV/Hz$^{1/2}$. It should be noted that selecting the correct Op-Amp is essential for optimizing the noise and frequency response of the entire photometric system. The total noise current of the photometric system, i.e. detector + feedback resistor + operational amplifier is given by:

$$i_{n(TOTAL)} = \sqrt{<i_{n(D)}>^2 + <i_{n(feedback)}>^2 + <i_{n(amplifier)}>^2} \; \frac{Amps}{\sqrt{Hz}} \quad (5)$$

The total noise of the photometric system depends on the detector, resistor and Op-Amp components used. Cooling the system to reduce noise and increase stability will be discussed later. As seen in equation 4, amplifier noise depends on the frequency of operation; the next section will examine how.

Response Time in Photodetectors

A brief discussion on detector response time is useful at this time since it will illustrate the trade-offs between detector noise and detector response time. Detector response time for a PIN detector depends on the following three components:

1. RC time constant
2. Carrier transit time
3. Diffusion time

The first component of the response time (t_q) is dependent mainly on the photodetector capacitance and input resistance of the amplifier. The detector capacitance is a function of the area (A), resistivity (r) of the detector and bias voltage (V_b). For the case where the photodetector is not fully depleted by the applied bias voltage, the detector capacitance varies as:

$$C_d \propto \frac{A}{\sqrt{(V_b + 0.5)p}}$$

In this case, lower RC time constants, and therefore improved bandwidths, can be achieved with the use of smaller detectors and higher bias voltages. However, higher bias voltages increase the dark current, resulting in higher noise, as given by equation 2. For a photodetector which is fully depleted by the applied bias voltage (which is often the case for PIN diodes), the detector capacitance is not decreased by further increases in the bias voltage, and bandwidth improvement is only achieved with the use of smaller detectors and/or reduction in the input resistance of the amplifier. The second component of the detector response time is the carrier transit time (t_2). This is the time required for the carriers to be collected, and is essentially the distance the carriers need to travel divided by the average velocity of the carriers. Increases in bias voltage will usually increase carrier velocities, and therefore reduce transit times, but result in higher dark currents and noise. The final component of response time is the diffusion time (t_3). In a photodetector which is not fully depleted, this is the time taken for carriers generated outside the depletion layer to be collected. Carrier diffusion is normally a slow process, and may result in a tail in the response time characteristic.

Photovoltaic vs Biased Operation

A photodiode can be operated in photovoltaic or in biased mode. In the photovoltaic mode, no bias voltage is applied to the photodetector. In this case, the only source of detector noise is the thermal noise generated by the photodiode shunt resistance equation 3. This noise current exhibits a flat noise vs. frequency spectrum from DC to approximately the photodiode's cut-off frequency. Photodetectors operated in the photovoltaic mode normally have extremely low noise, but the price to be paid for low noise is very slow response times.

On the other hand, photodetectors operated in a biased mode will have faster response times, but the noise will be larger since the bias voltage generates a leakage current (dark current), which results in shot noise as expressed in equation 2.

Optimizing Receiver Design

Each receiver design should be optimized for the type of photometric application. For example, low-noise, low-bandwidth applications requiring high sensitivities are achieved with photometric systems using: photovoltaic detectors with high shunt resistances, large-value feedback resistors, and Op-Amps with very low input leakage currents. In this case, cooling the receiver will have a large impact on the total noise.

On the other hand, applications requiring fast response times (High Bandwidth) will require: fast detectors operated in the biased mode, low values of feedback resistors such that the RC time constant of the receiver will allow the photometric system to achieve the desired bandwidth. The amplifier noise voltage should be very low and the cut-off frequency of the amplifier should be greater than the desired bandwidth the system is to operate at. Also, the amplifier noise increases as the square of the capacitance seen by the amplifier, therefore the detector capacitance should be small for high frequency applications if low noise is required. In this case, cooling the receiver (detector + resistor + amplifier) will not have a large impact on the noise performance of the module.

Minimizing system noise can be achieved through the following:

- Minimizing detector and feedback resistor temperature
- Maximizing detector shunt resistance and feedback resistance
- Minimizing pre-amplifier current and voltage noise

Minimizing detector and feedback resistor temperature can be achieved via TE-cooling (Thermo-Electric Cooling). With state of the art TE-Coolers, this can be integrated with standard detector packages. This should be done if reducing the thermal noise will reduce the total system noise. From equation 5, it is seen that the total noise will not be reduced if the amplifier noise is the main contributor to the total noise. For example, if the amplifier noise is an order of magnitude larger than the detector and the feedback resistor noise, lowering the temperature to decrease the detector and feedback resistor noise by an order of magnitude, will only result in a 1% improvement in the total noise.
Maximizing detector shunt and feedback resistance will lower detector and feedback resistor noise as seen in equation 3, but the increased resistance will increase the response time of the photometric system. Therefore, using large values of shunt and feedback resistance should only be done if fast response time for the photometric system is not required.
Minimizing pre-amplifier current and voltage noise will add cost to the system, but this should be done if amplifier noise is the main contributor to total noise. If detector noise is much greater than amplifier noise, then reducing amplifier noise will have no impact on the total noise as can be seen by equation 5.
For high frequency applications, PIN detectors with fast response times will be required, and the feedback resistor will be limited to a value such that the amplifier can achieve the desired frequency. As a final note, Avalanche Photodiodes (APDs) are well suited for high frequency applications even if the excess noise of the APD will increase detector noise. This is because the amplifier noise, in many applications, is much greater than the noise of a PIN detector, and the use of an APD results in increased sensitivity for gains up to the point where the APD noise is comparable to that of the amplifier.

Stability

Stability of the detector and amplifier with time and temperature will have an important effect on system performance and must be taken into account. These factors can significantly limit performance in photometric applications requiring long-term baseline stability in changing temperature environments. Temperature stabilization via TE-Cooling will eliminate output variations with changes in temperature.

Conclusion

Incorporating cooling with high-shunt detectors and high-value feedback resistors are ideal for low-light level/low bandwidth applications requiring temperature stability. Fully-optimized low-light level receivers are commercially availableas complete systems for easy integration at the component level into OEM test and instrumentation equipment requiring high sensitivity, direct voltage-output, and long-term measurement stability.
One example is the HTE detector from PerkinElmer Optoelectronics. The HTE mounts a photovoltaic detector with a high shunt resistance, a low-noise precision preamplifier and a feedback resistor up to 1GW on a two-stage thermo-electric cooler as shown in figure 3.

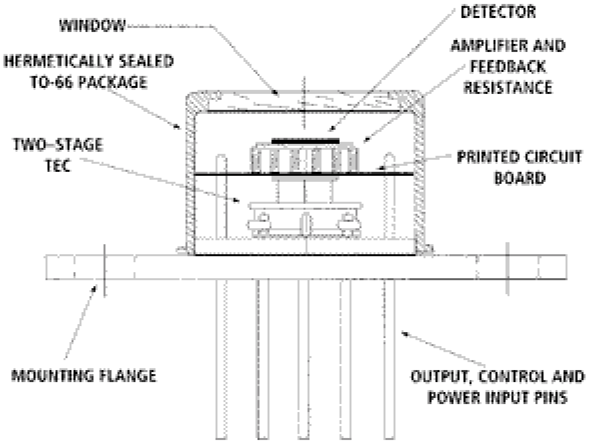

Figure 3. Schematic of the HTE detector from PerkinElmer Optoelectronics

Cooling minimizes thermal noise from the detector and feedback resistor, and maintains the preamplifier at a constant temperature to prevent output offset drift. The HTE output stability under temperature cycling is shown in figure 4. A common mounting platform permits integration of Silicon, InGaAs and Germanium detectors with active areas up to 6mm in diameter. Using a 2.5mm diameter silicon detector, and NEP of 2 x 10^{-15} W/$Hz^{½}$ at 900 nm is achieved at a bandwidth of 275 Hz.

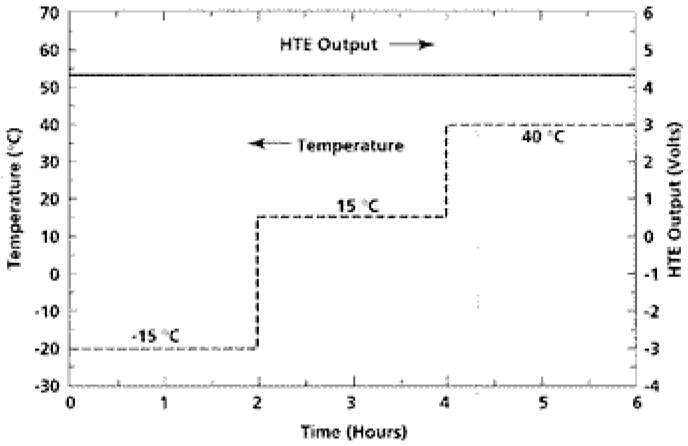

Figure 4. HTE Output Stability

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3. *Light Detection Using Photodiodes. M. Fonasz*
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