**HUV Series (1100BG; 1100BQ; 2000B; 4000B)**

**Features**
- Built-in Low Noise Amplifier
- Shielded Amplifier
- Groundable Case
- Large Active Area
- Wide Spectral Range
- Oxide Passivated Structure

**Operating Data and Specifications at 23°C**

**Typical Performance at 0 V Bias (Photodiode) and +15 V (Amplifier)**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>HUV-1100BQ</th>
<th>HUV-2000B</th>
<th>HUV-4000B</th>
<th>Units</th>
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<tr>
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<td>Sq. mm</td>
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<td>Responsivity at 200 nm</td>
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</table>

**Notes**

1. Spectral range 185-1150 nm applies to units with B or BQ suffix, 250-1150 nm for units with BG suffix.
2. Does not apply to units with BG suffix.
3. Gain bandwidth product.
4. Doubles every +10 °C.
5. Adjustable to 0 volts with external trim potentiometer.

**Typical Spectral Response**

![Typical Spectral Response Graph](image-url)
Operational Amplifier/
Photodiode Combinations

Mechanical and Electrical Data

**HUV-1100BQ(BG)**

- **Active Area**: 2.54 mm x 19 mm
- **Photodiode Reference Plane**: 2.2 mm x 6.21 mm x 9.20 mm

**Notes**
1. 25 kΩ offset voltage controls optional.
2. All dimensions in millimeters.
3. Distance of outer window to active surface is 1.98 mm nominal.
4. Pin circle is 5.84 mm diameter.

**HUV-2000B**

- **Dimensions**: 22.1 mm x 19.7 mm
- **Photodiode Reference Plane**: 3.9 mm x 12.6 mm x 7.6 mm

**Notes**
1. Other values of R₁ can be obtained by request.
2. It may be necessary to shunt R₁ with ~1 pF to reduce gain peaking.
3. All dimensions in millimeters.

**HUV-4000B**

- **Dimensions**: 24.0 mm x 17.53 mm
- **Photodiode Reference Plane**: 5.4 mm x 5.72 mm

**Notes**
1. Other values of R₁ can be obtained by request.
2. It may be necessary to shunt R₁ with ~1 pF to reduce gain peaking.
3. All dimensions in millimeters.
4. Making pin socket is AMP 1-583773-4 (2 required).
Basic Circuits

Load Resistor

Operational Amplifier — Straight Feedback Loop

Operational Amplifier — T Feedback Loop

Differential Amplifier
1. Photo-Effect

When the junction of a semiconductor is illuminated and a connection is made to both sides of the junction, a current will flow during the period of illumination. This phenomenon is known as the photovoltaic effect, which is the operating mechanism for photovoltaic (PV) photodiodes and solar cells. In this case, there is no external bias applied and the cell generates an e.m.f. when illuminated.

If an external bias is applied in the reverse direction at the p-n junction, current will also flow under illumination. The current generated is composed of both the photo-induced current and the reverse leakage (dark) current. The reverse leakage current will remain constant for fixed bias and fixed temperature conditions. This is called the photoconductive (PC) mode.

In both modes of operation, PV and PC, the photocurrent will vary linearly with the intensity of the incident light.

2. Photovoltaic (PV) vs. Photoconductive (PC)

The photovoltaic detector is designed for low noise, low frequency applications. The PV frequency response, shunt resistance, and junction capacity are active area dependent. The equivalent noise current generated by the device at zero voltage is a virtually flat Johnson noise spectrum from DC to the cutoff frequency.

The photoconductive detector is designed to detect high speed light pulses or the high frequency modulation of a continuous light beam. The reverse voltage increases the junction field strength, which accelerates the electron/hole transit times. Reverse bias also reduces the junction capacity, thereby minimizing the capacitive loading effects on the frequency response. PC photodiodes may operate over frequencies from DC to over 1 GHz with rise times ranging from hundreds of picoseconds to tens of nanoseconds depending on operating conditions. The noise current generated by the PC photodiode is a combination of shot noise, excess noise, and, in the case of a guard ring structure device, Johnson noise. Shot noise is produced by the reverse bias current and exhibits a 1/f excess noise characteristic below 1 kHz. The Johnson noise is generated by the channel resistance between active area and guard ring diodes.

The design decision to use a PV or PC photodiode is predicated primarily on the frequency response requirements of the given application. Below 100 KHz, the PV photodiode provides better signal-to-noise performance than that obtained from an equivalent active area PC photodiode. Below 1 KHz, the PV photodiode is far superior in signal-to-noise performance.

3. Device Construction

All of the silicon photodiodes manufactured by EG&G Electro-Optics are of PIN construction. The P region is a layer which has been doped to a P+ level during a furnace diffusion process. The I region is the intrinsic bulk silicon which may be of either P or N type silicon. The N region is a layer which has been doped to a N+ level in another furnace diffusion process.

Figure 1 shows a cutaway view of a typical guard ring photodiode. The photodiode is fabricated from a P type silicon wafer of controlled thickness. A P+ diffusion is performed on the back surface to facilitate rear contacting. A N+ diffusion is performed on the front surface, using photo masking techniques, which accurately diffuses the active area and guard ring. Metal contacts are sputtered on the front and rear contact areas and the N+ diffusion is passivated.

![Guard Ring Planar Diffused Silicon Photodiode](image)

The photodiode dark current is the sum of the reverse leakage through the bulk silicon and across the photodiode surface. The dark current leakage increases with increasing area. The surface leakage current increase is proportional to the square root of the active area while the bulk leakage current is directly proportional to the active area. Figure 2 shows the total dark current as a function of the area with and without the guard ring. Note that large area photodiodes do not have as significant a dark current reduction with the guard ring since a higher percentage of the dark current is due to bulk leakage. Under operating conditions where the active area and the guard ring are biased at the same potential, the surface leakage is shunted around the load resistor and flows through the guard ring to ground. In this manner, the much lower bulk leakage becomes the limiting source of shot noise current through the load resistor. Since the shot noise current of the detector varies directly as the square root of the leakage current, the total noise performance of the detector is greatly improved by the addition of a guard ring to detectors manufactured from P type material.
5. Silicon Photodiode Characteristics

Planar diffused photodiodes are usually fabricated from material having a range of resistivity from 10 to 10,000 ohm-cm. The resistivity of the silicon and the bias voltage determine the junction depletion depth, junction capacitance, responsivity profile, series resistance, response time, and dark current. A nomograph has been prepared that permits rapid determination of photodiode depletion depth and junction capacitance for a given resistivity, active area, and operating bias. Figure 5 is the nomograph that shows these parameters and their interdependence.
6. Detector Biasing

Photodiodes are designed to be operated at specific bias voltages which are dictated by the operating conditions. Whenever possible, the user should follow the recommendations of the device data sheet in order to achieve optimum performance. Circuit designers should be aware that, if a device is not operated at the recommended bias voltage, many of the operating characteristics listed in the data sheet will change. The nomograph of Figure 5 shows some of the changes which are bias voltage dependent. The following is a list of parameters and the effect that an increase of bias voltage has on them:

A. Dark current Increases
B. Noise current Increases
C. Junction capacitance Decreases
D. Series resistance Decreases
E. Channel resistance Increases
F. Depletion depth Increases
G. Infra-red responsivity Increases
H. Rise and fall time Decreases

7. Capacitance

Junction capacitance, in conjunction with load impedance and series resistance, can produce a system RC time constant that will be in excess of the photodiode charge collection time. It is for this reason that the system designer should determine the value of the junction capacitance and its relative importance to the particular application.

The junction capacitance of a photodiode can be determined for various bias voltages using the nomograph of Figure 5 if the active area and the silicon resistivity are known. A straight line drawn from the proper value on the Resistivity scale to the operating voltage on the Detector Bias scale will intersect the Capacitance scale at some point. This capacitance constant multiplied by the photodiode active area, in square millimeters, will be the value of the photodiode junction capacitance in picofarads.

The voltage at which the junction capacitance becomes constant for increasing values of applied voltage is called the full depletion voltage. The full depletion voltage can be determined from the Figure 5 nomograph. A straight line drawn from the proper value on the Resistivity scale through a value on the Depletion Depth scale equal to the detector thickness will intersect the Detector Bias scale at the voltage at which full depletion occurs. The example shown on the nomograph illustrates a detector manufactured of 8 KOhm-cm, P type material, 300 microns thick. The full depletion bias voltage for this device is 120 volts.

8. Series Resistance

Series resistance is an important parameter to consider in high frequency applications. When the junction transit time is minimized, the limiting factor for high frequency operation is the RC time constant. This is the product of the junction capacitance and the sum of the series plus load resistances.

In an equivalent electrical diagram, the series resistance appears in the series with the photodiode junction impedance. The resistance of the undepleted bulk silicon can be calculated from the following formula:

$$ R = \frac{e}{L} $$

where:
- $e$ = Resistivity of the silicon (ohm-cm)
- $L$ = Photodiode thickness less the depletion depth (cm)
- $A$ = Active area (sq cm)

In addition to the resistance of the undepleted bulk silicon, the resistance of electrode contacts must also be considered. Contact resistance may vary from 10 to 100 ohms, depending on the geometry of the contact. When choosing detectors for high speed applications, proper contact design is essential.

One resistance to the photocurrent which is often overlooked is the spreading resistance. This resistance appears between the point where the carriers are generated and the electrode contact where the photocurrent is collected. This resistance is difficult to quantify, as each case is different; however, this resistance is related to the distance the carriers must travel across the surface of the silicon. For optimum high speed performance, the active area should be as close to the illuminating spot size as possible.

9. Response Time

The photodiode response time is the root-mean-square sum of the charge collection time in the depletion region and the RC time produced by the series plus load resistance and junction plus stray capacitance. The charge collection time is bias voltage dependent and is equal to approximately one half the depletion depth divided by the carrier drift velocity. Photon energy absorbed outside the depletion region will produce carriers that are collected by diffusion and the response time of these carriers will be much slower than the carriers swept from the depletion region. Under certain biasing conditions, a photodiode can have a fast response time for short wavelengths and a slower response time for long wavelengths.

In the majority of applications, the designer will find that the limiting factor in photodiode response time will be the RC time. In a RC limited situation, the photodiode operating bandwidth will be equal to $1/(2\pi R C)$ or 0.159/RC, and the rise time (10% to 90%) to a step waveform of radiation will be equal to 2.2 RC. The fall time from a step waveform will be equal to the RC time plus the carrier life time. Carrier life time produces a delay in the start of fall time due to the fact that photon generated carriers are still being swept out of the depletion region. The rise and fall times are generally equal for fully depleted photodiodes but are dissimilar when the photodiode is operated in the photovoltaic mode or at low bias voltages.

10. Spectral Response

The photodiode responsivity profile is directly related to the depletion depth obtained for a given operating bias voltage and silicon resistivity. The following equation is
given to illustrate the dependence of the relative responsivity on the silicon resistivity.

\[ I = I_0 \left(1 - e^{-\delta t}\right) \frac{q}{hc} \lambda \]

where:
- \( I \) = Photocurrent (amps)
- \( I_0 \) = Maximum photocurrent for total photon absorption (amps)
- \( \lambda \) = Wavelength (microns)
- \( \delta \) = Absorption coefficient of silicon at \( \lambda \) (cm\(^{-1}\))
- \( h \) = Planck’s constant (6.624 x 10\(^{-27}\) ergs/second)
- \( c \) = Velocity of light (2.998 x 10\(^8\) meters/second)
- \( t \) = Depletion depth (cm)

At 1.06 microns, the absorption coefficient of silicon is approximately 35 cm\(^{-1}\). The depletion depth obtained with 10 ohm-cm silicon with 90 volts bias is 1 x 10\(^{-3}\) cm as compared to 15 x 10\(^{-3}\) cm for 2500 ohm-cm silicon. Substituting these values into the efficiency equation indicates that the 10 ohm-cm photodiode will respond to 35% of the total 1.06 micron radiation but the 2500 ohm-cm photodiode will respond to 41% of the total 1.06 micron radiation. In both cases, surface reflection losses are assumed to be identical and are not included in the efficiency values. In order to complete the spectral response profile, it is necessary to consider the short wavelength response for the two photodiodes. At 0.45 micron, the absorption coefficient of silicon is approximately 3.4 x 10\(^4\) cm\(^{-1}\). Computing the value of \( I \) will show that both detectors will respond to 100% of the 0.45 micron radiation. Reflection losses have been ignored in this case also.

Figure 6 presents typical relative spectral responses for the two cases previously described. The two responsivity curves have been normalized to the peak of the 2500 ohm-cm curve.

The dashed portion of the responsivity curve for wavelengths below 0.50 micron is an approximation due to the difficulty in accurately determining the effects of the reflection losses and the front window absorption losses in this wavelength region. The front window is a term used to describe the front surface of the silicon in which the photons are absorbed but do not contribute to the photocurrent. The front window thickness for photodiodes without antireflective coatings is typically 0.20 micron. The absolute responsivity peak for the 2500 ohm-cm curve is 0.52 A/W. Manufacturers of planar diffused photodiodes have demonstrated the ability to improve monochromatic responsivity by 10% to 30% by the application of antireflective coatings to the detector active area.

Photodiodes of very high efficiency at long wavelengths can be produced using thick, very high resistivity silicon. Consider the case of a photodiode manufactured from 40,000 ohm-cm, P type silicon. Operating this device at 300 volts bias will result in a depletion depth of 0.1 cm. Calculating the value of \( I \) for 1.06 micron radiation will show that this photodiode will respond to 97% of the total 1.06 micron radiation. Reflection losses, again, have been ignored.

11. Quantum Efficiency

Figure 7 shows a typical spectral response curve for a UV enhanced photodiode operating at 0 volts bias. The spectral range is from 0.19 to 1.1 microns. The responsivity curve, for this device, typically peaks at 0.9 micron with a responsivity of approximately 0.62 A/W.

![Figure 7. Typical spectral response - UV series.](image)
Figure 8 is the quantum efficiency curve for the responsivity given in Figure 7. The quantum efficiency is calculated from the formula:

\[ \text{Q.E.} = \frac{hc}{q} \times \frac{R}{\lambda} \times 100\% = \frac{S}{\lambda} \times 124\% \]

where:
- \( h \) = Planck's constant (6.624 x 10^{-27} ergs/second)
- \( c \) = Velocity of light (2.998 x 10^8 meters/second)
- \( q \) = Electronic charge (1.6 x 10^{-19} coulombs)
- \( R \) = Responsivity (A/W)
- \( \lambda \) = Wavelength (microns)

![Quantum Efficiency Curve](image)

Figure 8. Typical quantum efficiency — UV series.

12. Noise — Photoconductive Mode

The noise current generated by a planar diffused photodiode operating in the reverse bias mode is a combination of shot noise, excess noise, and thermal (Johnson) noise.

Shot noise is generated by current flowing through the device. This current may be either the dark current or the photocurrent; however, the predominant shot noise generator is the dark current. The shot noise produced by the dark current can be calculated by the formula:

\[ i_s = (2qI_0 \Delta f)^{1/2} \]

where:
- \( q \) = Electronic charge (1.6 x 10^{-19} coulombs)
- \( I_0 \) = Dark current (amperes)
- \( \Delta f \) = Noise equivalent bandwidth (hertz)

Below 1 KHz, the shot noise increases with a 1/f characteristic and is referred to as excess noise.

The thermal noise contribution is provided by the series resistance, load resistance, and, in the case of a guard ring device, the channel resistance. The thermal noise current is equal to:

\[ i_s = \left( \frac{4kT \Delta f}{R} \right)^{1/2} \]

where:
- \( k \) = Boltzmann's constant (1.38 x 10^{-23} joules/K)
- \( T \) = Temperature (K)
- \( \Delta f \) = Noise equivalent bandwidth (hertz)
- \( R \) = Resistance: series, channel, or load (ohms)

The interrelation of these noise sources can be seen by referring to Figure 9, which is a noise model for a guard ring structured, planar diffused photodiode operating under reverse bias.

The designer is normally interested in the total noise present at the input to the preamplifier or, as shown in Figure 9, the total noise voltage, \( V_n \), present across the load resistor.

\[ i_s = (2qI_D \Delta f)^{1/2} \]

\[ e_c = (4kT R_C \Delta f)^{1/2} \]

\[ e_s = (4kT R_S \Delta f)^{1/2} \]

\[ e_L = (4kT R_L \Delta f)^{1/2} \]

Figure 9. Noise model for reverse biased, guard ring structured photodiode.

To simplify the analysis, it is assumed that \( R_L \leq R_C \). If in practice \( R_L \) is significant with respect to \( R_C \), then the designer can calculate their equivalent parallel resistance.

The total noise voltage present across \( R_L \) is the square root of the sum of the squared noise voltages as follows:

\[ e_n \text{total} = (e_1^2 + e_2^2 + e_3^2)^{1/2} \]

where:

\[ e_1 = \frac{e_s R_L}{[(R_L + R_s)^{2/2}] C_L} \]
\[ e_2 = \frac{e_1 (1 + \omega^2 C_2 R_2)^{\frac{1}{2}}}{[1 + \omega^2 C_2 (R_L + R_S)^2]^{\frac{1}{2}}} \]

\[ e_3 = \frac{i_s R_L}{[1 + \omega^2 C_2 (R_L + R_S)^2]^{\frac{1}{2}}} \]

The preceding three equations relate the spot noise voltage at a specific operating frequency. The operating bandwidth of the individual noise generators \((e_1, e_2, e_3)\) can be computed from the relationship: \(f = 3\text{dB} = 0.159/RC\). This operating bandwidth can be converted to a noise bandwidth by multiplying \(f = 3\text{dB}\) by the factor 1.59, assuming a 6 dB/octave rolloff slope.

13. Noise — Photovoltaic Mode

The shunt resistance generates a thermal noise current that exhibits a flat noise vs. frequency spectrum from DC to approximately the photodiode cutoff frequency. The RMS value of the noise current is inversely proportional to the square root of the shunt resistance as shown in the following Johnson (thermal) noise formula:

\[ i_{\text{th}} = \left( \frac{4kT \Delta f}{R_{\text{sh}}} \right)^{\frac{1}{2}} \]

where: \(k = \text{Boltzmann's constant (1.38 \times 10^{-23} \text{ joules/K})}\)

\(T = \text{Temperature (K)}\)

\(\Delta f = \text{Noise equivalent bandwidth (hertz)}\)

\(R_{\text{sh}} = \text{Shunt resistance (ohms)}\)

14. Noise Equivalent Power (NEP)

In many photodiode applications, the designer is concerned with the minimum detectable power of the photodiode. The noise equivalent power (NEP) figure of merit defines the minimum incident power required to generate a photocurrent equal to the total photodiode noise current. In formula form, this would appear as:

\[ \text{NEP} = \frac{\text{Noise current (Amps)}}{\text{Responsivity (Amps/Watt)}} \]

It should be noted that NEP is an ambiguous figure of merit if the test conditions are not specified. Experienced designers will qualify a value of NEP by specifying the test conditions in parenthetical notation as follows:

\[ \text{NEP (source wavelength, test frequency, noise bandwidth)} \]

Example:

NEP (900 nm, 10 Hz, 1 Hz) = 3 \times 10^{-15} \text{ Watts/Hz}^{1/2}

Photodiode manufacturers generally specify NEP for the photodiode only, and do not consider the noise contribution from other sources in the circuit.

15. Response Linearity — Photoconductive Mode

The reverse biased photodiode signal current is linear over a wide range of irradiance. It is limited at high irradiance levels by the permissible power dissipation quoted for the device, providing that the load plus series resistances are not current limiting. At low irradiance levels, the signal linearity is limited by the shot noise current for the operating bandwidth, neglecting any measurement system noise.

Some general rules for determining maximum linear signal are:

\[ e_{\text{signal}} (V) \leq 0.3 \times V_{\text{BIAS}} \]

\[ i_{\text{signal}} (A) \leq \frac{0.3 \times V_{\text{BIAS}}}{R_S + R_L} \]

The photodiode will have a linear operating range of 7 to 9 decades when followed by a properly designed circuit. The range for 1% linearity is defined as being from 100 times the noise, 100:1 S/N, to the point at which the detector response deviates from the predicted response curve by 1%. Greater range can be achieved if larger deviations can be tolerated.

16. Response Linearity — Photovoltaic Mode

In low light level applications, the linearity limit is determined by the noise current for the operating noise bandwidth. At high irradiance levels, the limit is determined by the forward voltage which appears across the junction and the rate at which the carriers can be swept from the junction. The following formula for determining maximum linear photocurrent is based on empirical evaluations of photovoltaic photodiodes.

\[ I_{\text{pm}} = \left( \frac{25 \times 10^{-3}}{R_S + R_L} \right) \log_e \left( \frac{P \times R_{\text{sh}}}{R_S + R_L} \right) \]

The active area dependency of the series and shunt resistances creates a singular linearity solution for each photodiode. Figure 10 is a graphical presentation of a 1% linearity equation for the various photodiode active areas normally encountered in instrument applications.

If photodiodes are used in conjunction with a load resistor, the response to incident light may become nonlinear even before the current levels shown in Figure 10 are reached. The linear range of a photodiode is also limited by the forward voltage generated across the diode junction by the photocurrent flowing through the series and load resistors. For linear response:

\[ \text{Load voltage} \leq 100 \times 10^{-3} \text{ V} \]

Linearity will also be affected if current densities are too high. The low field strength of photovoltaic diode junctions limits the rate at which the carriers can be swept from the junction. For linear response:

\[ \text{Current density} \leq 50 \times 10^{-6} \text{ A/sq. mm of illuminated area} \]
At wavelengths longer than approximately 900 nm, photons start to penetrate the silicon, deep enough to reach the back surface. The rear surface is partially reflective and its condition is a factor in long wavelength applications.

In applications where all of the light energy must be kept within the photodiode active area, the ideal spot size is the active area dimension minus the beam movement dimension. In the case of a photodiode with an active area diameter of 2.54 mm and a beam movement of 1 mm, the ideal spot size for the most uniform response would be 1.54 mm.

18. Angular Response

The responsivity of a photodiode is quoted for incident radiation that is normal to the plane surface of the photodiode active area. When the angle of incidence varies from the normal angle of incidence, the photodiode response will decrease by a factor that approximates the cosine of the incident angle. The angular response is wavelength dependent and is greatly affected by the active area reflectivity. Figure 11 shows the typical deviation from a true cosine response for a planar diffused, oxide passivated photodiode for two wavelengths of incident radiation. Reflections from package surfaces will also affect angular response.

19. Responsivity vs. Temperature

Photodiode responsivity is temperature dependent. The responsivity temperature coefficient value is wavelength dependent. Typically, the temperature coefficient for wavelengths shorter than 700 nm is negative; at wavelengths longer than 700 nm, the temperature coefficient is positive. Figure 12 is a table of responsivity temperature coefficient vs. wavelength data for two photodiode types.
The equation to calculate the photodiode responsivity at a different temperature is:

$$E_{\text{out}} = I_{\text{in}} \times R_f$$

This formula does not consider any offset voltages. This subject is covered in Section 23.

The term “gain” does not apply to the transimpedance mode of operation. Gain is the ratio of the amplifier output to the amplifier input and both terms must be the same: volts/volts; amps/amps; watts/watts. In the transimpedance mode, the input and output terms are different; therefore, the term “gain” does not apply.

It should be noted that the formula for $E_{\text{out}}$ does not reflect the closed loop “gain peaking” that can occur because of the summation of the open loop gain and the related phase angle with the transimpedance and its associated phase angle. If the open loop gain and feedback gain are added algebraically and compared to the sum of the respective phase angles, it may become evident that a sum positive gain will occur at the frequency where the sum phase angle crosses 180 degrees. This situation of positive gain at 180 degrees phase angle is generally referred to as “gain peaking” and most designers recognize this situation as being the basis for amplifier instability.
The cause of gain peaking in photodiode/op-amp combinations is the total capacity presented at the amplifier input which must be driven in the closed loop configuration by the output voltage through the feedback impedance. The solution to gain peaking is to add a small amount of capacitance across the feedback resistor so as to modify the closed loop gain/phase angle relationship. Figure 13 depicts gain peaking in a typical photodiode/op-amp combination where the detector is a large area, photovoltaic photodiode. The curves show the results of adding small amounts of capacitance across the feedback resistor.

Figure 13. Gain peaking in photodiode/op-amp circuit.

22. Photodiode/OP-AMP Noise Characteristics

The various noise generators which contribute to the total output noise voltage of a photodiode/op-amp combination are shown in Figure 14. For large area photovoltaic detectors, the output noise voltage at frequencies greater than 50 Hz is determined by the amplifier noise voltage generator, the photodiode impedance, and the feedback impedance. In most cases, gain peaking of the noise voltage will occur but this can be controlled as previously discussed. From 10-50 Hz, the total noise voltage is affected by the combination of photodiode noise current, amplifier input noise current, and the value of feedback resistance. Below 10 Hz, the magnitude of the 1/f characteristic of the amplifier noise current will tend to control the magnitude of the output noise. Figure 15 is a plot of the output noise voltage for a large area photovoltaic detector coupled to a typical operational amplifier. Note in Figure 15 how the noise performance is improved by the addition of a 2 picofarad feedback capacitance.

Figure 14. Photodiode/op-amp electrical model.

Figure 15. Total output noise vs. frequency.
Smaller active area photodiodes with larger shunt resistance and lower junction capacitance will produce a lower noise and extend the gain peaking to a higher frequency.

As gain peaking is determined by the individual characteristics of feedback impedance, amplifier gain/phase angle, and photodiode source impedance, it becomes difficult to define an accurate total noise equation. A reasonable solution is to neglect gain peaking, which can be compensated, and to define the total noise by its contributing sources. The following equation is derived from Figure 14, where the various noise generators are identified. This provides a good approximation of the total noise present at the output of the photodiode/op-amp combination.

\[ e_{nT} = Z_f \left[ \left( \frac{e_{nA}}{Z_s} \right)^2 + i_n A^2 + i_{nsh}^2 + i_{nf}^2 \right]^{1/2} \]

where:
\[ Z_f = R_f (1 + \omega^2 C_p R_f)^{1/2} \]
\[ Z_s = R_{sh} / (1 + \omega^2 C_p R_{sh})^{1/2} \]
\[ i_{nsh} = \left( \frac{4K T \Delta f}{R_{sh}} \right)^{1/2} \]
\[ i_{nf} = \left( \frac{4K T \Delta f}{R_f} \right)^{1/2} \]

In applications involving large area photodiodes, the amplifier input noise voltage generator is the major contributor to the total output noise voltage. Therefore, it is important, in these applications, to select an operational amplifier that has a minimum value of input noise voltage. Conversely, in applications involving small area photodiodes, the optimum noise performance is obtained with an operational amplifier having a very low value associated with the input noise current generator.

23. Amplifier Output Offset Voltage

The DC offset voltage present at the output terminal of a photodiode/op-amp combination is a function of feedback resistance, shunt resistance for a PV photodiode, and dark current for a PC photodiode. The equation for determining DC output offset voltage is:

\[ e_{offset} = (V_{offset} + \Delta V_{offset}) \left( 1 + \frac{R_f}{R_{sh}} \right) + [(i_B + i_D)(R_f) \times R_f] \]

where:
\[ V_{offset} = \text{Amplifier input offset voltage (volts)} \]
\[ \Delta V_{offset} = \text{Amplifier input offset voltage drift (V/°C)} \]
\[ R_f = \text{Feedback resistor (ohms)} \]
\[ R_{sh} = \text{Photodiode shunt resistance (ohms)} \]
\[ i_B = \text{Amplifier input bias current (amperes)} \]
\[ i_D = \text{Photodiode dark current (amperes)} \]

This equation has three terms, \( R_{sh} \), \( i_B \), and \( i_D \), which have a nonlinear dependence on temperature. When calculating DC offset voltages for temperatures other than those given in the data sheet presented earlier in this catalog, it is important to consider the temperature effects.

The equation to calculate shunt resistance at a different temperature is:

\[ R_{sh2} = \frac{R_{sh1}}{2(T_2 - T_1) \times 6} \]

where:
\[ R_{sh1} = \text{Known shunt restance at temperature } T_1 \text{ (ohms)} \]
\[ T_1 = \text{Starting temperature (degrees C)} \]
\[ T_2 = \text{New temperature (degrees C)} \]

The equation to calculate either photodiode dark current or amplifier input bias current at different temperature is:

\[ i_B^2 = \frac{i_B}{2(T_2 - T_1) \times 10} \]
\[ i_D^2 = \frac{i_D}{2(T_2 - T_1) \times 10} \]

where:
\[ i_B = \text{Known input bias current at temperature } T_1 \text{ (amperes)} \]
\[ i_D = \text{Known dark current at temperature } T_1 \text{ (amperes)} \]
\[ T_1 = \text{Starting temperature (degrees C)} \]
\[ T_2 = \text{New temperature (degrees C)} \]