



Choosing Your **Detector**

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Although the choice of an optical detector is often complex, there are three factors that you must almost always take into account: the active area of the detector, the minimum acceptable signal-to-noise ratio (SNR), and the cost. Note that these three factors are not independent; other characteristics such as the wavelength of the light, the light level, the shape of the light source to be measured, and the speed or frequency of the light will influence one or more of the three factors. To choose the proper detector for your application, you should consider all of this information and calculate the SNR for each of the three detector types available. This calculation must be performed for the entire signal processing electronics, not just for the detector itself; only then can you make a tradeoff between cost and SNR.

The area of the detector certainly affects both cost and SNR. Diffuse light, for example, often requires the use of a large-area detector. The largest single-element detector is the 20-in. photomultiplier tube (PMT). Approximately

Signal-to-noise ratio, active area, and cost requirements drive the choice of detectors.

11,000 of these tubes have been installed in the facility for the Super Kamiokande neutrino experiment to detect the Cherenkov radiation created as neutrinos pass through 50,000 tons of water (see *oemagazine*, June 2001, p. 20). For such a large array, an electron tube was chosen instead of a solid-state sensor because the cost per unit area was considerably lower than that of a solid-state detector.

In a confocal microscope, light passes through a pinhole to eliminate photons from outside the image plane. In contrast to the Super Kamiokande, for which there was an obvious detector choice, some confocal microscopes use avalanche photodiodes (APDs) and some use PMTs. A 100- μm -diameter APD can act as both detector and pinhole, but a PMT is much easier to align. Interestingly, the cost of each approach is almost the same.

Noise Effects

The SNR ratio is often the most important factor in choosing a detector. The noise in a detector has components that are proportional to the signal and those that are independent of the signal. The components that are independent of the signal consist of the thermal noise, or Johnson noise, and the dark current noise found in all types of detectors. The Johnson noise (i_j) is found only in solid-state detectors such as APDs and photodiodes (PDs), and can be described by

$$i_j = (4kTB/R_{sh})^{1/2} \quad [1]$$

where k is the Boltzman constant, T is the absolute temperature, B is the frequency bandwidth, and R_{sh} is the shunt resistance.

We define the dark current noise, or dark-current shot noise (i_{sd}), as

$$i_{sd} = (2qI_dB)^{1/2} \quad [2]$$

where q is the electron charge and I_d is the dark current. The signal also has a noise component that, just like the dark current noise, is caused by statistical fluctuations. It is given by the corresponding formula

$$i_{ss} = (2qI_sB)^{1/2} \quad [3]$$

where I_s is the photocurrent created in the detector when the light is converted via the photoelectric effect into electrons. For a simple detector, then, we express the SNR as

$$\begin{aligned} \text{SNR} &= I_s / (i_j^2 + i_{sd}^2 + i_{ss}^2)^{1/2} \\ &= I_s / ((4kTB/R_{sh}) + (2qI_dB) + (2qI_sB))^{1/2} \end{aligned} \quad [4]$$

Choosing Your Detector

Obviously, we can improve the SNR by reducing the bandwidth. Many real-world applications, such as measuring a color change in a hand-held glucose monitor, lend themselves to this approach. Other applications, such as detecting light scattered from a defect on a semiconductor wafer, require high bandwidth so that the measurement can be made quickly. In the case of relatively high light levels striking the detector, we can determine the SNR solely by the shot noise of the photocurrent; here, the SNR becomes proportional to $(I_s)^{1/2}$. This regime is known as the shot-noise limit and represents ideal behavior for the detector. We reach this limit when I_s is much greater than $0.26/R_{sh}$ and I_s is much greater than I_{sd} .

At high light intensity, when the photocurrent is large

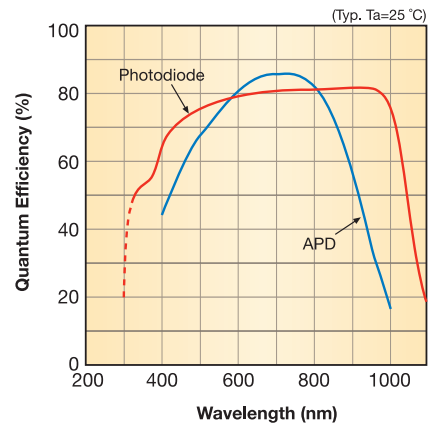
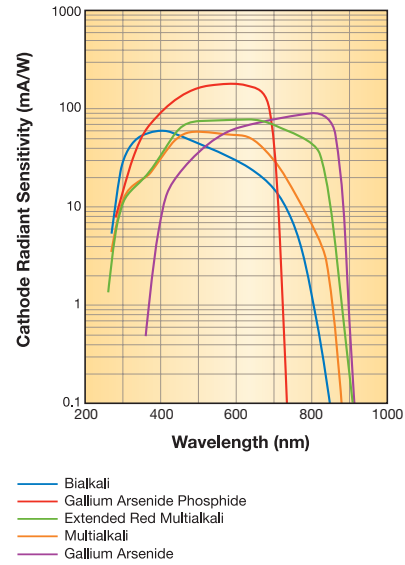


Figure 1 The conversion efficiency of a PMT (expressed as radiant sensitivity) varies by cathode material (top). Beyond 850 nm, sensitivity begins to drop rapidly. In contrast, PDs and APDs can be effective over a significantly broader range; PMT sensitivity can be converted to quantum efficiency by dividing it by the wavelength in nanometers and multiplying by 124.

enough to place us in the shot-noise limit, the best choice of detector is usually a PD. The final choice of device will be driven by the wavelength of the light and a cost tradeoff between optics that reduce the size of the light spot that falls on the detector and the cost per square millimeter for the active area of the detector. For the wavelength range of 200 to 1100 nm, your best choice is a silicon detector. For the near-IR (NIR) spectral region (1000 to 2600 nm), indium-gallium-arsenide (InGaAs) detectors provide a good solution. Between 2600 and 10,000 nm, a variety of detectors are available, including thermopiles and devices made of lead sulfide, lead selenide, indium arsenide, or mercury cadmium telluride.

In most photodetector applications, the detector produces a photocurrent, and a digitizer placed across the load resistor produces a signal. Often, the light levels are not high enough

for this process to succeed. In such a case, we must amplify the photocurrent to a level that can be converted to a digital signal by an analog-to-digital converter. To amplify the signal, we use a transimpedance amplifier (TIA), which also converts the output current of the photodetector to a voltage. We will present an abridged discussion of the TIA; the literature contains numerous other amplifier references to fill in the details.

Amplifier noise, v_n , which consists of a voltage instead of a current, is expressed as

$$v_n = [v_a^* \{ (1 + R_f/R_{sh})^2 + (4\pi^2/3) B^2 C^2 R_f^2 \} + R_f^2 i_a^{*2} + 4kTR_f]^{1/2} B^{1/2} \quad [5]$$

where v_a^* is the noise voltage of the amplifier (typically 5 nV/Hz^{1/2}), R_f is the feedback resistance, C is the detector capacitance, and i_a^* is the amplifier input bias-current noise. The first term of equation 5 represents the multiplication of the amplifier noise voltage; making the detector shunt resistance larger than the feedback resistance is a good method for reducing this noise component.

At high frequency, a large detector capacitance generates increased amplifier noise. Even at lower bandwidths, excessively high detector capacitance can increase amplifier noise. The second term of equation 5 is the shot noise from the amplifier input bias current, while the last term is the Johnson noise from the feedback resistor. Because the gain of a TIA is proportional to R_f , maximizing the feedback resistor will minimize this contribution to the noise. For the lowest noise, you should try to select a PD with maximum shunt resistance and low capacitance. This is what is done with the PDs used as x-ray detectors in computed tomography applications for which the noise must be reduced to minimize the x-ray exposure while the speed (bandwidth) must be increased to increase throughput and reduce body-motion artifacts.

Managing Noise

Many applications exist for which the initial photocurrent is so small that the amplifier noise exceeds the amplified signal. Such a case requires a detector with internal gain but lower noise than a TIA. There are two choices for such a detector: APDs and PMTs. APDs are typically limited to active areas of 10 mm or less and gains of 200. PMTs can have areas as large as 50 cm, negligible noise, and gains as large as 10^6 . PMTs often operate in the shot-noise limit because of their nearly noise-free gain.

The only limitation to PMTs is that the conversion efficiency, expressed as radiant sensitivity in milliamps per watt, is much smaller than that of a PD or an APD (see figure 1). We can convert the radiant sensitivity to quantum efficiency (QE) by dividing it by the wavelength in nanometers and multiplying by 124. The gallium-arsenide-phosphide photocathodes found in the most sensitive PMTs have QEs of better than 40%, compared to the 85% peak QEs offered by PDs or APDs.

As figure 1 shows, most PMTs provide little sensitivity in the NIR spectral region (beyond 850 nm); in contrast, silicon detectors are sensitive out to 1100 nm. When the light levels get very low or the bandwidth is large, however, the limiting

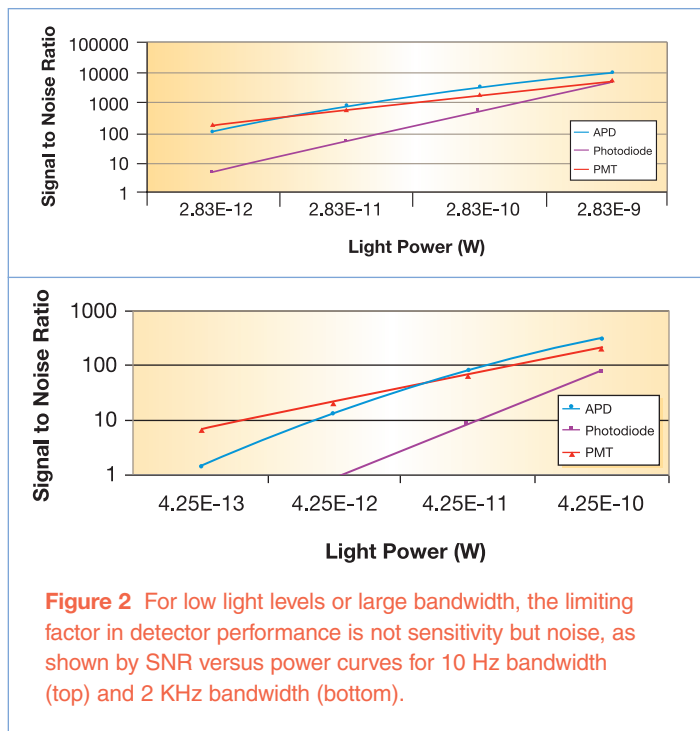


Figure 2 For low light levels or large bandwidth, the limiting factor in detector performance is not sensitivity but noise, as shown by SNR versus power curves for 10 Hz bandwidth (top) and 2 KHz bandwidth (bottom).

factor shifts from the sensitivity to the amount of noise created by the device that generates the gain (see figure 2). For low optical input, even at a bandwidth of only 10 Hz, a PMT offers a better SNR than a PD or an APD with an amplifier. In this case, the PMT is operating in the shot-noise limit, while the PD SNR is limited by the amplifier. Even at 1 nW of optical power, a PD is generally only as good as a PMT and is not as good as an APD.

In the end, the choice of detectors comes down to application and implementation. Even at 30 pW, the proper PD can achieve an SNR of almost 100:1, which might be sufficient for the application. In fact, PDs integrated with low-cost complementary metal oxide semiconductor amplifiers are available in a single package that reduces cost and increases performance. There are NIR PMTs that offer QEs of only 1% at 1270 nm, compared to InGaAs and germanium detectors that achieve QEs as high as 90%. Detecting very weak emission at that wavelength from singlet oxygen, even with liquid-nitrogen-cooled solid-state detectors, is very difficult, however. In such a case, the noise-free gain of 1×10^6 offered by the PMT offsets the low QE.

The choice of detector depends on many variables. For fluorescence measurements, you may be able to use PDs to monitor polymerase chain reactions, but you may choose a PMT to detect DNA in a gene sequencer. For two-photon microscopy, both APDs and PMTs are appropriate. Remember, the most obvious choice is not always the most suitable or cost-effective choice. There is a lot to benefit by making an SNR calculation to help select the best candidate. **oe**

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