OVERVIEW

The equation used to calculate the signal to noise ratio in an SPM is given in Eqn.1 below.

\[
\frac{S}{N} = \frac{I_s}{\sqrt{2qFBG(I_s + (2I_D + I_B))}} \quad \text{(1)}
\]

where,

\[
I_s = \frac{P \lambda \cdot PDE \cdot G \cdot q}{hc/\lambda} \quad \text{(2)}
\]

- \( S/N \) is the signal to noise ratio
- \( I_s \) is the SPM signal current
- \( F \) is the excess noise factor
- \( B \) is the bandwidth
- \( G \) is the SPM gain
- \( I_D \) is the dark current
- \( I_B \) is the background noise

In addition, the following assumptions are used,
- Continuous measurement of current
- Bandwidth \( B = 1 \text{Hz} \)
- Background current \( I_B = 0 \)
- \( \lambda = 500 \text{nm} \)
- \( I_D = 0.4 \mu\text{A} \) (1mm SPM), \( 3 \mu\text{A} \) (3mm SPM) \( \text{@} V_{BR} + 2V \)
- \( F = 1.1 \text{ @} V_{BR} + 2V \)
- \( G = 2.4 \times 10^6 \)

Equation 1 is used to plot SNR as a function of the optical power (light intensity) and is shown in Figure 1.

Silicon Photomultiplier Signal to Noise Ratio

The ability to detect single photons represents the ultimate sensitivity in optical detection. To achieve such sensitivity a number of technologies have been developed and refined to suit particular applications. Until recently, the traditional vacuum-based PMT has been the detector of choice for many applications. However, since its release into the market over the last decade, the so-called silicon photomultiplier (SPM) has offered a real alternative to the PMT, achieving a similar performance in terms of gain, photon detection efficiency and timing. In addition the SPM has all the benefits of silicon technology such as compactness, magnetic insensitivity and high volume CMOS production.

When assessing the suitability of a detector for a given application, a key metric is the signal to noise ratio (SNR). This is defined as the ratio of the signal current (photocurrent) or voltage to the inherent noise produced by the detector. This technical note presents the SNR for SensL SPM detectors at a variety of signal levels.

![Figure 1, Signal to noise ratio as a function of optical power at 2V above the breakdown voltage.](image)
Equation 1 can also be used to plot the SNR for a given light level as a function of the applied bias voltage. In the case of Figure 2, this is shown for 2pW on a 1mm SPM. The breakdown voltage of the device is 27.5V.

Figure 2, Signal to noise ratio as a function of bias voltage for a 1mm SPM.

Figure 4, Signal to noise ratio as a function of bias voltage for different light intensities incident on a 1mm SPM.

Figure 5, Normalized signal to noise ratio as a function of bias voltage for different light intensities incident on a 1mm SPM.

Certain SPM parameters are a function of SPM bias, and so this must be incorporated into the calculation.

- $F$ and $I_D$ have a square dependence on bias
- $G$ has a linear dependence on bias
- The PDE as a function of bias is plotted in Figure 3 below.

Figure 3, PDE as a function of bias voltage.

Figure 4 shows the same type of plot as in Figure 2, but repeated for a variety of incident light levels. The light levels are shown as both optical power and photons per second. (See Appendix A for more information on converting optical power into photons/sec).

It can be seen, that as the light level increases, the curve flattens off at higher bias voltages. This effect is more clearly seen if the plots are normalized to their maximum levels, as shown in Figure 5. This means that at higher light levels, there is a broader range of bias voltages that can set to achieve a near-optimal SNR.

The same plots are shown for a 3mm SPM in Figures 6 to 8.
In order to calculate the number of photons that are equivalent to a given optical power, one can use Equation 3, below, to give the energy of each photon of a given wavelength ($\lambda$),

$$E = \frac{hc}{\lambda}.$$  \hspace{1cm} (3)

where,

- $E$ is the energy in Joules
- $h$ is Planck's constant ($6.6\times10^{-34}$ J s)
- $c$ is the speed of light ($3.0\times10^8$ m s$^{-1}$)

A watt of power is equivalent to a joule per second, so a given optical power (in watts) can be divided by the power of one photon at a given wavelength (equation 3) to give the number of photons, e.g. 2 pW at 500 nm,

$$2\times10^{-12} \div 4\times10^{-19} = 5\times10^6 \text{ photons/sec}$$