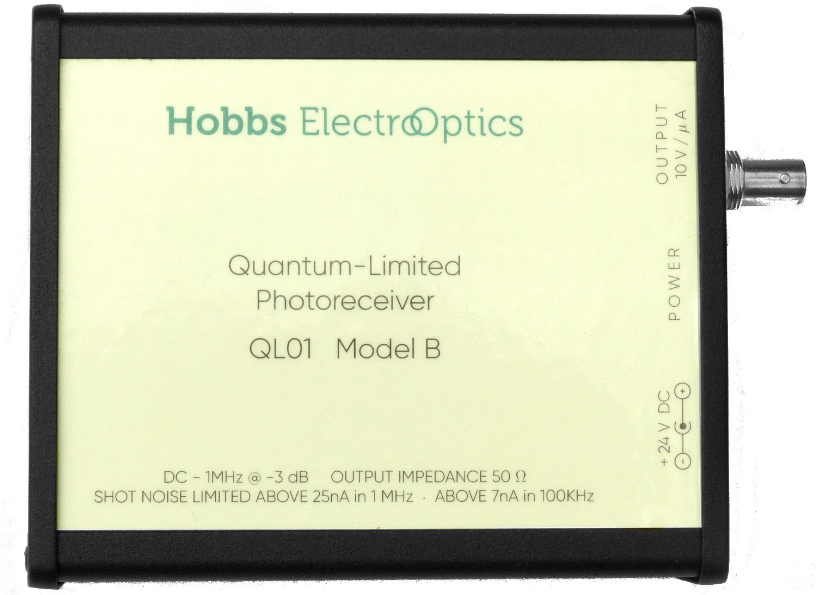
Hobbs ElectroOptics

QL01 Series

Quantum-Limited Photoreceivers



User's Guide And Reference

Rev. 1.25

QL01 Series

Quantum-Limited Photoreceivers

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Philip C. D. Hobbs

Hobbs ElectroOptics/ElectroOptical Innovations, LLC.

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1 Introduction

Making good optical measurements is rarely simple, but it is particularly difficult in very low light, as anyone knows who's ever tried it.

Of course, it's easier if you can get more light somehow, maybe with a brighter laser or a larger collection aperture. That isn't always possible, unfortunately. Chemical, biological, and microelectronic samples are often easily damaged by cranking the illumination power too high, for instance, and large collecting apertures are bulky and expensive.

Low light naturally requires large feedback resistors in the transimpedance amplifier in order to reduce thermal (Johnson) noise. Decent-sized photodiodes have a lot of capacitance, though, which in combination with those large resistors form slow RC time constants that limit measurement speed, signal-to-noise ratio, or both.

The Hobbs ElectroOptics QL01 is a highly sensitive photoreceiver that achieves shot-noise limited performance with very dim light, from 10 nanowatts up to a few microwatts, with a previously unattainable combination of sensitivity and bandwidth. It uses a proprietary bootstrap architecture to reduce the effect of photodiode capacitance by a factor of over 1000, with sub-nanovolt noise densities. This allows the Model B to offer shot-noise-limited detection performance at 25 nA out to its full 1 MHz bandwidth, and at 7 nA in 100 kHz. The Model A trades off a bit of low-light performance for a 7x increase in detector area for more light collection and ease of alignment.

Low-light applications in solid state physics, spectroscopy, chemistry, biology, and other fields will see an immediate improvement in their measurements when they switch to the QL01. For applications with a bit more light available, forthcoming versions C and D will extend the bandwidth to 3 MHz at 1 MΩ transimpedance. Fiber-coupled versions with performance from 800-1700 nm are in the works as well.

These instruments are designed to survive the accidents that sometimes happen in a research lab, with medical-grade power supplies, a thick aluminum box, a stainless steel mounting thread, and a solid metal BNC output connector securely attached to the box itself.

The QL01 series are the first of a family of advanced photoreceivers from Hobbs ElectroOptics. These are all-new designs based on expertise gained through our own research and from designing dozens of advanced instruments for our consulting clients. We also do specials and OEM products, so if you have an unusual requirement, give us a call or send an email.

Philip C. D. Hobbs
Principal
(914) 236-3005
phil.hobbs@hobbs-eo.com

Hobbs ElectroOptics/ElectroOptical Innovations, LLC.
160 North State Road, Suite 203
Briarcliff Manor, NY 10510
http://hobbs-eo.com

2 Typical Specifications

QL01 Quantum-Limited Nanowatt Photoreceiver

FUNCTION	Single-channel, low noise optical to electrical converter
INPUT	Free space optical detector.
PHOTOCURRENT RANGE	**QL01-A/B:** 0 - 1 μ nominal, overrange to 1.15 μA
OUTPUT	BNC connector, output impedance 50 Ω (A high-Z load is preferred, as this prevents increased photodiode leakage due to internal power dissipation.)
DETECTOR AREA	**QL01-A:** 2.65 mm square detector, 7 mm^2 area **QL01-B:** 1 mm square detector, 1 mm^2 area
TRANSIMPEDANCE	10 MΩ (10 V/μA)
BANDWIDTH	DC - 1 MHz @ -3 dB
RISE / FALL TIME	400 ns typical, 10% - 90%, see Figure 6.1
OFFSET CURRENT	±10 nA maximum @ 25°C
OFFSET VOLTAGE	±20 mV maximum @ 25°C

QL01 Quantum-Limited Nanowatt Photoreceiver

NOISE (INPUT-REFERRED) @ 25 °C	**QL01-A:** Noise floor < 60 fA/$\sqrt{\text{Hz}}$ (DC - 100 kHz average): Shot noise limited above 8 nA (DC- 100 kHz) or 45 nA (DC - 1 MHz). See Figure 6.2 **QL01-B:** Noise floor < 60 fA/$\sqrt{\text{Hz}}$ (DC - 100 kHz average): Shot noise limited above 7 nA (DC - 100 kHz) or 25 nA in DC - 1 MHz . See Figure 6.3
NOISE EQUIVALENT POWER (NEP)	Optical power needed to reach SNR of 1.0. At at 850 nm, the QL01-A/B's 60 fA/$\sqrt{\text{Hz}}$ noise current equals 100 fW NEP in 1 Hz.
SPECTRAL RESPONSE	350-1100 nm, see Section 7
QUANTUM EFFICIENCY	$>$ 90% peak, $>$ 10% 380-1090 nm. See Figure 7.1
SPECTRAL RESPONSIVITY	**QL01-A:** Peak 0.62 A/W @ 850 nm, $\lambda_{10\%}$ 400 - 1100 nm **QL01-B:** Peak 0.65 A/W @ 870 nm $\lambda_{10\%}$ 380 - 1100 nm

QL01 Quantum-Limited Nanowatt Photoreceiver

OVERSHOOT:	2% typical, measured with an input pulse with 100 ns time constant (See Figure 6.1)
OPERATING TEMPERATURE	0°C - 60°C Note: Photodiode leakage increases with temperature, leading to increased DC offset voltages and more noise.
SHIELDING	Solid extruded aluminum enclosure with die-cast aluminum end plates and conductive gaskets for EMI rejection
POWER	24 V DC @ 150 mA maximum; universal 100-240 V, 50-60 Hz medical-grade power brick supplied
INDICATOR	The green LED on the back panel lights when all power supply voltages are normal
DIMENSIONS AND MOUNTING	Hammond 1457L1201EBK enclosure with removable stainless steel flange with 1/4-20 or M6-1 tapped hole and four self-adhesive rubber feet. Flanged end plates with mounting slots are optional.

3 Photos

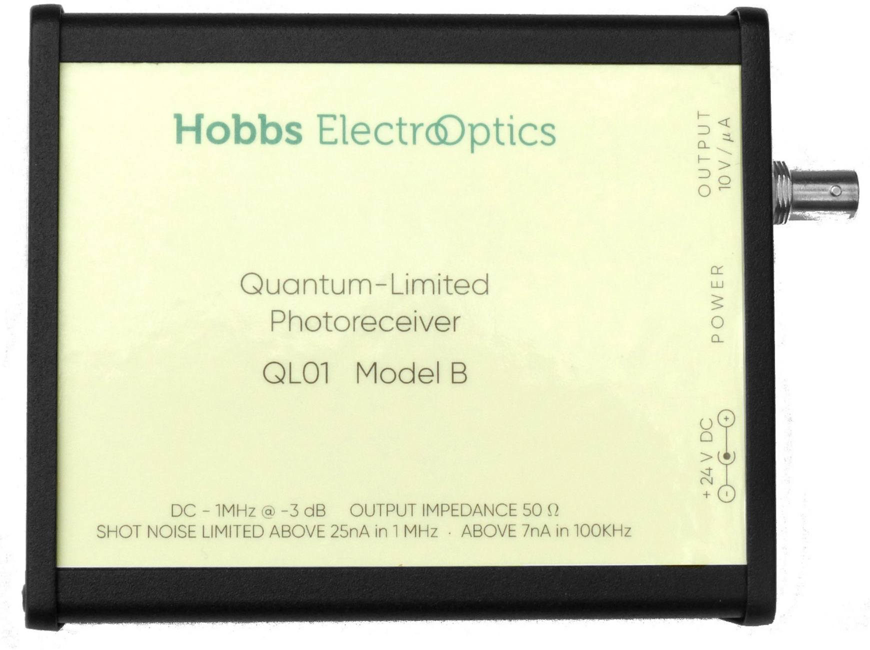


Figure 3.1: Top view of the instrument

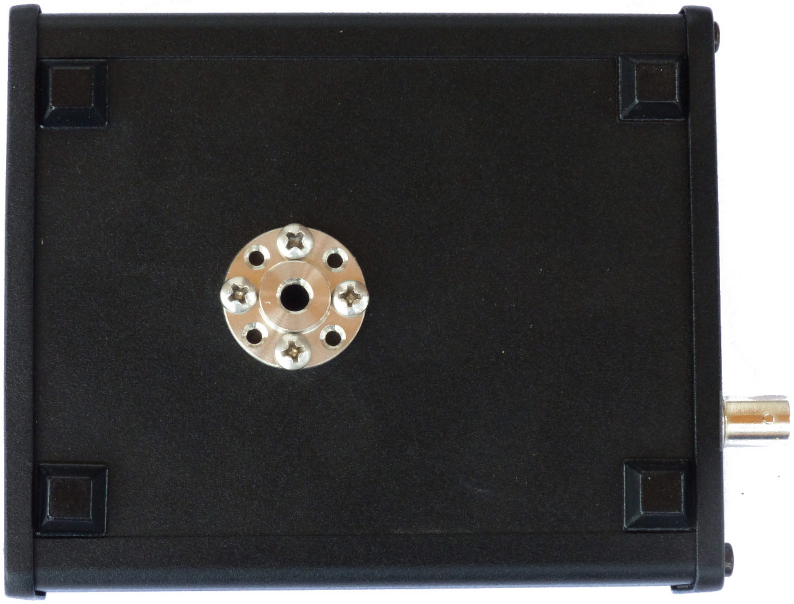


Figure 3.2: Bottom view showing 1-3/4" mounting flange with 1/4"-20 or M6 threaded mounting hole

Figure 3.3: End view showing power connector, power indicator LED, and output BNC

4 Quick Guide To Using The QL01

The Hobbs ElectroOptics QL01 is designed to be very simple to use: basically you put it in your optical system, connect the power supply and output cable, tweak the alignment, and your low-level measurement troubles just got a lot less troublesome. There are ways to go wrong though, so here's some advice.

- **Use the power brick that came with your QL01.** This is a medical-grade unit with all the relevant agency approvals, and has low conducted and radiated electromagnetic interference (EMI). A poor quality brick can cause all sorts of noise and interference problems, and cheap knock-offs may even be dangerous.

- **Minimize stray light.** Stray light introduces shot noise, and artificial light is usually strongly modulated by the power source. It isn't just 100/120 Hz, either. Light from electronic-ballast fluorescent lamps carries a lot of junk at harmonics of the switching frequency, usually 20-40 kHz, extending up past 1 MHz. A nanowatt or two of that can easily spoil your measurement.

- **Watch out for pickup.** While the QL01 is very well shielded, there has to be an aperture so that light can reach the photodiode. Other things can get in there too, especially if there is wiring carrying high frequency signals or fast pulses near the photodiode. A bit of distance helps a lot; you can't just stick a LED up next to the QL01's photodiode, hit it with a pulse, and expect to get a good measurement of the QL01's transient response. That's why HEO's test fixture uses a lens to image the test source on the photodiode.

- **Beware of saturation.** The QL01's maximum output is specified as 10 V. There's some overrange available, but linearity will be degraded if you go much beyond 11 V. The unit is internally protected against photocurrents up to about 3 mA (5 mW optical power at 850 nm) (far above even direct sunlight), but may be damaged above there.

This should only occur if a bright laser beam were inadvertently to hit the photodiode, which shouldn't happen in a low-light measurement system.

Short pulses with high peak power and very low duty cycles can also cause problems. You can check this by using a few optical neutral density (gray glass) filters of density ND 0.3 or 0.5 in different combinations. Their attenuations will add if the system is operating linearly. For instance, an ND 0.3 filter should reduce the output voltage by about half (3 dB optical, 6 dB electrical), and a second one by half again, to a quarter of the initial value. These filters are rarely that accurate, so a more stringent test is to measure each one individually and make sure that the effect of using the two together is the sum of the individual attenuations.

- **Keep it cool.** One of the techniques leading to the QL01's high performance is applying reverse bias to the photodiode. This reduces its capacitance by several times and improves the high-frequency noise floor by the same factor. However, photodiode leakage current increases strongly with temperature, so it's best to operate the unit below 30 °C to avoid increased offset voltage and shot noise due to leakage. Prolonged operation with a DC-coupled 50-Ω load may cause a significant amount of internal heating, so it's best to use high-Z loads. The QL01's output is series-terminated, so you don't have to worry about cable reflections causing measurement errors with an open-circuit load at the far end.

- **Don't short the output.** Because of its 50-Ω output, it's very convenient to use the QL01 with an external filter for narrowband applications, and this works fine. However, some bandpass and highpass filters present a short-circuit load at DC, and these should be avoided. While the QL01 will typically survive an output short indefinitely, the resulting heat will cause extra noise and drift, and above half-scale output it may cause the internal voltage regulators to shut down. If this happens, the power LED will turn off.

5 Theory of Operation

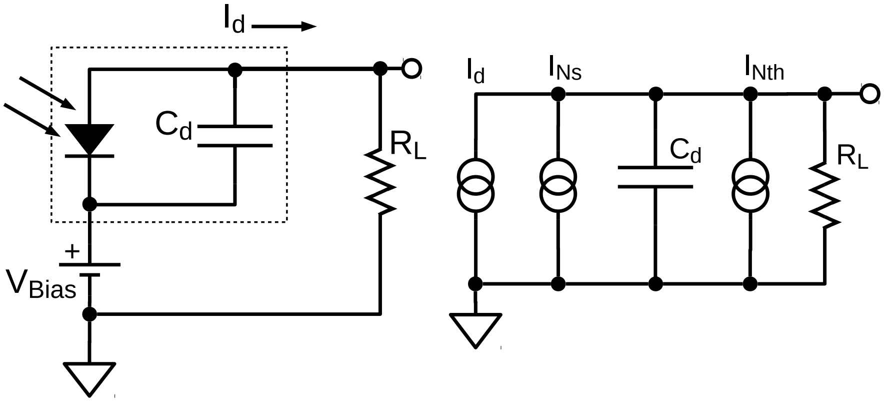
In this section we discuss the problems of low noise photoreceiver design, with specific reference to the QL01. Some of the figures are from *Building Electro-Optical Systems: Making It All Work* [1], where you'll find lots more on this and many other topics. For any missing background on circuit design and low noise design in particular, see *The Art of Electronics* by Horowitz and Hill [2], especially Chapter 8.

5.1 Noise In Photoreceivers

Photodiodes are amazingly good transducers. They're highly linear, spatially uniform, and work well over more than an octave of optical frequency (some over more than two octaves). Their main drawback is *capacitance.*

Capacitors don't have noise of their own, so why is capacitance a problem? The easiest way to look at it is to consider a simple front end consisting of a photodiode and a load resistor, as shown in Figure 5.1, which we expect to be followed by a buffer amplifier.

The bandwidth of this circuit is set by the RC time constant $R_L C_d$. The effective load



(a) Topology (b) Noise model

Figure 5.1: The simplest front end: a load resistor

impedance Z_L is R and C in parallel,

$$\mathrm{Z}_L = \frac{R_L}{1 + j\ 2\pi f C_d R_L}, \tag{5.1}$$

and the output voltage is $I_{\text{photo}} Z_L$.

The output voltage rolls off by 3 dB where the real and imaginary terms become equal, *i.e.*

$$\mathrm{B}W_{RC} = \frac{1}{2\pi R_L C_d}. \tag{5.2}$$

Above there, most of the photocurrent gets swallowed by C_d before it ever gets to the external circuit, so lower capacitance is a win. The low-capacitance champions are silicon PIN photodiodes run at large reverse bias, some of which come in as low as 40 pF/cm^2, though most are a few times higher (100-150 pF/cm^2). InGaAs devices can be easily 100 times higher (4-10 nF/cm^2). The ones used in the QL01A have a zero-bias capacitance of about 70 pF. With the QL01-A's 10-MΩ transimpedance, the 3 dB bandwidth in that case would be

$$\frac{1}{2\pi \cdot 10\ \mathrm{M}\Omega \cdot 70\ \mathrm{pF}} = 227\ \mathrm{Hz}. \tag{5.3}$$

which is almost a factor of 5000 slower than the QL01. The total dark noise current is just the Johnson (thermal) noise of the load resistor,

$$i_N = \sqrt{\frac{4kT}{R_L}}. \tag{5.4}$$

Measurements in which this thermal noise dominates are said to be *Johnson noise limited.* You don't want to be in that situation if you can help it, because you worked hard for those photons, and they're just going to waste.

Referring to the noise model in Figure 5.1, we see that there are three current sources: the signal photocurrent (I_{d}), its shot noise (I_{Ns}), and the Johnson noise of R_{L} ($\mathrm{I}_{\mathrm{Nth}}$). All of these are wired in parallel, so they get treated exactly alike: the total noise voltage rolls off along with the signal, so the signal-to-noise ratio (SNR) is frequency-independent, which is a bit counterintuitive at first. The capacitance problem comes in when we attach an amplifier.

All amplifiers have some amount of noise in both voltage and current. In the photocurrent range of the QL01, we'd pick a FET-input amplifier, whose current noise is very small. Its voltage noise density e_{NAmp} will be reasonably constant above about 1 kHz, so as the signal rolls off as $1/f$ in accordance with (5.1), the SNR drops until eventually the system noise is dominated by the amplifier. The amplifier's voltage noise density e_{NAmp} begins to dominate the noise of R_L when

$$f_0 = \mathrm{BW}_{RC} \frac{e_{\mathrm{NAmp}}}{\sqrt{4kTR}}. \tag{5.5}$$

The OPA656 is a typical high performance FET op amp whose maker promotes it for use with photodiodes. Its input-referred voltage noise density is about 7 nV/$\sqrt{\mathrm{Hz}}$.

With our photodiode and load resistor, the amplifier noise starts to dominate at 13 kHz, a factor of 10 (20 dB) short of the performance of the QL01. You don't want to be amplifier noise limited either, because once again your hard-earned signal is being seriously degraded by circuit noise. It is important to keep the two aspects of the problem separate in our minds, because transimpedance amplifiers can fix one (rolloff) but not the other (noise).

5.2 Shot noise

Of course, when we're actually detecting light, there's also shot noise to consider. Shot noise is the quantum version of rain on a tin roof: because photoelectrons are generated at random times (a *Poisson process*), there's an irreducible amount of noise due to the $\sqrt{N}$ fluctuations in the counting statistics. Measurements where shot noise dominates other noise sources are said to be *shot noise limited* or *quantum limited*. Photocurrent and photodiode leakage both have full shot noise[1], so we'll lump them together and say that the noise current spectral

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[1] Except in very special situations (squeezed states) that don't happen by accident—if you're in one, you already know about it.

density is

$$i_{\mathrm{N}shot} = \sqrt{2eI_{photo}} \tag{5.6}$$

where e is the charge of the electron, about $1.602 \cdot 10^{-19}$ coulombs. (This formula is not mysterious— it's just $\sqrt{N}$ converted to a current and quoted in the frequency domain.)

Measurements where the noise of the photocurrent dominates are said to be in the *shot noise limit*. That's where you want to be if at all possible, because it's the counting statistics of your actual signal electrons and not circuit problems that set the SNR. Of course the SNR can probably still be improved, but that will involve getting more light rather than changing the circuit. Signal averaging and lock-in detection are also useful, of course, but they're slow. A clean fast measurement is always better, and that's what the QL01 is all about.

Two very useful rules of thumb follow from (5.6): first, shot noise dominates Johnson noise when $I_{\mathrm{photo}}R_L > 52$ mV at 300 K, and second, the SNR is within 1 dB of the shot noise limit when $I_{\mathrm{photo}}R_L > 200$ mV. (You can easily derive these by equating the shot noise and Johnson noise formulas and solving for $I_{\mathrm{photo}}R_L$.) Thus if we have lots of light we can reduce R_f considerably, and thereby reduce the effect of photodiode capacitance. Milliamps are easy; nanoamps are hard.

We'll talk more about calculating when we're in the shot noise limit in Section 6.6.

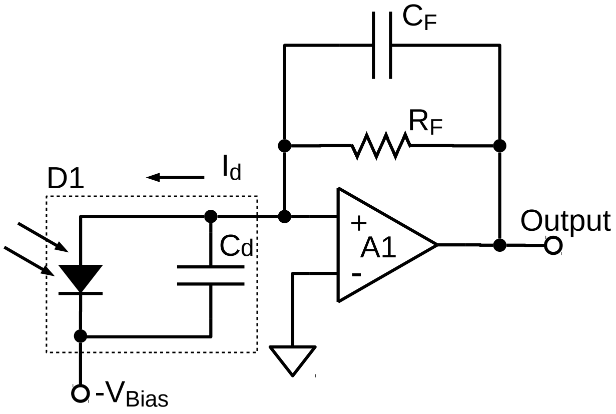

Figure 5.2: Schematic of a conventional transimpedance amplifier

5.3 Transimpedance Amplifiers

We may observe that the signal swing across the photodiode capacitance is the root of the problem—if there's no swing, there's no capacitive current. Thus if we apply feedback around *A1* to wiggle the far end of R_L so as to keep the photodiode end still, all of the photocurrent has to flow through R_L, and ideally there's no rolloff. This circuit is called a *transimpedance amplifier* (TIA), shown in Figure 5.2. (Load resistor R_L has become feedback resistor R_F but it's the same resistor.)

The circuit works by applying progressively higher voltage gain at high frequencies, which of course amplifies both the signal and the noise. Thus instead of a decreasing signal and a flat noise floor, we have a flat frequency response and a rising noise floor. In fact the SNR of the op amp TIA is identical to that of the same amplifier used as a buffer on our previous circuit, and the amplifier's noise still dominates above 13 kHz. (There really is no free lunch.) Its *noise gain* is the noninverting gain of the stage, which is

$$A_{Vn} = 1 + R_f/j2\pi f C_d. \tag{5.7}$$

(The small capacitor C_f across feedback resistor R_f is to prevent instability and control the noise gain at high frequency.) Another way to look at it is that the op amp imposes its input noise $e_{\,\mathrm{NAmp}}$ across the photodiode, whose capacitance differentiates it, leading to a real noise current

$$i_N = 2\pi f C_d \cdot e_{\mathrm{NAmp}}, \tag{5.8}$$

which is often called '$e_N C$ noise'.

In TIAs designed for high photocurrents, R_f will be much smaller, and so the noise gain will be much less. Also of course the large amount of shot noise will swamp the $e_N C$ contribution most of the time.

The combination of rising $e_N C$ noise, flat shot noise, and the finite bandwidth of the amplifier makes the shape of the noise floor depend on the photocurrent. While the QL01's

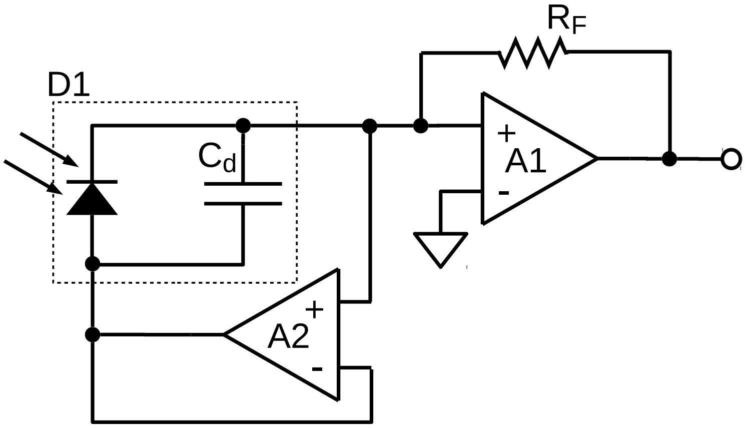

Figure 5.3: Conceptual schematic of a bootstrapped transimpedance amplifier

advanced design minimizes this effect, it cannot be entirely avoided, as you can see in Figures 6.2 and 6.3.

5.4 Bootstraps

Another approach, shown in Figure 5.3, is to use an auxiliary amplifier *A2* to apply feedback to the ground end of the photodiode to make it follow the signal end. In this case, we want an amplifier with a gain as close as possible to 1.00000—but not above that, or it's likely to oscillate. The advantage of a bootstrap is that it doesn't have to be DC-accurate, so we can use discrete devices whose noise is much lower than a FET op amp's. Like the TIA, the bootstrap imposes its input noise across the photodiode, which leads to an $e_N C$ noise contribution as in (5.8), but a much smaller one since $A2$ is so quiet. The main amplifier $A1$ doesn't need to be nearly as good, because from its point of view the photodiode capacitance is effectively gone.

5.5 The QL01 Difference

The QL01's frequency response is flat to 1 MHz, and it is shot-noise limited for photocurrents above 45 nA in its full bandwidth (above 25 nA for the B version). This represents a

20 dB improvement over the op amp TIA of Figure 5.2. The QL01's design uses two main features to achieve its high performance: reverse biasing the photodiode, which reduces its capacitance by more than a factor of 5, and a proprietary bootstrap circuit with sub-nanovolt noise density and a gain of more than 0.999 over a wide bandwidth, reducing the effect of capacitance by more than a factor of 1000.

Design Trade-offs

While it is possible to reduce capacitance a bit further by applying more bias, doing so starts to increase the photodiode leakage current. Leakage has full shot noise and is a strong function of temperature, increasing about 9%/°C, so it has to be no more than a few nanoamps at room temperature to preserve the QL01's low-light performance.

6 Performance Verification

This section presents measured noise and transient response data for the QL01-A and -B along with a discussion of how to verify this performance yourself.

6.1 Pulse Response and Bandwidth

The easiest way to verify the bandwidth is to measure the response to a square pulse. The transient data plotted below were taken using a Highland Technology P400 digital delay generator driving a red LED via an RC filter with a 100 ns time constant (2 nF in parallel with the generator's 50 Ω output) followed by a 1 kΩ series resistor. A lens of 80 mm focal length is used to couple the light into the QL01's photodiode. (The resulting pulses are slightly asymmetric, accounting for the minor difference between rise and fall times shown.)

With this setup, the 10%-90% rise and fall time should be about 400 ns. Alternatively an averaged noise floor measurement at full scale (1 μA) or a swept-sine measurement can be used, but the former needs a lot of averaging and the latter is harder to get right because of the nonlinearity of the LED.

6.2 Measuring The Noise Floor Accurately

Data for the noise plots were taken using another LED driven from a quiet DC power supply (Hewlett-Packard 6112A). The strongly rising $e_N C$ noise floor of a simple TIA such as that in Figure 5.2 continues well beyond its useful bandwidth, with the total noise power going as bandwidth cubed. This makes a lot of high frequency noise that is a nuisance to get rid of, and it makes the SNR appear poorer than it really is when viewed on an unselective instrument such as an oscilloscope or voltmeter. The QL01 largely eliminates this extra noise with a Gaussian lowpass filter whose bandwidth is 1.2 MHz. Thus it is convenient to use with an oscilloscope. For narrowband applications, it is simple to add additional filtering to obtain a corresponding SNR benefit. (Be sure to use a filter that is not a short circuit to ground at DC—highpass and bandpass filters sometimes are.)

Noise floor measurements with spectrum analyzers and some digital scope FFTs may require correction. The reason for this is interesting: when measuring noise, the individual power spectra are very noisy (the variance equals the mean), so you have to do a lot of averaging to get a smooth curve. The result is nearly always displayed on a log scale in decibels (dB). The key distinction is which you do first: whether you take the log of the average or the average of the logs. Analog spectrum analyzers and scopes which average the logs will read 2.5 dB low on Gaussian noise.[1] Taking the log applies less gain to the peaks than the valleys, and so systematically shifts the mean value downwards by what turns out to be $10\ \log_{10}(\sqrt{\pi}) \approx 2.5$ dB. (Sine waves have peaks that are all the same amplitude, but noise doesn't.) There's a similar but smaller effect when using average-reading voltmeters (not true RMS). They're calibrated with a sine wave input, and they read 1 dB too low when measuring noise. For stats fans, it's actually $10\ \log_{10}(\pi/4) \approx -1.05$ dB in that case.

In addition, it is necessary to determine the noise bandwidth of the measurement. The plots in Section 6 were taken with a Tektronix TDS 784A oscilloscope using its FFT function, and averaging a few hundred spectra. Each acquisition took $t_a = 100\ \mu$s, 5000 points at 50 Ms/s. If we choose the rectangular window, the noise bandwidth B of each frequency point is exactly $1/t_a$ or 10 kHz. The TDS 784A is one of those scopes that averages the logs instead of taking the log of the RMS average power per point. Thus to compute the 1-Hz noise density, we need to add 2.5 dB for the log averaging correction and subtract 40 dB to convert to a 1-Hz bandwidth. The measured spectrum was corrected as

$$\text{PSD (dBV @ 1Hz)} = P_{\text{meas}}(\text{dBV}) - 37.5, \tag{6.1}$$

and the agreement with first-principles calculations is within a fraction of a decibel.

Other choices of FFT window are possible, and have certain advantages, especially in reducing the spectral artifacts near the spike at zero frequency. However, their noise band-

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[1] See the classic HP/Agilent/Keysight application note AN-150, ”Spectrum Analysis Basics”.[3]

widths will be larger than $1/t_a$ by some unknown amount and so will require additional correction.

The dynamic range of an oscilloscope digitizer is quite limited—only 6 to 8 bits' worth in most cases—so it is important to eliminate interfering signals such as room lights and to use the most sensitive input range that avoids clipping the noise peaks.

Note: When using scope FFTs, you have to use an analog filter between the scope and the QL01 to avoid aliasing and turn its vertical bandwidth to its lowest setting (usually 20 MHz). HEO's test jig uses a very accurate 5-section, 4.7 MHz *LC* lowpass from TTE Inc., but you can also use the inexpensive filters from Mini Circuits if you're careful to ensure that the filter rolls off by at least 60 dB by the Nyquist frequency (half the sampling frequency). These sorts of filters normally require a 50-Ω termination, which is not recommended with the QL01 due to heating at higher output levels. It's a good idea to use a large-value capacitor in series between the filter and the scope, which will avoid this problem while letting the filter operate correctly. A 10-μF, 25 V aluminum-polymer or tantalum is a good choice and is inexpensive. Be sure to connect the positive terminal to the QL01 side. Multilayer ceramic capacitors are less suitable at such large values, as their capacitance drops very rapidly with voltage even well within their ratings. Note that a 50-Ω load will reduce the measured voltage by a factor of two (6 dB), so you have to correct for that in the data.

6.6 Finding the Shot Noise Limit

The QL01-A is specified to be shot noise limited above 45 nA in a full 1 MHz bandwidth. But what do we actually mean by that, and how is it calculated? Referring to Figure 6.2, we can calculate the noise floor in the band between given frequencies f_1 and f_2 by summing the noise power in the frequency bins that lie inside. With data quoted as a power spectral density (PSD) in dBV normalized to a 1-Hz bandwidth,[2] we first convert dBV to volts

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[2] Power is measured in watts (V^2/R) and not squared volts, but since this calculation is independent of the load impedance, we almost always quote it like this.

6.3 Transient Response (Model A and B)

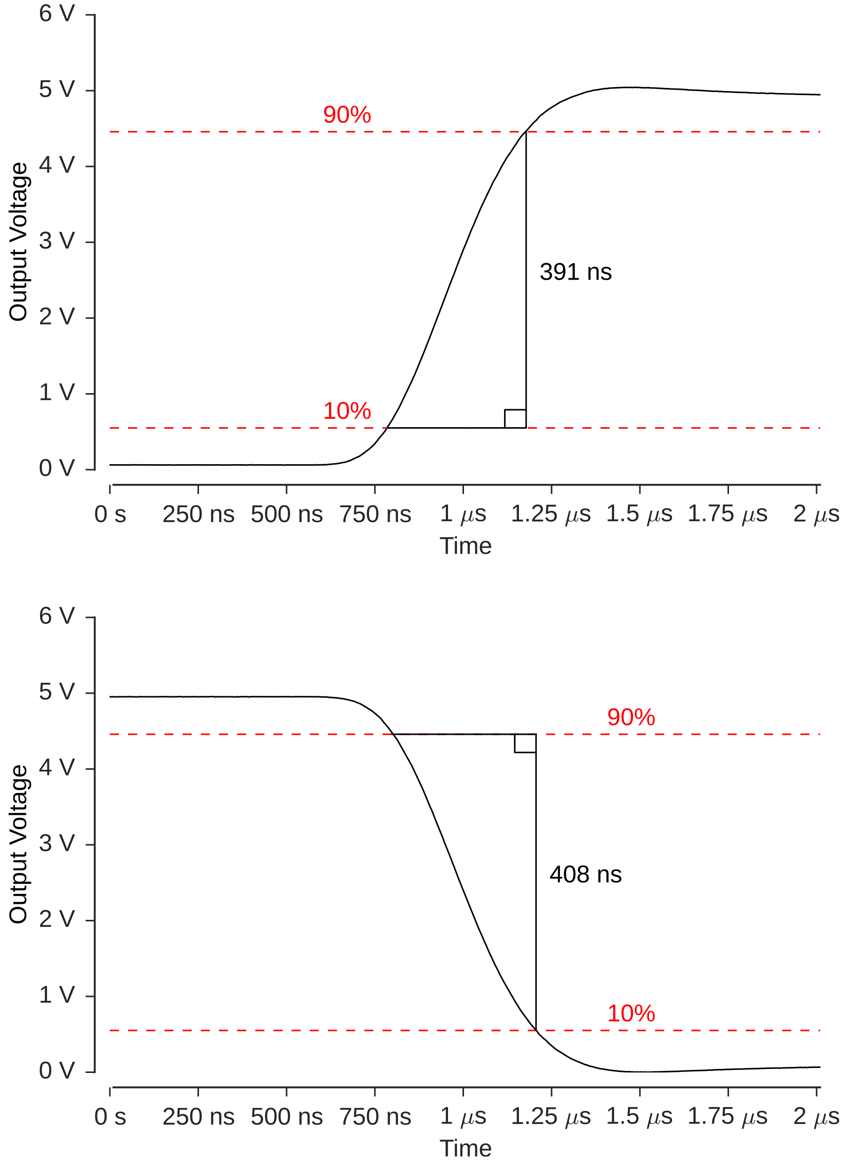


Figure 6.1: Step response of the QL01. The light source was a LED driven by a fast pulse generator via a 100 ns RC time constant. A lens was used to get good optical coupling between LED and photodiode while keeping them apart so as to to avoid preshoot due to capacitive pickup. (Slight asymmetry of the pulses results in minor differences between rise and fall times.)

squared per hertz, sum up the bins, multiply by the bin width B, and take the square root to get back to volts. The squared noise voltage in the ith bin is

$$V_i^2(V^2) = B\left(10^{0.1\mathrm{PSD}_i(\mathrm{dBV\ @\ 1\ Hz})}\right) \tag{6.2}$$

The ith bin covers the frequency interval $[iB, (i+1)B)$, so we can sum straightforwardly

$$V_{\mathrm{Ndark}} = \sqrt{\sum_{i=f_1/B}^{f_2/B-1} V_i^2} \tag{6.3}$$

What we mean by ”shot noise limited” is that squared shot noise voltage exceeds the dark noise in this frequency band. The QL01 has a fixed transimpedance of 10 MΩ, so we can compute the shot noise voltage from (5.6). Shot noise is white (*i.e.* independent of frequency), so the frequency integral is easy:

$$V_{\mathrm{Nshot}} = (10\mathrm{M\Omega})\sqrt{2eI_{\mathrm{photo}}(f_2 - f_1)} \tag{6.4}$$

Setting $V_{\mathrm{Ndark}} = V_{\mathrm{Nshot}}$ and solving for I_{photo}, we find that we are in the shot noise limit when

$$I_{\mathrm{photo}} \geq \frac{1}{2e(f_2 - f_1)}\left[\frac{V_{\mathrm{Ndark}}}{10\mathrm{M\Omega}}\right]^2 \tag{6.5}$$

That’s how we verify that the QL01 is shot noise limited at the photocurrent levels in the specifications. There’s one additional caveat: data from spectrum analyzers and oscilloscope FFTs always have a big spike near zero frequency. This is not noise; it’s the δ-function from the Fourier transform of the DC offset of the system. Thus in evaluating 6.3 and (6.5) it is important to choose a frequency band that’s at least a bin or two away from 0. (You can choose by looking at the noise spectrum and seeing where the spike ends.) Since in reality this is the quietest region, computing the noise from (say) 20 kHz to 1 MHz gives an accurate and slightly conservative estimate of the shot noise limit.

The QL01 is highly linear, so this approach works well. Another approach that's a bit more data-driven is to sum up the squared voltages from dark noise and dark plus shot noise, subtract the dark sum from the light sum to get the sum of the photocurrent noise contribution, and compare that to the dark sum. That will lump in all sources of noise on the photocurrent, including spurious modulation and source noise as well as shot noise.

6.4 Model A Noise Floor

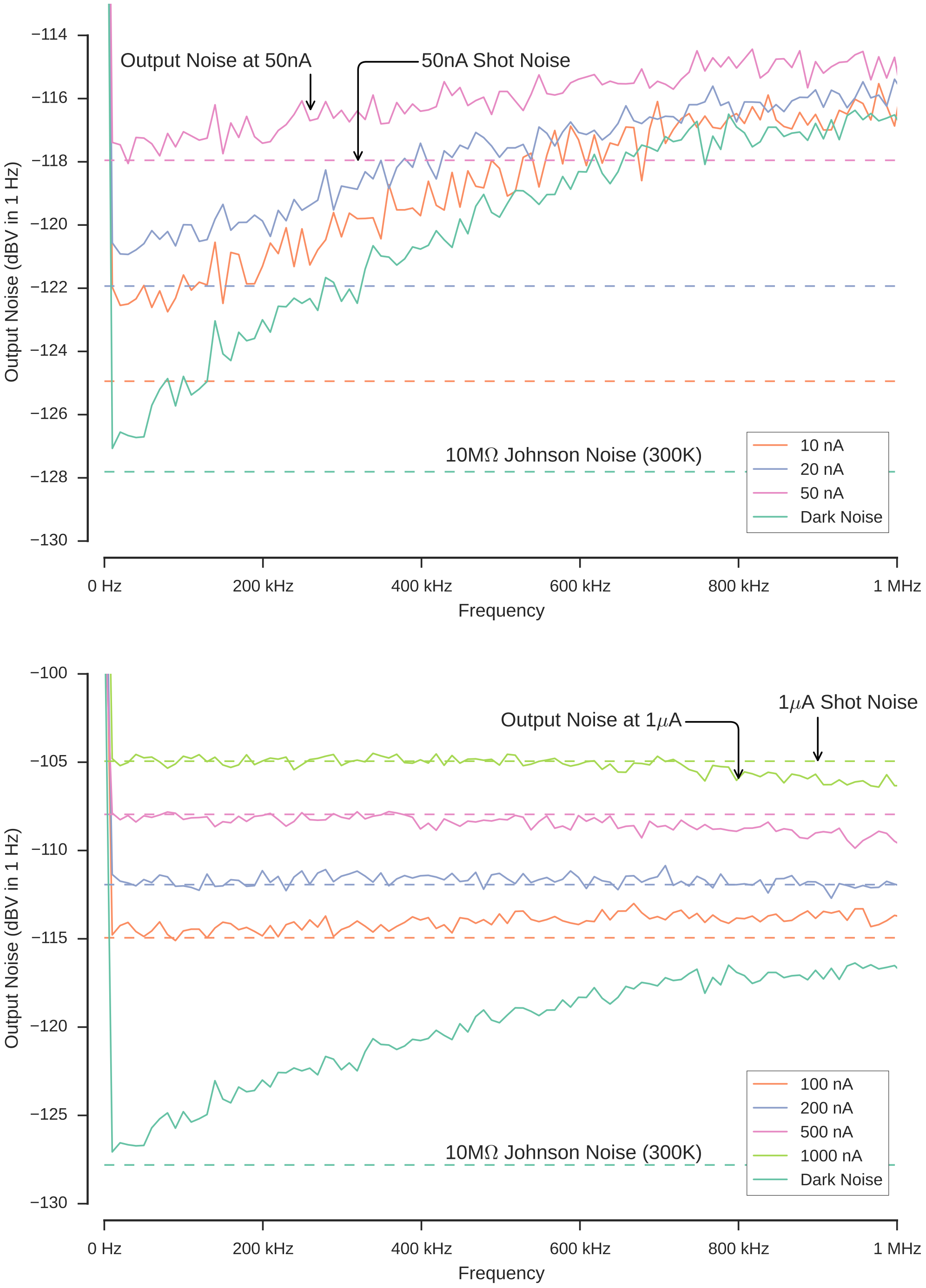
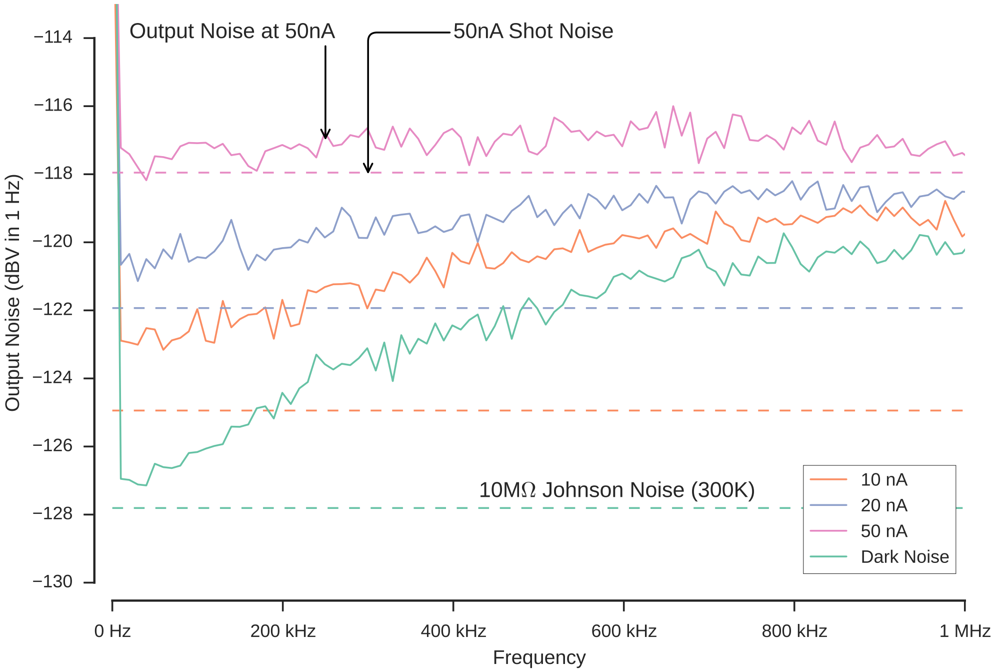


Figure 6.2: QL01-A Noise floor measurements, taken with natural light or a LED with a quiet bias supply

6.5 Model B Noise Floor



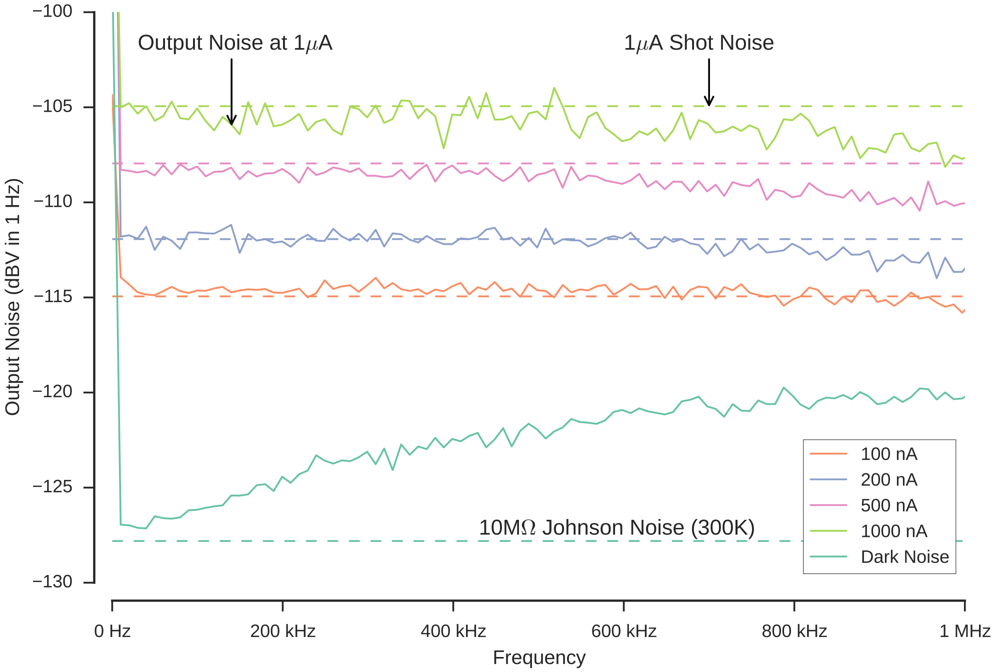


Figure 6.3: QL01-B Noise floor measurements, taken with natural light or a LED with a quiet bias supply.

7 Quantum Efficiency

The output voltage of the QL01 is the product of the incident optical power, the responsivity of the photodiode and the transimpedance gain (10 MΩ). The photodiodes used in the QL01A/B are silicon devices with efficient anti-reflection coatings providing peak quantum efficiency (QE) over 90%. The QE is the number of electrons produced per incident photon which is related to the responsivity in amps of output current per watt of incident power (A/W). Photodiodes are quantum detectors, that is ideally they produce 1 electron for every incident photon (at a QE of 1). The responsivity at a given wavelength (R_λ) is related to the quantum efficiency at that wavelength (QE_λ) by

$$\mathrm{QE}_\lambda = \frac{R_\lambda hc}{\lambda e}. \tag{7.1}$$

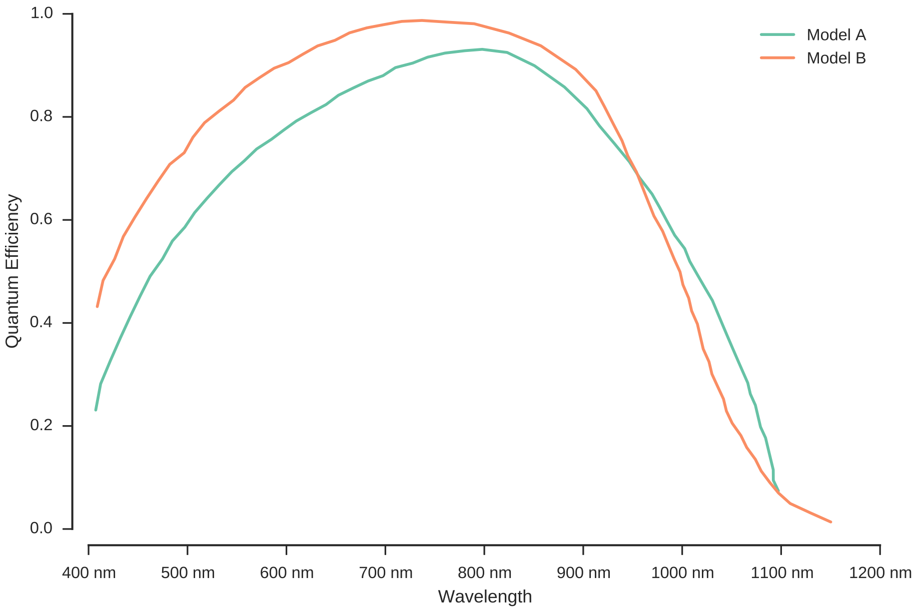


Figure 7.1: Quantum efficiency of the QL01-A/B *vs* wavelength, showing $>$ 90% peak QE.

References

[1] Philip C. D. Hobbs. *Building Electro-Optical Systems: Making It all Work, Second Ed.* Wiley Series in Pure and Applied Optics. Wiley, 2009. ISBN: 9780470402290. URL: http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470402296.html.

[2] Paul Horowitz and Winfield Hill. *The Art of Electronics, Third Ed.* Cambridge, 2015. ISBN: 9780521809269. URL: http://www.cambridge.org/tw/academic/subjects/physics/electronics-physicists/art-electronics-3rd-edition?format=HB.

[3] Keysight Inc. *Application Note 150: Spectrum Analysis Basics*. URL: http://literature.cdn.keysight.com/litweb/pdf/5952-0292.pdf.

Table of Symbols

EMI	Electromagnetic interference.
FFT	Fast Fourier transform (to transform from time to frequency and back).
Ms/s	Megasamples per second.
NEP	Noise equivalent (optical) power.
OEM	Original equipment manufacturer.
QE	Quantum efficiency.
RMS	Root-mean-square.
SNR	Signal-to-noise ratio (signal power / noise power).
TIA	Transimpedance amplifier.

Hobbs ElectroOptics
http://hobbs-eo.com
info@hobbs-eo.com

160 North State Road, Suite 203
Briarcliff Manor, NY 10510
(914) 236-3005