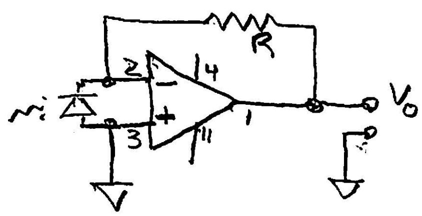
Making a photodiode light detector, for several purposes:
* Measuring falloff of light with distance from the source (laser, or LED / other divergent source)
* Making the detector for a photometer for analysis of dye conc. and showing Beers' law

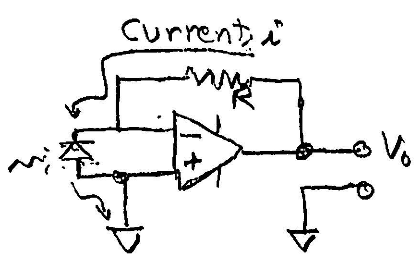
First step: make the detector, a current-to-voltage converter using an op amp and a photodiode

I used a standard schematic, below (though I initially had the inverting and non-inverting inputs swapped, and I kept wondering about the voltage generated across the PD):



I made the circuit on the powered project board. The photodiode is a Hamamatsu PH208A, dating from the '70s, when it was used in in-camera light sensors. I used it in a device that several colleagues and I designed to measure light on plant leaves at any position; it's light enough to move with the leaves and not impede them. I have lots of them left over from those studies.

Simple view of how the circuit works: Here's an annotated schematic, showing a photogenerated current flowing into the photodiode through the feedback resistor (and on to ground).



- A very good first approximation is that the gain of an op amp is infinite. Therefore, any difference in voltages between pin 2, the inverting input, and pin 3, the noninverting input, would cause an infinite output signal on pin 1. So, if pin 3 is at zero volts, we expect that pin 2 will also be at $V_- = 0$, if this can be achieved (the circuit is not saturated).
- Now, V_- = (output voltage, V_o) – (drop across the feedback resistor)
  $= V_o - iR$
  In normal operation, then, $V_o = iR$, a nice proportional response to current.
- Suppose V_o is too low. Then, $V_- < 0$, and this gets amplified arbitrarily, though it stops when V_o reaches zero. The converse happens if V_o is too high. Thus V_o approaches iR as closely as possible (within the design parameters of the op amp).

In the system I built, after calibration a current of 130 μA running through R = 70 kΩ gives an output voltage V_o at about 9.1 V.

I chose a rail-to-rail op amp, a TLC2274IN (this can put out a signal from zero to full supply voltage, necessary for measuring down to low light levels). Indeed, it showed the ability to go to a real zero with the PD in darkness (oddly, Al foil pushed over the PD in window light caused a slight bump up).

I checked the output, including its range – yes, rail-to-rail.

Next: making an LCD panel for readout, so that the device is compact, with 9V battery power and no need to carry a VOM

About 1 year ago I bought a small LCD digital voltage meter, a Velleman model PMLCDL, which reads 3-1/2 digits (0-2000 or 0-200.0 with the decimal point on. (I'd bought it with plans to make a bike speedometer with a Hall-effect sensor to count wheel rotations.) It goes full scale with a 200-mV input, so I planned ahead for dividing the op-amp output voltage.

I decided to mount the digital voltmeter and, shortly, the PD detector, on a small ceramic project board. Annoyingly, the voltmeter has a projecting potentiometer on the bottom that makes it impossible to plug it into a project board without a risky tilt. I got a 14-pin socket with long pins, put it into the project board, and pushed the voltmeter pins into it.

I then had to test how it works. Short story: It comes alive nicely with 9V from a battery applied to its power terminals. I then made a voltage divider to get a bit less than 200 mV from the power supply, checking it with a VOM. Weirdly, the signal and power cannot share a common ground! If this occurs, the panel reads -1. I had to create a 2nd voltage source with a separate battery. This quirk is not noted in the instruction pamphlet. (The pamphlet also mentions jumper wires to allow higher V inputs, but (1) there are no jumpers supplied and (2) it appears to have an internal jumper on the reverse side of the board, so that the 200 mV max. is enforced; there's no way to get the circuit out of its holder without risking damage.)

Next: reconstructing the PD circuit on the project board.

I did it first with long, looping jumpers from the Raspberry Pi CanaKit. These tended to shade the PD, so I (1) moved the op amp, feedback resistor, and voltage divider resistors close to the voltmeter and made flat jumper wires. (I did this reconfiguration after testing the whole system outdoors in the sun, calibrating the system).

To keep the signal at or below the 200-MV saturation point, I made a voltage divider, about 1:45, with a 3.3 MΩ resistor and a 68 kΩ resistor. This gave me about 195 mV at saturation.

Next: calibration, by way of choosing the feedback resistor

I had picked an arbitrary value (1 MΩ) for testing in the kitchen under window light. Of course, the red laserpointer beam saturated the circuit. I took the complete device outside and pointed it perpendicular to the direction of the Sun. Note that I made two "slots" for the feedback resistor(s). After several tests I ended up with 220 kΩ in parallel with 100 kΩ, for an effective 70 kΩ. This just missed saturating in full sun, at about 192 mV. Interestingly, the reading, without the decimal point as 1920, is just about the photosynthetic photon flux density of full fun, around 2000 µmol m-2 s-1.

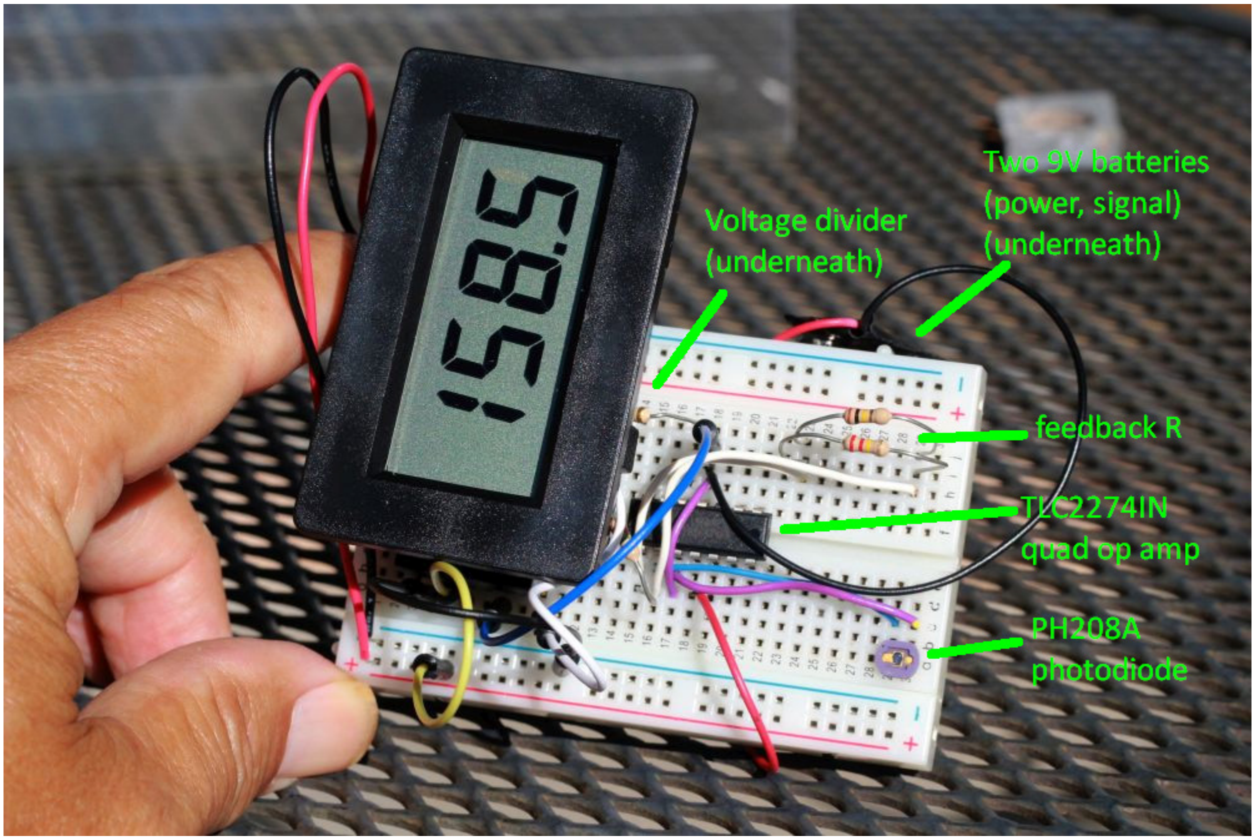
It is of interest that the red laserpointer far supersaturates the circuit. Using different angles of incidence and some rough filtration to reduce its intensity, it appears that the flux of red photons per unit area is about 4x higher than the flux of sunlight's photons per area. That makes sense:

- First, the red laser light show up clearly, even on a sunlit surface; it's very much more intense than sunlight (even allowing for sunlight being spread out over many wavelengths).
- Second, we can look at the claimed power output of the laserpointer, 5 mW. This power is concentrated in a beam that is oval, with axes about 5 mm by 3 mm, for an area of about 12 mm^2. The energy flux density is then about $(5x10^{-3}W)/(1.2x10^{-5}\ m^2)$, or about 400 W m^{-2}. This is only about the energy intensity of visible sunlight, however. Another "however:" the beam looks like it covers 5 mm x 3 mm to the naked eye, but the significant intensity is restricted to an area about 4 mm x 2.5 mm, as can be seen on passing the beam through a strong neutral density filter. Thus, the area is about 8 mm^2, so the intensity in the beam center is about 12/8 higher, about 600 W m^{-2}. Yet one more "however:" at a given energy flux density, there are more photons in red light than in white light; the energy per photon is less, by a factor of about 550/650 (the red light has a wavelength of 650 nm). This makes the photon flux density equivalent to white light of about 710 W m^{-2}. This still doesn't explain the apparently 4x higher photon flux density in the red laserpointer beam than in sunlight, but we're not off by a great factor.

A few additional notes

1. Proper orientation of the photodiode: place it so that the prong/lead on the side with the tiny black dot goes into the project board hole connecting to the inverting (-) input.

2. Here's a photo of the completed device, in operation:



3. Does the output current of the PD seem consistent with a device that essentially converts all incident (well, absorbed) photons into transport of electrons?

- Full sunlight in our area is about 2000 μmol m^{-2} s^{-1}, in units that we use in photophysics and photosynthetic studies; we call this measure the photosynthetic photon flux density, PPFD. A mole of photons is Avogardro's number of photons, 6 x 10^{23}. Our device tends to measure just those in the photosynthetically active part of the solar spectrum, which is also close to the visible spectrum, the wavlength range from 400 nm to 700 nm.
- A quick check on how many photons (quanta) are expected: simple measurements tell us that the energy flux in the visible/photosynthetically active part of the solar spectrum at our level is about 500 watts per square meter. To convert this to photons per m^2 per s, we need to know the average energy of a photon in this region. Consider a photon of yellow light, in the middle of the range. It has a wavelength of 550 nm. By the proposal of Planck, its energy E is hν, where h is Planck's constant (an interesting story), 6.62x10^{-34} Js (joule-seconds). Now, the frequency, ν, is related to the wavelength, λ, and the speed of light, c, as ν=c/ λ. We then have E = hc/ λ.

Plugging in the numerical values, we get E = 3.6 $\times10^{-19}$J. If we have 2000 μmol = 2×10^{-3} mol of these photons hitting a square meter, we have an energy flux density of

$$Q = (2\times10^{-3}\text{ mol m}^{-2}\text{ s}^{-1})(6.02\times10^{23}\text{ photons mol}^{-1})(3.6\times10^{-19}\text{J photon}^{-1})$$
$$= 438\text{ J s}^{-1}\text{ m}^{-2} = 438\text{ W m}^{-2}$$

This looks close

- So, how many photons are hitting our PD's active area per second? It appears to have an active area about 1.0 mm on a side, for an active area of 1 mm^2 or 1×10^{-6} m^2. The photon flux density is (2×10^{-3} mol m^{-2} s^{-1})(6.02×10^{23} photons mol^{-1}), or 1.20×10^{21} photons m^{-2} s^{-1}. On 1 square mm, 1.20×10^{15} photons are intercepted per s. Now, each electron flowing represents a fraction 1.6×10^{-19} coulomb. If the PD has 100% quantum efficiency, we'd expect a current of

$$I = (1.20\times10^{15}\text{ photons s}^{-1})(1.6\times10^{-19}\text{ C photon}^{-1})$$
$$= 1.92\times10^{-4}\text{ C s}^{-1}$$
$$= 192\ \mu\text{A}$$

We get near that, 130 μA, for a quantum efficiency of about 70%. This is reasonable.

4. Some indoor reading seemed exceptionally low, as if the photodiode is not responding linearly to light level. One thing I tested was that the output goes to zero, not to some negative bias, in zero light. To do this, I made a new circuit on the powered project board, using a double-ended power supply, +7.5V to -7.5V (not +-9V; the absolute ratings on the op amp are +-8V). In darkness, the reading did go to an exact zero.

It still seems odd that the photodiode can drive current at zero voltage. I looked for an equivalent circuit, finding nothing very enlightening.

The very low readings in moderately dim light still had me wondering about the linearity of the photocurrent with light interception (irradiance). I looked for specifications on the PH208A, but it's out of date (and my old Hamamatsu book is buried somewhere). However, various sites indicate linearity over wide ranges of irradiance. I also compared camera light-meter readings, low- vs. high-light, and they were in the same ratio as this photometer.