This note is for construction of the UVAMO Spinning Waveplate Polarimeter's (SWP) photodiode, as well as a guide to build one yourself. This is followed by a modification guide, as well as design considerations for those wanting to build their own photodiode circuit.

We will start with an introduction to how photodetection works using a photodiode, then we will discuss the circuit used in the UVAMO SWP.

1 Photodetection

The goal of this circuit is simply to measure the intensity of the input light. This is simple using a silicon PIN junction photodiode and a transimpedance amplifier.

1.1 Reverse Biased Photodiodes

Generally, diodes allow current to pass through them in only one direction with a constant voltage drop. This is usually accomplished by connecting a positively doped semiconductor with a negatively doped one. This allows current to flow one way, while blocking it from flowing the other way up to a breakdown voltage.

Certain specialized diodes known as *photodiodes* function in reverse bias as shown in figure 1. When a photon of sufficient energy[1] - and hence a sufficient frequency - strikes the surface of the diode, an electron is released through the photoelectric effect. The hole it leaves is replaced quickly by another electron being pushed by the bias voltage. As such, when a laser or sufficiently intense beam is incident on the photodiode, a current known as a *photocurrent* is generated in the direction of the reverse bias. This is the photodiode's working principle.

We use a 780nm laser, so let's try to find the output current if we strike the photodiode with 10mW. Assuming every photon of energy $E_p = \frac{hc}{\lambda} = 1.59eV$ is converted to an electron, we would get a current of

[1] This energy is defined by the PIN junction

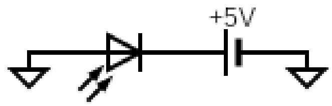

Figure 1: Reverse Biased Photodiode

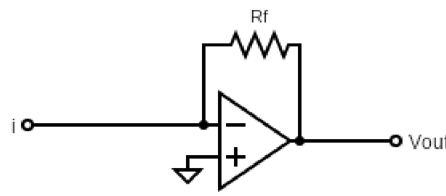

Figure 2: Transimpedance Amplifier

$$10mW \cdot \frac{eV}{1.602 \times 10^{-19}J} \cdot \frac{e^-}{1.59eV} \cdot \frac{1.602 \times 10^{19}C}{e^-} = 6.3mA$$

This current is then measured using a *transimpedance amplifier*.

1.2 Transimpedance Amplifier

We aren't able to measure current directly - instead, we measure voltage. A simple way to measure current is to measure the voltage on each side of a *shunt resistor*[2]. This would give a $\Delta V = iR$, which can be used to calculate the current i. The main issue with this method is the introduction of a new resistor in the circuit. It will affect the total circuit resistance and hence the current flow, so it will not give an accurate measurement.

Using an operational amplifier with a single shunt resistor R_f, we can measure a $V_{out} = -R_f \cdot i_{in}$ without introducing any meaningful resistance to the rest of the circuit. This design, shown in figure 2, is known as a *transimpedance amplifier*, and is used to accurately measure current flow.

[2]This is simply the name given to a resistor measuring current

2 SWP Photodiode Circuit

The circuit used in the UVAMO SWP contains an OPT101, a combined photodiode-transimpedance integrated circuit. It is attached to a 3d printed case with lips to avoid light entering through the cracks. It has seven gain stages determined by the input optical power. We chose to have stages for 500nW, 1μW, 10μW, 100μW, 500μW, 1mW and 5mW.

The OPT101 has an internal 1MΩ feedback resistor, with pins allowing for adding series impedance to the internal resistor, or disabling it and using external impedances. Three gain stages use the series option, while the other 4 use the disabling option. This is due to the feedback resistance being lower than 1MΩ. The gain stages are chosen with a 7 position rotary switch allowing for different feedback resistance values.

The PCB's power input, as well as the signal output, are in the form of 2-pin Molex header connectors. These pins allow for any desired connector to be easily soldered and used with the board. In our case, we have a made-in-house DIN-6 power box, while we connect the output signal to a BNC for measurement.

The circuit is made in KiCad 8.0.3, and is shown in figure 3.

The PCB uses standard resistor/capacitor pairs mounted on opposite sides of the board to pick gain stages. The rotary switch sends the feedback through different paths, giving different feedback values at each, hence switching the gain.

KiCad project files can be found on GitHub, along with a BOM for the DigiKey parts. These parts can be ordered by inputting the CSV file into DigiKey's 'upload a file' function. There is also a zipped file containing Gerber and Drill files which can be sent directly to PCBWay (still zipped) for production. A basic 2-Layer PCB will get 5 boards made for $ 5.00 plus shipping. Note that the board is 40mm x 50mm.

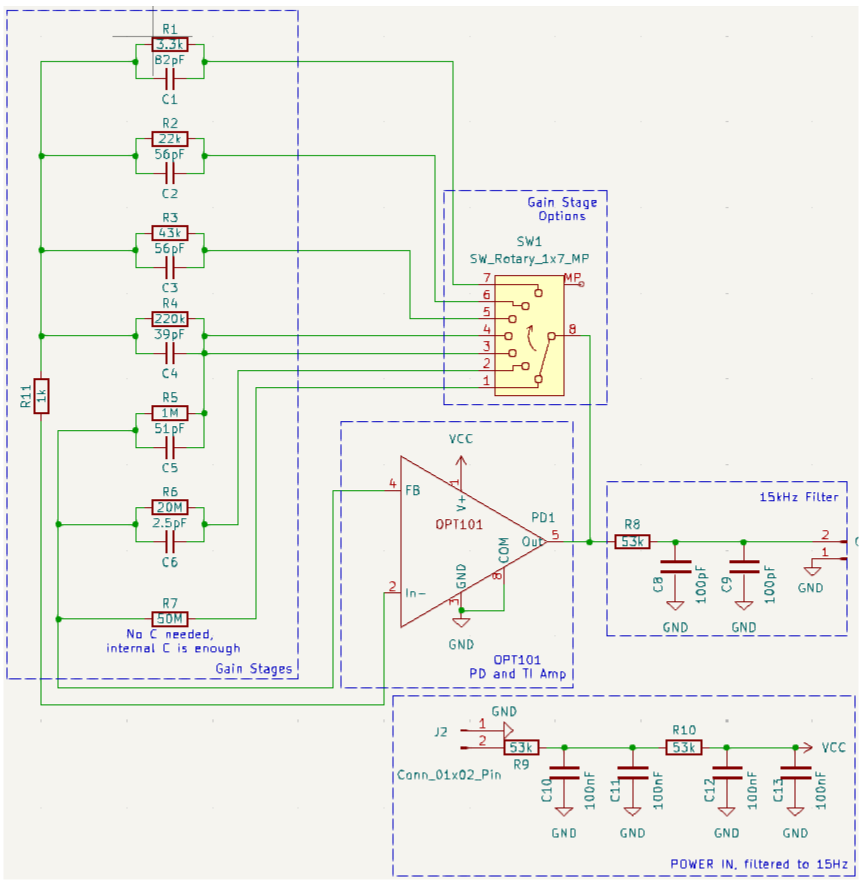

Figure 3: Caption

3 Making Changes

This section will talk about the possible changes one can make to the circuit to make it better fit their needs. An important resource that you should have ready is the OPT101 datasheet, found on `https://www.ti.com/product/OPT101`, or on the SWP GitHub with all other datasheets.

3.1 Exchanging Parts

The simplest change one can make is to replace resistors and capacitors on the gain stages. This allows for different input intensities that are not immediately available on the base circuit.

To determine the needed feedback resistance, one needs to calculate the gain needed for the input power to give 12V maximum. This is 80% of the max 15V supply. There is no one way to go about this, but it's a good exercise in unit conversion. Refer to the OPT101 datasheet for a photosensivity vs. wavelength graph, as this will determine the needed resistance.

We then need a feedback capacitor to stabilize the feedback loop, whose value is determined by the value of the feedback resistor. Refer again to the OPT101 datasheet for recommendations for capacitance values. The capacitor corresponding to each resistor is placed in the resistor's location on the reverse.

There are two ways to hook up feedback resistors and capacitors. Either they can be placed in series with the OPT101's internal 1MΩ feedback resistance by connecting pins 4 and 5, or the internal resistor can be bypassed by connecting pins 2 and 5. On the printed circuit board, R1-R4 are bypassing, and so those resistances are the exact gain values, while R5-R7 are wired in series, meaning the actual gain value has 1MΩ added.

The first major customization is to solder different feedback resistors and capacitors to your gain needs. Use 0603 (1608 metric) chip resistors and capacitors for this, as this is the pad size on the board. Soldering with a microscope using a temperature around 650 °F will make this trivial.

You may also want to filter the output differently. Simply use different values to achieve a different RC time constant. To calculate your cutoff frequency, recall that

$$f_{-3dB} = \frac{1}{2\pi RC}$$

3.2 Editing the Circuit

Using KiCad 8.0.3 or later, you can open the project file. **I would ask that you don't remove the open source logo, as this project and its derivatives are meant to be open source.**

3.2.1 Footprints

You may change footprints for individual parts in the schematic editor. Selecting a part and pressing 'E', you can edit the footprint field. Using the library button (books icon in footprint field), you can select different parts, or use your own. Remember to use the PCB editor to reroute tracks and ensure connections.

3.2.2 Photodiode

Using a different photodiode will require a lot more work. Recall that the OPT101 is a monolithic photodiode-transimpedance amplifier IC. You will have to provide smooth reverse bias and a separate transimpedance stage.

A good option for this purpose is the Thorlabs FDS100 photodiode. Any opamp will work for transimpedance amplification, but using one labeled for transimpedance amplification will ensure no issues. A good but relatively pricey option is the OPA847. Its 3.9GHz Gain-

Bandwidth product will ensure that it won't limit most photodiodes' bandwidth.

3.2.3 Make it your own

If you want something else from the photodetector, you can change the entire circuit, or even make a new printed circuit board. Keep in mind that changes may affect the performance of the SWP, and this needs to be taken into account before large changes are made.

For example, you could use the circuit as a blueprint for homemade photodetectors. When using a good photodiode-transimpedance stage, these can perform on or above the level of off-the-shelf photodetectors at a much cheaper price. Using parts specifically for your wavelengths can make them even better at the cost of robustness.

At this point, you are ready to take the photodetector and use it however you'd like!

4 Design Considerations

This section will explain the basic design principles followed when making this circuit, as well as to follow when making edits. There are a few specific goals we want to achieve with this photodetector:

1. Switchable Gain

   We want to be able to set different gain values to avoid railing our opamp. This is done, as explained above, using a rotary switch in the feedback path. By hooking the output of the opamp to the common pin of the switch, we can alternate between series and bypass feedback from the OPT101.

2. Easy Construction

   The hardest parts to solder on this board are the resistors and capacitors. 0603 sized chips were used as they are relatively easy to hand-solder while not taking up too much space. 0805 may also work, but will take up more space, and may require a larger board.

3. Low Noise

   We don't have to worry about RF circuit design, as we want to measure sine waves of frequencies up to 400 Hz. We also want to measure numerous points along this wave, and so we chose to filter the output to 15 kHz to avoid too much phase shift while still rejecting pointless signals. Higher frequency signals won't have even come from our photodiode as its response time is too slow. This means it is simply electronic noise, so we get rid of it.

   As well, we deal with electronic noise with smart design choices. Using thicker traces kept as short as possible diminishes possible parasitic effects. We also use a 2-sided ground plane regularly connected with vias to avoid inductance in ground traces. Power is filtered to 15Hz in a second order low pass filter. We need not worry about loading nor phase shift as it's meant to be a DC signal that is immediately put into an opamp.

4. Compatibility with Polarimeter

   This is almost entirely done in conjunction with the case. We need a board that will

   (a) Attach to the case

   (b) Have the photodiode's active area lined up with the input beam

   (c) Block outside light

   These are all done by setting up screws and positions based on the case. For example, the photodiode is centered in the board, and the case is made with grooves to let the board sit flush, blocking as much incoming light as possible.