1. Circuit analysis

The circuit used to readout the current coming from the photodiode (PD) is shown below. This circuit uses a differential transimpedance amplifier (TIA) configuration to achieve high gain/bandwidth whilst removing common mode noise.

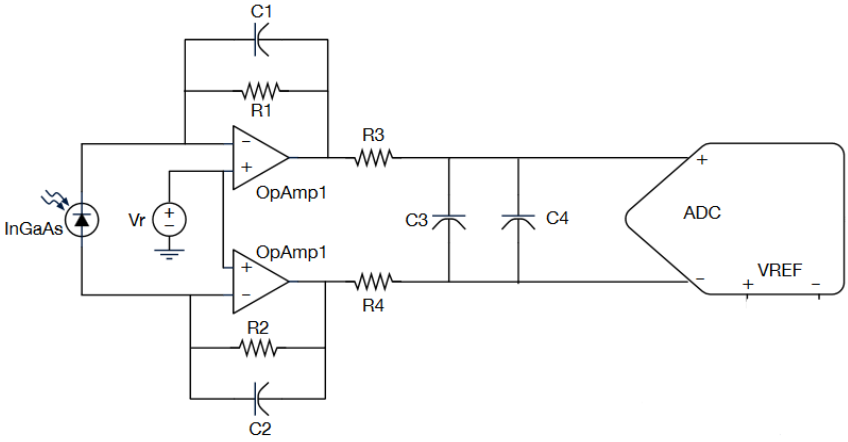

Figure 1 - Amplification and sampling circuit

Information regarding this circuit can be found:

- Here for an introduction to TIA part 1, 2, 3 and 4 available on the same blog
- Good/simple summary on TIA stability here
- More in depth analysis of TIA's from Texas Instrument (TI) here and here
- And information regarding the overall topology here

1.1 Circuit specifications

Circuit specifications are defined based on the needs of the Plastic Scanner system. More specifically, the system needs:

- Bandwidth: to achieve the desired readout speeds
- Resolution/dynamic range: both in achieving high dynamic range, linearity and in limiting noise if necessary
- Stability: self-explanatory
- To comply with other aspects: needs to run off the desired supply, fit a budget/manufacturability constraint, etc...

1.1.1 Bandwidth

It is proposed to define the bandwidth of the system based on the following criteria:

$$BW = \frac{\ln\left(\frac{1}{x}\right)}{2 \times \pi \times t_s}$$

Where x represents the percentage within which the signal needs to settle, t_s the target settling time and BW the bandwidth of the system in Hz. For example, if the desire is that the system settles within 10% of its final value, the resulting bandwidth should be $BW = \frac{0.35}{t_s}\ Hz$, which is traditionally used for digital signaling. A more stringent constraint should be placed on the system based on the desired accuracy.

1.1.2 Resolution & dynamic range

The following specification is based on the PD and the range of readout currents it will have within the system. Using the minimum and maximum current of the photodiode, we can define the dynamic range of the readout values (ratio between max and minimum values) as well as constraints on the system noise and linearity to achieve proper readout. Further information is given in section 2.1.

1.1.3 Stability

Stability is a concern in any feedback system and should be checked for this system. Refer to section 2.1 for more information.

1.1.4 Other aspects

Other less direct aspects that should be accounted for eventually concern compatibility with the system (single 5V supply, multiple supplies with regulators?), component availability and cost.

1.1 Photodiode

The photodiode and optical system provide two important pieces of information regarding the design of the complete system, namely the specifications on resolution and dynamic range (complete optical system) and the electrical model of the photodiode.

1.1.1 Complete optical system

Refer to Appendix A: Optical and photodiode considerations for the analysis. The result of the analysis shows that the current coming out of the photodiode will range from a few nA's to less than 100 uA. This gives a dynamic range of 100 dB that will be required from the ADC. In practice, this dynamic range will be smaller (80 or even 60 dB) to reduce the constraints on the ADC, but a more accurate ADC can be kept for prototyping.

1.1.2 Electrical characteristics

The photodiode is modelled as shown below, where a parallel capacitance and resistance are added to the circuit. The value of these two components can be found in most photodiode datasheets.

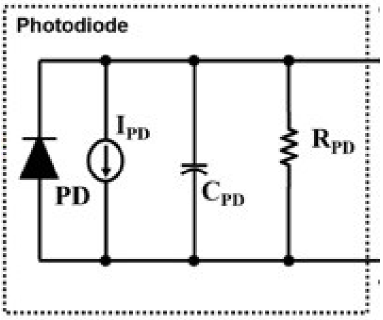

Figure 2 - Photodiode model

In the case of the diode currently used on DB2.1, these are the following specifications:

$$C_{PD} = 6\,pF\ max$$
$$R_{PD} = 40\,M\Omega\ min$$

2. Circuit design example

Using the analysis and specifications from the previous section, an example (based on the current Plastic Scanner circuit) is given below to explain how to choose components.

2.1 Specifications

Resolution and dynamic range: as can be seen from the calculations above, the resolution of the system is in the nA range, with a 100 dB dynamic range meaning a maximum current readout of 100 uA. This means that a 17-bit ADC would provide enough dynamic range to cover the smallest to largest value.

Bandwidth: because the system is running off an Arduino, there is no need for it to settle faster than within a ms. The worst case settling happens when the system goes from the minimum to the maximum readout value, and it needs to settle within half an LSB (min step of the ADC). This is equivalent to saying that it needs to settle within $0.5 * \frac{1}{128000}$ of the final value. Plugging this into the equation shown earlier:

$$BW = \frac{\ln\left(\frac{128'000}{0.5}\right)}{2 \cdot \pi \cdot 1ms} \sim 2\ kHz$$

Noise: noise specifications of the system are defined such that the overall input referred noise of the system stays below half and LSB. This would mean that the input referred current noise over the bandwidth of the passive output filter (see R3, R4 and C3, C4 on circuit schematic) should be lower than ~1nA.

The values taken here seem very conservative and not needed for the Plastic Scanner to run properly. They can be adapted in the future with a better understanding of the critical specifications of the system.

2.2 Differential TIA

The first stage of the circuit is the differential TIA. This consists in two parallel TIA's that differentially amplify the current coming from the PD.

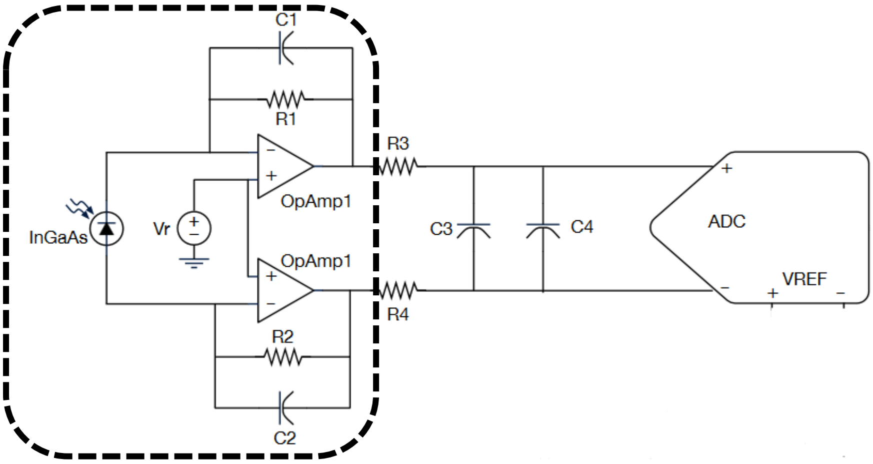

Figure 3 - Differential TIA section

This topology offers the advantage of removing common mode noise (i.e : noise coming from the reference voltage V_R).

DC behavior: the output voltage is equal to the formula below, which gives the gain of the system:

$$V_{OUT} = I_{PD} \cdot 2 \cdot R_{1/2}$$

AC behavior: Most of the explanation for the constraint on stability is provided in the reference documents linked to in section 1. The key takeaways here are:

- Condition for stability: $C_F \geq \frac{1}{4\cdot\pi\cdot R_F\cdot GBW} \cdot \left(1 + \sqrt{1 + 8 \cdot \pi \cdot R_F \cdot C_S \cdot GBW}\right)$, where C_F is the feedback capacitance C1 or C2, R_F the feedback resistance and C_S the lump capacitance at the non-inverting input of the amplifier
    - If C_F is equal to the value of the right side, the system will reach its highest bandwidth. For values lower, the system will tend towards instability. For values higher, it will become slower and its stability (phase margin) will increase
- Max achievable bandwidth of the system: $f_{-3dB} = \sqrt{\frac{GBW}{2\cdot\pi\cdot R_{F(C_S)}}}$
- Feedback filter bandwidth: $f_{BW} = \frac{1}{2\pi R_F C_F}$, valid for values much lower than the max achievable bandwidth

In conclusion, the actual bandwidth of the system will be dominated by f_{BW} as long as it is much lower than the max achievable frequency of the system and the condition for stability is satisfied.

Noise analysis: again, the reference documents provide a detailed noise analysis that can help size the system. The total noise of the system is referred to its input as:

$$i_{EQ} = \sqrt{i_B^2 + \frac{4kT}{R_F} + \left(\frac{e_N}{R_F}\right)^2 + \frac{(e_N 2\pi F C_S)^2}{3}}$$

Where i_B and e_N are values provided in the datasheets of the amplifiers and F is the bandwidth of the passive output filter of the system (see R3/4 and C3/4). As long as this noise stays lower than the photodiode noise/ADC quantization noise, it does not have to be addressed.

2.3 Passive filter (low pass)

The passive filter is comprised of R3/4 and C3/4 and provides more aggressive filtering after the amplification. This filtering allows reducing the noise over the signal and should be sized to allow sufficient settling margin at the input of the ADC. The cutoff frequency of the filter is:

$$f_{cutoff} = \frac{1}{2\pi(RC)}$$

Where R = R3 + R4 and C = C3 + C4.

2.4 ADC

ADC should be chosen to comply with dynamic range and speed specifications. In this case, a 17-bit ADC would be able to read voltages from 5V all the way down to $38\ \mu V$.

2.5 Final values

Final values are calculated with the photodiode 0090-3111-185 and OPA2376 used on DB2.1.

a. Gain

The system runs from 5V supplies with a reference voltage at midpoint (2.5V). Therefore, it is desirable to set the gain of the system to reach full scale at maximum photodiode current. With the estimations done in section 2.1, this gives:

$$Gain = \frac{5V}{100\ uA} = 50'000$$

In practice however, 100 uA is too conservative and a factor of 10 is added here to match the Plastic Scanner. **This results in R1 = R2 = 250kOhm. Use low tolerance resistors for these two as any mismatch will result in non-linearity.**

b. Bandwidth & stability

The bandwidth of the system is set by the parasitic and feedback impedance of the system as well as by the GBWP of the opamp. Using datasheet values, this gives:

$$C_S = 6 + 6.5 + 13\ pF = 25.5\ pF$$

Without accounting for any PCB parasitic capacitance. The GBWP of the OPA2376 is 5.5 MHz, which gives:

$$C_F \geq \frac{1}{4 \cdot \pi \cdot R_F \cdot GBW} \cdot \left(1 + \sqrt{1 + 8 \cdot \pi \cdot R_F \cdot C_S \cdot GBW}\right)$$

$$C_F \geq 2\ pF$$

The final bandwidth of the system is:

$$f_{BW} \sim 13\ kHz$$

Which is larger than what is needed (2 kHz). Additionally, a passive filter is added after the TIA/before the ADC to filter out noise, with bandwidth:

$$f_{cutoff} = 5.6\ kHz$$

Which is also large enough for the system settling time.

c. Noise

Using the formula in 2.2, the input referred noise can be calculated as:

$$I_{EQ} = 0.25\ pA/\sqrt{Hz}$$

At a bandwidth of 5.6 kHz, this results in a noise around 1.5 nA, which is at/below the noise floor of the photodiode.

d. Other aspects

When choosing an opamp, other aspects that might be critical:

- Input bias current: ideally an opamp has no current flowing through its input, but in reality, it always has small leakage currents. This current will create an offset at the output of the TIA which could render it useless (i.e: if the leakage current is 1 uA, this would result in a half volt voltage at the output). This current should be kept much smaller than the photodiode current
  - In the OPA2376, this leakage current is max 10 pA
  - In most CMOS/FET amplifiers this is not an issue, but bipolar technologies have significantly higher input bias current
- Input offset voltage: this voltage difference appears at the terminals of the opamps due to mismatch in the fabrication of the devices. This offset will appear at the output of the system with a gain of $\left(1+\frac{R_F}{R_D}\right) \sim 1$. This effect introduces small dynamic range reductions as well as gain non-linearity
  - The OPA2376 has a very small offset voltage of max 25 uV. Compared to the dynamic range of the system, it can be neglected safely

3. Other comments

All diodes are similar one with another, but there are some variations:

- The 855nm diode has the profile looking more like a Lambertian source, whereas others have very narrow emission angles (see figures below). This is because the 855nm diode has no lens on top of it. Not sure how the choice was made or if it impacts the system, but if there are any noticeable issues with this diode it could be caused by it (i.e: viewing angle can behave differently vs geometry variations)

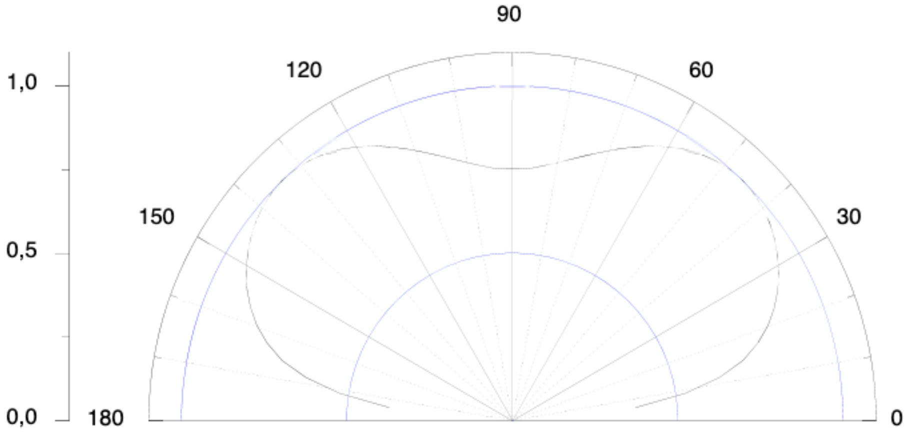

Figure 4 - 855nm diode view angle

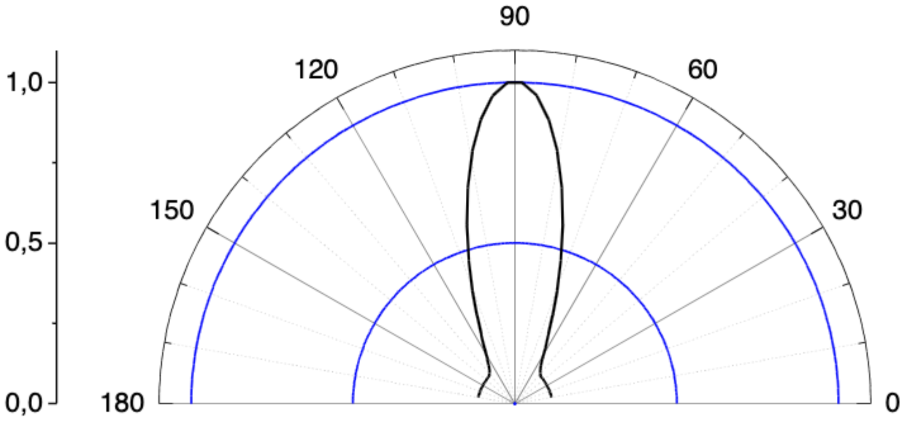

Figure 5 - 940nm view angle

- Diode power (flux & intensity): diodes have power outputs that vary from mW to tens of mW's, as well as varying radient intensity due to their different viewing angles as shown above. For example, the 855 nm diode has a power of 27 mW but a radient intensity of 5.5 mW/sr, whereas the 940nm has 27 mW of power (min) for 18 mW/sr radient intensity (min). Other examples are the 1050nm and the 1200nm diodes which have 11 mW and 3 mW of total power respectively with similar viewing angles. Assuming the system is very linear (behaves similarly independent of light intensity) and covers the fully dynamic range, this can be mitigated through calibration

Appendix

Appendix A: Optical and photodiode considerations

In order to get an idea of the current ranges at the input of the TIA's, some rough calculations are done to estimate incoming light and out current of the photodiode. This is a good starting point which can be tuned after further measurements.

a. Dark current + ambient light noise

According to the TI document (DLPA072), dark current in photodiodes ranging from 900nm to 1700nm, uncooled, can be around 1 to 5 nA. We can use this value as reference dark current for the photodiode we are using (no info on datasheet).

According to document AN521 (Silicon Labs – irLED selection document), ambient light noise in IR can vary between less than 1 up to 50 uW/cm2. Here is an estimate of the resulting power arriving on the sensor (diameter of its active area is 0.3mm, responsivity around 1):

Ambient light irradiance [uW/cm2]	Power @ sensor [nW]	Resulting current [nA]
1	3	3
10	30	30
50	150	150

Because the system is ideally enclosed, it makes more sense to take the lower values as reference. This current, in addition to the dark current would result in an output current in the few nA range to tens of nA.

b. IR diode signal

Because a lot of information on the geometry of the device is unknown/hard to model, this section is simplified to obtain an idea of the maximum signal power than can arrive onto the photodiode coming from the LED, to know the maximum current we want to measure at the photodiode terminals. Figure below shows expected path on the left and geometry used for calculations (right).

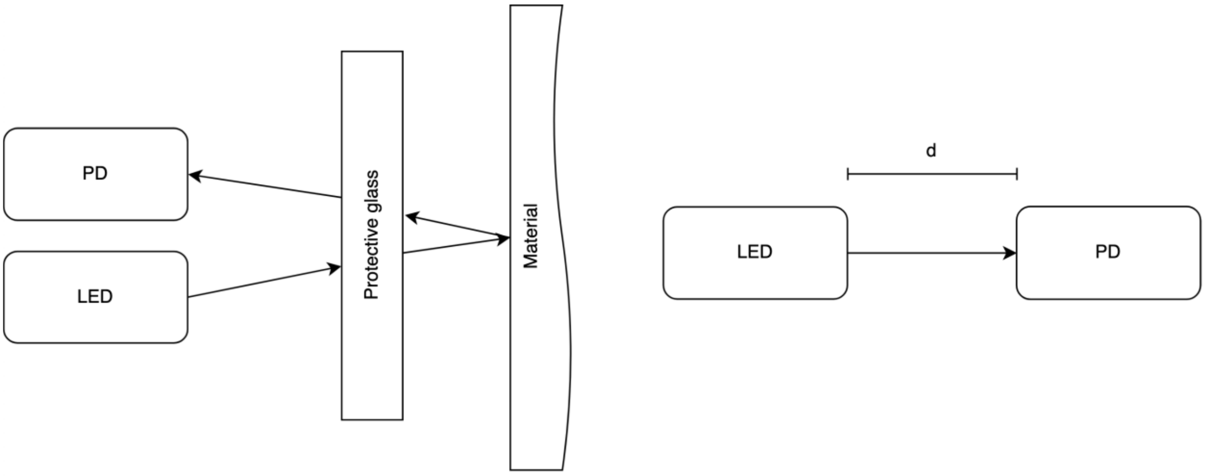

Figure 6 – Full path for IR light (left) and simplified model (right)

In practice of course, the actual power coming in will probably be a small fraction of this number, so the calculations here give a very conservative idea of the actual powered measure on the PD, that can be used as a maximum upper limit.

In order to calculate the incoming power, two variations are accounted for:

- Diode radient intensity: 5 mW/sr (855 nm) and 30 mW/sr (other diodes)
- Separation distance d of 1, 5 and 10cm between diode and photodiode

Radient intensity [mW/sr]	Distance [cm]	Power in [uW]	Current [uA]
5	1	14.1	14.1
5	5	0.6	0.6
5	10	0.1	0.1
30	1	84.8	84.8
30	5	3.4	3.4
30	10	0.8	0.8

As can be seen from the table, the current coming from the photodiode will in the worst case be lower than 100 uA for this specific scenario (and in practice probably much lower). This gives us a first estimation on the dynamic range of the photodiode, which is in the order of 100 dB (ratio of 100’000 between min and max values) at 1cm distance, but could very well drop to 60 dB or less for larger distances (or more accurate estimations).