S2014, BME 101L: Applied Circuits Lab 7: Optical Pulse Monitor

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1 Design Goal

For this lab we'll be designing and building an optical pulse monitor to detect pulse by shining light through a finger and seeing the change in the opacity of the finger as the amount of blood in the blood vessels changes.

The first half of the lab consists of determining characteristics for photodiodes and phototransistors and building a transimpedance amplifier to convert their current outputs to voltage signals for the levels of light that pass through fingers.

The second half of the lab adds a second stage amplifier and filter to make the signal have an appropriate voltage range to observe the pulse using the KL25Z boards and PteroDAQ software.

2 Background

2.1 Semiconductor diode

A *diode* is a two-terminal device that allows current to flow in one direction (the *forward* direction), but not in the other (the *reverse* direction). Figure 1 shows the schematic symbol used for diodes, as well as the symbols for optoelectronic parts based on diodes.

A *semiconductor diode* is a semiconductor with two differently doped regions: one n-doped (with free electrons) and one p-doped (with holes as charge carriers). The junction between the two types of semiconductor is where everything interesting happens.

When the n-doped semiconductor is connected to a higher voltage than the p-doped semiconductor, then the majority charge carriers on each side are pulled away from the junction, and a non-conducting *depletion layer* is formed. This is *reverse biasing* in which no current flows. When there is no applied voltage from the outside, there is still a small depletion layer formed.

When the n-doped semiconductor is connected to a lower voltage than the p-doped silicon, then the majority carriers in each type of semiconductor are pushed towards the junction and cross over, allowing current to flow (*forward biasing*). The voltage has to get large enough to eliminate the normal depletion layer before conduction starts—this minimum forward voltage is often called the *diode voltage* or *threshold voltage*.

2.2 Photodiode

A *photodiode* is a semiconductor diode whose junction is exposed to light. [3] The one in your parts kit is PD204-6C, which comes in a 3mm clear package.

To use it as a photodiode, the diode is *reverse-biased*—that is, the positive voltage is connected to the n-doped semiconductor, and the negative voltage to the p-doped semiconductor. This biasing attracts the majority charge carriers away from the junction between the two types of semiconductor, creating a *depletion* region that does not conduct.

However, when a photon is absorbed in the semiconductor in or near the depletion layer, it can knock an electron loose, resulting in a pair of charges (a hole and an electron), that can move under the influence

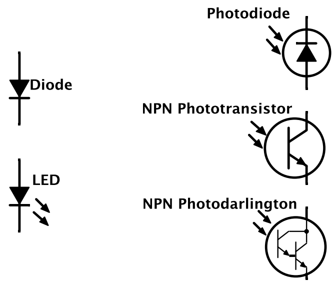


Figure 1: The symbols for diodes, light-emitting diodes (LEDs), and photodiodes are essentially all the same, with the addition of arrows to indicate light coming out of LEDs and going into photodiodes. LEDs sometimes have circles around them, and photodiodes sometimes do not—the arrows are the essential difference, not the circles. Sometimes the arrows are drawn with wavy lines instead of straight ones.

The arrows in the diode and transistor symbols indicate the direction of conventional current flow (forward biasing). The positive end (the *anode*) points to the negative end (the *cathode*)—the -ode names can be kept straight is you remember that the cathode rays of cathode-ray tubes are electron beams. The photodiode is normally used reverse biased, which is why I've drawn it with the opposite orientation from all the other symbols.

We do not have a photodarlington in our parts kit—they are basically a phototransistor with an extra transistor for more current gain. The provide larger currents than phototransistors (32mA seems to be a common number) and are even slower and less linear.

of the electric field to the conducting regions. This movement of charges creates a current which is proportional to the number of photons absorbed (as long as the hole and electron do not recombine).

There is a very small current due to thermal effects even with no photons knocking loose electrons (referred to as the *dark current*). To avoid noise problems, the dark current should be much smaller than the smallest current you plan to measure.

Photodiodes tend to be used in one of two ways:

photoconductive mode A fixed reverse-bias voltage is used and the photocurrent is measured. The larger the reverse-bias voltage, the thicker the depletion region, and the lower the capacitance of the photodiode. The reduced capacitance makes the photodiode faster at responding to changes in light level (which is particularly important if light is being used to transmit information—the speed of information transfer may be limited by the response speed of the photodiode).

Increasing the reverse-bias voltage also increases the dark current, without changing the photocurrent much, reducing somewhat the dynamic range of the sensor.

photovoltaic mode If we don't allow much current to flow, then the photocurrent charges up the capacitance until the voltage is high enough that the diode starts to conduct in the forward direction. This voltage is almost independent of the amount of light, but the amount of current we can take from the photodiode at that voltage is linear with the amount of light. (This is how a solar cell works—a solar cell is just a very large photodiode used in photovoltaic mode.)

For this lab, we'll use a photodiode in photoconductive mode, fixing the reverse-bias voltage and measuring the current.

2.3 Phototransistor

A phototransistor is a two-terminal device whose current is proportional to the illuminance of the transistor. It can be thought of as a photodiode combined with an amplifying bipolar transistor. The two terminals are the collector and the emitter (in the schematic symbols in Figure 1, the emitter is the terminal with arrow, and the collector is the other terminal).

For an NPN phototransistor, the collector and emitter are n-doped semiconductor, and the base is a thin layer of p-doped semiconductor between the conductor and emitter. The base in a regular bipolar transistor controls the flow of current between the collector and emitter. If the base-emitter junction is reverse-biased, then the transistor is turned off, and no current flows. If the base-emitter junction is forward-biased, then current flows from the collector to the emitter proportional to the base-emitter current (the current gain of a bipolar transistor is usually quite large—more than 100).

In a phototransistor, the base is not wired to anything—a configuration known as a *floating base*. The floating base normally results in the base having a voltage intermediate between the collector and the emitter, so that the base-collector junction is reverse biased and the base-emitter junction is forward biased.

The base-emitter current that controls the transistor comes from the photocurrent generated at the reverse-biased base-collector junction.

The phototransistor we have in our kits (WP3DP3BT, in a 3mm blue-tinted package) is an NPN silicon transistor [2], which means that the emitter and collector are n-doped silicon and the base is p-doped silicon. In order to have the forward and reverse biases of the floating base correct, we need to have the base be more positive than the emitter (forward bias) and less positive than the collector (reverse bias). That means that we want the collector wire to be connected to a more positive voltage than the emitter wire. It is probably a good idea to have at least $V_{CE(SAT)}$, the saturation voltage for the phototransistor (available from the data sheet), difference between the collector and emitter voltages.

The data sheet also gives the dark current (which is very small) and the on current (for bright light).

Because of the current gain of the bipolar transistor, the current through a phototransistor is much larger than through a photodiode, often about 1000 times larger. However, the high gain comes at a price—the RC time constant of base-collector junction is also multiplied by the gain (the "Miller Effect"), so phototransistors are about 1000 times slower also.

A phototransistor has a narrower dynamic range than a photodiode. The phototransistor has a fairly linear response over about 3 decades, while a photodiode is fairly linear over 7 or more decades. (That is, there is a range of about 1000:1 in irradiance over which the phototransistor can be well modeled as current proportional to irradiance, but there is about a 10000000:1 range for a photodiode.) The increased linearity makes photodiodes more popular for measuring instruments, even though the photocurrents are so much smaller.

Both photodiodes and phototransistors provide a current output that is proportional to the light power input, so their sensitivity can be expressed in A/W. If a photodetector collects all the light from a circle 3mm in diameter (7.07mm^2) , then a light intensity of 1mW/cm^2 corresponds to a power input of about 71μW.

A phototransistor may have a sensitivity of 2.8 A/W, while a photodiode might have only 50 mA/W.

2.4 Transimpedance amplifier

A *transimpedance amplifier* takes a current input and provides a voltage output. The gain (output/input) is expressed in ohms, hence the "trans*impedance*" name. Figure 2 shows a typical transimpedance amplifier

Since there is no current flowing through the input of an op amp, any current I that flows downward through the photodiode D1 in Figure 2 must flow through the resistor R1. Remember that an op amp

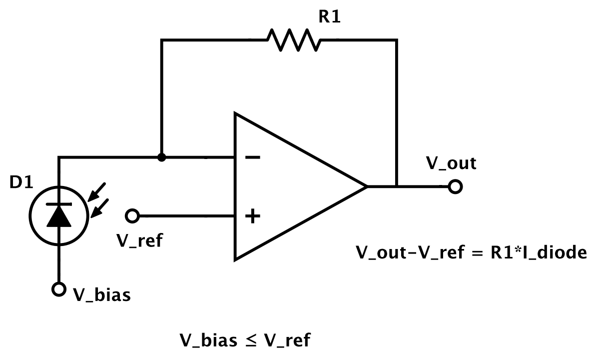


Figure 2: A transimpedance amplifier with a photodiode as the current source. The feedback loop holds the two inputs of the op amp U1 at the same voltage V_{ref}, and the bias on the photodiode D1 is $V_{bias} - V_{ref}$.

in a negative feedback loop essentially holds the negative input at the same voltage as the positive input, which means that the voltage across R1 is $V_{out} - V_{ref}$. Ohm's Law gives us

$$V_{out} = IR_1 + V_{ref} \ .$$

That is, the gain of the amplifier is just the impedance of the feedback element, and output with zero input current is V_{ref}.

There is nothing in the design of the transimpedance amplifier that requires that the feedback element be a resistor—any impedance can be used to get a gain that varies with frequency. If there is a DC component to the current, though, we usually want a finite impedance at 0Hz (so not a capacitor alone or in series with other impedances as a feedback element).

Note that a transimpedance amplifier differs from just using a pull-up resistor to convert current to voltage, because the transimpedance amplifier ensures that the voltage across the photodiode, $V_{ref} - V_{bias}$, remains constant, independent of the current. This property is used for measuring the properties of ion channels in electrophysiology, where the photodiode is replaced by a pair of electrodes—one inside and one outside the cell. By changing V_{ref} we can change the voltage across the pair of electrodes, while measuring the resulting current changes.

High-gain transimpedance amplifiers (sometimes called *patch-clamp amplifiers* for their early applications in electrophysiology) are essential to the nanopore and nanopipette work at UCSC. In those projects, the currents involved are very small (10–100pA) and the interesting changes are also small (as low as 0.5pA), and so the amplifiers need to be designed for very low noise. This course will not get into the esoteric field of low-noise design, as the currents we will deal with are 1000s of times larger (though still pretty small).

2.5 Light-emitting diodes (LEDs)

Light-emitting diodes are semiconducting diodes that emit light when there is sufficient forward current through them. Note that LEDs often have a fairly large diode voltage compared to other diodes, and you need to exceed the diode voltage before you get enough current to turn on the LED.

Light is emitted when a free electron from the n-doped side combines with a hole from the p-doped side. The drop in the energy for the electron is released as a photon. Because the electrons vary in energy, the photons are not all the same wavelength, so LED light is not spectrally pure, but the variation is generally not very large, at least when compared to thermally produced light, like blackbody radiation and incandescent light bulbs.

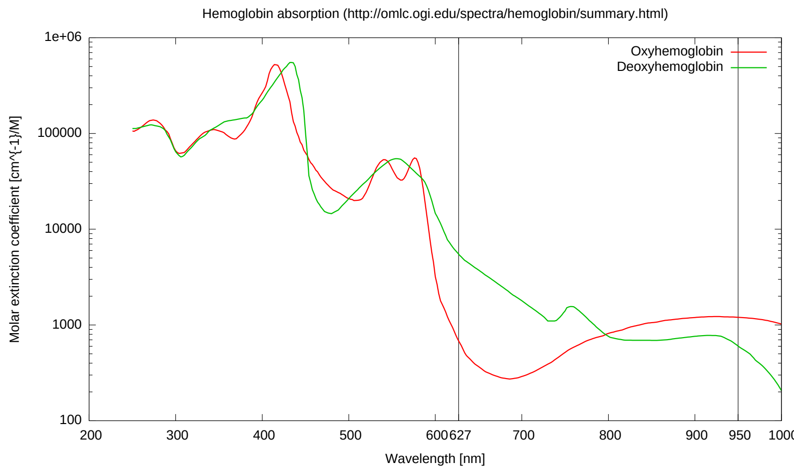


Figure 3: Oxyhemoglobin is most transparent around 686nm (272.8 cm^{-1}/M), but is still reasonably transparent at 627 ± 22.5nm (370–2130 cm^{-1}/M). At 950 ± 27.5nm, it absorbs more (1136–1225). Deoxyhemoglobin is not very important here, since hemoglobin saturation is usually well over 95% in healthy individuals. (If we were making a pulse oximeter, to measure the ratio of oxy- and deoxy-hemoglobin, then we'd need to use two wavelengths, choosing ones at which the molar extinction ratios were quite different.) Data for figure from `http://omlc.ogi.edu/spectra/hemoglobin/summary.html`

For a no-math view of how LEDs (and semiconductor diodes in general) work, try the website `http://electronics.howstuffworks.com/led.htm`

We have two LEDs in our parts kits: the SFH 4512, which is in a 5mm blue package with peak emission at 950nm (well matched to silicon photodetectors) and the WP710A10ID which comes in a 3mm red package and has a peak output at 627nm.

Note that visible-wavelength LEDs often report two wavelengths: the physical peak and a "dominant" wavelength, which takes into account the varying sensitivity of the human eye. The dominant wavelength is closer to the peak of human sensitivity, around 555nm [5]. When you are trying to look at the LEDs with photodetectors, rather than human eyes, the adjustments for human eye sensitivity are just a nuisance.

2.6 Optical properties of blood

Our photodiode and phototransistor has maximum sensitivity in the infrared (around a wavelength of 940nm), which is typical for silicon photodiodes and phototransistors. But we're planning to use a 627nm LED, where silicon photodetectors are only about 70% as sensitive as at their peak. [4]

We want to monitor the amount of blood in the finger based on how much light is absorbed, so we need to look at the light absorption of hemoglobin. For this to work, a lot of the light needs to make it through the finger, so we need a wavelength at which flesh is not too opaque. As a good first approximation, we could look at the absorption spectrum of hemoglobin, the main coloring agent of blood—see Figure 3.

Because we don't want enormously bright lights, we'll want a wavelength at which there is only moderate absorption. The red LED seems to have an advantage over the IR LED, though not a huge one. A different LED with a peak around 700nm (like the WP3A8HD) would probably be even better. Note: the blocks I drilled to mount the LED and photodetector will only take 3mm components, not 5mm ones, so we won't be able to use the IR emitters this year.

3 Pre-lab assignment

3.1 Data sheets

Look up the data sheets for the photodiode, phototransistor, and LEDs in your parts kit.

photodiode Find the dark current and photocurrent for the photodiode. What irradiance (in W/cm^2) at what wavelength is the photocurrent measured at? With what reverse bias voltage? If we reduce the bias voltage to 0v (short-circuiting the photodiode), what is the photocurrent?

What is the sensitivity in A/W if the photodiode collects all the light from a 3mm diameter circle? Use the 70% scaling factor from peak sensitivity to sensitivity around 627nm.

phototransistor Find the dark current and on current for the phototransistor. What is the sensitivity in A/W if the phototransistor collects all the light from a 3mm diameter circle? Compare with the photodiode.

LEDs Look up the specs for the LEDs. Figure out the current you want to operate them at (not over the maximum!), what the forward voltage would be at that current, and what series resistor you would need to power the LED with that current from a 3.3v supply.

Note that the IR emitter data sheet gives the total radiant flux (in mW) at max current, but the red LED data sheet does not.

What they give is luminous intensity in millicandelas, much more awkward number to work with. That unit suffers both from being adjusted by the human eye response and by being a brightness in a particular direction—to get the total light output one would have to know how the intensity varies with direction and integrate over all possible directions. They give us a spatial distribution that shows the intensity of the beam dropping to 90% at 10° and 50% at 20°. I used the formula for the solid angle of a cone with apex angle 2θ:

$$\Omega = 2\pi(1 - \cos\theta)\text{sr}$$

to estimate the luminous flux from the luminous intensity for that beam shape. I got that it was about 0.3 lumens/candela, which is in pretty good agreement with the calculator at `http://led.linear1.org/lumen.wiz`, which estimates that a beam angle of 40° would have 0.379 lumens/candela.

At 627nm, the CIE luminosity function is about 0.336 [1], which means that there are about 683*0.336 lumens/watt. Combining this conversion factor with the beam shape conversion factor, we get a conversion from light intensity to total radiant flux of 1.3–1.65mW/candela.

Use this conversion factor to compute the total radiant flux of your red LED at the current you plan to drive it with.

3.2 Determining gain needed

Now that you know how much light to expect out of the red LED, try to figure out how much of that will be available at the photodetector. We have two major losses to think about: absorption by hemoglobin and scattering.

If we pretend that a finger is just a sack of blood, and that the only light absorption is from hemoglobin, we can estimate the absorbance of a finger from the molarity of the hemoglobin, the molar extinction coefficient, and the path length of the light (the thickness of your finger). According to `http://www.globalrph.com/labs_h.htm#Hemoglobin_`, typical concentrations for hemoglobin in blood are 120–172g/L.

To make a rough estimate, use 150g/L and a molar extinction coefficient of around $700\text{cm}^{-1}/M$. The molecular weight of hemoglobin is about 64,500 g/mol.

Remember from chemistry that the absorbance is $-\log_{10}\frac{I_{out}}{I_{in}}$, where I_{out} is intensity of the light out, and I_{in} is the intensity of the light in. Compute how much light is left if all the output of the LED goes into your finger but the hemoglobin absorbs some of it.

The above calculation of transmitted light is not complete by itself, as it is based on the assumption that the light is either transmitted or absorbed. But if you shine a red light through your finger, you'll see that the finger glows almost equally in all directions—scattering may be as important as absorption! Assume that your "ball of blood" model of your finger is a perfect sphere, with the light that isn't absorbed radiating equally in all directions. If you are looking at just a 3mm diameter detector pressed up against the finger, how much of the total light makes it to the sensor?

Now, using the sensitivity of your photodetectors (in A/W) and the power of the light arriving at the photodetector, estimate the photocurrent of your detector. Because the calculations of the expected photocurrent are very crude estimates, the actual currents may be a factor of 10 off in either direction, but this should give you a place to start your amplifier design.

3.3 Amplifier design

Design a transimpedance amplifier that will amplify the expected photocurrent to about 1v–2v.

We'll be powering this amplifier from the KL25Z board's 3.3v supply, not from a symmetric power supply as we did for the audio amplifier. Because op amps do not work well when their outputs are very close to the power rails, and the output will be at V_{ref} when the input current is 0μA, we'll want to make V_{ref} be at least 0.1v away from the power rails. Note: because the output is V_{ref} when the input is 0, V_{ref} is often referred to as a *virtual ground*.

You also need to choose V_{bias} for your photodiode or phototransistor. Remember that a photodiode must be reverse-biased and a phototransistor should have at least $V_{CE(SAT)}$ voltage difference between the collector and emitter—what constraints does that put on V_{bias} and V_{ref}? Are there nodes in your circuit that can be used for V_{bias} or do you need to create another voltage source?

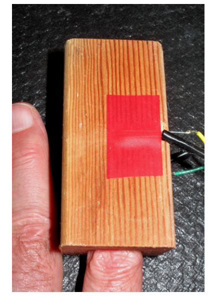
Section 4.2 of the MCP6004 data sheet explains that "rail-to-rail" outputs really only means that the output can get to about 25mV away from the power rails (non-rail-to-rail op amps may have to stay 0.7v away from the power rails). The data sheet's Figure 2-14 "Output Voltage Headroom vs. Output Current Magnitude" shows how far the output has to be from the power rails for different current outputs.

But there is no point to making the virtual ground V_{ref} be in the middle of the power-supply range, since the photocurrent only flows in one direction, so V_{out} will always be on one side of V_{ref}. Which way does the photocurrent flow? Will we have $V_{out} \geq V_{ref}$ or $V_{out} \leq V_{ref}$?

To make the V_{ref} voltage source, you can either use a voltage divider (if you take no current from the source) or a voltage divider followed by a unity-gain buffer. The unity-gain buffer is not an ideal voltage source, as it cannot supply infinite current, but it can supply quite a bit of current without the voltage changing much, unlike the simple voltage divider—Figure 2-13 of the MCP6004 data sheet shows the current limit as a function of the supply voltage.

(a) End view of the block showing the finger hole and holes for LED and photodetector.

(b) Top view of the block showing the hole for the LED and channels for taking the wires out the side of the block.



(c) How the block is used with finger inside, LED on the top, and photodetector on the bottom.

Figure 4: Alignment block for LED and photodetector. The photodetector goes on the bottom, to avoid stray light through the back of the package.

4 Procedures: part 1

4.1 Try it and see: LEDs

Hook up your red LED and series resistor, power it from your 3.3v supply, and measure the voltage and/or current. Does the LED light up? does it have the current you computed?

Do the same for the IR LED (which may have a different diode voltage or different current, and hence a different series resistor needed). Suggestion for looking at the IR LED: use a digital camera. The blue light sensor of most cameras is also sensitive to infrared.

4.2 Try it and see: photodiode and phototransistor

Measure the current through the phototransistor with about 1V across it in the ambient light of the lab. What happens to the current as you shadow the phototransistor? What are the highest and lowest currents you get in the lab? How do these compare to the specs for dark current and very bright light?

Do the same for the photodiode. Note that the currents through the photodiode are expected to be quite small—how do you measure small currents most easily?

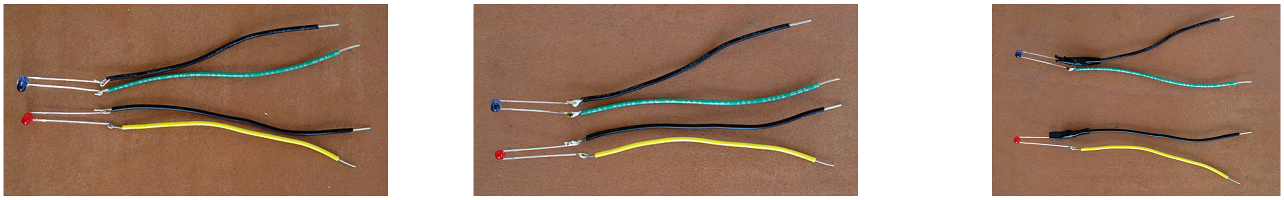
4.3 Assembling the finger sensor

I've drilled some blocks of wood with 3/4" holes for your finger and 3mm (actually 1/8") holes for an LED and a phototransistor or photodiode. Figure 4 shows the block and how it is used.

Insert the LED into the top hole of the block and carefully bend the leads to one side into the channel, so that they are flush with or lower than the surface of the block. Do the same for the photodetector on the opposite side.

Because the block would interfere with plugging the LED and photodetector into a breadboard, you will need to solder wires onto the leads of the components to lengthen the leads. Figure 5 shows how to extend the leads.

Assemble the optoelectronics and the block, and use a little electrical tape to hold the components in place. With the assembled block, power the LED through its series resistor and measure the photocurrents without your finger in place and with a finger in the block covering the hole for the phototransistor.



(a) Mechanically join the wire and the lead by bending the ends of the wires into little hooks with the long-nose pliers, linking them together, and crimping the hooks closed.

(b) Solder the joints. It helps to put the lead and the wire both into jaws of a "helping hand" so that they are held motionless while you apply the solder and the soldering iron.

(c) Wrapping a little electrical tape around one of the leads and solder joints helps keep the leads from shorting together.

Figure 5: The leads on the optoelectronic devices need to be lengthened to make connection to the breadboard easier. Use a color code for the wires so that you can tell which lead is which. I chose to use black for whichever of the wires of the device had to be connected to the lower voltage.

Is the photocurrent close to what you computed in the pre-lab? If not, you may want to adjust the transimpedance amplifier design, so that it will have the gain you need for the observed photocurrent.

Wire the phototransistor up to your transimpedance amplifier, whose output is connected to an analog pin on the KL25Z board, for recording with PteroDAQ. Without your finger in place, the transimpedance amplifier should saturate at the highest value, as the current is hundreds of times larger than with a finger in place. When you put a finger in, the current should drop way down and the amplifier should produce a voltage around 1–3v. If the voltage stays at 3.3v, then your transimpedance gain is probably too high. If it drops below 1v, then your transimpedance gain may be too low.

When you get the gain set right, you should be able to see a small fluctuation in your signal that corresponds to your pulse. The fluctuation will be too small to see easily with the PteroDAQ live trace, so you should look at it with an AC-coupled oscilloscope as well.

You'll may also see a lot of 60Hz noise picked up by capacitive coupling and a large slow drift in the DC portion of the current. The second design project for this lab is to add filtering and more amplification, so that the 60Hz noise and the DC drift are removed, while the signal for your pulse is amplified to be large enough to be easily visible.

5 Pre-Lab for second part

The simple one-stage transimpedance amplifier does not produce a large enough signal to see a pulse clearly. But if we just increase the gain, we run into the problem that the DC part of the input signal saturates the amplifier and we can't see any fluctuation at all. We can also run into problems with 60Hz noise interfering with the signal we want to see.

We can solve the 60Hz problem by taking advantage of what you learned about aliasing: if we sample with a period that is a multiple of 1/60 second, then we'll be in the same place on the 60Hz waveform on each sample and the 60Hz noise will not be visible in the output. Picking 60Hz, 30Hz, or 20Hz as our sampling frequency will give us enough resolution to see the pulse waveform, without much problem from the 60Hz noise.

We can solve the DC-shift (and reduce the 60Hz noise problem) by *filtering*—changing our amplifier design so that the gain varies with frequency. What frequencies are we interested in keeping? A person's pulse is normally in the range 40 beats/minute to 200 beats/minute, depending on their genetics, age, physical condition, whether they are exercising, and so forth. This translates to 0.6Hz to 3.3Hz for the fundamental frequency of the pulse waveform. If we want to see some of the shape of the waveform, we might want to see the first few harmonics of the waveform (say, up to 4 times the fundamental), meaning that the range of signal we are interested in is 0.6Hz to 13.3Hz.

If we use simple RC filter designs, we'll want to make the filters a little wider, with a low-pass filter whose corner is around 20Hz–30Hz, and a high-pass filter whose corner is 0.2Hz–0.3Hz.

Since the gain of the transimpedance amplifier is the same as the feedback impedance, we can implement the low-pass filter just by replacing the feedback resistor R1 with an impedance that is essentially R1 at very low frequency, but which gets smaller above the low-pass corner frequency. Design a simple circuit that provides such an impedance.

We can't handle the high-pass filter in the same way, because we need for the transimpedance amplifier to hold the voltage on the phototransistor constant, so we can't reduce the gain of the amplifier at 0Hz.

What we *can* do is to add a second-stage voltage amplifier after the transimpedance amplifier, with a high-pass filter between the stages (or incorporated into the second stage). This second stage can amplify the small AC pulse signal, while the DC signal is blocked. The second stage can be inverting or non-inverting, depending which way up you want the output signal to be.

Redesign your amplifier, adding a high-pass filter after the first stage to remove DC, and amplify the desired signal enough to see it clearly with the PteroDAQ. You'll probably want about a 1v–2v AC signal at the output of the amplifier.

If you use V_{ref} as a virtual ground for the second stage, you may want to change it from what you chose when designing just a single stage, since AC output will be centered about the virtual ground of the second stage.

6 Procedures for second stage

Add the filtering and observe the output with the PteroDAQ data acquisition system.

7 Demo and writeup

For the first half of the lab, show me a single-stage amplifier that produces a DC voltage in a reasonable range when a finger is in the block, and a (small) fluctuation related to the pulse on the oscilloscope.

For the second half of the lab, show me a clear PteroDAQ trace of a heartbeat from a finger in the sensor.

The writeup should include schematics for both the single-stage and two-stage amplifier, calculations used to get initial component values, adjustments to components that were needed to make the circuit work properly, and a plot of the output from the final amplifier design. Use the amplifier output file to compute the pulse rate for the individual.

You will probably encounter some problems with the crude wooden-block finger-tip sensor. Describe changes you would make to improve the sensor.

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