ENGN/PHYS 207—Fall 2020
Assignment #6
Transimpedance Amplifier Design: Lights, Current, Voltage!

Circuits You'll Build

1. Transimpedance amplifier (TIA): op-amp based circuit used to convert a photodiodes small photocurrent current to a measurable voltage. [1]. Note: The photodiode-TIA in Figure 1(C) will become a core functional block of your PPG circuit for the final project. Layout the components tightly and carefully, economizing on space!

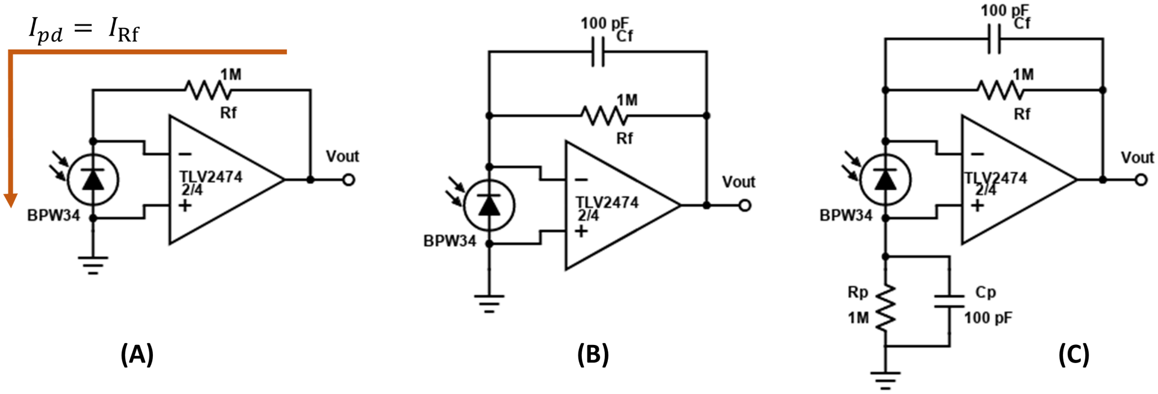

Figure 1: Op-amp based transimpedance (TIA) amplifier design. The TIA's circuits job is to convert a photocurrent I_{pd} into corresponding voltage signal. (A): Simplest possible TIA design with single feedback resistor and photodiode in photovoltaic mode. Path of current flow through feedback resistor and photodiode is indicated. Note the direction of current flow. (B): Compensation capacitor C_f incorporated into design. The parallel combination of R_f and C_f form a low-pass filter, which also serves to stabilize TIA behavior. (C): Symmetric design incorporating parallel combo of Rp and C_p.

Lab Skills You'll Learn

1. Working with photodiodes!
2. New features of waveform generation–namely the offset voltage
3. Working with opto-electronics

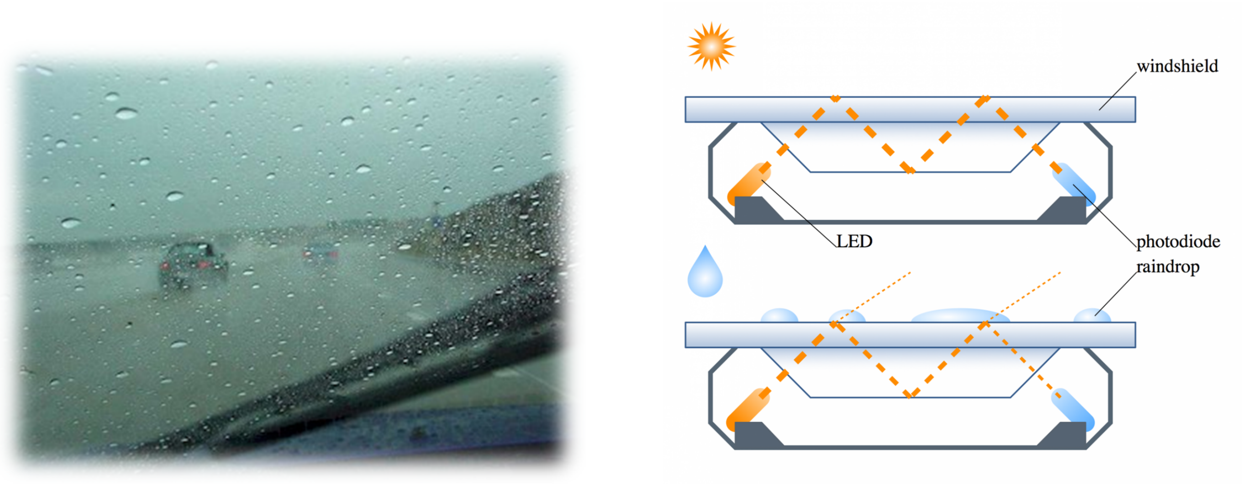

Figure 2: Rain-sensing windwhield wipers. Circuits principle of operation shown at right. Note the photodiode! Image adapted from: `https://openroadautogroup.com/blog/how-rain-sensing-wipers-work`

Where you'll find photodiodes in real life

Before we venture further, let's declare this National Photodiode Appreciation Day. (Hey, why not?) To help you appreciate the wide-ranging application of photodiodes, consider the following applications:

Every optical media disk you have ever played relies on a phododiode reading a time-varying light intensity. Yes, blu-ray DVDs are a bit old school, but the binary "pits" mechanically encoded either direct light to a photodiode or not.

How about wind-shield wipers–everyone loves a good pair, especially when it is raining. Rain sensing windshield wipers (Figure 2) are commonly used in realtively high-end automobiles to automatically adjust the wiper speed depending on the presence and intensity of rain. Usually the optical rain sensors operate on the principle of total internal reflection. The sensor is generally located behind the driver's rear-view mirror. An infrared light laser source beams the light pulses at an angle to the windshield. If the glass is not wet, then most of the light comes back to the photodiode detector. If the glass is wet, then some of the light is refracted and less light is detected by the sensor tuning on the wiper. The wiper speed is set based on how fast the moisture builds up between the sweeps.[2]

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[1] J. Caldwell, 1 MHz, Single-supply, Photodiode Amplifier Reference Design. Texas Instruments application note: TIDU535, November 2014.

[2] Akshay Bhat, Stabilize Your Transimpedance Amplifier, Maxim Integration APPLICATION NOTE 5129, Feb 03, 2012.

1 Theory of Photodiodes and TIAs: Lights, Current, Voltage!

Transimpedance amplifiers are commonly used to amplify the light-dependent current of photodiodes. These circuits are deceptively simple; the proper design of a single supply photodiode amplifier requires the consideration of many factors including stability and input and output voltage range limitations.[3]

1.1 Photodiodes

The photodiode is a type of photodetector capable of converting light to a small current which is proportional to the level of illumination.[4]

You should be aware that the sensitivity of photodiodes depends on the wavelength of incident light. In our case, we are going to use both red and IR led incident light.

1. What are the wavelengths of light these LEDs generate?
2. What is the sensitivity of the BPW photodiode to each of these wavelengths of light?

In this design, we will operate the phododiode in ***photovoltaic mode***. As a refresher, this mode has zero voltage potential across the photodiode. Thus, no dark current flows through the photodiode. To help picture the situation here, see Figure 3. Note that photodiode current is non-zero with incident light, even when the photodiode voltage is zero!

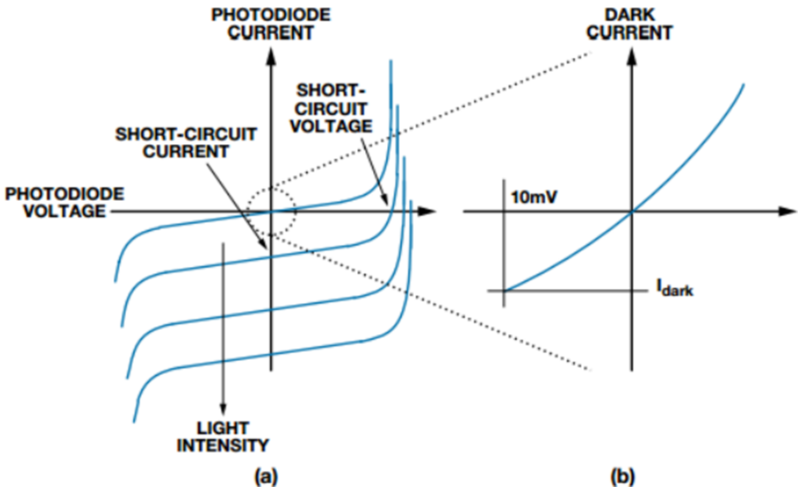

Figure 3: photodiode I-V curves. We will operate in photovoltaic mode $V_p = 0$, such that the photogenerated current is the *only* current that flows.

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[3] J. Caldwell

[4] Y. Zhen, OpAmp for Photodetection Applications; Microchip application note AN1494

1.2 TIA in simplest form

In its simplest form, a transimpedance amplifier consists of an op amp and a feedback resistor (**Figure 1(A)**). For this design, exposure to light will cause a reverse current through the photodiode.

The photodiode is connected such that this current causes the op amp output voltage to increase. This is true because the photocurrent only flows in the "reverse" direction. The current to be amplified is the photodiode current I_{pd}. It is easy to show that output voltage to changes according to the equation

$$V_{out} = I_{pd}R_f$$

This just says that the output voltage is proportional to the photodiode current, scaled by the feedback resistor value.

How do we know what value to choose for R_f? The value of the feedback resistor R_f should be set as large as possible to give a high transimpedance gain to the photocurrent. Usually, this gain should be high enough to use most of the op amps output voltage swing when the photocurrent is at its maximum value. Well OK, we have a working dynamic range of $approx$3.3V. Actually, we have a bit less than this because the rail-to-rail TLV247x op-amp has about 180 mV of ***headroom***, meaning its true working range is actually about 180 mV to 3.12 mV. At any rate, we don't want to saturate our op-amp, so we can estimate the max value of R_f as follows:

$$R_{f,\,max} = 3.12\text{V}/I_{pd,\,max}$$

OK, well then, what's the max photodiode current? That's a little trickier to answer with certainty because the photodiode current depends on the incident light intensity. Nevertheless some clues may be gotten from looking at the BPW34 datasheet. In particular look for the figure labeled "Photocurrent/Open-circuit voltage". Note: datasheet for similar photodiodes are much more descriptive. For instance see this datasheet: `https://www.vishay.com/docs/81170/vbp104sr.pdf`. What is a reasonable estimate for the photocurrent magnitude you would expect?

1.3 Compensation Capacitor: Stabilizing the amplifier

Check out **Figure 1(B)**. Here, we've added a feedback capacitor C_f.

For most photodiode amplifiers, a feedback capacitor, C_f, is necessary to maintain stability. This capacitor compensates for the photodiode capacitance at the inverting input of the op amp. "What on earth? Translate into English, please!!" you say. Fair enough, let's do our best to offer a simple explanation (this is an advanced topic which we won't treat fully here). Basically, the photodiode has non-negligible internal capacitance—typically in the ballpark of 50 pF. After all, it has a huge depletion layer separating two layers of charge. As you know it takes time to charge capacitors. Thus, there is a time lag associated with this capacitance charging. Meanwhile, the op-amp is busy trying to work its negative feedback magic—which also takes finite time. The feedback capacitor C_f has to charge up too! If the time lags are large enough, things can get out of sync and what was supposed to be negative feedback starts looking more like positive feedback.

A mechanical analogy may help. Imaging you are trying to limit how much a pendulum (kid on a swing) travels in terms of arc length. If you apply the force opposing the motion at just the right instant, all good. However, what if you get π out of sync and now the stopping because a starting push. The oscillations will grow!

Similar phase lags occur within the TIA. These phenomena make the photodiode amplifier unstable. What's the fix, doctor?! A small capacitor C_f can be added in the feedback loop to eliminate this ***gain peaking*** phenomenon. Again, gain peaking is an advanced topic that we will not study in detail in 207, but you can get the main idea from the figures below.

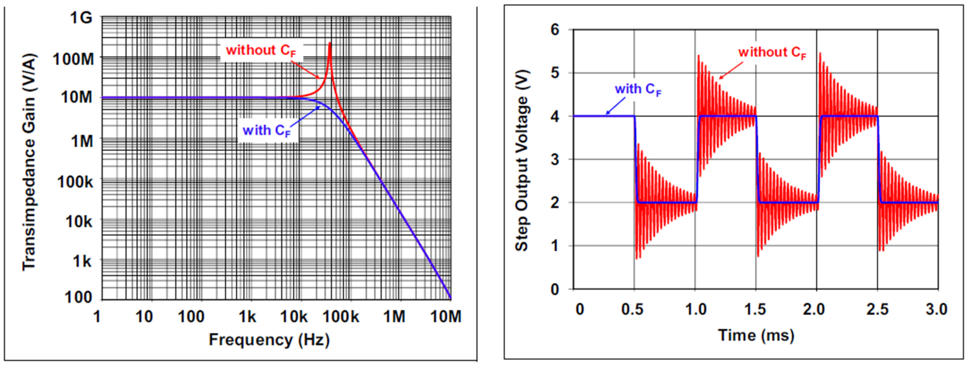

Figure 4: Effect of adding a stabilizing feedback capacitor.Image credit: Luis Orozco, "Optimizing Precision Photodiode Sensor Circuit Design", Analog Devices Technical Article MS-2624.

Also, more obviously, R_f and C_f form a low-pass filter with the now very familiar cutoff frequency of

$$f_o = \frac{1}{2\pi R_f C_f}$$

The low pass filter with the cutoff frequency to a sufficiently low value filters out high frequency ringing associated with gain peaking. In short, a feedback capacitor stabilizes the behavior of the TIA and sets up a low-pass filter which is beneficial for filtering unwanted high frequency noise. What size capacitor do we need? Well, that's a fairly complex topic (The curious cat may review Microchip article), but suffice to say a few pF usually does the trick. Here we use a 100 pF, which overcompensates. Not to worry— overcompensation reduces the usable bandwidth of the TIA to frequencies below the low pass cutoff, but this reduced bandwidth may is not an issue for our low frequency PPG application.

1.4 Symmetric Design

Lastly, we'll add the same RC parallel combo to the design connected to the non-inverting input, as shown in **Figure 1(C)**. What's the deal with this, you ask? Fair question. Firstly, note that anytime current is flowing there IS a voltage drop across both R_f and R_p. The same magnitude voltage drop, to be clear (since they are both 1MΩ). The voltage drop occurring across R_p lifts the non-inverting input away from ground (0V), when $I_{pd} > 0$, ie when light is incident on the photodiode. This has some modest benefit for amplifier behavior—-they don't like to operate around ground, it's hard for them to get up and moving when they start the day at 0V. Just like it is difficult for us to operate full speed when we have just gotten up and out of bed! So symmetrizing the design (if that's even a word) helps the op-amp start at its mid-way point, where it operates much better (just like we humans typically operate better at mid-day). The overall effect is fairly small, but why not go for the gusto.

The last random fun fact you should know about this amplifier—which we will state here without proof:

The output resistance of the photodiode amplifier is roughly equal to R_f/A_{OL}, where AOL is the open loop gain of the op amp. Given the 1 MΩ resistor, estimate the output resistance of the amplifier. What magnitude of loads can it drive?

2 Photodiode and TIA in Practice

Theory is wonderful and all, but now it is time to build, experiment and play!

Build the circuit shown in **Figure 1(C)**.

Note: power connections are not explicitly shown; make sure your op-amp is powered with 3.3V and GND.

For orienting the photodiode, check out Figure 5:

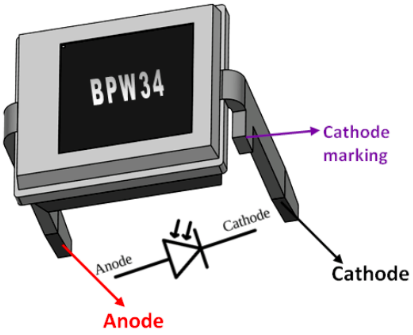

Figure 5: Orienting a photodiode with the cathode marker. Image credit: `https://components101.com/diodes/bpw34-photodiode`

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For testing, the main goal is to **demonstrate proof of concept** that the photodiode + TIA circuit is indeed capable of detecting and amplifying small changes in incident light intensity. You need to d*o this for both red and IR wavelengths of light.*

Since the TIA-photodiode circuit fundamentally converts light into electrical current into voltage, we must a time-varying light intensity incident upon the photodiode as our input source. To be explicit, we do NOT connect the AWG into this circuit for testing.

A few overview thoughts and ideas on generating time-varying light for testingbefore digging into the circuits weeds.

1. One very good approach is to send pulses of light to the photodiode. How to do this in practice? Just look back at your lab 4! The main idea is that a brief pulse of incident light on the photodiode should produce a corresponding voltage pulse at the output of the TIA.
2. Another good and practical approach is to input a time-varying light intensity to the photodiode. The main idea and setup is summarized in Figure 6. Details below!

Here are some details to help with testing. Basically, we are going to use an LED which has a time varying current and therefore time-varying light intensity given by:

$$i_{LED}(t) = \underbrace{I_{baseline}}_{constant} + \underbrace{i_o \cos(\omega t)}_{time-varying}$$

where $I_{baseline}$ is the dc current and i_o represents the amplitude of ac current (time varying current). As a starting point, we'll aim for $I_{baseline} \approx 5$ mA and $i_o = 0.1$ - 1 mA. Note that 5 mA baseline current through the LED should typically appear is faintly to moderately illuminated. The small change in current might possibly be visible to the naked human eye.

The LED can be thus driven with a varying light intensity as follows, illustrated in Figure 6.

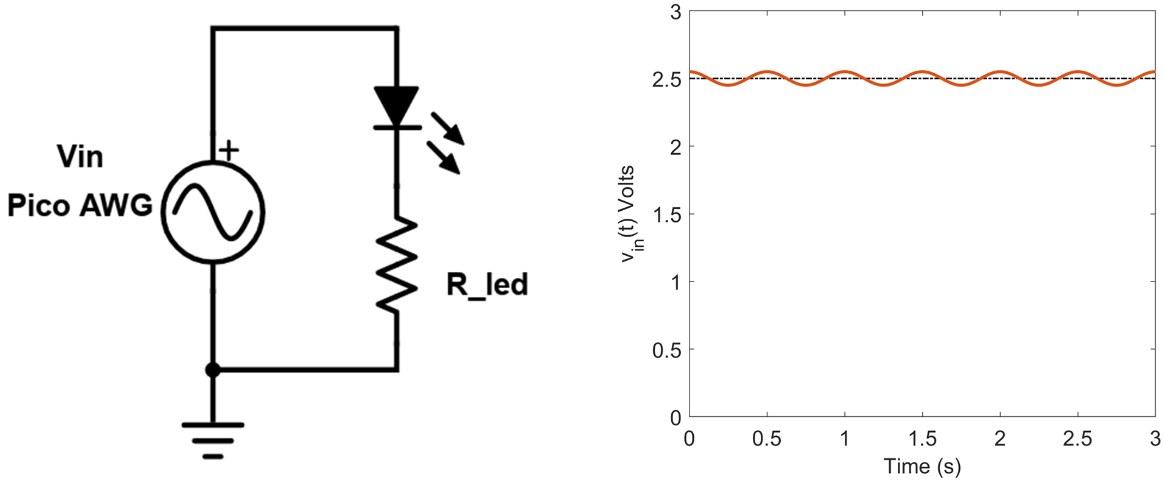

Figure 6: Left: Simple series circuit for generating a time varying LED light intensity using waveform generator. Right: The waveform has an constant offset (dc) component plus a small oscillatory (ac) component. In this example, the offset is 2.5V and the amplitude of oscillations is a much smaller 50 mV.

1. Make a simple circuit with the red LED in series with a ***current limiting resistor*** driven by the ~~picoscope wave generator (AWG)~~ BK Precision function generator. (Our Picoscope offset max value allowed is 1V; the BK precision function generator can achieve 2.5V offset)
2. ~~AWG~~ BK Precision function generator settings to make a time varying voltage of $v(t) = V_{offset} + v_o \cos(\omega t)$ are:

    (a) Offset value for the output wave $\approx$ 2.5 V.
    (b) Set the frequency to $f = 2$ Hz.
    (c) Set the amplitude of oscillation to the proper value such that the time-varying current is $i_o = 0.1$ - 1 mA.

3. Given these input voltage values, choose an appropriate value for the current limiting resistor to complete the design.

4. Align the red led to shine onto the photodiode. You may need to modify the baseline light intensity by either changing the baseline current. Alternatively, if the incident light too intense, you can by inserting sheets of paper or—better yet—your finger! similar optical attenuation media. You should also try beaming the light into your finger and catching the transmitted (or reflected) light with the photodiode—just as you will do with the the final PPG circuit! How big is the peak-peak oscillation? How large will the singal be after you amplify by ×30 downstream—using your active filter, of course! (See how the pieces of the circuit puzzle are coming together?)

5. Do your best to shield the photodiode from ambient light sources flickering at 60 Hz. We have paper, cardboard, etc on hand.

6. If all is working well and the incident light level is "just right" you should see a time varying output voltage from the TIA. Of course it should have a frequency of 2Hz, and hopefully some appreciate amplitude of oscillation (a few tens of mV ought to work just fine. This signal will get amplified downstream).

7. Adjust, fiddle, strategize as necessary until you can clearly and convincingly see the photodiode + TIA circuit providing a sensible output

8. Now repeat proof of concept with the IR LED. Be mindful that is has a lower turn on voltage $approx 1.2$V compared to the red LED ($\approx$ 1.8V).

3 What to Turn In

1. Up to 2 paragraphs of explanatory text clearly and concisely highlighting what proof of concept tests you carried out and what key findings clearly demonstrate proof of concept that your system works as advertised.

2. Proof of concept graphics with captions that clearly demonstrate your system working properly—i.e. that the photodiode + TIA properly detects and amplifies both red and IR incident light (separately, not simultaneously). It's up to you to decide what is sufficient proof. So long as you can make a convincing case, you've got yourself a winner!

3. All content described above must fit neatly on 2 pages max.

4. Appendix: Show your derivation for the voltage output as a function of the photocurrent and circuit components in **Figure 1(C)**. This just comes from the TIA-photodiode worksheet we did in class.