ENGN/PHYS 207—Fall 2020
October 21, 2020
Transimpedance Amplifier Design Worksheet: Lights, Current, Voltage!

Transimpedance amplifier in 3 easy steps

Let's look at Transimpedance Amplifiers. Because, hey, why not? They are op-amp based circuit used to convert an electrical current into a measurable voltage signal. We'll build up to the final circuit that we'll build in lab this week (to be incorporated into your PPG final project!) in 3 easy steps. Our circuits road map is shown in Figure 1.

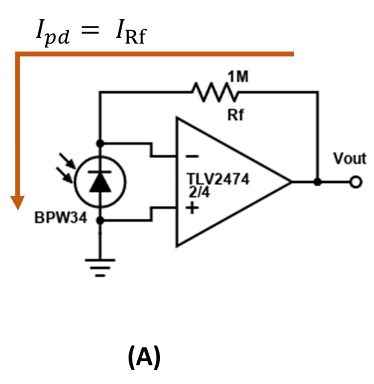

Figure 1: Op-amp based transimpedance (TIA) amplifier design. The TIA's circuits job is to convert a photocurrent I_{pd} into corresponding voltage signal. (A): Simplest possible TIA design with single feedback resistor and photodiode in photovoltaic mode. Path of current flow through feedback resistor 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.

1. **Circuit (A)**:
   (a) Is this op-amp in negative feedback?
   (b) Do both golden rules apply?
   (c) Show that

   $$V_{out}(t) = I_{pd}(t)\, R_f \tag{1}$$

   Note carefully the direction of current flow. This just says that the *output voltage is proportional to the photodiode current*, scaled by the feedback resistor value.

   (d) What value of R_f would you choose in practice? Assume you have a rail-to-rail op-amp powered by +3.3 V and GND. Assume the photocurrent magnitude is $\approx 1\mu$A, so you want 1 Volt of output for every 1 μA of photocurrent.

(e) Lastly, what is the voltage difference across the photodiode? The point here is that op-amp holds the photodiode in ***photovoltaic mode***. This decreases the dark current to 0!

2. **Circuit (B)**: Here we have added a feedback capacitor C_f in parallel with R_f. Looks like a familiar best-circuits buddies are back again!

   (a) Intuitively, what kind of filtering is involved here?

   (b) Show that

$$V_{out}(t) = I_{pd}(t)\, R_f \left(\frac{1}{1 + j\omega R_f C_f} \right) \tag{2}$$

   (c) Compute the cutoff frequency.

   (d) Our plan in the future is to shine brief pulses of red and IR light onto the photodiode. The pulse width for each is T =≈220 μs. Compute the corresponding fundamental frequency $f = 1/T$. Will these pulses pass through or be attenuated?[1] if you find these 220μs would be cut off, what could and should you do in practice to remedy the situation?[2]

3. **Circuit (C)**: Compared to circuit B, we've made a symmetric design by added another resistor R_p and capacitor C_p. They are connected between the non-inverting input and ground.

   (a) Intuitively, what kind of filter does the $R_p||C_p$ combo make?

   (b) Assuming that $R_p||C_p = R_f||C_f$, which is indeed our actual design here, show that:

$$V_{out}(t) = 2\, I_{pd}(t)\, R_f \left(\frac{1}{1 + j\omega R_f C_f} \right) \tag{3}$$

   (c) Compute the cutoff frequency of this circuit. Did it change relative to circuit B?

   (d) Assume there is a constant photocurrent flowing is I_p =1 μA. Compute the output voltage. Note the factor of 2 out front in the RHS Eqn 3.

   (e) Also, compute the voltage at non-inverting terminal of the op-amp. The point here is that this added resistor forces the op-amps inputs out of negative saturation (held at ground potential). This typically results in much better op-amp performance. The op-amp doesn't really like to come out of saturation and get quickly to work right after getting out of bed (being in our metaphorical ground state).

[1] The actual situation is a bit more complex. Our phasor analysis is built upon sine waves. Here we have square waves. Fourier theory teaches us that we can build square waves from a summation of sine waves with integer multiples of the fundamental $x(t) = \sum_n a_n \cos(n\omega t + \phi_n)$. So the high order harmonics (higher values of n) may get cut off. But so long as the fundamental passes through we should be reasonably OK in practice.

[2] Just in case, we have a whole range of ≈10 pF capacitors in Circuits lab.