

EE521: Measurement & Instrumentation HW 3

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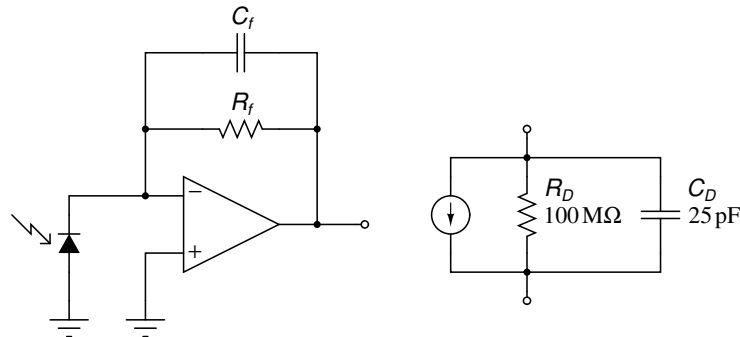
1 Problem

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Transimpedance amplifiers (TIA) have been widely used in modern instruments involving optical measurement. The primary function of a TIA is to convert a current signal (such as from a photodetector) to a voltage.

A simple transimpedance photodetection circuit and the corresponding model of the PIN (Positive Intrinsic Negative) photodetector are shown in the figures below:



The AD795 is a FET input, low noise operational amplifier. The input photo diode has a responsivity of 0.85 A/W .

- (a) Design a TIA that will detect light in the range of $1\text{ }\mu\text{W}$ to 1 mW , with a minimum bandwidth from DC to 10 kHz .

ANSWER

My strategy is: for the maximum input, the output should also be maximum, subject to full power bandwidth/slew rate. Then I will check if this circuit is feasible by doing a noise analysis comparing minimum detection level to the noise floor.

The AD795 has the following properties:

Parameter	Value	Unit
Full Power Response ($V_o = 20\text{ V}_{\text{p-p}}$)	16	kHz
Slew Rate ($V_o = 20\text{ V}_{\text{p-p}}$)	1	$\text{V}/\mu\text{s}$
Small Signal Bandwidth	1.6	MHz

Full power bandwidth is computed by constraining the maximum slope of the sine wave to be equal to slew rate,

$$\max\left(\frac{dA \sin \omega t}{dt}\right) = \text{slew rate} \quad (1)$$

$$\omega A = \text{slew rate} \quad (2)$$

And plugging in the values for this problem gives,

$$2\pi 10 \text{ kHz } A = 1 \text{ V}/\mu\text{s} \quad (3)$$

$$A_{\max} = 15.9 \text{ V}_p \quad (4)$$

But! Because the Op-amp is rated for a $\pm 15 \text{ V}$ power supply and because the output range requires a 4 V overhead, we'll choose a lower, safer value,

$$A = 10 \text{ V}_p \quad (5)$$

(Note: this is a LOT more than needed because the input signal is not bipolar: the output will only go from 0 V to -10 V , thus the AC V_p is really only 5 V with a -5 V offset.)

Now we choose a resistor to give this voltage for the maximum input current (i.e. when 1 mW of power is incident on the PIN),

$$1 \text{ mW} \cdot 0.85 \text{ A/W} = 0.85 \text{ mA} \quad (6)$$

$$R_f = \frac{10 \text{ V}}{0.85 \text{ mA}} \quad (7)$$

$$\approx 10 \text{ k}\Omega \quad (8)$$

Next, the capacitor must be chosen to permit a reasonable bandwidth.

$$f_{3\text{dB}} = \frac{1}{2\pi R_f C_f} \quad (9)$$

$$= 10 \text{ kHz} \quad (10)$$

For a safety margin, I divide the capacitance by 2 to keep us away from the 3 dB bandwidth,

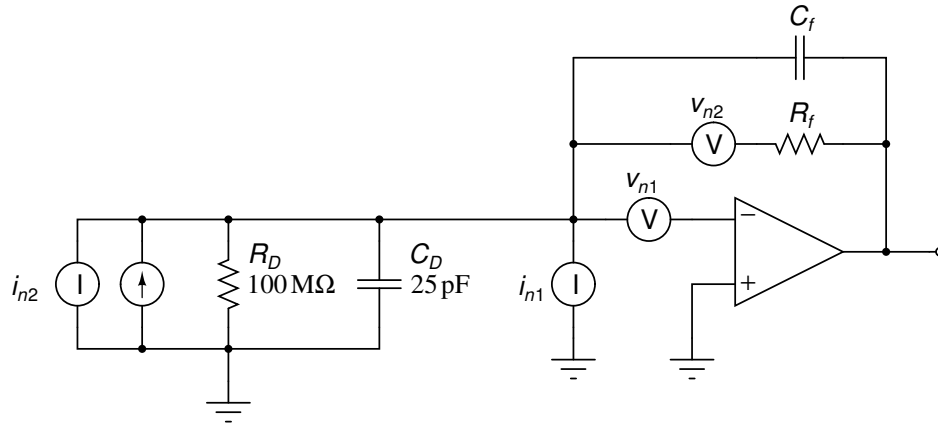
$$C_f = \frac{1}{2} \cdot \frac{1}{2\pi 10 \text{ k}\Omega \cdot 10 \text{ kHz}} \quad (11)$$

$$\approx 800 \text{ pF} \quad (12)$$

□

(b) Draw the noise equivalent circuit of your transimpedance amplifier circuit.

ANSWER



The various possible sources of noise are:

Shot noise¹ (i_{n2}) $I_{\text{rms}} \leq \sqrt{2qI_{\text{dc}}B}$ Shot noise takes on the largest value it can when crossing PN junctions in diodes and transistors (is this correct?), because the events of electrons crossing a boundary are independent in these devices. These events are not independent in a metallic conductor however, which means that shot noise is much less in a metallic conductor and also in simple resistive circuits. According to Horowitz and Hill, shot noise is also reduced in transistor current sources due to negative feedback.

Johnson noise² (v_{n2}) Any resistor has this noise which has a gaussian distributed amplitude. $V_{\text{rms}} = \sqrt{4kTRB}$

1/f (**flicker**) noise This depends on the construction of resistors.

Op-amp noise (v_{n1} and i_{n1}) These noise values are specified on the op-amp's datasheet. Low noise amplifiers (such as the AD795) should have a plot of the power spectral density for these noises.

Dark current This is not exactly noise, but rather a leakage current generated by biasing the diode. The dark current linearly combines with the detection current. Since we are biasing the diode with 0 V, there should be no dark current. Otherwise, the dark current would also be responsible for generating additional shot noise (I think...).

□

¹ $q = 1.60217646 \times 10^{-19}$ C (charge of an electron)

² $k = 1.3806503 \times 10^{-23} \frac{\text{m}^2\text{kg}}{\text{s}^2\text{K}}$ (Boltzmann's constant)

- (c) Based on the noise equivalent circuit, conduct a comprehensive noise analysis of your circuit. you should consider at least: the shot noise, the thermal noise, and the operational amplifier noise. (You may refer to the AD795 specifications, and the Burr-Brown document³ for further reference).

ANSWER

Assuming that the open-loop gain of the op-amp is very large, we apply the golden rule of op-amps,

$$V_{\text{inverting}} = V_{\text{non-inverting}} \quad (13)$$

$$= 0 \text{ V} \quad (14)$$

Applying Kirkhoff's Current Law to the node which v_{n1} connects to gives (another possibility for solving this problem is to use modified nodal analysis),

$$I_D + i_{n1} + i_{n2} = \frac{v_{n1} + v_{n2} - V_o}{R_f} + (v_{n1} - V_o)sC_f + \frac{v_{n1}}{R_D} + v_{n1}sC_D \quad (15)$$

Then, do some scary symbolic manipulation...

$$(I_D + i_{n1} + i_{n2})R_f R_D = v_{n1} (R_D + sR_f R_D C_f + R_f + sR_f R_D C_D) + v_{n2} (R_D) - V_o (R_D + sR_f R_D C_f) \quad (16)$$

$$V_o = \frac{-(I_D + i_{n1} + i_{n2})R_f R_D + v_{n1} (R_D + sR_f R_D C_f + R_f + sR_f R_D C_D) + v_{n2} (R_D)}{R_D + sR_f R_D C_f} \quad (17)$$

But, because R_D is so large, let's assume it is ∞ and drop all terms that do not include R_D , thus,

$$V_o = \frac{-(I_D + i_{n1} + i_{n2})R_f R_D + v_{n1} (R_D + sR_f R_D C_f + sR_f R_D C_D) + v_{n2} (R_D)}{R_D + sR_f R_D C_f} \quad (18)$$

$$= \frac{-(I_D + i_{n1} + i_{n2})R_f + v_{n1} (1 + sR_f C_f + sR_f C_D) + v_{n2}}{1 + sR_f C_f} \quad (19)$$

More stuff to follow....

□

³ <http://focus.ti.com/lit/an/sboa060/sboa060.pdf> NOISE ANALYSIS OF FET TRANSIMPEDANCE AMPLIFIERS

- (d) Plot the total noise spectrum (noise vs. frequency) of your circuit and summarize your findings.
- (e) What is your shot noise limited signal-to-noise ratio? (Assume the only noise is from the shot noise of your PIN photodetector, and the rest of your circuit is perfect, what is the best signal-to-noise ratio you can achieve within the required detection dynamic range and bandwidth)