Lab 3

Design of Optical Communication System

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***Abstract*—We explored the trans-impedance amplifier, derived it's closed loop gain and explained why it is unstable if there's a finite capacitance C_{pd}. Then we simulated the circuit to verify our observations. Then we built an Optical Communication System with the components we designed.**

Keywords—Trans Impedance Amplifier; Optical Communication System; Analog Systems; Visible Light Communication; VLC;

I. Introduction

Trans Impedance Amplifier is a current to voltage converter, most often implemented using an operational amplifier. The TIA can be used to amplify the current output of photo detector to voltage. The trans-impedance amplifier presents a low impedance to the photodiode and isolates it from the output voltage of the operational amplifier. [1]

II. Analysis of the TIA

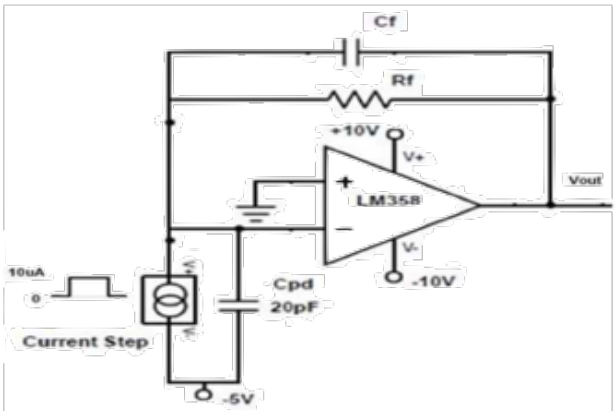

Fig. 1 – The Trans-Impedance Amplifier

A. Closed Loop Gain

The closed loop gain is A(s). β(s)

A(s) is the amplification when the feedback is removed. This is equal to $A_{OL}(s)$, the open loop gain.

$$A(s) = Aol$$

β(s) is the fraction of output voltage that reaches the inverting pin of the amplifier.

This is equal to [Eq. 1a]

$$\beta(s) = \frac{XCp}{XCp + Rf} = \frac{\frac{1}{sCp}}{\frac{1}{sCp} + Rf} = \frac{1}{1 + s * Cp * Rf}$$

The loop gain is [Eq. 1b]

$$A(s) * \beta(s) = \frac{Aol}{1 + s * Cp * Rf}$$

B. The cause of instability

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Amplifiers have a -20dB slope after their 3dB frequency (Bandwidth). Like so

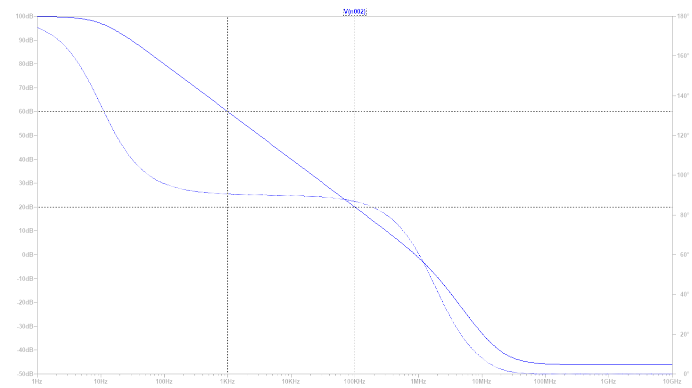

Fig. 2 – Frequency response of LM358 – Slope: -20 dB/dec

The parasitic capacitance causes a zero that causes a slope of +20 dB/sec in the bode plot of 1/ β

The result is, Rate of Closure is -40 dB/dec, which is unstable as calculated from its phase margin. The 'zero' occurs because of the non-zero parasitic capacitance C_p, so the TIA is unstable when there is a finite C_p.

To make the TIA stable, a compensating capacitor C_f is connected in the feedback path.

C. Simulation and Analysis

AC analysis

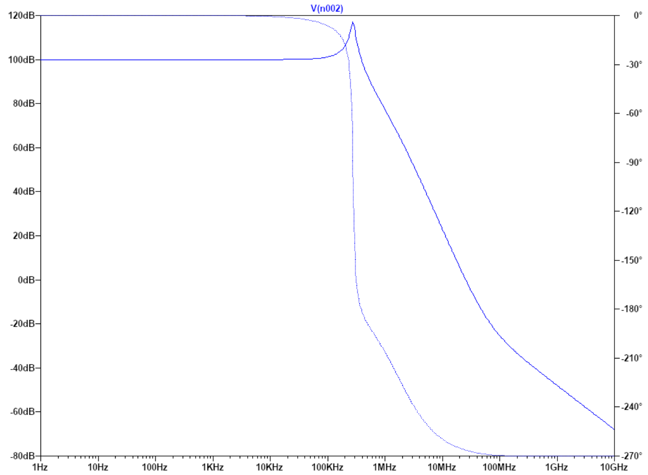

Fig. 3a – AC analysis of TIA

Bode plot of uncompensated TIA

Transient Analysis

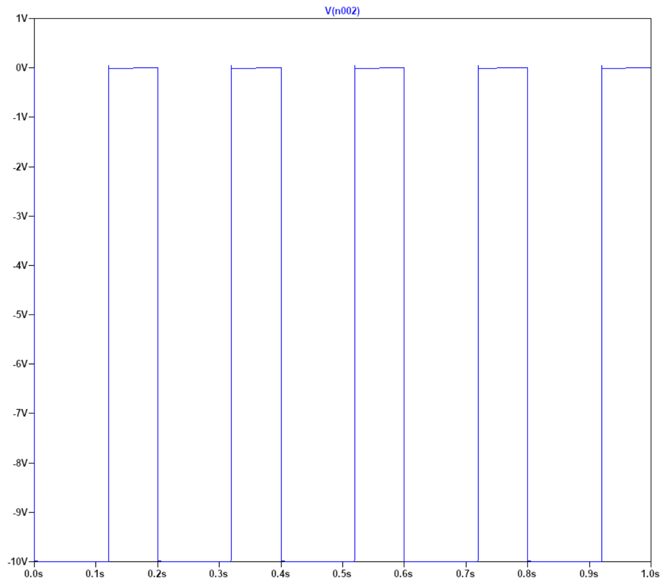

Fig. 3b – Transient analysis of TIA

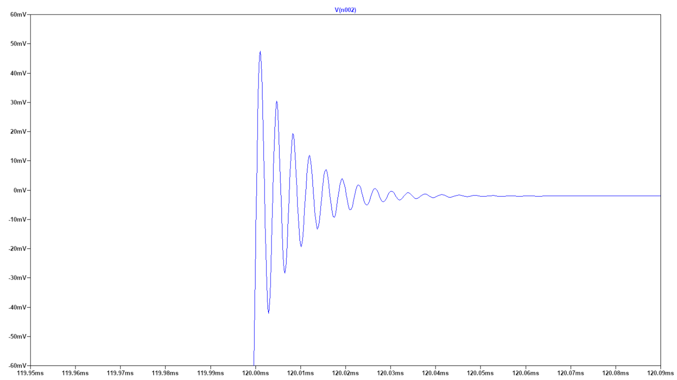

Fig. 3c – Ringing in an uncompensated TIA - Zoomed

Input Impedance

$$Xin = \frac{-Rf}{Aol}$$

Open-loop-gain of LM358 from ti.com [2] is 100 dB = 10^5

- On substitution, input impedance is close to 1.
- From Simulation .TF, the input impedance is 1.0005.

The value resultant from simulation is in agreement with the calculated value.

III. Frequency Compensation

The gain peaks in AC analysis and the ringing in the Transient analysis [Fig 3b, and 3c] indicate instability of the TIA. To make the TIA stable, we compensate by adding a pole – a capacitor on the feedback path.

This pole counter-acts the effect of the zero caused by the parasitic capacitance C_p and makes slope of the Bode plot of 1/β, 0. Making the Rate of Closure -20 dB/dec. This makes the TIA stable.

We add a feedback capacitor C_f. Finding the loop gain by splitting into A and β circuits. The A(s) of the circuit is same as the previous case – A_{OL}. For β, there is another impedance in parallel with feedback resistance R_f. [Eq. 2a]

$$\beta(s) = \frac{Xcp}{Xcp + (Rf \mid Xcf\ )} = \frac{1 + SRfCf}{1 + SRf(Cp + Cf)}$$

Now there is a pole and a zero and the Bode plot of the TIA looks like this:

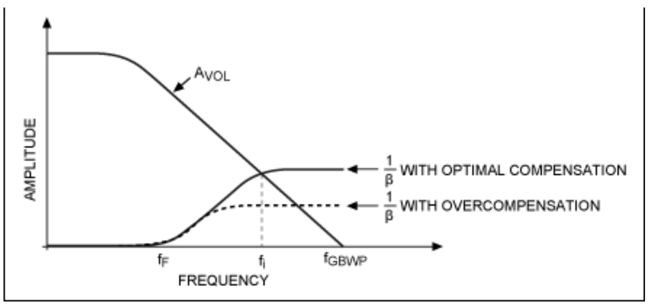

Fig. 4 – Compensated TIA Bode plot [3]

The frequency at the intercept is [Eq. 2b]

$$Fi = \frac{1}{2PiRfCf}$$

The equation 2b has two unknowns. The intercept frequency and the feedback capacitance. To solve for C_f, we need another simultaneous equation.

Since both the curves in Fig. 4 are at an absolute slope of 20dB/dec, the triangle is more or less isosceles, so the intercept frequency is the average of the other two vertices.

The frequency is in a logarithmic scale, so [Eq. 2c]

$$\log(Fi) = \frac{\log(Ff) + \log(Fu)}{2}$$

F_f being the frequency of 'zero' in the Bode plot of 1/ β and can be calculated by finding the 'zero' frequency [Eq. 2d]

$$Ff = \frac{1}{2PiRf(Cf + Cp)}$$

Since we know Gain-Bandwidth product of an amplifier is constant and gain at 0dB is 1, F_U is the unity gain frequency of the amplifier.

The equation Eq. 2c can be rewritten as [Eq. 2e]

$$Fi = \sqrt{\frac{Fu}{2PiRf(Cf + Cp)}}$$

Solving the equations Eq. 2b and Eq. 2e, we get a quadratic equation, which on solving yields C_f [Eq. 2f]

$$Cf = \frac{1}{4PiRfFu}(1 + \sqrt{1 + 8PiRfCpFu})$$

According to TI.com [2], the gain-bandwidth product of LM358 opamp is 0.7 MHz So the unity gain frequency is 0.7 MHz

Our circuit uses a feedback resistance R_f = 100 K.

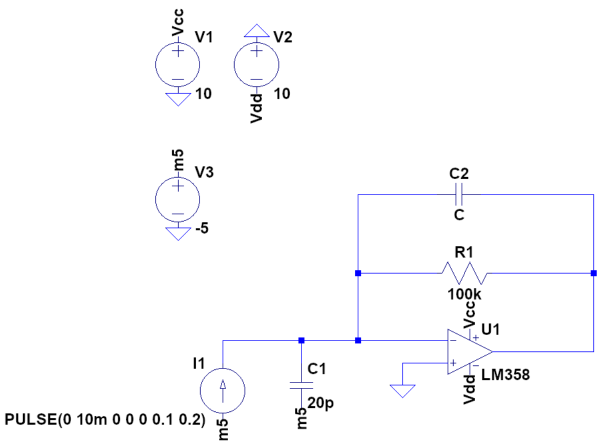

Fig. 5a – TIA circuit diagram – Ltspice

Using the equation Eq. 2f, we calculate C_f to be 7.97 pF.

Simulating post compensation, we get

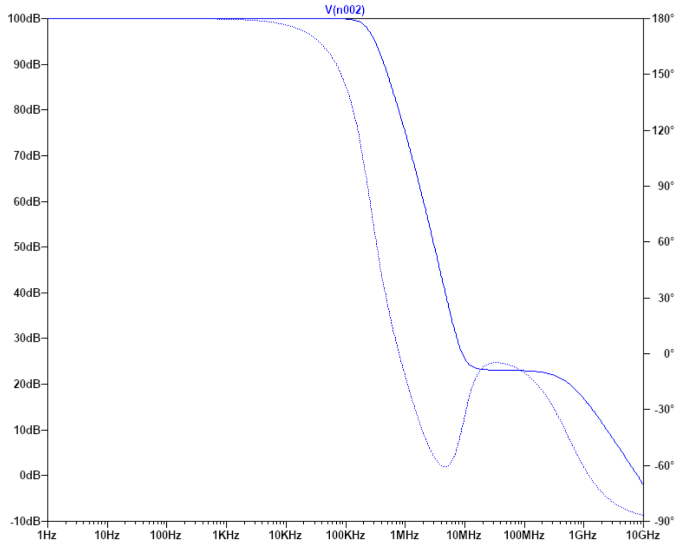

Fig. 4a – AC analysis of a compensated TIA

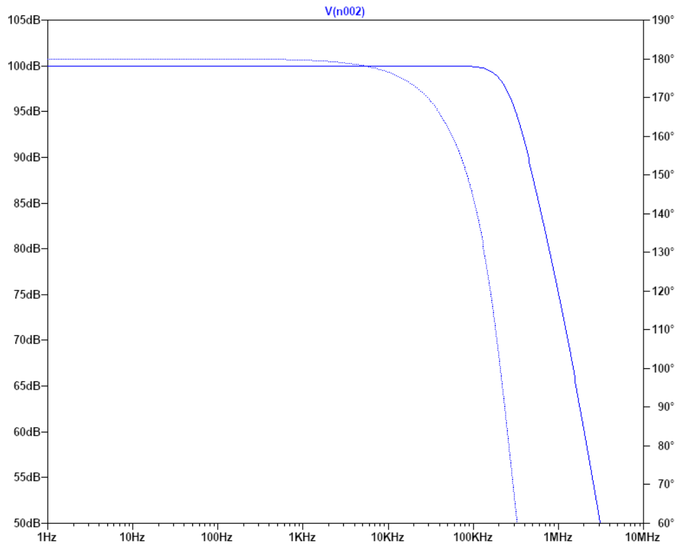

Fig. 4b – AC analysis zoomed

There are no gain peaks in the AC analysis showing that the amplifier is now stable. [Fig. 4a and 4b]

Similarly, on zooming on the transient analysis, we find the no ringing takes place after we added a compensating capacitor in the feedback loop. [Fig. 4c]

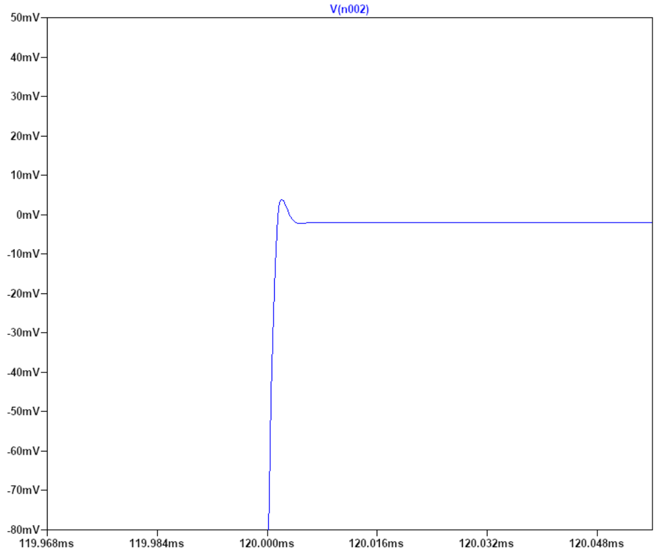

Fig. 4c – Transient analysis of a compensated TIA - Zoomed

IV. Building an Optical Communication Circuit

Now that we know how to stabilize a TIA, we can build an optical communication circuit with an LED and a TIA connected across a photo diode.

The photo diode acts as a current source – producing current in proportion to the intensity of light it receives and the TIA converts this to voltage.

Using the same R_f and C_f values as in the previous section (100 K Ohm and 8 pF), we observed the output of the TIA for an input square wave of 1 KHz.

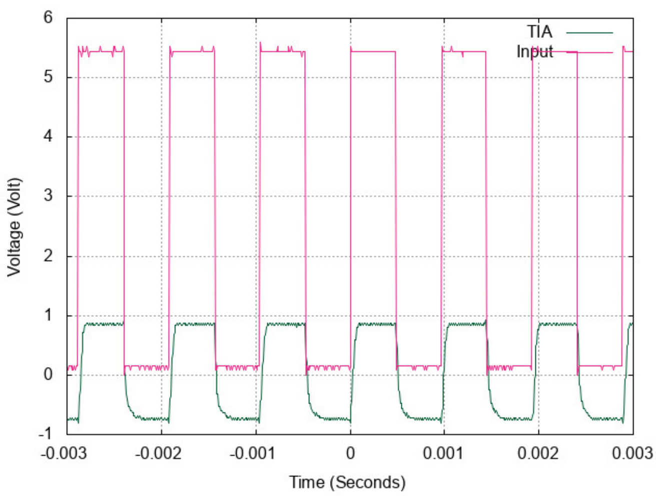

Fig. 5a – TIA 1KHz

The above is the plot [Fig. 5a] of 1 KHz input vs output at the TIA. After the TIA, a comparator is placed to get better output. Fig. 5b shows a 1KHz input vs the output collected at the comparator.

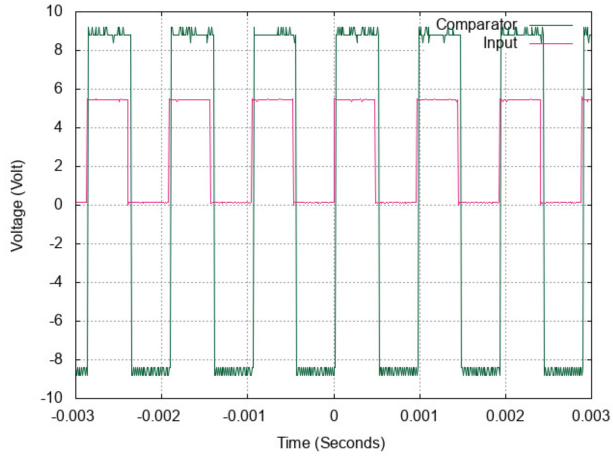

Fig. 5b – Comparator output – 1Khz

And then we took samples at a few other frequencies to observe how the TIA behaved.

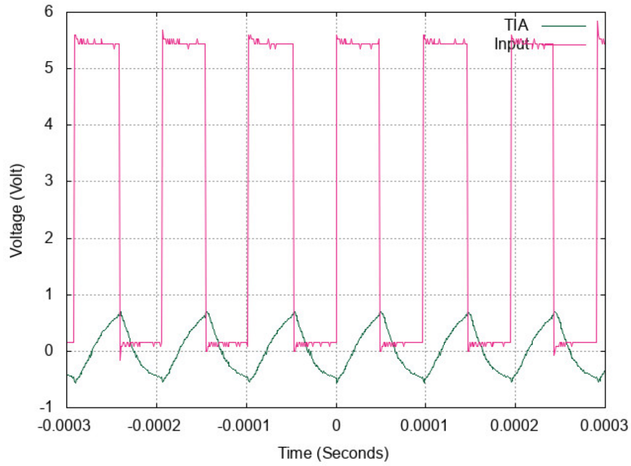

Fig. 5c – TIA 10 KHz

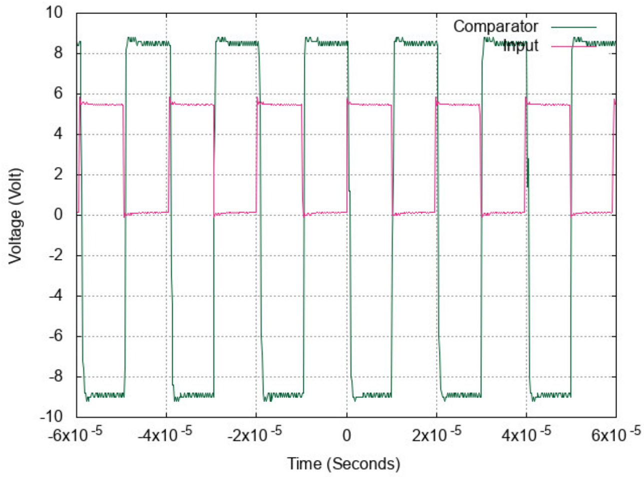

Fig. 5d – Comparator output at 49 KHz

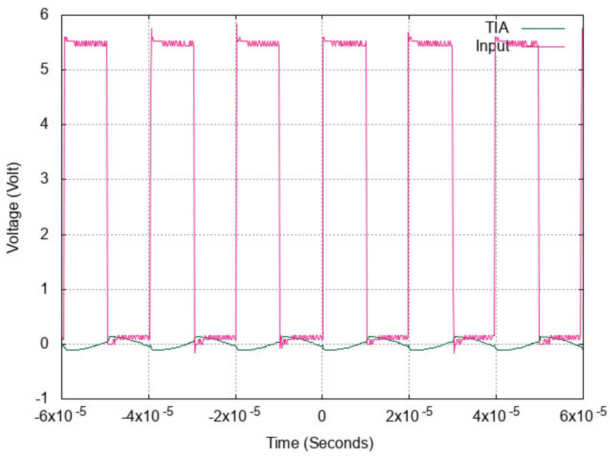

Fig. 5e – TIA 50 KHz

Then, the distance between the transmitter and the receiver is altered with a fixed input signal to study how the system is affected. We took readings at 3cm, 4cm, and 5cm.

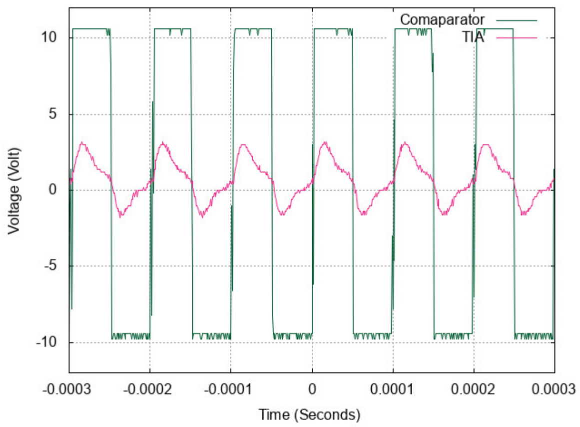

Fig. 6a – TIA and comparator – 10 KHz & 3 cm

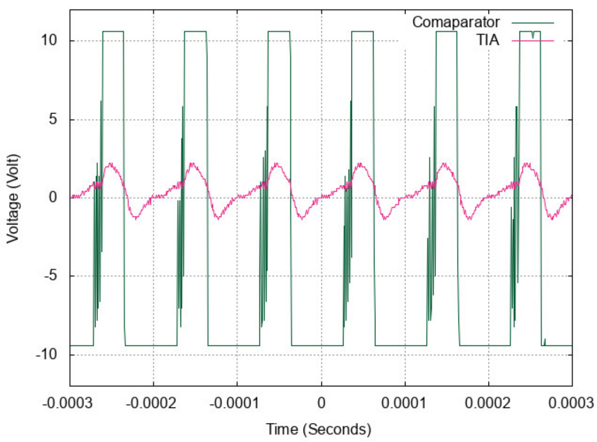

Fig. 6b – TIA and comparator – 10 KHz & 4cm

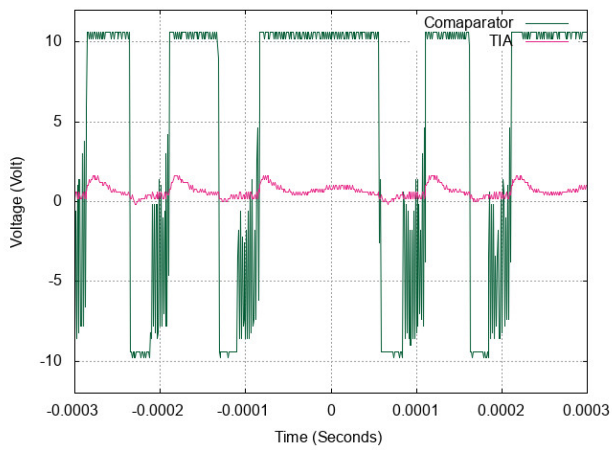

Fig. 6c – TIA and comparator – 10 KHz & 5 cm

As expected, increase in distance produced more noise and distorted the signal. The decrease of intensity of light incident on the photodiode, as the distance increases is the reason for the reduced Signal to Noise Ratio.

Conclusion

A TIA without compensation is unstable due to the 'zero' created by the parasitic capacitance of photo diode and the opamp. A compensating capacitance placed in the feedback path, parallel to the feedback resistor will stabilize this circuit.

An Optical Communication System can be constructed leveraging the properties of a TIA. A comparator placed after the TIA produces definitive voltages, since the signal is digital, the input signal can be detected even though amplitude drops as distance and/or noise increases.

Citations

[1] https://en.wikipedia.org/wiki/Transimpedance_amplifier

[2] http://www.ti.com/product/LM358

[3] https://www.maximintegrated.com/en/app-notes/index.mvp/id/5129