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 Cpd. 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;

# 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]

# Analysis of the TIA

## Closed Loop Gain

The closed loop gain is A(s). β(s)

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| Fig. 1 – The Trans-Impedance Amplifier |

A(s) is the amplification when the feedback is removed. This is equal to AOL(s), the open loop gain.

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

This is equal to [Eq. 1a]

The loop gain is [Eq. 1b]

## The cause of instability

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

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| 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 Cp, so the TIA is unstable when there is a finite Cp.

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

## Simulation and Analysis

**AC analysis**

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| Fig. 3a – AC analysis of TIA  Bode plot of uncompensated TIA |

**Transient Analysis**

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| Fig. 3b – Transient analysis of TIA |

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

**Input Impedance**

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.

# 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 Cp 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 Cf. Finding the loop gain by splitting into A and β circuits. The A(s) of the circuit is same as the previous case – AOL. For β, there is another impedance in parallel with feedback resistance Rf. [Eq. 2a]

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

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| Fig. 4 – Compensated TIA Bode plot [3] |

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

The equation 2b has two unknowns. The intercept frequency and the feedback capacitance. To solve for Cf, 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]

Ff being the frequency of ‘zero’ in the Bode plot of 1/ β andcan be calculated by finding the ‘zero’ frequency [Eq. 2d]

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

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

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

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 Rf = 100 K.

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| Fig. 5a – TIA circuit diagram – Ltspice |

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

Simulating post compensation, we get

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| Fig. 4a – AC analysis of a compensated TIA |

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| 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]

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

# 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 Rf and Cf 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.

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| Lab%203/Oscilloscope_readings/Fw__Oscilloscope_readings/1knFile0.csv.png  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.

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| Lab%203/Oscilloscope_readings/Fw__Oscilloscope_readings/1kfFile0.csv.png  Fig. 5b – Comparator output – 1Khz |

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

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| Lab%203/Oscilloscope_readings/Fw__Oscilloscope_readings/10kfile0.csv.png  Fig. 5c – TIA 10 KHz |

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| Lab%203/Oscilloscope_readings/Fw__Oscilloscope_readings/49kfile0.csv.png  Fig. 5d – Comparator output at 49 KHz |

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| Lab%203/Oscilloscope_readings/Fw__Oscilloscope_readings/50knile0.csv.png  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.

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| Lab%203/Oscilloscope_readings/the_three/comp4cmtia.csv.png  Fig. 6a – TIA and comparator – 10 KHz & 3 cm |

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| Lab%203/Oscilloscope_readings/the_three/comp5cmtia.csv.png  Fig. 6b – TIA and comparator – 10 KHz & 4cm |

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| Lab%203/Oscilloscope_readings/the_three/comp6cmtia.csv.png  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>