THE UNIVERSITY *of* EDINBURGH

Analogue Mixed Signal Laboratory 3 Lab Report

School of Engineering

CONTENTS

Lab report PART A

1. Introduction:

In this report, we are going to build a receiver device for Guided optical transmission. We already have an optical transmitter, but there are lots of noise created within the transmission channel. Therefore, what the receiver is composed by several amplifier and filter.

This is the diagram we designed, and the bode diagram simulated by LT-Spice. During the actual construction process, the Bode plot is likely to change, resulting in slight deviations from the actual effect. However, we do not need all of the outcome value to be that specific, and here are the ideal Design specifications for each subsystem. The derivation of them is detailed in following part.

Subsystem	Specification
Power Supply (Tx and Rx)	±15V
Trans-Impedance Amplifier (TIA)	Bandwidth (fc) of between 3 MHz and 8 MHz
HPF (DC blocker)	Filter order = 1, Passive HPF, fc≤2kHz
Low Pass Filter, LPF-1	Filter order≥4, Active LPF, 3MHz≤fc≤8MHz
Amp-1 (pre-amplifier)	Voltage gain of 4 V/V
Amp-2 (post-amplifier)	Inverting amplifier, Variable gain= [0dB, 20dB]
LPF-2	Filter order≥1, Passive HPF, 3MHz≤fc≤8MHz
LPF-3	Filter order≥1, Passive HPF, fc = 100kHz

Table 1 Requirement for Each Subsystem

2. Subsystems:

(A) Power protection

We need a power supply for all of the amplifier chip we use. Because all amplifier chips will be connected to the same power grid. Therefore, a power protection is needed to prevent damage to other subsystems when a circuit in certain subsystem is short-circuited.
This is what we designed for power protection.

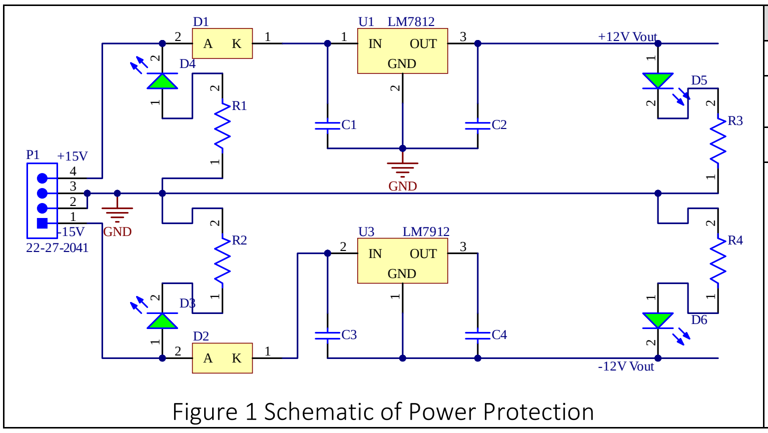


Figure 1 Schematic of Power Protection

Components	Value
R1, R3	2.2KΩ
R2, R4	33KΩ
C2, C4	0.1uF
C1, C3	0.33uF

Table 2 Value for Power Protection

(B) Trans-impedance amplifier

This is a subsystem with the function of converting microcurrent to voltage signal, and amplifier it. Because the output of Photo Diode is current. The schematic are as follows.

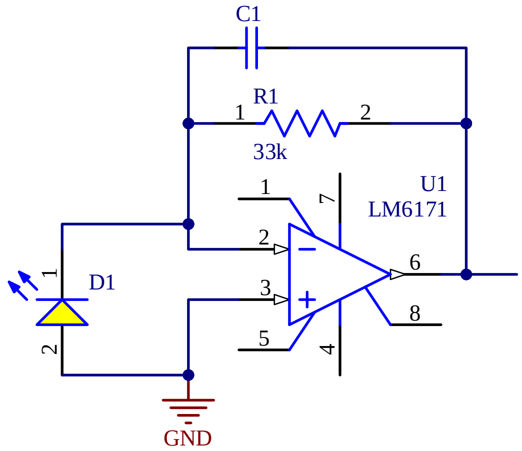


Figure 2 Schematic of TIA

C1 is optional, however the reason we need C1 is aiming to reduce the peaking phenomenon in Bode plots. We will come back to calculate the value when we get the overall bode plot for whole system.

With no C1, we can quickly deduce through the working principle of the amplifier:

$$V_{out} = -I_{PD} \times R_1$$

In theory, we can choose any value we want for R1. However, we have another restriction here. We are required to make a theoretical -3dB bandwidth located at 7 MHz. The theoretical -3dB bandwidth is given by:

$$f_{-3dB} = \sqrt{\frac{GBW}{2\pi C_T R_1}}$$

Where **GBW** is given in the datasheet of LM6171, which is **100MHz**. $\boldsymbol{C_{PD}}$ for the photodiode in this lab is **11 pF**. We assume $\boldsymbol{C_{IN}}$ to be **10 pF**. Therefore, the total capacitance ($\boldsymbol{C_T}$) on the inverting terminal of the op amp is **21pF**.

We got **R1 = 33k** ohms, then the $f_{c(TIA)} = \sqrt{\frac{100M}{2*\pi*21p*33k}} = 4.793MHz$.

(C) First order high pass RC filter

This part we are going to remove all of the DC component of the signal. So, we need a DC blocker. Where we decide

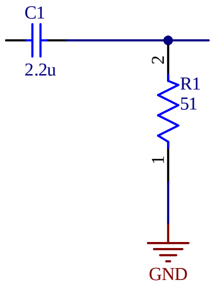


Figure 3 Schematic of HPF

Components	Value
R1	51Ω
C1	2.2uF

Table 3 Value of HPF

Therefore, the **lowest -3dB band boundary** is

$$f_{-3dB(HPF)} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2 \times \pi \times 51 \times 2.2 \times 10^{-6}} = 1419Hz$$

(D) Sallen-Key Active Filter

Sallen-Key is a tool included a 2-pole filter and an amplifier. We need more than 4-order filter; therefore, we need 2 Sallen-key in series. The diagram are as follows.

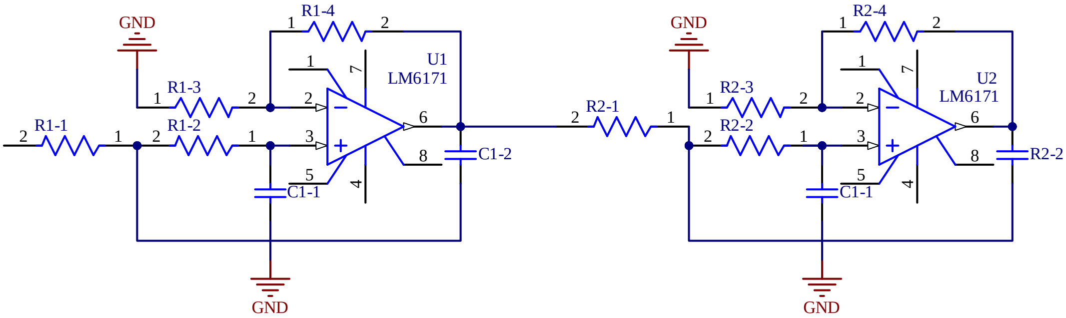


Figure 4 Schematic of Sallen-Key

From the guidelines of Active Low-Pass Filter Design, we are request to make our character close to this value. And also, to make sure our overall fc(3-8Mhz) and Gain meet the restriction, we finally decide these reference values.

	FSF	Q	Gain, K (dB)	Fc (MHz)
Stage 1	1.000	0.5412	1.1	3.0~8.0
Stage 2	1.000	1.3065	3	\

Table 4 Expected Characteristic of Sallen-Key

Where $fc = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$. And $Q = \frac{\sqrt{R_1R_2C_1C_2}}{R_1C_1+R_2C_1+R_1C_2(1-K)}$.

After Calculation, we find a series of value which is almost perfect for what we need.

	R1(Ω)	R2(Ω)	R3(kΩ)	R4(kΩ)	C1(pF)	C2(pF)
Stage 1	390	390	10	1	47	68
Stage 2	68	150	10	30	47	47

Table 5 Values of Sallen-Key

Let us recalculate the Q-factor and fc:

$$K_1 = 1 + \frac{R_{1-4}}{R_{1-3}} = 1.1, \qquad K_2 = 1 + \frac{R_{2-4}}{R_{2-3}} = 4,$$

$$Q_1 = \frac{\sqrt{390 \times 390 \times 47p \times 68p}}{390 \times 47p \times 390 \times 47p + 390 \times 68p(1-1.1)} = 0.51,$$

$$Q_2 = \frac{\sqrt{68 \times 150 \times 47p \times 47p}}{68 \times 47p + 150 \times 47p + 68 \times 47p(1-4)} = 1.31$$

$$f_{C1} = \frac{1}{2\pi\sqrt{390 \times 390 \times 47p \times 68p}} = 7.22MHz,$$

$$f_{C1} = \frac{1}{2\pi\sqrt{68 \times 150 \times 47p \times 47p}} = 33MHz;$$

Due to the f_{C1} extremely smaller that f_{C2}, we guess the overall cut-off frequency is close to the smaller one, which is 7.22MHz. However, based on our outcome from simulation on LT-spice and our experiment on Bread Board, the **cut-off frequency** is around **7.06MHz**:

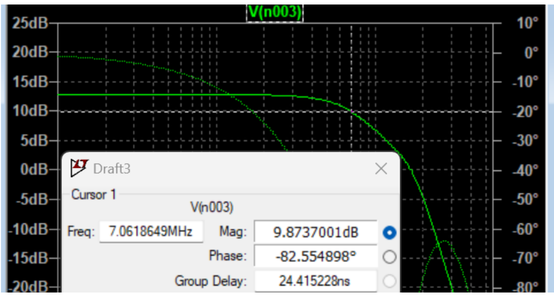


Figure 5 Simulated cut-off frequency of Sallen-Key

R3 and R4 decided the Voltage gain of the Sallen Key, and other 4 components decided the cut-off frequency of the Low pass filter. If you need different cut-off frequency for this system, you can switch the value of them a little bit, but I won't recommend that, because it will affect the Q-factor, which is an important indicator of filter accuracy and stability. A higher figure of merit means greater accuracy and less out-of-band interference. So, when you need higher Q-factor, please adapt R1, R2, which means don't change the fc after you settle down them.

(E) Post-amplifier (Inverting Amp)

We design it as an amp with variable gain. The gain need to varies between 0 to 10.

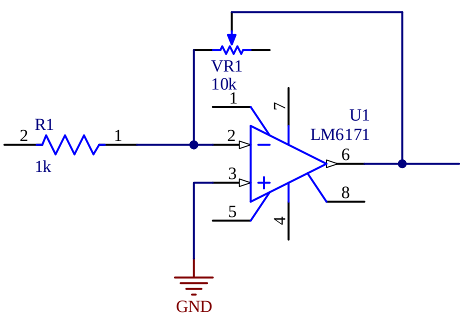


Figure 6 Schematic of Post-Amp

Components	Value
U1	LM6171
R1	1kΩ
R2	Variable resistance: max 10kΩ

Table 6 Values of Post-Amp

(F) PATH 1, Pre-oscilloscope, LPF-2

The main function is to eliminate all high frequency noise generated in the receiver circuit. The designed $\boldsymbol{f_{-3dB}}$ is equal to about **4MHz**, we have the formula for LPF, so we choose resistors and capacitors as follows:

PATH 2, Pre-speaker, LPF-3

The main function is to make the bandwidth similar to the range where human's ear could hear. The schematic is same as LPF-2, but the desired $\boldsymbol{f_{-3dB}}$ is **100kHz**, so we choose as follows:

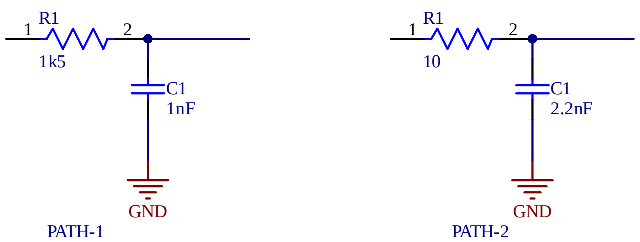


Figure 7 Schematic of LPF-2 & LPF-3

PATH	Components	Value
1	R1	18Ω
	C1	2.2nF
2	R1	1.5KΩ
	C1	1nF

Table 7 Values of LPF-3

(G) Audio Amplifier

The design of this subsystem is totally already in the datasheet of LM386. In datasheet you can choose a lot of different gain or other characters. The gain you choose is due to your voltage level before the audio amp. Here we choose this, which **gain** equal to **20**, the components value are as follows.

Components	Value
R1	10K
C1	0.05uF
R2	10
C2	250uF
U1	LM6171

Table 8 Values of Audio Amp

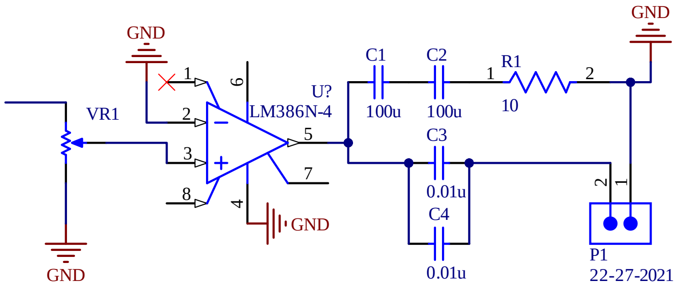
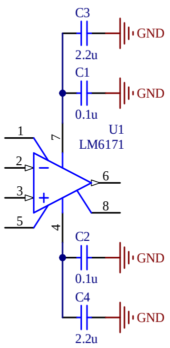


Figure 8 Schematic of Audio-Amp

(H) By-pass Circuit

 Figure 9 Schematic of By-pass	This is what we called by-passing. Bypassing the power supply is necessary to maintain low power supply impedance across frequency. On bread board and PCB, 0.01uF is too small to take the responsibility to undertake the commission, so we changed it to **0.1uF**.

3. Overall design:

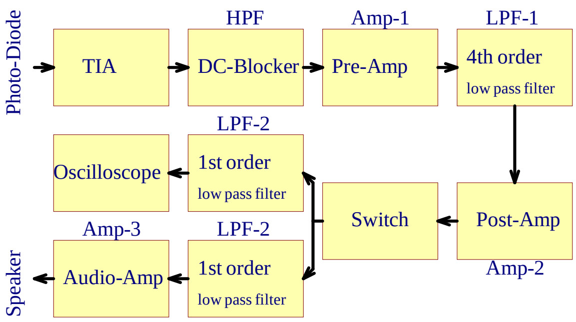


Figure 10 Flow Chart of Signal

We can conclude the signal-flow chart as above. This flow chart demonstrated the direction of the signal we wanted.

After designing the schematics, the schematic are as follows. Due to the space is limited, you can check the value of each subsystem in last part (the introduction of each part), also you can check the appendix.

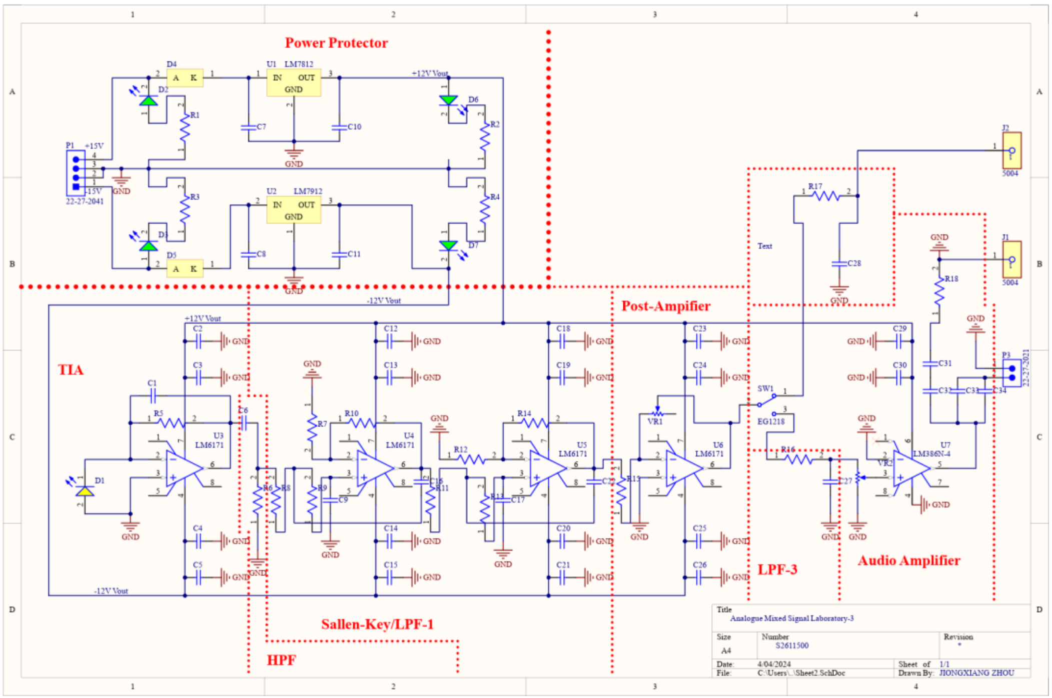


Figure 11 Overall Schematic

After checking twice, we can use EDA software to generate PCB schematic. We should clear the rules for PCB for this project:

Rules	Requirement
Clearance (Track Aura)	≥ 0.5mm
Power & GND Rail	≥ 1mm
Signal Tracks	≥ 0.5mm

Table 9 Rules for PCB Design

After setting up the rules, we can start out layout. All of the components should be laid on the top layer, and the tracks should be bottom layer. We are welcome that the number of jumper and bridge wire no more than 2.

The PCB schematic (2D and 3D) are as follows:

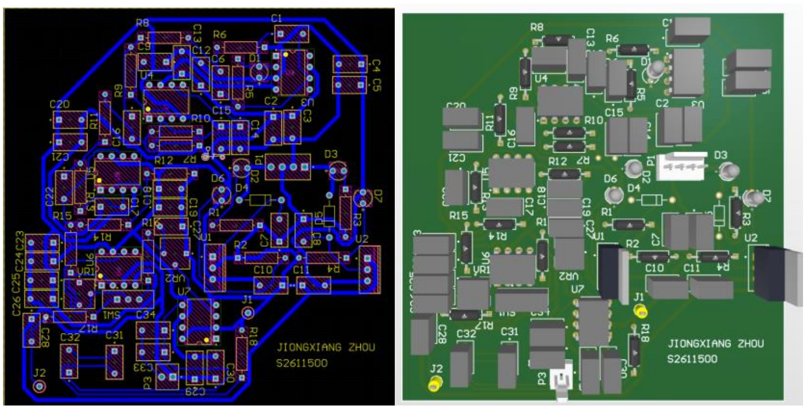


Figure 12 PCB-2D & 3D

Lab report PART B

1. TASK F & I

(i) Bread board

Task F request us to do an FRA (frequency response analyse) for our receiver. Our link should be as this diagram:

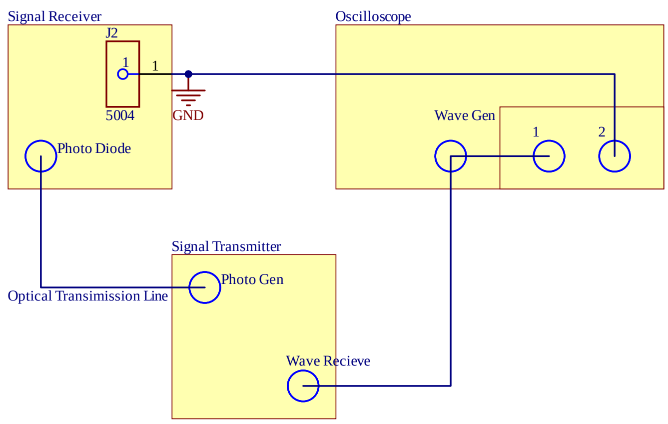


Figure 13 Link for Frequency Analyse

And the initial set up of signal source (Wave Generator) are as follows:

Name	Value
Wave Form	Sine
Frequency	200kHz
Amplitude	125mV

Table 10 Set-up of Wave Resource

Then we should turn up or turn down the variable resistor, so that the voltage level (peak to peak) of output is no more than 2V. Then we switch up the Amplitude of source gradually, at **step of 500kHz**, until we reach **8kHz**. Every time we change the Amplitude, take down the V_{out}. After all recording, calculate the Gain. Outcome table of Bread board are here:

Freq, f (kHz)	Vin (mV)	Vout (V)	Vout/Vin	Gain	Vin (mV)	Vout (V)	Vout/Vin	Gain
	Bread Board				PCB			
200	125	0.659	5.272298614	**14.44**	125	0.667	5.339492736	**14.55**
500	125	0.658	5.266232149	**14.43**	125	0.666	5.327212243	**14.53**
1000	125	0.698	5.584701947	**14.94**	125	0.690	5.520774393	**14.84**
1500	125	0.741	5.929253246	**15.46**	125	0.750	5.997910763	**15.56**
2000	125	0.785	6.280583588	**15.96**	125	0.794	6.353309319	**16.06**
2500	125	0.788	6.30231346	**15.99**	125	0.815	6.516283941	**16.28**
3000	125	0.758	6.060382005	**15.65**	125	0.789	6.309573445	**16**
3500	125	0.653	5.22396189	**14.36**	125	0.692	5.539875439	**14.87**
4000	125	0.484	3.868120546	**11.75**	125	0.484	3.872576449	**11.76**
4500	125	0.314	2.511886432	**8**	125	0.324	2.591194421	**8.27**
5000	125	0.204	1.634933151	**4.27**	125	0.208	1.667247213	**4.44**
5500	125	0.132	1.053173687	**0.45**	125	0.138	1.10153931	**0.84**
6000	125	0.079	0.630957344	**-4**	125	0.092	0.732824533	**-2.7**
6500	125	0.045	0.362242998	**-8.82**	125	0.058	0.46398079	**-6.67**
7000	125	0.027	0.217770977	**-13.24**	125	0.035	0.282487997	**-10.98**
7500	125	0.016	0.126182753	**-17.98**	125	0.021	0.166149868	**-15.59**
8000	125	0.010	0.079067863	**-22.04**	125	0.013	0.104833479	**-19.59**

Table 11 Frequency Response on BB & PCB

(ii) PCB

(Same, Process has been omitted)

Compare 2: Different Condition in Diagram (between BreadBoard & PCB)

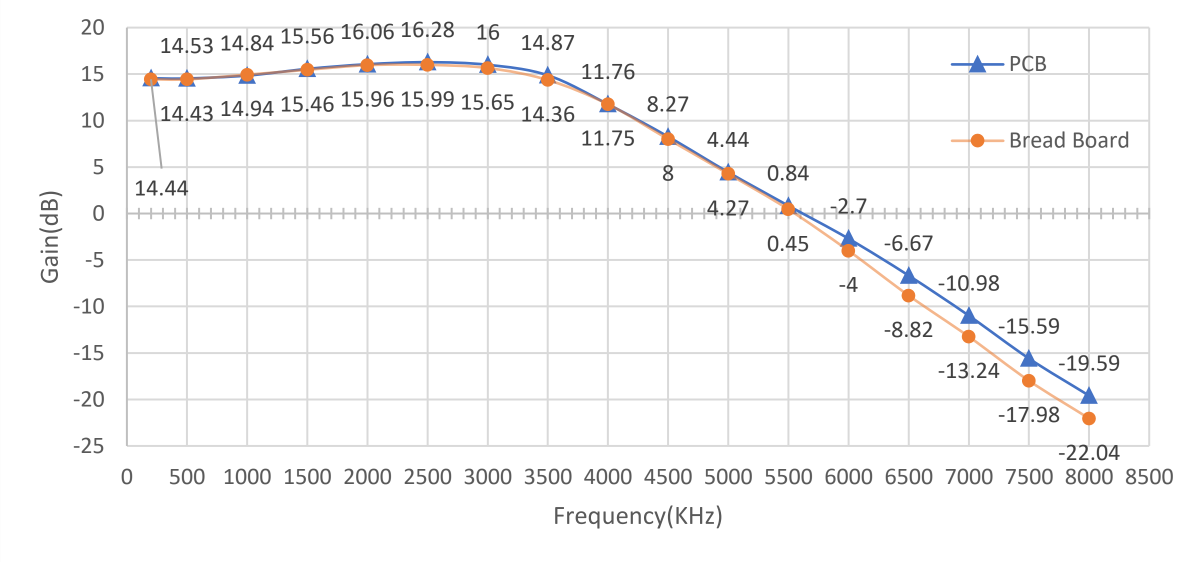


Figure 14 Bode Plot

We can see the peaking is not that obvious, and the flat band is perfect, and the f_{-3dB} are located at around **4.00MHz**, which meets the requirement.

The different between the Bread Board and PCB is might because the unavoidable inside capacitance with in the bread board, or the magnetic field of tracks are different and so on. This issue may all cause the difference between PCB and Bread Board. However actually, the error is acceptable.

Comment 1: Practical Bandwidth versus Expected Bandwidth

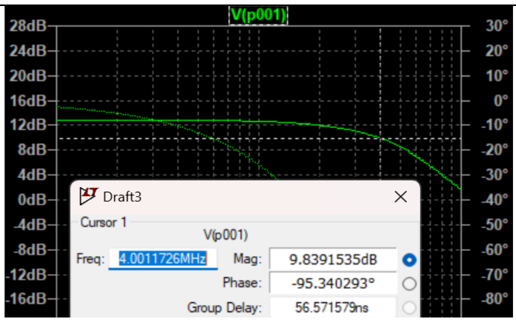


Figure 15 Expected Bode Plot (Simulated by LT-spice)

Subsystem	Bandwidth (f_{-3dB})
LPF-1	7.06MHz
LPF-2	4.02MHz

Table 12 Expected Bandwidth of Subsystems

There is a huge gap between the bandwidth of LPF-2 and LPF-2. Therefore, our expectation is that the cut-off frequency is almost dominated by the smaller one, which is LPF-1, which is around **4.0MHz**. It is the same as we get from our bode plot. So, the establishment of the circuit is overall successful. More analyse about FRA can refer to Sallen-Key.

Comment 2: Frequency Response Shape

Within the passband, the flatness is good, which means in the pass band(1419Hz-4.0MHz), signals could be amplified stably and effectively. At the end of the pass band, no peaking phenomenon. In this condition, we do not need to apply a huge capacitor in TIA, after calculation, we got the optional capacitor in TIA is around 4.7nF. According to experiment we get, this small capacitor didn't create too much difference after applying it, the bode plot are the same as we had last time, so the outcome is omitted here.

In the stop region, the magnification decreases monotonically and steadily without fluctuations. This shows that our system can effectively suppress signal transmission in the area after 4MHz.

2. TASK J

Link characterisation can be measured by Rise and Fall times. We should use rectangular pulse to see how many times the output will take to get stable. The connection is the same to task I. The setup for the signal generator is as follows:

Name	Value
Wave Form	Rectangular/Pulse Wave
Frequency	100kHz
Amplitude	125mV
Duty Cycle	50%
Output Impedance	50Ω

Table 13 Set-up for Wave Resource

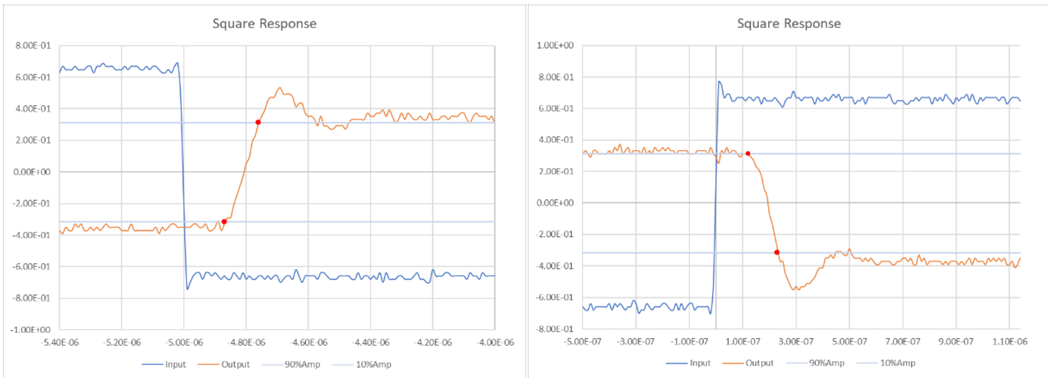


Figure 16 Square Response

The red dot displayed are the time when the output reach 10% amplifier and 90% amplifier. Therefore, what we want is the subtraction of their X-value.

Then we can measure the rise time and fall time on the digital oscilloscope. The outcome is:

<table>
<tr><th>Name</th><th>Time</th><td rowspan="3">$B_{theoretical} = \frac{0.35}{t_r} = 3.89MHz$</td></tr>
<tr><td>Rise Time (t_r)</td><td>90ns</td></tr>
<tr><td>Fall Time (t_f)</td><td>88ns</td></tr>
</table>

Table 14 Rise & Fall time

<u>Compare: Practical Bandwidth and Estimate Bandwidth (from rise time)</u>

We can get **B = 3.89MHz**, which is in the range of ±2.75% of the practical value, which is acceptable.

3. TASK K

Keep the same set up as in task J, using the square wave whose amplitude is **125mV**. We can find that the received signal peak to peak Value, $\boldsymbol{V_{Rxd}}$ **= 1.094V**. Assuming R_{load} = 50Ω.

$$P_{Signal} = \frac{(V_{Rxd})^2}{4R_{load}} = \frac{0.698^2}{4 \times 50} = 0.0024(Watt)$$

Then we turn off the signal resource, which make the output are totally controlled by noise. We repeated the same process as in task J, export the Voltage-time plot to PC. Use the data analysis function of Excel to count the frequency of different levels of voltage during one oscilloscope detection period, and calculate the variance. We expect that the histogram should roughly show a normal distribution, which also means that the noise the receiver create is normal.

Using the formula in excel: VAR.P to calculate the variation of V_{Noise}. Then we get the $\boldsymbol{\sigma^2_{Noise}} = \mathbf{2.72 \times 10^{-5}}$. Estimate the signal-to-noise ratio, SNR, using:

$$SNR = \frac{P_{Signal}}{\sigma^2_{Noise}} = \frac{0.0024}{2.72 \times 10^{-5}} = 88.235$$

Using Shanon equation to estimate maximum possible data rate, R:

$$R \leq B \log_2(1 + SNR) = (4.0M) \log_2(1 + 88.235) = 2.592 \times 10^7 bps(bits\ per\ seconds)$$

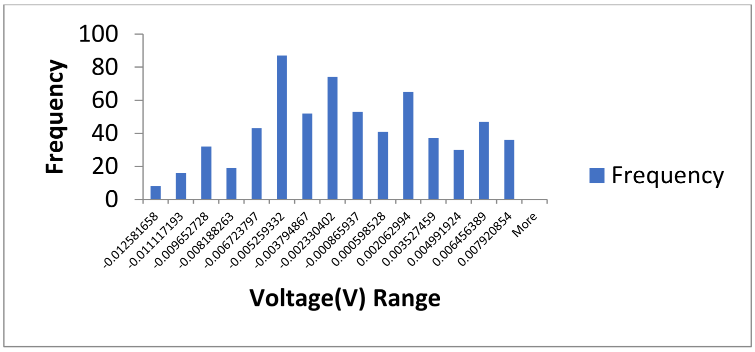


Figure 17 Histogram of Noise Distribution

When the transmission line caries an OOK data, the overall Q-factor could describe the merit that relates to the error performance.

$$Q - factor = \frac{V_{Rxd}}{2\sigma_{Noise}} = \frac{0.698}{2 \times \sqrt{2.72 \times 10^{-5}}} = 66.918$$

Discuss: estimated maximum attainable data rate, R, and the Q-factor in relation to error performance

Shannon Theorem demonstrated that when the information rate is smaller than (or equal to) the channel capacity C, then in theory, there must be one or more specific way to make the information transmit through the channel with an arbitrary small error probability. Based on the outcome we calculated above, we can see our transmitter-optical line-receiver as a channel, whose capacity (**max data rate**) is $\mathbf{2.592 \times 10^7}\,\boldsymbol{bps}$, which equal to $\mathbf{25.92}\,\boldsymbol{Mbps}$. This order of magnitude is comparable to some high-speed broadband connections such as fibre optic broadband. This also shows the reliability of optical cable communication. Also in fact, our channel is short, so the signal-to-noise ratio is relatively large, which makes the maximum transmission efficiency appear to be very high.

About the Q-factor, through the above formula, we can easily find that the Q factor in this experiment is the square root of the signal-to-noise ratio. Signal-to-noise ratio and Q-factor are therefore closely related. The Q factor represents the ratio of the energy stored by the system at the resonant frequency to the energy lost per cycle. The higher the Q factor, the stronger the energy storage capacity of the system and the larger the amplitude. At the same time, the bit error rate is reduced, thereby improving the signal quality. The value of **Q factor** measured in this experiment is **66.918**, which is generally considered good in electronics.

Appendix.

I. Components Detailed Model:
Integrated Circuits (IC): TI LM6171BIN(LM6171), TI LM386N-4(LM386), TI LM79(LM9171), TI LM78L12;/ **Resistor**: Yageo MFR-25FBF52-47K5;/ **Capacitor**: KEMET C330C105M5U5TA (Pitch 5.08mm) & Kyocera AVX TAP105K035SCS (Pitch 2.54mm) ;/ **Connector**: Molex 70553-0038(4-way), Molex 70543-0036(2-way), Sullins PBC01SAAN;/ **Photodiode**: Vishay TEFD4300F;/ **LED**: Broadcom HLMP-3301;/ **Potentiometer**: Bourns 3362P-1-104LF;/ **Diode**: Diotec 1N4007.

II. Specific terminal Pitch Recommend		
Components	**Value**	**Pitch**
Resistor		7.62mm
Capacitor	47pF, 68pF, 0.01uF,	2.65mm
	other	5.08mm