DEPARTMENT OF ELECTRONIC AND TELECOMMUNICATION ENGINEERING
UNIVERSITY OF MORATUWA

Project Report

EN2090 - Laboratory Practice - II

# Analog Lux Meter



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**Abstract**

This project was done to implement a Lux meter using analogue circuitry. The Lux meter is used to measure the luminous flux per unit area.Defining high accuracy and steadiness in readings is the main problems when designing a lux meter.The results that were generated by the Lux meter were compared with a commercial grade Lux meter. We did a discussion based on the results generated by the implemented Lux meter. The report contains detailed descriptions about the circuits and a discussion about the results.

# Contents

# 1 Introduction

The Lux Meter measures the luminance flux per unit area[1]. This value varies greatly with respect to its location and even with a small change in illuminance. Even if,human eye is very sensitive to illuminance(light intensity travelling per unit area to any given direction)[2], the feature illuminance is immeasurable to the human eye. Therefore, an instrument which deals with a wide range of lux values and can reproduce the same value at the relevant lighting condition again and again is necessary to measure the illuminance. This instrument is called lux meter.

Commercial lux meters (Figure 1) are manufactured using complex components and many ASIC (Application Specific Integrated Circuit)s. As instructed we try to use basic analogue electronic components such as operational amplifiers, transistors, diodes etc. to implement the meter. A TEMT 6200 photo transistor is used in sensing the light intensity.It directly outputs a voltage proportional to the light intensity. An Atmega328P microcontrollers are used to drive the LCD display and for analog digital conversions.

After careful analysing and testing of several types of circuits, we came up with the most appropriate circuit design to implement the concept. There are several practical problems that we faced while designing and implementing the design, making selections and justifications, limitations of the components and many other issues related to power, performance and area.We referred data sheets to find appropriate solutions to realize the design.

This report presents the method which we used to develop our device in several stages, the practical problems we faced, selections and justifications, limitations and measurements of our device with comparison to another commercially available lux meter which we used for the calibration of our device as well as the problems we encountered in the process of developing this device and the solutions.


Figure 1: A Commercial Lux Meter [3]

# 2 Method

## 2.1 Components used

The design is divided into four categories for the ease of analysis. The four parts and the main components in those parts are as follows.

1. Amplification and Clipper Circuit
   (a) TEMT6200
   (b) LT1097
   (c) DG419
2. Digital implementation and comparator circuit
   (a) TL072
   (b) TTL7432
   (c) TTL7408
   (d) 2N3904
3. Microcontroller circuit
   (a) ATMega328P
   (b) ICSP connector
   (c) Rotary Encoder
   (d) Graphic LCD
   (e) ADS1115
4. Power supply circuit
   (a) MC34063
   (b) 1N5819 Schottky diode
   (c) LM7909
   (d) LM7805
   (e) LM7809

## 2.2 Selections, justifications and other alternatives

1. Amplification and Clipper Circuit

   (a) **Photo Sensor**
   The photo sensor is the most important component of this instrument because the whole functionality depends on the input from the light sensor.There were three possible types of light sensors that could be used to implement the lux meter.

   - Light Depending Resistor (LDR)
   - Photo diodes
   - Photo transistor

   The Light Depending Resistor (LDR) is one of the cheapest options that we had. The resistance changes with the illuminance in the LDR. If we were to use a LDR we had to use it in a Wheatstone bridge arrangement and the error will be high. Apart from that, when considering about the sensor, the sensitive illuminance[4] is from 0 to 10klx and the sensitive wavelength or spectral response[4] is from 350nm to 850nm which also includes the upper IR and lower UV regions which are unnecessary for our purpose. Therefore, we avoided using a LDR.
   The photodiode is also a possible light sensitive device which can be used in the implementation. It emits electrical current which is proportional to the light falling on it. Therefore, its use is relatively easy. The issue with the photodiode is its sensitive wavelength lies from 790nm to 1050nm and the peak wavelength is around 850nm[5]. It is out the range that we are concerned of.
   The phototransistor, being another possible component was selected by us for the implementation as photo transistor enables a higher current flow than the photodiode[6]. Apart from that, the phototransistor that we used *TEMT6200* has a sensitive wavelength in the 450nm to 610nm with a peak wavelength of 550nm[7] which makes it ideal for our purpose. When compared with the photodiode[5], it has a slower response time but it is a potential advantage because there can be time delays witnessed in our sequential logic implementation. Among the available phototransistors, there were two options with *TEMT6000* and *TEMT6200* but the TEMT6000 has a lower wavelength sensitivity including the higher IR region[8] but TEMT6200 has an IR blocking filter.

   (b) **Amplifier**
   As the maximum current flow through the phototransistor is around 20mA[7], the voltage output of the by the sensor is very small. Therefore, it needs to be amplified. To construct the non-inverting amplifier, we used an OpAmp *LT1097CN8*. We first thought of using an instrumentation amplifier which we selected as AD620AN. It has a high CMRR of 110dB[9] which is good but is very expensive. The more conventional OpAmps like TL072 have less CMRR which is not suitable for such sensitive applications. Therefore, we found *LT1097CN8* which is a Low Cost, Low Power Precision Op Amp to be more suitable with a high CMRR of 130dB and a favourable offset voltage of 50µV[10]. As it is cheaper than the instrumentation amplifier IC and has a higher CMRR, we selected LT1097CN8 to implement the non-inverting amplifier. The factors like slew rate and the GBP(Gain Bandwidth Product) is not considered as it is not a high frequency application.

(c) **Analog Switch**
The analog switch is used to change the gains of the amplifier that is used in the circuit. We used *DG419* which is a monolithic CMOS analog switch due to its low power consumption, low leakages, high speed and low on-resistance. It is a Single Pole Dual Throw Switch (SPDT)[11] which connects one of two lines to a common line. From other analog switches like DG417 and DG418, the DG 419 was selected due to its guaranteed Break-before-make[11] where on connection is completely opened before closing the other line. DG419 also has a special layer to prevent Latch-up caused in analog switches. Apart from that, the switching time is 100ns[12] and it gives time for the control signal stabilization. The on-resistance is 20Ω[12] and it is negligible when compared with the resistors used to set the gain which helps to maintain the accuracy of the amplifier circuit.
For the implementation of clipper and filter, we used the commonly used TL072 OpAmp.

2. Digital implementation and comparator circuit

(a) **Digital Circuit**
For the logic implementation we had two options of either using TTL logic or CMOS logic. The CMOS logic has less power dissipation but the propagation delay is higher than TTL[13]. As the timing is more crucial in the implementation for this design, we chose TTL logic ICs. For the sequential logic implementation, we chose a Latch over a Flip-Flop to eliminate the need of a timing circuit which will inherently complex the design. There were different types of latches available and among them, we used the D Latch because it gave the simplest logic circuit possible, reducing the propagation delay.

(b) **Comparators**
The comparators are used to determine the voltage levels and due to implement the comparators we used TL072 Op-Amps by following the basic characteristic of the Op-Amp. It would have been better to use single supply Op-Amps like LM358 and LM2904 as we intend to get 0 and 1. We overcame the issue related to TL072 by using a transistor switch with 2N3904 general purpose NPN transistor.

3. Microcontroller circuit

(a) **Microcontroller**
The microcontroller is used to drive the Graphic LCD to display the output of the implemented Lux-meter. As a large number of GPIO pins are not necessary for this implementation, we chose the ATMega328P considering both its size and cost.

(b) **ICSP connector**
In the PCB, we included a In-circuit Serial Programmer connector due to the ease in calibration. We can easily change the calibration constants after the complete implementation done to suit the purpose.

(c) **Display**
There are various types of displays like $16 \times 12$ LCDs and OLEDs. We chose a Graphic LCD because we preferred a larger display. The Graphic LCD has $128 \times 64$ display and draws only 7.5mA[14].

(d) **Analog to Digital Conversion**
The ADC is used to convert the analog inputs to digital to be able to be display in the LCD. Normally the ADC can be done using the ADC pins in the microcontroller but the microcontroller only supports up to 10 bit ADC[15]. But to increase the accuracy and the sensitivity of the implementation, we decided to use an external ADC. Therefore, we used the ADS1115 which is a low-power, 16-bit, $I^2C$ compatible ADC[16].

4. Power supply circuit

(a) **Power regulators**
As we intended to supply power thorough a battery to make the implementation portable, there was an issue of maintaining a constant supply voltage of 9V because the real voltage of a battery with 9V nominal voltage tends to differ greatly. Therefore, we decided to boost the voltage first and then regulate it to 9V. apart from that, due to dual rail Op-Amps that we are using,-9V voltage is also necessary. We were posed with the challenge to get a negative voltage and the need of an inverter also emerged. Taking all these into account and considering the professional standards in creating a marketable product, we settled on using a standard 9V cell.
To act as a step-up booster and an inverter, we used the *MC34063* switching voltage regulator. The main reason to use it, is the ability of it to use as both booster and an inverter. The problem arose with MC34063 due to the ripple in the output inherent to DC-DC converter but again with the use of capacitors in the linear regulator LM7809 we could obtained a satisfactory waveform.
As the LM7809 needs at least a voltage drop of 2.5V[17] we used it to regulate 12V to 9V. Another LM7805 is used directly to regulate the supply voltage to 5V. In the inverter, we had the issue of ripple which was inherent to switching voltage regulator, we obtained an output voltage of -12V from MC34063 and then regulated it using linear voltage regulator LM7909. We could have used Switched capacitor voltage convertors that perform supply voltage conversion form positive to negative like LT1054 and TL7660. The issue with them is that high currents above 100mA[18] cannot be drawn through them. Therefore, we settled on to use the MC34063.

(b) **Schottky Diodes**
To use the MC34063 it is necessary to have a diode. The best selection for this is Schottky diode. We selected a Schottky diode due to the following three reasons. Fast response time, Ability to work in higher frequency and the low barrier voltage. We selected 1N5819 because it has a high reverse voltage.

## 2.3 Circuit Development

### 2.3.1 Amplifier and Clipper circuit

The main component of the implemented lux meter is the light sensor. For the light sensor we have used a photo transistor as justified above. The phototransistor generates a current based on the amount of light falls on it. the base of the transistor is the light source. A voltage is created across the resistor as the generated current flows through it. As the current generated by the photo transistor is small, the voltage directly shown across the resistor will not be sufficient to be displayed. Therefore, this voltage should be amplified and for that a non- inverting amplifier is used here we used a non-inverting amplifier to prevent the inverting of voltage and non-inverting amplifier always guarantee that the voltage is amplified. We designed an amplifier that can switch the gains based on a logic value. A detailed calculation on the amplifier can be found below.The amplifier circuit is shown in Figure 5 in Appendix A.

1. High Gain stage

   $$Voltage\ gain \ = \ 1 + \frac{R_F}{R} \ = \ 11$$

2. Low Gain stage

   $$Voltage\ gain \ = \ 1 + \frac{R_F}{R} \ = \ 1 + \frac{10}{2000} \ \approx \ 1$$

Then we propagate the amplified output to the next stage. As we did the implementation and calibration of the lux meter, in an artificially illuminated environment, we show the effect of artificial light sources affecting the lux values. As those light sources are supplied from 50Hz source, this noise also had 50Hz frequency which we needed to remove from the design. Therefore, we implemented a low pass filter. There were two viable options of an active low pass filter with a buffer and no amplification or a passive low pass filter. With the implementation of a passive low pass filter, we witnessed the attenuation of the waveform when a load was applied to the output of the filter. This was not favourable for our design. The filter circuit is shown in Figure 6 in Appendix A.
The calculation for the cut-off frequency of the implemented low pass filter can be found as shown below.

$$Cut-off\ frequency \ = \ \frac{1}{2\pi RC} = \ \frac{1}{2\pi 1000 \times 47 \times 10^{-6}} \ = \ 33.863Hz$$

Apart from these changes done to the waveform, there were abnormalities visible. Even if we intended to set the waveform between 0 to 5V. There are instances where voltage exceeds 5V and times when voltage becomes negative. The prominent reason for this is the use of a 9V dual rail supply Op-Amps for the design. On the other hand, electromagnetic interference and other surges related to the power supply can contribute to this issue. To address the above issue, we implemented a clipper.
The clipper had two objectives namely, clipping voltages above 5V and clipping the negative voltages we also had two options with clipper namely, diode clipper and the Op-amp precision clipper. When considering the diode clipper, there is a practical difficulty in setting the voltages of reference because the barrier voltages of the diodes must be taken into account. Even the output can get attenuated when a load is connected as diodes can sink current. Even considering these issues, we decided to implement an Op-Amp precision clipper. The first clipper is used to clip the voltages above 5V. here the input voltages supplied to the inverting terminal of the Op-Amp and the non-inverting terminal is supplied with 5V. when the input voltage exceeds 5V, the output terminal of the Op-Amp output –9V according to the characteristic of Op-Amp. Then the diode becomes forward biased. As the forward bias resistance of the signal diode 1N4148 is very small and has a very high reverse bias resistance, the signal diode acts almost like a switch. As the forward bias resistance very less, the clipper turns into a unity gain. Amplifier with 5V of output and it does not change with the load applied. When the voltage at the inverting terminal of the Op-Amp less than 5V. The output terminal of the Op-Amp has a voltage of 9V according to the

characteristic of the Op-Amp. Then the signal diode has a reverse bias and the negative feedback of the Op-Amp gets removed. By the other connection, the voltage below 5V can be seen in the second stage which implemented to clip the negative voltages.The clipper circuits are shown in Figure 7 in Appendix A.

### 2.3.2 Microcontroller circuit

The output from the clipper is now in an ideal state to be sent to the ADC. If a higher voltage is sent to ADC, it will cause latch-up and destroy the ADC. Normally the ADC of the microcontroller is only 10bits but we used an external ADC of 16bits to increase the resolution, the more faithful the digital signal will be to the original the range of the sampler is 5V. The following parameters related to the ADC can be calculated.
$Resolution = \frac{V_{max}-V_{min}}{2^N} = \frac{5}{2^{16} = 7.5\times10^{-5}\text{V}}$

The microcontroller circuit is shown in Figure 10 in Appendix A.

### 2.3.3 Digital implementation and comparator circuit

The Switching circuit uses a sequential logic circuit to switch between the Lux range based on the output voltage given to the microcontroller.

#### Digital Circuit

A denotes the state in the sequential logic circuit. $A = 0$ denotes that the lux range 1-1000lx. $A = 1$ denotes that the lux range is 1klx to 10klx. Using the analogue switch, $A = 0$ changes the gain of the amplifier from to 11 and $A = 1$ changes the gain approximately to 1. A depends on X and Y which are the inputs of the circuit. X and Y are obtained as follows.
The following calculations are done with relation to the Figure 2.
$X = 1 : \ V_{out} > 5 \times \frac{1.5}{1.5+8.2} = 4.23\text{V}$

$\overline{Y} = 1 : \ V_{out} > 5 \times \frac{120}{1500+120} = 370\text{mV}$

Here $V_{out}$ is the voltage that is given as an input to the microcontroller for ADC and the output of the analogue circuit.We used TTL Logic to implement the sequential logic circuit because the propagation delay is less and it is around 10ms.
In this implementation, the $3^{rd}$ and the $7^{th}$ instances of the Table 1 are not considered.

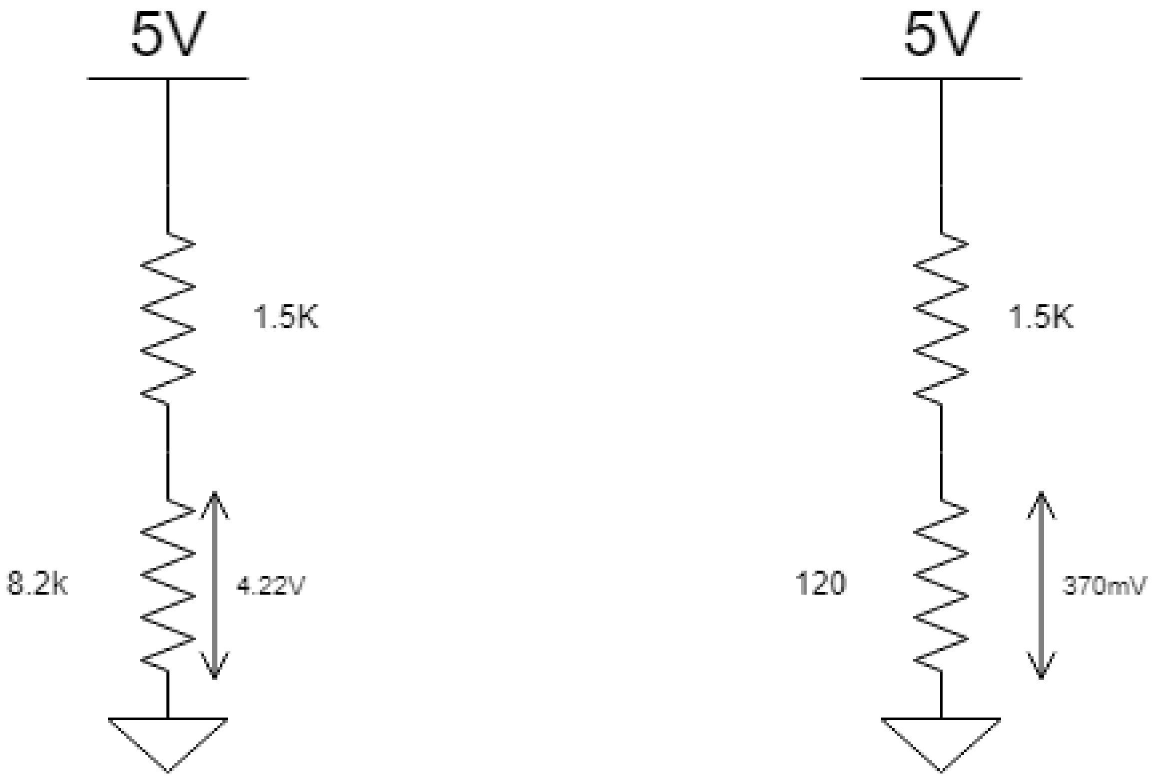


Figure 2: Potential divider circuits to obtain X and $\overline{Y}$

| | Present State | Inputs | | Next State | $D_A$ |
|---|---|---|---|---|---|
| | A | X | $\overline{Y}$ | A | |
| 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 1 | 0 | 0 |
| 3 | 0 | 1 | 0 | 1 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 |
| 5 | 1 | 0 | 0 | 0 | 0 |
| 6 | 1 | 0 | 1 | 1 | 1 |
| 7 | 1 | 1 | 0 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 |

Table 1: The excitation table of the sequential logic circuit

Using the Table 1, the digital circuit can be designed.
According to the K-Map shown in Table 2, it is clear that;

| A | $X\overline{Y}$ | 00 | 01 | 11 | 10 |
|---|---|---|---|---|---|
| 0 | | 0 | 0 | 1 | 1 |
| 1 | | 0 | 1 | 1 | 1 |

Table 2: The Karnaugh Map of $D_A$

$$D_A = X + A.\overline{Y}$$

The Figure 3 can be drawn using the expression obtained from the Table 2. The schematics of the logic

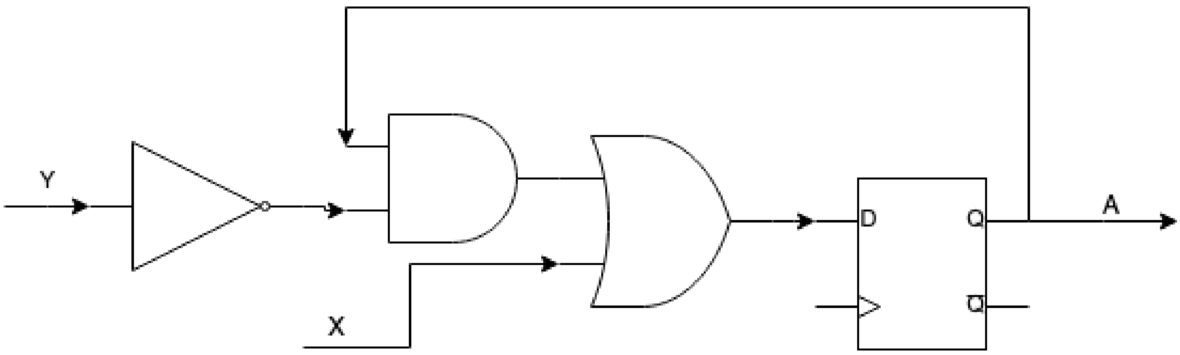


Figure 3: The implementation of logic circuit using logic gates

implementation is shown in Figure 9 in Appendix A.

### 2.3.4 Power Supply circuit

The power supply is one of the crucial elements of the implemented lux meter. As we can not obtain exactly 9 V from a standard dry cell with a nominal voltage of 9 V. We implemented a step up booster to boost 9 V to a value around 12 V. Then again we used a linear LM 7809 to regulate the 12 V to 9 V because it requires a minimum voltage drop of 2.5V[17].The Step Up booster circuit is shown in Figure 11 in Appendix A.
Apart from that, to get a negative voltage to supply the dual rail opAmps that we are using , we again made an inverter using the same MC 34063. The following calculations show the design of the power supply circuits.

$$|V_{OUT}| = 1.25 \times ()1 + \tfrac{12}{1.5} = 11.25V$$

When considering the inverter, same resistor values can be used. Even if we needed an output voltage of 11.5V to exactly meet the requirements of the LM7809. Even this voltage was sufficient.The inverter circuit is shown in Figure 12 in Appendix A.

## 2.4 Calibration

After the successful implementation of the lux meter, it is necessary to calibrate the ADC voltage readings to display the corresponding lux value. To determine the corresponding lux value we used the Hitoki commercial lux meter obtained from the workshop. Therefore, the accuracy of the implemented lux meter is analogous to the commercial lux meter used for calculation. To get the necessary ambient light conditions of different lux values, we made a light box using an old cardboard box and a LED panel from an old LED bulb. After desoldering the malfunctioning LEDs we bought the LED panel to a working condition and did the calibration using that, we were able to get values in the range of 0 to 3000 lx using the prepared lux meter but for the higher lux values we couldn't obtain consistent values. After obtaining a sufficient number of values, we used a least square fit to obtain a parabola including most of the values.

### 2.5 Enclosure Designing

To make the implemented lux meter attractive and ensure the safety and probability of the implemented lux meter, we decided to make an enclosure . The enclosure was designed using solid works and the raw material was ply wood. Then we also included a diffuser together the ambient light and make it properly fall on the sensor. The Figure 13 in the Appendix B shows the implemented lux meter. The sensor is made as a separate module which is able to be separated from the display module to ensure the ease in obtaining the readings.

# 3 Results

After embedding the modified code into the MCU to display lux values, again we compared the implemented lux meter with the commercial lux meter. Then we obtained a graph plotting both the implemented lux meter readings and the commercial lux meter readings.

The Figure 4 shows the comparison of the two lux meters namely the implemented lux meter and the

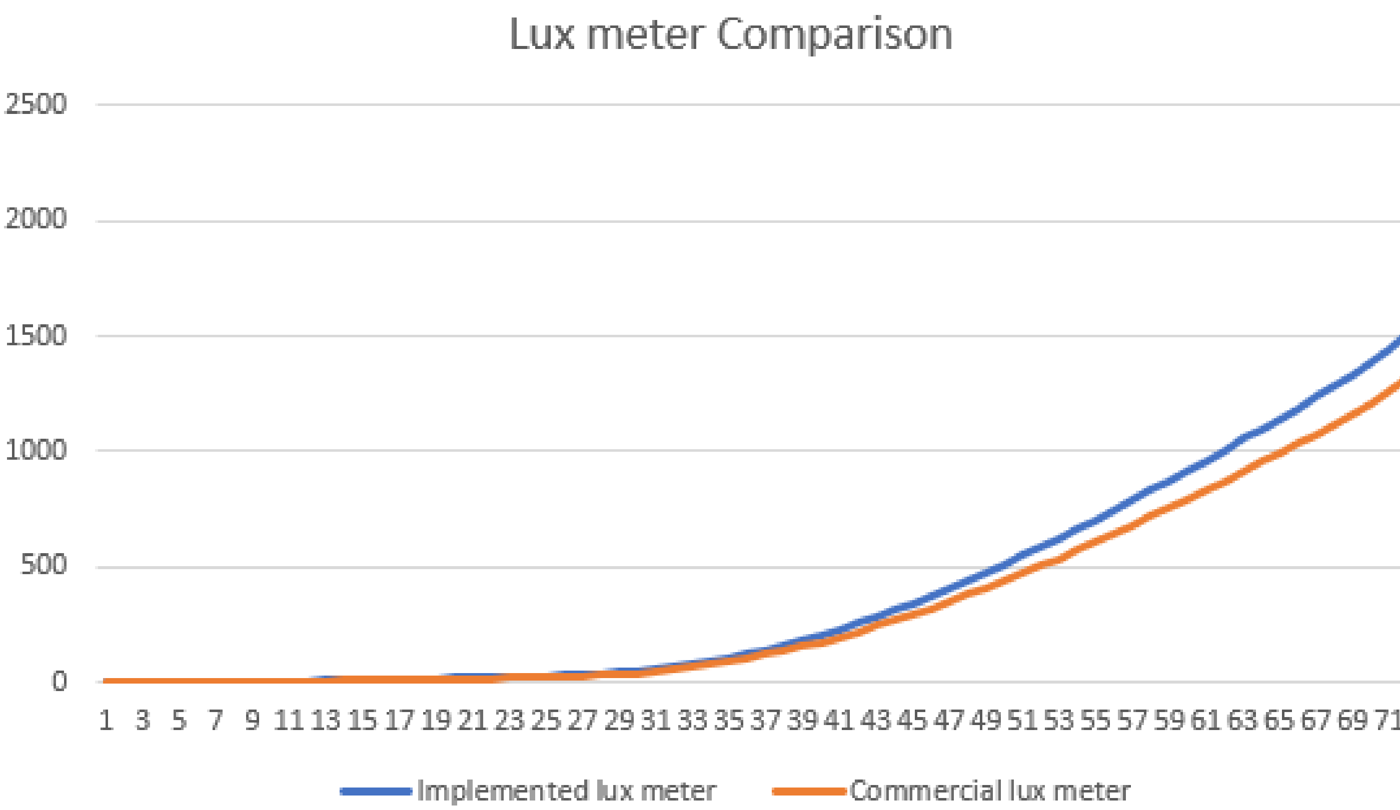


Figure 4: The comparison of the values of the two lux meters

commercial lux meter based on 75 values taken in the lower lux range because the light box that we implemented was impotent to provide us with higher lux values.

# 4 Discussion

As seen from the graph, the lux meter performs well in the lower lux range where calibration was properly done. Apart from that we could notice a very high response time comparative to the lux meter. Therefore , we can conclude that the implemented analog lux meter is a proper implementation of a lux meter.

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# Appendices

## A Circuit schematics

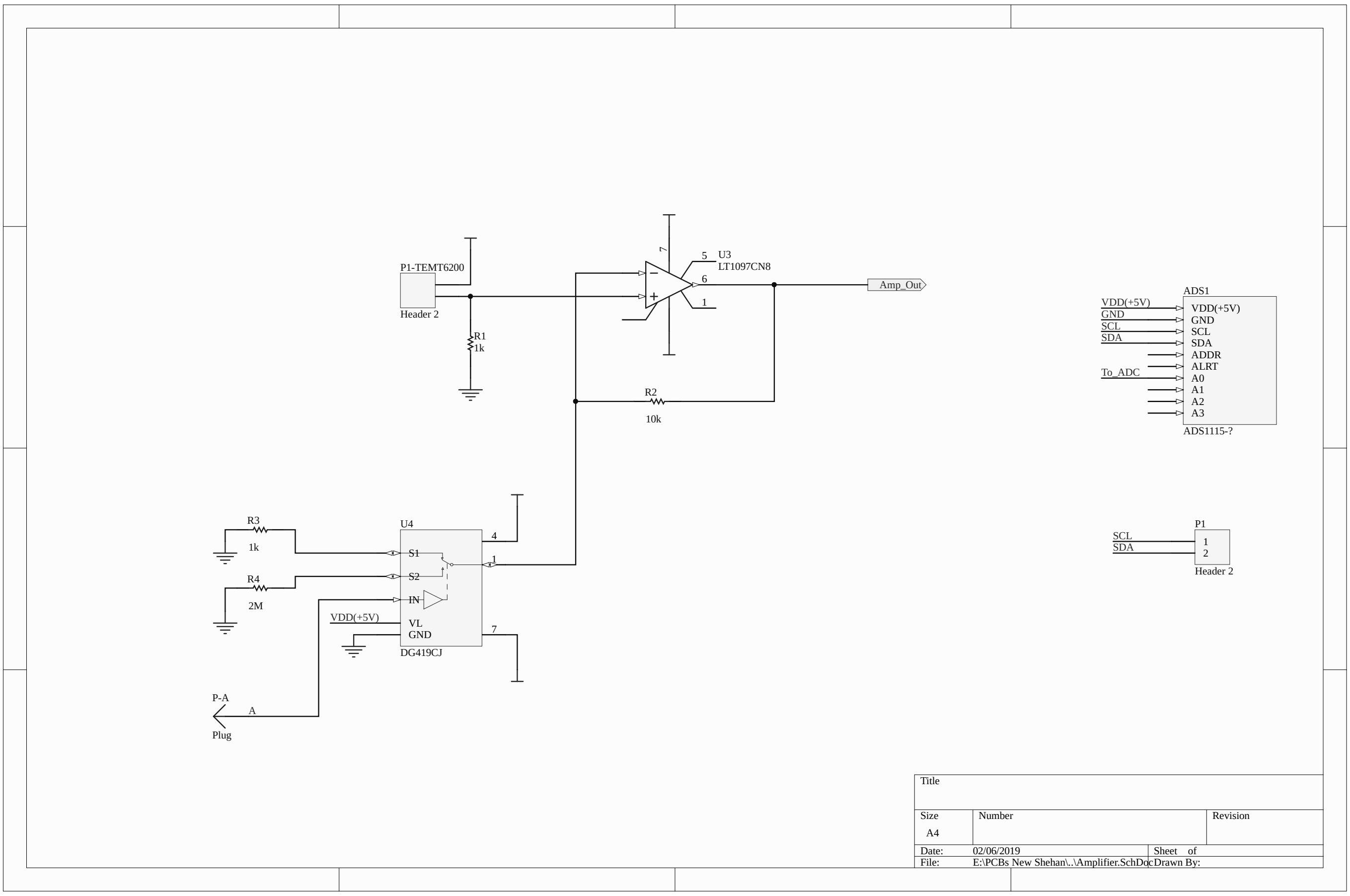


Figure 5: Amplifier circuit

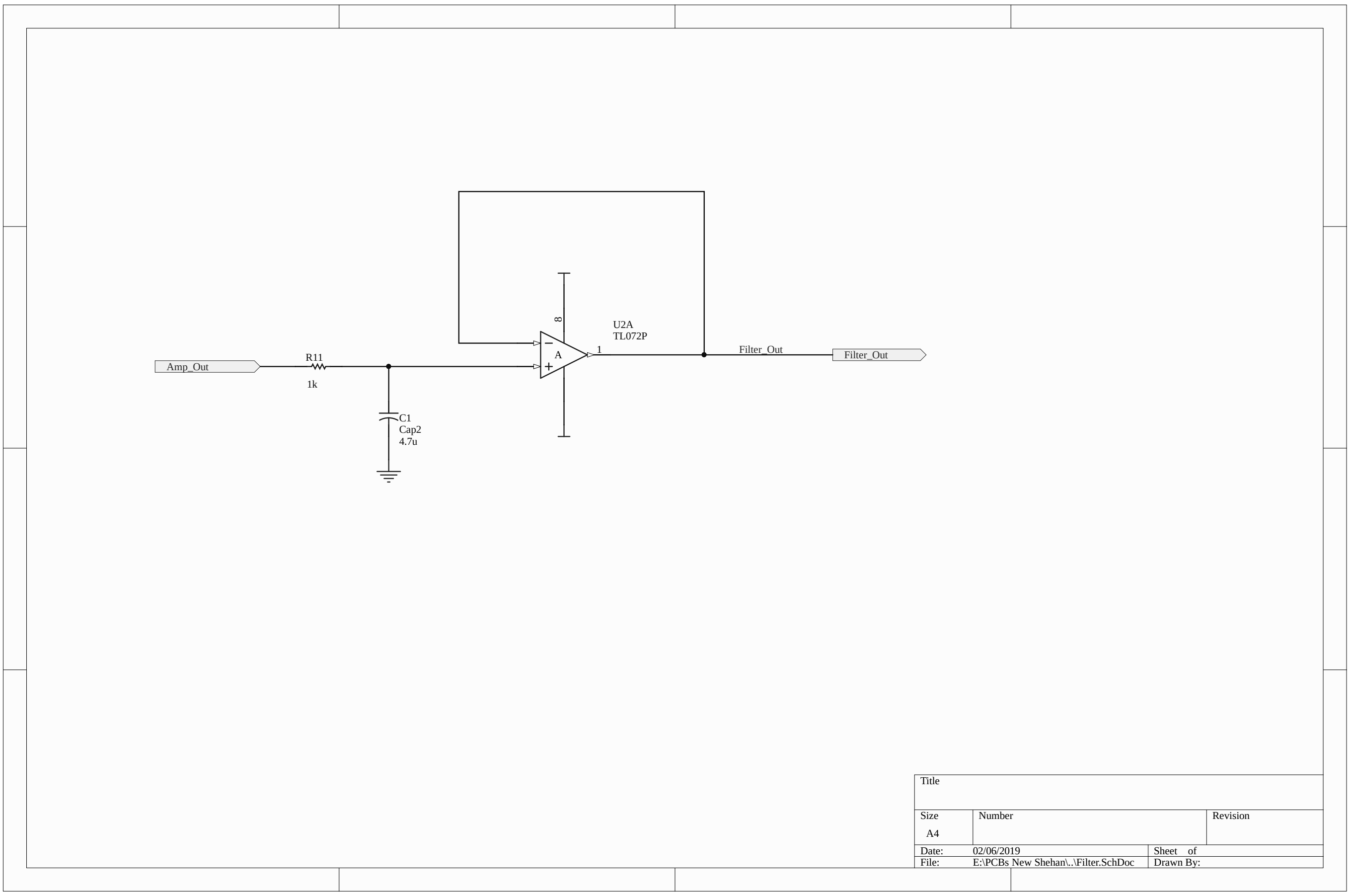


Figure 6: Filter circuit

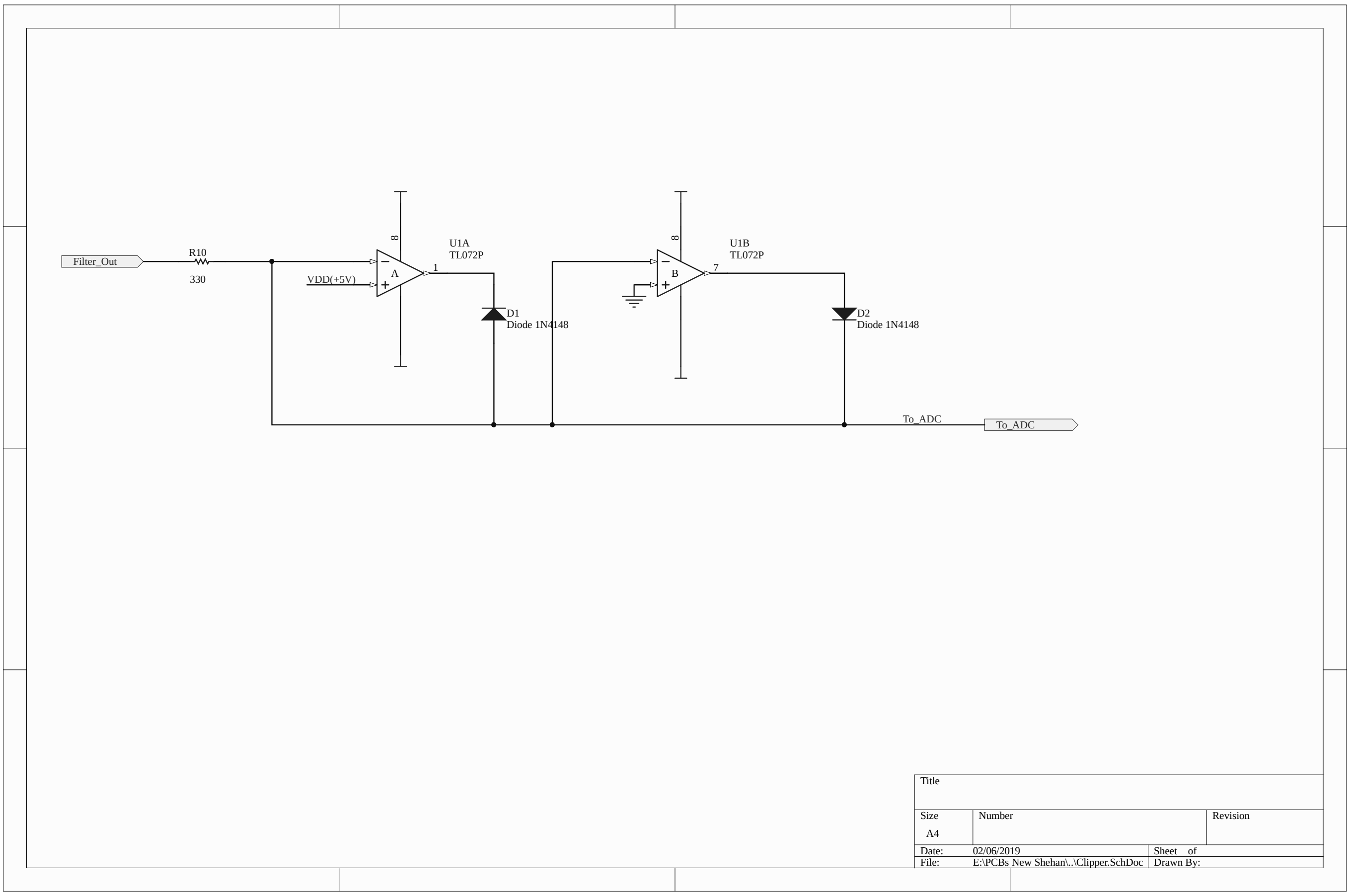


Figure 7: Clipper circuit

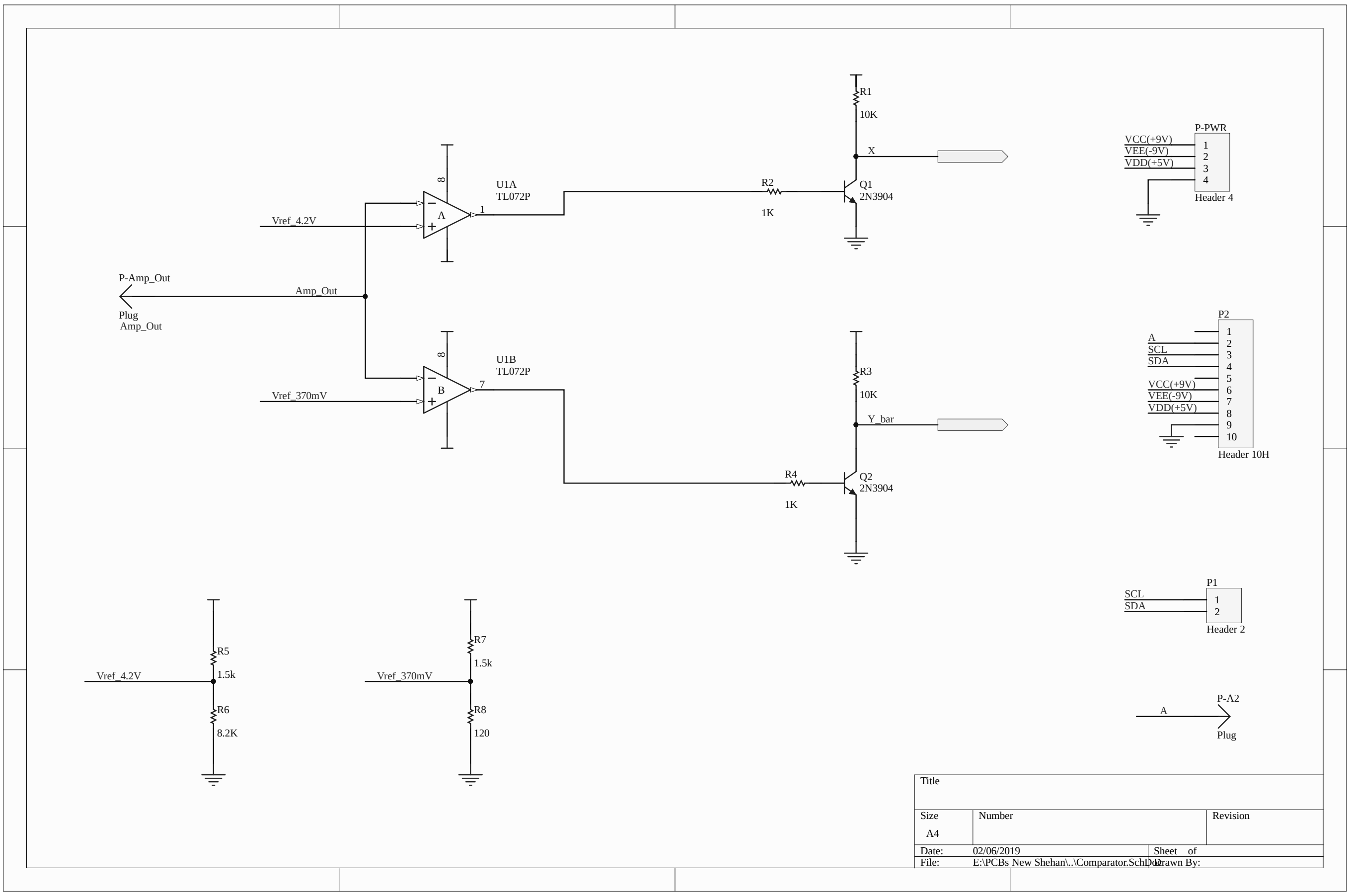


Figure 8: Comparator circuit

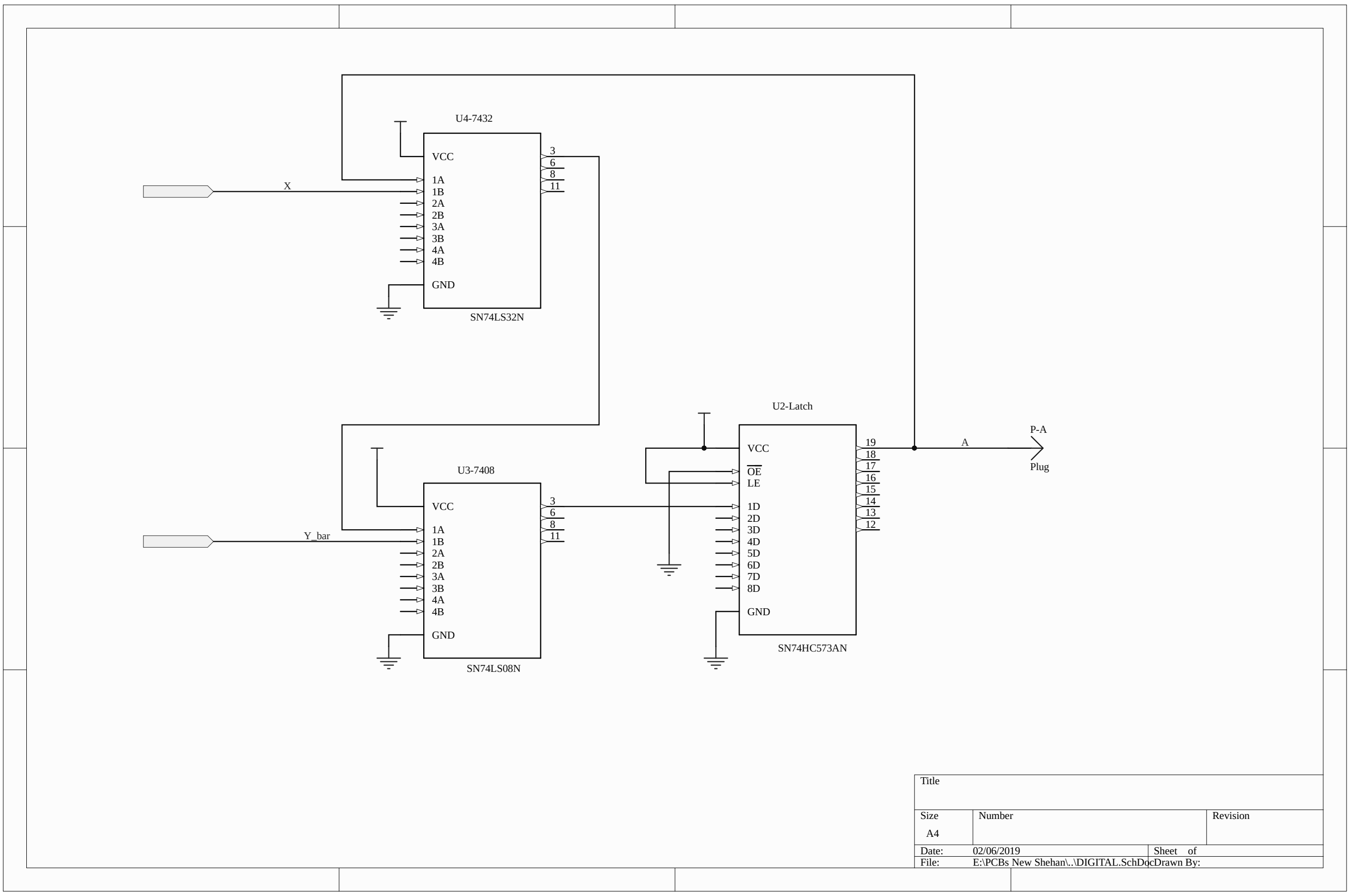


Figure 9: Digital circuit

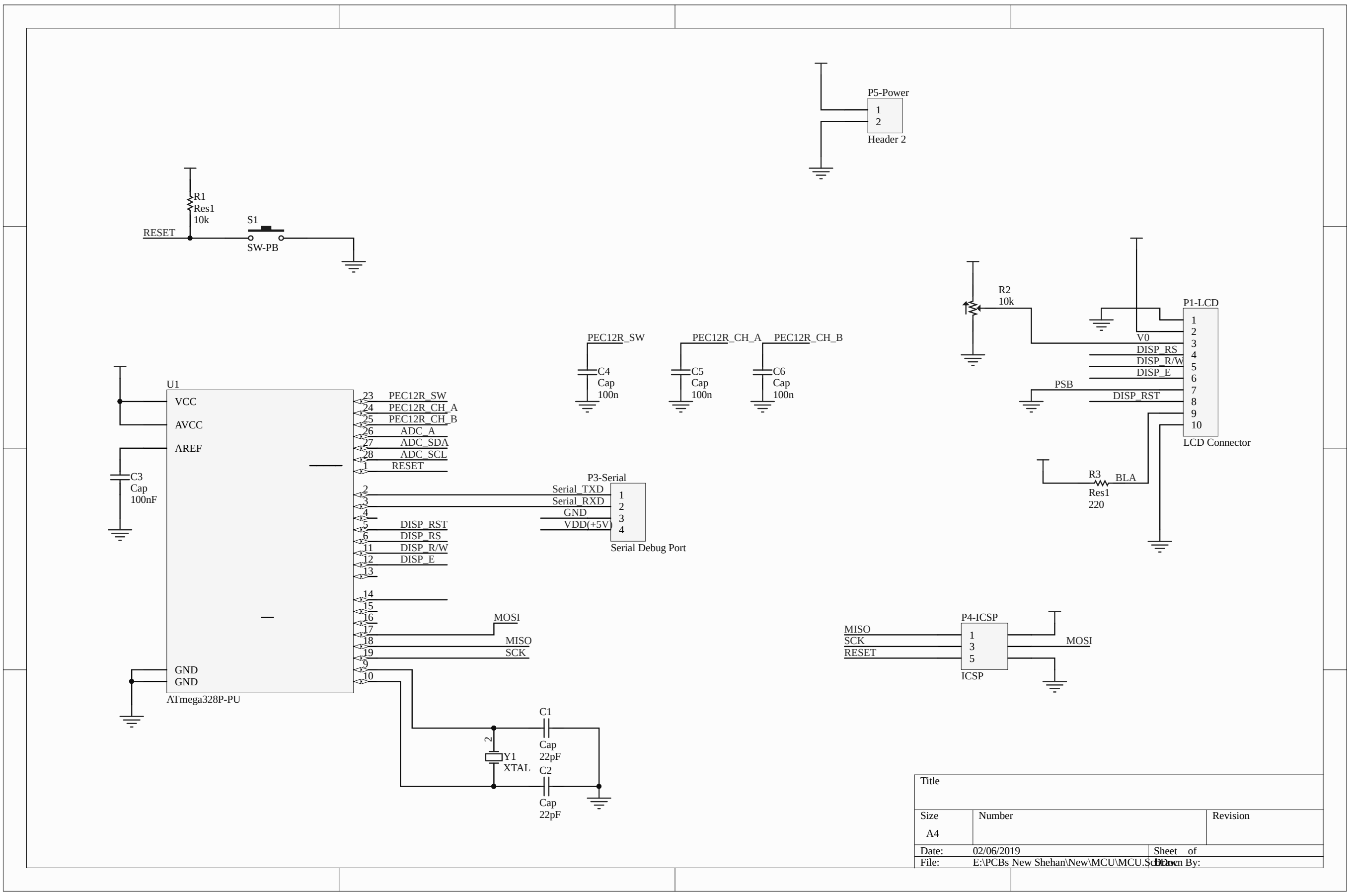


Figure 10: Microcontroller circuit

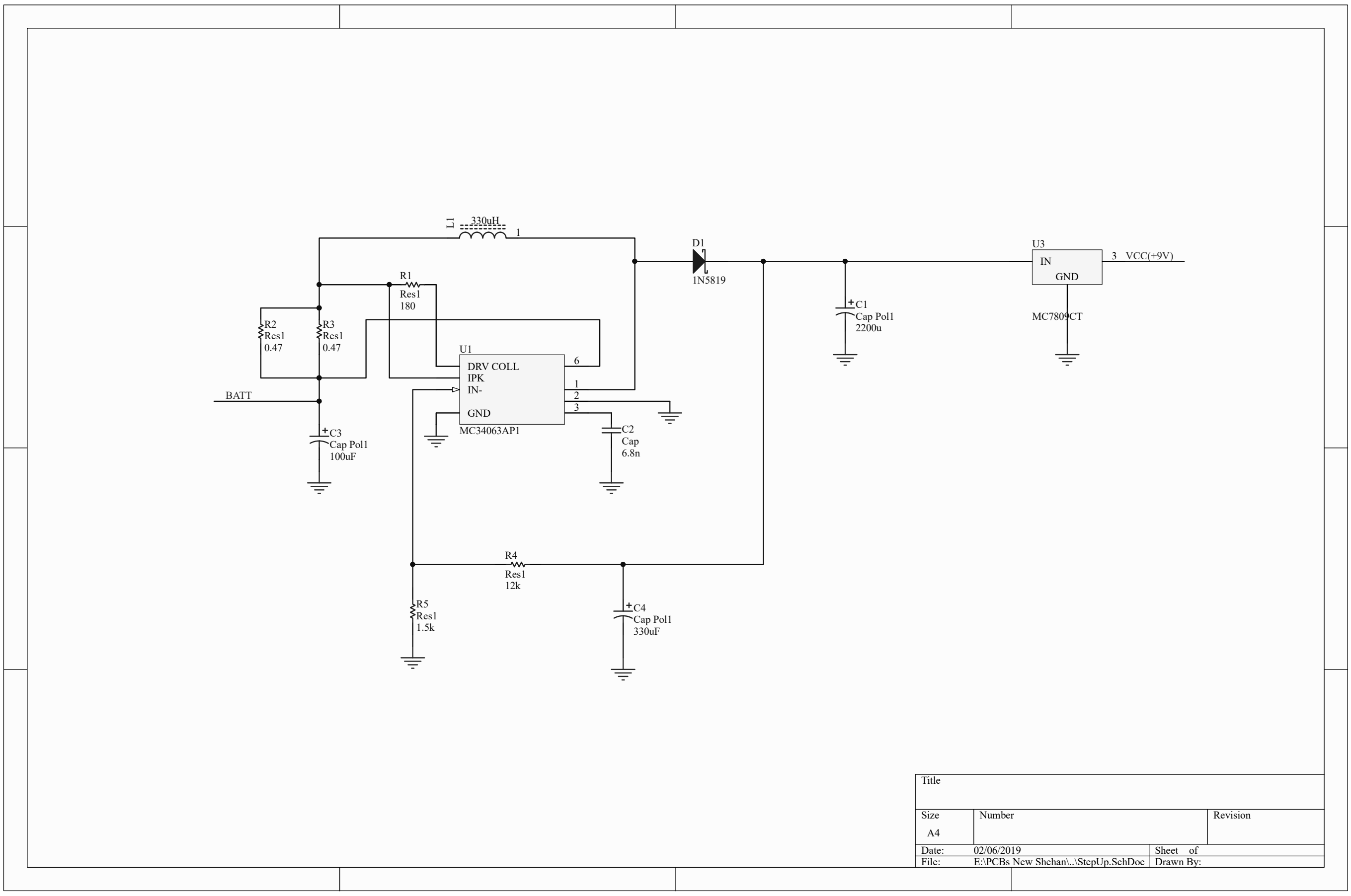


Figure 11: Step Up circuit

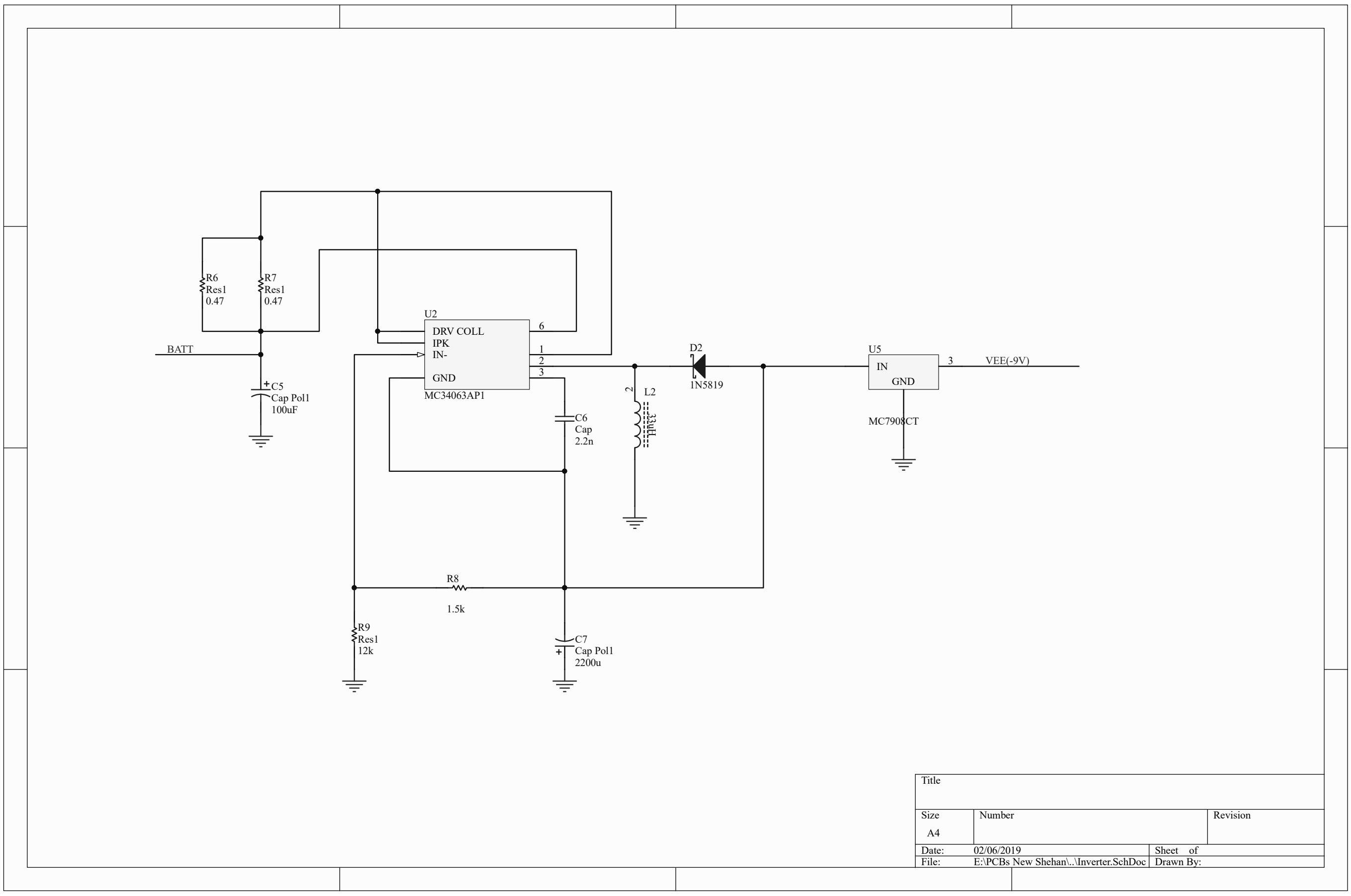


Figure 12: Inverter circuit

# B Enclosure

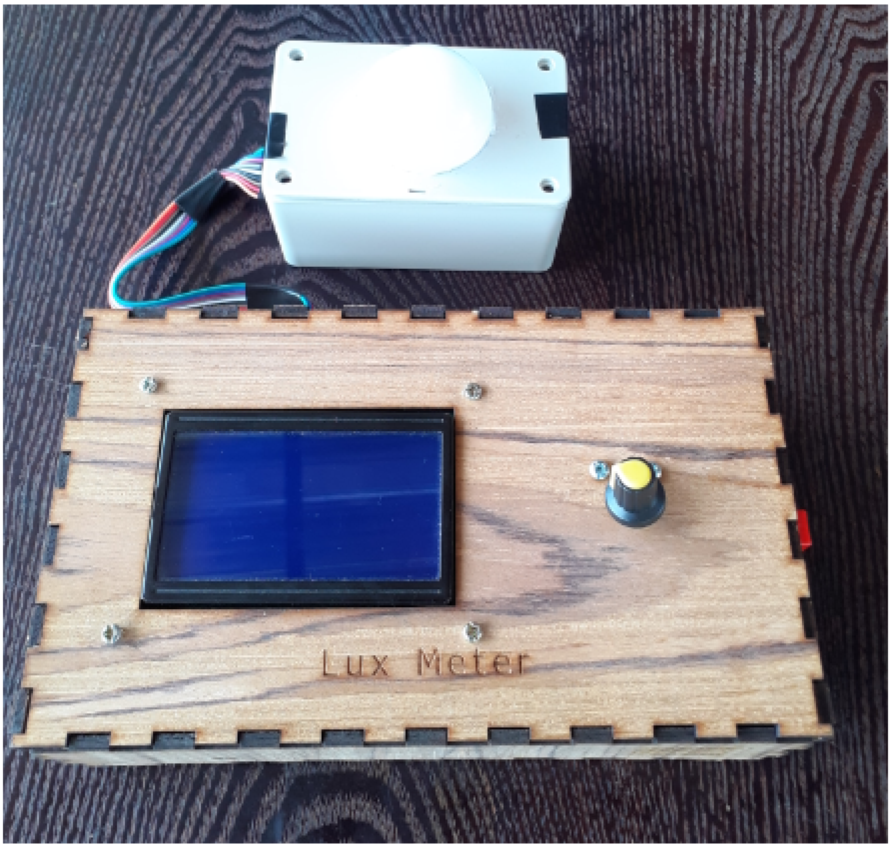


Figure 13: The implemented lux meter