# Task 4: LED Driver

**Optical Uplink**


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**Abstract**

The design, simulation, and construction of an LED driver circuit are described. In task 4 of the optical uplink project, a signal conditioning circuit and current driver are explored. A signal conditioner using the MCP6004 operational amplifier as a Schmitt trigger was built in order to output a square wave with 50% duty-cycle. The current driver was constructed using a MCP6004 operational amplifier which drives an 2N3904 BJT. The current driver receives the output voltage from the conditioner and converts it to a current signal which controls an IR1503 LED. The output of LED driver was required to operated at approximately 20 kHz, 50% duty-cycle, with a current of at least 100mA amplitude. The final current operated at a frequency of 20.1 kHz, a duty cycle of 50.1% and a 150mA peak amplitude.



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# 1 Introduction

This report describes the design, implementation and test of an LED (light emmitting diode) driver.

This report describes design, implementation and test of an LED driver comprised of a ring oscillator, Schmitt trigger, and a current driver. The ring oscillator is comprised of complementary metal oxide semiconducting field effect transistors (CMOS) inverters connected in series. Figure 1 demonstrates where in the optical uplink project the LED driver is placed.


Figure 1: Block diagram for optical uplink [1]

The specifications for this lab are summarized in Table 1.

Table 1: LED driver specifications

| Specifications | Required |
|---|---|
| Frequency | 20kHz±5% |
| Duty-cycle | 50% |
| Amplitude | ≥100mA |

The LED driver circuit supplies the LED with a controlled current. A signal conditioner takes the output from a ring oscillator and creates a 50% duty-cycle square wave. The square wave is then in turn recieved by a current driver. The current driver creates a sufficiently large current in order to operate the LED. A voltage driven output to light the LED is not used due to increased sensitivity from temperature change.

# 2 Circuit Development

This section covers the design choices associated with the various circuits constructed. The individual circuits designed were a Schmitt trigger configured op amp as the signal conditioner and an op amp driving a BJT for the current driver. The input waveform was generated using the ring oscillator from Lab 3. The supply voltage was created using a voltage regulator.

The order in which the circuits are discussed is as follows: first, the ring oscillator, followed by the signal conditioner, then the current driver, and then finally the voltage regulator..

## 2.1 Ring oscillator

The CMOS ring oscillator consists of three CMOS inverters connected in series with the output of the last inverter connected to the input of the first inverter. The ring oscillator will also have a capacitor at each output connected to ground. The schematic for the CMOS ring oscillator can be seen in Figure 2.

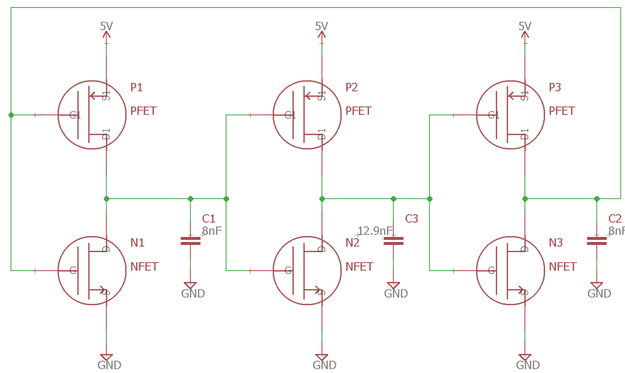


Figure 2: CMOS ring oscillator schematic

The operation of the ring oscillator uses a series of inverters. The output of one inverter inverts the input signal. Therefore, if there are a series of inverters, then each odd inverter will have the same inverted output as the first. In this instance, there are three stages of inverters used, with the output of the third inverter being fed back into the input of the first inverter. This feedback from the output to the input causes an oscillation. The simulated output of the ring oscillator is depicted in Figure 3.

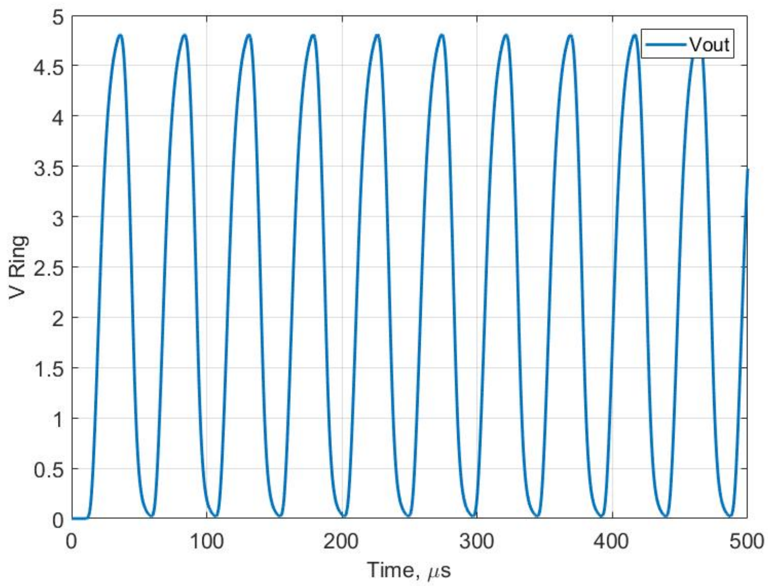


Figure 3: Simulated CMOS ring oscillator output

The output of the ring oscillator seen in Figure 3 is not a square wave, but instead a distorted sinusoid. However, the signal will be converted into a square wave by using a schmitt trigger. The resulting signal will be used to drive the LED driver circuit.

## 2.2 Signal conditioner

The in order to activate the IR LED correctly it has to driven with a square wave. The generated waveform from the ring oscillator circuit is, however, a distorted sinuisoid. The signal must therefore be transformed into a square wave. This requires the use of a signal conditioner. A Schmitt trigger was chosen to implement the signal condition. The Schmitt trigger is an positive feedback configuration for a noninverting amplifier. The Schmitt trigger is described most succinctly by its transfer function, seen in Figure 4.

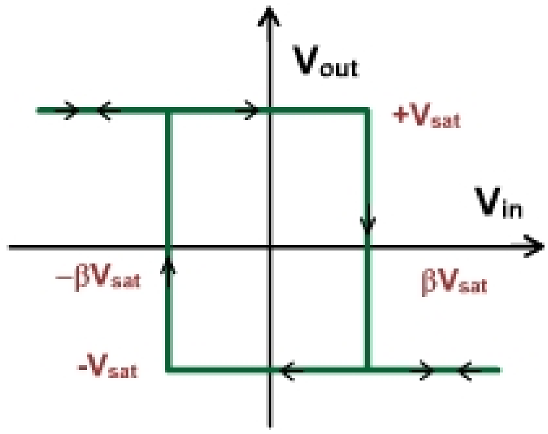


Figure 4: Transfer Function of Schmitt Trigger [2]

The Schmitt trigger outputs two discrete voltages, which are set by the reference node at $V_-$. This voltage determines when the output voltage drops to the low or up to its high voltage. The simulated circuit is shown in Figure 5.

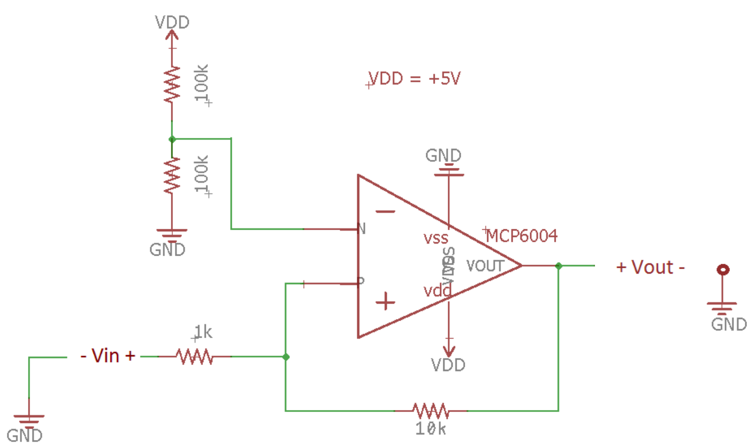


Figure 5: Simulated signal conditioner circuit

The input to the signal conditioner is the 5V peak sinuisoid from the ring oscillator. In order to attain a 50% duty-cycle, the reference voltage should be set to half of the input signal. As a result, the voltage divider at the reference node is a 50/50 voltage divider, resulting in 2.5V at the reference node. The feedback configuration is set to $10\frac{V}{V}$ to ensure that the output from the signal conditioner is 5V. When the input signal is about the reference voltage, the Schmitt trigger is "high" and when the signal is below the reference voltage the output is "low". This results in an output square wave. The output waveform can be seen in Figure 5.

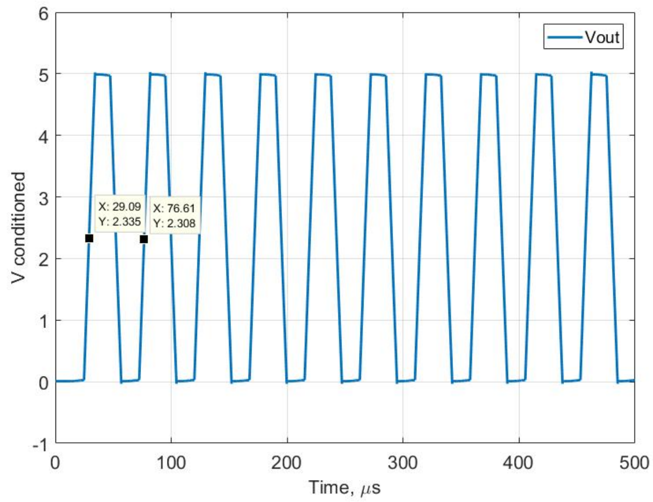


Figure 6: Simulated conditioned signal

The output was simulated by doing transient analysis in NGSpice integrated with Matlab. The signal was measured to have a 20 kHz frequency, a 48% duty-cycle, and a 5V peak amplitude. The reason that the output does not switch instantaneously from high to low is because the op amp is slew rate limited. This output was then passed to a current driver.

## 2.3 Current driver

The current driver for this lab was created using an MCP6004 op amp. The op amp is to act as the driver for the gate of a 2N3904 Bipolar Junction Transistor (BJT). The generic circuit for the current driver is shown in Figure 7.

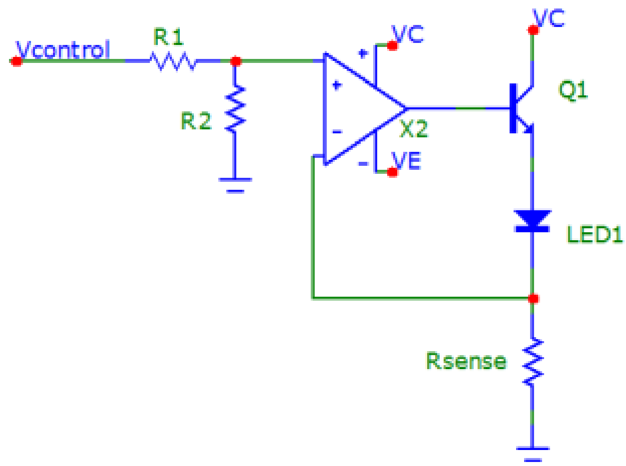


Figure 7: Generic current driver circuit [1]

The key to operation of the current driver is the BJT transistor. A BJT transistor, in contrast with the metal oxide semi-conducting field effect transistor (MOSFET), is capable of producing current by both types of Charge Carriers. This effectively allows the BJT to behave as a NPN or PNP transistor depending on the size of the input current. This also allows the BJT to use a smaller current signal to control a larger current.

The operation of a BJT is paramount for this lab. The MCP6004 is only capable of outputting around 20mA of current. The IR LED in use, however, has a forward current of 100mA [4]. A much larger current has to generated in order for the LED to operate. Figure 8 shows the IV curve for the IR1503 LED.

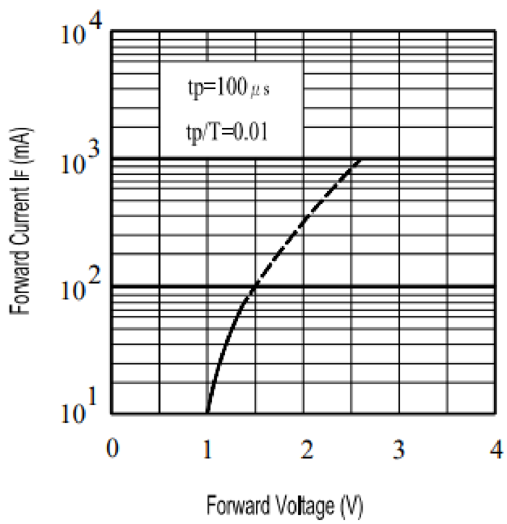


Figure 8: The IV characteristic of the IR1503 [4]

The MCP6004 is used to set the node voltage for $R_{sense}$. The op amp is assumed to be ideal, so $V_- = V_+$. In order to ensure that the LED is forward biased, the node voltage should be less than the sum of the voltage drops from $V_{supply}$ over the BJT and the diode [3]. The lab briefing [3] states to set $V_{-}$ less then 3V.

In order to attain a suitable voltage, a voltage divider is placed at the input to the op amp. The source voltage is the output from the signal conditioner, and was found to be 5V. In order to be less than 3V, a 50/50 voltage divider was used in order to create an input of 2.5V. With this voltage, and the maximum forward current of 200mA, the value for $R_{sense}$ can solved using Ohm's Law. The final value for $R_{sense}$ is 13Ω.

The simulated circuit for current driver is seen in Figure 9.

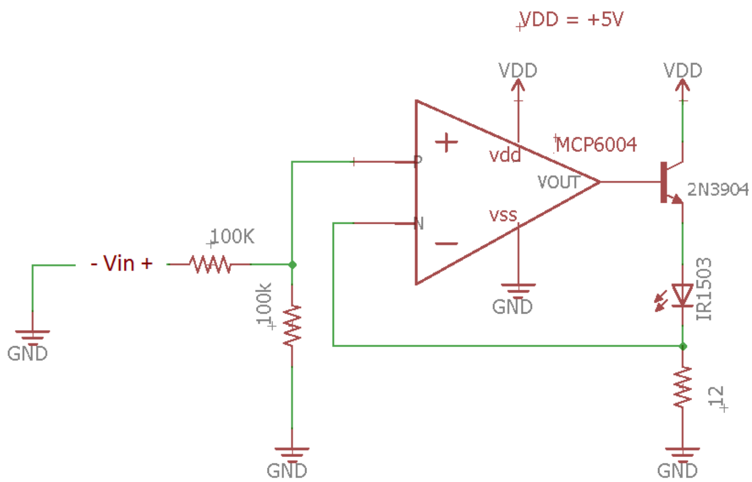


Figure 9: Simulated LED driver circuit

The circuit required no changes from design to simulation. The current through the LED can be seen in Figure 10. The simulation was performed using a transient analysis integrated with Matlab.

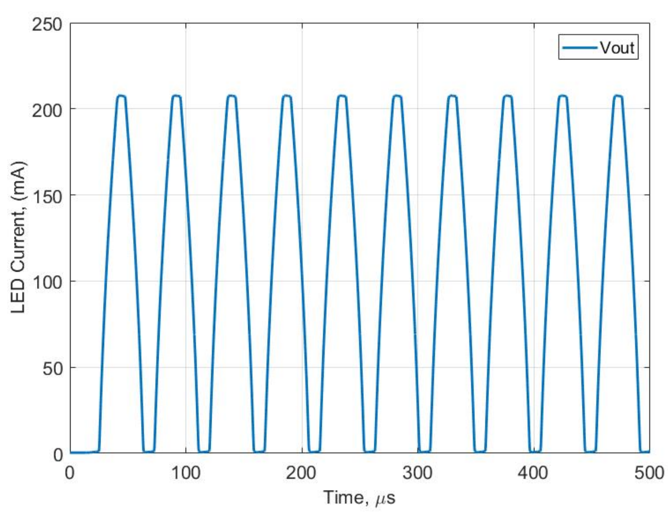


Figure 10: Simulated current through the LED

The current through the LED matched the calculated value of 200mA. The LED is in an operational state. The LED also operates with the correct frequency and duty-cycle from the signal conditioner.

## 2.4 Voltage regulator

The Voltage regulator used was a LM7805. The voltage regulator is used because the CMOS ring oscillator and LED driver were designed to run on a source voltage of 5V. The power supply provided, however, is a 9V DC battery. The voltage, therefore, needs to be reduced. The voltage regulator operates by taking an input voltage and step it down to some lower voltage by shedding the difference in energy between the two potentials in the form of heat. Figure 11 shows the circuit configuration for the LM7805.

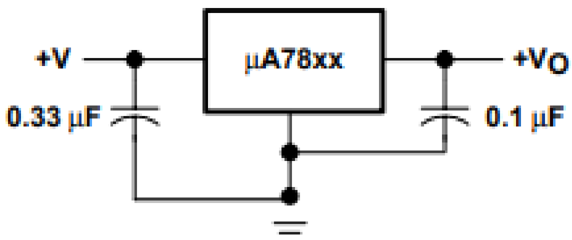


Figure 11: Configuration of voltage regulator[5]

The equivalent circuit model for the LM7805 is shown. Notably, the circuit was not included in simulations and was constructed during the Implementation phase.

## 2.5 Simulated summary

The final simulated circuit is shown in Figure 12.

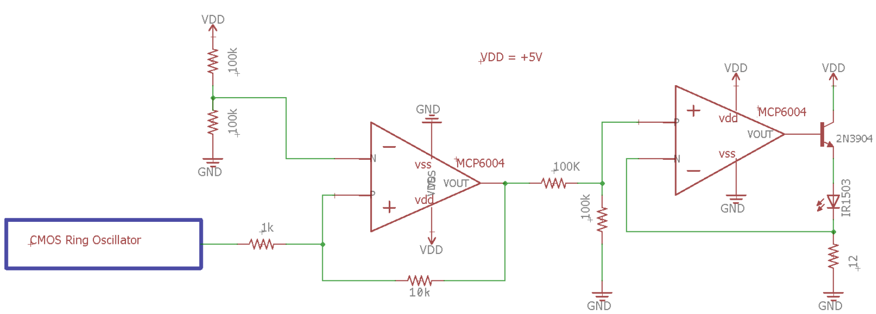


Figure 12: Simulated LED driver

The summary of simulated results from this circuit is shown in Table 2.

Table 2: Simulated Results

| Component | Simulated Values |
|---|---|
| Conditioned Voltage | 5V |
| Conditioned Frequency | 20kHz |
| Conditioned Duty-Cycle | 48% |
| Output Current | 200mA |
| $R_{sense}$ | 12Ω |

The simulated circuit operated as expected and provided enough current in order to drive the LED. The resulting waveform through the LED is the correct frequency and duty-cycle in order to detected by the optical uplink receiver.

# 3 Experimental Implementation

The final circuit is shown in Figure 13.

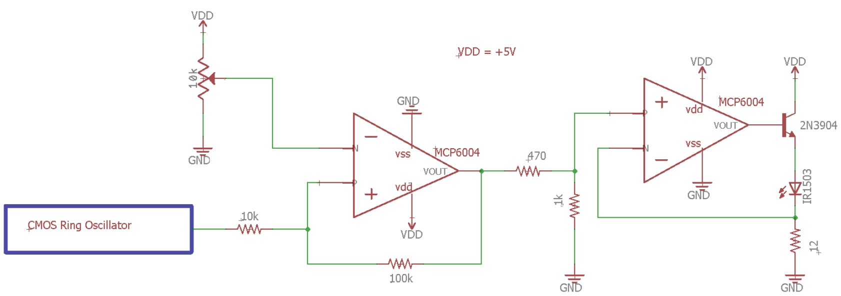


Figure 13: Experimental design

In order to meet specifications, several minor changes to all circuits were made. The individual changes are discussed in their respective subsection as follows, the ring oscillator, the signal conditioner, and finally the current driver.

## 3.1 Ring oscillator

The ring oscillator required that the capacitances be increased in order to create the correct output waveform. A 560pF and a 1.2nF capacitor were added in parallel with the ring oscillator capacitors. The output from the ring oscillator is shown in Figure 14.

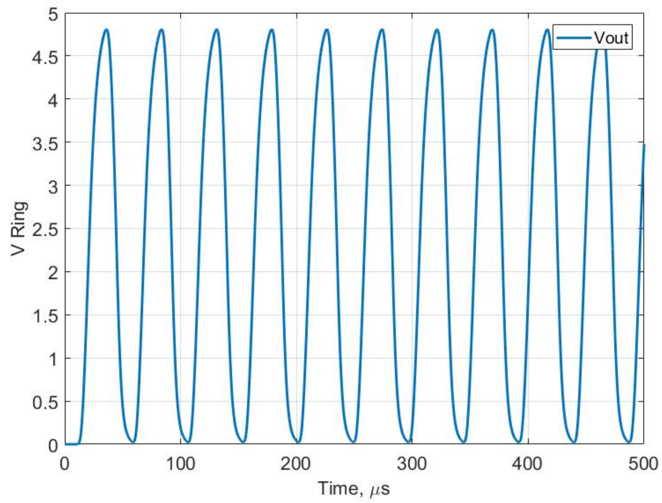


Figure 14: Experimental output of ring oscillator

The output wave form was 20.19kHz, with a duty-cycle of 50.03%. The changes required by the circuit are summarized in Table 3.

Table 3: Ring oscillator comparisons

| Component Values | Simulated | Experimental |
|---|---|---|
| $C_1$ | 8.2nF | 8.2nF —— 560pF |
| $C_2$ | 8.2nF | 8.2nF —— 1.2nF |
| $C_3$ | 8.2nF | 8.2nF |

After the required changes the circuit operated correctly.

## 3.2 Signal conditioner

The signal conditioner required several small changes in order to be functional. The changes are shown below in Figure 15.

The 100kΩ resistor voltage divider was switched to a 10kΩ potentiometer in order to facilitate easier adjustment of the output duty-cycle. The resistors in the feedback configuration were changed to 10kΩ and 100kΩ. This was done in order to minimize the loading effects between the signal conditioner and the current driver. The output waveform is shown in Fig 16.

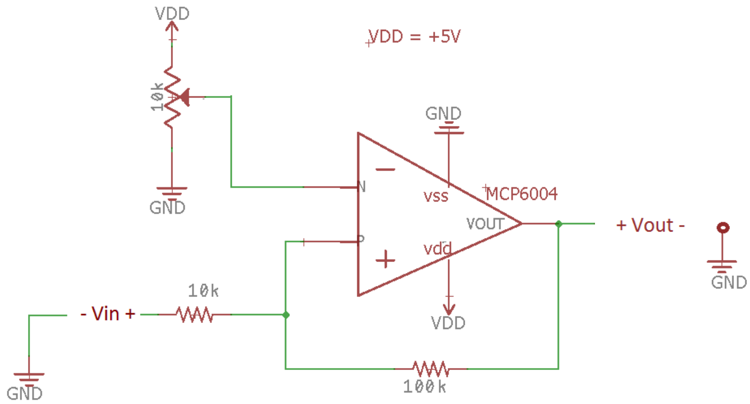


Figure 15: Experimental signal conditioner schematic

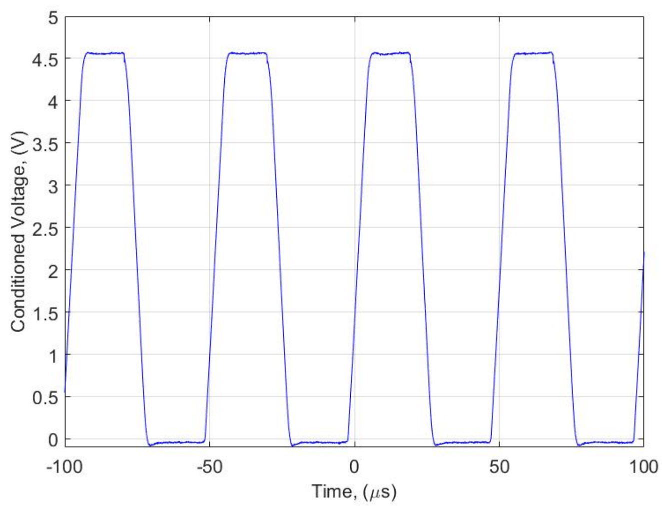


Figure 16: Voltage output of signal conditioner

The output waveform operated with a 4.5V peak, 20.26kHz and 45% duty-cycle. Table 4 summarizes the differences between the simulated and implemented current driver.

Table 4: My caption

| Component Values | Simulated | Experimental |
|---|---|---|
| $R_1$ | 100kΩ | 470Ω |
| $R_2$ | 100kΩ | 1kΩ |
| $R_{sense}$ | 12Ω | 12Ω |
| Output current | 200mA | 150mA% |

Overall, the circuit required only minor changes to operate within specification.

## 3.3 Current driver

The constructed current driver that supplies the LED with a controlled current needed a design change from the simulated model. The voltage divider required a change to lower resistance values. The reason for this to reduce loading effects between the signal conditioner and the current driver. This also slightly increased the peak voltage of the signal conditioner output. The schematic for the current driver is shown in Figure 17.

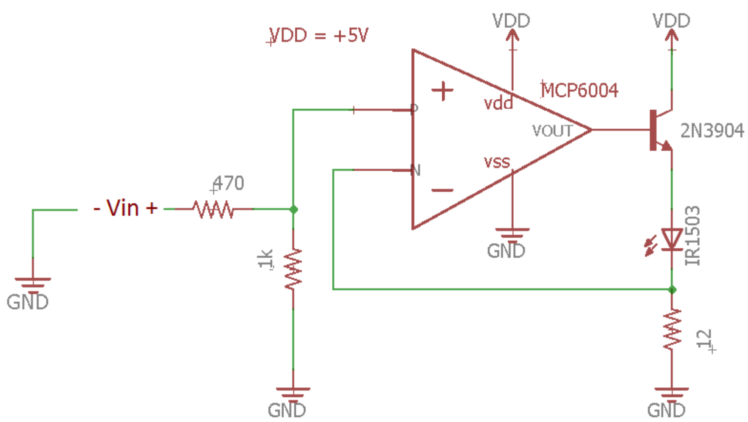


Figure 17: Final schematic of current driver

The resulting output of current through the 12Ω resistor is shown in Figure 18.

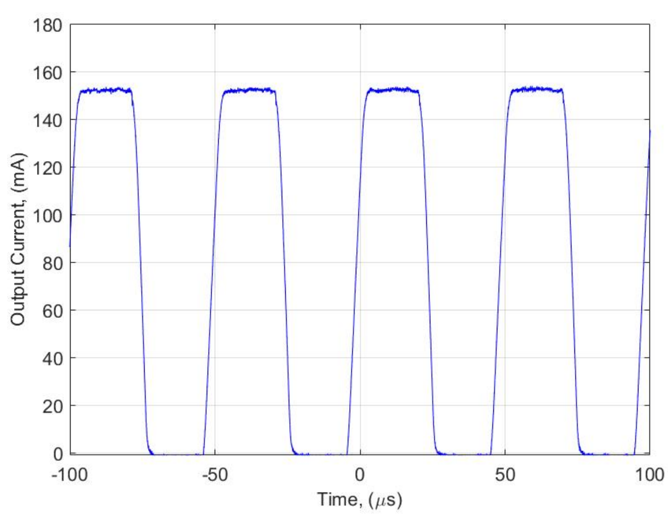


Figure 18: Experimental output of current driver

The experimental output differed from the simulated output shown in Figure 10. The greatest difference between them is the output current peak. The simulated peak current was ≈ 200mA, while the experimental output was ≈ 150mA. The duty cycle remains unaffected because the circuit allows it to be variable by adjusting the potentiometer depicted in the signal conditioner schematic, Figure 15.

# 4 Discussion

This lab served as introduction to MOSFETS and implementation of digital logic. When using transistors to create digital devices, it is often assumed that the device behaves ideally. When the device is logic high, it is one voltage, and when it is logic low it is another. Based on this logic, it is assumed that the switching on and off of the MOSFETS happen instantaneously. Based on the results of the ring oscillator and other inverter circuits, the MOSFETS do not switch instantaneously. Instead, power is consumed by the MOSFETS when they transition from one state to another. This consumption of power causes a small time delay. Each of the circuits described in this report are discussed in the following subsections, excluding the astable multivibrator. The astable multivibrator was not constructed during the experimental phase of this task.

Table 5: Simulated vs. experimental results

| Component Values | Simulated | Experimental |
|---|---|---|
| Output Current | 200mA | 150mA |
| Output Frequency | 20kHz | 20.1kHz |
| Output Duty-cycle | 48% | 50.1% |

## 4.1 Ring oscillator

The ring oscillator circuit designed with the CMOS did not initially meet the specifications required in the lab. The simulations were accurate, but real-world parasitic capacitances from the board and jumper wires impacted the circuit. To remedy the situation, a capacitor of 4.7 nF was added in parallel after the second inverting gate. By increasing the capacitance, we lowered the frequency from 22.8 kHz to 19.8 kHz. The comparison between the simulated results and experimental is expressed in Table 6

Table 6: Comparison of ring oscillator results

| Component Values | Simulated | Experimental |
|---|---|---|
| $C_1$ | 8nF | 8.2nF |
| $C_2$ | 8nF | 13.9nF |
| $C_3$ | 8nF | 8.2nF |
| Frequency | 20.1kHz | 19.8kHz |
| Amplitude | 5V | 4.9V |

The reason this oscillator is chosen over the astable multivibrator as the signal generator is mostly arbitrary and simply design choice for the optical uplink project [5]. Although one of the benefits of the ring oscillator is that from the sensitivity testing it is less affected by component tolerances than the astable multivibrator. This is significant since the capacitors available for circuit construction are 10% tolerances.

# 5 Conclusion

The design, simulation, and implementation of the LED driver have been explained. Lab specification required that the signal generator have a frequency of approximately 20kHz, a duty-cycle of approximately 50%, and an amplitude of at least 100mA. The LED driver takes a sinuisoidal waveform of variable duty-cycle and outputs a 50% durt-cycle square wave. The waveform is then converted to a suffeciently large driving current by the current driver. The LED driver was constructed using the following parts: a 10kΩ, 100kΩ, 470Ω, 1kΩ, 12Ω and a 10kΩ potentiometer; a MCP6004 quadrature operation amplifier; an IR1503 LED; and finally a 2N3904 BJT. A 9V battery supply is stepped down to 5V with an LM7805 voltage regulator. The frequency was 20.1kHz, with a duty-cycle of 50.1%, and an amplitude of 150mA. An important lesson about the behavior circuits including both op amps and transistors was learned. The meshing of op amps and transistors provide novel solutions to real world problems

## References


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