

# 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 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 semi-conducting 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 LED driver is required by the optical uplink project. The signal generator chosen for the overall design does not output a high enough current in order to operate the IR LED. In addition, the waveform from the signal generator is a distorted sinuisoid without a 50% duty-cycle. For ideal operation, the LED should receive a 50% duty-cycle square wave. In addition, it requires a forward voltage of at least 100mA in order to operate.. The specifications for this lab are summarized in Table 1.

Table 1: LED driver specifications

Specifications	Required
Frequency	20kHz $\pm$ 5%
Duty-cycle	50%
Amplitude	$\geq$ 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.

Section 2 of this report describes the design and simulations of the signal conditioner and the current driver. Experimental results are addressed in section 3. A discussion of the results, sources of error, and areas of possible improvement are outlined in section 4. Section 5 concludes this report.

## 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. A voltage regulator supplied a steady 5V from a 9V battery source.

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

## 2.1 Signal conditioner

In order to activate the IR LED correctly it must be driven with a square wave. The generated waveform from the ring oscillator circuit is, however, a distorted sinusoid. 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 2.

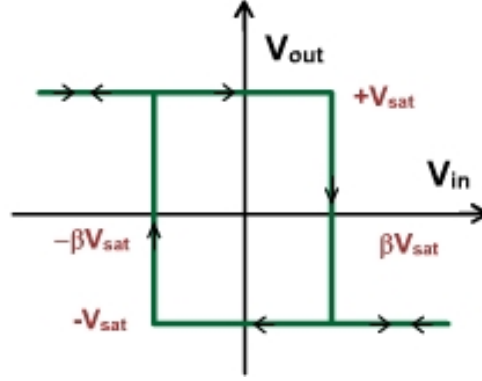


Figure 2: Transfer Function of Schmitt Trigger [2]

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 3.

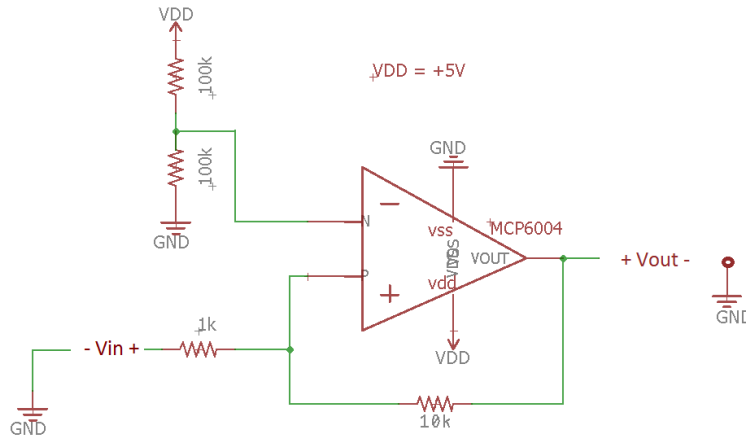


Figure 3: Simulated signal conditioner circuit

The input to the signal conditioner is the 5V peak sinusoid 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 10V/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 3.

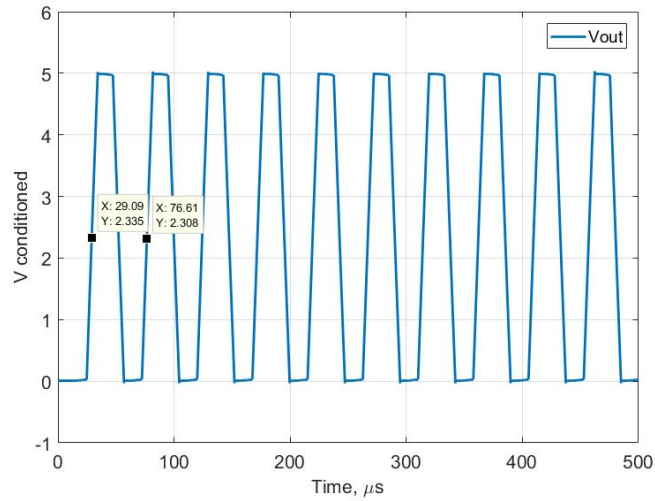


Figure 4: Simulated conditioned signal

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 slow rate limited. This output was then passed to a current driver.

## 2.2 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 5.

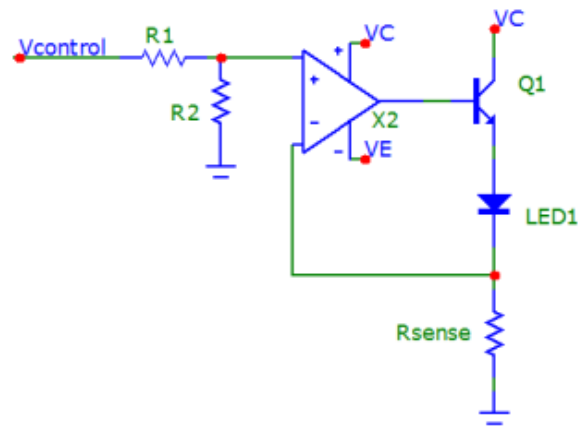


Figure 5: Generic current driver circuit [1]

The key to operation of the current driver is the BJT. A BJT, 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 electrical properties of a BJT are 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 be generated in order for the LED to operate. Figure 6 shows the IV curve for the IR1503 LED.

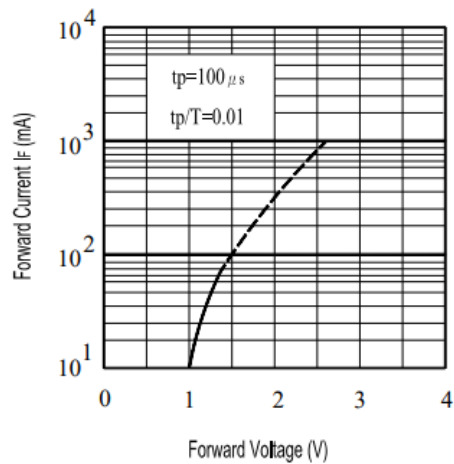


Figure 6: The IV characteristic of the IR1503 [4]

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 than 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 be solved using Ohm's Law. The final value for  $R_{sense}$  is  $12\Omega$ . The simulated circuit for current driver is seen in Figure 7.

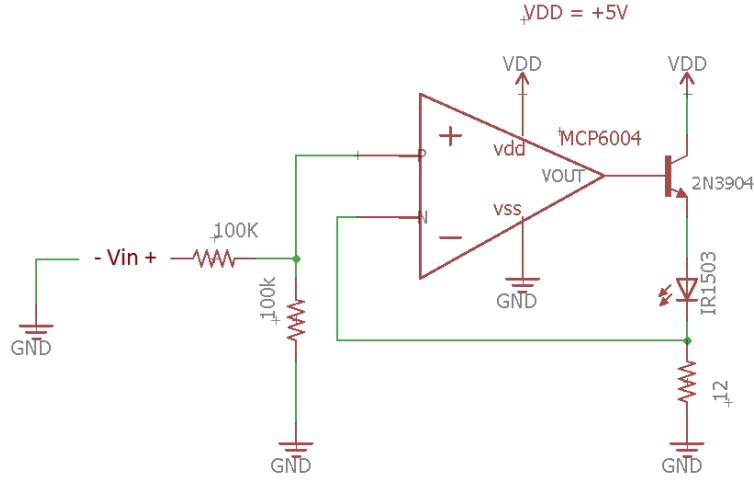


Figure 7: Simulated LED driver circuit

The circuit required no changes from design to simulation. The current through the LED can be seen in Figure 8. The simulation was performed using a transient analysis in NGSpice integrated with Matlab.

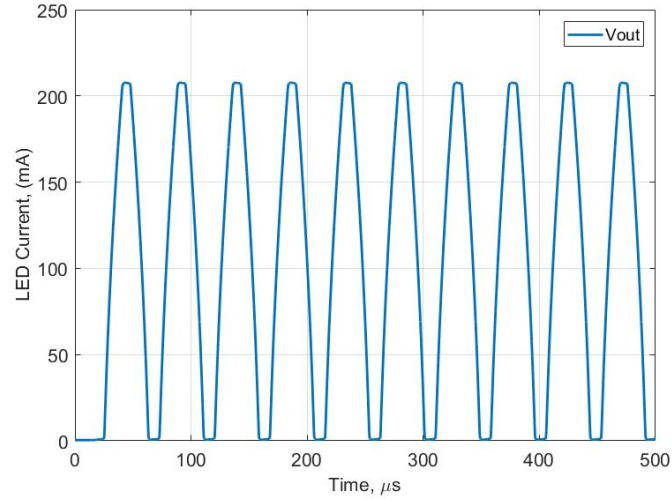


Figure 8: Simulated current through the LED

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.

### 2.3 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 9 shows the circuit configuration for the LM7805.

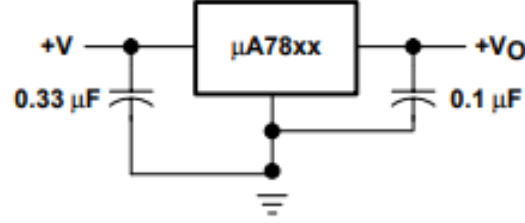


Figure 9: Configuration of voltage regulator[5]

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

## 2.4 Simulated summary

The final simulated circuit is shown in Figure 10.

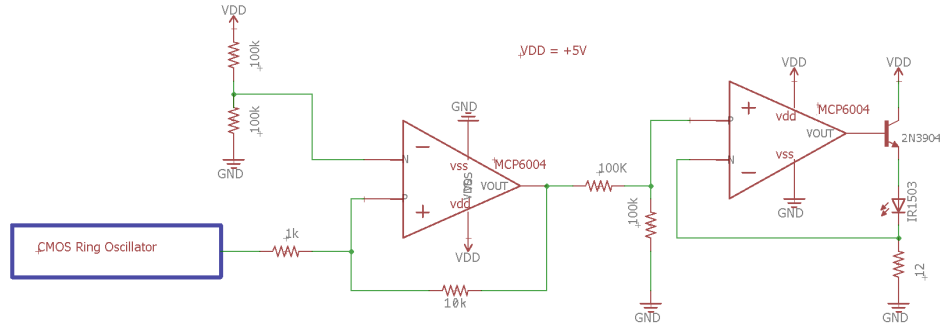


Figure 10: Simulated LED driver

The simulated circuit did require any changes from calculations. One of the most significant margins of error for simulations is that the operation of the simulations is quite dependent on which simulation model for the 2N3904 is used. The "SP3" model from ON Semiconductor was utilized for these simulations [6]. Different models are capable of behaving in unexpected ways due to their interaction with the NGSpice simulation software. 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
$R_{sense}$	$12\Omega$

The simulated signal conditioner outputted only a 48% duty-cycle directly and is slightly less than the required 50%. However, the final waveform through the LED operated with a 50% duty-cycle as required by specifications. 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.

### 3 Experimental Implementation

The final circuit is shown in Figure 11.

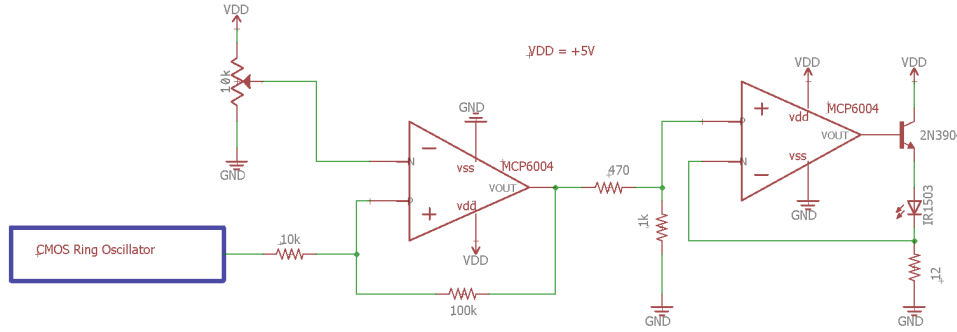


Figure 11: Experimental design

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 signal conditioner then the current driver.

#### 3.1 Signal conditioner

The signal conditioner required several small changes in order to be functional. The changes are shown below in Figure 12.

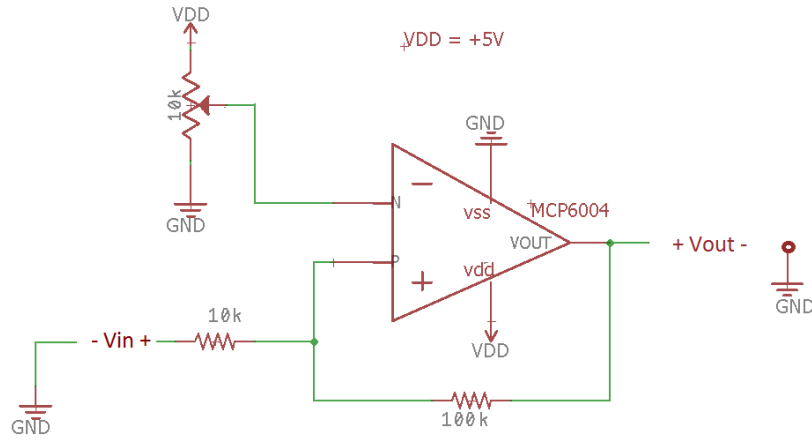


Figure 12: Experimental signal conditioner schematic

The  $100k\Omega$  resistor voltage divider was switched to a  $10k\Omega$  potentiometer in order to facilitate easier adjustment of the output duty-cycle. The resistors in the feedback configuration were changed to  $10k\Omega$  and  $100k\Omega$ . 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 13.

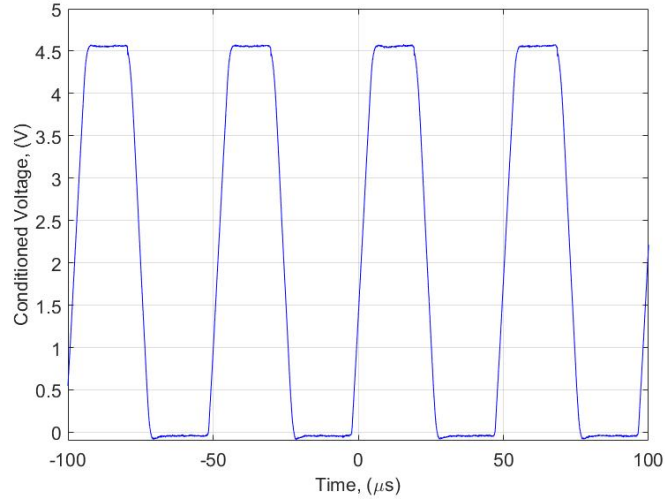


Figure 13: Voltage output of signal conditioner

The output waveform operated with a 4.5V peak, 20.26kHz and 45% duty-cycle. Table 3 summarizes the differences between the simulated and implemented current driver.

Table 3: Comparison of implemented driver

Component Values	Simulated	Experimental
$R_1$	100k $\Omega$	470 $\Omega$
$R_2$	100k $\Omega$	1k $\Omega$
$R_{sense}$	12 $\Omega$	12 $\Omega$
Output current	200mA	150mA
Output current	200mA	150mA

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

### 3.2 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 14.

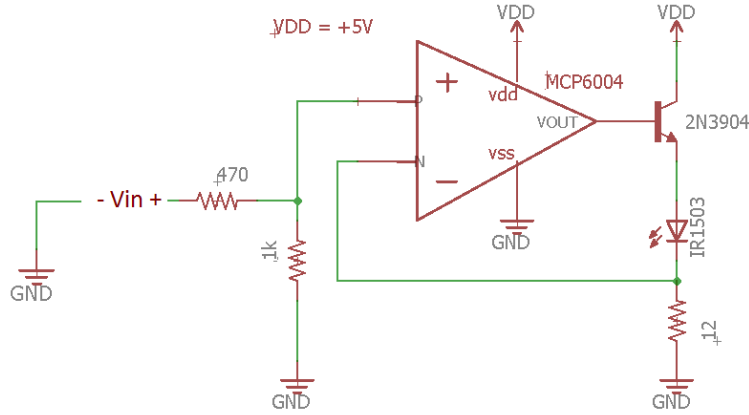


Figure 14: Final schematic of current driver

The resulting output of current through the 12 $\Omega$  resistor is shown in Figure 15. The output from the current driver operated with at 20.1kHz with a 50.1% duty-cycle.

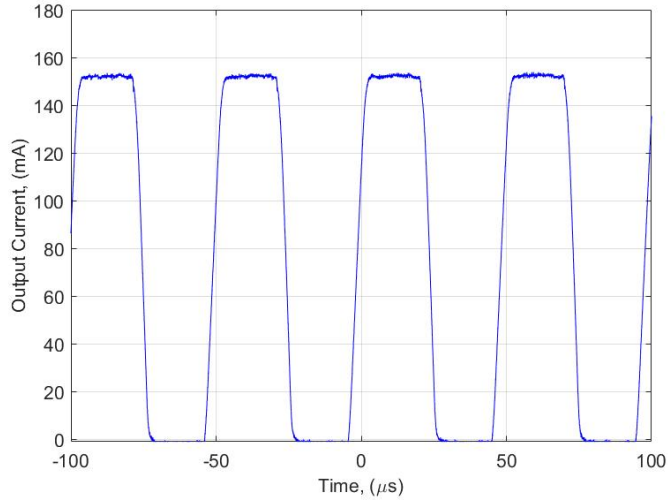


Figure 15: Experimental output of current driver

The experimental output differed from the simulated output shown in Figure 8. The greatest difference between them is the output current peak. The simulated peak current was  $\approx 200\text{mA}$ , while the experimental output was  $\approx 150\text{mA}$ . The duty cycle remains unaffected because the circuit allows it to be variable by adjusting the potentiometer depicted in the signal conditioner schematic, Figure 12.

## 4 Discussion

After several minor changes, the circuit operated correctly. This lab served as introduction to circuits that include both transistors and op amps. The two types of components have been studied separately, but never in conjunction. The specifications are outlined in Table 4.

Table 4: Driver specifications

Specifications	Required
Frequency	$20\text{kHz} \pm 5\%$
Duty-cycle	50%
Amplitude	$\geq 100\text{mA}$

Notably, the ring oscillator had to have its output frequency increased. This was due, in part, because of parasitic inductances and capacitances from the board and jumper wires. The propagation of the signal from the oscillator to output resulted in a decrease of frequency. Therefore, increasing the input frequency resulted in a correct output of the LED driver.

Another factor that determined the operating frequency is the fact that most of the components are temperature dependent. The MCP6004 IC, with increasing temperature, has an increased frequency output. The voltage regulator's efficiency, however, decreases with increasing temperature. The current through the LED is also a function of temperature. The behavior of this circuit can be heavily dependent on ambient temperature. This is a vital stipulation as, depending on the bandwidth of the MFBP filter designed

before, the LED signal may fall inside the stopband of the MFBP filter. The receiver would then fail to receive the LED signal and the optical uplink would not operate. The summary of the final results can be seen in Table 5.

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%

The final circuit fell well within specifications and operated correctly after several component alterations.

## 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 sinusoidal waveform of variable duty-cycle and outputs a 50% duty-cycle square wave. The waveform is then converted to a sufficiently large driving current by the current driver. The LED driver was constructed using the following parts: a 10k $\Omega$ , 100k $\Omega$ , 470 $\Omega$ , 1k $\Omega$ , 12 $\Omega$  and a 10k $\Omega$  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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