LED Driver Design Project

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Contents

Introduction

The objective of the Design Task was to give experience with a small open-ended design problem in which we can benefit from the knowledge gained throughout the course.

From the specifications, we had to design a LED Driver to be powered with a 1.2-1.5 Volt battery at a constant 20mA. We had decided to use a boost converter to boost the 1.5 volts to a high enough voltage to forward bias the LED. Using the boost, we decided to incorporate a debouncing circuit for our button as well as a toggling circuit to turn our momentary switch into a toggle. Finally, we constructed a simple constant current source circuit to maintain a 20mA constant current. Many complications were found throughout the real-life implementation which will be documented in this report.

Boost Converter Schematic & Design

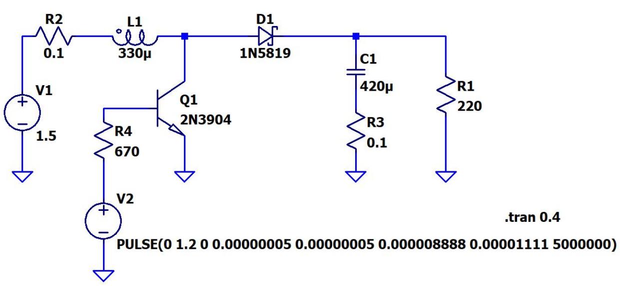


Figure 1: Schematic of Boost Converter

The Boost Converter, as seen in the above figure, is standard design with a 220Ω load. We chose a load of 220Ω as we found this to be the equivalent resistance of the LED on hand. However, choosing the correct values and components in the actual implementation was not particularly simple. Initially, we calculated Duty Cycle based off common formulas.

$$D_{min} = 1 - \frac{V_{in\_max}}{V_{out\_min}} = 1 - \frac{1.5}{3} = 0.5$$

$$D_{max} = 1 - \frac{V_{in\_min}}{V_{out\_max}} = 1 - \frac{1.2}{8} = 0.85$$

We had chosen the minimum and maximum Voltage input as according to the specifications (1.2 and 1.5 Volts respectively). Ideally, we wanted 8 volts to allow for a Linear Regulator and at worst 3 volts with a low voltage ripple would be acceptable. Hence, our max voltage output was chosen to be 8 volts and the minimum to be 3 volts (enough to drive a red or green LED).

$$L_{min} > \frac{D_{min} * V_{in\_max} * (1 - D_{min})}{2 * f * I_{out}}$$

$$= \frac{0.5 * 1.5 * (1 - 0.5)}{2 * 90000 * 0.03} = 69.44\mu H$$

$$C_{min} > \frac{I_{out}}{f * V_{ripple}} = \frac{0.03}{90000 * 0.001} = 333.33\mu F$$

Our choice of inductor and capacitor was narrowed down using the above formula. The desired output current was 30mA to ensure there was enough current for the constant current source. We wanted a small voltage ripple of 1 mV and our signal generator frequency to not go beyond 90000 Herz. Ideally, we wanted a smaller voltage ripple as it will cause less instability in our circuit hence the value for 1 mV. We also thought we might have time at the end for an extension upon our circuit to build our own signal generator hence we wanted the maximum frequency to be 90kHz to make that design easier with a crystal oscillator. The circuit seen in the schematic is the same circuit being simulated below. The inductor and capacitor values as well as the diode were chosen based off of what was implemented in real life (which were guided by the calculations). However, the transistor in the simulation differs from the real-life implementation transistor which drastically affects the results of the boost.

Boost Converter Simulation

The following simulations are reflective of an ideal implementation. They do not reflect the components chosen in the real life implementation but do reflect that the design chosen can output satisfactory voltage and current provided the appropriate components are chosen.

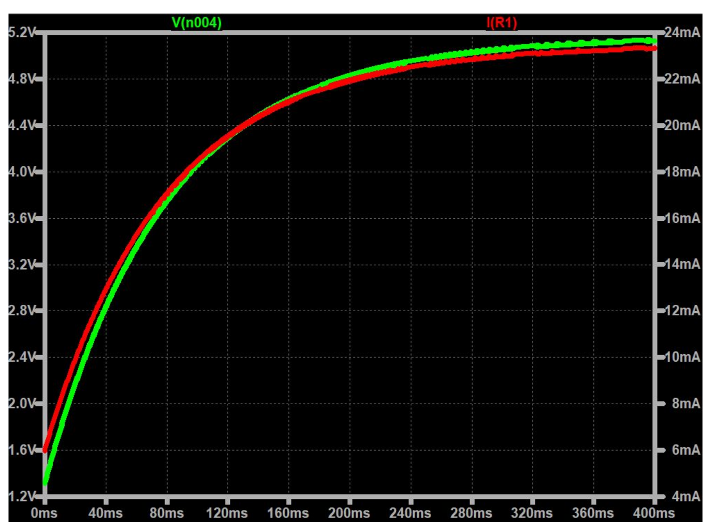
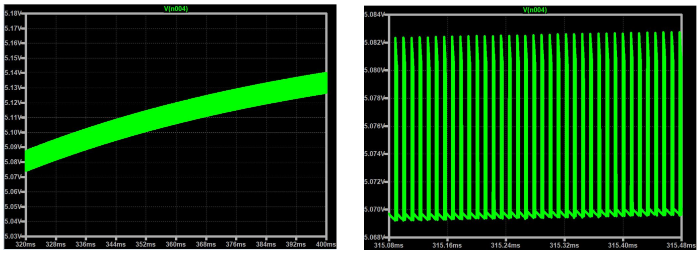


Figure 2: Output of Boost Converter (Voltage Across R1)

As can be seen in the figure above, the voltage and current across the resistor is able to produce above 20mA of current as well as a voltage above 5 volts. Although the results are not as ideal as the calculations, these results are solid enough to be able to drive the LED as well as provide enough current for a constant current source.



(a) Voltage Output Ripple Zoomed Out

(b) Voltage Output Ripple Zoomed In

Figure 3: Voltage Output Ripple

Unfortunately, the simulation shows voltage ripple of about 6 mV which is 6x the wanted voltage ripple.

Boost Converter Implementation

Unfortunately due to the time constraint of the project and the date at which we started to work on the project, we did not have enough time to obtain a manufactured inductor. Instead, we decided to hand-wound our inductor to a micro-Henry value. The purpose of highlighting this fact is that we did not have an inductor with a known value as well as the fact that it is hard to hand-wound an inductor to a specific value. However, during the lab we used the LCR bridge to find its value to be about 320 microHenry. The ESR of the inductor also was measured to be 0.1Ω. Important note is that we are relying upon the accuracy of the LCR bridge to have given us accurate values. There are about 15 turns of 1 mm diameter enamelled copper wire around the ferrite core toroid.

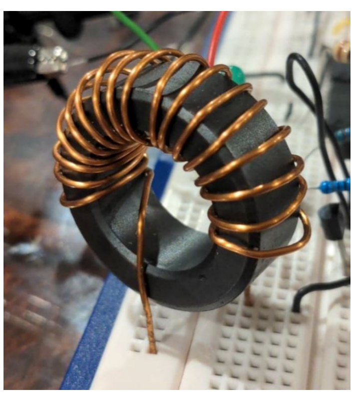


Figure 4: Hand Wound Inductor

The transistors that we were able to obtain were the BC338. The diode we used is the same as used in the simulation, the 1N5819. We found that the simulation with a similar transistor (BC547B) was not able to provide 20mA of current. We were not able to find a model for the BC338 on LTSpice or on the internet hence we used the BC547B which has similar characteristics in the datasheet. At best the simulation shows about 3.7 volts with 17mA across the 220Ω load resistance (seen in the figure below).

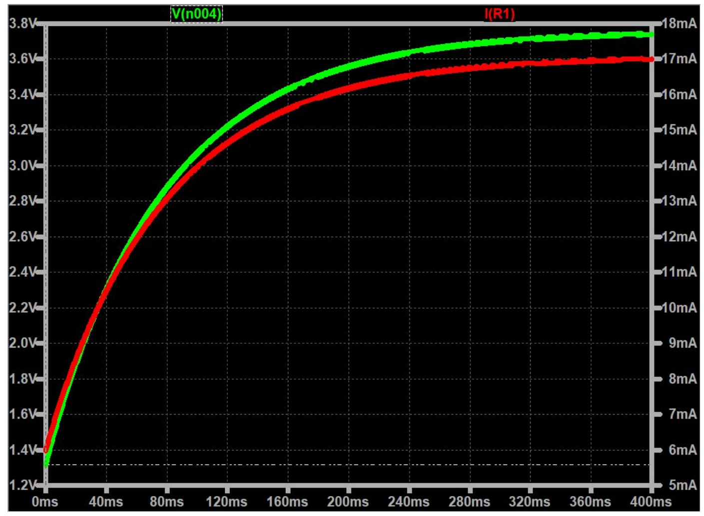


Figure 5: Hand Wound Inductor

Boost Converter Performance

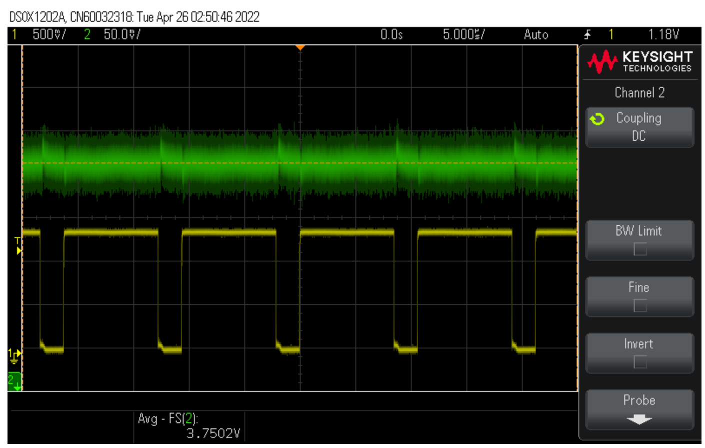
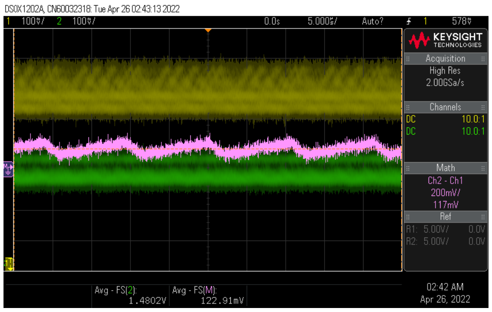


Figure 6: Boost Output Voltage (Green waveform)

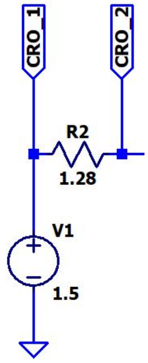
The above figure shows the real-life performance of the boost converter with a load resistance of 217.1Ω. We can see that the average voltage is 3.75 volts with an approximate ripple of 50mV. The average voltage is surprisingly accurate with the simulation. However, the voltage ripple is considerably worse. We can also see switching ripple albeit it is insignificant compared to the ripple of the boost. Using Ohm's law, we calculate that the current is 17.2 mA which is similar to the simulations. Therefore, power across the load comes to be 64.7 milliWatts.

By connecting a current shunt, we are able to measure the current at the input. The average value taken of the voltage across the 1.28Ω resistor is 122.91 mV. Again, using Ohm's law we find that the current is 96mA. Therefore, input power is 144 milliWatts with an input voltage of 1.5 volts.

The power efficiency of the boost is terrible at $\frac{64.7}{144} * 100 = 44.93\%$. Again, the likely culprit for these results are the transistor used in the implementation. I believe a lot of the power lost is from the transistor as it can get very hot. As for the ripple, I think a lack of feedback from the output is



(a) Voltage Across Resistor



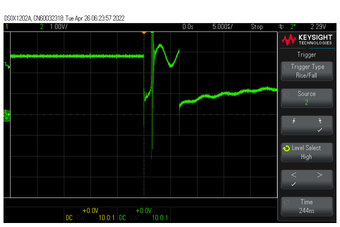
(b) Measuring Input Current

Figure 7: Finding Input Current

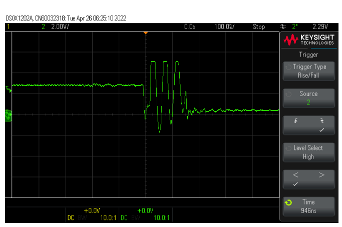
largely responsible. A decoupling capacitor does help considerably to reduce ripple as seen in previous labs however, boost converters are known for their poor transient response. Perhaps adding an input decoupling capacitor may help to reduce ripple, or if power efficiency is better, adding a linear regulator may be necessary.

Button Bounce

Button Bounce is an unintentional side effect of a mechanical switch. Depicted in the figures below, we can see ripples when the button is pressed and released. The consequence of these ripples make toggling a challenging task as it will toggle on or off with each ripple. Hence, we want to change the change of voltage over time. By essentially making an RC circuit, we can manipulate the time constant to ensure that the mechanical bouncing has a small effect on the voltage at the cost of rise and fall time of the waveform. We can then follow up the waveform with a schmitt trigger to provide a clean pulse signal with a lower rise and fall time.



(a) Falling Edge Waveform 1

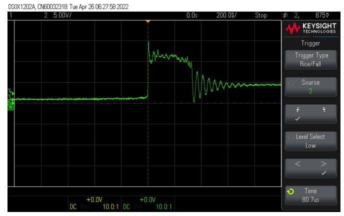


(b) Falling Edge Waveform 2

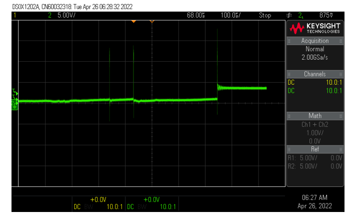
Figure 8: Button Bounce Falling Edge

Debounce Schematic

As can be seen from the Debounce Schematic figure, when the switch is off, the capacitor is being charged with 30kΩ in series. This is a simple RC circuit where its transient



(a) Rising Edge Waveform 1



(b) Rising Edge Waveform 2

Figure 9: Button Bounce Rising Edge

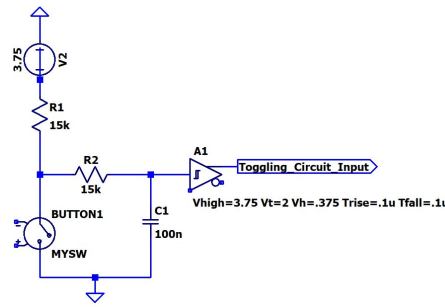


Figure 10: Debounce Schematic

response is modelled by

$$\begin{aligned}\text{Voltage Across Capacitor} &= Vcc - Vcc * e^{-\frac{t}{RC}}\\ &= 3.75 - 3.75 * e^{-\frac{t}{0.003}}\end{aligned}$$

When the switch is on, the circuit then transforms into another simple RC circuit, but this time discharging with only 15kΩ. The transient response can be modelled by

$$\begin{aligned}\text{Voltage Across Capacitor} &= Vcc * e^{-\frac{t}{RC}}\\ &= 3.75 * e^{-\frac{t}{0.0015}}\end{aligned}$$

Debounce Simulation

To model the bouncing of the mechanical switch, we had to include multiple pulses with different frequencies at the rising and falling edge.

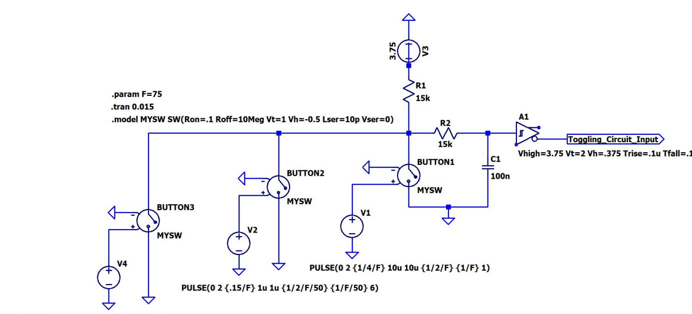


Figure 11: Boost Output Voltage (Green waveform)

We can then see the RC circuit reducing the rate of change of voltage over time (Green waveform) and the schmitt trigger producing a smooth pulse wave (Pink Waveform) despite the jagged waveform from the mechanical switch.

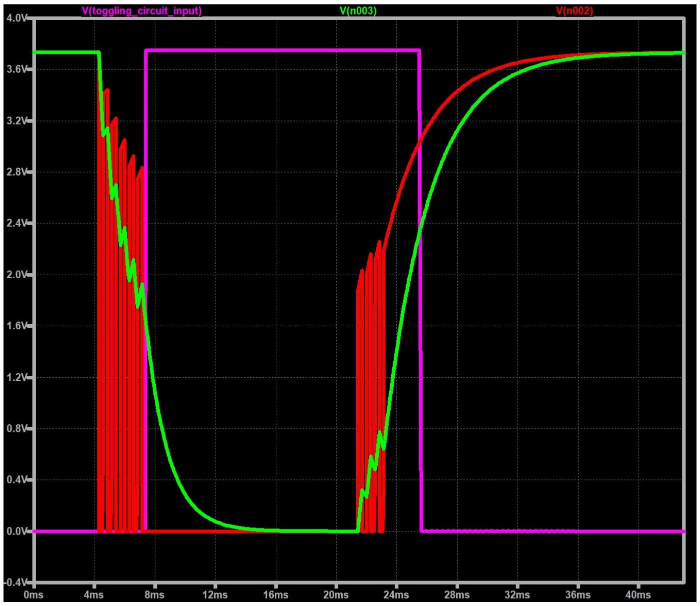
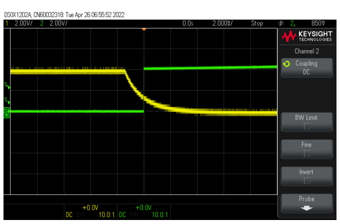
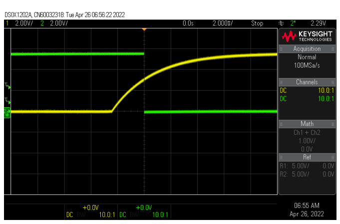


Figure 12: Boost Output Voltage (Green waveform)

Debounce Performance



(a) Voltage Output Ripple Zoomed Out



(b) Voltage Output Ripple Zoomed In

Figure 13: Button Bounce Rising Edge

The performance of the circuit in real life is just as simulated albeit with a smaller time constant likely due to the error in resistance value and capacitor value leaning towards smaller values.

Note that the hysteresis and V_t values chosen for the simulation were based off the datasheet for the SN74HC14N. Explicitly, for a V_{cc} of about 3.75 volts, the values chosen were based off the data sheet parameters and their test conditions at 2 and 4.5 volts as seen in the figures below.

PARAMETER		TEST CONDITIONS		V_{CC}	Operating free-air temperature (T_A) 25°C MIN	TYP	MAX	−40°C to 85°C MIN	TYP	MAX	−55°C to 125°C MIN	TYP	MAX	UNIT
V_{T+}	Positive switching threshold			2 V	0.7	1.2	1.5	0.7		1.5	0.7		1.5	V
				4.5 V	1.55	2.5	3.13	1.55		3.13	1.55		3.13	
				6 V	2.1	3.3	4.2	2.1		4.2	2.1		4.2	

Figure 14: Vt+ Parameter Schmitt Trigger Datasheet

Toggling Schematic

The toggling of the push button can be achieved through many solutions however, for this design I have chosen to use

PARAMETER		TEST CONDITIONS		V_{CC}	Operating free-air temperature (T_A) 25°C MIN	TYP	MAX	−40°C to 85°C MIN	TYP	MAX	−55°C to 125°C MIN	TYP	MAX	UNIT
V_{T-}	Negative switching threshold			2 V	0.3	0.6	1	0.3		1	0.3		1	V
				4.5 V	0.9	1.6	2.45	0.9		2.45	0.9		2.45	
				6 V	1.2	2	3.2	1.2		3.2	1.2		3.2	
ΔV_T	Hysteresis (V_{T+} - V_{T-})			2 V	0.2	0.6	1.2	0.2		1.2	0.2		1.2	V
				4.5 V	0.4	0.9	2.1	0.4		2.1	0.4		2.1	
				6 V	0.5	1.3	2.5	0.5		2.5	0.5		2.5	

Figure 15: Vt+, Vt- & DeltaVt Parameter Schmitt Trigger Datasheet

digital logic. I have chosen to use digital logic as it is robust to noise as well as works over a vast range of different supply voltages (Previous Lab) and considering our boost converter is incredibly noisy (ripple), it seems appropriate and convenient to use here.

As can be seen in the schematic, there is a RC circuit at the bottom of the flip flop which acts to "clear" the initial state of the flip flop such that it outputs LOW on startup. This is important otherwise there is no guarantee that the output is LOW on startup. The flip flop simply changes its output on each clock cycle (rising or falling edge is not important and is found on the datasheet) due to the output fed back to the input.

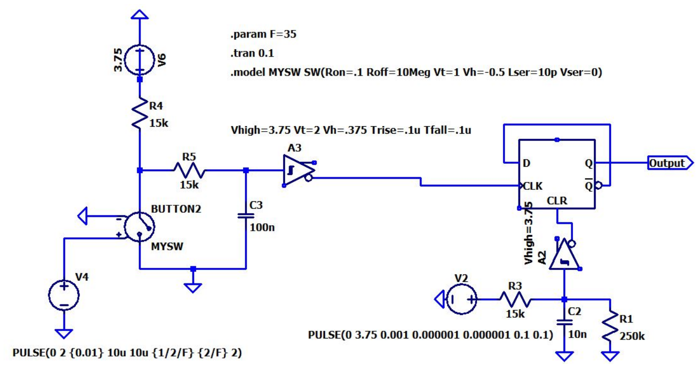


Figure 16: Toggling Circuit Schematic

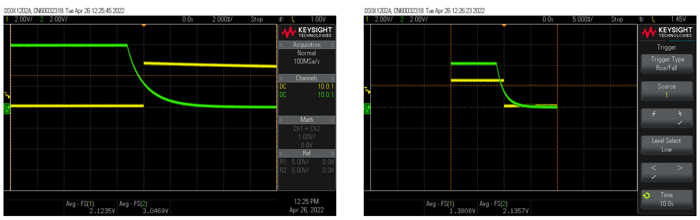
Toggling Simulation

As seen in the simulation, the circuit is functioning as designed. The pink waveform is the voltage at CLR, the green waveform is the output and the red waveform is the input. We can clearly see the output is changing at the rising edge of the input and the CLR ensuring that the output is LOW on startup.

Toggling Performance

We can clearly see from the Toggling Real-Life Waveforms figure, on the falling edge of the pushbutton waveform (Green Waveform) we see a change in the output (yellow Waveform). Note we are using the SN74LS175N D-flip flop for the real-life implementation which has its CLK input inverted. The toggling circuit behaves exactly as simulated. There is also a voltage drop evident which was accounted for in the simulation.

Figure 17: Input, Output and CLR waveforms



(a) Rising Edge Waveform 1

(b) Rising Edge Waveform 2

Figure 18: Toggling Real-Life Waveforms

Constant Current Source Schematic

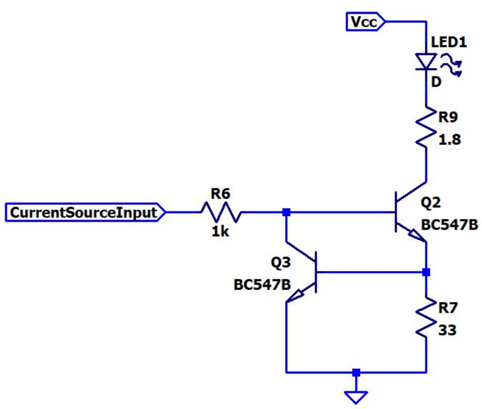


Figure 19: Schematic of Constant Current Source

The input from the toggle turns the Q2 Transistor on and off - acting as a switch. Q3 ensures that the voltage across R7 is fairly constant at 0.7 volts (Vbe voltage). Hence, R7 value controls the current through the LED which is currently designed for 20mA. I.e. $\frac{0.7}{0.02} = 35\Omega$ however, it is difficult to find a 35Ω resistor and we settled for a 33Ω as we had it on hand. Note that the base current into Q3 is negligible hence allowing for Emitter current approximately equal to Collector current of Q2. R9 was added as a current shunt resistor for more accurate measurements as previously done.

Constant Current Source Simulation

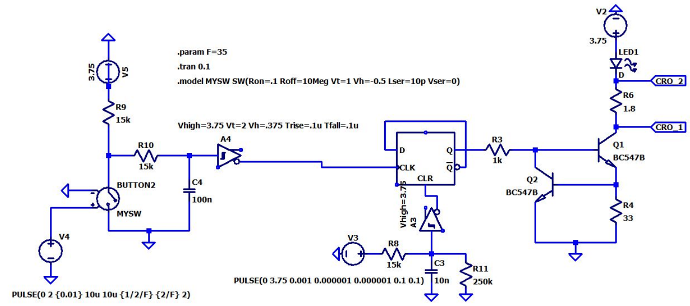


Figure 20: Simulated Schematic for Constant Current Source

From the above circuit, we are able to demonstrate each section performing their function minus the Boost Converter. The following simulations show 20mA through the LED.

Figure 21: Q2 Base Voltage (Green) & LED Current (Red)

As shown in the above figures, the circuit is fairly resilient to voltage changes as with 1 volt less in both the toggle and Vcc voltage, the circuit is able to produce 19mA. It is extremely constant and holds well in the simulation. With higher voltages, the circuit stays constant at 20mA.

Figure 22: Q2 Base Voltage (Green) & LED Current (Red) reduced voltage

Constant Current Source Performance

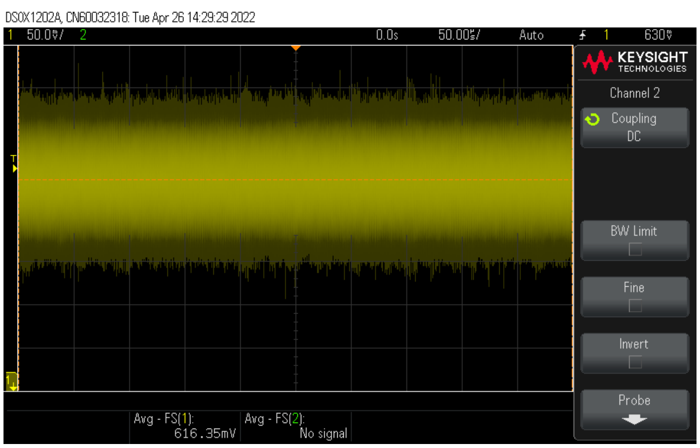


Figure 23: Voltage Waveform Across the 33 Ohm Resistor (Current Source)

Unfortunately, the constant current source implementation in real life did not work out. The culprit is the voltage ripple from our Boost Converter. As can be seen from the figure, there is about 100mV of ripple. This is far too much for the current source to handle and will not be able to function properly. Also, the boost itself is not drawing more than 20mA of current and therefore cannot possibly be outputting 20mA across the load. At best, the average current drawn is 18.67mA as depicted in the above figure ($\frac{616.35mV}{33\Omega} = 18.67mA$)
Figure 24 shows that the current source is not constant as it has a drastically different current going through it ($\frac{579.37mV}{33\Omega} = 17.55mA$). Albeit the simulation showed a mA difference with a difference in voltage of 1 volt, the difference in voltage between Figure 23 and Figure 24 is 0.3 volts. The constant current source is not functional.

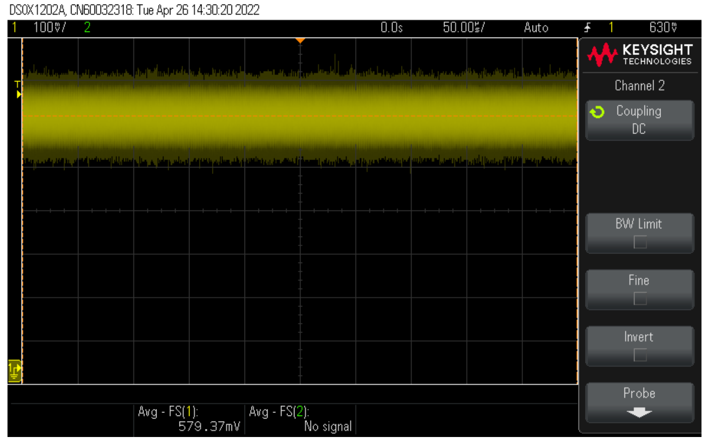


Figure 24: Voltage Waveform Across the 33 Ohm Resistor lower voltage (Current Source)

General Performance

Power Efficiency

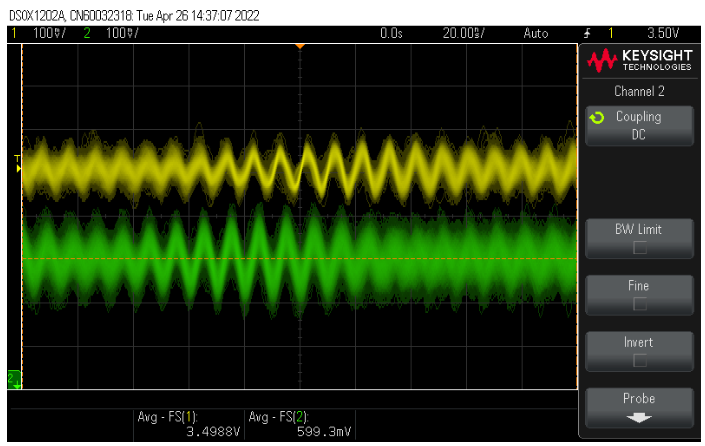


Figure 25: Voltage Waveform Across the 33 Ohm Resistor (Current Source) & Voltage across LED + 33 Ohms

By connecting a current shunt at the output of the Boost Converter, we can measure its output current from there. Alternatively, measuring the current going into the current source is a close approximation to the power dissipated as that is the dominant load. From Figure 25, we can see the current is about 18.16mA with a voltage of 3.4988. Therefore, about 63 milliWatts. The input power (not shown) was 1.4 volts with 101mA Current, which is about 141.4 milliWatts. Therefore, our boost power efficiency is very poor at about 44.55%. However, this is likely due to our choice of transistor as previously discussed and quite likely our voltage ripple is causing instability hence power loss.

Input Supply Voltage Range

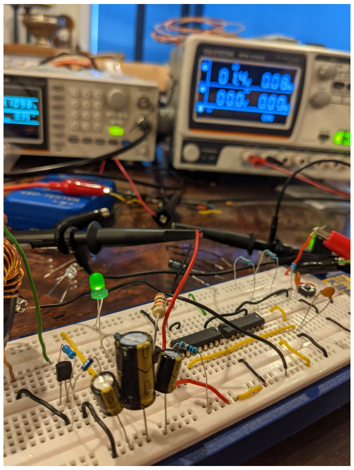
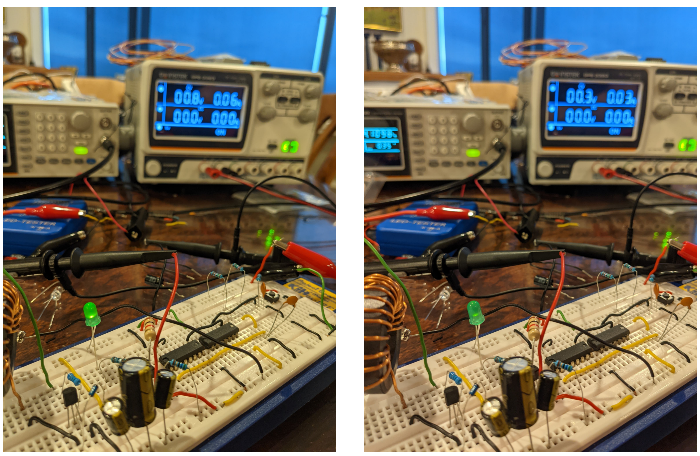


Figure 26: 1.4 Voltage Driven LED



(a) 0.6 Voltage Driven LED (b) 0.3 Voltage Driven LED

Figure 27: Varying Input Voltages

Surprisingly, despite our failure to create a constant current source, our LED was forward biased even at very low battery voltage as can be seen in the figures above (0.3 volts!). However, the signal generator may have had a higher voltage at this point and hence was driving the circuit. Albeit, the circuit can comfortably produce more than 10mA until 1 volt.

Conclusion

Conclusively, we found that our simulations held very well. If we had chosen a better transistor to give us higher output voltage, I believe we would have had a greater chance at resolving the ripple issue as well as the constant current source issue. Ultimately, our circuit was not far off of completing the specifications and was able to illuminate the LED.

Circuit Schematic

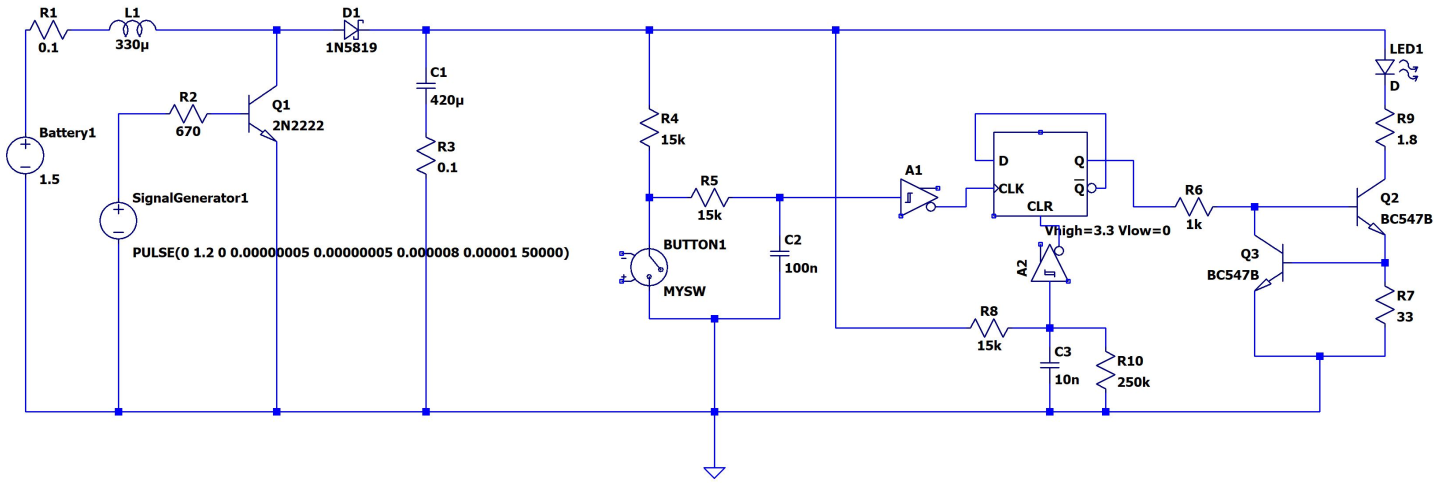


Figure 28: Schematic of Designed Circuit Connected

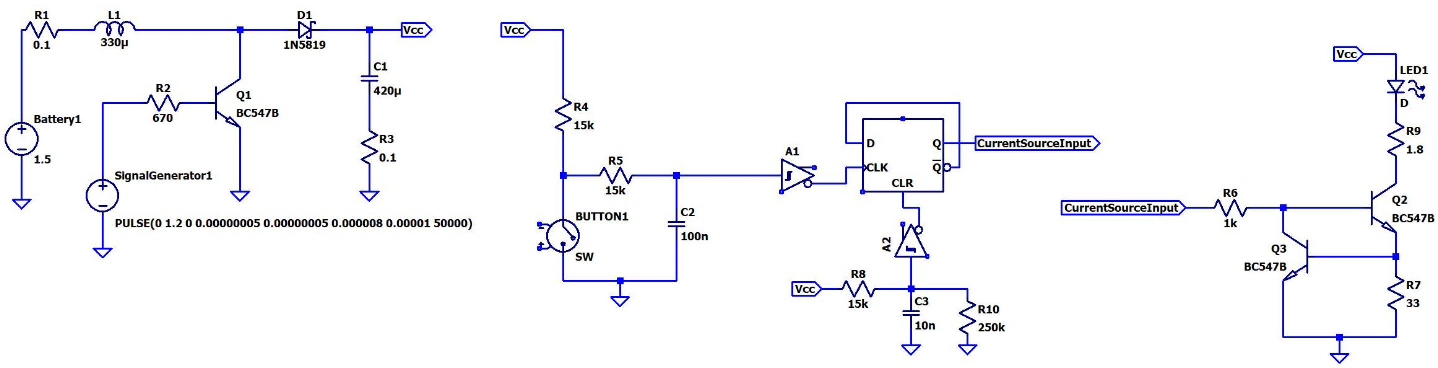


Figure 29: Schematic of Designed Circuit with Separated Sections