Senior Capstone Project: Circuit and Microelectronic Systems

Solid State Lighting with Blue Laser Diodes

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Abstract

A new source of solid-state white illumination is proposed using methods involving blue lasers and yellow phosphor. This model was shown to be feasible through multiple tests and analyses. The mixture of blue light and yellow phosphor produces illumination comparable to white light, which is examined with CIE calculations. Different configurations of mirrors, lenses, and the lamination of phosphor were weighed against each other for the most optimal projection of light. Switching mode current supplies are also proposed which present lower power consumption compared to the habitually used linear supplies to drive LEDs and lasers.

Introduction

LED bulbs have already gone to the mass-market and have proven to be more efficient and affordable compared to incandescent and fluorescent lighting. However, next-generation lighting may truly dominate from a different type of solid-state device -- the laser diode. Laser-based lighting has the potential to be more efficient given the right safety measures and proper circuitry. Moreover, if taken care of properly, these diodes will have a comparably long lifetime.

Luxury car manufacturer BMW has already developed a headlight prototype proving this technology in their i8 concept car, stating that their headlights “are more efficient than LED lights, highly flexible, ten times smaller, pleasant to the eye and absolutely safe” [1]. Similar studies have been done by a research group from the Chinese Academy of Sciences in Beijing, China, where they studied the white light effect with an InGaN near-ultraviolet laser diode, blue phosphors, and yellow phosphors. Their research has proven the longevity and stability of the lighting methods. [2]

There has also been development in other consumer-based optoelectronic devices such as those seen in the main product line of Prysm, Inc. Re-igniting familiar technology used in cathode-ray tube (CRT) displays, the company has invented Laser Phosphor-based Displays (LPDs), consisting of three main components – a phosphor panel, a laser engine, and a laser processor. They boast these LPDs to have 75% lower power consumption, brilliant images, sharp text, near 180 degree viewing angles, and no motion blur. [3]

Figure 1a – Three blue lasers reflect off planar mirrors and hit a yellow phosphor to produce white light.

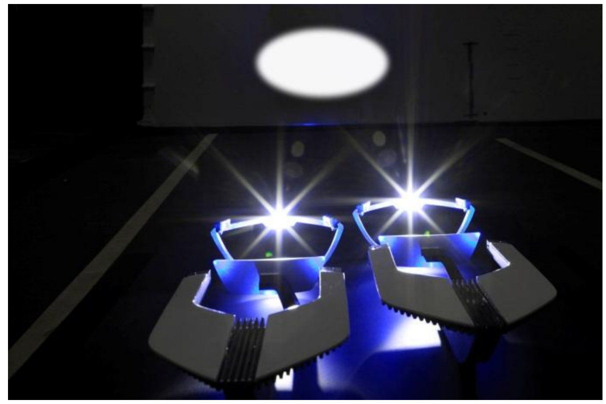


Figure 1b – BMW's prototypes prove to shine a perceivable light across to the other side of the room.

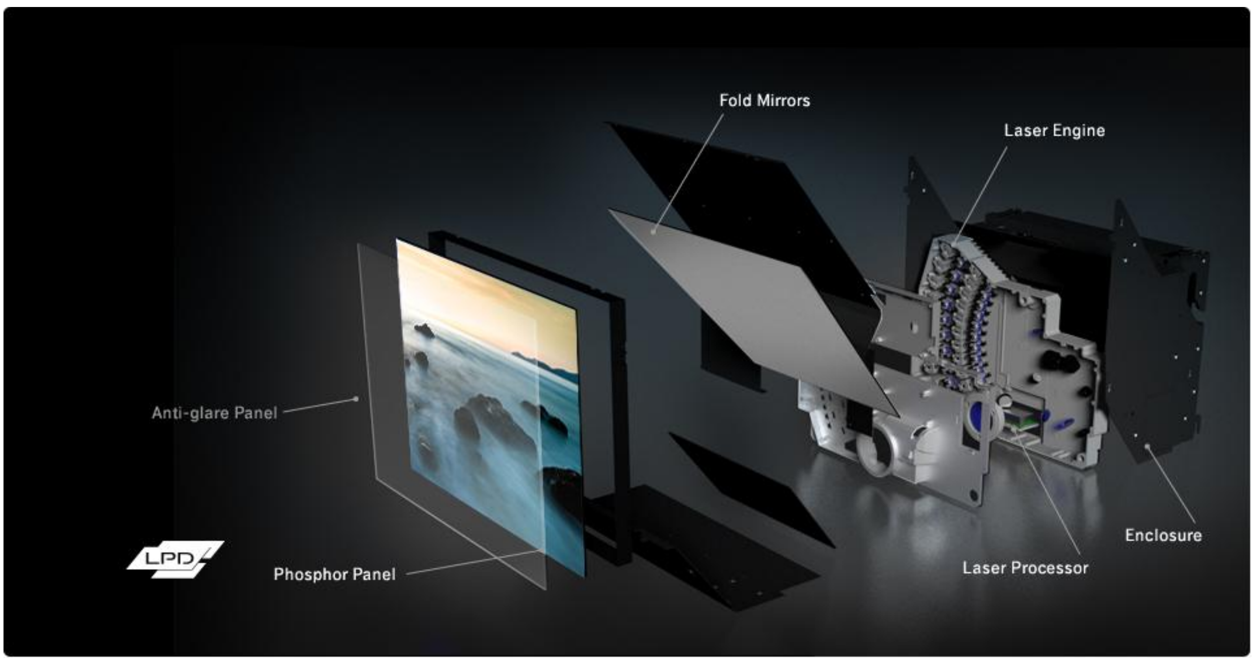


Figure 2 – Prysm's LPDs revive a familiar technology and take the next step.

Our project focuses on the theory behind this type of lighting as well as explains why it should shine over LED technology.

Theory Behind Solid State & Laser-Based Lighting

Our main application for this project is illumination, more specifically, automotive headlights. Our primary source of light is from a laser diode, and lasers, by definition, are monochromatic and emit at a small divergence angle. In order to create white light from a laser source, there are two main methods. The first one is to get the three primary colors of additive light – red, green, and blue – and combine them to make a white "laser". Unfortunately, this method requires power to be supplied to each individual diode and accurate optics to line up the three different lasers. Also, in terms of illumination applications, it is potentially dangerous to the human eye to utilize. The second method utilizes only a blue laser and yellow phosphor. The scattering of the laser and the emission of yellow light from the laser hitting the phosphor (known as Stokes shift – see **Figure 3**) will together be perceived as white light [5]. At this point, the light can no longer be technically called a laser because it is no longer monochromatic and the divergence angle of the light is very wide. Therefore, it is already theoretically safer to utilize the Laser-phosphor method rather than the laser array.

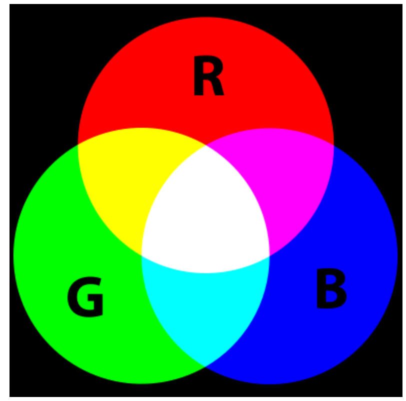
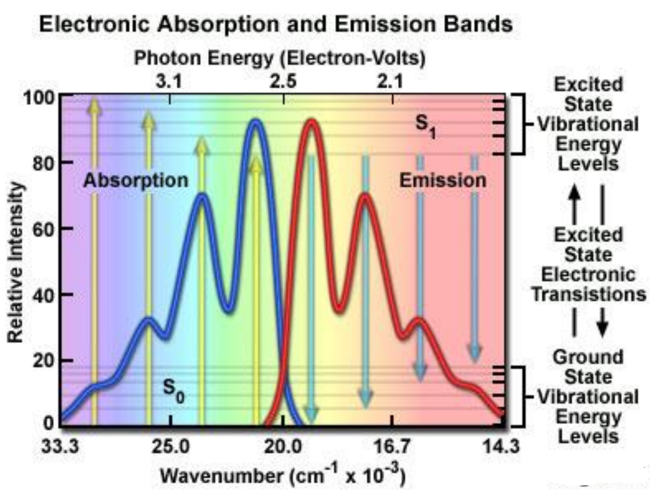


Figure 4 – The additive color space [4]



Stokes Shift (simplified)

$$\frac{hc}{\lambda_1} = \frac{hc}{\lambda_2} + E_T, \qquad where$$

$$h = Planck's\ constant$$
$$c = speed\ of\ light$$
$$\lambda_1 = wavelength\ absorbed$$
$$\lambda_2 = wavelength\ emitted$$
$$E_T = heat\ energy$$

Figure 3 – Stokes Shift

White light can be categorized in several ways. To simplify exactly what kind of white we will be producing, we look at the color temperature scale – a linear scale in units of Kelvin that describe the color of an ideal blackbody radiator at different temperatures. **Figure 5** shows both the basic color temperature scale as well as it on the CIE 1931 XYZ color space diagram [6][7].

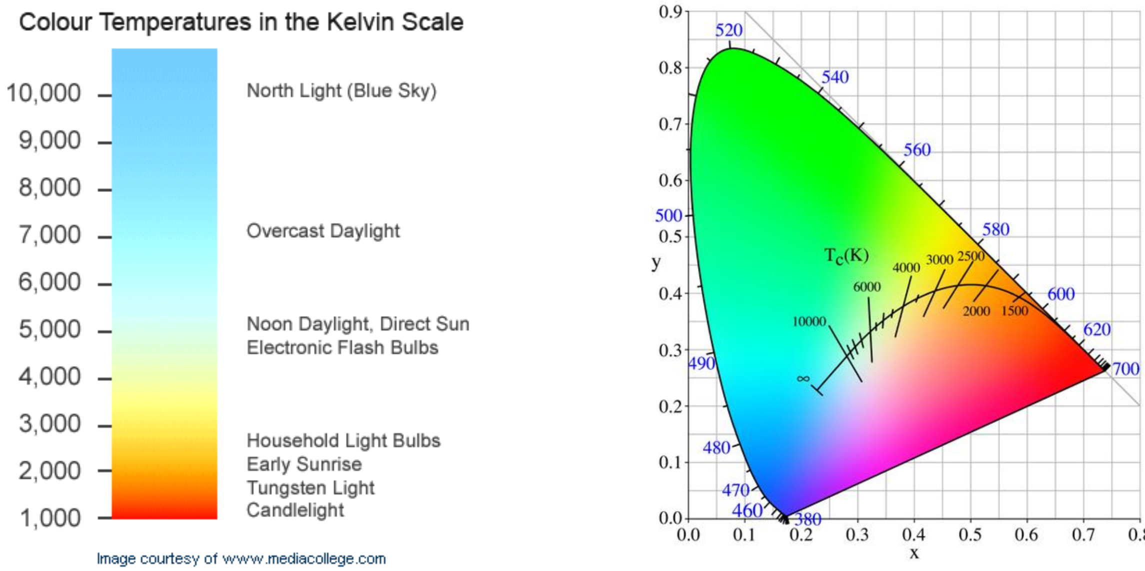


Figure 5 – (Left) Linear color temperature scale, (Right) CIE 1931 XYZ chromaticity space with lines of constant correlated color temperature

We note that on these diagrams, the most natural white light is somewhere between the color temperature range of 4000-6000 K – approximately the CIE coordinate range (0.32, 0.33) to (0.39, 0.37). This is an ideal range because any lower would give late night drivers a hazy atmosphere that encourages drowsiness, and any higher would quickly fatigue drivers' eyes [8].

The color temperature of our white light will be mainly dependent on the amount of phosphor. With no phosphor, there will just be a blue laser. On the other hand, too much phosphor will emit only yellow light. The following shows research with different thicknesses of yellow phosphor on a blue LED.

Table 1. Test results of five samples with different phosphor concentrations

Sample	Phosphor Concentration (wt %)	Colorimetric Data (x, y)	Color Temperature/ Tc (K)
1	0	(0.1406,0.0463)	>=30000
2	13	(0.1911,0.1443)	>=30000
3	17	(0.2831,0.2895)	9670
4	29	(0.3112,0.3361)	6515
5	50	(0.4009,0.4808)	4122

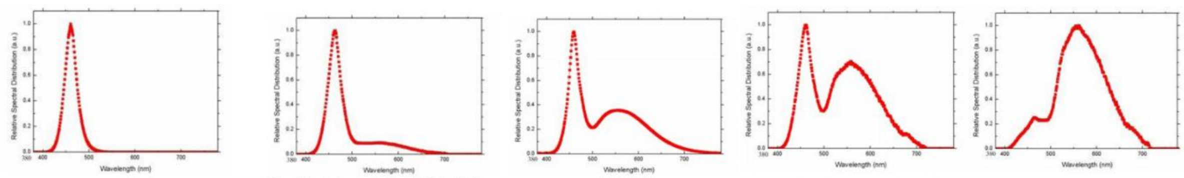


Figure 6. Spectral property of sample 1 without the phosphor coating

Figure 7. Spectral property of sample 2 with 13wt% phosphor concentration

Figure 8. Spectral property of sample 3 with 17wt% phosphor concentration

Figure 9. Spectral property of sample 4 with 29wt% phosphor concentration

Figure 10. Spectral property of sample 5 with 50wt% phosphor concentration

Figure 6 – Various yellow phosphor thicknesses on blue LEDs

The samples tabulated correspond to the spectral curves for increasing phosphor concentration. The curve we want for our light should be somewhere between the 4th and 5th curves from the aforementioned research. [9]

LED Lighting

LED Pre-Experiment

White LED bulbs are already out in the market. Most of them utilize multiple high-intensity blue LEDs coated with a phosphor that emits yellow light. The combination of the two spectra produces white light as seen in **Figure 7a.** In this pre-experiment, we utilize the yellow phosphor coated on these LEDs and reflect the light from a couple of standalone 465nm LEDs (See **Figure 7b**) to determine whether or not 465nm LEDs will excite the phosphor and whether or not the light produced is white.

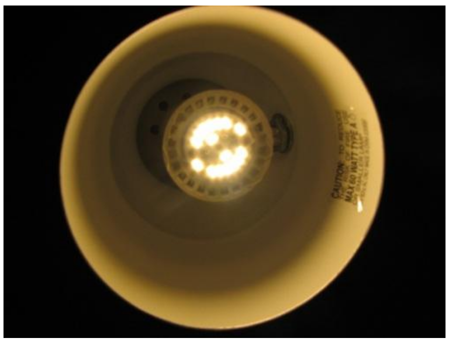


Figure 7a – 9W "bright white A19" LED bulb by ecosmart

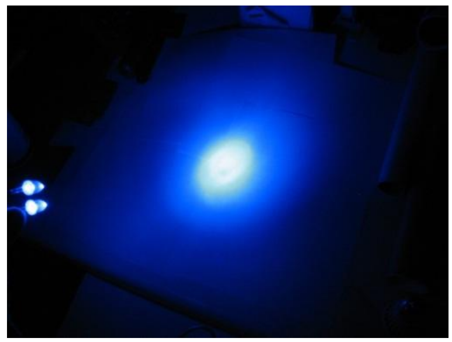


Figure 7b – A couple of 465nm LEDs from RadioShack

Since the current camera seems to saturate at the light levels produced in our experiment (NOTE: In **Figure 7b**, the center of the blue light appears white), we will use the image of a picture to distinguish the difference between blue and white light. The images below show the image under a fluorescent (CFL) bulb as well as under an LED bulb.

Figure 8a – Under CFL bulb

Figure 8b – Under LED bulb

Utilizing our blue LEDs we shine the light on the picture. In addition, we attempt to rid of most ambient light so that the only light being emitted is from our experiment. We then shine the blue LEDs on the phosphor coats in the LED bulb. Then we reflect the light onto the picture, and note the change in color. **Figure 9** shows the picture in both lights.

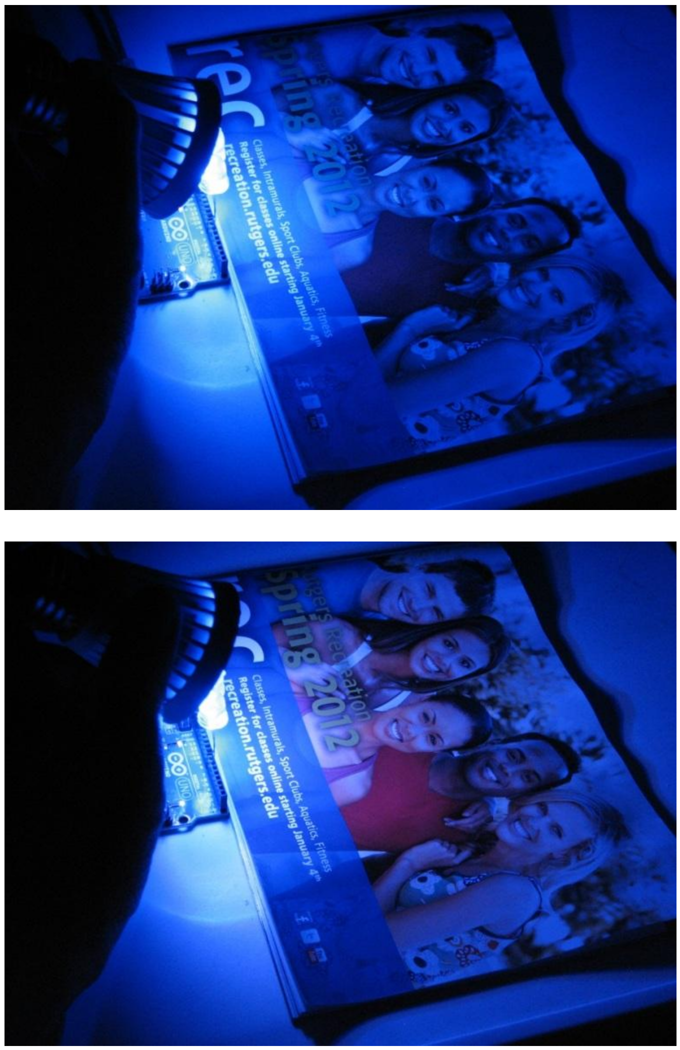


Figure 9 – (Top) Reflecting off the PCB on the LED bulb; (Bottom) Reflecting off the phosphor on the LED bulb

We realize the reduction of white light intensity when the blue light is reflected off the yellow phosphor as opposed to shining straight though (like in the commercial bulb). However, there is indeed white light being produced since the picture in the bottom image appears to have more color than that in the top image. The range in colors reflected in the picture indicates that there is a range of wavelengths produced in the experiment.

Producing White Light with LEDs

We take the standalone 465nm LEDs from our pre-experiment, and focus on the different configurations of phosphor coating as well as the power levels used to produce our own white light. The following factors are taken into account:

- The voltage and current flowing through the LEDs
- Coating configuration – directly on LED, reflecting off a flat/concave/convex mirror, passing through a lens
- The amount of phosphor used for the coating

The following diagrams depict how we produce our white light. The bottom diagram shows that there will be reflection from hitting the lens. Also, these do not describe the exponential scattering of light as it propagates through space:

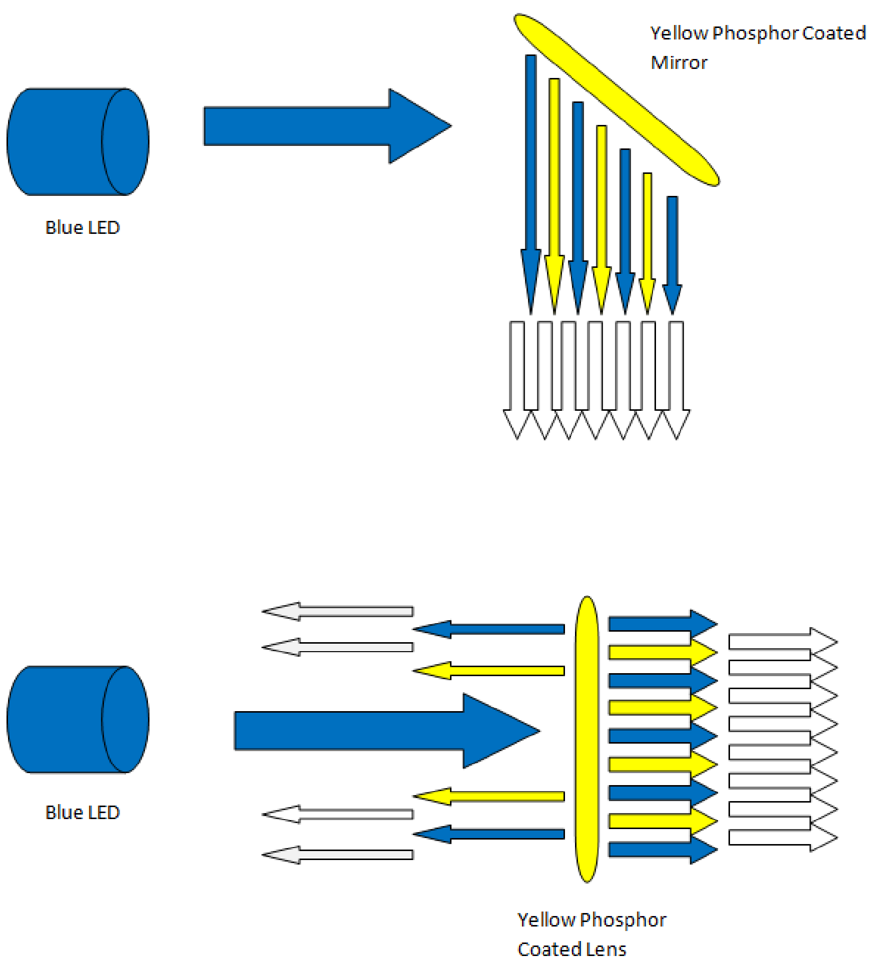


Figure 10

With careful consideration – and a limited amount of supplies – we came up with six different configurations:

- 1 – directly on the LED
- 3 – on a flat mirror
- 1 – on a convex mirror
- 1 – on a lens-like surface

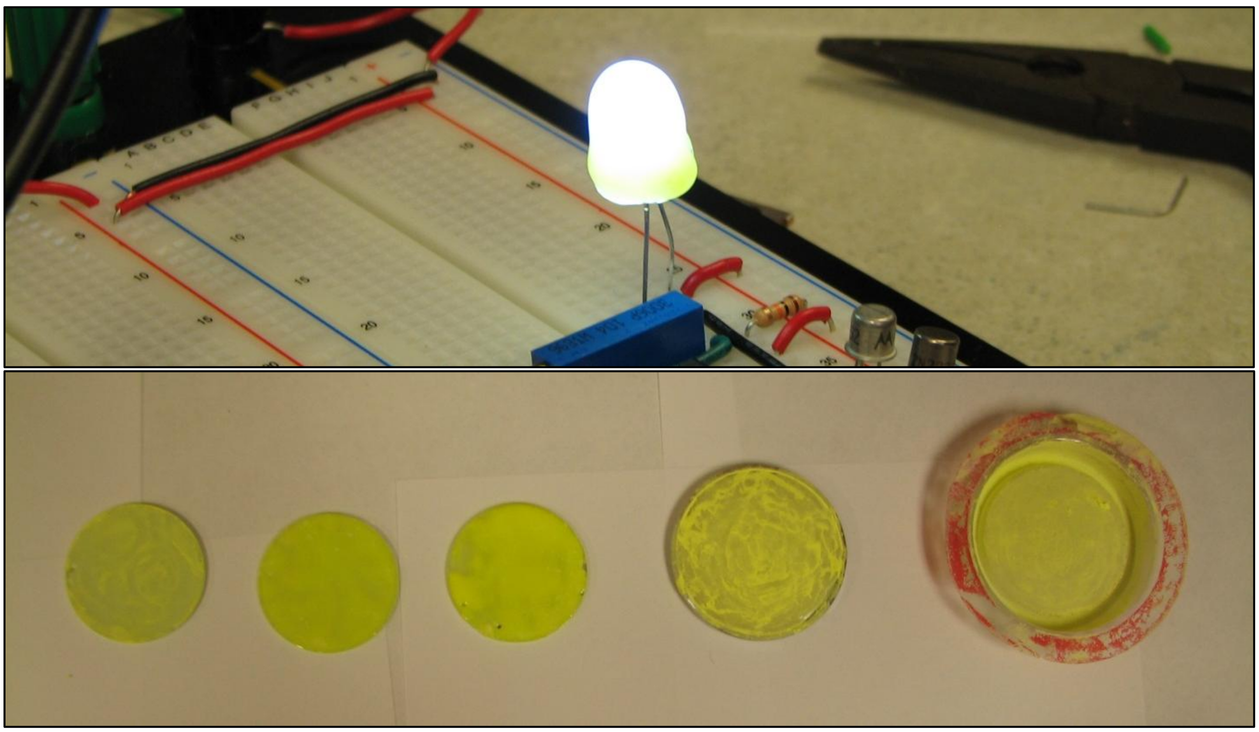
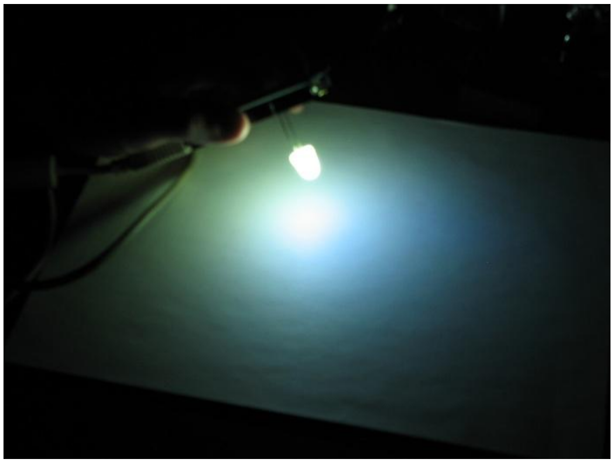


Figure 11 – (Top) Phosphor coating on LED, (Bottom) Phosphor coating on several surfaces.

Looking at **Figure 11**, we note that the first three surfaces from the left are flat mirrors, the fourth is a convex mirror, and the last is simply plastic that we denote as our “lens”. With exception to the second two flat mirrors, all coatings were made by applying a thin film of transparent glue over the top of these surfaces along with a thin top layer of phosphor powder. The two exceptions were coated with a slurry mixture consisting of yellow phosphor and clear epoxy.

The following images depict the light created by these coatings as well as their corresponding CIE 1931 XYZ coordinates. The order of the surfaces corresponds to the order shown in **Figure 11** from left to right. The coordinates were determined by using “Colorlab 1.0” – a color processing MATLAB toolbox made specifically for general-purpose quantitative colorimetric applications [10].



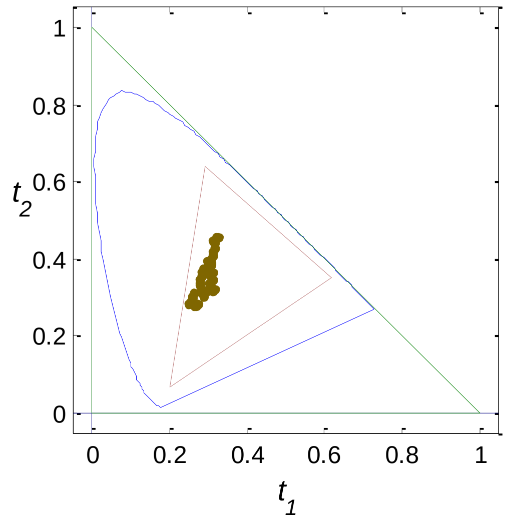
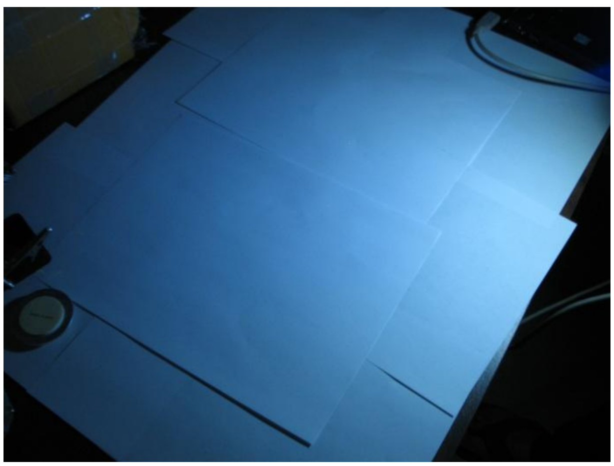


Figure 12a – Coated LED



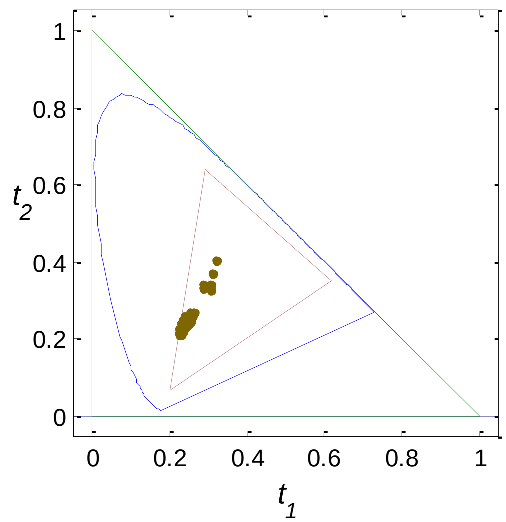
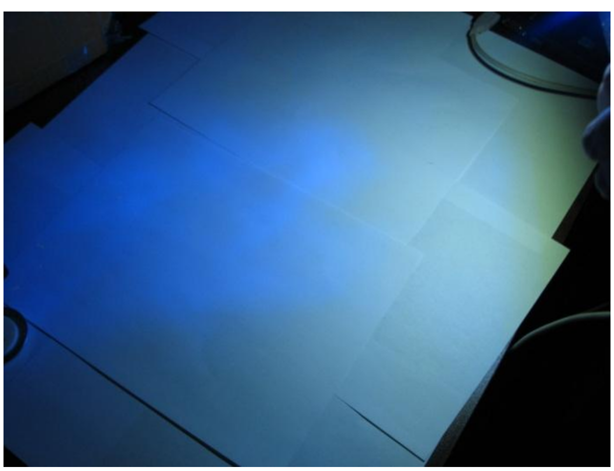


Figure 12b – Mirror 1



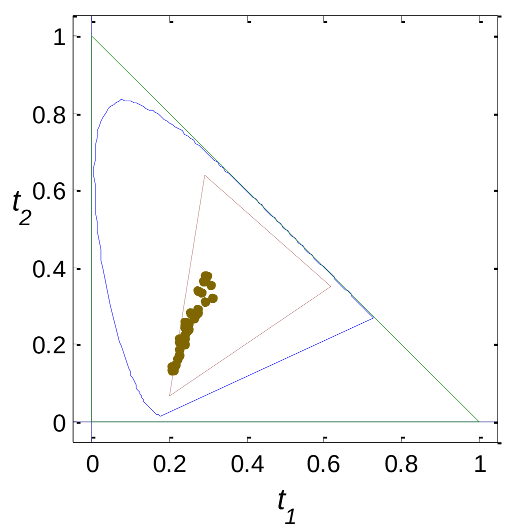
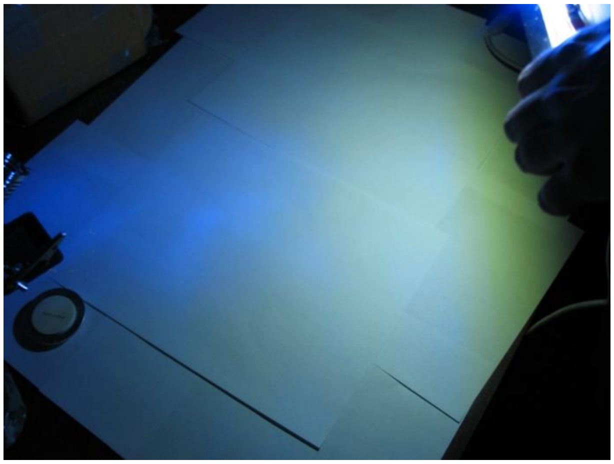


Figure 12c – Mirror 2



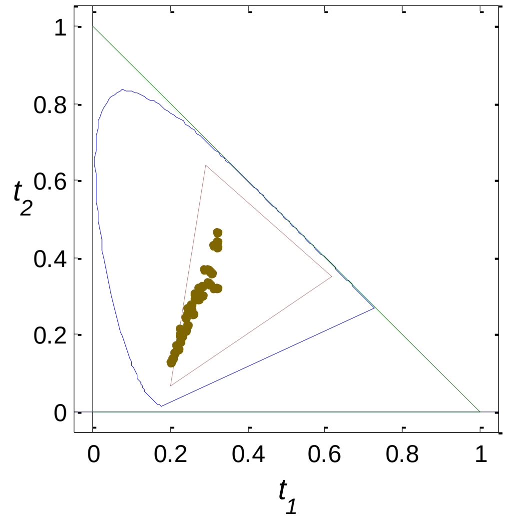
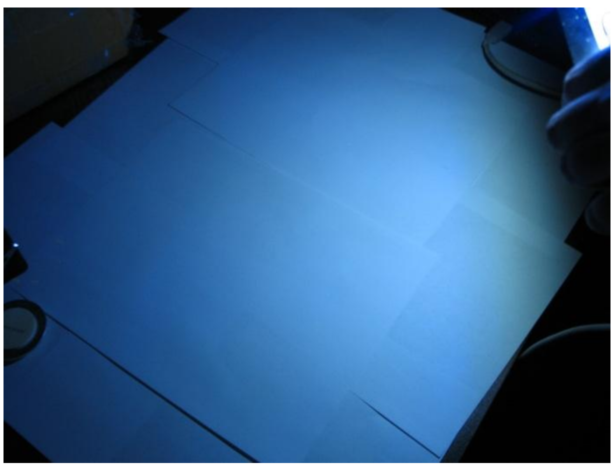


Figure 12d – Mirror 3



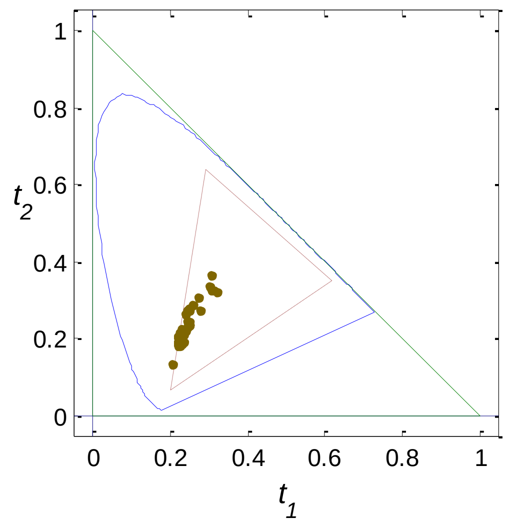
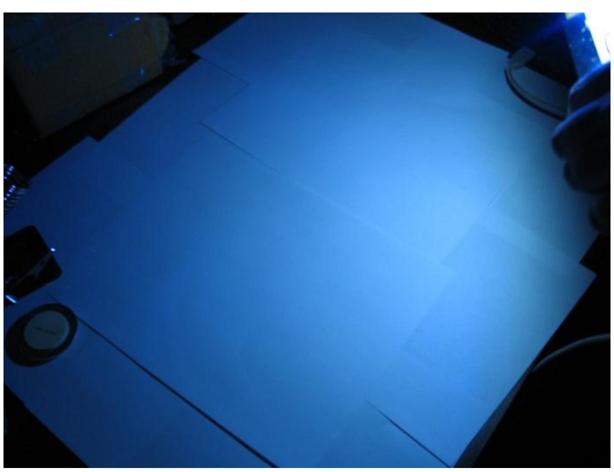


Figure 12e – Mirror 4



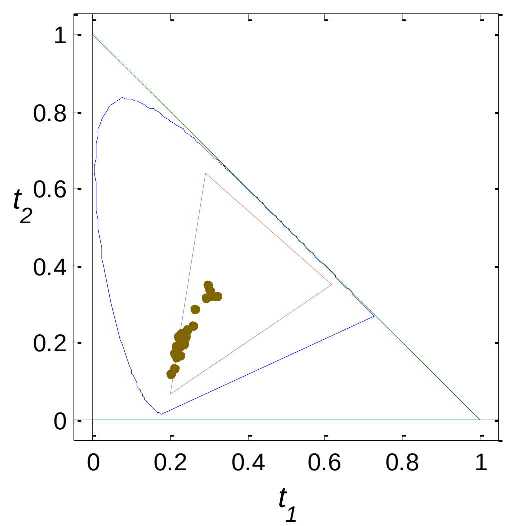


Figure 12f – Mirror 5

Looking at each of the CIE 1931 XYZ plots, we can conclude that there is white light depicted in each corresponding picture (NOTE: the dotted triangle refers to the standard RGB color space widely used by computer monitors). Since the only light emitting in the room was coming from the LED and the phosphor, they must have been the only sources of the white light. **Figures 5a, 5c,** and **5d** are particularly interesting because we can easily see the gradient from blue to yellow – with white being the intermediate color. Their data plots clearly support this observation, showing points in both the blue and yellow coordinates, trailing through "pure white" at (0.333, 0.333). (See **Appendix** for actual plot data.)

We take each of these configurations and measure luminous emittance using a general-purpose lux meter – lux being the unit of measurement equivalent to lumens per square meter. The following plots show us particular measurements we find intriguing in our study. (A complete table of our data is in the **Appendix**)

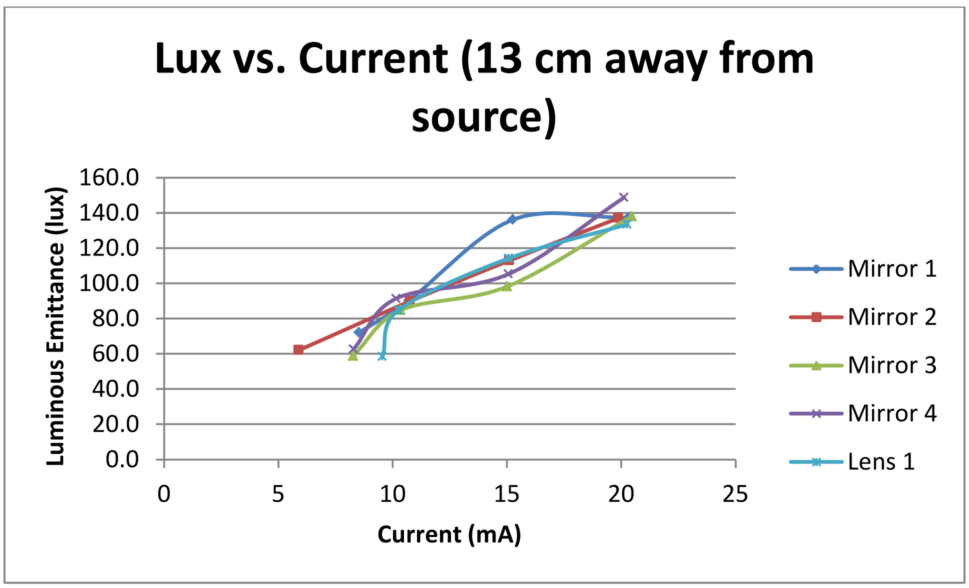


Figure 13

From our understanding of semiconductor physics, higher current flowing in the diode means that more electron-hole pairs are combining, and therefore, emitting more photons. Thus we can expect that the Lux emitted from the LED should be proportional to current. The data in Figure 13 clearly show a proportional relationship between current and Lux. Some configurations showed some variance, Mirror 1 and 3. This could come from the variance of the powder coating on the mirrors. Mirrors 2 and 4 and Lens 1 showed much lower variance.

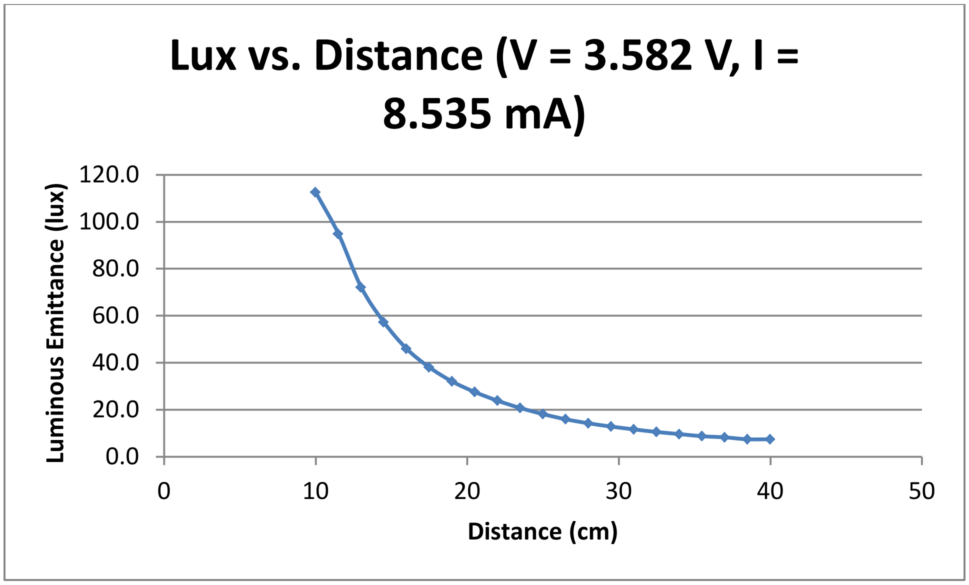


Figure 14a – Measurements using Mirror 1

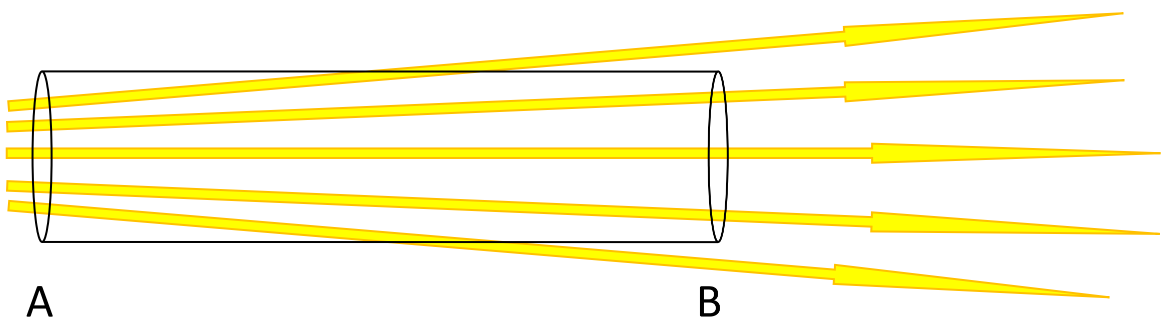


Figure 14b – Light ray density at varying distances

Figure 14a shows us the exponentially decaying characteristics of lux as distance from the source increases. We can say that this is similar to electric field lines coming from a charged particle, except in our case, we are looking at rays of light emitting from a source. **Figure 14b** visually depicts the general behavior of light. Looking at a constant cross-sectional area from point A to point B, there are more rays of light passing through point A than point B.

Referring specifically to Mirrors 2 and 3, we can see that despite their lower lux values compared to other configurations, they have the most consistency. This is a result of the highly reflective and smoother coating made by the epoxy-phosphor slurry. The other surface configurations have a larger divergence angle due to their rough coatings. This is a result of inequality between incident and reflection angles when light rays hit the surface.

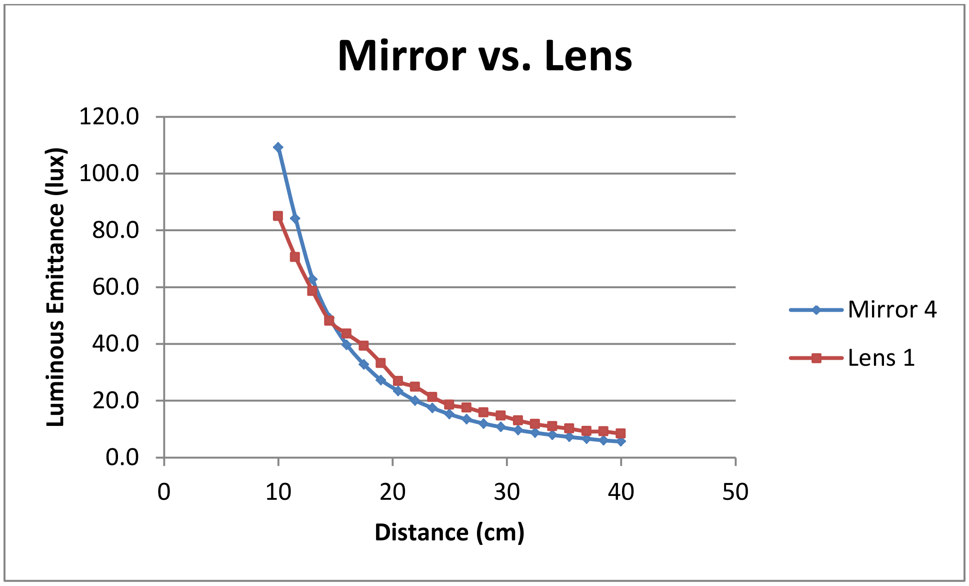


Figure 15 – Comparison between using a mirror or a lens-like surface

Figure 15 represents the comparison of the lux of the mirror and the lens. Even though both show a similar curve, at shorter distances, the mirror fairs well, but when looking at the larger distances, the lens shows greater lux than the mirror.

The flat mirror that we used was not 45^{o} incident to the light emitted by the LED. Because of this, as the meter's distance from the mirror is increased, the meter is no longer directly in the center of the beam. Therefore the lux of the mirrors is attenuated, accounting for the all of the mirrors faster roll off compared to the lens. With the lens, the LED was pointed directly at the meter through the lens, and so the meter would not have deviated from the center of the beam. However, this is not a complete explanation. If this was the only factor, there should be a much larger difference between the mirror and the lens configurations. The reflection from the lens, as well as the change in focal length causes the light passing through to be weaker. In other words, there should be a downward shift in the lux vs. distance curve for the lens.

Theoretically, with a measureable spot size for the light and the average lux measurement from that distance, we can measure luminous flux (a.k.a. lumens). Unfortunately, with a lot of scattering and imperfections with the light source, the spot size is difficult to measure. However, we can at least get a rough idea of luminous flux from lux, just enough to be able to compare the qualities of photometry between an LED-based light source and a laser-based light source.

Laser Lighting

Why Laser-based Lights May Dominate LED Lights

Lasers have three main features – high intensity light, a collimated beam, and monochromaticity. Therefore, there is always a warning included in any device utilizing a laser because the high, concentrated power of these sources are strong enough to burn the human eye. Of course, some wavelengths of lasers are weaker than others, but it is generally never a good idea to make eye contact with any of these beams directly. [11]

The criticism of laser lighting usually involves the preceding explanation; however, the light we study in this project is not exactly laser – more so laser-based. In other words, the original source is indeed a laser, but after phosphor conversion, beam scattering, and diffusion, the light cannot be defined as a laser. **Figure 16** roughly describes how the light will form. (NOTE: It is practically the same method used with the LED)

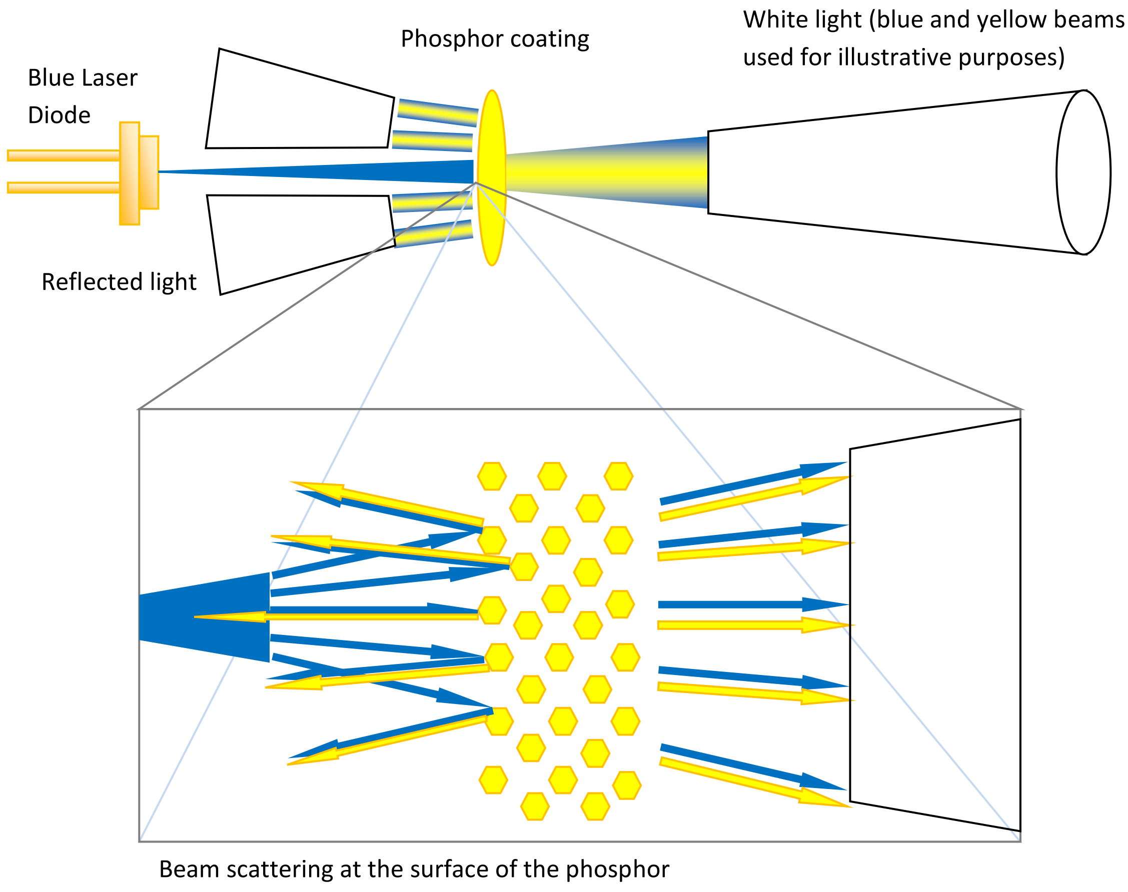


Figure 16 – Formation of white light using a blue laser diode as the primary source

We use a blue laser diode because they are highly divergent due to the smaller cavity – compared to a gas laser with a long cavity [11]. Typically, this is corrected by using a collimating lens; however, we exploit this characteristic in our lighting application. As the light hits the phosphor, there is scattering due to the rough surface of the coating. Some rays come out blue, while others come out yellow – behaviors similar to what happened with the blue LED. The result is a bright white light no longer collimated and no longer monochromatic.

Compared to a single LED, a laser diode is generally higher powered and brighter than its solid state counterpart with practically the same amount of real estate [11]. Since the intensity of lasers are normally higher than that of LEDs, less of an array of diodes is needed for a light source, and therefore, less material is used overall – assuming that diode fabrication is optimized.

Besides all of these benefits, laser-based lighting has a few difficult obstacles to overcome:

- This technology requires a blue laser diode, which are still fairly novel and are typically sold at an impractically high price for the consumer market. (NOTE: This may be because blue laser diodes have the highest divergence angle out of the current visible diodes, so higher price may be correlated with smaller divergence. There are distributors selling 1W 445nm laser diodes for about $50, so perhaps with a lighting application – where there is only need for stimulated emission and not collimation – diodes can potentially be made cheaper.)

- There is still some safety concern. If the apparatus created around the laser diode breaks, there is a possibility for the laser beam to escape and create damage. For example, if this is used for a car headlight, an accident may break the headlight, and if the power to the diode is not cut off immediately, the laser may blind witnessing bystanders.

Producing White Light with Lasers

Because we would deal with a high-intensity 445nm (blue) laser diode, we would need laser safety training to properly handle the device. This requires laser safety training, which lies beyond what we can do under a limited undergraduate project-based course. Unfortunately, there is currently no data.

Optimized LED/Laser Diode Driver

LED's and Lasers are diodes, and as such have an exponential I-V relationship. A consequence of this is that after the threshold voltage, small changes in voltage results in very large changes in current though the diode. The optical power is proportional to the current through the diode. So if we want relatively constant optical output power, the current through the diode has to be regulated, not the voltage across it. This is particularly important because higher currents can damage the diode and optical power can be irreversibly diminished [13]. Current must be constant in a range greater than the threshold current and less than the critical current where the diode can be damaged.

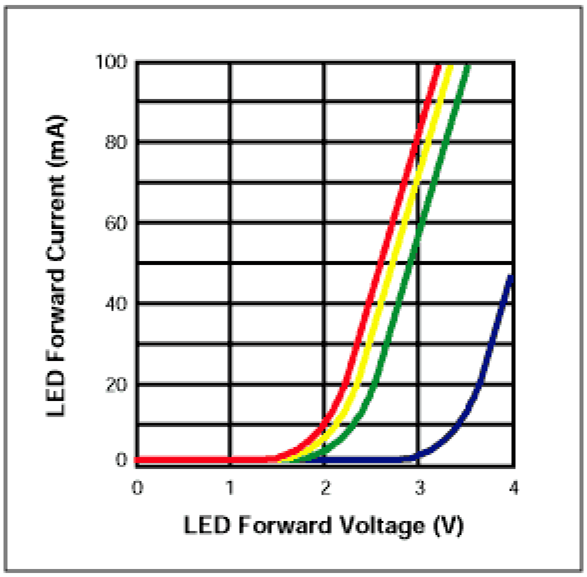


Figure 17 – Diode I-V characteristics

There are two major types of regulators: Linear and Switching mode regulators. Linear regulators tend to have much cleaner waveforms but also are less efficient in terms of power transfer. Switching mode regulators often have power transfer efficiencies, power in vs power delivered to the load, near 90%. 90% efficiency means that almost all of the supplied power appears across the load, in our case a LED or Laser diode. But with this efficiency, comes significant current and voltage ripples if the switching frequency or the output filter components are not sized properly. While a large current ripple can increase the diode junction temperature, ripples less than 50% have less than 10% increase in the junction temperature [14]. Adequate heat sinking could rectify this setback and increase lifetime.

Linear LED/Laser Driver

The first circuit developed is a linear regulator. A current is supplied to the pair of transistors in a Darlington pair configuration. This current creates a voltage across R1. This voltage is input to the inverting terminal of an operational amplifier. The other input has a voltage reference created by a voltage divider. The operational amplifier is effectively in a negative feedback configuration. The output is connected to the inverting terminal through the Darlington pair and R2. Thus the input terminals can be considered to be virtually shorted. There should be relatively no current into the negative input of the amplifier so the reference voltage that is on the non-inverting terminal should be across R1. Therefore the current through R1 can be regulated by creating the voltage (I_{load}*R1) with the voltage divider. The current through R1 is approximately equal to the load through the Diode. There is an error of the base current into the Darlington pair, which should be negligible.

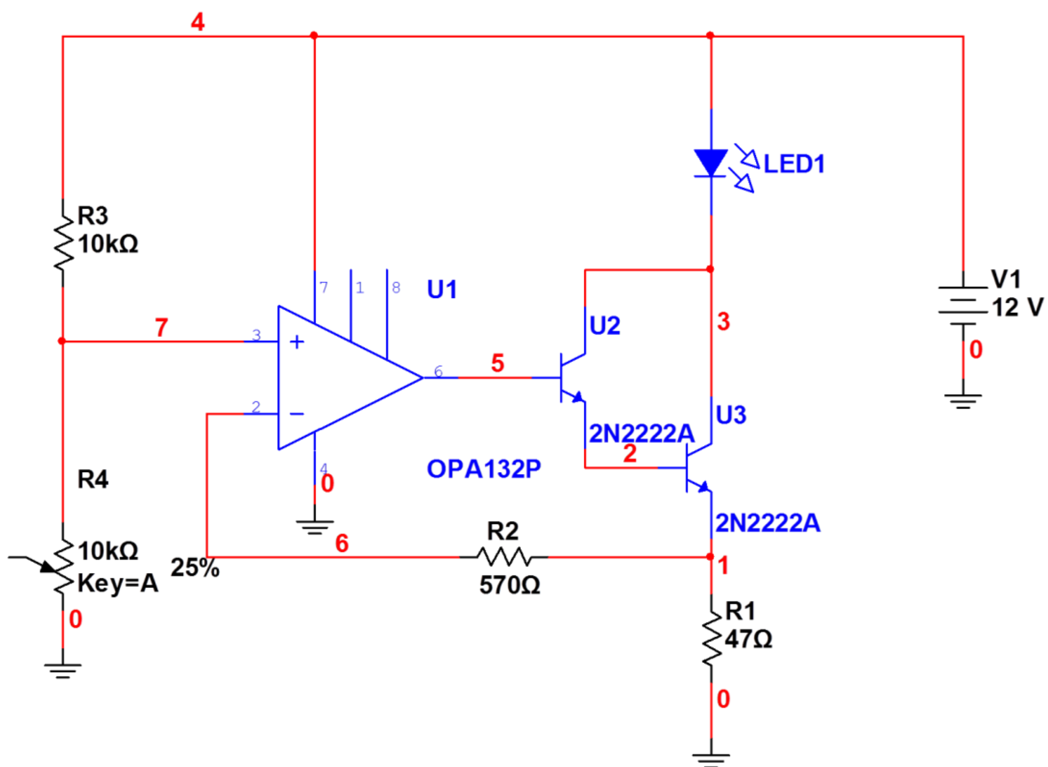


Figure 18 – Linear Regulator

This circuit will be accurate if a precision reference is used instead of a voltage divider for the reference voltage, but the circuit has more failings. Its power efficiency is quite low being a linear current supply. With a LED with a 3.5V operating voltage and .05A flowing through the load, more power will be dissipated in the transistors and R1 than in the LED. The advantages of using lasers over LEDs and Halogens would be lost if the circuit that we used to drive the lasers dropped most of the power across the control circuitry.

Switching Mode LED/Laser Driver

For our application, we would be stepping down a 12V supply to about 4.5V so a buck converter configuration is used. In a switching mode power supply, the load and output filter is periodically exposed to the full supply voltage at a certain duty cycle. For the other part of the duty cycle power stored in the output filter is delivered to the load. This is where the efficiency of the topology comes from. Common feedback in this topology involves testing to see if the current and the voltage have reached a threshold and then reset the latch controlling the supply switch.

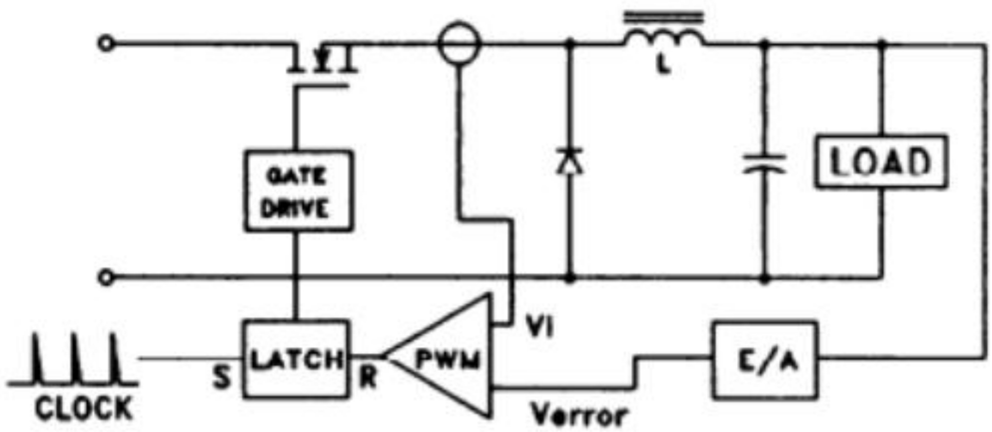


Figure 19 – Buck Converter w/ Current Feedback

In our design we only consider the current into the load and let the voltage remain uncontrolled. We also forgo the latching and the discrete period. The Circuit is Free Running, meaning that the switching frequency is not constant. It is allowed to track the output current more thoroughly and has better loop control than designs with a constant switching frequency [14]. This also saves on a lot of hardware and makes the circuit much simpler and cheaper.

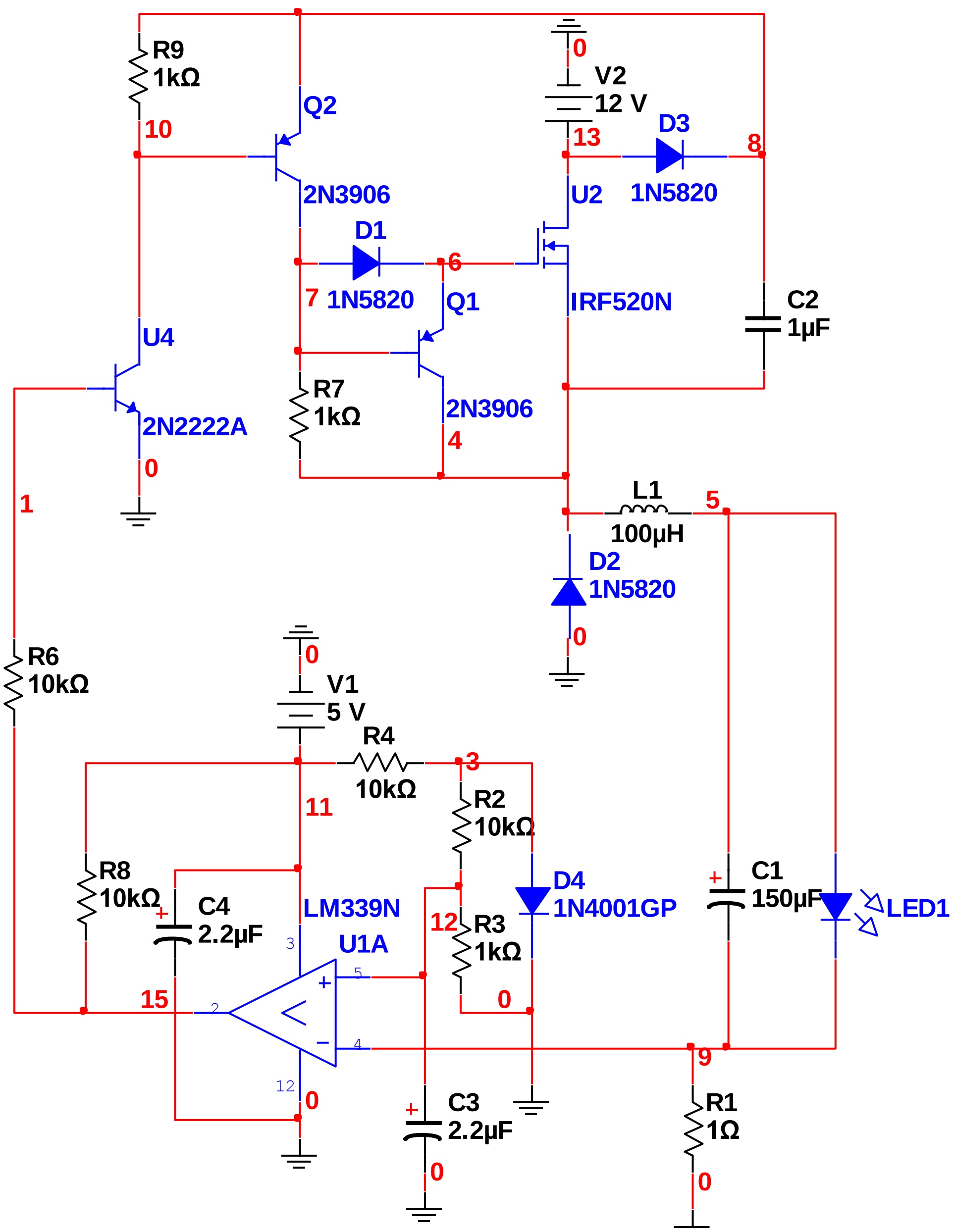


Figure 20 – Comparator-based Switching Mode Driver

Our next design uses a 339 comparator to compare the voltage developed across a current sense resistor with a reference generated by a voltage divider and the constant voltage drop across D4. If the sense voltage is too low, the 339 turns U4 on, drawing current from Q2. This turns Q2 on fully pulling the gate of the switch, U2, up to a voltage much higher than the supply voltage. This voltage is generated by a C2 and D3. When the switch is off, most of the supply voltage appears across C2. During the time the switch is on, the source of U2, and therefore the bottom of C2 are brought near to the supply voltage.

Thus the gate of U2, being attached to the top of C2 is almost 12V higher than the source, turning the switch fully on. Without C2 and D3, the gate to source voltage would never reach the threshold voltage needed to turn the switch on. When the sense voltage is greater than the reference voltage, U4 and Q2 turn off. This allows Q1 to turn on. This pulls the gate down to the source voltage and drains the gate capacitance.

To avoid unwanted oscillations and to facilitate a soft turn-on of the circuit, the sense resistor is paced in series with the output filter, the inductor and the capacitor [15]. Since the circuit is free running, unwanted oscillations should be minimized to increase stability of the circuit. Lasers and LEDs also benefit from soft turn-ons. Without soft turn-ons, thermal shock can decrease life time of the diodes.

Low Part Count Switching Mode Driver

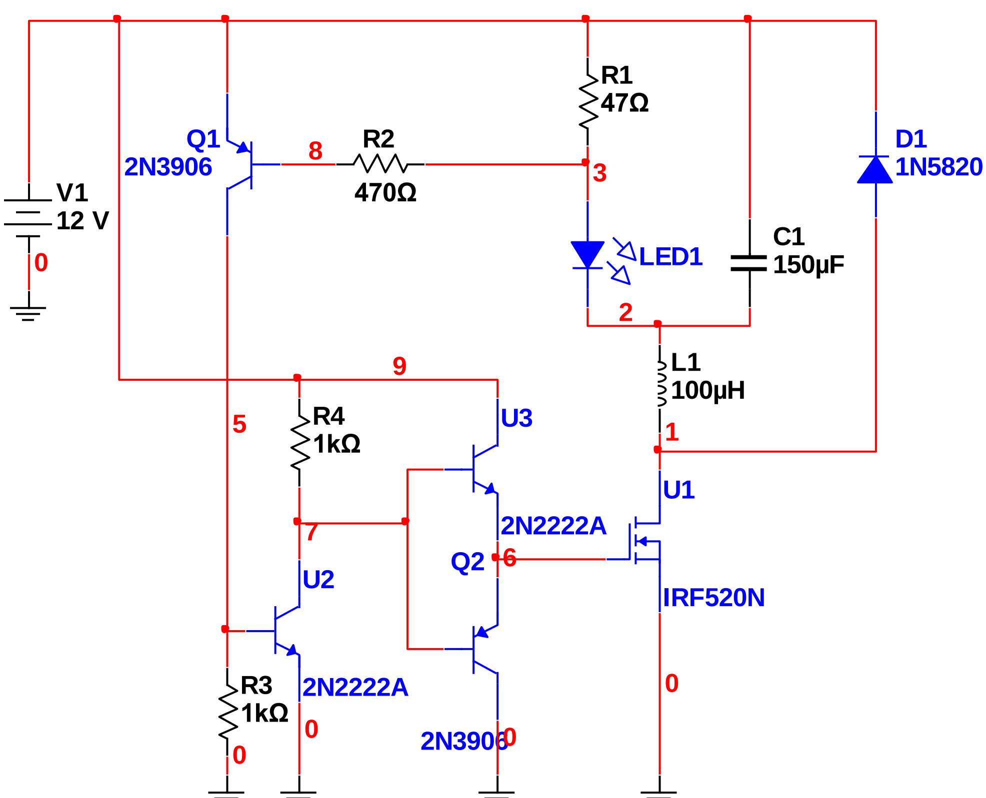


Figure 21 – Low Part Count Switching Mode Driver (need to change schematic)

The third circuit is very similar to the second circuit except with fewer parts and the buck converter components moved around. The switch is now below the load and the output filter. Because of this the bootstrap circuits are not needed. The source of the switch is always grounded so it is very easy to generate large gate to source voltages. The comparator is also removed and replaced with Q1. R1 is sized so that at the desired load current, Q1's V_{be} on voltage is reached and begins conducting. This turns U2 on which turns Q2 on. This discharges U1's gate capacitance and pulls the gate down to the source voltage. When the current through R1 is less than the desired current Q1 and U2 turn off. U3 then turns on, charging the gate capacitance of U1 and brings the gate voltage up to the supply level. The low part count makes this option the cheapest of the designs, but also a little temperamental.

Circuit Testing

An important metric with these circuits is the ratio of the Power In vs. the Power Out. To gauge the utility of each of the available circuits, the efficiency of each were tested with a LED load. LED's are not the best analogs for our planned laser diode. The bias currents at given voltages are much larger with Lasers than with LED's. Typical operating currents for high intensity LED's are from 20mA to 50mA while the Laser we are trying to emulate has an operating range of 100mA to 1A. The load used was 4 blue LED's in parallel with small protection resistors to account for this difference. The blue LED's have a similar “on” voltage to the blue laser diode; the LED's operate from 3.5 to 4V while the Laser diode operates from 4V to 5V. These are of the same magnitude so no additional components were added to the load. Below is compiled data from testing the efficiencies of the circuits and various waveforms.

	Linear Regulator	Comparator SMPS	Low Parts SMPS
Vin	8.55	11.9	7.889
Iin	0.052083333	0.1	0.01413
Vout	3.27	4.12	3.192
Iout	0.04787234	0.185	0.027245
Pin	0.4453125	1.19	0.11147157
Pout	0.156542553	0.7622	0.08696604
η Efficiency	35.15341545	64.0504202	78.0163408

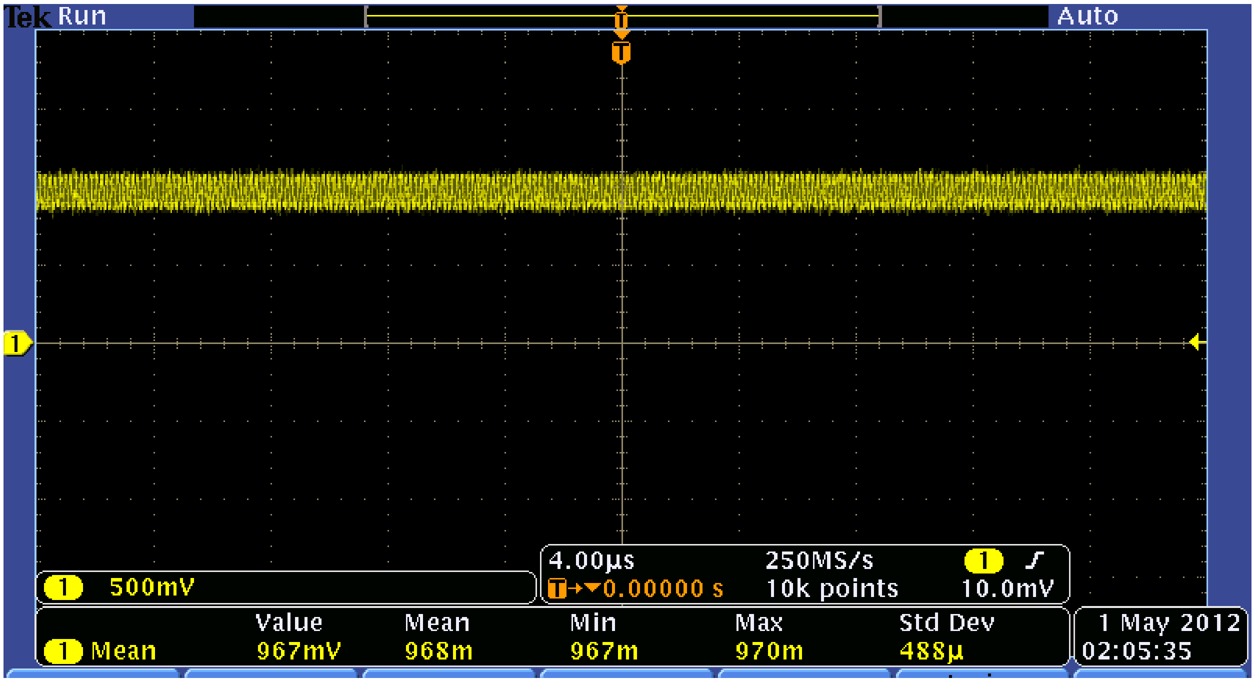


Figure 22 – Voltage across the sense resistor in the Linear regulator

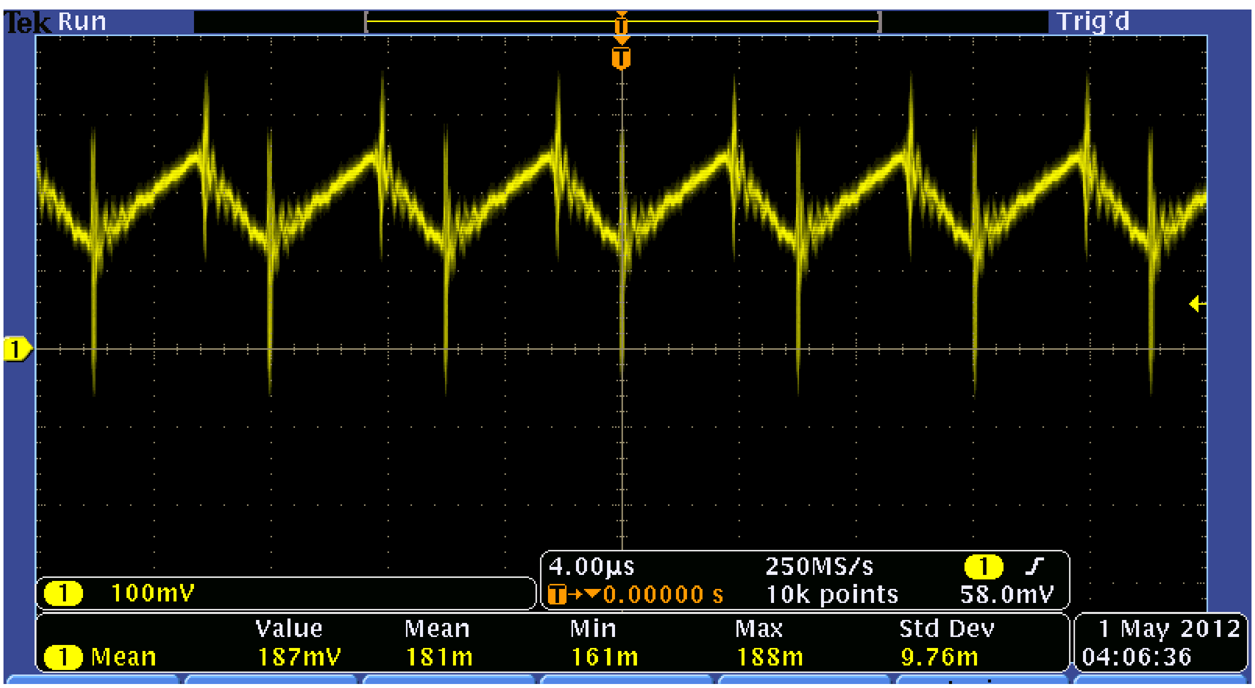


Figure 23 –Voltage across sense resistor in the Comparator based SMPS

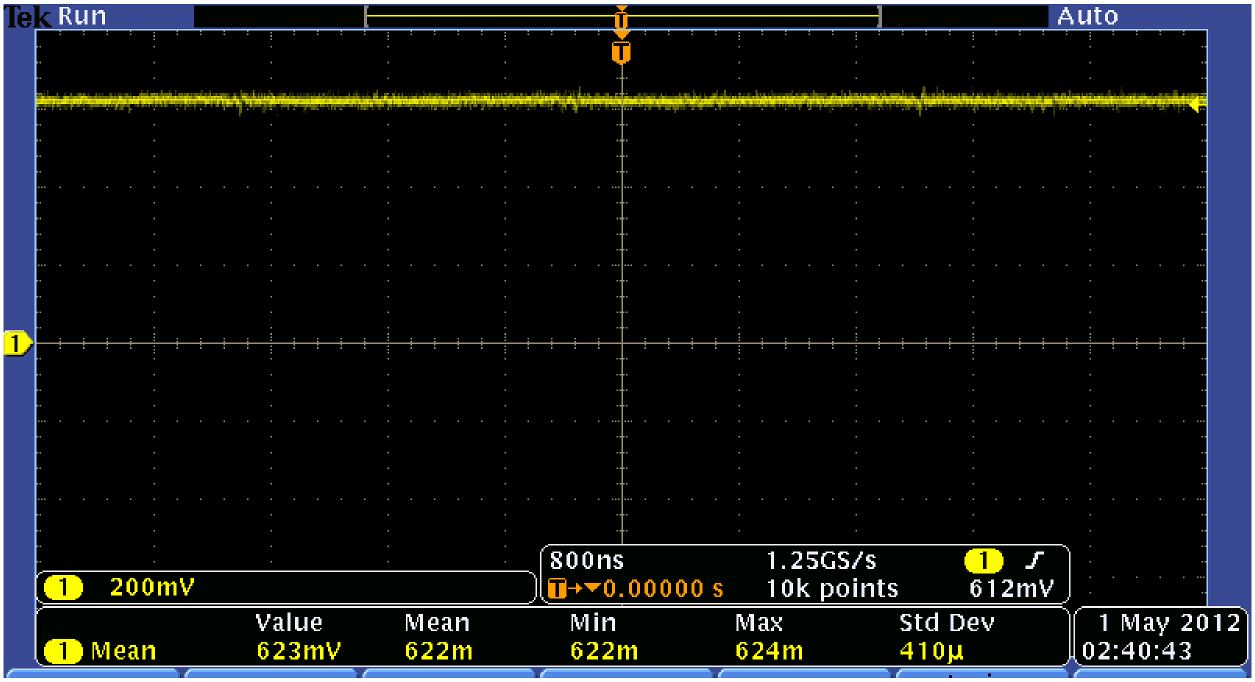


Figure 23 – Voltage across the sense resistor in the Low Parts SMPS

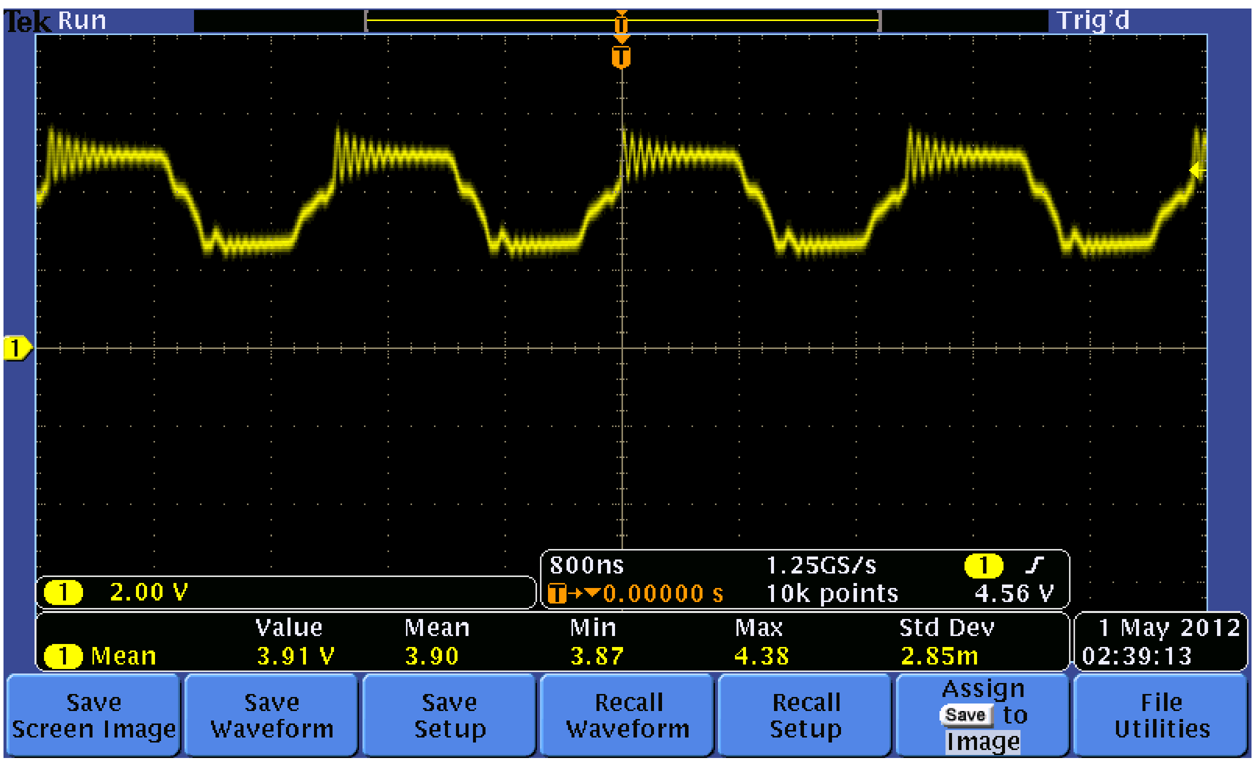


Figure 24 – Switch's gate waveform in the Low Parts SMPS

From **Figure 22** and **Figure 23** it can be seen that the linear supply and the Low Parts switching mode power supply have the more constant output current. This is expected from a linear supply. Curiously, It appears that the linear supply is oscillating at a very high frequency.

It is not quite evident from **Figure 23** that the Low Parts SMPS is switching. The current is very linear compared to the comparator based SMPS in **Figure 24**. The gate wave form for the Low parts SMPS is included to show that the circuit is in fact switching. But the gate voltage during the portion of the cycle where the switch should be off is not as low as it should be. The threshold voltage of the IFR520 is about 2V. Therefore the switch may be partially on during this time. This means that there is needless power being dissipated in the switch. For this, this circuit may not be the best candidate for the Laser driver.

The discrepancy between Figure 22 and Figure 23 might also be explained by the fact that the Low Parts SMPS is switching at a much higher frequency. It is switching at 500 kHz while the Comparator SMPS is switching at 166kHz. With high switching speeds in switching mode power supplies, the ripple will be much smaller.

Looking at the efficiencies of the three circuits, the linear power supply is much too inefficient for our purpose. Of the Two SMPS's, The Low Parts SMPS is definitely the better choice, however the circuit showed some spikes in current and Q1 got quite hot. The totem pole driver on the gate of the switch also needs to be looked at to make sure it is fully turning the switch off. The extra hardware needed to do the switching for the high side switch in the Comparator SMPS and the bias currents for the Comparator its self contribute to the drop in efficiency over the Low parts SMPS. The Low Parts circuit, if it can be further improved, would be ideal for our laser driving needs.

Possible improvements might be replacing D1 in **Figure 21** with a switch to reduce power lost across D1 during the half of the cycle it is on. The totem pole driver is also good at switching the gate of the switch on and off quickly but might be consuming too much power doing so.

Conclusion

Solid state illumination is a novel technology that aims to create low power solutions. The combination of blue lasers and yellow phosphor is proposed as it is a drastic improvement for creating white illumination compared to previous inefficient and unreliable lighting devices.

- The spectrum emitted/reflected by each of the mirrors and lens were compared using MATLAB programming to create CIE analysis. Four out of five mirrors showed ranges of white spectrum on the CIE graph. Mirrors 2 and 3 during analysis showed a wider and an evenly distributed range of white light.
- Through the LUX analysis, we can see that mirrors 2 and 3 are most stable and most consistent among the mirrors and the lens. The reason behind this consistency is the highly reflective

coating from the epoxy. The epoxy coating leads the reflection angle equal to the incident angle. The surface of mirrors 1, 4 and the lens are rough therefore the phosphor coating is scattered causing a larger divergence angle.

- An array of power supplies was built and simulated. The switching mode power supplies showed greater power efficiencies over the linear power supply. Efficiency was further improved by restructuring the circuit so that fewer components were needed for operation. The SMPS proved to be an adequate source of bias current for LED's and laser models.

The combination of these ideas and features in conjunction with exploitation of a blue laser diode's large divergence angle could be the next step in lighting and display technologies.

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Project Management & Logistics

Primary Teammate Responsibilities

Robert Gatdula

- Main contact between team and supervisor
- Overlooked the overall progress of the project
- Involved in the phosphor coating process
- Experiments
    - White light generation
    - Lux measurements
- Main author from pg. 2 – 13, 16 – 17

Jared Murray

- In charge of designing and LED/laser diode driver circuit
- Experiments
    - Simulated and tested driver circuit
    - Lux measurements
- Main author from pg. 18 – 26

Avery Heizler

- Researched MATLAB scripts for CIE 1931 XYZ plots
- Measured lux values for the various configurations
- Experiments
    - Lux measurements
- Contributing author from pg. 2 – 13

Meet Shah

- Involved in the phosphor coating process
- Researched ways to manipulate light for optimal illumination
- Experiments
    - White light generation
- Main author from pg. 13 – 15

All members

- Overall design of the project
- Wrote “Abstract” and “Conclusion” sections
- Proofreading/revising of this project report

Cost Report

Part	Price	#	Total	Distributor
LED465E - Epoxy-Encased LED, 465 nm, 20 mW, TO-1 3/4, Qty. of 5	22.00	1	22.00	ThorLabs
Laser Shades (445nm eye protection)	29.95	2	59.90	Wicked Lasers
HTY550 (100 g) Phosphor	195.00	1	195.00	PhosphorTech Corporation
Various Electronics Parts (see below)	9.36	-	9.36	Digikey
Shipping & Handling	-	-	52.50	-
TOTAL	-	-	**338.76**	-

ELECTRONICS PARTS					
Manufacturer #	**Digikey #**	**Description**	**QTY**	**Unit Price**	**Cost**
ERJ-L14KF10CU	P100NACT-ND	0.1Ohm 1/3W	2	0.78	1.56
IRF520PBF	IRF520PBF-ND	100V Nmos	2	0.96	1.92
BA2904FVM-TR	BA2904FVMCT-ND	HighT Opamp	2	0.74	1.48
ERJ-6ENF1001V	P1.00KCCT-ND	1K 1/8W 1%	5	0.07	0.35
ERJ-6ENF1003V	P100KCCT-ND	100K 1/8W	5	0.07	0.35
EVM-AASA00B16	AAS16CT-ND	1M trimmer	2	0.99	1.98
EVN-DJAA03B15	DJA15CT-ND	100K trimmer	2	0.86	1.72

Appendix

CIE 1931 XYZ Coordinate Tables

Coated LED			Mirror 1			Mirror 2	
X	Y		X	Y		X	Y
0.308700249	0.319737688		0.307610395	0.326183485		0.309164492	0.321912281
0.311595327	0.446043347		0.222438621	0.212072393		0.273328077	0.341726542
0.300813157	0.375960447		0.249067507	0.241516129		0.237022682	0.199875076
0.304627269	0.399152815		0.241323191	0.234983111		0.291628677	0.366718838
0.309033853	0.40983307		0.250388201	0.247400151		0.214089292	0.148389605
0.312884766	0.443123922		0.232214757	0.221690957		0.20838662	0.140682151
0.298467468	0.338051882		0.233874115	0.250968109		0.237085844	0.216790519
0.310035103	0.347485314		0.309091563	0.370518243		0.289166658	0.378829595
0.260114949	0.313633585		0.238130156	0.252357179		0.245945239	0.254124926
0.263310429	0.310689562		0.243374073	0.242987785		0.262163985	0.269182912
0.258623768	0.299185402		0.257953951	0.260363728		0.204607036	0.144222736
0.266238624	0.278662876		0.247751116	0.248419736		0.23685895	0.228410245
0.313006153	0.322915852		0.226457278	0.213809991		0.290406819	0.312426126
0.293328497	0.376013243		0.225301944	0.227530596		0.254751693	0.282574935
0.320036387	0.457638051		0.321939553	0.402980508		0.241420326	0.26206431
0.324994481	0.456688658		0.236116797	0.230795291		0.236110032	0.245456591
0.305062296	0.384678905		0.226827146	0.225379735		0.224867599	0.172084471
0.276873778	0.346413177		0.222611034	0.215772249		0.224216838	0.206706018
0.283212726	0.311983066		0.233245433	0.223579294		0.230947291	0.214492975
0.277941859	0.3302148		0.240514566	0.230277457		0.2816235	0.335709123
0.303330981	0.388644727		0.254364155	0.253715419		0.26666808	0.277440667
0.301464766	0.361935264		0.232289866	0.239899713		0.222201237	0.174387482
0.279987507	0.357165615		0.245255033	0.238138583		0.225616051	0.218974613
0.280478563	0.363481843		0.23331625	0.231611775		0.250611312	0.281726062
0.27650646	0.346376721		0.246885	0.248048289		0.247408467	0.238452309
0.284113669	0.302428122		0.305890298	0.339668011		0.29633806	0.380444065
0.313372246	0.429969988		0.284617403	0.343032873		0.21904703	0.164806577
0.287909597	0.375939126		0.23914225	0.234343921		0.208329287	0.135848223
0.294701962	0.39533021		0.262147355	0.268188697		0.240572404	0.25023688
0.27088771	0.284060003		0.231169964	0.231924193		0.244015543	0.234737253
0.308077067	0.36587005		0.286970569	0.330681589		0.202668532	0.134286464
0.251770839	0.288932157		0.225775212	0.226473511		0.214792774	0.148252019
0.281120781	0.319920803		0.245151565	0.243220607		0.285226075	0.367475285
0.276525954	0.337693162		0.237228632	0.228664396		0.307148526	0.356679421
0.308760205	0.417851394		0.227598752	0.222362859		0.258930213	0.281804284
0.248193476	0.283562162		0.245571064	0.24024227		0.24024365	0.260235251
0.25821702	0.302337915		0.240390558	0.257525358		0.231774929	0.200817142
0.262088903	0.277438713		0.254350585	0.269560791		0.270600879	0.285912614
0.307370106	0.34317318		0.231483664	0.243398906		0.269532947	0.291809569
0.296566476	0.316962314		0.23025003	0.238908563		0.226148466	0.185842224

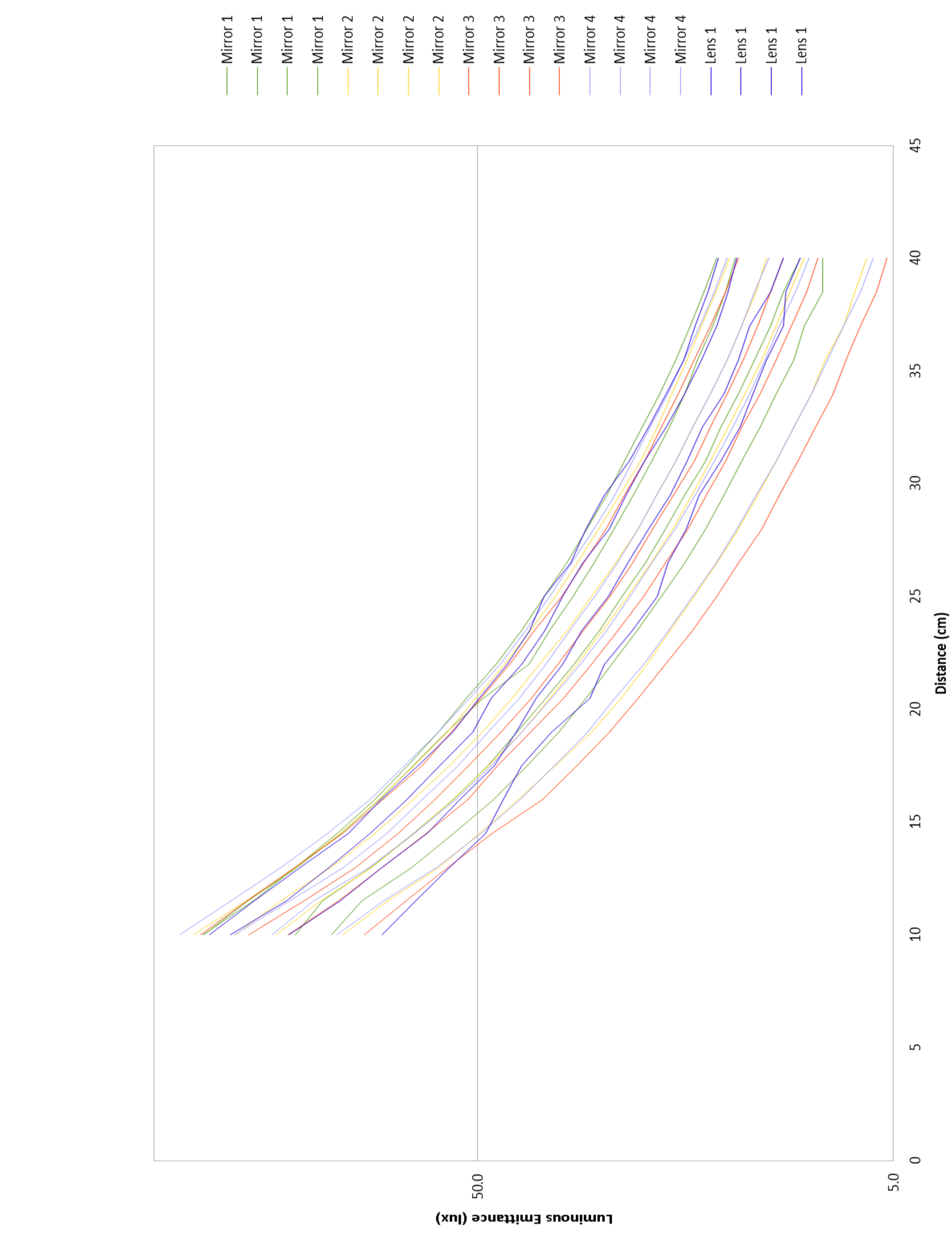
Mirror 3			Mirror 4			Coated Plastic	
X	Y		X	Y		X	Y
0.309164492	0.321912281		0.309036711	0.32648925		0.307328736	0.324434398
0.31972733	0.468300239		0.243992904	0.274733435		0.200030404	0.12069708
0.319066061	0.428677434		0.246751441	0.235087698		0.230713967	0.211980943
0.243296727	0.225396774		0.247816835	0.273812044		0.235745786	0.197484346
0.214995774	0.175651365		0.249277243	0.247755668		0.236252132	0.217407083
0.299745706	0.365300977		0.220792342	0.183985956		0.221578955	0.2217077
0.205099326	0.137712794		0.237847974	0.26234295		0.217146085	0.169034224
0.317992122	0.441388317		0.317991399	0.324493068		0.290423879	0.315879323
0.297963395	0.335443749		0.298409989	0.334662384		0.317991399	0.324493068
0.239669198	0.243623293		0.236894674	0.220404405		0.22760109	0.224585659
0.271254855	0.3127038		0.228768951	0.186859137		0.236387627	0.226383563
0.317525719	0.323492002		0.21718169	0.187108695		0.221104534	0.216628992
0.265785611	0.308134231		0.224709201	0.217131894		0.220490342	0.192376564
0.251585703	0.280885432		0.219101975	0.205150835		0.220994888	0.169348037
0.260890032	0.302138658		0.233674242	0.214519648		0.258703589	0.246917475
0.201276979	0.129492397		0.247812146	0.236961611		0.217137435	0.188913275
0.225921368	0.183302894		0.22798763	0.211925088		0.224489526	0.192413749
0.255808698	0.255253415		0.226590442	0.199800703		0.3028065	0.335829853
0.260090816	0.307957184		0.305429192	0.365146891		0.226880309	0.19780232
0.230128176	0.198211966		0.218541086	0.201231047		0.24492093	0.234924435
0.309875286	0.431419105		0.245317623	0.243757231		0.222780113	0.214134862
0.280548925	0.301879011		0.258440157	0.289996882		0.214091754	0.188416481
0.24493435	0.257080516		0.21686003	0.192647273		0.231959671	0.208648701
0.273063473	0.292850129		0.242286693	0.22939518		0.226101961	0.169079281
0.219962718	0.165261044		0.239803187	0.226284045		0.211148175	0.173928736
0.272004227	0.320484711		0.248323017	0.274043389		0.220426765	0.192044213
0.221901591	0.197425389		0.273912185	0.308765969		0.212222608	0.170392995
0.303133925	0.358904394		0.22275844	0.197060653		0.228436995	0.208361696
0.302591088	0.329508673		0.23134558	0.213578007		0.213105884	0.162740807
0.251375771	0.265114338		0.202464318	0.133999555		0.296949536	0.349664744
0.297717228	0.369877032		0.233023814	0.192854222		0.211293112	0.175366769
0.20737047	0.152408833		0.224850191	0.183576429		0.228662955	0.202351479
0.236810916	0.212072835		0.236813409	0.222770635		0.223943265	0.194251418
0.225851213	0.215460815		0.221859153	0.214606459		0.239301612	0.224916359
0.281179895	0.303843615		0.221680003	0.214338748		0.26338397	0.286738919
0.260917303	0.295601923		0.304370223	0.328257697		0.231671936	0.211071589
0.22457633	0.204325359		0.274393536	0.27282234		0.214259821	0.191303629
0.282001566	0.326390554		0.229926706	0.22763101		0.234909856	0.214963875
0.244796795	0.26756738		0.246427559	0.235836302		0.224536097	0.190602157
0.286589538	0.368421303		0.245907412	0.279911574		0.211456005	0.132591554

Luminous Emittance with an LED Light Source

	Mirror 1				Mirror 2			
VOLTAGE (V)	3.582	3.71	3.982	4.112	3.603	3.36	4.027	4.108
CURRENT (mA)	8.535	10.71	15.27	20.31	5.9	10.77	15.12	19.89
DISTANCE (cm)	LUX	LUX	LUX	LUX	LUX	LUX	LUX	LUX
10	112.5	137.1	228.0	229.0	105.6	152.5	191.9	241.0
11.5	94.8	118.1	178.7	173.2	82.2	119.1	149.1	179.8
13	72.1	90.3	136.2	137.2	62.1	89.9	113.0	137.1
14.5	57.2	71.4	106.6	109.2	49.7	71.0	88.6	106.9
16	45.9	57.3	86.2	88.5	39.9	57.4	71.5	86.5
17.5	38.0	47.2	71.5	73.7	32.6	47.0	58.6	71.1
19	32.0	40.3	59.5	62.2	26.6	39.3	48.8	59.3
20.5	27.5	34.3	48.5	53.2	22.6	33.6	41.4	50.6
22	23.8	29.4	37.6	45.2	19.6	28.8	35.5	43.1
23.5	20.7	25.5	33.5	39.3	17.2	25.0	30.5	37.4
25	18.1	22.5	29.5	34.6	15.1	21.8	26.6	32.6
26.5	15.9	19.8	26.3	30.6	13.3	19.2	23.3	28.8
28	14.2	17.7	23.5	27.4	11.8	17.0	20.6	25.6
29.5	12.8	15.9	21.1	24.5	10.6	15.3	18.6	22.8
31	11.6	14.2	19.1	22.2	9.6	13.8	16.7	20.3
32.5	10.5	13.0	17.3	20.1	8.7	12.5	15.2	18.5
34	9.6	11.8	15.9	18.3	7.9	11.4	13.8	17.1
35.5	8.7	10.8	14.8	16.7	7.3	10.4	12.6	15.7
37	8.2	9.9	13.6	15.4	6.6	9.6	11.6	14.5
38.5	7.4	9.2	12.7	14.3	6.2	8.9	10.7	13.4
40	7.4	8.4	12.0	13.3	5.8	8.2	10.1	12.4

	Mirror 3				Mirror 4			
VOLTAGE (V)	3.685	3.829	4.005	4.162	3.572	3.824	4.029	4.153
CURRENT (mA)	8.275	10.35	15.01	20.47	8.294	10.15	15.07	20.12
DISTANCE (cm)	LUX	LUX	LUX	LUX	LUX	LUX	LUX	LUX
10	93.8	143.0	177.5	232.0	109.2	156.3	192.1	261.0
11.5	74.3	108.0	130.5	179.1	84.2	123.8	141.8	196.2
13	58.9	84.8	98.2	138.1	62.7	91.4	105.3	148.7
14.5	46.3	66.7	77.7	105.6	49.1	71.1	82.9	114.8
16	35.0	52.9	63.4	84.6	39.6	56.4	68.1	90.8
17.5	28.9	44.8	52.6	68.1	32.7	46.5	55.7	75.1
19	24.2	37.3	44.0	57.9	27.2	39.2	47.2	62.2
20.5	20.6	31.1	37.2	49.3	23.4	33.2	39.7	52.4
22	17.7	26.6	32.1	41.9	20.0	28.4	34.3	44.3
23.5	15.2	23.0	27.8	36.5	17.4	24.5	30.1	38.3
25	13.3	20.0	24.1	31.4	15.2	21.5	26.2	33.5
26.5	11.8	17.7	21.2	27.8	13.4	19.1	23.1	29.8
28	10.4	15.6	19.0	24.6	11.9	16.8	20.6	26.3
29.5	9.4	14.1	16.9	22.2	10.7	15.0	18.6	23.4
31	8.5	12.7	15.1	19.9	9.6	13.5	16.7	21.2
32.5	7.7	11.6	13.8	18.1	8.7	12.2	15.2	19.3
34	7.0	10.5	12.6	16.5	7.9	11.1	13.8	17.5
35.5	6.5	9.6	11.5	15.1	7.2	10.2	12.6	16.0
37	6.0	8.8	10.6	13.8	6.6	9.4	11.6	14.6
38.5	5.5	8.1	9.9	12.7	6.0	8.6	10.8	13.5
40	5.2	7.6	9.2	11.8	5.6	8.0	10.0	12.6

	Lens 1			
VOLTAGE (V)	3.52	3.714	3.837	4.062
CURRENT (mA)	9.555	10.25	15.08	20.27
DISTANCE (cm)	LUX	LUX	LUX	LUX
10	84.9	142.0	197.0	221.0
11.5	70.5	107.2	144.3	172.0
13	58.5	84.8	114.2	133.5
14.5	48.0	66.2	90.8	102.4
16	43.5	55.2	74.1	85.2
17.5	39.2	45.6	61.8	69.6
19	33.2	40.5	51.5	57.4
20.5	26.9	36.2	46.5	49.6
22	24.8	31.2	39.2	42.5
23.5	21.2	28.1	34.5	37.5
25	18.5	24.3	31.3	34.6
26.5	17.5	21.8	28.0	29.9
28	15.8	19.4	24.2	27.5
29.5	14.7	17.2	22.0	24.8
31	13.0	15.7	19.9	21.6
32.5	11.7	14.4	17.6	19.4
34	10.9	12.8	15.9	17.6
35.5	10.1	11.8	14.5	16.0
37	9.2	11.1	13.3	15.0
38.5	9.1	9.9	12.5	14.0
40	8.4	9.2	11.9	13.2


Mirror 1
Mirror 1
Mirror 1
Mirror 1
Mirror 2
Mirror 2
Mirror 2
Mirror 2
Mirror 3
Mirror 3
Mirror 3
Mirror 3
Mirror 4
Mirror 4
Mirror 4
Mirror 4
Lens 1
Lens 1
Lens 1
Lens 1
Luminous Emittance (lux)
50.0
5.0
Distance (cm)
0
5
10
15
20
25
30
35
40
45