Design of DC Light Bulb for the DC House Project

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Kent Liang

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Committee Membership

Title: Design of DC Light Bulb for the DC House Project

Author: Kent Liang

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Committee Chair: Dr. Taufik, Professor

Committee Member: Dr. Xiao-Hua Yu, Professor

Committee Member: Dr. James G. Harris, Professor Emeritus

Abstract

Title: Design of DC Light Bulb for the DC House Project

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This thesis focuses on the design and implementation of an economical and energy efficient DC Light Bulb for the DC House Project. For the DC lighting system, emphasis is on the DC-DC LED driver, dimmer circuit, LED lighting array, and physical packing design. In this paper, a DC Light Bulb is designed, simulated, and tested to operate at a wide input voltage ranging from 24 VDC to 72 VDC, to be fully dimmable using pulse-width modulation technique, and to produce lumination intensities equivalent to a standard 100 W A19 incandescent light bulb at one-tenth the total power consumption. The DC Light Bulb's physical design also takes advantage of the same physical dimensions of a standard A19 incandescent light bulb using an E26 Edison screw base. Results from computer simulations and hardware tests demonstrated the feasibility of the proposed DC Light Bulb in terms of overall efficiency, line regulation, load regulation, power consumption, total lumens, luminous efficacy, and thermal profile.

Acknowledgements

I would like to thank my parents for giving me the opportunity and continued support as I pursue both a Bachelor's Degree in Electrical Engineering and a Master's Degree in Electrical Engineering. I would like to acknowledge my advisor Dr. Taufik for his exceptional teaching style, friendliness, patience, support, and overall as a great mentor. I would also like to thank my friends, fellow classmates, and professors for their encouragement, inspiration, and entertainment through my college education.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 : DC House Project

The DC House Project is an on-going student based project that consists of various senior projects and Master's thesis. The DC House Project's main goal is to provide a source of direct current electrical power to individuals in the form of a housing unit. As the project progresses, these housing units would expand to form a grid of DC powered neighborhoods. The DC House incorporates various forms of renewable energy conversions, such as photovoltaic power generation, hydropower generation, wind power generation, and human power generation. Through the DC power generated, household applications such as a fan, a lighting system, a stove, a TV, a laptop, and a refrigerator can be powered directly. The uniqueness of having a DC powered ready-home just makes sense for geographical locations where the utility grid is inaccessible.

Phase 1 of the DC House Projects established the foundation of a DC powered ready home. During this phase (AY 2010 – 2011), the DC House's distribution system design and load flow analysis were modeled [45]. Photovoltaic, wind power, hydroelectric, bicycle power generation systems were also modeled and tested through prototype systems [48]. Conversion systems from generation to household application connectivity, such as multiple-input DC-DC converter and a variable voltage DC wall outlet were also demonstrated through prototype models [48].

The on-going Phase 2 of the DC House Project (AY 2011 – 2012) focuses on integration of household applications, improvements from generation to household connectivity conversions, and alternative forms of low cost power generation. Home applications include a DC light bulb design and a cell phone charging station. Connectivity conversion systems include improving the variable voltage DC wall outlet and improving the multi-input DC-DC converter design. Feasibility of low cost small-scale power generation applications includes a low speed car alternator and a human powered seesaw. During this phase, the modeling and construction planning of the DC House are also evaluated.

Phase 3 of the DC House Project (AY 2012 – 2013) will focus on field-testing of the DC House's generation systems, household applications, and conversion systems. A working DC House model will then be presented to the public.

1.2 : Thesis Objectives

For this thesis, a strong focus is in the design, implementation, and testing of an economical and energy efficient DC Light Bulb for the DC House Project. For this DC lighting system, emphasis is on the DC-DC module design, LED lighting array circuit, PWM dimmer feature, and physical packaging design that takes advantage of the traditional A19 60W incandescent light bulb dimension using a standard E26 Edison screw base.

Chapter 2: Background

2.1 : Motivation

Sparsely human populated areas such as small villages in developing countries or remote locations away from urban cities often do not have access to electricity, due to inaccessibility to an electrical grid tied AC power source. For example, in 2009, 1.3 billion people or about 20% of the entire world's population were without electricity. This equates to roughly 587 million people in Africa, 675 million people in developing Asia, and 55 million people in Eastern Europe/Eurasia that had no access to electricity [1]. The capital required to built the electrical infrastructure (such as distribution substations, transmission lines, service transformers, etc.) and the recurring operational costs, which includes equipment repairs and replacements, are often hard to justify financially for low populated areas. According to Edison Electric Institute (EEI), from 2004-2008, United States invested \$4.6 M/GW/year, New Zealand invested \$22.0 M/GW/year, and The Netherlands invested \$12.0 M/GW/year in high voltage (>230kV) transmission normalized by year [2]. The cost of distribution transmission (<230kV) would be considerably more costly compared to high voltage transmission, due to increased in resistive losses (I^2R) through the transmission conductors (related by Ohm's Law, $V=IR$, and power loss through a conductor, $P=I^2R$; when voltage decrease, current increases by the square term, I^2). The power grid's high infrastructure cost creates an opportunity for engineers to use new technologies to meet the electricity needs in rural areas by using alternative means that are less expensive, such as the renewable energy generation methods presented in the DC House Project.

Through the successful completion of the DC House Project, it would provide self-sustaining DC power through various forms of renewable energy conversions, such as photovoltaic, hydropower, wind, and human power generation. The DC power generated could then be used to provide basic living necessities such as room lighting after sunset, cooking using an electric stove, and refrigeration of perishable foods. For this thesis, a focus will be on developing a DC lighting system, "DC Light Bulb," that would accommodate the lumination requirements for the DC House Project. The DC Light Bulb's economical impact, environmental impact, sustainability, and ethical impact are analyzed in the following sections.

2.1.1: Economical Impact

Economical impact can be defined by the measure of workforce, education, and health care development. The DC Light Bulb plays an integral role in influencing economical growth through human capital, financial capital, and natural capital.

In terms of human capital, the DC lighting system influences economical growth through an increase in employment productivity and educational literacy. More available lumination means an individual can work longer hours or work during the night when natural sunlight is not available. For example, lighting would allow a seamstress or tailor to fit his/her customer with the perfect suit or dress, without having to worry about the time of day. For example, lighting would also allow adult education and literacy classes during the evenings [3] or more time for students to read, write, and learn math, science, and other topics. Thus, the DC Light Bulb would influence human productivity that creates economic value.

In terms of financial capital, the DC Light Bulb provides lumination that creates a more productive labor force and thus a larger revenue stream. For example, lighting in a clothing assembly line allows employees to work different shifts around the clock means more products to market and more return in net profit. The more money allows entrepreneurs or businesses to buy the necessary manufacturing equipment needed to make their products or provide services to their surrounding community, thus creating economical growth.

In terms of natural capital, the growth in employment, educational literacy, businesses, and economical wealth allows individuals, entrepreneurs, business owners and their employees the opportunity to take part in keeping the natural environment sustainable. For example, services such as recycling consumer products and packaging materials is a way the economy can balance the resources they use to improve their quality of life while disposing what they don’t need back into the environment in a sustainable way.

2.1.2: Environmental Impact

Environmental impacts associated with the use of the DC Light Bulb include the manufacturing, shipping, use, and disposable of the system. During the manufacturing stage, toxic chemicals are used to fabricate the semiconductors components. Toxic chemicals such as acetone used in polishing the silicon wafers cause nose, throat, eye irritation, and possible coma. Benzene used as photo-electrochemical etching causes damage in bone marrow, anemia, excessive bleeding, and immune system effects to name a few hazards [4]. These toxic chemicals must be eventually disposed back into the environment in one form or another. During the transportation stage, the DC lighting system must travel many thousands and thousands of miles through cargo trucks, trains, boats, and airplanes before reaching the developing countries that would eventually use the DC lighting system. During the time it took to get the product from point A to point B it has caused the release of an enormous amount of carbon dioxide into the atmosphere and thus contributing to global climate change [5]. During the use of the DC lighting system, it can potentially be hazardous if using low-intensity red LEDs, for it leaches Pb at levels exceeding regulatory limits [6]. However, for this particular project white/natural color LEDs were used and thus this hazard is avoided. Lastly, the disposable of the lighting system after it exceeds the end of its life expectancy may end up in electronic-waste landfills. It is estimated that only about 15-20% of e-waste is recycled, and the rest of these electronics go directly into landfills and incinerators in the United States [7]. Given this staggering estimation, it can be easily assumed that developing countries most likely do not have the necessary facilities to recycle electronic waste. Thus, the environmental impact is very high in this stage of the lighting system's life cycle.

The DC Light Bulb is a subsystem incorporated into the DC House Project. This lighting system uses the DC power generated through natural resources provided by the sun that powers the photovoltaic solar panels, natural wind that powers the wind turbines, flow of stream water that spins the generator, and human powered see-saw that charges the battery.

The DC lighting system in conjunction with the DC House will improve the environment dramatically. For example using self-sustaining dc power, removes the need of high power AC transmission lines and towers that blocks the line of sight for homeowners. Also, a DC powered system eliminates the need of harmful underground AC transmission lines that are often made from lead based materials. The use of natural resources to power a person's home saves the consumer money, while leaving a smaller footprint on the environment. Overall, the use of a self-sustaining DC powered house improves the overall land usage through a smaller required footprint to supply electricity to the home.

The DC lighting system has minimal impact on species in the environment. The majority of the DC lighting fixture will be integrated into the DC house. External DC lighting will be housed in weatherproof lighting fixtures. However, studies have shown that light pollution can threaten wildlife by disrupting biological rhythms and cause blindness to birds during their bi-annual migrations [8]. As a result, turning down the brightness to a soft yellow color at night would reduce interfering with wild animals at night. In other words, reducing the lighting intensity at night would reduce birds from being disoriented from the bright light, thus leading to fewer crashes into night-lit towers [8].

2.1.3: Sustainability

The DC Light Bulb is designed to be maintenance free. However, issues may arise with insufficient input power supplied to the LED driver and LED lighting array. Inadequate input power may be caused by lack of supply voltage due to dirty solar panels that degrades its overall sun radiation to dc power conversion. Inadequate input power may also be caused by a calm day with not enough constant wind to spin the wind turbine, thus generating insufficient power to drive the DC lighting system. Similarly, lack of water generated input power and or human generated input power can also cause the lighting system to not operate. Another issue may be caused by not keeping the lighting system clean from debris, thus causing insufficient ventilation to maintain normal operation. Since light intensity is related to heat dissipation, without adequate ventilation to release the accumulated heat, the lighting system may eventually overheat and malfunction.

The DC Light Bulb takes advantage of renewable resources through the use of solar, wind, water, and human generated electricity. Since the sun, wind, and water are highly sustainable, using renewable technology to take advantage of such resources is highly appropriate.

2.1.4: Ethical Impact

Ethical implications related to the design, manufacture, use, of the DC Light Bulb can occur. It is often that the project being developed has been attempted by someone else. It would be unethical to use the other inventor's design schematic as the student's without authorization. A better approach is to study and analysis his/her design and incorporates the technology, pros, and cons of the design as an aid to developing the student's design. Credit should always be cited when an idea or invention is borrowed. In addition, one should gather more research from various designs and academic books to formulate a more defined and academically develop design. The purpose of the design project is to evaluate the student's ability to incorporate a design using the skills developed through the rigorous academic engineering program and ability then to incorporate desirable system functionalities learned through justifiable and creditable research of other scholarly designs, while giving credit where it is deserved.

Ethical implications during the operational phase of the DC lighting system can impact its overall use. The desired case is to use the DC lighting system as a way to extend lighting past sunset. With additional lighting, children can further educate themselves through reading and writing. Parents can catch up or get a heads start on the next day's worth of work, such as preparing food, repairing garments, cleaning, and or preparing his or her business functions, such as auditing accounts, and much more that was once impossible without lighting to see what he or she was doing. However, additional lighting created by the DC lighting system can also influence the demand for longer work hours throughout the day and more irregular work schedules brought on by profit hungry business owners and entrepreneurs. For business owners, more lighting means more products to market and thus an increases revenue stream. An unethical implication that often occurs in such businesses is the demand of increase in productivity while maintaining the same level of pay to its employees. In developing countries, where money is scarce, large corporations and business often dominate both politically and economically on the living standards of its employees. Thus the use of additional lighting can quickly play a negative implication on the standard of living in low-income families. For example, where families were once supportive of one another and shared lengthy bonding activities, can quickly turn into family separations. The adults are slaved away at work and the children are left misguided throughout the day, thus the possibility of a life of drugs and crime.

2.1.5: Health and Safety

Health and safety concerns associated with the design and use of the DC Light Blub may occur. Since the lighting system is powered by electricity and the light generates heat, the concern of getting electrocuted and burned may be an issue if not handled with proper care. To reduce the chances of electrical shock, the installation of the lighting system must follow the NEC 2010 design, installation, and safety standards. To reduce the chance of getting a burn, the lighting fixture should be mounted at a distance where it is appropriately away from the reach of children and adults. If such distances cannot be achieved, appropriate lighting protection wire guards should be installed around the light fixture to minimize change of getting burnt and damage to the lighting array.

2.2 : Lumination Methods

The four most common methods of lumination are oil lighting, incandescent lighting, compact fluorescent lighting (CFL), and light-emitting diode (LED) lighting. In the following sections, advantages and disadvantages of each lumination method will be evaluated based on efficiency, brightness output, operating lifetime, and dimming capability.

2.2.1: Oil Lighting

Oil lighting is the most common source of lumination in rural areas such as small villages in developing countries and in remote locations away from urban cities. Oil based lighting is simply a clay pot filled with some form of oil that is dipped with wick and provides an open flame lumination for a period of time. The size and shape of oil lamps varied by culture, religion, and era. Figure 2-1 illustrates a traditional Indian Diyas (oil lamp) used during Diwali ceremonies [9]. Figure 2-2 illustrates a modern kerosene lantern used for camping [10]. The simplicity of oil lamps allow them to run off of different forms of fuels such as olive, fish, and nut based oils used by ancient Mediterranean cultures; castor oil used by Egyptians cultures; peanut, carrot, and nettle oils used by African cultures; and ghee (a form of butter) oil used by

Indian cultures. The lighting filament or wick were also simple to obtain, often made from linen, tow, or, dried plants such as flax, papyrus, or rush [11].

Figure 2-1: Simple Indian Clay Diyas (Oil Lamp) used during Diwali [9].

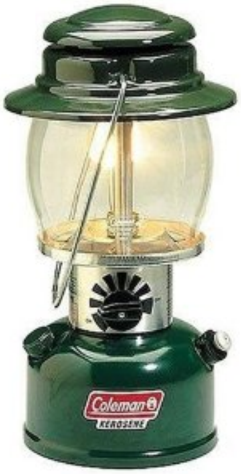
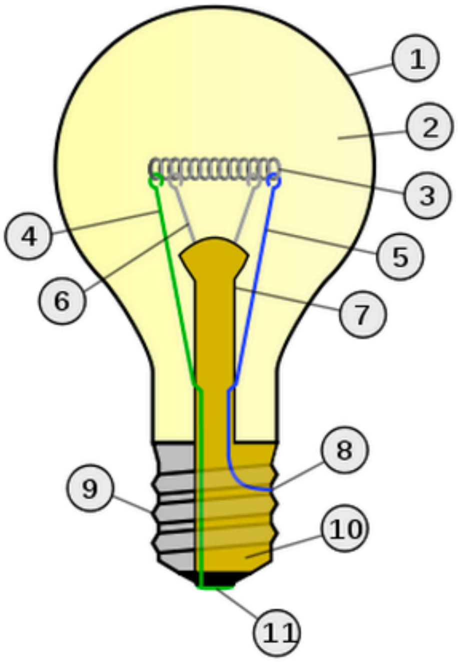


Figure 2-2: Coleman 1-Mantle Kerosene Lantern [10].

Before the availability of electricity, oil lamps were the simplest form of illumination. It was easy to construct out of clay, stone, or some form of metal. The fuel source and lighting wick were also easily obtained through nature. However, it is inefficient and can often be a fire hazard if left unattended. Candles (paraffin wax based oils) produce a luminous efficacy of about 0.16 to 0.30 lumens per watt or about one hundred times less than an incandescent light bulb [12, 13]. On average the flame temperature is around 1000 °C [13]. Candles produce a color temperature of 1000K - 1700K and a color rendering index of 100 [13, 32]. Dimming the brightness on an oil lamp is relatively hard. The wick thickness only determined the lifetime of lumination (smaller diameter wicks allow longer lifetime) but has no direct control on how bright it would burn. As technology progresses and availability of electricity in urban cities increases, the introduction of incandescent light bulbs became the common form of illumination.

2.2.2: Incandescent Lighting

The introduction of incandescent lighting has been around since the mid 1800's. Thomas Edison filed his first patent, "Improvement In Electric Lights," in October of 1878 that described the design of a practical incandescent lamp using a carbon filament [14]. An incandescent light bulb produces lumination by supplying an electric current source through a wire filament until it reaches a high enough temperature that causes it to glow. This translates to about 10% useable light efficiency or 90% in wasted heat energy [15]. The wire filament is often made from carbon or tungsten and is preserved from oxidation using a glass enclosure filled with some form of inert gas (such as argon or nitrogen), halogen gas, or pure vacuum. Figure 2-3 illustrates a standard A19 120VAC 60W incandescent light bulb.



1. Outline of Glass bulb
2. Low pressure inert gas (argon, nitrogen, krypton, xenon)
3. Tungsten filament
4. Contact wire (goes out of stem)
5. Contact wire (goes into stem)
6. Support wires (one end embedded in stem; conduct no current)
7. Stem (glass mount)
8. Contact wire (goes out of stem)
9. Cap (sleeve)
10. Insulation (vitrite)
11. Electrical contact

Figure 2-3: Standard Incandescent Light Bulb Construction [15].

Incandescent light bulb comes in various dimensions, such as the standard “A” (or A19), reflector shape (Rxx), candle shape (Bxx), parabolic aluminized reflector (PARxx), and multifaceted reflector shape (MRxx) to name a few [15]. In United States “xx” designates the maximum diameter of the bulb or “xx” times 1/8th of an inch. For example a traditional A19 bulb would have a maximum diameter of 19 times 1/8th of an inch or a 2.375 inch diameter. In United States, the screw base’s (Ezz) diameter is defined by “zz” times 0.03937 inch, where “zz” is in millimeters. A standard E26 Edison screw base would have a diameter of 26 times 0.03937 inch/mm or 1.024 inches. According to the U.S. Department of Energy (DOE), incandescent lamps are categorized into three types, standard “A” bulb, energy-saving incandescent (or halogen), and reflector bulb [16].

Incandescent lamp have higher efficacy (Lumens per Watt) compared to an oil lamp, however overall it is considered having a poor illumination output. A standard “A” bulb produces an efficacy of 10-17 Lm/W, an energy-saving (halogen) produces 12-22 Lm/W, and a reflector type incandescent bulb produces 12-19 Lm/W. A standard “A” bulb have a typical operating lifetime of 750-2500 hours, halogen bulb have a typical lifetime of 2000-4000 hours, and a reflector type incandescent bulb have a typical lifetime of 2000-3000 hours. Overall, all three types of incandescent bulb produces a good color rendition index (CPI), where the color temperature range from warm (2700K) to neutral (3200K) color temperatures. Incandescent light bulbs are relatively inexpensive to buy, often costing less than $1.00 per bulb, but due to its shorter operating lifespan (for example, standard “A” bulbs have a lifetime of 750-2500 hours), it would cost more to operate over a longer period of time. According to a study done by Xcel Energy, it would cost $5.25/year to operate an incandescent light bulb, where a compact fluorescent light (CFL) bulb would cost $1.61/year; assuming $0.07/kWh and an initial bulb cost of $1.00 for incandescent and $6.00 for CFL [17]. The study also translates that an incandescent light bulb must be replaced every 9 months (assuming it has a lifetime of 750 hours), where a CFL would require replacing every 10 years (assuming it has a lifetime of 10,000 hours). In other words, the incandescent light bulb must be replaced thirteen times in ten years. Incandescent light bulbs are slowly transitioning out due to more efficient lumination technologies, but they are still commonly used for mood lighting

Incandescent light bulbs are also dimmable via a dimmer knob or sliding lever to control the illumination output. Early dimmer switches consist of a variable resistor that allows the user to rotate a contact arm (or knob) to adjust the amount of resistance, thus the amount of current that is allowed to flow into the light bulb filament. Figure 2-4 illustrates a simple variable resistor dimmer circuit. The lower the resistance, the more current is allowed to flow. Despite this simple dimmer switch design, a lot of energy is wasted in the form of heat through the variable resistor.

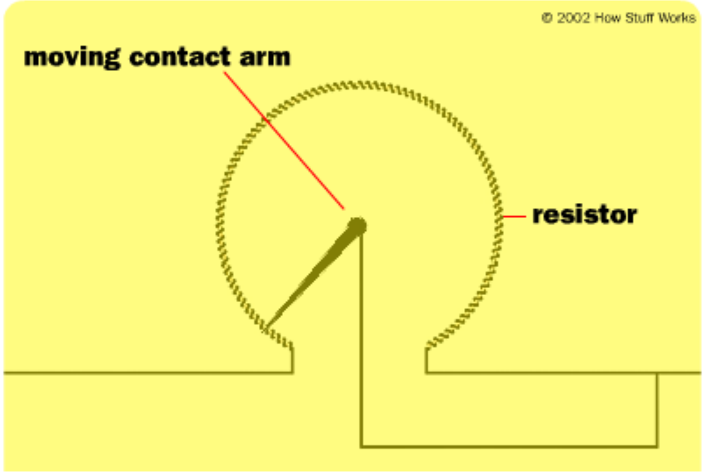


Figure 2-4: Simple Variable Resistor Dimmer Switch [20].

The most common type of incandescent dimmer switch is the triode alternating current (TRIAC) switch. Figure 2-5 illustrates a typical TRIAC dimmer switch circuitry and switching waveform. Depending on the dimmer's knob or slider position, the variable resistor's resistances is either increased or decreased. With a high resistive path, it takes longer for current to flow and to charge the firing capacitor, thus a longer time to build enough gate voltage to turn-on the TRIAC switch. Essentially, a TRIAC switch is a bidirectional voltage-controlled switch that alters the input AC source voltage on and off repeatedly over every switching period. The constant on and off reduces power loss through the resistive element (thus improving overall efficiency), but creates a buzzing sound due to abrupt voltage switching. The continuous on and off of the AC voltage switching causes steep change in current per time through the inductive light bulb filament and causes the magnetic field to also change abruptly. As a result, vibration and buzzing is created through the light bulb filament. Higher quality incandescent dimmers include a LC filter (choke inductor and interference capacitor) that temporarily stores and supplies extra current at a delayed interval to smooth out the sharp change in voltage levels, thus reducing the buzzing effect [20]. Despite the possible buzzing in lower-end incandescent dimmers, incandescent light bulbs are great in mood lighting applications. In the next section, the more efficient CFL bulb will be reviewed and its dimming capabilities will also be evaluated.

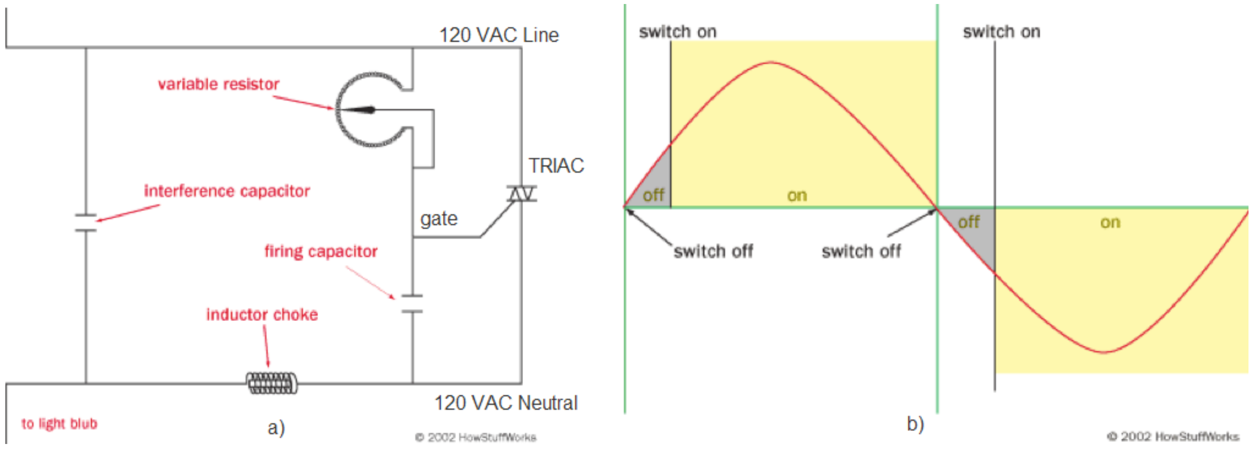


Figure 2-5: TRIAC Dimmer Switch: a) Circuitry and b) Switching Waveform [20].

2.2.3: Compact Fluorescent Lighting

Compact fluorescent light (CFL) bulb is a more energy efficient alternative to incandescent light bulbs. According to U.S. Department of Energy, CFL have an efficacy of 50-70 Lm/W and an operating lifetime of 10,000 hours [16]. Despite CFL having a good color rendition index, it somewhat suffers when it comes to light dimming. CFL is a type of gas-discharge lamp that uses constant current to energize mercury and inert gases within its burner (gas-filled tube section of the lighting enclosure) [18]. The exited mercury atoms are then converted into ultraviolet light that interacts with the white fluorescent coating and phosphors mixture in the lamp tube to produces visible light. Fluorescent lamps are characterized as a negative differential resistant device [19]. If current were allowed to flow freely through the device, its resistance would decrease as its voltage increased. Eventually the device would fail due to over-voltage. To prevent high voltage, magnetic or electric ballast is used to regulate the amount of current through the fluorescent lamp. Ballast used in early fluorescent tube lighting was often bulky and costly. Through advancement in lighting technology, engineers were able to integrate the electronic ballast into the base of the lamp housing, thus reducing the cost. Despite the 3-10 times greater initial cost in CFL compared to incandescent lighting, it uses 3-4 times less wattage and last 6-15 times longer compared to the latter [18]. CFL comes in many different shapes and sizes and often complement dimensions are available for incandescent light bulbs, such as the standard “A” (or A19) bulb. Figure 2-4 illustrates the various available CFL bulb sizes and shapes.

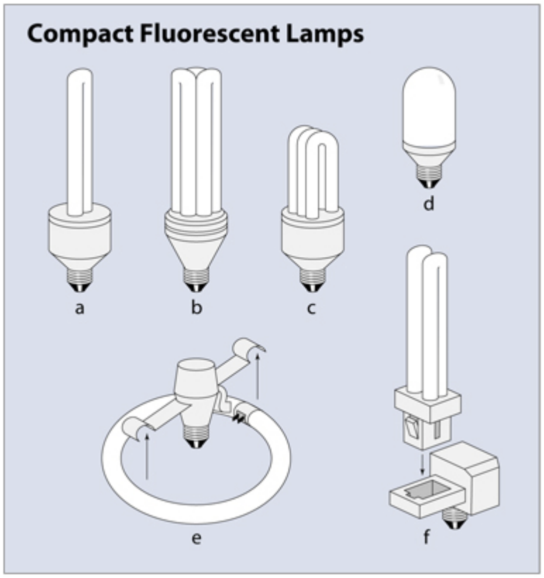


Figure 2-6: Various CFL sizes and shapes, including (a) twin-tube integral, (b and c) triple-tube integral, (d) integral model with casing that reduces glare, (e) modular circline and ballast, and (f) modular quad-tube and ballast varieties [18].

CFL bulbs are also somewhat dimmable, depending on the CFL's ballast type, internal lighting circuitry, and the dimmer circuitry. Traditionally, incandescent light bulbs can dim lower than CFL bulbs. Typical CFL bulbs can only dim down to between 10%-30% of its measured light output [21]. Some common CFL dimming issues are caused by light dropping out, light not turning on, and light turning off unexpectedly (or flickering). Light drop out occurs when the dimmer knob or slider position does not correspond to the light intensity. For example, when the dimmer's slider is fully down, but the light is still partially lit or when the slider is mid-way to full up, but the brightness remains at the same light intensity. Lights not coming back on can occur after the dimmer was set to a low light setting and then turned off. The lower dimming level may not provide sufficient voltage to turn CFL back on. Thus the dimmer knob or slider must be set to full brightness before turning back on. Lastly, the flickering of CFL lumination can occur when there are source voltage fluctuations, such as the high in-rush current required during air-conditioning or refrigerator start-ups, or simply caused by poorly regulated line voltage from the utility. As a result, at lower dimmer levels, flicker can become more noticeable.

CFL bulbs are great in terms of having a high efficacy to power usages ratio, long lifetime, and justifiable higher cost when compared to incandescent bulbs and oil lamps, but it is more harmful to the environment after its end of use due to small traces of mercury averaging 4 mg in each bulb [22]. Mercury vapor that escapes into the air when a CFL breaks is also harmful to humans and then environment. The EPA suggests that each year 103 metric tons of mercury is released into the air each year, where half of these emissions come from coal power plants [23]. Mercury vapor is the main cause of water and biological contamination in fish. A CFL bulb requires mercury inside its bulb to generate lumination. Assuming a CFL bulb breaks, it is estimated that 11% of its mercury vapor escapes into the air or water. The EPA suggests that if all 272 million CFLs sold in 2009 were disposed in a landfill; it would generate 0.12 metric tons or 0.12% of the total mercury emission in the United States [22]. For this particular reason, a more environmental friendly lumination solution is required.

2.2.4: Light Emitting Diodes Lighting

Light Emitting Diode (LED) lighting is one of the newest forms of lumination methods used today. LED lighting is attractive due to its high efficacy ranging from 27 to 200+ lumens per watt, long lifetime ranging from 25,000 to 50,000 hours, and relatively low operating power consumption ranging from a few mW to 20W for typical home applications [24]. However, the relatively high cost ($10 to $150) influences slower adoption into homes and businesses.

LEDs are often a category under solid-stage lighting (SSL), which describes a type of semiconductor used to convert electricity into light [25]. The characteristic of a LED is similar to a diode, when it is forward biased electrons from the anode terminal are allowed to recombine with electron holes at the cathode terminal. LED undergoes electroluminescence when the electron meets a hole; it releases photon light energy as it drops into a lower energy band [26]. The electroluminescence process is illustrated in Figure 2-7.

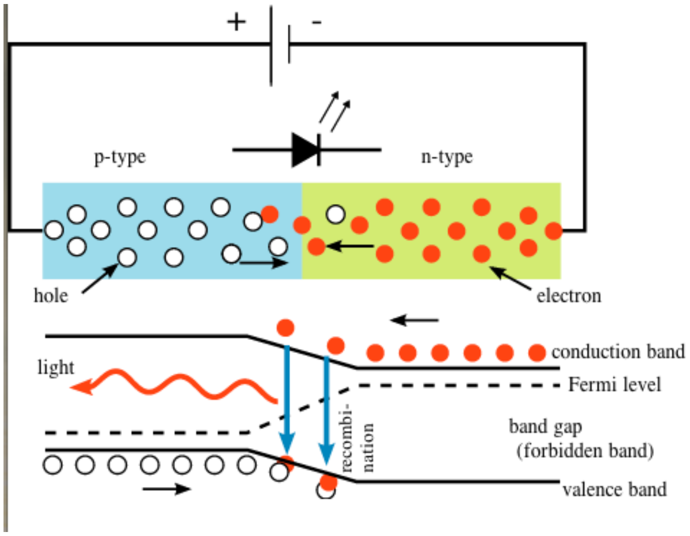


Figure 2-7: PN Junction of a LED Undergoing Electroluminescence [26].

The two most common methods used to achieve white LED light are the phosphor method and the RGB method. A popular phosphor-based white LED method involves coating a indium gallium nitride (InGaN) blue LED with a yttrium aluminum garnet (YAG) yellow phosphor to shift the shorter blue wavelength to a longer wavelength, thus creating a perceived white light seen by our eyes [26, 27]. Figure 2-8 illustrates the effect of YAG phosphor coating on a blue LED. The phosphor method is often favored over the RGB method when manufacturing high power white LEDs due to its simplicity, repeatable color rendering index, and lower cost. The RGB method involves mixing three primary colors: red, green, and blue LEDs to create a multi-color white LED. This method often requires a color sensing circuit to control the shade of each color's intensity. The RGB method may be favored in situations where the ambient temperature is outside the recommended LED operating conditions, or in situations where accurate color rendition is required. LEDs experience gradual lumen depreciation after about 35,000 to 50,000 hours of operation due to primary heat generated at the LED's junction [28]. Using a RGB white light module to correct the change in lumen imbalance between each color may extend its useful service life.

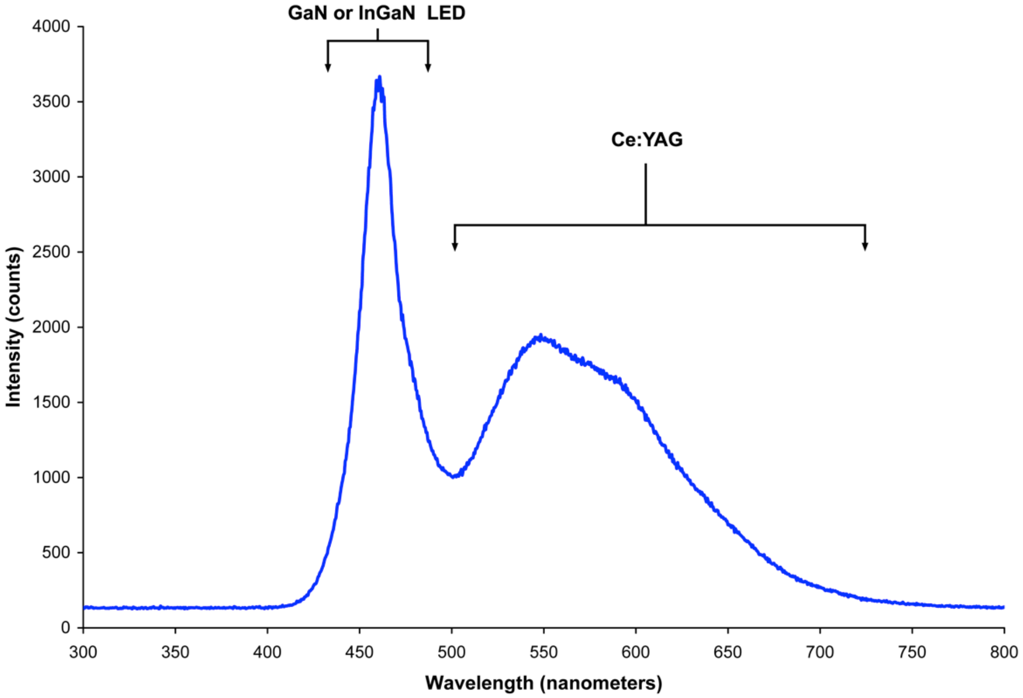


Figure 2-8: Phosphor Based White LED: Effects of YAG Phosphor Coating on a Blue LED [26].

As mentioned earlier, LEDs share similar current versus voltage operating characteristics (I-V curve) as a diode. Figure 2-9 illustrates a typical I-V diagram for a diode. For a diode or LED, a very small change in voltage can cause an exponential change in current. The brightness of a LED is directly dependent on the amount of current during the forward conduction mode. The high cost in LED lighting is partially the result of requiring a constant-current circuitry to power the LED and to prevent the LED from exceeding the maximum current rating.

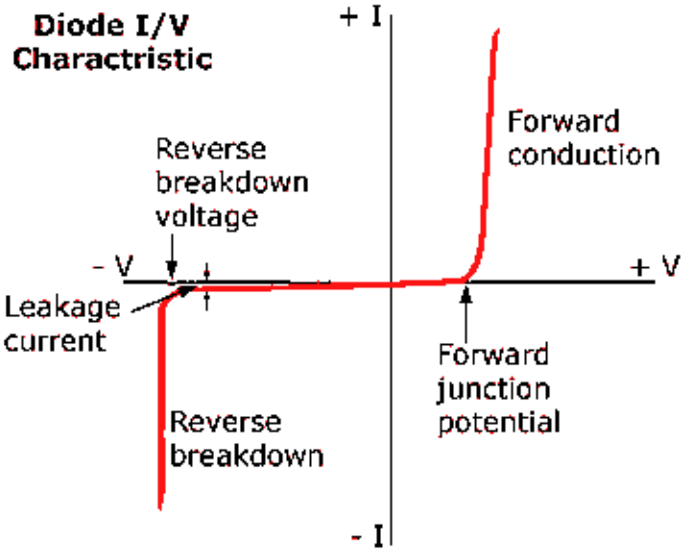


Figure 2-9: Typical Diode I-V Characteristic [29].

LEDs vary in shape, size, and lumens/watt output. U.S. Department of Energy suggests that in 2010, typical off the shelf 120VAC LED bulbs had efficacies of 64 Lm/W for LED A19 (warm white) lamp, 93 Lm/W for LED warm white package, and 130 Lm/W for LED cool white package [27]. In the same study, typical incandescent bulb had efficacy of 15 Lm/W, halogen had 20 Lm/W, and CFL had 63 Lm/W. Figure 2-10 illustrates a reasonably priced EcoSmart 120VAC 8.6W (40W) A19 LED light bulb costing $9.97 [30]. The EcoSmart light bulb produces 430 lumens or an efficacy of 50 Lm/W. Despite the higher cost, LED light easily out perform incandescent and CFL bulbs in terms of lumination output and efficacy.

Figure 2-10: EcoSmart A19 8.6-Watt (40W) LED Light Bulb [30].

Some off-the-shelf LED bulbs are dimmable, depending on the light bulb's internal circuitry and type of dimmer used. Often times, LED bulbs are not compatible with line-voltage incandescent dimmers, such as the TRIAC dimmer presented in Figure 2-5. Due to insufficient power to operate at lower dimming settings or due to line-voltage fluctuation causing steep current spikes, can damage the LED light bulb and incandescent dimmer circuitry [31]. Some manufacturers modified their LED light bulbs to accommodate incandescent dimmers and provide a list of compatible dimmers on their website. More expensive dimmers designed specifically for LED light bulbs are also available. Two common types of LED dimmers use low-voltage controls such as a variable resistor or a 0-10VDC controller to control the amount of current flowing through the LEDs. As suggested from the LED I-V curve in Figure 2-9, the LED brightness is dependent on the amount of current that flows through it. Analog dimming can vary the LED's current but have poor resolution. Voltage-controlled pulse width modulation (PWM) dimming offers more dimming resolution, thus leading to less flickering of the lights at lower shade settings. PWM dimming uses a variable resistor to adjust the amount of voltage (0-10VDC) sent to its electronic circuitry to pulsate the on and off time, thus varying the amount of current seen through the LED during each switching period (usually at a frequency two times greater than the line frequency).

2.2.5: Summary of Lumination Technologies

Oil, incandescent, CFL, and LED lighting methods will be summarized and compared based on efficacy, lifetime, color rendition index, color temperature, estimated cost, and dimmer capability. In conjunction to these comparisons, to better understand the various methods consumers and lighting manufactures evaluate the brightness of a product, such as a light bulb or a flashlight, a review of foot-candles, luminous flux per unit area (LUX), lumens, luminous efficacy, color rendition index, and color temperature will also be explained.

Foot-candles or LUX is a measure of the throw of the light, or a measure of how well it projects light at a particular spot some distances away [34]. Foot-candle or LUX is not a measurement of the lights overall brightness. Equation 2-1 describes the mathematical relationship between foot-candles and LUX.

$$1\, foot - candle = 10.76391\, LUX = 10.76391\, \frac{Lm}{(m)^2} \tag{2-1}$$

Figure 2-11 illustrates an example of two different flashlights with relatively the same amount of LUX (200 LUX versus 210 LUX) at the center spot some distances away. The top flashlight has a better overall brightness (lumens per area; Lm/m^2) compared the bottom flashlight with a narrower beam. Consumers often use a light meter to measure the amount of light (in foot-candles or LUX) produced from a given illumination source. However, lighting manufacturers often describe their product's brightness in terms of lumens.

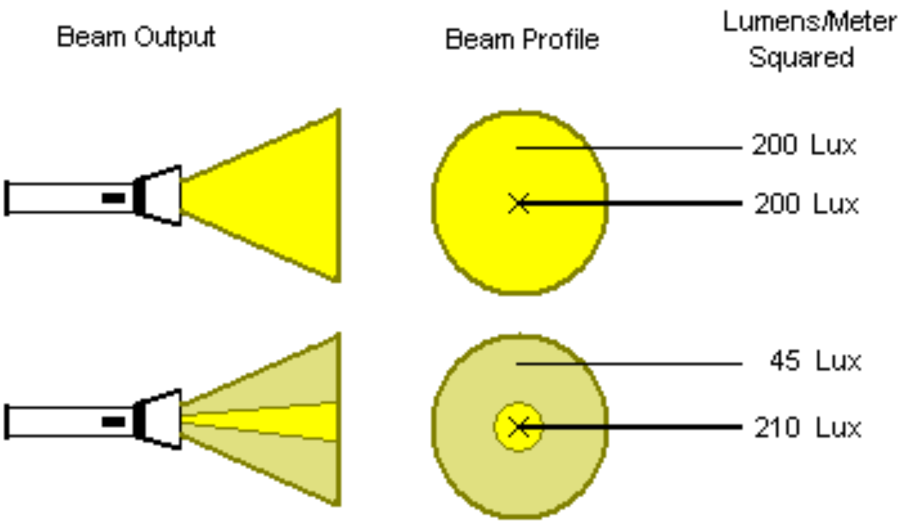


Figure 2-11: Two Flashlights With Relatively The Same Amount of LUX Some Distances Away [34].

Lumen is a measurement of the overall brightness per given area outputted by the light bulb or flashlight. When accounting for the overall brightness, the total surface area must be measured and calculated.

For example, if a room's dimension were 8 feet wide by 8 feet long by 8 feet high, then it would have a total surface area of 35.675 m^2 (Equation 2-2). A consumer reads 1.95 foot-candles from a light meter that is placed directly under the ceiling light bulb 8 feet away. Neglecting the height of the light bulb and the light bulb's base, this particular light bulb is then calculated to produce 748.8 lumens (Equation 2-3). Figure 2-12 illustrates this example and Figure 2-13 suggests that a standard A19 60W incandescent light bulb produces 780 lumens.

$$A_{room} = 6 * (8\,ft. * 8ft.) = 384\,ft.^2 * \left(0.3048\frac{m}{ft.}\right)^2 = 35.675\,m^2 \qquad (2\text{-}2)$$

$$Room\ Lumens = 1.95\,foot - candle * \frac{10.76391\frac{Lm}{m^2}}{1\,foot{-}candle} * 35.675\,m^2 = 748.8\,Lm \qquad (2\text{-}3)$$

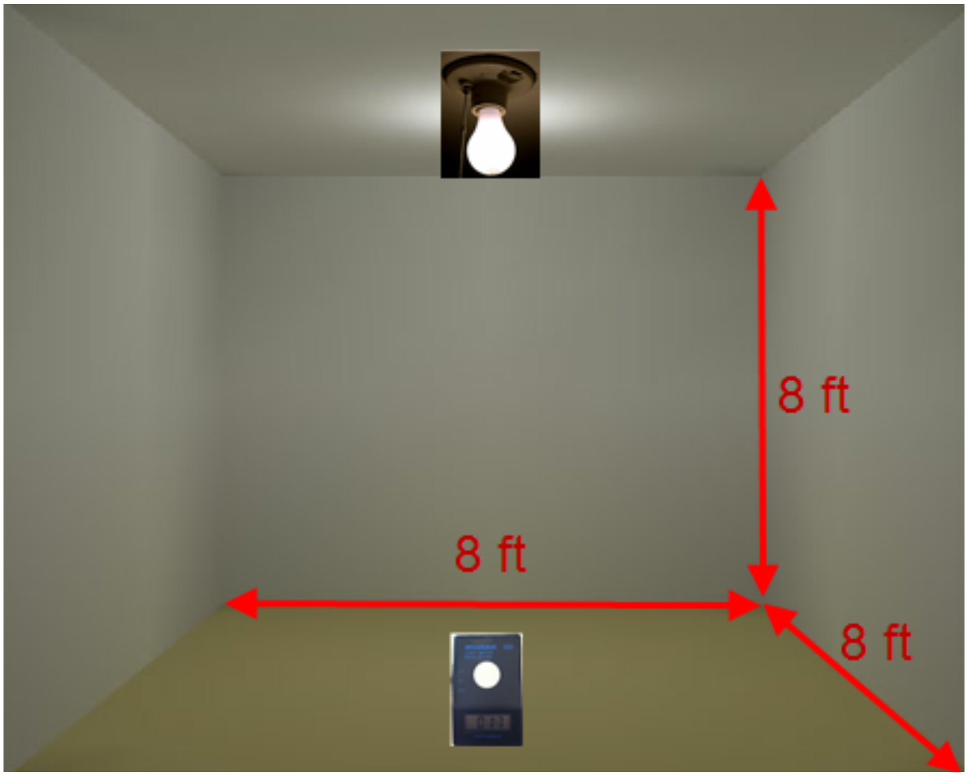


Figure 2-12: Example On How To Calculate Brightness In Lumens.

Figure 2-13: GE-60W A19 Incandescent Light Bulb: Brightness of 780 Lumens [35].

It is generally a pretty confusing process when trying to determine the amount of lighting required in a given room. A customer must consider variables such as room size, desired brightness, color temperature, and power consumption when trying to determine the right light bulb for his/her application. As the example presented previously, knowing foot-candles or LUX does not directly determine the overall brightness (lumens) in the particular room dimensions. Designing for specific room brightness would require a few trial-and-error iterations. According to U.S Department of Energy, it is generally a rule-of-thumb to select a light bulb's brightness based on its rated lumens rather than on its power usage. Figure 2-14, suggests the typical amount of lumens that a standard CFL bulb would produce when compared to a traditional incandescent light bulb's wattage rating.

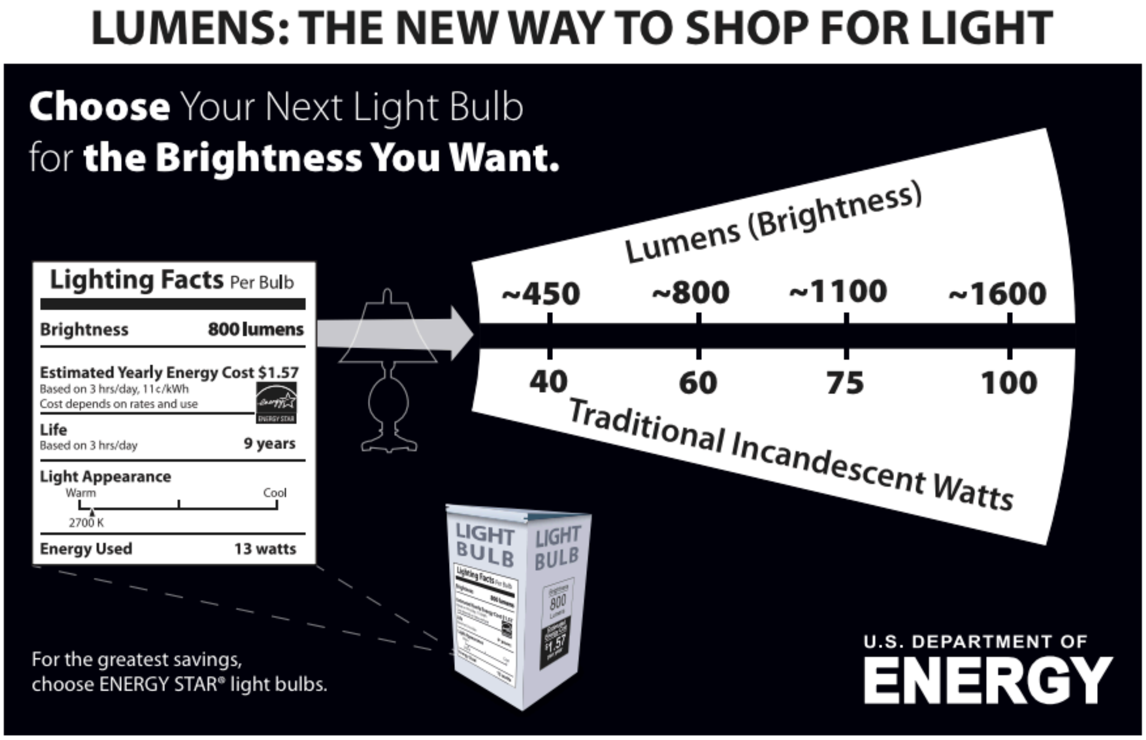
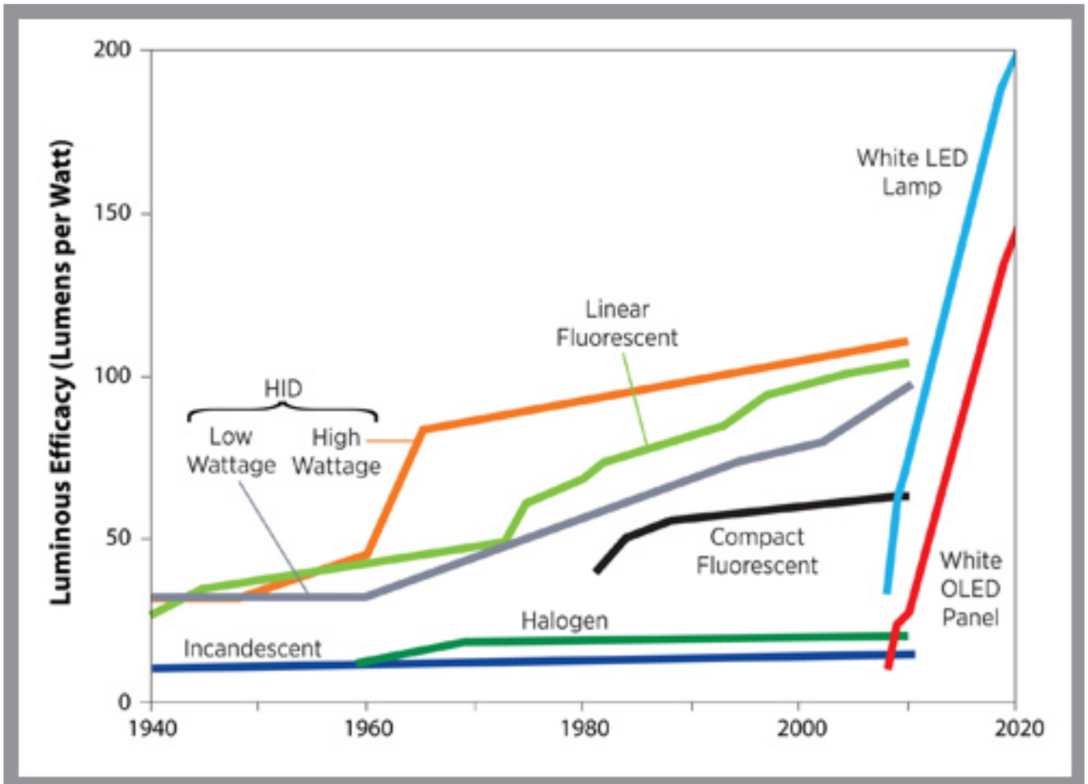


Figure 2-14: Selecting an Energy-Efficient CFL Bulb Based on Lumens Rather Than Watts [36].

Lighting manufactures have made LED based light bulbs to closely follow the same lumens profile of CFL bulbs. The brightness selection process shown in Figure 2-14 is somewhat still valid when using LED based light bulbs. However, with the constant advancements in LED technology, selecting the brightness of a LED light bulb, or a LED flashlight, or any high power LED application should not be based solely on the amount of lumens it can produce but also its luminous efficacy.

Luminous efficacy is a measure of how well a light source can produce light per given source power (lumens/watt). Figure 2-15 illustrates the projected trend of LED's efficacy proposed by U.S. Department of Energy.



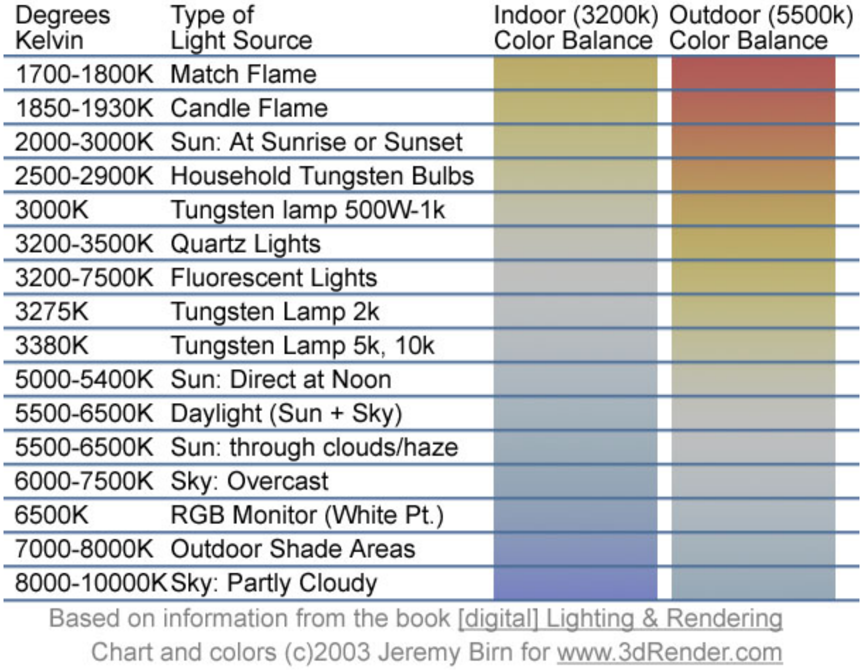
While traditional lighting technologies are relatively mature and offer less potential for improvement, SSL is still at a comparatively early stage and continues to achieve dramatic advances in efficacy.

Source: DOE SSL R&D Multi-Year Program Plan

Figure 2-15: Projected Luminous Efficacy of Solid-State Lighting [36].

As Figure 2-15 suggests, LED's brightness to power requirement ratio will improve almost linearly by the year 2020. This means LEDs will continue to get brighter and brighter at lower supply power requirements.

Next, color rendition index (CRI) and the color temperature scale are explained. CRI is the measure of how well an artificial light source is able to render the colors of skin tones, objects, and materials, when compared to a reference illuminant [37]. According to ENERGY STAR compliances, CRI is scaled with reference to an incandescent light source (or a candle flame) [38]. CRI is scaled from 0 to 100. A score of 100 CRI would produce the most accurate incandescent (yellowish hue) color replication. Typically, warm to cool white fluorescent light bulbs such as CFLs produces fair to good color rendering with a CRI score of 50 – 70. Due to the various inorganic semiconductor materials and phosphors tinting methods in altering the color wavelength in LEDs, they have a slightly better CRI scores ranging from 70 – 90.



Degrees Kelvin	Type of Light Source	Indoor (3200k) Color Balance	Outdoor (5500k) Color Balance
1700-1800K	Match Flame		
1850-1930K	Candle Flame		
2000-3000K	Sun: At Sunrise or Sunset		
2500-2900K	Household Tungsten Bulbs		
3000K	Tungsten lamp 500W-1k		
3200-3500K	Quartz Lights		
3200-7500K	Fluorescent Lights		
3275K	Tungsten Lamp 2k		
3380K	Tungsten Lamp 5k, 10k		
5000-5400K	Sun: Direct at Noon		
5500-6500K	Daylight (Sun + Sky)		
5500-6500K	Sun: through clouds/haze		
6000-7500K	Sky: Overcast		
6500K	RGB Monitor (White Pt.)		
7000-8000K	Outdoor Shade Areas		
8000-10000K	Sky: Partly Cloudy		

Based on information from the book [digital] Lighting & Rendering
Chart and colors (c)2003 Jeremy Birn for www.3dRender.com

Figure 2-16: Color Temperature Spectrum [33].

Lastly, the color temperature scale is a measure of the hue when compared to an ideal blackbody radiator. Color temperature is often expressed in terms of absolute temperature or kelvins (K). Depending on the referencing lighting source such as the brightness of a standard incandescent light bulb indoors or the brightness of a candle's flame outdoors, the color temperature will change slightly. For example, a CFL may be rated as having a cool white color of 3200K but it appears to be more yellow in color. As suggested earlier, selecting the desired brightness is often a tricky process that requires multiple trial and error attempts.

A summary comparing typical luminous efficacy, lifetime, CRI, color temperature, cost, and dimming compatibility for oil, incandescent, CFL, and LED is presented in Table 2-1. Lighting by oil lamps and candles offer the best color reproduction but suffers on luminous efficacy (brightness output) and no dimmability. Lighting by incandescent light bulbs have been around the longest, thus its relative cheap price. It has great CRI and good light controllability via a TRIAC dimmer, but its operating lifetime is very poor, often requiring replacements after 750 – 2500 hours or about every three months. Lighting by florescent lamps, such as CFL is ENERGY STAR's recommended lighting method today. It offers much higher luminous efficacy between 50 – 70 Lm/W and almost five times longer runtime (10,000 hours) when compared to incandescent light bulbs. However, its CRI score (65-88) is fair and estimated cost ($6.50) per bulb is around 20 times more than an equivalent incandescent light bulb ($0.35). CFL's dimmer capability causes flickering when using lower quality dimmers compatible with incandescent lamps. Lastly, LED lamps offer the best luminous efficacy, great CRI, and extremely long runtime (25,000 – 50,000 or about 5.7 years), but relatively expensive ranging from $10 - $150.

Table 2-1: Comparison Summary of Oil, Incandescent, CFL, and LED Lighting Technologies

Lighting Type	Lighting Size	Luminous Efficacy (Lumens/Watt)	Lifetime (hours)	Color Rendition Index (CRI)	Color Temperature (K)	Est. Cost per Bulb ($)	Dimmer Capability
Oil Lamp	Oil	0.16	0-6 (varies)	100 (excellent)	1000-1700 (yellow)	$4.99 - $300 (basic to decorative style)	No
	Candle	0.3	0-6 (varies)	100 (excellent)	1000-1700 (yellow)	$1.00 - $60.00 (basic to scented)	No
Incandescent	A19	10-17	750-2500	98-100 (excellent)	(2700-2800 (warm)	$0.35	Yes
	Halogen	10-22	1000-4000	98-100 (excellent)	2900-3200 (warm to neutral)	$0.65 - $2.00	Yes
	Reflector	12-19	2000-3000	98-100 (excellent)	2800 (warm)	$1.00 - $45.00	Yes
CFL	A19	50-70	10000	65-88 (fair to good)	2700-6500 (warm to cool)	$5.00 - $8.00	Yes (may flicker)
LED	A19	64	25000-50000	80-85 (good)	3000 (neutral)	$10.00 - $150.00	Yes (PWM)
	Warm White Package	27-54	25000-50000	70-90 (fair to good)	3300 (neutral)	$10.00 - $150.00	Yes (PWM)
	Cool White Package	60-92	25000-50000	70-90 (fair to good)	5000 (cool)	$10.00 - $150.00	Yes (PWM)

2.3 : Making the Case for LED Lighting

LED lighting technology is the latest trend in lumination applications. As Figure 2-15 suggests White LED lamp is expected to reach 200 Lm/W by the year 2020. As of April 2012, Cree sets the best R&D LED performance record with 254 Lm/W [39]. The U.S. Department of Energy suggests,

> *"It is estimated that switching to LED lighting over the next two decades could save the country $250 billion in energy costs over that period, reduce the electricity consumption for lighting by nearly one half, and avoid 1,800 million metric tons of carbon emission. DOE is not alone in recognizing the importance of that kind of savings; Congress recognizes it too, which is why the Energy Policy Act of 2005 mandates DOE to accelerate SSL (solid-state lighting) technology" [36].*

In an independent study presented to the U.S. Department of Energy, it is suggested that in 2010, LED lighting applications alone influenced 3.9 TWh/year in electricity savings, also shown in Figure 2-17 [40].

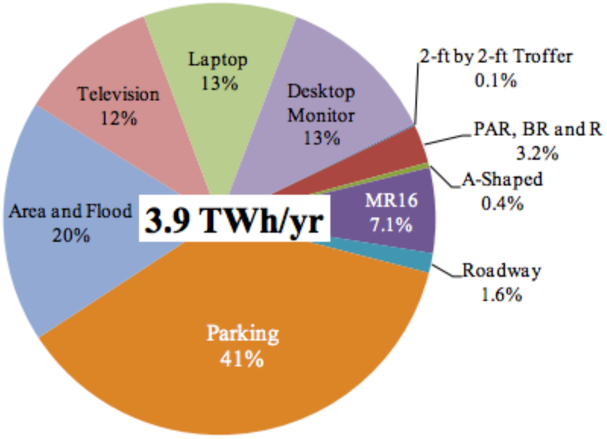
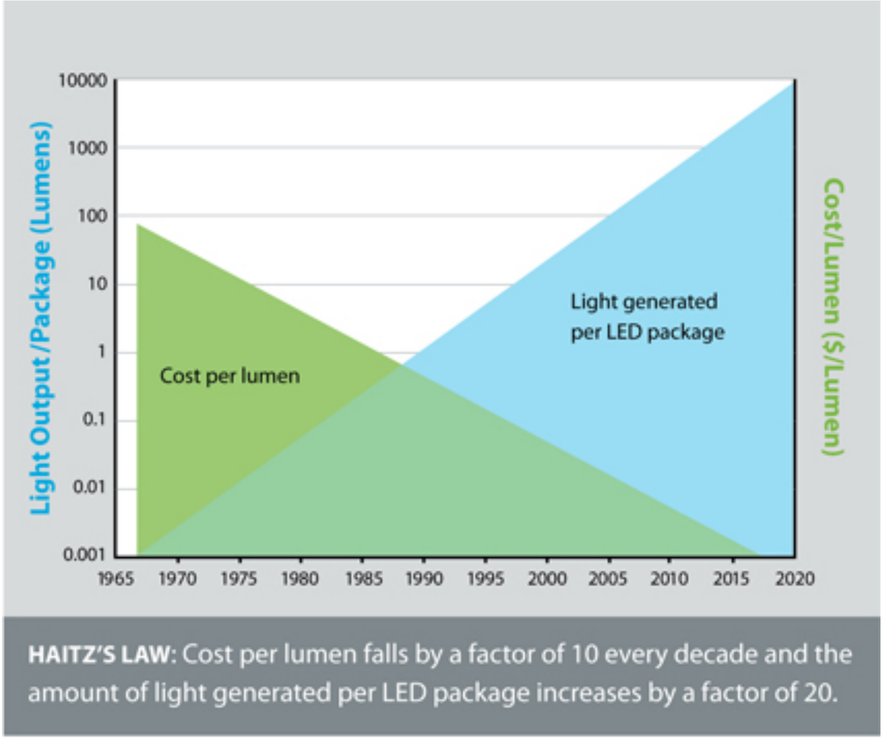


Figure 2-17: U.S. Site Electricity Savings in 2010 From LED Market Penetration [40].

Despite the current market's high cost in LED lamps, the expected cost per lumens would fall by a factor of 10 every decade and the amount of lumens per watt would increase by a factor of 20, also shown in Figure 2-18 [41].



HAITZ'S LAW: Cost per lumen falls by a factor of 10 every decade and the amount of light generated per LED package increases by a factor of 20.

Source: DOE SSL Multiyear Program Plan

Figure 2-18: DOE's Projected LED Cost Per Lumens [41].

The huge potential energy savings from solid-state LED lighting is very apparent and its price point per bulb would eventually decrease. As suggested earlier, DOE estimates that $250 billion dollars could be saved in the next two decades if LED lighting is fully integrated into the U.S. economy. This also triggered congress to pass the Energy Policy Act in 2005 in an attempt to speed up the advancements in LED technology. The independent study presented to the DOE suggests that if LED lighting was full saturated into the U.S. market a saving of 263

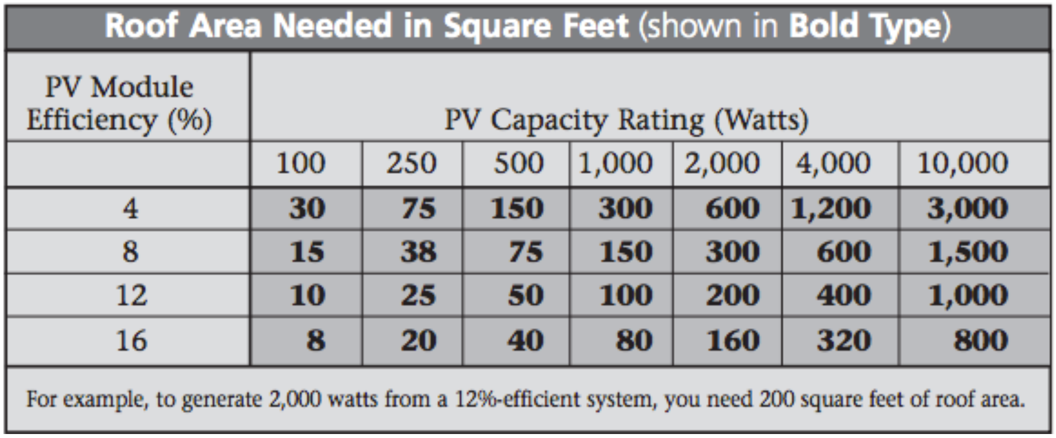
TWh/year could have been seen [40]. The staggering cost savings and luminous efficacy performance of LED technology will only improve over time.

2.4 : Availability of A19 LED DC Light Bulb

In this section, a look at the availability of standard “A” (A19) direct current LED light bulbs will be reviewed. Since the DC House Project operates off of purely DC generated power, it would be appropriate to design a lighting system that does not involve inverting (DC – AC) and then selecting a AC rated light bulb, where its internal electronics would rectify the AC to high frequency DC to power the LED array. Eliminating the DC – AC and AC – DC electronics would save on overall DC Light Bulb design time, prototype cost, PCB space requirement, number of components required, and overall packaging size.

Since majority of U.S. lighting market is tailored toward populated urban cities where consumers have access to the AC electrical grid, the availability of equivalent DC lighting systems are scarce due to low demand and implementation. The trend of AC system lighting technologies have evolved from incandescent to CFL to LED lighting, while maintaining the U.S. standard A19 bulb size with a medium base (E26 – U.S. standard Edison screw base). This practice is not true for DC systems. The major market for DC systems is in the auto industry, where the car’s battery runs off of 12 VDC. Standard car light bulb sizes are incompatible with the traditional AC base A19 light bulb size. The slow adoption in renewable energy methods such as photovoltaic (PV) power generation creates a small demand for DC lighting systems.

Typical solar panels have a rated efficiency around 11 – 15% [42]. Figure 2-19 suggests that a 500W PV system with solar panel efficiency of 12% would require 50 ft^2 of roof area, or a roof space of 7 feet by 7 feet [43].



Roof Area Needed in Square Feet (shown in **Bold Type**)

PV Module Efficiency (%)	PV Capacity Rating (Watts)						
	100	250	500	1,000	2,000	4,000	10,000
4	**30**	**75**	**150**	**300**	**600**	**1,200**	**3,000**
8	**15**	**38**	**75**	**150**	**300**	**600**	**1,500**
12	**10**	**25**	**50**	**100**	**200**	**400**	**1,000**
16	**8**	**20**	**40**	**80**	**160**	**320**	**800**

For example, to generate 2,000 watts from a 12%-efficient system, you need 200 square feet of roof area.

Figure 2-19: Recommended Roof Space Requirement Per PV Power Rating and Efficiency [43].

Typically, PV systems have a voltage bus of 12 VDC and have optional battery storage systems that operate at 12 VDC or 24 VDC. For this particular reason, the lighting industry is slowly introducing 12 VDC light bulbs using the traditional A19 bulb dimension. For example, Unlimited Solar Inc. offers a non-dimmable A19 12 VDC 5.6W LED light bulb that outputs a cool white (5000K) color at 400 lumens, also shown in Figure 2-20 [44].

Specifications

Bulb Type: E26 Standard Screw Base Globe Type
Life time: 40,000 Hours
View Angle: 160 Deg
Operating Voltage: 12 Volt AC/DC
Consumption: 5.6 Watt
Product Diameter: 2.25" or 60 mm
Product Length: 3.5" or 89 mm

Available Colors

Cool White
5000K to 6500K
400 Lumen

Warm White
3100K to 3400K
350 Lumen

Figure 2-20: Unlimited Solar Inc. A19 12 VDC 5.6W LED Light Bulb [44].

The limited availability of DC ready light bulbs in the standard A19 size offers opportunity for research and development in creating a new DC Light Bulb design. It would be beneficial to design a universal light bulb that accepts a wider input DC voltage range, offers higher efficacy (Lm/W), greater brightness coverage (lumens), dimming ability, low power consumption, relatively low cost, and most importantly retains the standard A19 light bulb size using a medium base. In the next chapter, a DC Light Bulb design will be presented.

Chapter 3: Design Requirements

In the following sections, a DC Light Bulb's design requirements for the DC House project will be presented. As mentioned in the previous chapter, due to limited market selection A19 DC light bulbs creates opportunities for research and development in designing more energy efficient and brighter lumination systems, while attempting to retain the traditional A19 incandescent light bulbs form factor. The new DC Light Bulb should attempt to accommodate a wide input voltage range, while remaining energy efficient. Some common bus voltages generated from renewable generation techniques are 12 VDC, 24 VDC, 48 VDC, and 72 VDC. The lighting system design should also be dimmable and be relatively inexpensive. The proposed DC Light Bulb will be designed based on electrical, lumination, size, and construction constraints.

3.1 : Electrical Design Constraints

The DC House Project is designed to be a self-sustaining DC powered ready-home that can meet the electrical needs to power the home's lighting system and appliances such as a fan, a radio, a small electric stove, and a mini refrigerator. Previous DC load flow studies indicate that the DC House operates best at 48 VDC when the home is supplied with roughly 500W from renewable generation sources such as photovoltaic power, hydropower, wind power, and human power generation [45] [49]. At the bare minimum the DC Light Bulb should be able to operate at 48 VDC.

Target performance specifications for the DC Light Bulb includes efficiencies greater than 80%, line regulation less than 5% when there is $\pm$ 15% fluctuations from the source voltage, and low power consumption. The desired 80% efficiency is within reason, when compared to typical DC – DC converters that achieves efficiencies between 78 – 92 % [46]. Line regulation is a measure of a power converter's ability to maintain the specified output voltage even when the input source voltage fluctuates. As illustrated earlier in Figure 2-9 (I – V curve of a diode or LED) the current can exponentially increase when a small forward voltage is applied. If a DC – DC converter is unable to maintain line regulation and it is driving a LED array at its output, immediate LED failure will occur. The overall lighting system load on any given branch should not exceed the maximum indoor luminaire rating of 21W or the maximum outdoor luminaire rating of 30W as suggested from previous DC load flow analysis for the DC House [45]. For example, if the DC Light Bulb's total power consumption is 10 W, then only two DC Light Bulbs can be placed in series for indoor lighting. This also means that three DC Light Bulb can be placed in series for outdoor luminaire. In the next section, the lumination design goals will be addressed.

3.2 : Lumination Design Constraints

From the staggering advancements in solid-stage lighting technology, in particular white LED's efficacy (Lm/W) ratios (as suggested in Figure 2-15), the DC Light Bulb design should take advantage of this to develop a lighting system that maintains low power consumption [36]. Figure 2-15 suggests that in 2010, about 75 lumens/watt was obtained. This luminous efficacy is used as a baseline in designing the DC Light Bulb's LED array. To gauge the desired total lumination, the suggested rule-of-thumb sizing process comparing total lumens versus power rating of a reference incandescent light bulb presented in Figure 2-14 should be used. Figure 2-14 suggests a 60W incandescent light bulb produces about 800 lumens. Since the total amount of light (lumens) that fills a room is also dependent on the total surface area of the room, the ability to adjust the brightness level can alleviate some of the guesswork in determining the appropriate lighting intensity required for task such as cooking (high brightness), reading (moderate brightness), or watching a movie (low brightness). Therefore, the DC Light Bulb design should incorporate a slide dimmer that allows the user to adjust the brightness level needed for any particular task.

In an independent study evaluating 33 office workers ability to perform routine office task such as reading documents placed horizontally on the desk, inputting data viewed on a computer screen, or taking notes while on the phone were evaluated under different lighting conditions. It was found that the workers performed best when there was sufficient lighting to make their surrounding environment appear clear and crisp. The result of the study, suggests that acuity slowly decays with age and recommends color temperatures ranging from 5000K –

5900K to produce optimum clarity, productivity, and comfort throughout a normal work day [46]. Therefore, the DC Light Bulb should output a cool white color temperature between 5000K – 5900K. In the next section, physical design of the DC Light Bulb will be defined.

3.3 : Physical Design Constraints

As technology progressed from incandescent to CFL and to LED light bulbs for AC powered systems, the trend in keeping the standard “A” (or A19) size remained consistent. The traditional A19 size has been around since Thomas Edison filed his patent on a practical incandescent lamp in 1878 [14]. With over one hundred years in consistency using the A19 light bulb size and United State’s standard E26 screw base (also called medium base), the availability of lamps, shades, and fixtures using this size must be immense. To keep with this trend, the DC Light Bulb should also have a similar form factor of a standard “A” light bulb using a medium base. Figure 3-1 suggests the dimensions of a standard A19 light bulb with an E26 screw base.

Figure 3-1: Standard A19 Light Bulb and E26 Screw Base Dimensions.

The slide dimmer should fit into a standard outlet/switch box. There should also be a wall plate to hold the custom slide dimmer circuitry. Figure 3-2 illustrates the custom slide dimmer enclosure's outlet box and wall plate dimensions. Construction constraints are addressed in the next section.

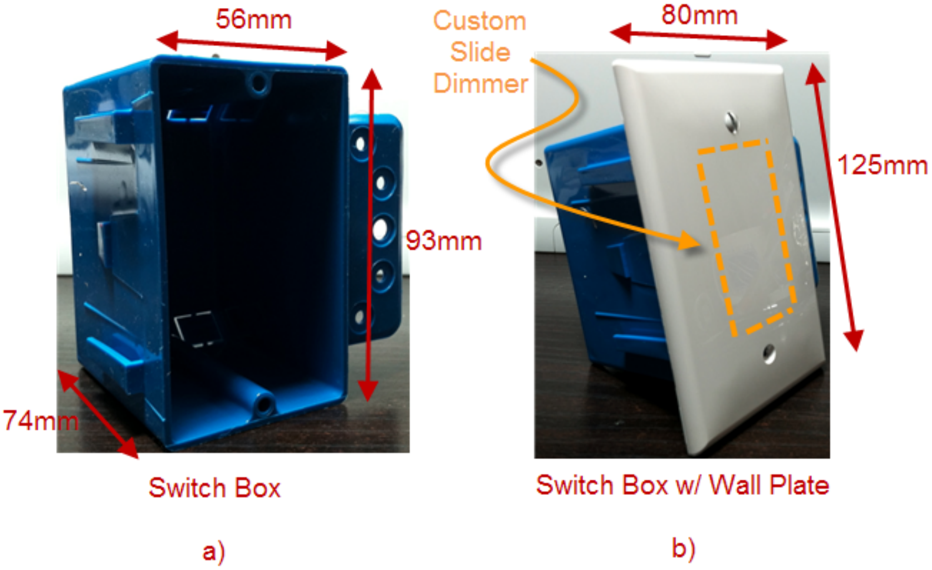


Figure 3-2: Custom Slide Dimmer Enclosure, a) Switch Box, b) Switch Box With Wall Plate.

3.4 : Construction Constraints

The DC Light Bulb should follow the safe installation of electrical wiring and equipment installation standards suggested by the National Fire Protection Association (NFPA 70), in particular the most current National Electrical Code, NEC 2011 [50]. The complete DC Light Bulb system (light bulb and dimmer box) should be easy to install with minimal skill required. Wiring between the main bus voltage, the DC Light Bulb, and to the dimmer box should be color coded and uses simple quick connects, such as the luminaire disconnects shown in Figure 3-3 [51].

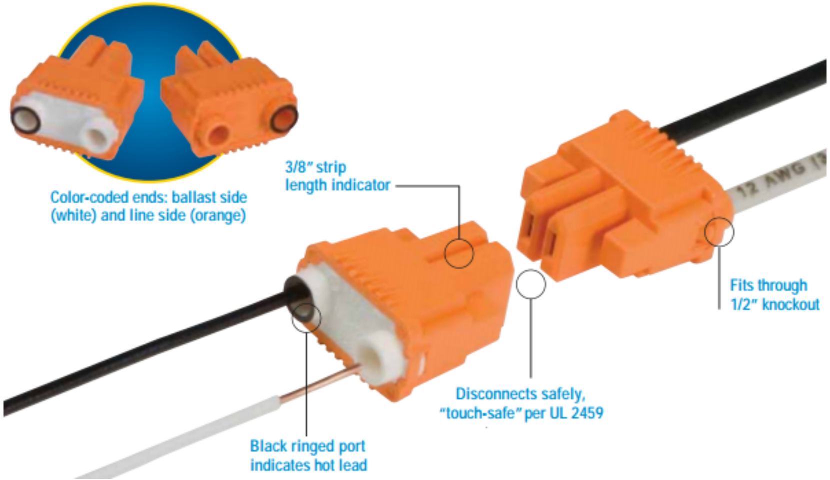


Figure 3-3: PowerPlug Luminaire Disconnect Plugs [51].

3.5 : Prototype Cost Constraints

Currently there is no DC light bulb available on the market that accepts a wide input DC voltage that range from 12 VDC – 72 VDC. Despite the availability of 12 VDC light bulbs, they do not provide sufficient lumens and are not dimmable [44]. Since the DC Light Bulb presented in this thesis will be the first prototype, a reasonable cost of \$100 - \$200 seems appropriate. This cost should cover all electrical components, custom PCB board design and manufacturing, wires, and a custom dimmer required per DC Light Bulb design.

3.6 : Summary of Design Requirements

A summary of the DC Light Bulb's electrical, lumination, physical, prototype cost, and construction design constraints presented in Sections 3.1 – 3.5 is provided in Table 3-1. A brief description supporting each specification is also provided in Table 3-1.

Table 3-1: DC Light Bulb Design Requirements.

		Design Requirements	Justification
Electrical	1	DC Light Bulb must operate at Vin = 48 VDC	Previous DC load flow study suggests the DC House operates best at 48 VDC when supplied with 500W from renewable generation [45] [49].
	2	DC Light Bulb should operate between 12 VDC < Vin < 72 VDC	Common renewable generation supply voltages.
	3	Have efficiency > 80%	Typical DC - DC converter can achieve efficiencies of 78% - 92% [46].
	4	Have line regulation < 5% @ ±15% Input DC Voltage fluctuation	A DC - DC converter with poor line regulation driving a LED array will be damaged. Small change in forward-voltage generates an exponential change in current across a LED [Figure 2-9].
	5	DC Light Bulb should not exceed 20 W	Previous DC load flow study suggest maximum indoor luminaire = 21W and outdoor luminaire = 30W [45].
Lumination	6	Have luminous efficacy > 75 lumens/watt	Projected luminous efficacy of solid-state lighting in 2010 is about 75 lumens/watt [Figure 2-15].
	7	Have brightness > 800 lumens	A 60W incandescent light bulb produces about 800 lumens [Figure 2-14].
		Brightness must be adjustable from 0 - 800+ lumens via dimmer circuit	A dimmer can alleviate some guesswork from determining the desired brightness level required during cooking, reading, or watching a movie.
	8	Have a cool white color temperature of 5000K - 5900K	Independent study indicates a color temperature of 5000K - 5900K is ideal for optimum clarity, productivity, and comfort throughout a normal work day [46].
Physical	9	DC Light Bulb design must retain standard A19 light bulb and E26 screw base dimensions	Technology progressed from incandescent, to CFL, and to LED light bulbs, but the trend was to maintain the standard A19 and E26 dimensions. Over 100 years of lamps, shades, and fixtures fitted for the A19 light bulb [14].
	10	Dimmer Enclosure must fitted into a standard switch box with a typical wall plate	Standard switch box dimensions: 93mm (L) x 56mm (W) x 74mm (H). Standard wall plate dimensions: 125mm (L) x 80mm (W). Refer to [Figure 3-2].
Construction	11	Meet all installation and wiring standards dictated by NEC 2011	NEC 2011 is a recognized safe installation of electrical wiring and equipment practices in USA [50].
	12	DC Light Bulb and dimmer box must be easy to install using minimal training	Luminaire disconnects can aid quick connection of DC Light Bulb wires [Figure 3-3].
Prototype Cost	13	Cost < \$100 - \$ 200	Total prototype cost includes all electrical components and chips, custom PCB board design and manufacturing, wires, and custom dimmer circuitry per bulb.

Chapter 4: Design Simulations and Components Selection

In this chapter, a proposed DC Light Bulb design that satisfies the design constraints and performance targets presented in Chapter 3 will be explained in greater detail. First, a high level overview of the DC Light Bulb design will be presented. Then, each subsystem of the DC Light Bulb design will be analyzed using schematic diagrams, component calculations and selections, and simulations showing its performance characteristics. Lastly, the complete DC Light Bulb design with all subsystems will be summarized.

4.1 : High Level Design

The DC Light Bulb for the DC House project provides variable lumination via slide-dimmer box and 48 VDC input source. Figure 4-1 illustrates the DC Light Bulb's fundamental (Level 0) block diagram.

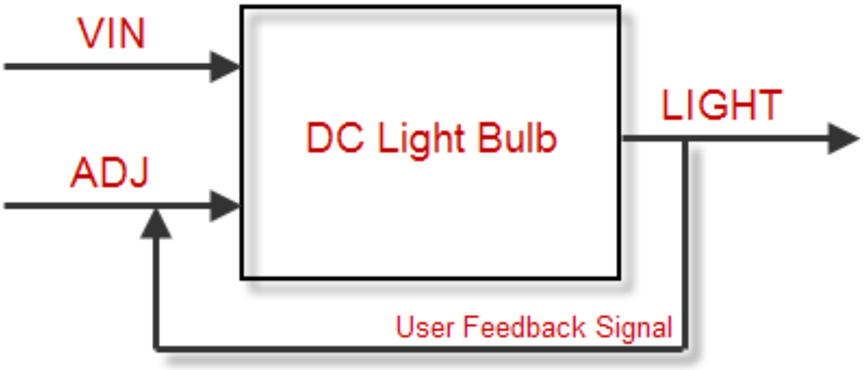


Figure 4-1: Level 0 - DC Light Bulb Block Diagram.

The VIN input is supplied from the DC House's main 48 VDC bus voltage. The ADJ input is the variable brightness signal supplied to the dimmer circuitry. The LIGHT output represents the lumination generated from the DC Light Bulb. The user is the feedback signal (between LIGHT and ADJ signals) that determines the desire brightness intensity by setting the dimmer's ADJ slider position. Table 4-1 summarizes the fundamental block diagram's input and output signal names and their functionalities.

Table 4-1: Level 0 - DC Light Bulb Functionality.

	Signal Name	Functionality
Inputs	VIN	48 VDC from DC house's main voltage bus.
	ADJ	Brightness level signal to the dimmer circuit. The user is the feedback signal that determines the desire brightness and sets the dimmer's ADJ slider position.
Outputs	LIGHT	Lumination generated from DC Light Bulb.

The DC Light Bulb's Level 0 block diagram can be further decomposed to Level 1, as shown in Figure 4-2. The DC Light Bulb consists of three main subsystems, LED driver, dimmer circuit, and the LED lighting array. The LED driver consist of all the electronics required to transfer a source of 48 VDC to drive the output LED lighting array, while offering the user the ability to adjust the brightness via the dimmer circuit. Similar to Level 0, VIN signal is supplied by the DC House's main 48 VDC bus voltage. GND signal is the return path from the main 48 VDC bus and used as a common ground for the DC Light Bulb's electronic circuitries. The user sets the ADJ signal by varying the slide potentiometer into the dimmer circuit. PWM5V is the resulting pulse width modulation (PWM) signal outputted from the dimmer circuit. Signals LED_P and LED_N represents the differential output voltage powering the LED lighting array subsystem. Lastly, LIGHT represents the lumination supplied from the DC Light Bulb. A summary of the input and output signals illustrated in the level 1 block diagram is provided in Table 4-1.

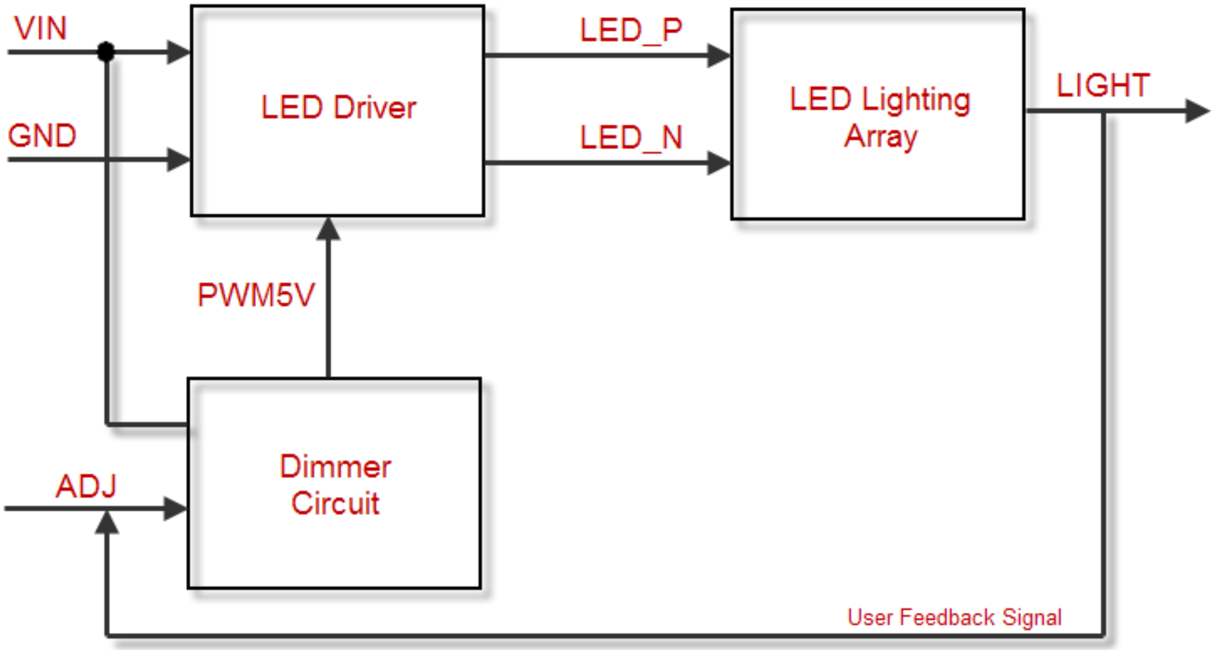


Figure 4-2: Level 1 - DC Light Bulb Block Diagram.

Table 4-2: Level 1 - DC Light Bulb Functionality.

Subsystem Name	I/O	Signal Name	Functionality
LED Driver	Inputs	VIN, GND	48 VDC from DC House's main voltage bus. GND is the common return and reference signal.
	Outputs	LED_P, LED_N	Differential output voltage powering the LED lighting array.
Dimmer Circuit	Inputs	ADJ, VIN	The user is the feedback signal that varies the ADJ signal via variable slide potentiometer to adjust the brightness level. VIN signal powers the dimmer's electronics.
	Outputs	PWM5V	The resulting pulse width modulation signal supplied to the LED driver.
LED Lighting	Inputs	LED_P,	Differential input voltage supplied by the LED driver.

Array		LED_N	Change in this voltage varies the output brightness.
	Outputs	Light	Output LED lumination.

4.2 : Low Level Design

In the following section, a detailed analysis of each subsystem of DC Light Bulb will be presented. The subsystem's design will be shown in a level 2 schematic and its component selection, sizing, and performance will be evaluated through LTspice simulations and manufacturer's datasheets. The dimmer circuit will be reviewed first. Follow by the LED driver and the LED array design.

4.2.1: Dimmer Circuit

The dimmer circuit essentially allows the user to adjust the output brightness of the DC Light Bulb. Since it was determined in Chapter 2 that LEDs are the desired choice when it comes to highest luminous efficacy (lumens/watt) and the lowest power consumption. Referring to the I-V curve of a LED (or diode) shown in Figure 2-9, varying a small change in voltage would create an exponential change in current. With this in mind, the two most common ways of dimming a LED is the analog method and the PWM method. The analog method consists of a variable potentiometer in series with a LED. With a constant voltage source, as the resistance is increased via the potentiometer the amount of current allowed to flow through the LED is decreased, thus a dimmer light output. As Figure 2-9 suggests the analog method is a poor choice, since it offers very little current limiting control and the LED will fail due to over current if the resistance is reduced to a very small value, such as when the slide potentiometer is fully off (roughly 0 Ω). The second approach is the PWM method that pulsates a constant voltage source over a given time (t_{ON}) per fixed period (T), also called duty cycle (Equation 4-1).

$$Duty\ cylce = D = \frac{t_{ON}}{t_{ON}+t_{OFF}} = \frac{t_{ON}}{T} \qquad (4\text{-}1)$$

The amount of voltage that the output (V_O) receives is then a function of its average voltage over the time it is on, assuming the input voltage (V_i) is supplying the voltage directly to the output (Equation 4-2).

$$\overline{V_O} = \frac{1}{T} * \int_0^T V_O(t) * dt = \frac{1}{T} * \int_0^{DT} V_i * dt = V_i * D \qquad (4\text{-}2)$$

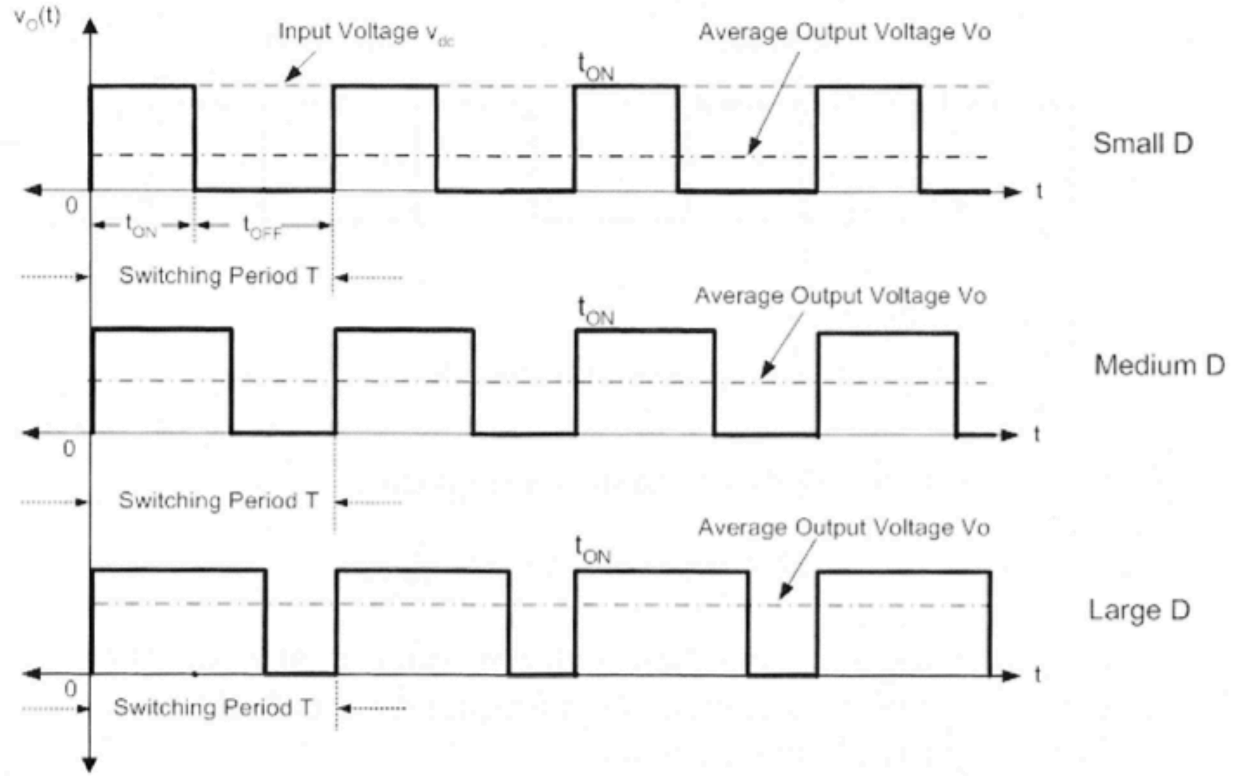


Figure 4-3: Pulse Width Modulation Explained [52].

Figure 4-3 illustrates that the available output voltage is a function of how long the pulse (t_{ON}) remains on or a function of the size the duty cycle (D). The greater the D means the greater the average output voltage. For a LED application, the larger the D means the more constant voltage per period it sees, thus a brighter lumination generated from the LED. If the D is small, it means that the amount of constant voltage per period the LED sees is less, thus a dimmer lumination. The PWM method is good for a LED application because it does not change the amount of current applied across the LED, thus reducing its chance of burning out due to over-current damage.

Linear Technology's voltage-controlled pulse width modulator TimerBlox, LTC6992-1, was selected as one of the components in the DC Light Bulb's dimmer circuit, shown in Figure 4-4 [53]. LTC6992-1 comes in a simple 6-pin SOT-23 package and its PWM duty cycle ranges from 0% - 100% (fully off to fully on). It can operate from a supply voltage (V+) between 2.25 V – 5.5 V. Voltage applied at the MOD pin controls the output duty cycle. Where V(MOD) ranges from 0.064*V(SET) – 0.936*V(SET). The oscillator output (OUT) swings from GND to V+ at a duty cycle determined by the MOD pin. The SET pin defines the switching frequency of the PWM chip. Reference voltage of V(SET) equals 1 V. Lastly, resistor configurations (R23 and R24) between the V+ and DIV pin defines the range of the output PWM duty cycle seen at OUT.

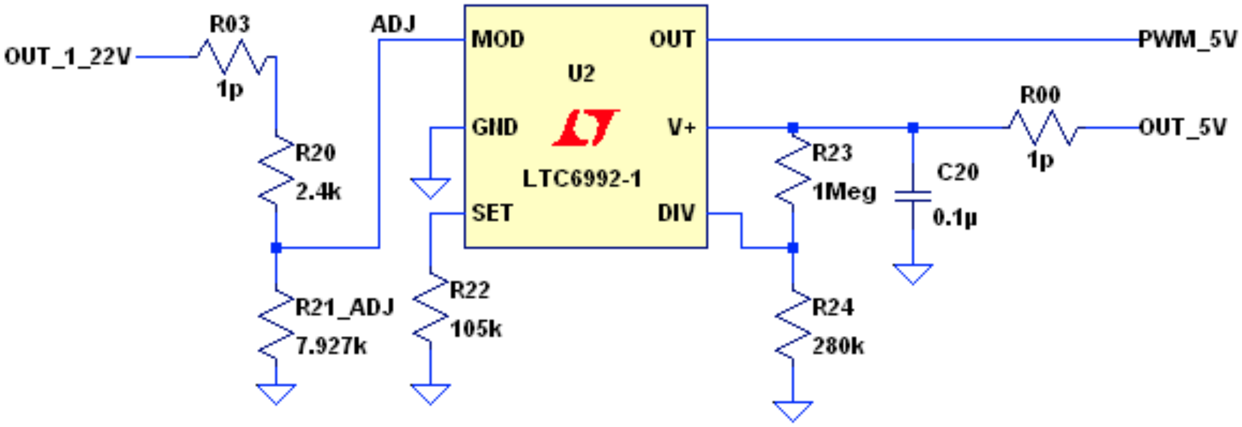


Figure 4-4: LTC6992-1 TimerBlox: Voltage-Controlled Pulse Width Modulator.

Note in Figure 4-4, R03 should represents a 0 Ω resistor, but LTspice requires that a resistor cannot equal zero.

Per Linear Technology's LTC6992-1 datasheet, high power LED direct voltage controlled PWM dimming (0 – 15000 Cd/m^2), a PWM switching frequency should be between 976.6 Hz – 15.63 kHz [53]. Where candela per square meter (Cd/m^2) is a measure of light emitted per unit area. Following Linear Technology's recommendation, the LTC6992-1 switching frequency was determined to be 7.5 kHz, when R22 = 105 kΩ, R23 = 1 M, R24 = 280 kΩ (referring to Figure 4-4). Equation 4-3 and Figure 4-5 were used in determining the optimum switching frequency of the PWM controller.

$$f_{SW} = \frac{1\ MHz!\ 50\ k\Omega}{N_{DIV} * R_{SET}} = \frac{1\ MHz * 50\ k\Omega}{64 * 105\ k\Omega} = 7.441\ kHz\ \approx 7.5\ kHz \tag{4-3}$$

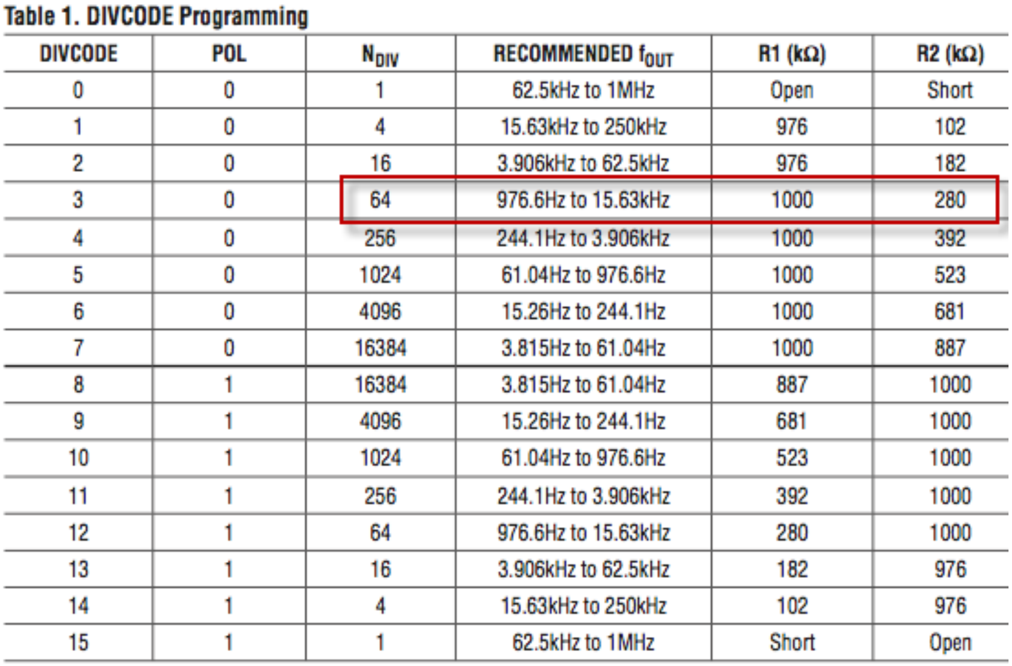


Table 1. DIVCODE Programming

DIVCODE	POL	N_{DIV}	RECOMMENDED f_{OUT}	R1 (kΩ)	R2 (kΩ)
0	0	1	62.5kHz to 1MHz	Open	Short
1	0	4	15.63kHz to 250kHz	976	102
2	0	16	3.906kHz to 62.5kHz	976	182
3	0	64	976.6Hz to 15.63kHz	1000	280
4	0	256	244.1Hz to 3.906kHz	1000	392
5	0	1024	61.04Hz to 976.6Hz	1000	523
6	0	4096	15.26Hz to 244.1Hz	1000	681
7	0	16384	3.815Hz to 61.04Hz	1000	887
8	1	16384	3.815Hz to 61.04Hz	887	1000
9	1	4096	15.26Hz to 244.1Hz	681	1000
10	1	1024	61.04Hz to 976.6Hz	523	1000
11	1	256	244.1Hz to 3.906kHz	392	1000
12	1	64	976.6Hz to 15.63kHz	280	1000
13	1	16	3.906kHz to 62.5kHz	182	976
14	1	4	15.63kHz to 250kHz	102	976
15	1	1	62.5kHz to 1MHz	Short	Open

Figure 4-5: LTC6992-1 Switching Frequency Programming [53].

The 1.22 VDC constant voltage source and a resistor divider network were used to vary the voltage across the MOD pin. Resistor R21_ADJ represents a 10 kΩ variable slide potentiometer used to vary the output brightness of the LED lighting array. The constant 1.22 VDC reference voltage is supplied by a LT3014, linear regulator chip (which will be described in greater detail shortly). Referring to Figure 4-4 and applying Equation 4-4, the voltage V_{ADJ} seen at the MOD pin is then calculated. V_{ADJ} at different R21_ADJ resistance values are summarized in Table 4-3.

$$V(MOD) = V_{ADJ} = V_{OUT\ 1\ 22\ V} * \frac{R21\ ADJ}{R21\ ADJ + R20} = 1.22V * \frac{1.668\ k\Omega}{1.668\ k\Omega + 2.4\ k\Omega} = 0.501\ V \qquad (4\text{-}4)$$

Table 4-3: Dimmer Slide Potentiometer V(MOD) Voltage Divider Network.

*Duty Cycle %	R21_ADJ (kΩ)	ADJ (V)	R20 (kΩ)	OUT_1_22V (V)
0.00%	0.133	0.064	2.4	1.222
6.61%	0.341	0.152	2.4	1.222
17.41%	0.584	0.239	2.4	1.222
28.09%	0.873	0.326	2.4	1.222
39.62%	1.23	0.414	2.4	1.222
50.07%	1.668	0.501	2.4	1.222
58.83%	2.226	0.588	2.4	1.222
67.94%	2.971	0.676	2.4	1.222
82.74%	3.99	0.763	2.4	1.222
93.18%	5.484	0.85	2.4	1.222
100.00%	7.927	0.938	2.4	1.222

*Note: Duty cycle was measured in LTspice simulation for each change in R21_ADJ.

Figure 4-6 illustrates LTC6992-1's duty cycle responses at varying V_{ADJ} voltages. V(ADJ) represents the voltage applied at the MOD pin and V(PWM_5V) represents the pulsing output voltage signal at the OUT pin of the PWM controller.

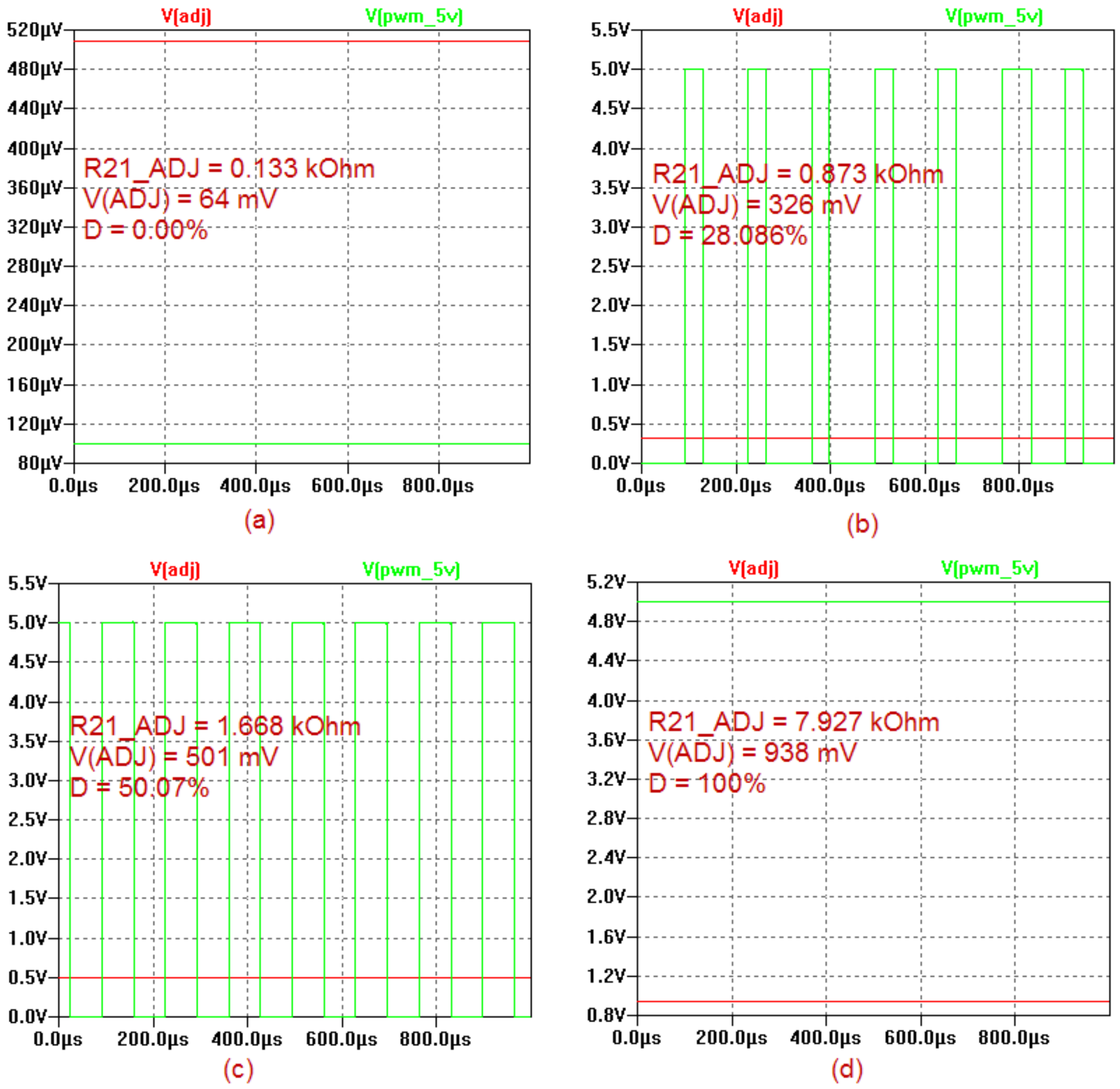


Figure 4-6: LTC6992-1 PWM at (a) D = 0%, (b) D = 28%, (c) D = 50%, and (d) D = 100%.

As briefly mentioned earlier, the LTC6992-1 PWM controller requires a source voltage between 2.25 V – 5.5 V at the V+ pin and requires a constant 1.22 V reference voltage at the voltage divider circuit (R20 and R21_ADJ) suggested in Figure 4-4. The MOD pin only requires a voltage of 0.064*V_{SET} to produce D = 0% and 0.936*V_{SET} to produce a D = 100%, so a 1.22 V source is more then sufficient to meet these requirements.

Since the DC House supplies 48 VDC, the voltage must be stepped down to at least 5.5 V to power the PWM controller. LTC6992-1's datasheet suggests the maximum (or worst case) required source current (I_S) into the chip is 420 µA [53]. With such a low current draw, linear regulators (sometimes refer to as low dropout linear regulator, LDO) were chosen to step down the 48 V to 5 V and to step down 5 V to 1.22 V.

Linear Technology's LT3014, low dropout micropower linear regulator was selected to meet the required 5 V and 1.22 V constant voltages needed to operate the LTC6992-1 PWM controller. LT3014 is a great choice because it accepts a wide input voltage of 3 V – 80 V, can supply an output current up to 20 mA, offer an adjustable output voltage between 1.22 V – 60 V, and comes in a simple 5-pin SOT23 package, and offers a dropout voltage of 350mV [54]. Traditionally, a LDO is great due to its simplicity and low cost, often requiring only two capacitors for storage and stability. It offers quiet operation since it generates little to no noise at its output, due to no switching elements or a transformer. LDO also offers great load handling compensation due to very short dynamic load response times [55]. However, an LDO is not recommended for high power voltage step downs since an LDO's efficiency (η) is roughly V_{OUT}/V_{IN}, thus its efficiency can be extremely low. For example, stepping down 48 V to 5 V creates an efficiency about 10.42% (Equation 4-5). For high power applications this would be a huge problem because the remaining 89.58% is wasted through the form of heat, thus a huge heatsink is required and overall cost goes up. For the case of the LTC6992-1 PWM controller, low efficiency is not a major concern. Since the PWM controller produces 2.1 mW (Equation 4-6) in worst case scenario and the voltage is stepped down from 48 V to 5 V produces an efficiency of 10.417% (Equation 4-5), it only sees a power loss of 20.939 mW (Equation 4-9). A power loss this low can be negligible. Figure 4-7 suggests an average power consumption across the LTC6992-1 chip to be 0.908 mW, when D = 100%.

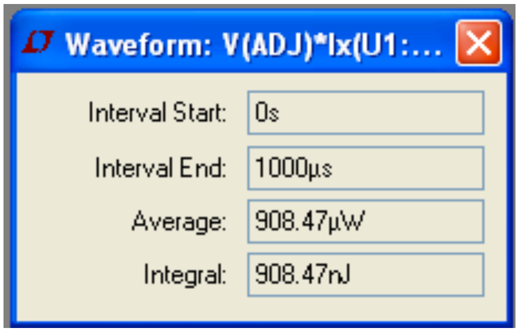
$$LDO\ \eta = \frac{P_{OUT}}{P_{IN}} \approx \frac{V_{OUT}}{V_{IN}} = \frac{5\ V}{48\ V} * 100 = 10.417\% \tag{4-5}$$

$$P_{OUT} = V_{OUT} * I_{OUT} = 5\ V * 420\ \mu A = 2.1\ mW \tag{4-6}$$

$$P_{IN} = \frac{P_{OUT}}{\eta} = \frac{2.1\ mW}{0.10417} = 23.039\ mW \tag{4-7}$$

$$P_{IN} = P_{LOSS} + P_{OUT} \tag{4-8}$$

$$P_{LOSS} = P_{IN} - P_{OUT} = 23.039\ mW - 2.1\ mW = 20.939\ mW \tag{4-9}$$



Interval Start: 0s

Interval End: 1000µs

Average: 908.47µW

Integral: 908.47nJ

Figure 4-7: LTC6992-1 Power Consumption at Full Load, D = 100%

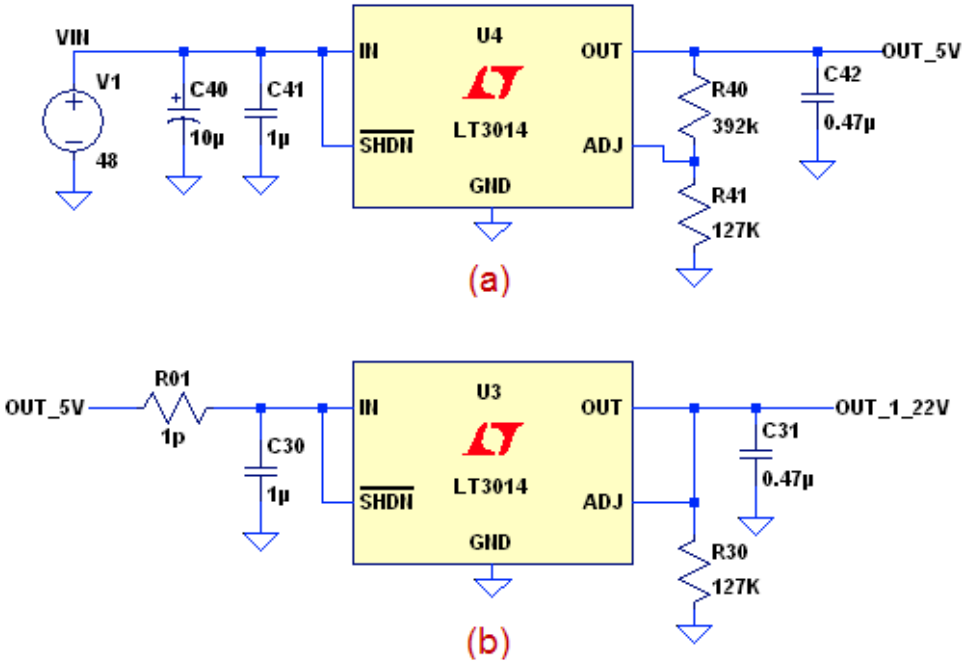


Figure 4-8: LT3014: Low Dropout Micropower Linear Regulator, (a) 48 V – 5 V LDO and (b) 5 V – 1.22 V LDO.

Figure 4-8 illustrates the LT3014 linear regulators used to step down 48 V – 5 V and 5 V – 1.22 V required to drive the LTC6992-1 PWM controller. The IN pin is tied to the source voltage. Per LT3014's datasheet, a bypass capacitor in the range of 0.1 µF to 10 µF is sufficient [54]. Since C40 is tied directly to the DC House main 48 VDC bus voltage, a higher quality capacitor with low ESR is desired. Possible options are ceramic X7R capacitor, aluminum electrolytic, or tantalum electrolytic capacitor. For C40 a 10 µF 75V tantalum electrolytic capacitor was selected since it offers the best noise limiting and stability filtering at a higher frequency and temperature range, while maintaining the lowest ESR [55]. The LDO's IN to GND and OUT to GND pins acts as a diode in the event the source voltage is connected backwards, thus protecting the chip an the load. The $\overline{SHDN}$ pin goes into low shutdown mode if it is tied to a low logic. The voltage divider resistors R40 and R41 tied to the OUT and ADJ pin sets the output voltage. For a 5 V output, Equation 4-10 and 4-11 are used to size resistor R40, assuming R41 is fixed at 127 kΩ. ADJ pin is referenced internally to V_{ADJ} = 1.22 V and to bias current I_{ADJ} = 4 nA at 25 ºC. LT3014's datasheet recommends that a minimum output capacitor of 0.47 µF with an ESR of 3 Ω or less should be used to prevent oscillations [54]. A 0.47 µF 25 V X7R ceramic capacitor was chosen, since the LDO produces a worst case output ripple voltage of 18.974 mV if the input swings from 12 V to 72 V (Equation 4-13). LT3014 offers a typical ripple rejection of 70 dB. Equations 4-12 and 4-13 suggest that the output voltage ripple is equal to an input voltage divided by a factor of 3162.

$$V(OUT\ 5V) = 1.22\ V * \left(1 + \frac{R40}{R41}\right) + I_{ADJ} * R40 \tag{4-10}$$

$$V(OUT\ 5V) = 1.22\ V * \left(1 + \frac{392\ k\Omega}{127\ k\Omega}\right) + 4\ nA * 392\ k\Omega = 4.987\ V \tag{4-11}$$

$$Ripple\ Rejection = 70\ dB = 20 * \log_{10} \frac{\Delta V_{IN}}{\Delta V_{OUT}} \tag{4-12}$$

$$\Delta V_{OUT} = \frac{\Delta V_{IN}}{10^{\frac{70dB}{20dB}}} = \frac{72\ V - 12\ V}{3162.278} = 18.974\ mV \tag{4-13}$$

For the 5 V – 1.22 V LDO, to effectively produce an output voltage of 1.22 V, a short is placed between OUT and ADJ pin, since ADJ is referenced internally to 1.22 V. Input and output capacitors C30 and C31 are sized using the same method for the 48 V – 5 V LDO. In this particular case a X7R 0.1 µF ceramic capacitor is sufficient for C30.

Common methods in evaluating a voltage regulator or DC – DC converters ability to maintain output voltage at a changing input voltage or at a changing load are line regulation and load regulation, respectfully. The first test is line regulation, which measures a power converter's ability to maintain the desired output voltage even when the input source voltage fluctuates. This relationship is shown in Equation 4-14.

$$\%\, Line\ Regulation_{at\ full\ load} = \frac{V_{OUT\ high\ input} - V_{OUT\ low\ input}}{V_{OUT\ nominal}} * 100\% \tag{4-14}$$

The second test is load regulation, which measures a power converter's ability to maintain the designed output voltage even when the output power fluctuates. Equation 4-15 expresses load regulation.

$$\%\, Load\ Regulation_{at\ nominal\ input\ voltage} = \frac{V_{OUT\ low\ load} - V_{OUT\ high\ load}}{V_{OUT\ high\ load}} * 100\% \tag{4-15}$$

LT3014 48V – 5 V Low Dropout Linear Regulator – Line Regulation Results

In the following section, the LT3014 Low Dropout Linear Regulator line regulation is tested. Figure 4-9 illustrates the schematic for the LT3014 (U4). U4 steps down the 48 VDC voltage bus to a 5 VDC voltage rail required to supply a constant 1.22 V source (U3) and to power the PWM Dimmer (U2) circuit.

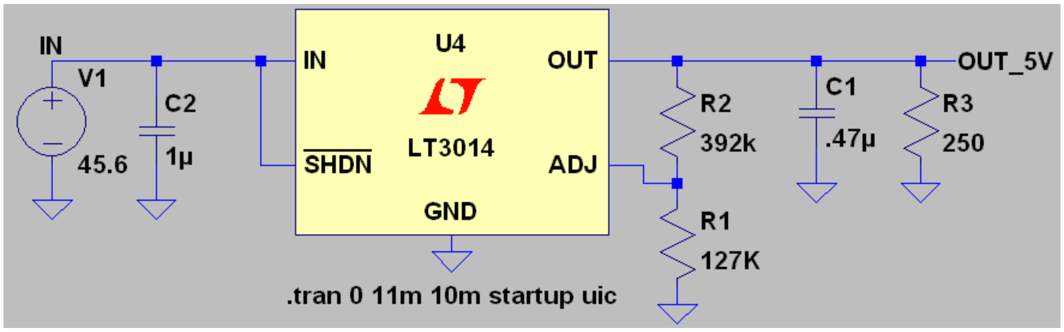
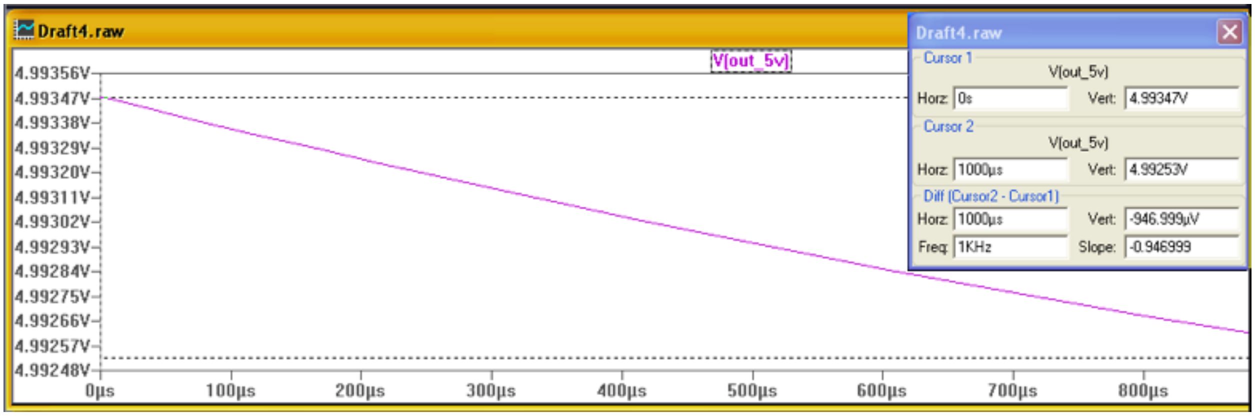


Figure 4-9: LT3014 48 V -5V LDO (U4) at 5% Vin and rated load 20 mA.

Figure 4-10 shows a sample V_{OUT} waveform at $V_{IN,\ low\ input}$ = 45.6V (5% of $V_{IN,\ Nominal}$). The output voltage is determined by taking the average of $V_{OUT,\ low\ input}$ and $V_{OUT,\ high\ input}$ as suggested in Equation 4-16.

$$\overline{V_{OUT}} = \frac{V_{OUT\ low\ input}+V_{OUT\ high\ input}}{2} \qquad (4\text{-}16)$$



Draft4.raw

Cursor 1

V(out_5v)

Horz: 0s Vert: 4.99347V

Cursor 2

V(out_5v)

Horz: 1000µs Vert: 4.99253V

Diff (Cursor2 - Cursor1)

Horz: 1000µs Vert: -946.999µV

Freq: 1KHz Slope: -0.946999

Figure 4-10: LT3014 48 V – 5 V LDO at $V_{IN,\ low\ input}$ = 45.6 V (5% $V_{IN,\ Nominal}$) and rated load 20 mA.

Table 4-4: LT3014 48 V – 5 V LDO Line Regulation Simulation Results.

% of $V_{IN,\ Nominal}$	$V_{IN,\ Nominal}$ (V)	$V_{OUT,\ Nominal}$ (V)	$V_{IN,\ Min}$ (V)	$V_{IN,\ Max}$ (V)	$V_{OUT,\ low\ input}$ (V)	$V_{OUT,\ high\ input}$ (V)	$I_{OUT,\ Rated}$ (mA)	% Line Regulation (%)
5%	48	4.993	45.6	50.4	4.993	4.9932	19.814	0.004
10%	48	4.993	43.2	52.8	4.9929	4.9933	19.814	0.008
15%	48	4.993	40.8	55.2	4.9928	4.9934	19.814	0.012

Table 4-4 summarizes the LT3014 48 V – 5 V LDO's line regulation at ±5%, ±10%, and ±15% $V_{IN,\ Nominal}$ voltage variations. The resulting line regulations indicate that the LT3014 can easily maintain an output voltage of 4.993 V with fluctuations less than 0.012%. LT3014's datasheet electrical characteristic suggests it produces a maximum line regulation of 10 mV. With a 5 V output and a 10 mV ripple means that its output voltage can decrease down to 4.95 V at its worst case. Applying Equation 4-14 suggests a 1% maximum line regulation using the datasheet specifications. LTspice simulation suggests that with a 15% swing in input voltage it produces a 0.012% line regulation, which is way within datasheet specifications.

LT3014 48V – 5 V Low Dropout Linear Regulator – Load Regulation Results

Next load regulation test is performed to evaluate the performance of the LT3014 48 V - 5 V LDO (U4), shown in Figure 4-11. A .step SPICE directive at RLOAD was used to increment the output in 10% load changes.

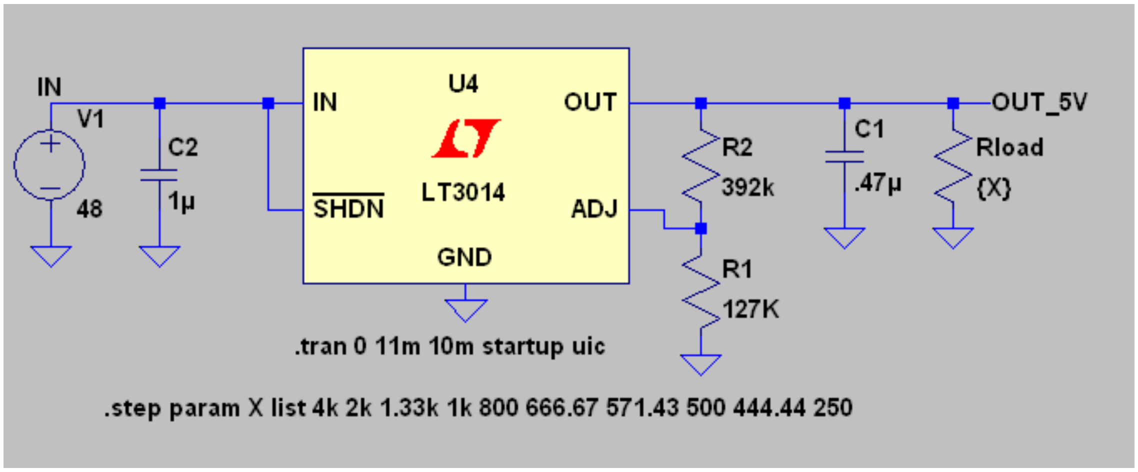


Figure 4-11: LT3014 48 V – 5 V LDO, R_{Load} = 4KΩ, 2KΩ, 1.33KΩ, 1KΩ, 800Ω, 666.67Ω, 571.43Ω, 500Ω, 444.44Ω, and 250Ω.

The resulting change in output voltage V(OUT_5V) versus change in output load resistances is shown in Figure 4-12. As the load resistance decreases, the required output current increases, thus the voltage slowly sags more and more.

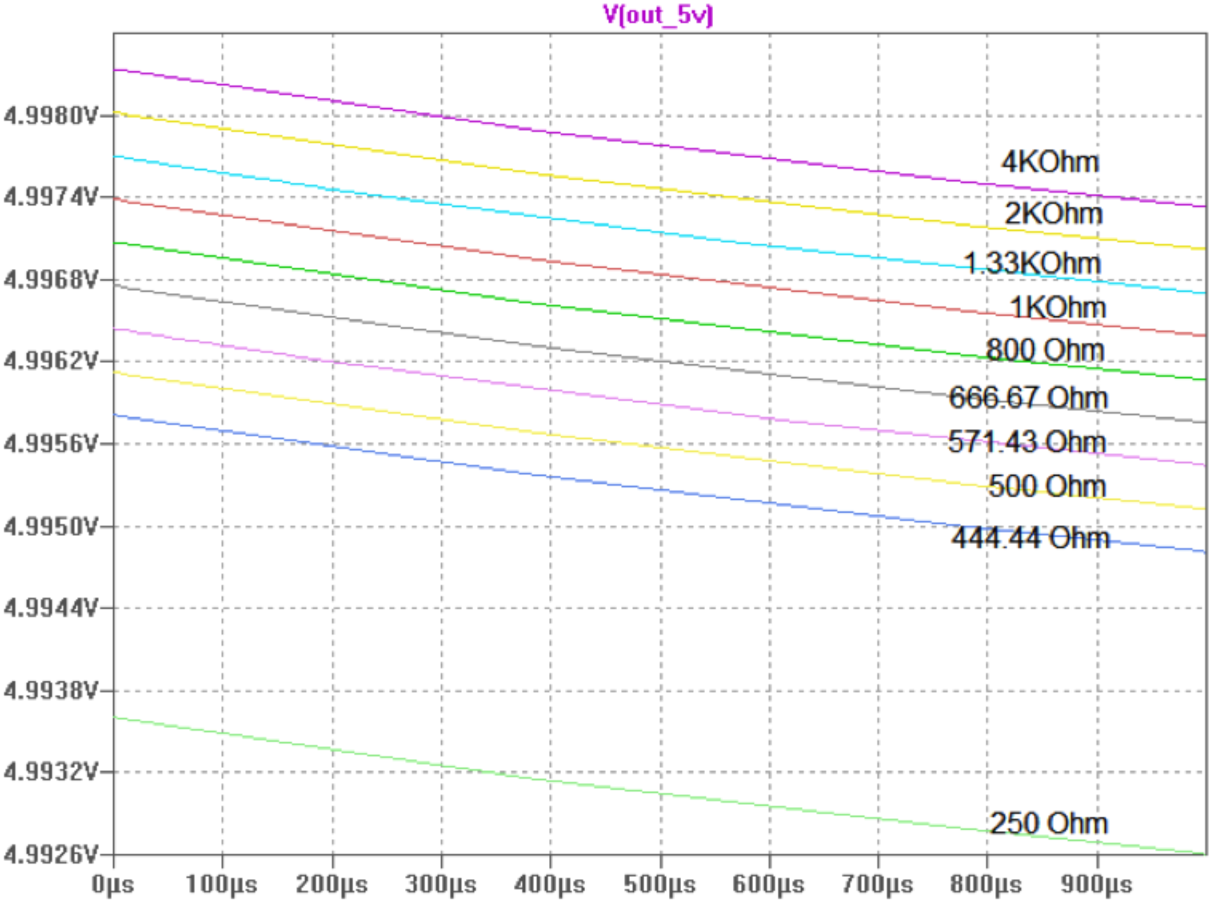


Figure 4-12: LT3014 48Vdc-5Vdc LDO Simulation Waveform at $V_{IN, Nominal}$ = 48V, I_{LOAD} varying from 10% to 100% of I_{Rated} = 20mA.

Table 4-5 summaries the load step changes versus output voltage V(OUT_5V). Applying the load regulation Equation 4-15 to Table 4-5, a 0.05% load regulation was obtained (Equation 4-17).

$$\% \, Load \; Regulation = \frac{4.9978V - 4.9953V}{4.9953V} * 100 = 0.05\% \qquad (4\text{-}17)$$

Table 4-5: LT3014 48Vdc-5Vdc LDO Load Regulation Simulation Results; $V_{IN,\,Nominal}$ = 48V.

% Load (%)	I_{OUT_5V} (mA)	R_{OUT_5V} (Ω)	V_{OUT_5V} (V)
10	2	4000	4.9978
20	4	2000	4.9977
30	6	1333.33	4.9972
40	8	1000	4.9969
50	10	800	4.9966
60	12	666.67	4.9963
70	14	571.43	4.9959
80	16	500	4.9956
90	18	444.44	4.9953
100	20	250	4.9931

LT3014’s datasheet electrical characteristics suggest a worst case load regulation ripple of 40 mV can occur. LTspice simulated load regulation of 0.05% is within the specifications defined by LT3014’s datasheet [54].

LT3014 5 V - 1.22 V Low Dropout Linear Regulator – Line Regulation Results

Next, the LT3014 5 V - 1.22 V LDO (U3) is tested for line regulation and load regulation using equations 4-14, 4-15, and 4-16. Figure 4-13 illustrates the LT3014 (U3) linear regulator at $V_{IN,\,low\ input}$ = 4.7434V (5% of $V_{IN,\,Nominal}$ = 4.993V). This LDO is used to provide a fixed 1.22V voltage source needed for the analog voltage-controlled pulse width modulation (PWM) circuitry (U2).

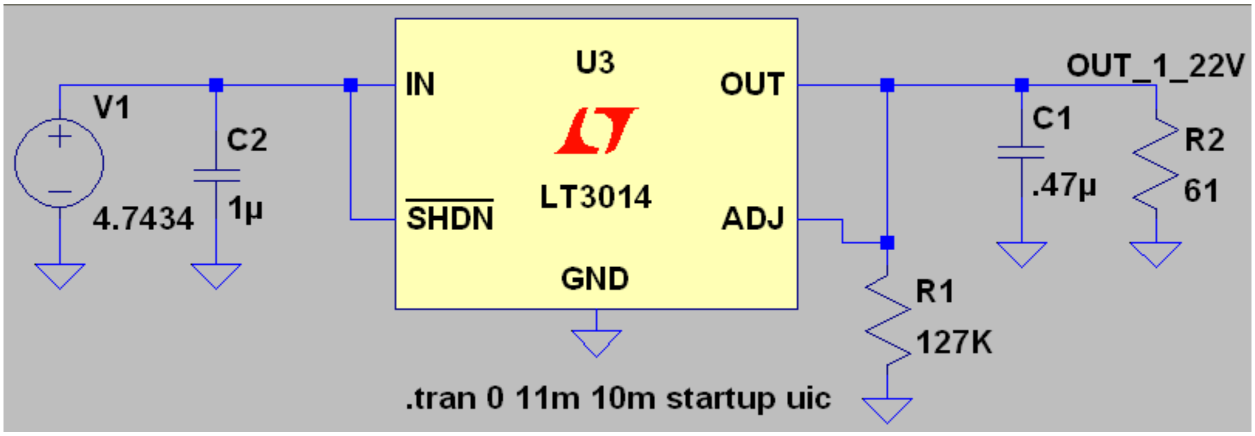
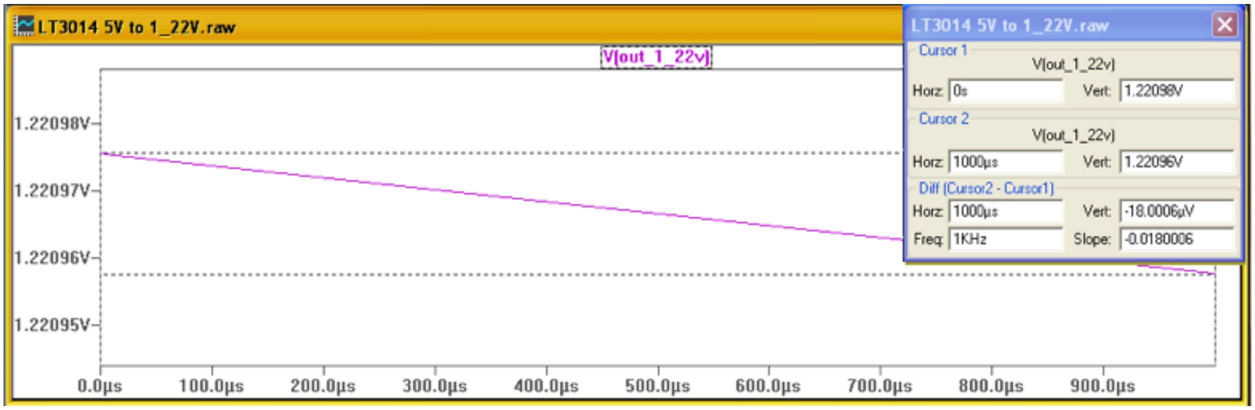


Figure 4-13: LT3014 5Vdc-1.22Vdc LDO (U3) at 5% Vin and rated load 20mA.

Figure 4-14 illustrates LDO U3's $V_{OUT,\text{ low input}}$ = 1.221 V at an input voltage $V_{IN,\text{ Min}}$ = 4.7434 V (5% of $V_{IN,\text{ Nominal}}$). Table 4-6 summarizes LT3014 5 V - 1.22 V LDO's line regulation at ±5%, ±10%, and ±15% of $V_{IN,\text{ Nominal}}$. The resulting line regulations indicate that the output voltage can be considered constant with no fluctuation.



LT3014 5V to 1_22V.raw

Cursor 1
V(out_1_22v)
Horz: 0s Vert: 1.22098V

Cursor 2
V(out_1_22v)
Horz: 1000µs Vert: 1.22096V

Diff (Cursor2 - Cursor1)
Horz: 1000µs Vert: -18.0006µV
Freq: 1KHz Slope: -0.0180006

Figure 4-14: LT3014 5 V - 1.22 V LDO at $V_{IN,\ low\ input}$ = 4.993V (5% $V_{IN,\ Nominal}$) and rated load 20 mA.

Table 4-6: LT3014 48 V – 5 V LDO Line Regulation Results.

% of $V_{IN,}$ Nominal	$V_{IN,}$ Nominal (V)	$V_{OUT,}$ Nominal (V)	$V_{IN,\ Min}$ (V)	$V_{IN,\ Max}$ (V)	$V_{OUT,\ low}$ input (V)	$V_{OUT,\ high}$ input (V)	$I_{OUT,}$ Rated (mA)	% Line Regulation (%)
5%	4.993	1.221	4.7434	5.2427	1.221	1.221	20.016	0
10%	4.993	1.221	4.4937	5.4923	1.221	1.221	20.016	0
15%	4.993	1.221	4.2441	5.742	1.221	1.221	20.016	0

LT3014 5 V - 1.22 V Low Dropout Linear Regulator – Load Regulation Results

Similarly, load regulation is found using the same approach (Equation 4-15) used for the LT3014 48 V – 5 V LDO. A schematic diagram of the LT3014 5 V – 1.22 V LDO (U3) is shown in Figure 4-15. A .step SPICE directive was applied at RLOAD to increment 10% output load steps.

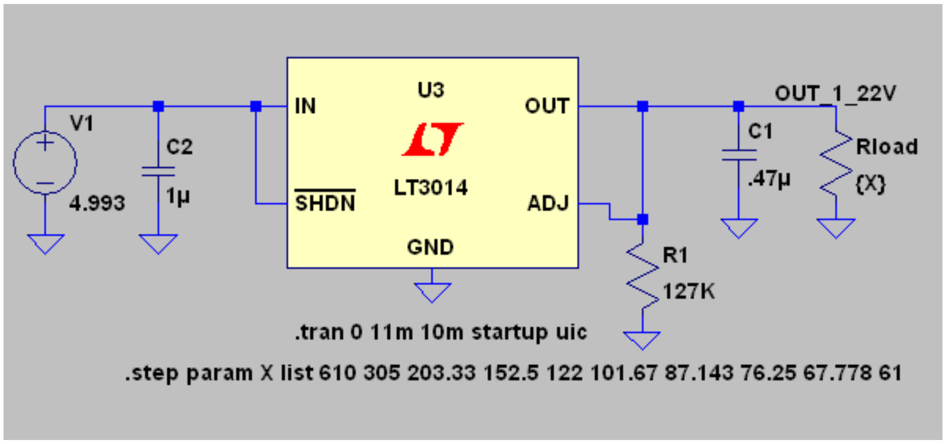


Figure 4-15: LT3014 5 V - 1.22 V LDO Schematic Diagram, R_{Load} = 610Ω, 305 Ω, 203.33 Ω, 152.5 Ω, 101.67 Ω, 87.143 Ω, 76.25 Ω, 67.778 Ω, and 61 Ω.

Figure 4-16 illustrates the output voltage, $V_{OUT\_1\_22V}$, for the LT3014 5 V – 1.22 V LDO. Figure 4-16 suggests that the output voltage decreases slightly with an increase in output load.

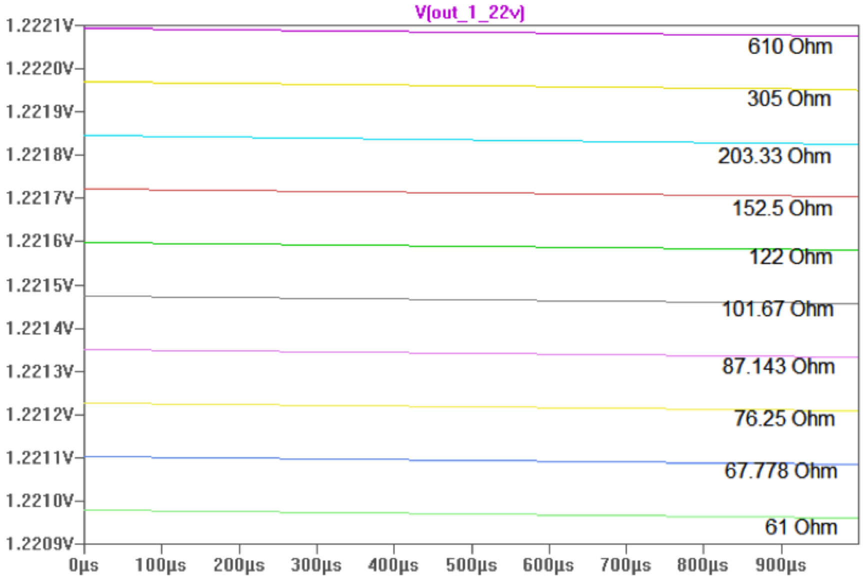


Figure 4-16: LT3014 5 V - 1.22 V LDO Simulation Waveform at $V_{IN,\ Nominal}$ = 4.993V, I_{LOAD} varying from 10% to 100% of I_{Rated} = 20mA.

Table 4-7 summarizes the output voltage, $V_{OUT\_1\_22V}$, versus the output current, I_{OUT_5V}, as the load is varied from 10% to 100%. Applying Equation 4-15 and Table 4-7, determines the 5 V - 1.22 V LDO's load regulation to be 0.08% (Equation 4-18).

$$\%\ Load\ Regulation = \frac{1.2221V - 1.2211V}{1.2211V} * 100 = 0.08\% \tag{4-18}$$

Table 4-7: LT3014 5 V - 1.22 V LDO Load Regulation Simulation Results; $V_{IN,\ Nominal}$ = 4.993V.

% Load (%)	I_{OUT_5V} (mA)	$R_{OUT\_1\_22V}$ (Ω)	$V_{OUT\_1\_22V}$ (V)
10	2	610	1.2221
20	4	305	1.222
30	6	203.33	1.2218
40	8	152.5	1.2217
50	10	122	1.2216
60	12	101.67	1.2215
70	14	87.143	1.2213
80	16	76.25	1.2212
90	18	67.778	1.2211
100	20	61	1.221

The complete DC Light Bulb's dimmer design is shown in Figure 4-17. The dimmer's worst case line and load regulations are summarized in Table 4-8.

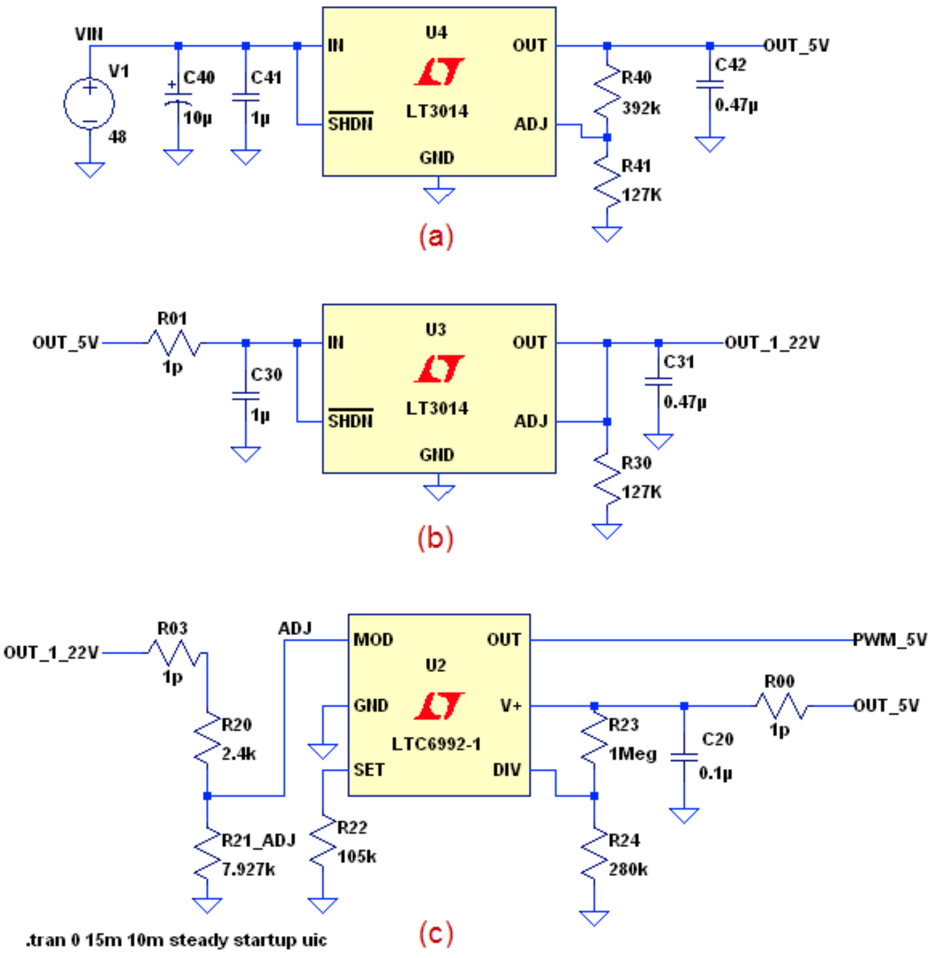


Figure 4-17: Complete Dimmer Circuit Design, (a) 48 V – 5 V LDO, (b) 5 V – 1.22 V LDO, (c) PWM Controller.

Table 4-8: Dimmer Circuit's LDO Worst Case Line and Load Regulations.

48 V - 5 V LDO	
Line Regulation @ 15% change in Vin	0.01%
Load Regulation from 10% to 90% load	0.05%
5 V - 1.22 V LDO	
Line Regulation @ 15% change in Vin	0.00%
Load Regulation from 10% to 90% load	0.08%

4.2.2: LED Array

Next, the LED array is designed and LED type is selected. As Chapter 3 suggests, one of the design requirements was to maintain the A19 dimension (Figure 3-1), which means the LED array and LED driver circuitry must fit within those parameters. After countless hours of research, it was determined to not be cost effective to design a custom light bulb housing from scratch. Custom computer aided design (CAD) and manufacturing can cost more than $1000 and should only be considered for mass production. Therefore, mechanical design of the Light Bulb is out of the scope of this thesis. As an alternative, a relatively inexpensive ($9.97) 120VAC LED light bulb made by EcoSmart (Figure 2-10) was used to house the new DC Light Bulb design. Figure 4-18 illustrates the disassembled EcoSmart light bulb housing. Figure 4-18 (b) suggests that the placement of the LEDs must fit within a circular area with a diameter less than 31 mm.

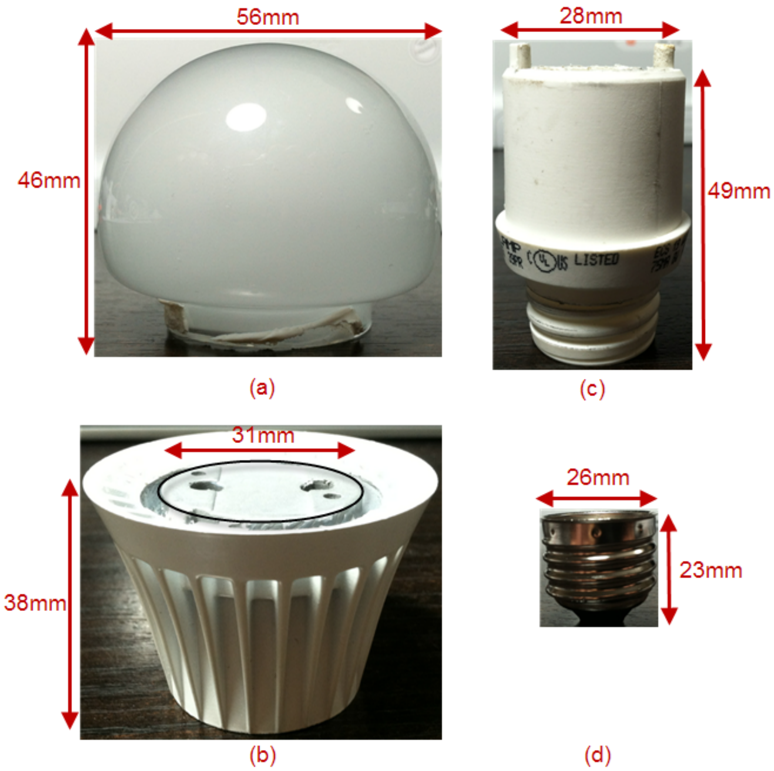
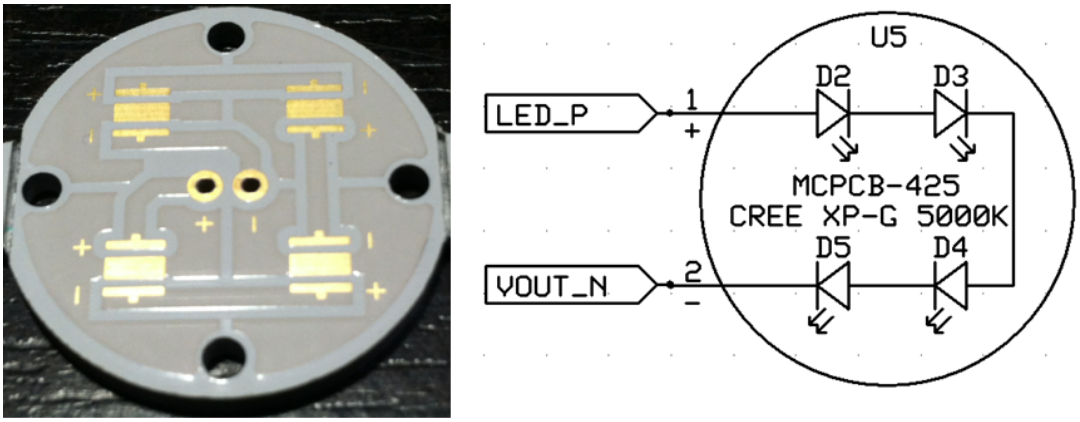


Figure 4-18: DC Light Bulb Enclosure Dimensions, (a) Light Diffuser, (b) Aluminum Heatsink, (c) Inner Sleeve for Electronics, (d) E26 Screw Base.

Metal core printed circuit boards (MCPCB) are often used for high power LED applications, because it dissipates heat better. A 25 mm custom MCPCB designed for CREE XPE/XPC/XPG series LEDs was chosen to meet the space requirement indicated in Figure 4-18 (b) [56]. Figure 4-19 illustrates the (a) physical 25 mm MCPCB design and (b) 4 CREE XPG LEDs in series configuration.



(a) (b)

Figure 4-19: 25 mm MCPCB for 4 CREE XPG LEDs in Series, (a) Physical Design, (b) Schematic Design.

CREE's high power XPG (XPGWHT-01-R250-00GC1) LED with a cool white (5000K) color temperature was selected. This LED was chosen because it offers great luminous efficacy of 110 lumens/watt. Note this closely follows the projected Lm/W for the year 2010, as suggested in Figure 2-15. This particular CREE LED was also chosen because it is rated up to 1.5 A at a forward voltage of 3.25 V. With this in mined, the DC Light Bulb was selected to operate at 1 A with a forward voltage of 3.15 V so that it can produce 110 lumens/watt. Figure 4-20 illustrates CREE XPG LED's forward current versus forward voltage characteristic at a junction temperature of 25 ºC. The estimated total output power for 4 LEDs in series is then calculated to be 12.6 W (Equation 4-19).

$$P_{OUT} = 4 * V_F * I_F = 4 * 3.15\ V * 1\ A = 12.6\ W \tag{4-19}$$

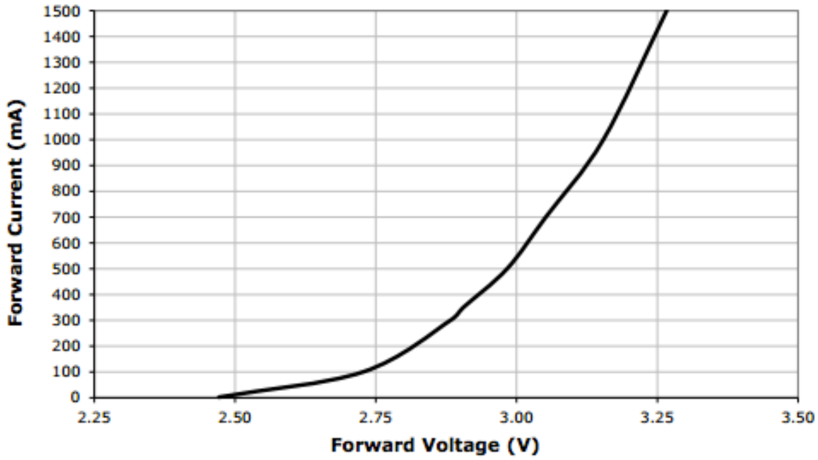


Figure 4-20: CREE XPG LED's Forward Current Vs. Voltage Characteristics [58].

Figure 4-21 suggests that driving the LED array at 1 A, maximum ambient temperature of about 110 ºC should not be exceeded. Chapter 5 will cover the physical thermal response of the DC Light Bulb operating from 0 hour to 12 hour at 30 minute increments.

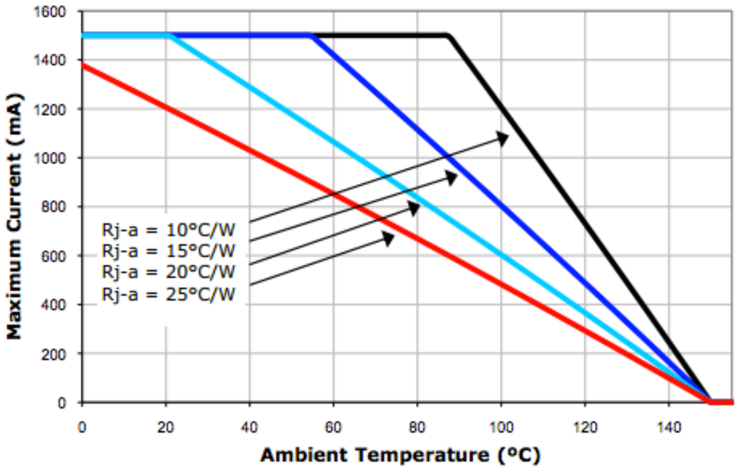


Figure 4-21:CREE XPG Cool White (5000K) Forward Current vs. Ambient Temperature [58].

4.2.3: LED Driver

In the following section, the DC Light Bulb’s LED driver circuit will be designed and simulated. Linear Technology’s LT3756-2, LED controller was selected to meet the 1 A output with PWM dimming capabilities. LT3756-2 offers a wide input voltage range of 6 V – 100 V, 3000:1 PWM dimming ratio, and can drive LEDs in a Buck, Boost, Buck-Boost, SEPIC, or Flyback topology [57]. This LED driver offers great versatility and flexibility to meet the wide power requirements in different lumination applications. As suggested in section 4.2.1, four CREE XPG LEDs in series would require 12.6 V at full load of 1 A. Therefore a Buck mode configuration was chosen for the LED driver’s output stage. Figure 4-22 suggests the final LED driver design for the DC Light Bulb.

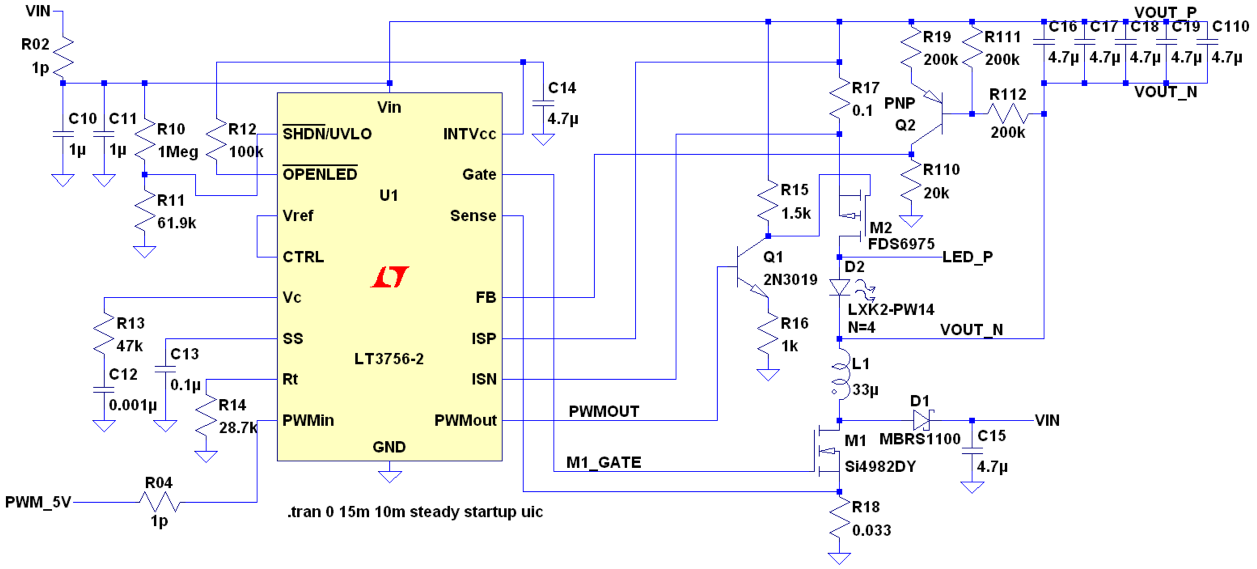


Figure 4-22: LED Driver Schematic in Buck Mode operating at 1 A Full Load.

The VIN pin is tied directly to DC House's main 48 VDC bus voltage. PWMin pin is connected to the PWM controller, LTC6992-1, suggested in Figure 4-17 (c). PWMout produces a high logic of 7.15 V when PWMin sees more than 1.5 V and PWMout produces a low logic of 0 V when PWMin sees less than 0.4 V at the PWMin pin. Figure 4-23 illustrates the input (PWMin) and output (PWMout) effects when a PWM signal is applied to the LED driver at duty cycles of 0%, 28.086%, 50.07%, and 93.176%. As the duty cycle increases, the time, t_{ON} stays on for a longer duration, while the switching frequency remains fixed at 7.5 kHz (defined by PWM controller settings and calculated in Equation 4-3).

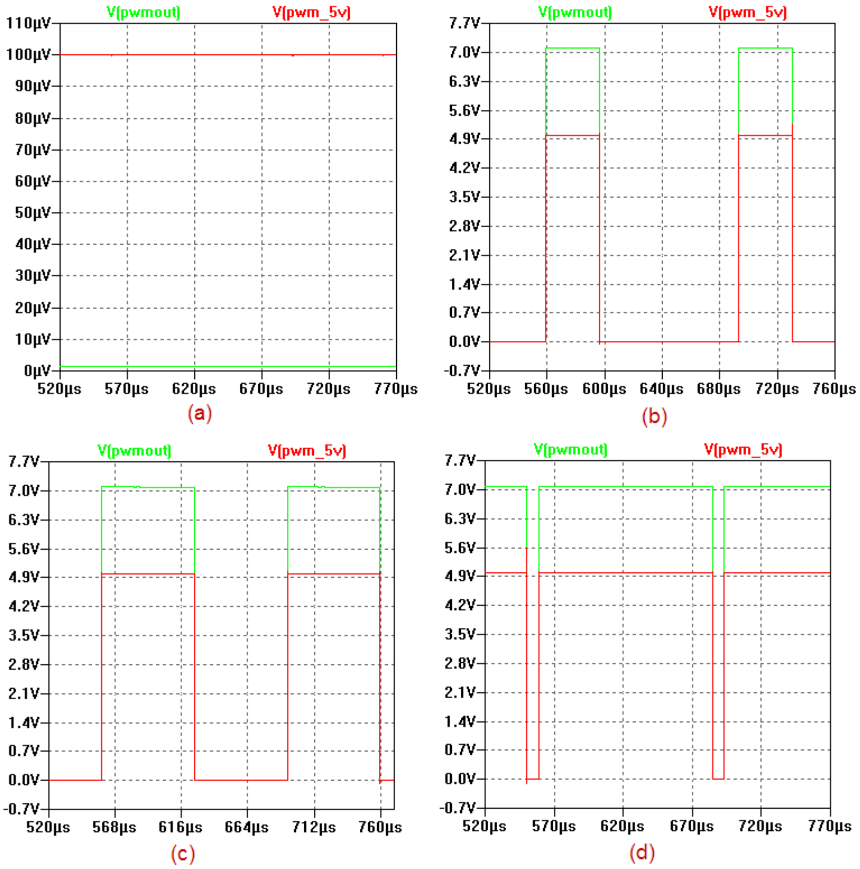


Figure 4-23: V(PWM_5V) vs. V(PWMOUT) For (a) D = 0%, (b) D = 28.086%, (c) D = 50.07%, (d) D = 93.176%.

Next, the Buck mode output stage of the LED driver will be analyzed and validated through LTspice simulations for V(PWMOUT) versus V(M1 gate), V(M2 gate), I(LED), and I(L1) relationship at various duty cycles. Figure 4-24 illustrates V(PWMOUT) versus V(M1 gate) for duty cycles of 0%, 28.086%, 50.07%, and 93.176%.

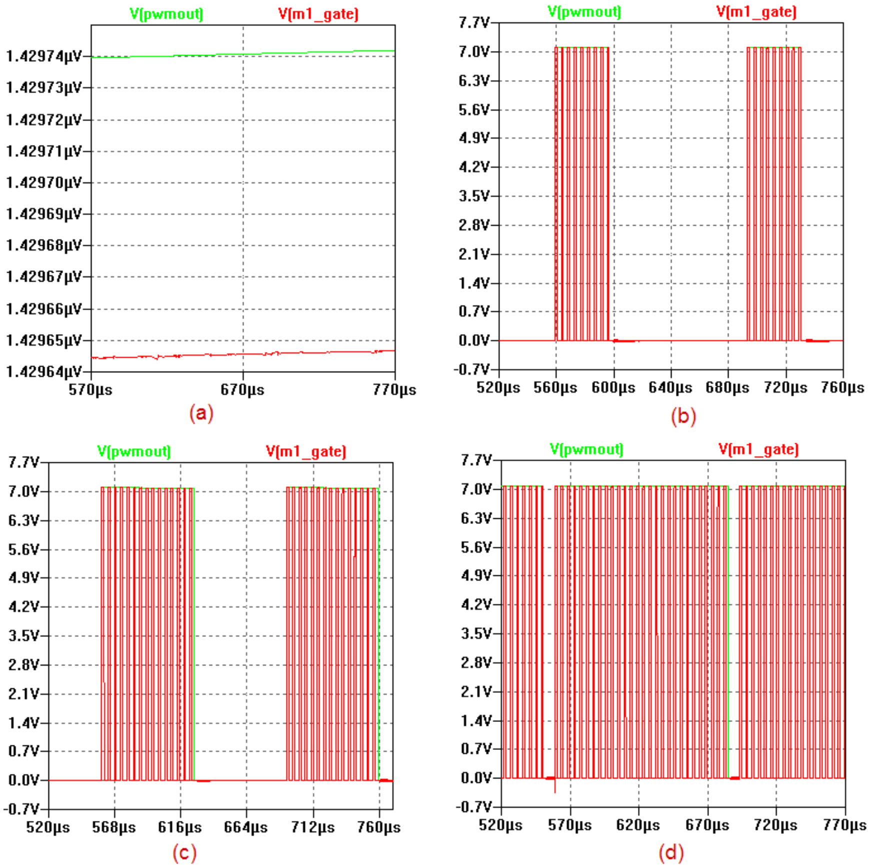


Figure 4-24: V(PWMOUT) vs. V(M1 Gate) For (a) D = 0%, (b) D = 28.086%, (c) D = 50.07%, (d) D = 93.176%.

M1 gate represents the LT3756-2's GATE pin. The GATE pin pulses the (M1) N-channel MOSFET on and off according to the current sense control loop seen by the SENSE pin. This current sense control loop also interacts with the voltage feedback loop seen at the FB pin and the differential voltage between ISP and ISN to ensure it does not exceed the internal 2 V threshold voltage set by the CTRL pin [57]. Through both the current and voltage control loops, constant current of roughly 1 A is maintained across the LED array. Figure 4-24 also suggests that the GATE only pulsates within the duty cycle duration set by the PWM signal supplied by LTC6992-1 PWM controller. Next, V(PWMOUT) versus V(M2 Gate) relationship is compared and analyzed through Figure 4-25.

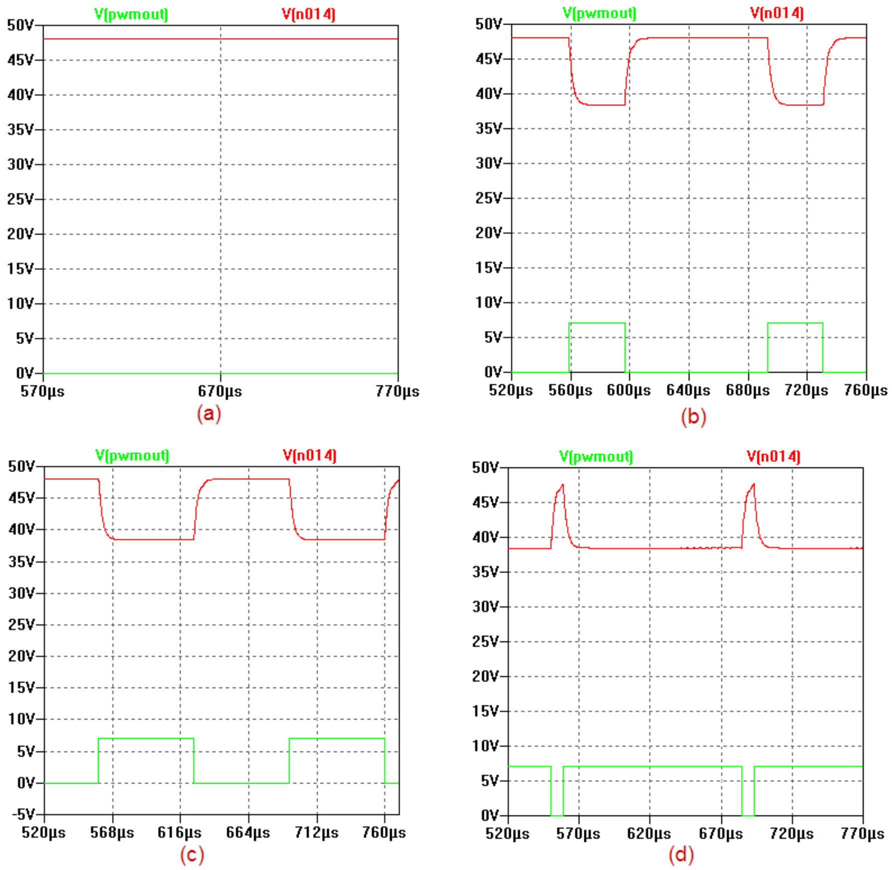


Figure 4-25: V(PWMOUT) vs. V(M2 Gate) For (a) D = 0%, (b) D = 28.086%, (c) D = 50.07%, (d) D = 93.176%.

M2 (n014) is a P-channel MOSFET that turns on when it sees a logic low signal (in this case 38V). When the (Q1) NPN BJT sees a logic low (0V) from the PWMOUT pin, it does not turn on and M2 gate is maintained at 48 V. When Q1 receives a logic high (7V) across its base terminal, it turns on and connects roughly 38 V to ground. Now M2's gate terminal sees a voltage decrease of 10 V when referenced to 48 V, thus a logic low occurs and M2 turns on. When M2 turns on it completes the path of current flow through the LED array. The use of a P-channel MOSFET is smart, because it eliminates the need of a high power MOSFET to handle its high current switching.

Next, V(PWMOUT) versus I(L1) and V(PWMOUT) versus I(LED) are reviewed and its simulation waveforms at various duty cycles are shown in Figure 4-26 and Figure 4-27, respectfully. LT3756-2 internal error amplifier sets the correct peak switch current seen by the inductor (L1) to maintain the LED current in regulation [57]. When the error amplifiers output increases, it means that the switch requires more current. If the error amplifier output signal decreases, it means the switch demands less current. The current control loop through the SENSE pin monitors that the current limit threshold voltage of 108 mV is not exceeded [57].

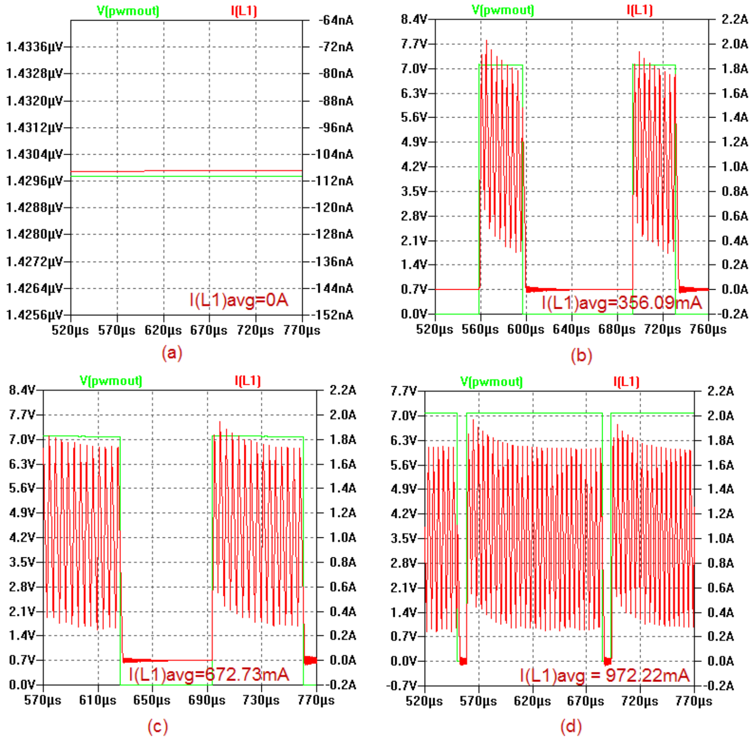


Figure 4-26: V(PWMOUT) vs. I(L1) For (a) D = 0%, (b) D = 28.086%, (c) D = 50.07%, (d) D = 93.176%.

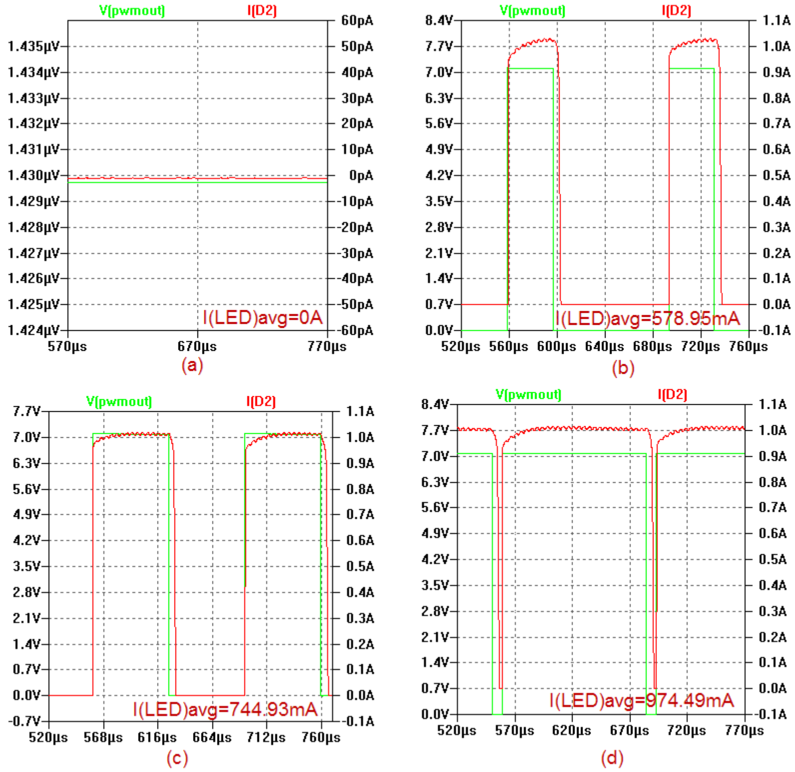


Figure 4-27: V(PWMOUT) vs. I(LED) For (a) D = 0%, (b) D = 28.086%, (c) D = 50.07%, (d) D = 93.176%.

4.3 : Summary of DC Light Bulb Design

The complete DC Light Bulb design and simulation results are summarized in Table 4-9. The DC Light Bulb was simulated to operate at input voltages from 24 V to 72 V. In order for it to work at 12 V, the output Buck Mode components must be recalculated and resized. Despite not meeting the suggested design goal of being a truly universal light bulb, it satisfies the required target constraints for the DC House project. Figure 4-28 illustrates the complete DC Light Bulb design schematic. Table 4-10 summarizes the simulation data collected. Figure 4-29 illustrates the DC Light Bulb's simulation efficiency versus varying LED load.

Table 4-9: DC Light Bulb Design and Simulation Results.

Parameters	Specifications
Wide Input Voltage Range (Simulated): VIN	24 V to 72 V
Output Voltage in Buck Mode: V(LED)	0 V to 25 V
PWM Dimming via 10 kΩ Potentiometer: Duty Cycle	0 % to 100 %
Efficiency at Full Load	*91.34%
Total Power Consumption	*14.85 W
LED Type	CREE XLAMP XP-G XPGWHT-01-R250-00GC1
Number of LEDs in Series	4
Color Temperature	Cool White (5000K)
Luminous Efficacy	110.48 Lumens/Watt
Luminous Flux at 1 A	348 Lumens
Max Forward Voltage	3.25 V
Max Forward Current	1.5 A
Max Temperature Recommended at Forward Current of 1A	110 ºC
Max LED Junction Temperature	150 ºC
Line Regulation at 15% Input Voltage Swing	0.01%
LDO Load Regulation from 10% to 90% Load	0.08%
Constant Current Regulation	Yes
Constant Voltage Regulation	Yes
Open LED Protection	Yes
*Simulated Results using LXK2-PW14 LED (x4)	

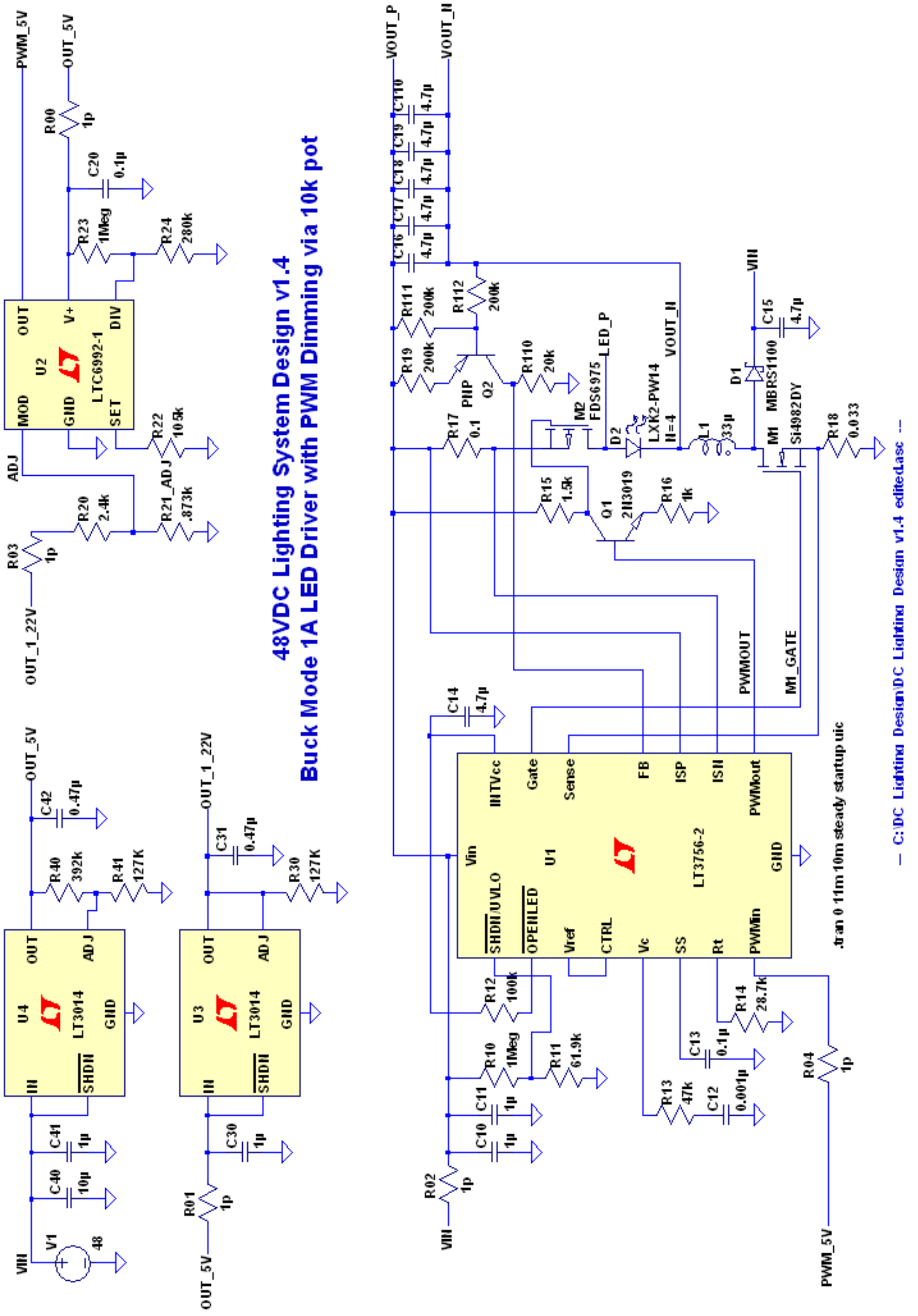


Figure 4-28: Complete DC Light Bulb Design Schematic.

Table 4-10: DC Light Bulb Simulation Data.

Duty Cycle %	PWMOUT f_{SW} (kHz)	R21_ADJ (kΩ)	ADJ (V)	Steady State Pin (W)	Steady State I(D2)avg (mA)	LED V_{OUT} (V)	Steady State LED Pout (W)	Efficiency (%)
0.000%	7.500	0.000	0.000	0.054	0.000	0.000	0.000	0.000%
0.000%	7.500	0.133	0.064	0.081	0.000	0.000	0.000	0.000%
6.606%	7.434	0.341	0.152	2.777	195.340	12.797	2.420	87.144%
17.409%	7.443	0.584	0.239	7.134	468.260	13.863	6.355	89.072%
28.086%	7.442	0.873	0.326	9.066	578.950	14.206	8.105	89.394%
39.616%	7.384	1.230	0.414	10.776	678.330	14.498	9.711	90.113%
50.070%	7.440	1.668	0.501	11.965	744.930	14.668	10.808	90.330%
58.827%	7.193	2.226	0.588	12.862	796.630	14.785	11.666	90.701%
67.938%	7.384	2.971	0.676	14.314	876.800	15.003	12.998	90.806%
82.743%	7.439	3.990	0.763	15.256	933.340	15.133	13.962	91.518%
93.176%	7.420	5.484	0.850	16.051	974.490	15.204	14.679	91.452%
100.000%	7.500	7.927	0.938	16.258	984.250	15.215	14.850	91.340%
100.000%	7.500	12.047	1.019	16.339	984.160	15.216	14.849	90.881%

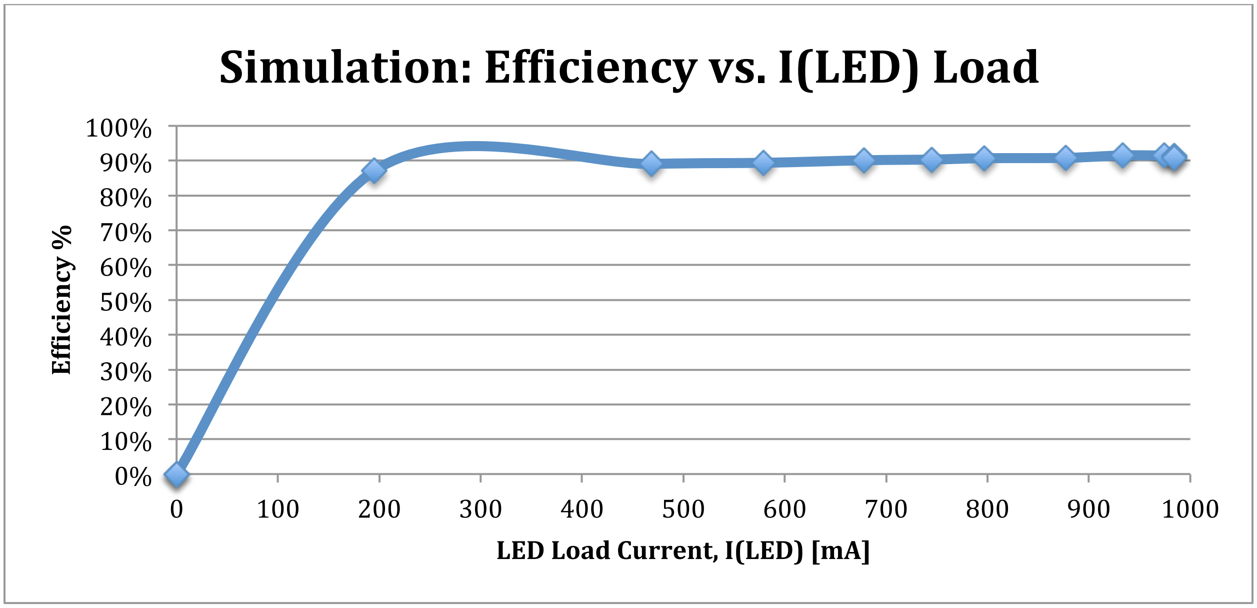


Figure 4-29: DC Light Bulb Simulation: Efficiency vs. I(LED).

Chapter 5: Hardware Design and Results

In this chapter, the DC Light Bulb's hardware design, implementation, and testing are reviewed. First, the design of a custom 4-layer PCB layout will be described. Next, the LED array and heatsink implementation will be covered. Then, laboratory test setups for efficiency, line regulation, lumination, and thermal measurements are evaluated. Lastly, the DC Light Bulb's hardware characteristics and electrical specifications are summarized and compared with the simulation data presented in Chapter 4.

5.1 : Custom 4-Layer PCB Layout Design

The design of the DC Light Bulb's custom 4-layer PCB involves a two-step process. First, a new schematic was created (based on the design generated in LTspice, Figure 4-28) using ExpressSCH (Figure 5-1). Then, this new schematic was used in aiding the component pad sizing and routing of the signal traces using ExpressPCB [60]. Linking the ExpressSCH schematic to the ExpressPCB layout file helps the designer by highlighting the pins that should be connected together, thus reducing the chance of incorrect routing of the signal traces. The DC Light Bulb's custom 4-layer layout design is shown in Figure 5-2.

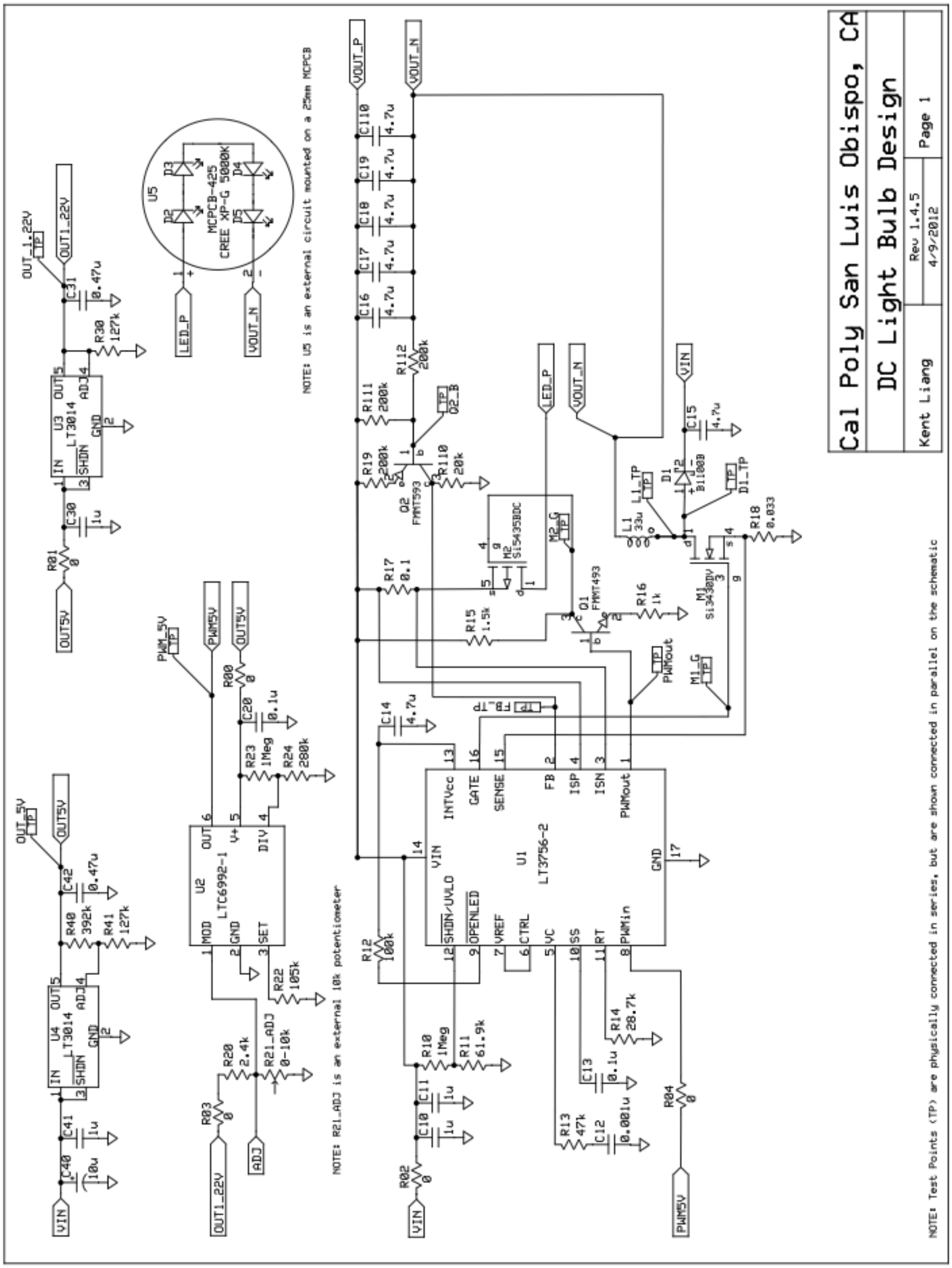
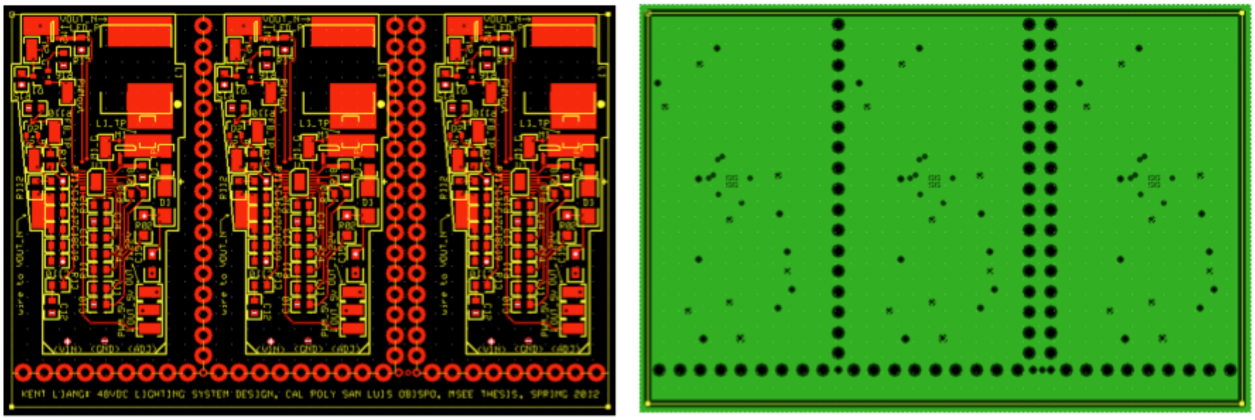
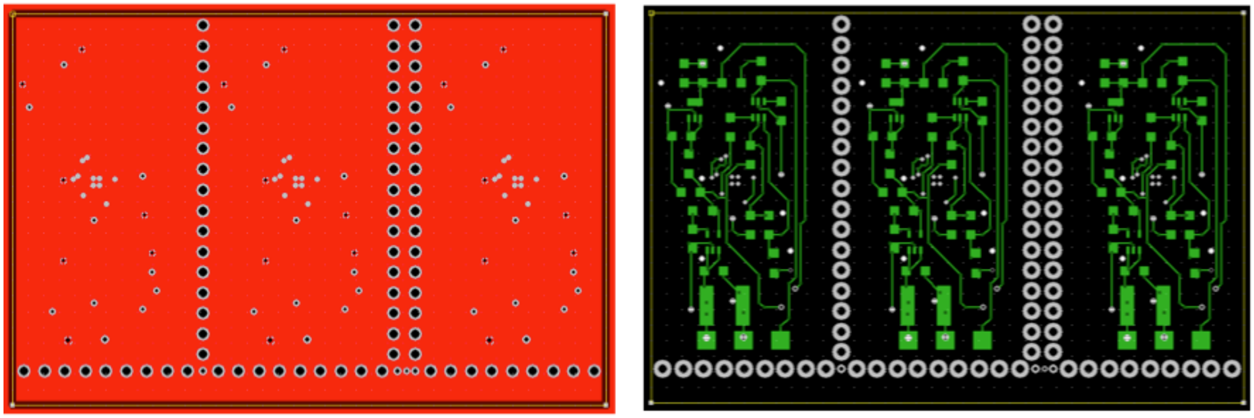


Figure 5-1: ExpressSCH – DC Light Bulb Schematic Design.



(a) 1st Layer: Top Signal Plane

(b) 2nd Layer: Inner Ground Plane

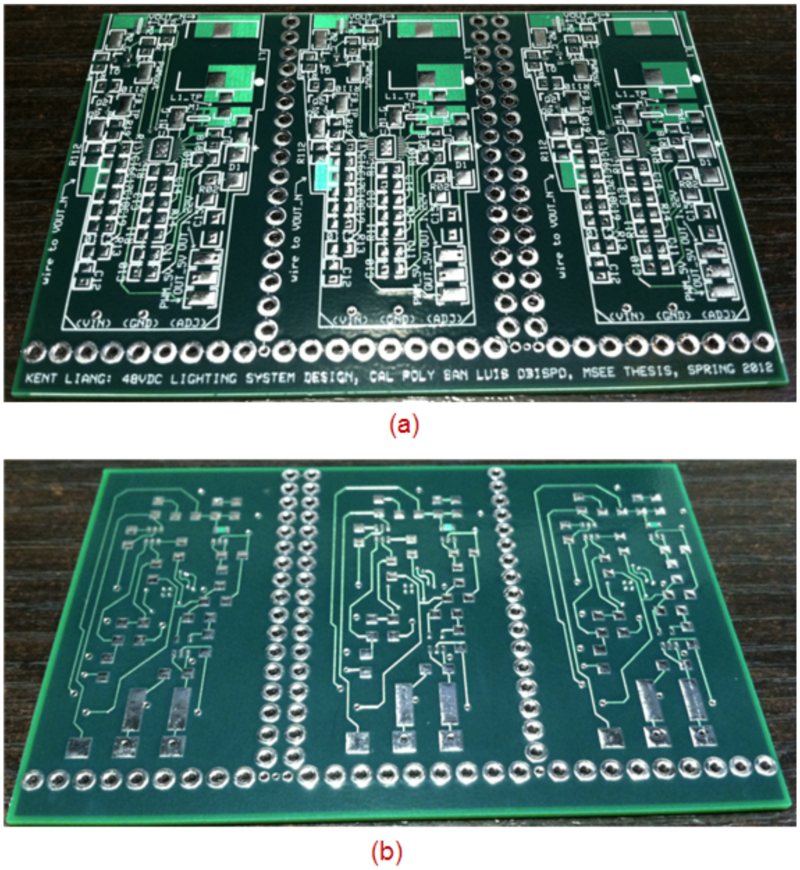


(c) 3rd Layer: Inner Power Plane

(d) 4th Layer: Bottom Signal Plane

Figure 5-2: ExpressPCB – 4-Layer PCB Layout Design, (a) Top Signal Plane, (b) Inner Ground Plane, (c) Inner Power Plane, (d) Bottom Signal Plane.

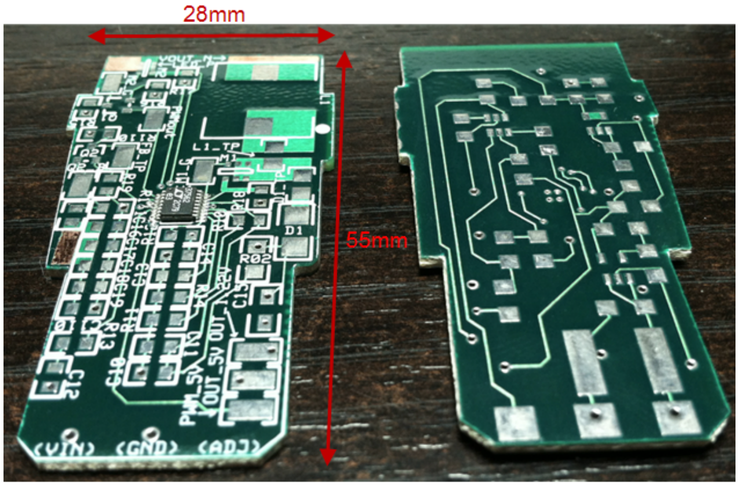
Figure 5-2 (a) illustrates the top signal plane. Referring to Figure 5-1, the high power Buck Mode output stage is specifically grouped together and placed on the top half of the 1st layer. Since the Buck Mode output stage supplies constant 1 A into the LED array, it would generate more heat and more noise due to the switching elements (in particular the MOSFETs M1, M2, and inductor L1). The LED driver chip (LT3756-2) and associated circuit resistors and capacitors are placed on the bottom half of the 1st layer. Figure 5-2 (b) and (c) illustrates the inner ground and inner power planes, respectfully. Having a solid ground plane instead of individual ground islands offer greater immunity to noise and electromagnetic coupling caused by high frequency switching and unbalanced ground loops. Due to the complexity of the DC Light Bulb's circuitry, having a dedicated power and ground plane reduces the routing required for 48 VDC (power plane) and ground traces. Lastly, Figure 5-2 (d) illustrates the bottom signal layer, where the dimmer circuitry (in particular the two LT3014 LDOs and LT6992-1 PWM controller and their associated resistors and capacitors) is placed. Figure 5-3 illustrates the finished 3.8 x 2.5 inch custom 4-layer PCB layout (also called MiniBoardPro by ExpressPCB) after manufacturing.



(a)

(b)

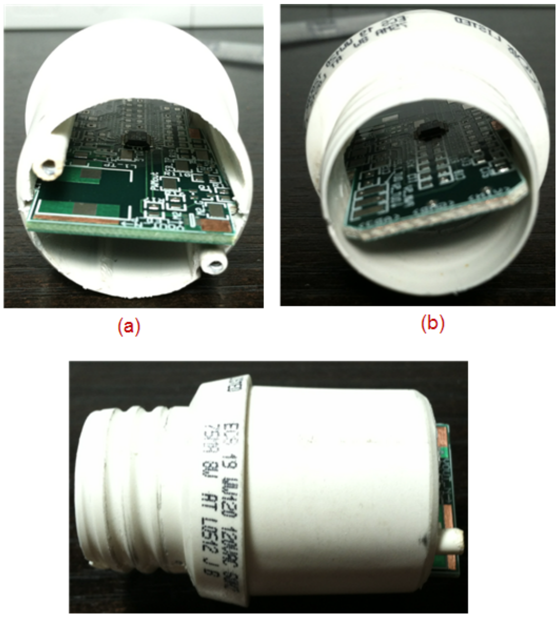
Figure 5-3: DC Light Bulb Custom 4-Layer PCB Layout After Manufacturing, (a) Top Layer, (b) Bottom Layer.



(a) (b)

Figure 5-4: DC Light Bulb Custom 4-Layer PCV After Being Cut to Size, (a) Top Layer, (b) Bottom Layer.

Figure 5-4 illustrates the DC Light Bulb's custom PCB after being cut to size. This PCB is roughly 56 mm x 28 mm in size. It was specifically sized this particular way because it is like a key that is required to fit into the inner light bulb sleeve. Figure 5-5 illustrates the custom PCB fitted into the light bulb's enclosure.



(a) (b)

(c)

Figure 5-5: Custom PCB Fitted into Inner Sleeve, (a) Top View, (b) Bottom View, (c) Side View.

Figure 5-6 illustrates the first DC Light Bulb prototype that has been populated with components and ready for testing. Note a current clamp probe was placed between the black loop wire to measure the current flowing through the inductor, L1. The red and white wires on the left side of Figure 5-6 supplies a differential voltage to power the LED array.

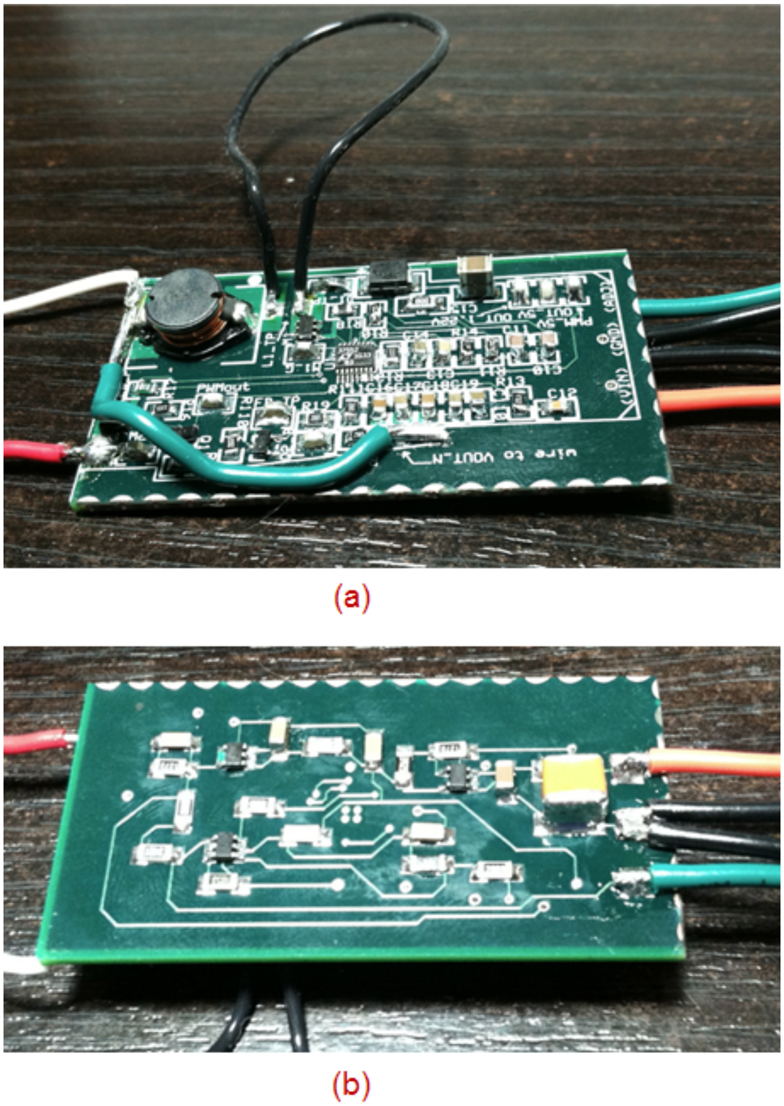


Figure 5-6: Custom PCB Populated With Components and Ready For Testing, (a) Top Signal Plane, (b) Bottom Signal Plan.

5.2 : LED Array and Heatsink Design

As suggested in Figure 4-29 and 4-19, the size of the LED array must fit into a circular area with a diameter less than 31 mm. A custom 25 mm MCPCB made by Cutter Electronics was used to mount four CREE XPG high power LEDs in a series configuration. A two part white color paste called Arctic Alumina was used between the MCPCB and the aluminum heatsink to provide a permanent thermal conductive bond. Figure 5-7 illustrates the physical mounting of the CREE XPG LEDs to the custom MCPCB and to the aluminum heatsink.

(a) (b)

Figure 5-7: CREE XPG LEDs Mounted on Aluminum Heatsink, (a) Top View, (b) Side View.

5.3 : Efficiency and Line Regulation Testing

5.3.1: Hardware Setup

Figure 5-8 illustrates the laboratory setup used during the DC Light Bulb's efficiency and line regulation testing. Table 5-1 lists the equipment used for data measurements.

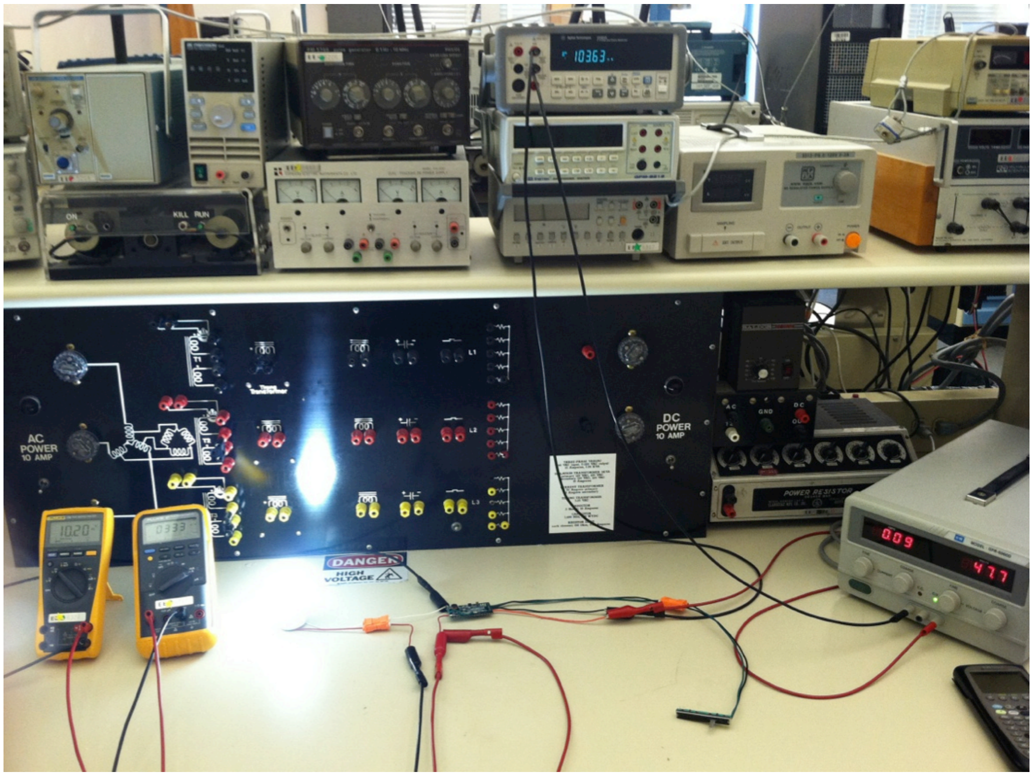


Figure 5-8: Setup for Efficiency and Line Regulation Testing.

Table 5-1: Equipment Used for Efficiency and Line Regulation.

Purpose	Equipment	Manufacture	Model
V_{IN}	DC Power Supply	GW	GPR-6060D
I_{IN}	Multimeter	Agilent Technologies	U341A
V_{OUT}	Multimeter	Fluke	179
I_{OUT}	Multimeter	Fluke	87
Duty Cycle	Oscilloscope	GW	Instek GDS-2204

5.3.2: Test Results

The DC Light Bulb was tested to evaluate its efficiency at incrementing load steps. The LED's brightness (load) levels were varied at 10 mA steps changes in input current (I_{IN}). A 10 kΩ slide potentiometer in the dimmer circuit was used to vary the PWM signal into the LED driver, thus changing the output load (brightness intensity) of the LED array. Table 5-2 summarizes the data collected and Figure 5-9 illustrates that efficiency increases at higher load currents. Note, duty cycle was measured using oscilloscope connected to the PWMOUT pin of LT3756-2. At full load (duty cycle = 100% or when the slide potentiometer is position all the way up) an efficiency of 85.631% was achieved. The hardware efficiency at full load produces a 6.25% difference compared to the simulated efficiency of 91.34% at full load, as suggested in Figure 4-10, and Equation 5-1 and 5-2.

Table 5-2: Efficiency Data Measurements.

Duty Cycle %	V_{IN} (V)	I_{IN} (mA)	P_{IN} (W)	V_{OUT}(V)	LED I_{OUT}(mA)	Pout (W)	Efficiency (%)
0.000	48.000	2.167	0.104	0.430	0.000	0.000	0.000%
2.970	48.000	10.675	0.512	9.160	27.000	0.247	48.267%
5.980	48.000	19.670	0.944	9.270	56.000	0.519	54.982%
8.870	48.000	29.194	1.401	9.370	85.000	0.796	56.836%
11.950	48.000	39.210	1.882	9.480	119.000	1.128	59.940%
14.930	48.000	50.430	2.421	9.590	156.000	1.496	61.803%
19.370	48.000	60.280	2.893	9.700	189.000	1.833	63.361%
22.380	48.000	69.920	3.356	9.760	222.000	2.167	64.559%
25.370	48.000	79.250	3.804	9.810	255.000	2.502	65.761%
28.330	48.000	90.220	4.331	9.920	293.000	2.907	67.117%
32.790	48.000	99.940	4.797	10.030	327.000	3.280	68.370%
35.840	48.000	110.680	5.313	10.130	364.000	3.687	69.407%
40.310	48.000	120.470	5.783	10.230	399.000	4.082	70.588%
43.270	48.000	130.130	6.246	10.330	432.000	4.463	71.444%
46.260	48.000	139.230	6.683	10.410	465.000	4.841	72.432%
50.730	48.000	149.970	7.199	10.510	503.000	5.287	73.439%
55.240	48.000	160.220	7.691	10.600	540.000	5.724	74.429%
57.310	48.000	170.230	8.171	10.690	577.000	6.168	75.488%
60.330	48.000	180.070	8.643	10.780	612.000	6.597	76.329%
64.740	48.000	190.360	9.137	10.880	650.000	7.072	77.397%
67.640	48.000	200.110	9.605	10.960	686.000	7.519	78.275%
72.100	48.000	210.640	10.111	11.060	724.000	8.007	79.198%
76.120	48.000	220.120	10.566	11.140	759.000	8.455	80.025%
80.610	48.000	230.210	11.050	11.230	792.000	8.894	80.490%
83.940	48.000	240.530	11.545	11.320	831.000	9.407	81.477%
88.040	48.000	250.430	12.021	11.400	867.000	9.884	82.224%
91.190	48.000	259.800	12.470	11.470	902.000	10.346	82.964%
95.520	48.000	269.840	12.952	11.550	940.000	10.857	83.823%
100.000	48.000	280.330	13.456	11.600	993.000	11.519	85.604%
100.000	48.000	280.000	13.440	11.590	993.000	11.509	85.631%

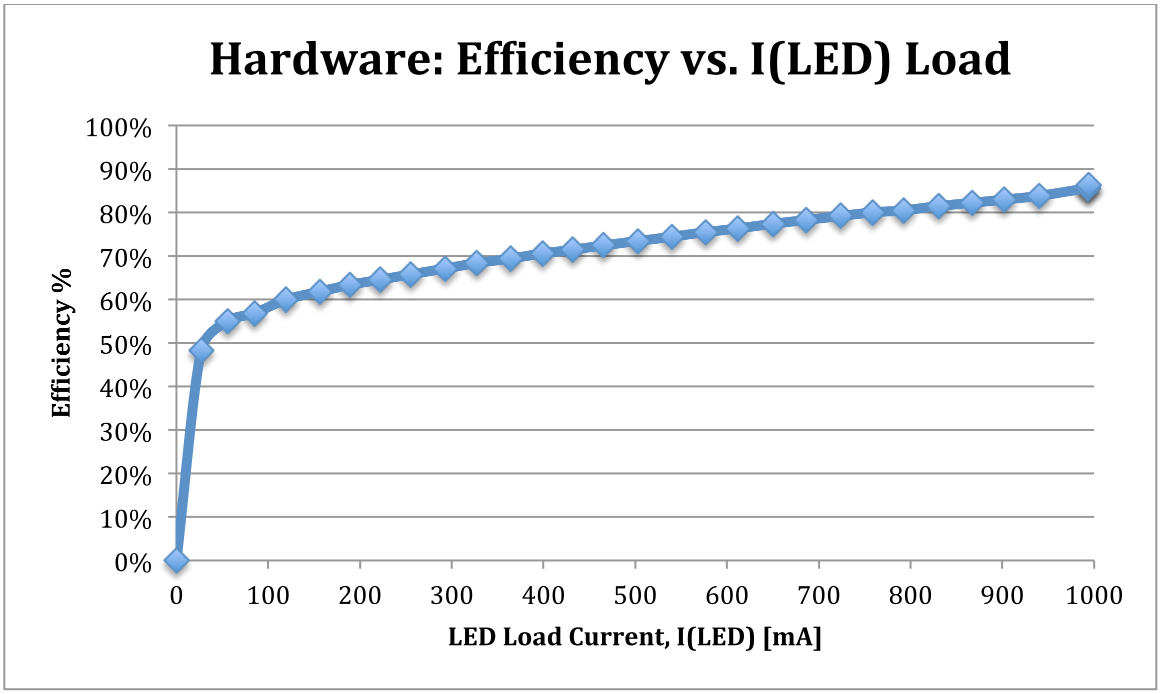


Figure 5-9: Hardware: Efficiency vs. Varying Output LED Load, I(LED).

$$\% \, Difference = \left| \frac{X_{simulated} - X_{measured}}{X_{simulated}} \right| * 100\% \qquad (5\text{-}1)$$

$$\% \, Difference = \left| \frac{91.34\% - 85.631\%}{91.34\%} \right| * 100\% = 6.25\% \qquad (5\text{-}2)$$

Next, the DC Light Bulb's line regulation was tested at ±5% to ±31% (roughly 5% increments) swing in input voltages to test its ability to maintain constant output voltage across the LED array. Line regulation was calculated using Equation 4-14. A worst-case line regulation of 2.53% occurred when the input voltage varied ±20%. Possible causes in line regulation deviation may be due to a slow feedback response in the LED driver (LT3756-2) or the DC Light Bulb was not in steady state when the data measurements were recorded. In the next section, the DC Light Bulb's circuit functionality is verified.

Table 5-3: Hardware: Line Regulation Measurements at Full Load.

% of $V_{IN, Nominal}$	$V_{IN, Nominal}$ (V)	$V_{OUT, Nominal}$ (V)	$V_{IN, Min}$ (V)	$V_{IN, Max}$ (V)	$V_{OUT, low input}$ (V)	$V_{OUT, high input}$ (V)	$I_{OUT, RATED}$ (mA)	% Line Regulation (%)
5%	48.00	13.44	45.60	50.40	11.71	11.68	993	0.223
10%	48.00	13.44	43.20	52.80	11.74	11.66	993	0.595
15%	48.00	13.44	40.80	55.20	11.86	11.64	993	1.637
20%	48.00	13.44	38.40	57.60	11.97	11.63	993	2.530
25%	48.00	13.44	36.00	60.00	11.47	11.47	993	0.000
31%	48.00	13.44	33.00	63.00	11.49	11.52	993	0.223

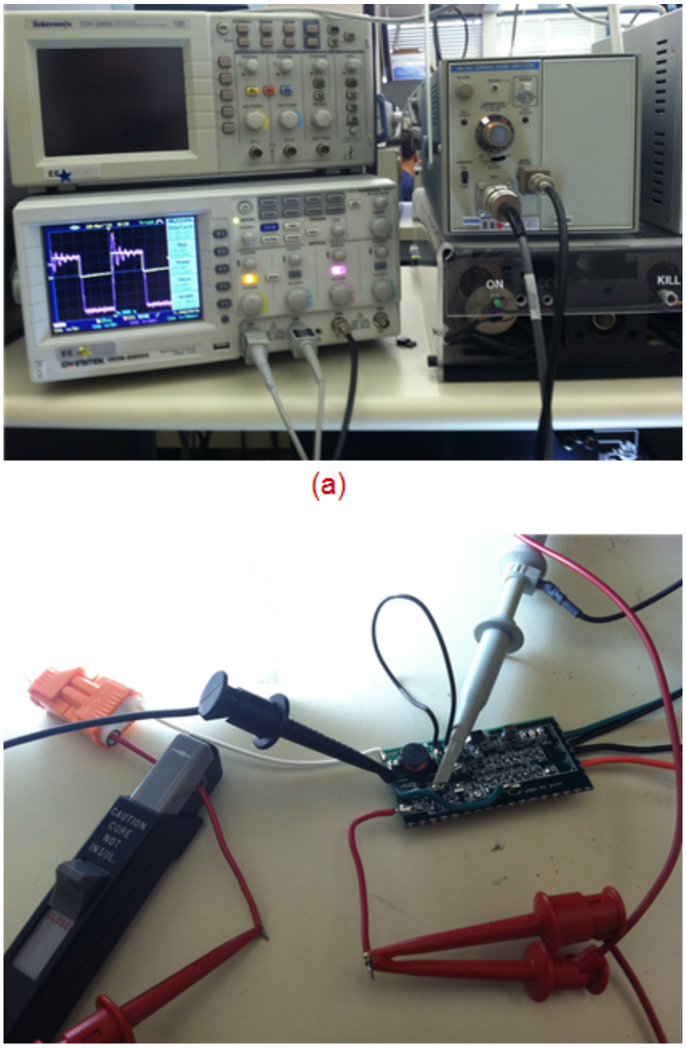
5.4 : Circuit Functionality Verification

5.4.1: Hardware Setup

Figure 5-10 illustrates the laboratory test setup used to verify the DC Light Bulb's circuit functionalities. A voltage scope probe is used to measure the PWM signal at PWMOUT pin of the LED driver. Another voltage scope probe is used to measure voltage at M1 and M2 MOSFET gate nodes. A current clamp probe is used to measure current through the LED and L1 inductor. The current clamp probe is connected to an AM 503 Current Probe Amplifier that converts the current to a voltage signal read on the oscilloscope. Table 5-4 summarizes the equipment used for the circuit functionality tests.

Table 5-4: Equipment used for Hardware Circuit Functionality Verification.

Purpose	Equipment	Manufacture	Model
V_{IN}	DC Power Supply	GW	GPR-6060D
I_{IN}	Multimeter	Agilent Technologies	U341A
Current to Voltage Converter.	Current Probe Amplifier	Tektronix	AM 503
V_{OUT}, I_{OUT}, Duty Cycle	Oscilloscope	GW	Instek GDS-2204



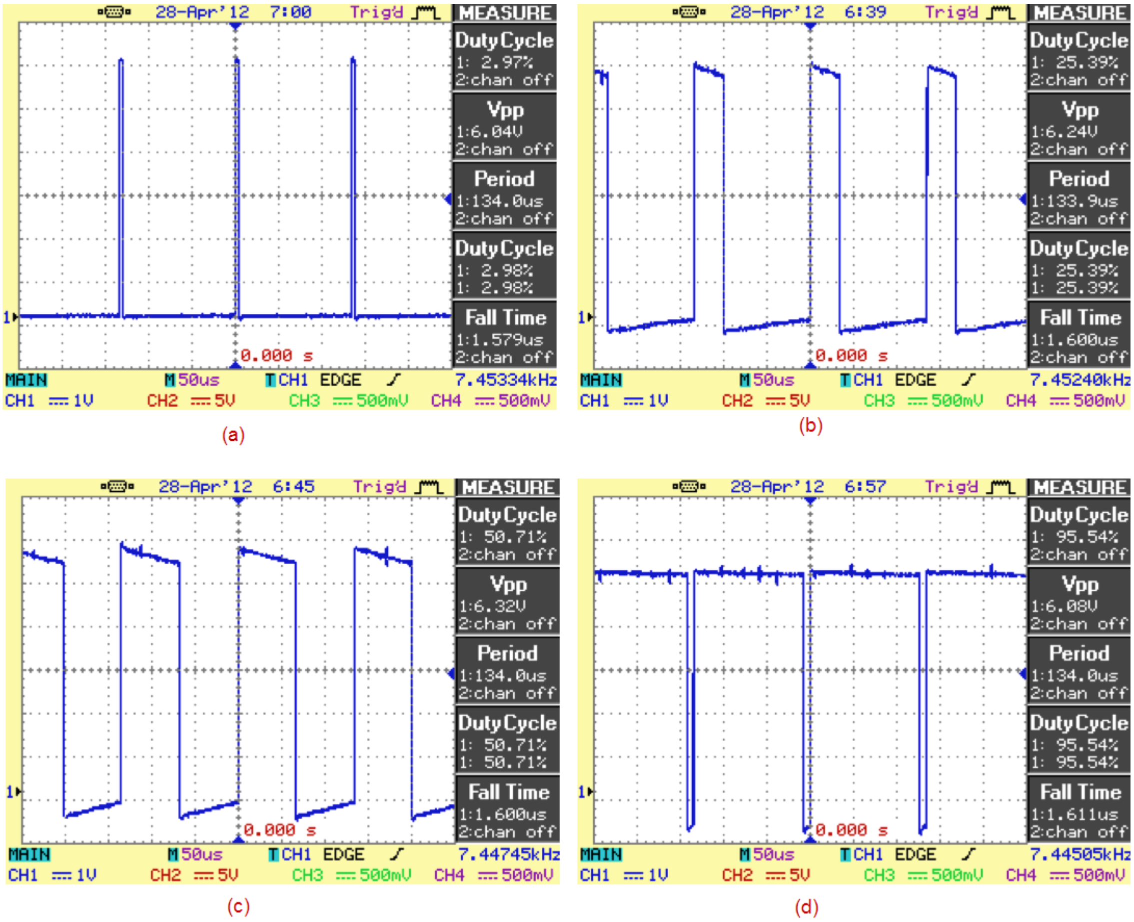
(a)

(b)

Figure 5-10: Setup for Circuit Functionality Verification, (a) Oscilloscope and Current Probe Amplifier for Waveform Measurements, (b) Current and Scope Probe Connections.

5.4.2: Hardware Results

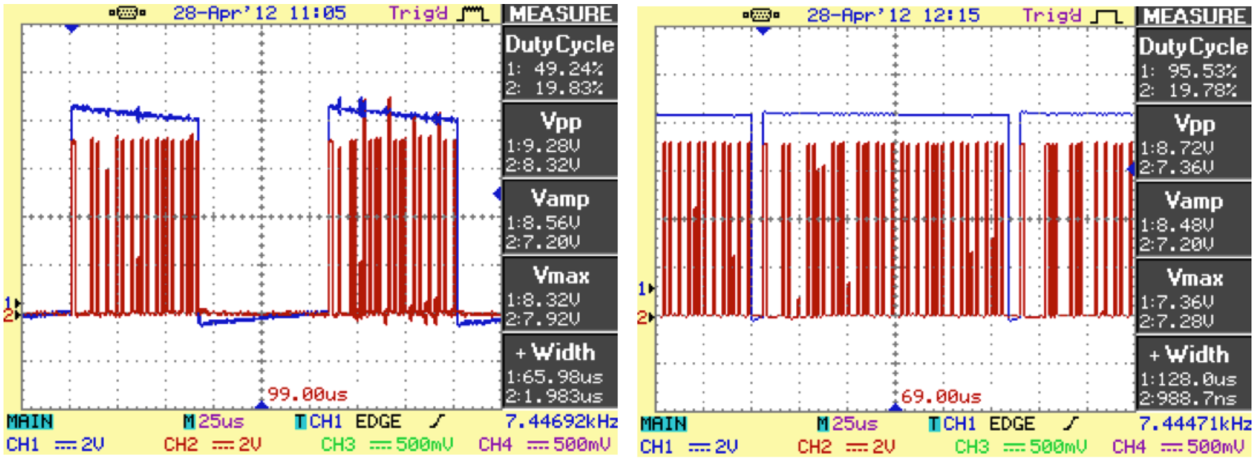
The first test performed was to make sure the PWM signal generated at the PWM5V (referring to Figure 5-1) pin of the PWM controller was indeed working properly. Figure 5-11 validates that as the 10 kΩ slide potentiometer is varied a resulting change in PWM signal is generated. Figure 5-11 illustrates PWM signals for duty cycles at 2.97%, 25.39%, 50.71%, and 95.54%. Note, that when the variable potentiometer is at full 10 kΩ it indeed produced a duty cycle of 100%.



(a) (b) (c) (d)

Figure 5-11: V(PWM_5V) For (a) D = 2.97%, (b) D = 25.39%, (c) D = 50.71%, (d) D = 95.54%.

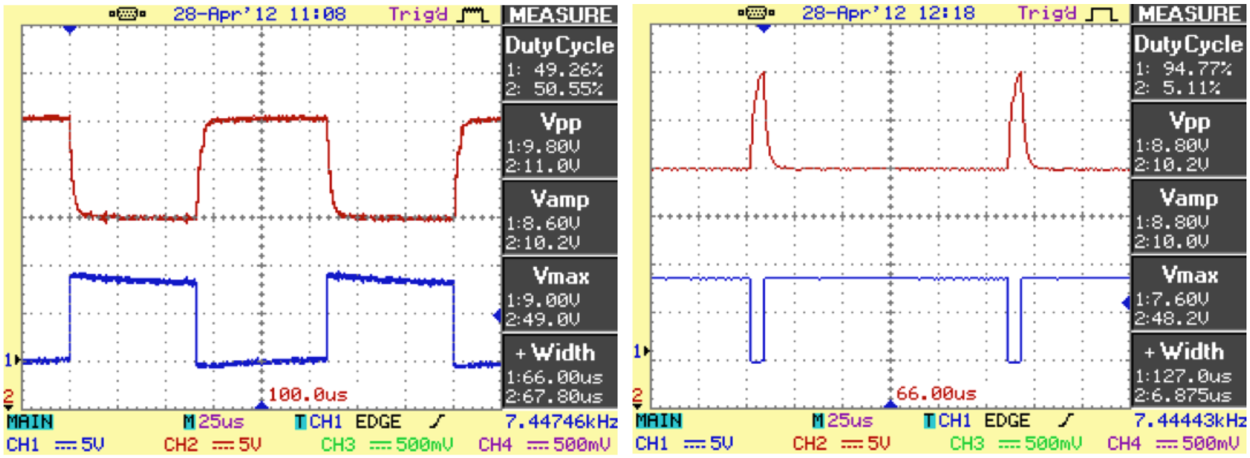
Next, the voltage into the gate of M1 MOSFET (M1_GATE) was compared to the PWMout pin of the LT3756-2 chip (PWMOUT). Figure 5-12 illustrates that LT3756-2 provides a pulsing voltage only during the on time. Comparing simulation results shown in Figure 4-14 (c) and (d) with the hardware waveforms in Figure 5-12 validates that the circuit is functioning correctly.



(a) (b)

Figure 5-12: [CH1] V(PWMout) vs. [CH2] V(M1_Gate) For (a) D = 49.24%, (b) D = 95.53%.

A similar circuit functionality test is performed for the M2_GATE pin. Figure 5-13 illustrates PWMOUT versus M2_GATE. Since M2 is a P-channel MOSFET, it turns on when it receives a logic low. Comparing the simulated waveforms shown in Figure 4-25 (c) and (d) with the hardware waveforms shown in Figure 5-13 (a) and (b) validates that when PWMOUT is at 0 V (logic low), M2_GATE remain at 48V (logic high). When PWMOUT outputs 7 V (logic high), M2_GATE is pulled down to 38 V (logic low) and turns on. M2 can be seen as a switch such that when closed it allows current to flow to the LED. M1 can be seen as a pulsing switch that trickle charges the inductor. The current feedback loop determines how frequently M1 needs to turn on, in order to maintain an output regulation of 1 A.



(a)

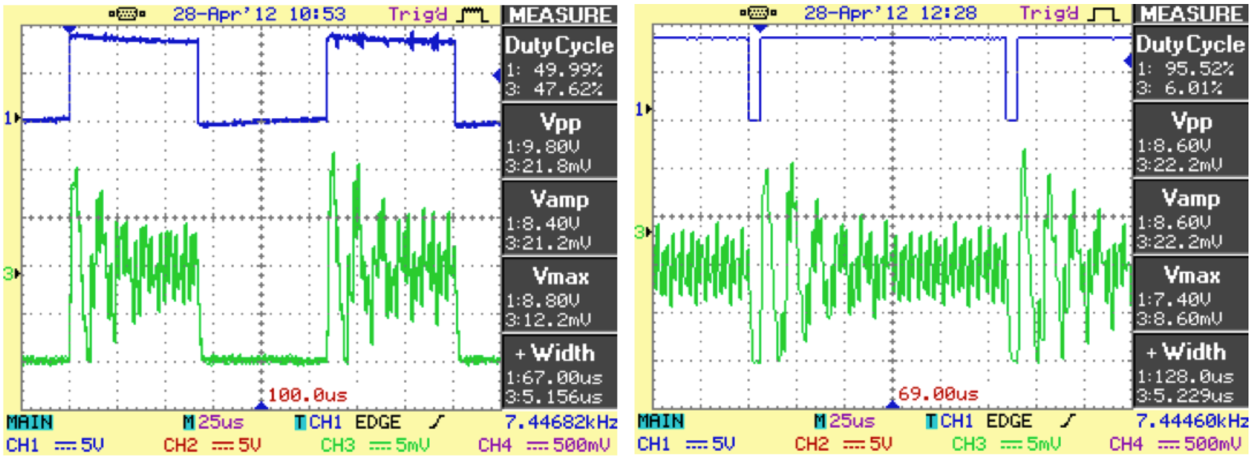
(b)

Figure 5-13: [CH1] V(PWM_OUT) vs. [CH2] V(M2_Gate) For (a) D = 49.26%, (b) D = 94.77%.

Figure 5-14 illustrates PWM signal PWMOUT relationship to the amount of current I(L1) flowing through inductor, L1. Since a current probe amplifier was used to convert the current signal to a voltage signal, the voltage waveform of L1 must be converted back to current to get the correct readings. Since the current amplifier produces 1 A per division (1 A/div) and the oscilloscope is scaled at 5 mV/div. then Equation 5-3 can be used to obtain the correct readings.

$$I(LED) = \frac{(\#\ vertical\ squares)\ x\ Scope\ (\frac{5mV}{div})}{\frac{2*Scope(\frac{5mV}{div})}{Current\ Probe(\frac{1A}{div})}} \qquad [\frac{A}{div}] \qquad (5\text{-}3)$$

Table 5-5 translates the inductors voltage reading to the correct current reading for duty cycles at 49.99% and 95.52%. Comparing simulated inductor waveforms in Figure 4-26 (c) and (d) to hardware waveforms in Figure 4-14 (a) and (b), respectfully indicates that the inductor somewhat produces an underdamped response as it reaches the end of its turn on time. This is also a good indicator that LT3756-2's internal current control loop is attempting to regulate the inductor's peak current so that the LED array sees a constant 1 A supply.



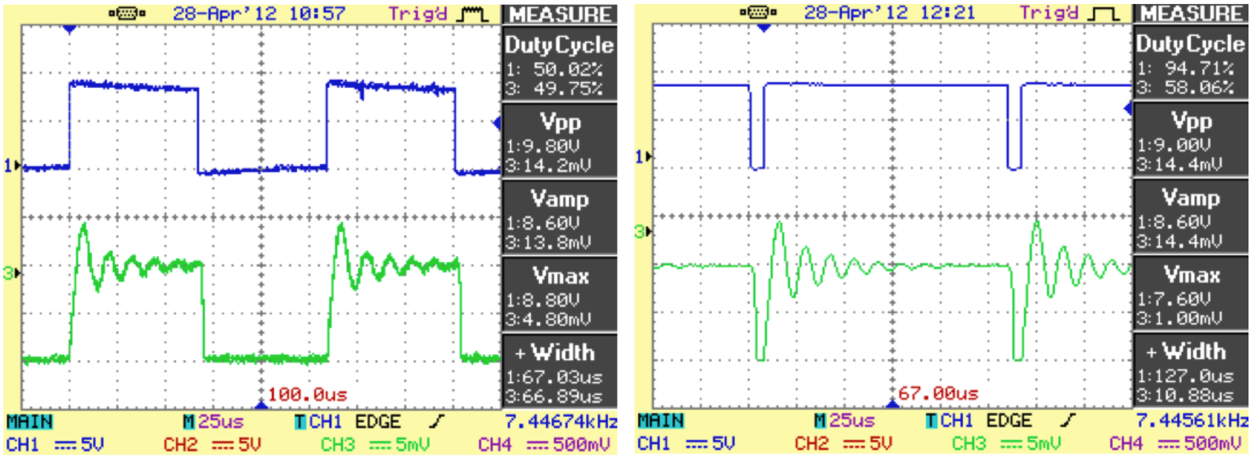
(a) (b)

Figure 5-14: [CH1] V(PWM_OUT) vs. [CH3] I(L1) For (a) D = 49.99%, (b) D = 5.52%.

Table 5-5: Inductor Current, I(L1) Conversion for Figure 5-14 (a) and (b).

Duty Cycle	49.99%	95.52%
$I(L1)_{peak-peak}$ (A)	2.18	2.22
$I(LED)_{amp}$ (mA)	2.12	2.22
$I(LED)_{avg}$ (mA)	1	1

Figure 5-15 illustrates the PWM signal (PWMOUT) versus current through the LED, I(LED) for duty cycles at 50.02% and 94.71%. Similar to the case for the inductor, a current probe amplifier was used to convert current to voltage. Therefore Equation 5-3 must be used to convert the oscilloscope voltage waveform to the correct current measurements. Table 5-6 summarizes the peak-peak, amplitude, and average current through the LED array shown in Figure 5-15.



(a)

(b)

Figure 5-15: [CH1] V(PWM_OUT) vs. [CH3] I(LED) For (a) D = 50.02%, (b) D = 94.71%.

Table 5-6: LED Current, I(LED) Conversion for Figure 5-15 (a) and (b).

Duty Cycle	50.02%	94.71%
I(LED)$_{peak\text{-}peak}$ (A)	1.42	1.44
I(LED)$_{amp}$ (mA)	1.38	1.44
I(LED)$_{avg}$ (mA)	1	1

5.5 : Lumination Measurement

5.5.1: Hardware Setup

Figure 5-16 illustrates the laboratory setup for lumination measurement at varying duty cycles. Two clear bookstand holders (29 cm tall) were equally placed between the DC Light Bulb. Using the bookstands as support, a Sylvania DS-2000 light meter was then placed directly above it. This setup created a fixed distance between the light bulb and the light meter. Similar to before, a DC power supply supplied a constant 48 VDC to the DC Light Bulb and a multimeter was used to read the input current. Table 5-7 summarizes the equipment used during the lumination measurement test.

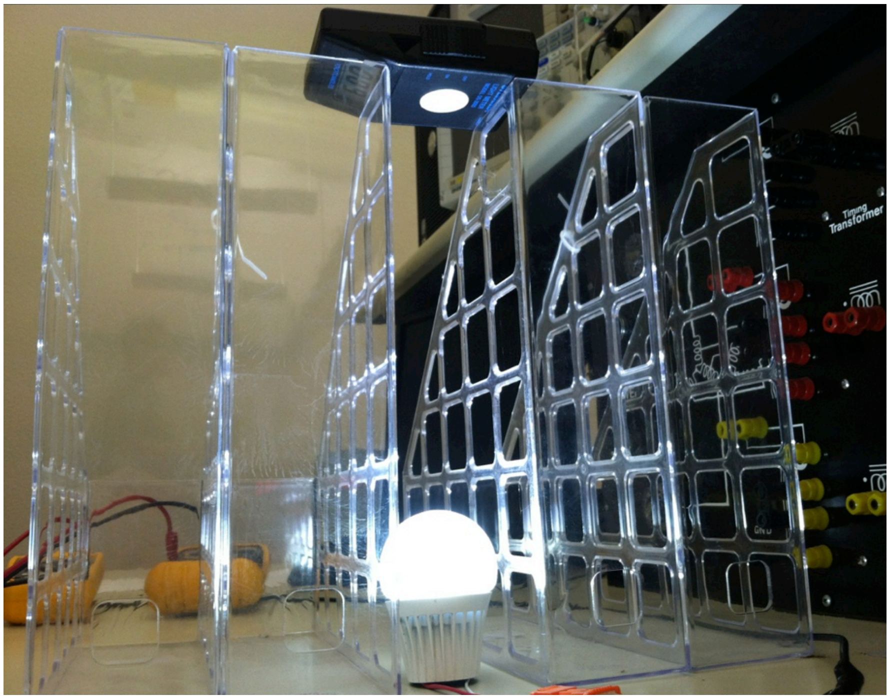


Figure 5-16: Setup for Lumination Measurement.

Table 5-7: Equipment Setup Used for Lumination Measurements.

Purpose	Equipment	Manufacture	Model
V_{IN}	DC Power Supply	GW	GPR-6060D
I_{IN}	Multimeter	Agilent Technologies	U341A
Light Reading	Light Meter	Sylvania	DS-2000
Measure Distance	Ruler	Generic	

5.5.2: Test Results

Referring to the lumination test fixture setup shown in Figure 5-16, the slide dimmer via the 10 kΩ potentiometer was slowly incremented (at 10 mA input current steps, not shown) from D = 0% to D = 100% and the light meter was used to record the amount of light it produced at each step. Note the light meter records the amount of light in the units of foot-candles. However, lighting manufacturers usually advertise their products using units of lumens. Therefore, to convert foot-candles to lumens, the surface area where the light shines into must be calculated. As mentioned earlier the light meter is fixed 29 cm away from the DC Light Bulb. The light bulb's aluminum base is 0.04 m tall and its diffuser have a diameter of 5.6 cm (or a radius of 0.028 m). The light bulb can be considered to be spherical shape and its directional light output fills only half of a sphere, applying Equations 5-4 to 5-9 is then applied to calculate the amount of lumens. Figure 5-17 illustrates how to calculate the surface area that the light fills. When D = 100% and the light meter reads 426 foot-candles, the DC Light Bulb produces 1420.1 lumens, which is almost the equivalent to a 100 W incandescent light bulb that produces about 1600 lumens. The DC Light Bulb is almost able to produce the same amount of light that a 100 W incandescent light bulb does, but remarkably requiring only 13.44 W. Appling Equations 5-10 and 5-11 suggests that with an input power of 13.44 W at full load the DC Light Bulb produces a luminous efficacy of 105.54 lumens/watt. Comparing this to the rated datasheet (CREE XPG LED) value of 110.48 lumens/watt suggests that the measured values were only 4.47% different from rated specifications.

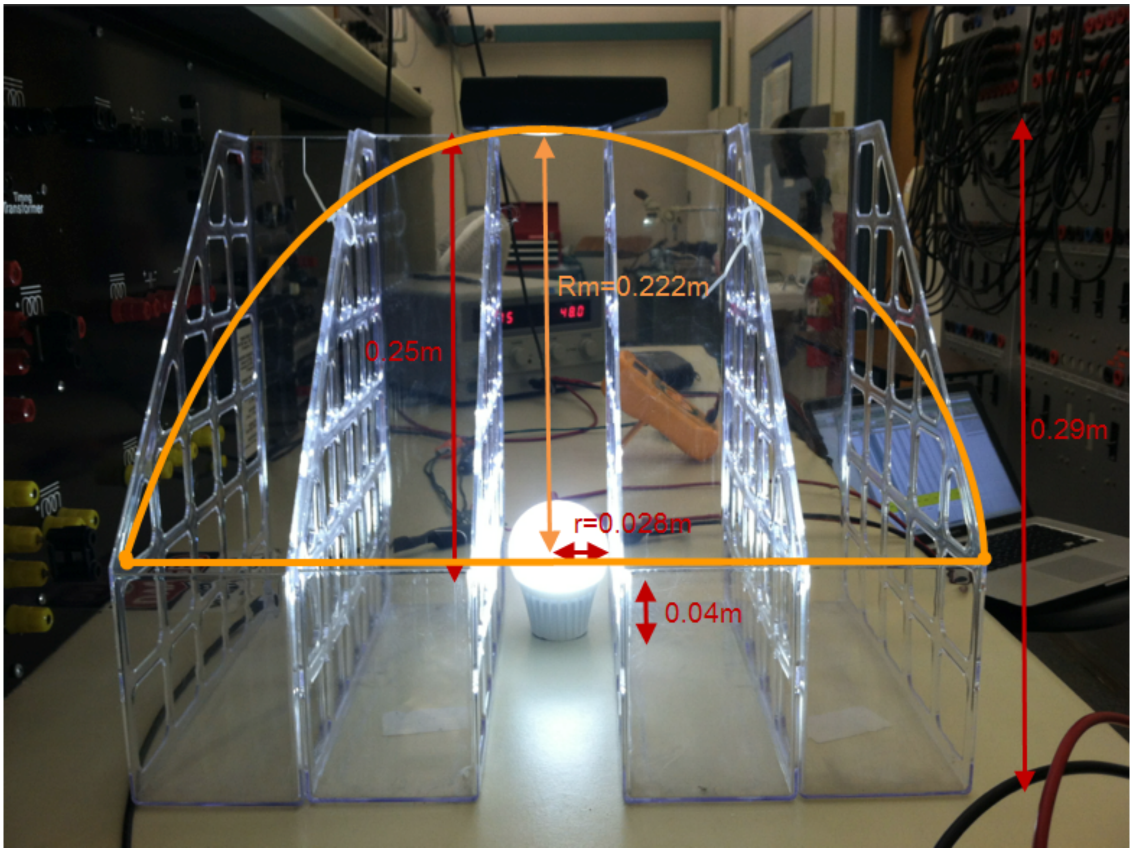


Figure 5-17: Conversion From Foot-Candles to Lumens.

$$A_{SPHERE} = 4 * \pi * r^2 \tag{5-4}$$

$$\frac{1}{2} A_{SPHERE} = 2 * \pi * r^2 \tag{5-5}$$

$$A_{MEASURED} = 2 * \pi * r_m^2 = 2 * \pi * 0.222\ m = 0.3097\ m^2 \tag{5-6}$$

$$1\ foot - candle = 10.76391 \frac{lumens}{m^2} \tag{5-7}$$

$$426\ foot - candle * \frac{10.76391 \frac{lumens}{m^2}}{1\ foot{-}candle} = 4585.4 \frac{lumens}{m^2} \tag{5-8}$$

$$4585.4 \frac{lumens}{m^2} * 0.3097\ m^2 = 1420.1\ lumens \tag{5-9}$$

$$luminous\ efficacy = \frac{lumens}{P_{IN}} \tag{5-10}$$

$$luminous\ efficacy_{MEASURED} = \frac{1420.1\ lumens}{13.456\ W} = 105.54 \frac{lumens}{W} \tag{5-11}$$

Table 5-8 summarizes the DC Light Bulb’s lumination at various duty cycles. Note the initial values (denoted with an *) are not consistence since the room’s light was on during the testing.

Table 5-9 summarizes the DC Light Bulb’s lumination measurements when its diffuser was removed. Overall, the DC Light Bulb’s efficacy remained within 12% of the CREE XPG LED’s datasheet projected luminous efficacy of 110.48 lumens/watt.

Table 5-8: Lumination Measurement Using Light Bulb Diffuser.

					With Diffuser						
Light	Duty Cycle %	LED Iout (mA)	Pin (W)	Pout (W)	Brightness (footcandles)	Brightness LUX (Lumens/m^2)	Brightness (Lumens)	Efficacy (Lumens/Watt)	Efficacy % Error (%)	Light Area (m^2)	Datasheet Rated Efficacy (Lumens/Watt)
off	0.000	0.000	0.104	0.000	*6	*64.583	*20.001	*192.292	*74.051%	0.310	110.480
on	2.970	27.000	0.512	0.247	*20	*215.278	*66.671	*130.116	*17.773%	0.310	110.480
on	5.980	56.000	0.944	0.519	33.000	355.209	110.008	116.514	5.462%	0.310	110.480
on	8.870	85.000	1.401	0.796	48.000	516.668	160.012	114.187	3.356%	0.310	110.480
on	11.950	119.000	1.882	1.128	62.000	667.362	206.682	109.816	0.601%	0.310	110.480
on	14.930	156.000	2.421	1.496	78.000	839.585	260.019	107.418	2.772%	0.310	110.480
on	19.370	189.000	2.893	1.833	92.000	990.280	306.690	105.995	4.060%	0.310	110.480
on	22.380	222.000	3.356	2.167	108.000	1162.502	360.027	107.273	2.902%	0.310	110.480
on	25.370	255.000	3.804	2.502	123.000	1323.961	410.031	107.789	2.435%	0.310	110.480
on	28.330	293.000	4.331	2.907	137.000	1474.656	456.701	105.460	4.544%	0.310	110.480
on	32.790	327.000	4.797	3.280	152.000	1636.114	506.705	105.627	4.393%	0.310	110.480
on	35.840	364.000	5.313	3.687	167.000	1797.573	556.708	104.789	5.151%	0.310	110.480
on	40.310	399.000	5.783	4.082	181.000	1948.268	603.379	104.345	5.553%	0.310	110.480
on	43.270	432.000	6.246	4.463	196.000	2109.726	653.382	104.604	5.319%	0.310	110.480
on	46.260	465.000	6.683	4.841	211.000	2271.185	703.386	105.249	4.734%	0.310	110.480
on	50.730	503.000	7.199	5.287	225.000	2421.880	750.056	104.195	5.689%	0.310	110.480
on	55.240	540.000	7.691	5.724	238.000	2561.811	793.393	103.164	6.622%	0.310	110.480
on	57.310	577.000	8.171	6.168	253.000	2723.269	843.396	103.218	6.573%	0.310	110.480
on	60.330	612.000	8.643	6.597	268.000	2884.728	893.400	103.363	6.442%	0.310	110.480
on	64.740	650.000	9.137	7.072	283.000	3046.187	943.404	103.248	6.546%	0.310	110.480
on	67.640	686.000	9.605	7.519	298.000	3207.645	993.408	103.423	6.388%	0.310	110.480
on	72.100	724.000	10.111	8.007	312.000	3358.340	1040.078	102.869	6.889%	0.310	110.480
on	76.120	759.000	10.566	8.455	328.000	3530.562	1093.415	103.487	6.330%	0.310	110.480
on	80.610	792.000	11.050	8.894	340.000	3659.729	1133.418	102.571	7.159%	0.310	110.480
on	83.940	831.000	11.545	9.407	358.000	3853.480	1193.423	103.367	6.438%	0.310	110.480
on	88.040	867.000	12.021	9.884	374.000	4025.702	1246.760	103.718	6.120%	0.310	110.480
on	91.190	902.000	12.470	10.346	390.000	4197.925	1300.097	104.255	5.635%	0.310	110.480
on	95.520	940.000	12.952	10.857	405.000	4359.384	1350.101	104.236	5.651%	0.310	110.480
on	100.000	993.000	13.456	11.519	426.000	4585.426	1420.106	105.538	4.473%	0.310	110.480
on	100.000	993.000	13.440	11.509	449.000	4832.996	1496.779	111.367	0.803%	0.310	110.480

Note:

*efficacy error due to inclusion of 6 footcandles from room light source

Datasheet: Rated Efficacy = 110.480 lumens/Watt

Table 5-9: Lumination Measurement Not Using Light Bulb Diffuser.

					Without Diffuser						
Light	Duty Cycle %	LED Iout (mA)	Pin (W)	Pout (W)	Brightness w/o diffuser (footcandles)	Brightness LUX (Lumens/m^2)	Brightness (Lumens)	Efficacy (Lumens/Watt)	Efficacy % Error (%)	Ligth Area (m^2)	Datasheet Rated Efficacy (Lumens/Watt)
off	0.000	0.000	0.104	0.000	*6	*64.583	*20.001	*192.292	*74.051%	0.310	110.480
on	2.970	27.000	0.512	0.247	*19	*204.514	*63.338	*123.610	*11.885%	0.310	110.480
on	5.980	56.000	0.944	0.519	35.000	376.737	116.675	123.576	11.854%	0.310	110.480
on	8.870	85.000	1.401	0.796	51.000	548.959	170.013	121.324	9.815%	0.310	110.480
on	11.950	119.000	1.882	1.128	67.000	721.182	223.350	118.672	7.415%	0.310	110.480
on	14.930	156.000	2.421	1.496	85.000	914.932	283.355	117.058	5.954%	0.310	110.480
on	19.370	189.000	2.893	1.833	101.000	1087.155	336.692	116.364	5.326%	0.310	110.480
on	22.380	222.000	3.356	2.167	116.000	1248.614	386.696	115.220	4.290%	0.310	110.480
on	25.370	255.000	3.804	2.502	134.000	1442.364	446.700	117.429	6.290%	0.310	110.480
on	28.330	293.000	4.331	2.907	148.000	1593.059	493.370	113.928	3.121%	0.310	110.480
on	32.790	327.000	4.797	3.280	166.000	1786.809	553.375	115.356	4.413%	0.310	110.480
on	35.840	364.000	5.313	3.687	185.000	1991.323	616.713	116.084	5.072%	0.310	110.480
on	40.310	399.000	5.783	4.082	197.000	2120.490	656.716	113.568	2.795%	0.310	110.480
on	43.270	432.000	6.246	4.463	212.000	2281.949	706.720	113.143	2.411%	0.310	110.480
on	46.260	465.000	6.683	4.841	228.000	2454.171	760.057	113.729	2.941%	0.310	110.480
on	50.730	503.000	7.199	5.287	244.000	2626.394	813.394	112.994	2.276%	0.310	110.480
on	55.240	540.000	7.691	5.724	259.000	2787.853	863.398	112.267	1.618%	0.310	110.480
on	57.310	577.000	8.171	6.168	275.000	2960.075	916.735	112.193	1.551%	0.310	110.480
on	60.330	612.000	8.643	6.597	289.000	3110.770	963.405	111.462	0.889%	0.310	110.480
on	64.740	650.000	9.137	7.072	304.000	3272.229	1013.409	110.909	0.389%	0.310	110.480
on	67.640	686.000	9.605	7.519	320.000	3444.451	1066.747	111.058	0.523%	0.310	110.480
on	72.100	724.000	10.111	8.007	336.000	3616.674	1120.084	110.782	0.273%	0.310	110.480
on	76.120	759.000	10.566	8.455	352.000	3788.896	1173.421	111.059	0.524%	0.310	110.480
on	80.610	792.000	11.050	8.894	366.000	3939.591	1220.091	110.415	0.059%	0.310	110.480
on	83.940	831.000	11.545	9.407	382.000	4111.814	1273.429	110.297	0.166%	0.310	110.480
on	88.040	867.000	12.021	9.884	397.000	4273.272	1323.432	110.097	0.347%	0.310	110.480
on	91.190	902.000	12.470	10.346	414.000	4456.259	1380.103	110.670	0.172%	0.310	110.480
on	95.520	940.000	12.952	10.857	430.000	4628.481	1433.441	110.671	0.172%	0.310	110.480
on	100.000	993.000	13.456	11.519	457.000	4919.107	1523.447	113.218	2.479%	0.310	110.480
on	100.000	993.000	13.440	11.509	469.000	5048.274	1563.450	116.328	5.293%	0.310	110.480
Note:											
*efficacy error due to inclusion of 6 footcandles from room light source											
Datasheet: Rated Efficacy = 110.480 lumens/Watt											

5.6 : Thermal Temperature Measurement

5.6.1: Hardware Setup

The final test performed on the DC Light Bulb was a 12-hour thermal stress test. Equipment used is summarized in Table 5-10. The DC Light Bulb was run at full load (D = 100%) and its temperature was recorded every 30 minutes, for a total of 12 hours.

Table 5-10: Equipment Used For Thermal Measurement.

Purpose	Equipment	Manufacture	Model
V_{IN}	DC Power Supply	GW	GPR-6060D
I_{IN}	Multimeter	Agilent Technologies	U341A
Temperature Measurement	Multimeter with Temperature Capability	EXTECH Instruments	MiniTec 26
Thermal Image	Thermal Image Camera	Fluke	Ti Series

Figure 5-18 illustrates the thermal image camera used to capture a couple of readings during the first few hours of the DC Light Bulb's 12-hour thermal stress test.

Figure 5-18: Fluke Thermal Imaging Camera [59].

5.6.2: Test Results

The DC Light Bulb was run at full load (D = 100%) for 12-hours and temperature measurements were recorded every 30 minutes. Table 5-11 summarizes the DC Light Bulb's thermal performance. An EXTECH MiniTec 26 with a thermocouple was used to take readings midway along the side of the aluminum heatsink. Comparing the thermal images of the DC Light Bulb's aluminum heatsink shown in Figures 5-22 and 5-24 to the data collected in Table 5-11 is off by about 10 ºC. The difference in measurements may be due to poor heat transfer between the heatsink and the thermocouple. Thermally conductive paste could potentially result in more accurate temperature readings shown in Table 5-11. Equations 5-12 and 5-13 were used to convert between Celsius and Fahrenheit temperature measurements. Figures 5-19 to 5-25 illustrate thermal temperature of the DC Light Bulb and custom PCB board for various time durations.

$$ºC = (ºF - 32) * \frac{5}{9} \tag{5-12}$$

$$ºF = ºC * \frac{9}{5} + 32 \tag{5-13}$$

Table 5-11: Thermal Temperature Measurements.

Time	Hour Mark	Minutes	DC Light Bulb	Temperature (ºC)	Temperature (ºF)	
10:40 AM	0	0	OFF	24	75.2	*
11:10 AM		30	ON	76	168.8	*
11:40 AM	1	60	ON	80	176.0	*
12:10 PM		90	ON	82	179.6	*
12:40 PM	2	120	ON	84	183.2	*
1:10 PM		150	ON	84	183.2	*
1:40 PM	3	180	ON	86	186.8	*
2:10 PM		210	ON	85	185.0	*
2:40 PM	4	240	ON	86	186.8	*
3:10 PM		270	ON	86	186.8	*
3:40 PM	5	300	ON	79	174.2	
4:10 PM		330	ON	78	172.4	
4:40 PM	6	360	ON	82	179.6	
5:10 PM		390	ON	81	177.8	
5:40 PM	7	420	ON	80	176.0	
6:10 PM		450	ON	81	177.8	
6:40 PM	8	480	ON	81	177.8	
7:10 PM		510	ON	79	174.2	
7:40 PM	9	540	ON	80	176.0	
8:10 PM		570	ON	81	177.8	
8:40 PM	10	600	ON	80	176.0	
9:10 PM		630	ON	82	179.6	**
9:40 PM	11	660	ON	84	183.2	**
10:10 PM		690	ON	85	185.0	**
10:40 PM	12	720	ON	83	181.4	**

*A sheet of paper was covering the DC Light Bulb, thus trapping extra heat

**The doors were closed, thus possible less air circulation

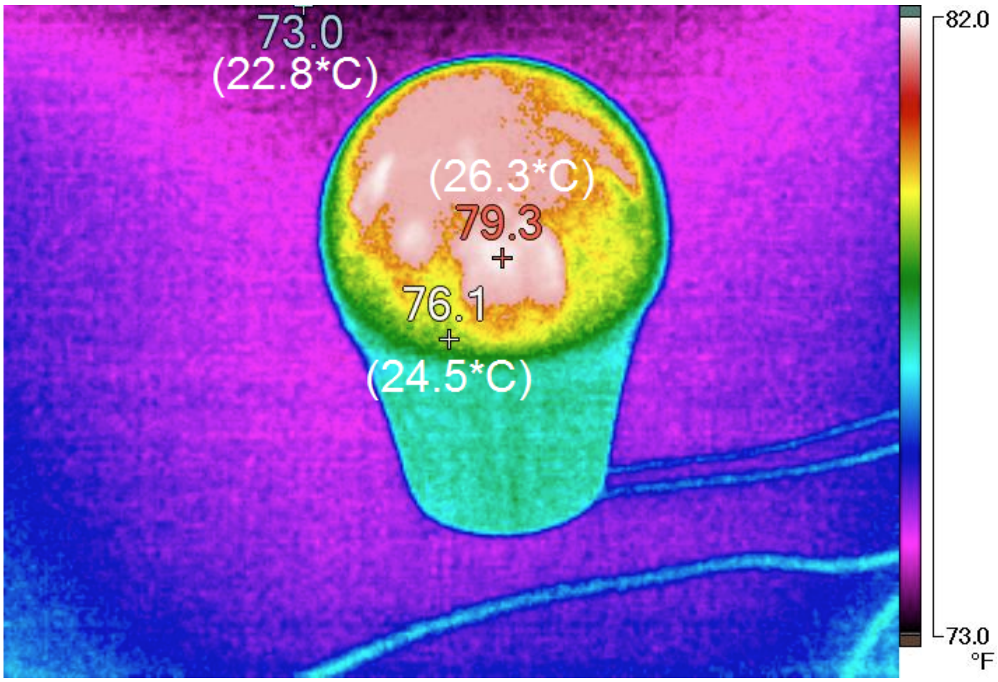


Figure 5-19: DC Light Bulb Off (0 Hours).

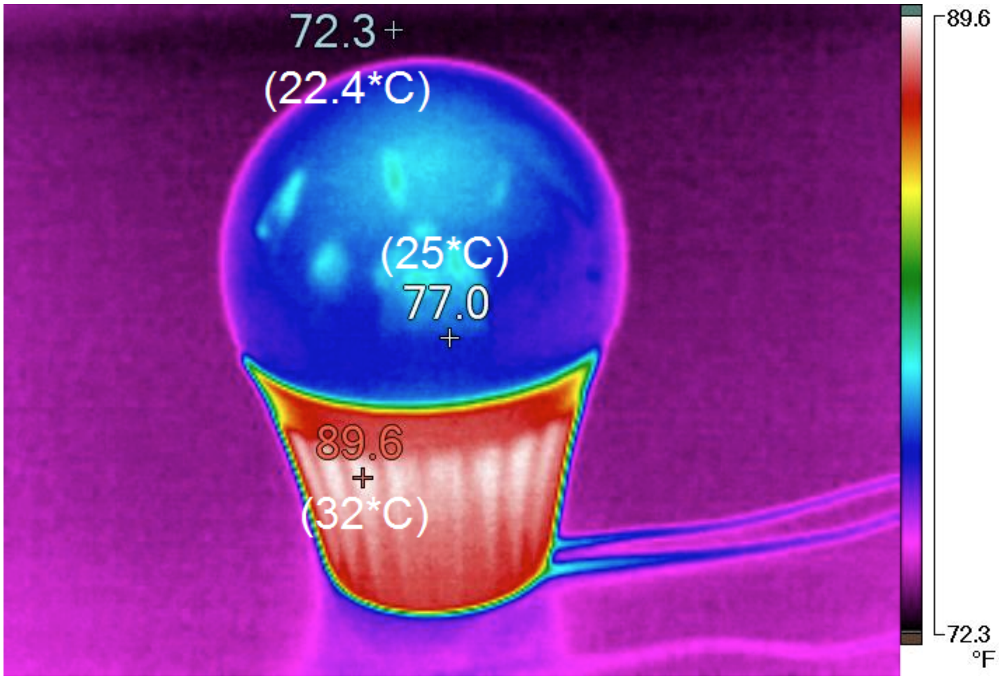


Figure 5-20: DC Light Bulb On (~15 minutes).

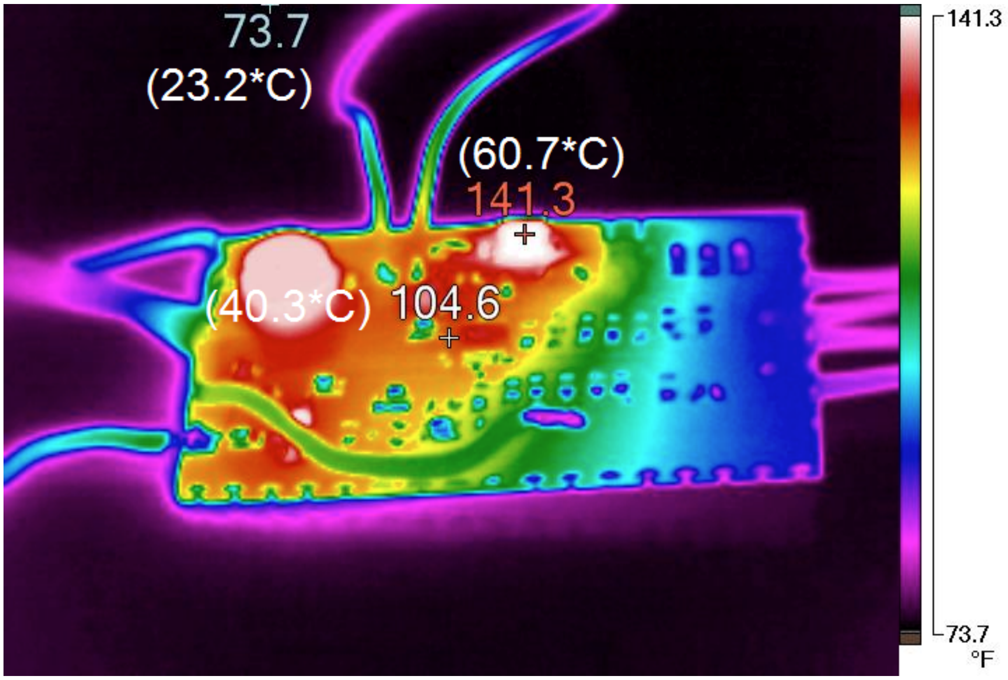


Figure 5-21: DC Light Bulb Circuit On (~15 minutes).

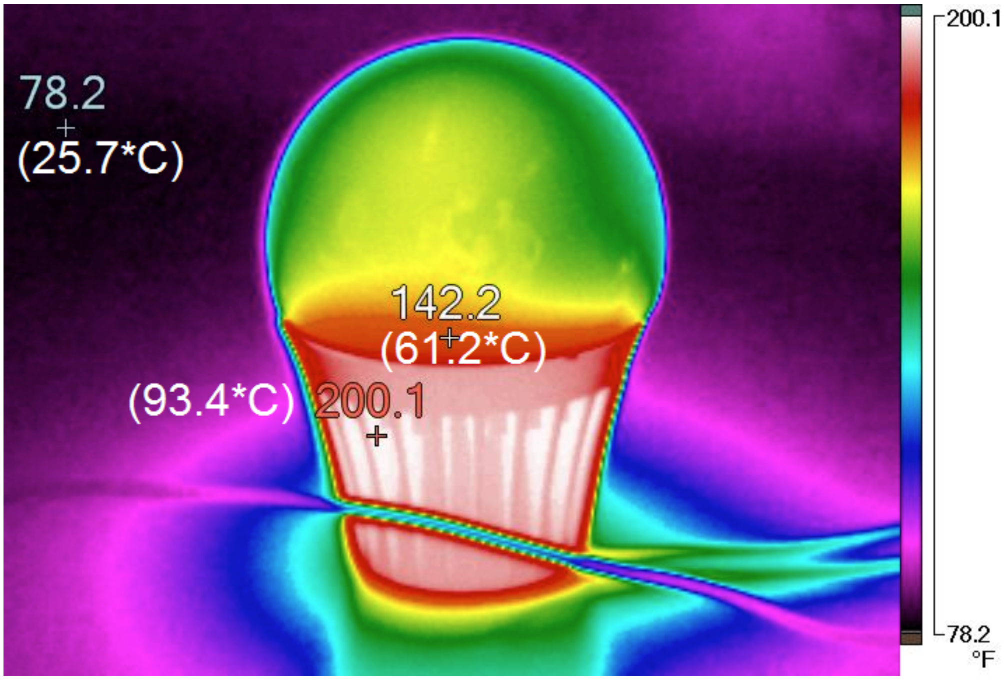


Figure 5-22: DC Light Bulb On (~4 Hours).

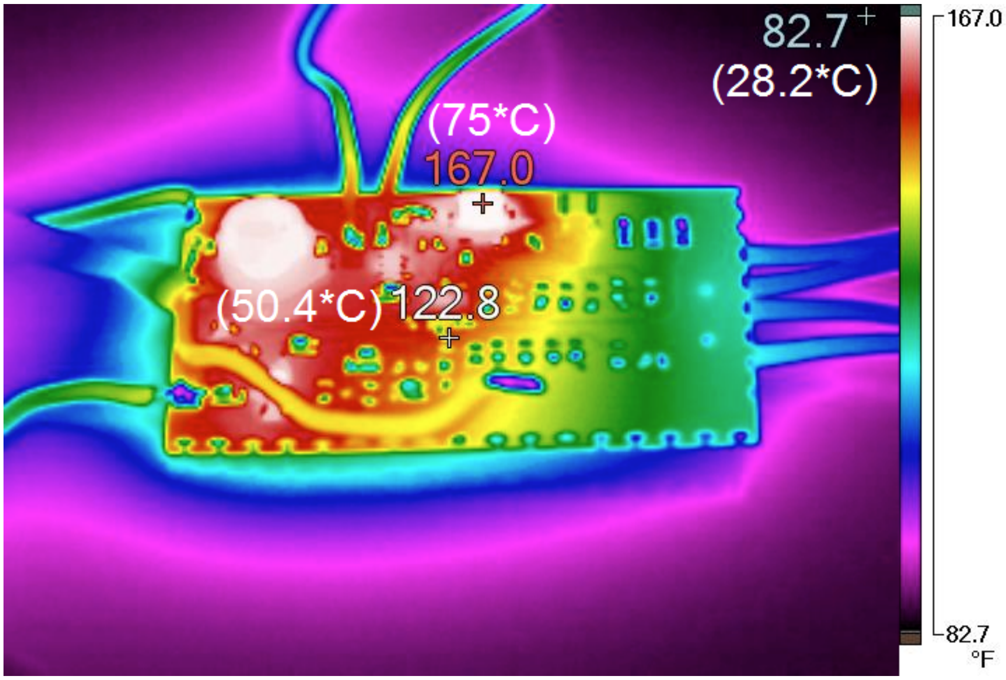


Figure 5-23: DC Light Bulb Circuit On (~4 Hours).

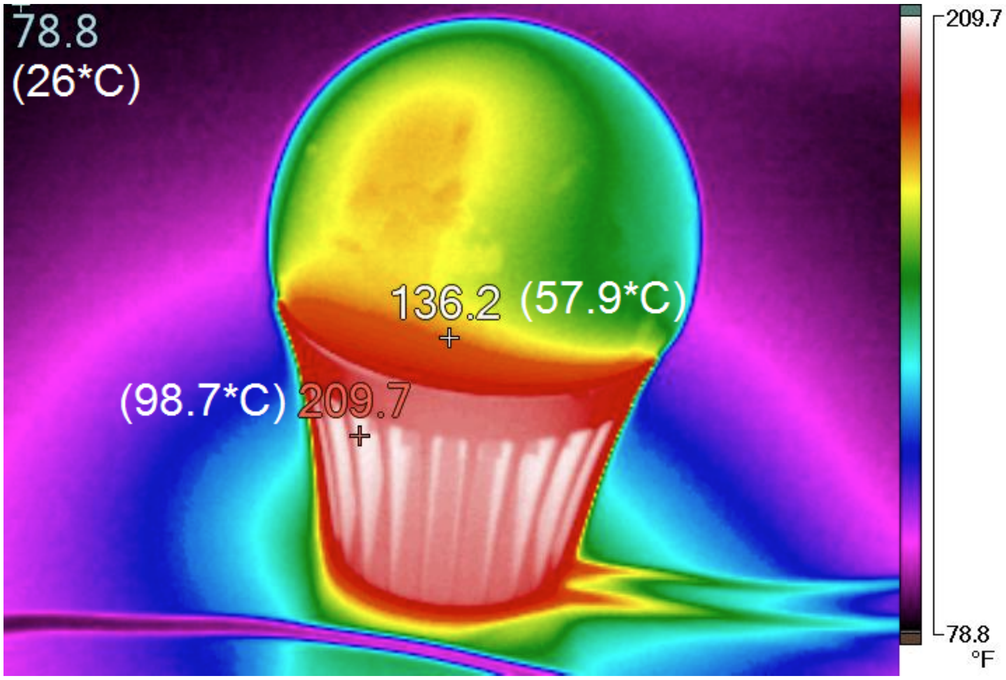


Figure 5-24: DC Light Bulb On (~ 6 Hours).

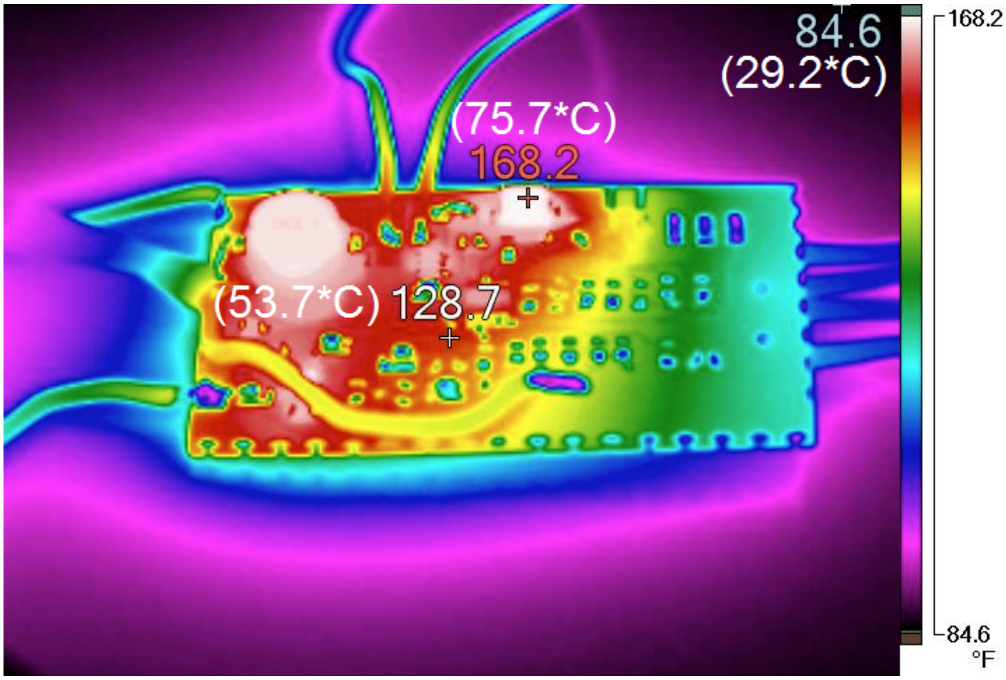


Figure 5-25: DC Light Bulb Circuit On (~6 Hours).

5.7 : Summary of Hardware Results

Overall, the DC Light Bulb was a success. It produced an efficiency of 85.63% at full brightness with a duty cycle of 100%. At maximum load it produced 1496.78 lumens (or 1563.45 lumens without the diffuser) at an output power of 13.44 W. It produced a luminous efficacy of 111.37 lumens/watt, which is within 0.803% of rated CREE XPG datasheet values [58]. The DC Light Bulb maintained excellent line regulation. At ±15% swing from V_{IN} of 48 VDC, it maintained a line regulation of 1.64%. At ±31% swing from V_{IN} of 48 VDC, it maintained a line regulation of 0.23%. Thermal tests suggest that the LED array's worst-case temperature of 98.7 ºC (shown in Figure 5-24) operates at only 65.8% of rated temperature (150 ºC). The DC

Light Bulb was tested to be fully dimmable from 0% to 100%. The DC Light Bulb's circuit functionality was verified to operate per simulation predictions and follow datasheet specifications. A summary of the DC Light Bulb's simulation and hardware results is provided in Table 5-12.

Table 5-12: DC Light Bulb Simulation vs. Hardware Summary.

	Simulation Results	Hardware Results
Parameters	Specifications	Specifications
Wide Input Voltage Range (Simulated): VIN	24 V to 72 V	*33 V to 63 V
Output Voltage in Buck Mode: V(LED)	0 V to 25 V	0.104 V to 13.456 V
PWM Dimming via 10 kΩ Potentiometer: Duty Cycle	0 % to 100 %	0% to 100%
Efficiency at Full Load	*91.34%	85.631%
Total Power Consumption	14.85 W	13.44 W
LED Manufacturer	LUXEON	CREE
LED Type	LXK2-PW14	CREE XLAMP XP-G XPGWHT-01-R250-00GC1
Number of LEDs in Series	4	4
Color Temperature	Cool White (6500K)	Cool White (5000K)
Luminous Efficacy	85 Lumens/Watt	111.367 Lumens/Watt
Luminous Flux at 1 A	400 Lumens	1563.450 Lumens
Max Forward Voltage	4.95 V	3.25 V
Max Forward Current	1.5 A	1.5 A
Max Temperature Recommended at Forward Current of 1 A	75 ºC	110 ºC
Max LED Junction Temperature	150 ºC	150 ºC
Line Regulation at 15% Input Voltage Swing	0.01%	1.64%
LDO Load Regulation from 10% to 90% Load	0.08%	-
Constant Current Regulation	Yes	Yes
Constant Voltage Regulation	Yes	Yes
Open LED Protection	Yes	Yes
*VIN only tested at +-31% swing from nominal of 48 VDC		

Figure 5-26 illustrates the DC Light Bulb's PCB with fully populated components. Figure 5-27 shows the custom PCB fitted into the inner light bulb housing. Figure 5-28 illustrates the fully assembled DC Light Bulb using an E26 base (lamp holder – white color) mounted on a standard ceiling junction box (blue color). Figure 5-28 also shows the custom slide dimmer in a standard switch box (blue color) with a white faceplate. Lastly, Figure 5-29 illustrates the DC Light Bulb operating at full load (D = 100%) from a 48 VDC voltage source.

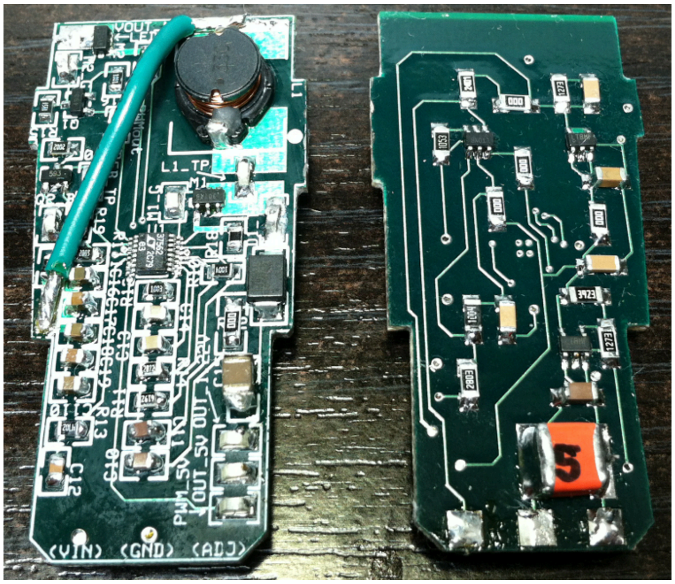


Figure 5-26: Custom DC Light Bulb 4-Layer PCB – Fully Populated, Top (left) and Bottom (right) Layer.

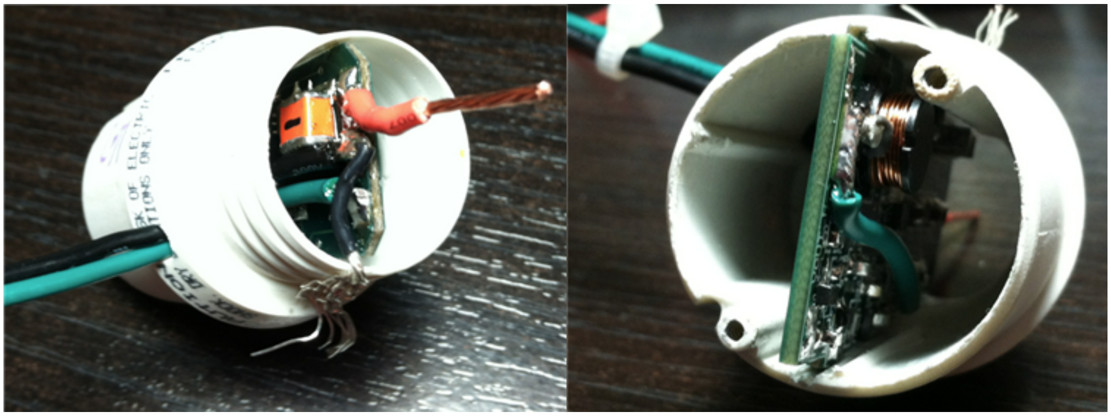


Figure 5-27: Fully Populated PCB Fitted Into Light Bulb's Inner Sleeve, Bottom (left) and Top (right) View.

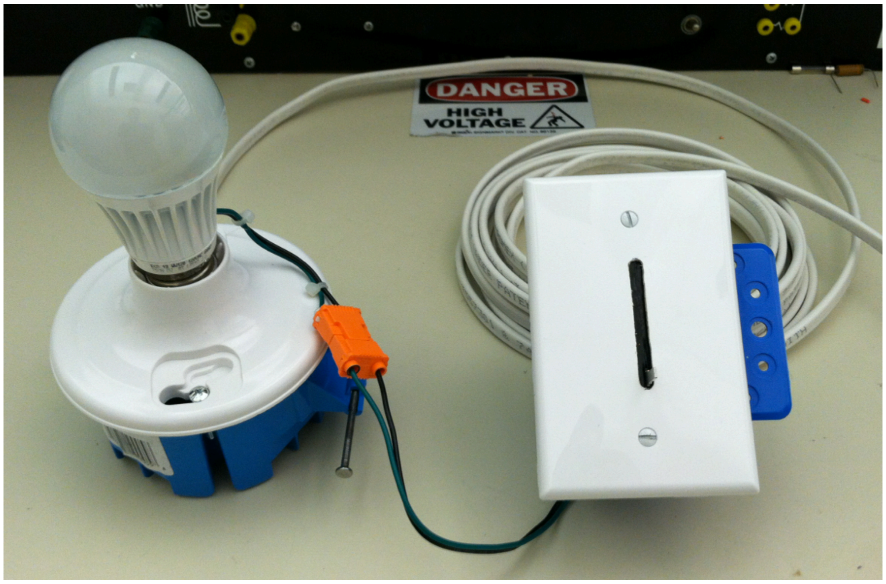


Figure 5-28: A19 DC Light Bulb (left) With Dimmer Box (right) – Fully Assembled.

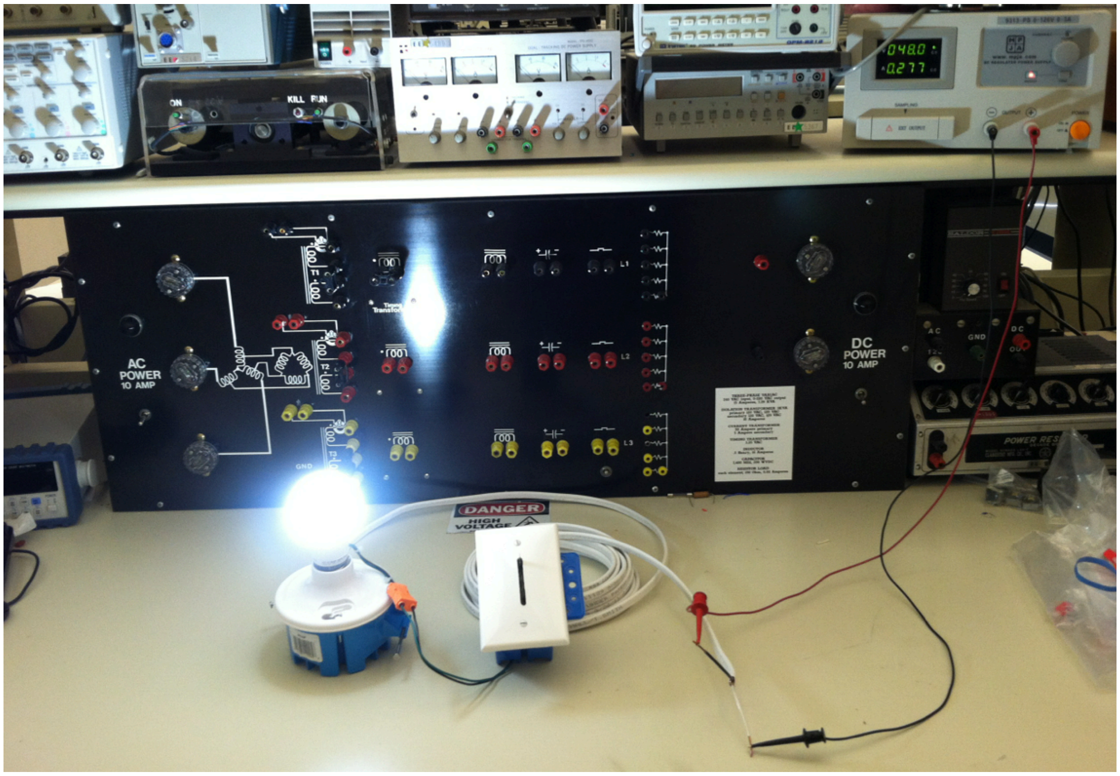


Figure 5-29: Fully Assembled DC Light Bulb Running at Full Load (D = 100%) From 48 VDC Input.

Chapter 6: Conclusion and Future Work

6.1 : Summary and Conclusion

For this thesis, a strong focus is in the design and implementation of an economical and energy efficient DC Light Bulb for Cal Poly San Luis Obispo's DC House Project. For the DC lighting system, emphasis is on the DC-DC LED driver, dimmer circuit, LED lighting array, and physical packing design. It is designed with specific electrical, lumination, physical, construction, and cost constraints, as suggested in Table 3-1.

The DC Light Bulb meets target electrical constraints. It is able to operate from the DC House's main 48 VDC bus voltage. It is also simulated to operate with a wide input voltage ranging from 24 VDC to 72 VDC and hardware tested to operate from input voltage ranging from 33 V to 63 V at full load (±31% swing from nominal input voltage of 48 VDC). The DC Light Bulb maintained excellent line regulation of 0.23% at ±31% swing from nominal input voltage of 48 VDC. It produced an efficiency of 85.63% with a total power consumption of 13.44 W at full load.

The DC Light Bulb also outperformed initially targeted lumination constraints. It produced 1496.78 lumens (or 1563.45 lumens without the diffuser) with a luminous efficacy of 111.37 lumens/watt at maximum brightness (with a duty cycle of 100%). A standard 75 W incandescent light bulb produces about 1100 lumens and a 100 W incandescent light bulb produces about 1600 lumens (Figure 2-14). The DC Light Bulb produced 1120.08 lumens with a total power consumption of 10.11 W The DC Light Bulb only consumed 13.24% of the total 75 W required by a standard (75 W) incandescent light bulb that produces 1100 lumens. The DC Light Bulb is also tested to be fully dimmable with duty cycle ranging from 0% to 100%. It was also designed using a cool white color temperature of 5000K.

The DC Light Bulb's physical design meets the same dimensions of a standard A19 incandescent light bulb with an E26 screw base (Figure 3-1). The DC Light Bulb's custom 4-layer PCB was also able to fit into the inner light bulb sleeve (Figure 5-5). The dimmer circuit also easily fit into a standard switch box as suggested in Figure 3-2 (b).

The DC Light Bulb follows common installation and wiring standards dictated by NEC 2011. The complete lighting system can be easily installed with minimal training. Color coded wires using plug-and-play luminaire connectors (Figure 3-3) make installation straightforward.

Lastly, the DC Light Bulb's total prototype cost under $99.68. Target prototype cost constraint suggests it would cost between $100 to $200 (Table 3-1). The Bill of Material is provided in Appendix A.

6.2 : Future Considerations and Recommendation

Overall the DC Light Bulb prototype was a complete success. However there is always room for improvements, such as a wider input voltage range, reduction in production cost, and use of bigger heatsink.

To make the DC Light Bulb truly universal, it should be designed to work from 12 VDC to 72 VDC. The DC Light Bulb was simulated to work between 24 VDC to 72 VDC. It was hardware tested to operate between 33 VDC to 63 VDC. It should work per simulated suggested results, however a ±31% swing from the nominal 48 VDC bus voltage provided by the DC House would most likely rarely occur. To create a wider input range, LT3756-2 component selection and sizing would have to be redesigned and re-simulated.

As suggested from Appendix A, the total prototype cost of the DC Light Bulb is $99.68. Potential cost savings would be choosing slightly lower performing components. For example, the higher cost of the 10µF 75V tantalum capacitor could be changed to an aluminum electrolytic capacitor or even a X7R ceramic capacitor. A tantalum capacitor was initially chosen because C40 is the main input capacitor into the entire DC Light Bulb's internal circuitry, thus best available filtering was desirable. Depending on how much ripple the main DC House's 48 VDC bus voltage produces, lower rated capacitors can be used. Another cost saving would be choosing a different LED at a lower cost. As Figure 2-18 suggests the cost per lumens have a linear decaying rate with time. Perhaps the time-to-market that the DC Light Bulb takes to be fully commercialized, the cost of high power LEDs would be significantly less. Another potential cost savings is to work with a manufacturer to produce a custom A19 enclosure rather than the EcoSmart A19 temporary solution. It should be kept in mind that a custom A19 enclosure only saves cost when produced in very high volume.

Another recommendation is to use a larger heatsink. Even though the DC Light Bulb 12-hour thermal test suggests a maximum temperature of 98.7 ºC (measured at its aluminum enclosure), which is below the suggested heatsink temperature of 110 ºC and way below the LED maximum junction temperature of 150 ºC, a larger heatsink can in the long run extend the operating lifetime of the DC Light Bulb.

In conclusion, the DC Light Bulb was an overall success. It was able to meet all design requirements. The DC Light Bulb was able to operate at 48 VDC, is fully dimmable from 0% to 100%, and has the same physical dimension of a traditional A19 incandescent light bulb. The DC Light Bulb produces 1496.78 lumens at a color temperature of 5000K and uses only 13.44W.

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Appendix A: Bill of Materials

Qty #	Cost Each ($)	Total Cost ($)	Ref.	Mfg.	Part No.	Detailed Description	Dimensions	Digikey Part #
1	$0.48	$0.48	C10	TDK Corporation	C2012X7S2A105K	CAP CER 1UF 100V 10% X7S 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	445-5205-1-ND
1	$0.48	$0.48	C11	TDK Corporation	C2012X7S2A105K	CAP CER 1UF 100V 10% X7S 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	445-5205-1-ND
1	$0.48	$0.48	C12	TDK Corporation	C2012X7R1H102K	AP CER 1000PF 50V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	445-1347-1-ND
1	$0.12	$0.12	C13	Yageo	CC0805KRX7R8BB104	CAP CER 0.1UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	311-1141-1-ND
1	$0.45	$0.45	C14	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$4.08	$4.08	C15	Kemet	C1210C475M1R2C7186	CAP CER 4.7UF 100V 20% X7R 1210	0.138" L x 0.091" W (3.50mm x 2.30mm)	399-5787-1-ND
1	$0.45	$0.45	C16	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$0.45	$0.45	C17	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$0.45	$0.45	C18	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$0.45	$0.45	C19	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$0.49	$0.49	C20	Kemet	C1206F104K3RACTU	CAP CER 0.1UF 25V 10% X7R 1206	0.126" L x 0.063" W (3.20mm x	399-5615-1-ND

							1.60mm)	
1	$0.32	$0.32	C30	Kemet	C1206C105K3RACTU	CAP CER 1UF 25V 10% X7R 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	399-1255-1-ND
1	$0.38	$0.38	C31	TDK Corporation	C3216X7R1E474M/0.85	CAP CER 0.47UF 25V 20% X7R 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	445-4021-1-ND
1	$16.23	$16.23	C40	Vishay/Sprague	T97R106K075LSA	CAP TANT 10UF 75V 10% 2824	0.299" L x 0.236" W (7.60mm x 6.00mm)	718-1737-1-ND
1	$0.56	$0.56	C41	AVX Corporation	12061C105KAT2A	CAP CER 1UF 100V 10% X7R 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	478-6226-1-ND
1	$0.38	$0.38	C42	TDK Corporation	C3216X7R1E474M/0.85	CAP CER 0.47UF 25V 20% X7R 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	445-4021-1-ND
1	$0.45	$0.45	C110	Taiyo Yuden	TMK212AB7475KG-T	CAP CER 4.7UF 25V 10% X7R 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	587-2990-1-ND
1	$1.01	$1.01	D1	Diodes Inc.	B1100B-13-F	DIODE SCHOTTKY 100V 1A SMB	3.94mm x 4.57mm	B1100B-FDICT-ND
4	$4.16	$16.64	D2	Cree Inc.	XPGWHT-01-R250-00GC1	LED XLAMP XP-G WHITE COOL	2.6mmx2.6mm?	XPGWHT-01-R250-00GC1CT-ND
1	$1.91	$1.91	L1	Wurth Elektronik	74456133 WE-PD4 L	INDUCTOR POWER 33UH 2.3A SMD	0.500" L x 0.393" W x 0.197" H (12.70mm x 10.00mm x 5.00mm)	74456133
1	$1.00	$1.00	M1	Vishay Siliconix	SI3430DV-T1-E3	MOSFET N-CH 100V 1.8A 6-TSOP	6-TSOP (0.065", 1.65mm Width)	SI3430DV-T1-E3CT-ND
1	$1.10	$1.10	M2	Vishay Siliconix	SI5435BDC-T1-GE3	MOSFET P-CH 30V 4.3A 1206-8	8-SMD, Flat Lead	SI5435BDC-T1-GE3CT-ND
1	$0.54	$0.54	Q1	Diodes/Zetex	FMMT493TA	TRANS HP NPN 100V 1000MA SOT23-3	SOT-23-3	FMMT493CT-ND
1	$0.54	$0.54	Q2	Diodes/Zetex	FMMT593TA	TRANS PNP 100V 1A HV SOT23-3	SOT-23-3	FMMT593CT-ND
1	$0.06	$0.06	R00	Panasonic - ECG	ERJ-8GEY0R0	RES 0.0 OHM 1/4W 1206 SMD	0.126" L x 0.063" W	P0.0ECT-ND

					0V		(3.20mm x 1.60mm)	
1	$0.06	$0.06	R01	Panasonic - ECG	ERJ-8GEY0R00V	RES 0.0 OHM 1/4W 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	P0.0ECT-ND
1	$0.06	$0.06	R02	Panasonic - ECG	ERJ-8GEY0R00V	RES 0.0 OHM 1/4W 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	P0.0ECT-ND
1	$0.06	$0.06	R03	Panasonic - ECG	ERJ-8GEY0R00V	RES 0.0 OHM 1/4W 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	P0.0ECT-ND
1	$0.06	$0.06	R04	Panasonic - ECG	ERJ-8GEY0R00V	RES 0.0 OHM 1/4W 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	P0.0ECT-ND
1	$0.04	$0.04	R10	Stackpole Electronics Inc.	RMCF0805FT1M00	RES 1M OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT1M00CT-ND
1	$0.04	$0.04	R11	Stackpole Electronics Inc.	RMCF0805FT61K9	RES 61.9K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT61K9CT-ND
1	$0.04	$0.04	R12	Stackpole Electronics Inc.	RMCF0805FT100K	RES 100K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT100KCT-ND
1	$0.04	$0.04	R13	Stackpole Electronics Inc.	RMCF0805FT47K0	RES 47K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT47K0CT-ND
1	$0.04	$0.04	R14	Stackpole Electronics Inc.	RMCF0805FT28K7	RES TF 28.7K OHM 1% 0.125W 0805	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT28K7CT-ND
1	$0.04	$0.04	R15	Stackpole Electronics Inc.	RMCF0805FT1K50	RES 1.5K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT1K50CT-ND
1	$0.04	$0.04	R16	Stackpole Electronics Inc.	RMCF0805FT1K00	RES 1K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT1K00CT-ND
1	$0.35	$0.35	R17	Susumu	RL1220S-R10-F	RES .10 OHM 1/3W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RL12S.10FCT-ND
1	$0.77	$0.77	R18	Panasonic -	ERJ-	RESISTOR .033 OHM	0.079" L x	P.033AQCT

				ECG	6BWFR033V	1/4W 1% 0805	0.049" W (2.00mm x 1.25mm)	-ND
1	$0.04	$0.04	R19	Stackpole Electronics Inc.	RMCF0805FT200K	RES 200K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT200KCT-ND
1	$0.10	$0.10	R20	Panasonic - ECG	ERJ-8ENF2401V	RES 2.40K OHM 1/4W 1% 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	P2.40KFCT-ND
1	$1.40	$1.40	R21_ADJ	TT Electronics/BI	PS45M-0MC2BR10K	POT 10K OHM SLIDE 45MM	Rectangular - 2.362" L x 0.354" W x 0.276" H (60.00mm x 9.00mm x 7.00mm)	987-1406-ND
1	$0.06	$0.06	R22	Stackpole Electronics Inc.	RMCF1206FT105K	RES TF 105K OHM 1% 0.25W 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT105KCT-ND
1	$0.06	$0.06	R23	Stackpole Electronics Inc.	RMCF1206FT1M00	RES 1M OHM 1/4W 1% 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT1M00CT-ND
1	$0.06	$0.06	R24	Stackpole Electronics Inc.	RMCF1206FT280K	RES TF 280K OHM 1% 0.25W 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT280KCT-ND
1	$0.06	$0.06	R30	Stackpole Electronics Inc.	RMCF1206FT127K	RES TF 127K OHM 1% 0.25W 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT127KCT-ND
1	$0.06	$0.06	R40	Stackpole Electronics Inc.	RMCF1206FT392K	RES 392K OHM 1/4W 1% 1206 SMD	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT392KCT-ND
1	$0.06	$0.06	R41	Stackpole Electronics Inc.	RMCF1206FT127K	RES TF 127K OHM 1% 0.25W 1206	0.126" L x 0.063" W (3.20mm x 1.60mm)	RMCF1206FT127KCT-ND
1	$0.04	$0.04	R110	Stackpole Electronics Inc.	RMCF0805FT20K0	RES 20K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT20K0CT-ND
1	$0.04	$0.04	R111	Stackpole Electronics Inc.	RMCF0805FT200K	RES 200K OHM 1/8W 1% 0805 SMD	0.079" L x 0.049" W (2.00mm x 1.25mm)	RMCF0805FT200KCT-ND
1	$0.04	$0.04	R112	Stackpole	RMCF08	RES 200K OHM	0.079" L x	RMCF0805

				Electronics Inc.	05FT200K	1/8W 1% 0805 SMD	0.049" W (2.00mm x 1.25mm)	FT200KCT-ND
1	$4.29	$4.29	U1	Linear Technology	LT3756-2	100Vin, 100Vout LED Controller	4.039mm x 4.90mm	LT3756EMSE-2#PBF
1	$2.16	$2.16	U2	Linear Technology	LTC6992-1	PWM with 0% to 100% Pulse Width Control	2.90 mm x 2.80mm	LTC6992CS6-1#TRMPBF
1	$2.21	$2.21	U3	Linear Technology	LT3014	80Vin, 20mA, LDO in ThinSOT	2.90mm x 2.80mm	LT3014ES5#PBF
1	$2.21	$2.21	U4	Linear Technology	LT3014	80Vin, 20mA, LDO in ThinSOT	2.90mm x 2.80mm	LT3014ES5#PBF
1	$1.88	$1.88	MCPCB	Cutter Electronics	MCPCB - 425	25mm quad optic designed for the Cree XPE/XPC/XPG	25mm diameter	MCPCB - 425
1	$9.97	$9.97	Housing	EcoSmart	ECS 19 WW 120	EcoSmart A19 LED Light Bulb		Home Depot SKU# 864680
10	$0.44	$4.40	TP	Keystone Electronics	5015	PC TEST POINT MINIATURE SMT	0.010" (0.25mm)	5015KCT-ND
1	$19.40	$19.40	Layout	ExpressPCB		4 layer mini-board		
70		$99.68						