LED Lighting Fixture

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Senior design II

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The University of Tulsa

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Objective

The objective of this project is to design and fabricate an LED lighting fixture to replace the existing fluorescent fixture in the University of Tulsa apartment bedrooms. Improvements in power consumption, color correlation temperature, power factor, audible noise, turn on time, and light output will be of primary focus.

Original Fixture

Currently the lighting fixtures in the apartment bedrooms utilize a single 11" round fixture containing two 13 watt bi-pin short twin tube fluorescent bulbs with two external magnetic ballasts and a plastic diffuser. As fitted the fixtures contain 2 Sylvania Dulux CF13ds/841 bulbs. These bulbs have a Color Correlation Temperature (CCT) of 4000K and a Color Rendering Index (CRI) of 82. The CCT and CRI of these bulbs are better suited to work spaces and are sub optimal for living quarters. The combined bulb output is 1,620 lumens which before diffuser losses is roughly equivalent to a single 100 watt incandescent bulb. The total utilization factor is about .4 with the diffuser accounting for approximately 30% reduction of the light output. This results in a total output of approximately 640 Lumens (measured by zonal integration). The magnetic ballasts create annoying audible noise at 120 Hz with high frequency harmonics. The magnetic ballasts also cause turn on delay, flicker, cause considerable electrical noise and have a very low power factor. The existing fixture also create the problem of disposing of the mercury containing bulbs after their 10,000 hour life time.

Design

LED selection

The starting point of the design was to determine a base light level. Based on the existing fixture and uncertainties about the optics of the new design base level of 900 Lumens was selected. Several LEDs were evaluated on criteria of CRI, CCT, efficacy, and cost. A table of the LEDs considered can be found in the appendix. Several LEDs were purchased to evaluate light quality, and ease of mounting. Lifetime cost analysis for overall fixture life reveled that efficacy (lm/W) was much more important than initial cost. The Cree MX-6 LED (2700k CCT and 82lm @ 300ma binning) was selected. It offered superior efficacy, common drive current of 350 ma, simple mounting, and reasonable cost. To achieve the 900lm mark at least 11 LEDs would be required. As a note this LED was made available during the first month of this project and has since (within the 4 month duration of this project) been surpassed by an LED with even better characteristics (Cree XP-G, roughly 20% efficacy improvement).

Power supply selection

After selecting an LED and determining the required number to achieve the required light output a commercial power supply capable of 120vac input was selected. To drive LEDs properly a constant current power supply is desired. This is due to forward voltage variation of the LEDS (both due to manufacturing and temperature). An improperly driven (unregulated or constant voltage) LED can suffer from reduced lifetime or even catastrophic failure. Because LED lighting is relatively new there are few commercially available power supplies with suitable characteristics. A small form factor is also desired for the ceiling mount retrofit lamp. The Dialight 9 Watt 350 ma driver was selected based on its small size and ability to drive up to 9 LEDs at 350 ma. Because the power supply is not able to drive the minimum requirement of 11 LEDs two power supplies were required. With the ability of the dual power supplies to drive up to 18 LEDs total and still further uncertainty of optical efficiency it was determined that in the prototype stage 16 LEDs would be used.

Thermal design

It is of critical importance to properly remove heat from the LED package. Thermal management of LEDs is often overlooked and leads to short lifetimes of LEDs. Unlike traditional light sources in which heat is radiated or removed by convection an LED package is cooled by conduction. The power LED package usually contains a thermal slug to which the LED die is directly bonded. Connection to the thermal slug can be achieved by a variety of methods including solder, thermally conductive epoxy, thermal tape and thermal grease. At the other side of the connection is a means of dissipating the heat produced by the LED. This is usually embodied by an actively or passively cooled heatsink. While each LED is only dissipating a single watt of power the area which this heat flux must travel is very small. The power densities of power LED slugs can exceed 1.3 megawatts/square meter. This level is almost 3 times higher than high performance computer CPUs. Metal core printed circuit boards (MCPCB) are frequently used to spread the high heat flux density into a much more reasonable and manageable level (under 25 kilowatts/square meter). A heat spreader similar to a MCPCB was designed in a way feasible to hand fabricate.

LED junction temperatures must be maintained below 150˚C. However light output and lifetime are greatly compromised at these temperatures. Most LED luminous flux ratings are given at a junction temperature of 25˚C. At 125˚C junction temperature the MX-6 LED only produces 72% of its rated light output would have an L70 lifetime (30% lumen reduction) of about 30,000 hours. By reducing junction temperatures higher efficacy and longer lifetimes result. A goal of 80˚C junction temperature was set for the thermal design. This results in a light output of 85% rated and an L70 lifetime of 100,000 hours. The prototype was decided to have 16 LEDs and correspondingly the heatsink was designed with 16 watts of power dissipation in mind.

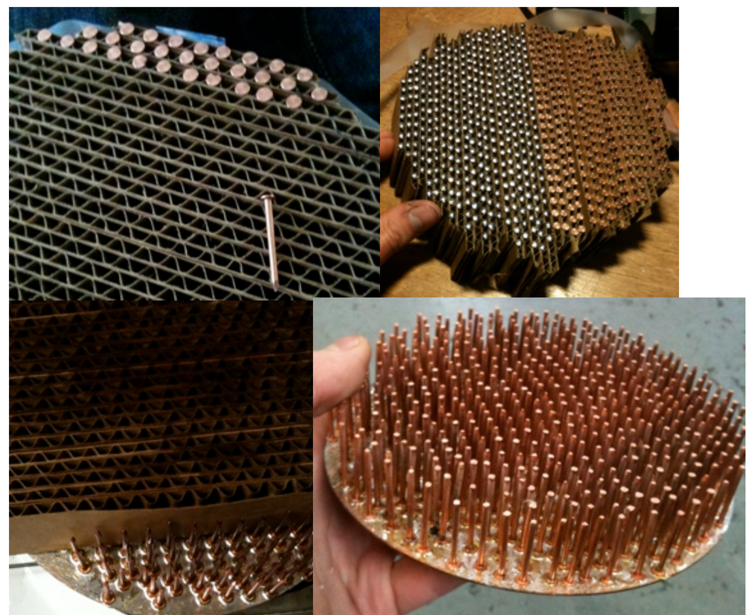
Using the thermal characteristics of the LEDs, the required power dissipation of 16W, a goal junction temperature of 80˚C and a max ambient temperature of 35˚C a heatsink with a thermal resistance of 2.5K/W or less was calculated to be required. After evaluating multiple commercially available heatsinks it was determined that one would need to be custom fabricated to meet the desired form factor and thermal requirements. Passive cooling was selected because of noise concerns associated with active cooling as well as an overall reduction in efficiency due to the extra power that would be consumed by a fan. Without the aid of computational fluid dynamics simulations designing a natural convection heatsink by formulas is very imprecise at best. It was determined that construction and testing of a prototype would be the best approach. The prototype copper pin fin heatsink was designed with very basic heat transfer formulas. The base consists of a 6” diameter 1mm thick copper disk and the pin fins (approximately 500) are in the form of 1” copper nails.

Optical design

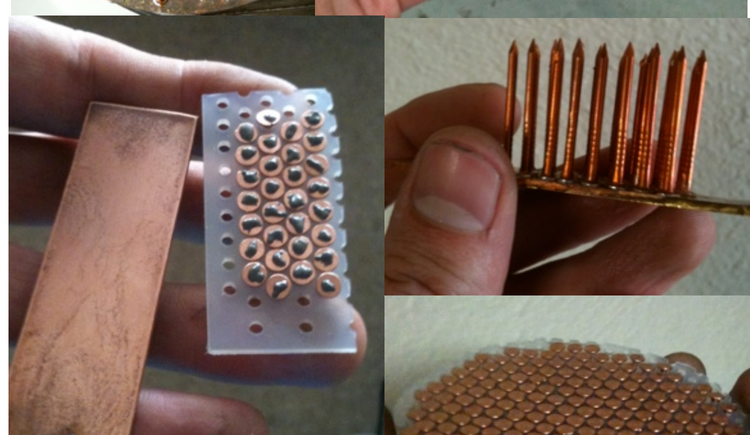
The optical design of an LED fixture has several requirements. It must obscure the very bright LED emitters to reduce glare. It must properly distribute the light in the room. It must do the previously mentioned tasks as efficiently as possible. The stock fixture only utilized about 40% of the light emanating from the bulbs. The diffuser alone reduced the light output by about 30%. This poor level of optical performance is unacceptable in a high efficiency lighting fixture. The available options for emitter obscuration are diffused direct or diffused indirect. Diffused direct involves placing a diffusing material in front of the downward pointing LED emitters as to obscure the emitter from direct view. Diffused indirect involves reflecting the light from the emitter off of a diffuse or specular surface before it travels into the space to be illuminated. Because the fixture is to be passively cooled by natural convection using a disk heatsink with downward facing emitters direct transmissive diffusion was selected.

Fabrication

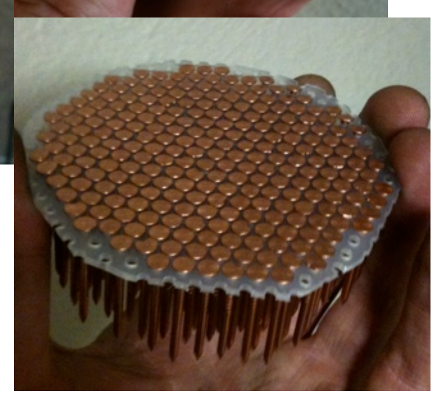
Heatsink



The design calls for about 500 copper nails to be attached to the 6” copper disk. Because of the high thermal conductivity of the copper disk soldering each nail individually was not an option. The nails would have to be placed in a fixture and soldered at one time. To begin the procedure one side of the copper base disk was entirely tinned with solder by heating on the stove and applying liberal quantities of flux and solder. The copper nails were fixed in sheets of corrugated cardboard stacked on edge. Each nail head was then individually hand tinned with a soldering iron. The tinned nails were held in the fixture and placed on top of the tinned disk on the stove. The assembly was then heated until the solder reflowed. After cooling and the cardboard fixture was removed the ~500 copper nails remain soldered to the copper disk forming a pin fin heatsink.



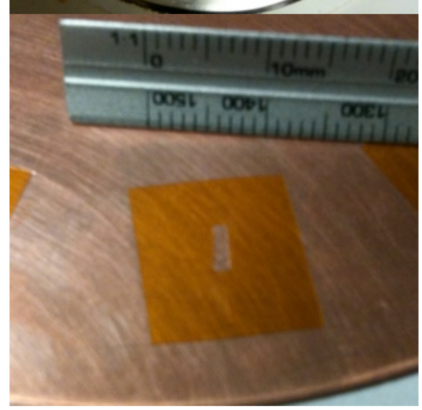
After experience was gained from the prototype a more efficient and precise method utilizing solder paste and a perforated sheet material was developed. With this method the nails are placed through the holes of precisely perforated plastic. Next solder paste is applied to the nail heads that lay flat and evenly spaced on the plastic. The sheet is then inverted on to the copper disk and the assembly is heated until the solder paste reflows. This method is considerably faster, more precise and more flexible. With the method developed for this project custom high performance copper pin fin heatsinks can be created in under an hour by hand without tooling or machining.



LED board

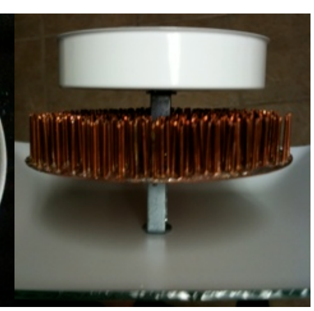
Traditional MCPCBs are comprised of an aluminum substrate, a thermally enhanced dielectric, and the copper circuit traces. Because MCPCB substrates are not easily available an alternative was developed. The DSC-MCPCB method developed during this project significantly out performs standard MCPCB technologies by eliminating the dielectric material between the LED slug and the heat spreader. This replaces the .3-4W/(m*K) thermally enhanced dielectric layer with 47W/(m*K) solder. An electrically isolated thermal slug is required, but this is a popular trend in modern power LEDs including the MX-6.

The first prototype was fabricated on a 6” copper disk. Because the LED package design included a .05 mm recessed thermal slug, a copper spacer was designed to both contact the slug directly and raise the LED off of the copper substrate. Soldering was achieved with solder paste and a raising the temperature of the entire assembly under monitoring from a thermocouple to approximate the recommended solder time/temperature profile. It was determined that the raised LED supported solely by the slug placed excessive levels of mechanical stress and caused several LED mechancal failures. A second attachment method was developed and used to fabricate a LED board with 14 LEDs on a 5” copper disk. A layer of .001” Kapton tape with silicone adhesive (500˚F rated) was used as an insulator between the LED and copper substrate. Patterned holes were then cut through the kapton tape to allow the thermal slugs to be directly soldered to the copper substrate. This resulted in even higher performance and simpler construction. Final slug to heat spreader thermal resistance was calculated to be .2K/W compared with traditional MCPCB designs which yields resistances in the range of 1.2-15K/W. This significant improvement allows for higher permissible heatsink temperatures which allow for smaller a heatsink and lower junction temperatures.



Assembly

A low cost incandescent fixture was purchased to be modified and allow simple attachment to the ceiling mounted junction box. The LED board was attached to the heatsink with screws and thermal grease as a thermal interface material. The cases of the power supplies were modified to fit into the upper ceiling mounted portion of the lighting fixture.



Testing

With the LED board and heatsink assembled the thermal resistance of the heatsink was evaluated. With a fixed input power of 14 watts a temperature rise of 21 degrees was observed. This indicates a heatsink thermal resistance of 1.5

K/W. This is far superior to the 2.5 K/W design specification and results in higher performance due to lower junction temperatures. Final junction temperatures are below 65˚C yielding an expected L70 life of 130,000 hours.

Results

Power consumption

The final LED fixture consumes 20 watts of power vs the 28 watts of the stock fixture. The power factor was improved from the stock level of .5 to a final value of .65. Further improvements could be made in power factor using a custom designed power supply with active power factor correction. The VA of the LED fixture is 30 VA vs the stock fixture 56.

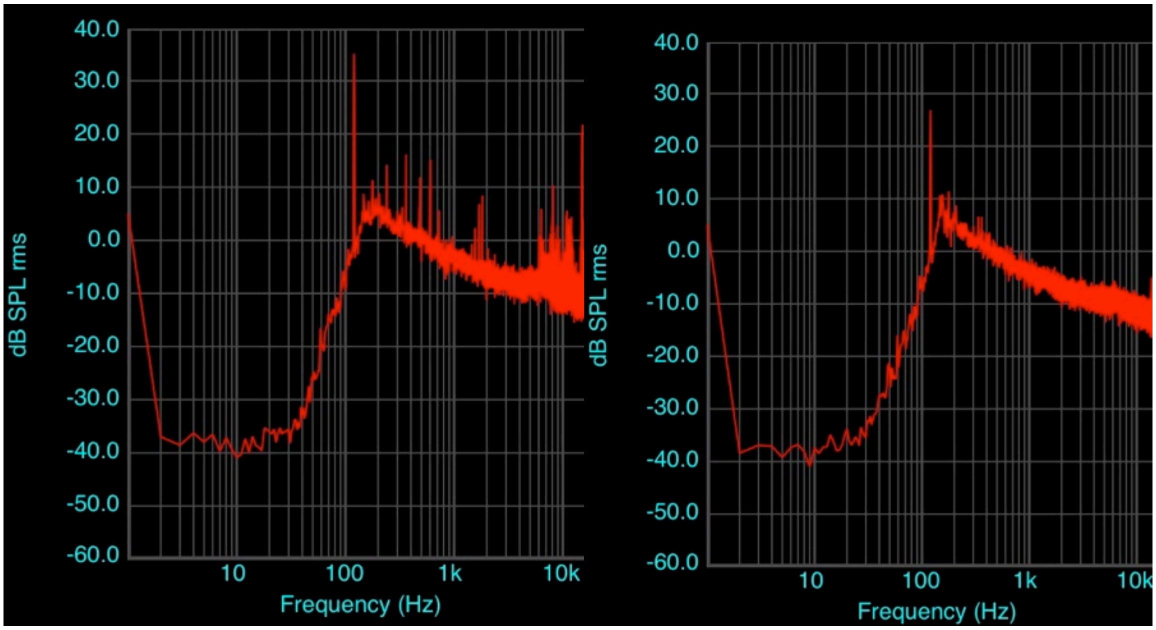
Light output

The LED fixture produces not only more light overall but also a more optimal light distribution. A greater percentage of the light is directed down in areas of high usage. The overall flux obtained from zonal integration of the LED fixture is approximately 1000 lumens vs the stock fixture of 640 lumens. The overall increase of light output results in work surface illumination levels increasing from the stock value of 2.8 foot-candelas to 7 foot-candelas. The CCT is also much more suited to living quarters at 2700K vs the stock 4000K. While the CRI of the Cree LED is approximately the same as the stock fixture, the overall quality of the illumination is far more natural than the stock fixture due to the higher illumination level and warmer tone.

Stock LED

Other characteristics

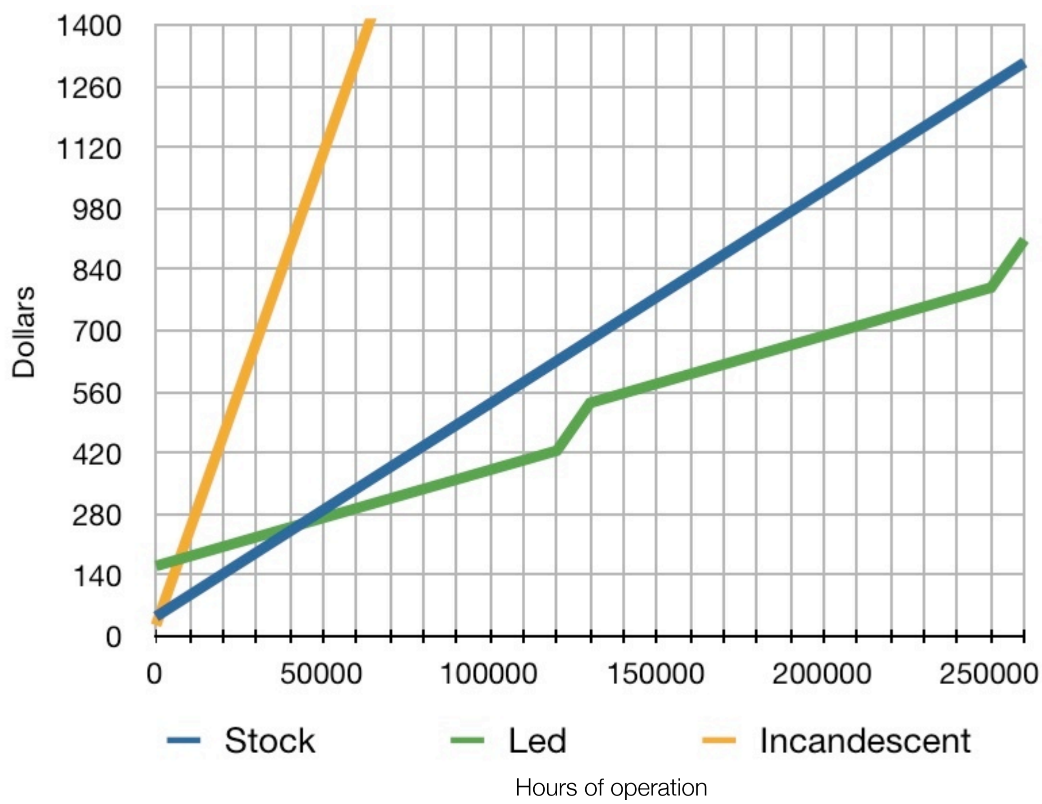
The LED fixture produced no audible noise where as the stock fixture produces significant (35 db) low and high frequency noise. In the FFT graphs below the LED fixture matches ambient noise.



Stock LED

Conclusion

The use of LEDs provides a cost effective (lifetime costs) alternative to existing lighting technologies in residential applications with many added benefits.



Schedule


Senior Design project schedule
LED Light Fixture
Andrew Harmon
20-Jan
27-Jan
3-Feb
10-Feb
17-Feb
24-Feb
3-Mar
10-Mar
17-Mar
24-Mar
31-Mar
7-Apr
14-Apr
21-Apr
28-Apr
Analyze Existing Fixture
Light output
Power consumption
Determine Fixture Requirements
Light output
Thermal requirements
Power supply req.
Design
LED Selection
LED Evaluation
Heatsink Design
Power supply selection
Optical design
Construction
LED Electrical
Heatsink
Optical
System Integration
Testing
Light output
Power consumption
Thermal
Deliverables
Proposal
Initial budget
Gantt chart
Fixture analysis
Design presentation
Final budget
Progress update
Testing results
Final report
Demonstration
Complete
Yet to be completed

Bill of Materials

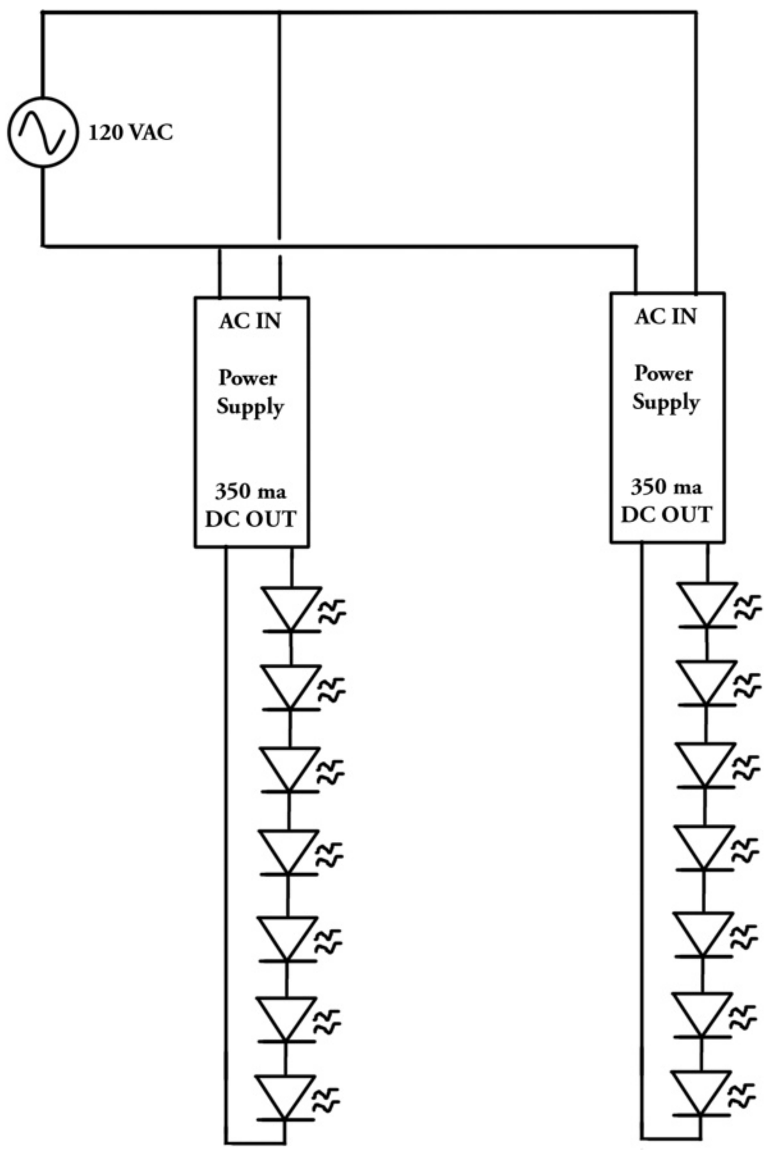
BOM for Fixture

Description	Quantity	Unit Price	Cost
Fixture for modification	1	$8.95	$8.95
LED, Cree MX-6 2700k	14	$4.60	$64.40
Copper Disk 6”	1	$8.55	$8.55
Copper Disk 5”	1	$7.80	$7.80
Copper Nails	500	$0.02	$10.50
Kapton tape	1	$0.10	$0.10
Thermal grease	1	$0.20	$0.20
Solder Paste	1	$1.00	$1.00
Power Supply, Dialight 9x1	2	$21.12	$42.24
		Total	**$143.74**

BOM for “Bulb”

Description	Quantity	Unit Price	Cost
LED, Cree MX-6 2700k	14	$4.60	$64.40
Copper Disk 5”	1	$7.80	$7.80
Kapton tape	1	$0.10	$0.10
Thermal grease	1	$0.20	$0.20
Solder Paste	0.1	$1.00	$0.10
		Total	**$72.60**

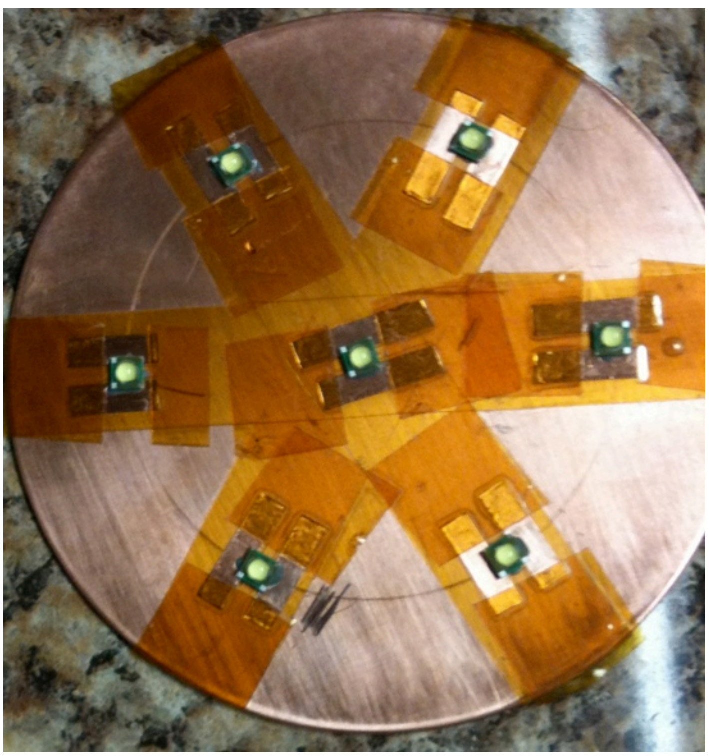
Schematic



120 VAC
AC IN
Power
Supply
350 ma
DC OUT
AC IN
Power
Supply
350 ma
DC OUT

Secondary project

After developing the DSC-MCPCB and heatsink fabrication techniques a second LED light was assembled. The goal of this light was a compact actively cooled light engine with a very high luminous flux. The light utilizes seven Cree XP-G LEDs (CCT 6650K, 130 lm/w, 5 watt rated power) mounted on a 3" DSC-MCPCB. The heatsink is a custom fabricated copper pin fin type actively cooled with a fan. The total power of the LEDs at an operating current of 1 amp is approximately 25 watts. The total luminous flux produced by the LEDs is about 2300 Lumens. The optical system is composed of 7 plastic TIR lenses with an 8° beam angle specifically designed for the Cree XP series LEDs. While running at power level of 25 watts only a 5°C temperature rise of the heatsink is noted due to the active cooling from the fan. Illumination at a distance of 1.5 feet exceeds 20,000 Foot-candela which far illumination levels of direct sun light. The LuxDrives Buck driver allows modulation of the drive current at a frequency at up to 10Khz. This high speed modulation provides a foundation for the creation of an ultra fast solid state strobe light. Several test images of the spray from an aerosol can were taken operating in the region of <600hz. This type of strobe can be used for velocity analysis and particle tracking.   The concentrated beam pattern also is well suited for search light applications. An image of the lamp as viewed from approximately 150 ft is also included below.



LED DSC-MCPCB

LED Board with lenses

Images of aerosol spray at a strobe frequency under 600 hz. Notice the traceability of individual droplet paths

View of the light in the beam path from 150 ft (note source diameter is only 3" yet is much brighter than both the Hg vapor flood lamp and Na vapor street light in the pictutre)