Europa Nav Lights Using Luxeon LEDs

Dr. Andrew Sarangan
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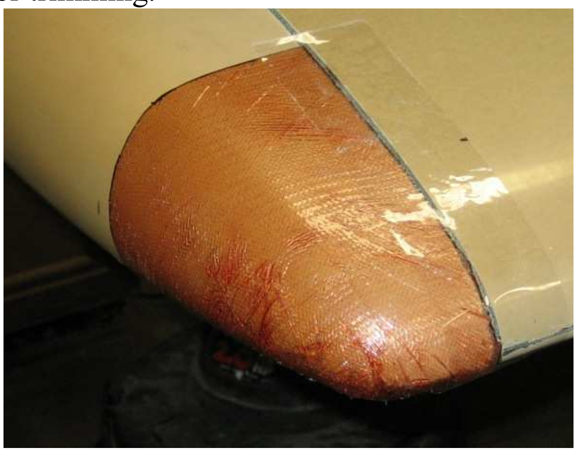
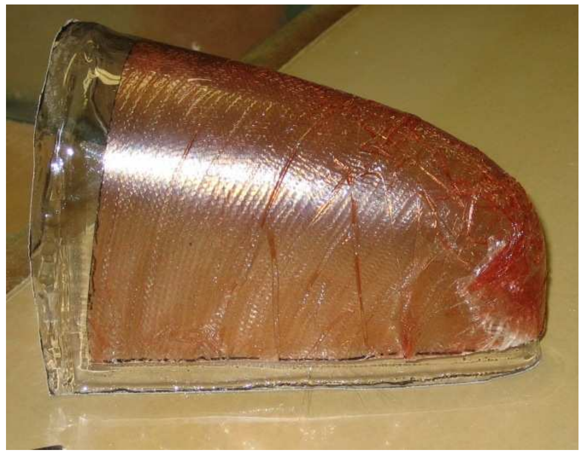
Installing an LED nav light system on the Europa XS wings involves the following tasks:
- Building flanges and mount points for the transparent light covers
- Building the reflector and mount points
- Building the LED assembly
- Building a current driver circuit

Fred Klein sells polycarbonate light covers designed to fit the XS wingtips. The first step is to trim the light covers so that they perfectly match the wingtip cutout. This is actually more difficult than it sounds. The best approach is to construct a fiberglass mold of the wingtip, and use that as a template for trimming.



Fiberglass molded over the wingtip and cut to the desired dimensions

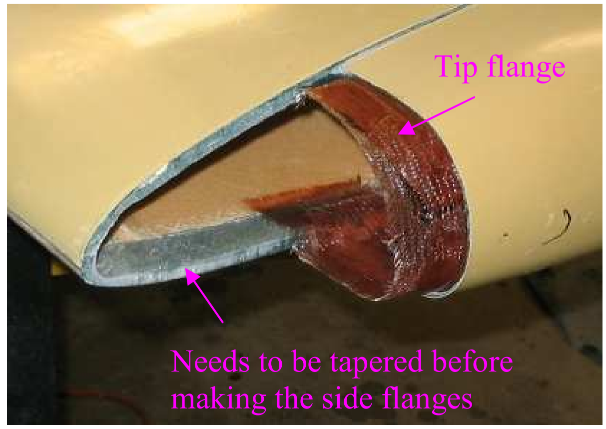


Template for trimming the light cover

Next, flanges need to be constructed for mounting the light covers. This is done by laying a 2”-wide two-layer bid on the inside surface of the wingtip, with about 1” projecting into the cutout area. Using a thin plastic wrap to protect from the wet epoxy, the light cover is gently positioned and held with scotch tape while ensuring that the bid conforms to its inside contour. This will require some pat down of the fiberglass from the inside surface. The only way to access this area is from behind the spar through the wing tip cavity. A brush or sponge attached to a wooden pole can be used to reach this area and manipulate the fiberglass. It is a bit awkward, but it works. The glass should be cured with peel ply to allow another layer of glass to be laid on top later.

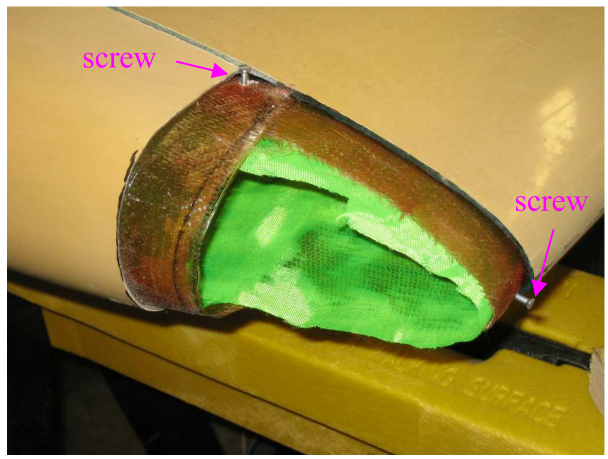
Constructing the tip flange

Before constructing the side flanges, the wing skin must be tapered down to the same thickness as the plastic light covers. Otherwise, there will be a step at this interface, making it difficult for the fiberglass to follow the surface.

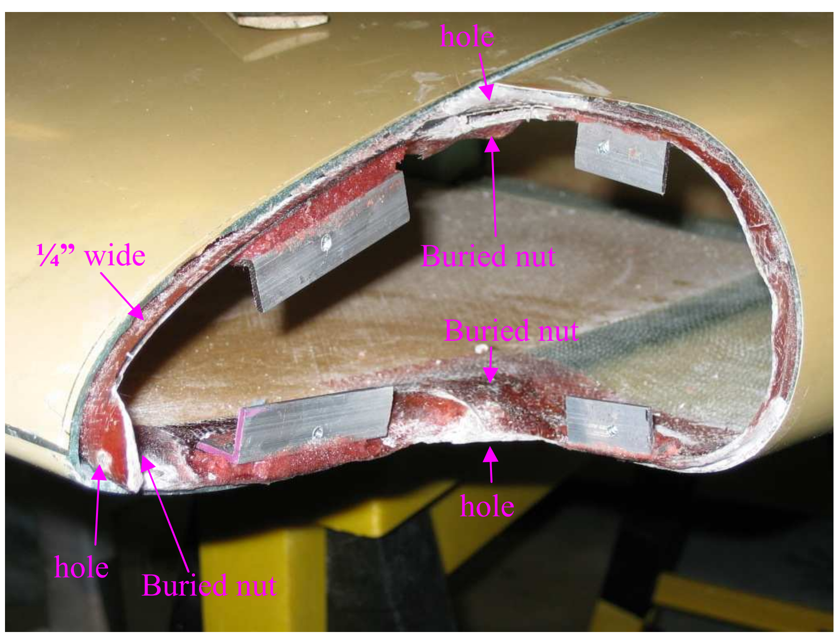


Tip flange after curing

After curing, the light cover is trial fitted and temporarily fastened with some scotch tape. Three #4 holes are then drilled through the light cover and the flanges – one on the leading edge and two on the top and bottom corners. After trial fitting #4-40 machine screws, the nuts should be bonded to the underside of the flanges with flox and one more layer of bid (modeling clay should be used to prevent epoxy from getting into the nuts). The entire flange is now three layers thick. After curing, the flanges are trimmed so that they are about ¼" wide, except near the screw holes where they should be about ¼" from the screw holes. Next, ½" x ½" 90-degree aluminum brackets are cut into four pieces to make the attachment points for the reflector. A #4 hole is drilled through each piece and a nut is epoxied on the back side of each hole. Several large holes should be drilled on the other side of the aluminum pieces for the flox to flow through then bonded under the flanges, ensuring that their front surfaces make 90-degrees to the flanges.



Both flanges

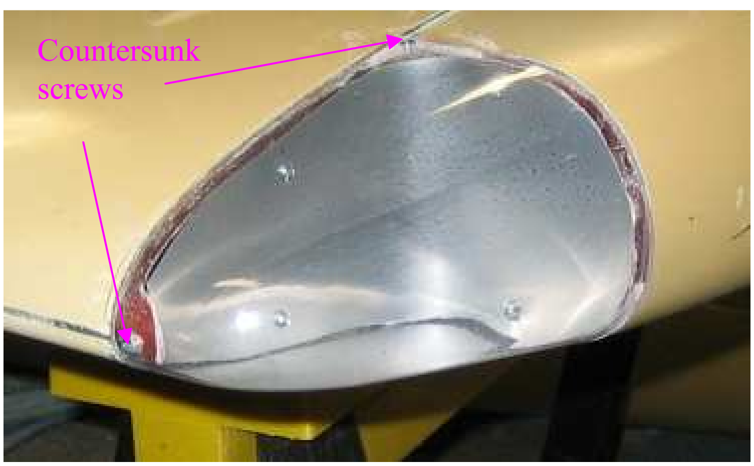


Reflector attachment points

The reflector is constructed from a piece of flashing aluminum trimmed to fit the cutout area. A piece of paper could be used to trace the approximate shape and transferred to the aluminum. Holes are then drilled to match the attachment points, and the reflector is installed with #4-40 machine screws.

Reflector

The transparent light cover should be trial fitted, and any excess aluminum should be trimmed off as necessary. The holes on the light cover should be tapered and used with flat-head countersinking machine screws for a smoother finish.



With reflector and light cover assembled

The LED assembly will be mounted directly on this aluminum reflector.

Lumileds Lighting makes the brightest LEDs in the industry, known as Luxeons. A single unit is capable of producing more than 150 lumens, which in theory should be sufficient to meet the requirements of CFR 23.1389. With two LEDs, the resulting illumination will be significantly higher than the FAA requirements. For the port side, two red Luxeon III Stars are used. For the starboard side, a green Luxeon V and a green Luxeon III Stars are used.

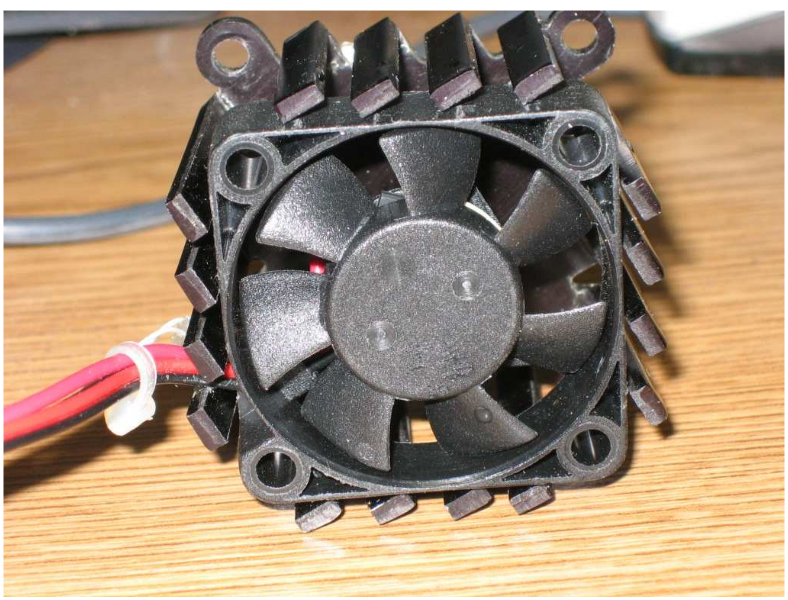
The LEDs must be mounted on a heatsink, which also serves as a mechanical platform for the assembly. Lumileds recommends using the Aavid heatsink, which measures 46mm x 46mm. The LEDs should be bonded to the heat sink using Arctic Silver Thermal Epoxy. Arctic Silver is one of the best thermal epoxies in the market. The instructions for its use should be followed carefully (surface prep, cleaning, curing etc..). The LEDs should be oriented such that the +ve pad of one LED is adjacent to the –ve pad of the other LED. The two LEDs must be electrically isolated from each other. Sometimes multiple LEDs are shipped in a single strip without separating them into pieces. If they are bonded this way, their substrates will be electrically shorted. Also, it is important to ensure that the black anodization on the heat sink is free of scratches to prevent electrical shorts.

Bonding Luxeon LEDs to the heatsink

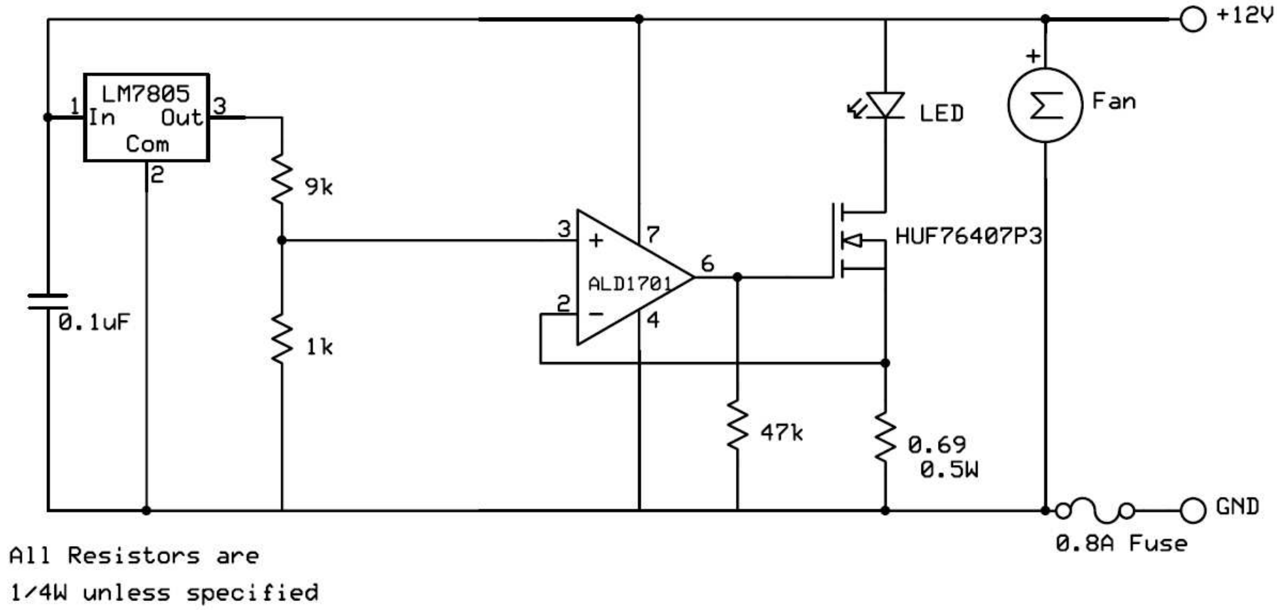
A small piece of wire is then soldered from the +ve pad of one LED to the–ve pad of the other LED. Two holes are drilled at the opposite ends of the LEDs to fit 22 gauge electrical wires for the +ve and –ve terminals. Another hole is drilled near the center of the heatsink to allow a thermistor to be bonded. The thermistor is used for monitoring the heatsink temperature. Since it doesn't carry much current, it could be wired with thin 30-gauge wires.

LED wiring and thermistor

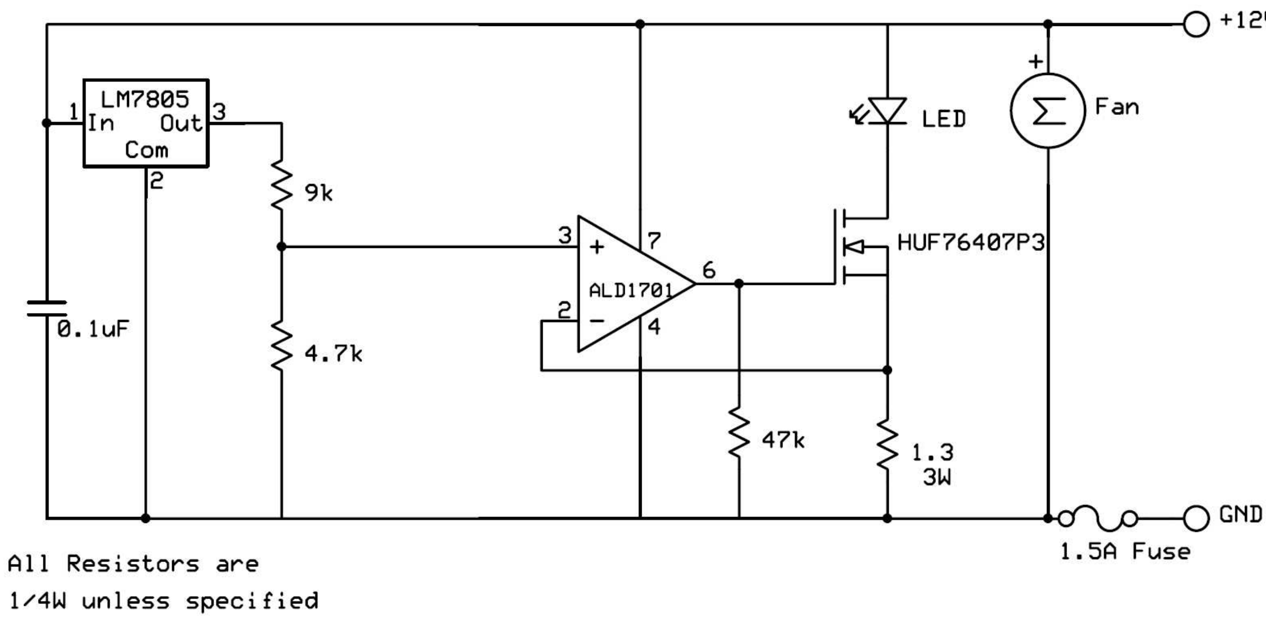
Next, a 40mm cooling fan is fitted behind the heatsink. The heatsink fins should have enough mechanical pressure to firmly hold the fan in place without any extra attachments. If necessary, it could be epoxied in place later. Cooling efficiency is greater if the fan is blowing onto the heatsink rather than drawing air from it; i.e., the power wires should be facing the heat sink. This fan draws 70mA and makes only 14dB of noise. Not that noise matters in an aircraft, but it is virtually impossible to hear the fan running even up close.



Cooling fan

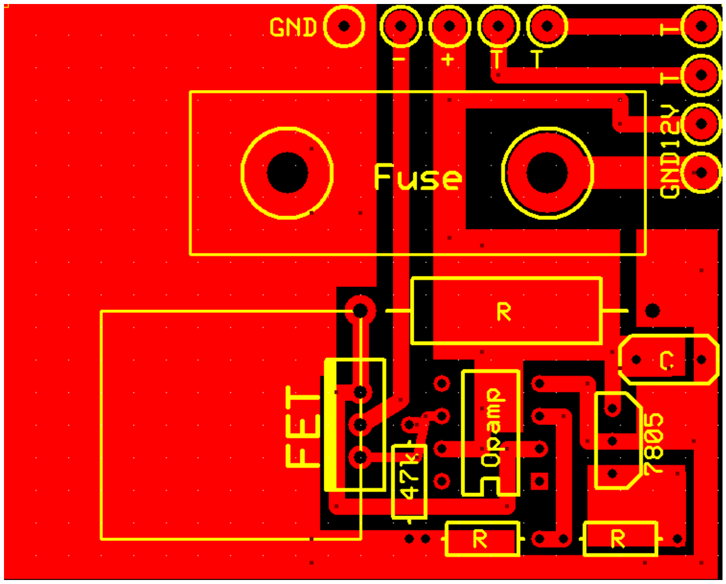


Green LED current driver circuit (700mA)

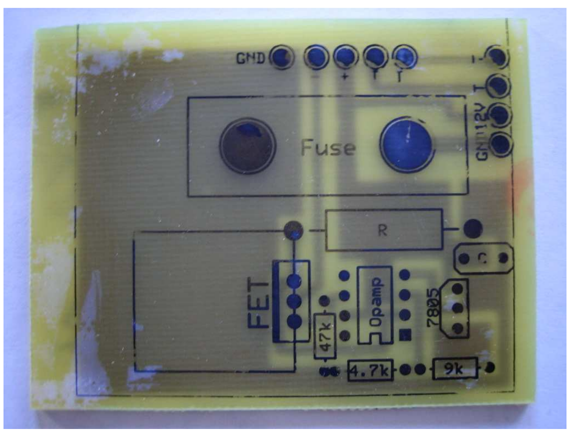


Red LED current driver circuit (1400mA)

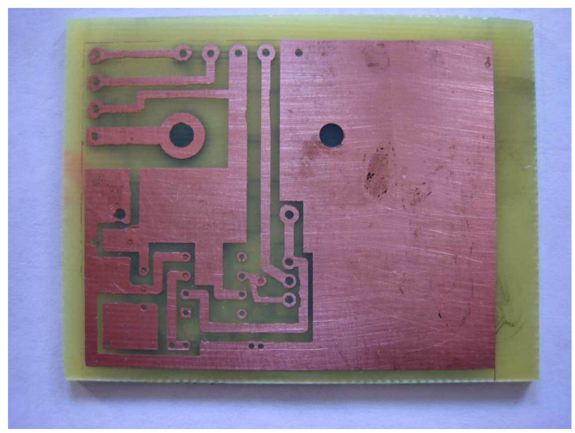
The driver circuitry is built using a power MOSFET, a precision opamp and a 5V regulator. The MOSFET requires a TO-220 heatsink. The simplest approach is to assemble the circuit on a generic breadboard. A more elegant approach is to make your own printed circuit board (PCB) using the template shown below. The pattern is transferred to a copper clad board using a laser printer toner transfer method, followed by a chemical etch to remove the unwanted copper. *A couple of modifications have been suggested to this circuit – (1) Install the fuse on the +12V line instead of GND, especially for a metal aircraft; (2) install a 0.1μF capacitor between Out and Com of the 7805 regulator. The PCB has to be modified to accommodate these changes.*



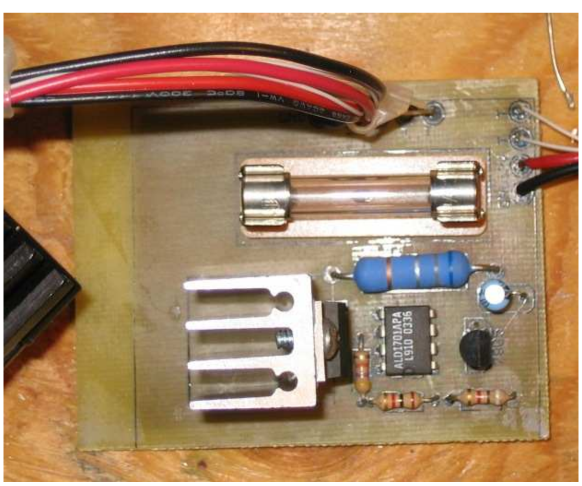
Printed Circuit Board Template



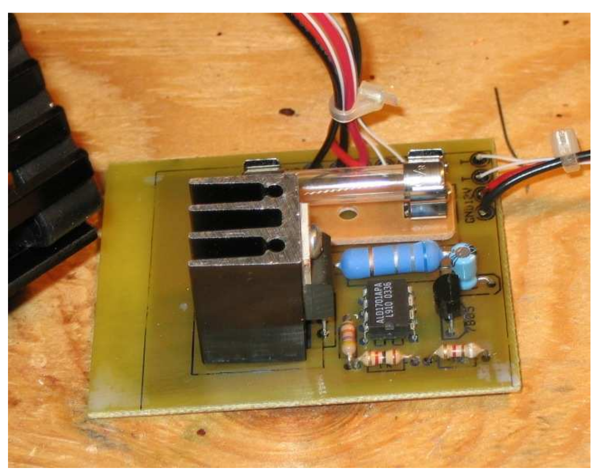
Printed Circuit Board



Printed Circuit Board

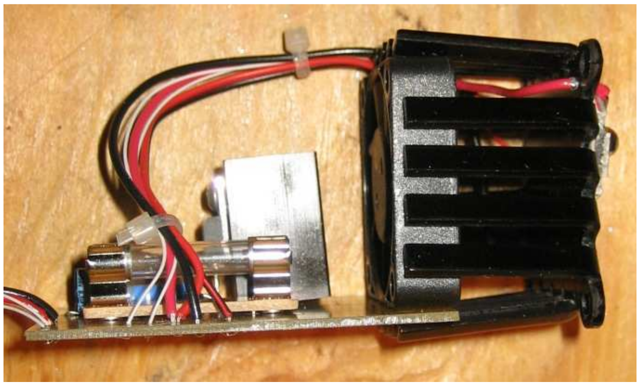


Assembled Circuit

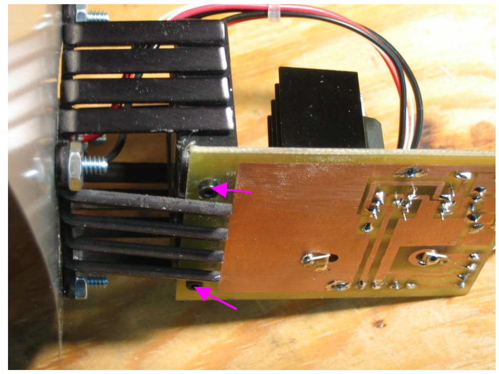


Assembled Circuit

After assembly, the board is tucked between the heatsink fins and the fan, and a couple of screws to attach it to the fan frame.

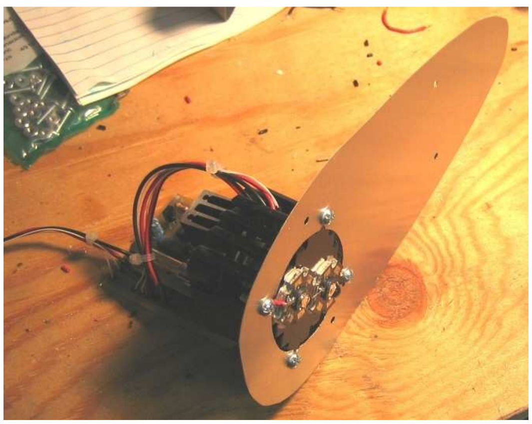


Circuit board mounted to heatsink

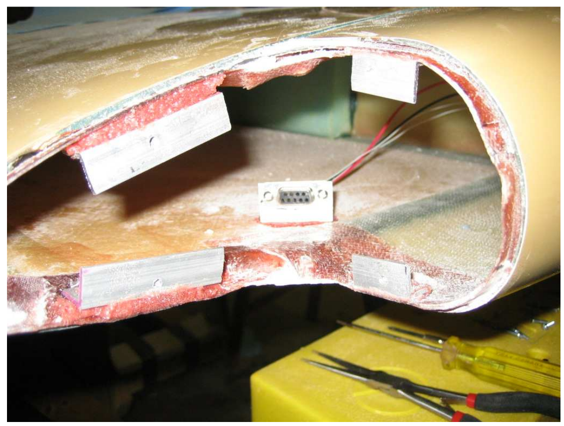


Circuit board mounted to heatsink

A hole approximately 30mm in diameter is cut in the reflector sheet with four #6 holes to mount the LED heatsink. The whole assembly is now ready for mounting to the aircraft.

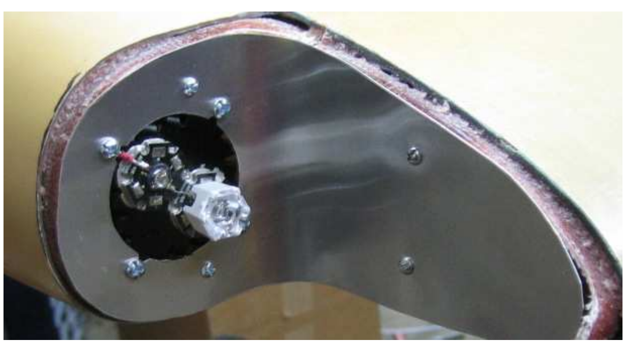


LED assembly mounted to reflector

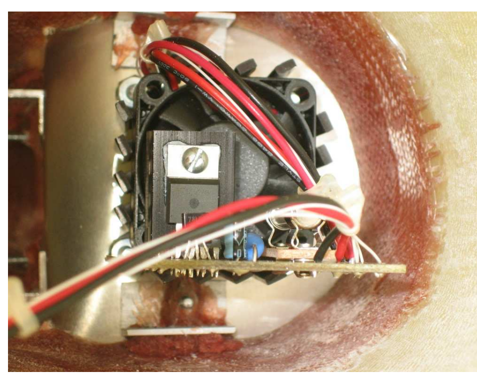


9-pin D-sub connector

The four leads to the LED assembly (+12V, Ground and two thermistor leads) can be terminated with a crimped 9-pin D-sub plug to make assembly and disassembly more flexible.



Mounted LED assembly



Mounted LED assembly view from behind

After the assembly is mounted to the aircraft, the 25-degree polymer lens is bonded to one of the LEDs. This improves the forward emission pattern of the LED. Finally, the light cover is attached.

<u>Specifications:</u>

Supply:	12V
Weight:	3.2oz (each side)
Wiring:	22 gauge (30-gauge for thermistor)

<u>Test Conditions:</u>

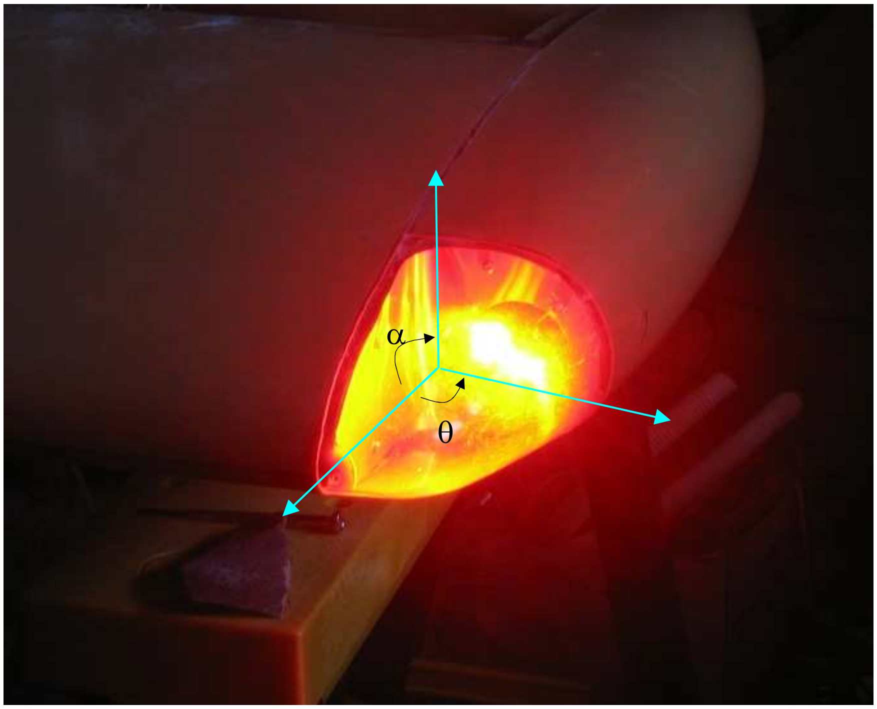
Ambient temperature: 10C

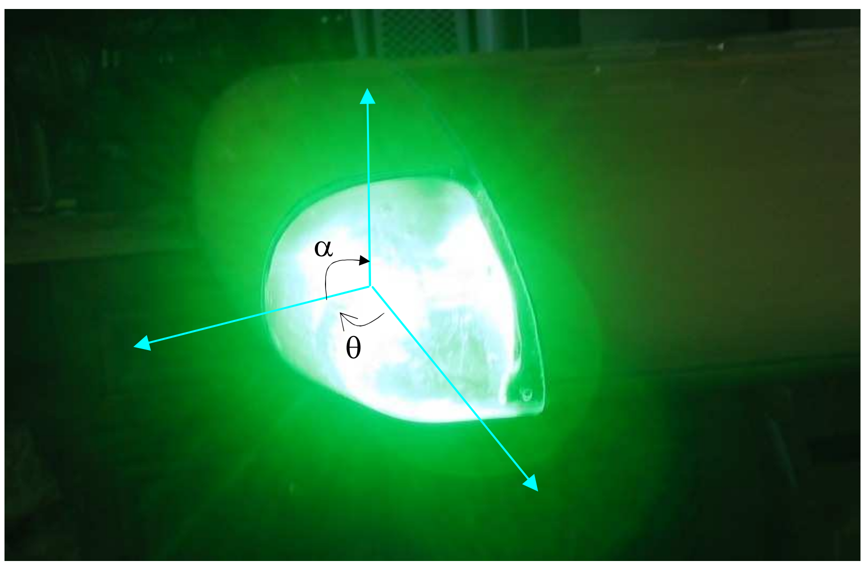
<u>Red Lamps:</u>

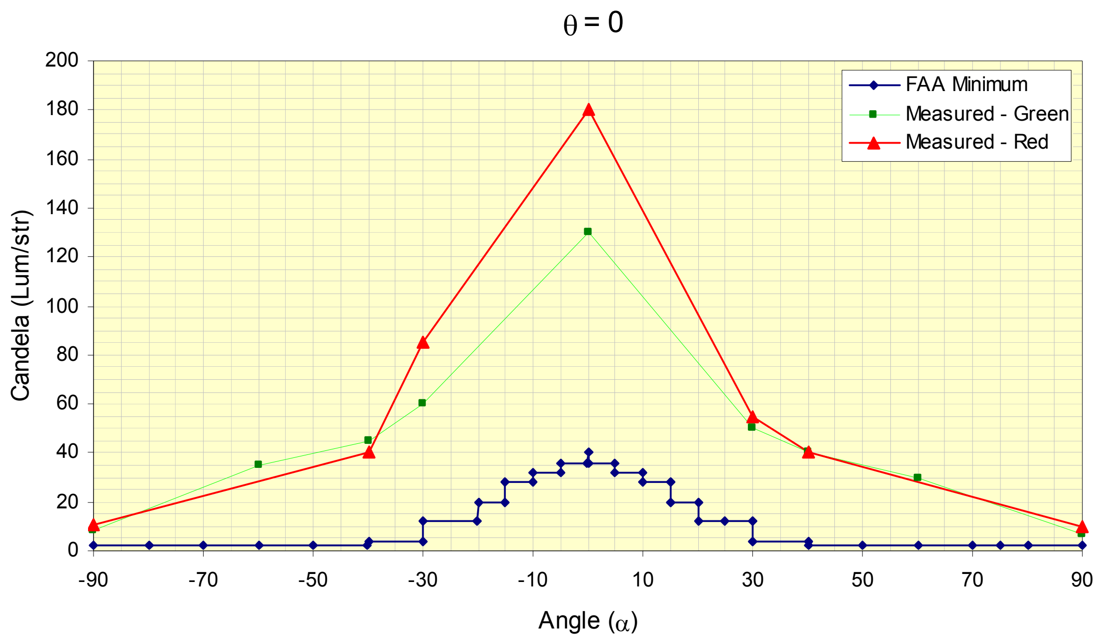
Current:	1.4A
Voltage drop in wiring:	0.5V
Power dissipated in FET:	5.5W
Power dissipated in R:	2.4W
Power dissipated in LED:	8.2W
Voltage drop in LED:	5.9V
Power transfer efficiency:	49%
Temperature of heatsink:	28C (18C rise over ambient)

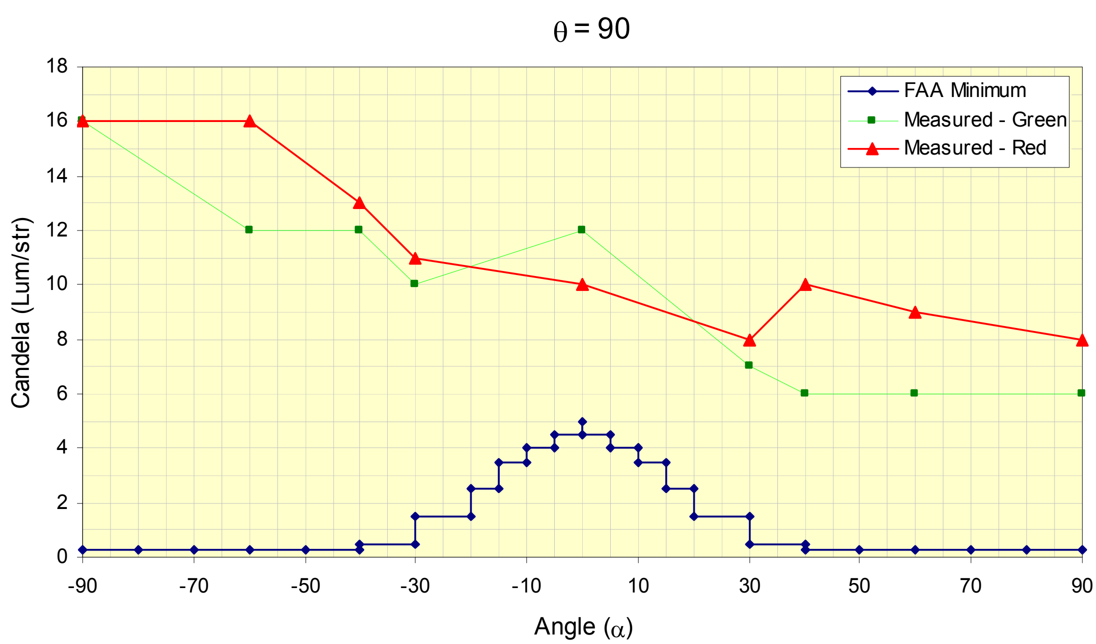
<u>Green Lamps:</u>

Current:	0.7A
Voltage drop in wiring:	0.5V
Power dissipated in FET:	1.0W
Power dissipated in R:	0.35W
Power dissipated in LED:	6.7W
Voltage drop in LED:	9.6V
Power transfer efficiency:	80%
Temperature of heatsink:	26C (16C rise over ambient)


α
θ


α
θ





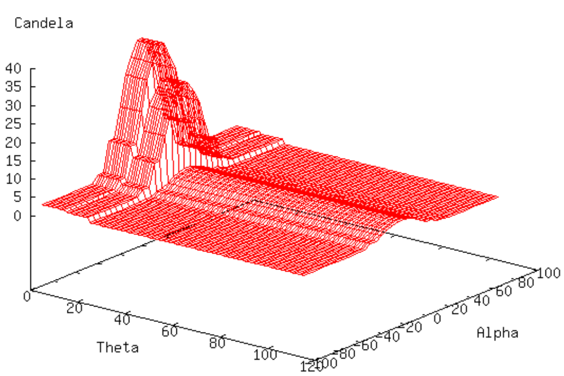
θ=110, I=5 Lum/str (FAA Min = 5)

How to Use the CFR Specifications of Minimum Intensity Distribution

The minimum intensity is specified in Candles (same as candela), which is the luminous flux (lumens) contained in one unit of solid angle (steradian). Therefore the unit of candela is lumens per steradian (lm/sr). The understanding of the units is not terribly important for this application.

The intensity distribution can be described as a function of θ (measured in the horizontal plane), and α (measured in the vertical plane), which can be written as a 2-D function $F(\theta,\alpha)$. This can be plotted in spherical co-ordinates using $(r,\theta,\alpha) = (F(\theta,\alpha),\theta,\alpha)$, or in Cartesian co-ordinates as surface plot with $(x,y,z) = (\theta,\alpha,F(\theta,\alpha))$. But some 2-D functions, as in this case, can be broken down into a product of two 1-D functions:
$F(\theta,\alpha) = F_1(\theta) * F_2(\alpha)$.

§ 23.1391 specifies the first function $F_1(\theta)$, and § 23.1393 specifies second function $F_2(\alpha)$. They give three numbers to describe $F_1(\theta)$, and 15 numbers to describe $F_2(\alpha)$. Actually they only give 8 values for $F_2(\alpha)$, but the function is symmetric above and below the plane, so we can get 2*8-1=15 values. Therefore, we have a total of 15*3=45 points to describe the function $F(\theta,\alpha)$. Any intermediate values must be interpolated. Here is the 2-D plot of $F(\theta,\alpha)$ in Cartesian co-ordinates:



It is not necessary to measure the light intensity at every possible angle with great precision. A few representative θ and α values at extreme positions can be chosen to verify that they exceed the minimum specified values. Of course this assumes a fairly uniform intensity distribution. If the light employs unusual constructions or reflectors, this assumption may not always hold true.

In my case, I chose to only make two cross-sectional measurements: $F(0,\alpha)$ and $F(90,\alpha)$. These are $F_1(0)*F_2(\alpha)$ and $F_1(90)*F_2(\alpha)$ respectively. Since $F_1(0)=40$ candela and $F_1(90)=5$ candela, they become:
$F(0,\alpha)=40*F_2(\alpha)$
$F(90,\alpha)=5*F_2(\alpha)$
Therefore, the plots are exactly the same shape except the second one is scaled down by a factor of 8.

To further complicate matters, most light meters will read values in Lux, which is lumens/m^2. At a distance of 1m, one Lux is equal to one candela, or one lumens/str. Since intensity falls off as a square of the distance, at a distance of 2m, one Lux will equal to 4 candela and so on.

Ideally, the light fixture must be suspended in mid-air and the measurements taken from a long distance away so that the light source can be approximated as a point source. The greater the distance compared to the dimensions of the light fixture, the more accurate the results will be. If the light fixture, including the reflectors is 4” in size, a distance of 400” (33 ft) with no obstacles in between will give accurate readings. But this is clearly impractical on an aircraft. The aircraft would have to be suspended 30ft up in the air to get that kind of clearance. A typical wing is only 2ft above the ground, and it is doubtful that the measurements taken from such small distances will be very accurate, and scattered light off the ground surfaces will add to this error. Fortunately, the exact number is not as important as that it exceeds the FAA minimum. So there is little reason to go into great trouble to make these measurements. If rough measurements exceed the FAA minimums with a healthy margin, there is no reason to worry about the accuracy.

Another important aspect is that these functions only define the outboard hemispheric intensity (θ=0 to 180) distribution for each position light. The other hemisphere, ie the inboard portion (θ=-180 to 0) is assumed to be negligible. In other words, each light should not radiate too much into the other light's hemisphere. How small this value has to be, is defined in § 23.1395. If the lights are properly shielded such that they do not radiate inboard, this should not be a big issue.

FAR 23.1391 Minimum intensities in the horizontal plane of position lights.

Angle from right or left of longitudinal axis, measured from dead ahead (θ)	$F_1(\theta)$ (candles)
0° to 10° 10° to 20° 20° to 110°	40 30 5

FAR 23.1393 Minimum intensities in any vertical plane of position lights.

Angle above or below the horizontal plane (α)	$F_2(\alpha)$
0°	1.00
0° to 5°	0.90
5° to 10°	0.80
10° to 15°	0.70
15° to 20°	0.50
20° to 30°	0.30
30° to 40°	0.10
40° to 90°	0.05

Parts:

- Two Polycarbonate light covers, Fred Klein fklein@orcasonline.com: $100
- Two Aavid Thermalloy heat sink #500400B00000, www.lumiledfuture.com: $3.20 x 2
- Two Red Luxeon III LED, #LXHL-LD3C, www.lumiledfuture.com: $4.63 x 2
- One Green Luxeon V LED, #LXHL-LM5C, www.lumiledfuture.com: $12.70
- One Green Luxeon III LED, #LXHL-LM3C, www.lumiledfuture.com: $3.46
- Two 25-deg Polymer Optics collimator, #124/128, www.lumiledfuture.com: $2.30 x 2

- Arctic Silver Thermal Epoxy, www.outletpc.com: $10.00
- Two Thermometrics Thermistors, #2890-95-MS, www.mouser.com: $1.75 x 2
- Two Adda Fans, #AD0412LBG70(T), www.mouser.com: $11.26 x 2
- Two HUF76407P3 MOSFETs, www.mouser.com, $0.82 x 2
- Two ALD1701APA OpAmps, www.mouser.com, $3.21 x 2
- Two L78L05ACZ Regulators, www.mouser.com, $0.54 x 2
- Two 441-EPD201V Fuse holders, www.mouser.com, $0.34 x 2
- Two TO-220 heat sinks, #276-1368, www.radioshack.com: $1.70 x 2
- Approx total cost: $190.00 (excludes shipping and general electronics supplies and hardware)

Design Considerations

Reflector

A reflector is an important item because it will redirect the light that is going inboard, which could be as much as 50%. A standard aluminum surface has a reflectivity of about 80%. The most economical and easy-to-handle material is flashing aluminum, which is normally used in roofing construction. It is about 0.01" thick and comes in rolled sheets. It is flexible, light and can be cut with a pair of scissors.

A removable reflector was an important consideration because it alleviates the need for a separate access panel. The entire wingtip cavity becomes accessible by removing the reflector. This could come in useful for future upgrades like strobe or antennas.

Heatsink & Ventilation

High-power LEDs are like CPU's. They generate a lot of heat and must be mounted on a heatsink with proper ventilation for reliable operation. In fact, almost all of the electrical power is converted to heat; only a tiny fraction is converted to light. That's ok, because incandescent lamps are much worse. Lumileds warns against operating the LED without a heatsink for more than few seconds. The goal is to keep the internal temperature below 100C for improved performance and a slower degradation (yes, LEDs do degrade with time). A temperature of 135C is the absolute maximum, but Lumiled's reliability data does not even extend past 117C, which should say something about the importance of temperature. With two LEDs running on a single heatsink, it is virtually impossible to keep the junction below 100C. With a sloppy design and no fan, one can easily exceed 140C. At that temperature, the LED is unlikely to last very long. It is important to remember is that even when the junction is at 100C, the heatsink will be barely warm so it has little or no effect on the fiberglass.

At first, a fan may not seem like a great idea. However, considering that these fans were designed to operate in computers non-stop for many years, they could very well be one of the most reliable components in the aircraft. The fan functions almost like a solid-state device. There is no audible noise or vibration. Without a fan, a bigger heatsink would be necessary, which would increase the space and weight requirements.

Current Driver

The LED current is controlled by a high current MOSFET and a current sensing resistor. The sensing resistor value was chosen after considering the maximum tolerable drop-out voltage, and the power dissipation in the MOSFET and the resistor. It is best to dissipate as much power in the resistor as possible to reduce the thermal load in the MOSFET. The voltage across the sensing resistor is compared against a reference voltage, which is generated from a 5V regulator and scaled down by a resistor divider. The opamp acts as the comparator, and drives the MOSFET up or down until its two input voltages become equal. The power transfer efficiency of this circuit is 80% for the green driver and 50% for the red driver. The efficiency of the red driver can be increased to 75% if three LEDs are used in series.

A single chip regulator might be an alternative to using a MOSFET and an opamp, but there were no chips that were capable of handling more than 1 Amp at 12V while ensuring a low-dropout voltage.

Red LED Current Driver

Each red LED needs 2.95V, and can be driven up to 1400mA. Since the supply is 12V, one could potentially connect three of these in series and only drop 9V. However, installing three LEDs on the 46mm heatsink could be very tight, and would present an extra-ordinary thermal load on the heatsink and drive the internal temperatures even higher. Furthermore, the light output from the red LEDs drops quite dramatically with temperature. Detailed calculations show that adding a third LED only amounts to adding 50% of its optical power. Hence two LEDs were chosen in this design. With 6V across the LEDs, the regulator need not have a low drop-out voltage, so a large sensing resistor was used to reduce the power dissipation in the MOSFET.

Green LED Current Driver

Green LEDs come in Luxeon III or Luxeon V. Both can be driven up to 700mA. The III uses 3.7V and the V uses 6.8V. Stringing them in series would give 10.5V, which is pretty close to 12V. However, the 1.5V extra margin necessitates a low-dropout design. Hence a low sensing resistor is used along with a high-precision rail-to-rail op-amp. A general purpose opamp would not work in this design because the reference voltage would be too close to the supply voltage rail.

Extra Red LED:

The Red LED driver has enough capacity to drive a third LED. A third LED could conceivably be installed inside the cockpit as a backlighting, and connected in series with the nav light. This configuration would illuminate the cockpit basically for free. The limitation, however, is that nav light has to be on in order for the cockpit light to be on, and any failure in the nav light would also fail the cockpit light.

Why not use a switching regulator?

Many readers have questioned why a switching regulator was not used in this design. Switching regulator can step-up or step-down the supply voltage at high efficiencies (80-90%), and can be configured as a constant-current or constant-voltage source. Firstly, the efficiency of the MOSFET DC regulator is not all that bad, especially if three red LEDs are used in series. Secondly, there was some misconception that increasing the regulator's efficiency could eliminate the cooling fan and heatsink. This is not true. The fan and the heatsink are for removing the heat generated *within* the LED; it is not for removing the heat generated in the regulator. Even if the regulator's efficiency were 100%, a heatsink and fan will still be required.

Nevertheless, a switching regulator could be used to save some electrical power. However, it comes at a price. Turning 1 Amp on and off at several hundred kHz can generate harmonics well into the MHz range unless extreme care is taken to shield this noise. If any VHF antennas are nearby, it could cause possible interference, especially in a composite aircraft.

Hence it was decided that the benefits of a DC regulator outweighed the benefits of a switching regulator for this application.