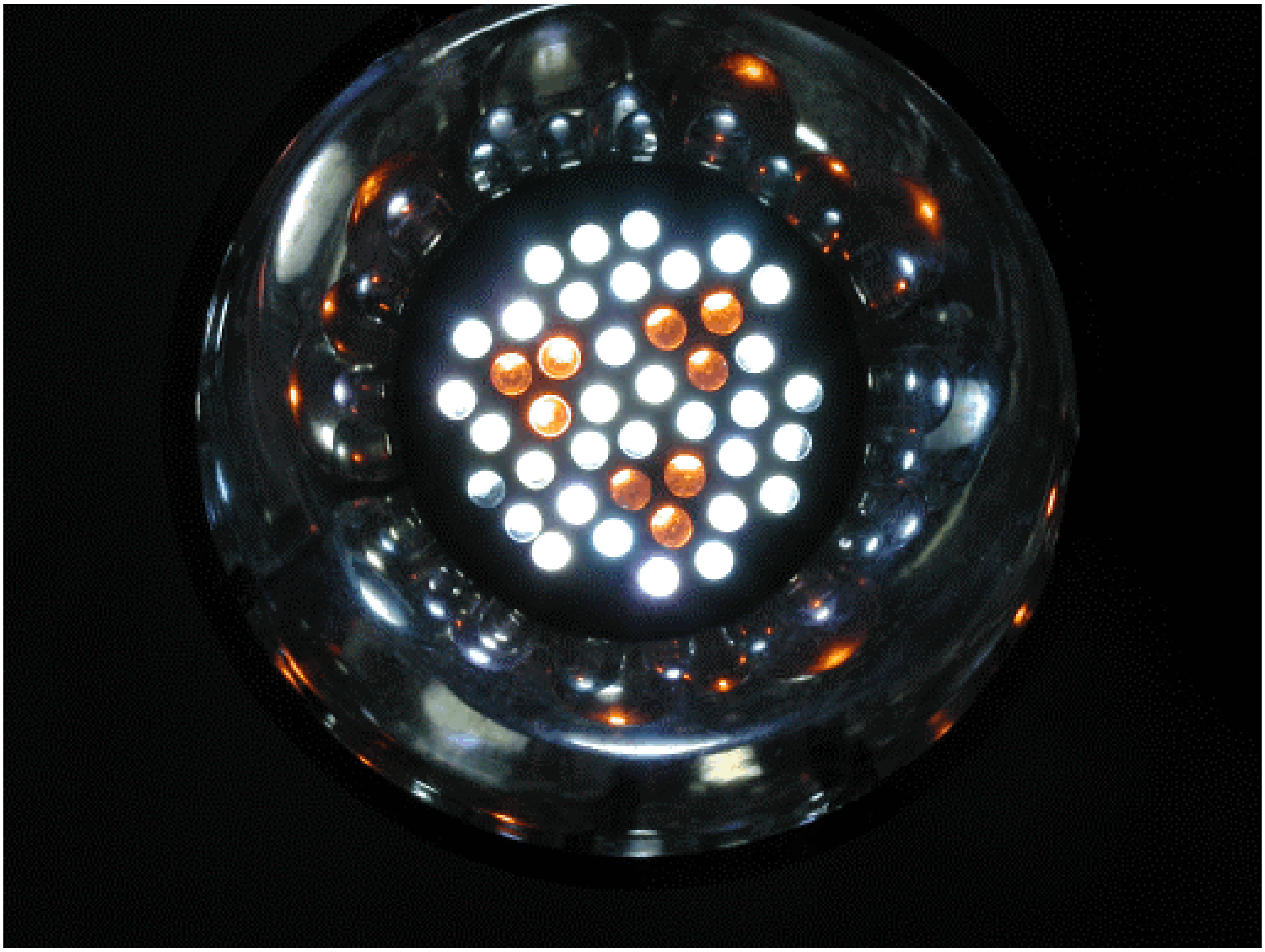
The Perfect LED Light



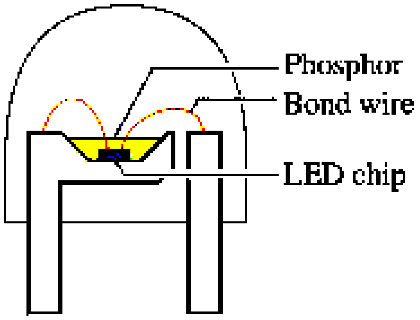
The perfect LED light is designed for cavers who want an efficient, uniform and constant bright light for caving. This article contains some very specific technical information and it is assumed the reader has a basic understanding of electronics. To build the light, the reader also must have some experience soldering, drilling, wiring and cutting small objects. The list of required tools include a multi-meter, Dremel drill and soldering station. The electronics are available from major semiconductor manufactures has "evaluation" kits, but nothing should prevent the reader from "rolling their own" design. The principle cost of the light is the white LED's. The best white LED's are made by Nichia Corporation and are expensive. However, it makes no sense to undertake the project without starting with the best LED's available.

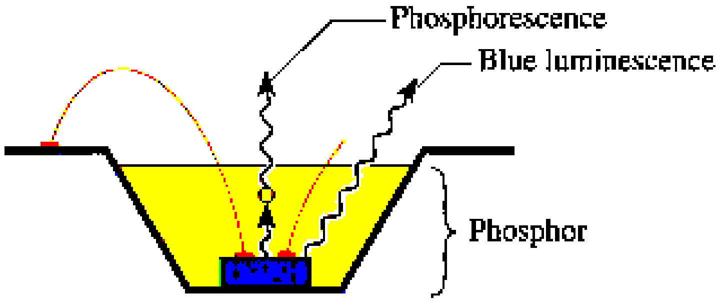
Contents

White Light Emitting Diodes

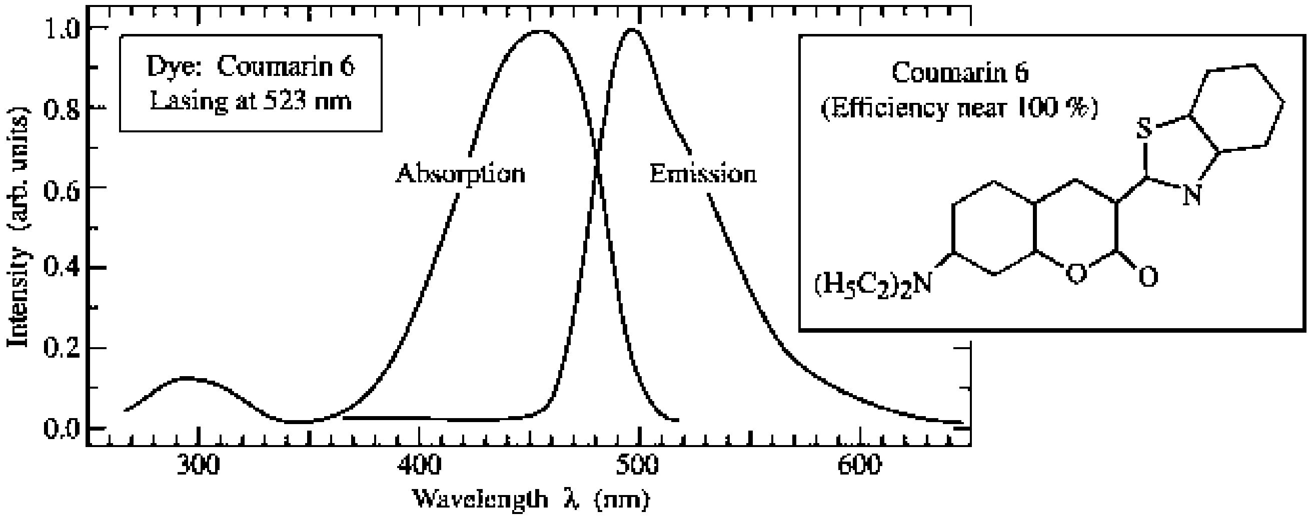
LED's come in a number of different sizes and forms. The ones pictured at the left are commonly referred to as either T-13/4 or 5mm. They are "polar" devices, that is, they have a cathode or negative terminal and an anode or positive terminal. One side of the clear plastic step at the base of the housing is shaved flat, on the cathode side. The cathode terminal or lead is also shorter than the anode. The wide spots on the leads are called standoffs.

LED's are specified by the angular spread of their light beams. The clear plastic housing forms the lens that focuses the beam of the LED. The greater the radius of curvature of the plastic housing, the tighter the focus of the beam is. The larger 10mm designs have a very narrow beam, while surface mount LED's have a wide beam. All LED's from a manufacture's line will produce the same amount of light, but how tightly focused or concentrated the beam is, determines how brightness of the beam. Manufactures specify the maximum brightness of the beam, not its total light output. Therefore it is difficult to compare the light output of two LED's from different manufactures solely by studying the specifications.

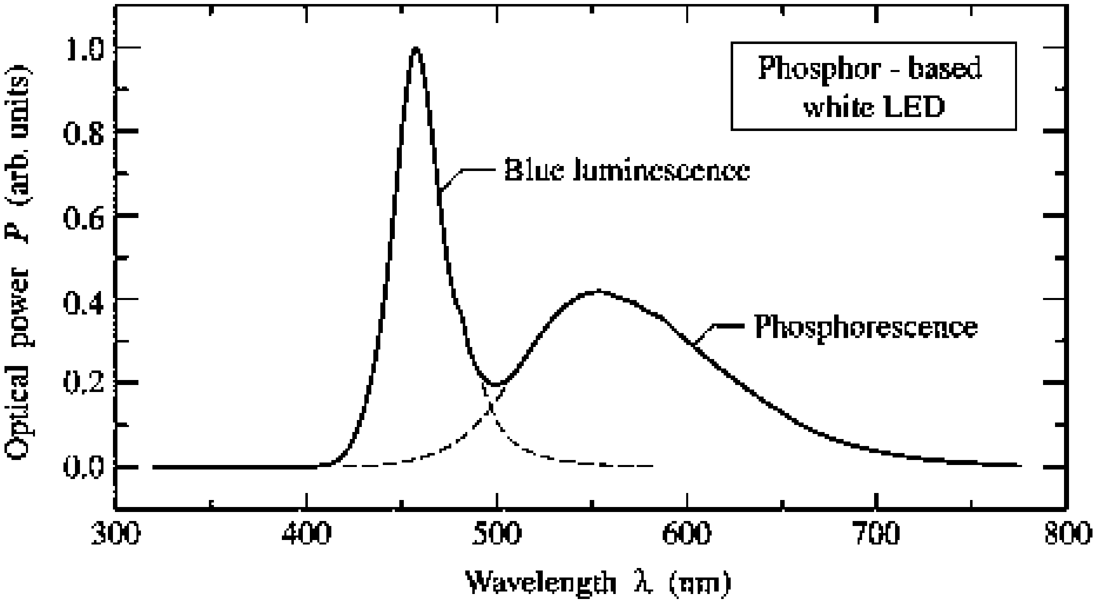




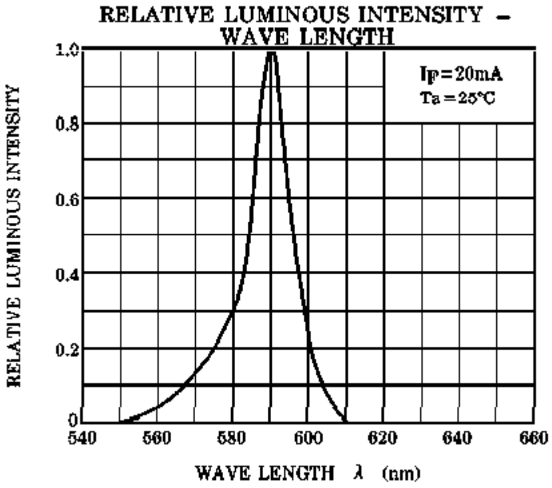
The other unique feature of a LED, like a laser, is the monochromatic color of its light. Typically, the wavelength of light from a LED will only vary by 15nm (the whole visible spectrum covers 700 to 400nm). The miracle of the Nichia design, for which they hold the key patents, is how to produce a wide spectrum, white light from a monochromatic source. The figure above schematically shows the Nichia design.



The GaInN ultra bright blue diode is placed in a well and covered with a phosphorescing dye. The energetic blue photons from the diode are largely absorbed by the dye. The energized dye then reemits the light at a lower energy and in a wider spectrum. The key is the proper selection of the dye, to have an absorption band matching the output of the LED, high efficiency converting light energy and a wide emission spectrum. The figure above shows the absorption and emission spectrum of the dye "Coumarin 6" and the chemical structure of its molecule.



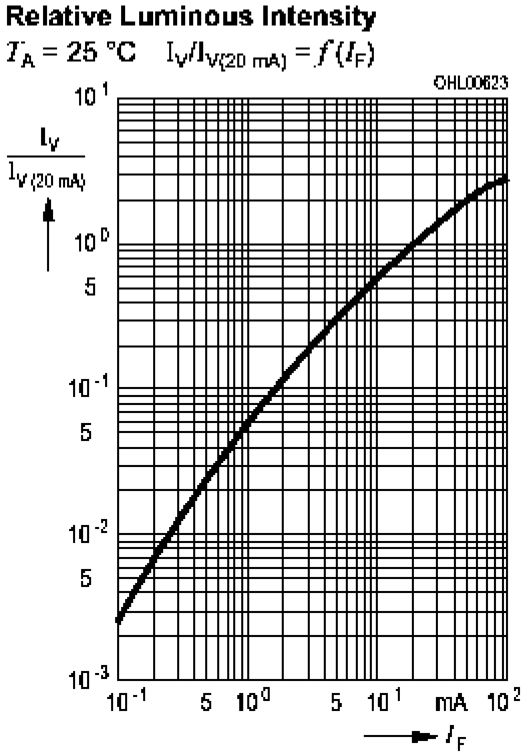
The output spectrum of the Nichia design is show above. The principle LED output is centered on roughly 450nm and the emission of the phosphorescence at 550nm. The "blueness" of the white light produced by the LED is caused by the amount of LED light that is not absorbed by the dye.



To compensate for the strong blueness of the Nichia LED, the perfect LED light combines some ultra bright yellow LED's from Toshiba in the design. The spectrum of the selected Toshiba LED is shown above. The LED is yellow in color, narrow beamed and for the same current four times brighter than the Nichia LED's. The ratio of Toshiba to Nichia LED's in the design is roughly 4:1. The effect of the yellow LED's is to pull the resultant spectrum away from the blue and provide an intense spot in the center of the beam to illuminate distant objects.

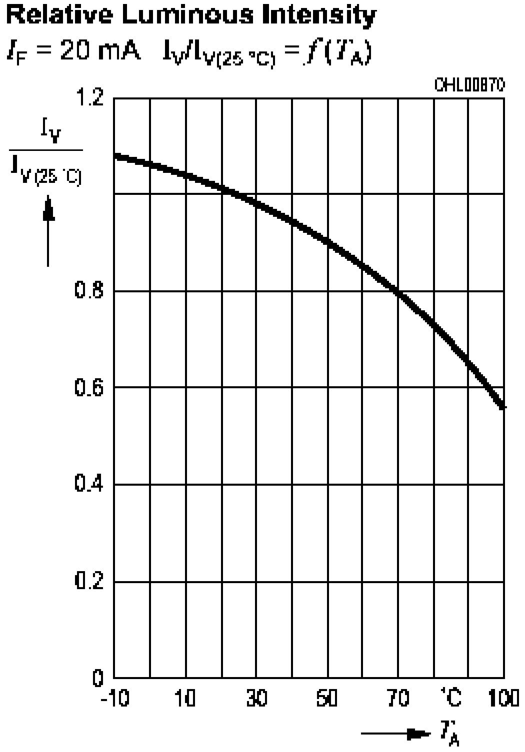
The power efficiencies of these LED's are comparable to typical incandescent lamps. With the cost of incandescent lamps only a tenth of that for a LED array, what are the compelling reasons to build an LED light? First, with proper design the LED's should never burn out. Second, the color of the light is independent of the amount of power. An incandescent lamp fades to yellow and orange as the power is reduced. Third, the LED's output is considerably more linear to the input power, allowing for a design with a much greater range of power settings. Lastly, the output bean of a LED is uniform. The uniform beam is due to the fact the surface area of the LED emitting light is much smaller than the wire used in an incandescent lamp. The LED is a true point light source.

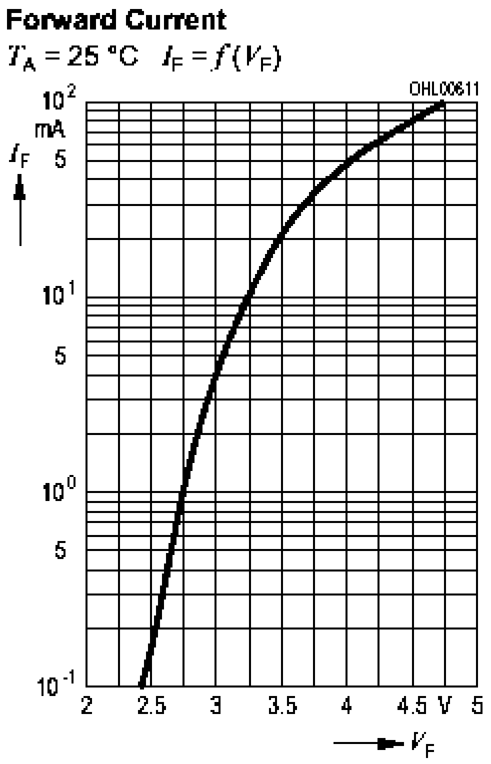
Design Parameters



The graph at the left shows the relative light output as a function of current for an Infineon white LED, similar to the Nichia design (unfortunately, data sheets for the Nichia product are difficult to find). The plot is normalized to the recommended operating current 20ma. The most important thing to get out of the graph is the LED is more efficient at lower current levels. For example, to get twice the output at 20ma, the LED would have to be driven with 50ma of current. This is because the higher the current in the LED, the more the electrons are converted into heat by collisions with the atoms in the lattice of the semiconductor. If the goal is to get as much light out of a set of batteries, the more LED's operated at lower current levels the better. Obviously, the design would reach diminishing returns with maybe a 100 LED's, but a design with 30 LED's will significantly out perform one with eight.

The graph at the right shows another important characteristic of the Infineon and Nichia LED's, the relative output as a function of temperature. Thermal management is an important consideration in the design of the light. Because LED's are basically no more efficient in converting electricity to light than incandescent lamps, the light will generate one to two watts of heat. If that heat is not dissipated, the temperature of the LED's will increase and their efficiency will decrease. For this reason, the LED's should be exposed directly to the air in designs producing more than one watt. The circuit board in which the LED's are mounted will be the primary head sink and should contain as much copper surface area as possible to spread out the heat loss. The LED's themselves should not be mounted with their plastic housings in direct contact with the circuit board. The Nichia LED's come with standoffs on their leads and these should be used as stops when inserting the leads into the circuit board. The amount of exposed leads will help dissipate the heat.





The graph at the left shows the current as a function of voltage for the Infineon LED, similar to the Nichia. From the plot showing relative intensity vs. current, the output will be 1/10th that of 20ma at 2ma. The corresponding voltage is 2.8v and this is the lower limit for a practical design. The upper power limit of the LED is 120mW, which works back to roughly 35ma. The corresponding voltage is 3.6v and this is the upper limit for the design.

The following table details the parameters for two designs, a Micro and Mega. Note, the forward voltage of the yellow LED's at 20ma is 2.5v. A resistor is used to bias them so that a single power supply can be used.

Model	Number of LED's	Voltage	Current per LED	Total Power	Enclosed
Micro	27 - 21 white, 6 yellow	3.1v	9ma	850mW	Yes
Mega	42 - 33 white, 9 yellow	2.8 to 3.6v	2 to 35ma	250mW to 5W	No

It is unimportant to drive all of the LED's in the array with exactly the same current, provided the power dissipation is less than 120mW. The manufacture writes specifications at 20ma, but this is only for comparison with other manufactures. For any set of LED's, their voltage will vary when driven by the exact same current and their current will vary when set to the exact same voltage. However, it is a waste of time to design an array for which the power per LED is constant, either through sorting the LED's or through bias resistors. The reason it is a waste of time is that there is no specification that each LED will produce the same amount of light when the same amount of power is applied. Furthermore, variation in intensity by as much as 20% will not be perceptible to the human eye. Aside from screening for defective LED's, sorting and biasing serves no purpose.

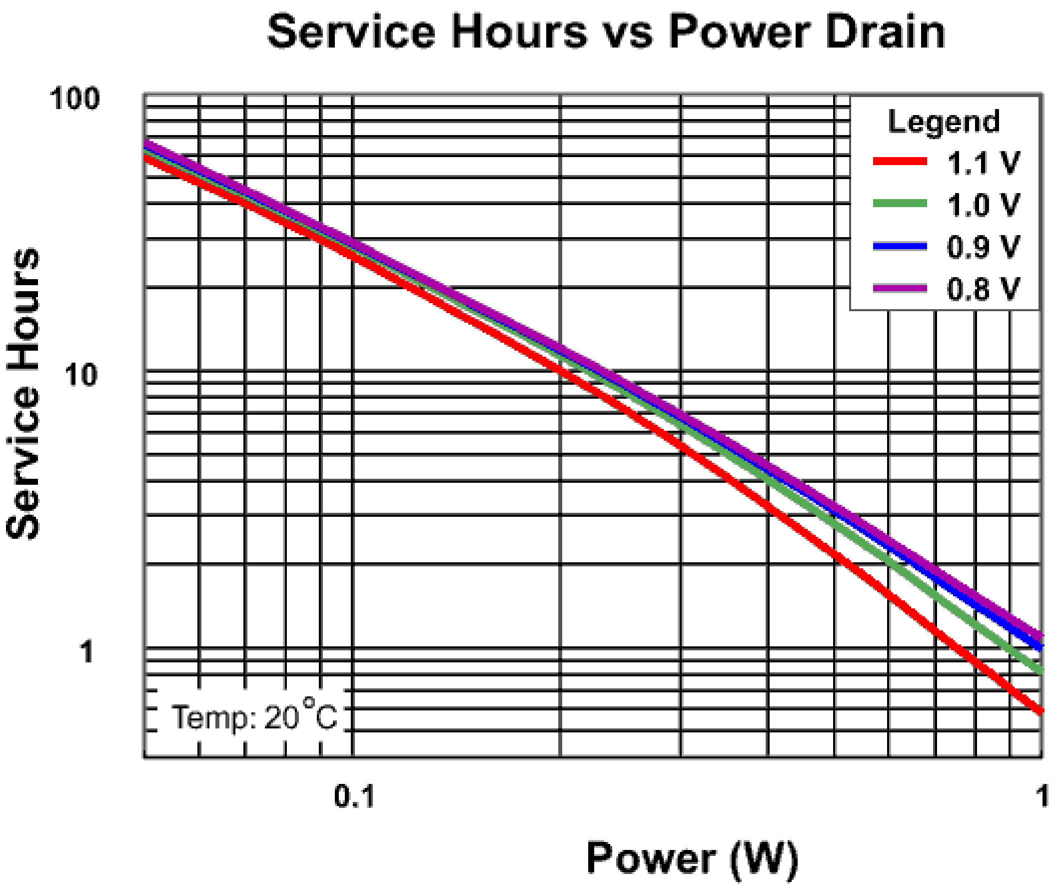
Circuit Topologies

The unloaded voltage of an alkaline battery, based on the chemistry, is 1.5v. Unfortunately, it is impossible to power LED's at 3.1v with two alkaline cells. The same problem exists when considering re-chargeable cells, NiCd or NiMH at 1.2v and $PbSO_4$ at 2.0v. The simplest solution is to use three alkaline batteries to directly power the LED's. That will work if there is enough LED's not to exceed the power ratings on a per LED basis and there is enough internal resistance in the batteries. That solution should only be considers as the in cave backup position.

The next best option is to place a small resistor in series with the battery and that is what a lot of LED "flashlight" manufactures have done. The problem with the series resistor is it wastes power and the LED's output will decrease as the batteries are expended. In the case of LED's, the dropping battery voltage is especially problematic because the color of the light does not change like incandescent lamps. What happens is the caver continues on with an every dimming light until he trips and falls on their face.

The solution is a regulated power source to convert the decreasing battery voltage into a constant voltage. With three alkaline cells, there is enough extra voltage to power some simple two transistor or linear regulator/transistor designs. The problem with the three-cell simple circuit design is the end of life voltage for an alkaline cell is 0.9v and 2.7v is not enough to power the LED’s. In order to utilize all of the energy in the batteries, a "switching" regulator design is required. Once that conclusion is realized, the choice is either a "step-up" or "step-down" regulator. Both types of circuits can reach 95% efficiency in converting the battery energy to power the LED's.

The answer has to which type of circuit to use lies in considering battery characteristics. The graph below shows the service hours as a function of power drain for Duracell AA Ultra batteries. To use the chart, divide the amount of power needed to supply the LED's by the number of batteries in the supply. The "micro" light is designed to supply 850mW and when powered by two AA batteries, each battery would need to supply 425mW. Given the loss of the regulator, the power requirement is more like 500mW. Going up from the 0.5 on the power axis gives about 3 hours. In this example, two batteries powering LED's at 3.1v requires a step-up circuit. In a practical design of a step-up circuit, the efficiency decreases has the difference between the output and input voltages increases and a more realistic overall efficiency is 75%, 600mW at the batteries and 2 hours of battery life.



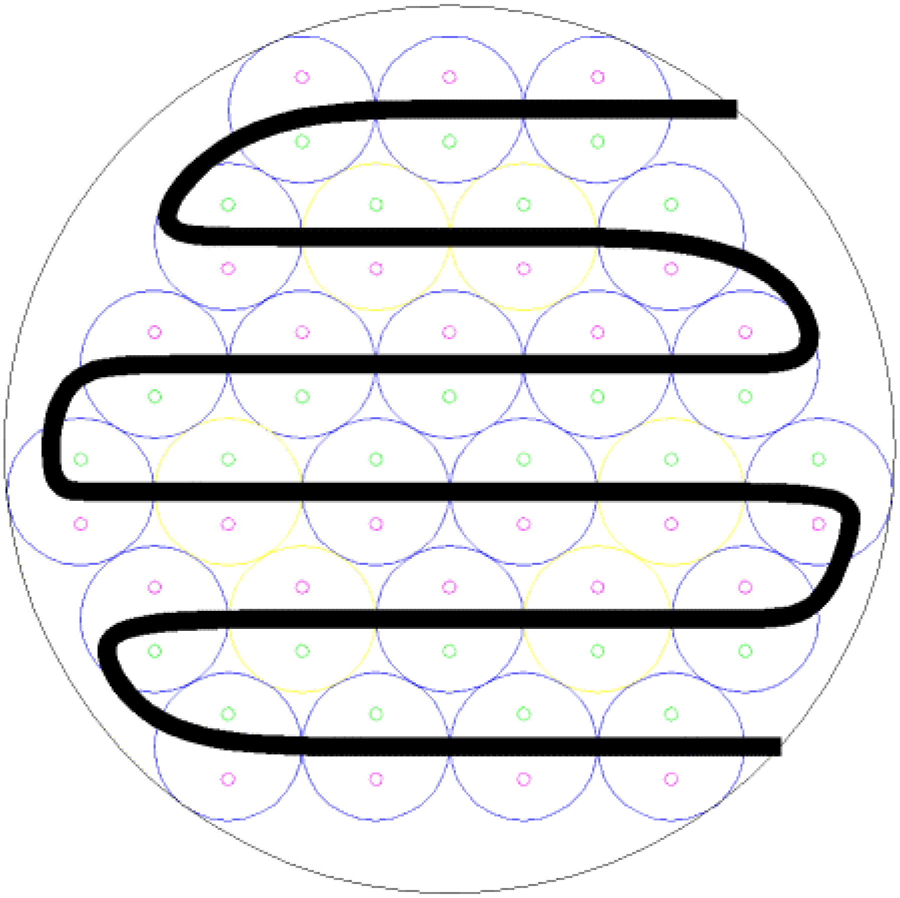
The "mega" light is designed to cover a very wide range of power settings, up to 5 watts. It is not practical to design a step-up converter at that power level. Even at modest power setting, a step-down converter will be more efficient. Consider a power setting of 1W and a power supply built of 8 AA batteries. The initial voltage of the eight batteries is 12v and the terminal voltage some where around 6.5v. Each battery would need to supply 125mW and going up just to the right of the 0.1 on the power axis gives about 20 hours of light. Additionally, the setup-down design does not suffer in-efficiencies until the battery voltage drops to 4.0v and the design can achieve 95% efficiency over the entire battery life. Using a step-down design with four times the number of batteries, a yield improvement of ten times in battery life and a brighter light is realized. Hence the mega light is the main caving light and the micro light the backup.

The step-up circuit used in the micro design is the **LM2621** and is available in a pre-assembled "kit" for $20. National Semiconductor says this about the product, "The LM2621 is a high efficiency, step-up DC-DC switching regulator for battery-powered and low input voltage systems. It accepts an input voltage between 1.2V and 14V and converts it into a regulated output voltage. The output voltage can be adjusted between 1.24V and 14V. It has an internal 0.17[Ohm] N-Channel MOSFET power switch. Efficiencies up to 90% are achievable using the LM2621." Once the leads are cut off the circuit board, it is only 1/2" by 3/4" rectangular and will fit inside the headpiece of the Petzl Micro headlamp.

The step-down circuit used in the mega design is the **LM2653** and it also is available has a kit for $20. National says, "The LM2653 switching regulator provides high efficient power conversion over a 100:1 load range (1.5A to 15 ma). This feature makes the LM2653 an ideal fit in battery-powered applications. Synchronous rectification is used to achieve up to 97% efficiency." The circuit board is only 1" by 1-1/2" rectangular and will fit inside the headpiece of the Petzl Mega Belt headlamp.

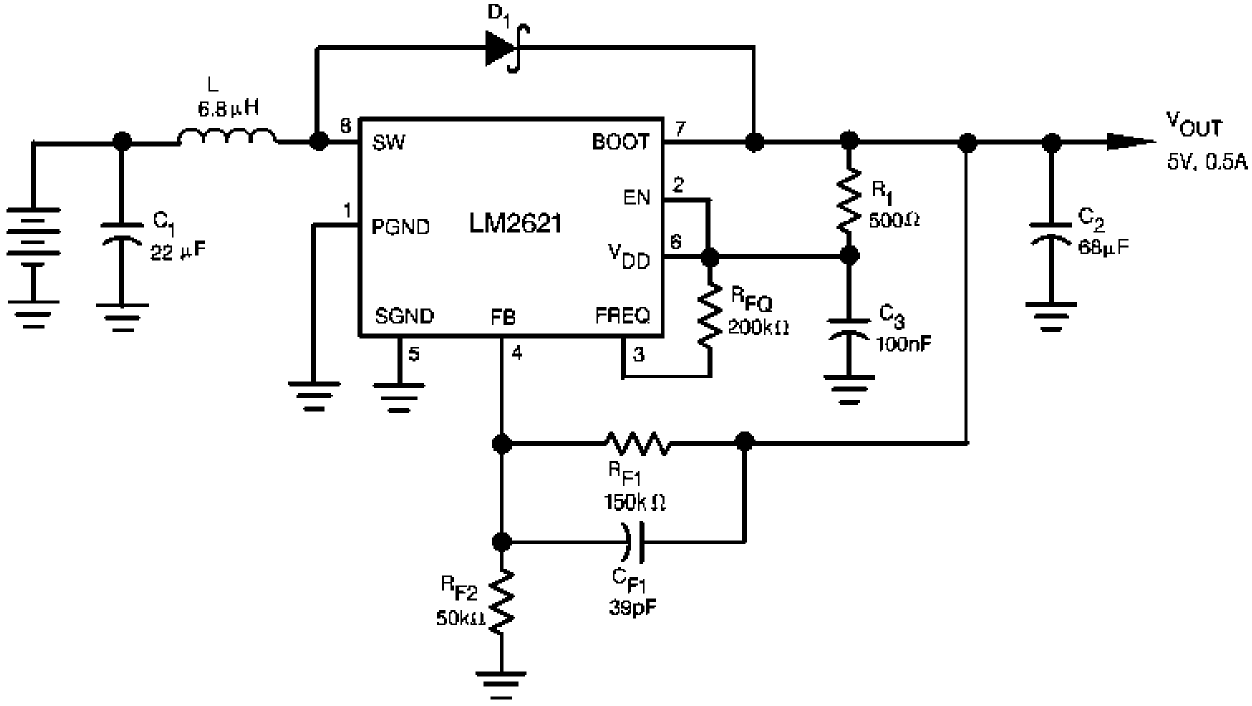
Micro Light Design

There are three parts to the construction of the micro light, the LED array, modification to the LM2621 evaluation circuit board and lastly modification or construction of a lamp housing.



The drawing below is the layout for an array of 27 5mm LED array, 21 white (blue in drawing) and 6 yellow LED's. The circle is 35mm in diameter. Although the leads of the LED's are spaced 0.10" apart, the a layout in which the LED's touch in three directions can not be built on the standard 0.10" perf-board. The board should be made of double sided, copper clad, generic circuit board, like the type available at Radio Shack. Fix the pattern of the layout on the circuit board and drill or punch out the holes for the LED's. The smaller pink and green circles indicate the holes for the LED leads. With an etching tool, etch out the black serpentine design, on both sides, which separates the positive and negative parts of the array. Remove the copper around the positive holes for the yellow LED's. The array is laid out without any extra space in between the LED's to account for misalignment of the holes for the leads. If placing the LED's is difficult, gently sand off the step around the bottom of the plastic housing. Solder all of the LED's in place, starting from one side of the array to the other. Periodically, test for shorts with a multi-meter and test for defective LED's or placement (reversing the leads) by powering the array with two alkaline batteries. Clip the leads off after testing, **except** for the yellow LED's. Bend, touch and solder together the positive yellow leads in a manner not to make contact with another parts of the circuit board. Connect a 15ohm, 1/2 w resistor between the collection of yellow positive leads and the positive section of the circuit board. Solder tack a black wire to the negative section of the circuit and an orange wire to the positive section.

The schematic of the LM2621 evaluation kit is shown below. The board comes pre-wired to output 5.0v and it must be modified to output 3.1v for the LED light. Note, the evaluation board is not capable of supplying more than 500ma and this design is set at about 300ma.



The equation for the output voltage is

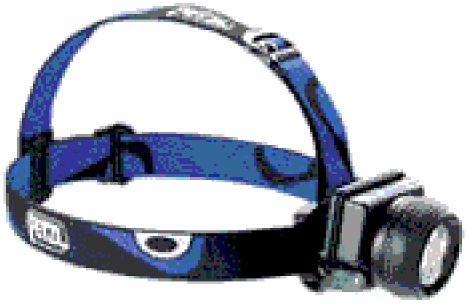
Rf2 = Rf1/(Vout/1.24 - 1)

or

Vout = 1.24*(Rf1/Rf2 + 1)

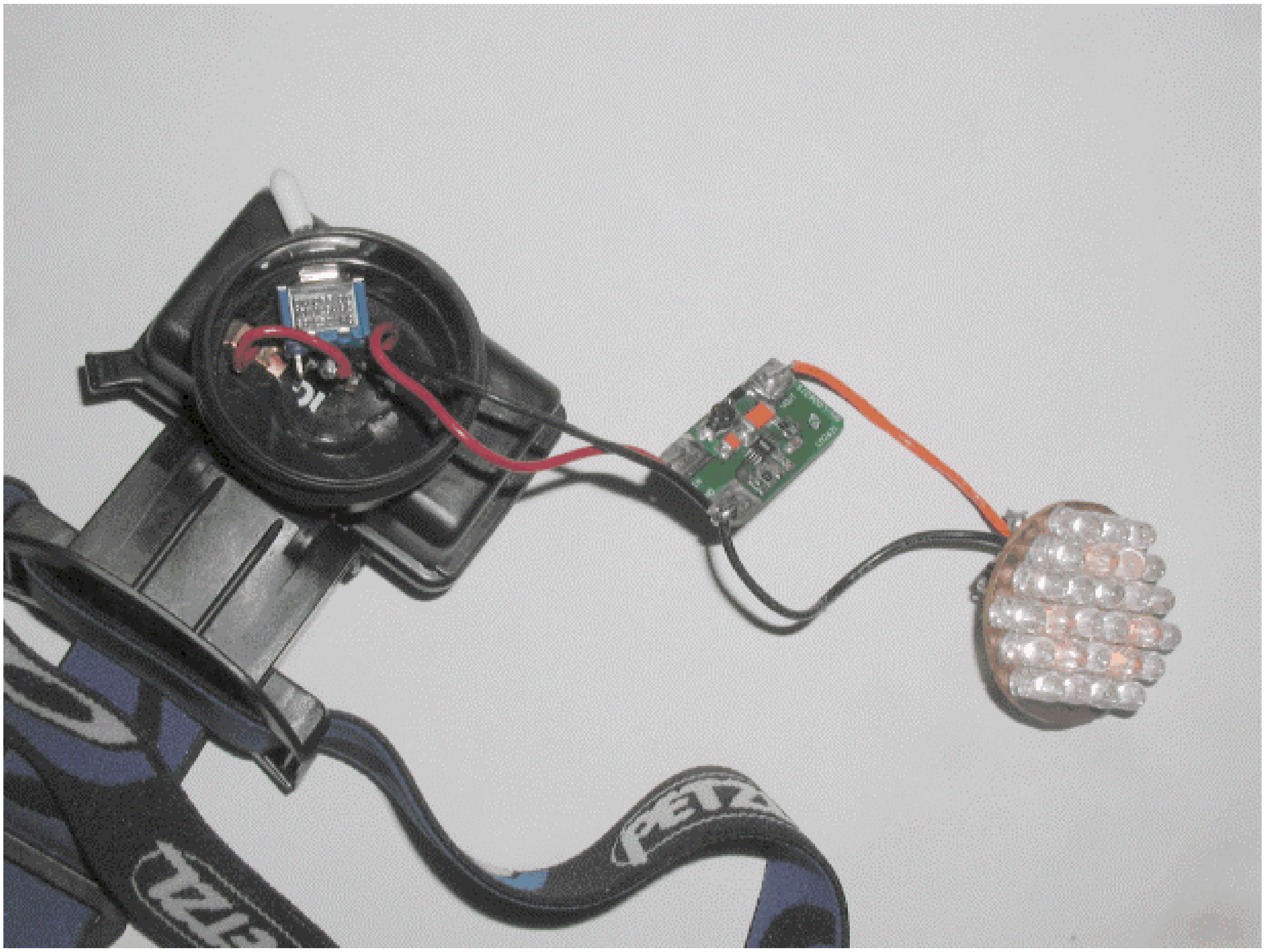
and with Rf1 = 150kohm and Rf2 = 50kohm, Vout is 4*1.23 or about 5.0v. To modify the circuit for 3.1v output, first remove Rf2. This is difficult for surface mount resistors, but a hot soldering tip and a small screwdriver to pry with will break the resistor lose. Once the resistor is removed, drill a hole through the pad of the old resistor that connected to the FB pin of the LM2621 package. Insert and solder a 220kohm resistor in the hole, tacking the other side of the resistor to the negative or ground terminal of the board. Power up the board and verify the output is 3.1v. The board comes with three very large connection terminals, gently cut them off. Connect the black wire from the LED board to the negative terminal of the LM2621 board and the orange wire to the Vout terminal. Power up the board and verify all of the LED's are lit.

The Petzl Micro headlamp can be modified to house the LED circuit and power supply boards. Begin by removing the batteries and unscrewing the lens cover. Remove the reflector from the lens cover. Remove the lamp bulb and the spare from the back of the headpiece. The headlamp is designed such that when the lens cover is screwed down, the reflector pushes down on the central post holding the lamp bulb and making a circuit connection. With a Dremel cutting disk, cut out the central post, flush to the back face of the headpiece. The post contains a copper tab used to make contact with the side of the bulb. Cut the copper tab and do not pull it out as it is attached to the leads to the battery. It is easiest to cut out the post with a saw blade attached to a Dremel tool.



With all of the parts removed from the headlamp, assembly can begin. First mount a single pole, single throw switch in the side of the cylinder of the headlamp. The switch needs to be the "micro" type. The hole to insert the switch through must be placed as close to the back of the cylinder as possible. Identify and solder a red wire to the positive copper battery lead coming from the battery compartment. Solder the other end of the wire to one of the terminals of the switch. Solder another red wire to the other terminal of the switch and its other end to the Vin terminal of the LM2621 board. Solder a black wire from the negative copper battery lead coming from the battery compartment to the negative terminal of the LM2621 board, which should also be in common with the negative side of the LED board. Insert two AA batteries and verify the switch turns on the LED array. Do not ever insert the batteries in the wrong orientation, there is no reverse voltage protection and doing so will destroy the power supply board.

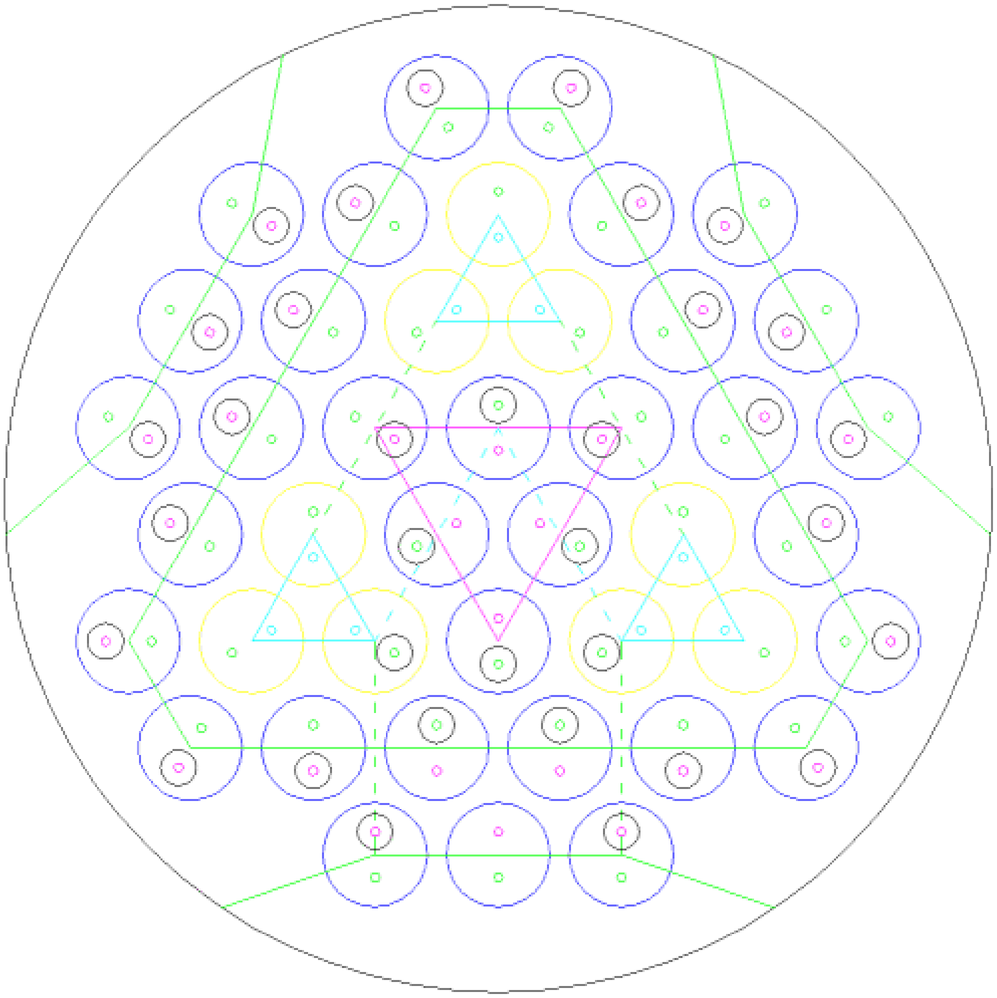
The construction is nearly complete. Wrap the LM2621 circuit board in black electricians tape and wedge one edge of the board it under the leads of the switch until it fits entirely within the cylinder of the headlamp. Fold the wires on top of the circuit board and place the LED array on top. Screw the lens cover back on the headlamp and it should hold the LED array in place without excess pressure. The screw base of the lens cover may have to be cut back a little to accommodate the power switch.

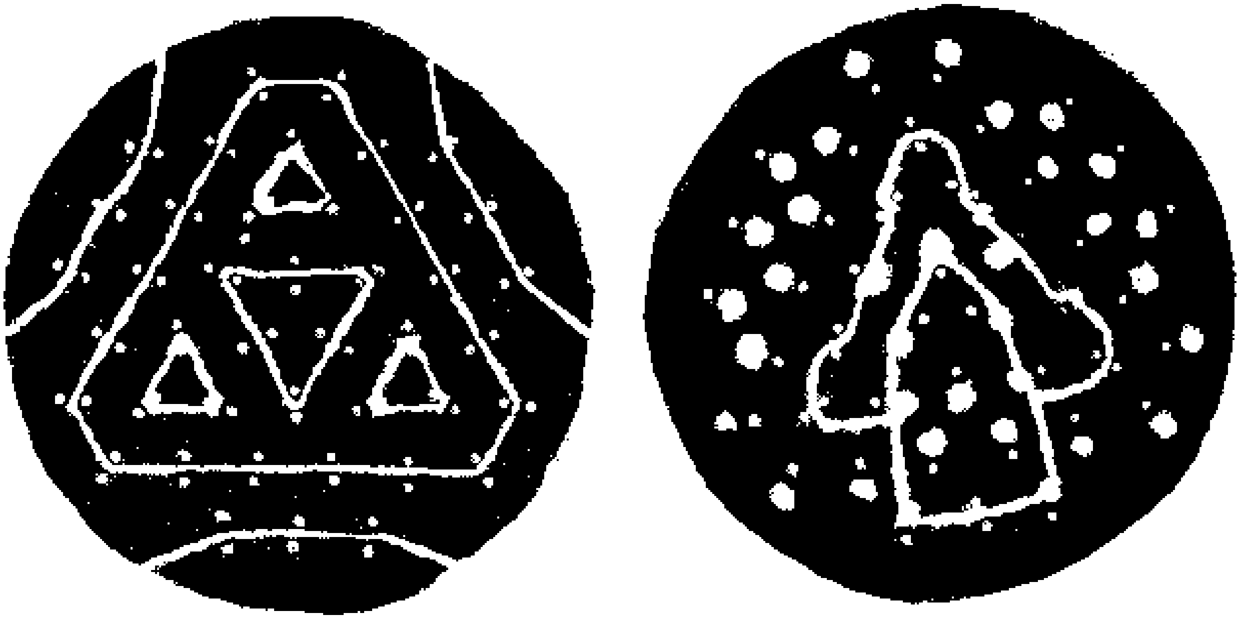


Mega Light Design

The drawing below is the layout for an array of 42 5mm LED array, 33 white (blue in drawing) and 9 yellow LED's. The circle is 55mm in diameter. The LED's in this layout do not touch each other and exact placement of the holes for the leads is not essential. The board should be made of double sided, copper clad, generic circuit board, like the type available at Radio Shack.

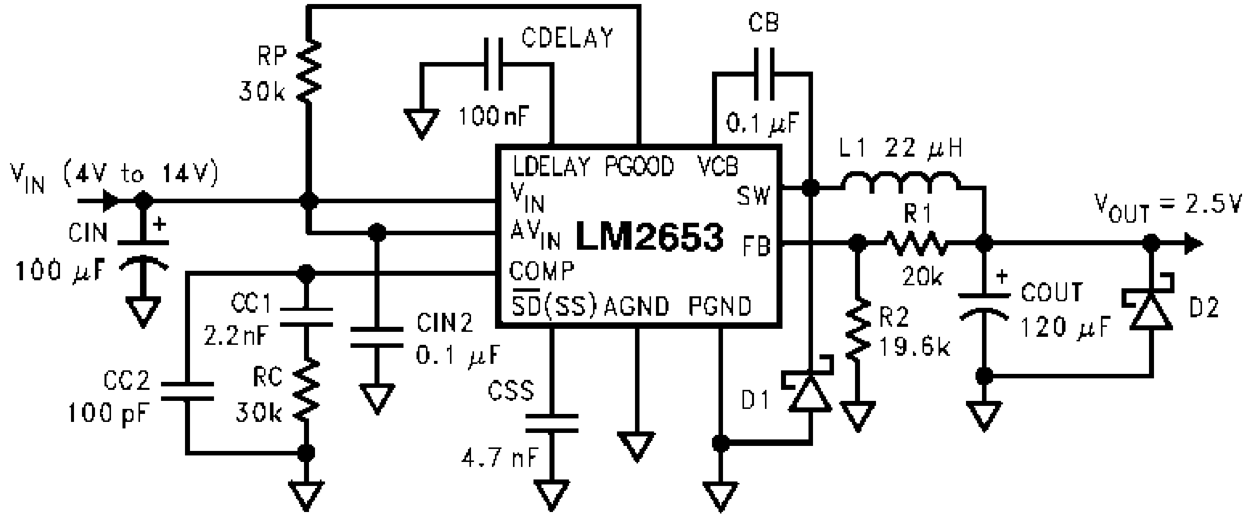
Close examination of the layout shows dashed lines indicating a different pattern for the backside of the board. Fix the pattern of the layout on the circuit board and drill or punch out the holes for the LED's. The smaller pink and green circles indicate the holes for the LED leads. With an etching tool, etch out the three nets of the circuit, on both sides, which separates the positive, yellow positive and negative or ground parts of the array. Remove the copper around the holes that have a second circle drawn around them. This prevents a lead from a different net from shorting the circuit. Around the perimeter of the array there are six positions in which another LED could be placed. In three of six positions drill a hole to accommodate a 6-32 screw.





The two disks above show the two sides of the circuit board after drilling and etching, less the holes for the screws. Referring to the right disk of the pair, the outside perimeter is ground, the triangle with the cutout is yellow positive and the wedge into the triangle is positive. The LED leads when inserted and soldered on both sides will connect the nets on the other side. Solder all of the LED's in place, on both sides, starting from one side of the array to the other. Periodically, test for shorts with a multi-meter and test for defective LED's or placement (reversing the leads) by powering the array with two alkaline batteries. Clip the leads off after testing. Connect a 10ohm, 1/2 w resistor between the yellow positive section and the positive section of the circuit board. Solder tack a black wire to the negative section of the circuit and an orange wire to the positive section.

The schematic of the LM2653 evaluation kit is shown below. The board comes pre-wired to output 2.5v and it must be modified for a variable output from 2.8 to 3.6v for the LED light.



The equation for the output voltage is

R2 = R1/(Vout/1.24 - 1)

or

Vout = 1.24*(R1/R2 + 1)

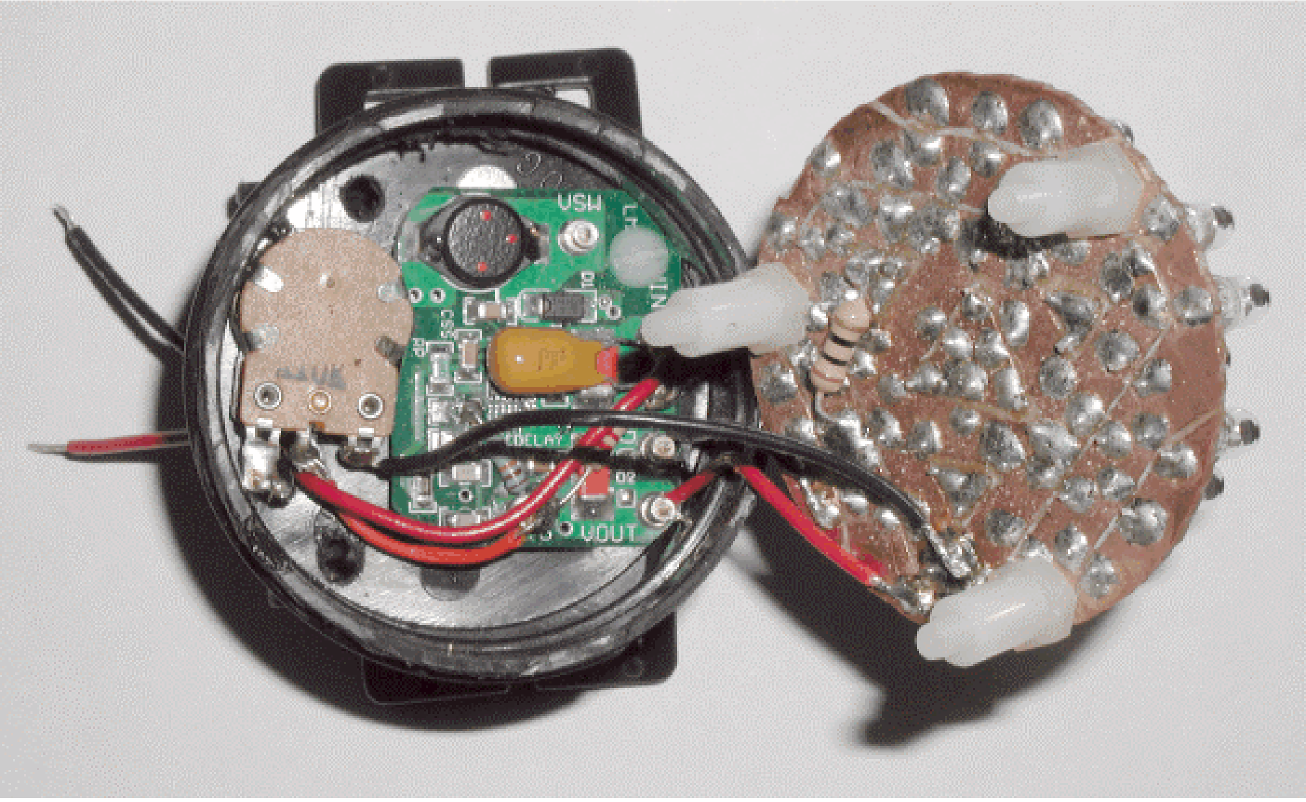
and with R1 = 20kohm and R2 = 20kohm, Vout is 2*1.23 or about 2.5v. To modify the circuit for a variable output, first remove R2. This is difficult for surface mount resistors, but a hot soldering tip and a small screwdriver to pry with will break the resistor lose. Once the resistor is removed, drill a hole through the pad of the old resistor that connected to the FB pin of the LM2653 package. A variable output requires a screw potentiometer and two resistors. The task requires setting the upper and lower ranges for the resistance. For Vout = 3.6v, R2 is roughly 10kohm. For Vout = 2.8v, R2 is 16kohm. The resistor network has one end of the 10k resistor tied to the FB net and the other end tied to a parallel resistor pair whose combined resistance is 6k when the potentiometer is turned in one direction and zero in the other direction. Select a potentiometer with a 10kohm range and a 12kohm resistor to fit the requirements. Note, the LM2653 can’t adjust to large changes in resistance on the FB net and it is not possible to use a rotary switch to a resistor network for pre-set voltages.

The LM2653 circuit board comes with solid terminals for making wire connections. There is a terminal for the PGOOD pin. Cut the lead from the terminal to the LM2653 package, the terminal will serve as the intermediate node in the resistor network. Connect the 10k resistor between the FB node and the isolated PGOOD terminal. Connect the 12k resistor between the PGOOD terminal and ground. Connect the mid-range pin of the potentiometer to the PGOOD terminal with a wire and the other side of the potentiometer to ground. Connect the orange wire from the LED array to the Vout terminal and the black negative wire to the ground terminal. Power up the board with at least five AA batteries and verify all of the LED's are lit while turning the potentiometer screw. Some potentiometers come with a built in switch that can be placed in series with the Vin lead to the circuit board for a power on-off switch. Connect black and red wires to the input power terminal of the circuit board. Do not ever insert the batteries in the wrong orientation, there is no reverse voltage protection and doing so will destroy the power supply board.

The Petzl Mega-belt headlamp can be used to house the mega LED circuit board and array. First cut the wire a few inches from the battery back, saving the pack for future projects. Unscrew the lens cover and remove the reflector. Remove the bulb assembly from inside the headpiece. With a Dremel cutting disk, remove all of the plastic studs in the headpiece and make the back surface as flat as possible. Drill three 6-32 size holes in the back surface, corresponding to the three holes in the LED array board. Drill a hole in the back surface for the potentiometer. The position of the hole should be as near to the edge of the cylinder wall as possible. Mount the potentiometer. Drill a 6-32 hole in the power supply board, right where the "LM2653" text is located. Position the board in the headpiece, next to the potentiometer and touching the back surface (trim the board as required). Drill another 6-32 hole in the back surface of the headlamp corresponding to the hole in the circuit board. Secure the circuit board in the headpiece with a 6-32 ***nylon screw and nut***. Push the black and red power leads through a hole in the back surface, for connection to the batteries. Fold the wires under the LED array board and align the board so the screw holes in the board and the headpiece match. Secure the LED array with three nylon screws and nuts.

The LM2653 circuit has a Vin supply range of 4.0 to 14v. The circuit will not function below 4.0v and therefore can't exploit the full charge of only four AA batteries (remember the terminal voltage of an AA battery is 0.9v). The circuit requires at least ***five*** AA batteries and several manufactures build battery packs based on five NiMH batteries. Radio Shack has battery holders with 9-volt style connectors for six and eight AA batteries. A 7.2v Li-Ion battery can also power the light. At the low power setting only, the light can be powered for three hours off a 9v radio battery, as a back-up battery source. Other battery combinations are two Li-SOX batteries or 6 and 12v sealed lead acid batteries.

The original lens cover when returned to the headpiece can protect the LED array from impact. However, a covered array should not be run a full power for extended periods as the contained heat will deform and melt the plastic. Alternately, a reflector can be fashioned from a discarded F-cell flashlight. Cut out a hole big enough for the Petzl headpiece in the reflector of the discarded flashlight and secure the reflector with glue.



Bill of Materials

Item	Mega	Estimated Cost	Micro	Estimated Cost
NSPW500BS White LED	33	33 x 2.80 = $92.40	21	21 x 2.80 = $58.80
TLYH180P Yellow LED	9	9 x 1.25 = $11.25	6	6 x 1.25 = $7.50
Wire, resistors, screws	n/a	$3.00	n/a	$3.00
Potentiometer/Switch	1 10kohm	$5.00	Switch only	$3.00
Petzl Headlamp body	Mega	$58.00	Micro	$24.00
Total		$170		$100

The white LED price is for quantities of 100. The wire, resistor, screws and miscellaneous parts can in total cost more than $3 because it is difficult to buy these items in single unit quantities.

Design Resources

Hosfelt Electronics - Toshiba TLYH180P Yellow LED

Nichia Corporation - Manufacture of NSPW500BS White LED, fax sales only.

Don's LED Page - Online reference material.

LED Museum - Online reference material.

Maha Batteries - Li-Ion and NiMH rechargeable batteries.

The Battery Barn - Rechargeable batteries and battery chargers.

Inner Mountain Outfitters - Caver's supermarket, Petzl headlamps.

Caving Technology - Two LED headlamps designs by Doug Strait and Pete Shifflett

HDS Systems - A commercial vendor of LED headlamps for caving.

About the Author

Garry Petrie is a component design engineer for Intel Corporation. He graduated in 1984 from the University of Washington with a Master of Electrical Engineering and has been designing integrated circuits for 17 years. At Intel, Garry is currently working on the next generation Pentium 4 processor. After being exposed to caving as a youth, Garry joined organized caving through the NSS in 1985 and has caved across the United States and on three continents. He is also author of WinKarst, a Windows based program for managing and visualizing cave surveys.

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