

Theory and Designs for Building a White LED Headlamp

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This article has been written to assist those who wish to construct a headlamp using white LEDs. (Some of the LED specifications may be slightly out of date, but the concepts and designs are still valid.)

BACKGROUND

White LEDs are actually solid state fluorescent lamps consisting of a LED emitting blue light which excites a phosphor which emits white light. These LEDs were developed by the Japanese company Nichia and subsequently have also been manufactured or marketed by HP, Chicago Miniature Lamp, and Sloan Precision Optoelectronics in addition to Nichia. When introduced several years ago, Nichia reported typical efficiencies to be 5 lm/watt. By Sept 1998 the average of current production had reached 10 lm/watt. As of mid-1999 they are yielding 15 lm/w. This efficiency is similar to commonly used (for caving headlamp applications) incandescent bulbs. It should be noted that efficiency (for Nichia LEDs) is not a specified parameter and thus is not guaranteed.

If efficiency of the current white LEDs does not exceed typical incandescent lamps, why bother? In a properly designed headlamp, LEDs are immune from burnout. LEDs make much more efficient use of available battery energy from nearly depleted batteries. When the current to white LEDs is reduced by their light output will remain at over 50% of its initial value. In contrast, an incandescent lamp would have its light output reduced to less than 2% of its initial value. These LEDs are therefore more practical for selectable power level arrangements than are incandescent lamps. The I vs. V characteristic of these LEDs is very well matched to that of a nearly depleted battery comprised of 4 alkaline cells. Several days of low level illumination are attainable from batteries that will not light an incandescent lamp at all.

As one who has been involved in several entrapment by flooding adventures, I find this inherent long reserve to be very attractive. While it is widely understood that for color vision the human eye is most sensitive in the green portion of the spectrum, it is less widely known that for scotopic (low level B&W) vision the eye's sensitivity peaks in the blue portion of the spectrum. The spectra of these LEDs are rich in the blue portion where fully dark-adapted eyes are most sensitive.

White LEDs are limited in their power handling capability. The common T1 3/4 size has an absolute maximum rating of 120mw. It should be noted that unlike incandescent lamps, the efficiency of white LEDs increases with decreasing power level. The 10 lm/watt figure given above is at a current of 20mA which corresponds to a power level of about 68mw. Due to the limited power capability of a single LED, a minimum of 7 is required to achieve a reasonable level of illumination. Seven LEDs driven by a total current of 200mA provide illumination approximately equal to a carbide caplamp running a 1" to 1 1/2" flame.

Unlike incandescent lamps, LEDs (with rare exceptions) require some means of regulating the current they draw when powered by a battery. In its simplest form this can be a resistor inserted in the circuit between the battery and the LED. The disadvantage of this arrangement is that the current to the LED will vary as the battery voltage varies. For application as a primary headlamp, a far better circuit is one that will supply a constant current to the LED even as the battery voltage varies. In its simplest form, this can be achieved using a circuit comprised of only 2 resistors and 2 transistors. This circuit can maintain a constant current to the LED as long as the battery voltage is at least 0.6V greater than that of the LED at the desired current.

In the common T1 3/4 size, Nichia offers white LEDs with viewing angles of 20, 50, and 70 degrees. The viewing angle is that angle within which the intensity is at least 1/2 of the peak intensity. These LEDs do not differ in total light output but only in how widely or narrowly that light is projected. Those LEDs with viewing angles of 20 and 50 degrees are of most interest for headlamp application. Unfortunately, to present (11/98) only the 50 degree LEDs are offered at reasonable prices by distributors. While it is possible to obtain any of these LEDs directly from Nichia, the small quantity price of \$12/each is prohibitive. The catalog distributor, ALLIED Electronics, lists a 20 degree LED by SLOAN Precision Optoelectronics at a good price but as of 11/98 they do not as yet have any inventory. To date the best price found for the 50 degree T1 3/4 size in small quantities is \$3.99 each from HOSFELT Electronics.

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$$R1 \approx 500/I$$
$$R2 \approx 0.54/I$$

Where I is the desired total LED current
R2 determines desired current

It should be understood that the LED depicted can be any number of LEDs in parallel. Q1 is the power dissipating element in this circuit and appropriate mounting consideration must be given to heat dissipation. Generally for TO-92 packages and small surface mount packages the collector lead is the one by which most of the heat is transported from the package. The PCB layout should maximize the copper connected to the Q1 collector lead. Q2 may be any SS PNP with good gain (H_{FE}). For Q1, a recommended device in a TO-92 package for through-hole construction technique is the ZETEX ZTX788A.

For surface mount construction technique a recommended Q1 is the ZETEX FM717 or FM718 which come in the SOT-23 package. Suitable Q2 in through-hole TO-92 package include 2N3906, 2N4403, and 2N5087. Suitable Q2 in surface mount package (SOT-23) include MMBT3906, BCW61D, and MMBT2907A. Resistors R1 and R2 may be 1/8 watt size unless the desired current is greater than .25 amp in which case the wattage of R2 should be increased. By use of surface mount devices for Q1 and Q2 it is possible to construct the current regulating circuit on a 0.32" x 0.32" x 1/32" double-sided PCB that will fit inside the base of a "PR" style (flanged base) bulb. By soldering the PCB that holds the LEDs directly to the flange of the bulb base one can thereby create an LED version of a "PR" style bulb.

In the case of some headlamps, the only required modification to the headlamp itself to accommodate the use of the LEDs will be enlargement of the hole in the reflector to accommodate the diameter of the LED cluster. By devoting the majority of the LED PCB to the cathode (negative) side of the circuit and soldering this PCB directly to the bulb base flange, the bulb base becomes part of the heatsink for the LEDs. Due to the limited area of PCB that can be fitted into a "PR" style base, about the absolute maximum current that can be handled by a current regulator circuit fitted into a "PR" base is .25 amp assuming use of 4 alkaline cells as the power source. Even so, this value assumes use of DS 2 oz clad board with the maximum area possible allotted to the collector lead of Q1. Pushing this limit risks reliability degradation due to the thermal stresses upon Q1. Those who wish to operate at higher currents or wish to simplify layout considerations on the PCB can enlarge the PCB that holds the LEDs and move the current regulator circuit to this PCB.

HELPFUL HINT: Even if you don't have the capability to fabricate PCBs by chemical etching techniques, simple PCB circuits such as these can be created using a Dremel-type tool to remove the unwanted copper from clad board stock. All that is required is a small burr and a steady hand.

USING OTHER POWER SOURCES: The current regulation circuit of Figure 1 will maintain regulation for battery voltages $>0.6V$ above that required by the LEDs. This circuit is marginally acceptable for use with 4V Pb-acid batteries if the average LED current is 15mA or less. For other battery choices such as 3 Ni-Cd or Ni-MH cells, or a single Li-ion cell, there is less than this required 0.6V of "headroom" for a significant portion of the discharge. For these applications an alternate circuit is offered in Figure 2 below. This circuit will maintain regulation for battery voltages as low as 0.1V above that required by the LED.

$$R1 = 0.064/I$$
$$R2 \approx 300/I$$

Where I is total LED current
 $C1 > 1\mu F$

The LM334 is a 3-terminal adjustable current source. It operates to maintain 64mV between its R and V- terminals (hence across R1) and does so by passing current into the V+ terminal and out of the R terminal. Assuming adequate cell voltage, the LED current is the beta of Q1 times the R2 current. R1 sets the LED current which is $64mV/R1$ for reasonably high Q1 beta. Hence $R1 = 64mV/I$ where I is the desired LED current. R2 is selected

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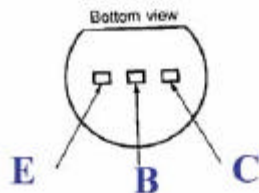
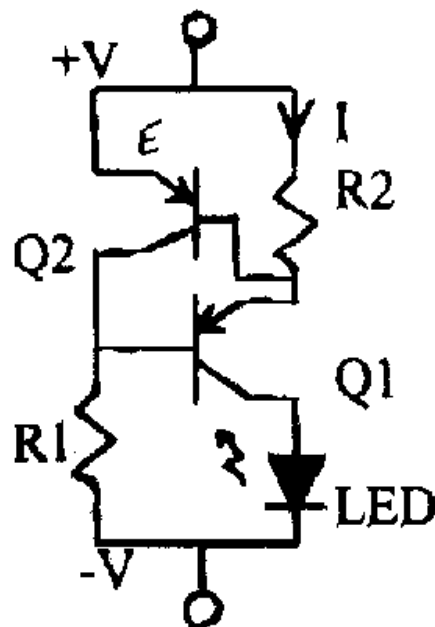


Figure 1:
Simple Regulator
and pinouts for
TO-92 packages

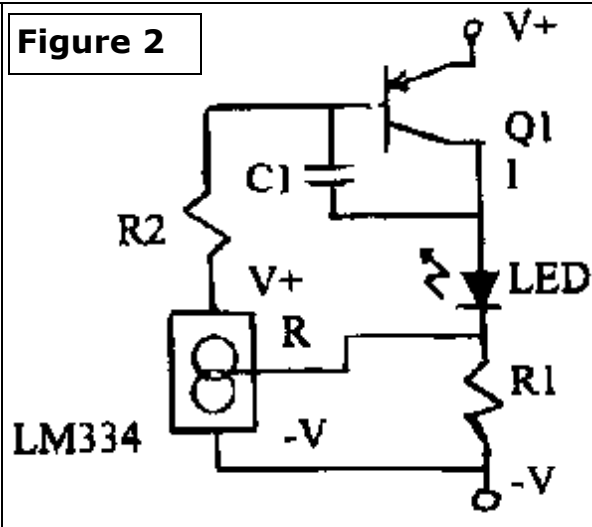


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to regulate the base current to an appropriate value when the battery voltage drops to the point that the circuit falls out of regulation. Under this condition the LM334 will draw all the current it can through R2. C1 prevents the circuit from oscillating and any value from 1 to 10µ F works well. Suggested Q1 choices are the same as given for the previous circuit. The LM334 IC is available in both TO-92 and SO-8 packages.

Another current regulation option exists. This is the use of a step-down switching regulator arrangement. For most applications the gains are probably insufficient to justify the added expense and complexity of the associated circuitry. As the difference between the average available voltage and the voltage of the LEDs at the desired operating current increases, the use of a step-down switching regulator circuit becomes increasingly attractive. I will not elaborate further on this option other than to say that of the ICs that I have examined for this application the MAXIM MAX887 appears most attractive.

Figure 2



CONSTRUCTION PROJECT USING A SPECIFIC HEADLAMP

There is an inexpensive headlamp on the market that is (with care) waterproof and utilizes 4 AA cells. This headlamp has been variously labeled "Optronics Nightblaster," "Safesport Waterproof Headlamp," and "Eveready Waterproof Headlamp" and can be found for \$10 or less.

Considering the price it is well made. I have successfully used this headlamp as a starting point for various lamp modification projects. I have used this lamp with "PR" lamp base LED assemblies. With careful attention to layout, it appears that this headlamp could accommodate up to 30 T1 3/4 size LEDs. To date the largest number I have used is a cluster of 7 operating at a total current of 200mA. Since these LEDs are operating near their maximum rated current, careful matching of LED characteristics is required. Component values for this lamp using the circuit of Figure 1: R1=2.2KΩ , R2=2.7Ω , Q1=ZETEX FMMT718, Q2=MMBT2907A.

If component cost is not a primary consideration, maintaining the same component values (and thus current) but increasing the number of LEDs to 10 or 13 will yield gains in light output of 15 and 28% respectively. Additional benefit of using the larger number of LEDs is the negation of the requirement to match characteristics and slightly longer runtime before the light intensity begins to decrease at the end of battery life. While my initial prototype utilized a 0.6" x0.6" PCB to mount the LEDs, I recommend that a larger PCB be employed to improve heat dissipation. Due to geometric considerations it is recommended that 1/32" thickness be used.

Performance of this lamp using fresh Eveready cells is as follows:

Constant brightness	9 hours
Additional hours to 50% brightness	6 hours
Additional hours to 25% brightness	2 hours
Additional hours to 10 % brightness	24 hours
Total hours to 10% brightness	41 hours

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Written November 1998, with revisions
April 2000 and 5 September 2000

Caving Technology Website Version 1, 21 April 2000
Caving Technology Website Version 2, 5 September 2000

SPELEONICS Version, July 2001

SOURCES OF COMPONENTS AND INFORMATION

Hosfelt Electronics 1-800-524-6464 White LEDs

Allied Electronics 1-800-433-5700,
<http://www.allied.avnet.com/> White LEDs

DIGI-KEY Electronics 1-800-344-4539,
<http://www.digikey.com/>
ZETEX transistors, catalog component distributor

Nichia Website www1a.meshnet.or.jp/nichia/
Information on Nichia White LEDs