DIMMABLE LED DESK LAMP

I recently noticed how cheap high-brightness white LEDs have become and I wanted to use some of them to make a dimmable desk lamp. I noticed how expensive decent LED desk lamps are and that few, if any, are dimmable. I used my engineering skills to come up with a solution. I designed a dimmable LED driver circuit that is simple and extremely energy efficient. I installed the circuit into a portable fluorescent lamp that I had purchased years ago at a flea market. The LED driver circuit is dirt cheap and is so simple that any electronics hobbyist who knows how to handle static-sensitive parts (i.e. the MOSFET, Q2) can easily build it. The light output is continuously adjustable from “night-light” to “retina-burner”. No joke! Looking directly into the LEDs at full power will probably damage your vision.

Because this circuit regulates LEDs very efficiently and allows precise dimming, it may be useful for other things besides a desk lamp. The simple, two-transistor circuit uses no ICs or exotic parts and employs an innovative technique of driving the LEDs. The circuit in figure 1 can drive a string of 7 to 35 LEDs without modification. The circuit automatically adapts to the number of LEDs in a string and does not waste surplus power as a linear current regulator would. The dimmer does not work smoothly with less than 7 LEDs due to the steep slope of the rectified 120V sine-wave at low points on the curve. Power consumption at full brightness of the circuit in figure 1 is about 2.5 watts. Additional LED strings can easily be added to potentially drive hundreds of LEDs. This circuit regulates the current through the LEDs and depending on how many LEDs are in a string, is unaffected by changes in the power-line voltage. Using the circuit in figure 1 (but with 34 LEDs in the string), the LED current started to drop when the power-line voltage was lowered to 96 volts. This drop-out voltage will change by about 3.5 volts for each LED that is added or deleted. This circuit also protects the LEDs from voltage spikes by disconnecting them from the power-line when a surge is encountered.

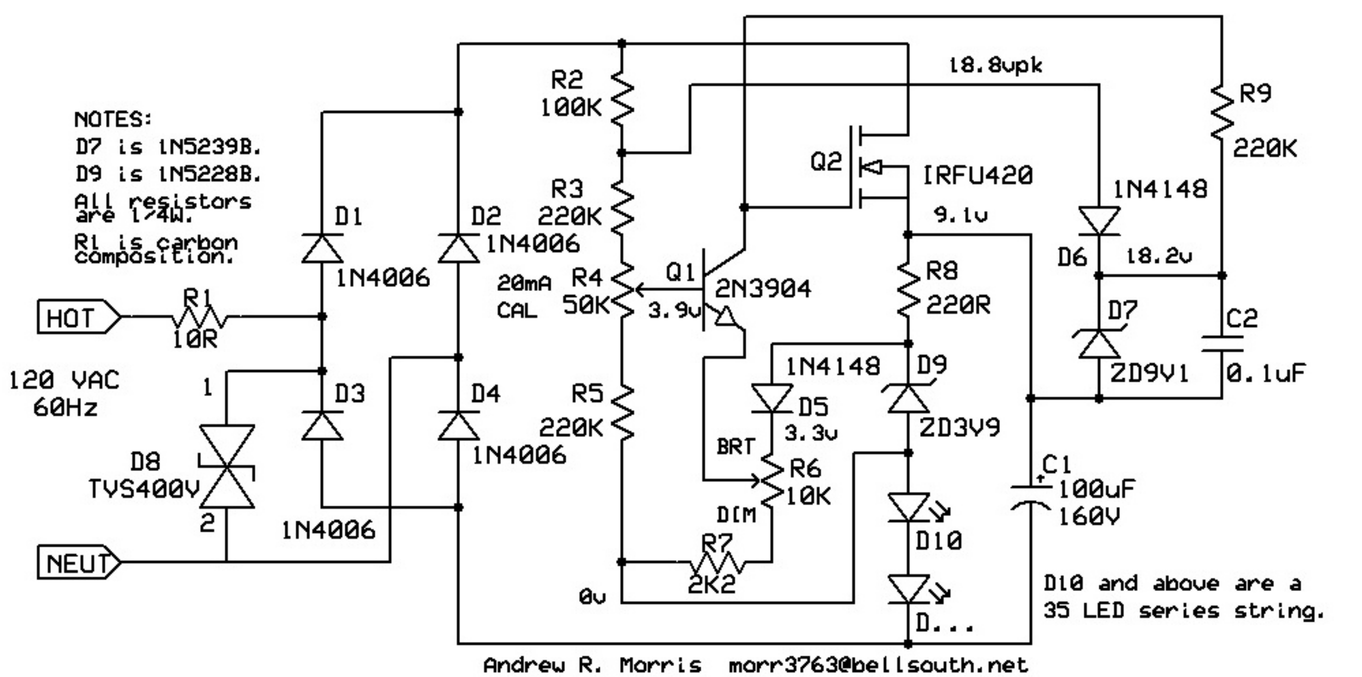

Figure 1. Schematic of the LED driver in its simplest form.

This circuit regulates the LED current by charging capacitor C1 on the rising slope of the 60Hz, full-wave rectified sine-wave. When the desired voltage at R8 is reached, Q1 begins conducting, turning Q2 off and stopping further charging of C1. R8 converts the voltage on C1 to a current through the LEDs. The LEDs are dimmed and the current through them is precisely controlled by stabilizing the voltage across R8 instead of the entire LED string. This is also why the LED driver automatically adapts to the number of LEDs in the controlled string.

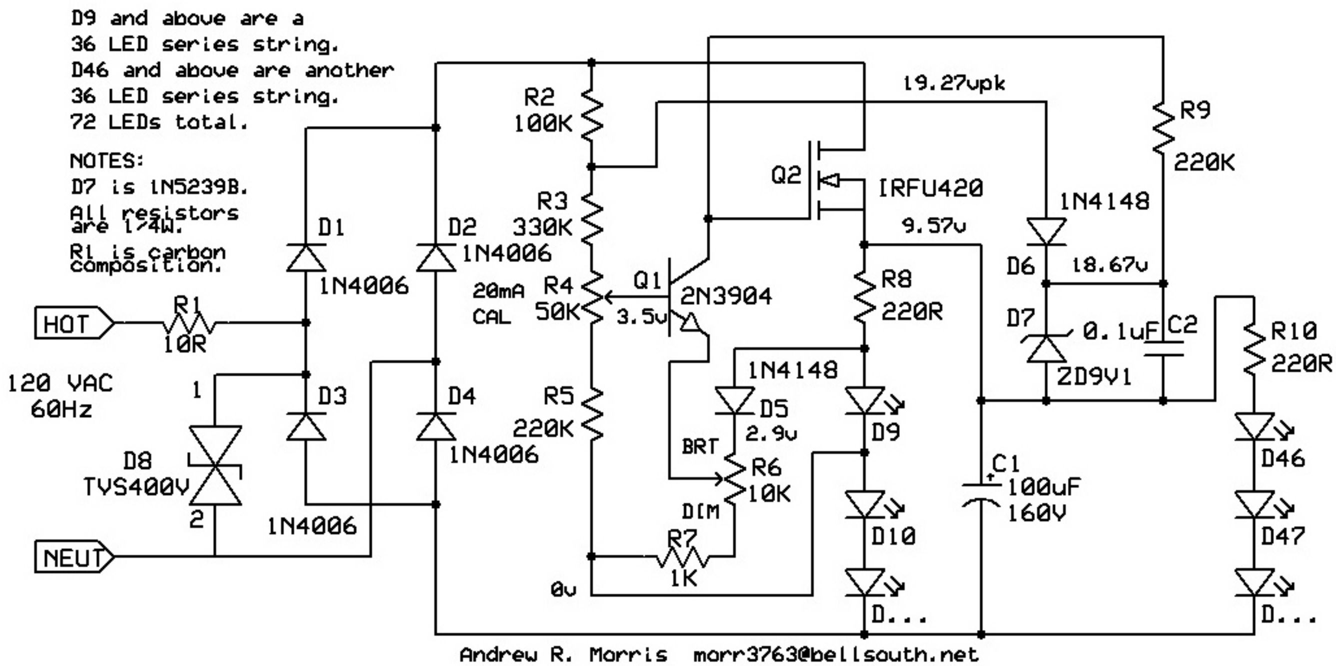

Figure 2. Schematic of the LED driver as used in the desk lamp, using 72 identical LEDs.
This circuit draws about 5 watts of power at maximum brightness. The dropout voltage was measured at about 100 volts.

This circuit is basically an analog 120Hz RFI-free switch-mode current regulator. R8 is the current sense resistor and D9 is the voltage reference. The value of R8 is chosen to keep the peak LED current low, while maintaining 20mA average current at the maximum brightness level. This reduces the stress on the LEDs, while still leaving plenty of power supply headroom. The trimmer, R4 is used to calibrate the circuit to 20mA maximum LED current without using 1% resistors in the design. R4 also accommodates variations in the value of C1 (to be explained later). Note that in figure 2, an LED is used in place of D9, functioning like a 3.5 volt zener diode. Note that its cathode is pointed downward in the schematic like the other LEDs. This prevents wasting power in a zener diode, but D9 may glow a bit dimmer than the other LEDs, especially when dimmed, due to some of its current being diverted through R6. Also, if D9 is physically mounted with the other LEDs, but separated from the electronics, a third wire will have to be added. A fourth wire will have to be added if one or more secondary LED strings are added. If an LED is used for D9, R3 will have to be changed and R4 will have to be readjusted. Use a zener for D9 if you don’t want an LED glowing in the control box and it’s not practical to run an extra wire, or you don’t want one LED glowing dimmer than the others. D9 does not glow noticeably dimmer until all the LEDs are approaching their minimum brightness. D9 will go out completely when the rest of the LEDs have reached their minimum brightness. You can use this phenomenon to find the optimum value for R7. You should pick a value for R7 where D9 goes out right at the end of the pot’s (R6) electrical travel. Note that in the specified pot, there is some space between the ends of the pot’s electrical travel and the ends of its mechanical travel.

Due to the voltage drop across R8 and D9, this circuit is only suitable for high-voltage, low-current applications such as this one. Note that there is 120Hz ripple in the voltage across C1 that will affect the peak LED current. This peak current needs to be addressed in order to avoid damage to the LEDs. According to the LED datasheet, the absolute maximum average LED current is 30mA. The absolute maximum repetitive peak current is 100mA. The ripple, in volts peak-to-peak, is equal to the load current divided by the (frequency times the capacitance) i.e. Vp-p = I/(C*F). For 20mA, 100uF and 120Hz, that will be 1.67Vp-p. When calculating the voltage across R8 required for a specific LED current, add half the ripple value or 0.835Vpk (in this case) to the value that would be calculated if the LEDs were seeing smooth DC. This will cause Q2 to switch off at the desired ripple peaks, producing the desired average LED current. In this case, at 20mA of LED current, there would be 4.4VDC across R8. Add 0.835V ripple peak, and with Ohm's law you can calculate (4.4 + 0.835)/220, or 23.8mA of peak LED current. If you had 16 LED strings on a 100uF capacitor (C1), each having its own R8 counterpart (220 ohms in this case), the ripple would be 0.32/(120*100uF), or 26.7Vp-p or 13.3Vpk. The peak current would be (4.4 + 13.3)/220, or 80.6mA. Note that this would reduce the number of LEDs you can have in each string by dropping your headroom by 13.3V plus the additional MOSFET (3 ohms) drop. The amount that C1 can recharge through Q2 in the available time will also reduce the available headroom. Increasing the value of C1 will reduce the ripple and regain much of the lost headroom.

The voltages marked on the schematics are referenced to the anode of D9 (in figure 1). They are the calculated voltages at the point where Q2 switches off on the rising slope of the 60Hz full-wave rectified sine-wave. R2, D6, D7 and C2 form a bootstrap circuit that provides the bias voltage needed to turn Q2 on. D5 is temperature compensation for the Vbe of Q1 and it also blocks a sneak path that would otherwise slow the circuit start-up. Otherwise, if C1 is discharged, emitter current from Q1 would flow through R8 to C1, causing Q1 to hold Q2 off until C1 reaches a certain voltage (charging through R2). Then Q1 would turn off and Q2 would turn on, starting the circuit. This phenomenon still occurs in the figure 1 circuit (with D5 added), but much more quickly because of R7 and D9. The turn-on delay is longest when R6 is set at minimum brightness. This phenomenon does not happen at all in the figure 2 circuit because LED D9 is back biased, blocking the sneak path. The purpose of R7 is to improve the control range of R6. The LEDs reach their minimum brightness at some point before the voltage at Q1's emitter goes all the way to zero. The optimum value of R7 will vary with the particular circuit configuration. The LED current cannot go all the way to zero because the entire regulator circuit is in series with all the LEDs but D9 (which is part of the regulator itself) and the regulator circuit requires some minimum current in order to function. The minimum LED current was measured at 0.33mA, a 60:1 adjustment ratio.

R1 reduces the in-rush current during power-up and line-voltage spikes and acts like a slow-blow fuse in case of a short. R1 should be mounted in a way that simplifies replacement and is away from anything that can melt or burn if it blows. Use a carbon composition resistor for R1, as a carbon-film resistor cannot tolerate the high in-rush current. A fusible resistor would be preferred, if you can find one. C1 is a 160V part in order to maintain a good margin in its operating voltage. If using 20 or fewer LEDs, a smaller, cheaper 100V part could be used for C1. To aid in figuring out the voltage on C1, each LED drops 3.5 volts, plus there is a 9.1 volt drop in the regulator circuit (figure 1).

Multiple LED strings can be added in parallel with C1 (see figure 2). A counterpart to R8 and D9 would need to be added to each string. In this case, replace D9 with an LED, thereby adding an LED instead of a zener to each string. To get good power supply headroom, a maximum of 34 LEDs per string is recommended. This does not include D9 and its counterpart in the other strings. With multiple LED strings, R8's counterpart in each string will force the current through each additional string to track that of the controlled string. R8's resistance will be far greater than the variability in the DC resistances of the LEDs, minimizing current-related brightness differences between the LED strings. Also, with so many LEDs in a string, differences in their DC resistances will tend to average out.

When adjusting the LED current, adjust R4 for 4.4VDC across R8 with R6 set at maximum brightness. The meter will average out the ripple. When using an LED for D9, as in figure 2, wait a few minutes for the voltage across R8 to stabilize before finalizing the adjustment. This is due to the heating of, and temperature coefficient (tempco) of the LED (D9) being used as a voltage reference. The tempco of the LEDs is not known, as LEDs are not normally used as voltage references. In this case the temperature-related LED current variation is not enough to put the LED current above the 30mA maximum when cold. If you intend to run the LEDs close to the 30mA maximum, temperature compensation is recommended. You would do this by putting a silicon diode in series with R8 and putting it in thermal proximity of D9. If the tempco of the LEDs was known, due to testing, you could calculate the value of R8 needed to precisely compensate for it. The tempco of a silicon diode is -2mV/degC. The breadboard of the circuit in figure 2, after having been set to 4.4VDC across R8, read 5.0VDC after coming out of the freezer with frosty LEDs. The maximum allowable LED current would have put 6.6VDC across R8; therefore no temperature compensation is needed. Of course, the reference LED is not the only thing affected by temperature. The value of C1 will also change with temperature, affecting the ripple and therefore the average LED current, as the circuit regulates on the ripple peaks. The tempco of Q1 is largely compensated by D5.

LEDs of other colors may be used in the strings, but different colored LEDs have different threshold voltages. This means that the primary and secondary strings must have the identical combination of LEDs for them to track each other. If this is not possible in the intended application, a diode must be added to the primary string and a PNP transistor added to each secondary string to force them to track the primary string (see figure 3). Just make sure that the primary string has at least as much voltage as the secondary string(s) so that the transistor(s) in the secondary string(s) have the necessary headroom in which to work. The voltages in the different strings should be closely matched in order to minimize the power wasted in the transistors. The transistors should have about 2-3 volts between their emitters and collectors.

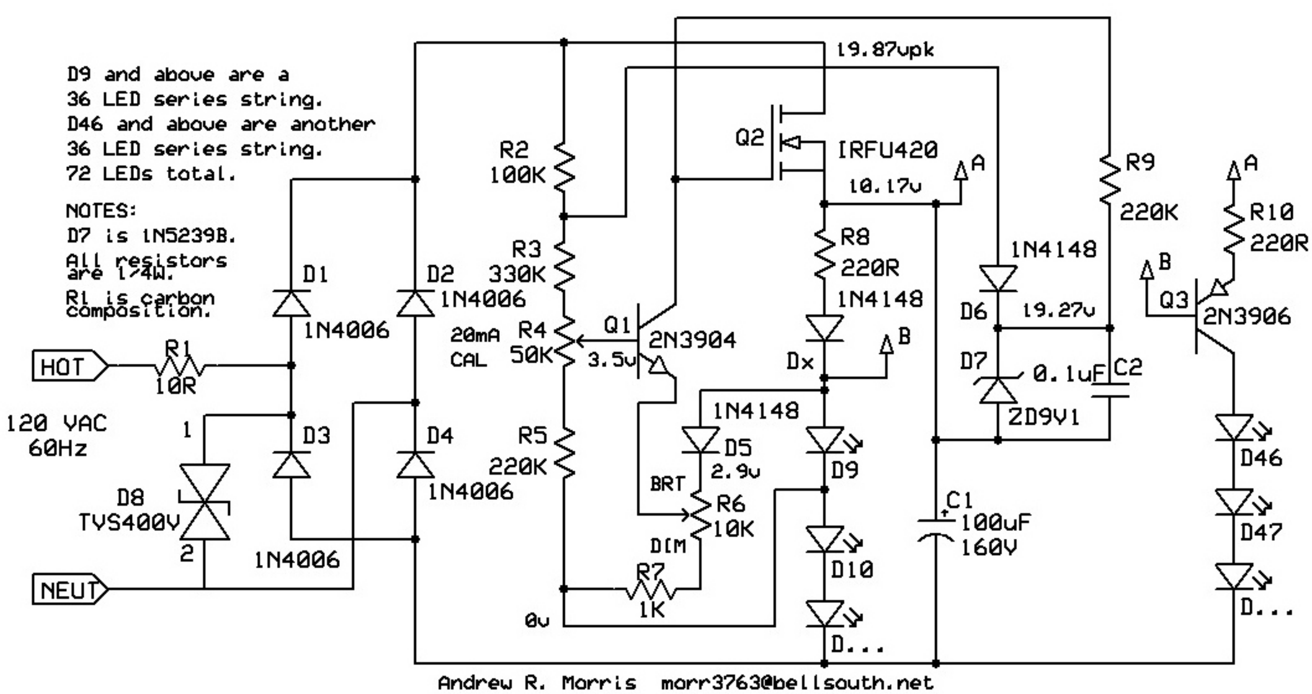

Figure 3. Forcing the secondary string(s) to track the primary string.
If all strings cannot have the same combinations of LEDs, transistors must be added to force the secondary string(s) to track the primary string. Each additional LED string will require an additional transistor. Dx also cancels some of the temperature sensitivity of the reference LED (D9). Dx should be in thermal proximity of

D9 and Q3 should be in thermal proximity of D46 in order to minimize temperature effects on the LED currents. Of course, the tempco of C1 will probably dwarf the LEDs' temperature effects, due to its effect on the ripple. The more LED strings (assuming 100uF for C1), the more ripple and the worse effect temperature changes in C1 will have on the average LED current. Additional LED strings will be connected in the same way as Q3.

D8 is optional, but highly recommended, in order to limit the input voltage spikes to a level that the input diodes and Q2 can tolerate, because there is no electrolytic input capacitor to absorb such spikes. If D8 is not available, replace the input diodes with 1N4004 (400V), as these will hopefully fail before the 500V MOSFET. They will clamp the input voltage before shorting out and blowing R1, hopefully saving the LEDs. If Q2 fails first, the LEDs will probably be destroyed. In a residential environment, voltage spikes of this magnitude will probably only occur during a thunderstorm. With or without D8, it's a good idea to turn the circuit off during a thunderstorm.

Note that this circuit requires a true sine-wave power source. The circuit and the LEDs will probably be destroyed by a UPS or an inverter.

To prevent potential damage to the LEDs when powering the circuit up for the first time, replace the LED string with a single LED. Turn the brightness control and R4 at mid-position. If you have access to a variable transformer, gradually bring the voltage up until the LED glows moderately brightly. Turn the dimmer control up and down and verify that the LED responds. If it passes this test, then it's safe to connect the rest of the LEDs. If you don't have a variable transformer, use a 12VAC transformer for this test. If a fault is found, test both transistors before powering the circuit up again. Use proper static procedures when handling Q2. I damaged one by not following proper ESD procedure.

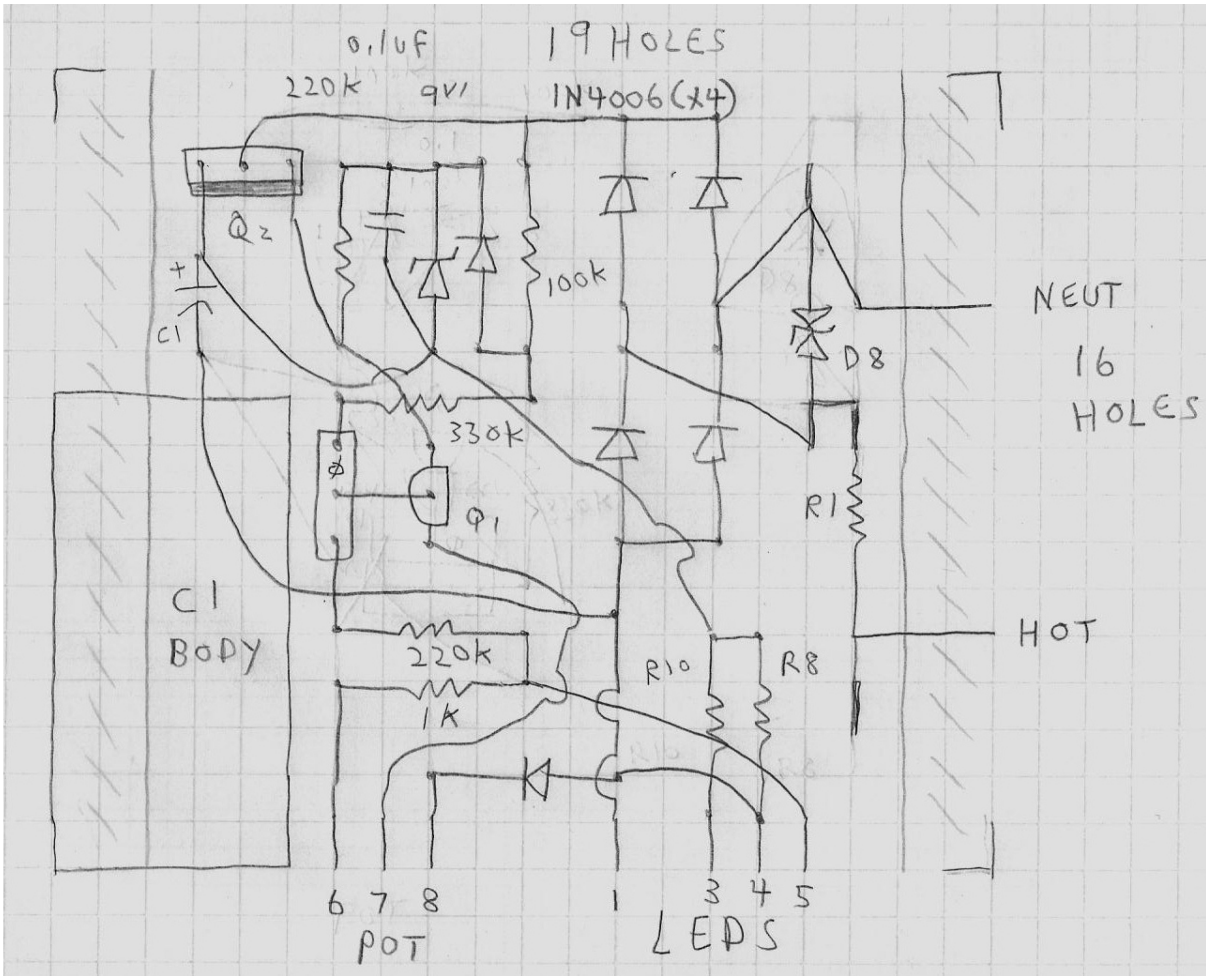

Figure 4. Layout of the dimmable LED driver in the desk lamp.
Notice the simplicity of the circuit. This layout was designed for a specific lamp. Your layout may be totally different, but you can start here. R1 and D8 are soldered in a way to simplify replacement, in the event of a lightning strike or a serious power surge. D8 is quite hefty, but if the surge is too great for it to absorb, it will fail shorted, blowing R1, saving the LEDs and the rest of the electronics. Most likely, only R1 will blow. In addition to the monetary cost, it is a lot of work to remove and replace 72 LEDs. I would have bought a smaller TVS diode (D8), had a suitable part been available.

BTW, when constructing the circuit, make Q2 the last part you install, or wrap a small bare copper wire around its pins to short it out during assembly. Don’t forget to remove the short before powering the circuit up. Q2 is very sensitive to static electricity. I did not do that and Q2 failed after one use. Fortunately, it failed in the off state, instead of shorted. That would have destroyed all of my LEDs. Q1 and Q2 are quite cheap compared to the cost of the LEDs. Replace both transistors just to be safe whenever the performance of the circuit is in question. Replace Q1 first to minimize the risk of static damage to Q2.

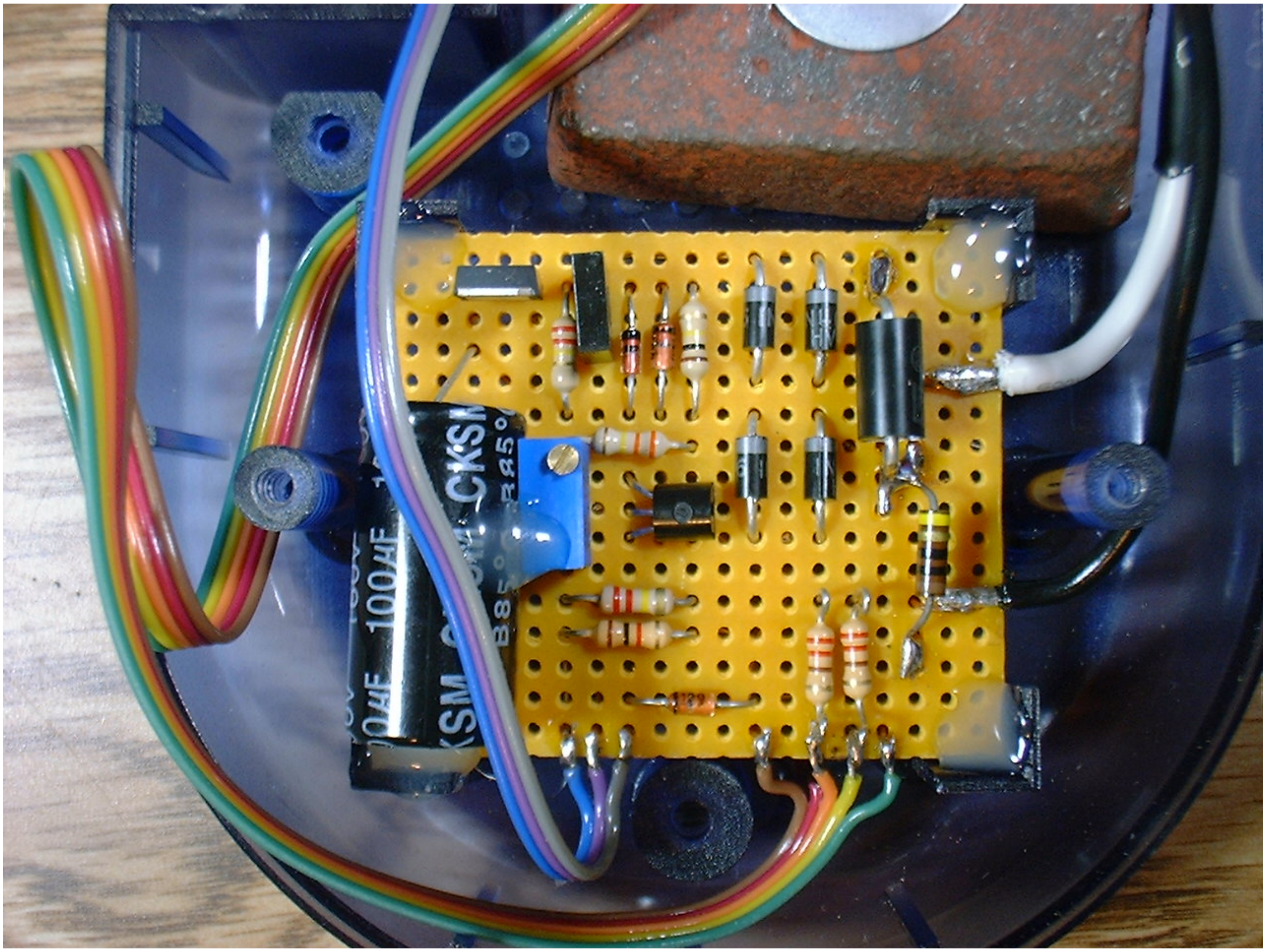

Figure 5. Photo of the dimmable LED driver circuit inside the desk lamp.
Most of the components are horizontally mounted because there is plenty of room on the board and there is a clearance issue with the brightness pot mounted in the cover. An additional pot nut and lock washer were added to back the pot out in order to keep the knob from protruding too far. Note that R1 and D8 are mounted in a way to simplify replacement.

Also, notice that the ribbon cable going to the LED array has five conductors, while the red one is not used. This was done intentionally to relieve high-voltage stress on the insulation because low-voltage wire is being used here. This ribbon cable is the only four-conductor wire I had on hand and it is not intended to be used at this voltage level. The unused red wire puts some space and extra insulation between the common LED wire and the three high-side LED wires that are about 100V higher. Due to the small amount of current flow (40mA for the common LED wire) and the short length, voltage drop in this small-gauge wire is insignificant.

The leads of the two 220 ohm resistors (R8 and R10) in the lower right of the circuit board are brought up into loops to be used as test points when adjusting R4 for 20mA, or 4.4 volts across R8. The same was done to R10 to see how well the secondary LED string tracks the primary one.

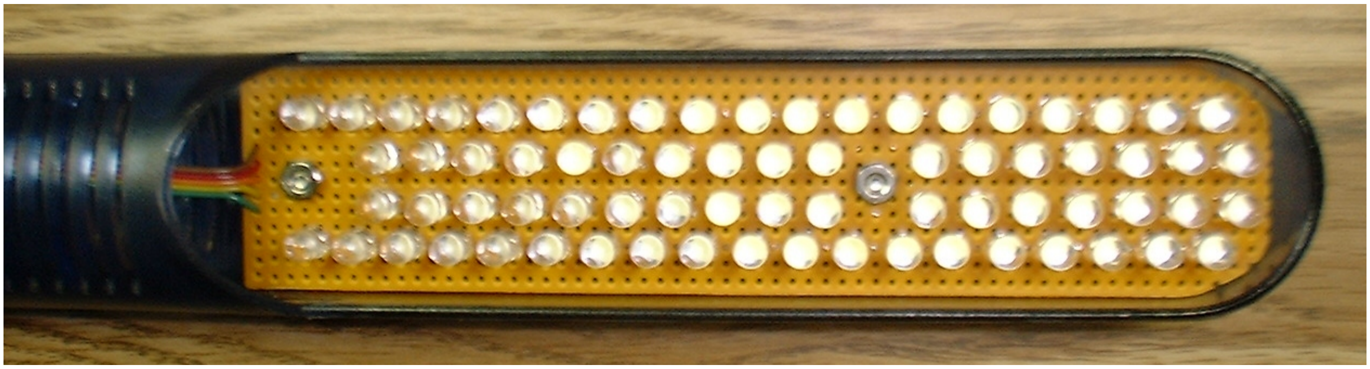

Figure 6. Photo of the 72-diode LED array.

The LEDs are laid out in two mirror-image strings where the anodes are on the far left top and bottom and the cathodes are left center, connected together. From this point of view, the leads of the LEDs are oriented horizontally in the top and bottom rows and vertically in the two middle rows. The brown (#1) wire is the common cathode of the two LED strings. The red (#2) wire is used only as a spacer, as described earlier. The orange wire (#3) is the anode of the secondary LED string. The yellow wire (#4) is the anode of the primary (i.e. controlled) LED string. The green (#5) wire is a tap between the first and second LEDs in the primary string. This first LED (lower left in the photo) is the voltage reference for the current regulator. When the LEDs are at minimum brightness, this LED will go out completely. If this is an issue, use a zener for D9 as shown in figure 1. You will then need 3 wires instead of 4 wires going to the LED array. You would also have to add an identical zener in series with the secondary string. These two zeners would, of course, waste a little bit of power that could be used to produce a little more light, or would raise the power supply dropout voltage by 3.9 volts (if you still used 35 LEDs per string).

When breadboarding and testing this circuit, an isolation transformer is strongly recommended to prevent shock and damage to test equipment. Allied Electronics sells a suitable transformer for around $21. The part number has been included here and in the parts list for your convenience (70009022).

Figure 7. Photo of the modified desk lamp.
This was formally a 9-watt portable fluorescent desk lamp. It now uses about 5 watts of power at full brightness and, unlike the fluorescent version, can be dimmed.

While there may be many ways to drive a string or an array of LEDs, there are probably not so many dimmable solutions with this combination of simplicity and energy efficiency.