A Solid-State Tuning Eye

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In 1935, RCA introduced the first in a series of tubes designed to provide an indication of a voltage, as a visual aid in the tuning of a radio. You adjust the radio's tuning until the shadow in the eye is at the minimum width. These tubes are known as electron-ray tubes, or tuning indicators, or tuning-eyes, or magic eyes. The first tube was the 6E5, and it was followed by the 6U5, 6G5, Rogers 6X6, 6N5/6AB5, 6H5, the elusive 6T5, 6AF6G, 1629, and a range of European versions starting with the EM1, EM4, EM34 and family, and the side-view EM80 family. A 6U5 could be added to a radio for little more than the cost of the tube, but made the radio noticeably more desirable, interesting and "cool". It would have been a sign of wealth to have a radio with an eye tube, so was an example of conspicuous consumption in the midst of the depression. These radios worked fine without the tube, so when they wore out (and they truly do not last very long) they were often not replaced. As a result, radios from that vintage usually have dim of dead tuning-eye tubes. This has made them scarce. In the winter 2020 edition of the OVRC newsletter, Gordon Hamilton "dropped the gauntlet" for someone to create a replacement for these eyes, and I could not resist.

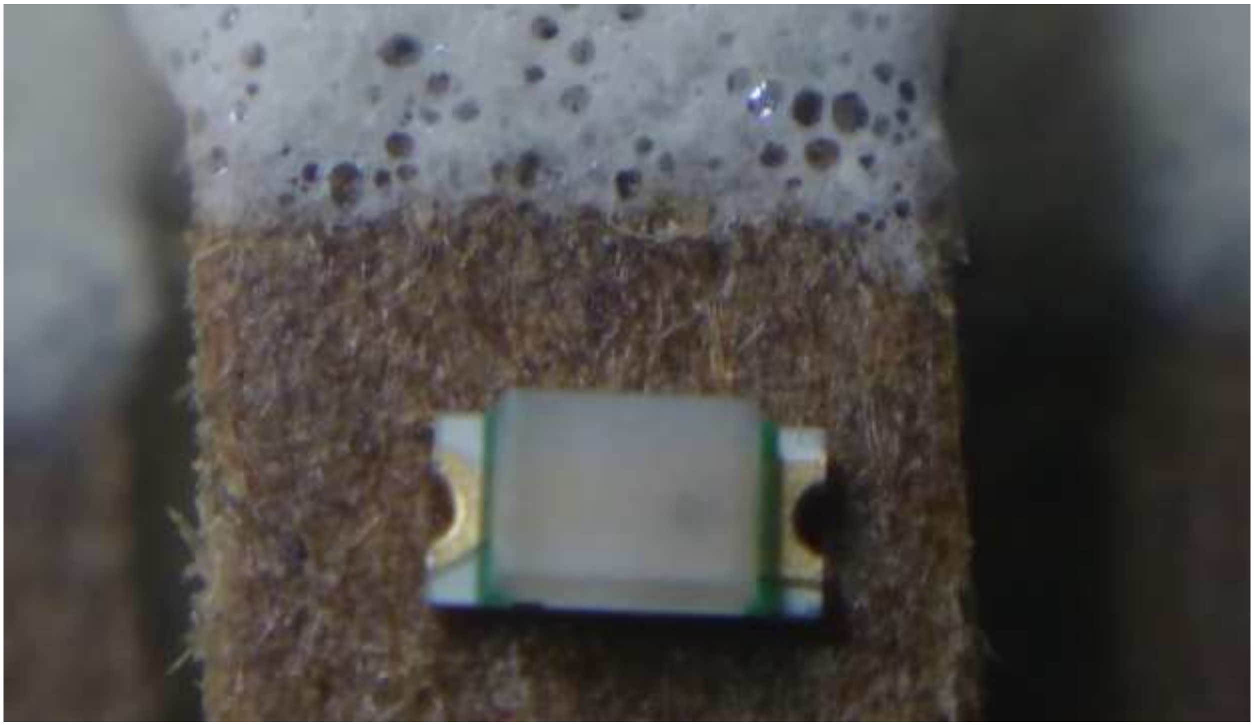
My solid-state replacement (without and with a diffuser) next to a real 6U5.

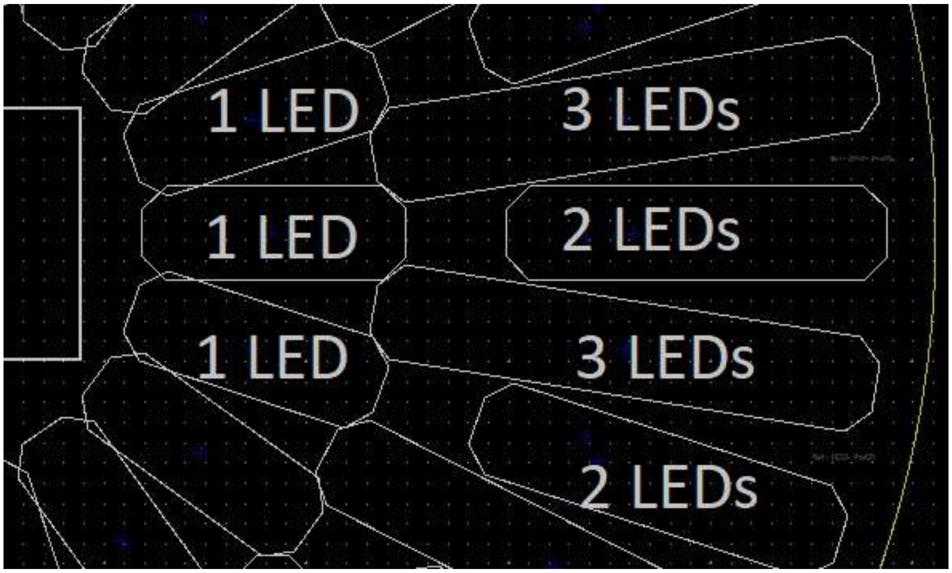
I wanted something that looked and behaved similar to a 6U5, would fit into the same space, could replace a 6U5 without any modifications to the radio, and can be made with readily available material. I decided that this could be done with small green LEDs in a radial array. The target of a 6U5 is about 0.9" in diameter, and the inner light shield is about 0.4", so I needed a ring of light about 0.25" in radius, with an inner diameter of 0.4". I needed enough small LEDs to fit enough into the area to make it look convincing, and this forced me to surface-mount LEDs. I have worked with surface-mount components before, and I decided that the "0603" size (0.06" X 0.03" or 1.6mm by 0.8mm) was about as small as I wanted to go. I could fit 40 around the circumference of a 0.4” circle. The result is shown above, and in action on video at http://rabjohn.ca/data/documents/VID_20210204_164118351.mp4 .

The LED Board

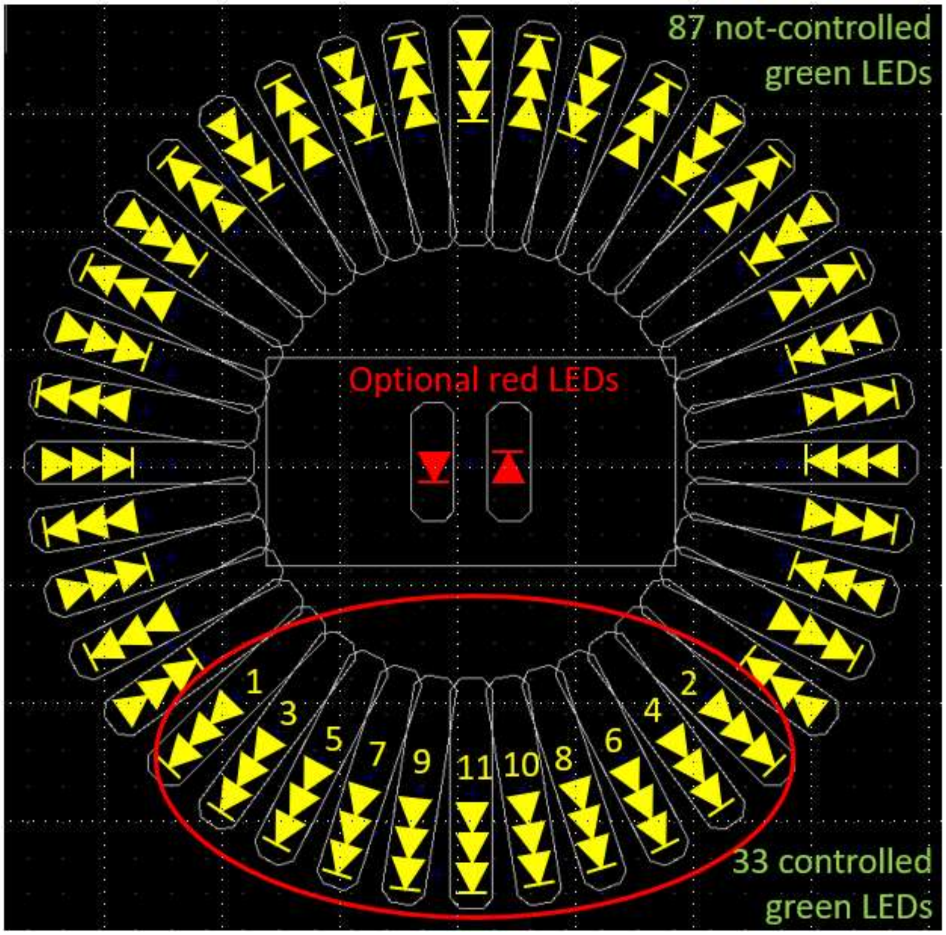
The round LED board has 120 LEDs, some resistors, and a connector that interfaces with the driver board that contains the rest of the electronics, all of it surface-mount technology. The only practical way to build this is with a custom circuit board. I have had custom circuit boards made once in the past. (see http://rabjohn.ca/data/documents/Raster-Converter-Doc-V1p1.pdf) The Digikey web site recommended “KiCad” as a free PC-based tool to design circuit boards. https://www.digikey.ca/en/resources/design-tools/kicad There is a series of Youtube videos there that take you slowly through the process. I entered the schematic diagram in its very capable schematic editor, then placed and routed the conductors on a 2-sided PCB. The tool checks design rules and verifies that the PCB matches the schematic. For a typical circuit board, this is very easy to learn and fool-proof. This LED board was unusual and more custom than my first board (mainly because space was tight and parts were mounted at odd angles), but I managed the get the KiCad tool to do it. The tool produces a set of “Gerber” files that any PCB manufacturing company can use. I found a Chinese manufacturer that accepted my data and sent me custom 26mm diameter double-sided boards with plated-thru holes, solder mask, and silkscreen for under $6 US (total for 20 boards) plus shipping! https://jlcpcb.com/ At this price, it’s not worth messing around with etching your own boards. I received them in under 2 weeks (the boards were made in about 2 days, the rest of the time the boards were in transit), and they work.

When I laid out the first iteration, I decided that the innermost LEDs would be too close together, so I broke up the strips of three into alternating strips of three and two+one. I wanted to maintain a consistent 3-stack for electrical reasons, so the missing LEDs were moved further inside. After I assembled the first iteration, I realized that there was adequate room for soldering so that I did not need to split every second LED, so I modified the board to version 2 with 40 segments of 3 LEDs each.


Green LED on the head of a match.



LED board V1



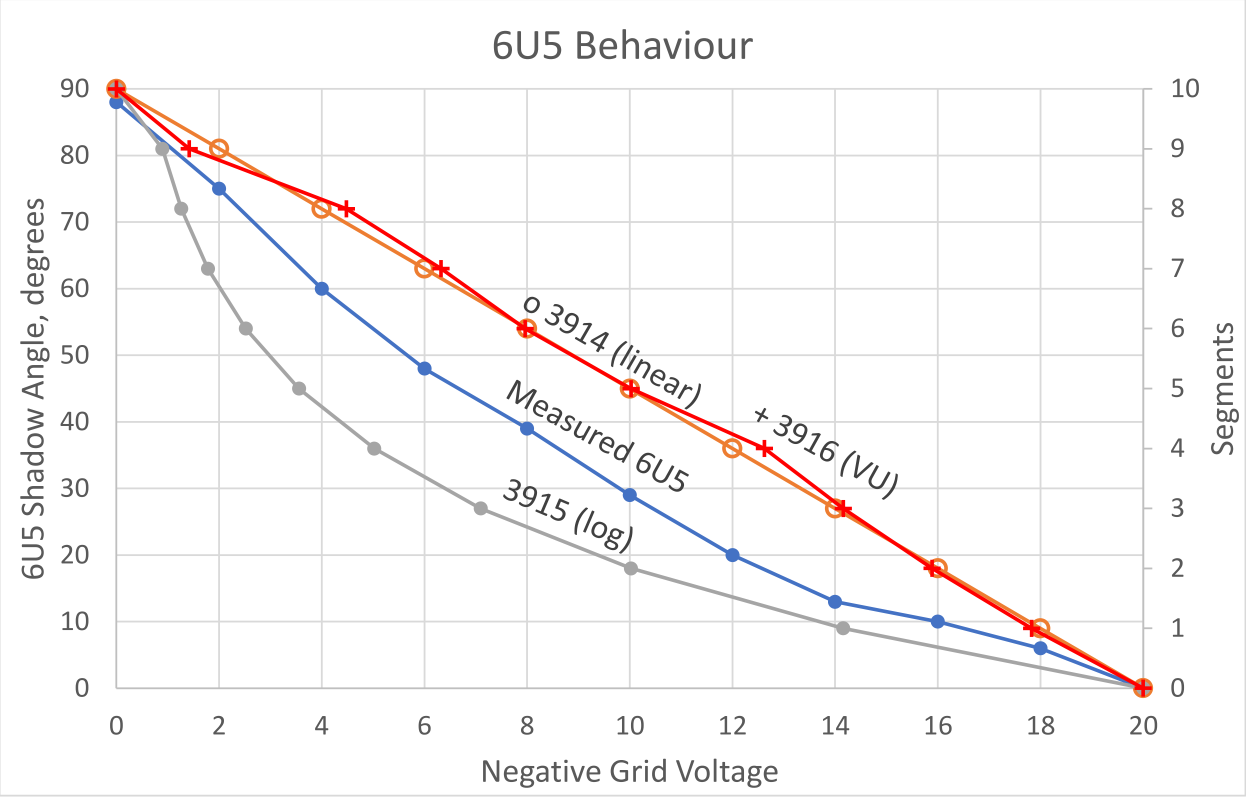
Version 2 of the LED board

The LED I selected was the Rohm SML-D12P8WT86, which is a green AlGaInP diffused LED with a dominant wavelength of 560nm, a 0603 outline, and a height of 0.55mm. It has the shortest wavelength in this series of LEDs, yet when compared to my 6U5, it is slightly too yellow; a slight shift downward in wavelength might make it look better. This is subtle, really only apparent in side-by-side tests. There are other green LEDs based on InGaN that offer a shorter dominant wavelength around 527nm (the Avago/Broadcom HSMQ-C191 for example). The problem is that these LEDs have a forward voltage of over 3V, which means that only a stack of 2 (not 3) can be supported from a 6.3V filament supply. Either we would need to live with strips of 2 LEDs, or we would need to significantly complicate the circuit (voltage doubler, or a more elaborate series/parallel layout). And, I fear that they may look too “blue”. The Rohm 0.55mm thick LED that I used is not as “diffused” as I was hoping; the LED chip location is still very visible. In the next iteration, I might try a thicker LED package which would make it look more diffused, perhaps the Avago/Broadcom HSME-C190 (although it’s advertised wavelength is 573nm, even more “yellow” than the one I used). So, I think my LED choice was not too far off, and 10 cents each in quantity (digikey), they were also the cheapest option.

The Electronics

Three quarters of the LEDs (87 to be exact) are simply lit all the time, just as three quarters of a 6U5 is lit all the time. The other quarter of the LEDS (11 strips of three) are driven by the

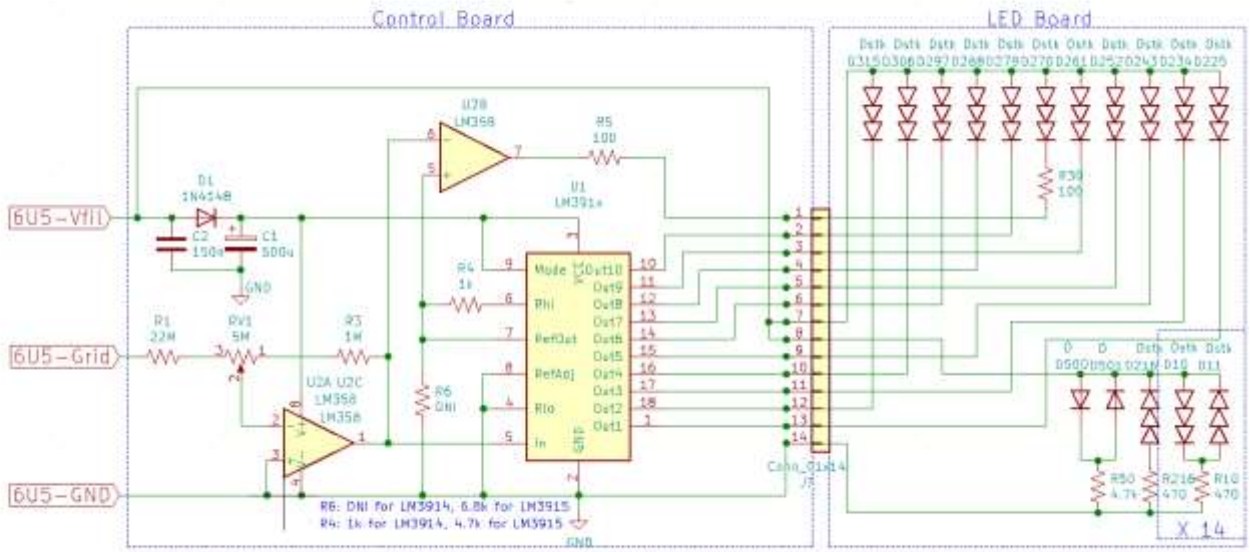
LM3914/LM3915/LM3916 series of bar-graph ICs. These ICs have all the circuitry needed to drive a 10-segment bar-graph display (I'll talk about the 11th segment later). The differences between them are: the 3914 is a linear display with voltage (10 steps, 10% per step), the 3915 is log with voltage (10 steps, 3dB per step), and the 3916 is quite similar to a 3914, but with "VU meter" scale (where the upper 5 segments are 1dB per step for indicating clipping, but the lower 5 segments are farther apart and not evenly spaced). Which version should I select? I measured the shadow angle of a 6U5/6G5 versus grid voltage. See video at http://rabjohn.ca/data/documents/6U5_video_2.mp4 It turns out that it is somewhere between linear and log. I graphed the measured eye data with the data for the different versions of the bar-graph IC, and neither is clearly a superior fit. Once I finished making the device, I compared it to a real tube with a slow triangle wave applied to the grid. Subjectively, comparing a 6U5 to the device with a LM3914 and a LM3915, I felt that the LM3915 better mimicked the 6U5's behaviour. A 6E5 looked more linear, so might be best imitated with a LM3914. Though all of these are easily available in DIPs as old stock, only the LM3914 is currently in production, albeit in a surface-mount package. But, use whatever you can get; any of these are viable options, and they have the same pin-out. I purchased mine from Maddison Électronique in Montréal.



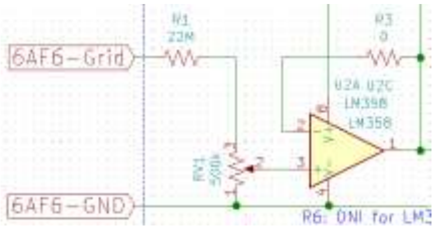
There is nothing unusual about the driver circuit, which I show below. I discovered that I could use AC (filament voltage) directly on the LEDs, even those driven by the LM391x. In order to translate the 0 to -8V (for a 6E5) or 0 to -22V (for a 6U5) to a 0 to 1.28V (RefOut) for the LM391x, I used a simple op-amp circuit. A potentiometer RV1 makes the sensitivity adjustable, so it can look like anything between a 6E5 and 6U5, and beyond. It has an input impedance of 22M (just because larger resistors are hard to find), which should be high enough for most applications.

Though I designed this to replace a 6U5/6E5, it can also replace one section of a 6AF6G/6AD6G (or even one section of a 6AL7GT) that has a no triode, just a "ray control electrode" that swings from 0 to 150V.

The op-amp can be configured as a simple buffer as shown in the sub schematic. The circuit board is configured to be populated in either way.



Overall Schematic



← Op-amp configuration for a 6AF6G

Since I needed an op-amp and the most common op amps come in pairs, what should I do with the remaining op amp? When a 6U5/6E5 receives the most negative voltage on the grid, the edges of the shadows overlap and this area becomes extra bright. I used the extra op-amp to add an 11th segment, a segment that lights up extra brightly at the maximum negative voltage. This 11th segment brightness is set by R5, and the threshold is set by R4. If you prefer, you can increase the value of R5 to make the brightness the same as the other segments.

The brightness of the 10 segments depends on the current pulled from RefOut, pin 7 (which, in this design, is configured to its default voltage of 1.28V). The voltage divider in a LM3914 draws approximately enough current, so R6 is not required (but note that the on-chip resistors have poor tolerance, so your results may vary). The voltage divider in LM3915 draws less current, so R6 will be needed to adequately increase brightness. This is another reason that a LM3915 is preferred: the LED brightness will be more consistent because the current will be dominated by the value of R6 rather than poorly controlled on-chip resistors. A 4.7k or 6.8k resistor for R6 is about correct for a LM3915; the resistor is not needed for the LM3914. Also, there are different resistors in the LM391x ladders that drives the comparators. So, R4 (the 11th resistor on the voltage divider) must be increased to about 5K when a LM3915 is used.

The other segments are always on, and their brightness is set by the resistors on the LED board. There are 14 sets of 6 green LEDs (3 in series in one direction, 3 in the opposite direction) and their brightness is set by a series resistor from the 6.3V filament voltage. I have used 470 ohms to match the brightness of the 10 controlled segments. There is one more set of 3 series LEDs to add up to the 40 LEDs (11 controlled, plus 28 (14X2), plus 1 = 40)

Note that I show R5 on both boards (as R30 on LED board); clearly only 1 needs to be populated, and I recommend that you populate R30 on the LED board. This way, if the boards are accidentally plugged in backwards, the LEDs are not damaged.

If you don't feel the need to make the sensitivity adjustable, you can use fixed resistors. For 6U5 characteristics (-19V closes the eye) eliminate RV1 (connect all three terminals together) and use 1.5M for R3. For a 6E5 characteristic (-8.5V closes the eye) use 3.3M for R3. For 6AF6G characteristics (+150V closes the eye), connect 2 and 3 of RV1 together and place a 180k resistor from 1 to 3.

The circuit as configured takes 63mA RMS with an open eye, and 84mA RMS with the eye tightly closed. Of course, the current waveform is quite peaky, but is much lower than the original 300mA of a 6U5, or even a 6AB5/6N5 at 150mA. This circuit should only be used in parallel filament circuits.

Here is a full bill of materials:

Designation	**Value**	**Size**	**Comment**
R1	22M	¼ w	Sets input impedance and gain
RV1 (6U5/6E5 version)	5M	¼ w	Sets gain
RV1 (6AF6 version)	0.5M	¼ w	Sets gain
R3 (6U5/6E5 version)	1M	¼ w	Sets gain
R3 (6AF6 version)	0		
R4 (LM3914 version)	1k	¼ w	Sets 11th segment threshold
R4 (LM3915 version)	4.7k	¼ w	Sets 11th segment threshold
R5	0		Use R30 on the LED board
R6 (LM3914 version)	DNI to 15k	¼ w	Sets brightness of other segments
R6 (LM3915 version)	4.7k	¼ w	Sets brightness of other segments
U1	LM3914…5…6	18 DIP	See text
U2	LM358	8 DIP	
C1	500uF	10V	
C2	0.15uF	>10V	
D1	1N4003	Wire	Any old rectifier diode
J1	Sullins PPPC072LJBN-RC	Thru-hole	2X7 Position Header Connector, female, Through Hole, Right Angle, 0.100"
J2	Amphenol 95157-114LF	SMT	2X7 Position Header Connector, male, Surface Mount, 0.100" (2.54mm)
D (Qty 120)	Rohm SML-D12P8WT86	0603	Green diffused surface-mount LED
R2-R24 (Qty 15)	470 ohm	0603	Sets brightness of always-on segments
D500/D501 (Qty 2)		0603	Red LED. Optional. Emulates filament.
R50	4.7k	0603	Sets brightness of red LED
R30	100 ohm	0603	Sets brightness of 11th segment

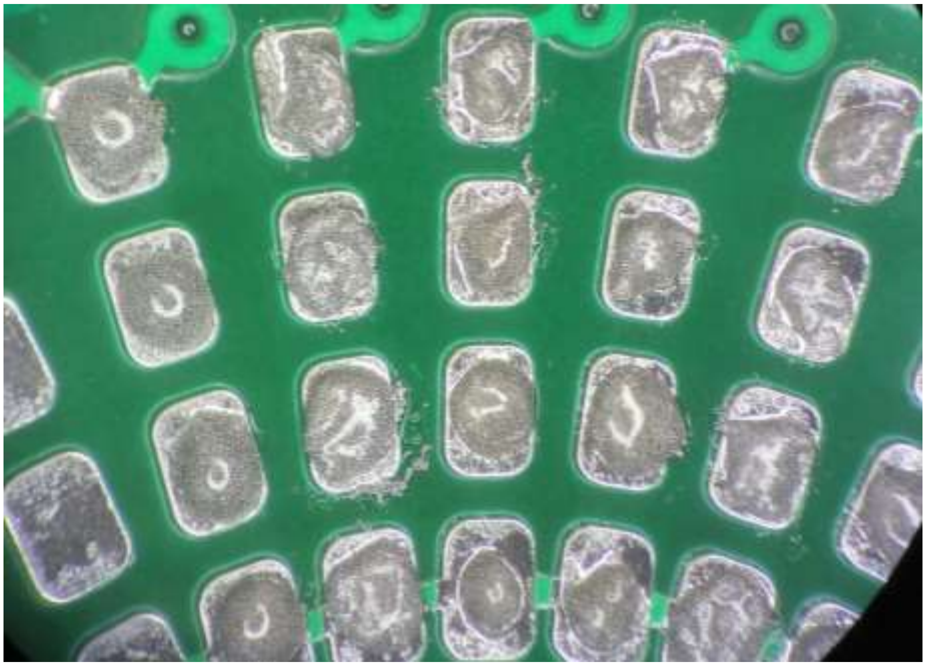
Assembly Instructions

There are 2 boards as shown in the schematic. The boards connect to each-other with a 14 pin (2X7) connector. The LED driver board is straight-forward, uses thru-hole components and can be built without the use of a custom circuit board. I had a custom board made for the driver, but it is not necessary; the first version I built used perforated board and hand wiring. The LED board, however, uses surface-mount components and is quite dense. Assembling this takes a steady hand and patience but is not particularly difficult.

To assemble the LED board, lead-tin solder paste (not lead-free) is the best way to go. I know people who would succeed with wire solder, but solder paste is so much easier. Start on the LED side of the board.

Bare board as received from board manufacturer

Place a blob of solder paste onto each pad. I squirt the paste onto a clean surface, and use a toothpick to transfer a small amount to the circuit board. Magnification is essential; I use a stereo inspection microscope. I will usually paste the pads for about 24 LEDs at once. Solder quantity is not too critical; you want enough to ensure a good joint, but not so much that the components float, or bridges occur. I try to cover most of the pad, and I am generally guilty of too much solder rather than too little. If there is some solder paste between pads, don’t worry, it will ball up and fall off after reflow. You will use less than 1 gram of solder for the entire board



Solder paste applied

Next, place the LEDs onto the solder blobs using tweezers. It is very important that you observe the polarity of the LEDs (see figure 3); you do not want to rework this board if you can possibly avoid it! Note that the joint is formed under the LED, so make sure that the solder paste is squished under the LED’s gold pad. Repeat this until all 120 LED’s are in place. If you want the red LEDs in the middle to simulate the filament, add them now. I did not add the red LEDs, because I ended up using that space for mounting the diffuser. It took me under 3 hours to complete the LED board assembly, but it does take concentration and a steady hand. Experience (both general microscope and tweezer work, and specific work with SMT components) certainly helps, too.

LEDs placed before reflow. The LEDs are 1.6mm long by 0.8m wide.

The next step is to reflow the solder. The board must be heated to over 200C until the solder melts and becomes shiny. There are numerous ways to do this: oven, hot plate or burner, soldering iron, hot air, or infrared. I elected to use a hot-air gun, one sold for paint stripping. The board is simply heated until the solder reflows, which takes under 1 minute. My preferred technique is to use a hot plate under a microscope, but I no longer have access to a suitable hot plate. This allows you to watch it progress, though this should not be necessary. My hot-air gun technique worked perfectly first time with no rework required.

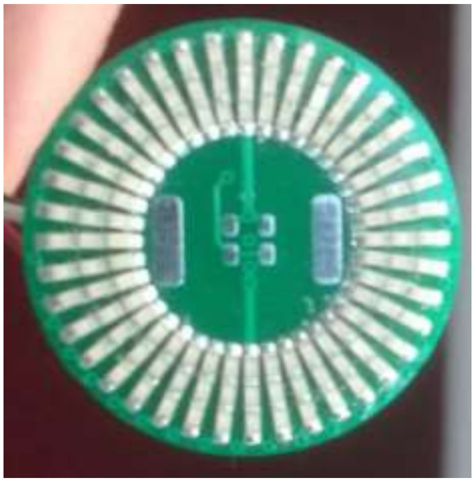
Reflowed before cleaning

Reflow detail before cleaning

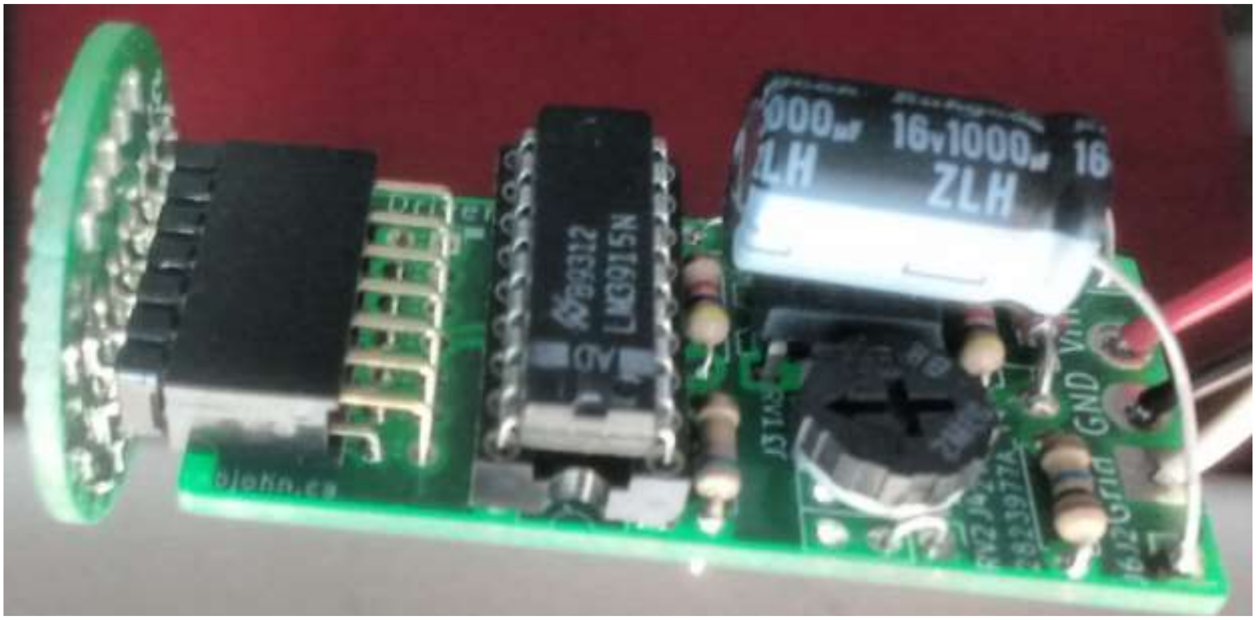
Once the board cools, test all the LEDs (in threes) by applying (for example) 9V to them thru a 1K resistor. If any rework is needed, now is the time to do it, as the board is much more difficult to handle after the back is populated. A hand assembled board will not be very uniform, but that does not matter, the joint under the device is what is important.

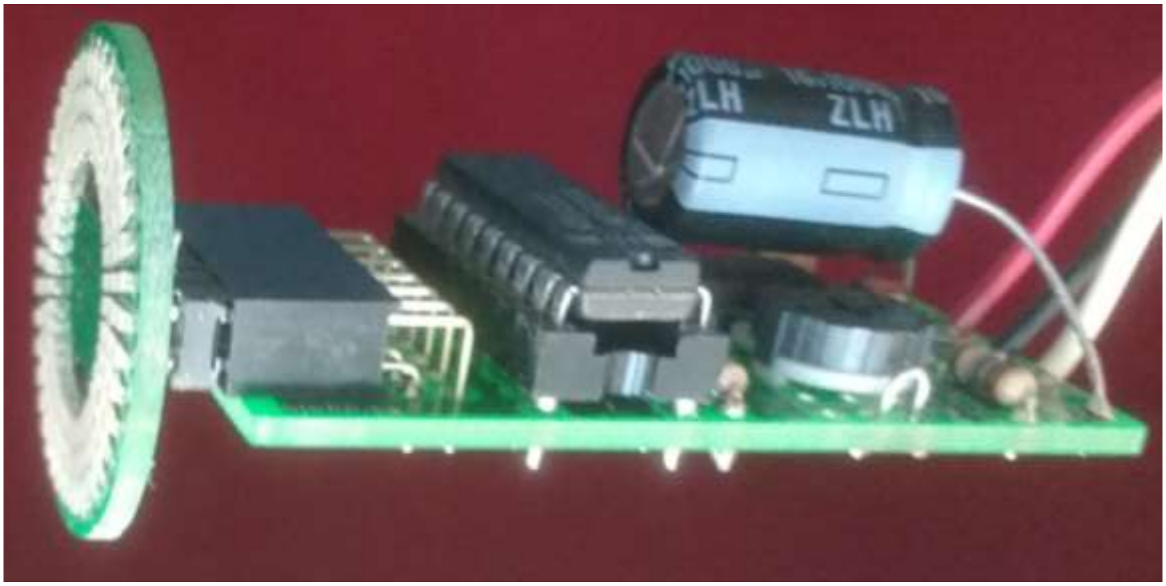
To complete the LED board, mount the chip resistors on the back using a fine-tip soldering iron (I use solder paste again, similar approach to the front side, but use a soldering iron for reflow), then solder on the connector.

The front of the LED board populated with 120 LEDs is shown below.

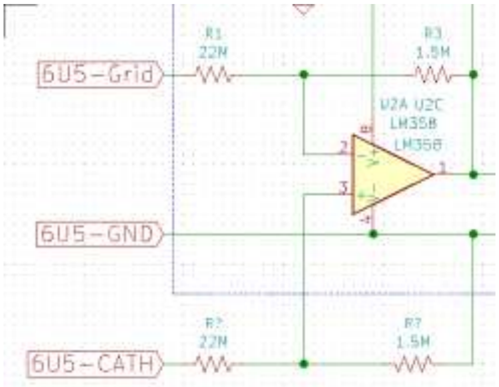


The two boards, assembled, connected with a 14-pin header connector are shown below.





The assembly can be mounted in a cardboard tube for protection. Or, the whole assembly can be placed into the glass envelope of a 6U5 tube. I cut the glass close to the base, cleaned out the socket, placed the electronics into the socket and slid the glass envelope over the electronics. Heat-shrink tubing holds it all together, but note that the glass envelope is not as rugged as an intact tube, so be gentle when shrinking the tubing. Of course, the grid goes to pin 3 of the 6U5 base. In almost all cases, pin 5 and 6 are tied together to ground at the socket, so either can be used for ground. This would leave pin 1 to supply the 6.3VAC at Vfil. Note that in the unusual case where the 6.3VAC filament supply comes from winding with a grounded centre tap, you will need to modify the circuit. Here's an idea: I have not tried this. Note that you give up the ability to adjust gain with a potentiometer.



I believe the project benefits from a light diffuser to smooth out the pixilation caused by the array of LEDs. I have not yet found a perfect solution. I find that a piece of clear plastic (cut from a container that fruit comes in) roughed up with sandpaper does a fair job. I find that circular scratches (I placed it on an arbor in a drill and sanded a circular pattern into the plastic with 100 grit sandpaper) tend to smear the light radially, and that's where you want more smear. You also want *a little* smear circumferentially, and I do this by lightly sanding in a radial direction on the other side of the plastic. The distance between the diffuser and the LEDs is critical. I glued a nut to the middle of the LED board, and threaded the diffuser onto a bolt that I screwed into the nut. The position of the diffuser can be adjusted by twisting it on the bolt.

I have some boards available which I will sell for $5 per set. The most expensive parts are the LEDs, which will cost a total of about $12 from Digikey (depending on quantity), and the LM3915, which are around $3 from Maddison.

Solid-state tube next to an authentic 6U5.