Illumination Circuitry for Liquid Crystal Displays

Tripping the Light Fantastic . . .

Jim Williams

Current generation portable computers and instruments utilize back-lit liquid crystal displays (LCDs). Cold Cathode Fluorescent Lamps (CCFLs) provide the highest available efficiency for backlighting the display. These lamps require high voltage AC to operate, mandating an efficient high voltage DC-AC converter. In addition to good efficiency, the converter should deliver the lamp drive in the form of a sine wave. This is desirable to minimize RF emissions. Such emissions can cause interference with other devices, as well as degrading overall operating efficiency. The circuit should also permit lamp intensity control from zero to full brightness with no hysteresis or "pop-on."

The LCD also requires a bias supply for contrast control. The supply's negative output should be regulated, and variable over a considerable range.

The small size and battery powered operation associated with LCD equipped apparatus mandate low component count and high efficiency for these circuits. Size constraints place severe limitations on circuit architecture, and long battery life is usually a priority. Laptop and hand-held portable computers offer an excellent example. The CCFL and its power supply are responsible for almost 50%

of the battery drain. Additionally, these components, including PC board and all hardware, usually must fit within the LCD enclosure with a height restriction of 0.25".

Cold Cathode Fluorescent Lamp (CCFL) Power Supplies

Any discussion of CCFL power supplies must consider lamp characteristics. These lamps are a difficult load to drive, particularly for a switching regulator. They have a "negative resistance" characteristic; the starting voltage is significantly higher than the operating voltage. Typically, the start voltage is about 1000V, although higher and lower voltage bulbs are common. Operating voltage is usually 300V to 400V, although other bulbs may require different potentials (see Appendix E for a comparison of various backlights). The bulbs will operate from DC, but migration effects within the bulb will quickly damage it. As such, the waveform must be AC. No DC content should be present.
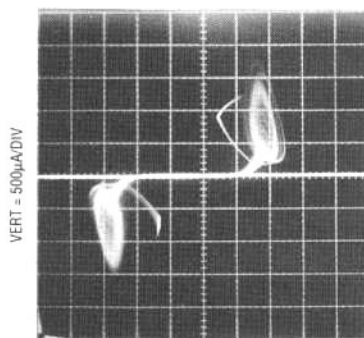
Figure 1A shows an AC driven bulb's characteristics on a curve tracer. The negative resistance induced "snap-back" is apparent. In Figure 1B another bulb, acting against the curve tracer's drive, produces oscillation.

HORIZ = 200V/DIV

AN49 · TA01

1A.

HORIZ = 200V/DIV

AN49 · TA02

1B.
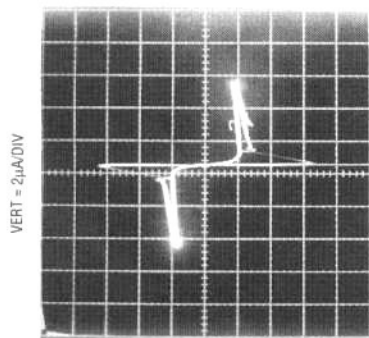
Figure 1. Negative Resistance Characteristic for Two CCFL Bulbs. "Snap Back" is Readily Apparent, Causing Oscillation in 1B. These Characteristics Complicate Power Supply Design

These tendencies, combined with the frequency compensation problems associated with switching regulators, can cause severe loop instabilities, particularly on start-up. Once the lamp is in its operating region it assumes a linear load characteristic, easing stability criteria.

Bulb operating frequencies are typically 20kHz to 100kHz, and a sine-like waveform is preferred. The sine drive's low harmonic content minimizes RF emissions, which could cause interference and efficiency degradation.[1]

Figure 2's circuit meets CCFL drive requirements. Efficiency is 78% with an input voltage range of 4.5V to 20V. 82% efficiency is possible if the LT1172 is driven from a low voltage (e.g., 3V-5V) source. Additionally, lamp intensity is continuously and smoothly variable from zero to full intensity. When power is applied the LT1172 switching regulator's feedback pin is below the device's internal 1.23V reference, causing full duty cycle modulation at the V_{SW} pin (trace A, Figure 3). L2 conducts current (trace B), which flows from L1's center tap, through the transistors, into L2. L2's current is deposited in switched fashion to ground by the regulator's action.

L1 and the transistors comprise a current driven Royer class converter[2] which oscillates at a frequency primarily set by L1's characteristics (including its load) and the 0.02µF capacitor. LT1172 driven L2 sets the magnitude of the Q1-Q2 tail current, and hence L1's drive level. The 1N5818 diode maintains L2's current flow when the LT1172 is off. The LT1172's 100kHz clock rate is asynchronous with respect to the push-pull converter's (60kHz) rate, accounting for trace B's waveform thickening.

The 0.02µF capacitor combines with L1's characteristics to produce sine wave voltage drive at the Q1 and Q2 collectors (traces C and D respectively). L1 furnishes voltage step-up, and about 1400Vp-p appears at its secondary (trace E). Current flows through the 15pF capacitor into the lamp. On negative waveform cycles the lamp's current is steered to ground via D1. Positive waveform cycles are directed, via D2, to the ground referred 562Ω-50k potentiometer chain. The positive half-sine appearing across these resistors (trace F) represents 1/2 the lamp current. This signal is filtered by the 10k-1µF pair and presented to the LT1172's feedback pin. This connection closes a control loop which regulates lamp current. The 2µF capacitor at the LT1172's V_C pin provides stable loop
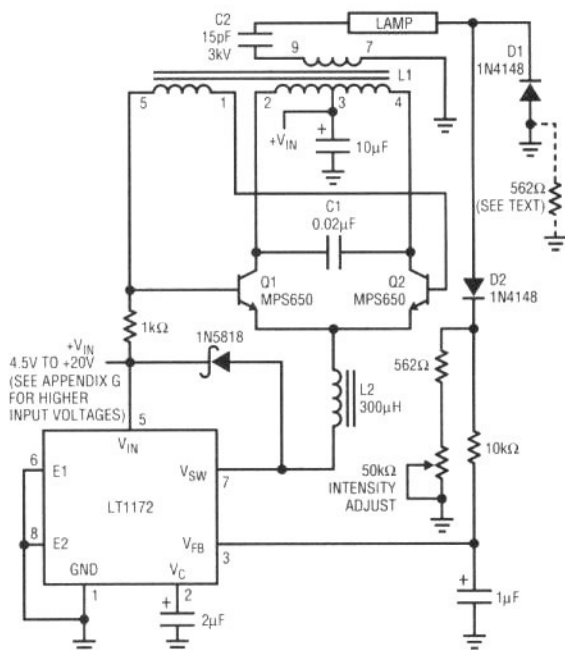
C1 = MUST BE A LOW LOSS CAPACITOR.
   METALIZED POLYCARB
   WIMA FKP2 (GERMAN) RECOMMENDED.
L1 = SUMIDA-6345-020 OR COILTRONICS-CTX110092-1.
   PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = COILTRONICS-CTX300-4
Q1, Q2 = AS SHOWN OR BCP 56 (PHILLIPS SO PACKAGE)
DO NOT SUBSTITUTE COMPONENTS
COILTRONICS (305) 781-8900, SUMIDA (708) 956-0666

Figure 2. Cold Cathode Fluorescent Lamp (CCFL) Power Supply

compensation. The loop forces the LT1172 to switch-mode modulate L2's average current to whatever value is required to maintain a constant current in the lamp. The constant current's value, and hence lamp intensity, may be varied with the potentiometer. The constant current drive allows full 0%-100% intensity control with no lamp dead zones or "pop-on" at low intensities.[3] Additionally, lamp life is enhanced because current cannot increase as the lamp ages.

Several points should be kept in mind when observing this circuit's operation. L1's high voltage secondary can only

Note 1: Many of the characteristics of CCFLs are shared by so called "Hot" cathode fluorescent lamps. See Appendix A, "Hot" Cathode Fluorescent Lamps.

Note 2: See Reference 3.

Note 3: Controlling a non-linear load's current, instead of its voltage, permits applying this circuit technique to a wide variety of nominally evil loads. See Appendix D, "A Related Circuit."
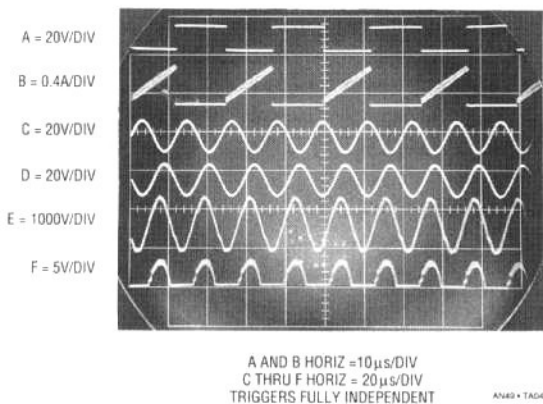
A = 20V/DIV
B = 0.4A/DIV
C = 20V/DIV
D = 20V/DIV
E = 1000V/DIV
F = 5V/DIV

A AND B HORIZ =10µs/DIV
C THRU F HORIZ = 20µs/DIV
TRIGGERS FULLY INDEPENDENT   AN49 • TA04

Figure 3. Waveforms for the Cold Cathode Fluorescent Lamp Power Supply. Note Independent Triggering on Traces A and B, and C through F

be monitored with a wideband, high voltage probe fully specified for this type of measurement. *The vast majority of oscilloscope probes will break down and fail if used for this measurement.*[4] Tektronix probe types P-6007 and P-6009 (acceptable) or types P6013A and P6015 (preferred) probes must be used to read L1's output.

Another consideration involves observing waveforms. The LT1172's switching frequency is completely asynchronous from the Q1-Q2 Royer converter's switching. As such, most oscilloscopes cannot simultaneously trigger and display all the circuit's waveforms. Figure 3 was obtained using a dual beam oscilloscope (Tektronix 556). LT1172 related traces A and B are triggered on one beam, while the remaining traces are triggered on the other beam. Single beam instruments with alternate sweep and trigger switching (e.g., Tektronix 547) can also be used, but are less versatile and restricted to four traces.

Obtaining and verifying high efficiency[5] requires some amount of diligence. The optimum efficiency values given for C1 and C2 are typical, and will vary for specific types of lamps. C1 sets the circuit's resonance point, which varies to some extent with the lamp's characteristic. C2 ballasts the lamp, effectively buffering its negative resistance characteristic. Small values of C2 provide the most load isolation, but require relatively large transformer output voltage for loop closure. Large C2 values minimize transformer output voltage, but degrade load buffering. Also, C1's "best" value is somewhat dependent on the type of

lamp used. Both C1 and C2 must be selected for given lamp types. Some interaction occurs, but generalized guidelines are possible. Typical values for C1 are 0.01µF to 0.047µF. C2 usually ends up in the 10pF to 47pF range. C1 *must* be a low loss capacitor and substitution of the recommended device is not recommended. A poor quality dielectric for C1 can easily degrade efficiency by 10%. C1 and C2 are selected by trying different values for each and iterating towards minimum input supply current. During this procedure insure that loop closure is maintained by monitoring the LT1172's feedback pin, which should be at 1.23V. Several trials usually produce the optimum C1 and C2 values. Note that the highest efficiencies are not necessarily associated with the most esthetically pleasing waveshapes, particularly at Q1, Q2 and the output.

Other issues influencing efficiency include bulb wire length and energy leakage from the bulb. The high voltage side of the bulb should have the smallest practical lead length. Excessive length results in radiative losses which can easily reach 3% for a 3 inch wire. Similarly, no metal should contact or be in close proximity to the bulb. This prevents energy leakage which can exceed 10%.[6]

These considerations should be made with knowledge of other LCD issues. See Appendix B, "Mechanical Design Considerations for Liquid Crystal Displays." This section was guest written by Charles L. Guthrie of Sharp Electronics Corporation.

Special attention should be given to the layout of the circuit board since high voltage is generated at the output. The

Note 4: Don't say we didn't warn you!
Note 5: The term "efficiency" as used here applies to *electrical* efficiency. In fact, the ultimate concern centers around the efficient conversion of power supply energy into light. Unfortunately, lamp types show considerable deviation in their current-to-light conversion efficiency. Similarly, the emitted light for a given current varies over the life and history of any particular lamp. As such, this publication treats "efficiency" on an electrical basis; the ratio of power removed from the primary supply to the power delivered to the lamp. When a lamp has been selected the ratio of primary supply power to emitted lamp light energy may be measured with the aid of a photometer.
Note 6: A very simple experiment quite nicely demonstrates the effects of energy leakage. Grasping the bulb at its low voltage end (low field intensity) with thumb and forefinger produces almost no change in circuit input current. Sliding the thumb-forefinger combination towards the high voltage (higher field intensity) bulb end produces progressively greater input currents. Don't touch the high voltage lead or you may receive an electrical shock. Repeat: Do not touch the high voltage lead or you may receive an electrical shock.

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output coupling capacitor must be carefully located to minimize leakage paths on the circuit board. A slot in the board will further minimize leakage. Such leakage can permit current flow outside the feedback loop, wasting power. In the worst case, long term contamination build-up can increase leakage inside the loop, resulting in starved lamp drive or destructive arcing. It is good practice for minimization of leakage to break the silk screen line which outlines transformer T1. This prevents leakage from the high voltage secondary to the primary. Another tech-nique for minimizing leakage is to evaluate and specify the silk screen ink for its ability to withstand high voltages.

Once these procedures have been followed efficiency can be measured. Efficiency may be measured by determining bulb current and voltage. Measuring current involves measuring RMS voltage across the 562Ω resistor (short the potentiometer). The bulb current is:

$$I_{BULB} = \left(\frac{E}{R}\right) \times 2$$

The X2 factor is necessitated because the diode steering dumps the current to ground on negative cycles. The shunting effects of the 10K-1µF RC across the 562Ω resistor introduce a small current measurement error. Because of this, best accuracy is obtained by measuring across a temporarily inserted 562Ω 1% unit in the ground lead of the negative current steering diode. Once this measurement is complete this second 562Ω resistor may be deleted and the negative current steering diode again returned directly to ground. Bulb RMS voltage is mea-sured at the bulb with a properly compensated high voltage probe. Multiplying these two results gives power in watts, which may be compared to the DC input supply E x I product. In practice, the lamp's current and voltage contain small out of phase components but their error contribution is negligible.

Both the current and voltage measurements require a wideband True RMS voltmeter. The meter must employ a thermal type RMS converter—the more common logarith-mic computing type based instruments are inappropriate because their bandwidth is too low.

The previously recommended high voltage probes are designed to see a 1MΩ-10pF-22pF oscilloscope input.

The RMS voltmeters have a 10MΩ input. This difference necessitates an impedance matching network between the probe and the voltmeter. Details on this and other efficiency measurement issues appear in Appendix C, "Achieving Meaningful Efficiency Measurements."

Two Tube Designs

Some displays require two tubes instead of the more popular single tube approach. These two tube designs usually require more power. Accommodating two tubes involves separate ballast capacitors (see Figure 4), but circuit operation is similar. Higher power may require a different transformer rating. Figure 2's transformer can supply 7.5mA, although more current is possible with appropriate transformer types. For reference, an 11mA capability transformer appears in Figure 4.
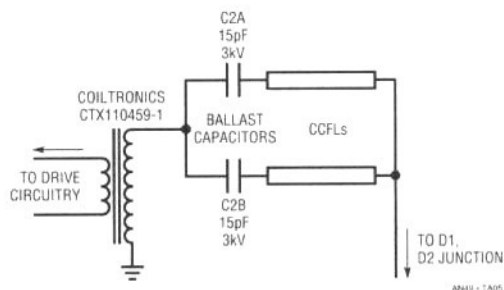

Figure 4. Driving Two Tubes. Capacitors Provide Ballast, Isolating the Tubes

The two tube designs reflect slightly different loading back through the transformer's primary. C2 usually ends up in the 10pF to 47pF range. Note that C2A and B appear with their lamp loads in parallel across the transformer's sec-ondary. As such C2's value is often smaller than in a single tube circuit using the same type lamp. Ideally, the transformer's secondary current splits evenly between the C2-lamp branches, with the total load current being regu-lated. In practice, differences between C2A and B and differences in lamp wiring layout preclude a perfect cur-rent split. Practically, these differences are small, and the lamps appear to emit equal amounts of light.

Low Power CCFL Supply

Figure 5 is the other extreme. This design, the so-called "dim backlight," is optimized for single tube operation at very low currents. The circuit is meant for use at low input voltages, typically 2V to 6V. Figure 2's circuit drives 5mA maximum, but this design tops out at 1mA. This circuit maintains control down to tube currents of $1\mu A$, a very dim light! It is intended for applications where the longest possible battery life is desired. Primary supply drain ranges from hundreds of microamperes to 100mA with tube currents of microamps to 1mA. In shutdown the circuit pulls only $110\mu A$. Maintaining high efficiency at low tube currents requires modifying the basic design.

Achieving high efficiency at low operating current requires lowering Figure 2's quiescent power drain. To do this the LT1172, a pulse width modulator based device, is replaced with an LT1173. The LT1173 is a "burst mode" type regulator. When this device's feedback pin is too low it delivers a burst of output current pulses, putting energy into the transformer and restoring the feedback point. The regulator maintains control by appropriately modulating the burst duty cycle. The ground referred diode at the V_{SW} pin prevents substrate turn-on due to excessive L2 ring-off.

During the off periods the regulator is essentially shut down. This type of operation limits available output power, but cuts quiescent current losses. In contrast, Figure 2's LT1172 pulse width modulator type regulator maintains "housekeeping" current between cycles. This results in more available output power but higher quiescent currents.

Figure 6 shows operating waveforms. When the regulator comes on (trace A, Figure 6) it delivers bursts of output current to the L1-Q1-Q2 high voltage converter. The converter responds with bursts of ringing at its resonant frequency. The circuit's loop operation is similar to Figure 2.[7]

Some bulbs may display non-uniform light emission at very low excitation currents. See Appendix F, "The Thermometer Effect."

LCD Bias Supplies

LCD's also require a bias supply for contrast control. The supply's variable negative output permits adjustment of display contrast. Relatively little power is involved, easing RF radiation and efficiency requirements. The logic sections of display drivers operate from single 5V supplies, but the actual driver outputs swing between +5V and a negative bias potential. Varying this bias causes the contrast of the display to vary.

An LCD bias generator, developed by Steve Pietkiewicz of LTC, is shown in Figure 7. In this circuit U1 is an LT1173 micropower DC to DC converter. The 3V input is converted to +24V by U1's switch, L2, D1, and C1. The switch pin (SW1) also drives a charge pump composed of C2, C3, D2, and D3 to generate −24V. Line regulation is less than 0.2%

Figure 5. Low Power CCFL Power Supply. Circuit Controls Lamp Current over a 1µA to 1mA Range

C1 = MUST BE A LOW LOSS CAPACITOR.
  METALIZED POLYCARB
  WIMA FKP2 (GERMAN) RECOMMENDED.
L1 = SUMIDA-6345-020 OR COILTRONICS-CTX110092-1.
  PIN NUMBERS SHOWN FOR COILTRONICS UNIT
L2 = TOKO 262LYF-0091K
  (408) 432-8251
  DO NOT SUBSTITUTE COMPONENTS

Note 7: The discontinuous energy delivery to the loop causes substantial jitter in the burst repetition rate, although the high voltage section maintains resonance. Unfortunately, circuit operation is in the "chop" mode region of most oscilloscopes, precluding a detailed display. "Alternate" mode operation causes waveform phasing errors, producing an inaccurate display. As such, waveform observation requires special techniques. Figure 6 was taken with a dual beam instrument (Tektronix 556) with both beams slaved to one time base. Single sweep triggering eliminated jitter artifacts. Most oscilloscopes, whether analog or digital, will have trouble reproducing this display.
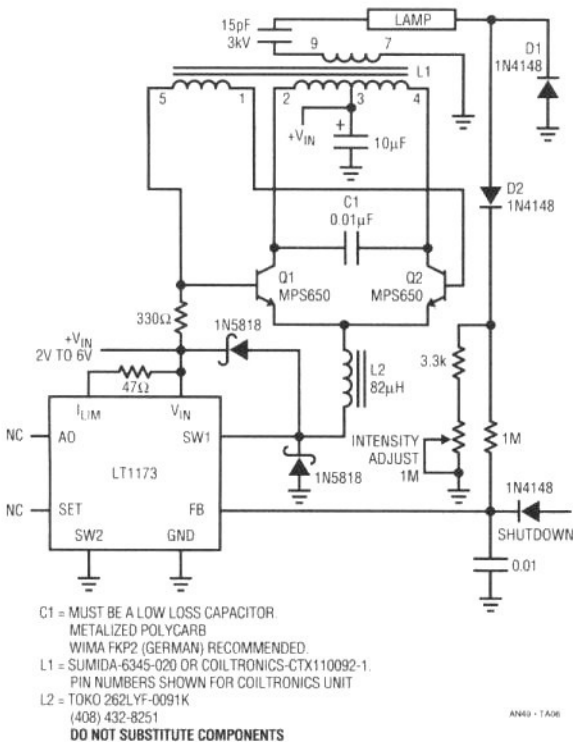
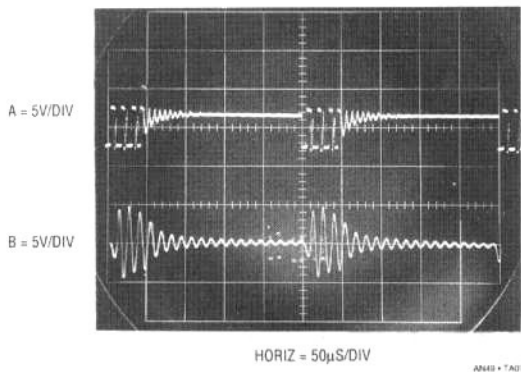A = 5V/DIV

B = 5V/DIV

HORIZ = 50µS/DIV

Figure 6. Waveforms for the Low Power CCFL Power Supply. LT1173 Burst Type Regulator (Trace A) Periodically Excites the Resonant High Voltage Converter (Q1 Collector is Trace B)

Figure 7. DC to DC Converter Generates LCD Bias

from 3.3V to 2V inputs. Load regulation, although suffering somewhat since the −24V output is not directly regulated, measures 2% from a 1mA to 7mA load. The circuit will deliver 7mA from a 2V input at 75% efficiency.

If greater output power is required, Figure 7's circuit can be driven from a +5V source. R1 should be changed to 47Ω and C3 to 47µF. With a 5V input, 40mA are available at 75% efficiency. Shutdown is accomplished by bringing the anode of D4 to a logic high, forcing the feedback pin of U1 to go above the internal 1.25V reference voltage.
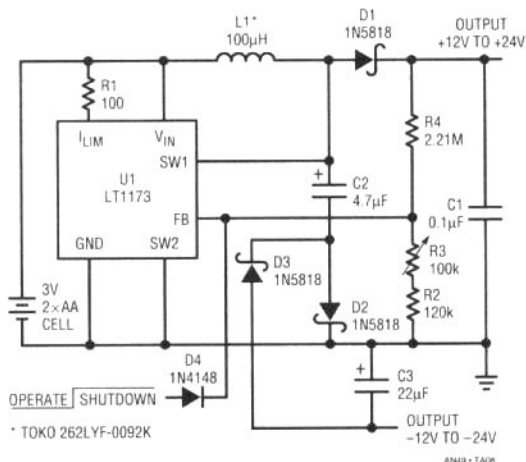
Shutdown current is 110µA from the input source and 36µA from the shutdown signal.

A similar modification of a boost converter can provide negative bias from a 5V supply is shown in Figure 8. The converter, developed by Jon Dutra of LTC, is half switcher and half charge pump. The charge pump (C1, C2, D2, and D3) is driven by the flying node at V_{SW}. The output is variable from −12V to −24V, providing contrast control for the display.
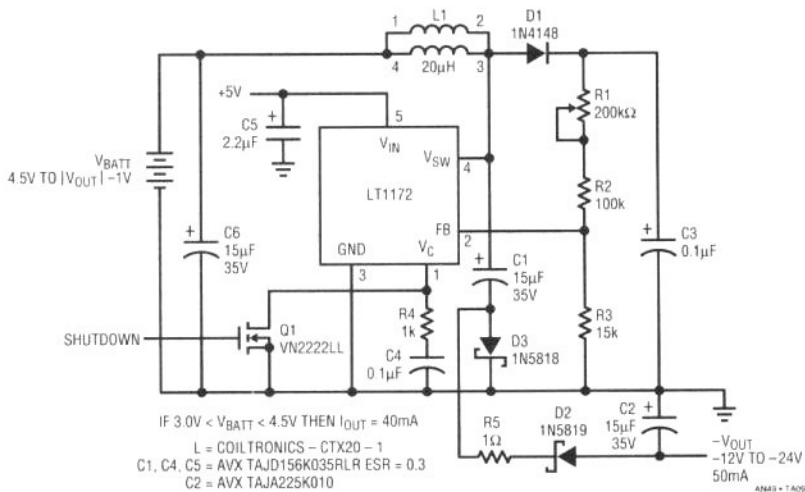

Figure 8. The Dutra Configuration Combines Switching Regulator and Charge Pump Techniques to Generate Negative Bias for LCD Drivers

On low voltage supplies (6V or less) V_{IN} and V_{BATT} can be tied together. With higher battery voltages, high efficiency is obtained by running the LT1172 V_{IN} pin from 5V. Shutting off the 5V supply automatically turns off the LT1172. The maximum value for V_{BATT} is equal to the negative output +1V. Also, the difference between V_{BATT} and V_{IN} must not exceed 16V. R1, R2, and R3 are made large to minimize battery drain in shutdown, since they are permanently connected to the battery via L1 and D1. Efficiency is about 80% at I_{OUT} = 25mA.

Note: *This application note was derived from a manuscript originally prepared for publication in EDN Magazine.*

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APPENDIX A

"HOT" CATHODE FLUORESCENT LAMPS

Many CCFL characteristics are shared by so-called "Hot" Cathode Fluorescent Lamps (HCFLs). The most significant difference is that HCFLs contain filaments at each end of the tube (see Figure A1). When the filaments are powered they emit electrons, lowering the tube's ionization potential. This means a significantly lower voltage will start the tube. Typically the filaments are turned on, a relatively modest high voltage impressed across the tube, and start-up occurs. Once the tube starts filament power is removed. Although HCFLs reduce the high voltage requirement they require a filament supply and sequencing circuitry. The CCFL circuits shown in the text will start and run HCFLs without using the filaments. In practice this involves simply driving the filament connections at the HCFL tube ends as if they were CCFL electrodes.
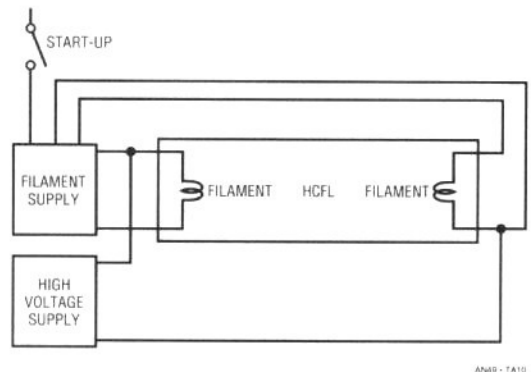

Figure A1. A Conceptual Hot Cathode Fluorescent Lamp Power Supply. Heated Filaments Liberate Electrons, Lowering the Tube's Start-Up Voltage Requirement. CCFL Supply Discussed in Text Eliminates Filament Supply

APPENDIX B

MECHANICAL DESIGN CONSIDERATIONS FOR LIQUID CRYSTAL DISPLAYS

Charles L. Guthrie, Sharp Electronics Corporation

Introduction

As more companies begin the manufacturing of their next generation of computers, there is a need to reduce the overall size and weight of the units to improve their portability. This has sparked the need for more compact designs where the various components are placed in closer proximity, thus making them more susceptible to interaction from signal noise and heat dissipation. The following is a summary of guidelines for the placement of the display components, and a summary of suggestions for overcoming difficult design constraints associated with component placement.

In notebook computers, the thickness of the display housing is important. The design usually requires the display to be in a pivotal structure so that the display may be folded down over the keyboard for transportation. Also, the outline dimensions must be minimal so that the package will remain as compact as possible. These two constraints drive the display housing design and placement of the display components. This discussion surveys each of the problems facing the designer in detail and offers suggestions for overcoming the difficulties to provide a reliable assembly.

The problems facing the pen based computer designer are similar to those realized in notebook designs. In addition, however, pen based designs require protection for the face of the display. In pen based applications, as the pen is moved across the surface of the display, the pen has the potential for scratching the front polarizer. For this reason, the front of the display must be protected. Methods for protecting the display face while minimizing effects on the display image are given.

Additionally, the need to specify the flatness of the bezel is discussed. Suggestions for acceptable construction techniques for sound design are included. Further, display components likely to cause problems due to heat buildup are identified and methods for minimization of the heat's effects are presented.

The ideas expressed here are not the only solutions to the various problems, and have not been assessed as to whether they may infringe on any patents issued or applied for.

Flatness and Rigidity of the Bezel

In the notebook computer, the bezel has several distinct functions. It houses the display, the inverter for the back-light, and in some instances, the controls for contrast and brightness of the display. The bezel is usually designed to tilt to set the optimum viewing angle for the display.

It is important to understand that the bezel must provide a mechanism to keep the display flat, particularly at the mounting holds. Subtle changes in flatness place uneven stress on the glass which can cause variations in contrast across the display. Slight changes in pressure may cause significant variation in the display contrast. Also, at the extreme, significantly uneven pressures can cause the display glass to fail.

Because the bezel must be functional in maintaining the flatness of the display, consideration must be made for the strength of the bezel. Care must be taken to provide structural members, while minimizing the weight of the unit. This may be executed using a parallel grid, normal to the edges of the bezel, or angled about 45° off of the edges of the bezel. The angled structure may be more desirable in that it provides resistance to torquing the unit while lifting the cover with one hand. Again, the display is sensitive to stresses from uneven pressure on the display housing.

Another structure which will provide excellent rigidity, but adds more weight to the computer, is a "honeycomb" structure. This "honeycomb" structure resists torquing from all directions and tends to provide the best protection for the display.

With each of these structures it is easy to provide mounting assemblies for the display. "Blind nuts" can be molded

into the housing. The mounting may be done to either the front or rear of the bezel. Attachment to the rear may provide better rigidity for placement of the mounting hardware.

One last caution is worth noting in the development of a bezel. The bezel should be engineered to absorb most of the shock and vibration experienced in a portable computer. Even though the display has been carefully designed, the notebook computer presents extraordinary shock and abuse problems.

Avoiding Heat Buildup in the Display

Several of the display components are sources for heat problems. Thermal management must be taken into account in the design of the display bezel. A heated display may be adversely affected; a loss of contrast uniformity usually results. The Cold Cathode Fluorescent Tube (CCFT) itself gives off a small amount of heat relative to the amount of current dissipated in its glow discharge. Likewise, even though the inverters are designed to be extremely efficient, there is some heat generated. The buildup of heat in these components will be aggravated by the typically "tight" designs currently being introduced. There is little ventilation designed into most display bezels. To compound the problem, the plastics used are poor thermal conductors, thus causing the heat to build up which may affect the display.

Some current designs suffer from poor placement of the inverter and/or poor thermal management techniques. These designs can be improved, even where redesign of the display housing, with improved thermal management, is impractical.

One of the most common mistakes in current designs is that there has been no consideration for the build up of heat from the CCFT. Typically, the displays for notebook applications have only one CCFT to minimize display power requirements. This lamp is usually placed along the right edge of the display. Since the lamp is placed very close to the display glass, it can cause a temperature rise in the liquid crystal. It is important to note that variations in temperature of as little as 5°C can cause an apparent non-uniformity in display contrast. Variations caused by slightly higher temperature variations will cause objectionable variations in the contrast and display appearance.

To further aggravate the situation, some designs have the inverter placed in the bottom of the bezel. This has a tendency to cause the same variations in contrast, particularly when the housing does not have any heat sinking for the inverter. This problem manifests itself as a "blooming" of the display, just above the inverter. This "blooming" looks like a washed out area where, in the worst case, the characters on the display fade completely.

The following section discusses the recommended methods for overcoming these design problems.

Placement of the Display Components

One of the things that can be done is to design the inverter into the base of the computer with the mother board. In some applications this is impractical because this requires the high voltage leads to be mounted within the hinges connecting the display bezel to the main body. This causes a problem with strain relief of the high voltage leads, and thus with U.L. Certification.

One mistake, made most often, is placing the inverter at the bottom on the bezel next to the lower edge of the display. It is a fact that heat rises, yet this is one of the most overlooked problems in new notebook designs. Even though the inverters are very efficient, some energy is lost in the inverter in the form of heat. Because of the insulating properties of the plastic materials used in the bezel construction, heat builds up and affects the display contrast.

Designs with the inverter at the bottom can be improved in one of three ways. The inverter can be relocated away from the display; heat sinking materials can be placed between the display and the inverter; or ventilation can be provided to remove the heat.

In mature designs, it may be impractical to do what is obvious and move the inverter up to the side of the display towards the top of the housing. In these cases, the inverter may be insulated from the display with a "heat dam". One method of accomplishing this would be to use a piece of mica insulator die cut to fit tightly between the inverter and the display. This heat dam would divert the heat around the end of the display bezel to rise harmlessly to the top of the housing. Mica is recommended in this application because of its thermal and electrical insulating properties.

The last suggestion for removing heat is to provide some ventilation to the inverter area. This has to be done very carefully to prevent exposing the high voltage. Ventilation may not be a practical solution because resistance to liquids and dust is compromised.

The best solution for the designer of new hardware is to consider the placement of the inverter to the side of the display and at the top of the bezel. In existing designs of this type the effects of heat from the inverter, even in tight housings, has been minimal or non-existent.

One problem which is aggravated by the placement of the inverter at the bezel is heat dissipated by the CCFT. In designs were the inverter is placed up and to the side of the display, fading of the display contrast due to CCFT heat is not a problem. However, when the inverter is placed at the bezel bottom, some designs experience a loss of contrast aggravated by the heat from the CCFT and inverter.

In cases where the inverter must be left at the bottom, and the CCFT is causing a loss of contrast, the problem can be minimized by using an aluminum foil heat sink. This does not remove the heat from the display, but dissipates it over the entire display area, thus normalizing the display contrast. The aluminum foil is easy to install and in some present designs has successfully improved the display contrast.

Remember that the objection to the contrast variation stems more from non-uniformity than from a total loss of contrast.

Protecting the Face of the Display

One of the last considerations in the design of notebook and pen based computers is protection of the display face.

The front polarizer is made of a mylar base and thus is susceptible to scratching. The front protection for the display, along with providing scratch protection, may also provide an anti-glare surface.

There are several ways that scratch resistance and anti-glare surfaces can be incorporated. A glass or plastic cover may be placed over the display, thus providing protection. The material should be placed as close to the display as possible to minimize possible parallax problems due to reflections off of the cover material. With anti-glare materials, the further the material is from the front of the display the greater the distortion.

In pen applications, the front anti-scratch material is best placed in contact with the front glass of the display. The cover glass material normally needs to be slightly thicker to protect the display from distortion when pressure is being exerted on the front.

There are several methods for making the pen input devices. Some use the front surface of the cover glass to provide input data and some use a field effect to a printed wiring board on the back of the display. When the pen input is on the front of the display, the input device is usually on a glass surface.

To limit specular reflection in this application, the front cover glass should be bonded to the display. Care must be taken to insure that the coefficient of thermal expansion is matched for all of the materials used in the system. Because of the difficulties encountered with the bonding of the cover glass, and the potential to destroy the display through improper workmanship, consulting an expert is strongly recommended.

APPENDIX C

ACHIEVING MEANINGFUL EFFICIENCY MEASUREMENTS

Efficiency measurement is difficult. The most important points for getting good efficiency measurements are:

- Use proper equipment.
- Measure carefully.
- Measure with the CCFL you intend to use. Simple resistive loads or substitute lamps can cause 5-10% errors.

- Measure with the circuit components and layout you intend to use.

Obtaining reliable efficiency data for the CCFL circuits requires attention to measurement technique. The combination of high frequency, harmonic laden waveforms and high voltage makes meaningful results difficult to obtain.

The choice, understanding and use of test instrumentation is crucial. Clear thinking is needed to avoid unpleasant surprises![1]

Probes

The probes employed must faithfully respond over a variety of conditions. Measuring across the resistor in series with the CCFL is the most favorable circumstance. This low voltage, low impedance measurement allows use of a standard 1X probe. The probe's relatively high input capacitance does not introduce significant error. A 10X probe may also be used, but frequency compensation issues (discussion to follow) must be attended to.

The high voltage measurement across the lamp is considerably more demanding on the probe. The waveform fundamental is at 20kHz to 100kHz, with harmonics into the MHz region. This activity occurs at peak voltages in the kilovolt range. The probe must have a high fidelity response under these conditions. Additionally, the probe should have low input capacitance to avoid loading effects which would corrupt the measurement. The design and construction of such a probe requires significant attention. Figure C1 lists some recommended probes along with their characteristics. As stated in the text, almost all

standard oscilloscope probes *will fail*[2] if used for this measurement. Attempting to circumvent the probe requirement by resistively voltage dividing the lamp voltage also creates problems. Large value resistors often have significant voltage coefficients and their shunt capacitance is high and uncertain. As such, simple voltage dividing is not recommended. Similarly, common high voltage probes intended for DC measurement will have large errors because of AC effects. The P6013A and P6015 are the favored probes; their 100MΩ input and small capacitance introduces low loading error. The penalty for their 1000X attenuation is reduced output, but the recommended voltmeters (discussion to follow) can accommodate this.

All of the recommended probes are designed to work into an oscilloscope input. Such inputs are almost always 1MΩ paralleled by (typically) 10pF-22pF. The recommended voltmeters, which will be discussed, have significantly different input characteristics. Figure C2's table shows higher input resistances and a range of capacitances. Because of this the probe must be compensated for the

Note 1: It is worth considering that various constructors of text Figure 2 have reported efficiencies ranging from 8% to 115%.

Note 2: That's twice we've warned you nicely.

TEKTRONIX PROBE TYPE	ATTENUATION FACTOR	ACCURACY	INPUT RESISTANCE	INPUT CAPACITANCE	RISE TIME	BAND-WIDTH	MAXIMUM VOLTAGE	DERATED ABOVE	DERATED TO AT FREQUENCY	COMPENSATION RANGE	ASSUMED TERMINATION RESISTANCE
P6007	100X	3%	10MΩ	2.2pF	14ns	25MHz	1.5kV	200kHz	700V$_{RMS}$ at 10MHz	15-55pF	1M
P6009	100X	3%	10MΩ	2.5pF	2.9ns	120MHz	1.5kV	200kHz	450V$_{RMS}$ at 40MHz	15-47pF	1M
P6013A	1000X	Adjustable	100MΩ	3pF	7ns	50MHz	12kV	100kHz	800V$_{RMS}$ at 20MHz	12-60pF	1M
P6015	1000X	Adjustable	100MΩ	3pF	1.4ns	250MHz	20kV	100kHz	2000V$_{RMS}$ at 20MHz	12-47pF	1M

Figure C1. Characteristics of Some Wideband High Voltage Probes. Output Impedances are Designed for Oscilloscope Inputs

MANUFACTURER AND MODEL	FULL SCALE RANGES	ACCURACY AT 1MHz	ACCURACY AT 100kHz	INPUT RESISTANCE AND CAPACITANCE	MAXIMUM BANDWIDTH	CREST FACTOR
Hewlett-Packard 3400 Meter Display	1mV to 300V, 12 Ranges	1%	1%	0.001V to 0.3V Range = 10M and < 50pF, 1V to 300V Range = 10M and < 20pF	10MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Hewlett-Packard 3403C Digital Display	10mV to 1000V, 6 Ranges	0.5%	0.2%	10mV and 100mV Range = 20M and 20pF ±10%, 1V to 1000V Range = 10M and 24pF ±10%	100MHz	10:1 At Full Scale, 100:1 At 0.1 Scale
Fluke 8920A Digital Display	2mV to 700V, 7 Ranges	0.7%	0.5%	10M and < 30pF	20MHz	7:1 At Full Scale, 70:1 At 0.1 Scale

Figure C2. Pertinent Characteristics of Some Thermally Based RMS Voltmeters. Input Impedances Necessitate Matching Network and Compensation for High Voltage Probes

voltmeter's input characteristics. Normally, the optimum compensation point is easily determined and adjusted by observing probe output on an oscilloscope. A known amplitude square wave is fed in (usually from the oscilloscope calibrator) and the probe adjusted for correct response. Using the probe with the voltmeter presents an unknown impedance mismatch and raises the problem of determining when compensation is correct.

The impedance mismatch occurs at low and high frequency. The low frequency term is corrected by placing an appropriate value resistor in shunt with the probe's output. For a 10MΩ voltmeter input a 1.1MΩ resistor is suitable. This resistor should be built into the smallest possible BNC equipped enclosure to maintain a coaxial environment. No cable connections should be employed; the enclosure should be placed *directly* between the probe output and the voltmeter input to minimize stray capacitance. This arrangement compensates the low frequency impedance mismatch.

Correcting the high frequency mismatch term is more involved. The wide range of voltmeter input capacitances combined with the added shunt resistor's effects presents problems. How is the experimenter to know where to set the high frequency probe compensation adjustment? One solution is to feed a known value RMS signal to the probe-voltmeter combination and adjust compensation for a proper reading. Figure C3 shows a simple way to generate a known RMS voltage. This scheme takes advantage of the recommended voltmeter's insensitivity to waveform shape. The CMOS flip-flop is driven from a stable 10.00V source.
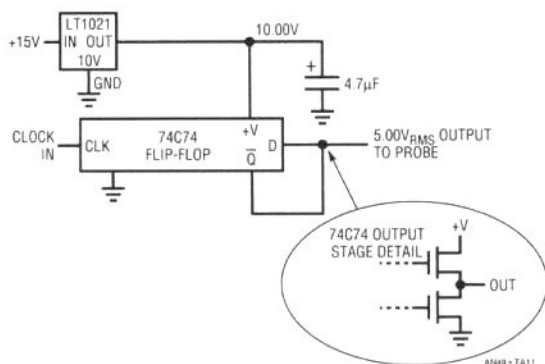
The CMOS output stage, which is purely ohmic, produces essentially errorless switching between the power supply rails. Clocking the flip-flop produces a square wave output with a 10.00V amplitude. The result is a known 5.00V$_{RMS}$ output. Now, the probe's compensation is adjusted for a 5.00V voltmeter reading. This procedure, combined with the added resistor, completes the probe-to-voltmeter impedance match. If the probe compensation is altered (e.g., for proper response on an oscilloscope) the voltmeter's reading will be erroneous.[3]

RMS Voltmeters

The efficiency measurements require an RMS responding voltmeter. This instrument must respond accurately at high frequency to irregular and harmonically loaded waveforms. These considerations eliminate almost all AC voltmeters, including DVMs with AC ranges.

There are a number of ways to measure RMS AC voltage. Three of the most common include *average, logarithmic,* and *thermally* responding. Averaging instruments are calibrated to respond to the average value of the input waveform, which is almost always assumed to be a sine wave. Deviation from an ideal sine wave input produces errors. Logarithmically based voltmeters attempt to overcome this limitation by continuously computing the input's true RMS value. Although these instruments are "real time" analog computers their 1% error bandwidth is well below 300kHz and crest factor capability is limited. Almost all general purpose DVMs use such a logarithmically based approach and, as such, are not suitable for CCFL efficiency measurements. Thermally based RMS voltmeters are direct acting thermo-electronic analog computers. They respond to the input's RMS heating value. This technique is explicit, relying on the very definition of RMS (e.g., the heating power of the waveform). By turning the input into heat, thermally based instruments achieve vastly higher bandwidth than other techniques.[4] Additionally, they are insensitive to waveform shape and easily

Figure C3. The RMS Calibrator. MOSFET Output Stage Detail Shows Purely Ohmic Switching to Power Rails

Note 3: The translation of this statement is to hide the probe when you are not using it. If anyone wants to borrow it, look straight at them, shrug your shoulders, and say you don't know where it is. This is decidedly dishonest, but eminently practical. Those finding this morally questionable may wish to re-examine their attitude after producing a days worth of worthless data with a probe that was unknowingly readjusted.

Note 4: Those finding these descriptions intolerably brief are commended to References 5, 6 and 7.

accommodate large crest factors. These characteristics are necessary for the CCFL efficiency measurements.

Figure C4 shows a conceptual thermal RMS-DC converter. The input waveform warms a heater, resulting in increased output from its associated temperature sensor. A DC amplifier forces a second, identical, heater-sensor pair to the same thermal conditions as the input driven pair. This differentially sensed, feedback enforced loop makes ambient temperature shifts a common mode term, eliminating their effect. Also, although the voltage and thermal interaction is non-linear, the input-output RMS voltage relationship is linear with unity gain.
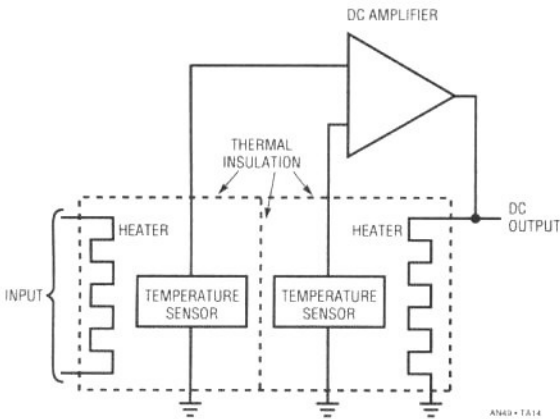
Figure C4. Conceptual Thermal RMS-DC Converter

The ability of this arrangement to reject ambient temperature shifts depends on the heater-sensor pairs being isothermal. This is achievable by thermally insulating them with a time constant well below that of ambient shifts. If the time constants to the heater-sensor pairs are matched, ambient temperature terms will affect the pairs equally in phase and amplitude. The DC amplifier will reject this common mode term. Note that, although the pairs are isothermal, they are insulated from each other. Any thermal interaction between the pairs reduces the system's thermally based gain terms. This would cause unfavorable signal-to-noise performance, limiting dynamic operating range.

Figure C4's output is linear because the matched thermal pair's non-linear voltage-temperature relationships cancel each other.

The advantages of this approach have made its use popular in thermally based RMS-DC measurements.

The instruments listed in Figure C2, while considerably more expensive than other options, are typical of what is required for meaningful results. The HP3400A and the Fluke 8920A are currently available from their manufacturers. The HP3403C, an exotic and highly desirable instrument, is no longer produced but readily available on the secondary market.

APPENDIX D

A RELATED CIRCUIT

The high voltage compliance current loop approach of the CCFL power supply suits other applications. The current sensing permits precise high efficiency control of a wide variety of difficult loads. A HeNe Laser represents such a load. Lasers are negative impedances operating at very high voltages. Typically, they require 6kV-10kV to start, with an operating voltage in the 1kV-3kV region. Best optical characteristics are achieved by controlling the current through the laser. Simple high voltage drive does not provide this. Figure D1 adapts the CCFL circuitry to control a laser. Both tube current stability and electrical efficiency are improved over the more conventional voltage mode drive.

The start-up and sustaining functions have been combined into a single closed loop current source with over 10kV of compliance. When power is applied, the Laser does not conduct and the voltage across the 190Ω resistor is zero. The LT1170 switching regulator FB pin sees no feedback voltage, and its switch pin (V_{SW}) provides full duty cycle pulse width modulation to L2. Current flows from L1's center tap through Q1 and Q2 into L2 and the LT1170. This current flow causes Q1 and Q2 to switch, alternately driving L1. The 0.48μF capacitor resonates with L1, providing boosted, sine wave drive. L2 provides substantial step-up, causing about 3500V to appear at its secondary. The capacitors and diodes associated with L2's secondary

form a voltage tripler, producing over 10kV across the Laser . The Laser breaks down and current begins to flow through it. The 47kΩ resistor ballasts the Laser, limiting current. The current flow causes a voltage to appear across the 190Ω resistor. A filtered version of this voltage appears at the LT1170 FB pin, closing a control loop. The LT1170 adjusts its pulse width drive to L2 to maintain the FB pin at 1.23V regardless of changes in operating conditions. In this fashion the Laser sees constant current drive, in this case 6.5mA. Other currents are obtainable by varying the 190Ω value. The 1N4002 diode string clamps excessive voltages when Laser conduction first begins, protecting the LT1170. The 10μF capacitor at the V_C pin frequency compensates the loop and the MUR405 maintains L1's current flow when the LT1170 V_{SW} pin is not conducting.

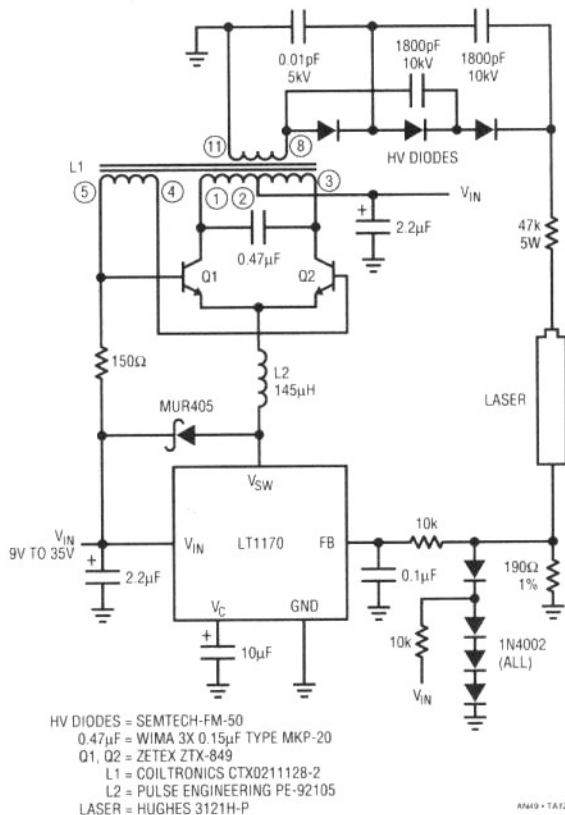The circuit will start and run the Laser over a 9V – 35V input range with an electrical efficiency of about 75%.

HV DIODES = SEMTECH-FM-50
0.47μF = WIMA 3X 0.15μF TYPE MKP-20
Q1, Q2 = ZETEX ZTX-849
L1 = COILTRONICS CTX0211128-2
L2 = PULSE ENGINEERING PE-92105
LASER = HUGHES 3121H-P

Figure D1. *Laser* **Power Supply is Essentially a 10kV Compliance Current Source**

APPENDIX E

BACKLIGHT CHARACTERISTICS

DISPLAY TYPE	RUN VOLTAGE	START VOLTAGE	DISCHARGE CURRENT IN mA	BRIGHTNESS IN nt	POWER CONSUMPTION IN WATTS
CXA-M10M	480 ± 80	1200 MIN	4-6	5000 TYP	2.4
EMI-1231	355 ± 60	1200 TYP	5 ± 1	10,000	1.8
LM000105	340 ± 60	1200 MIN	5 ± 1	5000 MIN	1.7
CXA-1301	335 ± 25	1000 TYP	5 ± 1	2300 MIN	1.7
CXA-M10M	300 ± 30	1300 MIN	5.3 TYP	8000 MIN	1.8
CSA-0113	290 ± 60	1000 TYP	3.0	4500	.87
EHI-1231	280 TYP	1100 MIN	3.5-7	10,000 TYP	2

Figure E1. Characteristics of Some Sharp Corporation LCD Backlights

APPENDIX F

THE THERMOMETER EFFECT

Bulbs operating at very low currents may display the "thermometer effect"; that is, light intensity may be non-uniformly distributed along the bulbs length. Although bulb current density is uniform, the associated electro-magnetic field is not. The field's low intensity, combined with its gradient, means that there is not enough energy to maintain uniform phosphor glow beyond some point.

Bulbs displaying the thermometer effect emit most of their light near the high voltage electrode, with rapid emission fall-off as distance from the electrode increases. Placing a conductor along the bulb's length largely alleviates "thermometering." The trade-off is decreased efficiency due to energy leakage (see footnote 6 and associated text). It is worth noting that various bulb types have different degrees of susceptibility to the thermometer effect.

APPENDIX G

OPERATION FROM HIGH VOLTAGE INPUTS

Some applications require higher input voltages. The 20V maximum input specified in Figures 2 and 4 is set by the LT1172 going into its isolated flyback mode (see LT1072 and LT1172 data sheets), not breakdown limits. If the LT1172 is driven from a low voltage source (e.g., 5V) the 20V limit may be extended by using Figure G1's network. If the LT1172 is driven from the same supply as L1's center tap the network is unnecessary.
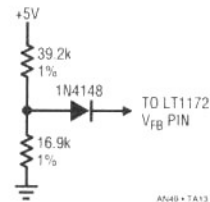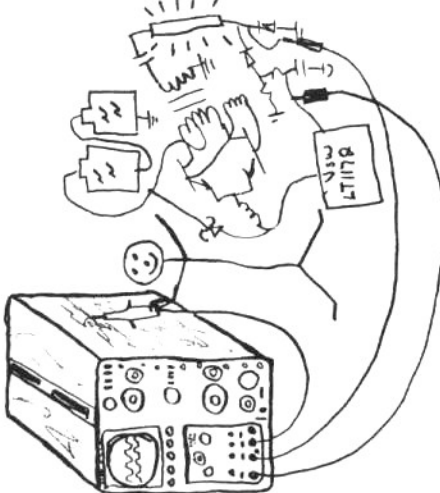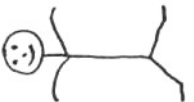

Figure G1. Network Allows CCFL Operation Beyond 20V Inputs