

High Current LED - Isolated Low Voltage AC Drive Application Note

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APPLICATION NOTE

Abstract. This application note describes the powering of high current light emitting diodes (LEDs) through a line isolation transformer and a two transistor current regulator, to ensure optimal performance and long life. LED characteristics are explained, followed by an example design to illustrate the concept.

INTRODUCTION

Light emitting diodes, called LEDs, have existed for many years. LEDs behave similarly to normal diodes in that they have a forward voltage drop associated with the forward current. Early LEDs emitted radiation only in the infrared (IR) spectrum. Later, visible red LEDs emerged using various III-V compounds, such as aluminum gallium arsenide (AlGaAs). Other colors, such as yellow, amber and green came shortly thereafter. The breakthrough for more colors came with the blue LED; originally, this was silicon carbide. The applications for these early LEDs were largely limited to low power displays, because the output was limited.

A breakthrough in LED technology is opening the door to a wide variety of high power illumination applications, which is now commercially available. This new generation utilizes an Aluminum-Indium-Gallium-Phosphorus (AlInGaP) substrate to emit significantly higher power red or amber light intensity. Additional colors, such as green and blue, built on an Indium-Gallium-Nitrogen (InGaN) substrate soon followed. The full color spectrum, including white, is now possible by using the proper mixing and filtering of multiple colors. Today, the colors of amber, red-orange, and red are typically from AlInGaP substrates, while royal blue, blue, cyan, green and white are from InGaN substrates.

The conversion efficiency of electrical energy into light energy is very important. Today's LEDs vary between 10 and 20 percent efficiency. The rest of the energy is converted to heat. This heat must be effectively dissipated, as the operating junction temperature of the LED die must be maintained between -40°C and $+125^{\circ}\text{C}$.

Incandescent lamps, including the tungsten-halogen type, have efficiencies of only about 4 to 10 percent for visible light. These emit a broad, almost continuous spectrum of

energy, including not only visible light, but also ultraviolet (UV) and infrared (IR) as unusable heat. Technically, only 15 to 20 percent of an incandescent lamp's energy is converted directly into heat; a surprisingly large amount of heat generated by them is caused by the IR radiation being absorbed by the surrounding area. This heat can be reflected out away from the lamp, but if there is a lens or filter in front of the lamp the heat is trapped.

The only practical way to obtain different colors with incandescent lamps is with the use of a filter. This is not the case with LEDs. LEDs produce a rather narrow spectrum of light and therefore are intrinsically more efficient at converting electrical energy to a particular color than incandescent lamps with a filter. There is less electrical energy needed for the same lumen output, as the filter will attenuate the light output substantially. Therefore color LEDs are the most efficient way to obtain colored light.

White LEDs have the same efficiency as incandescent lamps, but are less efficient than fluorescent lamps. The white LEDs have a particular advantage over most known white light sources; this advantage is longer lifetime. Many incandescent lamps are rated between 750 hours and 2000 hours of life. A fluorescent lamp including like the compact incandescent type can offer between 8000 and 12,000 hours of life. All of these lamps have filaments. The greater number of 'on-off' cycles the shorter the lamp life due to filament breakage. White LEDs on the other hand do not have filaments and thus do not have this failure mode.

LEDs, regardless of color, have an extremely long lifetime, if their current and temperature limits are not exceeded. Lumileds Lighting LLC™ [1, 2] has published lifetime data stating that after 50,000 hours the LEDs will have 70 percent or greater of the original light output. Using an engineering rule of thumb with data already collected, and plotted, on semi-log graph paper, LEDs are projected to have 50 percent or greater of the original light output after 100,000 hours. There are 8736 hours in a normal year and 8760 hours during a leap year, which equates to 8742 hours per year. This calculates to over 11 years and 5 months of continuous service with light greater than 50 percent of the initial output. Remember, in order to obtain maximum life, the LEDs must be operated within the manufacturer's

specified limits of both current and diode junction temperature. LEDs should be used where extremely long life is desired and the cost of lamp replacement is very high.

Characterization

The maximum forward current varies with the different type, style, and manufacturer of LEDs. Lumileds [1, 2], has specified the maximum forward currents at 30 mA, 75 mA, 150 mA, 350 mA, and 700 mA for differently constructed LEDs. The higher current devices have special thermally designed packages to transfer the heat from the junction to the heat sink. This paper will concentrate on circuits using the Lumileds 350 mA LED devices. The same rules can

apply to devices having other current ratings by simply scaling the current and power of the designs.

The LED forward voltage drop varies between 2.50 Vdc and 4.00 Vdc at the rated forward current; see Figure 1. This variation is due to material used, AlInGaP and InGaN, and the various manufacturing tolerances. This variation in forward voltage drop must be taken into account for each LED lamp design. Lumileds sorts their devices according to color, intensity, and forward voltage drop at maximum rated current. The device forward voltage characteristics provide a better match at maximum current than the match at lower current, see Figure 2.

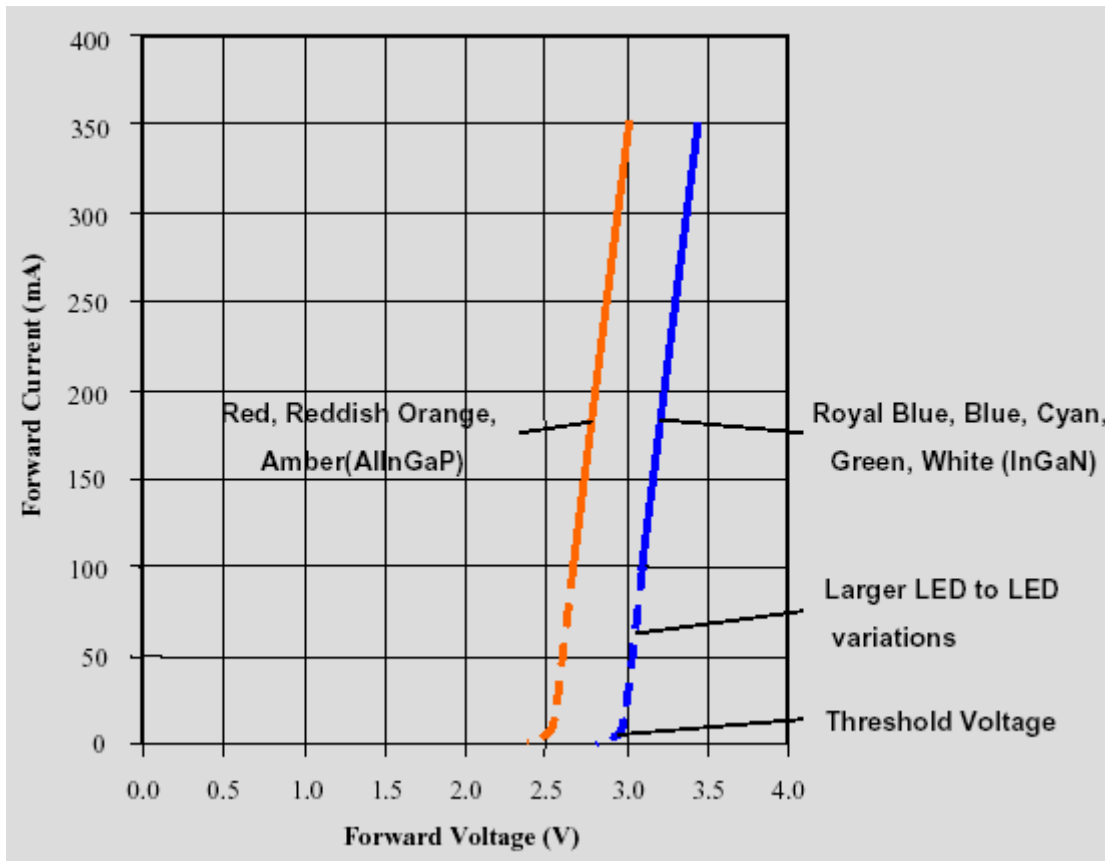


Figure 1. Typical Forward Voltage of Different Colors (Courtesy: Lumileds)

Power (in Watts) is the product of the forward voltage multiplied by the forward current. For LEDs rated 350 mA DC, the total wattage is calculated by taking the minimum and maximum forward voltage multiplied by 0.35 A.

$$0.350 * 2.50 = 0.88 \text{ Watts minimum}$$

$$0.350 * 4.00 = 1.40 \text{ Watts maximum}$$

For an average, LEDs rated 0.350 A, (350 mA), are considered 1 watt devices. This makes calculation easy for a first order approximation.

Because the amount of light is limited from a single LED, multiple LEDs are used to increase the amount of light.

LEDs are specified at their rated current. It is easy and advantageous to place LEDs in series because LEDs in series have the same current. Since LEDs are current devices, a current control system is used to operate the LED to be within the manufacturer’s specifications.

LEDs can be operated in parallel. In order to operate LEDs in parallel, the devices must be matched using forward voltage drop. This matching should occur at the LED manufacturer. The process of keeping the proper voltage and current through the LEDs is called ballasting. Ballasting techniques are used extensively in other lighting applications like fluorescent lamps.

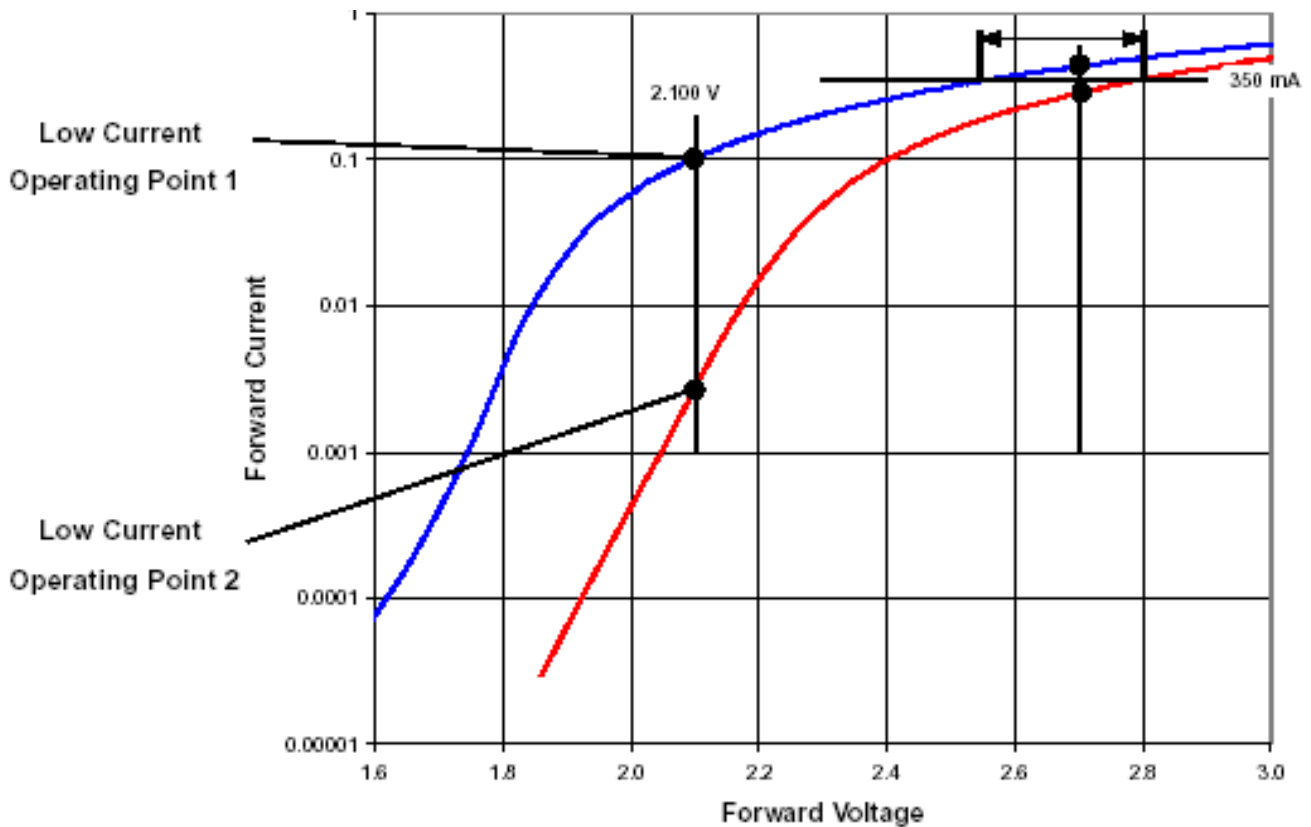


Figure 2. Forward Voltage Matching of LEDs at 350 mA DC (Courtesy: Lumileds)

Energy Supply Voltage Variation, AC Line Power

The first source considered is the ac power line. The ac power line normally varies within five percent of the stated value. Like any other source, the variations can be much greater. The ac line is considered to vary ten percent. In the United States and Canada, the normal 120 Vac line can take on values between 108 Vac to 132 Vac. There is another condition called 'brown out' where the ac line voltage drops another ten percent to 96 Vac. A 'brown out' condition occurs when the electrical utility company lowers the value of ac voltage generated. This happens under extreme high demand conditions; the utility does this to keep the generating equipment operational and within safe operating conditions while still providing some electrical energy to its customers. Under this condition 120 incandescent lamps operate but at a reduced light output and reduced wattage. Most electric motors operate in a more economical fashion. The ac line voltage variation from the normal can be stated as +10/-20% for worst-case normal conditions.

Many products are sold both in North America and also in Europe. In Europe there are two standards: 220 Vac-50 Hz for continental or mainland Europe and 240 Vac-50 Hz,

which is in the United Kingdom. The European Norm (EN) standards use 230 Vac-50 Hz as the test voltage. One way to overcome all of the ac line voltage issues is to design a switching power supply that can operate from as low as 85 Vac and as high as 270 Vac and produce a constant DC voltage or constant DC current as the output. This is occurring today with battery chargers for lap top computers and cellular phones; with only line cord changes. These are called universal input, because they can operate anywhere through out the world.

Low Voltage AC

There are many applications where the ac voltage is considered low voltage. The following are considered low voltage applications: 6.0 Vac, 12 Vac, 18 Vac and 24 Vac. The low voltage is obtained from the 120 Vac or the 230 Vac through the use of a step-down isolation transformer. Isolation is often required for use in outdoor applications.

Two Transistor Constant Current Design

An easy approach to achieve constant current is to use two transistors in a configuration shown in Figure 3.

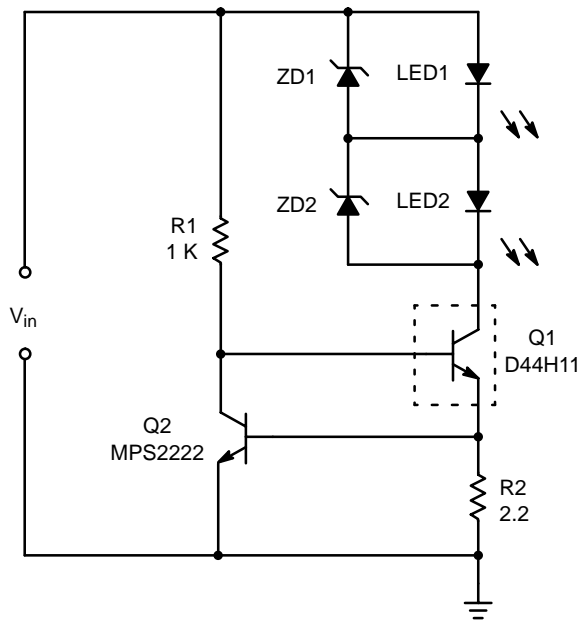


Figure 3. Two Transistor Constant Current Regulator

Referring to Figure 3, V_{in} is a dc source that may or may not be filtered. R2 sets the level at which the current will be limited. When the current through the LEDs, and Q1, develops a voltage across R2 that reaches approximately 0.7 V, it begins to turn on Q2. As Q2 turns on, it starts to steal base drive away from Q1. This in turn will cause Q1 to conduct less current. Conversely, as the voltage across R2 decreases, Q1 will conduct less and R1 will provide more base current to Q1. Consequently Q1 will turn on harder. In this manner, the peak current through the LEDs will be set to a level determined by the equation:

$$I_{led} = 0.7 V/R_s \quad (eq. 1)$$

R1 provides the base drive current for Q1. There must be adequate base current to supply the required collector (LED) current at low line voltage. Since the failure mode for LEDs is an open circuit, the zener diodes serve to provide a conduction path in the event of an LED failure. The value of the zener voltage can be 4.3 V or 4.7 V which is above the normal forward voltage drop of the LEDs. This scheme will allow an LED to fail and permit the other LEDs to continue to operate.

Constant Current Supply for 12 Vac

Driving LEDs from a low voltage AC source requires the use of an isolation transformer, bridge rectifier, and current regulator. Interestingly, a bulk capacitor is not necessarily needed if a full wave bridge rectifier is used. The reason for this is that the output of the full wave bridge circuit is a haversine waveform at effectively twice the input frequency. For a 60 Hz system this becomes a 120 Hz waveform. Visible flicker does not normally appear above

100 Hz. If flicker does become an issue, a capacitor can be placed after the bridge rectifier to smooth the waveform. On the other hand, a capacitor will add cost and cause more power to be dissipated in the LEDs and current regulator. To use this circuit, the following items must be considered:

1. AC line variation.
2. Voltage drop across the bridge rectifiers.
3. Electrolytic capacitor selection, if used.
4. Effective load resistance.
5. Electrolytic capacitor ripple current, if applicable. The ripple current rating can be found in the capacitor manufacturer’s data sheets.

This topology has the rectification inside the lamp module, eliminating the need for any polarity protection. In addition, the ac to dc rectification is very economical, by using cost effective, axial leaded 1N4004, or surface mount MRA4004, diodes in lieu of the single larger bridge rectifier like the MDA2504, which must be on a heat sink. Each item is discussed as follows:

AC Line Variation: The normal ac line can fluctuate by 10 percent and +10/–20 percent for worse case conditions. Therefore, the transformer secondary can vary between 10.8 Vac and 13.2 Vac if the normal secondary voltage is 12.0 Vac. There are many legacy systems and transformers where the output voltage is 12.6 Vac; this can be a benefit. If the transformer secondary is 12.6 Vac the lower limit is $12.6 * 0.9 = 11.34$ Vac and the upper limit is $12.6 * 1.1 = 13.86$ Vac under normal ± 10 percent variations.

Bridge Rectifier Voltage Drop: The typical forward voltage drop of a silicon diode is considered to be between 0.6 and 0.7 volts. In many cases, the maximum forward voltage drop can be as high as 1.0 V.

Electrolytic Capacitor Selection: If it is determined that a capacitor is necessary, it should be chosen for value in farads, working voltage, and temperature operation. The working voltage is the lowest standard value above the maximum peak rectified line voltage. For a 12.6 Vac transformer at high line, the minimum working voltage is $13.86 \text{ Vac} * \sqrt{2} = 19.6 \text{ Vdc}$. The standard capacitor voltage for this system is 25 Vdc electrolytic. There are two maximum temperature ratings: 85°C and 105°C. The 105°C devices have longer life and higher ripple current ratings. The value of the capacitor in farads can be determined by using the equation developed by Savant [3].

$$C = \frac{V_{MAX}}{\Delta V / f_R R_L} \quad (eq. 2)$$

- C = Value of the capacitor in farad
- V_{MAX} = Peak ac line voltage
- ΔV = Peak–peak capacitor voltage
- f_R = Twice the ac line frequency (120 for a 60 Hz system)
- R_L = Effective load resistance

Example 1. 12 Vac System for Two Amber LEDs

A resort hotel wants to light a walkway between the parking lot and side entrance with amber colored LEDs. Each light assembly has two LEDs wired in series as shown later in Figure 5. The LEDs are the 350 mA type. An electrolytic filter capacitor will not be used. The following conditions are assumed to exist.

1. LED current will be defined to be 315 mA, a derating of 10%.
2. The maximum forward drop for amber LEDs is given to be 3.27 V.
3. The sense resistor voltage is 0.7 V as described above.
4. The low line condition is 108 Vac.
5. The normal transformer output is 12 Vac at 120 Vac–60 Hz.
6. The transformer is a Class A, which is limited to 100 VA.
7. There are 20 lamp assemblies used for the project.

Design Procedure:

First, after algebraically manipulating equation (1), we can determine the value of the sense resistor of Figure 3.

$$R2 = 0.7/I_{led} \quad (\text{eq. 3})$$

In this case, the resistor value is calculated to be 2.2 Ω . Next, if we assume the transistor that drives the LEDs, Q1, will have a current gain, beta, of $\beta = 75$ at a collector current of 315 mA, then the required base drive current will be given by the equation:

$$I_b = I_c/\beta \quad (\text{eq. 4})$$

This yields a required base drive current of 4.2 mA. Therefore R1 must be set to a value that will ensure 4.2 mA at minimum line voltage. To ensure some guard band,

assume a current through R1, I_{rb} , of 10 mA. Q2 will conduct the excess of approximately 6.0 mA. To calculate the value of R1 we use the following equation:

$$R1 = (V_{peak} - 1.4 - 1.4)/I_{rb} \quad (\text{eq. 5})$$

V_{peak} is the stepped down peak voltage at the lowest line voltage. To calculate V_{peak} , the RMS voltage is multiplied by $\sqrt{2}$. If the lowest line voltage is 90 Vrms, then the stepped down V_{peak} would be 12.7 V. The first “1.4” term in the equation comes from two bridge diode drops. The second “1.4” term is from the R2 voltage of 0.7 V and the V_{be} drop from Q1. In this case, the value of R1 calculates to 990 Ω . A standard 1.0 K will be used.

Next, it is necessary to analyze the power dissipated in the various components at high line to ensure reliable operation. Q1 will begin conducting current when the rectified dc voltage (120 Hz haversine) becomes greater than the LED diode drops and the sense resistor voltage. The current will rapidly increase as the dc voltage increases until it reaches its regulated value. During this transition time, Q1 is in saturation. Significant collector–emitter voltage will not appear across Q1 until the regulated current level has been achieved and Q1 comes out of saturation and moves into the linear region. At this point there will be the regulated current flowing through Q1 while simultaneously having significant collector–emitter voltage resulting in power dissipated in the device. This will start to occur when the dc input voltage becomes greater than the sum of the LED forward drops, at the rated current, and the sense resistor voltage which is also the point at which the feedback through Q2 has obtained control of the system. In this case, with two LEDs each at 3.27 V and the sense resistor voltage of 0.7 V the input must exceed 7.24 V. See the picture below.

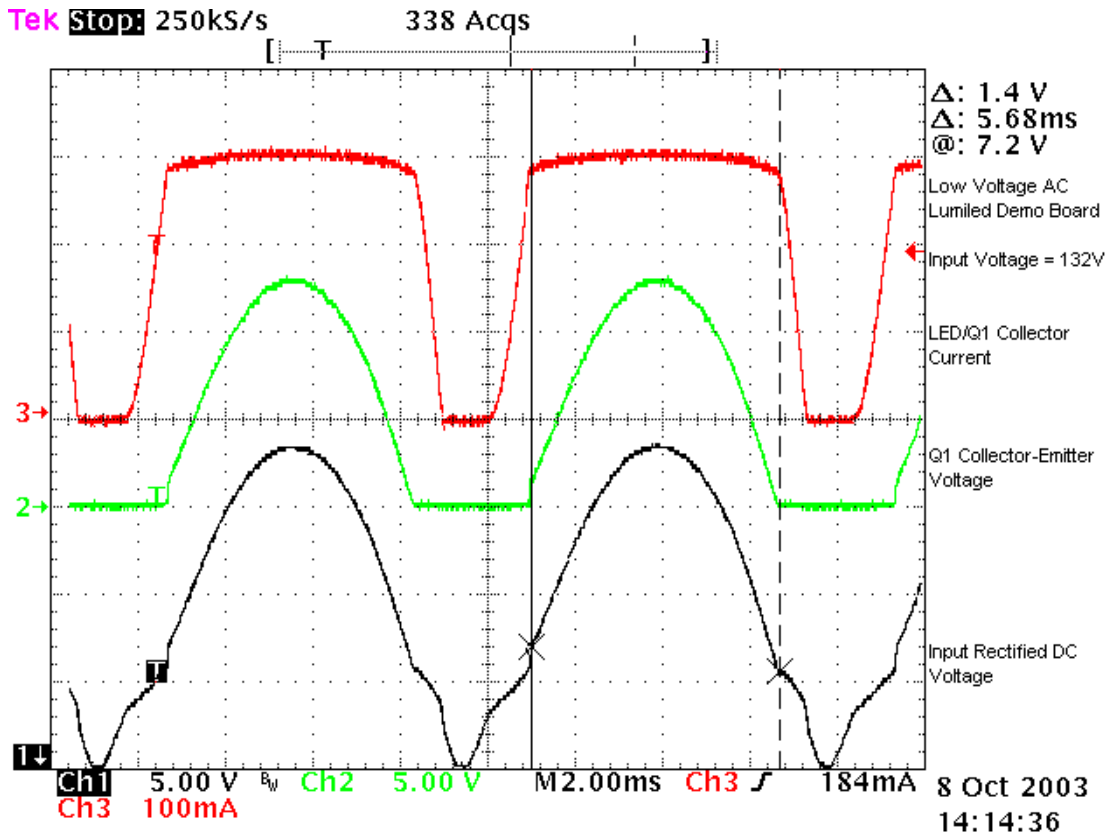


Figure 4. Waveforms from Low Voltage AC Lumiled Demo Board @ 132 Vac

The highest peak collector–emitter voltage during conduction time will be the high line V_{peak} less the forward drop of the LEDs, at the regulated current, plus the sense resistor voltage of 0.7 V. To calculate the time when significant power is being dissipated in Q1, the expression for a full wave rectified waveform can be used:

$$V_{in}(t) = V_{peak} | \sin(\omega t) | \quad (eq. 6)$$

where $\omega = 2 \pi f$ and $f = 60$ Hz, and V_{peak} is the peak input voltage at high line less two bridge diode drops (17.26 V). Solving for t yields the point at which Q1 will start dissipating power with respect to the zero point of the haversine. Assuming a symmetry of the waveform, t is then multiplied by two and the result when subtracted from the haversine period (8.33 ms) yields the power dissipation time. In this example, this time calculates to 6.0 ms. The difference between the calculated and measured times is due to the nonlinearity of Q1 coming out of saturation as can be observed collector– emitter voltage waveform of Figure 4.

Since the LED current is regulated at 315 mA, its waveform can be estimated as a square wave and its RMS current is given by:

$$I_{cerms} = I_{peak} \sqrt{(t_{on}/T)} \quad (eq. 7)$$

where $I_{peak} = 315$ mA, t_{on} = the power dissipation time of Q1, and T = period of haversine (8.33 ms). This calculates to an RMS collector/LED current of 268 mA. The peak collector–emitter voltage of Q1 will be the input voltage less the LED and sense resistor drops. However, the collector–emitter voltage will only appear when Q1 is in full conduction, otherwise the voltage is zero. If the collector–emitter voltage is considered to be a half sinusoid of duration, t_{on} , and period, T , the RMS voltage is then calculated by:

$$V_{cerms} = V_{pkce} \sqrt{(t_{on}/2T)} \quad (eq. 8)$$

where V_{pkce} is the peak voltage from collector–emitter and V_{cerms} is the RMS voltage from collector–emitter of Q1. In this case, the RMS voltage is 6.03 V. The average power of Q1 is then the product of the RMS voltage and RMS current.

$$P_{ceav} = (V_{cerms})(I_{cerms}) \quad (eq. 9)$$

In this example, the average power calculates to 1.61 W. A heatsink would likely be needed. Additionally, the collector–emitter voltage rating of Q1 must be greater than the maximum input rectified dc voltage less the LED forward voltage drops. The LED power can be calculated in a similar manner.

The power dissipated in the sense resistor is calculated with the well known I_{RMS}^2R formula. The sense resistor in this case dissipates 0.16 W, so a 1/4 W resistor can be used. The base drive resistor power dissipation can be calculated in the same manner.

The isolation transformer is chosen, or designed, to achieve a few different goals.

1. First, the transformer must provide the proper secondary voltage for the design. This will depend on the number of LEDs the application must drive. The goal is to choose a transformer with adequate headroom for the application, but not so much that it drives down efficiency. The higher the output voltage above that which is required by the number of LEDs will cause the pass transistor, Q1, to dissipate more power.

2. Secondly, the proper VA rating of the transformer must be observed. Again, like the output voltage, enough for the application, but not so much as to be able to supply excessive power in the event of a short circuit on the output. Line isolation transformers generally have significant series dc resistance in their primary winding. The reason for this is that in the event of a short circuit on the output the high resistance will drop the input voltage so that less power is delivered to the secondary.
3. Third, the transformer must meet the proper safety agency requirements for the application. This means it must provide proper isolation and temperature ratings. In this application, it would need to be decided how many lamp assemblies will be driven from a single transformer.

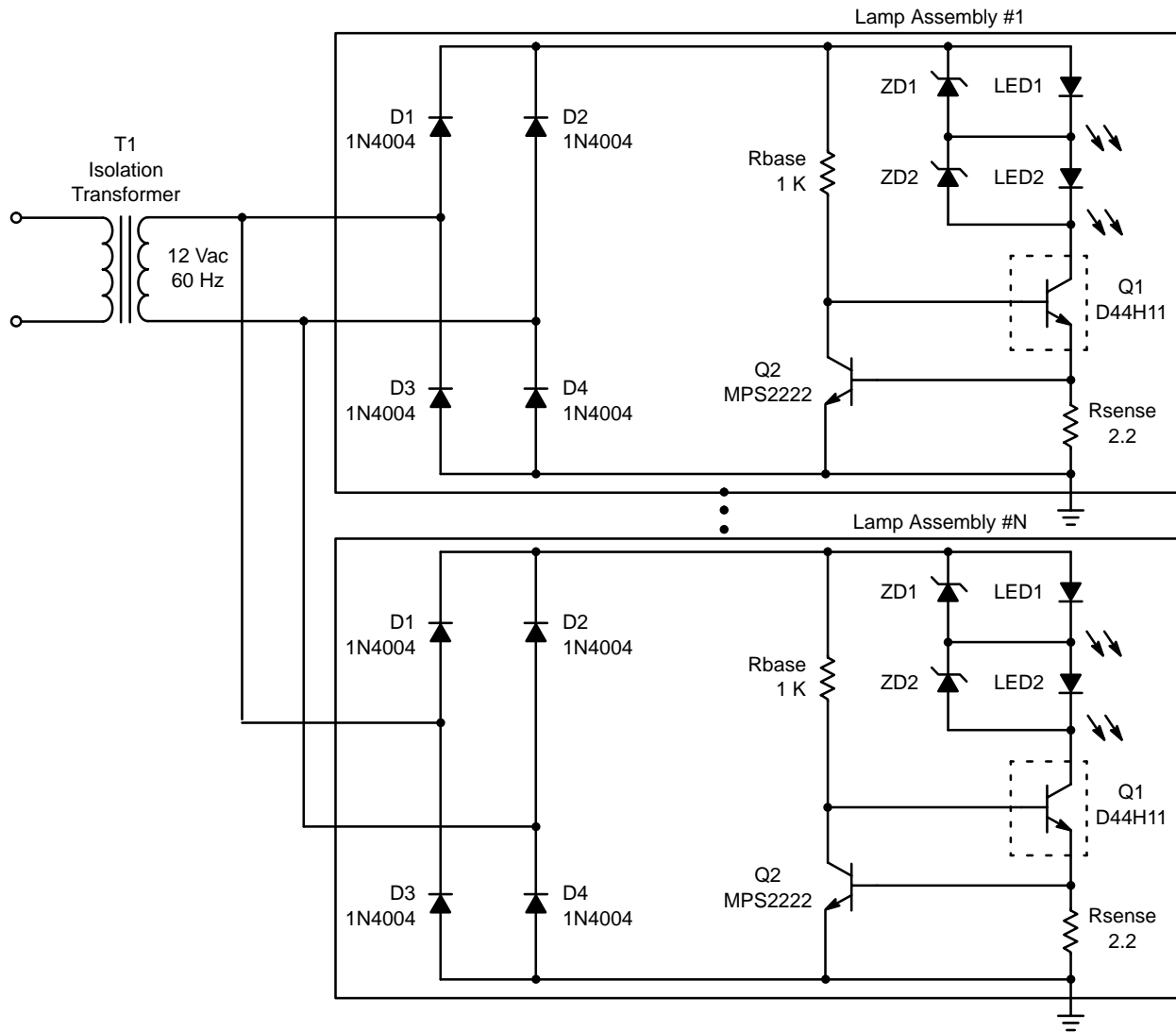


Figure 5. Multiple Lamp Assemblies for Design Example

SPICE Simulation

An Intusoft SPICE simulation was created for the low voltage AC circuit described above. The Lumiled LED models were generated by modifying generic diode models to simulate the proper voltage drop at the specified current. This was accomplished by adjusting the saturation current, I_0 , and empirical constant, N , in the fundamental diode current equation:

$$i_d = I_0(e^{v_d/NV_t} - 1) \quad (\text{eq. 10})$$

In this equation v_d is the forward diode drop of the LED. V_t is defined as:

$$V_t \equiv \frac{kT}{q} \approx 26 \text{ mV} \quad (\text{eq. 11})$$

where k is Boltzmann’s constant, T is absolute temperature, and q is the charge on an electron. The Lumiled specification for the (typical) forward drop on an amber LED is 2.85 V at 350 mA. By solving the diode equation for I_0 and adjusting the diode model accordingly, good correlation can be achieved between the model and the actual circuit as can be seen below.

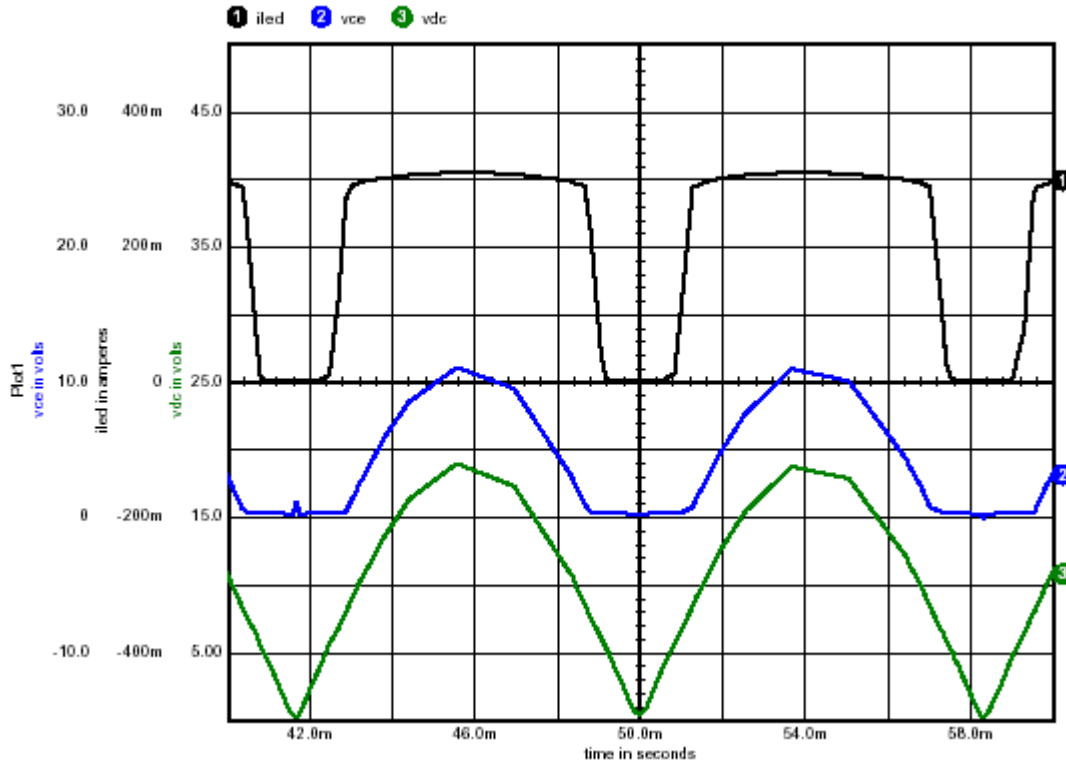


Figure 6. Intusoft SPICE Simulation of Low Voltage AC Lumiled Circuit

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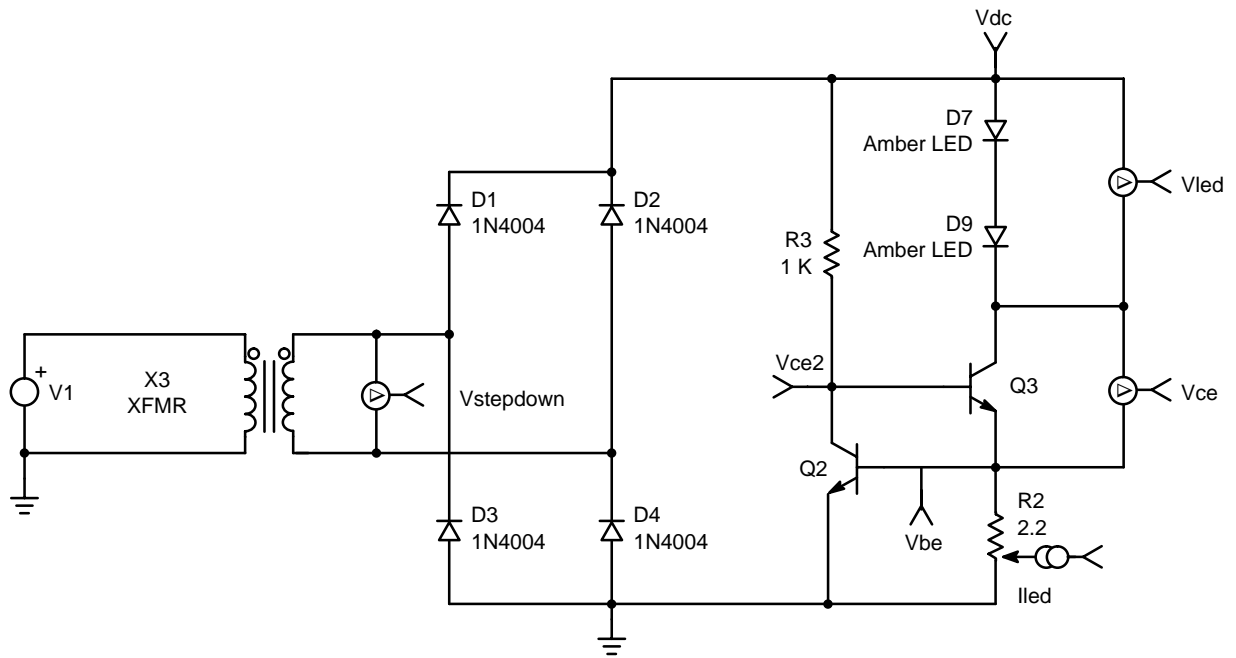


Figure 7. SPICE Simulation Schematic of Low Voltage AC Lumiled Circuit

Jumper	120 Vin	220 Vin
JMP2	Out	In
JMP3	In	Out
JMP4	Out	In

NOTE: To parallel the primary windings, insert a jumper from pin 1 of T1 to pin 3 of T1. Also insert a jumper from pin 2 to pin 4 and insert JMP3.

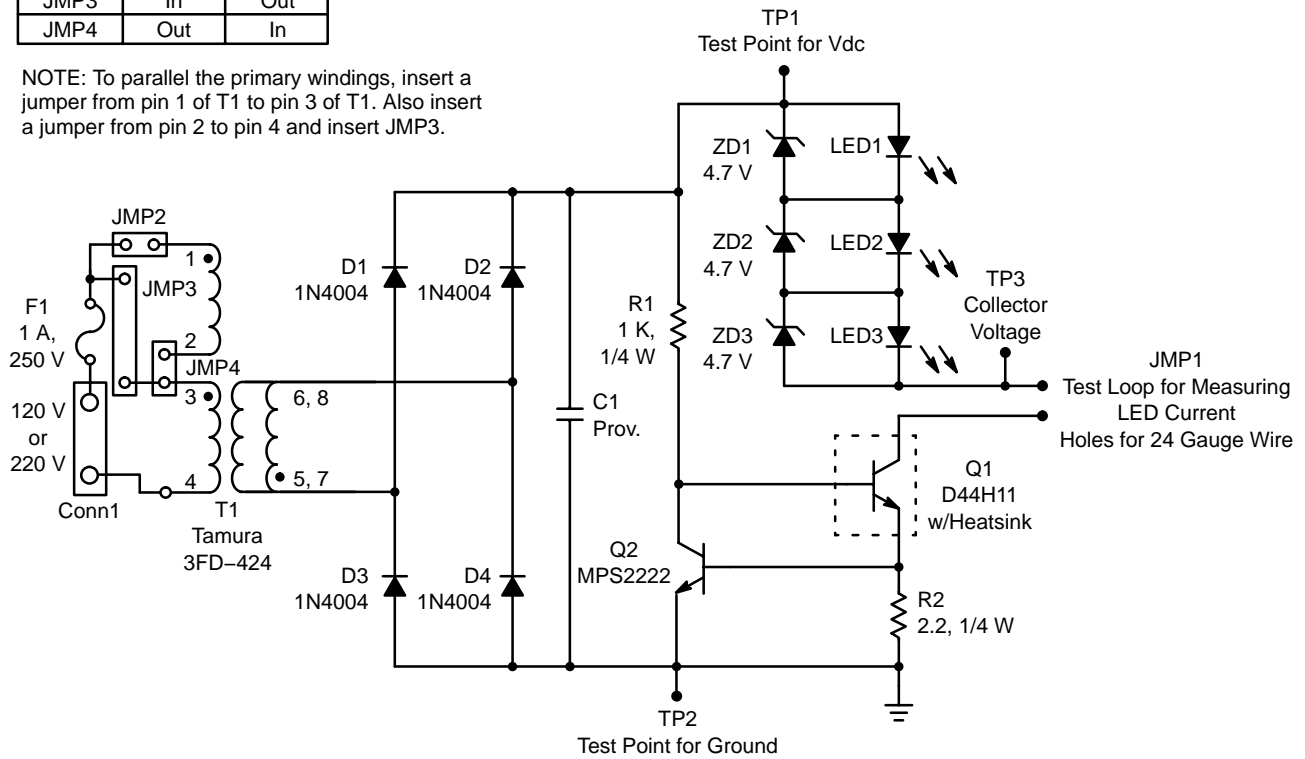


Figure 8. Schematic of Low Voltage AC Lumiled Demo Board

AND8137/D

BILL OF MATERIALS

Sch Ref	Vendor	Part Number
Conn1	Phoenix Contact	1715035
D1-D4	ON Semiconductor	1N4004
Q1	ON Semiconductor	D44H11
Heatsink	AAVID	529802b02100
Q2	ON Semiconductor	MPS2222
R1		1K, 1/4W
R2		2.2, 1/4W
T1	Tamura	3FD-424
ZD1-ZD3	ON Semiconductor	1N5917
TP1	Keystone	5000
TP2	Keystone	5001
TP3	Keystone	5002
LED1-LED3	Lumileds	LXHL-M*** (*Indicates color)
F1	Littlefuse	F625-ND (Digi-Key Part Number)
C1	Kemet	C320C104K5R5CA 399-2054-ND (Digi-Key Part Number)

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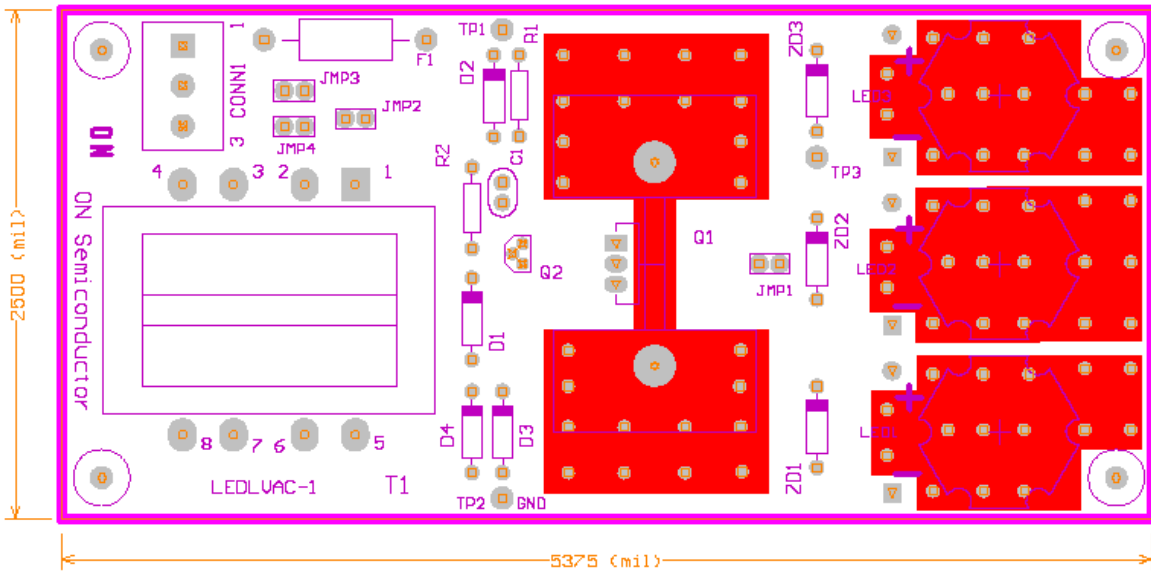


Figure 9. Top Side Foil of Low Voltage AC Lumiled Demo Board

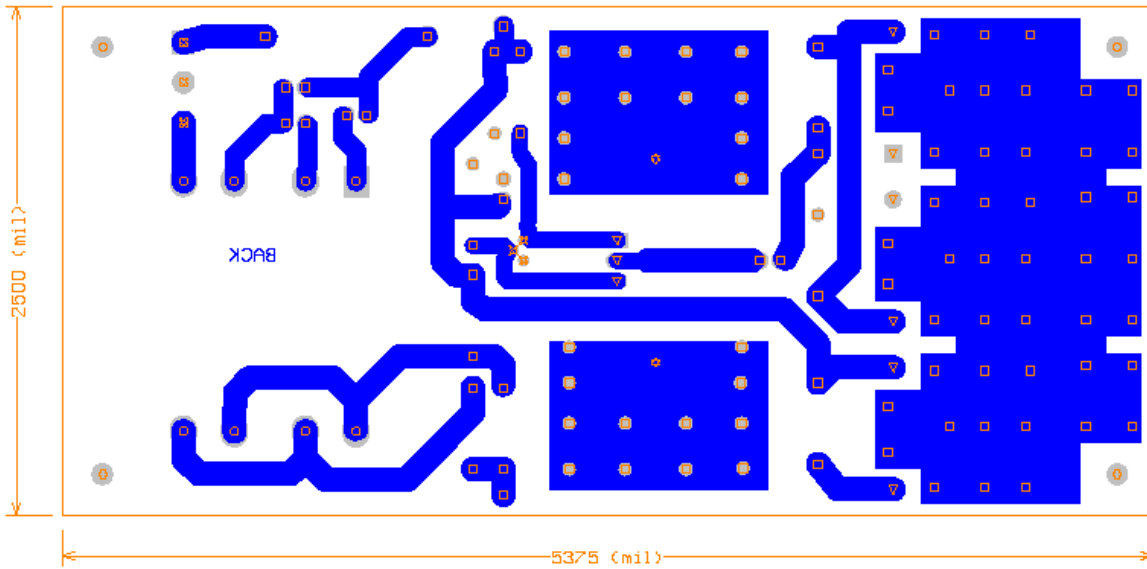



Figure 10. Bottom Side Foil of Low Voltage AC Lumiled Demo Board

References

1. Lumiled, www.lumiled.com.
2. Luxeon, www.luxeon.com.
3. Savant, Roden, Carpenter, "Electronic Design, Circuits and Systems, 2nd Ed", Benjamin/Cummings Publishing, Redwood City, CA 94065, © 1991, ISBN 0-8053-0285-9, pp. 39-43.

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