

High Current LED - Capacitive Drop Drive Application Note

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APPLICATION NOTE

Abstract. This application note describes the basics for powering high current light emitting diodes (LEDs) utilizing a capacitive divider circuit off the AC mains. A linear regulator is used to control the LED current in order 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 higher power illuminating 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% 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% 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% 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 light 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 the 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, 3, 4] has published lifetime data stating that after 50,000 hours the LEDs will have 70% 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% 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% 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 has specified the maximum forward currents at 30 mA_{dc}, 75 mA_{dc}, 150 mA_{dc}, 350 mA_{dc}, 700 mA_{dc}, and 1000 mA_{dc} 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_{dc} 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 V_{dc} and 4.00 V_{dc} at the rated forward current; see Figure 1. This variation is due to material used, AlInGaP and InGaN, operating junction temperature 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 forward voltage characteristic provides a better match at maximum current than the match at lower current, see Figure 2.

Wattage 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.

$$0.350 \times 2.50 = 0.88 \text{ W minimum}$$

$$0.350 \times 4.00 = 1.40 \text{ W maximum}$$

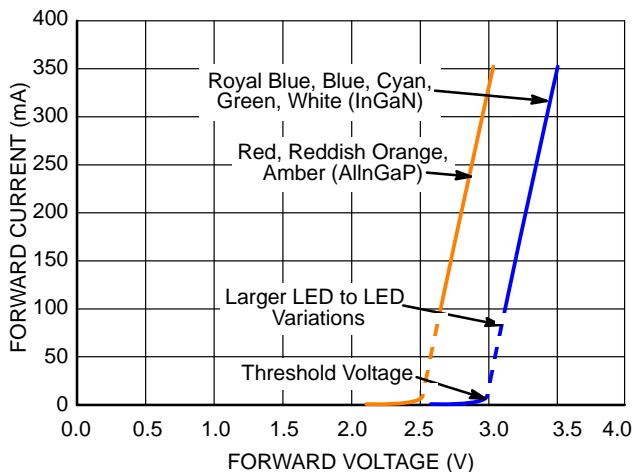


Figure 1. Typical Forward Voltage of Different Colors

For an average, LEDs rated 0.350 A, (350 mA), are considered 1.0 W 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 technique must be used to ensure the LEDs are maintained 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.

Energy Supply Voltage Variation, AC Line Power

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 V incandescent lamps operate but at a reduced light output and reduce 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.

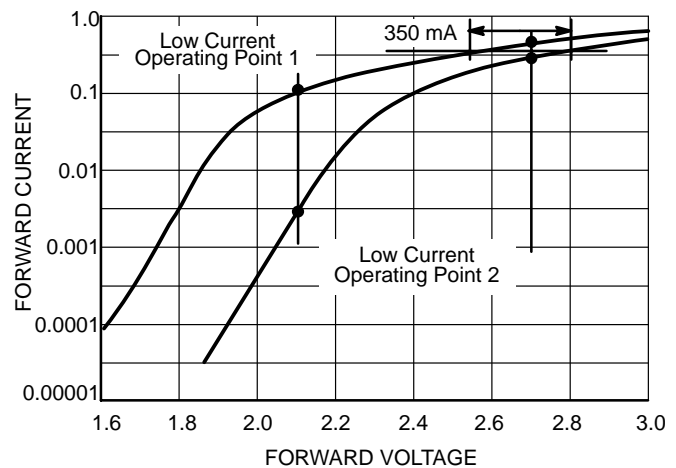


Figure 2. Forward Voltage Matching of LEDs at 350 mA DC

Constant Current Design for 12 Vdc

The easiest constant current approach for low voltage DC systems is to use an adjustable linear regulator such as the LM317 or the MC33269. The circuit is shown in Figure 3.

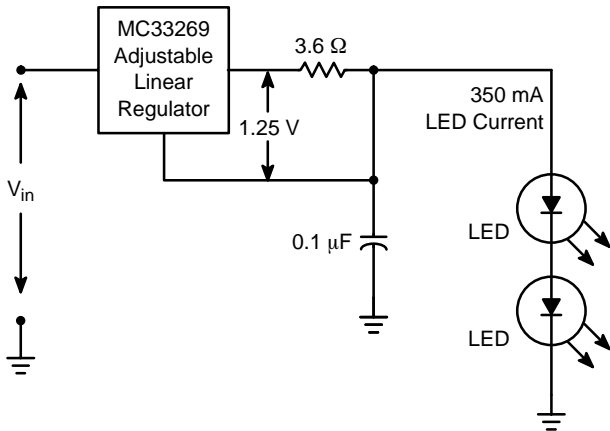


Figure 3. Constant Current Regulator

In this scheme, the adjustable regulator is configured as a current regulator. The regulator will act to maintain a voltage of 1.25 V across the series resistor. The 1.25 V is the reference voltage of the regulator. Consequently the load current can be determined by:

$$I_{LED} = \frac{1.25}{R_s} \quad (\text{eq. 1})$$

If an LED peak current of 350 mA_{dc} is required, the sense resistor is calculated to be 3.6 Ω.

Capacitive Drop

Capacitive drop supplies have been used in many consumer products, such as smoke detectors. These types of supplies are accepted by regulatory agencies, provided the product is sealed, and the consumer can not touch any connections. A concept schematic is shown below in Figure 4 for a half-wave type capacitive drop circuit. A capacitive drop supply is essentially a voltage divider such that a series capacitor drops the input voltage down to a more usable level. Each capacitive drop supply is good for a narrow range of AC line voltage and AC line frequency applications. The 120 Vac, 60 Hz design is different than a 230 Vac, 50 Hz circuit. Since the front end capacitor drops the bulk of the AC line voltage, the rms input current, I_{ac}, can be defined by Equation 2 as a first order approximation. As an example, Equation 3 shows the amount of current using a 33 μF capacitor for two AC line voltages: 120 Vac, and 100 Vac.

$$I_{RMS} = \frac{V_{AC}}{X_{AC_CAPACITOR}} = \frac{V_{AC}}{\frac{1}{2\pi FC}} = 2\pi FCV_{AC} \quad (\text{eq. 2})$$

$$1.49 = 2 * \pi * 60 * 33e-6 * 120 \quad 1.5 \text{ Aac in the } 33 \mu\text{F cap}$$

$$1.24 = 2 * \pi * 60 * 33e-6 * 100 \quad 1.25 \text{ Aac in the } 33 \mu\text{F cap}$$

(eq. 3)

Only half of the above current flows to the load, the remaining current is recirculated to discharge the coupling capacitor.

Half-Wave Capacitive Drop Circuit

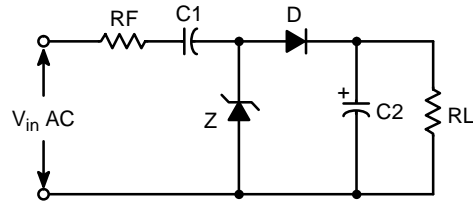


Figure 4. Half-Wave Capacitive Drop Supply

The half-wave circuit, of Figure 4, operates in the following fashion. During the positive portion of the AC voltage, AC current flows through the input resistor RF, C1, D, and the parallel combination of RL and C2. When the input voltage has charged C2 to one diode drop below the Zener diode voltage, V_Z, the current will have another parallel path in which to flow. The excess current flows through the Zener diode, Z, while capacitor C2 remains charged and the voltage across the load RL remains effectively constant. During this time, C1 charges to a high voltage state. The capacitor C1 is a high voltage AC rated capacitor. Once C1 is charged it must be discharged in order to keep a charge on C2. During the negative half of the AC voltage, C1 is discharged through the forward conduction of the Zener diode, Z. As an engineering rule of thumb, this approach can provide a load current of 10 mA_{dc} for each 1.0 μF of AC capacitance. This means that a 10 μF, 125 Vac capacitor can supply about 100 mA_{dc} of current, and a 33 μF 125 Vac capacitor is needed to supply a 0.35 A_{dc} LED. The following is the limit and purpose of each component.

- RF Fusible link metal film resistor and additional current limit for AC line transients
- C1 AC rated capacitor
- Z Zener diode, 5.6 V device is used for a 5.0 VDC output
- D Diode; e.g. 1N4004
- C2 Electrolytic capacitor of at least 100 times the value of C1
- RL Load

Figure 4 can be modified for LED operation by adding a constant current circuit, such as the previously described

LM317 circuit. This is shown in Figure 5, where the value of Zener is defined to be a 24 V, 3.0 W, device, 1N5934B. This circuit can operate one, or two, LEDs at 350 mA peak.

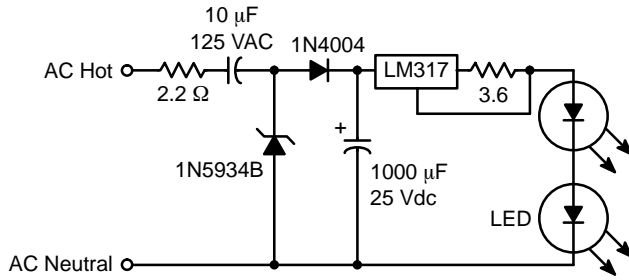


Figure 5. Two LED, Half-Wave, Capacitive Drop Circuit

SPICE Simulation of Half-Wave Capacitive Drop Circuit

The half-wave capacitive drop circuit was simulated on IsSPICE from Intusoft with the schematic as shown in Figure 6.

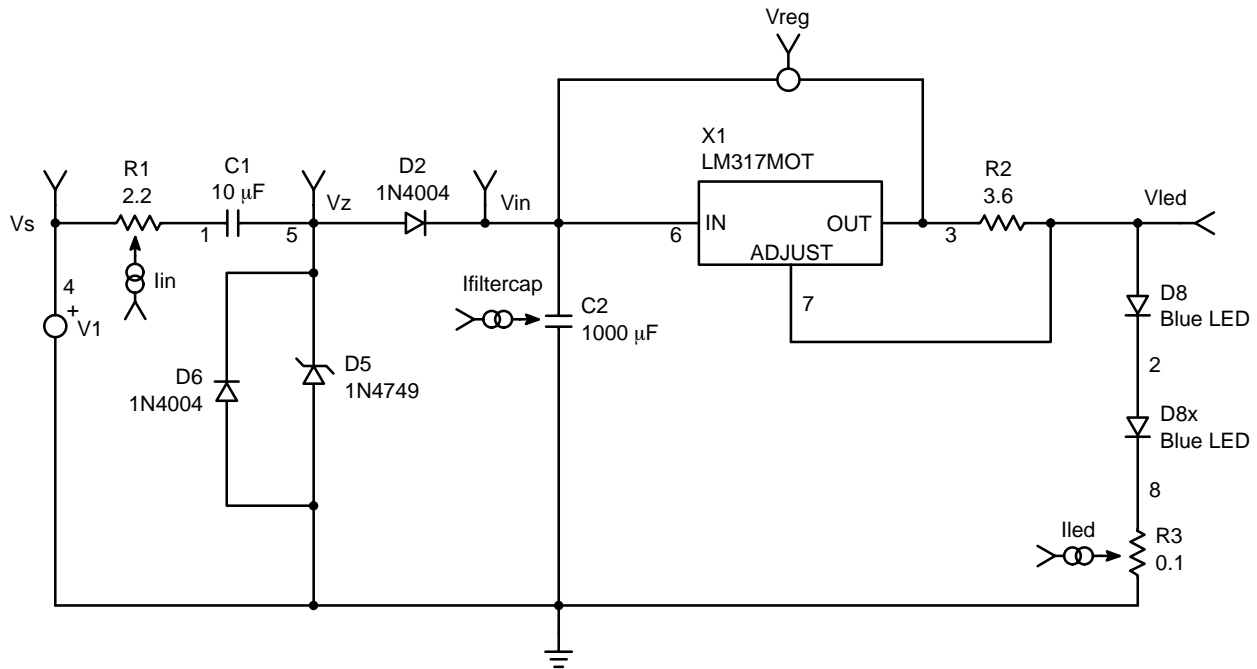


Figure 6. Half-Wave Capacitor Drop Lumiled Circuit

Several points should be noted. First, the schematic shows a diode in parallel with the Zener diode, D5. The reason is the forward voltage drop of a Zener diode is higher than a standard rectifier such as the 1N4004. A parallel diode will shunt some of the current, causing the Zener to dissipate less power and therefore run cooler.

Secondly, to model the LEDs, the generic diode model was modified to match the much larger LED forward voltage drop. To do this, the fundamental diode equation was evaluated:

$$i_D = I_o(e^{v_D/NV_T} - 1) \quad (\text{eq. 4})$$

In this equation i_D is the diode current, v_D is the forward drop of the diode, N is the emission coefficient (usually between 1 and 2), I_o is the reverse saturation current, and V_T is defined as:

$$V_T \equiv \frac{kT}{q} \approx 26 \text{ mV} \quad (\text{eq. 5})$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), T is the absolute temperature (K), and q is the charge on an electron. At 350 mA the forward drop for a blue LED from Lumileds is about 3.5 V. Letting $N = 2$, Equation 4 can be solved for I_o . Modifying the IsSpice model with these numbers yields the simulation results shown in Figure 7.

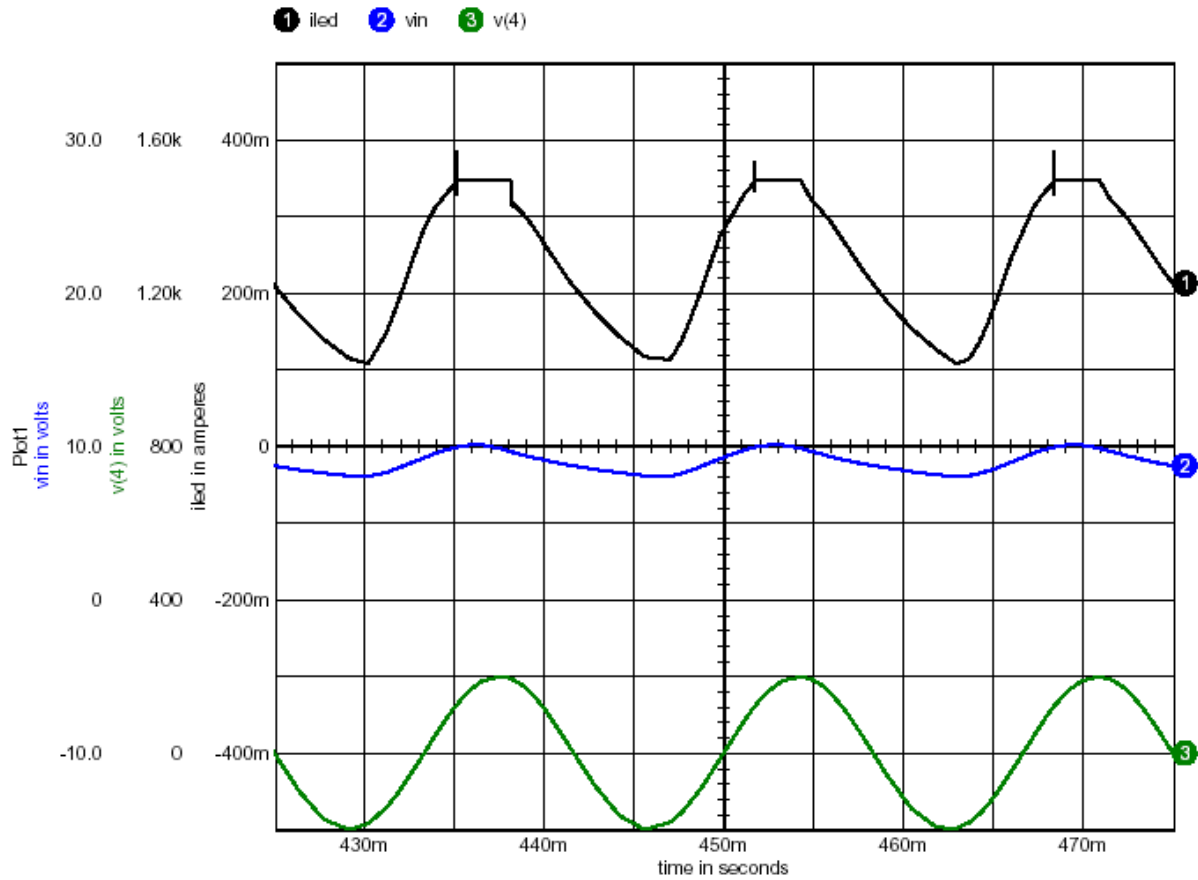


Figure 7. Simulation Results of Half-Wave Capacitive Drop Circuit

Figure 7 shows the LED current, the DC input voltage to the LM317 regulator, and the 132 Vac input voltage.

The circuit shown in Figure 6 was built and tested. The results of the actual waveforms are shown in Figure 8. The

simulation results shown in Figure 7 show good correlation with the actual waveforms shown in Figure 8. The LED model appears to be a good first order model.

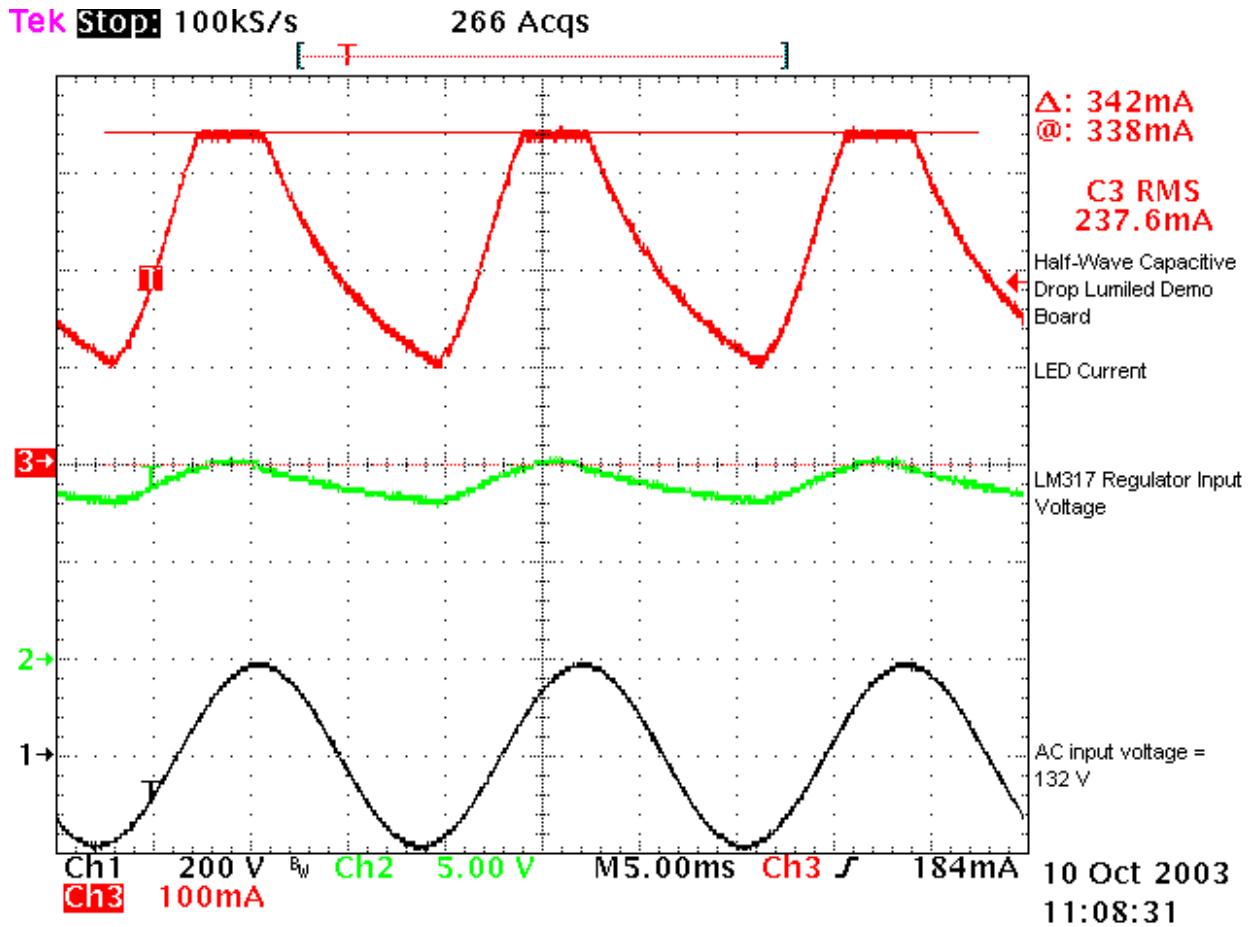


Figure 8. Oscilloscope Measurements of Half-Wave Capacitor Drop Lumiled Circuit

Notice that in both the actual and simulated results, the LED current is clamped to 350 mA as per Equation 1. During the time the AC input is negative, the energy source for the load is the 1000 μF capacitor. As the capacitor's energy is depleted, the LM317 comes out of regulation and the LED current decreases. Depending on the individual observer, light flicker at the line frequency rate may be noticeable under certain conditions. To reduce or eliminate any possibility of noticeable flicker larger electrolytic capacitor may be used. Another method to reduce the flicker effects is to use a full-wave version of the capacitive drop supply.

Full-Wave Capacitive Drop Circuit

The full-wave version of the capacitive drop circuit is shown in Figure 9. The engineering rule of thumb on this approach is 20 mAdc of load current is possible for each 1.0 μF of AC coupling capacitor. The full bridge approach would use only a 15 μF , 125 Vac rated capacitor. Figure 10

is a three LED, full-wave, capacitive drop supply using an LM317 as the current limiting element.

In the full bridge version, the coupling capacitor, C1, is charged and discharged through the full bridge. Depending upon the load, the value of the Zener may vary and may not be needed except during high line conditions. The resistor, R_d , is mainly used as a filter, and to help maintain regulation.

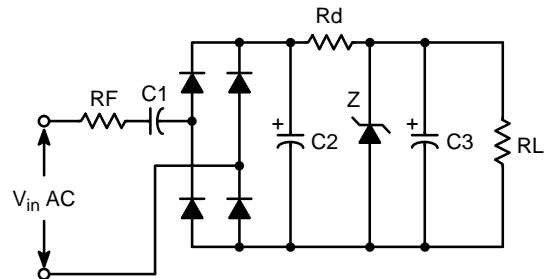


Figure 9. Full-Wave Capacitive Drop Supply

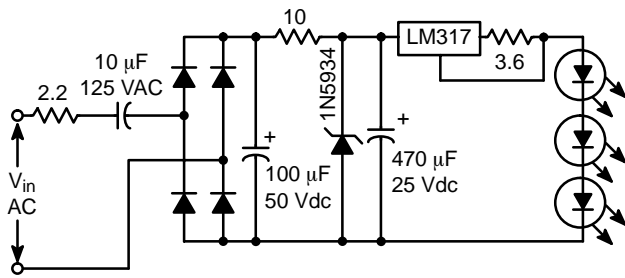


Figure 10. Three LED, Full-Wave, Capacitive Drop

The current flowing through the coupling capacitor is determined by using Equation 2. In the full bridge version, this is less than half the value of the half-wave capacitive drop approach. The value of the coupling capacitor may be able to be reduced if there are no losses in the Zener diode. The DC average value of the current flowing past the bridge rectifiers is calculated as shown in Equation 6.

$$I_{DC-AVERAGE} = I_{RMS} \sqrt{2} \frac{2}{\pi} = 2\pi 2 \frac{\sqrt{2}}{\pi} F C V_{AC} \quad (\text{eq. 6})$$

$$= 4\sqrt{2} F C V_{AC}$$

Making the assumption, that all of the $I_{DC-AVERAGE}$ is used for the LED, and is equal to 0.35 A. The value of the coupling capacitor, C, can be calculated for low line, 100 Vac, 60 Hz. This is shown in Equation 7. This is the value of the AC coupling capacitor used in Figure 10.

$$C = \frac{I_{LED}}{4\sqrt{2} F V_{AC}} = \frac{0.35}{4\sqrt{2} * 60 * 100} = 10.3e - 6 = 10 \mu F \quad (\text{eq. 7})$$

As mentioned above, since there are no losses in the Zener diode, an 8.0 uF capacitor will be used.

SPICE Simulation of Full-Wave Capacitive Drop Circuit

The full-wave capacitive drop circuit was also simulated using IsSPICE from Intusoft. The LEDs were modeled as before. The simulation schematic is shown in Figure 11.

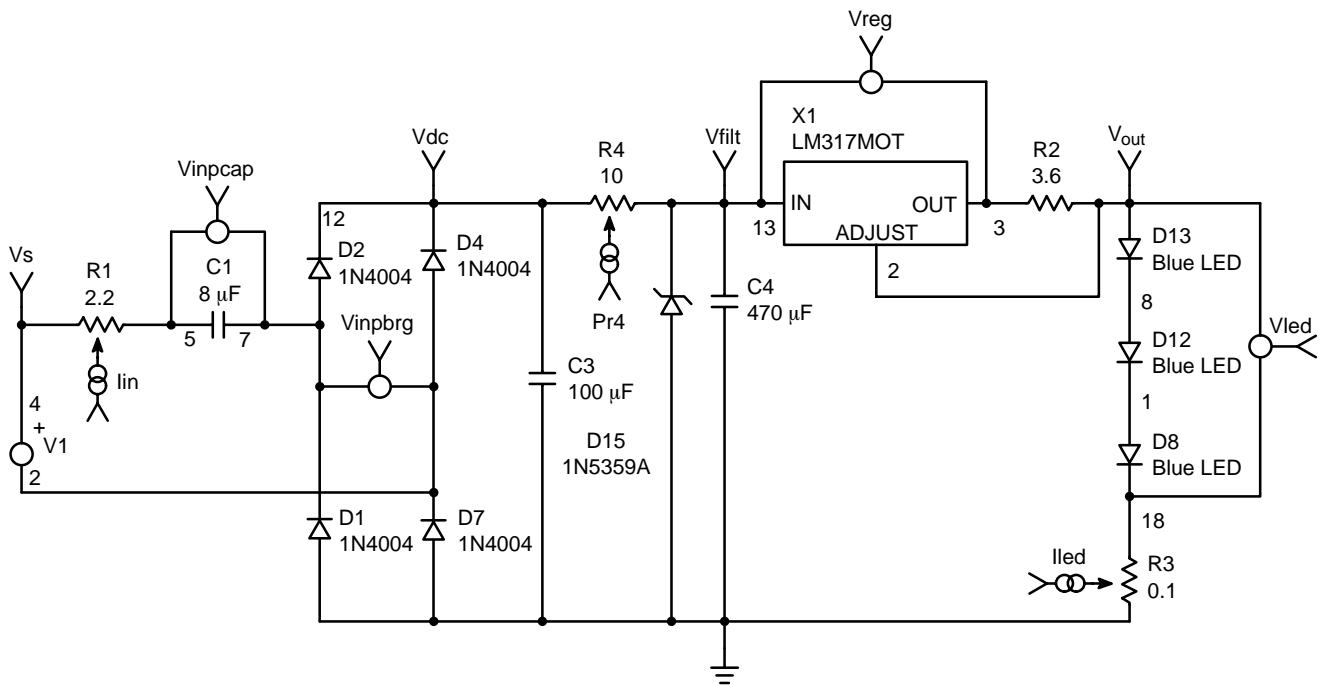


Figure 11. Simulation Schematic of Full-Wave Capacitive Drop Circuit

The results of the simulation are shown in Figure 12.

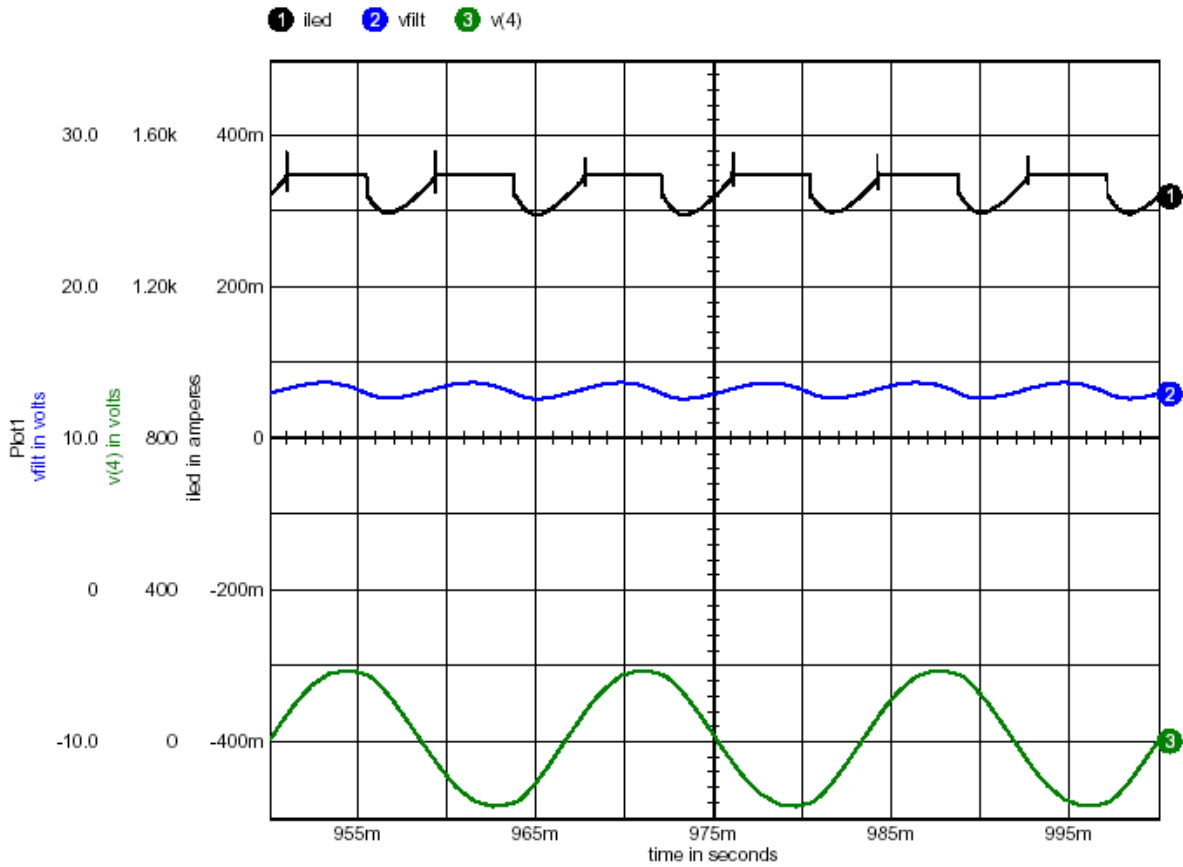


Figure 12. Results of Simulation of Full-Wave Capacitive Drop Circuit

As before, the waveforms shown are the LED current, the input voltage to the LM317 regulator, and the input AC

voltage. Again this shows good correlation with the actual oscilloscope measurements of Figure 13.

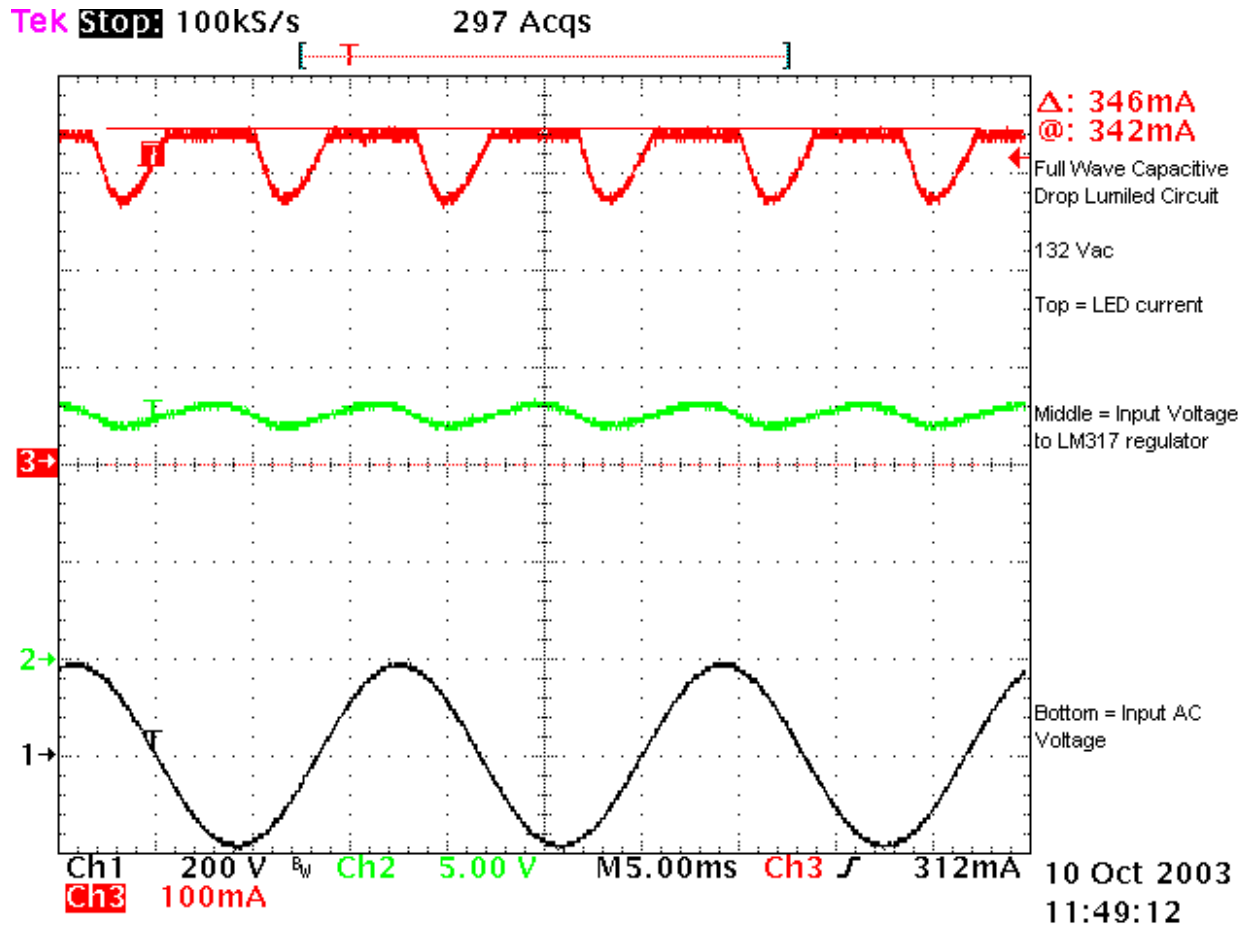


Figure 13. Oscilloscope Measurements of Full-Wave Capacitive Drop Circuit

Demo Board Circuit

The actual demo board circuit schematics and BOM are shown below.

AND8146/D

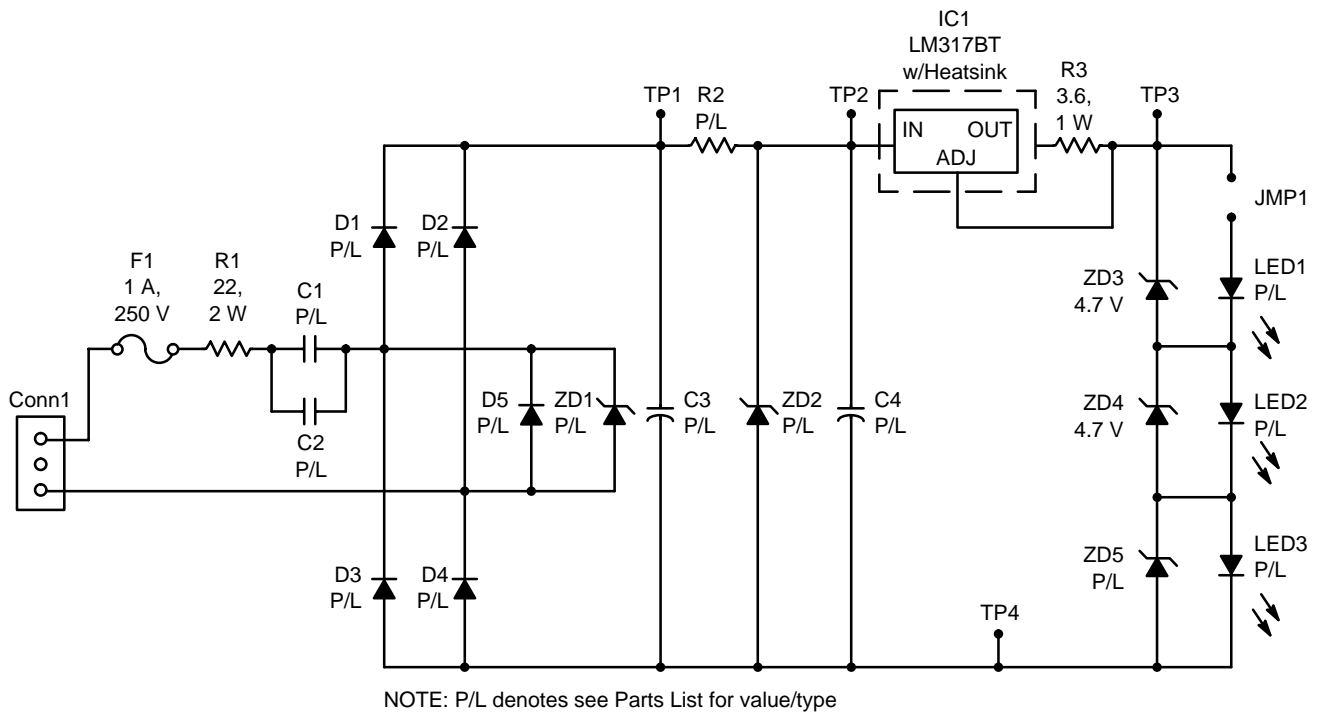


Figure 14. Lumiled Demo Board Half/Full-Wave Capacitor Drop Circuit

AND8146/D

HALF-WAVE PARTS LIST

Sch. Ref.	Vendor	Part Number/Description
Conn1	Phoenix Contact	1715035
C1	Panasonic	JSU23X106AQC (10 μ F, 230 Vac Dry Film Cap)
C2		Out
C3		Out
C4	Panasonic	EEU-FC1E102 (1000 μ F, 25 V)
D1	ON Semiconductor	1N4004 (1.0 A, 400 V, Axial)
D2, D3		Out
D4		24 Ga Bare Wire Jumper
D5		Out (Prov. for 1N4004)
F1	Littlefuse	224001 (1.0 A, 250 V, Pigtail Fuse)
IC1	ON Semiconductor	LM317BT (1.5 A, Adj. Regulator)
IC1	AAVID	566010B02800 (Heatsink)
JMP1		24 Ga Insulated Stranded Wire approximately 2"
R1		2.2 Ω , 2.0 W
R2		24 Ga Bare Wire Jumper
R3		3.6 Ω , 1.0 W
TP1	Keystone	5000 (Test Point – Red)
TP2	Keystone	5000 (Test Point – Red)
TP3	Keystone	5002 (Test Point – White)
TP4	Keystone	5001 (Test Point – Black)
LED1-LED2	Lumileds	LXHL-M*** (* indicates color)
LED3		24 Ga Bare Wire Jumper
ZD1	ON Semiconductor	1N5934B (24 V, 3.0 W)
ZD2		Out
ZD3-ZD4	ON Semiconductor	1N5917 (4.7 V, 3.0 W)
ZD5		Out

AND8146/D

FULL-WAVE PARTS LIST

Sch. Ref.	Vendor	Part Number/Description
Conn1	Phoenix Contact	1715035
C1	Panasonic	ECH-A22405JX (4.0 μ F, 220 Vac)
C2	Panasonic	ECH-A22405JX (4.0 μ F, 220 Vac)
C3	Panasonic	EEU-FC1H101 (100 μ F, 50 V)
C4	Panasonic	EEU-FC1E471 (470 μ F, 25 V)
D1, D2, D3, D4	ON Semiconductor	1N4004 (1.0 A, 400 V, Axial)
D5		Out
F1	Littlefuse	224001 (1.0 A, 250 V, Pigtail Fuse)
IC1	ON Semiconductor	LM317BT (1.5 A, Adj. Regulator)
IC1	AAVID	566010B02800 (Heatsink)
JMP1		24 Ga Insulated Stranded Wire approximately 2"
R1		2.2 Ω , 2.0 W
R2		10 Ω , 2.0 W
R3		3.6 Ω , 1.0 W
TP1	Keystone	5000 (Test Point – Red)
TP2	Keystone	5000 (Test Point – Red)
TP3	Keystone	5002 (Test Point – White)
TP4	Keystone	5001 (Test Point – Black)
LED1, LED2, LED3	Lumileds	LXHL-M*** (* indicates color)
ZD1		Out
ZD2	ON Semiconductor	1N5934B (24 V, 3.0 W)
ZD3, ZD4, ZD5	ON Semiconductor	1N5917 (4.7 V, 3.0 W)

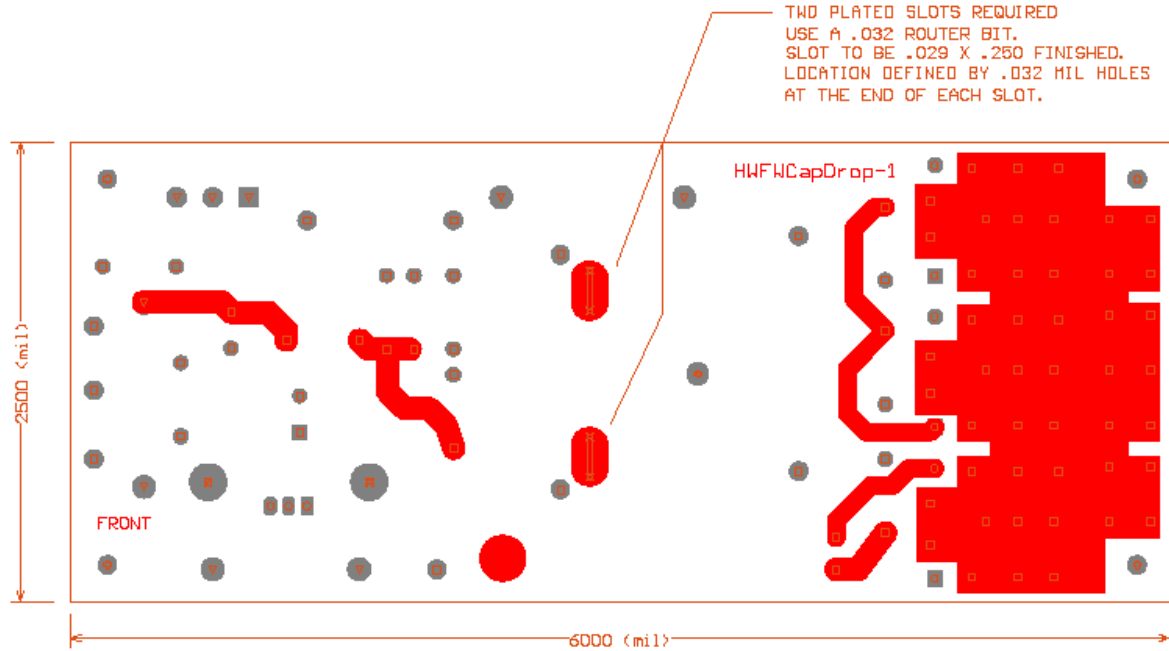


Figure 15. Top Side Foil of Capacitive Drop Lumiled Demo Board

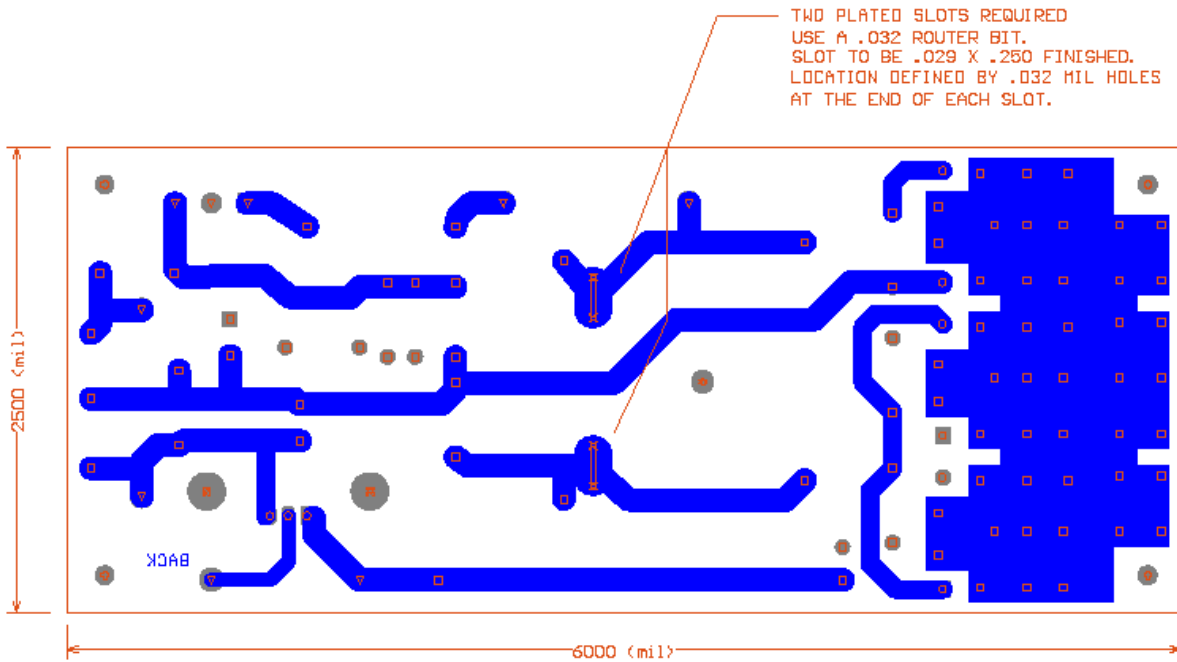



Figure 16. Bottom Side Foil of Capacitive Drop Lumiled Demo Board

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2. Luxeon, www.luxeon.com.
3. Lumileds, www.lumileds.com/pdfs/DS45.PDF,
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