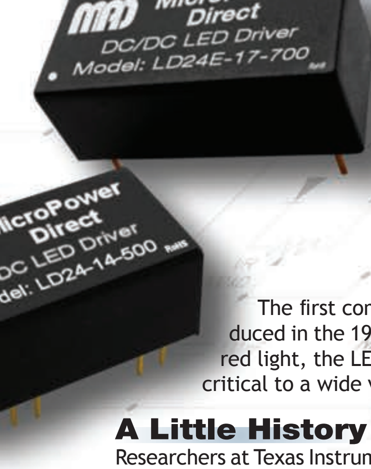


# Application Guide

# Driving LEDs

The first commercial Light Emitting Diode (LED) was introduced in the 1960's. From its early beginnings as a low intensity red light, the LED has emerged as a highly versatile component, critical to a wide variety of applications.

## A Little History

Researchers at Texas Instruments discovered in 1961 that applying an electric current to a gallium arsenide (GaAs) junction, caused an infrared radiation emission. They applied for and received a patent for the infrared LED. At General Electric Company, the first LED to produce light within the spectrum visible to the human eye (about 655 nm) was produced in 1962. Early LEDs were not very practical for most applications due to their low intensity, lack of color variety and high expense. They found use primarily as indicators.

The first commercially viable LEDs were produced by the Monsanto Company starting in 1968. These were fabricated using gallium arsenide phosphide (GaAsP). The most significant early application was as segments in alphanumeric displays. Fairchild Optoelectronics produced the first very low cost LEDs in the early 1970's.

Continuing research led to the introduction of more colors (green and yellow) and a wider usable wavelength. In the 1980's, high brightness LEDs using gallium aluminium arsenide phosphide (GaAlAsP) were introduced. These devices were bright enough to begin replacing incandescent bulbs in automotive and traffic applications. By 1990, gallium aluminium indium phosphide (GaAlInP) was being used to produce "super bright" LEDs.

In the 1990's researchers in Japan developed a method of producing gallium nitride (GaN) P-N junctions in a production environment. Using GaN, very high intensity blue LEDs were introduced. By adding indium (InGaN), a high intensity green LED was produced. Finally, lighting quality white LEDs were introduced. More recently, the power output and light output efficiencies have been significantly increased.

Today, low cost, high brightness LEDs are available in all colors. Surface-mount LEDs have been introduced and are available in single-color, bicolor, and tricolor models. Research continues into the fabrication process, packaging options, and performance improvements, which in turn increases the applications for which LEDs are a viable alternative.

## Basic Theory

LEDs are complex, PN junction semiconductors. The typical structure (and electronic symbol) is shown in Figure 1. When forward biased, current flows from the anode (or P Side) to the cathode (or N Side). As the current passes through the device, charge carriers (electrons & holes) are injected into the junction. A recombination of the charge carriers occurs when an electron meets a hole. The electron drops to a lower energy level, releasing energy in the form of a photon. This effect is called injection electroluminescence.

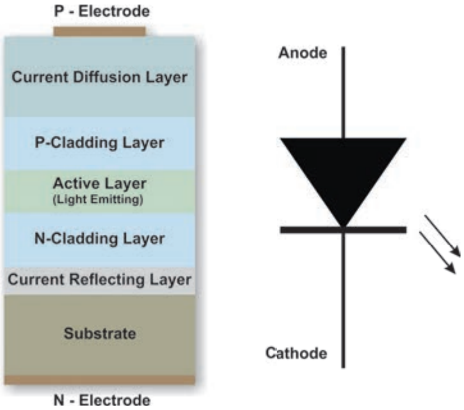


**Figure 1: LED Construction & Symbol**

In semiconductors fabricated from materials such as geranium or silicon (typically used in signal processing), this energy is released as heat. When materials such as gallium arsenide are used, the released energy becomes electromagnetic radiation. The color and visibility of the emission is dependent upon its wavelength. Color that is visible to humans ranges from red (longest wavelength) to violet (shortest wavelength). Figure 2 illustrates the color wavelength and the relative sensitivity of the human eye.

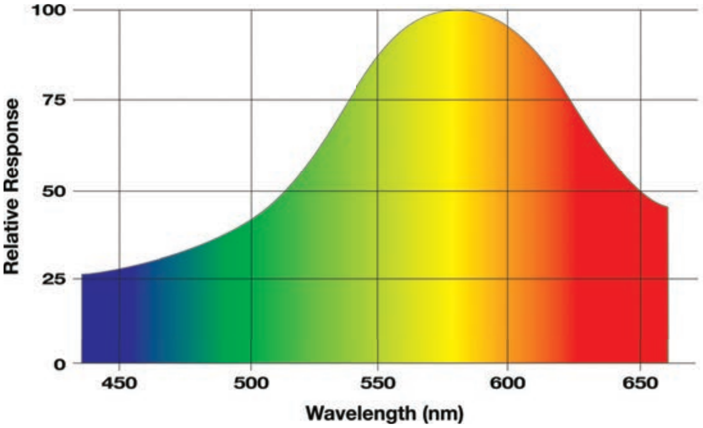


**Figure 2: Color Wavelength**

LEDs are highly directional, monochromatic devices. They are typically fabricated from gallium based crystals. These crystals are then doped with various inorganic materials (aluminium, arsenide, phosphide, indium, etc) to produce emissions in a narrow frequency range. In this way the fabrication process is used to produce die that emit distinct colors. This output is given as the peak wavelength in nanometers (λnm). Process variations will typically yield chips with an output range of approximately ±5 to ±10 nm. Table 1 gives the typical materials used to fabricate LEDs to achieve different colors/wavelength ranges.

Much of the light generated by an LED is reflected back into the device. This is a result of the high refractive index mismatch between the semiconductor materials used in fabrication and the surrounding air. One way to improve light extraction is to add a current reflecting layer, as shown in Figure 1. Also called a current blocker or Bragg reflector (mirror), this layer redirects light back out of the device, significantly increasing the light output of the LED.

**Table 1: LED Materials & Colors**

| LED Color | Die Material | Peak Wavelength (nM) |
|---|---|---|
| Infrared | GaAs, AlGaAs | >760 |
| Red | GaAsP, AlGaAs | 610 - 760 |
| Orange | GaAsP,<br>AlGaAs, GaP | 590 - 610 |
| Yellow | GaAsP,<br>AlGaAs, GaP | 570 - 590 |
| Green | GaP, AlGaInP, AlGaP,<br>GaN, InGaN | 490 - 570 |
| Blue | InGaN, GaN | 450 - 490 |
| Violet | InGaN | 400 - 450 |
| Ultraviolet | AlGaN, AlGaInN | <400 |

LEDs are produced in batches, which can lead to performance variations caused by differences in raw materials, handling, processing, etc from one lot to another. To help minimize the effects of any inconsistencies, manufacturers use a "binning" system. LEDs are sorted into groups according to brightness, color, forward voltage, etc.

## LED Terminology

**Ambient Temperature:** The temperature of the area surrounding an LED light source.

**Anode:** The "positive" terminal connection to an LED.

**Balance Resistors:** Resistors connected in series with LED strings to help balance the current in parallel connections. Typically very small values, they are sometimes referred to as ballast resistors.

**Beam Angle:** The angle between two lines on either side of the optical axis at a point where the luminous intensity is 50% of the center beam intensity. Typically ranges from 8° to 160°. High (or wide) beam angle LEDs (>70°) with their broader spread of light are useful in illumination applications. Low (or narrow) beam angle LEDs are typically used in indicator applications where a higher luminous intensity is required (for improved visibility). Sometimes called view angle, viewing angle or beam spread.

**Beam Lumens:** The total lumens contained within a light beam.

**Beam Spread:** See Beam Angle.

**Binning:** LEDs are sorted as part of the manufacturing process to help minimize operating tolerances. Sort criteria includes intensity, color, forward voltage, etc.

**Brightness:** See Luminance.

**Bulb:** Typically used in reference to a lamp. An "LED bulb" is a finished lamp assembly that contains LEDs.

**Candela:** (cd) The luminous intensity of a light source in a given direction. At a wavelength of 555 nanometers (green), one candela will have a radiant intensity of 1/683 watt per steradian.

**Cathode:** The "negative" terminal connection to an LED.

**Color Temperature:** A measurement that indicates the hue of a specific type of light source. Warm color temperatures tend to enhance red/orange, adding a yellow tint to white. They are typically used in homes, restaurants, etc. Cool color temperatures enhance blue, adding a bluish tint to white. They are often used in offices, hospitals, etc. Given in kelvins

**Dominant Wavelength:** (λd) The wavelength (or color) of an LED as perceived by the human eye. Visible LEDs are typically specified by their dominant wavelength or color. Sometimes referred to as hue wavelength or hue sensation.

**Eye Sensitivity:** A curve depicting the sensitivity of the human eye as a function of wavelength (color).

**Field Angle:** Similar to "Beam Angle", but given at a point where the luminous intensity is 10% of the center beam intensity.

**Foot-candle:** The illumination on a one square foot surface set one foot from a one candla light source. Equal to one lumen per square foot.

**Forward Current:** (IF) The current that flows through the LED semiconductor junction when it is forward biased.

**Forward Voltage:** (VF) The voltage drop across the LED semiconductor junction when it is forward biased.

**Iluminance:** A measure of the intensity of light on a surface. Measured in foot-candles or lux, it is inversely proportional to area.

**IP Code:** The International Protection Code rates electronic enclosures as to the degree of protection provided against the intrusion of solid objects, dust, water, etc. Also called the Ingress Protection Rating.

## LED Construction

LEDs are produced using a wafer deposition process. The materials used depend upon the type of LED desired. Metal contacts are added through a photoresist/evaporation process. Finally, the wafer is sawn into individual LED chips (typically about 0.25 mm square).

After processing, the chip is ready for use in either a through hole lamp or an SMD lamp. A through hole lamp (also called a leaded or radial lamp) is illustrated in Figure 3. The chip is mounted on a lead frame. It is placed in a cup (or well) at a part of the lead frame called the anvil (because of its shape). The anvil is part of the cathode lead. The well is coated in highly reflective material to help direct emitted light back out of the package.

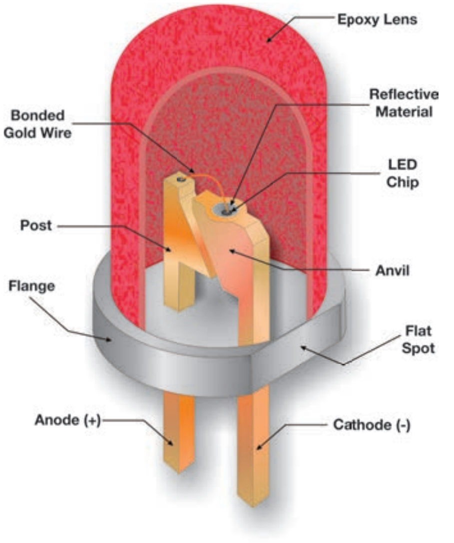


Figure 3: Radial LED Bulb

The chip is attached to the cathode lead using conductive epoxy (in some configurations the die may have a wire bond connection to the cathode off the top of the chip). Gold bonding wire is used to connect the die to the anode post of the lead frame.

The whole assembly is encapsulated within an epoxy lens. The encapsulant protects the chip and wire bonds from damage due to vibration or shock. The diffusion of the encapsulation (set by adding glass particles to the epoxy) is also a factor in setting the viewing (or beam) angle of the light generated by the chip. Other factors are the shape & size of the chip; the shape & size of the reflector cup; and the distance between the chip and the top of the lens (set by extending the lead frame into the assembly).

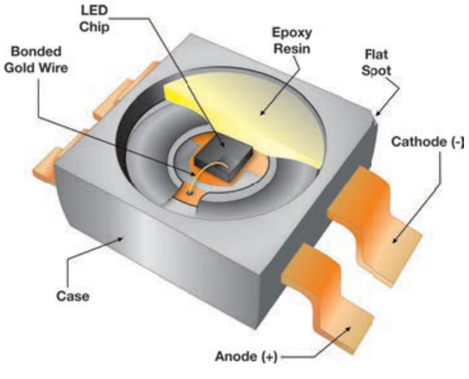


Figure 4: SMD LED Bulb

Through hole LED lamps have been available for many years. They are produced in a variety of standard package sizes (typically 3 to 10 mm), and colors. They are very reliable, offer robust performance and low power consumption.

Through hole LED lamps are used in a wide variety of applications. They are often found in outdoor LED panels, front panel indicators, instrumentation indicators and small area back lighting.

An SMD type LED is illustrated in Figure 4. Here, the lead frame has been partially enclosed in epoxy, typically by an injection molding operation. Again, the chip is mounted on a lead frame. It is attached to the cathode lead by conductive epoxy, and a wire bond is used for the connection to the anode. As is the case with the radial bulb, the chip sits in a cavity formed by highly reflective material that helps increase light output by redirecting emissions out of the package. The cavity is filled with an epoxy resin that protects the chip and acts as a lens for the light output.

SMD packaging is sometimes used for higher power LEDs. As is the case with any high power device, care must be taken to safely remove excess heat generated by the power dissipated within the chip. Otherwise, the bulb may be damaged from overheating. For high power products, the die is typically connected (thermally) to a heat sink placed in the bottom of the package. In the actual application, this integrated heat sink may be connected to external heat sinking or air flow. This connection can be made via plating on the PC board, heat pipes (or vias), etc.

Surface Mount LEDs are also cost-efficient solutions for low-power, compact designs. The products come in a variety of available color, lens, and package types and are highly durable.

SMD LEDs are smaller than leaded components. Because they are low profile and mounted directly on the PCB, they are sometimes used with light guides (or pipes) to direct the light output as required by the application. Most manufacturers provide them on tape & reel for use with high speed, automated assembly equipment.

SMD LEDs are very small (making them an ideal choice for space-limited applications); highly resistant to shock and vibration and are very light weight. They are used in a variety of applications, including automotive lighting, push button backlighting, and front panel indicators. Their small size & weight, combined with low power consumption make them a good choice for mobile equipment and the ability to package them on reels makes them attractive to high volume applications where reduced assembly cost is required.

Table 2: Comparison Of Lighting Technologies

| | Life Span | Operation Basis | Turn On | Light Direction | Color Temperature | Reliability |
|---|---|---|---|---|---|---|
| **LED** | >60 kHrs | Semiconductor | < 1 Sec | Directional | 2,600 - 10,000 k | High |
| **Incandescent** | 1.2 kHrs | Heat | < 1 Sec | Full | 2,300 - 3,300 k | Low |
| **Compact Fluorescent** | 8.0 kHrs | Mercury Vapor | < 60 Sec | Full | 4,000 - 8,000 k | Low |
| **Halogen** | 1.0 kHrs | Heat | <150 Sec | Full | 2,500 - 3,000 k | Low |

## Powering LEDs

LEDs are current controlled semiconductor devices. The intensity of the light output is proportional to the current flowing through the junction. Care must be taken to observe the correct polarity of the LED and not to exceed the maximum current rating. In either case, catastrophic damage to the LED may occur. The voltage flowing in the circuit has to be enough to provide the forward drop required by the LED (or LED's) connected.

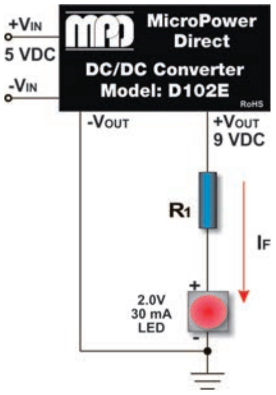


Figure 5: Constant Voltage

Many existing LED applications use "off the shelf" commercial power supplies for a power source, typically due to cost and availability. These power sources are overwhelmingly constant voltage devices. A simple connection is shown in Figure 5. The power source for this circuit is the D102, a standard (5V input, 9V output @ 300 mA) DC/DC converter. To protect the LED, the resistor R1 is used to limit current flow. The following equation is used to calculate the correct value of R1:

$$R_1 = \frac{V_S - V_F}{I_F}$$

Taking specifications from a typical LED datasheet, we can use a forward voltage drop of 2.0V and an optimum forward current is 300 mA. This would yield a value for R1 of:

$$R_1 = \frac{9.0V - 2.0V}{0.03A} = 233\Omega$$

With a simple current limiting resister, the LED could be powered and protected. However, the limitations of this approach are soon apparent.

The voltage controlled power source is the main problem. Any changes in the output load will result in variations in the output current (as the power source regulates the output voltage). Load variations can be caused by any number of circuit components. These can range from changes in the power supply input, circuit changes over temperature, or variations in the LED forward voltage drop (for multiple LED connections). Any changes in the output current will cause a change in LED brightness. Significant changes could cause damage.

LEDs typically have a positive temperature coefficient (PTC). When in use, as the LED warms up the forward voltage will start to drop. This will cause the LED to draw more current which, in turn, will increase its temperature. Uncontrolled, this can lead to thermal runaway and a catastrophic failure of the LED. Even short periods of operation under conditions exceeding recommended operating temperature limits can significantly reduce the operating lifetime of an LED.

In more complex LED circuits, such as parallel output connections, unbalanced voltages may cause a variety of issues. These could include variations in brightness or color shifting from one LED string to another, unacceptable in most applications if they are visible to the human eye. In the event of a catastrophic failure of one LED, the whole system could fail in a chain reaction.

A voltage controlled source can be effective for low current applications where the input range to the supply is tightly controlled. For more complex applications or higher current requirements, it is better to use a constant current source.

## Constant Current Drivers

As the name implies, a constant current driver regulates the output current level. For any changes in input line, temperature or output load, the output current is maintained within a regulation band. The output voltage level is varied to achieve this.

For designers of LED lighting systems, this often meant a choice between expensive constant current output power supplies; or the use of linear or switching regulators that typically used an external sensing resistor to monitor and control the current output.

Recently, many low cost, constant current drivers have come on the market; including a full line offered by **MicroPower Direct**. Now available over a wide range of power and with DC or AC inputs, these units offer designers a quick, compact, and economical solution to driving LED lights in a variety of configurations for a wide range of applications.

Figure 6 shows a simplified connection of a constant current driver. As with most of these devices, this driver allows the user to set the output current to the desired level for the specific application. In this case, 30 mA. So, for our example, IOUT is equal to:

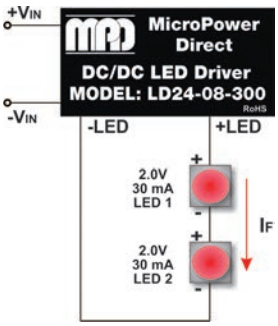


Figure 6: Constant Current

$$I_{OUT} = I_F = 30 \text{ mA}$$

Once set, the driver will maintain the output current level to within a tight regulation band

## Using An LED Driver

To illustrate LED driver connections, we will use the **LD24-08-300**. This unit is a low cost DC/DC driver with a constant current output. It is packaged in a small, encapsulated 0.8 x 0.4 case. The specifications of this model are summarized below.

Figure 7: LD24-08-300 Specification Summary

| **Input** | | |
|---|---|---|
| Parameter | Value | Units |
| Input Voltage Range | 7 - 30 | VDC |
| Max Input Voltage | 40 | VDC |
| **Output** | | |
| Parameter | Value | Units |
| Output Voltage Range | 2 - 28 | VDC |
| Output Current | 300 | mA |
| Output Power | 8 | W |
| Efficiency | 95 | % |
| **Analog Dimming** | | |
| Parameter | Value | Units |
| Adjust Voltage Range | 0.3 to 1.25 | VDC |
| Output Current Adjustment | 25 to 100 | % |
| **Digital Dimming** | | |
| Parameter | Value | Units |
| Max Operation Frequency | 1.0 | kHz |
| Switch On Time | 200 | nS |
| Switch Off Time | 200 | nS |

## LED Terminology Cont.

**Light Emitting Diode:** (LED) A diode that emits photons (as light) when forward biased.

**LED Strip:** LEDs that are attached to a flexible PC board up to about 16 feet long and put on reels. The user can than trim the strip to the size required.

**Lumen:** A lumen is the luminous flux of light produced by an LED that emits one candela of luminous intensity over a solid angle of one steradian (sr).

**Lumen Maintenance:** The ability of an LED light to maintain intensity over time. A high power LED will typically retain 70% of its intensity for up to 50k hours.

**Luminance:** The luminous flux emitted or reflected from a source; in this case an LED. Given in lumens (lm).

**Luminosity Function:** Established by the CIE, this function approximates the average visual sensitivity of the human eye to light of different wavelengths. Two functions are defined. The photopic luminosity function is used for everyday light levels; while the scotopic luminosity function is used for poor light levels. Also called the luminous efficiency function.

**Luminous Efficacy:** A measure of the effectiveness of a light source in converting electrical energy into light. It's the ratio of luminous flux to power & is expressed as lumens per watt (lm/W).

**Luminous Flux:** (F) A measure of the total perceived power of a light source in all directions. The measurement factors in the sensitivity of the human eye by incorporating the luminosity function. Expressed in lumens. Sometimes called luminous power. See Luminosity Function.

**Luminous Intensity:** The perceived power emitted by a light source in a single direction. It is the luminous flux per unit solid angle steradian (sr). Expressed in candelas (cd).

**Lux:** (lx) The measure of light intensity, as perceived by the human eye. One lux equals one lumen per square meter.

**Nanometer:** (nm) A unit of length in the metric system, equal to one billionth of a meter. Used as a measure of the wavelength of light.

**Operating Life:** The number of hours an LED is expected to be operational. For illumination applications where light output is considered critical, output degradation to 70% lumens is typically used. For applications where light output is not as critical (such as decorative lighting), 50% is typically used. Given in hours.

**Peak Wavelength:** ($\lambda p$) The single wavelength where the radiometric emission spectrum of an LED reaches its maximum

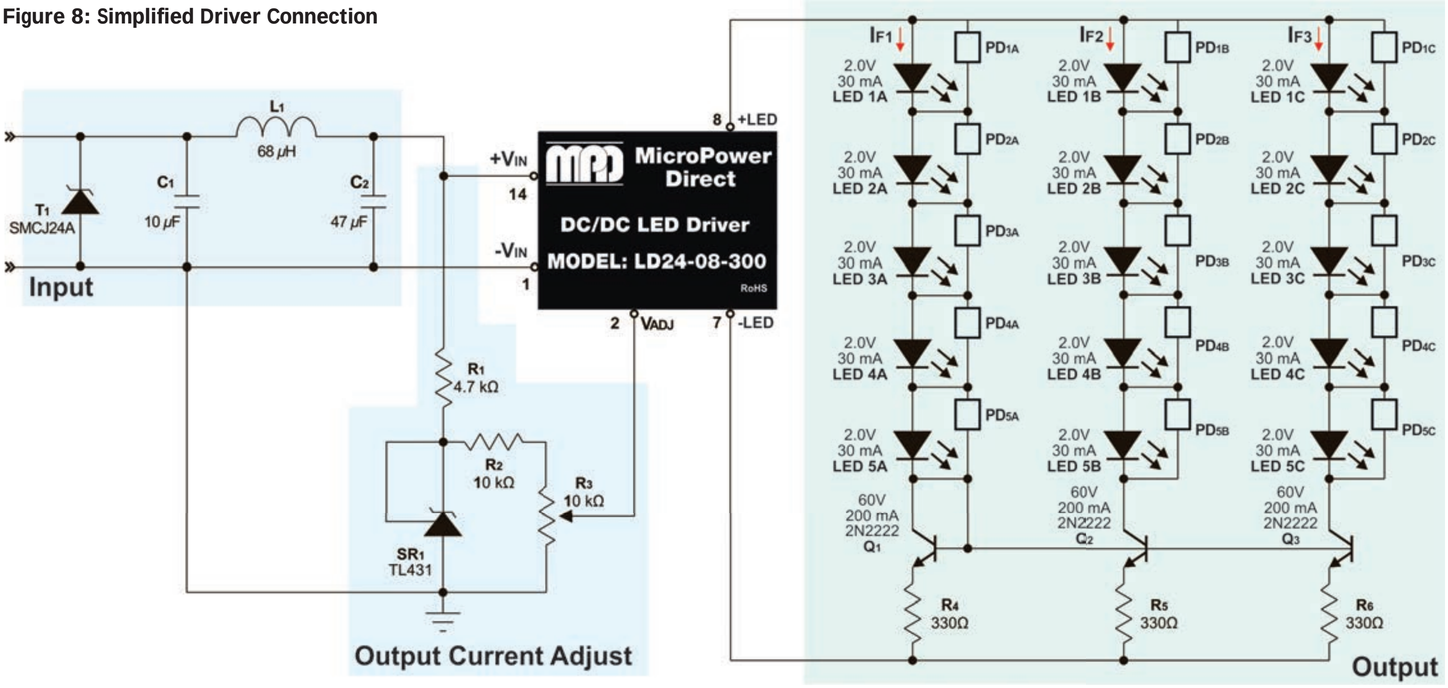
**PWM:** Pulse Width Modulation. A circuit that varies the brightness of an LED by changing the duty cycle of the output current of the LED driver.

**Radiant Flux:** The total power of electromagnetic radiation (including infrared, ultraviolet, and visible light) emitted from an LED. Measured in watts, it is also called radiant power.

**Radiant Intensity:** A measure of the intensity of electromagnetic radiation, defined as power per unit solid angle. Given in watts per steradian.

**Reverse Breakdown Voltage**: Amount of reverse bias that will cause a P-N junction to break down and conduct in the reverse direction.

Figure 8: Simplified Driver Connection



A simplified parallel connection using the **LD24-08-300** is shown in Figure 8 above.

The **LD24-08-300** is a buck converter, the most common type of DC/DC driver now available. With a buck converter, the output voltage is always slightly lower than the input. In this case, about 2V. With an upper range limit set at 30V, it is capable of driving LED strings with a combined forward voltage drop of 28V maximum.

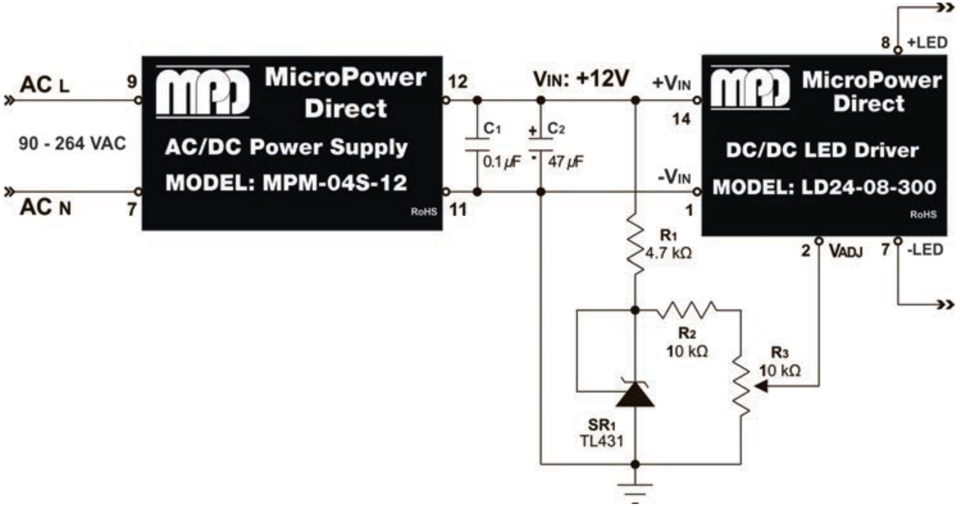
The other components shown are optional, to be used dependent upon the requirements of the specific application.

### DC Input

The transient voltage suppressor (TVS) $T_1$ is used to meet the surge requirements of EN 61000-4-5. The clamping voltage of the TVS must be <40 VDC maximum. This will prevent any surge from exceeding the maximum input of the driver (40 VDC). Exceeding the maximum input rating could damage the driver.

The Pi filter shown ($C_1$, $C_2$ and $L_1$) will help to meet conducted emission requirements. With the addition of the filter, the unit should meet the levels of EN 55015.

Figure 9: AC/DC Input Stage



### AC Input

Our example of Figure 8 shows a DC/DC driver connected to a stable DC input. Many applications, for a variety of reasons, will require an AC input. There are drivers available that integrate an AC input into the package with the driver. Another option is too add an AC/DC power supply to the input stage of the circuit (as shown in Figure 9). This is a distributed (or two-stage) connection.

In this connection, we take the AC line in (90 to 264 VAC) and connect it to the **MPM-04S-12**. This is a miniature, 4W AC/DC power supply that provides a tightly regulated 12 VDC output at 333 mA. The 12 VDC output powers the LED driver.

The two stage approach can simplify the safety approval process (most AC/DC power supplies on the market are approved to EN 60950) and may increase design flexibility. Besides the output power, other specifications to consider when selecting the input AC/DC supply would include input range, safety approvals, PFC rating (which may be needed for various system energy ratings) and operating temperature range.

### Output Current Adjustment

The Figure 8 illustration shows a simple analog circuit for setting the output current of the driver. The output is varied by changing the voltage level at the $V_{ADJ}$ input (pin 2). Per the specifications, the output current can be varied from 75 mA to 300 mA by changing the $V_{ADJ}$ level from 0.30 VDC to 1.25 VDC. Care must be taken not to exceed 1.25 VDC to avoid possible damage to the driver. If the pin is left open, the output current is 300 mA (full), if it's grounded, the driver shuts down.

Our circuit has a 12 VDC input to the LED driver. To insure that we do not exceed the 1.25 VDC limit on the $V_{ADJ}$ pin, a shunt regulator is connected in parallel with the resistor network $R_2$ and $R_3$. Over input levels of 5V to 30V, the shunt regulator ($SR_1$) will maintain the voltage across $R_2$ and $R_3$ at 2.5 VDC. By adjusting $R_3$, the voltage level on the $V_{ADJ}$ pin is varied. The output current is equal to:

$$I_{Out} = \frac{0.08925 \text{ X } \left(\frac{R_3}{R_2 + R_3}\right) V_{CNT}}{0.372}$$

The $V_{CNT}$ used in the formula is the voltage level used to set-up $V_{ADJ}$. In this instance, it is the 2.5 VDC level set by the regulator $SR_1$. Quite often it is $V_{IN}$ or some regulated bus level that is available.

For our example, we need an output current level of 90 mA (30 mA for each of three output stacks). The $V_{ADJ}$ setting is equal to:

$$V_{ADJ} = \frac{I_{OUT} \text{ X } 0.372}{0.08925}$$

To set the output at 90 mA, this gives us a $V_{ADJ}$ setting of:

$$V_{ADJ} = \frac{0.09 \text{ X } 0.372}{0.08925} = 0.375 \text{ VDC}$$

We can also derive the $V_{ADJ}$ level from the formula:

$$V_{ADJ} = \frac{R_3}{R_2 + R_3} \text{ X } V_{CNT}$$

We need to know what value to set $R_3$ at to get a 0.375 VDC at the $V_{ADJ}$ input. Since we know the $V_{ADJ}$ level required, we can now calculate a value for $R_3$ using the following formula:

$$R_3 = \frac{R_2 \text{ X } V_{ADJ}}{V_{CNT} - V_{ADJ}}$$

Thus, the correct value of R3 is:

$$R_3 = \frac{10,000 \times 0.375}{2.5 - 0.375} = 1.76\,k\Omega$$

So for our example, adjusting R3 to 1.76 kΩ will set the VADJ level at 0.375V which will in turn set the output current at 90 mA.

Due to component tolerances, rounding and a slight non-linearity in the IOUT/VADJ curve of the **LD24-08-300**, these formulas may not yield exact results. However, with a little tweaking the results should be satisfactory.

Figure 10 shows a slightly different approach using two low cost, switching regulators. Working from inputs that can range from 15 VDC to 32 VDC,the top regulator (SR1) keeps the input to the LED driver at 12 VDC.

The other regulator (SR2), driven off the same input line maintains the control voltage at 5 VDC. The resister network of R1 and R2 can now be used to set the output current level of the LED driver. The same equations we have just discussed are still applicable to this circuit with the change of VCNT from 2.5 VDC to 5 VDC.

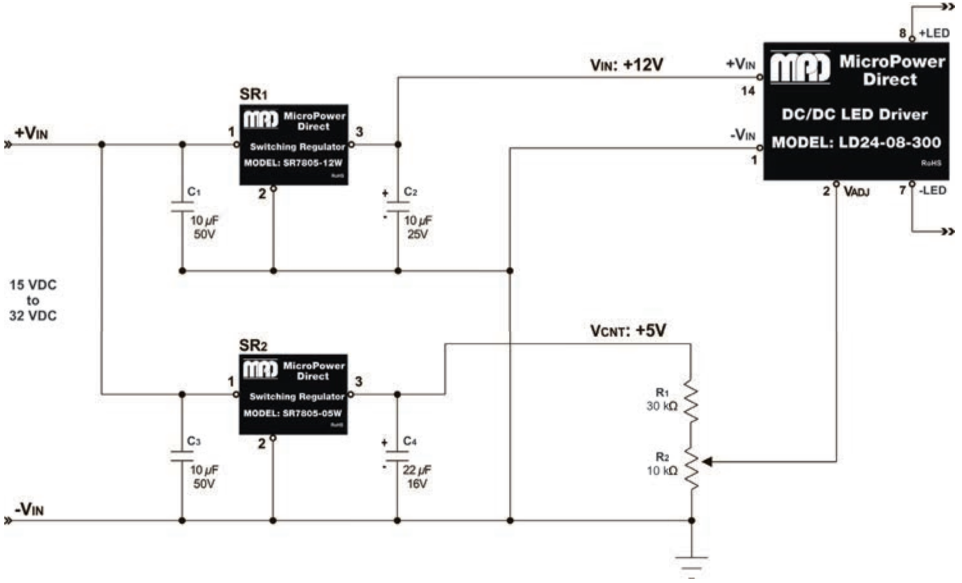
## Dimming LEDs

The circuits just discussed could also be used to dim the LEDs. This is accomplished by simply lowering the driver output current below the specified drive current for the LEDs being used. While this method is common, it does not give the best results for many applications.

An LED operates at its maximum efficiency when operated at the rated drive current specified by the manufacturer. Operating an LED at lower than its rated forward current will not only decrease the system efficiency, but may cause color (or wavelength) shifting. In illumination applications, this could cause visible changes to lighting.

A preferred method is using pulse width modulation (PWM). Since LEDs reach full light output almost instantaneously, it is possible to change the intensity level by rapidly turning the LED on/off. By changing the duty cycle of the on/off time, the perceived intensity of the light is varied up or down. Keeping the frequency rate at greater than 100 Hz will avoid any flicker that is visible to the human eye.

**Figure 10: Input Using Switching Regulators**



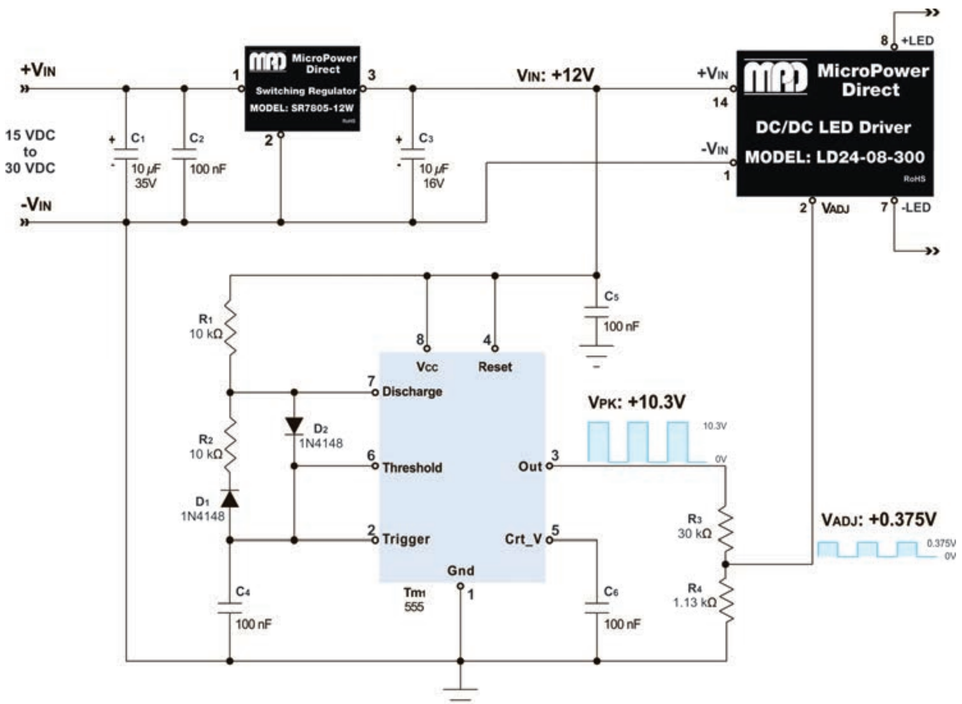


**Figure 11: Digital Dimming (PWM Dimming)**

Figure 11 shows a simple method of achieving digital (or PWM) dimming. Here, instead of using a DC voltage level to set the output current level, we are using a 555 timer to apply a series of pulses to the VADJ input.

The 555 operates over a supply voltage range of 4.5 VDC to 15VDC. Here we have it connected to the 12 VDC output of the switching regulator (this is also the VIN of the LED driver). Care should be taken to minimize ripple at the Vcc input. Excess ripple could cause timing errors.

The timer is connected for astable (free run) operation. The frequency is set by R1, R2 and C4. The timing capacitor (C4) charges through R1 and D2. When it reaches the level of ²/₃ Vcc, the discharge pin (pin 7) goes low and C4 will discharge through D1 and R2 to the internal discharge transistor. When the C4 voltage drops to ¹/₃ Vcc, the discharge pin goes high and C4 begins to charge again. The frequency is derived from the following formulas.

TON ($\tau$) is equal to:

$$T_{ON} = 0.67 \times R_1 \times C_4$$

TOFF is equal to:

$$T_{OFF} = 0.67 \times R_2 \times C_4$$

The total period (T) is equal to:

$$T = T_{ON} + T_{OFF}$$

Which gives us a frequency (f) of:

$$f = \frac{1}{T}$$

And finally a duty cycle (*D* expressed as a decimal) of:

$$D = \frac{\tau}{T} = \frac{R_1}{R_1 + R_2}$$

For these examples we are ignoring the 0.6V drop across the diodes. The diodes (D1 and D2) allow duty cycles below 50% to be set. Diode D1 bypasses R2 while C4 is charging. Diode D2 is optional (but recommended), essentially blocking R2 during the charge period. For our example, we want a 50% duty cycle. To achieve this, we need to calculate the correct value of R2. We can use the following equation:

$$R_2 = \frac{R_1}{D} - R_1$$

For our 50% duty cycle, this gives us:

$$R_2 = \frac{10,000}{0.5} - 10,000 = 10\,k\Omega$$

Theoretically, this circuit will allow for duty cycles over a range of approximately 5% to 95%. If manual adjustment is desired, a potentiometer may be substituted for R2 (with some adjustment of the circuit).

The 555 timer is very accurate, so inaccuracies in using these formulas are probably due to tolerances in the external components used. The timing capacitor (C4) should be a tantalum, mylar, or equivalent (ceramic disc capacitors should not be used). The size of C4 is generally not critical, but it should be as low leakage as possible.

The timing resistors (R1 & R2) should be metal film. In order to avoid excessive current flow through the internal discharge transistor, it is recommended that $R_1$ be at least 5 kΩ.

The timer also requires a minimum value of current to operate the internal threshold comparator (typically about 0.25 µA). Care must be taken not to install values of $R_1$ & $R_2$ that would limit the threshold current to a level that is insufficient to trip the comparator. To calculate the maximum value of resistance, use the following formula:

$$R_{MAX} = \frac{V_{CC} \times V_{CAP}}{I_{THR}}$$

The voltage at the threshold pin (pin 6) is $^1/_3$ $V_{CC}$, which in turn gives us a $V_{CAP}$ voltage of $^2/_3$ $V_{CC}$. Using this, we can calculate $R_{MAX}$ as follows:

$$R_{MAX} = \frac{12 - 8}{0.25 \times 10^{-6}} = 16\ \text{M}\Omega$$

If timer accuracy over temperature is critical to the application, external components with a slight positive temperature coefficient should be used. This will counteract the typically small negative temperature coefficient of the timer and cancel any timing drift over temperature.

The output of the timer is a high power totem pole circuit. The bypass capacitor ($C_5$) eliminates any current spikes this causes on the $V_{CC}$ input. The value of $C_5$ is not critical and is typically between 0.01 µF and 10 µF. Howevr, $C_5$ should be mounted as close to the timer as possible.

The peak output voltage level of the timer is equal to:

$$V_{PK} = VCC - 1.7\ VDC$$

For our circuit this equals:

$$V_{PK} = 12\ VDC - 1.7\ VDC = 10.3\ VDC$$

This gives us an output that is a series of pulses with a 10.3 VDC peak value. The turn on/off rate is 50%. To safely apply this signal to our driver/LED circuit, the peak value must be reduced to the correct level. In our example, this has already been calculated at 0.375 VDC.

To achieve this, we are using a simple divider network ($R_3$ & $R_4$).Using some earlier equations, we can calculate the correct values for this diver network. For $V_{ADJ}$, we have:

$$V_{ADJ} = \frac{R_4}{R_4 + R_3} \times V_{PK}$$

Once again, we need to know what value to set $R_4$ at to get a 0.375 VDC at the $V_{ADJ}$ input. Since we know the $V_{ADJ}$ level required, we can calculate a value for $R_4$ using the following formula:

$$R_4 = \frac{R_3 \times V_{ADJ}}{V_{PK} - V_{ADJ}}$$

Thus, the correct value of $R_4$ is:

$$R_4 = \frac{30{,}000 \times 0.375}{10.3 - 0.375} = 1.13\ \text{k}\Omega$$

Now, in our example, a pulse wave is applied to the $V_{ADJ}$ input of the driver. This signal has a 0.375 VDC peak amplitude and a 50% duty cycle. With this control signal applied to the $V_{ADJ}$ input, the output of the driver will be a pulse train with a 50% duty cycle and a peak current of 30 mA. The LEDs will appear to be running at 50% intensity with no variation in color.

Connecting the LEDs to the driver is typically done in series strings, or parallel strings. A series connection (as shown in Figure 12), is the simplest and most common type.

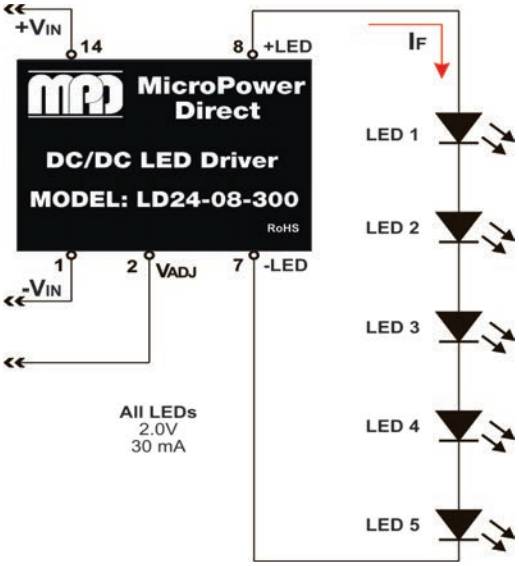


Figure 12: Simplified Series Connection

## Output Circuits

### Series Connection

Driving multiple LEDs in series avoids uneven light levels resulting from current variations. All of the LEDs in the string see the same forward current, insuring maximum brightness matching.

The output voltage of the driver is equal to:

$$V_{OUT} = V_F \times n$$

Where $V_F$ is the specified LED forward voltage and n is the number of LEDs in the string. In this case, we have a typical VF of 2 VDC and five LEDs, resulting in a 10 VDC output. Most DC/DC LED drivers are step-down buck regulator types. Care must be taken that the specified input range of the driver exceeds the required output level by an appropriate margin.

The output current of the driver is equal to:

$$I_{OUT} = I_F$$

All LEDs in the string see the same current. In our example, this would be 30 mA.

**Series Connection Advantages:**

- Circuit complexity is very low
- Each LED sees the same current
- High circuit efficiency (no need for balancing resistors)

**Series Connection Disadvantages:**

- The required driver output voltage can become very high for large LED strings
- Entire string fails if one LED opens

A shorted LED has little effect on the circuit operation (light output will dim by $^1/_n$, where n equals the number of LEDs in the string). However, if the LED string fails open for any reason (LED failure, mechanical connection, etc), the whole circuit fails.

### Parallel Connection

Figure 13 illustrates a parallel (actually a series-parallel) connection. The driver is now powering fifteen LED's connected in three parallel strings. For this circuit, the driver $I_{OUT}$ is equal to:

$$I_{OUT} = I_{F1} + I_{F2} + I_{F3}$$

For our circuit, this equals:

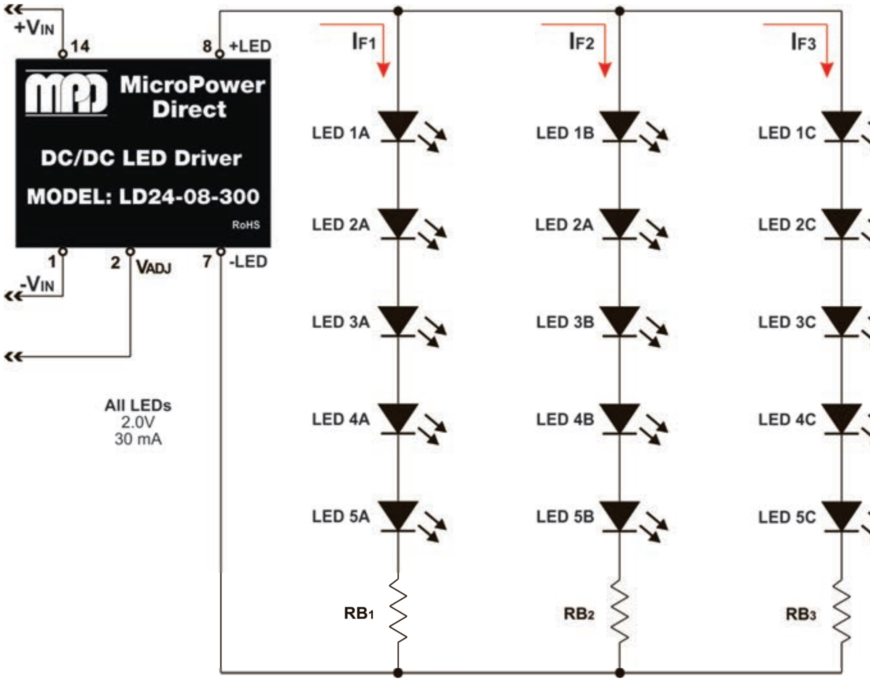
$$I_{OUT} = 30\ mA + 30\ mA + 30\ mA = 90\ mA$$

The driver output voltage required is still equal to the total of the $V_F$ drops in one string (assuming the strings are balanced). In our case, this is again 10 VDC.

The major advantage of using parallel strings is the number of LEDs that can be powered without exceeding the upper voltage limitation of the driver. In this case, the **LD24-08-300** has an upper output voltage limitation of 28 VDC. The highest number of LEDs with a 2V forward voltage drop it could power in a serial connection would be fourteen (with no guard band). Using a parallel connection, the output voltage required is that of one string (in this case about 10V), allowing our driver to power many more LEDs.

The major problem with the parallel connection is that small differences in circuit tolerances can cause significant differences in the current drawn by each string (or stack). This can lead to problems ranging from differences in the perceived intensity

Figure 13: Simplified Parallel Connection



or color of the LEDs to catastrophic failure of one or more stings.

The balancing resistors ($RB_1$, $RB_2$ & $RB_3$) are used to help compensate for current variations caused by differences in the typical VF of the LED strings. Small imbalances in the typical VF of the strings could cause significant variance in the string current. The typical resistance value is small (<20Ω).

Our example circuit illustrated in Figure 8 (page 4) uses a current mirror to regulate the current through the individual strings. This is a current sink mirror, in which $Q_1$ is connected as a diode and controls the current flowing through $Q_2$ and $Q_3$. If the transistors are well matched (for specifications such as $V_{BE}$ and operation over temperature), the current through each stack should be reasonably close. To help maintain accuracy over temperature, the transistors need to be thermally connected. Mounting them to the same heat sink is a common method of achieving this. The balancing resistors ($RB_1$, $RB_2$ & $RB_3$) are still used (partly to compensate for small changes in $V_{BE}$).

**Parallel Connection Advantages:**

- Ability to drive higher numbers of LEDs

**Parallel Connection Disadvantages:**

- Lower Efficiency
- Increased Circuit Complexity
- Low reliability

Low reliability (as configured in Figure 13) is caused by increased risk of failure due to potential current variations. A shorted LED will cause increased current to flow through the remaining LEDs in the same string as the faulty LED. Since the total current is fixed by the driver output, this increase in the faulty string will cause the other strings to dim as the current in those strings drops. The increased current could also cause further LED failures in the defective string as the current increases. An open LED will cause the whole string to cease operating. This will increase current in the remaining strings by a factor of $^1/_{(s-1)}$ where s is the number of LED strings connected.

**Matrix Connection**

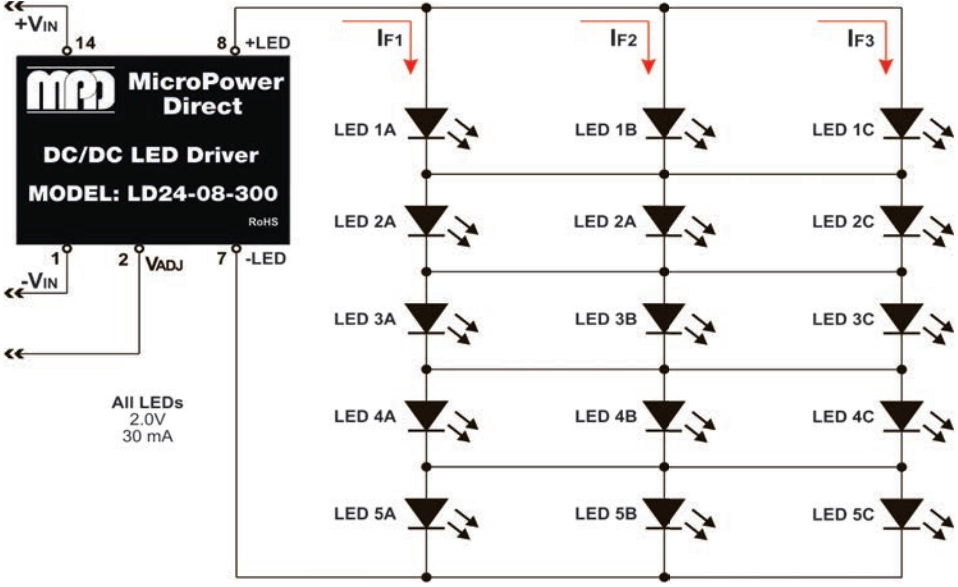
To help improve the reliability of parallel connections, the matrix connection shown in Figure 14 may be used. Also called a cross connection circuit, connections have been added between the parallel LED strings. This essentially results in a number of series connected LEDs that are "stacked" in parallel.

In this circuit, the required string voltage and driver output current remains the same as our parallel example. Like the parallel circuit, the number of LEDs that can be powered without exceeding the upper voltage limit of the driver is much higher than with a series connection.

However, the matrix connection, is somewhat more fault tolerant, and since the balancing resistors needed for parallel operation are not used here, the efficiency of this connection is improved. But even current distribution across the matrix remains a problem. Inequalities in current flow (again caused by component tolerances) may cause visible differences in the brightness or tone of the light output. Any differences in thermal characteristics caused by current variations could cause these issues to deteriorate over time.

A shorted LED will cause the parallel row containing the faulty device to fail, but the remaining rows will continue to operate normally. If an LED fails open, only the remaining LED's on that row will see an increase in current (by a factor of $^1/_{(L-1)}$, where L equals the number of LED's in that string). Again, the remaining LED's will operate normally.

Figure 14: Simplified Matrix Connection



**MultiChannel Connection**

It is typically recommended that series connections be used whenever possible. This would avoid the current and thermal distribution issues of parallel and matrix connections. The most robust connection would be to use a separate driver for each LED string (or a multichannel driver). This would combine the control and reliability advantages of a serial connection with the increased capacity of the parallel/matrix connections. The obvious disadvantage to either of these approaches is the increase in cost and complexity.

## Circuit Protection

LEDs are highly reliable devices, with average life spans that approach 50,000 hours. By far, the most common field failure is the gradual degradation of light output to 50% of rated value.

However, failures due to mechanical/temperature stress, misapplication, faulty packaging, etc do occur. The most common "catastrophic" field failure is for the LED to fail open. When this happens, as we have seen, it can quickly cause the entire circuit to fail.

A common cause of catastrophic failure is the application of excessive forward voltage or current. The use of a constant current buck regulator (as shown in our examples) will protect against most instances of this. However, components can be misadjusted or surges may be induced by external circuits or events.

Figure 8 shows protection devices (PDx) connected in parallel with each LED. Available from a number of vendors, these devices are typically a form of voltage triggered switch that activates if the LED fails open. They then provide a current bypass that prevents the failure of the rest of the LED string. Once the LED is replaced, the PD would automatically reset and again present a high impedance to the current flow. To keep cost down, it is typically possible to connect one PD across two LEDs.

## Standards

LED lamps and systems are covered by a variety of industry packaging, test and safety standards. Which approvals are important to a particular project is highly dependent upon the application. The more common UL standards applied are:

| Standard | Description |
|---|---|
| UL 60950 | Safety of IT Equipment<br>(Commonly used with AC input power supplies) |
| UL 8750 | Safety of LED Equipment<br>(Covers drivers, controllers, arrays and modules) |
| UL 1310 | Safety of Indoor & Outdoor Class II Power Supplies |
| UL 1310 | Safety of Components for use in Signs & Outline Lighting Systems |

There are similar (or even harmonized) standards or norms issued by other agencies. At this time, no single standard has emerged as an industry or market requirement for the driver portion of LED systems.

International Protection (IP) ratings are typically used as criteria for LED driver packaging. Defined in IEC 60529, they classify the level of protection provided against the intrusion of solid objects, dust, and liquids by electrical packaging. It consists of the letters IP followed by two digits. The first digit indicates the protection level against the ingress of solid objects, and the second digit against the ingress of water.

Most LED drivers are rated at IP67 or IP65. The first digit (6) rates the package as totally protected against dust. The second digit (5) rates the package as protected against low pressure water jets (limited ingress permitted), while (7) rates the package as totally immersible.

## In Summary

The use of LEDs is growing at a very fact pace. This rapid expansion in their application is driven by maturing technologies that have increased their cost effectiveness and the introduction of many new products.

With this note, we have tried to provide an overall look at the issues involved in powering LEDs. When applying LED drivers use the technical expertise of your vendor.

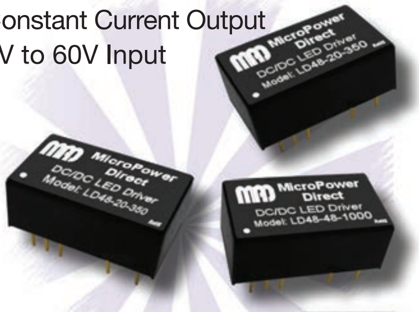
# Go Direct

# For Low Cost, High Performance LED Drivers

## LD48-xxx

### Wide Input DC/DC LED Drivers

- Up to 1A Output
- Constant Current Output
- 7V to 60V Input



- Efficiency to 97%
- PWM & Analog Dimming

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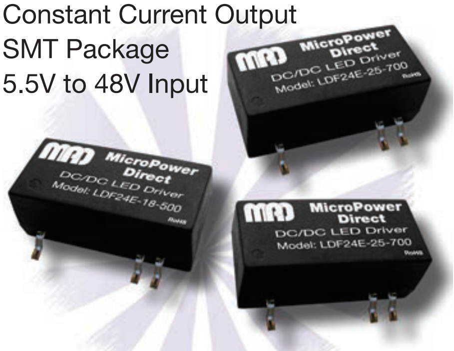
## LDF24-xx

### Miniature SMT DC/DC LED Drivers

- Constant Current Output
- SMT Package
- 5.5V to 48V Input



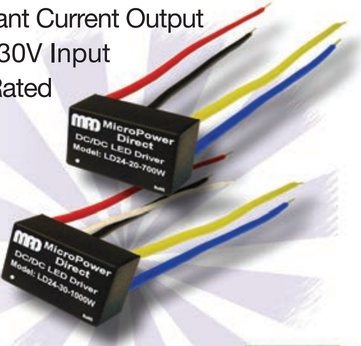
- PWM & Analog Dimming
- Up to 700 mA Output

RoHS

## LD24-xxW

### Compact, Wired DC/DC LED Drivers

- Constant Current Output
- 7V to 30V Input
- IP67 Rated



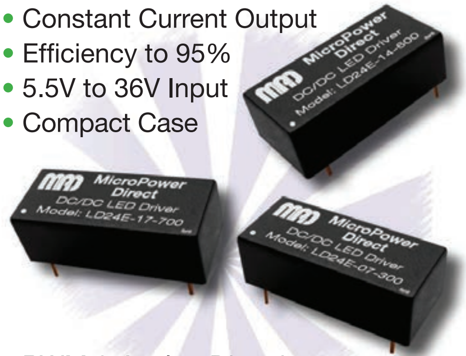
- Efficiency to 95%
- 4" Wire Connections

RoHS

## LD24E-xxx

### Very Low Cost DC/DC LED Drivers

- Constant Current Output
- Efficiency to 95%
- 5.5V to 36V Input
- Compact Case



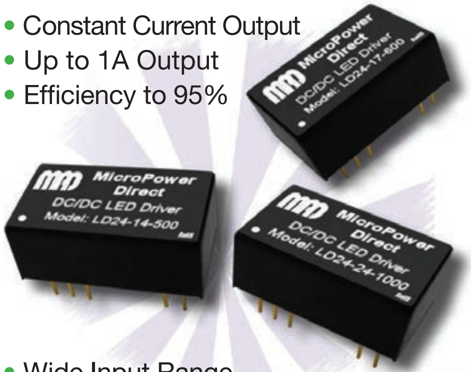
- PWM & Analog Dimming
- Up to 700 mA Output

RoHS

## LD24-xxx

### Compact, 0.3 - 1A DC/DC LED Drivers

- Constant Current Output
- Up to 1A Output
- Efficiency to 95%

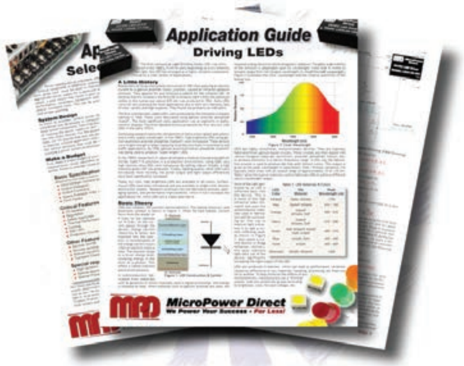


- Wide Input Range
- PWM & Analog Dimming

RoHS

## Application Notes

### Download Free From **MPD** Web Site



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