

Charge-Pump and Step-Up DC-DC Converter Solutions for Powering White LEDs in Series or Parallel Connections

White LEDs are becoming popular as portable equipment LCD backlights because they are less complex, less expensive, and smaller than CCFL backlights. Portable equipment like PDAs, Cell Phones, and Digital Cameras are requiring backlights because they are converting to color LCD displays. This article discusses charge-pump and step-up dc-dc converter solutions for powering white LEDs in series or parallel configurations using regulated voltage and current source power supplies. Trade-off of size, efficiency, battery life, LED-matching are discussed.

ALSO SEE: [Charge Pump Versus Inductor Boost Converter for White LED Backlights](#)

With the increasing popularity of color LCD displays in cell phones, PDAs, and digital cameras, white LEDs are becoming popular illumination sources. While monochrome displays can use colored light sources such as electroluminescent back lights or colored LEDs, color displays require a white light source to properly display color.

There are two main methods of providing a white light source: white LEDs and CCFLs (cold-cathode fluorescent lamps). CCFLs have been used for years in notebook computers; however, because of the size, complexity, and cost advantages, white LEDs are becoming the light source of choice for the small handheld devices.

White LEDs require a relatively low DC voltage (between 3 and 4V), while CCFLs require a very high (200-500Vrms) AC waveform and an expensive and bulky transformer-based circuit for power (Figure 1). The low voltage of the white LEDs means that simple inductor-based or capacitor-based circuits may be used to power them.

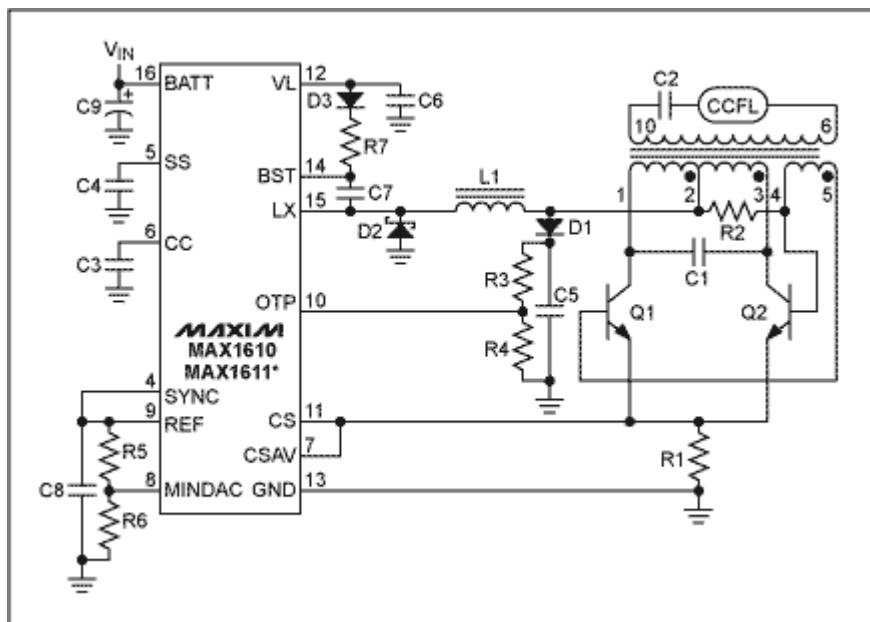


Figure 1. CCFL circuits require the use of a transformer (T1) to generate the high voltage required by the fluorescent tube.

The forward voltage drop of the white LEDs (3 to 4V) is higher than the voltage required to drive other common LEDs, such as red (typically around 1.8V) and green (typically 2.2V to 2.4V). While the other LEDs can be driven from a typical battery voltage, white LEDs are more likely to need a separate power supply.

Driving the LEDs

The intensity of white LEDs is controlled by varying the amount of current through them. Full light output occurs around 20mA, with brightness decreasing to zero as the current goes to zero. Digital cameras and cell phones typically need 2 to 3 LEDs, while PDAs usually require 3 to 6 LEDs.

There are two methods of driving multiple LEDs: parallel or series (Figure 2). Driving the LEDs in series ensures equal current through each LED but requires higher voltages than driving in parallel. Driving the LEDs in parallel requires a lower voltage (one forward drop vs. the drop of all the series LEDs), but the LED-to-LED variation in the diodes' forward voltage drop can cause a variation in brightness between the LEDs, unless each LED is independently regulated.

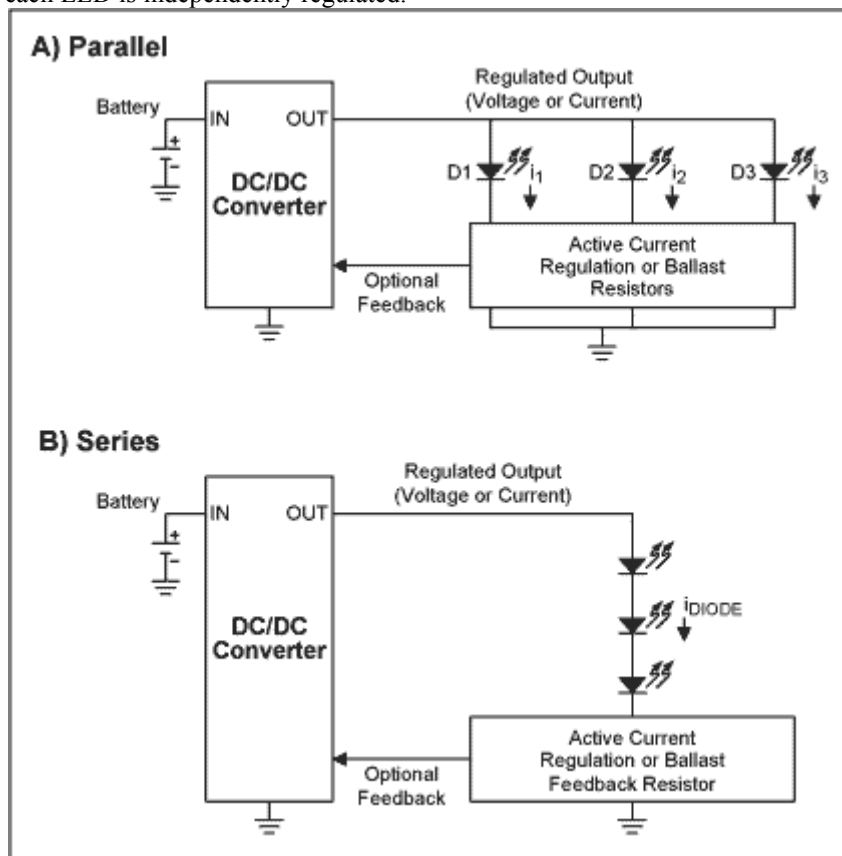


Figure 2. Driving LEDs in parallel requires a lower voltage (A), while driving LEDs in series ensures equal current through each diode.

Since the battery voltage of most handheld devices is too low to directly drive the white LEDs, either in parallel or series, a DC to DC converter is needed. These fall into two types: charge-pumps or switching regulators. A charge-pump is better when the LEDs are driven in parallel since this type of DC to DC converter is efficient for low step-up ratios (the ratio of the output voltage to the input voltage). Switching regulators are generally used to power white LEDs in a series configuration because the higher voltage required is easier to generate with a switching topology.

Driving Parallel LEDs

There are three main methods of driving parallel connections of LEDs, as shown in Figure 3:

- Use a supply and independently regulate the current through each diode.
- Use a supply with a regulated voltage and rely on diode matching and ballast resistors to regulate the current through all the diodes.
- Use a supply with a regulated current and rely on diode matching and ballast resistors to regulate the current through the unregulated diodes.

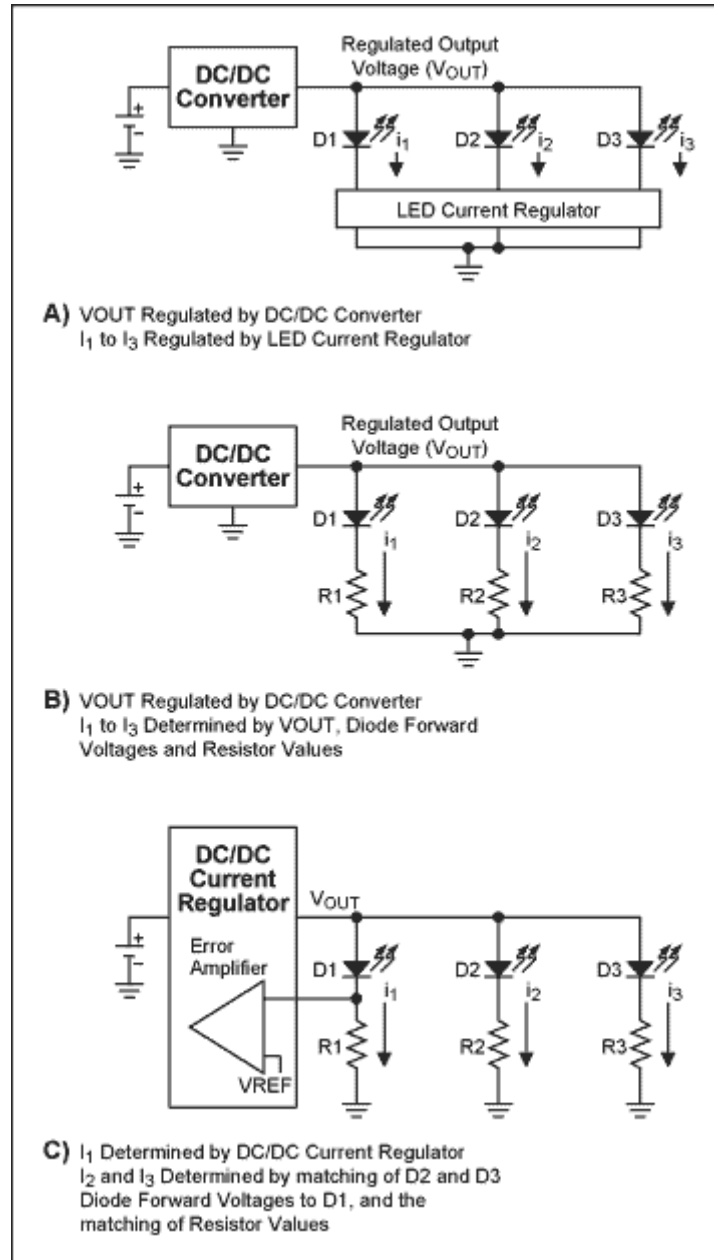


Figure 3. Three methods of driving parallel LEDs. A) Independently regulating the current through each diode. B) Using a regulated output voltage and relying on ballast resistors and diode matching. C) Using a regulated output current and relying on ballast resistors and diode matching.

Method A - Independently Regulating the Current Through Each Diode

If a supply voltage exists that is high enough to drive the forward drop of the LEDs (say, a $5V \pm 10\%$ supply), the only concern for driving the LEDs is how to control their current, not how to generate a supply to power them. This 5V supply might be around to power some audio circuitry, a compact flash slot, an RF power amplifier, for example.

A simple method of controlling the LED current is to use a device designed for such a task. Figure 4 shows an IC being used to drive 3 white LEDs. The MAX1916 provides a low-cost solution for regulating the current through the LEDs accurately. It has an LED-to-LED current match of 0.3%, an absolute current accuracy of $\pm 10\%$, and operates with an input-to-output dropout voltage of only 225mV when driving each LED at full brightness (20mA). Absolute current accuracy is less important than LED-to-LED current matching, since a current mismatch will result in one LED being brighter or dimmer than the others, causing a non-uniformity in the display illumination. Absolute current needs to be controlled, though not as well, since a wide variation in this parameter only results in variations in brightness from one device to another (e.g. from one cell phone to another).

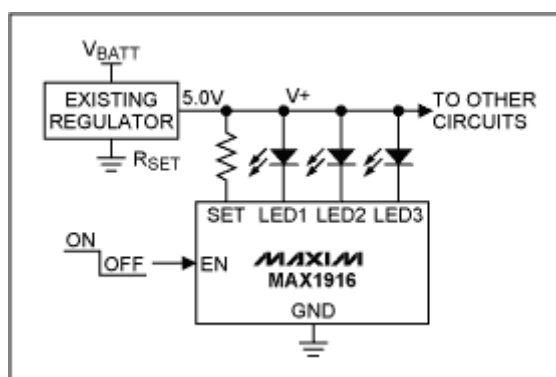


Figure 4. When an existing supply is available, a current regulator such as the MAX1916 may be used to regulate the diode current. The MAX1916 is available in a small 6-pin SOT package, and provides a 0.3% diode-current-matching.

Current through the LEDs (and thus brightness) is set using resistor R_{SET} . Through internal circuitry, the current through the LEDs is approximately 230 times the current into the SET pin. The detailed equation relating the R_{SET} resistor value to the LED current is given on page 6 of the MAX1916 datasheet.

There are several ways of dynamically adjusting the brightness of the LEDs. One method is to drive the R_{SET} resistor with a DAC (Figure 5a). Thus the current through R_{SET} (and therefore the LEDs), is varied as the DAC's output voltage is varied. Representative DACs include the MAX5360-MAX5361 and the MAX5363-MAX5364. A cheaper method is make your own DAC by using two or three resistors, as shown in Figure 5b. The current to the SET pin (and the the LEDs) is varied by tri-stating the I/O pins or setting them high. Maximum brightness occurs when all I/O pins are set high. Minimum brightness occurs when the I/O pins are tri-stated.

A final method for controlling the LED brightness is driving the Enable pin (EN) of the MAX1916 with a digital PWM signal, as shown in Figure 5c. When the Enable pin is high, the part is fully on, when low, the part is off. Many processors have PWM ports, and if one is available, it may be used to drive the Enable pin. Maximum brightness occurs for 100% duty cycle, and minimum brightness (off), occurs for 0% duty cycle. (Duty cycle is the ratio of time that the PWM is high to the period of the PWM signal.) The response time of the MAX1916 Enable pin is fairly fast (see datasheet), so it can be driven at rates (PWM frequencies) much higher than the eye's ability to perceive flicker.

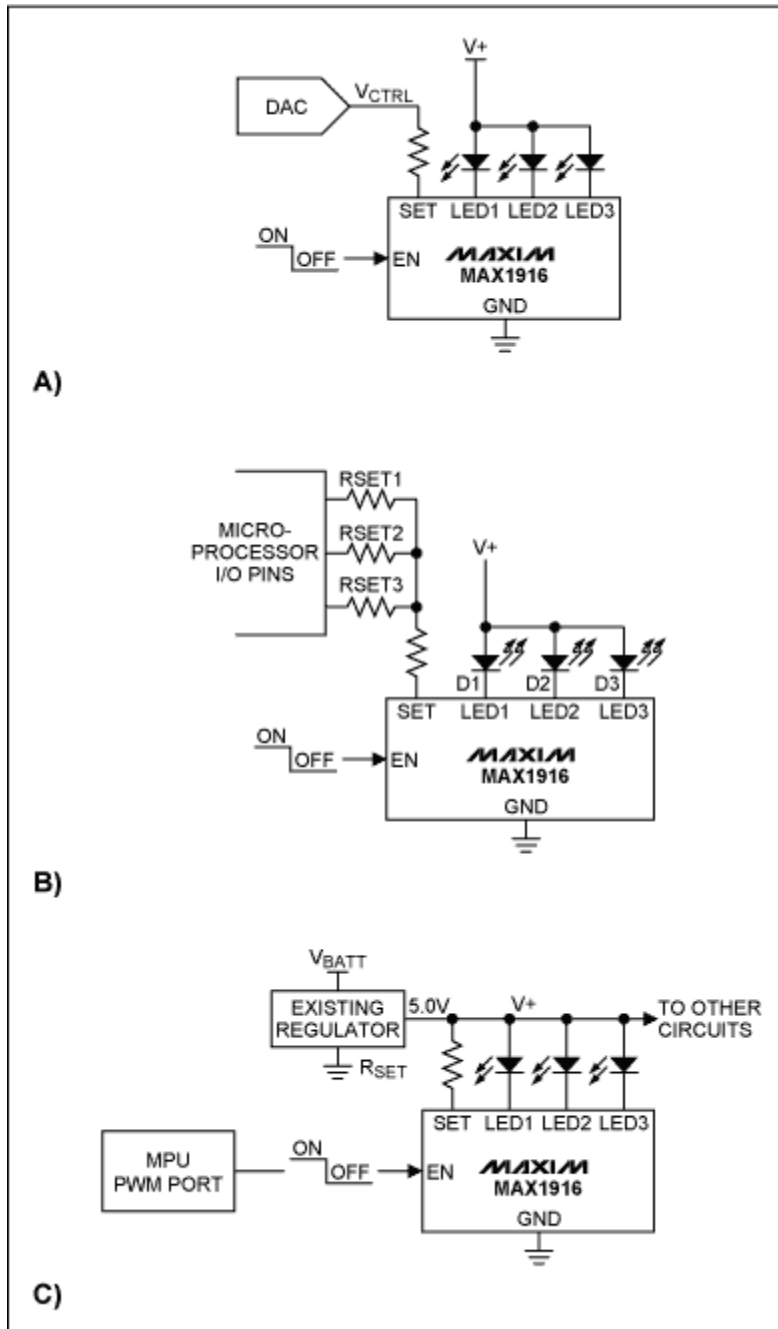


Figure 5. There are several methods for adjusting the brightness of the white LEDs when using the MAX1916 current regulator.

Generating a Supply for the White LEDs

If an existing supply is not available to power the LEDs, a separate LED supply must be generated. There are two main methods available for making this supply: charge-pump voltage converters and switching regulators. Charge-pump converters provide the smallest and cheapest solution, since they rely on capacitors for voltage conversion. However, charge-pump converters are only efficient when generating discrete multiples of their input voltages (say 1.5x, 2x, etc.), since they use capacitors to generate their output voltages. Switching regulators, however, provide high efficiency over a wide range of input-to-output voltages, since they use inductors for voltage conversion. Thus, the tradeoff between switching regulators and charge-pump converters is one of efficiency and size vs. cost.

Method B - Using a Supply with a Regulated Output Voltage

Like method A, method B is often used when an existing supply is available (such as a 5V supply), or it can be used when a standalone voltage regulator is used to generate the white LED power. Method B is less accurate than the previous one, since the voltage to the LEDs is regulated and not the individual diode currents, but steps can be taken to increase the accuracy, as will be discussed. There are two errors that one must be concerned with when using method B: absolute current through each diode; and diode-to-diode matching. Absolute current is important, since it affects the overall brightness of the display. Diode-to-diode matching is important, since it affects brightness uniformity across the display.

Referring to Figure 3b, the current through any diode can be determined by using Ohm's law, and by noting that the voltage across any resistor (R_X) is given by $V_{OUT} - V_{DX}$, where X signifies either the diode number (1, 2, or 3) and the corresponding resistor number (also either 1, 2, or 3); and V_D is the diode's forward voltage drop.

By inspection, we see that the current through the diodes (I_X) is given by:

$$(1) I_X = (V_{OUT} - V_{DX})/R_X$$

Note that the forward voltage drop of a diode is a function of current, and for a given current, the forward drops of the diodes do not always match due to normal manufacturing tolerances. Figure 6a shows the I-V curves for two white LEDs taken from a commercially-available handheld device. You can see that at the same current, the voltages across the diodes are not equal. Shown in Figure 6b, is the voltage difference between the diodes with different diode currents.

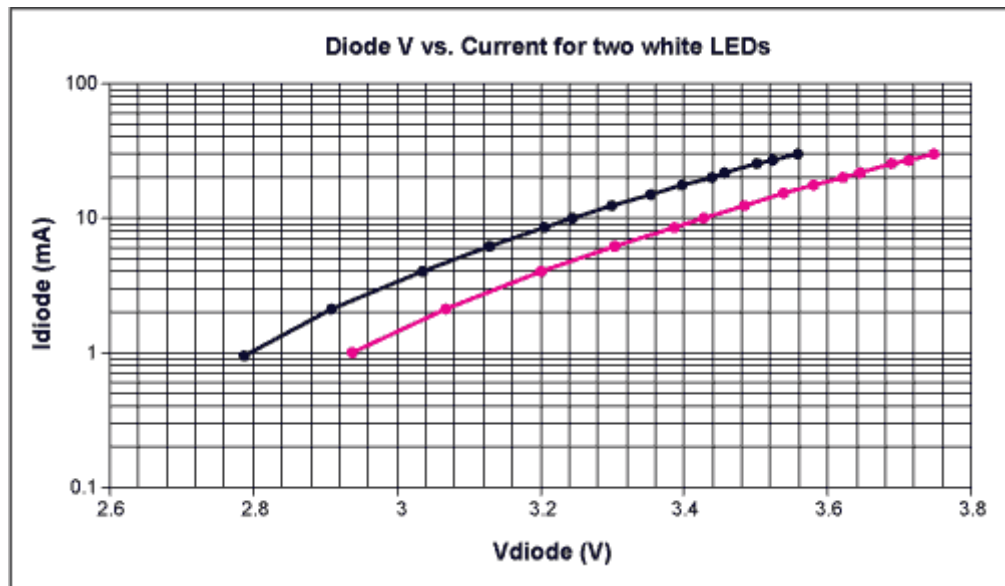


Figure 6a. The I-V curves for two white LEDs taken from a commercially-available handheld device

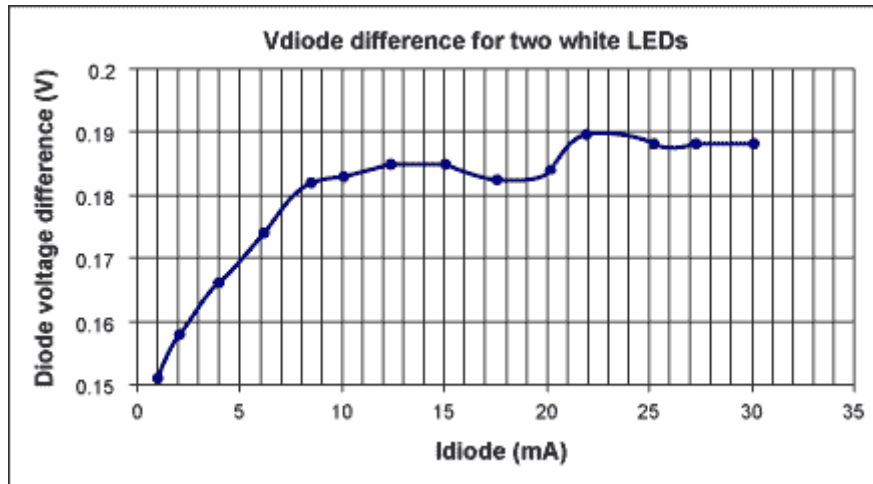


Figure 6b. The voltage difference between two white LEDs vs. Diode Current.

Mismatches in Diode Current

To get a feel for how the mismatch in forward voltages affects the current matching when using the circuit in Figure 3b, one can take the ratio of the diode currents using Equation 1. For example, the ratio of I_1 to I_2 is given by:

$$(2) I_1/I_2 = R_2/R_1 \cdot ((V_{OUT} - V_{D1})/(V_{OUT} - V_{D2}))$$

If we simplify Equation 2, by assuming that $R_1 = R_2$ (a valid assumption for high-precision resistors), Equation 2 reduces to:

$$(3) I_1/I_2 = (V_{OUT} - V_{D1})/(V_{OUT} - V_{D2})$$

Thus for higher values of V_{OUT} , Equation 1 approaches a value of 1, which corresponds to exact matching of diode currents. So, for better diode-to-diode matching, a higher output voltage should be used.

(Referring to Equation 1, it can be seen that if V_{OUT} is increased, R_X must be increased if I_X is to remain constant. This makes intuitive sense, since the V_{OUT} voltage is dropped across both the diode and the resistor. We want the diode current to remain constant; which means its voltage remains constant. The only way to increase the drop across the resistor, with the constant current, is to increase its value.)

While higher output voltages lead to closer matching of diode currents, they also lead to higher power dissipation (Power = $V \cdot I$). Thus one must trade off power consumption with current matching. A good starting point for achieving adequate matching is to use a 5V supply. While, for example, one could achieve better efficiency with a 4.1V supply, the diode's forward voltage mismatches would most likely cause intolerable variations in diode brightness.

Note that with a 5V supply, if 3.7V is dropped across the diodes, there is 1.3V being dropped (wasted) across the resistor. This lower efficiency is the price of simplicity. However, with the added complexity of the circuit of Figure 3a, higher efficiencies can be achieved. This circuit does not require a high voltage for tight regulation, since it relies on active circuitry to regulate diode current, instead of resistors. So, while the circuit in Figure 3b requires 5V to properly regulate, the circuit in Figure 3a only requires a voltage of V_d + the dropout voltage of the current regulator (where dropout voltage is the device's input to output voltage at a given current) For example, the MAX1916 has a 225mV dropout voltage at 20mA, so with a 3.7V diode voltage, it only requires 3.925V, vs. 5V. This results in an energy savings of 21.5% $(5V - 3.925V) / 5V$.

Absolute Accuracy

For the circuit in Figure 3b, possible errors in the value of the absolute diode current can be calculated using Equation 1, along with graphs of V_D vs I_D (Figure 6a and 6b) for the white LEDs being used. How to do this? Start by substituting in Equation 1 the desired operating current for I_X (say 20mA), the nominal voltage for V_D at that current (from the graphs), the value for V_{OUT} (say 5V), and solve for R_X . This is the resistor value that should be used. Using that value for the resistor, solve Equation 1 using worst case I_D vs V_D data from the LED manufacturer. This will tell you the worst-case error that you can expect for the diode current. As discussed above, the error can be minimized by having a higher V_{OUT} voltage.

Adjustment Methods

In Figure 3b, the diode current may be adjusted by changing the output voltage, V_{OUT} , if nothing else is being powered from this supply. Note though, that by lowering V_{OUT} , the mismatches in the diode currents will increase. If it's not desirable to change the output voltage (either because some other circuitry is using that supply, or because a lower V_{OUT} would cause too many errors due to diode mismatches), the current may be adjusted by placing resistors in parallel with R_X , which may be switched in and out of the circuit using logic-level MOSFETs (Figure 7). Switching these resistors in and out effectively changes the value of the resistors, R_X , thus changing the current through the diodes (see Equation 1).

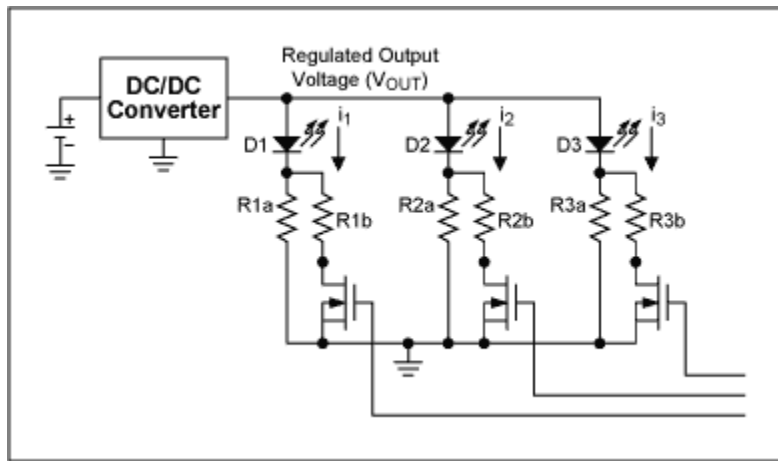


Figure 7. Adjustment method for the circuit of Figure 3b. Logic-level MOSFETs N1 - N3 switch in and out resistors R1b - R3b, effectively changing the value of the ballast resistors. This resistance change, changes the current through the diodes, thus adjusting the LED brightness.

Charge-pump Converter

The MAX1595 (Figure 8a) provides a simple method of generating the necessary 5V supply to power parallel LEDs. From a 3V supply, the regulated charge-pump provides a guaranteed 125mA at 5V. The MAX1595 operates at a 1MHz switching frequency, allowing the use of small ceramic capacitors. The IC requires only three external capacitors, and is available in a space-saving 8-pin μ MAX package and a 12-pin QFN package. Figure 8b shows the efficiency vs. load current for the device. For an adjustable output voltage, please refer to the MAX1759 datasheet.

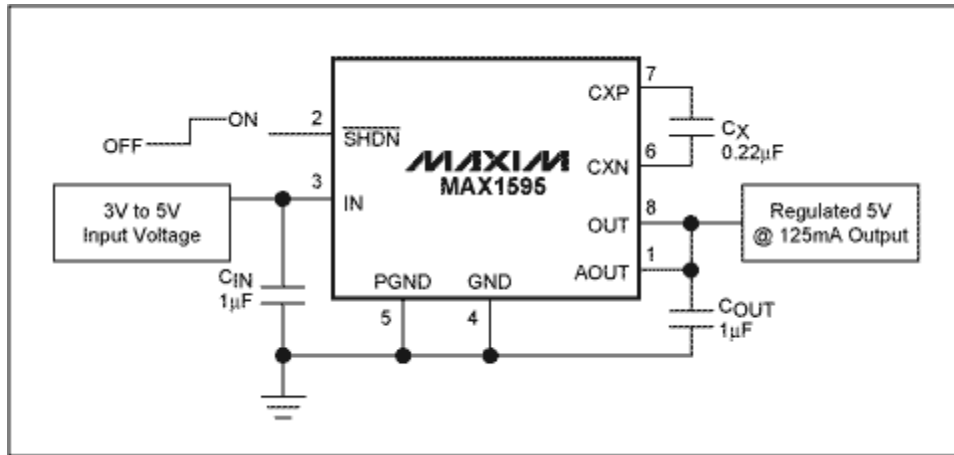


Figure 8a. The MAX1595 regulated charge-pump provides a simple method of generating the necessary 5V supply to power parallel LEDs.

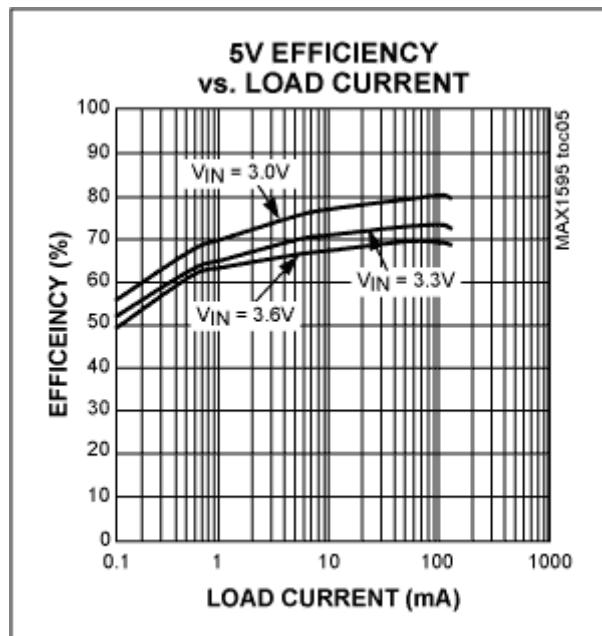


Figure 8b. Efficiency vs. load current for the MAX1595 regulated charge-pump

Method C - Using a Converter With a Regulated Output Current

Figure 3c shows the concept of a converter regulating current instead of voltage. In this scenario, the current through one of the diodes (D1 in the figure) is converted to a voltage across a sense resistor (R1), and it is that voltage which is regulated by the converter. The converter can either be a switching regulator, a charge-pump converter, or a linear regulator.

The Equation for the LED current is the same as in Equation 1, and is repeated for convenience:

$$(4) I_X = (V_{OUT} - V_{DX})/R_X$$

However, unlike the case above, V_{OUT} is not regulated, but I_1 is regulated, and its value is given by:

$$(5) I_1 = V_{FEEDBACK}/R_1$$

Because only one current is regulated, differences in forward voltages of the LEDs cause differences in LED currents just like the previous example. These errors can be reduced, like the above example, by increasing V_{OUT} . Unfortunately, due to the feedback in this circuit you cannot simply increase the value of R_X to get this effect. In fact, one can see from Equation 5 that increasing this value will result in an undesirable decrease in the diode current.

However, by breaking up $R1$ into $R1A$ and $R1B$ (as in Figure 9), the output voltage can be increased (for better current matching) while keeping the $D1$ current constant. When this method is employed, one must substitute $R1 = R1A + R1B$ into equation 4; and substitute $R1 = R1B$ into Equation 5. No substitutions are needed in Equation 4 for $R2$ and $R3$, since the converter directly regulates the current through $D1$, while the current through the remaining diodes is controlled by diode matching and the ballast resistors $D2$ and $D3$. To keep the diode currents equal, however, resistors $R2$ and $R3$ each should be equal to the sum $R1A + R1B$.

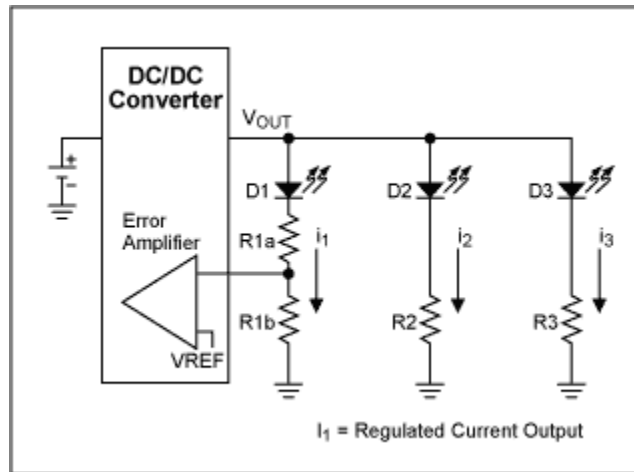


Figure 9. Diode matching for the circuit of Figure 3c may be increased by increasing the ballast resistor $R1 = (R1A + R1B)$. Increasing $R1$ increases the output voltage (which increases matching). Using setting $R1B$ in this Figure equal to $R1$ (in Figure 3c) keeps the voltage seen at the error amplifier constant, which keeps the diode current constant.

Driving LEDs in Series

Driving white LEDs in series has the inherent key advantage of uniform brightness since the same current flows through all of the diodes. The disadvantage is that it requires a higher voltage since the forward drops add together. Even just three white diodes in series will require a voltage between 9 and 12 volts. Switching regulators are commonly used for this configuration because they are efficient at generating these voltages. When choosing a converter to drive the LEDs, one must be concerned with the output voltage rating of the switching regulator.

For example, the MAX1848 is a switching regulator specifically designed to drive up to three white LEDs in series (Figure 10a). The device has a 2.6V to 5.5V input voltage range, and a maximum output voltage of 13V. The 13V output allows the device to drive up to three LEDs. The input voltage range allows the IC to be powered from a single LiIon battery or 3 NiCd/NiMH batteries. The MAX1848 comes in a space-saving 8-pin SOT-23 package. It features a fast 1.2MHz PWM operation, which utilizes small external components, also saving space. Over voltage detection protects the IC in the event that an LED becomes open circuit. Another alternative is the MAX1912, shown in figure 10b.

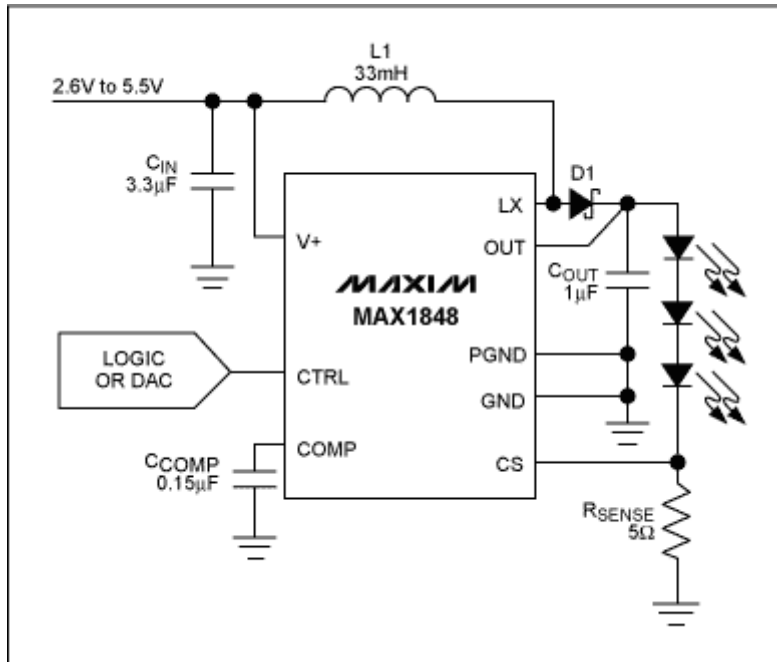


Figure 10a. The MAX1848 switching regulator is specifically designed to drive up to 3 white LEDs in series. The device has a 2.6V to 5.5V input voltage range, which allows the IC to be powered from a single Lilon battery or 3 NiCd/NiMH batteries. The MAX1848 comes in a space-saving 8-pin SOT-23 package.

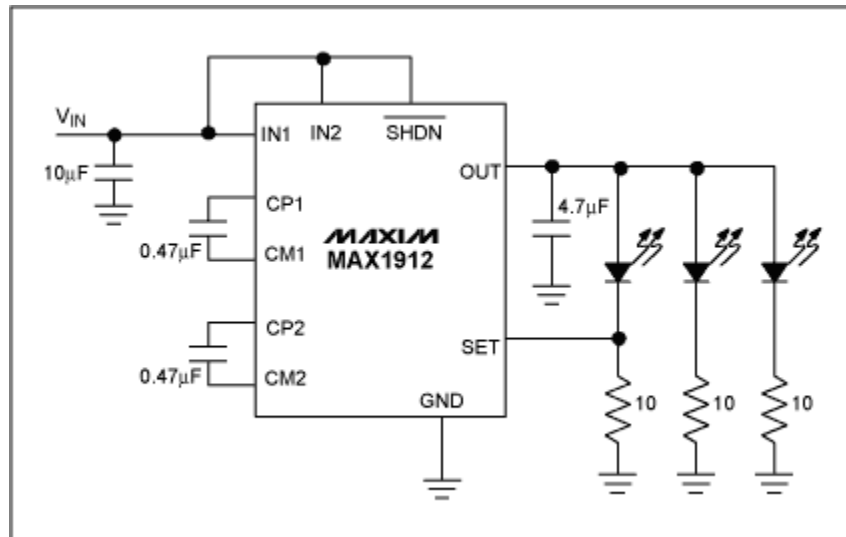


Figure 10b. The MAX1912 charge-pump converter is capable of driving three white LEDs in parallel, and provides LED regulation by regulating the current through one of them. The IC requires only four small ceramic capacitors to generate a regulated supply up to 60mA from an unregulated input supply voltage of 2.7V to 5.3V

The LED current, and thus brightness, may be adjusted by driving the CTRL pin with a DAC voltage or a filtered PWM signal. The equation relating LED current to the voltage at the CTRL pin is given in the MAX1848 datasheet.

The efficiency of the MAX1848 when driving LEDs is shown in Figure 11. Maximum efficiency is around 87%.

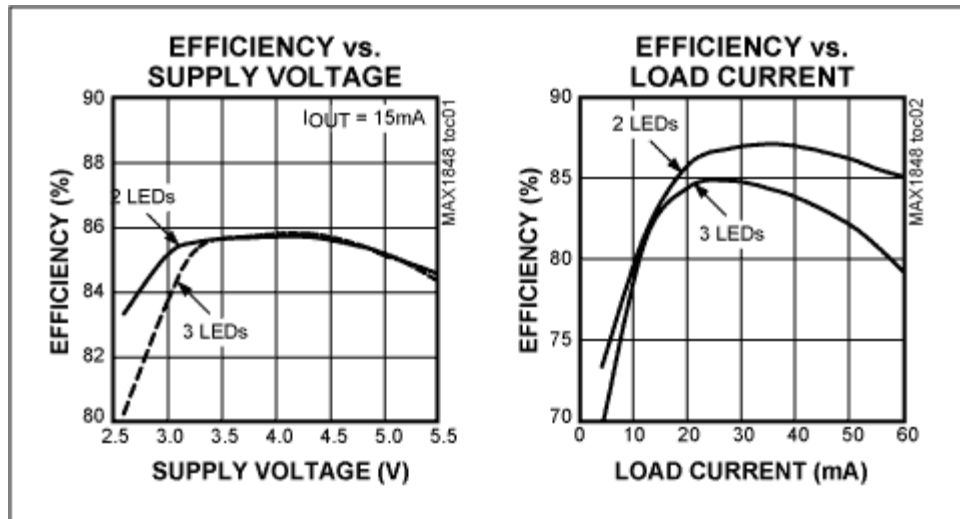


Figure 11. Efficiency for the circuit of Figure 10.

Driving More LEDs

For larger displays, requiring more LEDs, a switching regulator with a higher output voltage must be used. The MAX1698 (Figure 12), is such a regulator. It works with input voltages as low as 0.8V, and its output voltage is only limited by the voltage rating of the external N-Channel MOSFET. The low 300mV feedback voltage (at the FB pin) helps maximize efficiency. The MAX1698 achieves greater than 90% efficiency.

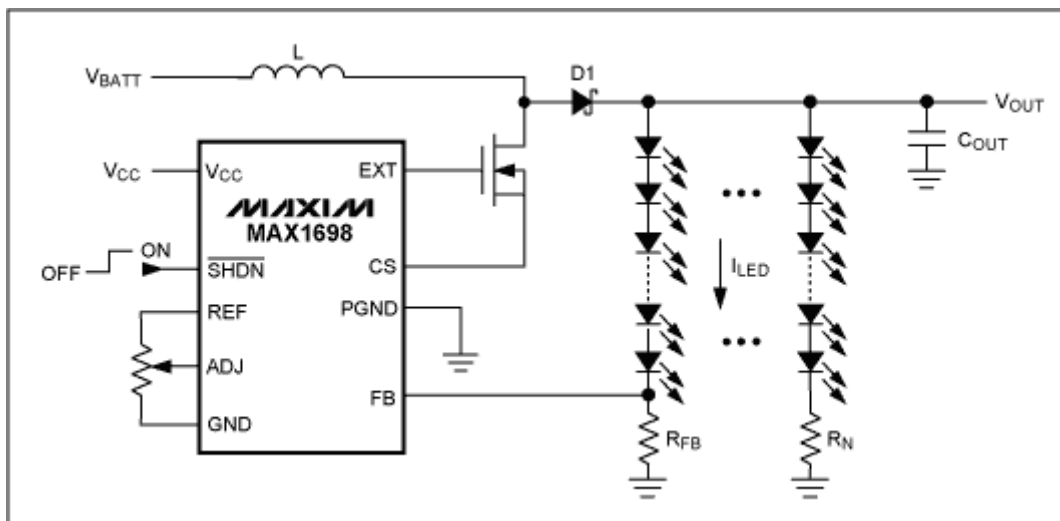


Figure 12. The MAX1698 can drive many LEDs in series, due to the high voltage afforded by its use of an external MOSFET. This high voltage makes the IC useful for illuminating large displays.

The LED brightness can be adjusted by connecting the wiper of a potentiometer to ADJ and the high and low ends of the potentiometer to REF and GND, respectively. For digital adjustment, use a digital potentiometer such as the MAX5360-MAX5364 or MAX5380-MAX5384. For analog adjustment, an analog potentiometer may be used.

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MORE INFORMATION

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MAX1595:	QuickView	-- Full (PDF) Data Sheet (360k)	-- Free Sample
MAX1610:	QuickView	-- Full (PDF) Data Sheet (152k)	-- Free Sample
MAX1848:	QuickView	-- Full (PDF) Data Sheet (336k)	-- Free Sample
MAX1910:	QuickView	-- Full (PDF) Data Sheet (328k)	-- Free Sample
MAX1912:	QuickView	-- Full (PDF) Data Sheet (328k)	-- Free Sample
MAX1916:	QuickView	-- Full (PDF) Data Sheet (224k)	-- Free Sample
MAX5360:	QuickView	-- Full (PDF) Data Sheet (336k)	-- Free Sample
MAX5361:	QuickView	-- Full (PDF) Data Sheet (336k)	-- Free Sample
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