design ideas

Edited by Bill Travis

Light a white LED from half a cell

Anthony Smith, Scitech, Biddenham, Bedfordshire, UK

Whether you use them as indicators or to provide illumination, LEDs are hard to beat in efficiency, reliability, and cost. White LEDs are rapidly gaining popularity as sources of illumination, as in LCD backlights, but with forward voltages typically ranging from 3 to 5V, operating them from a single cell presents obvious difficulties. This design exploits the ultralow operating voltage of a single-gate Schmitt inverter, such as the Texas Instruments (www.ti.com) SN74AUC1G14 or the Fairchild (www.fairchildsemi.com) NC7SP14 (**Figure 1**). When you first apply battery power, Schottky diode D_1 conducts, and the familiar Schmitt-trigger astable multivibrator starts to oscillate at a frequency determined by timing components C_2 and R_1. When IC_1's output goes high, transistor Q_1 turns on, and current begins to ramp up in inductor L_1. The maximum, or peak, level of inductor current is $I_{L(PEAK)}=(V_{BATT}-V_{CE(SAT)})\times t_{ON}/L_1$, where V_{BATT} is the applied battery voltage, $V_{CE(SAT)}$ is Q_1's saturation voltage, and t_{ON} is the duration of the high-level pulse at the Schmitt trigger's output. If Q_1's saturation voltage is, for example, less than 50 mV, you can ignore $V_{CE(SAT)}$ and simplify the expression to $I_{L(PEAK)}=V_{BATT}\times t_{ON}/L_1$.

At the end of t_{ON}, when the inverter output goes low, Q_1 turns off, and the voltage across L_1 reverses polarity. The resulting "flyback" voltage immediately raises Q_1's collector voltage above V_{BATT} and forward-biases the LED and D_2, which appear in series. This action illuminates the LED with a maximum forward current equal to $I_{L(PEAK)}$ and raises IC_1's supply voltage, V_{BOOT}, to a diode drop above V_{BATT}. D_1 is now reverse-biased and remains so for as long as the circuit continues to oscillate. The resulting "bootstrapped" supply voltage for IC_1 ensures that the astable multivibrator continues to operate even when V_{BATT} falls to very low levels. You should choose values for C_2 and R_1 to produce a time constant of microseconds, thereby allowing a small inductance value for L_1. For example, a test circuit using values of C_2=68 pF, R_1=39 kΩ, and L_1=47 µH produces an operating frequency of approximately 150 kHz at V_{BATT}=1V. The resulting value of t_{ON}=3 µsec leads to a peak inductor current of approximately 65 mA and produces excellent brightness in the white LED. Even with V_{BATT} as low as 500 mV, the corresponding peak current of 33 mA produces reasonable LED intensity.

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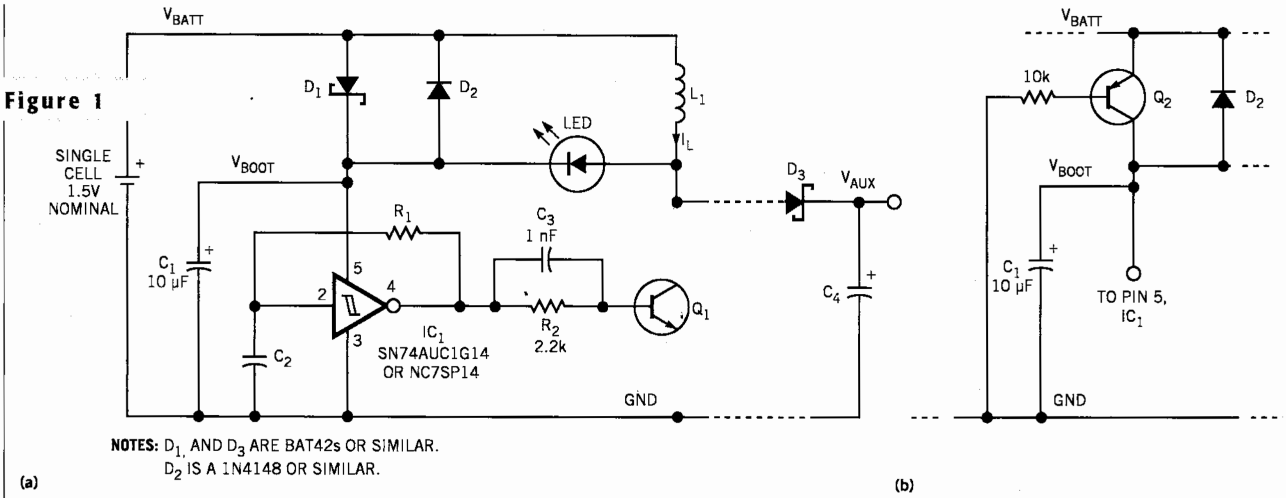
The inductance value should be as low as possible to maintain a high peak current and, hence, adequate LED brightness at the lowest supply voltage. However, L_1 should not be too small, or the peak current could exceed the LED's maximum current rating when V_{BATT} is at a maximum. Remember that the inductor should be adequately rated to en-

Figure 1



NOTES: D_1 AND D_3 ARE BAT42s OR SIMILAR.
D_2 IS A 1N4148 OR SIMILAR.

This circuit produces dazzling intensity in a white LED from very low battery voltages (a). A modification allows even lower battery voltages (b).

sure it does not saturate at the highest value of peak current. Switching transistor Q_1 should have very low saturation voltage to minimize losses and produce the highest possible peak current. The addition of D_3 and C_4 enables the circuit to generate an auxiliary supply voltage, V_{AUX}, which you can use to drive low-power circuitry without adversely affecting the LED's intensity. With a battery voltage of 1V, the test circuit produces good light intensity in the white LED and delivers almost 1.5 mA at 4.7V to the auxiliary load. Even at V_{BATT}=500 mV, the circuit delivers 340 μA into a 10-kΩ load and maintains reasonable LED brightness. Note that IC_1 cannot take power from the auxiliary rail, because V_{AUX} can easily exceed the maximum voltage rating of the two suggested device types.

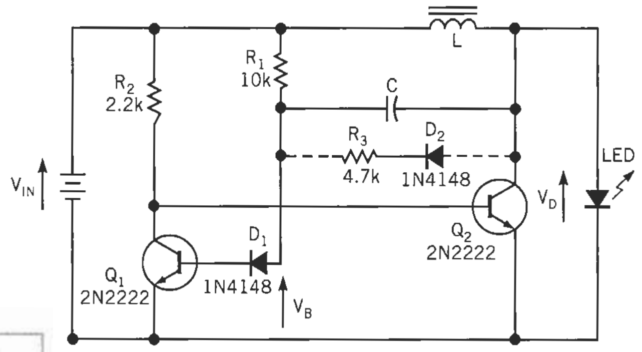
The minimum start-up voltage depends largely on the device you use for D_1. Tests using a high-quality Schottky diode produce a minimum power-up voltage of just 800 mV. You can further reduce this level by replacing D_1 with pnp transistor Q_2 (**Figure 1b**). This modification allows the test circuit to start up at just 650 mV at room temperature. Note, however, that Q_2's collector-base junction becomes forward-biased under quiescent conditions, which results in wasted power in its base-bias resistor. Despite its simplicity, the circuit can produce spectacular results with high-brightness LEDs. The Luxeon range of LEDs from Lumileds (www.lumileds.com) allows the circuit to demonstrate its prowess. With L_1 reduced to 10 μH and V_{BATT}=1V, the circuit generates a peak current of 220 mA in a Luxeon LXHL-PW01 white LED, resulting in dazzling light intensity.□

LED driver delivers constant luminosity

Israel Schleicher, Bakersfield, CA

THE CIRCUIT IN **Figure 1** is similar in principle to that of a previous Design Idea (**Reference 1**) but offers improved, more reproducible performance. The output current is almost constant over an input-voltage range of 1.2 to 1.5V and is insensitive to variations of transistor gain. Transistors Q_1 and Q_2 form an astable flip-flop. R_1 and C define the on-time of Q_2. During that time, Q_1 is off, and the voltage at the base of Q_1 and the current in inductor L ramp up. When the voltage at the base of Q_1 reaches approximately 0.6V, Q_1 turns on, and Q_2 turns off. This switching causes "flyback" action in inductor L. The voltage across the inductor reverses, and the energy stored in the inductor transfers to the LED in the form of a down-ramping pulse of current. During flyback time, voltage across the LED is approximately constant.

Figure 1



NOTE:
WHITE LED REQUIRES R_3 AND D_2.

This circuit delivers virtually constant luminosity for a white or a yellow LED.

The voltage for yellow and white LEDs is approximately 1.9 and 3.5V, respectively. When the current through the LED falls to zero, the voltage at the collector of Q_2 falls sharply, and this circuit condition triggers the next cycle. Assuming the justifiable approximation that the saturation voltage of Q_2 is close to 0V and that the LED's forward voltage, V_D, is constant, you can easily derive the expression for the average dc current through the LED:

$$I_{AVE}=\frac{V_{IN}^2R_1C}{2V_DL}\log_e\left(\frac{V_{IN}+V_D-V_B}{V_{IN}-V_B}\right).$$

At first glance, I_{AVE} depends strongly on V_{IN}. But close examination of the logarithmic term reveals that, with a proper selection of V_B, the logarithmic term can become a sharply declining function of V_{IN}. The logarithmic term thus fully compensates for the term V_{IN}^2 in the expression. That compensation is precisely the purpose of the diode, D_1, in series with the base of Q_1. The circuit drives a high-brightness yellow or white LED. **Table 1** shows the proper component selection for both colors. **Table 1** also shows some measured results at V_{IN}=1.35V. Because the voltage across the white LED falls from 3.9 to 3.1V during flyback, capacitor C subtracts current from the amount available to the base of Q_1. This subtraction might retrigger the circuit before the current in L falls to zero. The addition of R_3 and D_2 solves this problem. During flyback, the current that flows through R_3 compensates for the current withdrawn through C.□

TABLE 1—COMPONENT SELECTION FOR YELLOW OR WHITE LED

LED	L (mH)	C (pF)	D_1	Current drain (mA)	LED current (mA)	Frequency (kHz)	Power-conversion efficiency (%)
Yellow	1	470	1N4003	5.6	3.3±0.1	40	83
White	2	1800	1N752	12.4	3.7±0.2	15	78

REFERENCE

1. Nell, Susanne, "Voltage-to-current converter drives white LEDs," *EDN*, June 27, 2002, pg 84.

White-LED driver touts high efficiency

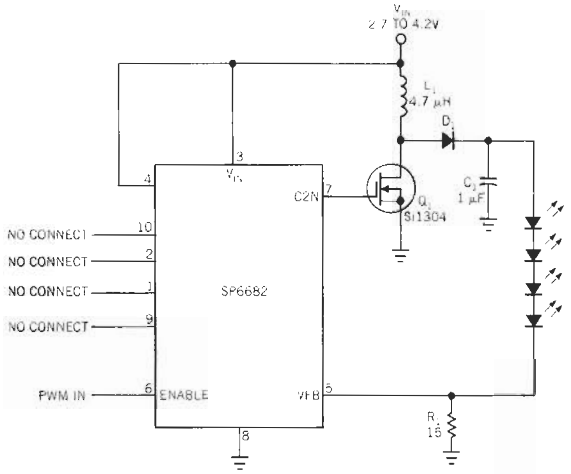
Dimitry Goder, Sipex Corp, San Jose, CA

WHITE LEDs, the most recent addition to the LCD backlight, find common use in providing backlight for color LCDs. Thanks to their size and white-light output, they appear in small, portable devices with color displays, such as PDAs and cellular phones. Like other LEDs, a white LED needs a constant-current source—typically, on the order of 15 to 20 mA. The forward voltage of a white LED is approximately 3.5V. Most products use multiple LEDs to provide adequate backlight for a display. Because the LED's brightness depends on its forward current, these multiple diodes commonly connect in series to ensure that the same current flows through each of them. You need approximately 14V to forward-bias four series-connected LEDs, starting from the nominal operating voltage, 2.7 to 4.2V, of a single-cell lithium-ion battery. Boost regulators usually provide this operating voltage. A current-sense resistor, which you insert in series with the LEDs, closes the feedback loop. However, it is important to minimize the voltage drop across this resistor to increase efficiency. Currently available integrated boost regulators commonly use a 1.24V bandgap voltage as the feedback reference, which results in 1.24V loss across the current-sense resistor, a loss that represents approximately 7% loss in efficiency. **Figure 1** shows an interesting LED-drive circuit.

You use the SP6682, a standard, regulated charge-pump circuit, in an unusual manner to control the external switch, Q_1. This IC incorporates an internal 500-kHz oscillator, which would normally drive charge-pump capacitors to double the input voltage. The circuit in **Figure 1** uses no charge-pump capacitors. Instead, the oscillator output appears on Pin 7 and drives Q_1 on and off. Q_1, L_1, D_1, and C_1 function as a conventional boost regulator, which builds up voltage across C_1. When this voltage exceeds the sum of the diodes' forward drop, current starts to flow. The circuit senses current across R_1 and compares it with a 0.3V reference voltage inside the chip. This circuit provides efficiencies as high as 87%, a figure that exceeds that of any integrated boost regulator. Several factors are responsible for the increased efficiency. First, the chip integrates the 0.3V reference voltage, which is significantly lower than the typical 1.24V. This reference voltage appears in series with the LEDs and therefore constitutes an efficiency loss proportional to the value of the reference. Second, a discrete MOSFET provides low on-resistance and high switching speed, parameters superior to those of any integrated switch.

Q_1 is a low-cost device that comes in a tiny SOT-23 package. Also, the excellent drive capability of the charge-pump IC ensures low switching losses. By changing the type of the MOSFET you use, you can make a trade-off between desired efficiency and cost. The breakdown voltage of the MOSFET limits the maximum output voltage; you can adjust the voltage to drive a system with as many LEDs as you need. (Larger displays use eight to 12 LEDs.) For dimming purposes, applying a PWM signal to the Enable pin causes the regulator to shut down and restart. This function allows you to precisely control LED brightness.☐

Figure 1



This circuit uses a charge-pump IC to provide power to a series string of LEDs.

LINEAR TECHNOLOGY

DESIGN NOTES

Versatile High Power LED Driver Controller Simplifies Design

Design Note 406

Ryan Huff

Introduction

The increased popularity of high power LEDs over the last several years has challenged electronic engineers to come up with accurate and efficient, yet simple drive solutions. The task is more difficult as the market for LEDs enters the realm of high-powered lights, such as those for automobile headlights or large LCD backlights. High light-output solutions usually involve large arrays of individual LEDs stacked in series. Conventionally, driving high power strings with accurate current is at odds with simplicity and efficiency—typically involving an inefficient linear regulator scheme or a more complicated, multiple IC switching regulator configuration. There is a simpler and better way via a low parts count, single IC solution for driving high power LED strings. At the heart of this highly efficient, simple and accurate solution is the LTC3783 controller IC.

Fully Integrated, High Power LED Driver Controller

The LTC3783 has all of the functions that are normally required to run an LED string: an accurate current regulation error amplifier, a switch mode power supply (SMPS) controller with FET drivers, and two different ways to control the brightness of the LED string.

The current regulating error amplifier uses the voltage drop across a sense resistor in series with the LED string to precisely regulate the LED current. The SMPS control portion of the LTC3783 takes advantage of current mode operation to easily compensate the loop response of the many possible topologies such as boost, buck, buck-boost, flyback and SEPIC. The integrated FET drivers allow fast switching of the power MOSFETs that are needed to efficiently convert input power to LED power without having to add external gate drive ICs.

LED Dimming

Two different ways of controlling LED brightness are included. Analog dimming varies the LED current from a maximum value down to about 10% of this maximum (a 10:1 dimming range). Since an LED color spectrum is related to current, this approach is not appropriate for some applications. However, PWM or digital dimming, switches between zero current and the maximum LED current at a rate fast enough that visual flicker is not apparent, typically greater than 100Hz. The duty cycle changes the effective average current. This method allows up to a 3000:1 dimming range, limited only by the minimum duty cycle. Because the LED current is either maximum or off, this method also has the advantage of avoiding LED color shifts that come with the current changes associated with analog dimming.

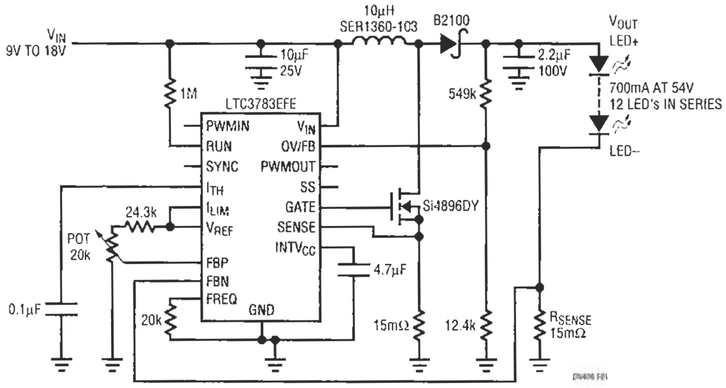


Figure 1. LTC3783 in a Boost Configuration to Drive 12 LEDs in Series

01/07/406

Boost Circuit

Figure 1 shows a boost configuration using all off-the-shelf components. The input voltage, which ranges from 9V to 18V, is boosted to an LED string voltage of 30V to 54V. The LED string can consist of twelve, 700mA LEDs of any color in series for a total of up to 38W of LED power. At an input voltage of 18V and an LED string voltage of 54V, this circuit achieves an astounding power efficiency of over 95%! This high efficiency results in no greater than a 25°C temperature rise for any circuit component.

Buck-Boost Circuit

Figure 2 shows a buck-boost solution that can be used when the input voltage range overlaps the LED string voltage. Here the input voltage ranges from 9V to 36V and the LED string ranges from 18V to 37V. This 8-LED series string runs up to 1.5A. At the nominal input voltage of 14.4V and an LED string voltage of 36V at 1.5A (54W output power), the efficiency is almost 93%. Again, this was achieved using exclusively off-the-shelf components.

LED Protection and Other Features

The LTC3783 can operate from a wide 3V to 36V (or higher) input voltage supply range. A programmable undervoltage lockout ensures that too low of an input voltage is ignored by the chip. If an LED string is inadvertently left open, an overvoltage protection feature ensures that the output voltage does not exceed a programmable level. A soft-start function is included in order to limit the in-rush of current from the input supply during start-up. The switching frequency can be set by a single resistor to any value between 20kHz and 1MHz, or it can be synchronized to an external clock.

Conclusion

Driving high power LED strings with the LTC3783 yields a highly efficient, low parts count and flexible solution. Furthermore, being able to use standard off-the-shelf components helps to simplify the design without sacrificing performance.

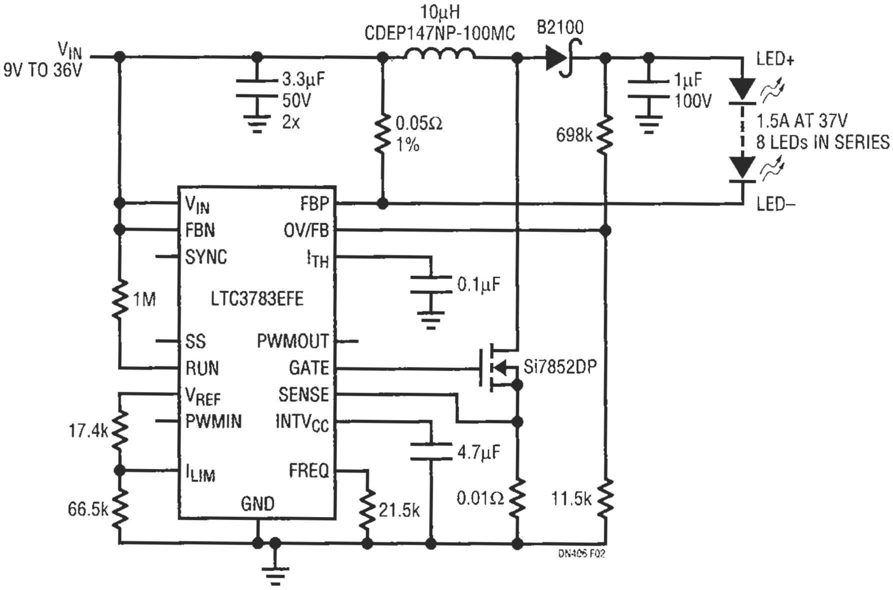


Figure 2. LTC3783 in a Buck-Boost Configuration to Drive 8 LEDs in Series

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READERS SOLVE DESIGN PROBLEMS

Use a CFL ballast to drive LEDs

Christian Rausch, Unterhaching, Germany

Designers use ballast ICs, such as International Rectifier's (www.irf.com) IR53HD420, in CFLs (compact fluorescent lamps) for heating the filaments, igniting the lamps, and supplying the lamps with current (**Reference 1**). Manufacturers produce these ICs in high volumes, and they cost approximately $2. This Design Idea shows how you can use a CFL-ballast IC for driving LEDs instead of CFLs. A ballast IC essentially is a self-oscillating half-bridge for offline operation. It typically operates from 320V dc, which is approximately the same power as that from a 230V-ac mains rectifier or a 120V voltage doubler. The IC generates square-wave voltages with an amplitude of 320V p-p and a frequency of tens of kilohertz.

Usually, this square-wave voltage connects to a series combination of a CFL tube and a current-limiting inductor, L_1 (**Figure 1**). Together with a parallel capacitor and using the LC resonance, you can warm up, ignite, and supply the tube with current. This approach works well because CFL tubes have high impedances when they are off and low impedance when they are running. The tube voltage is typically 150V p-p.

By putting several LEDs in series and connecting them to a bridge rectifier, you can effect an imitation of a CFL, at least in the on-state. Imitating the off-state is less important, because LEDs need no ignition procedure. At the given values for R_T and C_T, the bridge runs at 70 kHz. The circuit supplies 64 LEDs with a current of approximately 80 mA. The infrared LEDs illuminate the field of view of a CCD camera in a machine-vision system. The circuit prototype uses a 2.7-mH inductor from a dead CFL.

The LED current comprises dc current plus a small ripple current; keep

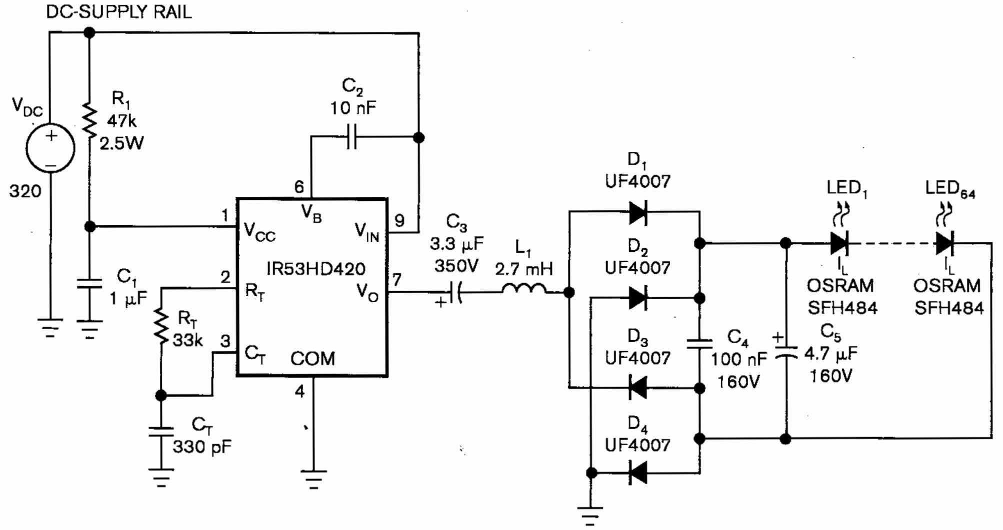

Figure 1 A CFL ballast drives a long string of LEDs.

DIs Inside

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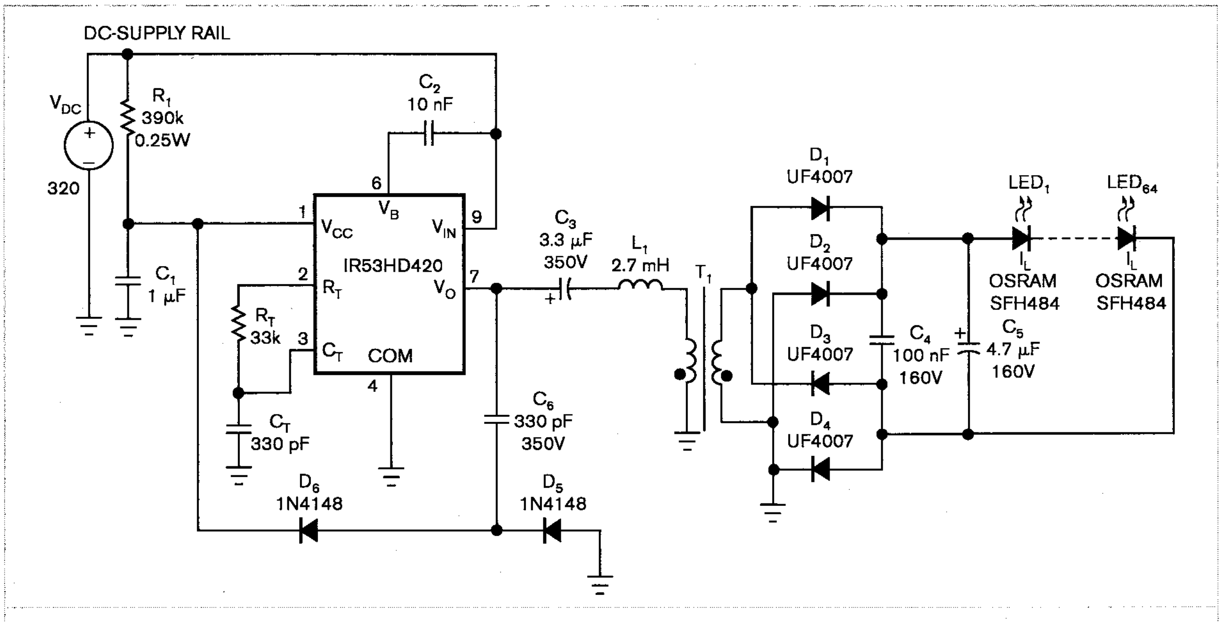

Figure 2 Adding a transformer to the circuit of Figure 1 allows you to connect as many LEDs as necessary.

the ripple current low for high efficiency and long LED lifetime. LED manufacturers usually demand values of a few percentage points. Such a low ripple current may be difficult to achieve with one electrolytic capacitor, C_5, but a parallel combination with an additional foil capacitor, C_4, works well enough in most cases. The voltage at the input of the LED rectifier is fairly constant during one oscillation period, so the inductor current has a triangular shape, which is good for EMC (electromagnetic compatibility). The equation for the average LED current is $I_{LEDAVG}=(½\times V_{DC}-N\times V_{FLED})/(4\times f\times L_1)$, where V_{DC} is the supply voltage, N is the number of LEDs in series, V_{FLED} is the LED forward voltage, f is the oscillation frequency, and L_1 is the inductance of the current-limiting inductor.

Although the circuit of **Figure 1** works well, it has some deficiencies that the circuit of **Figure 2** remedies by adding C_6, D_5, D_6, and T_1, wound on an EPCOS EP13 coil former, with an ungapped-EP13-core of T38 material with an inductance of 7000 nH. Both the primary and the secondary windings are 90 turns of 0.2-mm wire; the secondary winding is wound on top of the primary winding. Stray inductance is not important in this case, and the inductance for both the primary and the secondary windings is 50 mH. The circuit in **Figure 2** has several advantages over the one in **Figure 1**. For example, the supply current for the ballast IC of **Figure 1** must flow through R_1 and into the IR53HD420, where it gets clamped to 15.6V. At a supply current of about 6 mA, R_1 must dissipate more than 2W. In **Figure 2**, R_1 can have a much higher value, because it must supply only a small start-up current. After start-up, a charge pump comprising C_6, D_5, and D_6 pumps enough current into the V_{CC} pin so that the internal zener diode clamps to 15.6V. The design equation for the charge pump is $I_{SUPPLY(AVG)}=f\times C_6 2\times V_{DC}-15.6V$. The dissipation of R_1 now stays below 0.25W.

WITH THE TRANSFORMER, YOU CAN GROUND ONE END OF THE LED STRING EITHER DIRECTLY OR THROUGH A CAPACITOR.

Also, the summed forward voltages of the LEDs in **Figure 1** must be smaller than one-half the supply voltage. For the circuit in **Figure 2**, by tailoring the transformer-winding ratio, you can connect as many LEDs as needed, as long as you do not exceed the ratings of the components. (LED voltages even higher than V_{DC} are possible.) A less obvious problem of the circuit in **Figure 1** is that the full voltage swing of the bridge appears at both ends of the LED string. This situation does not present a problem when all the LEDs are close together and the LEDs are close to the bridge. However, in many light fixtures, you wish to separate the LEDs from the electronics. Due to stray capacitances, this approach would lead to high capacitive currents from the LEDs to ground, corrupting the efficiency and producing EMC problems. With the transformer of **Figure 2**, you can ground one end of the LED string either directly, as shown, or through a capacitor. Now, you can use long cables to easily separate the LEDs from the electronics. **EDN**

REFERENCE

■ "IR53H420(D)420, Self-Oscillating Half Bridge," Preliminary Data Sheet No. PD60140-K, International Rectifier, Aug 19, 2003, www.irf.com/product-info/datasheets/data/ir53h420.pdf.

Drive a blue LED from a 3V battery

Sergi Sánchez, Federal Signal Vama SA, Vilassar de Dalt, Spain

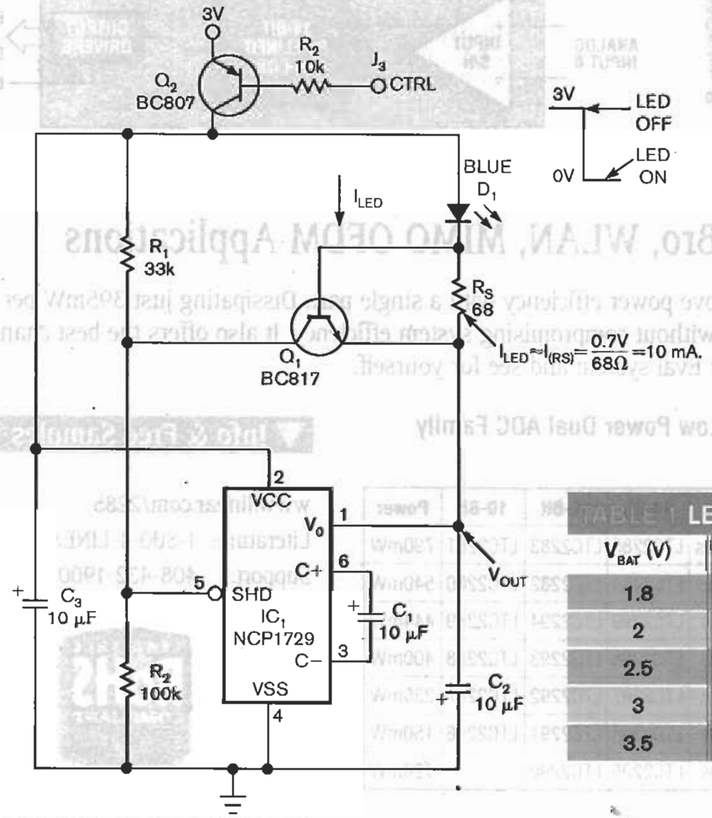

Figure 1 This circuit uses the On Semiconductor NCP1729 voltage inverter, IC$_1$, to produce enough voltage to drive blue LED D$_1$.

Using a blue LED can pose problems when available power-supply voltages don't meet or exceed the LED's 3V forward-voltage drop. This Design Idea shows how to drive a blue LED from a 3V battery or another power supply. The circuit in **Figure 1** uses the On Semiconductor (www.onsemi.com) NCP1729 voltage inverter, IC$_1$, to produce enough voltage to drive blue LED D$_1$. Transistor Q$_1$ serves as a constant-current limiter for the LED's forward current. When current through the LED and R$_S$ increases to a level that develops enough base-emitter voltage to turn on Q$_1$, Q$_1$'s collector draws current from the voltage divider comprising R$_1$ and R$_2$ and forces IC$_1$ to shut down. The voltage inverter restarts when the voltage drop across R$_S$ falls below Q$_1$'s base-emitter turn-on threshold. Pulling transistor Q$_2$'s base to ground through R$_2$ turns on the circuit.

In this application, the LED exhibits a voltage drop of approximately 3.3V at 10 mA forward-bias current. **Table 1** illustrates the LED's applied voltage, V$_{BAT}$+|V$_{OUT}$|, and Q$_1$'s base-emitter voltage for various battery-voltage values. **EDN**

TABLE 1 LED APPLIED VOLTAGE

V_{BAT} (V)	V_{OUT} (V)	$V_{BE(Q1)}$ (V)
1.8	−1.5	0.41
2	−1.37	0.46
2.5	−0.79	0.42
3	−0.27	0.4
3.5	0.23	0.41

Simple single-cell white-LED driver uses improvised transformer

Jim Grant, Scientific Controls, Orlando, FL

A white LED delivers a wide color spectrum and better visibility than do monochromatic LEDs. However, a white LED presents a higher forward-voltage drop than do its colorful counterparts and thus poses problems for operation from a single 1.5V cell. The self-oscillating step-up converter in **Figure 1** features a minimal component count and an easily assembled transformer, T_1.

During the time it takes to charge T_1's primary inductance, resistor R_1 and T_1's added secondary winding provide sufficient base current to turn on Q_2. Q_2's collector current increases until its base current can no longer hold the transistor in saturation. When Q_2 comes out of saturation, T_1's magnetic flux and secondary-voltage polarity reverse. During T_1's primary-discharge interval, the combination of T_1's secondary voltage in series with Q_1's base-emitter voltage applies reverse bias to Q_2's base and turns off the transistor. When Q_2 turns off, the voltage across T_1's primary inductance adds to the battery voltage and applies a forward bias to the LED, D_1. The current through R_1 determines the power applied to the LED and applies forward bias to Q_1's base-emitter junction to provide temperature-compensated bias voltage for Q_2.

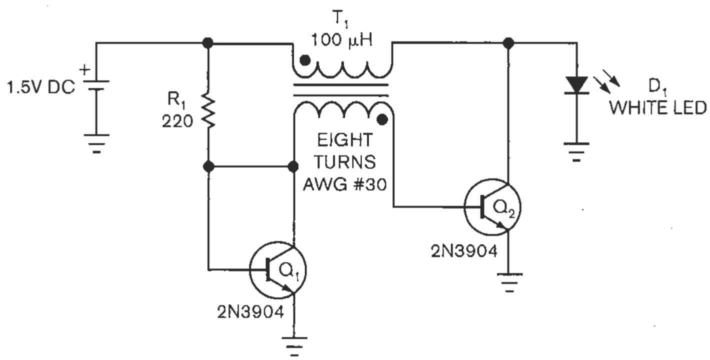

Figure 1 Two transistors and an easily assembled transformer drive a white LED from a single 1.5V battery.

The breadboarded circuit's transformer, T_1, comprises eight turns of AWG #30 insulated wire wound around the body of an unshielded 100-µH axial-lead inductor, producing approximately 400 mV p-p across the secondary winding. (**Editor's note:** Observe the winding's polarity dots. If the circuit fails to oscillate, reverse the connections to either the primary or the secondary winding.) The circuit operates over an input voltage range from just above Q_1's base-emitter voltage drop of approximately 0.6V to the LED's forward-voltage drop of approximately 3V. The circuit's switching frequency exceeds 340 kHz at 1.5V input. EDN