Power to the LEDs

Driver circuits for high-power LEDs

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LEDs have started living up to their name in recent years: 'Advanced Power TopLEDs' from Osram are used as daytime running lights in the new Audi R8 (photo: Audi AG).

Although the acronym 'LED' has stood for 'light-emitting diode' since the 1960's, LEDs have only recently started to emit significant amounts of light. High-power LEDs need suitable drivers to enable them to emit light under a wide variety of conditions. Here we present a summary of driver designs ranging from simple to sophisticated.

We can't say it too often: LEDs are essentially current-driven devices. This is simply due to the fact that they have non-linear current versus voltage characteristics with a distinct 'corner', which depends on the colour or the technology-dependent forward voltage. To make things even worse, the 'corner' or threshold voltage is temperature dependent and varies from one device to the next. **Figure 1** shows the measured current versus voltage characteristics of three high-power white LEDs (also called high-brightness LEDs or HB LEDs) from different manufacturers. However, these characteristic curves could just as easily be measured with three different examples of the same type or at three different temperatures. Although even a small change in voltage causes a large change in the LED current and thus the brightness of the LED, a small change in current (in the normal operating range) does not produce any significant change in LED brightness.

Linear LED driver

This means that LEDs must be powered by a stiff current source. The combination of a voltage source and a series resistor that limits the current through the LED to the desired or permitted value can only be used if the supply voltage is more or less constant or an especially inexpensive solution is required.

In many cases, a linear voltage regulator with a suitable load resistance can be regarded as a 'good' LED current source (LED driver). **Figure 2** shows a linear LED driver for powering three HB LEDs with a supply voltage (U_B) of 12 V. In contrast to standard three-pin linear regulators such as the LM317T, the MIC29152 [1] has a supplementary Enable input that can be used to switch the regulator on or off, but it is also quite suitable for PWM dimming at a frequency of several hundred hertz. Pull-up resistor R2 is only necessary if the EN input is driven by a switch contact or an open-collector signal. A TTL or CMOS logic signal can also be used for this purpose. R2 can be omitted in this case, or it can be connected to the logic supply voltage instead of $+U_B$.

The IC can easily source 350 mA with three LEDs and a 12-V supply voltage, and it doesn't need a heat sink. The LED current is determined by the ratio of U1 and R1 (I_{LED} = $U1/R1$ = 1.24 V / 3.9 Ω = 318 mA). If you want the full 350 mA, you can connect a 39-Ω resistor (E12 series) in parallel with R1. The losses in the linear circuit are dissipated in current sense resistor R1 (approximately 0.5 W) and the low-dropout (LDO) regulator.

Due to the low dropout voltage (the minimum voltage between the input and output of the LDO regulator necessary for reliable operation at a specific current), a single HB LED can also be operated from a supply voltage ($+U_B$) of 5 V. At the other extreme, up to seven LEDs in series can be driven by this circuit if the supply voltage $+U_B$ is raised to the maximum permissible value of 26 V (and the voltage rating of the capacitors is increased accordingly).

Efficiency

The basic prerequisite for using a linear LED driver is that the supply voltage is greater than the forward voltage of the LED(s). The product of the difference voltage and the LED current gives the approximate value of the dissipated power with a linear LED driver (ignoring losses in the driver IC and other components connected in parallel, but including the loss in the current sense resistor, since it is connected in series with the LED). A simple expression for the efficiency can be derived from this: $\eta = U_{LED}/U_B$. This means that a relatively high supply voltage leads to low efficiency.

However, it is possible to achieve even better efficiency than a more sophisticated switch-mode LED driver if the difference voltage is small, although this requires an LDO regulator that does not need much voltage headroom to control the LED current (the dropout voltage is usually well below 1 V) and the lowest possible voltage drop (around 0.5 V to less than 0.1 V) across the current-sense resistor usually present in such a circuit.

As a rule of thumb, you can say that a linear driver is always an attractive option if the voltage headroom (LDO dropout voltage) is less than 10%, since its efficiency will be on the same order as that of a switch-mode LED driver but with distinctly less effort, lower cost, and possibly better performance characteristics. Another aspect worth considering is that linear LED drivers do not produce any electrical or electromagnetic interference (as long as they are not dimmed using a PWM signal).

LED controller

The circuit shown in **Figure 3** is similar to the circuit in Figure 2. The MIC5190 is an LDO controller that does not supply the output current directly, but instead drives the LED via a power MOSFET (T1). This makes it an LED controller. On the one hand, this means the LED current can have almost any desired value with a voltage drop across the MOSFET that can be limited to almost any desired value, while on the other hand the HB LED can be connected to the positive supply rail, which means that RGB LEDs with a common anode can be used if necessary.
Another difference is that here the LED is connected to the drain lead of the MOSFET. This yields sufficient gate-source voltage for the N-channel MOSFET. The LED current sense voltage is only 0.5 V in this circuit. The LED current is thus given by the expression $I_{LED1} = 0.5$ V/R1. The MOSFET may require a heat sink, depending on the LED current.
This example also indicates how a three-channel LED driver (for example, for a high-power RGB LED) can be implemented. For simplicity, the drive circuitry of the second and third channels using two additional LDO controllers is not shown here. The LED currents can be set individually using R1, R2 and R3, which can be used with an RGB LED to obtain the best white balance.
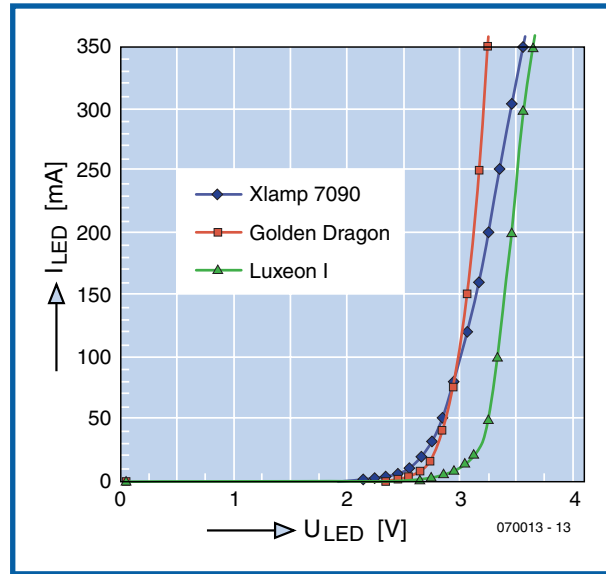PWM dimming (or colour adjustment in the case of an

Figure 1. Current versus voltage characteristics of high-power LEDs from different manufacturers. Although even a small change in voltage causes a large change in LED current and thus the brightness of the LED, a small change in current has almost no effect.
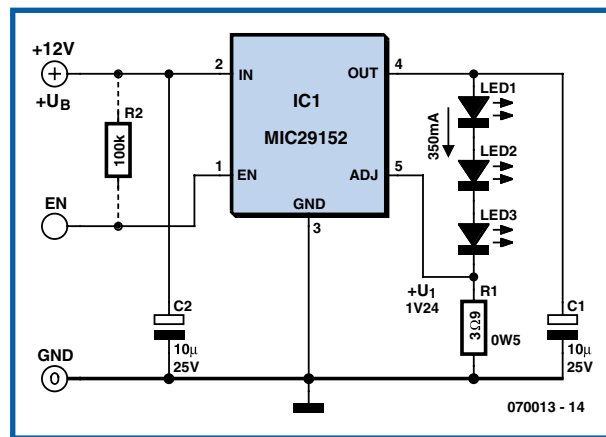

Figure 2. A linear LED driver for powering three high-power LEDs from a 12-V supply (maximum total forward voltage 10.5 V). The Enable input can even be used for PWM dimming at a few hundred hertz.

RGB LED) is again possible using the Enable inputs. Once again, the pull-up resistor R50 can be omitted if EN1 is driven by a logic-level signal. This LED controller does not need any capacitors in the output circuit, so relatively high PWM dimming frequencies can be used thanks to the short response time.
The circuit shown in Figure 3 can be used to power one LED per channel in a 5-V system. If you want to connect several LEDs in series (in which case it is naturally no longer possible to use common-anode RGB LEDs), you can simply increase the supply voltage to a suitable level and connect the most positive anode to the supply rail. If you do not have MOSFETs suitable for logic-level drive, you will need a separate power supply for VCC2 (refer to the MIC5190 data sheet [2]).

Switch-mode LED driver

There are two conditions under which it is practically imperative to use a switched-mode LED driver. The first condition is when there is a large difference between the supply voltage and the net forward voltage of the LED(s), combined with a high LED current. The second condition is when the total LED forward voltage is larger than the
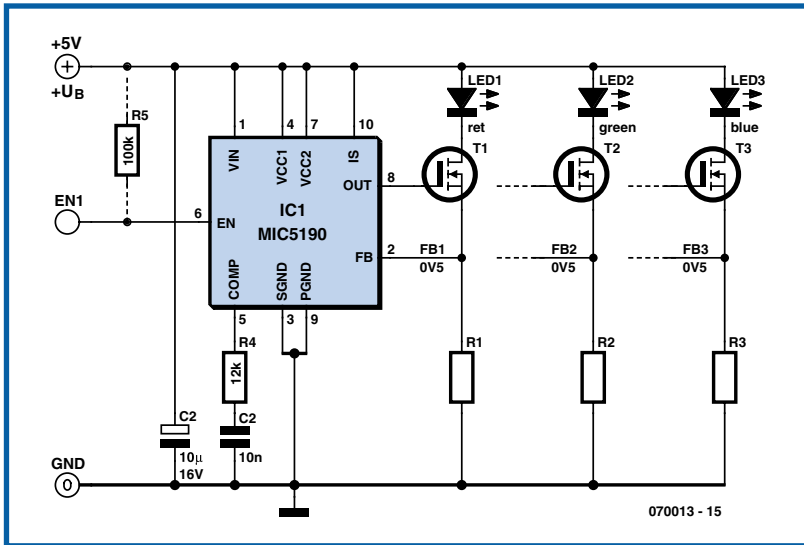
Figure 3. The IC used here is a LDO controller that does not supply the output current directly, but instead drives an LED via a power MOSFET.

sense voltage to the level of the available reference voltage or starting with a small reference voltage. As more and more step-down voltage converters for output voltages below 1 V are becoming available, it should be relatively easy to find a suitable candidate among modern ICs.

The especially simple and tiny MIC4628 HB LED driver (**Figure 4**) can power up to three HB LEDs in series with a 24-V supply voltage (typically available in industrial systems). The Enable input can be driven by a 24-V signal or a contact if necessary, but it can also be driven by a logic signal. In this case, R5 can be omitted or connected to the logic supply voltage instead of $+U_B$.

The value of C1 must be selected according to whether PWM dimming is to be used. The suggest value of 220 µF can be used for the least possible LED current ripple if dimming is not necessary. If PWM dimming is necessary, use a value of 10 µF for C1 (tantalum or aluminium electrolytic) so it can discharge faster. The circuit remains stable despite the smaller value of C1, although the ripple current (as measured with a 100% PWM dimming ratio) is somewhat larger.

With the given component values, the voltage divider at the output (R3/R4) limits the output voltage to approxi-

available supply voltage. The first case involves a 'step-down' LED driver, while the second case involves a 'step-up' LED driver (all pretty logical, isn't it?). However, even more complicated solutions are possible.

In contrast to a step-down voltage converter (also called a 'buck regulator'), a step-down LED driver is a switch-mode current source instead of a switch-mode voltage source. In the same way as a linear voltage regulator can be used to make a linear LED driver, a switch-mode voltage source can be converted into a current source relatively easily by using a current-sense resistor (R_S) in combination with the reference voltage U_{REF} (typically 1.2 V) to generate the desired LED current. The LED current is then given by the expression

$$I_{LED} = U_{REF} / RS$$

The drawback of this approach is the relatively high reference voltage, which degrades the overall efficiency despite the use of a switch-mode current source. This can be remedied by amplifying a significantly smaller current-
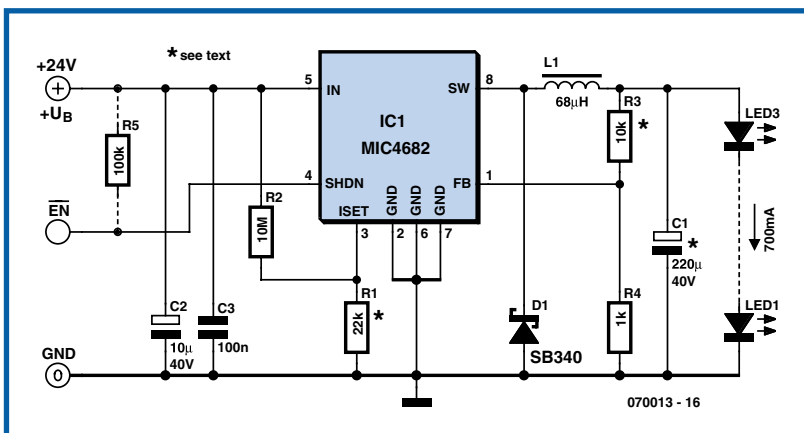

mately 14 V if the LED string is open (be careful with connecting the LEDs if the circuit is already switched on!). R1 sets the LED current. Its value is taken from a diagram on the MIC5682 data sheet [3]. A value of 22 kΩ for R1 yields a LED current of approximately 700 mA.

One criterion for selecting a suitable switch-mode LED driver is its switching frequency (the available range is a few dozen hertz to several megahertz). This essentially determines the size of the coil, and it inversely affects the level of LED current ripple that can be achieved. However, dynamic losses can increase strongly at high frequencies, depending on the design, thus decreasing the achievable efficiency.

Figure 4. This simple step-down LED driver can power up to three series-connected high-power LEDs when used with a supply voltage of 24 V.

LEDs on the mains

An extreme case of a step-down LED driver is powering LEDs directly from the mains voltage. Here the objective is to obtain a relatively high LED current, usually at a very low LED voltage, from a very high and highly variable voltage. The main challenge here is the extremely low PWM duty cycle resulting from the ratio of the LED forward voltage and the actual supply voltage (usually the rectified AC mains voltage).

With a single white LED and a 230-V mains voltage plus a 15% overvoltage allowance, the worst-case duty cycle would be approximately 1%. The number of suitable converter ICs that can meet such requirements is rather small.

An example of a possible implementation of a step-down LED driver for operation from the AC mains has already been published in *Elektor Electronics* under the title 'HV9901 – a novel LED driver' [4].

A completely new approach is provided by LEDs that can be operated directly from the AC mains without a driver. In any case, the Acriche LED modules displayed by Seoul Semiconductor at the Electronica 2006 trade fair (**Figure 5**) certainly drew attention. A few other companies, such as Lynk Labs, are also active in this area.

Figure 5. The Acriche LED modules from Seoul Semiconductor can be operated directly from the AC mains without a transformer. This is a 2-watt single-LED module. The manufacturer plans to boost the light yield from the current 48 lumen/W to 80 lumen/W in Q4 2007 and 120 lumen/W in 2008.

the LED, since especially with a relatively low battery voltage the required peak currents in MOSFET switch and the converter coil can be correspondingly high. For this reason, such converters usually require a minimum supply voltage of more than 2 V so they can continue to provide satisfactory operation with two nearly discharged batteries. Although step-up LED drivers for high-power LEDs that can operate from a single cell (nominal voltage
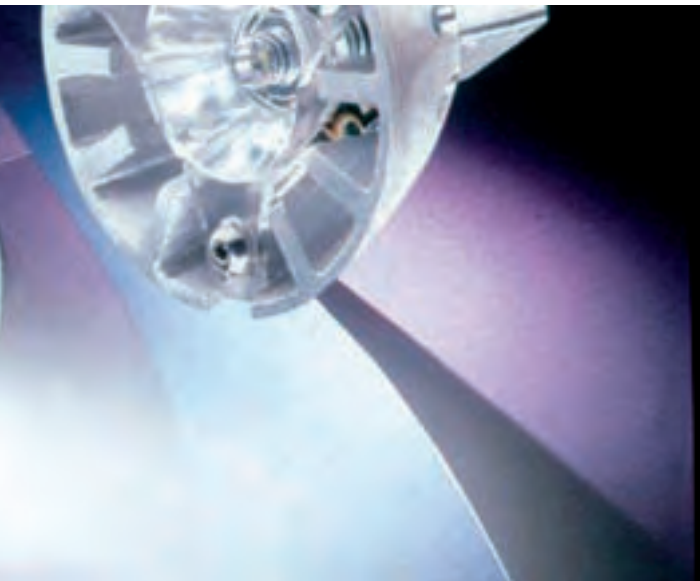
Manufacturers

**Manufacturers of LED drivers
(list not necessarily complete)**

www.allegromicro.com
www.analog.com
www.austriamicrosystems.com
www.catsemi.com/
www.fairchildsemi.com
www.infineon.com
www.intersil.com
www.ixys.com
www.linear.com
www.maxim-ic.com
www.melexis.com
www.micrel.com
www.microchip.com

www.monolithicpower.com
www.national.com
www.nxp.com
www.onsemi.com
www.ricoh.com/LSI/
www.rohm.com
www.semtech.com
www.sipex.com
www.st.com
www.supertex.com
www.ti.com
www.zetex.com

Step-up LED driver

The other end of the supply-voltage spectrum is found with very low supply voltages, usually provided by batteries. A step-up LED driver (also called a boost regulator) is essential in such cases. The number of LEDs to be driven varies, and it can be as much as ten or more LEDs in series, which yields a total LED forward voltage of more than 30 V.

A step-up LED driver of this sort using a MIC2196 boost controller [5] with an N-channel MOSFET can easily drive a six-chip Ostar LED with a rated power of 24 W. Here you have to bear in mind that with this type of boost topology, the input voltage must be lie below the LED forward voltage. This versatile circuit is described in detail in the documentation of an evaluation board available from Micrel [6].

Here the challenge to the designer is not so much the voltage ratio as amount of power that must be supplied to
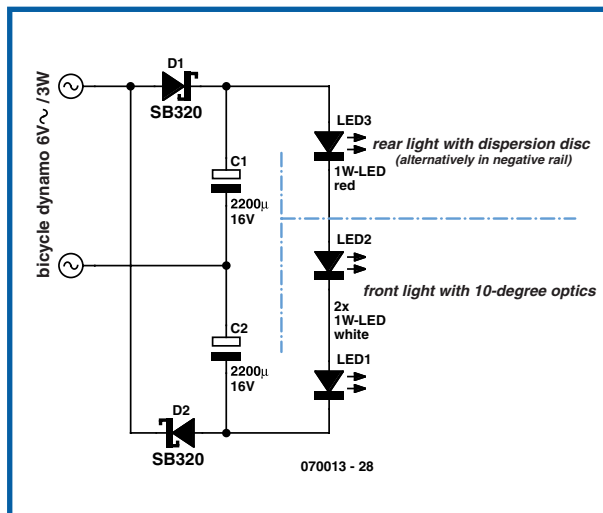
The triumphal march of high-power LEDs is imminent. This is the author's suggestion for a dynamo-driven LED lighting system for bicycles [7].

1.2–1.5 V) are technically feasible, they are not necessarily economically feasible.

Another tricky issue with step-up drivers is PWM dimming. Entire essays can be written about the advantages and disadvantages of PWM dimming, so here we limit ourselves to the remark that if you want to have a large dimming range (0–100% if possible), you need a step-up LED driver with a relatively high switching frequency and a relatively small control-loop time constant.

One of the critical situations that must be mastered with a step-up converter is operation with an open load circuit. A failed LED normally leads to an open circuit, and only rarely to a short circuit. There are several possible approaches to open-circuit protection. The simplest solution is a Zener diode with a breakdown voltage greater than the maximum total LED forward voltage. The disadvantage of this is that the Zener diode must conduct the LED current in case of an open circuit, and the resulting power dissipation ($U_Z \times I_{LED}$) is always greater than the total power dissipation of the LEDs. A much more elegant solution is to use a voltage limiter such as with a voltage regulator, but this usually requires a supplementary input pin on the IC.

Alternatively, the Zener diode can be connected directly to the current-sense feedback input and the current-sense voltage ca be provided via a resistor that normally does not carry any current. In this case, a situation in which the setpoint value of the control loop is exceeded can be simulated if the LED chain is open. This avoids unnecessary output power dissipation in case of an open-circuit condition and eliminates the need for an additional pin. These tricks are incorporated in the circuit diagram shown in **Figure 6**, which is a step-up LED driver based on an MIC2196.

Mixed-mode operation

Besides the previous described step-down and step-up LED drivers, there are implementations that support mixed-mode operation. LED drivers of this sort are necessary in situations where the battery voltage is higher than the LED forward voltage when the battery is fully charged but

drops below the LED forward voltage during operation. LED drivers of this sort are usually based on Sepic, CUK, buck/boost, or inverting buck/boost topologies.

These LED driver topologies are also used when the supply voltage is fixed (such as in a car) but the number of LEDs can vary. A combined step-up/step-down solution can be used as a versatile but complicated 'general-purpose' LED driver in such situations.

Another type of step-up circuit is the charge-pump LED driver, which is based on capacitors instead of the coils used by the previously described types of switch-mode LED drivers. In simplified terms, a charge pump uses MOSFET switches operated in a suitable switching arrangement to generate an output voltage by 'stacking' the charges stored in the capacitors. It is usually only possible to obtain a multiple of the input voltage, which is the main drawback of these compact circuits. In most cases, the LED forward voltage is not an exact multiple of the input voltage, so the charge pump is usually followed by a linear LED driver to regulate the current. This means that the efficiency depends indirectly on the input voltage, but it is relatively good if the LED forward voltage is just below an integer multiple of the input voltage. Modern charge-pump LED drivers can even adjust the multiplication factor automatically, which can be seen from their step-shaped efficiency characteristic curves.

(070013-I)

Weblinks

[1] www.micrel.com/_PDF/mic29150.pdf

[2] www.micrel.com/_PDF/mic5190.pdf

[3] www.micrel.com/_PDF/mic4682.pdf

[4] Elektor Electronics, January 2004

[5] www.micrel.com/_PDF/mic2196.pdf

[6] www.micrel.com/_PDF/Eval-Board/mic2196_led_eb.pdf

[7] www.led-treiber.de
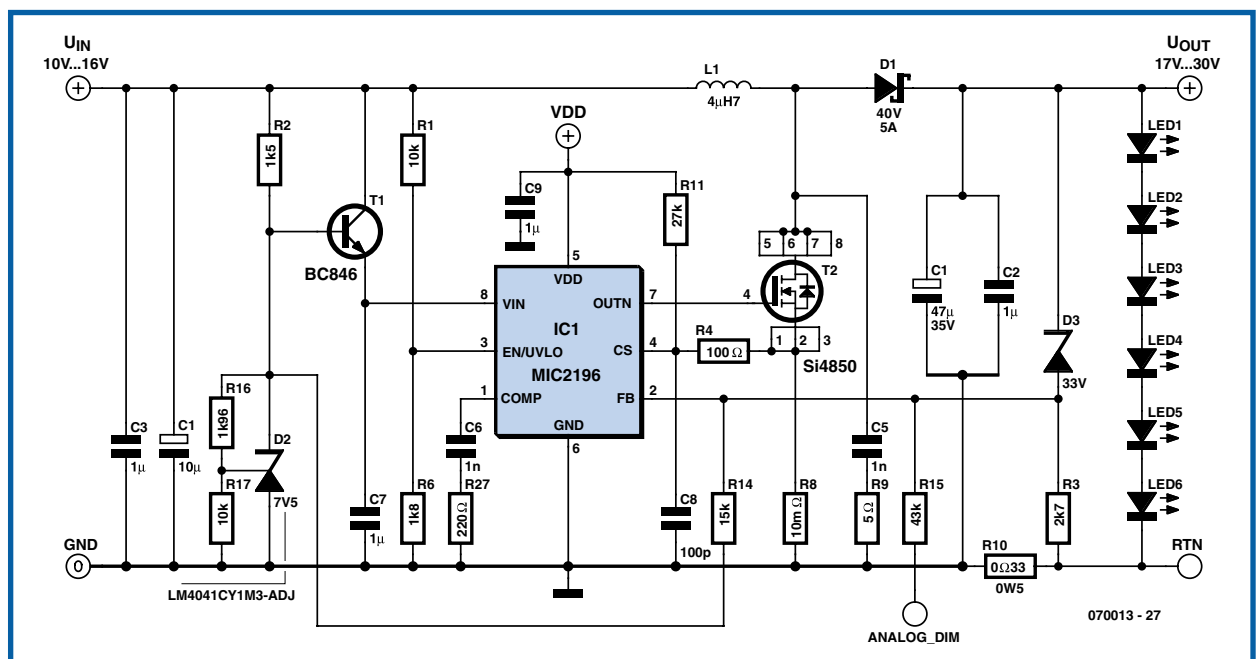
Figure 6. Circuit diagram of a step-up LED driver. Zener diode D3 provides open-circuit protection (see text).