More Light!

Practical high-power LEDs

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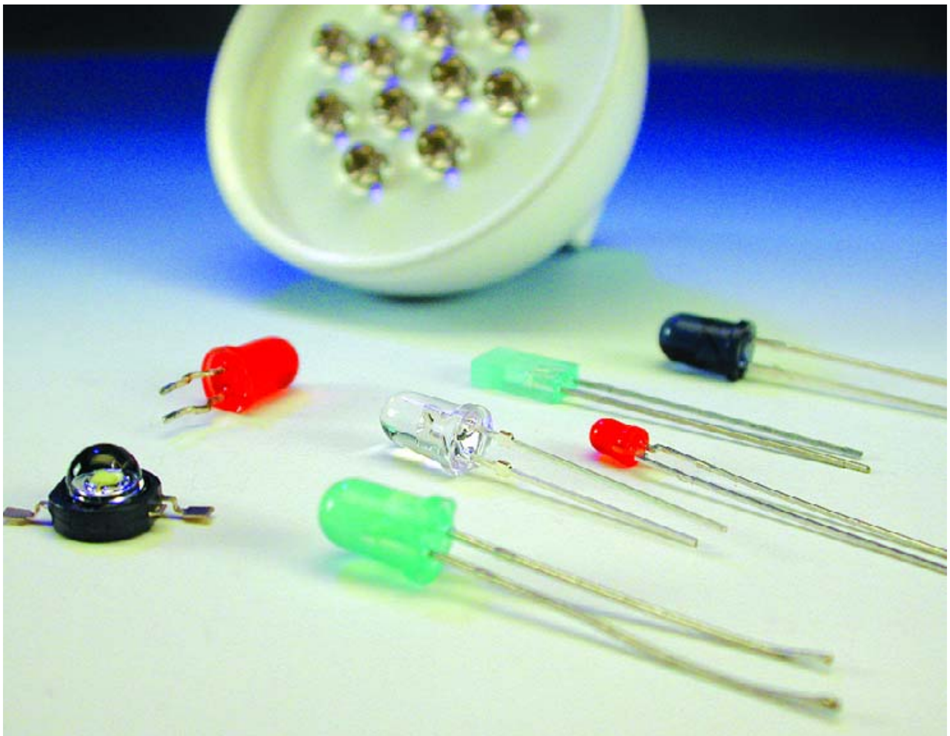
In recent years the LED has seen many improvements so that we see them fitted in more and more situations where filament lamps were traditionally used. They have many advantages and their excellent reliability is often an important consideration.



LED technology has come on leaps and bounds in the last few years and recently some of the higher output devices have become available commercially. Component supplier Conrad Electronics (www.int.conradcom.de) kindly donated samples for use in producing this article.

Electronic engineers are not necessarily lighting specialists so this article sets out to fill in some of the technical background and also explore a couple of simple circuits to drive a 1-watt high power LED.

Lumens or watts ?

In the electrical world we are familiar with the watt as a measurement of power. Transmitters or IR lasers for example, all have their outputs defined in watts. The equivalent 'power' of a light source is expressed in lumens. The lumen (lm) is a photometric unit for the luminous flux from a light source. The term photometric indicates that it takes into account the spectral response of the human eye and so gives an indication of how bright the source will be perceived. **Figure 1** shows the (daylight adapted) relative spectral luminous efficiency of the light wavelength to stimulate the eye (also known as the V-lambda curve). The eye is most sensitive to light with a wavelength of 555 nm (giving a relative efficiency of 1 on the curve). A monochromatic light source emitting at this frequency with a radiant flux of 1 W is equivalent to 683 Lumen. If we could keep the same output power but change the frequency of the light to 650 nm (red) the lumen calculation now becomes: 683 × 0.107 = 73 Lumen because at this frequency the relative efficiency has fallen to 0.107.

Infrared or ultraviolet light sources emit their energy at a frequency outside the eye response curve so the lumen value will be zero. The luminous flux is a measure of all the light emitted from the source irrespective of direction.

Lamps are also classified in terms of their luminous performance or efficacy. This parameter indicates how much light is produced for how much electrical energy consumed and is expressed in Lumens per watt (lm/W). This calculation always takes into account the power consumed by the complete lighting unit including electronic ballasts etc that are necessary for some types of lighting.

Table 1 shows a comparison of some common lamps. It is interesting to see the spread of figures for different types of lamp technology. The low-pressure sodium lamp holds the record for the greatest efficacy and its unflattering yellow light is a familiar sight in high streets up and down the UK. White light sources will always have lower efficacies because the energy is spread throughout the visible spectrum.

Candela

Take a look at any LED data sheet and you will soon come across the expression Candela (cd) rather than luminous flux when the light output of the device is quoted. The candela is the unit defining the luminous intensity from a small light source in a particular direction. A 1 cd light source emits 1 lm per steradian in all directions. A steradian is defined as the solid angle that has its vertex in the centre of a sphere (at the light source) so that 1 steradian has a projected area of 1 m^2 at a distance of 1 m. So:

Luminous intensity =
Luminous flux per steradian

The luminous intensity parameter is usually given for directional light sources like halogen lamps with built-in reflectors and also many LEDs. Along with this parameter it is also usual to specify the beam angle. The beam edges are where the luminous intensity has fallen to one half of the peak value. Lasers have an extremely

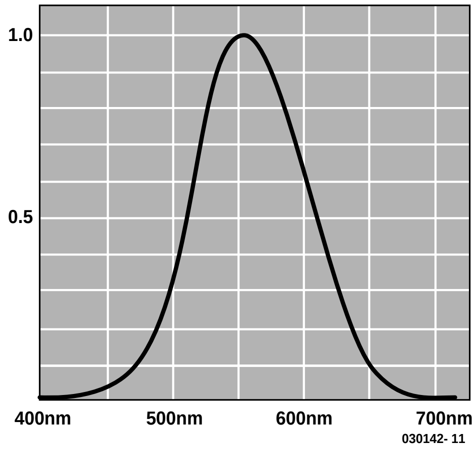


Figure 1. V-Lambda curve.

Table 1. Characteristics of common light sources.

Light source	Electrical energy (Watt)	Luminous flux (Lumen)	Luminous intensity (Candela)	Efficacy (lm/W)
Filament lamp	75	900	–	12
Fluorescent lamp	58	5400	–	90
Sodium low pressure	130	26000	–	200
Hg high pressure	1000	58000	–	58
Halogen 12 Volt	65	1700	–	26
Halogen reflector 10° beam	50	–	12500	–
Halogen reflector 60° beam	50	–	1100	–
LUXEON LED	1	18	–	18
NICHIA LED 20° beam	0.08	–	6.4	

Table 2. Beam angle to solid angle equivalence.

Beam angle (degrees)	Solid angle (Steradian)
360.0	12.566 (4·π)
180.0	6.283 (2·π)
60.0	0.842
40.0	0.379
38.0	0.342
35.0	0.291
30.0	0.214
25.0	0.149
24.0	0.137
20.0	0.095
15.0	0.054
10.0	0.024

Figure 2. Various 1 W LEDs from Luxeon.

Table 3. Osram Decostar 51 reflector lamps.

Beam angle (degrees)	Luminous intensity (cd)	Luminous flux (lm, calculated)	Efficacy (lm/W, calculated)
10.0	9100.00	217.576	6.22
24.0	3100.00	425.638	12.16
38.0	1500.00	513.475	14.67
60.0	700.00	589.251	16.84

Table 4. Nichia white LEDs.

Beam angle (degrees)	Luminous intensity (cd)	Luminous flux (lm, calculated)	Efficacy (lm/W, calculated)
20.0	6.40	0.611	7.64
50.0	1.80	1.060	13.25
70.0	0.48	0.545	6.82

high luminous intensity because the beam angle is so small. **Table 2** gives the correspondence between the beam angle in degrees and the equivalent solid angle or steradian.

It is not easy to make simple comparisons between different light sources when sometimes the luminous intensity and other times the luminous flux is quoted and it is also important to consider the spectral content of the light. We have probably had enough definitions to chew on so a few examples may help to get more of a feel for the terminology:

Example 1: Cycle lamp

The lamp consumes 3 W of electrical power and produces a luminous flux of approximately 30 lm. Giving a luminous efficacy of approximately 10 lm/W. when used as an isotropic light source (viewing angle 360° or $4 \cdot \pi$ steradians) the luminous intensity is about 2.4 Candela. Fitted with a reflector the luminous intensity measured in the centre of the beam will be about 250 Candela!

Example 2:
Low voltage halogen lamp

An Osram Halostar lamp (isotropic source, no reflector, type 64432 IRC) consumes 35 W electrical power, producing a luminous flux of 900 Lumen. This lamp achieves an efficacy of 26 lm/W, which is relatively good for a halogen lamp.

Example 3: Low voltage halogen reflector lamp

Lamps with built-in reflectors are rated by their light output and beam angle. The beam angle is a useful parameter for calculating the light spread in spot lighting applications. Many manufacturers produce lighting units using lamps of the same power fitted to reflectors with different beam angles. Table 3 shows specifications of the Osram Decostar 51 (51 mm reflector diameter) 35 W, 12 V reflector lamp.

The table gives the luminous flux and efficacy of the lamp with four different beam angles. In each case the light source is identical but it can be seen that the tighter the beam angle the lower the lamps efficacy becomes. It is difficult to design an efficient reflector producing a narrowly collimated beam. In order to make meaningful comparisons between different makes of reflector lamp it is necessary to know both the beam angle and the luminous intensity.

Table 5.
Luminous flux for Luxeon LEDs.

Colour	Typical Luminous flux (lm)
WHITE	18
GREEN	25
CYAN	30
BLUE	5
ROYAL BLUE	100 mW
RED	44
AMBER	36

Example 4: Nichia LEDs

At the time of writing the Japanese manufacturer Nichia produces the best white-light LEDs available. **Table 4** gives data for some of these LEDs (each 5mm diameter LEDs operating at 20 mA with a forward voltage of about 4 V). Again the values of luminous intensity and yield are given.

The values of luminous intensity are very low compared to halogen lamps but they consume much less power also (20 mA × 4 V = 80 mW) so when we calculate the efficacy, these LEDs turn out to be comparable with halogen.

Example 5: Luxeon LEDs

Luxeon has recently introduced its range of LumiLEDs (**Figure 3**). These devices can handle 1 W of electrical power (330 mA at 3.4 V for a white LED). The values given in **Table 5** apply for the *lambertian* (or diffused) distribution pattern version of the LED.

The white light version has better efficacy than all of the Decostar halogen lamps and the coloured versions achieve excellent outputs. The *Royal Blue* version emits light with a wavelength of 450 nm and the eye is so insensitive to this colour that the luminous flux is given in milliwatts. This parameter gives some indication of the LED efficiency; 10% of the 1 W of electrical power is converted to visible light (**Figure 4**).

Example 6: 12-V LED Spotlight, 50 mm

The company Signal-Construct produce LED spotlights (available from Conrad Electronics) that can be driven directly from a standard 12 V transformer used for low voltage halogen lighting. Power consumption is 1.2 W. The data sheet indicates that these lamps have a beam

Table 6. Data for 12 V LED Spotlights.

Beam angle (degrees)	Luminous intensity (cd)	Luminous flux (lm, calculated)	Efficacy (lm/W, calculated)
50.0	30	17.7	14.7

Figure 3. 12 V LED Spot.

angle of 50° with a luminous intensity of 30 cd.

The efficacy of these lamps is comparable to standard LEDs (e.g., the 50° Nichia LEDs). Each spot contains 12 LEDs. Assuming a current of 20 mA per LED at 4 V this gives a total power consumed by the LEDs of 0.96 W. The power difference (1.2 W – 0.96 W = 0.24 W) is most likely lost in the rectifiers and current control circuitry.

Are LEDs that cool?

One often reads that LEDs do not waste energy radiating heat and must therefore be far more efficient than, for example a halogen lamp. A close look at **Table 1** indicates that the luminous efficacy of both LEDs and halogen lamps are really quite poor and only a small percentage of the input energy is converted into visible light. What happens to all that wasted energy? A conventional filament lamp consists of a hot wire filament enclosed in a glass envelope. Current through the filament causes it to glow white hot at around 1000 °K so that a portion of the energy is radiated away as infrared (emission of IR radiation helps to keep the lamp relatively cool). Some of the heat is also conducted away (by convection) from the filament through the glass envelope and the body of the lamp.

With an LED it is not possible to make use of this 'radiant cooling', we need to ensure that the semiconductor does not get much hotter than 120 °C otherwise it will fail. At 120 °C the radiant cooling effect is very small and there is very little infrared energy emitted. In high power LEDs it is therefore necessary to remove the wasted energy partly by IR radiation but mostly by convection using some form of heat sink with a large surface area to dissipate heat to the surrounding air. Using present day technology, if you were to build an LED with the equivalent light output of a 35 W halogen lamp one of your biggest headaches would be how to keep the device cool enough.

This is the reason why, for example, Luxeon LEDs are supplied in packages that allow attachment to a heat sink. When calculating the thermal properties of the heat sink it is usual to assume that all of the energy delivered to the LED will be converted to heat. The small amount of energy producing light can really be ignored. Electrically speaking (watts optically per watts electrically) even the most recently developed LEDs still have poor efficacy.

Luxeon LEDs

At the time of writing LEDs produced by Luxeon can handle the most power. Luxeon is a company formed as a Joint Venture between Agilent and Philips. These LumiLEDs (**Figure 5**) are currently available commercially and can handle 1 W. The white light LEDs have a forward conduction voltage of 3.4 V so this gives a current of around 300 mA. Like all LEDs the LumiLED has a sharp forward voltage conduction characteristic that means that it is not possible to drive them directly from a voltage source without some form of current limiting or constant current source.

The rear face of the LED has a flat metallic surface allowing attachment of a heat sink for cooling purposes. Continuous operation at 1 W is only possible if a small heat sink is fitted to dissipate the heat, without a heat sink the LED will become too hot and must be derated (run at a reduced forward current).

The projected lifetime for these devices is up to 100,000 hrs, this represents more than 10 years of continuous operation! The output luminous intensity will however decrease with time so that LED displays that you build now will get dimmer with time, after about 10,000 hrs we can expect to see a 20% reduction and after 40,000 hrs a further 20 % reduction.

Comparing the life expectancy of an LED with a family car we could probably expect a vehicle to last for around 160,000 miles before it needs replacing, if we assume an average lifetime vehicular speed of 40 m.p.h. (admit-

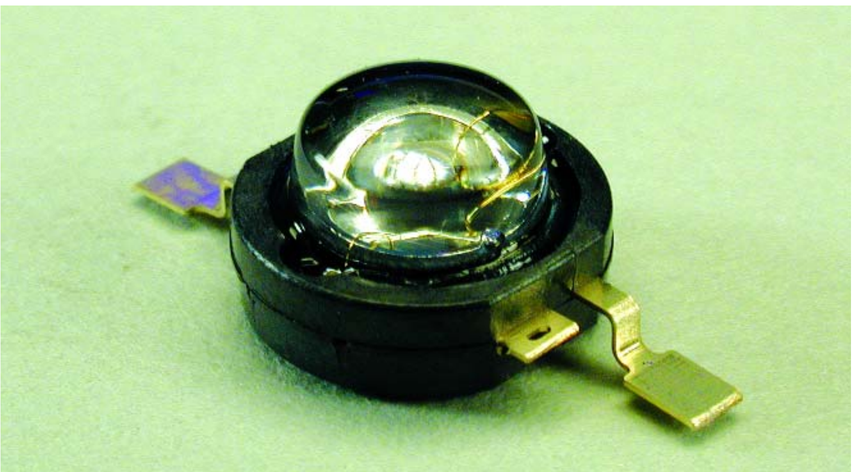


Figure 4. Luxeon LED.

tedly not very realistic for inner city dwellers in the U.K.) then with these figures the life expectancy of the car would be 4,000 hrs. Any LED fitted to the vehicle will easily outlive the car and will not need replacing, thus LEDs have advantages in applications where replacement would be difficult or expensive. There is a host of technical information available on the Internet showing applications along with electrical and thermal specifications including radiation patterns etc for the Luxeon LEDs. We have selected two circuits that might be useful to anyone wishing to experiment with these LEDs.

Luxeon LED driver using four NiMH cells

The simple circuit shown in Figure 6 is designed to drive a Luxeon 1 W LED from a 4 V to 6 V power source. The power can be provided ideally from four NiMH rechargeable cells. IC1 is a current source; it measures the LED current by sensing the voltage developed across the 0.2 Ω sense resistor R1 and resistor R2. The IC will adjust its output so that the voltage between the 'adj.' input and V– is 65 mV. The values shown in the circuit will give an LED current of approximately 250 mA. The reference voltage is proportional to the chip temperature referred to absolute zero and will only be 65 mV at room temperature (25 °C), as the chip temperature increases so will this reference voltage, leading to an increase in LED current. At 40 °C the LED current will be:

$$250\text{ mA}\ \frac{273+40}{273+25} = 260\text{ mA}$$

This should not be too much of a problem for most applications but it is important to ensure that IC1 is not fitted next to any component that will get warm e.g. T1 or the LED. One advantage of this circuit is the very low voltage drop across the sense resistor R1; this gives the circuit the characteristics of a low-drop current regulator. The input voltage should be kept below 6 V otherwise power dissipation in T1 will become excessive.

The 1 W LED is still quite expensive retailing at around seven pounds, for purposes of testing it is wise to use a 'dummy load' or in this case 'dummy LED' just to prevent damage to the LED during testing. Once the circuit has been checked the dummy LED can be removed and the LED fitted. Four 1N4007 diodes connected in series will simulate the loading provided by a single LED.

For testing connect the circuit to a variable power supply and increase the voltage gradually from zero. At about 3 V the circuit

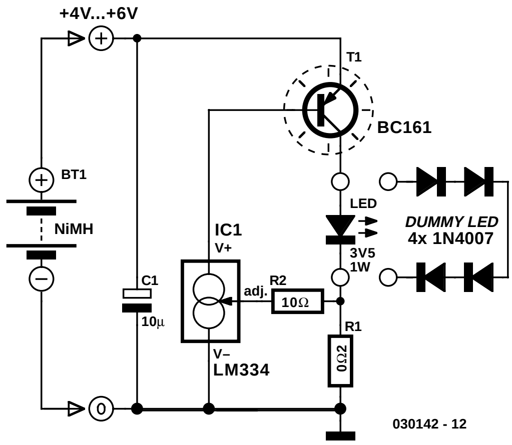


Figure 5. 1 W LED with Linear regulator.

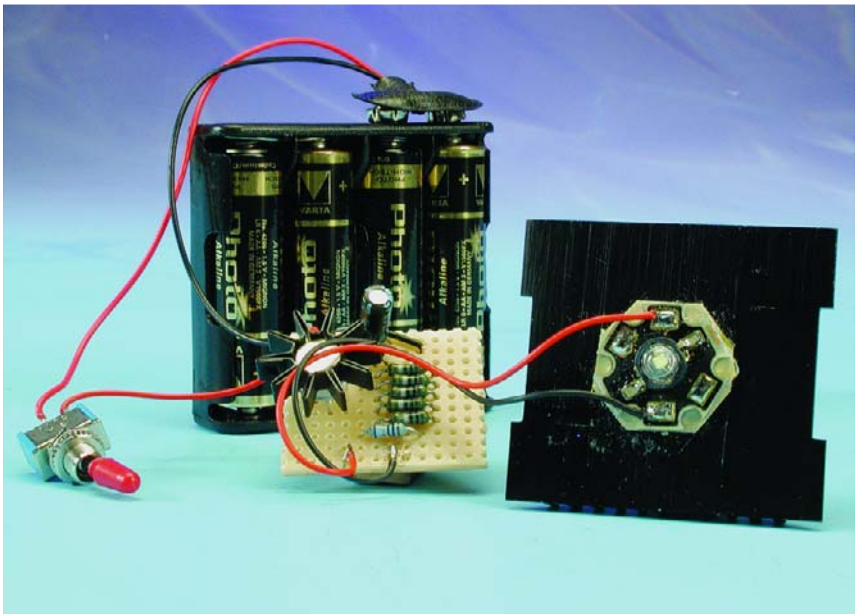


Figure 6. The low-drop current regulator built on prototyping board.

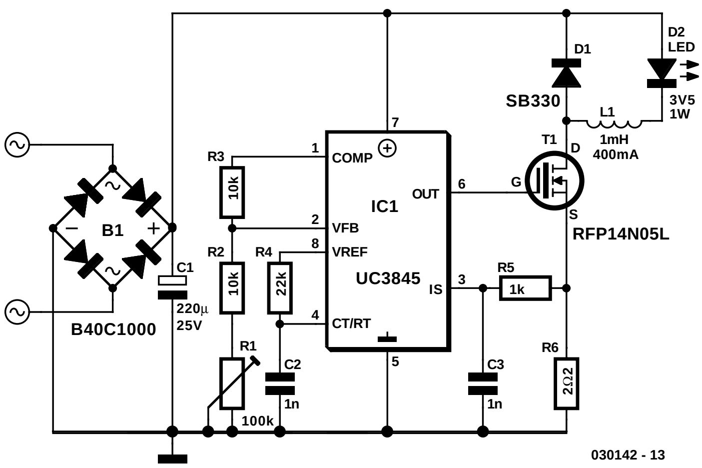


Figure 7. A simple switched regulator with 70 % efficiency.

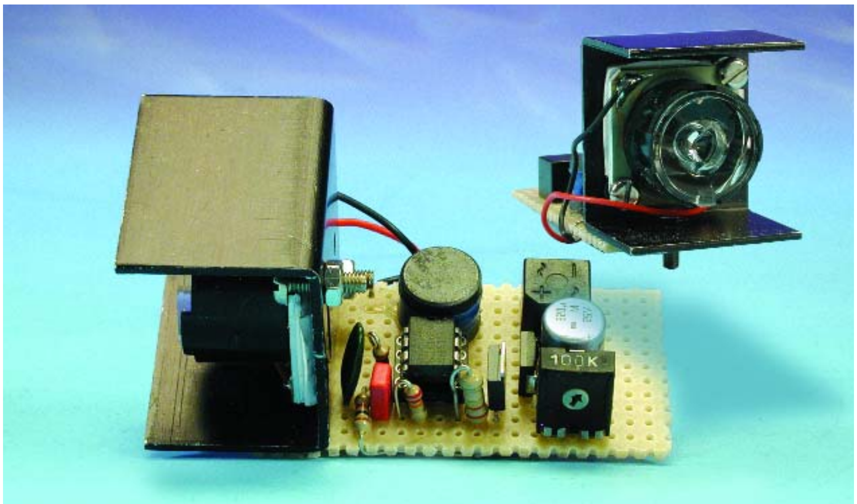


Figure 8. LED, heat sink and 12 V mains unit.

should be taking approximately 250 mA, increase the voltage to 6 V and check that the current does not increase. Once this test has been completed successfully disconnect the power and replace the dummy LED with the real LED. **Figure 7** shows the prototype circuit built on a small piece of PCB breadboard with a 1 W Luxeon Star LED.

LED operation from 12 V

The simplest technique of driving an LED from a 12 V power source is to use a linear regulator as shown above in **Figure 6**. This method is however not very efficient at 12 V because a lot of energy would be dissipated as heat in the regulator. A better alternative is to use a switching regulator as shown in **Figure 8**. This circuit drives a 1 W LED and can be powered either from an ac or dc source (e.g., a 12 V transformer for domestic halogen lighting or a car battery). The efficiency is about 70%, which is not particularly good, but on a positive note the circuit does not need any special components.

The circuit uses a standard PWM (Pulse Width Modulated) IC type UC3845 in 'current' mode. The RC network R4/C2 controls the switching frequency while the value of R2/P1 defines the output current. A relatively large inductor (L1) is used to ensure that the current ripple is kept low. Current through the LED is not regulated directly but instead the regulator controls peak current through the inductor. This technique avoids the need for a current sense in the LED path.

For circuit testing purposes the dummy LED can be used again as before. Once the input voltage exceeds 10 V the circuit will start to oscillate and P1 can be adjusted to give 250 mA through the LED. With a 12 V dc power source the circuit consumes about 120 mA. The LED current should not change when the input voltage is varied (at least not appreciably). When the tests are complete the dummy load can be replaced by a 1 W LED and the circuit can be powered directly from a 12 V halogen lighting transformer, this should give a suitably high-tech ambiance to your domestic lighting set-up!

The Luxeon STAR/O LED can also be used in this circuit. This device has integrated optics and must be fitted to a heat sink if it is to be used for continuous operation. The LED can be mounted to the heat sink using a flexible, (electrically) insulated gasket.

Back to the future

Future advances in LED technology will undoubtedly lead to a more widespread use of semiconductor light sources, there are already devices with operating currents of 700 mA and increasingly we see LEDs replacing filament lamps in applications such as traffic lights, production car tail-light clusters and backlighting LCD monitors.

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