Luxury LED Bicycle

Brighten your beam and banish burnt-out bulb blues

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Having treated himself to a new bicycle fitted out with all mod cons including a shiny hub dynamo, the author was looking forward to many miles of pedalling pleasure. But then disaster struck: after just a couple of hours use the bulb in the front light burned out! Not finding the prospect of repeated replacement attractive, he set out to substitute a power LED for the bulb.

It is not in an engineer's nature to be satisfied with a simple solution, such as replacing the bulb.

It is much more satisfactory to understand the problem properly from the ground up, and of course a problem like this can be viewed as an opportunity for a good rummage in the junk box to look for components that might be useful in devising a proper solution.

Tuning up

It often saves considerable effort to spend a few moments with Google before trying to solve a problem for oneself. The author found that the properties of hub dynamos had already been investigated in great depth by others, such as at [1].
However, the Internet is not a complete substitute for a proper fault diagnosis. **Figure 1** shows that on the author's lighting set a semiconductor device is wired across the bulb. The type P6KE7.5CA 'transient voltage suppressor' [2] is in effect two Zener diodes back-to-back, designed to clamp excess voltages. From the information in [1] it became clear what had happened. A hub dynamo, even at normal speeds, develops more than the specified 6 V. The suppres-

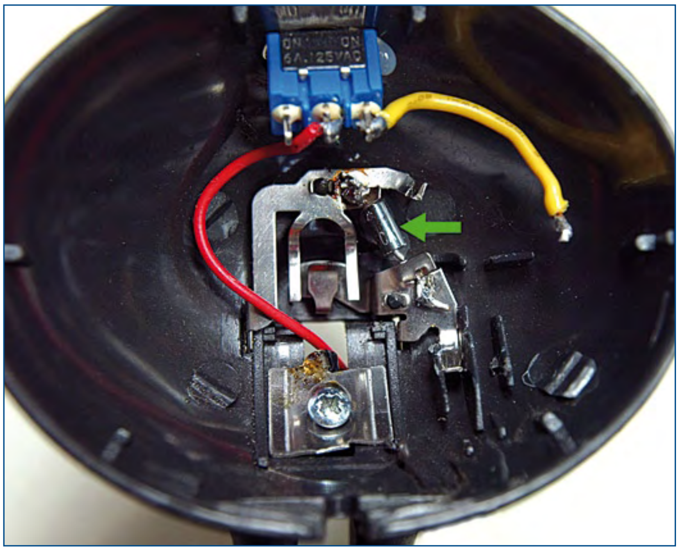


Figure 1. A suppression diode is wired in parallel with the filament lamp in the front bicycle light.

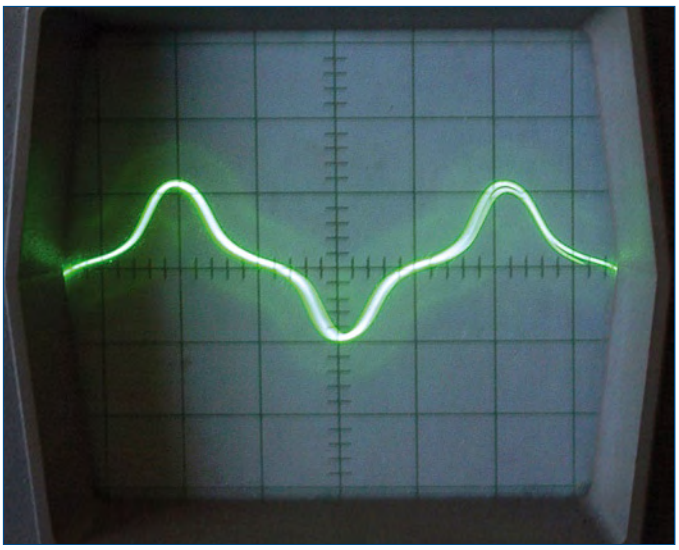


Figure 2. The voltage waveform from a hub dynamo is far from sinusoidal.

Light

sor, which is supposed to protect the bulb, is specified for a dissipation of 5 W, and begins to conduct at 6.5 V. At 0.5 A the voltage across the device will be about 7.5 V. (The dynamo can be thought of as a current source; without the suppressor a voltage of between 8 V and 10 V would appear across the bulb.) Even 7.5 V was, in the author's case, enough to destroy the bulb. Furthermore, the plot of dynamo output voltage against time (see **Figure 2**) is far from sinusoidal. An enquiry at a nearby shop confirmed the author's hunch that he was not alone in his experience: 6 V bulbs were strong sellers.

It was interesting to note that the rear light, which used LEDs, had not failed. LEDs with a series current limit resistor dissipate a power that increases linearly with applied voltage rather than exponentially, and so are more resilient to excessive voltages than bulbs.

Overture

The author had previously experimented with white power LEDs for bicycle lighting. At that time only 1 W devices were available, and, when used with a rim dynamo, the LED was not bright enough. Despite its higher efficiency the 1 W LED was not as bright as a 2.4 W filament bulb, although the whiter light was distinctly more noticeable and lifetime was of course better.

Act I: Power LED

Since then, 3 W LEDs have become available with efficiencies of over 110 lm/W, which is better than fluorescent lamps: a good start. A simple circuit using a 3 W LED is shown in **Figure 3**. The circuit achieves just slightly greater brightness than a halogen bulb. The current sourced by a hub dynamo is rarely much more than 0.5 A, and so a typical 3 W LED with a forward voltage of 3.3 V will be dissipating only around 1.6 W. However, the high efficiency of the device means that its light output is nevertheless greater than that of a 2.4 W halogen bulb.

Entr'acte

For maximum brightness the 6 V output of the dynamo needs to be converted down to 3.3 V to 3.8 V for the

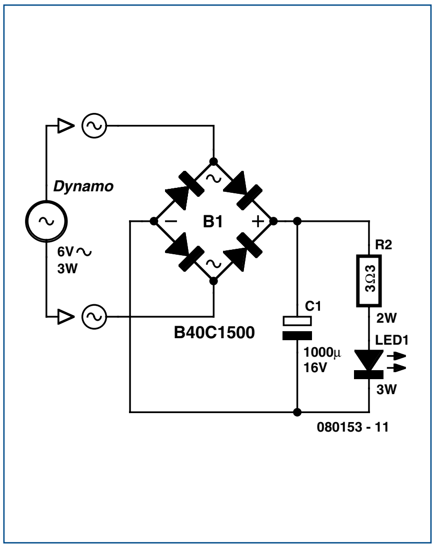


Figure 3. The first experimental circuit for using a 3 W LED in a bicycle light.

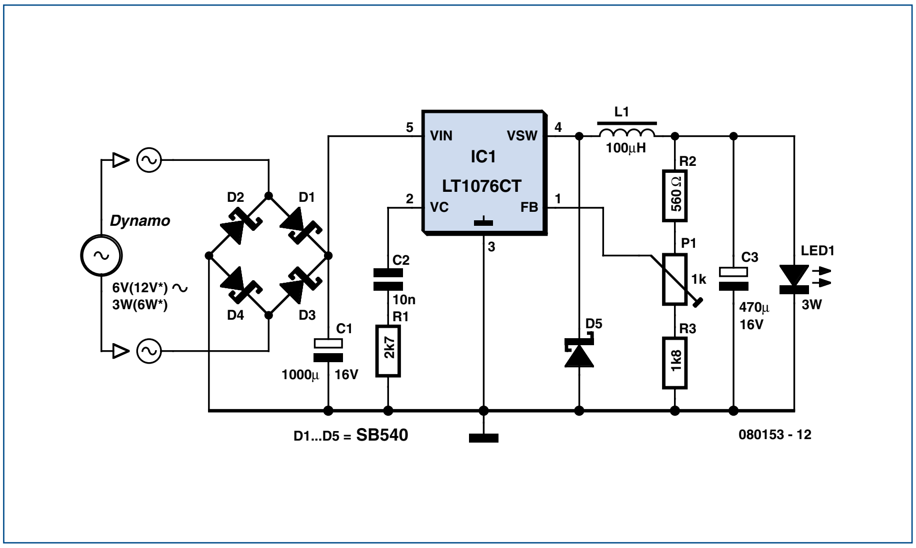


Figure 4. This final circuit for the bicycle light gets the maximum possible illumination from the 3 W LED.

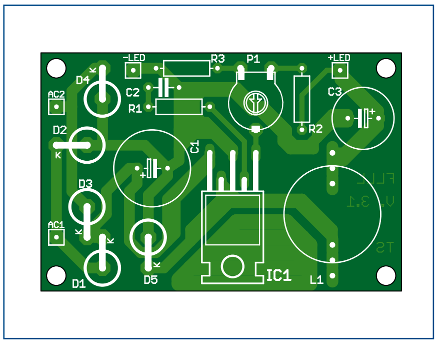


Figure 5. Eagle design files for the printed circuit board are available for download.

COMPONENTS LIST

Resistors
R1 = 2kΩ7
R2 = 560Ω
R3 = 1kΩ8
P1 = 1kΩ preset, miniature, horizontal mounting

Capacitors
C1 = 1000μF 35V, radial, lead pitch 5mm
C2 = 10nF
C3 = 470μF 16V, radial, lead pitch 5mm

Semiconductors
D1-D5 = SB540 (Schottky)*
LED1 = 3W power LED, white*

Miscellaneous
L1 = 100μH 1A (e.g. Reichelt L-PISR 100μ)*
Optics for power LED (20°- type)*
PCB # 080153-1 (artwork download on www.elektor.com)

* see text

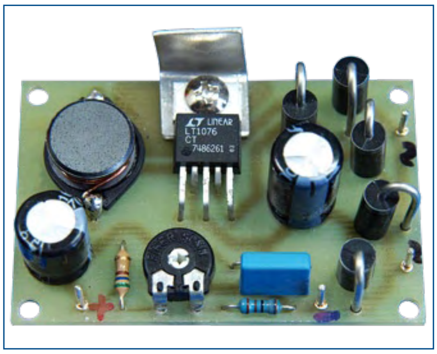


Figure 6. Very compact prototype of the switching regulator.

LED with as little power loss as possible, with a corresponding increase in current to 700 mA.
At such low voltages an ordinary step-down converter will operate at an efficiency of around 80 %. Rectifying the AC voltage from the dynamo using a bridge consisting of Schottky diodes will cost a voltage drop of twice 0.4 V, giving an additional power loss of 0.4 W at 0.5 A. Allowing 0.1 W for the rear LED light leaves us with just 2.5 W; 80 % of that is 2 W. Compared to the circuit in **Figure 3** we have gained a meagre 0.4 W.
So, theoretically at least, things are not looking good. However, according to [1] hub dynamos can develop up to 12 V. At 0.5 A that corresponds to a power of 6 W.
This is more than enough: working backwards from the 3 W required for the LED, we divide by 80 % to obtain an input power to the switching regulator of 3.6 W. At 0.5 A this means a voltage of 7.2 V. Adding on the 0.8 V dropped by a Schottky rectifier bridge, and we need 8 V at the output of the dynamo, which is well within its capabilities.
The switching regulator gives us a further advantage: it protects the LED from excessive current and, above a certain dynamo speed, ensures that the light output provided is constant.

Act II: The circuit

Figure 4 shows a type LT1076 step-down converter [3]. The device requires a minimal number of external components and draws only 8.5 mA to power its internal circuitry. It operates at 100 kHz, can start up from an input voltage of 3.5 V and can deliver up to 2 A.
D1 to D4 form the bridge rectifier, and D5 is the flyback diode. At 5 A the SB540 is somewhat overspecified for this application; at 0.5 A the diode only drops 0.33 V. Good 1 A Schottky diodes such as the SB140 can be substituted for D1 to D5, with a resulting drop in overall efficiency of around 2 %.
The RC network comprising R1 and C2 connected to pin 2 of IC1 provides frequency compensation. The regulator compares the voltage on pin 1 with its internal reference (2.21 V), and so the adjustable voltage divider comprising R2, P1 and R3 allows the output voltage to be adjusted from 2.7 V to 4 V.
L1 is a fixed 100 μH inductor designed for operation at 100 kHz and 1 A. A low ohmic resistance increases overall efficiency. However, the component is not particularly critical, and even a 100 μH toroidal suppression choke will give an efficiency of over 75 %.

Act III: Construction and test

The printed circuit board (**Figure 5**) makes construction straightforward. The layout design was done using Eagle, and the design files and a PDF of the layout are available for download from http://www.elektor.com. If IC1 is to be mounted flat against the board its pins must be bent accurately. A small heatsink made from a piece of aluminium angle (**Figure 6**) is adequate. IC1 dissipates a maximum of 0.5 W, so it is also possible to solder the M3 fixing nut to the copper pad on the reverse side of the board.
The coil suggested in the parts list is a low-cost SMD component to which two lengths of wire need to be carefully soldered. The printed circuit board also has pads for other package varieties.
After populating the board and checking over the soldering, the circuit can

Figure 7. The LED (mounted on its carrier board) and lens are bolted to a piece of aluminium angle to make the lighting module.

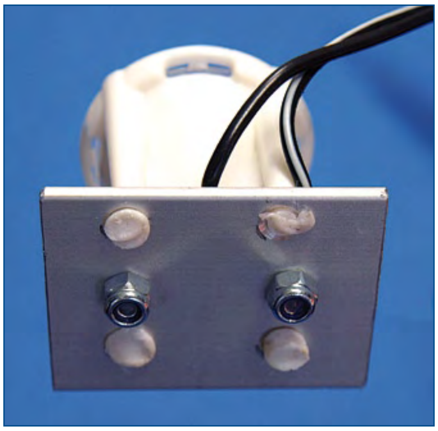


Figure 8. The module from behind: the four plastic lugs of the lens are melted slightly to secure them and the LED is isolated using plastic washers and fixed using M3 locknuts.

be connected to a bench supply or mains adaptor capable of delivering 9 V to 12 V at 0.5 A or more. The output is loaded using a 4 W 4.7 Ω resistor. It should be possible to adjust the output voltage over the range given above and IC1 should become gently warm to the touch. With 10 V at the input and 3.75 V across the 4.7 Ω resistor the overall efficiency of the circuit should be about 75 %: 4 W in and 3 W out.

Before turning the circuit off, adjust P1 to obtain the minimum output voltage so that when the LED is connected it is not immediately overloaded when the circuit is switched back on.

Before wiring up the power LED it, and the printed circuit board on which it is mounted, should be bolted to a length of aluminium angle (not forgetting a dash of thermally conductive paste). It is best if the lens is also fixed to the aluminium angle. This makes a compact lamp module (see **Figure 7** and **Figure 8**) which has the advantage of not immediately damaging your retina if you look directly into it. The module can be built into the old bicycle lamp enclosure with the filament bulb and suppressor removed. **Figure 9** shows the author's prototype where, with a judicious bit of filing, he managed to attach the module to the inside of the original lens in the lamp. The electronics can be mounted in a separate plastic enclosure.

Never look directly into a power LED when it is on!

Finale: Adjustment

As explained in the text box, the voltage across the power LED needs to be adjusted so that the correct current (approximately 0.7 A) flows through it. For maximum LED lifetime (over 20,000 hours) it is essential that this value is not exceeded. With adequate cooling, however, some devices can be run at up to 1 A.

The adjustment is straightforward. If we try to measure the current directly by putting a meter in series with the LED the resistance of the meter will significantly affect accuracy, and so instead we connect the LED module directly to the output and measure the input current. Starting at the bottom of the adjustment range (P1 set to the far left position) we gradually adjust it until the input current is 0.4 A at 10 V, for a total input power of 4 W. Since the overall efficiency of the circuit is approximately 75 %, this means that the power delivered to the LED is approximately 3 watts. If a 12 V input, for example from a mains adaptor, is used the corresponding input current is 0.33 A. The forward voltage of the LED falls with increasing temperature, and so the current though it will rise. P1 will therefore need to be adjusted several times until, after perhaps five minutes, thermal equilibrium is reached. The adjustment is then complete.

Warning: never look directly into the LED. The LED also gets hot!

Encore!

At low road speeds a hub dynamo delivers a low frequency AC voltage. At 5 km/h the LED blinks, becoming steady as the speed rises to 10 km/h. The circuit has not been tested with rim or other types of dynamo.
With a bit more pedalling effort (at speeds of over 30 km/h) the voltage from the dynamo, without suppressor diode, can reach 12 V. This will not cause any problems for the LED, which is protected by the circuit; however, if an ordinary 6 V 0.6 W filament bulb is used in the rear light it will soon be destroyed. It is therefore recommended to use an off the shelf LED-based rear light as well.

The attitude of the governments of some European countries towards our efforts to equip our bicycles with bright and reliable lamps is hardly what one might call 'enlightened': in the author's home country the law specifies the use of filament bulbs in bicycle lights, notwithstanding the fact that a brightly-shining home-made light is a definite improvement on an off-the-shelf regulation-compliant light, and much better again than an ordinary light with a blown filament!

(080153)

Links and References

[1] Hub dynamo laboratory test:
www.vintagebicyclepress.com/VBQgenerator.pdf

[2] P6KE7.5CA data sheet:
www.fairchildsemi.com/ds/P6%2FP6KE7V5CA.pdf

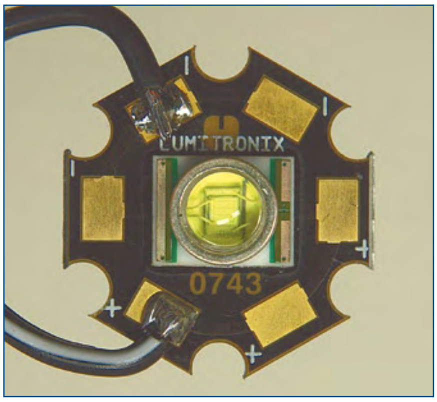
[3] LT1076 data sheet:
www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1003,C1042,C1033,P1007,D2659

Light show

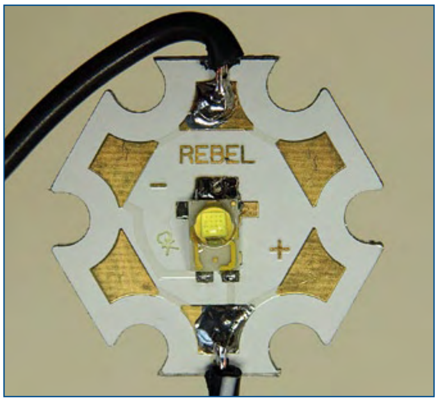
The power LED is the most important component in this circuit. The photographs show sample devices from three manufacturers, all offering efficiencies of between 90 lm/W and 110 lm/W, around the same as a good fluorescent light. Cheaper, but decidedly inferior, 3 W LEDs are also available on the market, but purchasing these is a false economy. It is also best to avoid the 'warm white' variants, which have lower efficiency. The devices shown come mounted on a small printed circuit board which includes an aluminium slug that simplifies extracting heat. When run at 3 W some 2 W is dissipated as heat and a power LED not equipped with cooling will have rather a short life.

There are good reasons for operating LEDs at a constant current rather than at a constant voltage. A typical differential resistance for an LED of the kind used in this project might be as low as 0.2 Ω, which means that a voltage step of 20 mV gives rise to a current step of 0.1 A. Now, 20 mV is not a large quantity, and the sharp temperature dependence of the LED's forward voltage means that a temperature change of 10 °C could easily lead to a current change of more than 0.1 A.

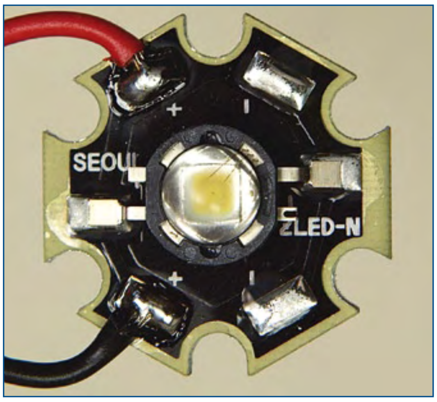
Unfortunately most switching regulator ICs are designed for constant voltage rather than constant current operation. The internal reference voltage of the IC used here is 2.21 V, which is too large to allow the construction of a simple current feedback loop using a series sense resistor: at 0.75 A the power dissipated in the sense resistor would be in the region of 1.6 W. We therefore must resort to controlling the current via the output voltage of the regulator, adjusted via P1 to suit the particular LED used. This is sufficiently accurate if the differential resistance is around 0.2 Ω.



This 3 W power LED from Cree is also an attractive piece of electronics in its own right.

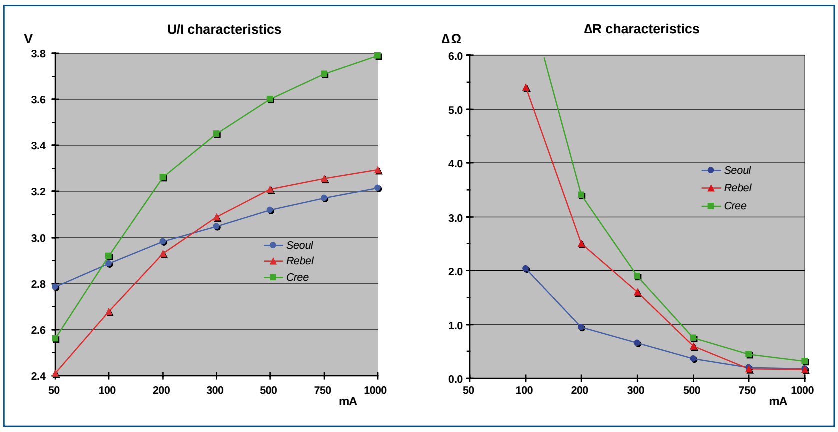


The Luxeon Rebel is particularly small and is mounted on a ceramic substrate.



The Seoul Z-LED is encapsulated not in hard plastic but in a silicone resin which offers long-term resistance to dulling.

In order to examine the differences between the various makes of LED, we made some measurements on a sample of each. The resulting characteristic curves are shown here. It is clear that the forward voltages are very different from one another and that the differential resistance of the LED is very low at currents of around 0.75 A. The consequences of this are as follows.



LED characteristic curves: voltage (left) and differential resistance (right) at various currents.