LED Torch

flashlight goes high-tech

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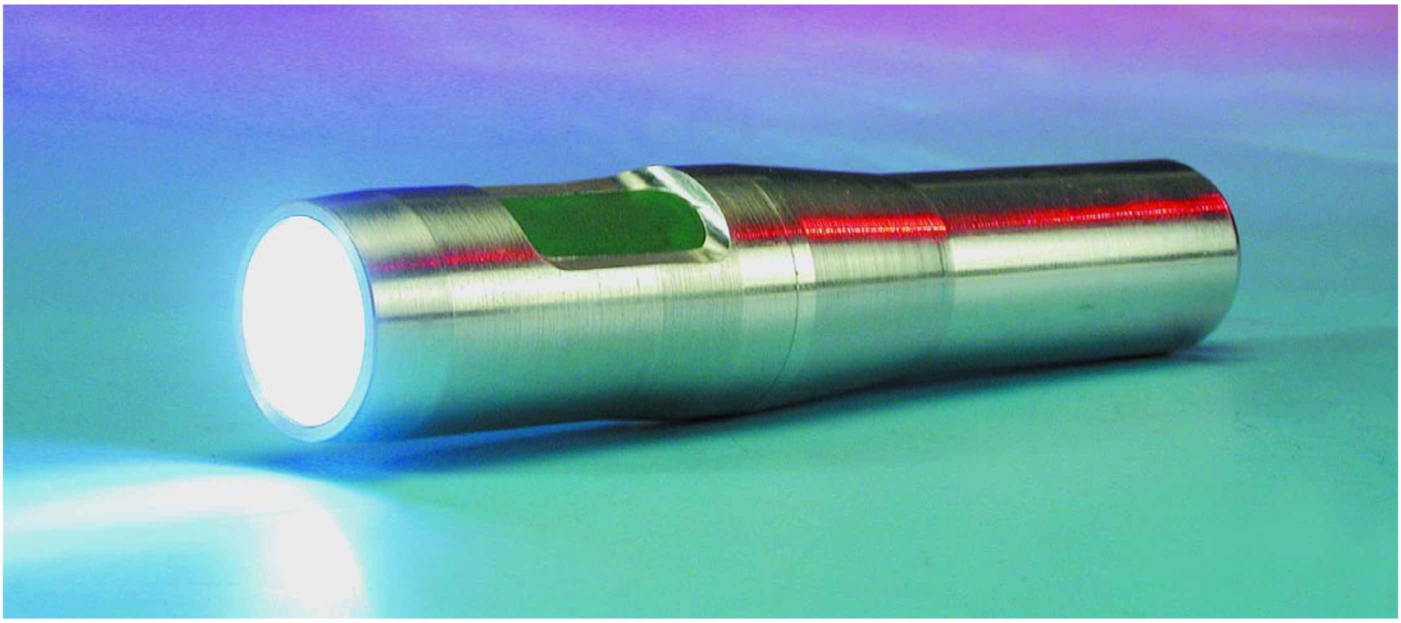
You would be forgiven for thinking that a torch is probably the ultimate minimalist circuit: all you need is a battery, switch and bulb and you're in business but add a microcontroller and you can build in some interesting features that make the humble torch rather more useful…



If you made a wish-list for the ideal torch it would probably start with the need for it to be small enough to fit comfortably in your pocket or rucksack but at the same time be powerful enough to provide enough light at a couple of metres distance to work by for many hours. The environmentally aware would also vote for a rechargeable power source that would hold its charge even if the torch had been lying in a drawer, unused for a couple of years. An indicator showing the amount of charge left in the battery would also be nice together with an automatic cut-off to guard against accidentally draining the battery. It would also be useful if the light level could be efficiently regulated to allow continuous operation for several nights and when the battery gets really low (to 1% of its capacity) still provide a useable emergency light level for a few hours.

To fulfil these criteria we have chosen to use white LEDs instead of a halogen lamp. Contrary to popular belief, the efficiency of a white light LED is not much better than a low power tungsten bulb and in fact worse than higher wattage (> 3 W) bulbs. The LED however offers a significant advantage over filament lamps; they are can be dimmed down to 1/1000th of their maximum power without any loss of efficiency. A tungsten filament, by contrast will glow less brightly and energy will be lost in producing heat but little light so that at half power its efficiency drops to zero. A further advantage is the improved life expectancy of an LED. You can expect it to last more than 1000 times longer than a tungsten lamp so spare bulbs are unnecessary. The LED package also incorporates some optics to direct the light beam so that the torch head

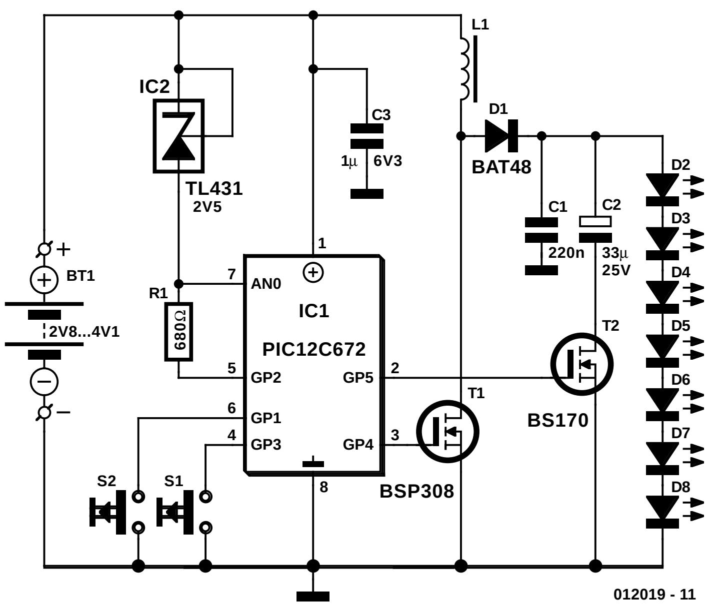


Figure 1. The voltage converter uses a microcontroller.

can be made smaller than a conventional bulb and reflector arrangement.

For the power source a lithium-ion rechargeable battery has been chosen. These cells are more expensive than NiCds but offer a number of advantages: A NiCd cell of the same capacity will weigh three times as much as a Li-Ion cell. Li-Ion also offers a much lower self-discharge of less than 10 % per year compared to 20% per month (!) for NiCds. They also do not suffer from the so-called 'memory effect'.

The circuit

The voltage of a Li-Ion cell varies from 4.1 V fully charged to 2.8 V when empty. The forward conduction voltage of a single white light LED is 3.6 V so it is not possible to limit the current to the LEDs with a simple resistor as you would normally for a red indicator LED. The circuit diagram in **Figure 1** uses a step-up voltage regulator formed by L1, MOSFET T1, diode D1 and smoothing capacitor C1 to supply the LED chain with a controlled power source. The efficiency of the circuit is approximately 94%.

Unusually for a torch, the step-up regulator is controlled by a PIC12C672 microcontroller (IC1). This device has an internal 4 MHz RC oscillator and an 8-bit A/D converter. Analogue input AN0 measures the reference voltage produced by IC2. To conserve energy IC2 is switched on (by pulling GP2 low) only during the measurement time. Capacitor C3 buffers the battery voltage (V_{BATT}) and the A/D converter measures this voltage at the VDD pin. The microcontroller adjusts power to the LEDs by altering the mark-space ratio of the output on pin GP4. The frequency of the signal on this output is a maximum of 30 KHz, less at lower power settings. In the very low power mode the microcontroller would use more power than the LEDs so in this case the microcontroller operates for most of the time in sleep-mode and is woken up every 18 ms to switch the power. In the low power setting capacitor C2 is used to store energy and smooth out the 18 ms flicker on the LEDs. In all other power settings transistor T2 is turned off to disconnect C2. C2 would otherwise prevent a clean switch-off of the light when the torch is set to flash mode.

Two push button switches on the torch allow the selection of six possible commands.

Functions

An advantage of using a microcontroller in this design is that the torch features are defined in software so if you need to change some aspect of the control it is relatively simple to do so (assuming you have the correct programming tools available). Looking a little more closely at the main features of the torch we have:

– The torch brightness can be adjusted in six steps; each step increases power by about three.

– At its lowest setting the light output is sufficient to illuminate close work, ideal for reading comics under the bedcovers! Astronomers will also find this setting useful for reading star maps without seriously impairing their night vision. This setting will use just 0.5 mA and means that one charge will last 120 days (one year if the torch is used for 8 hours per night).

– A built-in time out for each power level is included (see **Table 2**). This feature ensures that only 3% of the battery charge is lost if the torch is accidentally switched on. The torch will give a warning one-minute before it switches off by modulating the light level.

– When the battery voltage falls below 3.3 V the controller will automatically reduce power to the lamp ensuring that the battery has sufficient charge for at least 15 minutes illumination. When the battery voltage falls to 2.8 V the torch switches off to ensure that the battery is not damaged by too deep a discharge.

– After a recovery period the Li-Ion battery regains about 0.5% of its capacity and this will be sufficient for 1 hours operation at the 20 mW setting or 3 hours at 8 mW.

– The torch can be set to act as a warning flashing light with adjustable on/off ratio to conserve power.

– Standby mode uses the least energy. The light flashes at a low setting and can be useful for example for finding the torch in a dark tent. Before the lamp goes into standby mode it will flash to indicate the remaining energy left in the battery. Each flash represents 10% of the cell's capacity. When the cell has less than 10% of its energy left it will indicate after a short delay how much energy remains in steps of 1%.

Table 1 Shows how the torch is controlled using push buttons S1 and S2. **Table 2** gives the parameters of the torch at different light level settings. The column showing duration

Table 1. Function

Key pressed	Function
S1 briefly	Brightness level +
S2 briefly	Brightness level –
S1 and S2 briefly	Off
S1 longer	Flash mode +
S2 longer	Flash mode –
S1 and S2 longer	Battery check, then Standby, Reset Continuous mode

(per charge) for a fully charged battery ignores the effects of cell self-discharge.

Power control

The main function of the step-up regulator is to provide a regulated LED supply voltage despite the falling battery voltage. Taking a closer look at the regulator circuit we find that the energy (E) stored in the inductor (L) by the current (I) can be expressed in the formula:

$$E = \frac{1}{2} \cdot L \cdot I^2 \quad ..1)$$

The current I will increase linearly from 0 and is a function of the time that transistor T1 is switched on (T_{ON}).

$$I = \frac{V_{BATT} \cdot T_{ON}}{L} \quad ..2)$$

Substituting into equation (1) we get the average power (P) for the period:

$$E = \frac{1}{2} \cdot \frac{V_{BATT}^2 \cdot T_{ON}^2}{L}$$

$$P = \frac{1}{2} \cdot \frac{(V_{BATT}^2 \cdot T_{ON}^2)}{L \cdot (T_{ON} + T_{OFF})} \quad ..3)$$

It can be seen that the power to the LEDs is a factor of the battery voltage so that if no regulation were used the power would vary by a factor of 2 as the battery voltage drops from 4.1 to 2.8 V. The average current is P/V_{BATT}. The on to off ratio of the transistor (T_{ON} und T_{OFF}) is altered by the microcontroller to keep P constant.

In order to regulate the power it is necessary for the microcontroller to know the battery cell potential V_{BATT}. To reduce the component count the supply voltage is not directly measured, instead the battery voltage is used as the reference input (= full scale) and the input at AN0 is measured. The TL431AC Bandgap-reference produces a constant 2.495 V. For the 8-bit ADC the measurement result stored in the internal register AD_{RES} is given by:

$$AD_{RES} = \frac{V_{BATT} - 2.495V}{V_{BATT}} \cdot 255 \quad ..4)$$

Rearranging:

$$V_{BATT} = \frac{2.495V}{1 - AD_{RES}/255} \quad ..5)$$

V_{BATT} is measured every 100 ms to regulate the output power.

The microcontroller uses this battery voltage measurement to point to a stored look-up table for one of 16 possible values to control the T_{ON} and T_{OFF} times at output pin GP4.

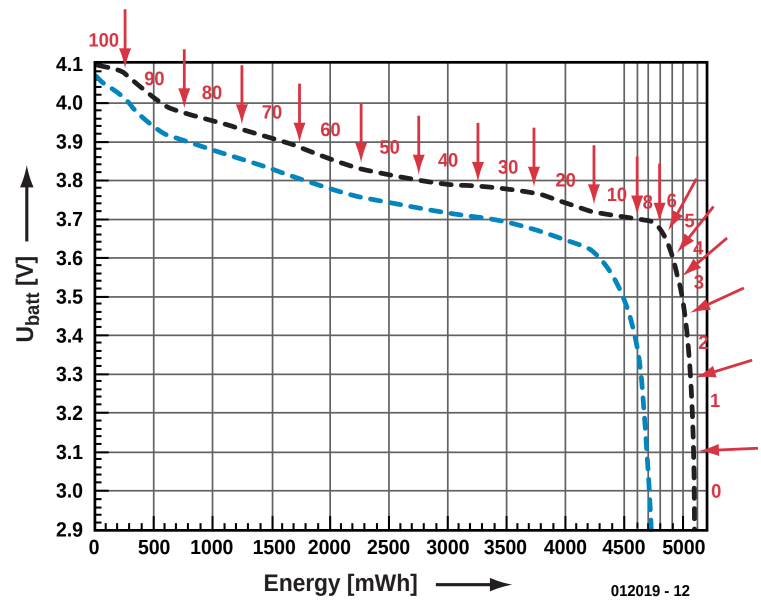


Figure 2. Typical Li-Ion cell discharge characteristics.

Table 2. Light level settings

Setting	Power	Current drain V_{batt} = 3.6 V	Duration (1.3 Ah)	Timeout period
0	0.5 W	140 mA	10 hr	20 min
1	0.2 W	55 mA	24 hr	40 min
2	65 mW	18 mA	3 days	2 h
3	20 mW	6 mA	9 days	5 h
4	8 mW	2.4 mA	22 days	10 h
5	4 mW	1.0 mA	55 days	10 h
Standby	–	30 µA	5 years	24 h
Off	–	2 µA	70 years	–

The value of 'back e.m.f.' (electromotive force) generated across inductor L1 is approximately $6 \times V_{BATT}$ when the transistor T1 is switched off (T_{OFF}). The transistor off time will be $T_{OFF} > 1/6 \times T_{ON}$ this ensures that the current I has time to fall to zero.

Internal resistances of the Schottky diode, inductor and battery produce losses in the circuit and reduce the circuit efficiency. The efficiency at maximum power setting reaches about 94%, but even LEDs from the

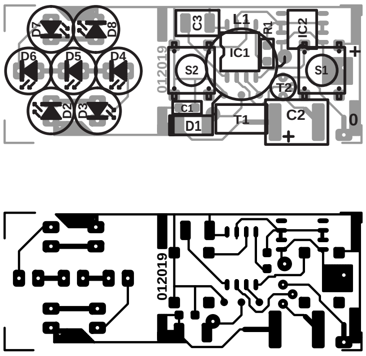


Figure 3. The two-part PCB uses SMD components.

COMPONENTS LIST

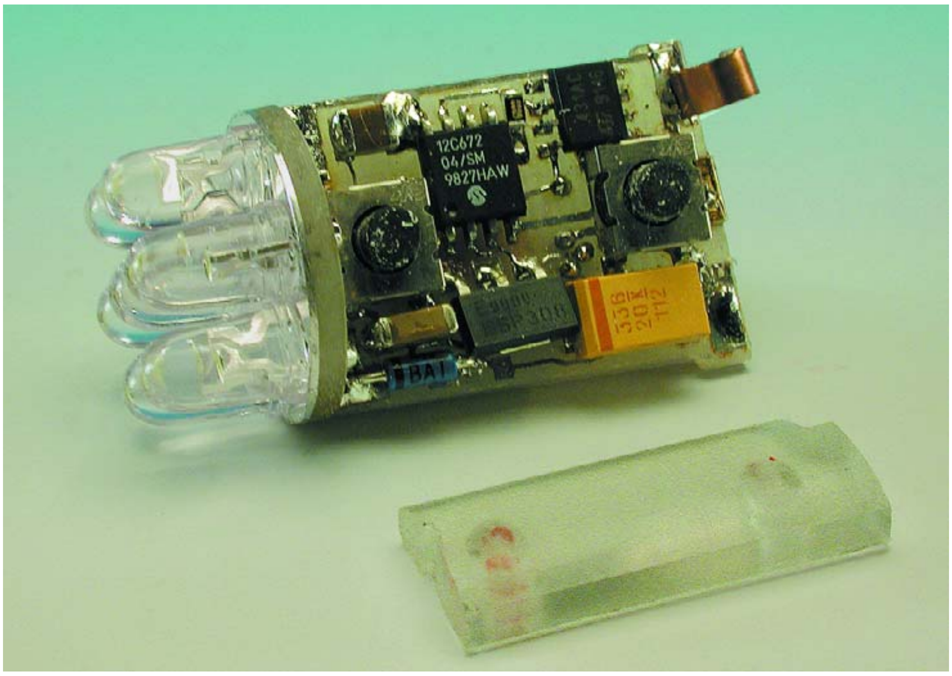
Resistor:
R1 = 680 Ω, SMD size 0805

Capacitors:
C1 = 220nF ceramic, SMD size 0805
C2 = 33µF 20V, SMD size 2220
C3 = 1µF 6.3V, SMD size 1210

Inductor:
L1 = 233µH (100kHz), ESR = 0.27 Ω
Pot core P9.0x5.0/N26 (A_l = 250) with 30.5 turns of 0.22mm dia. ECW

Semiconductors:
D1= BAT48 or 1N4148
D2-D8 = LED, 5mm, white, 6400mCd (Nichia, NSPW500BS) (www.nichia.co.jp/lamp-e.htm), available from Conrad Electronics
T1=BSP308, BSP319 (R_{ON}=50mΩ)
T2=BS170, BSS138 (R_{ON}=5Ω)
IC1=PIC12C672 04/SM, programmed, order code **012019-41**
IC2=LM9140-2.5 or TL431

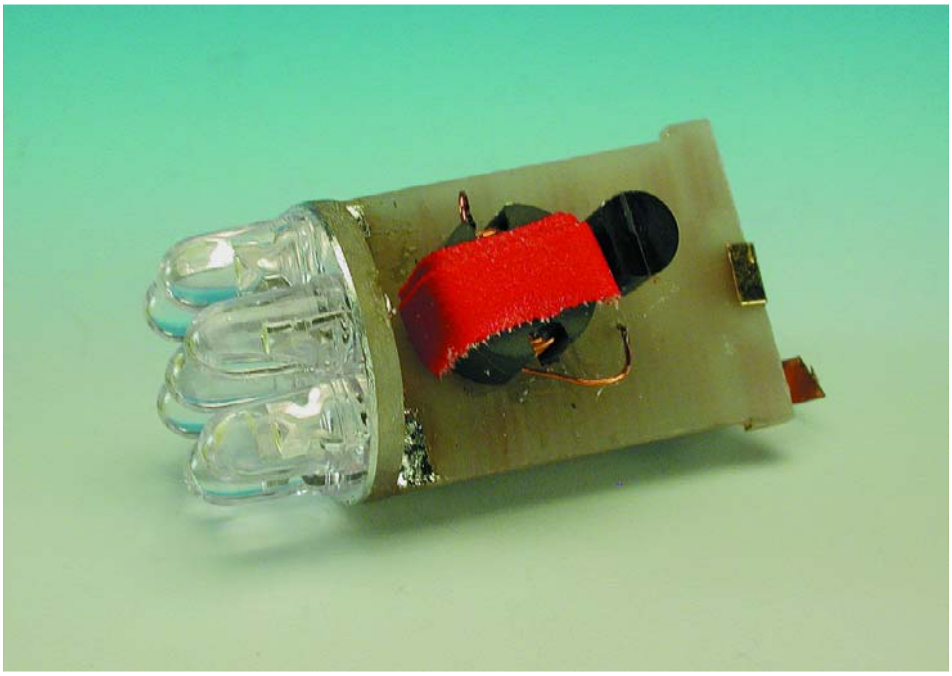
Miscellaneous:
S1,S2 = SMD switch, 1 contact (Mentor 1254.1007 or 1301.9314 or Omron B3FS-1052 from Farnell)
Battery = Sanyo UR18650 Li-Ion, 1350 mAh (18mm, length = 65mm, weight 40g) or Sanyo UR18500 Li-Ion, 1100 mAh (18mm, l = 50mm)



same manufacturer can have poorly matched efficiency values. At the present time the most efficient white light LEDs are made by Nichia. These LEDs specified are only intended for use by OEMs but it is possible to find some outlets that stock them.

Charge indication

An important design feature of the torch is that the user should never be left unexpectedly in the dark. It is therefore necessary for the controller to be aware of the charge remaining in the cell. This charge is dependant on the battery voltage, the discharge current, previous discharge history and cell temperature. In the torch we simply determine the charge remaining by measuring the cell voltage some time (1,000 s) after the light has been switched off. The discharge characteristics of a Li-Ion cell are shown in **Figure 2.** A feature of these cells is that when the load is removed the cell voltage rises slowly (1,000 s approximately) from the lower curve to the upper curve. The arrows and numbers on the



graph show the percentage of charge remaining in the battery and correspond to the figure indicated by the microcontroller. The measurement resolution is approximately ±30 mV, which corresponds to a worse case measurement error of about 4%.

This method of charge measurement is not particularly accurate but is acceptable for our application here. The cell self-discharge is typically less than 5% per year may so the torch will still be ready for use even if it has not been used for some time.

A time-out feature ensures that if the torch is accidentally left on it will not drain the battery. The time-out will occur (independent of power) after approximately 3% of the maximum cell capacity of 5 Wh (watt-hour) is used. When the charge in the cell falls below 10% the microcontroller will reduce power to the LEDs to the next lowest level. The cell voltage will rise slightly. When the remaining charge falls below a threshold the LEDs will be turned off. In this case it is still possible to switch the torch back on at a low setting for a short period.

With just 1% charge left in the cell the torch will function for 5 hrs at brightness level 4 or more than 12 hrs at level 5 so you should never be left completely in the dark.

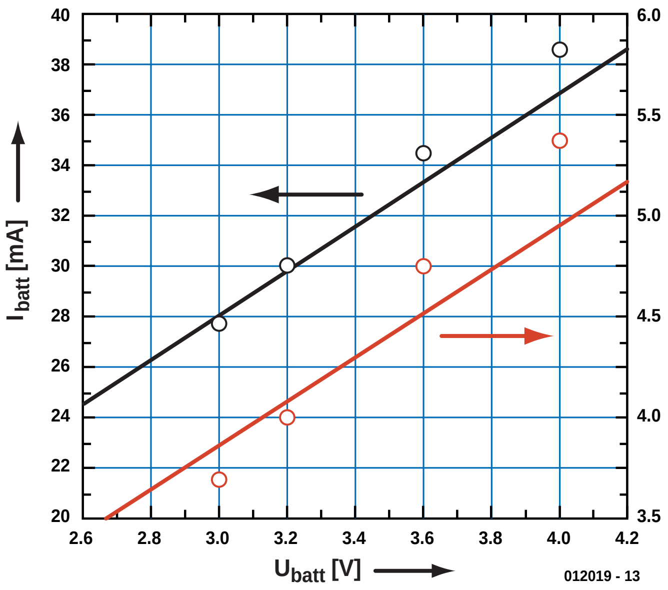


Figure 4. Current consumption of the LED torch.

The battery and coil

The battery specified in the parts list has a capacity of 1.3 Ah (approximately 5 Wh). This is a little bit generous for the torch but the cell size is widely used for Laptops so it is relatively economical. Mobile phone batteries are more difficult to obtain and are therefore more expensive.

More information on Li-Ion cells can be found on the Web at

www.sanyo.com/industrial/batteries/industrial_liion.html

or

www.panasonic.com/industrial/battery/oem/chem/lithion/index.html

Coil L1 has an inductance of 220 to 250 µH with I_{MAX} = 0.5 A and can be purchased off the shelf or alternatively hand-wound using the EPCOS core specified together with 0.2 to 0.22 mm diameter enamelled copper

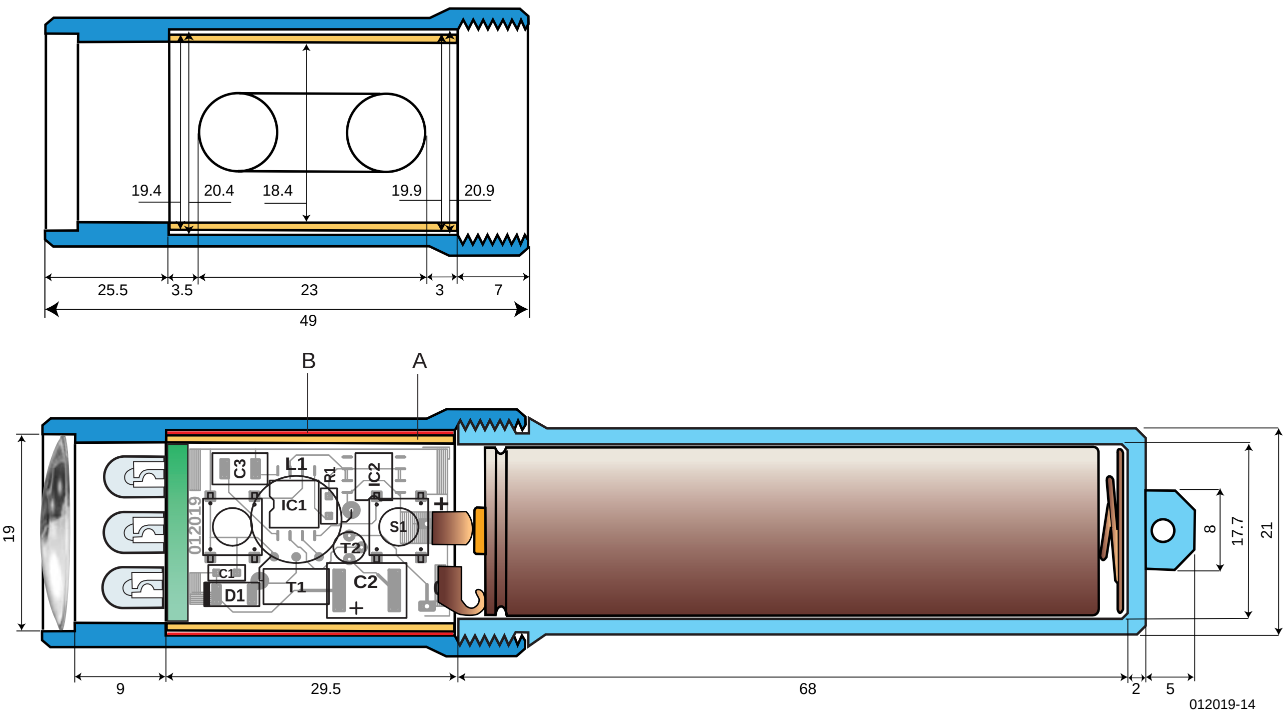
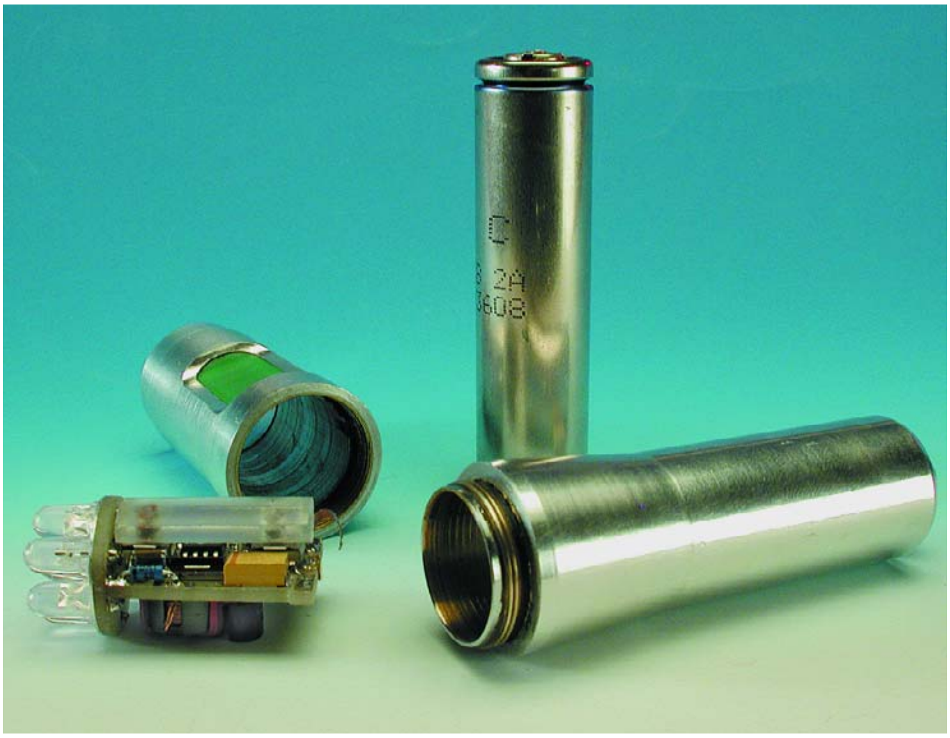


Figure 5. Mechanical layout for a splashproof case.

wire. Each winding layer should be separated by two turns of 0.1 mm thick tape. This will reduce the capacitance of the finished coil and also provide a smooth surface for the next layer of windings. The EPCOS core has an A_l value of 250 so to produce an inductance of 233 mH requires 30.5 turns:

$L = 30.5^2 \times 250\ nH = 233\ mH$

To be on the safe side add an extra turn (L will increase by 6%). After completing the coil it can be measured directly on an inductance meter or tested in-circuit as described under the next heading. If you are planning to fit a magnet to the torch casing to enable it to clamp on to metallic surfaces make sure that the magnet is sited at least 2 cm away from the coil otherwise it will reduce its inductance by about 10%.



Let there be light

The PCB layout is shown in **Figure 3.** Divide the PCB into its two parts and solder all the surface-mount components and LEDs onto the boards. The coil is the only 'conventionally' packaged component and should be soldered to the component side of the PCB. The two PCBs are then soldered together at right angles so that the pads serve both to secure the PCBs and carry power to the LEDs.

To test the circuit it is best to use a variable Power Supply Unit (PSU) with a current indicator (alternatively a low impedance ammeter in series with the supply lead will suffice). It is important to note that the microcontroller technical data sheet specifies a minimum ramp-up time for the supply voltage. If the supply voltage rises too slowly the internal reset does not function correctly and this can cause the FETs to conduct too heavily. This is not a problem when the circuit is battery powered but from an external PSU make sure you adjust the supply voltage (above 2.8 V) before switching the output to the circuit. Before powering-up for the first time set the PSU current limit to 0.4 A and add a 10 Ω resistor in series with the supply.

At power-up (providing no buttons are pressed) the PIC will begin the first of two test routines. These routines are invoked only when the battery is fitted. They will check that the clock frequency is 4 MHz (corresponding to a machine cycle of 1 µs), test the inductor and check the A/D converter.

During the first test routine the lamp will flash on and off with a period of 200 ms and a 50:50 duty cycle. If the ON time of the light is much greater than the OFF time (more than about 20%) then this indicates that the value of L1 is too high and it will be necessary to remove one or two turns from the winding. The lamp will go out after 1,000 periods (200 s) providing none of the buttons are pressed first. During ON times the lamp brightness is set by a T_{ON} time of 15 µs and a $(T_{ON}+T_{OFF})$ time of 100 µs. Current consumption should correspond to the lower line of the graph in **Figure 4**.

When everything is in order, briefly press one of the pushbuttons this will turn off the lamp and start the second test routine. In this routine the lamp is lit continuously at increasing power levels. Doubling the T_{ON} time increases the power four times. The current consumption of the circuit should correspond with the upper line in Figure 4.

The torch will switch off after 50 s if none of the keys are pressed. This time-out is necessary because you may not always be aware that a reset to the microcontroller has occurred. The torch may, for example undergo a mechanical shock sufficient to momentarily disconnect the battery and generate a reset. Pressing and releasing either push-button will return the torch to normal operation at brightness level 2.

Making a good case

Li-Ion cells are not the same size as standard AA cells so it is not a simple matter just to cannibalise a standard torch case.

Machine drawings are available for this project (**Figure 5**), detailing the construction of a suitable casing for the torch. Those of you who do not have a lathe or milling machine lying around at home may wish to take the drawings along to a local machine shop for a quotation. The drawings are produced in Micrographx format and can be downloaded from this month's Free Downloads at the *Elektor Electronics* website. Note that the PCB slides into tapered slots in the head of the torch, this ensures that the PCB and the splashproof pushbutton covers (boots) are securely held in place.

Solder two copper battery contacts to the PCB and fit a suitable spring in the base of the torch to ensure that the Li-Ion cell makes a good connection with the contacts.

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