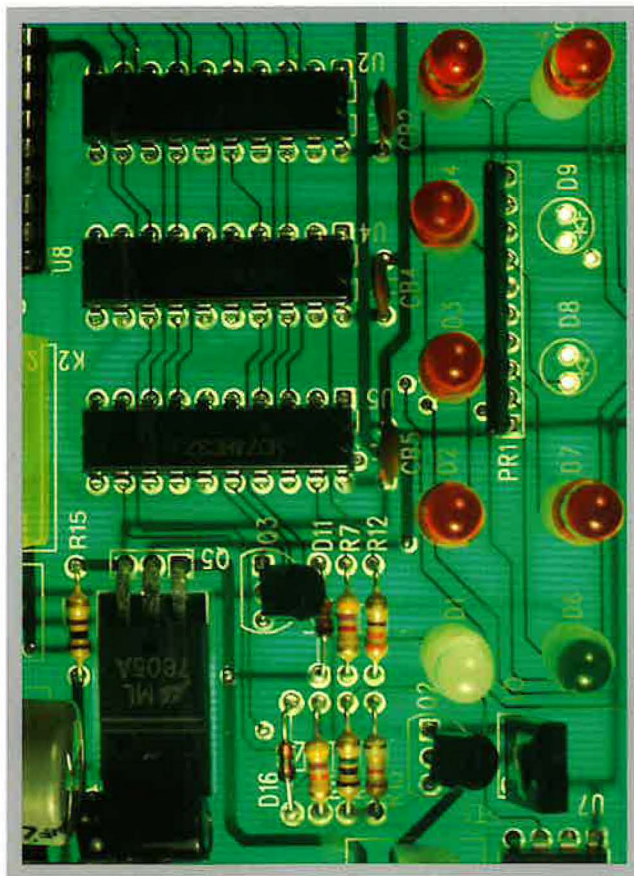


A Newnes Circuits Manual

Optoelectronics

CIRCUITS MANUAL

Second edition



R M MARSTON



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Second edition

R. M. MARSTON



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FOR EVERY VOLUME THAT WE PUBLISH, BUTTERWORTH HEINEMANN
WILL PAY FOR BTVCV TO PLANT AND CARE FOR A TREE.

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Basic LED display circuits

7 dot-matrix

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The simple LED (light-emitting diode) is the most important and widely used of all modern optoelectronic devices. It emits a fairly narrow spectrum of visible (usually red, orange, yellow or green) or invisible (infra-red) light when its internal diode junction is stimulated by a forward electric current, has good power-to-light energy conversion efficiency, and has a very fast response time (often less than $0.1\mu\text{s}$). This chapter explains LED operating principles and characteristics and shows a variety of ways of using LEDs as basic visual indicators, as simple 'flashing light' displays, and as micropower flashing lights.

LED basics

Introduction

Figure 2.1(a) shows the standard symbol used to represent a LED in this volume, together with its anode (a) and cathode (k) terminal notations. Normal LEDs are *pn* junction diodes and use the basic semiconductor structure shown in Figure 2.1(b), but are made from exotic semiconductor materials such as gallium arsenide phosphide (GaAsP) or aluminium-gallium

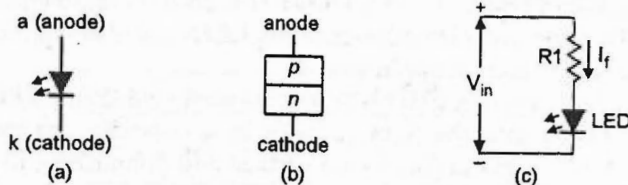


Figure 2.1 Standard LED symbol and terminal notations (a), basic semiconductor structure (b), and basic way of using a LED as a simple light generator (c)

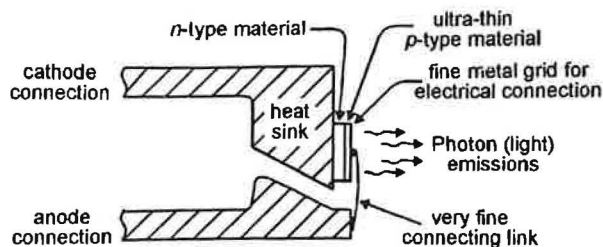


Figure 2.2 Typical internal structure of a normal LED

arsenide (AlGaAs), etc. Like normal junction diodes, they pass current easily in the forward direction but block it in the reverse direction.

Figure 2.1(c) shows the basic way of using a LED as a simple light generator, powered from a fixed-voltage supply. Resistor R1 limits the LED's forward current (and thus the LED brightness) to a sensible value. Normal LEDs operate in the basic way described in the next paragraph.

When a *pn* junction diode is conducting in the forward direction, it releases energy as its charge carriers (electrons and holes) recombine as the electrons jump from the semiconductor's conduction band to its valence band. In a normal silicon diode, most of this energy is released in the form of heat, plus a minute amount of radiant (light) energy in the form of photons. In a LED, however, the released radiant energy is – because of the special and exotic nature of the device's semiconductor material – several orders of magnitude greater than in a normal silicon diode, and LEDs thus act as excellent generators of visible or IR light. The generated light's wavelength (and thus its colour) depends on the precise formulation of the semiconductor material.

Figure 2.2 shows the typical internal structure of a normal LED. The *p* and *n* materials are fused together, with the *n* material bonded to a heat sink that also forms the cathode connection. The *p* material is ultra-thin and translucent, and is connected to the anode terminal via a very fine bonded-on metal grid and a fine wire link. When the LED is active, photons are generated at the *pn* junction and radiate outwards, through the surface of the translucent *p* layer and the metal grid, and finally emerge from the 'viewing' end of the LED. This standard type of LED is known (for obvious reasons) as a surface-emitting LED; more-complex edge-emitting LEDs are also manufactured for use in special data-transfer applications.

When a surface-emitting LED is active, its semiconductor emitting surface is uniformly bright and the light radiates in a cone-like manner, with its strength greatest at right angles to the surface and diminishing in strength at declining angles. This light radiation pattern is known as *Lambertian* and takes the form shown in Figure 2.3; the power levels fall to 50% of maximum at the 60° viewing angle points, i.e. the pattern has a half-power bandwidth

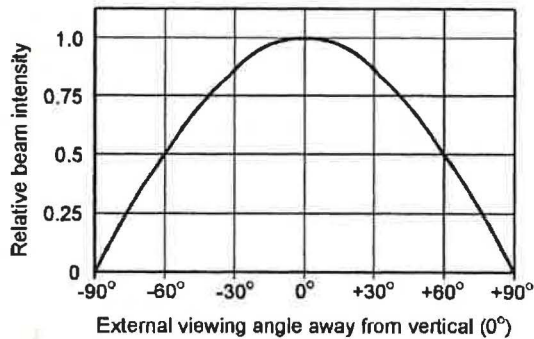


Figure 2.3 Lambertian radiation pattern produced from the semiconductor surface of a normal LED. The half-power width is 120°

of 120° . Most 'round' LEDs incorporate a simple lens that modifies the light pattern actually radiated by the LED.

Roughly 2V are developed across most LEDs when passing a useful forward current; *Figure 2.4* lists the typical forward volt drops (V_f) of different coloured standard 5mm diameter LEDs at forward currents of 20mA; the actual voltage value varies with the current value. If a LED is reverse biased it may avalanche or zener at a fairly low voltage value, typically less than 12V.

LEDs are available in a variety of styles, the most popular being the 'round' type that has the basic shape shown in *Figure 2.5* and which is made in standard diameter sizes of 3mm, 5mm (0.2in), 8mm, or 10mm. Round LEDs use a clear or coloured plastic case with a lens moulded into its dome, and are designed to be viewed end-on, looking towards the dome, as indicated in the diagram. The LED case has a polarity-identifying flat moulded into the side of its base adjacent to the cathode lead, which is usually shorter than the anode lead when untrimmed. Special fittings are readily available for fixing most sizes of LED to front panels, etc.

One important but confusingly-named LED parameter is its 'viewing angle', at the extremes of which the LED's optical output intensity falls to half of its maximum axial value. Some LEDs give a diffused output, in which the light intensity falls off gradually beyond the viewing angle and is thus

Colour	Red	Orange	Yellow	Green	Blue
V_f (typical)	2V	2V	2.1V	2.2V	3.3V

Figure 2.4 Typical forward voltage values of standard LEDs at a current-limited value of 20mA

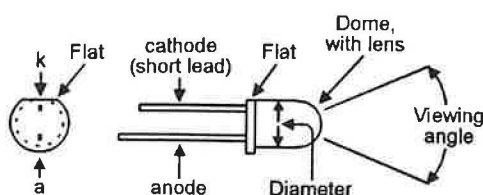


Figure 2.5 Typical physical details of 'round' LEDs and methods of recognizing their polarity

clearly discernible over a wide angular range; others (particularly Hyperbright types) have a sharply focused output in which the light intensity falls off very sharply beyond the specified viewing angle.

LEDs are available in five different brightness categories, which are usually known as Standard, High Brightness, Super Bright, Ultrabright, and Hyperbright. LED brightness level is almost linearly proportional to the operating current value over most of the LED's normal (DC) operating current range. The brightness is usually specified in millicandelas (mcd), with the LED passing an operating current of 20mA. The table of Figure 2.6 presents typical optical output power and viewing angle figures for the five types of 5mm round LED. Note in the Red LED column that the Ultrabright and Hyperbright devices (which use water-clear lenses) are 143 and 500 times brighter, respectively, than a standard red LED.

LED type	Viewing angle	Red	Green	Orange
Standard	60°	7mcd	5.2mcd	8mcd
High Brightness	40°	30mcd	25mcd	50mcd
Super Bright	30°	125mcd	120mcd	140mcd
Ultrabright	25°	1000mcd	—	—
Hyperbright	25°	3500mcd	—	—

Figure 2.6 Typical viewing angle and optical output power figures (in millicandelas) of five basic types of 5mm red, yellow and green LEDs

LED jargon and data

When designing LED-based circuits, it is useful to be able to decipher the jargon used in the manufacturer's data sheets. The two most important sets of jargon are those that relate to the LED's light output characteristics and those that relate to the LED's input-to-output power characteristics. Figures 2.7 to 2.11 help explain the most important pieces of this jargon.

All man-made light generators produce a spectrum of light wavelengths rather than a single wavelength. In tungsten lamps, the spectrum is very wide; in lasers, it is very narrow; in LEDs the spectrum is moderately narrow.

Figure 2.7

Figure 2.7 shows this example of peak-power orange, a

The LED between expressed variation in this case

In applications indicator, can be observed. Figure 2.8 shows orange, y

Figure 2.8

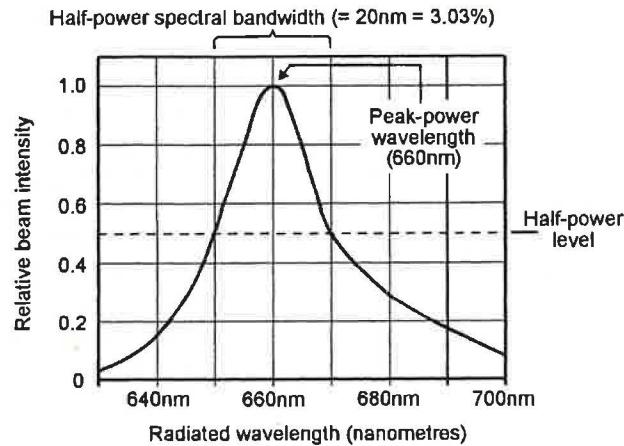


Figure 2.7 Typical light output spectrum of a red LED

Figure 2.7 shows the typical light output spectrum of a red LED, which in this example has a peak-power wavelength of 660nm; other typical LED peak-power wavelengths are 565nm for green, 595nm for yellow, 610nm for orange, and 880nm to 950nm for IR LEDs.

The LED's spectral bandwidth (sometimes called *linewidth*) is measured between the two half-power radiation (output intensity) levels and may be expressed in actual wavelength variation (20nm in this example) or as that variation expressed as a percentage of the peak-power wavelength (as 3.03% in this case).

In applications where a LED is required to act as a simple or flashing indicator, vital data such as its operating current and power level limits, etc., can be obtained from manufacturer's or retailer's basic data tables. Figure 2.8 shows a typical data table for a range of 5mm Standard diffused red, orange, yellow and green LEDs. Note that the listed maximum power and

	Red	Orange	Yellow	Green
I_f (typ.)	10mA	10mA	10mA	10mA
I_f (max)	30mA	30mA	25mA	30mA
V_f (typ.)	2.0V	2.0V	2.1V	2.2V
V_R (max)	5V	5V	5V	5V
Intensity (typ., at 10mA)	4mcd	14mcd	15mcd	10mcd
Viewing angle (typ.)	60°	60°	60°	60°
Peak wavelength	660nm	610nm	595nm	565nm
Power dissipation (max)	130mW	120mW	100mW	120mW

Figure 2.8 Typical data table for a range of 5mm Standard diffused LEDs

current values are DC-equivalent (rather than instantaneous absolute or pulse) values; the LED may be damaged if these DC values are exceeded.

A LED's operating current and power limits are determined mainly by the thermal characteristics of its very small active *pn* area. If a red LED is powered from a DC source, about 60mW are generated in its *pn* area at an operating current of 30mA, and may typically raise the temperature of its *pn* area to 55°C. At 60mA, the generated power rises to about 150mW and the *pn* area's temperature reaches its maximum operating limit of 100°C; any further rise in operating current (or power) may destroy the *pn* area.

In practice, the physical mass of the LED's *pn* area and its heat sink (see Figure 2.2) provide it with thermal inertia, and the *pn* area thus takes a finite time to heat up in response to sudden power surges. The relationship between surge current and response time is normally given in the LED's expanded data sheet, under the *Absolute maximum ratings* section, and is noted in terms such as '1A <10μs', and in this example means that the LED can safely handle a 1A current pulse for a maximum of only 10μs.

Note that the above '1A <10μs' value gives a direct relationship between permitted current and pulse duration values and can be safely translated into alternative values at currents *less* than 1A, thus giving values such as '100mA <100μs', or '50mA <200μs', etc. This data applies to non-repetitive pulses; if the pulses are repetitive, their *mean* power dissipation (integrated over one complete repetition period) must not exceed the LED's normal DC operating power limit.

The above data is of great value when designing LED remote control and remote signalling systems, in which the transmitter LED is energized by repetitive high-value current pulses. In such designs, additional basic design data must be derived from the manufacturer's expanded data sheets (available directly from the manufacturer or via their Web site on the Internet). Figures 2.9 to 2.11 show typical examples of such data sheets.

Figure 2.9 shows the typical relationship between luminous output intensity (normalized to unity at a forward current of 20mA) and forward current over a LED's normal 0–30mA operating range; the intensity is almost linearly proportional to forward current at values up to 20mA.

Figure 2.10 shows the typical relationship between the above LED's luminous output intensity (normalized to unity at a forward current of 20mA) and the LED's forward current value over the extended 10mA to 1A operating range (this particular LED has a DC forward current limit of 50mA, a surge current limit value of 1A <10μs, and a DC power limit of 150mW). Note that the normalized light intensity rises to a peak value of 1.6 at a forward current of 100mA but decreases at higher currents. The highest useful pulse current is thus 100mA, at which the maximum permitted pulse length is thus 100μs.

Figure 2.11 shows the typical relationship between the above LED's forward voltage and its forward current, over the extended operating range.

Relative luminous intensity,
normalised at 20mA

Relative luminous intensity,
normalised at 20mA

0.5

1000

500

200

100

50

20

10

5

2

1

Forward current (mA)

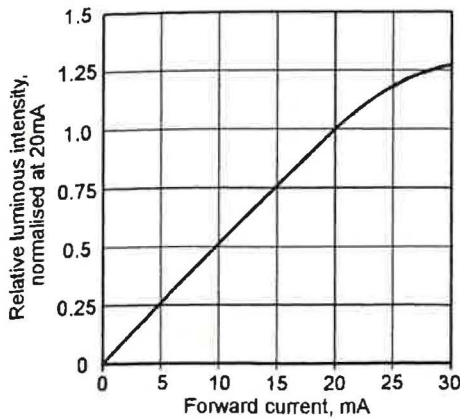


Figure 2.9 Typical relative luminous intensity versus forward current graph covering normal operating ranges

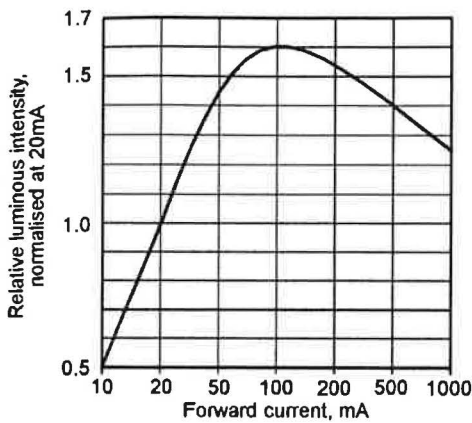


Figure 2.10 Typical relative luminous intensity versus forward current graph covering extended (pulse) operating ranges

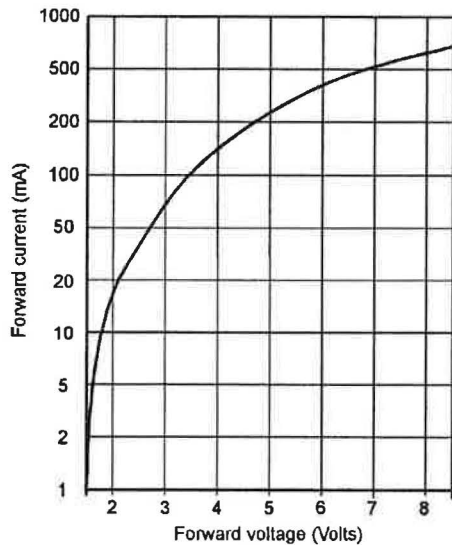


Figure 2.11 Typical forward voltage/current graph covering extended (pulse) operating ranges

Note that this particular LED generates a forward voltage of 3.5V when fed with a 100 μ s 100mA pulse, and its *pn* junction thus receives a peak power input of 350mW under this condition. If this pulse is applied in the form of a symmetrical squarewave, the mean values of both the current and the voltage are halved, and the *mean* power value is thus reduced by a factor of four, to 87.5mW in this case; this value is well within the safe operating limits of this particular LED.

Thus, the above data shows that this particular LED can be efficiently and safely used as a remote-control or signalling transmitter by feeding it with controlled squarewave signals with a peak value of 100mA and a minimum operating frequency of 5kHz (i.e. with a maximum cycle period of 200 μ s).

Basic LED indicator circuits

A LED can be used as a simple light-generating 'indicator' by wiring it in series with a current-limiting resistor and connecting the combination across a suitable DC supply voltage. *Figure 2.12* shows how to work out the resistance (*R*) value needed to give a particular current from a particular DC supply voltage. Thus, if a red LED has a forward volt drop of 2V at 20mA and is required to operate at 20mA from a 10V supply, *R* needs a value of (10V - 2V)/0.02A = 400 Ω . In practice, *R* can be connected to either the anode or the cathode of the LED.

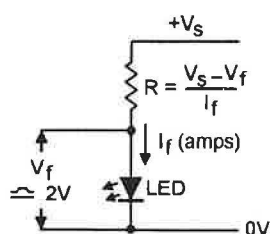


Figure 2.12 Method of finding the *R* value for a given V_S and I_f

A LED can be used as an indicator in an AC circuit by wiring it in any one of the three alternative ways shown in *Figure 2.13*. In *Figure 2.13(a)* the LED is wired in inverse parallel with a 1N4148 (or similar) silicon diode, to prevent the LED being reverse biased. The LED is fed with half-wave current in this mode, with only half of *R*1's current flowing through the LED; for a given LED brightness, the '*R*' value must be halved relative to that indicated in the *Figure 2.12* DC circuit. Thus, to operate the LED at a mean current of 10mA from a 100V AC supply, this design needs an *R*1 value of about 5k Ω , and *R*1 needs a power rating of at least 2 watts.

In *Figure 2.13(b)* the LED is wired in series with rectifier *D*1 (which must have a reverse-voltage rating greater than the peak voltage value of the AC

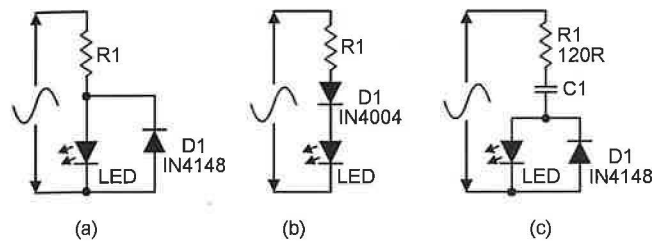


Figure 2.13 Ways of using a LED as an indicator in an AC circuit

supply), to protect the LED when it is reverse biased. The LED is fed with half-wave current in this mode, with all of this current flowing through R1, and for a given LED brightness the 'R' value must again be halved relative to that indicated in the Figure 2.12 circuit. Note in this circuit, however, R1's mean current and voltage values are both halved relative to those of the Figure 2.13(a) design. Thus, to operate the LED at a mean current of 10mA from a 100V AC supply, this design needs an R1 value of about 5k Ω , and R1 needs a power rating of at least 0.5 watts.

In Figure 2.13(c) the LED is wired in inverse parallel with silicon diode D1, and the LED's mean current is determined mainly by the values of the AC supply voltage and the impedance of capacitor C1 (R1 simply limits switch-on surge currents to a safe value). Note that, since a capacitor's voltage and current are 90° out of phase, negligible power is dissipated in C1 in this circuit, which is usually used at 110V to 240V AC power line voltages. When powered by a 50–60Hz AC supply, a C1 value of 0.47 μ F gives a mean LED current of about 10mA from a 120V supply, or 20mA from a 240V supply; the current value is directly proportional to the C1 value.

Special-purpose LEDs

LEDs are readily available in a variety of special-purpose forms, the best known of which are the 'direct connection' type, the 'flasher' type, and the multi-colour types.

Direct connection LEDs are designed to be connected directly across a fixed-value DC or AC voltage source. DC voltage types take the basic form shown in Figure 2.14(a) and incorporate a current-limiting resistor that is

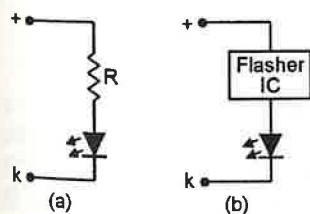


Figure 2.14 Basic forms of a direct connection DC LED (a) and a flasher LED (b)

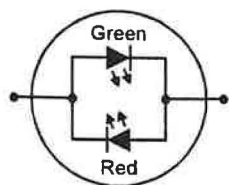


Figure 2.15 Bi-colour LED actually houses two LEDs connected in inverse parallel

housed in the LED body in 5V and 12V types, or in one of the LED leads in higher voltage types. AC voltage types (usually designed for use with 110V or 240V supplies) take one of the basic forms shown in *Figure 2.13* but are usually housed in an insulated panel-mounting assembly.

Flashing LEDs take the basic form shown in *Figure 2.14(b)* and have a built-in integrated circuit that gives the flashing effect. They are available in red, green and yellow, have a typical flashing frequency of 2Hz, and can (typically) use 6V to 12V DC supplies.

Multi-colour LEDs are actually 2-LED devices; *Figure 2.15* shows a bi-colour device that comprises a red and a green LED connected in inverse parallel, so that the colour green is generated when the device is connected in one polarity, and red is generated when it is connected in the reverse polarity. This device is useful as a polarity or null indicator.

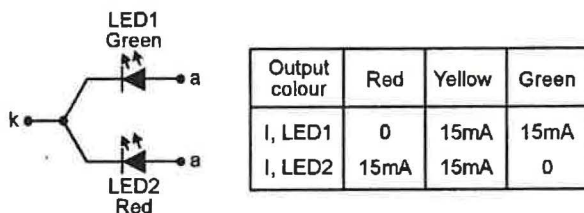


Figure 2.16 Multi-colour LED, giving three colours from two junctions

Figure 2.16 shows another type of multi-colour LED, which is sometimes known as a tri-colour type. This comprises a green and red LED mounted in a 3-pin common-cathode package. This device can generate green or red colours by turning on only one LED at a time, yellow by turning both LEDs on by equal amounts, or any colour between green and red by turning both LEDs on in the appropriate ratios.

Multi-LED circuits

If several LEDs need to be driven from a single power source, this can be done by wiring all LEDs in series, as shown in *Figure 2.17*, provided that the supply voltage is significantly greater than the sum of the individual LED forward voltages. This circuit thus consumes a minimum total current, but is

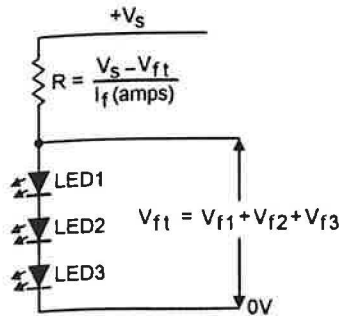


Figure 2.17 LEDs wired in series and driven via a single current-limiting resistor

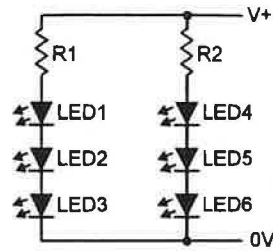


Figure 2.18 Any number of Figure 2.17 circuits can be wired in parallel, to drive any number of LEDs

limited in the number of LEDs that it can drive. Any number of these basic circuits can, however, be wired in parallel, so that any number of LEDs can be driven from a single source, as shown in the 6-LED circuit of Figure 2.18.

An alternative way of simultaneously powering several LEDs is to simply wire a number of the Figure 2.12 circuits in parallel, as shown in Figure 2.19; note, however, that this circuit is very wasteful of supply current (which equals the sum of the individual LED currents).

Figure 2.20 shows a 'what not to do' LED-driving circuit, in which all the LEDs are wired directly in parallel. Often, this circuit will not work correctly because inevitable differences in the forward characteristics of the LEDs causes one LED to hog most or all of the available current, leaving little or none for the remaining LEDs.

LED flasher circuits

Simple designs

One of the simplest types of LED display circuit is the LED flasher, in which a single LED repeatedly switches on and off, usually at a rate of one or two flashes

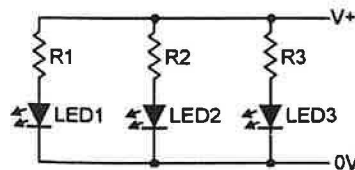


Figure 2.19 This circuit can drive any number of LEDs, but at the expense of high current

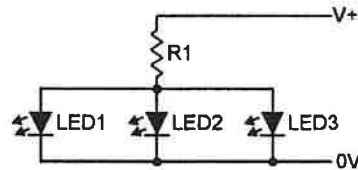


Figure 2.20 This LED-driving circuit may not work; one LED may hog most of the current

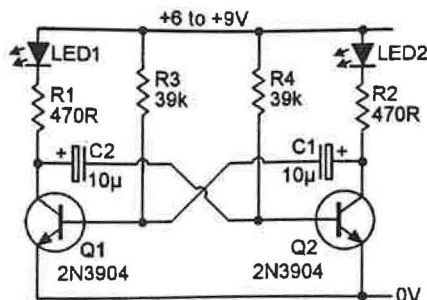


Figure 2.21 Transistor 2-LED flasher circuit operates at about 1Hz

per second. A 2-LED flasher is a simple modification of this circuit, but is arranged so that one LED switches on when the other switches off, or vice versa.

Figure 2.21 shows the practical circuit of a transistor 2-LED flasher, which can be converted to single-LED operation by simply replacing the unwanted LED with a short-circuit. Here, Q1 and Q2 are wired as a simple 1Hz astable multivibrator, in which Q1 and LED1 turn on as Q2 and LED2 turn off, and vice versa, and in which the astable switching rates are controlled by the values of C1–R3 and C2–R4.

Figure 2.22 shows an IC version of the 2-LED flasher, based on a 555 or 7555 timer IC that is wired in the astable mode, with its main time constants determined by the C1 and R4 values and giving a cycling rate of about 1Hz (one flash per second). The circuit action is such that output pin 3 of the IC alternately switches between the ground and the positive supply voltage levels, alternately pulling LED1 on via R1 or driving LED2 on via R2. The circuit can be converted to single-LED operation by omitting LED2 and R2.

Figure 2.23 shows a useful modification of the above circuit, in which the flashing rate is made variable via RV1, and two pairs of series-connected LEDs are connected in the form of a cross so that the visual display alternately switches between a horizontal bar (LED1 and LED2 ON) and a vertical bar (LED3 and LED4 ON), thus forming a visually interesting display. The cycling rate is variable from 0.3 to 3 flashes per second.

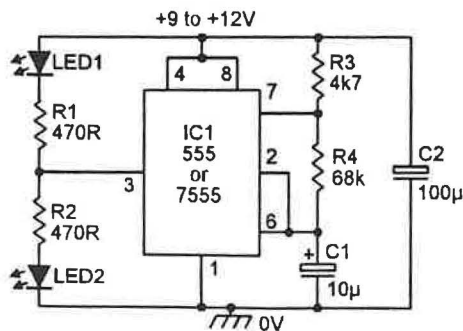


Figure 2.22 IC 2-LED flasher circuit operates at about 1Hz

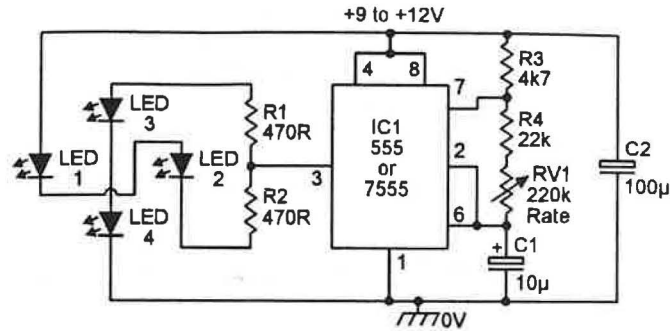


Figure 2.23 The rate of this 4-LED double-bar flasher is variable from 3 to 0.3 flashes per second

Micropower LED flashers

Simple LED flasher circuits of the types shown in *Figures 2.21 to 2.23* consume mean operating currents of several milliamps. Micropower LED flashers, on the other hand, consume mean operating currents that are measured in microamps (typically ranging from $2\mu\text{A}$ to $150\mu\text{A}$), and are intended mainly for use in battery powered 'emergency indicator', 'battery state', and 'burglar deterrent' applications.

In emergency indicator applications, micropower LED flashers can be used to indicate the positions of emergency exits, lanterns, torches, alarm buttons, or safety equipment, etc., under dark conditions (perhaps caused by a failure of a main lighting system). When used as battery state indicators, they are often fitted in smoke alarms and other low-current long-life units that are powered by 4.5V to 12V batteries. When used as burglar deterrents, they are prominently fitted to real or dummy burglar alarm control or alarm/siren boxes or CCTV cameras, etc.

To understand the basic principles behind micropower LED flashers you must first learn some basic facts concerning visual perception, as follows.

- (1) The human eye/brain combination is sharply attracted by sudden changes in visual patterns or light levels; it is particularly sensitive to some types of flashing light. *Figure 2.24* shows the typical 'light flash' response of the human eye/brain combination when presented with a bright LED-generated pulse of light.
- (2) Note from *Figure 2.24* that the flash must be present for at least 10ms to be seen (perceived) at full brilliance, and that – when the flash terminates – the 'persistence of vision' effect causes the perceived brilliance to decay fairly slowly, typically taking 20ms to fall to 50% of its maximum (pre switch-off) value. Consequently, the eye can only see

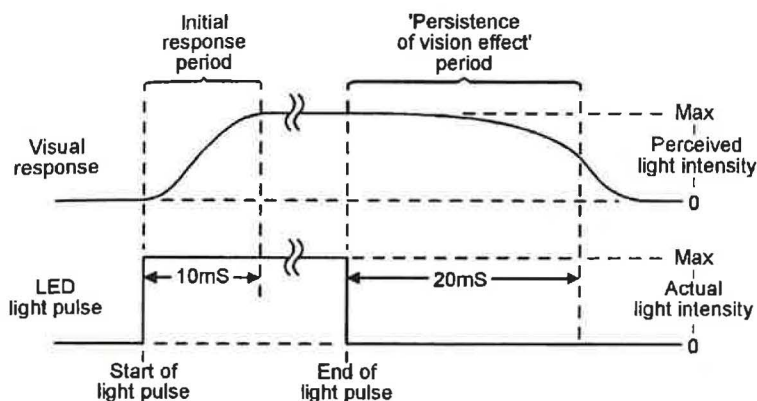


Figure 2.24 Typical 'light flash' response of the human eye/brain combination

flashing lights as *individual* flashes if they are separated by a period of at least 20ms; if they are separated by less than 20ms they are seen (because of the 'persistence of vision' effect) as a continuous light.

- (3) Also note from Figure 2.24 that, if the flashes are separated by at least 20ms, the brain 'sees' the individual flashes at full brilliance if they have a duration of 10ms or greater, but sees them at diminishing brilliance at durations below 10ms (a 2ms flash appears at roughly 1/5th of true brilliance; the perceived brilliance falls off rapidly at durations below 1ms). The perceived *duration* of a 20ms flash (30ms) is only 50% greater than that of a 10ms flash (20ms).
- (4) The human eye/brain combination is very sharply attracted by flashing lights that have repetition periods in the approximate range 0.5 to 5 seconds, but is less attracted by flashing lights that have repetition periods above or below this range.
- (5) Modern low-cost Super Bright LEDs, when generating a 10ms or longer light pulse, produce a brightness level that is adequately eye-catching for most practical purposes when pulsed by a 2mA current.

When the above sets of facts are put together, it transpires that the 'ideal' micropower LED flasher (when using a Super Bright LED) should produce a pulse with a duration (d) of 10ms at a current (I) of 2mA, at a repetition period (p) of 2 seconds (= 2000ms). Note that, under these conditions, the *mean* current (I_{mean}) of the LED is given by

$$I_{mean} = I \times d/p$$

and is a mere 10μA in this particular example (at a 30 second repetition period, I_{mean} is a minute 0.67μA).

V+	R3	Current drain	
		Loaded	No Load
3V	1.5k	68 μ A	60 μ A
4.5V	1.5k	80 μ A	70 μ A
6V	2.2k	86 μ A	75 μ A
9V	3.3k	97 μ A	85 μ A
12V	4.7k	107 μ A	95 μ A

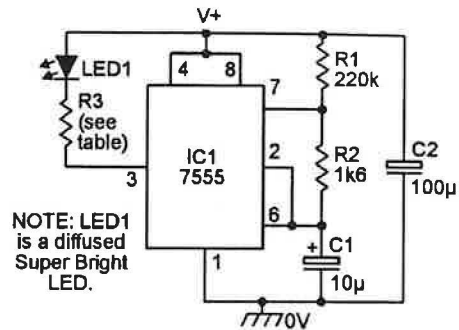


Figure 2.25 Circuit and performance details of a 7555-based micropower LED flasher unit

In practice, the *actual* mean current consumed by a micropower LED flasher circuit is equal to the sum of the LED and the driver currents, and is inevitably higher than the minimum figure indicated above. *Figures 2.25* and *2.26*, for example, show two alternative micropower LED flasher circuits that, when powered from 6V supplies, consume total currents of 86 μ A and 12 μ A respectively.

The *Figure 2.25* circuit is designed around a CMOS 7555 timer IC that is used in the astable mode and typically consumes an unloaded operating current of 75 μ A at 6V. In this mode, C1 alternately charges up via R1-R2 and discharges via R2 only, thus generating a highly asymmetrical output waveform on pin-3, which pulls the LED on via current-limiting resistor R3 during the brief discharge part of each operating cycle. The *Figure 2.25* table summarizes the circuit's performance details when optimized for operation at various spot voltages in the range 3V to 12V.

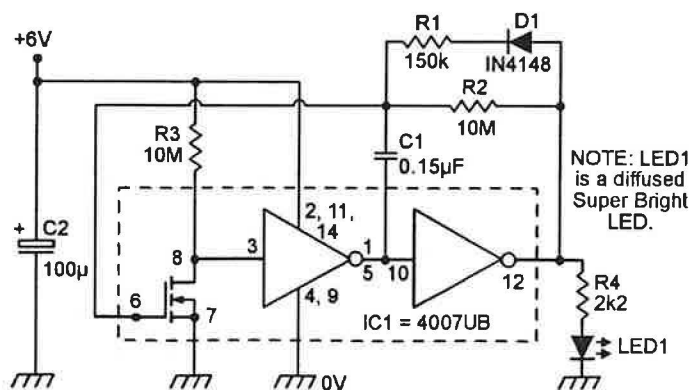


Figure 2.26 This 4007UB-based micropower LED flasher circuit consumes a mean current of 12 μ A at 6V

The *Figure 2.26* circuit is designed around a CMOS 4007UB IC, which contains two complementary MOSFET transistor pairs plus one CMOS inverter, all housed in a 14-pin DIL package. In this application the IC is wired as a micropower ring-of-three asymmetrical astable multivibrator which, when powered from a 6V supply, drives the LED on for 10ms at 2-second repetition intervals; the ON time is controlled by C1–R1, the OFF time by C1–R2, and the LED current (2mA nominal) is controlled by R4.

C2 is a vital part of the *Figure 2.26* circuit and acts as a low-impedance energy store that enables the circuit to work well even when powered from a fairly high-impedance source such as a weak battery. The complete circuit consumes an unloaded operating current of 2 μ A, and a loaded current (when driving the LED with 2mA pulses) of 12 μ A.

Note that the *basic* circuit of *Figure 2.26* can be used at any supply voltages in the range 4.5V to 12V, but that the actual component values must be selected to suit the specific supply voltage used. Also note that, at supply voltages of 6V or greater, the circuit can drive two or more series-connected LEDs without increasing the total current consumption, provided that R4's value is altered to set the LED ON currents at 2mA.

The table of *Figure 2.27* shows the nominal life expectancies of various types of alkaline cell/battery when continuously driving various types of micropower LED flasher circuit. The data relate to the circuits of *Figures 2.25* (drawing 86 μ A at 6V) and *2.26* (drawing 12 μ A at 6V), and to the once-popular but now obsolete LM3909 'LED flasher' IC (described in the 1st edition of this book but withdrawn from production by National Semiconductor in 1998/9), which draws a minimum operating current of 320 μ A.

Note in *Figure 2.27* that the 'predicted cell/battery life' figures relate to cells/batteries that have initial (unused) life expectancies of five years, i.e. in which their charges leak away at a steady rate of 1.67% per month. The total in-use monthly capacity drain equals the sum of the leakage and the loading drain figures, and forms the basis of the life prediction figures shown in the table.

Alkaline cell/battery type	Capacity (per cell or battery)	12µA load		86µA load		320µA load	
		monthly capacity drain & predicted cell/battery life					
		drain	life	drain	life	drain	life
AAA (1.5V)	1Ah	0.88%	3.3 Yrs	6.28%	1.0 Yrs	23.4%	0.3 Yrs
AA (1.5V)	2Ah	0.44%	4.0 Yrs	3.14%	1.7 Yrs	11.7%	0.6 Yrs
C (1.5V)	6.5Ah	0.135%	4.6 Yrs	0.97%	3.2 Yrs	3.6%	1.6 Yrs
D (1.5V)	13Ah	0.07%	4.8 Yrs	0.48%	3.9 Yrs	1.8%	2.4 Yrs
PP3 (9V)	0.55Ah	1.59%	2.6 Yrs	11.4%	0.6 Yrs	42.5%	0.2 Yrs

Figure 2.27 Table showing the life expectancies of various types of alkaline cell/battery when driving micropower LED flasher circuits

Low-voltage

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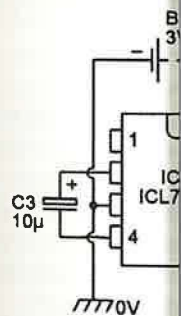


Figure 2.28 This mean current of

Low-voltage micropower LED flashers

The basic micropower LED flasher circuit of *Figure 2.26* can, if its component values are suitably selected, be reliably used at an absolute minimum supply voltage of 4.5V. Consequently, if you want to drive a micropower LED flasher from a 3V battery and do not want to use the 3V version of the 7555-based *Figure 2.25* circuit, one simple option is to drive the 6V *Figure 2.26* circuit from the 3V battery via a voltage-doubler circuit based on an ICL7660 IC. *Figure 2.28* shows the complete circuit of a micropower LED flasher unit of this type, which typically draws a mean operating current of about 35 μ A from the 3V battery.

In *Figure 2.28*, IC2 incorporates a free-running symmetrical squarewave generator that drives a ganged pair of CMOS bilateral switches that have their 'common' terminals connected to the two ends of C3 via pins 2 and 4. In the first half of each cycle, these switches connect pin-4 to the pin-3 0V line and connect pin-2 to the pin-8 '+3V' line, thus charging C3 up to the supply line voltage. In the second half of each cycle the switches change over and connect the positive end of C3 to the 0V line and connect the other end of C3 to pin-5, producing a -3V output on pin-5 and thus producing a total of 6V (double the input voltage) between pins 8 and 5. This 6V voltage-doubled output voltage is used to power the IC2 micropower flasher circuit via C2.

The total current drawn from the 3V battery in the *Figure 2.28* circuit equals double that of the 6V micropower flasher (12 μ A), plus the 'unloaded quiescent' current of IC2 (typically about 11 μ A when using a 3V supply at normal room temperatures), and usually totals about 35 μ A.

If you have some rare application where you need to power a micropower LED flasher from a 1.5V battery, you have two basic options. The cheapest option is to power the 3V version of the 7555-based *Figure 2.25* circuit from

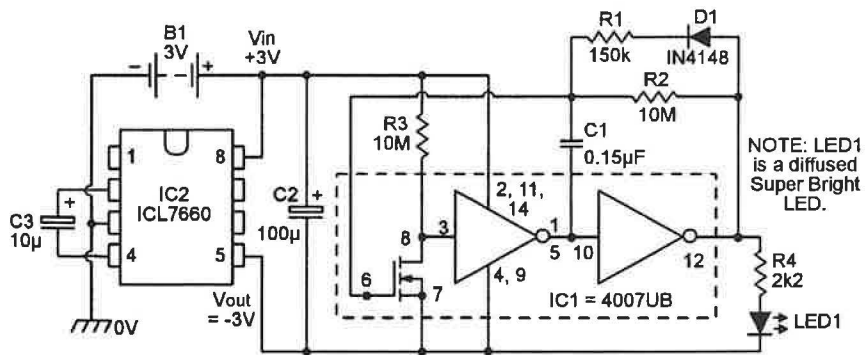


Figure 2.28 This 4007UB-based micropower LED flasher circuit consumes a mean current of 35 μ A from a 3V battery

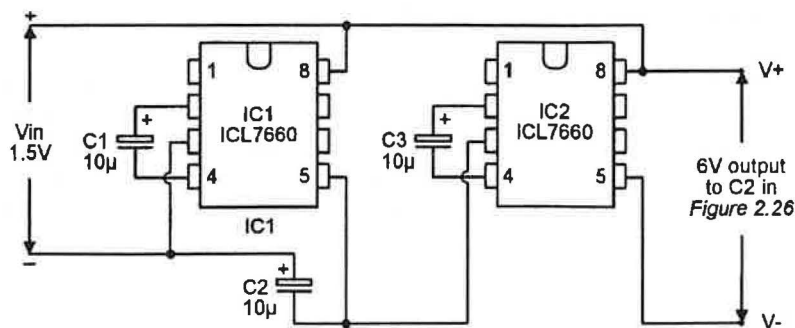


Figure 2.29 This cascaded ICL7660 voltage doubler gives a 6V output from a 1.5V battery or cell

the 1.5V source via the basic IC2-plus-C3 voltage doubler used in *Figure 2.28*. In this case the total current drawn from the 1.5V battery is about 142µA.

If you want to power a micropower LED flasher from a 1.5V battery with a minimum of drain current, the best (but rather expensive) option is to power the 6V *Figure 2.26* micropower circuit from the 1.5V battery via a cascaded pair of ICL7660 voltage doubler circuits, connected as shown in *Figure 2.29*. In this case the total current drawn from the 1.5V battery is four-times that of the 6V micropower flasher, plus the 'unloaded quiescent' current of IC2 (typically about 5µA when using a 1.5V supply at normal room temperatures), and totals about 53µA and will give about three years of continuous operation from an 'AA' sized alkaline battery.

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4017B

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Figure 2.29 of the 4017B which includes a CLOCK

output surfaces) does not suffer from parallax errors. This type of prism is widely used in high quality optical instruments and devices such as reflex cameras, binoculars, and automatic laser-aiming controllers.

Total internal reflection can occur whenever one transparent material interfaces with another that has a lower refractive index, thus giving a less-than-unity refractive index and a positive critical angle value at the interface junction. All modern fibre optic cables rely on this 'total internal reflection' principle for their very efficient low-loss operation (fibre optic cable principles are described in Chapter 10 of this volume).

Lenses

Normal optical lenses are light-bending refractive devices that are related to prisms but have curved (rather than flat) faces. Figure 9.18 shows the classic profile of a simple lens that has two parallel faces that are each radially curved in two dimensions, to form a section of a sphere. This type of lens can focus a parallel bundle of light rays onto a single point (the *focal point*), as shown in Figure 9.18(a); the distance between the centre of the lens and the focal point is the *focal length* of the lens. If a light point-source is spaced from the lens by a distance equal to the focal length of this type of lens, the lens converts the light into a parallel ('collimated') beam of light, as shown in Figure 9.18(b).

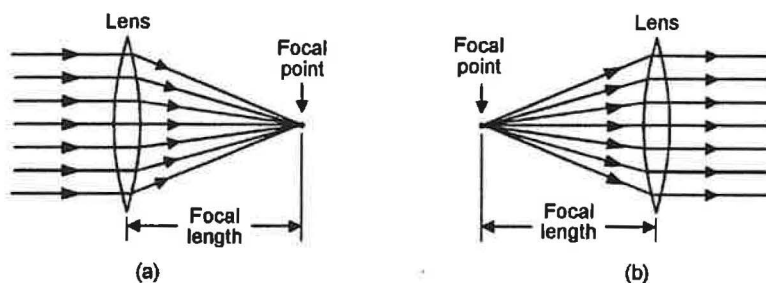


Figure 9.18 A simple lens can (a) focus a parallel bundle of rays onto a single point, or (b) convert the rays from a single point source into a parallel (collimated) beam of light

Figure 9.19 shows the basic way of using two simple lenses in a light-beam alarm or communication system. At one end of the system, the left-hand lens converts the transmitter's light point-source into a collimated (parallel) light beam, and at the other end of the system the right-hand lens converts the collimated beam back into a point of light, which is applied to the receiver's

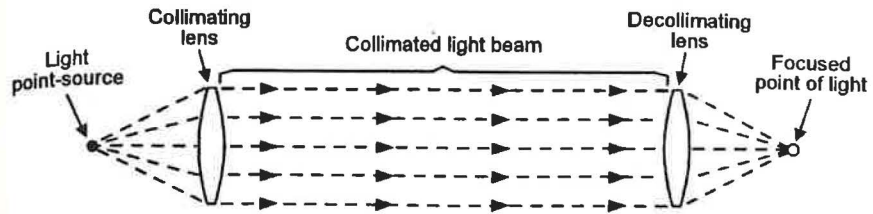


Figure 9.19 Basic way of using two lenses in a light-beam system

light-sensitive input. Identical lenses are used in the collimating and decollimating processes.

Systems of the above type generate a perfectly parallel beam only if the light point-source is infinitely small, and this is an impossibility. In practice, the beam widens with distance after leaving the collimating lens; the amount of widening is proportional to the width of the light source and inversely proportional to the diameter of the lens. For minimum widening, the lens diameter must be large relative to that of the source.

Simple lenses with one or both faces shaped as a section of a sphere are known as *spherical* lenses and are available in *convergent* and *divergent* types; convergent types make a parallel beam of light converge towards a common focal point; divergent types make a parallel beam of light diverge outwards. Figures 9.20 and 9.21 show a variety of lenses of these types.

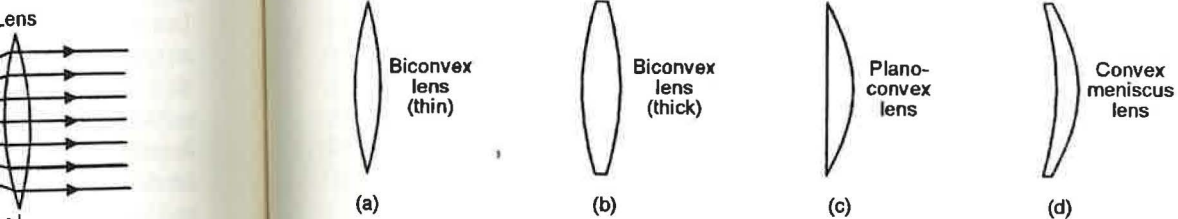


Figure 9.20 Four simple types of convergent spherical lens

Figure 9.20 shows four simple types of convergent spherical lens. The thin biconvex lens shown in (a) is the same type as shown in Figure 9.18; it operates equally well either way around, but its sharp edges are rather fragile. The thick biconvex type shown in (b) gives the same performance as the (a) type, but is more rugged. The plano-convex type shown in (c) has one flat and one curved face and must be used the correct way around, with the flat face pointing in the direction of the parallel light beam and the curved face aimed towards the light's focal point. The convex meniscus type shown in (d) has a very long focal length; it is the type used in most spectacles and contact lenses.

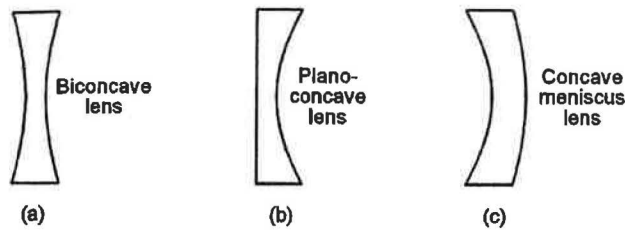


Figure 9.21 Three simple types of divergent spherical lens

Figure 9.21 shows three simple types of divergent spherical lens. The biconcave lens shown in (a) can be used either way around, but the plano-concave type shown in (b) must be used the correct way around. A concave meniscus type is shown in (c). Lenses of these various types are often used in conjunction with convergent lenses, to make high-quality compound lenses (as described shortly).

Most spherical lenses are of the simple type already shown, but other types are also available. The cylindrical biconvex lens shown in Figure 9.22(a), for example, is curved in one dimension only, and is used to focus a parallel light beam into a thin line, rather than a spot, or to convert a thin line of light into a collimated beam.

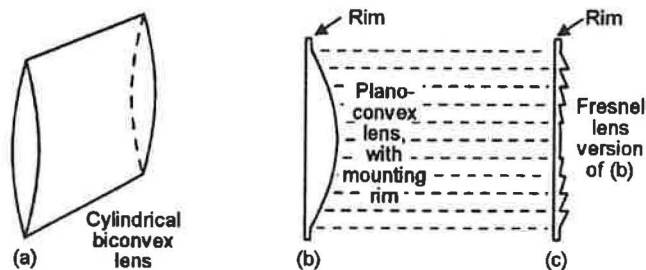


Figure 9.22 Three special types of spherical lens

In most normal lenses much of the sub-surface glass or plastic lens material performs no useful function. A *Fresnel* lens is one in which most of the non-useful lens material is removed, to make a lightweight or low-cost lens that performs almost as well as a normal lens in simple 'light-beam' types of application. Figures 9.22(b) and (c) show, in cross-section form, how a plano-convex lens with a mounting rim is transformed into its Fresnel equivalent. Here, the Fresnel lens is made up by effectively dividing the original (b) lens into ten horizontal slices, removing the 'dead' material from each slice, and then bonding the remainder onto a base of identical material that also acts

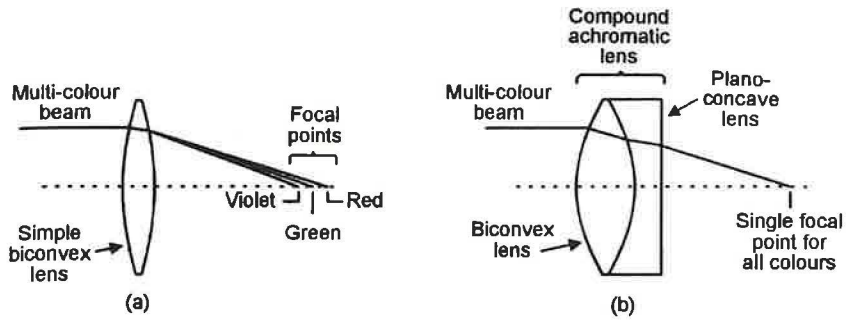


Figure 9.23 The compound achromatic lens shown in (b) is designed to minimize chromatic aberration of the type suffered by the simple (a) lens

as the lens rim. In practice, most Fresnel lenses are moulded, in plastic or glass.

The focused images generated by simple spherical lenses suffer from spherical and chromatic defects or aberrations. *Spherical aberration* makes a straight line appear curved in the focused image; if you wear spectacles, you can see a demonstration of this effect by standing in front of a set of library shelves and noting how the shelves above and below your eye level appear curved when you have your glasses on, but not when they are off.

In simple lenses, *chromatic aberration* makes faint coloured fringes appear around focused white or multi-coloured images. The effect occurs because the refractive index of the lens material (and thus the focal length of the lens) varies with the colour of light, as shown in Figure 9.23(a), making it possible to sharply focus only a small slice of the colour spectrum; the rest of the spectrum is out of focus, producing the 'fringe' effect. This problem can be overcome by using a compound lens made of one converging and one diverging lens, each with a different refractive index value, as shown in Figure 9.23(b). Such a lens can be made to give all colours the same overall focal length, and is known as an *achromatic* or *antispectroscopic* lens.

The strangest and most recently developed lens is the *graded-index* (GRIN) *rod lens*, which is used in modern fibre optic applications and operates in a different way to a normal lens. A GRIN rod is a glass or fibre rod that has a refractive index that decreases progressively with distance from the rod axis. This index variation causes light rays to follow a sinusoidal path as they travel along the rod, as shown in Figure 9.24(a). The length of one complete sinusoidal cycle in the rod is called the *pitch* (P) of the rod; the P value is determined mainly by the rod's diameter and refractive index profile; the value is typically about 20mm.

A GRIN rod lens is simply a slice of GRIN rod with a length less than a single pitch-length, so that its optical output signal is out of phase with the optical input signal. The most interesting and widely used GRIN rod lens has

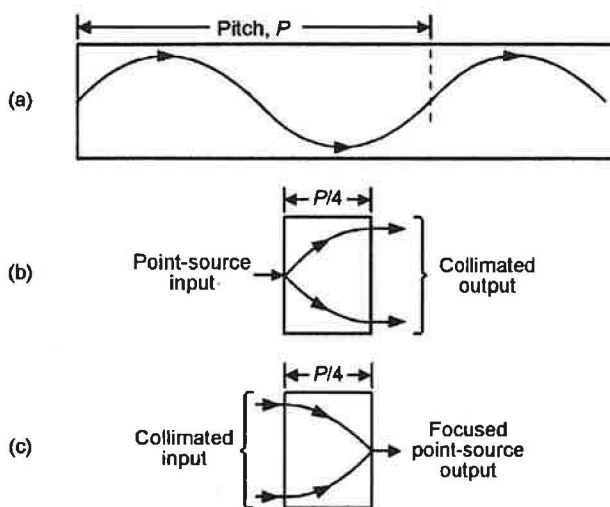


Figure 9.24 Light rays follow a sinusoidal path through a graded-index (GRIN) rod (a). A quarter-pitch GRIN lens collimates the light from a point-source (b), and focuses a collimated light beam into a point (c)

a quarter pitch (giving it a length of about 5mm) and has the interesting properties illustrated in *Figures 9.24(b)* and (c). Note in (b) that the light from a point source in contact with the centre of the left face of the lens emerges from the right face in fully collimated form, and in (c) that a collimated light beam entering the left face leaves the right face as a focused spot. The GRIN rod lens thus has some properties of a conventional lens, but has a very short focal length.

GRIN rod lenses are widely used in modern fibre optic and laser module applications. *Figure 9.25* shows an example that illustrates the advantages of a GRIN rod lens over a spherical lens in a fibre optic application in which the fibre optic cable's point-source 'light' output needs to be collimated when

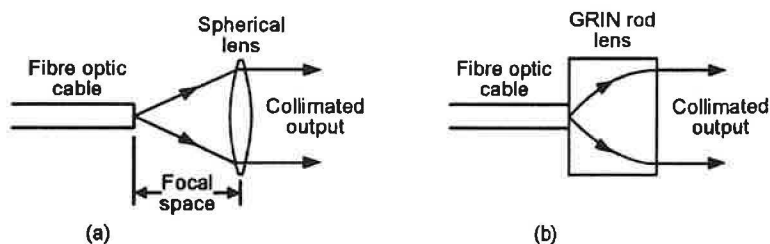


Figure 9.25 Method of collimating the light output from a fibre optic cable using (a) a spherical lens and (b) a GRIN rod lens

fed into the outside world. In the case shown in (a), the light is collimated by a conventional lens, which must be placed a precise fixed distance from the end of the cable, to which it is coupled by an air gap. In the case shown in (b), the GRIN rod lens is simply bonded directly to the polished end of the cable, and no carefully spaced air gap is required. More information on fibre optic and GRIN (graded index) operating principles is given in Chapter 10.

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Fibre optics and lasers

The two most revolutionary and important optoelectronic-associated events to have occurred since the mid-1960s are the development of practical fibre optic cables for use in interference-free wide-band communication systems, and the development of reliable long-life low-cost laser units for use in everyday gadgets such as CD-players and bar-code readers. The first half of this chapter explains the basic operating principles and applications of fibre optics; the second half gives similar treatment to LEDs and lasers.

Fibre optics

Introduction

A fibre optic cable can, in very simple terms, be regarded as a hair-thin flexible light pipe or *optical waveguide* that can efficiently carry modulated or unmodulated light signals from one point to another (even if the journey involves bends and loops) with complete immunity from electromagnetic interference. In most practical applications the cable must be linked to the light source and destination points via special connectors, to minimize signal losses.

Figure 10.1 shows the basic elements of a simple one-channel one-way fibre optic communication system, in which the output of the optogenerator LED is pulse-modulated and is coupled to the input of optosensor Q1 and its pulse-detecting unit via a length of sheathed fibre optic cable.

The *Figure 10.1* circuit can send data from point A to point B, but not the other way around. *Figure 10.2* shows a 2-way (bidirectional) version of the above circuit. Here, signals can be sent from A to B via Tx unit 1, cable 1, and Rx unit 1, and from point B to point A via Tx unit 2, cable 2, and Rx unit 2. In practice, special 2-core 'duplex' fibre optic cables are available for use in this type of application.

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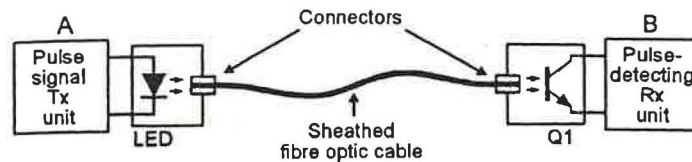


Figure 10.1 Simple single-channel 1-way fibre optic communication system

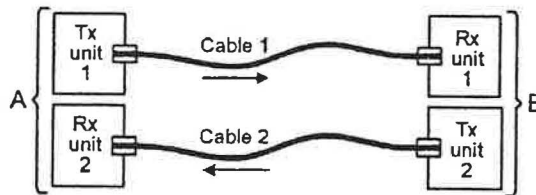


Figure 10.2 Simple single-channel 2-way fibre optic communication system

The Figure 10.1 and 10.2 circuits are designed for use in applications in which each fibre optic cable carries only a single data channel. If multi-channel operation is needed, the channels can be electronically multiplexed, or each channel can be superimposed in a high-frequency carrier wave in the manner of a normal radio or TV channel.

When the commercial possibilities of fibre optic cables were first postulated in the early 1960s, there was much speculation regarding the probable performance capabilities of such cables. Visible light has, for example, a frequency spectrum ranging from 430GHz (700nm wavelength) to 750GHz (400nm wavelength), and it was presumed that fibre optic cables would have bandwidths that would easily cover this 320GHz spectrum, thus enabling them to handle up to 64 000 5MHz data channels (Note: 1GHz = 1000MHz). In practice, modern fibre optic cables fall well short of this imagined ideal; many have real-life bandwidths of only a few hundred megahertz, and can handle only a few dozen 5MHz data channels.

In spite of their limitations, fibre optic communication systems outperform conventional wire-connected systems in many important respects. They are immune to electromagnetic interference, are electrically fully isolated, are low in weight, offer high security, and (unlike copper wires) are made from a cheap and very abundant raw material (silica).

Fibre optic principles

An optical fibre is a wire-like strand of high-purity glass or plastic in which the refractive index of the outer layer is lower than that of the inner core,

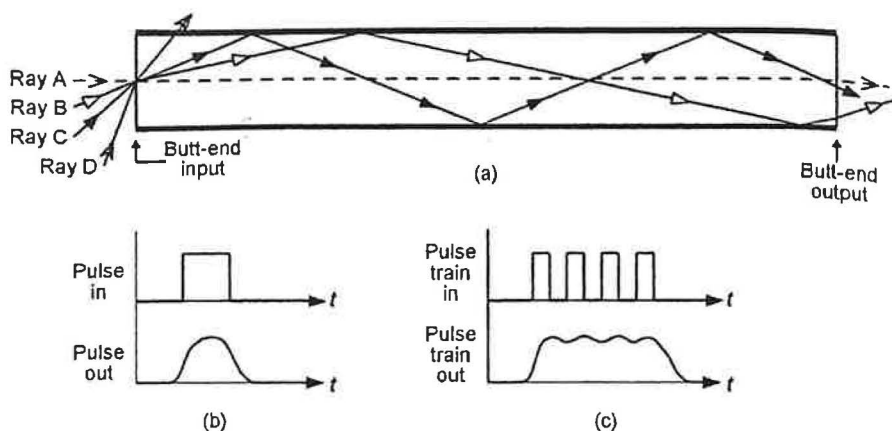


Figure 10.3 Diagram illustrating basic 'step-index' fibre optic operating principles

thus endowing the fibre with the optical phenomenon of total internal reflection (as described in Chapter 9). *Figure 10.3* illustrates some elementary fibre optic operating principles and helps explain some basic fibre optic jargon. The main (a) part of the diagram shows a simple glass rod or 'light pipe' in which the glass has a refractive index of 1.5; light rays travel through this glass at a speed of 200 metres/ μ s.

Imagine in *Figure 10.3* that a series of light-beam pulses are fed into the butt-end input of the glass rod via a focusing lens. The beam is made up of a vast number of photonic rays, which enter the butt-end input at a variety of angles of incidence. The diagram depicts the paths of four such rays, which travel in the following individual ways.

Ray A strikes the butt-end input of the glass rod at an angle of incidence of zero degrees, passes cleanly through the glass rod via the shortest possible route, and emerges from the rod's butt-end output after travelling through the rod at a mean speed of 200 metres/ μ s.

Ray B strikes the butt-end input at a moderately sharp angle of incidence, is refracted to an angle of 12° on entering the glass, and after travelling a fairly short distance strikes the rod's upper glass-to-air boundary, where (because it arrives at a fairly shallow angle) it is subjected to the phenomena of total internal reflection (fully described in Chapter 9), which reflects the ray downwards at an identical angle until it strikes the rod's lower glass-to-air boundary, from which it is reflected upwards again, and so on as the ray *propagates* its way along the rod until it eventually leaves its butt-end output. The ray thus follows the repeatedly reflected zig-zag course shown in the diagram; this beam travels a greater distance than ray A in its journey through the glass rod, actually travelling through it at a mean horizontal speed of 195 metres/ μ s.

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Ray D is refracted to a short distance it arrives at passes through to propagate

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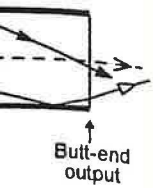
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Ray C, on entering the rod, is refracted to an angle of 22° on entering the glass and then propagates its way along the tube in the same basic way as ray B, but does so at sharper reflective angles and thus takes even longer than ray B to complete its journey through the glass rod, actually travelling through it at a mean speed of 185 metres/ μ s.

Ray D strikes the butt-end input at a very sharp angle of incidence, is refracted to an angle of about 60° on entering the glass, and after travelling a short distance strikes the rod's upper glass-to-air boundary, where (because it arrives at an angle greater than the critical angle of the boundary) it simply passes through the boundary and is dissipated into the air. This ray thus fails to propagate along the glass rod.

Note that *Figure 10.3* depicts the fibre optic rod's operation in a simplified 2-dimensional style, in which the rays simply bounce off the internal top and bottom faces of the rod. In reality, rays travel 3-dimensionally, bouncing off the rod's top, side and bottom faces, and thus tend to spin or skew as they travel along the rod.

Fibre optic jargon

Various 'jargon' words and phrases are widely used in fibre optics and have meanings that can be explained with the aid of *Figure 10.3*, as follows.

Step index. Fibre optic cable operation depends on the total internal reflection phenomenon that can occur at the points where a transparent material meets a material or substance with a refractive index lower than its own. In the *Figure 10.3* example, the glass rod has a refractive index of 1.5, and the surrounding air has a refractive index of 1.0, and reflection can occur at the precise point where the ray meets the abrupt or *step* reduction of the refractive index. Cables of this type are called *step-index* fibre optic cables. *Graded-index* (GRIN) cables are also available, and are described later in this chapter.

Maximum acceptance angle and numerical aperture. Light rays will only propagate through a fibre optic cable if the input ray applied to the cable's butt-end input falls within a certain angular range. In *Figure 10.3*, for example, rays A (arrival angle = 0°), B (24°), and C (45°) all propagate, but ray D (75°) does not propagate. The maximum input angle at which propagation will occur is called the cable's *maximum acceptance angle*, and is denoted by the symbol α_M . This basic parameter is often expressed in sine form, in which case it is called the cable's *numerical aperture*, NA, and equals $\sin \alpha_M$. Thus, a cable with a maximum acceptance angle of 32° has a numerical aperture of 0.53.

Operating mode. In *Figure 10.3*, light rays can propagate along the glass rod at a variety of angles or 'operating modes'. Rays that propagate at steep

reflective angles travel in *high-order mode*, and ones that propagate at shallow angles travel in *low-order mode*. Since the rays can travel in a variety of modes in this particular fibre optic rod, it is called a *multi-mode* or MM device. Some fibre optic cables can operate in only a single mode, and are called *single mode* (SM) or *monomode* devices.

Modal dispersion. When light rays propagate through a step-index multi-mode fibre optic cable or rod, their speed of linear travel depends on their angular operating mode. High-order mode rays travel at lower linear speeds than low-order ones. In the *Figure 10.3* diagram, for example, ray A travels at a linear speed of 200 metres/ μ s and takes 5ns to travel 1 metre; the slowest (highest-order) ray that can propagate through this particular rod travels at 141 metres/ μ s and takes 7.1ns to travel 1 metre.

Consequently, if a very fast sharp-edged light pulse is fed to the input of the *Figure 10.3* fibre optic rod, the individual photonic rays representing its leading or trailing edge at the rod's output are spread over a 2.1ns time spread in a 1 metre rod, or 21ns in a 10 metre rod, and so on. This 'spreading' is called *modal dispersion* and produces a degraded (blurred) output pulse, as shown in *Figure 10.3(b)*. Similarly, if a train of ultra-fast pulses are fed through the rod, modal dispersion may degrade them into the form of a single pulse, as shown in *Figure 10.3(c)*.

Modal dispersion is the major factor that limits the maximum pulse-operating rates (frequencies) of fibre optic cable, and is determined both by the design and the length of the cable. Cables with low modal dispersion figures offer higher maximum pulse operating rates than cables with high modal dispersion figures.

Material dispersion. The speed at which light travels through a fibre optic material depends upon the material's refractive index, and this varies with the light's wavelength. All real-life light sources have finite spectral bandwidths, and their different component wavelengths thus travel through the material at different speeds; such light thus undergoes spectral dispersion (spreading) as it travels through the fibre. This phenomenon is known as *material dispersion*, and, like modal dispersion, limits the maximum pulse-operating rates of fibre optic cable. Its degrading effects are directly proportional to the light source's spectral bandwidth, but are normally small compared to those caused by modal dispersion. Material dispersion can typically be reduced by a factor of about 200 by using a laser diode, rather than a normal LED, as the light source that feeds signals into the fibre optic cable.

Attenuation. When light passes through any translucent glass or plastic material its power is inevitably attenuated in the process. The amount of attenuation is directly proportional to the thickness (or length) of the material, and is measured in terms of dB/metre or dB/km. The high-quality glass used in spectacle lenses has a typical attenuation value of 6dB/metre (6000dB/km).

By contrast, the attenuation of a typical fibre optic cable is 1.3dB/km.

Four basic factors affect the attenuation of glass; the first is the absorption of light by the glass; the second is the scattering of light by the glass; the third is the reflection of light at the interfaces between the glass and the surrounding medium; the fourth is the mechanical loss of light at the ends of the cable.

In ordinary practice, the attenuation of a fibre optic cable is determined by the loss of light at the ends of the cable. This results in a loss of light at the ends of the cable, which is derived from the loss of light at the ends of the cable. *Figures 10.3* and *10.4* show the attenuation of a fibre optic cable of different lengths.

The *Figure 10.4* graph shows the attenuation of a fibre optic cable of different lengths. The attenuation of a fibre optic cable is determined by the loss of light at the ends of the cable. The attenuation of a fibre optic cable is determined by the loss of light at the ends of the cable. The attenuation of a fibre optic cable is determined by the loss of light at the ends of the cable.



Figure 10.4
Attenuation in high-order mode

By contrast, the ultra-pure silica (silicon dioxide) glass used in glass fibre optic cables has a typical attenuation value of less than 0.0013db/metre (1.3dB/km) when used under optimum conditions.

Four basic mechanisms are primary causes of light attenuation in glass. Three of these (electron absorption, Rayleigh scattering, and material absorption) are *intrinsic absorption mechanisms* inherent in the basic nature of glass; the fourth mechanism (impurity absorption) is an *extrinsic absorption mechanism* caused by contamination (impurity) within the manufactured glass.

In ordinary glass, the extrinsic (impurity) absorption is the dominant mechanism in the basic attenuation process. In modern fibre optic cables, the impurities in the silica glass are reduced to the lowest commercially viable levels, and this results in the type of attenuation graph shown in *Figure 10.6*, which in turn is derived by combining the intrinsic and extrinsic absorption graphs shown in *Figures 10.4* and *10.5*. Note that these particular graphs are based on typical cable of the late 1980s to early 1990s era, and that most modern cables give attenuation figures that are somewhat lower than those shown.

The *Figure 10.4* graph shows the typical attenuation that occurs as a result of the intrinsic absorption mechanisms inherent in the basic nature of silica glass. Here, *electron absorption* occurs when photons are absorbed by individual atoms in the silica glass, raising one of the atom's electrons to a high-energy (excited) state in the process. Electron absorption causes heavy ultra-violet absorption that peaks at 140nm but extends well beyond 400nm wavelengths.

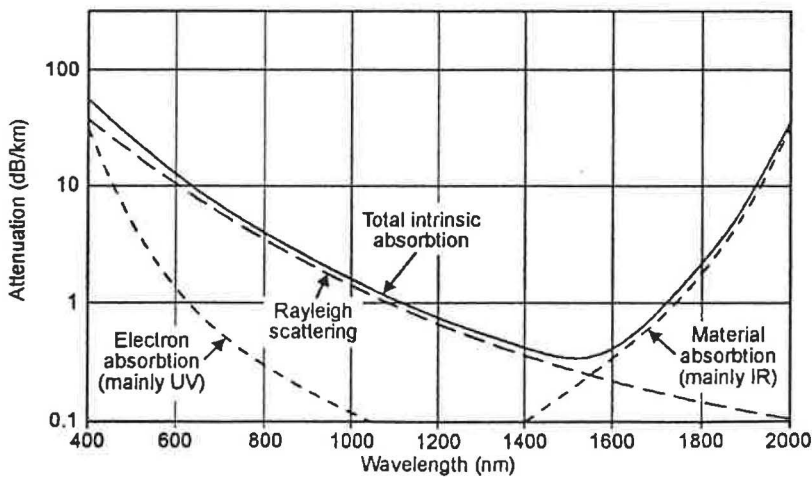


Figure 10.4 Graph showing typical attenuation due to intrinsic optical absorption in high-grade silica fibre optic glass cables of the late 1980s to early 1990s era

The *Rayleigh scattering* shown in *Figure 10.4* occurs when photons meet molecule-sized density irregularities in the glass and undergo shifts in their refraction angles. The consequent attenuation effects are severe when the photon's wavelength is similar to the dimension of the irregularity, but decline steadily as wavelength increases above 400nm.

The *material absorption* shown in *Figure 10.4* occurs when photon energy is absorbed by the atomic/molecular bonds associated with the basic glass material, and causes heavy attenuation of infra-red at wavelengths greater than 2000nm. The net result of the effects of the three intrinsic absorption mechanisms is that the optical attenuation of the glass is high (70dB/km) at 400nm, falls smoothly to a minimum value of about 0.4dB/km at 1500nm, and then rises rapidly again (because of material absorption) at longer wavelengths.

The *Figure 10.5* graph shows the basic form of the attenuation that occurs as a result of extrinsic absorption mechanisms in most high-grade normal-quality silica fibre optic glass. These losses are caused primarily by the presence of hydroxyl (OH) ions in the glass, which result in three large peaks of absorption within the 400nm to 2000nm spectrum. The largest peak occurs at 1370nm, and the other two occur at 950nm and 725nm; a very minor additional peak occurs at 1230nm.

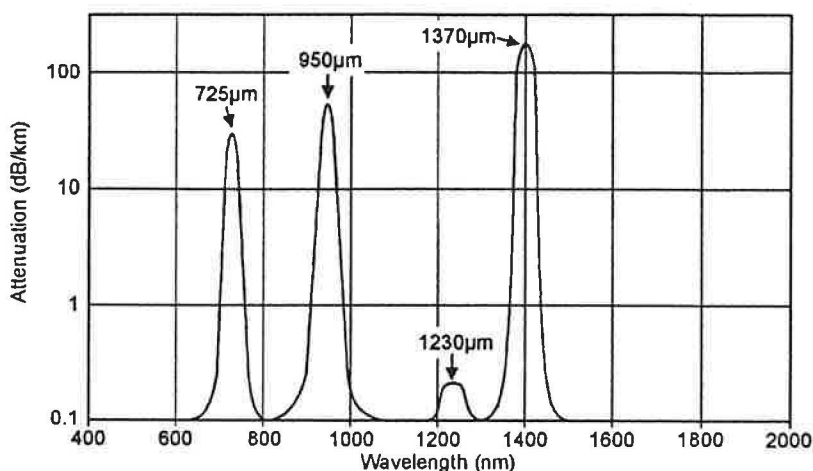


Figure 10.5 Graph showing typical attenuation due to extrinsic optical absorption in high-grade silica fibre optic glass cables of the late 1980s to early 1990s era

The *Figure 10.6* graph shows the typical attenuation that occurs as a result of all intrinsic and extrinsic absorption mechanisms in high-grade normal-quality silica fibre optic glass. Important points to note from this particular

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Attenuation (dB/km)

Figure 10.6 absorption 1990s era

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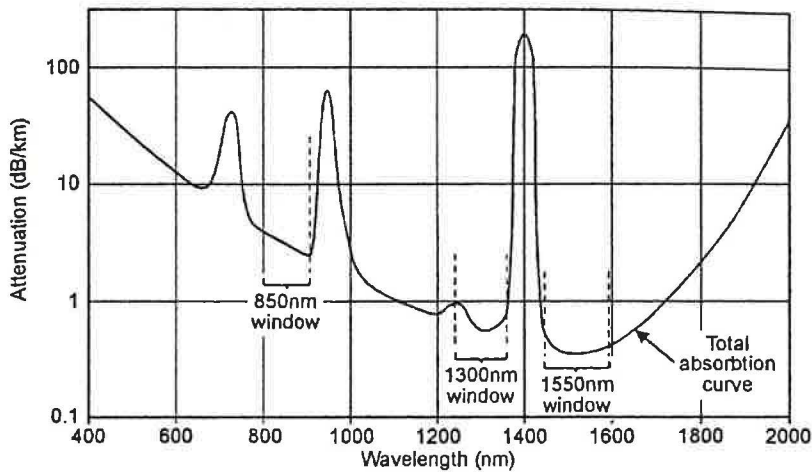


Figure 10.6 Graph showing typical attenuation due to all forms of optical absorption in high-grade silica fibre optic glass cables of the late 1980s to early 1990s era

graph are that attenuation is very high (greater than 10dB/km) over most of the visible-light (400nm to 700nm) spectrum and in various other areas, and that there are three 'window' areas in the infra-red range (at 850nm, 1300nm and 1550nm) at which attenuation figures attain local 'low' values. Practical glass fibre optic communication systems are nearly always operated within one or other of these 'window' ranges.

Polymer cable. The most widely used type of fibre optic cable is made from silica glass and can only be correctly cut with a special tool. This type of cable is meant for use with IR light, primarily in medium- to long-haul (greater than 250 metres) communication and data-transfer systems. There is, however, an alternative and cheaper type of fibre optic cable; it is made from plastic polymer and can easily be cleanly cut with a sharp blade, and is best suited to use with visible red (rather than IR) light, in very-short-haul (up to 50 metres maximum) applications.

Figure 10.7 shows the typical attenuation graph of a modern polymer fibre optic cable. This particular cable gives a mean attenuation of about 200dB/km (0.2dB/metre) when averaged over the full visible light spectrum, but about 1500dB/km (1.5dB/metre) when used in the low infra-red ranges.

Practical fibre optic cable types

The simple glass type of fibre optic rod or cable shown in *Figure 10.3* is too crude to be of real practical value, since its internally reflective glass-to-air

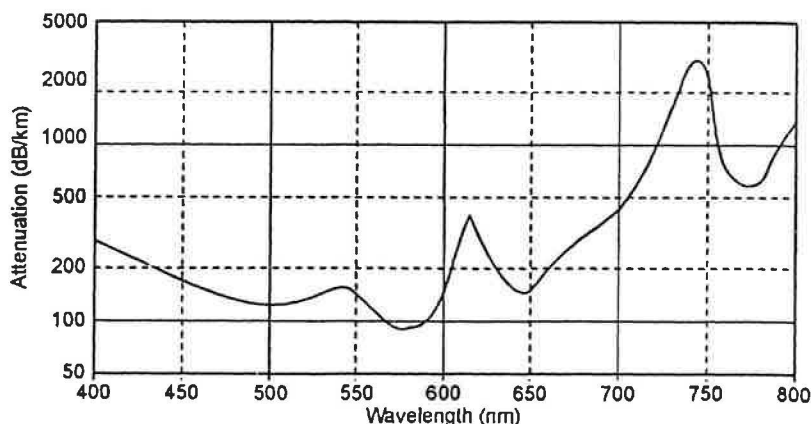


Figure 10.7 Graph showing typical attenuation due to all forms of optical absorption in modern plastic polymer fibre optic cable

junction is highly susceptible to external damage from scratches and contamination, and the very large differences between the refractive index values of its two media (about 1.5 for glass, 1.0 for air) give excessively large modal dispersion values.

All practical, modern, fibre optic cables are designed to give low values of modal dispersion, and use either a multi-mode or single-mode step-index form of construction, or a graded-index (GRIN) form of construction, as shown in *Figures 10.8 to 10.10*, which also show the basic refractive index (n) profiles and typical dimensions of their 'glass type' fibres. Each of these fibres has a solid core that is surrounded by a solid cladding with a refractive index value lower than that of the core; this cladding makes the cable's modal dispersion value immune to the effects of external surface scratches, etc. The outer core is further enclosed in an opaque primary outer sheath that provides further physical protection and immunity to optical interference.

Descriptions of the three basic cable types are given below; when reading these descriptions, remember that a human hair has a typical thickness of about $50\mu\text{m}$, and note that fibre optic cable basic dimensions are conventionally notated in an 'a/b/c' or 'a/b' form, in which 'a' is the outside diameter of the fibre core in μm , 'b' is the outside diameter of the fibre cladding in μm , and 'c' is the outside diameter of the cable's primary outer sheath in μm . Thus, a 50/125/250 μm cable uses a 50/125 μm fibre that is protected by a 250 μm -diameter primary sheath.

Multi-mode step-index. *Figure 10.8* shows basic details of this type of fibre optic cable, in which a relatively thick core (typically $50\mu\text{m}$ or $62.5\mu\text{m}$ in glass fibres) is covered by a layer of cladding with a refractive index value that is

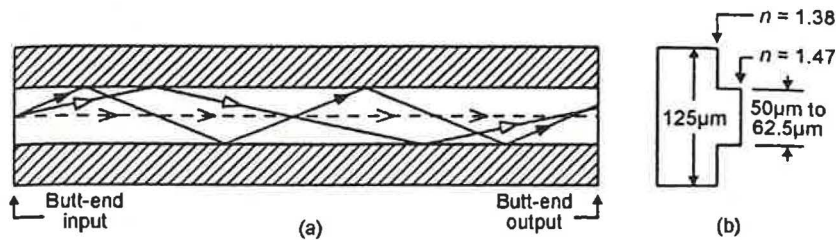


Figure 10.8 Basic details (a), plus refractive index profile and typical dimensions (b), of the glass fibre used in a modern multi-mode step-index fibre optic cable

only a few percent lower than that of the core, thus giving the fibre's butt-end input a fairly narrow (typically 11° to 24° maximum) acceptance angle and thus endowing the fibre with fairly low values of modal dispersion. These characteristics and dimensions make it easy to couple optical signals into and out of this type of cable. The most popular 'glass' versions of this cable have basic fibre dimensions of 50/125 μm or 62.5/125 μm . Typical bandwidth-length product values vary from 1 MHz/km for plastic cables to 33 MHz/km for glass types; these cables are thus used mainly in short- to medium-haul low-data-rate applications.

Single-mode step-index cables. Figure 10.9 shows basic details of a typical single-mode step-index fibre optic cable, in which light travels through the core only in the very shallow 'low-order' mode. Here, a very thin (5 to 8 μm) glass core is covered by a fairly thick layer of cladding with a refractive index value only slightly lower than that of the core, thus giving the fibre's butt-end input a very narrow (less than 6° maximum) acceptance angle and endowing the fibre with a very low modal dispersion value. These characteristics and dimensions make it difficult to couple optical signals into and out of the cable, which require great precision in cutting and coupling. Never-

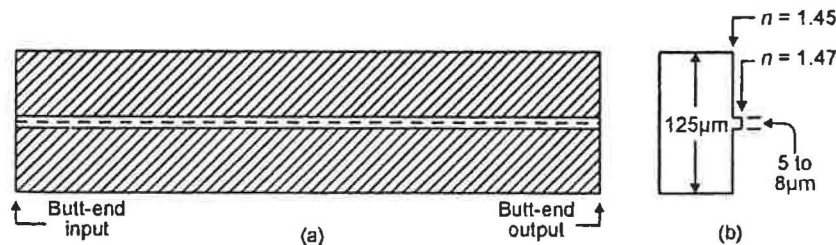


Figure 10.9 Basic details (a), plus refractive index profile and typical dimensions (b), of the glass fibre used in a modern single-mode step-index fibre optic cable

Fibre optic cable type	Fibre dimensions	Operating wavelengths	Maximum operating bandwidth	Maximum data rate (bits/sec/km)	Basic description
Polymer multi-mode 'light pipe' cable	1mm/2.2mm	400 to 700nm (visible light range)	1MHz/km	500kb/s/km	Easy-to-use cable, for use in very-short-haul very-low-data-rate applications
Multi-mode step index, glass	50/125µm or 62.5/125µm	850nm 1300nm 1550nm	33MHz/km	16Mb/s/km	Used mainly in short- to medium-haul low-data-rate applications
Graded-index (GRIN), glass	50/125µm or 62.5/125µm	850nm 1300nm 1550nm	0.5 to 1.0GHz/km	250Mb/s/km to 500Mb/s/km	Used mainly in short- to medium-haul high-data-rate applications
Single-mode step-index, glass	50/125µm or 62.5/125µm	850nm 1300nm 1550nm	Up to 10GHz/km	Up to 5Gb/s/km	Used mainly in medium- to long-haul very-high-data-rate applications

Figure 10.11 Table listing the main features of the four major types of fibre optic cable

have very severe operational (bandwidth and attenuation) limitations. For most high-performance professional uses, glass multi-mode step-index or graded-index (GRIN) cables should be used. Single-mode step-index glass cables are very specialized devices, intended mainly for use in commercial very-high-performance medium- to long-haul applications.

Using fibre optic cable

Figure 10.12 shows the basic elements that are used in a simple 1-way fibre optic communication system. The transmitter (Tx) unit houses a pulse-driven light generator such as a LED or laser diode, which has its output fed into the butt-end input of the cable via a dedicated low-loss coupler. At the other end of the cable, another low-loss coupler feeds the optical signal into a

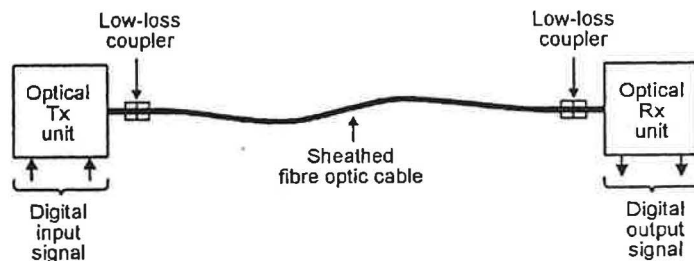


Figure 10.12 Basic elements of a simple 1-way fibre optic communication system