1

Optic fiber and light – a brilliant combination

The starting point

For thousands of years we have used light to communicate. The welcoming campfire guided us home and kept wild animals at bay. Signal bonfires were lit on hilltops to warn of invasion. Even in these high-tech days of satellite communications, ships still carry powerful lamps for signaling at sea; signaling mirrors are standard issue in survival packs.

It was a well-known 'fact' that, as light travels in straight lines, it is impossible to make it follow a curved path to shine around corners. In Boston, Mass., USA, 1870, an Irish physicist by the name of John Tyndall gave a public demonstration of an experiment that not only disproved this belief but gave birth to a revolution in communications technology.

His idea was very simple. He filled a container with water and shone a light into it. In a darkened room, he pulled out the bung. The light shone out of the hole and the water gushed out.

It was expected that the light would shine straight out of the hole and the water would curve downwards – as shown in Figure 1.1.

Now see Figure 1.2 for what actually happened.

The light stayed inside the water column and followed the curved path. He had found a way to guide light!

The basic requirements still remain the same today – a light source and a clear material (usually plastic or glass) for the light to shine through. The light can be guided around any complex path as in Figure 1.3.

Being able to guide light along a length of optic fiber has given rise to two distinct areas of use – light guiding and communications.

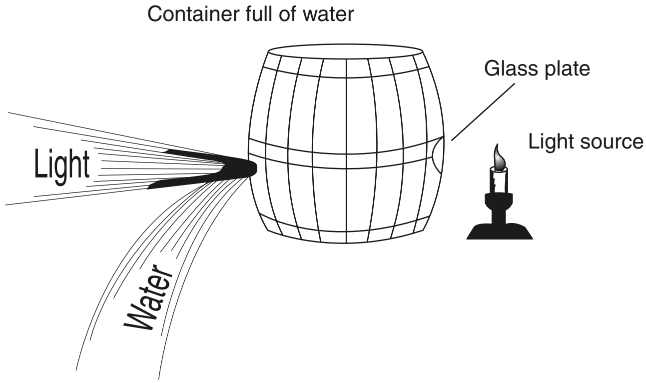


Figure 1.1 What was expected to happen

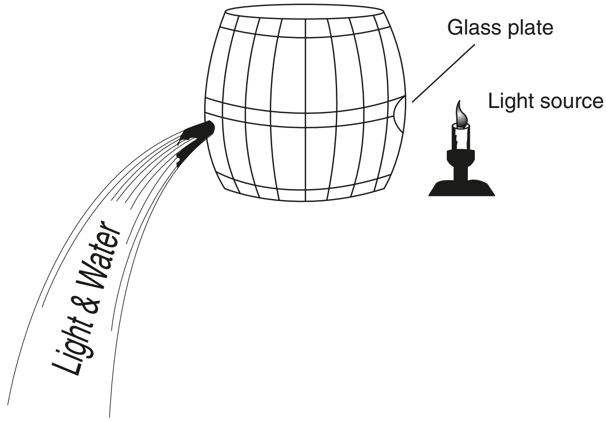


Figure 1.2 What actually happened

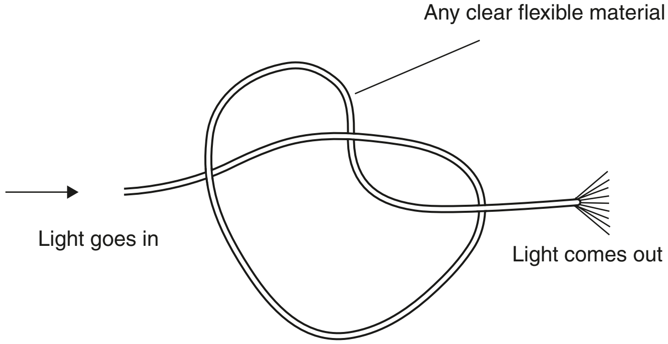


Figure 1.3 Light can go anywhere

Light guiding

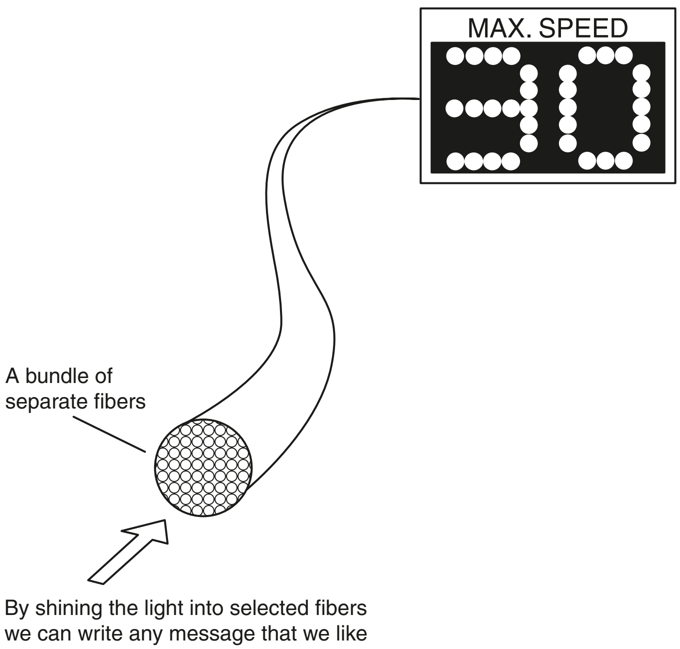
There are many applications of light guiding – and more are being devised every day.

Here are a few interesting examples.

Road signs

A single light source can be used to power many optic fibers. This technique is used in traffic signs to indicate speed limits, lane closures, etc. The light source is built into a reflector. The front face of the reflector can then be covered with the ends of a whole series of optic fibers. These optic fibers convey the light to the display board where they can be arranged to spell out the message (Figure 1.4).

Figure 1.4 Each fiber goes to one of the 'lights'



This method has the advantage that, since the whole display is powered by one electric light bulb, we never get the situation where the message can be misread – it is either all there or it's all missing.

The same method can be used to illuminate instrument panels. Instead of a series of separate light bulbs, one of which is bound to be unlit at any critical time, the whole display is powered by a single bulb, with a spare one ready to switch in when required.

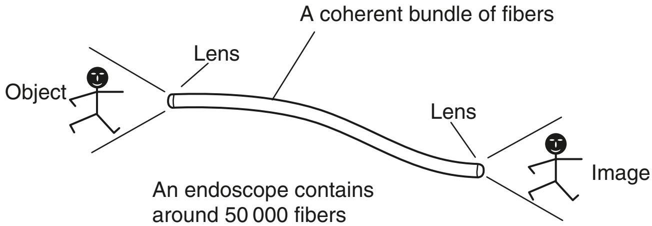
Endoscopes

As the light travels down the fiber, light rays get thoroughly jumbled up. This means that a single fiber can only carry an average value of the light that enters it.

To convey a picture along a single fiber is quite impossible. To produce a picture, a large number of optic fibers must be used in the same way that many separate points of light, or pixels, can make an image on a cathode ray tube.

This is the principle of an endoscope, used by doctors to look inside us with the minimum of surgery (Figure 1.5). This is a bundle of around 50 000 very thin fibers of 8 μm (315 millionths of an inch) diameter, each carrying a single light level. An endoscope is about one meter in length with a diameter of about 6 mm or less. For illumination, some of the fibers are used to convey light from a 300 watt xenon bulb. A lens is used at the end of the other fibers to collect the picture information which is then often displayed on a video monitor for easy viewing.

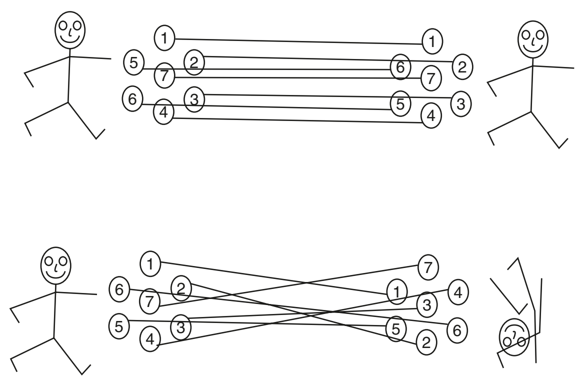
Figure 1.5
An endoscope



To rebuild the image at the receiving end, it is essential that the individual fibers maintain their relative positions within the endoscope otherwise the light information will become scrambled. Bundles of fibers in which the position of each fiber is carefully controlled are called *coherent bundles* (Figure 1.6).

Many fiber endoscopes are in everyday use, although the move now is towards the use of miniature cameras instead of fibers.

Figure 1.6
A coherent bundle (top) gives a good image. If it's not coherent (bottom) the image is scrambled



Hazardous areas

If we have a tank containing an explosive gas, a safe form of illumination is essential. One solution is to use a light source situated a safe distance away from the tank, and transmit the light along an optic fiber. The light emitted from the end of the fiber would not have sufficient power to ignite the gas.

All at sea

Lighting on both ships and small boats is more difficult and more critical than lighting a building. The marine environment is very hostile to electrical installations. The salt water is highly corrosive to the brass and copper used to make the connections to the lights and the corrosive spray envelops the largest ship or the smallest harbor launch.

Imagine a dark winter's night, a gale is blowing spray in horizontal sheets and our harbor launch is heading out to sea to meet the incoming ship. The mountainous seas crash into our launch and we need both our hands to avoid being swept overboard.

Lighting is no longer a nice-to-have like the streetlight outside our house, it is vital and in many situations our lives will depend on it. In this environment optic fibers have much to offer in reliability, visibility and ease of maintenance.

A single light source can be used to illuminate many different locations at the same time. Optic fibers can convey the light to the exact place it is needed so we can see the edge of a step, the edge of the deck or the next hand-hold as we stumble along the deck in total blackness. By using filters, we can even add colors to each light to reduce glare or to identify different positions or controls. An optic fiber can also provide the ultimate in underwater inspection lights.

It not only allows us to have light just where we need it but we can have just the amount that we need. Too much light is often as irritating as too little as it causes glare and loss of our night vision, and it can take 20 minutes or so before our eyes fully readjust to the darkness.

Reliability is much enhanced by enabling the light source and all the electrical wiring to be mounted below decks in a dry environment. Changing the light source is very easy – much appreciated by anyone who has climbed a mast on a winter's night to change the bulb in a navigation light. Physical damage can damage one of the optic fibers but the others will continue working.

Flexible lighting

If an optic cable allows light to escape it may be of no use for data communication but it can make very innovative light sources with virtually endless uses. A 320 mW visible light laser can cause over 200 m (660 ft) of the fiber to glow and, being powered by a sealed battery, it can provide up to three hours of light, safe enough for use in hostile environments, such as with explosive gases, and hardy enough to withstand the worst environments. The system can be completely portable or permanently installed into a building.

The range of fibers extends from ultra thin silica of 0.7 mm (about 1/32 in) diameter for permanent installation in buildings to a highly flexible cable with a plastic sheath giving a minimum bend radius of only 5 mm (1/5th in) and an overall diameter of 8 mm (1/3rd in).

The cladding may consist of materials such as FEP (Fluoro Ethylene Polymer), a plastic similar to PTFE (Poly Tetra Fluoro Ethylene), which has three properties that make it ideal for a wide range of environments. It is very chemical resistant, is unaffected by water and can operate over an extreme range of temperatures.

Having read through the above characteristics, it is much easier to think of new uses than it is to imagine lighting situations in which it would not be appropriate.

Here are a few applications: marking escape routes for fire fighters; mountain and mine rescue; underwater routes for divers; helicopter landing zones; oil refineries; planes; ships, tunnels. The list is almost endless (see Bibliography).

Communications

In 1880, only four years after his invention of the telephone, Alexander Graham Bell used light for the transmission of speech. He called his device a *Photophone*. It was a tube with a flexible mirror at its end. He spoke down the tube and the sound vibrated the mirror. The modulated light was detected by a photocell placed at a distance of 200 m or so. The result was certainly not hi-fi but the speech could at least be understood.

Following the invention of the ruby laser in 1960, the direct use of light for communication was reinvestigated. However, the data links still suffered from the need for an unobstructed path between the sender and the receiver. Nevertheless, it was an interesting idea and in 1983 it was used to send a message, by Morse code, over a distance of 240 km (150 miles) between two mountaintops.

Enormous resources were poured into the search for a material with sufficient clarity to allow the development of an optic fiber to carry the light over long distances. The early results were disappointing. The losses were such that the light power was halved every three meters along the route. This would reduce the power by a factor of a million over only 60 meters (200 feet). Obviously this would rule out long distance communications even when using a powerful laser. Within ten years however, we were using a silica glass with losses comparable with the best copper cables.

The glass used for optic fiber is unbelievably clear. We are used to normal 'window' glass looking clear but it is not even on the same planet when compared with the new silica glass. We could construct a pane of glass several kilometers thick and still match the clarity of a normal window. If water were this clear we would be able to see the bottom of the deepest parts of the ocean.

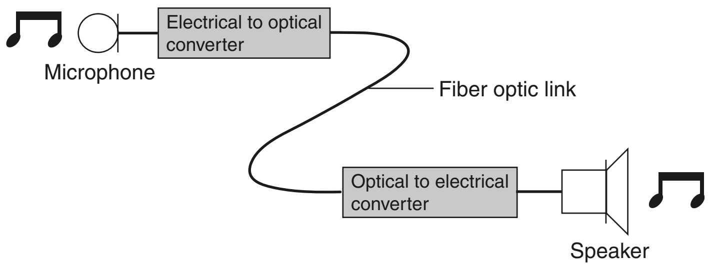
We occasionally use plastic for optic fiber but its losses are still impossibly high for long distance communications, but for short links of a few tens of meters it is satisfactory and simple to use. It is finding increasing applications in hi-fi systems, and in automobile and other control circuitry.

On the other hand, a fiber optic system using a glass fiber is certainly capable of carrying light over long distances. By converting an input signal into short flashes of light, the optic fiber is able to carry complex information over distances of more than a hundred kilometers without additional amplification. This is at least fifty times better than the distances attainable using the best copper coaxial cables.

The system is basically very simple: a signal is used to vary, or modulate, the light output of a suitable source – usually a laser or an LED (light emitting diode).

The flashes of light travel along the fiber and, at the far end, are converted to an electrical signal by means of a photo-electric cell. Thus the original input signal is recovered (Figure 1.7).

Figure 1.7
A simple fiber optic system



When telephones were first invented, it took 75 years before we reached a global figure of 50 million subscribers. Television took only 13 years to achieve the same penetration and the Internet passed both in only four years. As all three of these use fiber optics it is therefore not surprising that cables are being laid as fast as possible across all continents and oceans. Optic fibers carry most of the half million international telephone calls leaving the USA everyday and in the UK over 95% of all telephone traffic is carried by fiber. Worldwide, fiber carries 85% of all communications. Some of the main international routes are shown in Figure 1.8.

Figure 1.8
Some of the main under-sea fiber routes

Terminology

A brief note on some terms: optic fiber, fiber optics and fiber.

- ▷ *optic fiber* is the transparent material, along which we can transmit light
- ▷ *fiber optics* is the system, or branch of engineering concerned with using the optic fibers. Optic fiber is therefore used in a fiber optic system
- ▷ *fiber* is a friendly abbreviation for either, so we could say that fiber is used in a fiber system.

Safety first

There is more safety information contained in the section on connectors but it is worth repeating here in case the reader is now sufficiently interested in the subject to rush out and play with some optical fiber.

- ▷ Optical fiber ends are extremely sharp, don't let them penetrate the skin
- ▷ Dispose of any fiber off-cuts in a suitable container. Don't leave them sticking in the carpet!
- ▷ Don't look into the end of a fiber if it is connected (or even if you suspect it may possibly be connected) to a transmitting system. Harmful infrared energy may damage your eyes
- ▷ Use fiber optic tools carefully and use any solvents or cleaners according to the manufacturer's instructions.

Quiz time 1

In each case, choose the best option.

1 A transparent material along which we can transmit light is called:

(a) a fiber optic

(b) a flashlight

(c) an optic fiber

(d) a xenon bulb

2 A simple fiber optic system would consist of:

(a) a light source, an optic fiber and a photo-electric cell

(b) a laser, an optic fiber and an LED

(c) a copper coaxial cable, a laser and a photo-electric cell

(d) an LED, a cathode ray tube and a light source

3 Optic fiber is normally made from:

(a) coherent glass and xenon

(b) copper

(c) water

(d) silica glass or plastic

4 It is not true that:

(a) endoscopes use coherent bundles of fibers

(b) silica glass is used because of its clarity

(c) a photocell converts light into electric current

(d) plastic fiber is normally used for long distance communications

5 Plastic optic fibers:

(a) have lower losses than glass fibers

(b) are used in the automobile industry

(c) are suitable for long distance communications

(d) are used as a form of electrical to optical converter

2

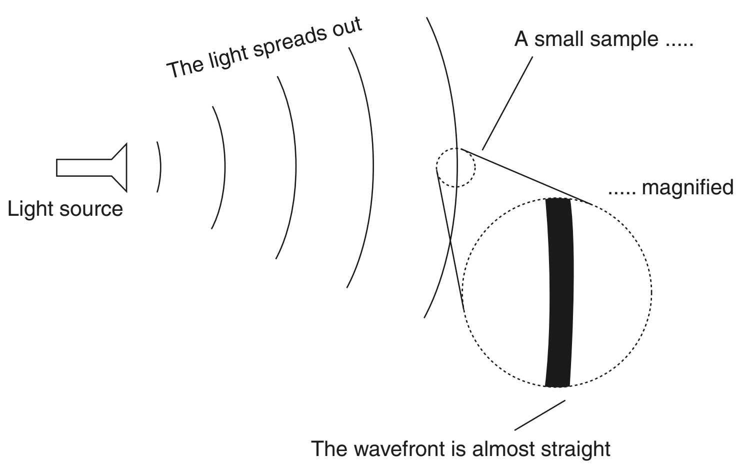
What makes the light stay in the fiber?

Refraction

Imagine shining a flashlight. The light waves spread out along its beam. Looking down and seeing the wave crests it would appear as shown in Figure 2.1.

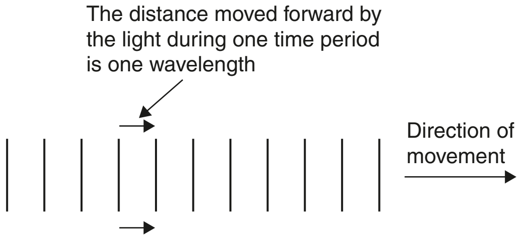
As we move further from the light source, the wavefront gets straighter and straighter. At a long distance from the light source, the wavefront would be virtually straight. In a short interval of time each end of the wavefront would move forward a set distance.

Figure 2.1
The wavefront becomes straighter



If we look at a single ray of light moving through a clear material the distance advanced by the wavefront would be quite regular as shown in Figure 2.2.

Figure 2.2
The wavefront moves forward



There is a widely held view that light always travels at the same speed. This 'fact' is simply not true. The speed of light depends upon the material through which it is moving. In free space light travels at its maximum possible speed, close to 300 million meters or nearly eight times round the world, in a second.

When it passes through a clear material, it slows down by an amount dependent upon a property of the material called its *refractive index*. For most materials that we use in optic fibers, the refractive index is in the region of 1.5.

So:

Speed of light in free space/speed of light in the material = refractive index

Units

As the refractive index is simply a ratio of the speed of light in a material to the speed of light in free space, it does not have any units.

Using the example value of 1.5 for the refractive index, this gives a speed of about 200 million meters per second. With the refractive index on the bottom line of the equation, this means that the lower the refractive index, the higher the speed of light in the material. This is going to be vital to our explanation and is worth emphasizing:

lower refractive index = higher speed

Let's have a look at a ray of light moving from a material of high refractive index to another material with a lower index in which it would move faster. We can see that the distances between the successive wave crests, or the wavelength, will increase as soon as the light moves into the second material.

Now, the direction that the light approaches the boundary between the two materials is very significant. In Figure 2.3 we choose the simplest case in which the light is traveling at right angles to the boundary.

We will now look at a ray approaching at another angle. As the ray crosses the boundary between the two materials, one side of the ray will find itself traveling

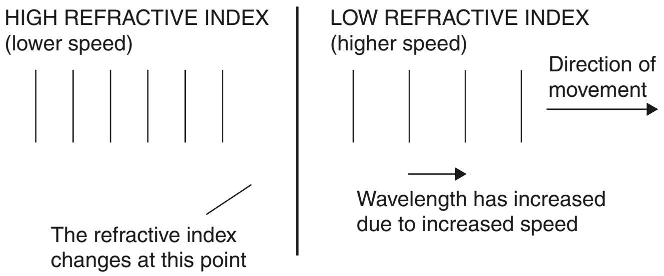


Figure 2.3
The light changes its speed

in the new, high velocity material whilst the other side is still in the original material. The result of this is that the wavefront progresses further on one side than on the other. This causes the wavefront to swerve. The ray of light is now wholly in the new material and is again traveling in a straight line albeit at a different angle and speed (Figure 2.4).

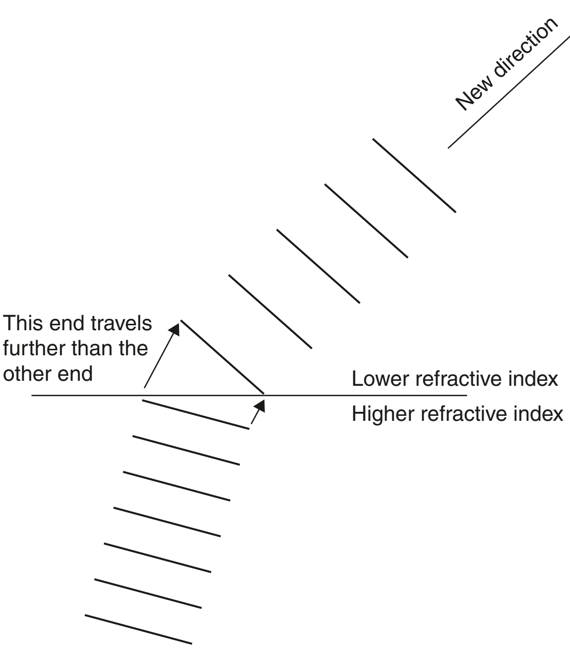


Figure 2.4
The light is refracted

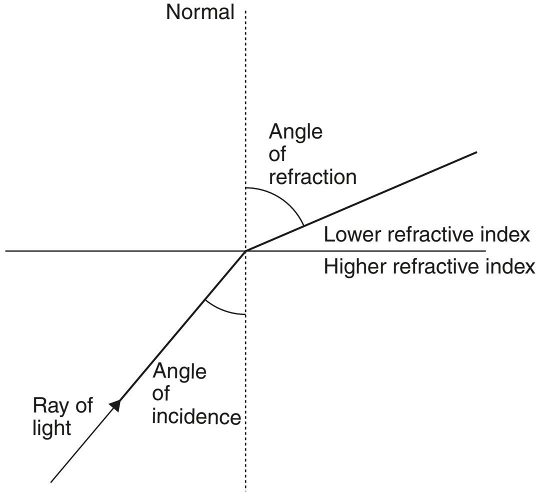
The amount by which the ray swerves and hence the new direction is determined by the relative refractive indices of the materials and the angle at which the ray approaches the boundary.

Snell's law

The angles of the rays are measured with respect to the *normal*. This is a line drawn at right angles to the boundary line between the two refractive indices. The angles of the incoming and outgoing rays are called the angles of *incidence* and *refraction* respectively. These terms are illustrated in Figure 2.5.

Notice how the angle increases as it crosses from the higher refractive index material to the one with the lower refractive index.

Figure 2.5
The names of the parts



Willebrord Snell, a Dutch astronomer, discovered that there was a relationship between the refractive indices of the materials and the sine of the angles. He made this discovery in the year 1621.

Snell's law states the relationship as:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Where: n_1 and n_2 are the refractive indices of the two materials, and $\sin\theta_1$ and $\sin\theta_2$ are the angles of incidence and refraction respectively.

There are four terms in the formula, so provided that we know three of them, we can always transpose it to find the other term. We can therefore calculate the amount of refraction that occurs by using Snell's law.

A worked example

Calculate the angle shown as θ_2 in Figure 2.6.

The first material has a refractive index of 1.51 and the angle of incidence is 38° and the second material has a refractive index of 1.46.

Starting with Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

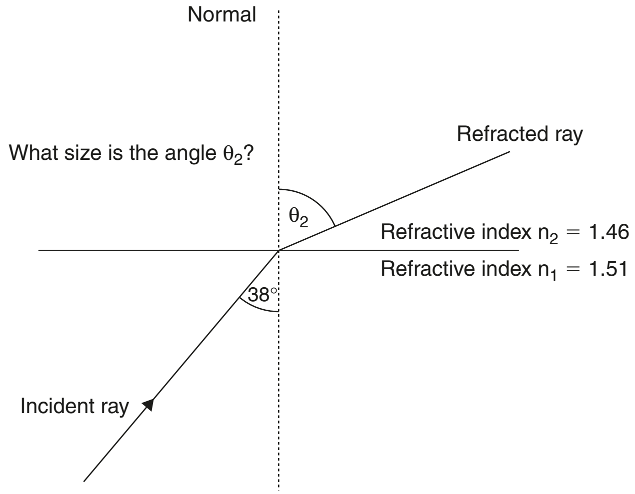


Figure 2.6 An example using Snell's law

We know three out of the four pieces of information so we substitute the known values: $1.51 \sin 38° = 1.46 \sin \theta_2$

Transpose for $\sin \theta_2$ by dividing both sides of the equation by 1.46. This gives us:

$$\frac{1.51 \sin 38°}{1.46} = \sin \theta_2$$

Simplify the left-hand side:

$$0.6367 = \sin \theta_2$$

The angle is therefore given by:

$$\theta_2 = \arcsin 0.6367$$

So:

$$\theta_2 = 39.55°$$

Critical angle

As we saw in the last section, the angle of the ray increases as it enters the material having a lower refractive index.

As the angle of incidence in the first material is increased, there will come a time when, eventually, the angle of refraction reaches 90° and the light is refracted along the boundary between the two materials. The angle of incidence which results in this effect is called the critical angle.

We can calculate the value of the critical angle by assuming the angle of refraction to be 90° and transposing Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin 90°$$

As the value of sin 90° is 1, we can now transpose to find sin θ_1, and thence θ_1, (which is now the critical angle):

$$\theta_{critical} = \arcsin\left(\frac{n_2}{n_1}\right)$$

A worked example

A light ray is traveling in a transparent material of refractive index 1.51 and approaches a second material of refractive index 1.46. Calculate the critical angle.

Using the formula for the critical angle just derived:

$$\theta_{critical} = \arcsin\left(\frac{n_2}{n_1}\right)$$

Put in the values of the refractive indices:

$$\theta_{critical} = \arcsin\left(\frac{1.46}{1.51}\right)$$

Divide the two numbers:

$$\theta_{critical} = \arcsin(0.9669)$$

So:

$$\theta_{critical} = 75.2°$$

Total internal reflection

The critical angle is well named as its value is indeed critical to the operation of optic fibers. At angles of incidence less than the critical angle, the ray is refracted as we saw in the last section.

However, if the light approaches the boundary at an angle greater than the critical angle, the light is actually reflected from the boundary region back into the first material. The boundary region simply acts as a mirror. This effect is called total internal reflection (TIR). Figure 2.7 shows these effects.

The effect holds the solution to the puzzle of trapping the light in the fiber. If the fiber has parallel sides, and is surrounded by a material with a lower refractive index, the light will be reflected along it at a constant angle – shown as ø in the example in Figure 2.8.

Any ray launched at an angle greater than the critical angle will be propagated along the optic fiber. We will be looking at this in more detail in Chapter 4.

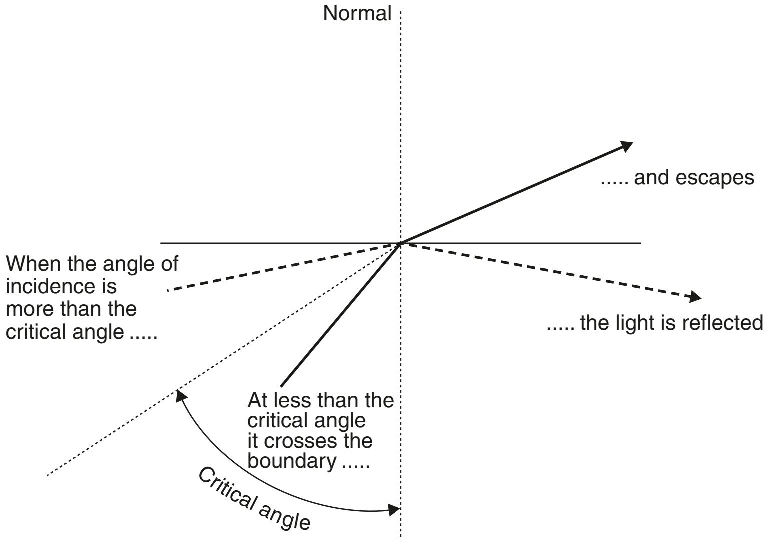


Figure 2.7 Total internal reflection

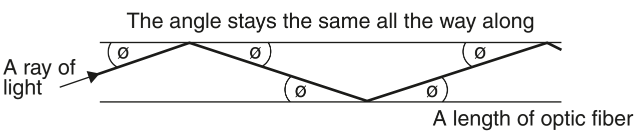


Figure 2.8 Light can bounce its way along the fiber

Quiz time 2

In each case, choose the best option.

1 The speed of light in a transparent material:

(a) is always the same regardless of the material chosen

(b) is never greater than the speed of light in free space

(c) increases if the light enters a material with a higher refractive index

(d) is slowed down by a factor of a million within the first 60 meters

2 A ray of light in a transparent material of refractive index 1.5 is approaching a material with a refractive index of 1.48. At the boundary, the critical angle is:

(a) 90°

(b) 9.4°

(c) 75.2°

(d) 80.6°

3 If a ray of light approaches a material with a greater refractive index:

(a) the angle of incidence will be greater than the angle of refraction
(b) TIR will always occur
(c) the speed of the light will increase immediately as it crosses the boundary
(d) the angle of refraction will be greater than the angle of incidence

4 If a light ray crosses the boundary between two materials with different refractive indices:

(a) no refraction would take place if the angle of incidence was 0°
(b) refraction will always occur
(c) the speed of the light will not change if the incident ray is traveling along the normal
(d) the speed of light never changes

5 The angle '?' in Figure 2.9 has a value of:

(a) 80.6°
(b) 50°
(c) 39.3°
(d) 50.7°

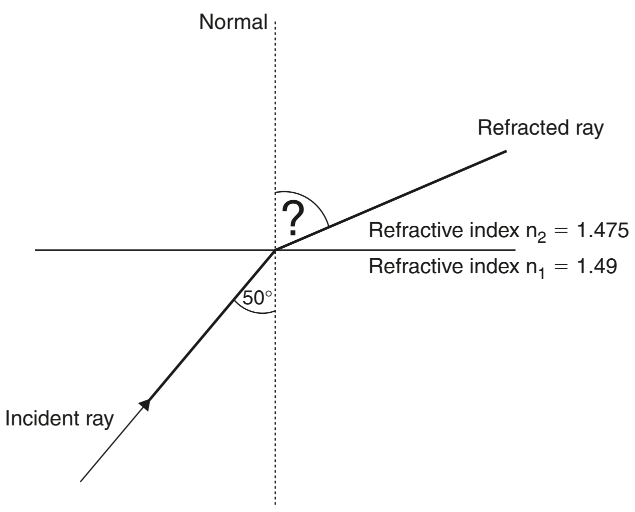


Figure 2.9 Question 5: calculate the angle?