

# 3

## The choice of frequency

### Electromagnetic waves

Radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency ( $f$ ) and is measured in Hertz (Hz), where  $1 \text{ Hz} = 1 \text{ cycle per second}$ .

The speed of the electromagnetic wave ( $v$ ) in free space is approximately  $3 \times 10^8 \text{ ms}^{-1}$ . The term ' $\text{ms}^{-1}$ ' means meters per second. The distance traveled during each cycle, called the wavelength ( $\lambda$ ), can be calculated by the relationship:

$$\text{wavelength} = \frac{\text{speed of light}}{\text{frequency}}$$

In symbols, this is:

$$\lambda = \frac{v}{f}$$

By transposing we get the alternative forms:

$$\text{frequency} = \left( \frac{\text{speed of light}}{\text{wavelength}} \right) \left( f = \frac{v}{\lambda} \right)$$

and:

$$\text{speed of light} = \text{frequency} \times \text{wavelength} \quad (v = \lambda f)$$

### Some useful multiples

Here are some common multiples used in fiber optics:

M	Mega = 1 000 000 = $1 \times 10^6$
k	kilo = 1 000 = $1 \times 10^3$
m	milli = $\frac{1}{1\,000} = 1 \times 10^{-3}$
$\mu$	micro = $\frac{1}{1\,000\,000} = 1 \times 10^{-6}$
n	nano = $\frac{1}{1\,000\,000\,000} = 1 \times 10^{-9}$
p	pico = $\frac{1}{1\,000\,000\,000\,000} = 1 \times 10^{-12}$

Note: micron is the previous name for the micrometer  $1 \times 10^{-6}$  m and is still commonly used within the fiber optics industry. Another common term is ‘nano-meter’, i.e. one thousand millionths of a meter, which is used when describing the wavelength of light and is given the abbreviation *nm*.

### Electromagnetic spectrum

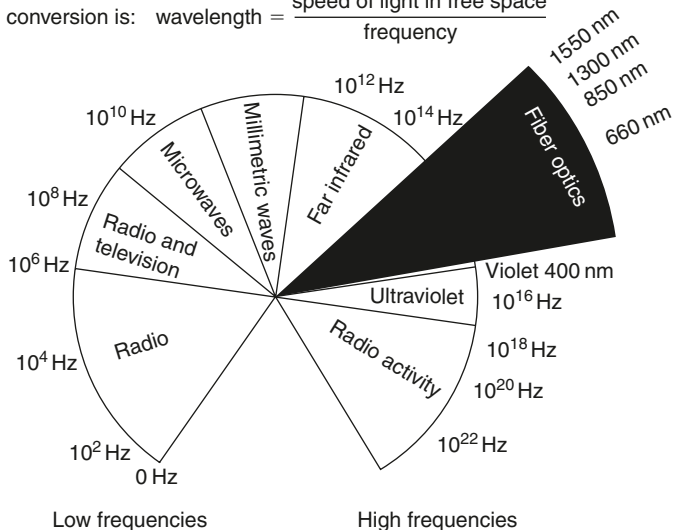
In the early days of radio transmission when the information transmitted was mostly restricted to the Morse code and speech, low frequencies (long waves) were used. The range of frequencies able to be transmitted, called the *bandwidth*, was very low. This inevitably restricted us to low speed data transmission and poor quality transmission (Figure 3.1).

**Figure 3.1**

Fiber optics use visible and infrared light

In fiber optics, we find it more convenient to use the wavelength of the light instead of the frequency.

The conversion is:  $\text{wavelength} = \frac{\text{speed of light in free space}}{\text{frequency}}$



As time went by, we required a wider bandwidth to send more complex information and to improve the speed of transmission. To do this, we had to increase the frequency of the radio signal used. The usable bandwidth is limited by the frequency used – the higher the frequency, the greater the bandwidth available.

When television was developed we again had the requirement of a wider bandwidth and we responded in the same way – by increasing the frequency. And so it went on.

More bandwidth needed? Use a higher frequency. For something like sixty years this became an established response – we had found the answer!

Until fiber optics blew it all away.

The early experiments showed that visible light transmission was possible and we explored the visible spectrum for the best light frequency to use.

The promise of fiber optics was the possibility of increased transmission rates. The old solution pointed to the use of the highest frequency but here we met a real problem. We found that the transmission losses were increasing very quickly. In fact the losses increased by the fourth power. This means that if the light frequency doubled, the losses would increase by a factor of  $2^4$  or 16 times.

We quickly appreciated that it was not worth pursuing higher and higher frequencies in order to obtain higher bandwidths if it meant that we could only transmit the data over very short distances.

The bandwidth of a light based system was so high that a relatively low frequency could be tolerated in order to get lower losses and hence more transmission range. So we explored the lower frequency or red end of the visible spectrum and then even further down into the infrared.

And that is where we are at the present time.

Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber or perhaps for fault testing where leaking visible light can be a diagnostic aid.

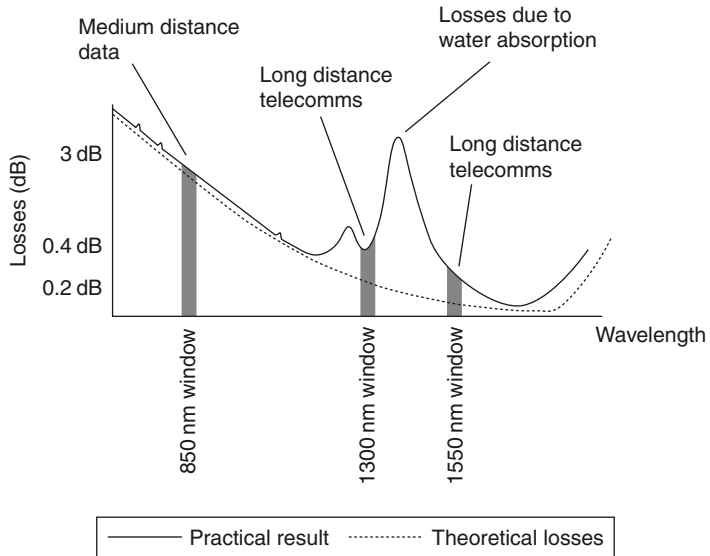
## Windows

Having decided to use infrared light for (nearly) all communications, we are still not left with an entirely free hand. We require light sources for communication systems and some wavelengths are easier and less expensive to manufacture than others. The same applies to the photodetectors at the receiving end of the system.

Some wavelengths are not desirable: 1380 nm for example. The losses at this wavelength are very high due to water within the glass. It is a real surprise to find that glass is not totally waterproof. Water in the form of hydroxyl ions is absorbed within the molecular structure and absorbs energy with a wavelength of 1380 nm. During manufacture it is therefore of great importance to keep the glass as dry as possible with water content as low as 1 part in  $10^9$ .

It makes commercial sense to agree on standard wavelengths to ensure that equipment from different manufacturers is compatible. These standard wavelengths are called *windows* and we optimize the performance of fibers and light sources so that they perform at their best within one of these windows (Figure 3.2).

**Figure 3.2**  
The infrared windows used in fiber optics



The 1300 nm and 1550 nm windows have much lower losses and are used for long distance communications although we have started to see their introduction into local area networks and campus networks due to the higher bandwidth available when using lasers (rather than LEDs) at these longer wavelengths. The shorter wavelength window centred around 850 nm has higher losses and is used for shorter range data transmissions and local area networks (LANs), perhaps up to 10 km or so. The 850 nm window remains in use because the system is less expensive and easier to install.

### Quiz time 3

In each case, choose the best option.

**1 The common windows used in fiber optic communications are centred on wavelengths of:**

- (a) 1300 nm, 1550 nm and 850 nm
- (b) 850 nm, 1500 nm and 1300 nm
- (c) 1350 nm, 1500 nm and 850 nm
- (d) 800 nm, 1300 nm and 1550 nm

---

**2 A wavelength of 660 nm is often used for visible light transmission.**

**The frequency of this light in free space would be:**

- (a)  $660 \times 10^{-9}$  Hz
- (b)  $4.5 \times 10^{14}$  Hz
- (c)  $300 \times 10^8$  Hz
- (d)  $45 \times 10^{12}$  Hz

---

**3 In free space, light travels at approximately:**

- (a)  $186\,000\text{ ms}^{-1}$
- (b)  $3 \times 10^9\text{ ms}^{-1}$
- (c)  $300\text{ ms}^{-1}$
- (d) 0.3 meters per nanosecond

---

**4 The window with the longest wavelength operates at a wavelength of approximately:**

- (a) 850 nm
- (b)  $1550\ \mu\text{m}$
- (c) 1350 nm
- (d)  $1.55\ \mu\text{m}$

---

**5 The 850 nm window remains popular because it:**

- (a) uses visible light and this allows plastic fibers to be used
- (b) the fiber is less expensive to install and has lower losses than any other windows
- (c) the system is less expensive and easier to install
- (d) allows higher data transmission rates

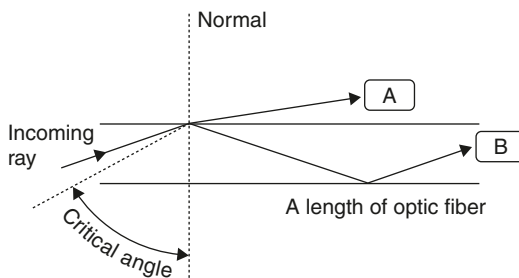
# 4

## Propagation of light along the fiber

Have a look at Figure 4.1. What path would be taken by the incoming ray? Would it finish up at A or B?

**Figure 4.1**

Does the ray go to A or B?



In Chapter 2 we saw that light approaching the outer edge of the optic fiber at an angle greater than the critical angle would be reflected back into the fiber and would bounce its way along as in the ray path B.

This diagram suggests that a useful transmission system can be built from a simple length of clear glass. Unfortunately, it is not that straightforward – as soon as we touch the fiber, we transfer some grease from our skin onto its surface. This causes a problem.

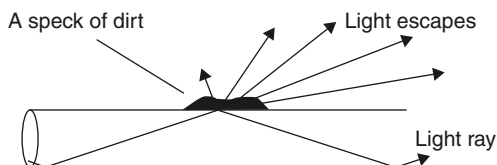
## Problem

The contamination on the surface changes the refractive index of the material surrounding the glass. Previously, it was air which has a refractive index of 1 and it is now grease which, in common with all other materials, has a refractive index greater than 1.

This will locally increase the critical angle and some of the light will now find itself approaching the surface at an angle less than the new critical angle. It will then be able to escape (Figure 4.2).

**Figure 4.2**

Any contamination causes a power loss?



Dirt, grease, rain, in fact any contamination will allow leakage of the light. The whole situation would be impossible. We would not even be able to support the fiber, let alone keep it perfectly clean.

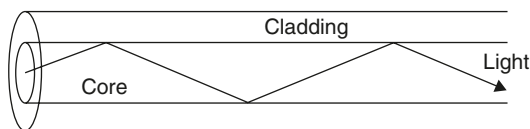
For every problem there is a solution.

## Solution

Cover the fiber with another layer of glass as shown in Figure 4.3.

**Figure 4.3**

How to keep the core clean?



The original glass, called the core, now has a new layer, the cladding, added around the outside during manufacture. The core and the cladding form a single solid fiber of glass.

The optic fiber is very thin. Typical dimensions are shown in Figure 4.4.

As mentioned earlier, a  $\mu\text{m}$  is a millionth of a meter and was previously referred to as a micron (a term we still hear). A typical core size of  $50\ \mu\text{m}$  is about the thickness of one page of this book.

Our everyday experience with glass tells us that it is very brittle. We cannot bend a piece of window glass – it just shatters.

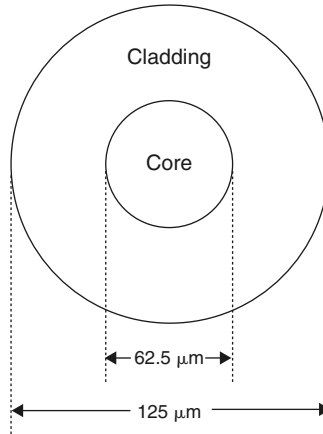
With optic fiber however, this is not the case. We can easily bend it in a full circle as can be seen in Figure 4.5.

So, why the difference?

We shouldn't really ask 'why can we bend a glass fiber?' but rather 'why isn't all glass that flexible?'

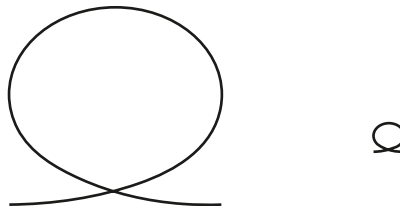
**Figure 4.4**

A typical size of fiber



**Figure 4.5**

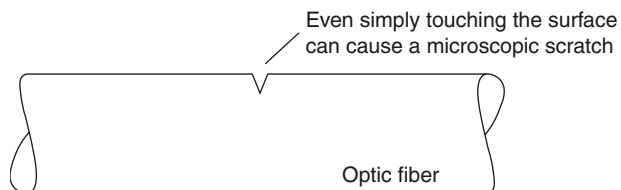
Bendy glass – shown full size. The bend can be as tight as that on the right before it breaks



When we manufacture glass, its surface is perfectly smooth until we damage it. Glass is very delicate and the normal manufacturing process is enough to cause damage. Even simply touching its surface with a finger is enough. The result is microscopic cracking of the surface (Figure 4.6).

**Figure 4.6**

A very small surface flaw



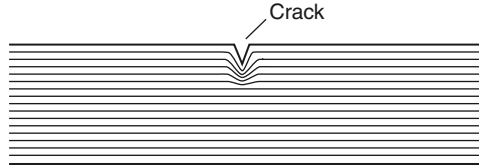
When we stretch it or start to bend it, we cause lines of stress to occur in the material. The stress lines are concentrated around the end of the crack (Figure 4.7). The stress builds up until it exceeds the strength of the material which responds by relieving the stress by extending the crack a little further.

This concentrates the stress even more and the material again responds by extending the crack. In this manner the crack propagates through the material at very high speeds and the glass shatters (Figure 4.8). In glass, the crack propagation speed is



**Figure 4.7**

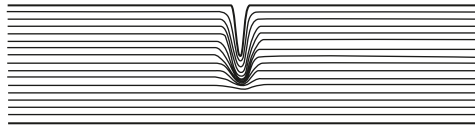
A build-up of stress around the tip of the crack



**Figure 4.8**

The crack propagates

Stress is relieved by extending the crack but this causes more stress and makes the situation even worse

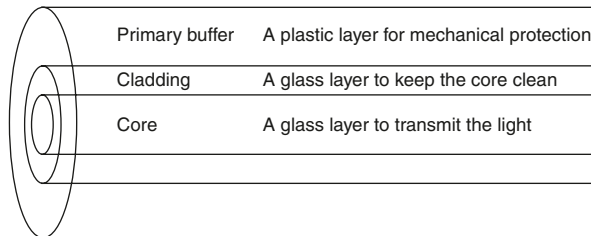


about  $1700 \text{ ms}^{-1}$  (4000 mph). An optic fiber would break in less than a tenth of a microsecond and a window pane in a leisurely 3 microseconds.

The difference then, between the optic fiber bending in a circle and the sheet of window glass, is the presence of those minute surface scratches. To protect the optic fiber from surface scratches, we add a layer of soft plastic to the outside of the cladding. This extra layer is called the primary buffer (sometimes called the primary coating or just the *buffer*) and is present only to provide mechanical protection and has nothing to do with light transmission (Figure 4.9).

**Figure 4.9**

The completed optic fiber

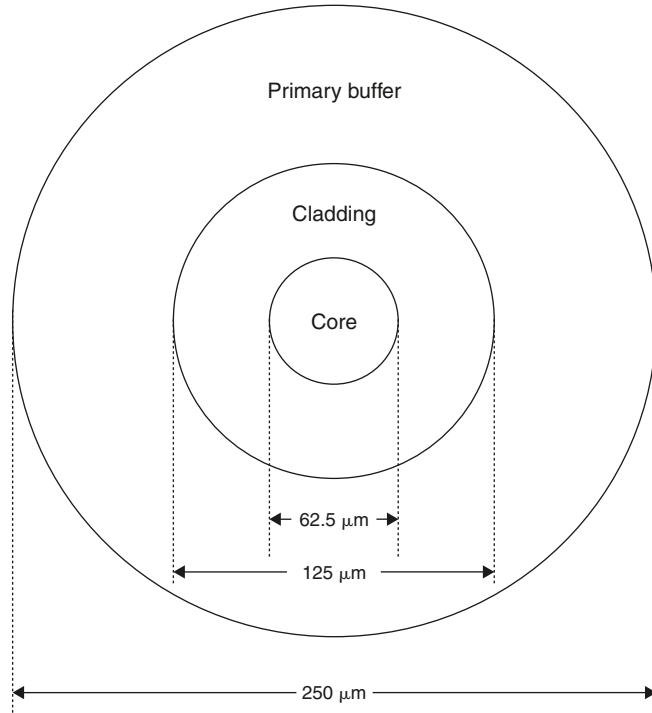


During manufacture, the core and cladding are made simultaneously, and immediately after the glass has cooled sufficiently the primary buffer is added so that it can be stored on a drum without damage.

Typical dimensions are shown in Figure 4.10. To enable the glass to be used industrially, it has a further protective layer or layers added. The choice of material for the outer layer, called the jacket, depends upon the use to which the cable is to be put. Chapter 8 looks at the choices in more detail.

**Figure 4.10**

The primary buffer diameter is a standard size in many fibers



**Three points which are important to appreciate:**

- ▷ the optic fiber is solid, there is no hole through the middle
- ▷ the buffer and the jacket are only for mechanical protection
- ▷ the light is transmitted through the core but to a small extent it travels in the cladding and so the optical clarity of the cladding is still important.

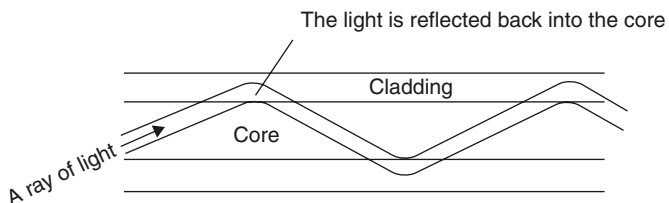
So, why does the light enter the cladding?

If the angle of incidence is greater than the critical angle, the light ray is reflected back into the first material by the process of refraction (TIR).

To be refracted it must enter the cladding, as shown in Figure 4.11.

**Figure 4.11**

Light enters cladding during reflection



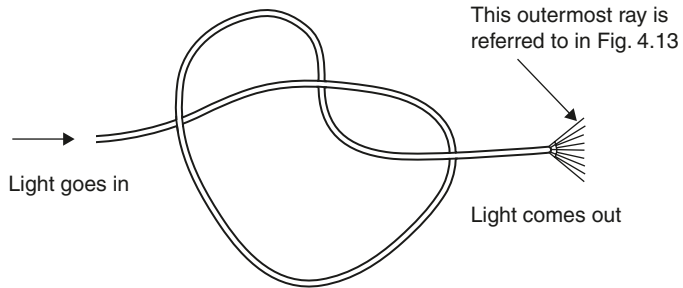
We can now see that an opaque cladding would prevent the ray from being propagated along the fiber since the light would not be able to pass through the cladding.

## Getting the light into the fiber

When we shine light along a fiber, it shines out of the far end.

We can see the light spreading out from the end of the fiber in Figure 4.12, and we can calculate the angle at which it spreads out by Snell's law.

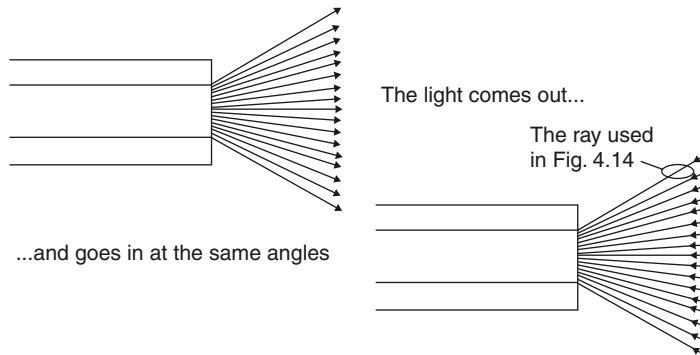
**Figure 4.12**  
See how the light spreads out from the end



### Here is the situation

The ray shown has bounced its way along the fiber at the critical angle. It leaves the fiber as the one on the outermost edge (Figure 4.13).

**Figure 4.13**  
All light paths are reversible



Let's assume the same values that we have used previously.

- ▷ core refractive index = 1.5
- ▷ cladding refractive index is 1.48.

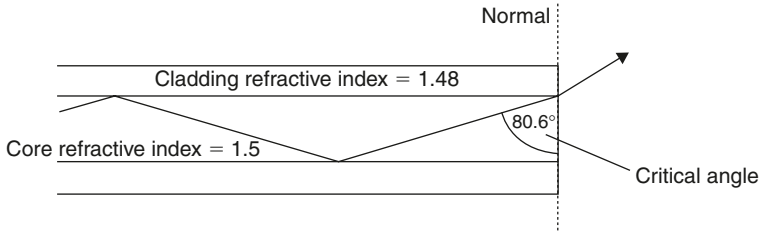
This gives an approximate critical angle (as in Figure 4.14) of:

$$\theta_{\text{critical}} = \frac{1.48}{1.5} = 0.9866 = 80.6^\circ$$

As the angle is measured from the normal, the angle between the cladding boundary and the ray is actually  $90 - 80.6^\circ = 9.4^\circ$  as shown in Figure 4.15.

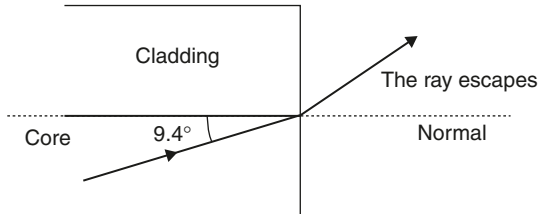
**Figure 4.14**

The ray travels along the fiber at the critical angle



**Figure 4.15**

The new angle of incidence



The refractive index of the air is 1 (near enough), so we can calculate the angle at which the ray leaves the fiber by applying Snell's law once again. Remember that the normal is the line at right angles to the change in the refractive index so it is now horizontal as in Figure 4.15.

Here we go:

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

We know values for three out of the four terms:

- ▷  $n_1$  = refractive index of the core = 1.5
- ▷  $\sin \theta_1$  = sine of the angle of incidence ( $9.4^\circ$ )
- ▷  $n_2$  = refractive index of air = 1.0
- ▷  $\sin \theta_2$  = sine of the angle of refraction.

It doesn't matter whether we use  $n_1$  and  $\sin \theta_1$  to refer to the core or to the air. The good news is that the result will come out the same whichever way we do it so this is one part we can't get wrong.

Load in the numbers that we know into the formula:

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

We get:

$$1.5 \sin 9.4^\circ = 1.0 \sin \theta_2$$

So:

$$1.5 \times 0.1637 = \sin \theta_2$$

And:

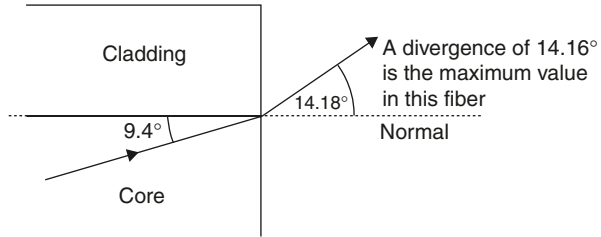
$$0.245 = \sin \theta_2$$

So:

$$\theta_2 = 14.18^\circ$$

We have now calculated the angle at which the light spreads out as  $14.18^\circ$ : not a very large angle but typical for a glass fiber (Figure 4.16).

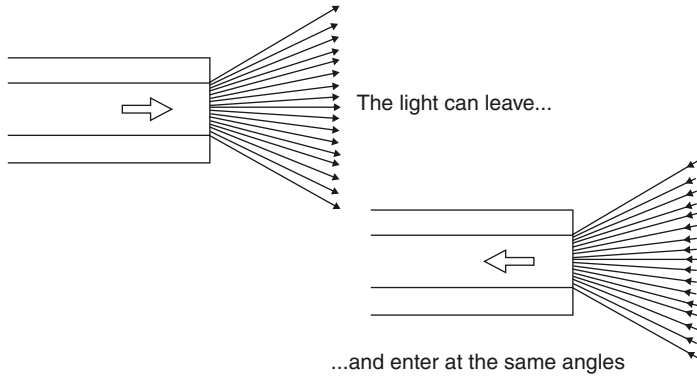
**Figure 4.16**  
The maximum angle of divergence



Incidentally, plastic fibers have a greater angle, around  $27^\circ$ .

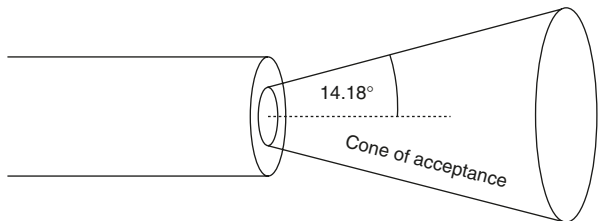
Since light direction is reversible, this  $14.18^\circ$  is also the angle at which light can approach the core and be propagated along the fiber (Figure 4.17).

**Figure 4.17**  
All light paths are reversible



The optic fiber is circular and therefore this angle is applicable in two dimensions and would look like a cone as shown in Figure 4.18.

**Figure 4.18**  
An acceptance angle of  $14.18^\circ$



## Cone of acceptance

The cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber.

### Note

The angle is measured from the axis of the cone so the total angle of convergence is actually twice the stated value.

Calculating the cone of acceptance was no easy job and it would be nice to find a more straightforward way of finding it. Luckily there is one and it involves a property of the fiber called the numerical aperture.

## Numerical aperture (NA)

The numerical aperture of a fiber is a figure which represents its light gathering capability. We have just seen that the acceptance angle also determines how much light is able to enter the fiber and so we must expect an easy relationship between the numerical aperture and the cone of acceptance as they are both essentially measurements of the same thing.

The formula for the numerical aperture is based on the refractive indices of the core and the cladding.

There is no fun to be had in deriving it, so here it is:

$$\text{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \quad (\text{no units})$$

and here is the short cut to the acceptance angle:

$$\text{acceptance angle} = \sin^{-1} \text{NA}$$

Let's try the short cut and see how it works out using our previous figures of  $n_{\text{core}} = 1.5$ , and  $n_{\text{cladding}} = 1.48$ .

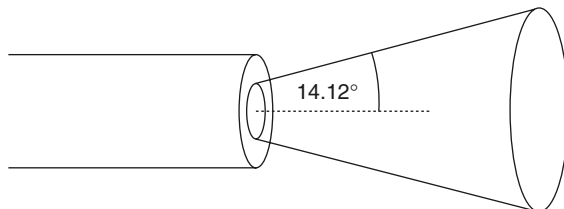
This would give a numerical aperture of:

$$\begin{aligned} \text{NA} &= \sqrt{1.5^2 - 1.48^2} \\ &= 0.244 \end{aligned}$$

resulting in an acceptance angle of  $\sin^{-1} 0.244$ , or  $14.12^\circ$  (Figure 4.19).

**Figure 4.19**

Acceptance angle =  
 $\sin^{-1} \text{NA}$

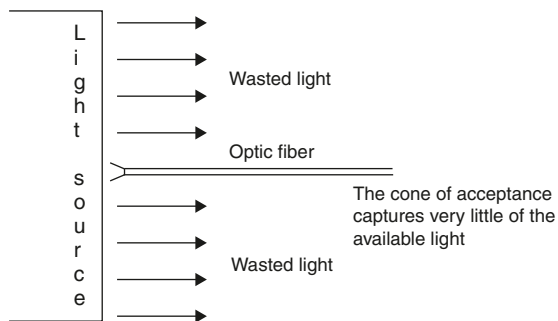


### A couple of calculator notes

- ▷ rounding off on the calculator has introduced a slight error in the final figure for the acceptance angle but it doesn't matter
- ▷  $\sin^{-1}$  on some calculators may be shown as arcsin or inv sin.

If a core of a fiber is only  $50\ \mu\text{m}$  thick (and many are less than this) and it only accepts light within its cone of acceptance whose typical value is  $12^\circ$ , it would accept only a very small proportion of the light if the end on the fiber were simply held up against a light source, as shown in Figure 4.20.

**Figure 4.20**  
A lens is often used to concentrate the light



To reduce this problem, lenses are normally employed to focus the light on to the end of the fiber.

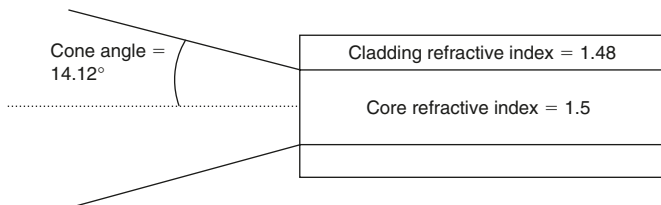
### What happens to the light which approaches the fiber outside of the cone of acceptance?

Let's follow a ray and find out.

Here is the situation. The exact angle chosen is not important since all angles respond in the same way.

Choosing the previous values of refractive index allows us to know the cone angle without doing all the calculations again (Figure 4.21).

**Figure 4.21**  
The acceptance angle is copied from Figure 4.19



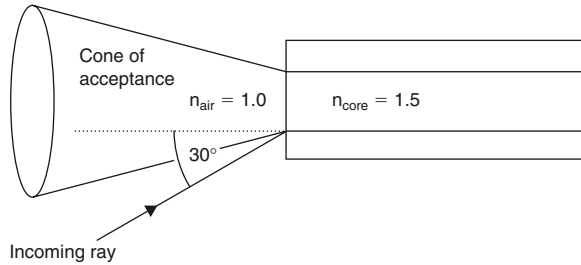
We choose an angle, anything over  $14.12^\circ$ , let's say  $30^\circ$  as in Figure 4.22, and now apply Snell's law:

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

$$n_{\text{air}} \sin \theta_{\text{air}} = n_{\text{core}} \sin \theta_{\text{core}}$$

**Figure 4.22**

We choose an angle outside the cone



Put in all the values that we know:

$$1.0 \sin 30^\circ = 1.5 \sin \theta_{\text{core}}$$

Transpose, by dividing both sides by 1.5:

$$\frac{1.0 \sin 30^\circ}{1.5} = \sin \theta_{\text{core}}$$

$$0.3333 = \sin \theta_{\text{core}}$$

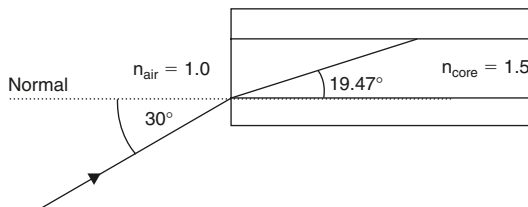
So:

$$\theta_{\text{core}} = \sin^{-1} 0.3333 = 19.47^\circ$$

The light ray continues across the core until it finds itself at the boundary between the core and the cladding as in Figure 4.23.

**Figure 4.23**

The light gets into the core



Now we have to be careful. It is easy at this stage to make a mistake.

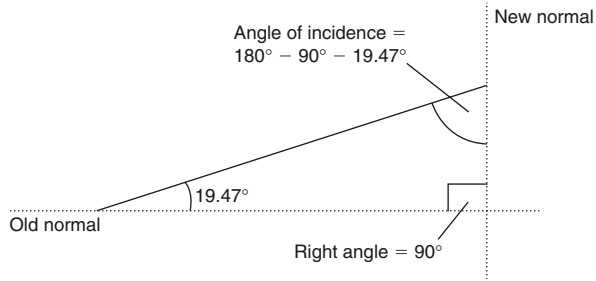
### There are two problems

- ▷ the normal between the core and the cladding is now vertical. We must remember that the normal is always drawn at right angles to the change in refractive index
- ▷ the angle used for Snell's law is the angle of incidence. This is the angle between the (new) normal and the approaching ray.

In our situation, shown in Figure 4.24, the ray and the two normals form a right angled triangle. In any triangle, the internal angles add up to 180°. If we subtract



**Figure 4.24**  
Changing the normal

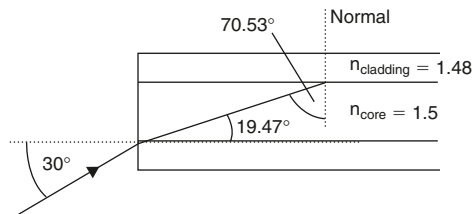


the 90° for the right angle and the 19.47° that we already know about, we find the new angle of incidence is:

$$180^\circ - 90^\circ - 19.47^\circ = 70.53^\circ$$

The ray will now either be reflected off the core/cladding boundary or it will penetrate the cladding.

**Figure 4.25**  
It approaches the cladding...



To decide, we need to know the critical angle between the core and the cladding. From Chapter 2 we may recall that the critical angle can be found from:

$$\theta_{\text{critical}} = \sin^{-1} \left( \frac{n_2}{n_1} \right)$$

Or, in this case:

$$\theta_{\text{critical}} = \sin^{-1} \left( \frac{n_{\text{cladding}}}{n_{\text{core}}} \right)$$

Putting in the figure gives:

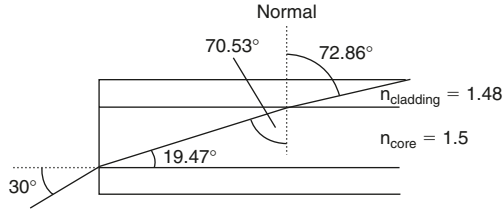
$$\theta_{\text{critical}} = \sin^{-1} \left( \frac{1.48}{1.5} \right)$$

Simplifying:

$$\theta_{\text{critical}} = \sin^{-1}(0.9867)$$

$$\theta_{\text{critical}} = 80.64^\circ$$

**Figure 4.26**  
... and into  
the cladding



The ray is therefore approaching the boundary at an angle less than the critical angle and will penetrate into the cladding.

Actually, we already knew this would happen because the original ray was approaching at an angle outside of the cone of acceptance and it is only the rays inside of the cone angle that will be propagated down the core.

So now, out comes Snell's law again to sort out the situation shown in Figure 4.26:

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

$$n_{\text{core}} \sin \theta_{\text{core}} = n_{\text{cladding}} \sin \theta_{\text{cladding}}$$

Put in the numbers that we know about:

$$1.5 \sin 70.53^\circ = 1.48 \sin \theta_{\text{cladding}}$$

Divide by 1.48:

$$\frac{(1.5)(0.9428)}{1.48} = \sin \theta_{\text{cladding}}$$

Simplifying:

$$0.9556 = \sin \theta_{\text{cladding}}$$

From this, the angle cladding can be found:

$$\theta_{\text{cladding}} = \sin^{-1} 0.9556$$

So:

$$\sin \theta_{\text{cladding}} = 72.86^\circ \text{ (give or take a bit for rounding off errors)}$$

The saga continues:

The ray now reaches the next boundary, between the cladding and the air. Will it escape into the air or will it be reflected back into the fiber?

The answer will again depend on how the angle of incidence compares with the critical angle.

**Figure 4.27**  
Part of Figure  
4.26

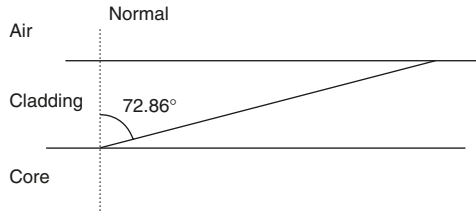
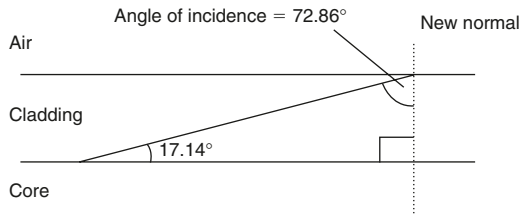


Figure 4.27 shows part of the previous diagram.

The angle between the core/cladding boundary and the previous normal is  $90^\circ$  and, as we know part of the angle is  $72.86^\circ$ , the other part must be  $90^\circ - 72.86^\circ = 17.14^\circ$  (Figure 4.28).

**Figure 4.28**  
Angle of  
incidence in  
the cladding



We now have a right angled triangle from which we can calculate the angle of incidence to be:

$$\text{angle of incidence} = 180^\circ - 17.14^\circ - 90^\circ = 72.86^\circ$$

Notice that this is the same angle as the angle of refraction from the last boundary. This just happens to be the case whenever the two boundaries are parallel to each other.

Now we check out the critical angle:

$$\theta_{\text{critical}} = \sin^{-1} \left( \frac{n_{\text{air}}}{n_{\text{cladding}}} \right)$$

$$\theta_{\text{critical}} = \sin^{-1} \left( \frac{1}{1.48} \right)$$

$$\theta_{\text{critical}} = \sin^{-1} 0.6757$$

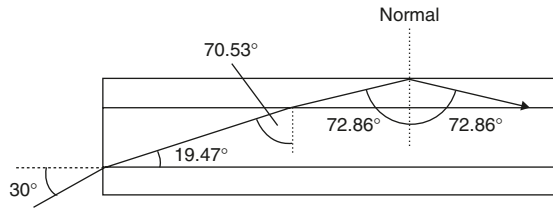
$$\theta_{\text{critical}} = 42.5^\circ$$

So, where does the ray go?

The angle of incidence is greater than the critical angle and so total internal reflection (TIR) will occur. Whenever light reflects off a straight surface it leaves

at the same angle as it approached at so we will have the situation shown in Figure 4.29.

**Figure 4.29**  
... and back into the fiber

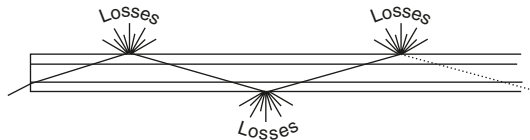


The ray is now moving back into the fiber. Where would it go? Have a guess.

To save a lot of tedious calculations, the answer is that it will propagate down the fiber using the whole of the fiber and not just the core. All the angles are simply repeats of those we have already calculated.

Figure 4.30 shows how it would look.

**Figure 4.30**  
The light is quickly attenuated



Surface contamination or the lack of clarity of the buffer, will cause serious losses along the outside of the cladding. The ray will be attenuated and will die out over the first kilometer (3300 ft).

## Names given to different rays

We have seen that rays approaching from within the cone of acceptance are successfully propagated along the fiber.

The position and the angle at which the ray strikes the core will determine the exact path taken by the ray. There are three possibilities, called the *skew*, *meridional* and the *axial* ray as shown in Figure 4.31. If light enters a fiber from a practical light source, all three rays tend to occur as well as those outside of the cone of acceptance as we have just investigated.

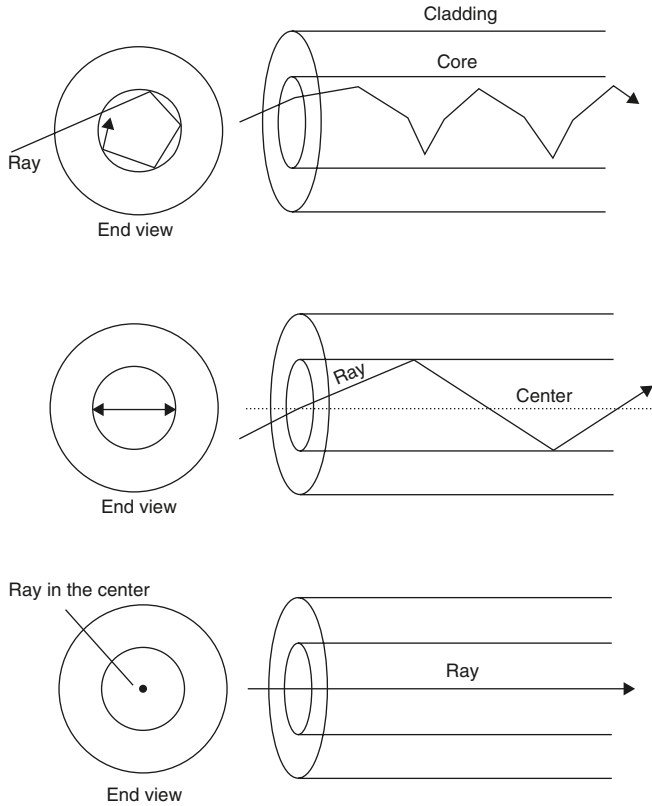
The skew ray never passes through the center of the core. Instead it reflects off the core/cladding interface and bounces around the outside of the core. It moves forward in a shape reminiscent of a spiral staircase built from straight sections.

The meridional ray enters the core and passes through its center. Thereafter, assuming the surfaces of the core are parallel, it will always be reflected to pass through the center. The meridional ray in the end view of Figure 4.31 just happens to be drawn horizontally but it could occur equally well at any other angle.

The axial ray is a particular ray that just happens to travel straight through the center of the core.

**Figure 4.31**

The skew ray does not pass through the center (top); the meridional ray passes through the center (middle); the axial ray stays in the center all the time (bottom)



## Quiz time 4

In each case, choose the best option.

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**1 No material could have a refractive index of:**

- (a) 1.5
- (b) 1.3
- (c) 1.1
- (d) 0.9

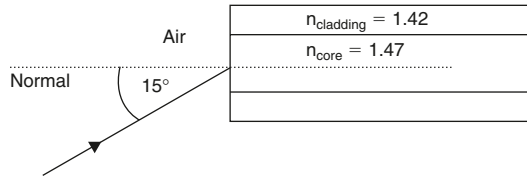
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**2 The ray enters the optic fiber at an angle of incidence of  $15^\circ$  as shown in Figure 4.32. The angle of refraction in the core would be:**

- (a)  $8.3^\circ$
- (b)  $10.14^\circ$
- (c)  $75^\circ$
- (d)  $15.54^\circ$

**Figure 4.32**

Question 2:  
calculate the  
angle of  
refraction



**3 The primary buffer:**

- (a) reflects the light back into the core to allow propagation of light down the optic fiber
- (b) must have a lower refractive index than the core
- (c) is a plastic layer around the cladding to protect the optic fiber from mechanical damage
- (d) must be airtight to prevent loss of the core vacuum

**4 As the meridional ray is propagated along the optic fiber it:**

- (a) travels in a sort of spiral shape
- (b) stays in the center of the fiber
- (c) passes repeatedly through the center of the core
- (d) is reflected off the inside surface of the primary buffer. This is called TIR

**5 If the refractive index of the core of an optic fiber was 1.47 and that of the cladding was 1.44, the cone of acceptance would have an angle of approximately:**

- (a)  $17.19^\circ$
- (b)  $72.82^\circ$
- (c)  $78.4^\circ$
- (d)  $34.36^\circ$