An Introduction to Fibre Optics and Fibre Optic Communications.

By Lloyd Butler VK5BR

With the National Broadband Network (NBN) well under way, it seemed to be a good time to introduce some basic information on Fibre Optics and communications using Fibre Optic Cable

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Introduction

We have all been attracted to a world of communication connected by electromagnetic waves which travel through space and by copper wired links. Over the years, there has been to be a continual effort to develop mediums which can support wider bandwidths to accommodated higher and higher digital bit rates. We have now reached an era where much of those communication requirements are being achieved by fibre optic links. Typical of this, in Australia, is the present roll out of the National Broadband Network. It seemed a good time to to introduce, in OTN, some basic information about fibre optic cables and how they operate.

Much like electromagnetic waves at microwave frequencies are often confined to a restricted transmission medium in a metal encased waveguide, infrared rays are guided within the silica glass core of a fibre optic cable.

The fact is that the infrared rays are also electromagnetic waves, just like those at microwave frequencies but shorter in wavelength and higher in frequency. Just as electric and magnetic field patterns are set up in the microwave guide, similar electric and magnetic field patterns are set up in the fibre optic cable. These field patterns are quite complex. However, to explain a few things, we will introduce some theory based on optical fundamentals.

An optical fiber is a single, hair-fine filament drawn from ultra-pure silica glass. The light rays are guided down the centre of the fibre, known as the "core". This core is surrounded by an optical material called "cladding" which traps the light in the core. The core and cladding materials are usually ultra-pure combinations of optical glass or glass and plastic.

Visible light, sensitive to our eyes, has a wavelength about 400 nanometers (nm or billionths of a meter) to 700 nm. For cables with glass fibers, wavelengths in the infrared region are used, typically around 850, 1300 and 1550 nm (Figure 1). These are windows between regions which produce have high absorption in the core. (See figure 2).

The band around 850 nm was first used for optical fibre communication in the 1970s and early 1980s. It was attractive because of the attenuation profile of fibre of the time but also because of the low cost optical sources and detectors that were available in this band. It is still used for shorter links but the longer wavelengths are more suitable for long distance communication because of the lower attenuation at these wavelengths. Typical attenuation is around 0.4 db per km for the region around 1300 nm and 0.26 db per km for the region around 1550 nm. There is also the question of dispersion which will be discussed further on. Distances of 50 to 100 km are achievable for 1300 nm cable and larger distances for 1550 nm cable.

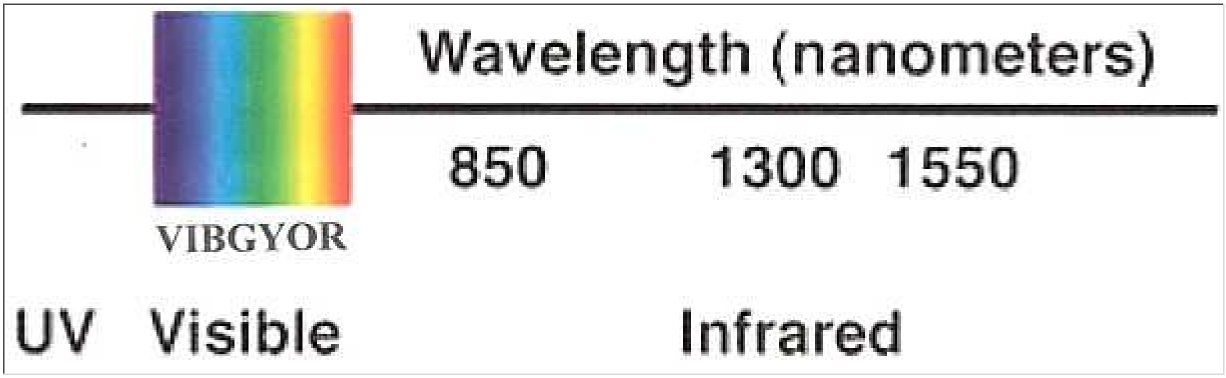


Figure 1
Optical Wavelengths

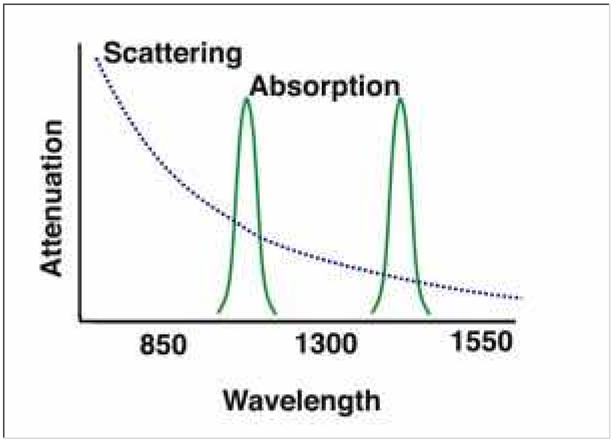


Figure 2
Wavelength of high attenuation and selected wavelength windows

Some Basic Optics
Refraction and Total Internal Reflection

The following paragraphs recall some basic optical theory of what happens when a ray of light passes from within one material into another of lesser refractive index. In the fibre optic cable, the cladding is made with a lesser index than the core and this basic theory is fundamental to understanding how the rays are confined to the core.

Refractive index of a material is a measure of the ratio of the speed of light in a vacuum (or air as an approximation) to its speed in the material.

When light passes from one medium (material) to another it changes speed. This is because the speed of a wave, and the refractive index, is determined by the medium through which it is passing.

As light passes from one transparent medium to another, at an angle to the plane of the junction, it changes speed, and bends. (Just think of the wave front of the ray having width. One side of the wave front hits the junction before the other side and the front twists.) How much this happens depends on the refractive index of the mediums and the angle between the light ray and the line perpendicular (or normal) to the surface separating the two mediums (i.e. medium/medium interface) (See Figure 3). Each medium has a different refractive index. The angle between the light ray sand the normal, as it leaves a medium, is called the angle of incidence. The angle between the light ray and the normal as it enters a medium is called the angle of refraction. The amount of bending follows Snell's Law which states:

Ni * Sin(Ai) = Nr * Sin(Ar) : where

Ni is the refractive index of the medium the light is leaving,
Ai is the incident angle between the light ray and the normal to the medium to medium interface,
Nr is the refractive index of the medium the light is entering,
Ar is the refractive angle between the light ray and the normal to the medium to medium interface.

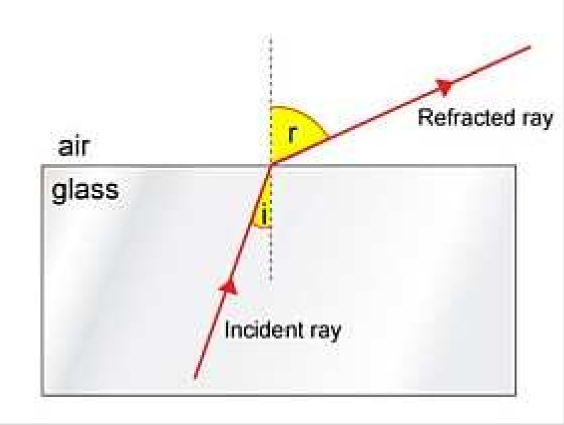


Figure 3
Refraction of light ray passing from glass to air

In figure 3, the light ray passes from the glass to the lower refractive index of air, speeds up, and the angle of refraction is larger than the angle of incidence.

In figure 4, the angle of incidence has increased to what is called the **critical angle** and the refracted angle in now 90 degrees so that the refracted ray is parallel with the X axis.

In figure 5, the angle of incidence is increased to beyond the critical angle and instead of a refracted ray, it becomes a reflected ray. This is called **total internal reflection**.

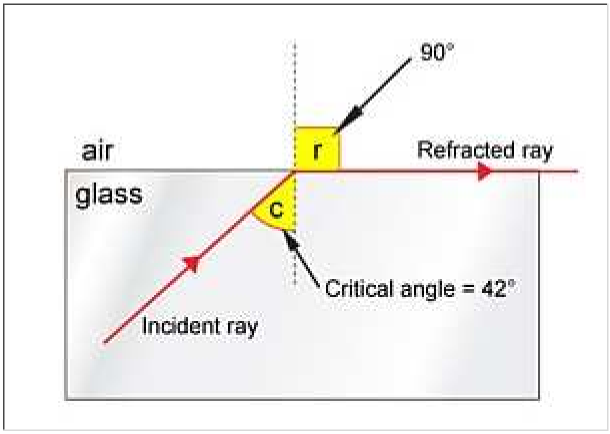


Figure 4
Angle of Incidence equal to the Critical Angle
Refracted ray parallel with glass/air interface

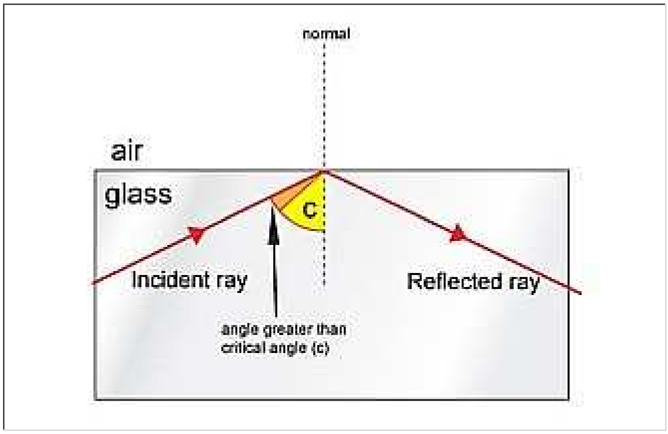


Figure 5
Angle of Incidence greater than the Critical Angle.
Ray reflected within the glass material

In the fibre optic cable, the cladding around the core is made with a lower refractive index than the core and the optic ray is confined to the core by reflection in the process shown in figure 5.

Fibre Optic Cable - Modes of operation

Fibre optical cable has been made over the years for several different modes of operation in the communication fields. Three common modes are illustrated in figure 6. **Stepped index multimode fibre** has a step down in the refracted index between between the core and the cladding and the optic rays are reflected at the core to cladding junction by the Total Internal Reflection process. This type of fibre has a core around 50 to 60 microns (1 micron is a millionth of a metre or 1*u*m). This allows many different paths or modes of operation as shown in the upper diagram of figure 6. Overall diameter (core plus cladding) is 125 microns.

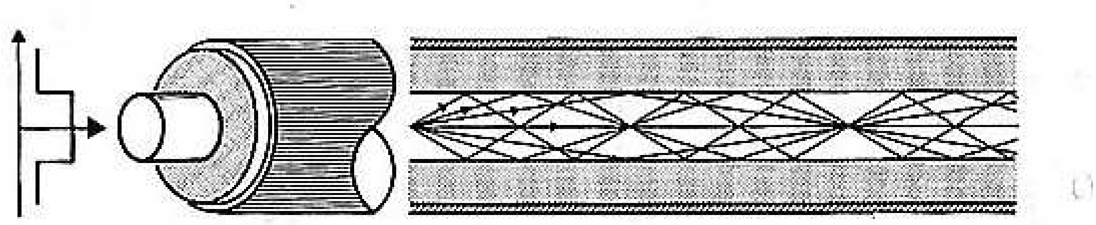
Low angle modes travel less distance down the cable than high angle modes. This causes the high angle rays to arrive at a destination later than the low angle rays. This is called **time dispersion**. Also different wavelengths have slightly different indices of refraction causing different arrival times. This is called **material dispersion**. Dispersion is defined as the arrival of multiple rays at their destination displaced in time with each other.The dispersion causes waveform distortion and bandwidth limitation. The greater the distance the more the dispersion, hence multimode fibres are more suitable for shorter distances, such as Local Area Networks or Video Surveillance.

In graded index multimode fibre, the refractive index of the core reduces parabolically from the centre of the core to that of the cladding. The optic rays travel along a helical path instead of the linear path of the stepped index fibre. This is illustrated in the centre diagram of figure 6. The effect results in a reduction in transit time and a reduction in dispersion. The dimensions of core and cladding are similar to those of the stepped index fibre.

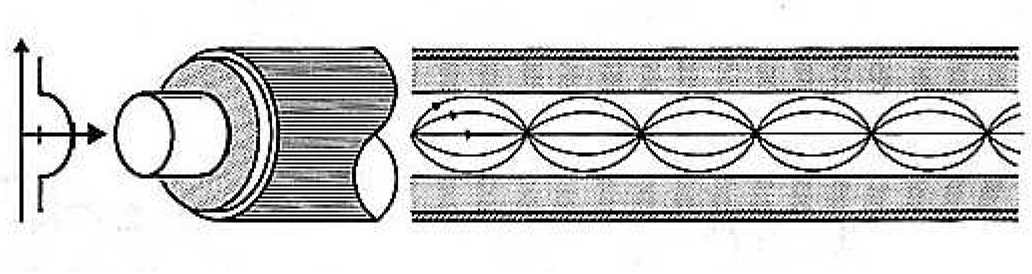
Single mode fibre is a stepped index cable with the core reduced to 8 or 9 microns (only about six times the wavelengths used). Apparently, the electric and magnetic fields around the optic ray (which is an EM wave) require minimum space to travel in the supporting medium. For a given core diameter, there is a minimum wavelength where multimode operation can take place. **Cut-off wavelength** can be defined as the wavelength below which a single mode fiber will act as a multimode fiber. At any wavelength above the cut off wavelength, operation will only be in a single mode.

Typical single mode fibre with the reduced core diameter has a Wavelength Cut-off of 1260 nm. As such it is suitable for the 1300 nm and 1550 nm bands. Dispersion due to the different ray paths is eliminated and with this, and the lower attenuation in these longer wavelength bands, the single mode fibre is more suitable for transmitting high speed data over long distances.

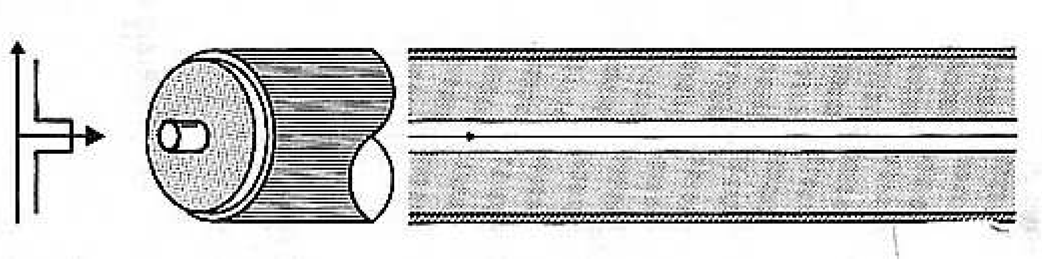
Material dispersion was mentioned earlier. But there is another type of dispersion called **WaveGuide Dispersion**. Some light rays travel directly in the cladding, as well as the core. As these have different refractive indices, the speeds of the two rays are different and this causes dispersion of the signal at their destination. As it turns out, at a certain wavelength, Waveguide Dispersion and Material Dispersion cancel. By fine tuning the dimensions of the single mode fibre and the refractive indices, cables have been developed to position this cancellation in either of the long wavelength bands.



Stepped Index Multimode Cable



Graded Index Multimode Cable



Monomode Cable

Figure 6
Modes of Cable operation
(Profiles of Refractive Index at left)

Short Wavelength Band (First Window)

This is the band around 800-900 nm. This was the first band used for optical fibre communication in the 1970s and early 1980s. It was attractive because of a local dip in the attenuation profile of fibre of the time. It was also attractive because of the low cost optical sources and detectors for this band.

Medium Wavelength Band (Second Window)

The second band around 1310 nm came into use in the mid 1980s. This band is attractive today because there is zero dispersion for single-mode fibre. Whilst sources and detectors for this band are more costly than for the short wave band, the fibre attenuation is only about 0.4 dB/km. This is the band in which the majority of long distance communications systems operate today.

Long Wavelength Band (Third Window)

The band between about 1510 nm and 1600 nm has the lowest attenuation available on current optical fibre (about 0.26 dB/km). In addition optical amplifiers are available which operate in this band. However, it is difficult and expensive to make optical sources and detectors that operate here. Also, whilst this band has lower attenuation than 1310 nm, the standard 1310 nm fibre, working on this third band, exhibits dispersion. Since the late 1990s, this band is where many new communications systems operate.

Optical Sources to feed Fibres

Common light emitters to feed fibre optic waveguides are the **LED (Light Emitter Diode)** and the **Laser diode (Light**

Amplification by Stimulated Emission of Radiation diode).

LEDs convert an electrical current into light. They are small, low cost and efficient in that they generate little heat. They generate a wide spectrum of wavelengths and a diverging light pattern which makes them suitable for multimode fibres but not for Single mode fibres. For analog use, their light output is not a linear function of diode current and negative feedback can be applied to reduce harmonic distortion. The step function rise time allows a bandwidth of around is 250 MHz. The laser diode is much faster and more suitable for high speed digital operation. Comparison in bandwidths of the two sources is shown in figure 7.

For those who are familiar with the operation of electronic oscillators, we might consider the Laser as an oscillator which operates at a frequency in the vicinity of light waves. Instead of electronic feedback to maintain continuous oscillation, light is amplified and fed back into the optical loop. If the oscillation is continuous, the output is at one frequency, or one light wavelength. If the laser is pulse modulated, the output becomes a band of frequencies centred around a carrier frequency and determined by the wave shape of the pulse.

A laser oscillator may comprise an optical resonator in which light can circulate between two mirrors. Within this resonator loop, there is a gain medium such as a laser crystal, to amplify the light. The amplification serves to restore light energy which is lost within the circular resonator path and hence continuous oscillation is maintained. The gain medium requires some external supply of energy, either optical pumping, or in the case of semi-conductor lasers, electrical pumping.

There are many examples on the Internet describing different arrangements to produce the Laser source. Some lasers use a diffraction grating which provides slots of width equal or less than the desired wavelength. Rays of shorter wavelength pass right through but longer waves are bent at an angle dependent on the wavelength. The larger the wavelength, the greater the angle of deviation and hence the desired wavelength can be selected from the angle of reception. Here the grating can act as a selective filter in the circular feedback path.

A laser diode is an electrically pumped semiconductor laser in which the active laser medium is formed by a p-n junction of a semiconductor diode, similar to that found in a light-emitting diode. The laser diode is the most common type of laser used for fiber optic communications. The laser diode has a typical bandwidth of 10 GHz. The laser source is essential for use with single mode fibres.

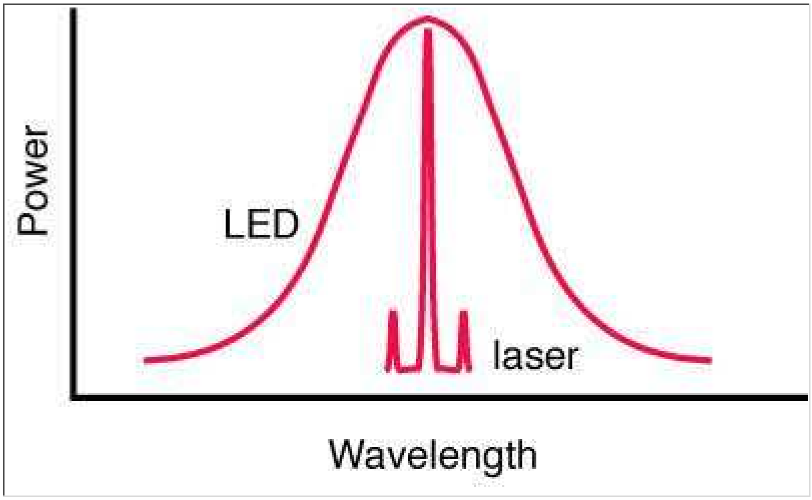


Figure 7
Comparative Spectrum of Laser & LED

Fiber Optic Receivers

Receivers use semiconductor detectors to convert optical signals to electrical signals. **Silicon photodiodes** are used for 850 nm multimode fibre. Lower noise level **Indium gallium arsenide detectors** are used for 1300 and 1550 nm fibre.

Optical Time Delay Reflectometer

For many years, time domain reflectometry has been used on metallic transmission lines to examine their attenuation characteristic and locate impedance anomalies (such as due to faults) in the line system. The instrument used is call a **Time Domain Reflectometer (TDR)**. Pulses are fed down the line and reflections of these pulses are returned back to the source when a deviation from the line characteristic impedance is encountered. A sample of the initiating pulses, together with the returned pulses, is displayed on a time base. This forms a plot which shows the time difference between the initiating pulses and the return pulses. Knowing the velocity factor of the transmission line and the sweep rate of the display, the distance to the point initiating the return pulse is determined.

An optical time-domain reflectometer (OTDR) makes use of similar principles to characterise the attenuation of a length of optical fibre. Similar to the TDR, optical pulses are fed into the fibre fiber under test. It also extracts, from the same end of the fibre, light that is scattered or reflected back from points along the fiber. The strength of the return pulses is measured and integrated as a function of time, and attenuation plotted as a function of fibre length. Figure 8 shows a typical display of the attenuation verses distance. The attenuation, as measured by the instrument, is derived from the combined loss of the forward pulse and that of the return pulse. No doubt, the instrument would be calibrated to correct for that combined loss.

Figure 8 clearly shows the loss in joining fibre lengths with physical connectors. Fusion splice gives lower loss. Splicing these fibre ends is a technique which has to be learned (figure 9).

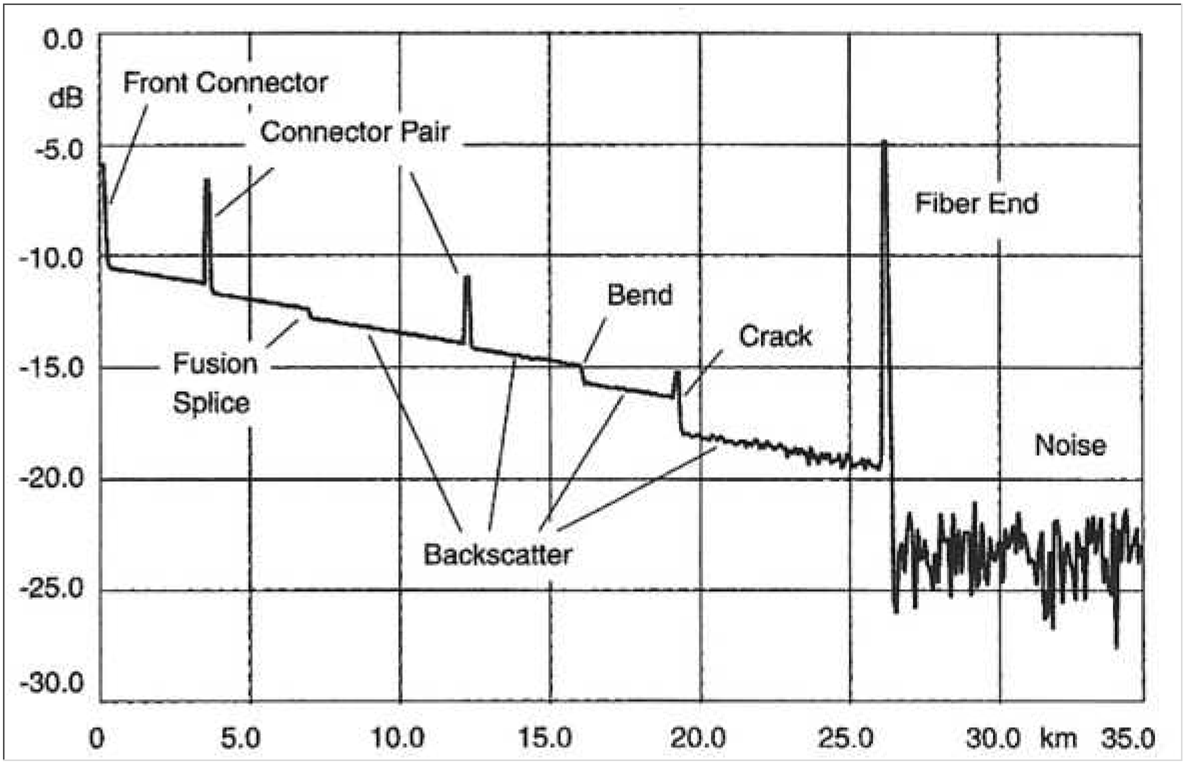


Figure 8 - Optical Time Delay Reflectometer
Typical Display

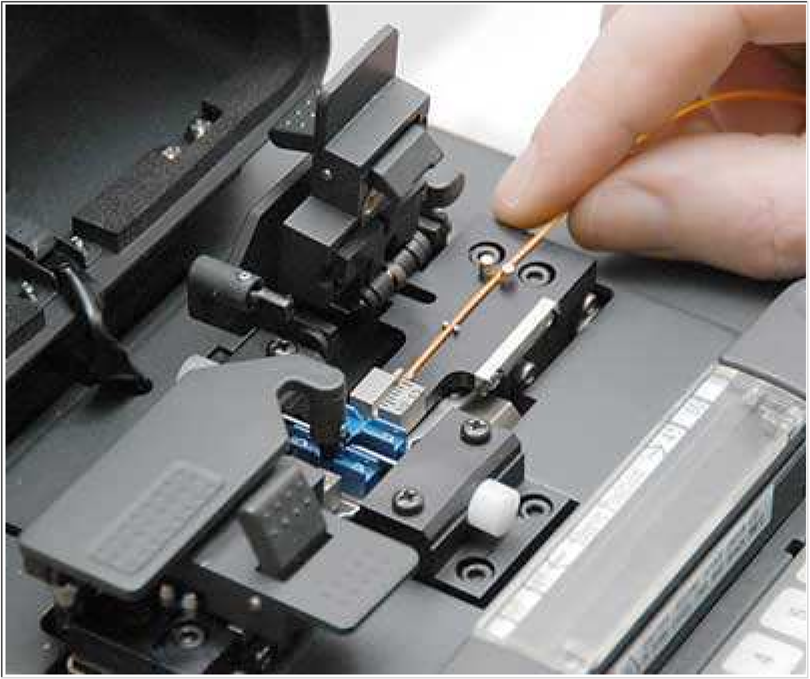


Figure 9
Preparing an Optical Fibre end for splicing with another Fibre End

Making Fibre Optic Cable

It is not intended to go into the detail of how the optical fibre is made. But it is interesting to mention that the long length of fine fibre is drawn from a silica glass cylinder called a preform. The preform may be from 1 to 10 cm in diameter and about 1 metre long. It is made up from chemicals in various proportions to fabricate the core and cladding regions for the particular fibre mode. More detail is given in Reference 6. During the 1980's, Amalgamated Wireless had a laboratory set up in North Ryde to experiment with making the fibre. Around that time, I had a need to learn about fibre optics and I had the pleasure of several times visiting that laboratory to see their operation. In more recent years, the country seems to have lost the skills to engineer and manufacture many of these techniques.

Why Fibre Optics?

Somewhere in this article we should discuss why we might prefer fibre optics to other transmission mediums. But before we answer "Why Fibre Optics?",perhaps we should first answer "Why Digital encoding?" which has gradually replaced many Analogue transmission systems.

Good transmission of pictures by analogue means , such as television, requires a dynamic signal range of about 20 dB. This is a power range between the lowest signal power level and 100 times that for the highest power level. For noise free pictures, the noise level needs to be below the lowest signal level. Also for good quality sound reproduction, the dynamic signal range needs to be 60 dB, or a signal power range between the lowest level and the highest level of a million times. Again the noise level needs to below the lowest signal level.

So with analogue, its a question of using a transmission system which can support a wide range of signal levels without noise interference at the signal lowest level. However if we encode steps of the progressive analogue signal into digital form , we transmit only two different levels of signal. To decode the received digital signal into its original form, we only need to detect between the two levels. The digital system can operate in a transmission system where the noise level would be prohibitive for analogue operation.

The development of modern digital communication systems calls for faster transfer of data, higher digital bit rates and higher bandwidths in the transmission systems used. Systems commonly in use have their own limitations. The copper conductor national telecommunications system, originally designed to connect telephones operating at speech frequencies, has been developed to connect the Internet service. The ADSL2+ system seems to be limited to downstream bit rates of 20 Mbits per second, or less, much determined by the length of cable pair (and signal attenuation) between the exchange and the consumer. Even so, this is really amazing considering the high attenuation of the normal telephone cable at high frequencies.

Radio connection, which the computer people call Wireless, has its limitation in bandwidth and line of sight limits. The problem is that to get sufficient bandwidth approved, the microwave region has to be used. It appears that two bands are commonly in operation, one at 2.4 GHz and one at 5 GHz. Bit rates are limited to around 20 MBits/sec with bandwidths limited to the 20 to 40 MHz region. Communication at microwave frequencies is limited to line of sight but the wide range of Internet operation has been enabled because of the connection via the established extensive mobile phone network.

The higher in frequency we go, the smaller proportion a given bandwidth is relative to the operating frequency. For the short wavelength of the light ray (or EM wave) travelling down our fibre optic cable, the wide bandwidths needed become a small fraction of the wavelength. Hence, these bandwidths are easily accommodated. NBN Co, at present installing fibre, has made reference to their system operation up to 100 MBits/sec and envisage up to 1000 MBits/sec. Signal attenuation in the fibre is quite low compared to copper based systems, such as coaxial cable. As discussed earlier, single mode fibres operating at wavelength of 1550 nmetres have attenuation figures as low as 0.26 db per kilometre.

Another advantage of fibre cable is that it is immune to interference from external electric and magnetic fields. It also has a security advantage in that its signal field is confined to the fibre core and cannot be tapped from induced fields outside of the cable.

In **Conclusion** the ultimate aim for the National Broadband Network (NBN) is a network of high standard, covering most of the Australian country with a digital communication system which supports very high speed transfer of data. It would be very difficult indeed to achieve the high speed required, had not **Optical Fibre Waveguides** been developed.

NBN Installing Fibre Optic Cable

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