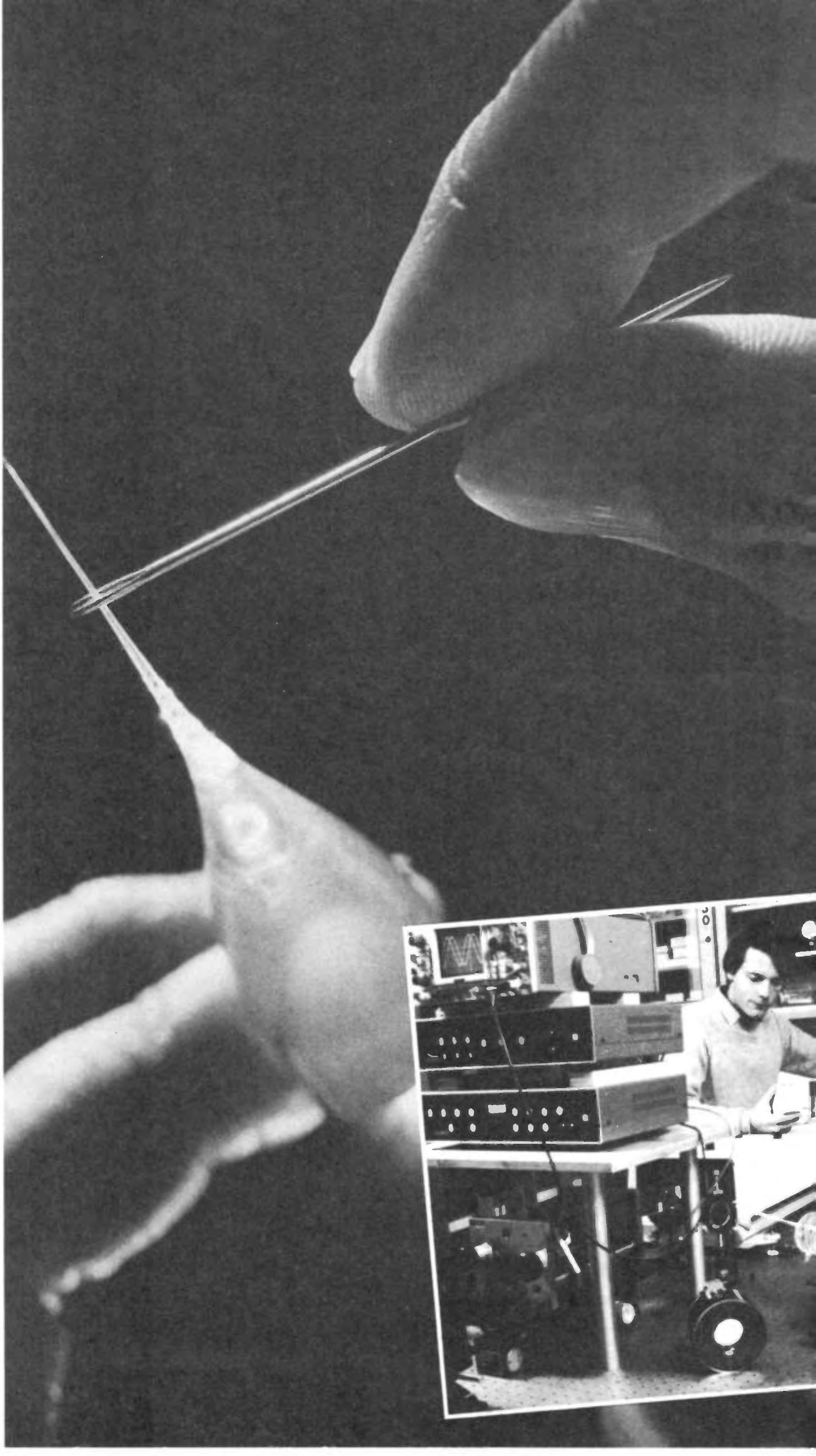
LASERS & FIBRE OPTICS



by D. Stewart

The laser beam sliced through the sheet of metal and James Bond's legs nearly parted forever, in the film. Fortunately, lasers have been used to do more good than harm. They have been used for instance in medicine to repair the retina of the eye without the use of stitches. Also in entertainment to produce three dimensional holography at discos and they will probably be the basis of three dimensional television. So what are the principles that make lasers possible?

Light Sources

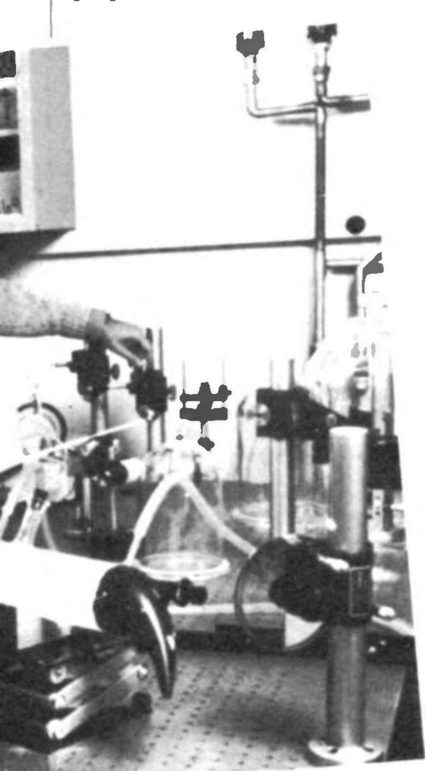
We could use a light bulb but we would not be able to switch it on and off as rapidly as we would like so we have to turn to semiconductor devices. There are two, the light emitting diode (LED) and the laser (light amplification by stimulated emission of radiation).

Both these devices work the same way. Referring to the energy band diagram of Fig. 1, if a p–n junction is forward biased, the hole-electron pairs recombine and a photon or packet of light is released. The main difference between LED's and lasers is that in LED's, the electrons fall from the conduction band to the valence band spontaneously while lasers have to be stimulated.

The wavelength emitted depends on the gap between the valence and conduction bands and for gallium aluminium arsenide (GaAlAs), this is 0.85μm which can be changed slightly by altering the percentage of aluminium.

Lasers

Here we will deal only with semiconductor lasers; ruby and gas lasers are mentioned in Applications. The chips are about 400μm square with perfectly perpendicular ends and mirror surfaces.



British Telecommunications PLC Inset JPL California Institute of Technology

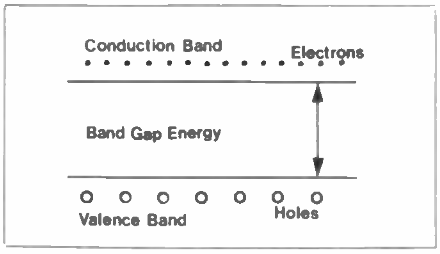


Figure 1. Valence – Conduction Bands

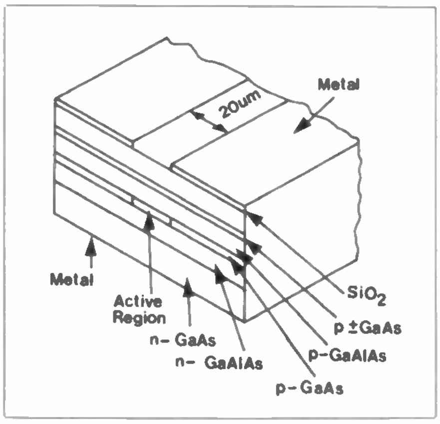


Figure 2. Double Heterojunction Laser

Now what could be prettier! Fig. 2 shows a double heterojunction with alternate layers of GaAlAs (Gallium Aluminium Arsenide) and GaAs. Early lasers were homojunctions and heterojunctions.

The layer of GaAlAs has 5% aluminium in the active region and 35% in the passive region. This prevents fracture should the device expand from the heat generated. Copper heat sinks are soldered onto the laser using indium as the solder since indium is soft and flexible.

When a spontaneously emitted photon is reflected by the end mirror and meets an electron about to emit another photon, stimulated emission occurs and more photons are released. This makes lasers brighter than LED's and lasers can operate for about eleven years at room temperatures giving an output of about 5mW.

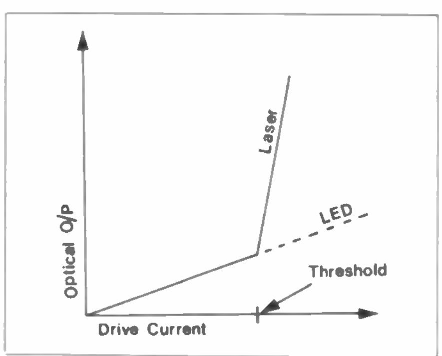


Figure 3. Laser and LED Outputs

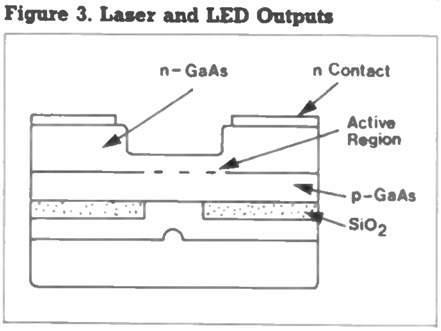


Figure 4. Burrus Diode

The bandwidth of lasers for information carrying purposes is also wider than that of LED's. This is because the line width is narrower than that of LED's hence increasing the useful bandwith. The spectrum emitted by an LED could be as wide as 20nm (nanometres: 1nm = 10^{-9}m), whereas the line width of a laser is only 1nm. The emission from a laser is more faithful because the lasing feature enables photons to stimulate other photons of the same wavelength.

The stripe is the active region and helps to reduce the threshold current (Fig. 3). The threshold current is the current at which lasing starts and the heterostructure geometry also helps to reduce this threshold. In practice the strip is between 5μm and 20μm but what is more important is that the refractive index of the stripe must be uniform to give a straight line in the characteristic.

LED'S

These operate in the infra-red range, at 0.85-0.95μm and are similar to lasers i.e. not pumped or stimulated. The LED's efficiency can be increased by creating a well and such high radiance diodes are called Burrus diodes (Fig. 4).

Even more efficient than Burrus diodes are edge light emitting diodes (ELED's). The sandwiched layers are the same as those of a laser so they are cheap to manufacture.

Instead of emitting light from the well, ELED's emit light from the edge in the same manner as lasers. Even the stripe is etched in the insulated oxide layer but with one big difference. The stripe does not appear over the full length of the chip in the ELED and therefore the region without a stripe is an absorption region. Light is absorbed here so no feedback takes place to produce laser action.

Light Detectors

Light travels in packets of energy called photons which are related to the velocity and wavelength of light as follows:–

$$\text{Energy per photon} = \frac{hc}{\lambda}$$

where c = velocity of light, λ = wavelength of light and h = Planck's constant.

Detectors operate in exactly the opposite manner to light emitters i.e. in light emitters, electrons were releasing light but in detectors, light releases electrons. These electrons move from the valence band to the conduction band of Fig. 1 and this can happen only if the energy given up by the photon is equal to the energy of the band gap. So in order to detect a source radiating at 0.85μm we need a detector that is sensitive to the same wavelength.

Two kinds of detector are available; the avalanche photodiode (APD) and the positive intrinsic negative (PIN) diode.

Good diodes will have the following characteristics: low capacitance, low dark current, fast response and high efficiency. Dark current means that the diode conducts even when light is not falling on it hence it will be difficult to detect a weak signal. Low capacitance decreases the time taken by carriers to cross the junction.

The efficiency is measured as follows: if say 100 photons fall on the detector, releasing 90 electrons, then the efficiency is 90%. At least 21 photons must fall on the detector to reproduce a digital one.

Avalanche Photodiodes

Fig. 5 shows the voltage–current characteristic of an APD and the forward current is the same with and without light. In the reverse direction, the dotted line shows current flowing in the dark.

For communications purposes lasers and detectors are operated at certain wavelengths that are optimum for optical fibre as we shall see later. These wavelengths are 0.85μm, 1.3μm and 1.55μum and silicon APD's are suitable for operation at 0.85μum but germanium ones are required for use at the other two wavelengths even though germanium ones have high dark currents.

One drawback of APD's is that they need high reverse biases typically 100V and there is the difficulty of running such high DC voltages along a route. Nevertheless, APD's have gains of 10^3, but those with lower gains are adequate.

An APD is shown in Fig. 6. The junction is placed near the surface so that the avalanche effect can be started by electrons in the heavily doped n+ region. But the strong field could break down the junction and a guard ring is required.

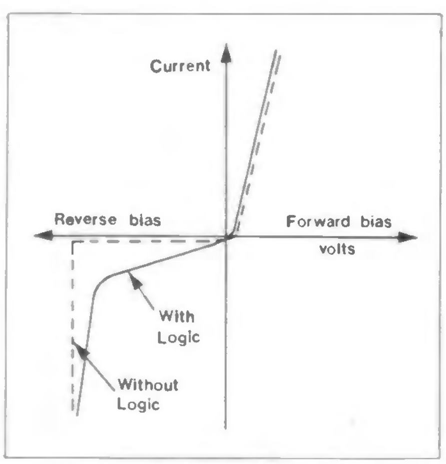


Figure 5. APD Responses

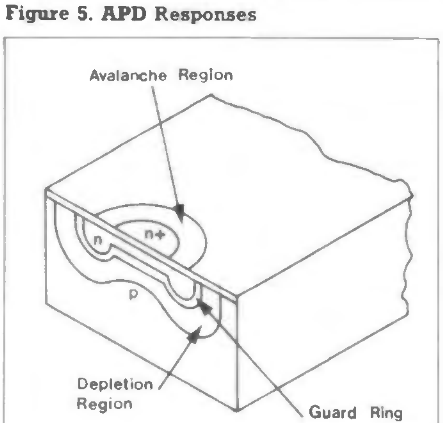
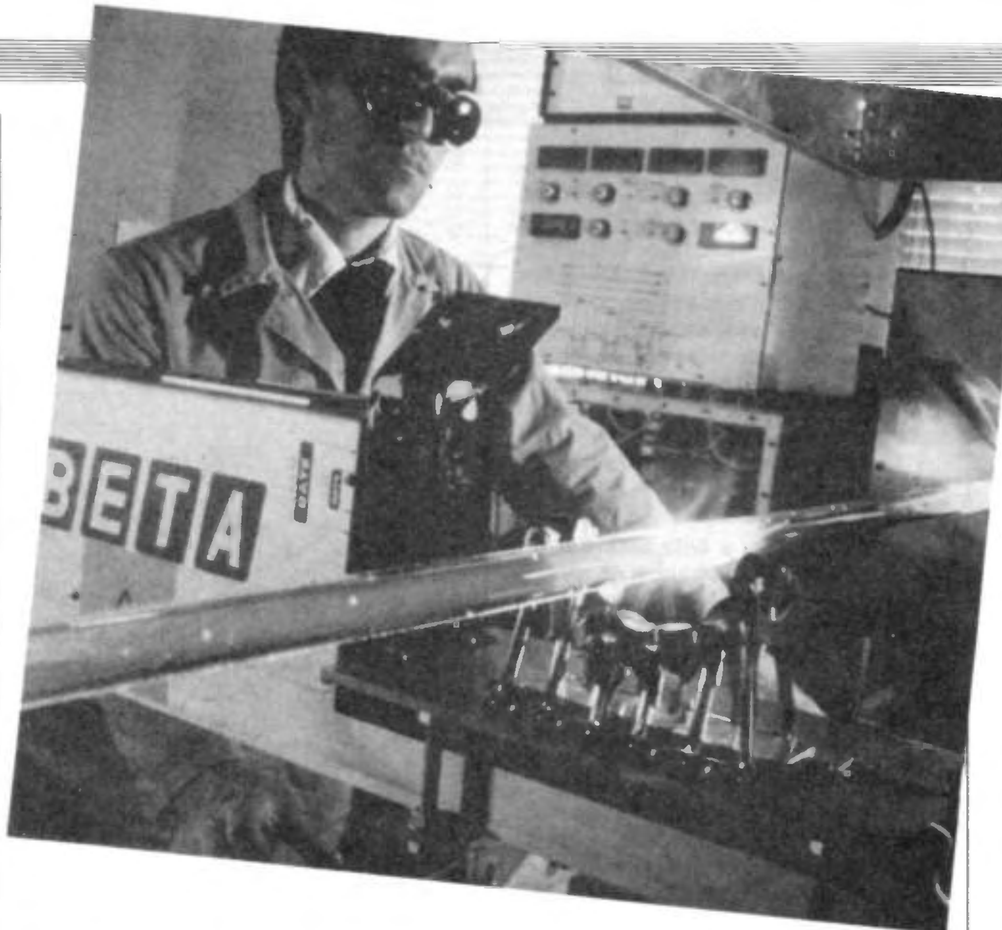


Figure 6. Avalanche Photodiode



PIN Diodes

The intrinsic layer is a low doped n type layer. We mentioned the need for low capacitance earlier and this can be achieved by increasing the width of the intrinsic layer. However, a limit is reached when the leakage current starts to increase and a suitable compromise is an i-region of about 100μm in a chip size of about 400μm square.

A phenomenon called the reach-through effect is used for rapid collection of electrons. It works like this. Take a PIN diode and apply a reverse bias, then shine a photon of light on it. In a p-type material holes are the majority carriers and electrons the minority carriers (opposite for n-type material). Under the influence of the reverse bias, the minority carriers flow across the junction but the majority carriers do not. This has the effect of clearing the carriers to the majority sides hence creating a depletion region right through to the heavily doped substrate.

PIN diodes need an FET amplifier as the next stage since the signal is weak but they have a faster response than the APD's.

Optical Fibres

Having discovered a light source and a suitable detector, it only remains to connect the two with a piece of glass. Not any old glass, a quick flash in window glass will get us nowhere. All the impurities need to be removed.

So we get a strand of pure fibre and connect the source to the detector, switch on the source and get nothing at the detector. Why? Because the light is very quickly reflected out of the fibre. Now we get clever and cover the fibre with more glass of a lower refractive index so that the rays are reflected back into the fibre.

This is much better but still has its drawbacks. To start with, no light emitting source emits a pure wavelength, though the linewidth of lasers is narrower than say the linewidth from a searchlight. So if we have several wavelengths close to each other and modulate them, the bandwidths would overlap and this would limit the useful bandwidth.

The same sort of thing also happens when light bounces down a fibre. There are three modes of propagation down a fibre and these are shown in Fig. 7.

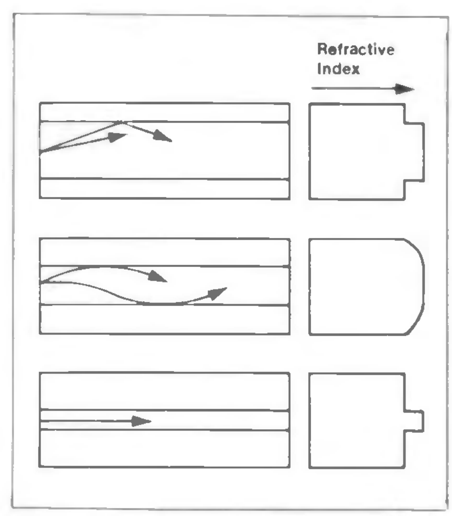


Figure 7. Propagation Modes

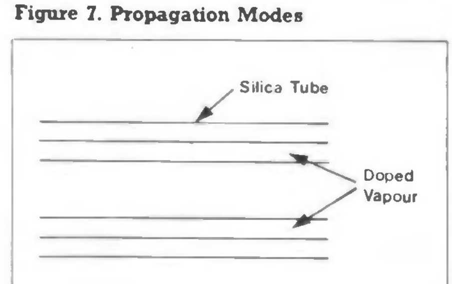


Figure 8. Vapour Deposition

Multimode Fibre

Rays travelling parallel to the axis will arrive at the detector quicker than those that have been bounced off the edges and once again this reduces the useful bandwidth. The core of multimode fibres is usually about 50μm and the refractive index about 1.5% higher than that of the cladding. Now we can see why we have been speaking of propagation in terms of wavelength instead of frequency. It is easier to compare wavelengths with the fibre dimensions just as we do in mocrowave waveguides and optical fibre is after all a light waveguide.

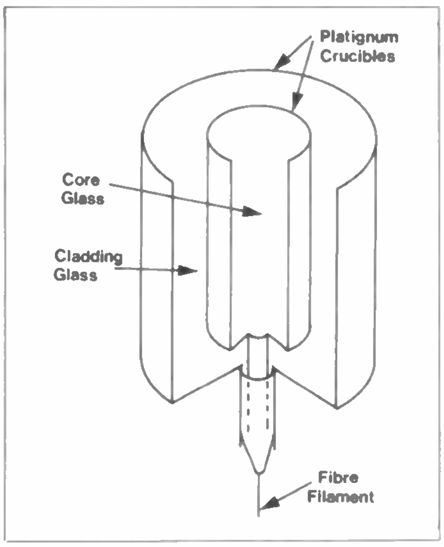


Figure 9. Double Crucible Method

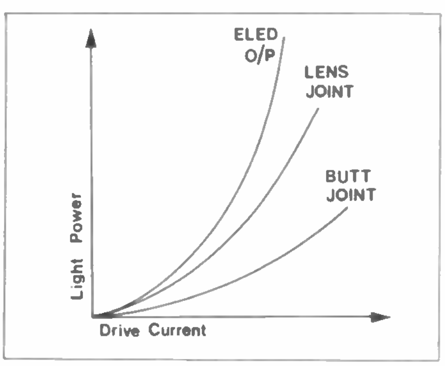


Figure 10. Coupling Efficiency

Graded Index Fibre

Instead of bouncing the waves off the cladding we can speed them up by making the refractive index between core and cladding gradual instead of a step.

Monomode Fibre

– or Singlemode as the Americans call it. If we select just one wavelength to propagate, then the core need be only about 6μm wide. It is difficult to launch power into a fibre this small and source to fibre connections need to be carefully aligned so as not to waste power.

Losses in Fibres

Care needs to be exercised during manufacture not to introduce physical deformities or chemical impurities which would cause absorption or scattering of the signal.

However impurities cannot be removed entirely and water for instance

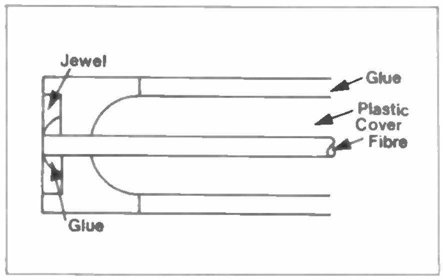


Figure 11. Butt Joint

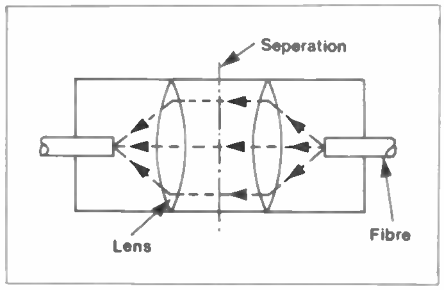


Figure 12. Lens Joint

can absorb signals at 0.95μm which is near the operating region of communications systems.

Absorption can also take place due to metallic impurities like iron, chrome, titanium, cobalt etc, the absorption depending on the amount of impurity and their oxides. Glass can be coloured green by introducing iron as an impurity, saphires are blue because of titanium and rubies are red because of chrome impurities. Absorption can also take place when molecules vibrate within the fibre and interact with the rays.

Scatter losses can be caused by bubbles in the glass, either in the raw material or during manufacture of fibres and these need to be boiled off. Scatter can also be caused if the refractive index of the fibre varies over small distances; this is called Raleigh Scatter and at 0.85μm the loss can be up to 2dB/km.

Fibre to Fibre Jointing

Just as source and fibres can be butt jointed, fibres can be butt jointed to other fibres. A watchmaker's jewel is mounted in a stainless steel ferrule, Fig. 11 and the

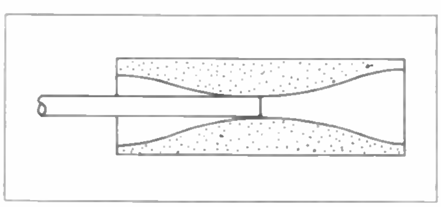


Figure 13. Fibre in Glass Sleeve

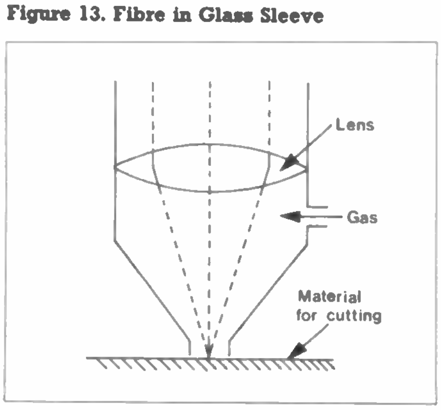


Figure 14. Laser for Cutting

fibre inserted in a hole in the jewel, held in place with adhesive and polished flat with the surface of the ferrule. Watchmaker's jewels are not too expensive and holes can be drilled more accurately than in metal.

Lens terminations can also be used as for source to fibre connections. In addition the lens mountings can be made in a factory and ready to use in the field when the fibre is laid. These are prepared in two halves with the fibre at the focal point of the lens, Fig. 12.

The two methods above are suitable when new routes are laid but what if a fibre is damaged and required to be reconnected? The ends need to be cut vertically and the cores aligned using a microscope. Then they can be fused using a hot wire heater or they can be inserted into a glass sleeve Fig. 13, about 10mm long. One fibre is inserted and the sleeve collapsed, then the other fibre is cemented in.

Laser And Optical Fibre Applications

Perhaps the best known application of lasers is in the field of eye surgery. Previously a xenon-arc lamp was used, but because of the long exposure time, anaesthetic was required. In addition the spot size focuses down to about 800μm, but lasers can provide a smaller spot, about 50μm, which is useful in such confined areas. Also a pulse of 1 Joule from a Ruby laser for 300μsec is sufficient and the eye does not require clamping since the time is so short.

Lasers can also be used for cutting, drilling and welding. For cutting, a carbon dioxide laser is used since it produces higher power than a ruby laser and aluminium for aircraft can be cut some 70% cheaper than by conventional means. A gas jet can be fed with the beam, Fig. 14, to blow away the swarf or if the swarf is hot, oxygen can be used to burn it.

Drilling holes less than 250μm in diameter with mechanical drills is difficult and usually ends in a broken drill bit. With lasers however, holes down to 10μm can be drilled quite easily and the Swiss watch industry drills holes in ruby stones using flash-pumped neodymium-YAg lasers.

In microelectronics, wires as thin as 10μm may need welding. In addition these may be dissimilar metals or in inaccessible areas like in a glass envelope or near heat sensitive areas and lasers are a useful friend.

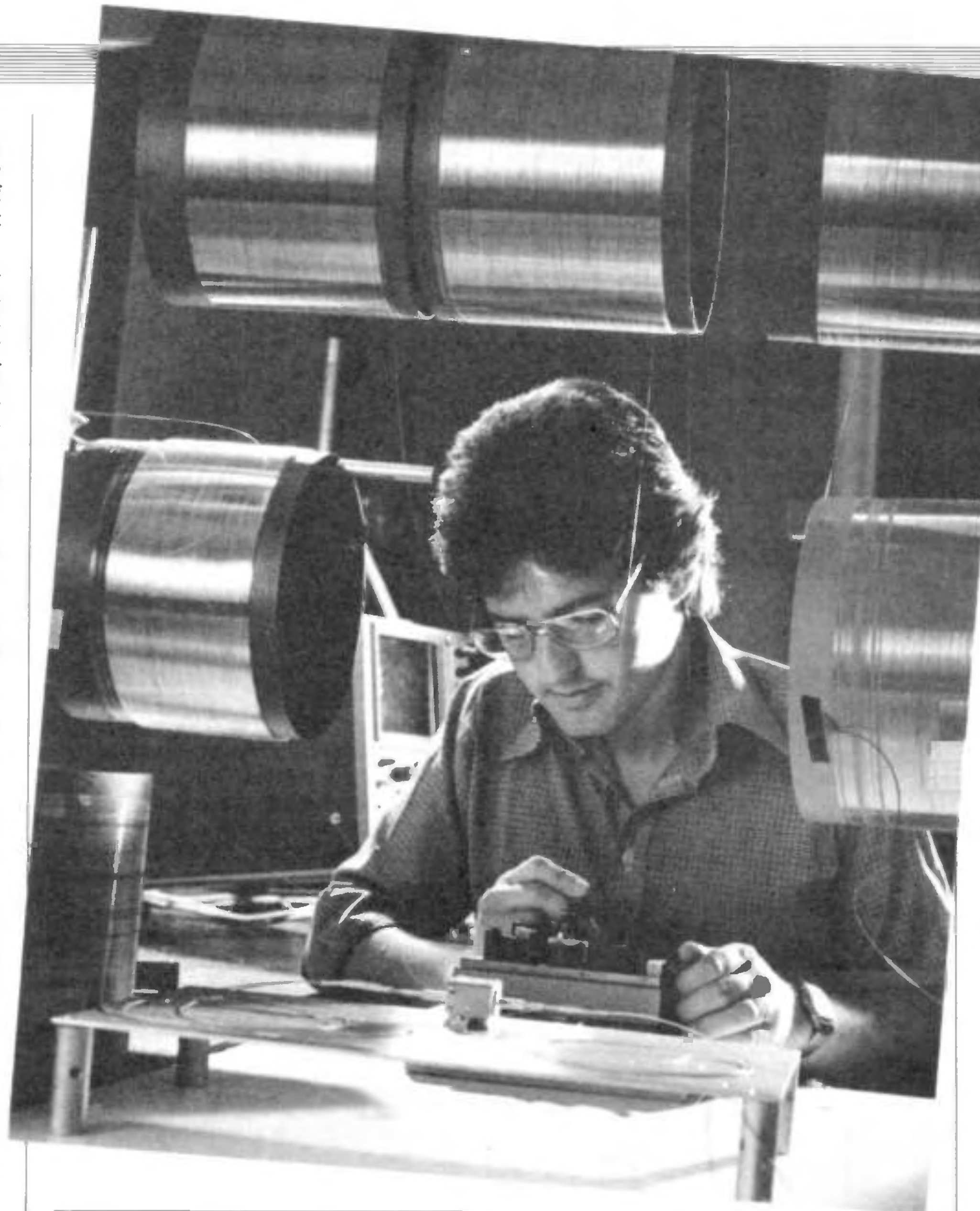
When a spacecraft re-enters the Earth's atmosphere, the heat generated around it is a barrier to electrical communication but transparent to optical waves so contact can be maintained during those crucial minutes. Lasers have also been used to study movements of the Earth's crust in order to predict earthquakes. The USA launched the Laser Geodynamics Satellite (LAGEOS) which was 60cm in diameter and weighed 411kg. It was at an altitude of

5,800km and had 426 retroreflectors, which are corners of glass cubes, hence the incident and reflected rays will be of the same length if the Earth's crust has not moved.

Retroreflectors can be used in tracking systems which are lighter and cheaper than radar. Light detection and ranging (LIDAR) has been used to study the atmosphere. The dangers of contaminating the atmosphere with aerosols and exposing us to radiation is well known. Therefore studies have been made of the atmosphere to detect aerosols which would produce kinks at X and Y of the curve of Fig. 15.

The main advantages of lasers then, are: small focussed image, accurate positioning, exact control of energy, operation in inaccessible areas or near heat sensitive areas without contamination.

Optical fibres are every bit as useful as lasers. These are useful in areas of high electrical noise, say for monitoring factory processes where machines are starting and stopping all the time. As an extension of this use they can be used for measuring high currents where the usual wire leads could result in an accident. Here Faraday's principle is used: the rotation of the plane of polarization of a light beam is proportional to the field strength and the length of the path through the field.



Manufacture

Manufacture of Light Sources.

The old method was to diffuse donor and acceptor elements into a substrate as is done in the manufacture of transistors, but the modern technique is liquid phase epitaxy.

A source crystal of GaAs is placed on top of aluminium and gallium in a crucible. A weight is placed on top and heat applied to the crucible. At 800°C, part of the source slice dissolves in the melt which reaches equilibrium. If the temperature is then dropped to 780°C, the equilibrium is disturbed and a GaAlAs layer is deposited on the source slice.

In this way several different layers can be grown including depositing a layer of GaAlAs on a substrate.

Manufacture of Fibres

The main techniques are vapour deposition and the double crucible method.

The vapour deposition method uses a flame to deposit layer after layer of core, then cladding on a rotating mandrel. This is then collapsed into a fibre. A starting rod could be used instead and the vapour applied to the end to build up the rod.

Fig. 8 shows the Corning method of vapour deposition where an oxygen flame is used to deposit a layer of pure silica inside a tube. This will form the cladding. To form the core, silica doped with aluminium, titanium, germanium or phosphorous oxide can be used. This is deposited as the next layer and the whole thing collapsed into a fibre. To form graded index fibre, glasses with suitable dopants are chosen so that the dopants diffuse through the glass uniformly.

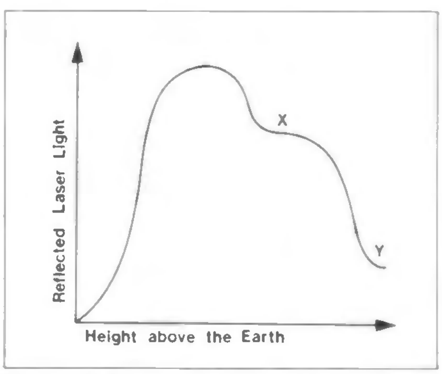


Figure 15. Aerosol in the Atmosphere

The double crucible method is shown in Fig. 9. The glass containing dopant will form the core and is placed in the inner crucible. Pure glass will form the cladding and is therefore placed in the outer crucible. The filament is pulled gently and a fibre of the correct composition is formed.

One of the problems of producing pure glass was that the glass was absorbing impurities from the platinum crucible. This can be overcome by RF induction heating, where a 5MHz field is created through the liquid glass which is at a temperature of 1300°K. The crucible is then not as hot as it would be and a silica crucible can be used. Any bubbles are then driven out by boiling and the pure glass can be used for making fibres.

Jointing

Source to Fibre Joints

A fibre can be brought in close contact (butt jointed) with an emitting source and a 50μm fibre will fit into the well of a Burrus diode. However, some energy does escape particularly in the case of edge emitters in contact with fibres. These losses can be reduced by using a lens to focus the energy into the core of the fibre. Fig. 10 shows the coupling efficiency of a lens compared to a butt joint.

Fibres have been used in flowmeters where a fibre is dipped in the liquid and the fibre vibrates at a rate proportional to the flow of the liquid. A further application of the fibre in liquid is in hydrophones for listening in water.

Optical fibres have been nearly as useful as lasers for getting into inaccessible areas. They have been used in industry for illuminating and examining areas that could not be visible otherwise. In medicine bronchoscopes have been used for looking into lungs when an over-enthusiastic diner has let a piece of food go the wrong way.

Optical Fibres In Communications

Perhaps the greatest use for fibres and lasers will be for communications since the optical spectrum has such a wide bandwidth. For instance, operating at 1.5μm, gives a frequency of 3×10^{14}. If this centre frequency is modulated to provide a bandwidth of only 10%, this could carry 10^{10} telephone channels.

Typical transmission rates for optical fibres as landlines will be 2, 8, 34, 140Mbit/s, and 280Mbit/s for submarine cables. Later, for wideband networks, 565Mbit/s may be employed.

A field trial took place between Hitchin and Stevenage in 1977-80. The cable was only 7mm in diameter and contained three fibres and four copper wires around a steel centre member. Over this 9km route repeaters were spaced at 3km and the system operated at 140Mbit/s.

Optical fibre definitely has the edge over copper wire. It is light, small and cheap. It is also non-corrosive – a big advantage, since cable chambers often get flooded. It has a smaller diameter, so more can be fitted in overcrowded ducts particularly in cities. It is also cheap. The cost of coaxial cable will rise by about 5% per year. In addition the cost of copper is also dependent on world prices whereas glass has no intrinsic value and the cost of fibre will actually fall as the technology improves.

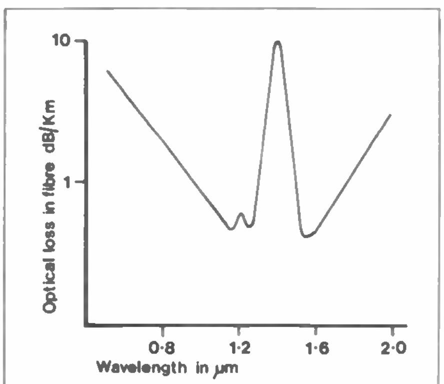


Figure 16. Optical Loss at Different Wavelengths

Optical fibre has minimum losses at certain wavelengths and a characteristic curve is shown in Fig. 16 from which it can be seen that the minimum loss occurs at 1.3μm and 1.55μm. At a transmission rate of 140Mbit/s and using 9.5mm coaxial cable, a repeater spacing of about 4.5km is possible. But optical fibre using 1.3μm and monomode operation requires

Wavelengths	·85um	1·3um	1·55um
Bandwidths GHz/Km	2-4	6	2-4
Attenuation dB/Km	2·5	1	0·5
Repeater spacing Km	12	30	60

Table 1. Graded Index Fibre

repeaters at only 39km intervals which amounts to a big saving in repeater costs.

Table 1 compares operation of graded index fibre at three different wavelengths. The largest bandwidth and repeater spacing is of course available with monomode operation and will be of greatest use in submarine systems. The other fibres are not necessarily useless. Most inland routes do not require such large bandwidths and it is difficult to align the cores of monomode fibres. Since fibres are aligned by their outer diameters, the core/cladding ratio must be concentric within 1/250.

Monomode fibres can now be made with losses as low as 0.16dB/km compared to 10dB/km when work started around 1972. However 0.16dB/km is of little use if a cable is going to be broken by accident since the average loss of connectors is about 0.5dB and it is estimated that on average a cable is likely to be broken twice per kilometre over a 30 year life.

Television Links

From the characteristic curves of Fig. 3 it can be seen that LED's have a linear output and can be used for transmitting an analogue signal. Television signals are analogue since the output is varying continuously and if this needs to be transmitted without converting to digital form, an LED must be used. A laser would of course give a signal 18dB higher.

Submarine Cables

Fig. 17 shows a simple communications link, a repeater being a receiver and transmitter back to back. Two large cable systems are imminent: The UK – Belgium No. 5 and TAT8 (TAT = TransAtlantic).

The world's first international optical fibre cable will cost £7.25 million and run from the UK to Belgium in 1985. It will be 122km long and operate at 1.3μm monomode, carrying 280Mbit/s systems and providing about 12,000 circuits. It will contain three repeaters at 30km intervals which is six times the usual spacing for coaxial cables.

TAT8 will cost more than £250 million of which Britain will have the second largest share. Although it will start service in 1988, its final configuration is not known but it will use between 6600km and 9900km of fibre depending on whether it lands in three countries or seven countries. This is the first time that branching units have been used on the ocean bed. In the past submarine cables have been laid between two land masses only, before proceeding to other ones. The cable will consist of two pairs of fibres each operating digitally at 280Mbit/s and giving a capacity of 8000 telephone channels altogether.

The Future

The past ten years has seen theory turned to practice with the development of fibre of such low loss that further achievement will be of no practical value.

Lasers had reached a critical limit at 500Mbit/s beyond which the laser diode does not respond to electrical modulation. Now Siemens has come up with a technique to push this rate up to 6Gbit/s! In the past the laser has been used both as a source of light and as a transducer. The new technique is to let it glow continuously instead of switching it on and off. The modulation can then be carried out by a crystal of lithium niobiate ($LiNbO_3$).

And so to the future. Man has always been frantic in exploiting new technology like a child receiving a new toy. Technology itself is neutral; we can use lasers for eye surgery or as beam weapons in space. We are free to decide to use technology as a slave; but sometimes man ends up a slave to technology.

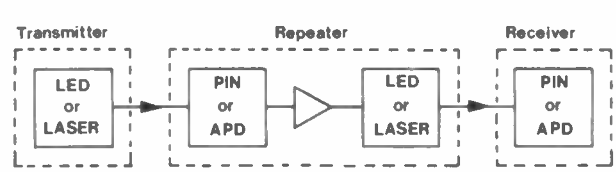


Figure 17. Simple Communications Link