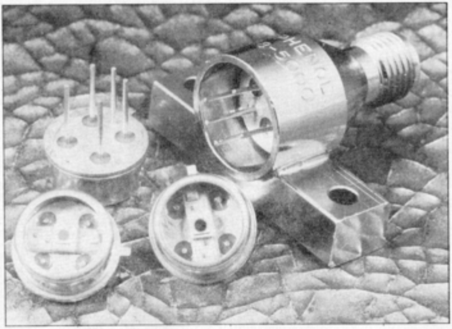
PHOTONICS



Photonics is the technology of using photons to convey information in a controlled manner. A photon is an elementary particle of light in the frequency range from 3×10^8 MHz to 6×10^{10} MHz (corresponding to wavelengths from 1000 nm —upper limit of infra-red region— to 5 nm —lower limit of ultraviolet region. Photonics must not be confused with opto-electronics —in which photons and electrons interact— or with electro-optics, which is a study of the relation between the refractive indexes of certain dielectrics and the electric fields in which they are situated.

Photons may not replace electrons in data processing and storage this century, but there are reliable indications that they will be used increasingly in data communications via optical-fibre cables. And, of course, they are already in use in the remote control of countless hi-fi and television sets; they are also indispensable in the Strategic Defence Initiative (Star Wars).

There is also the photonic computer now being developed at Heriot-Watt University, Edinburgh, and at the Bell Laboratories in Princetown, New Jersey. These computers use transphasors, the optical equivalent of transistors. Their main attraction is that they can work thousands of times faster than electronic ones because, although electrons, under ideal conditions, move almost as fast as light, they are slowed down to a per cent or two of that speed in silicon.

However, we will not be able to give a description of the photonic computer until that has been unveiled in some twelve to eighteen months' time. Instead, in this article we will concentrate on optical-fibre cable.

The basic principles of transmission in an optical-fibre cable were established by Hockam and

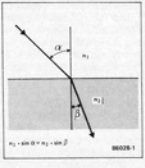


Fig. 1. Illustrating Snell's Law.

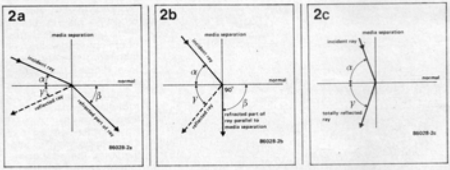


Fig. 2. Depending on the angle of incidence of the light ray, the transmission path is called low- or high-order mode: the greater the angle, the lower the mode.

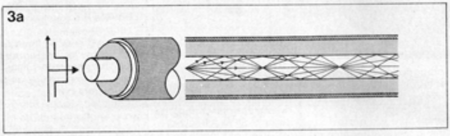


Fig. 3a. Multi-mode fibre.

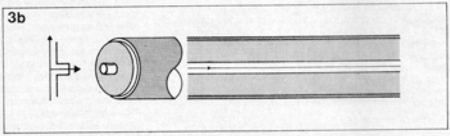


Fig. 3b. Mono-mode (or single-mode) fibre.

Kao, working at the Standard Telecommunication Laboratories at Harlow, Essex, in 1966.

Some fundamentals

Although light is a form of energy, it may also be considered as a wave motion. A *ray* of light is the direction along which the light energy, i.e., photons, travels. A *beam* of light is a collection of rays. According to the *principle of reversibility of light*, if a light ray is reversed, it always travels along its original path.

Light waves can be reflected or refracted. In reflection, some or virtually all of the light is thrown back into the original medium when the light strikes a surface of separation of two media. Highly polished metals reflect most of the light incident on them, whereas, for instance, plate glass reflects only about five per cent. Refraction is the change of direction that a ray of light undergoes when it enters another transparent medium.

In reflection, the incident ray, the normal, and the reflected ray lie in the same plane. Also, the angle of incidence with the normal is equal to the angle of reflection with the normal.

In refraction, the incident ray, the normal, and the refracted ray all lie in the same plane (see Fig. 1). Snell, a Dutch scientist, found in 1620 that the ratio sin α: sin β is a constant, where α is the angle of incidence and β is the angle of refraction. Snell's Law, as it is known, is usually expressed as

$$\sin \alpha / \sin \beta = n_2/n_1 = \mu \qquad (1)$$

where n_2 and n_1 are the refractive indexes of the two media, and μ is a constant.

Light is refracted because it has different velocities in different media. The Wave Theory of Light shows that the refractive index $_1n_2$ for two given media 1 and 2 is given by

$$_1n_2 = c_1/c_2 \qquad (2)$$

where c_1 and c_2 are the velocities of light in medium 1 and 2 respectively.

If medium 1 in (2) is a vacuum, the value is the *absolute refractive index*. The value for any other two media is the *relative refractive index*.

The absolute refractive index, n, of a medium is then

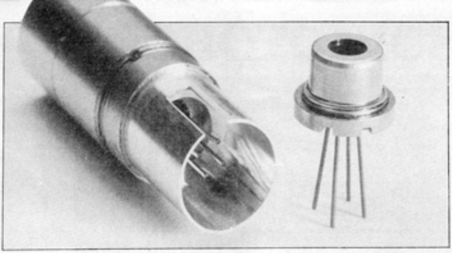
$$n = c/v \qquad (3)$$

where c is the velocity of light in a vacuum, and v is the velocity of light in the medium. As the absolute index of air is 1.000 29, in practice, the velocity of light in air can replace that in a vacuum.

There are, of course, situations where there is a partial reflection and a partial refraction of the light. For instance, in Fig. 2a, the angle of incidence is so small that a large part of the incoming light is refracted. In optical fibre, this would mean that a large part of the light would be lost in the cladding of the cable.

Fig. 2b shows the critical angle of incidence: the refracted light here is at an angle of 90° with the normal. At the critical angle, the refracted light may cause interference. It is, therefore, essential that the angle of incidence is greater than the critical angle — see Fig. 2c — when total reflection takes place. The condition for total reflection is that the ray of light travels from an optically dense medium with a relatively large refractive index to a less dense one with a smaller refractive index.

Rays of light that fall upon the media separation at an angle smaller than the critical are called high-order modes: they take



relatively longer to reach the end of the cable. Rays of light that travel almost parallel to the optical axis, i.e., at an angle greater than the critical, are called low-order modes. Low-order modes travel faster because they are reflected less often than high-order modes. Low-order modes are far less prone to losses than high-order ones.

The sine of the angle of incidence of the ray of light is called the numerical aperture: this is the prime factor where two optical waveguides are to be linked. The numerical aperture is also an indication of the difference between the refractive indexes of the core and the cladding: the smaller it is, the wider the bandwidth of the optical signal.

Optical-fibre cable

In multi-mode fibre (see Fig. 3a), the ray paths of the different modes are of different lengths and have, therefore, different transmission times. Because the modes are divided by a pulse, this is subject to progressive spreading as it travels along the fibre, causing it to interfere with adjacent pulses. In mono-mode (also called single-mode) fibre (see Fig. 3b), the core diameter is comparable with the wavelength of the light, so that there can be only one electromagnetic propagation mode and spreading of the pulse (called multi-path dispersion) is eliminated. Its small core size makes mono-mode fibre more difficult to use, but it can be made with an attenuation of less than 0.4 dB/km at a wavelength of 1.3 μm (as against 2 to 10 dB/km for multimode fibres). A typical bandwidth of mono-mode fibre is 10 GHz.

A typical design of optical-fibre cable is detailed in *Light work for submarine cables* elsewhere in this issue.

The fast rate of incremental improvements in optical fibre technology, which is due mainly to AT&T's Bell Laboratories, British Telecom, and Japan's NTT (Nippon Telegraph & Telephone), have made multimode fibres already obsolescent as far as long distance cables are concerned. (Multi-mode fibre cables need repeaters every few miles, whereas with mono-mode fibres distances between repeaters are of the order of 50 to 100 miles). The three organizations are already researching new core materials which, they hope, will eventually enable repeaterless transoceanic cables.

Currently, the central core of optical-fibre cables is made of doped silica sheathed in pure silica. New core materials now being studied include oxide-based and halide-based fibres. These could be from 2 to 1000 times more transparent than silica. They would also disperse less light than silica, which would result in cables with much greater capacities than present ones.

Data transfer

Optical-fibre networks need, of course, other than the cable a sender, receiver, coupler, and repeaters (see Fig. 4). There are two main types of optical sender: the infra-red diode and the laser diode (laser=light amplification by stimulated emission of radiation). Both enable light energy at wavelengths from 0.8 to 1.5 μm to be injected into the fibres. The most commonly used type is the infra-red diode, however, because it is relatively cheap, reliable, has a long life (10^6 to 10^7 hours), and is easy to use. Furthermore, they have only little drift with temperature, and their current can be modulated readily. For wavelengths from 0.7 to 0.9 μm silicon diodes are used, but in the range 1.1 to 1.5 μm AlGaAs (aluminium-gallium-arsenide) types are necessary, as the energy transfer of silicon diodes at those frequencies drops sharply. Infra-red diodes have the disadvantages that their bandwidth is limited and that they cannot emit parallel beams of light. The latter means that the light emitted must first be passed through an optical system where it is converted into a parallel beam.

Laser diodes do not need such an optical network and also have a higher output (up to 650 mW). Pulsed lasers may deliver up to 100 W bursts. Furthermore, the attainable bandwidth is much wider than possible with infra-red diodes. Because the

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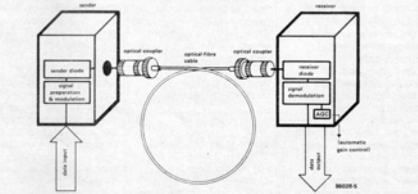
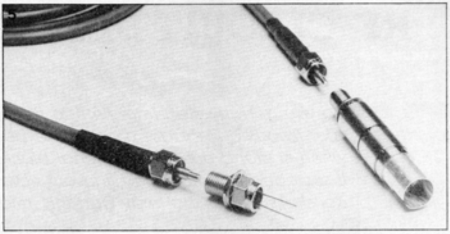


Fig. 4. Repeaterless optical-fibre network.



light rays in a laser beam are to all intents and purposes parallel, a larger part of the available energy is injected into the fibre. Unfortunately, lasers also have some drawbacks: they are difficult to manufacture; they are, therefore, expensive; their life at 10^5 hours is much shorter than that of IR diodes; and they drift with changes in temperature. The latter means that the relatively high current through them (in pulsed types a few amperes as compared with about 150 mA in IR diodes) must be regulated. As laser diodes take 4 to 8 ns before they emit infra-red light (at the onset they start emitting visible light), their quiescent current must also be regulated to make controlled operation possible.

Summarizing, laser diodes require auxiliary electronic circuits, whereas IR diodes require additional optical networks (lenses).

For the receiver there are also two possible devices: p-i-n diodes and avalanche diodes. A p-i-n diode is a photodiode that contains a region of almost intrinsic (i-type) semiconductor between the p-type and n-type regions.

P-i-n diodes combine fast reaction times (shorter than 1 ns which makes them very suitable for operation with laser-type senders) with small supply voltages, simple electronic circuitry, and relatively low prices. Unfortunately, they are very noisy, and this is the more troublesome since their low output must be amplified by a so-called trans-impedance amplifier: this device also acts as a current-to-voltage converter.

Avalanche photodiodes provide a substantial gain (40 to 60 dB) and are also very sensitive. Furthermore, they are far less noisy than p-i-n diodes. They are, however, more expensive, have a small demodulation bandwidth, and are only suitable for use with digital signals. Moreover, they require a very high supply voltage of 100 to 1000 volts, which, incidentally, shortens their life as compared with p-i-n diodes.

A description of a typical repeater is given in *Light work for submarine cables*.

A range of couplers is commercially available, and some typical examples of these are seen in the photographs. These are used where the connection is not permanent. For permanent connections, the two cables are spliced under the microscope with the aid of a small electric welding tool. If the splicing is carried out properly, the joint attentuation will be less than 0.15 dB.

T-junctions are also possible: a typical optical coupler for this purpose is shown in Fig. 6. This device is, incidentally, also suitable for use as a duplexer.

Another interesting possibility is wavelength multiplexing as illustrated in Fig. 7, which can greatly increase the capacity of the fibre cable. The light from the sender diode is paralleled and then projected via a lens onto a reflection filter that is inclined with respect to the axis of the lens. This filter reflects the light rays into a direction that depends on the wavelength. The lens converts the change of direction into a positional shift so that the reflected rays of all wavelengths converge, after which the compound ray is injected into the transmission fibre.

Fig. 5. Optical-fibre cable with couplers.

Fig. 6. Optical T-junction illustrating the duplexing concept.

Fig. 7. Construction and mode of operation of the optical multiplexer.

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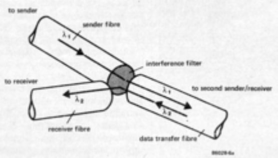

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