In communications, higher frequencies mean greater bandwidths. Optical frequencies, if they could be utilised, could provide an enormous information-carrying capacity. The major problem in using optical frequencies in communication is transmission

Glass fibres for communication show promise

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CIVILISATION as we know it is completely dependent on communication for its existence. Communication by electrical means surpasses all other known methods in its rate of transmission of information, the distance over which transmission is possible and, above all, flexibility. Electrical communication has been with us for quite a long time and, indeed, started nearly 150 years ago as part of the signalling process on the Great Western Railway.[1] The apparatus consisted of a single wire and a ground return, along which pulses of energy were transmitted using a battery and a switch. It was found some time later that speech and music could be transmitted by using a microphone and a loudspeaker, and this form of analogue modulation has been the most widely used in communication ever since.

Disadvantages

These original methods had two disadvantages. First, it was only possible to transmit one signal at a time, and, secondly, such low frequencies as speech cannot be radiated efficiently through an aerial of reasonable size. The next development was therefore to make the original signal cause a fluctuation in the amplitude not of a steady current, but of a high-frequency current, normally referred to as the carrier wave. The resulting 'modulated' carrier contains components with frequencies ranging from the difference between the original carrier frequency and the highest frequency component in the impressed signal up to the sum of these two frequencies. Information contained in the original signal is therefore translated to much higher frequencies as sidebands each side of the high-frequency carrier.

Such frequencies can not only be passed along suitable wire systems, such as a coaxial cable, but may also be transmitted efficiently as radio waves through space. Further, if signals from different sources are allowed to modulate carrier waves of different frequencies, then several signals can be transmitted at the same time.

At the receiving end, the modulated carriers can be separated by filters, after which the original signals can be removed from the carriers and reproduced as before. By this means, one pair of wires, or a radio link, or any other communication 'channel', can carry many signals simultaneously. The number of different signals or circuits that can be carried by one channel depends on many factors, but, to a first approximation, it is proportional to the average carrier frequency used. Thus the information-carrying capacity can be increased by increasing the frequency of operation.

Cost

Experience shows that, although high-frequency high-capacity systems cost more than low-frequency ones, the cost per circuit mile is lower.[2] Thus, for example, it is cheaper in practice to install a single system with a bandwidth of 100MHz than ten smaller systems each having a bandwidth of 10MHz. The highest frequency in commercial use today is about 10GHz, in the microwave region, and provides a capacity of some 15000 telephone or eight television circuits. Many such microwave links are in operation in all technologically advanced countries. However, more television and radio circuits are demanded, high-speed computer and data links are required and long-distance telephone traffic in Britain is doubling every six or seven years (and one sometimes feels that the price does too). The pressure for systems operating at even greater bandwidths is therefore very great.

Because different modes in a waveguide or coaxial cable travel at different velocities, it is essential for maximum bandwidth that only a single mode is allowed to propagate. This is why waveguides for higher frequencies have smaller cross-sections than those for lower frequencies. However, the decrease in size causes an increase in attenuation which becomes serious at frequencies approaching 100GHz. Attempts are therefore being made in several countries to develop a guide of large cross-section in which mode conversion effects are very small, so that energy will continue to propagate in the mode in which it is launched. For example, a considerable amount of work has been carried out by the British Post Office[3] into an overmoded waveguide with a circular cross-section of about 5cm operating in the 40–110GHz band which could carry 250000 telephone circuits. Considerable problems, particularly at bends, have had to be overcome, and the waveguide will have to be made as straight as possible. However, an experimental 30km section will be installed for in-service testing in 1973.

Optical frequencies

The advent of the laser in 1960 provided an exciting and challenging alternative possibility. A laser is essentially an electronic oscillator which operates at frequencies which may be 10^5 times higher than those used for microwave communication. If a laser could be used to provide the carrier wave, and it were possible to achieve a bandwidth of only 0·1% of the carrier frequency then the information-carrying capacity would be enormous by present-day standards. So far, however, optical communications has been all optics with very little communication. Before such high bandwidths become available many new techniques for modulation, multiplexing and detection, will have to be developed.

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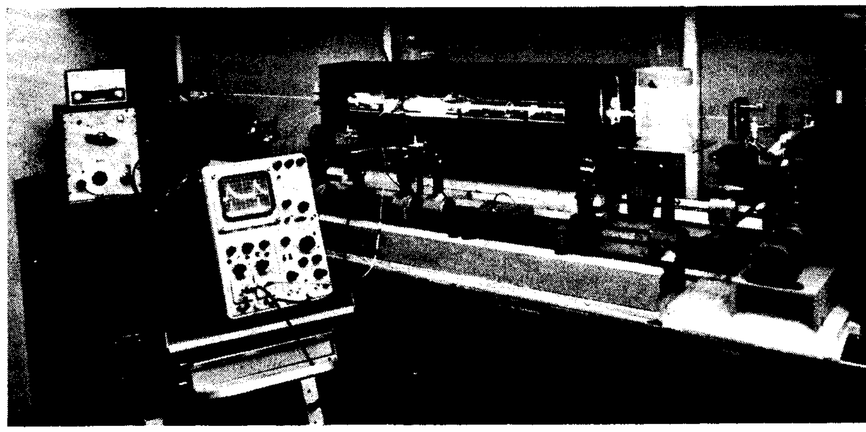
Initial attempts at using the laser in communications systems involved free-space propagation through the atmosphere similar to that in microwave line-of-sight links. However, such techniques are not likely to be used over distances greater than a few kilometres because of weather effects. In severe weather the attenuation can be very high, and the proportion of time during which the system is out of operation would depend on local weather conditions.

An even more basic objection to atmospheric propagation is the serious effect that very small fluctuations in the density of the air have on transmitted laser beams, even in clear weather. Thermal currents and turbulence change the local density, and hence the refractive index, thus causing the beam to break up while large-scale temperature gradients can bend the beam away from its target. The magnitude of the effect is such that a 5cm-diameter beam is deflected by an amount equal to its own diameter by a temperature gradient as small as 10^{-3} degC/cm.

Outer space

On the other hand, outside the Earth's atmosphere, diffraction is the only limiting factor, and propagation over vast distances becomes possible. For given transmitting and receiving apertures, the efficiency of transmission increases as the square of the frequency. At optical frequencies, thermal noise is of little importance, but it is replaced by shot noise in the optical signal owing to the comparatively large photon energy. For example, at microwave frequencies, a



1 Measurement of pulse dispersion in 200m of liquid-core fibre using a mode-locked He–Ne laser producing pulses of 0·5ns duration

power of only 1 mW results in about 10^{10} photons being associated with each wavelength in a train of radiation.

In contrast, at optical frequencies 1 mW corresponds to only about 10 photon/wavelength, and the granular nature of the signal is much more evident. The photon noise increases linearly with frequency, and thus the signal/noise ratio, again for fixed apertures, also increases linearly with frequency. By using a large aperture, the angular width of the beam can be made very small, and it has been calculated that communication should be possible, using existing techniques, over a distance of ten light years. Apart from the inconvenience of waiting 20 years for a reply, there seems to be no good reason at present why such a system should be developed.

At a more realistic level, a number of laser communication systems have been designed for communication with deep-space probes. One of the many problems is the magnitude of the Doppler shift in the transmitted frequency resulting from the high carrier frequency and high speeds involved.

For terrestrial communication, some means of protecting the laser beam from atmospheric fluctuations is essential, and there have been two main approaches to this problem.

In the first approach,[4] the laser beam is propagated in a pipe, which must either be evacuated or placed underground so that a constant temperature is maintained. Because the beam spreads by diffraction, it will eventually strike the walls even if the pipe is optically straight. If this were allowed to happen not only would the attenuation be high because of the loss on reflection, but multipath distortion would severely limit the bandwidth. The time taken by a ray of light to traverse the length of the pipe in a series of reflections is greater than the time taken by a direct axial ray. For example, after travelling 1 km a ray at 1° to the axis will have a delay relative to the axial ray of roughly 1 ns. Thus pulses could not be transmitted at a rate greater than $10^9 s^{-1}$ without one output pulse merging with adjacent pulses.

An improved method which has been under intensive development at Bell Telephone Laboratories, is effectively to correct for diffraction by periodic refocusing of the beam with weakly converging lenses. In such a system all rays travel the same optical distance, and therefore multipath distortion does not occur. The potential bandwidth is therefore enormous and would in practice be limited by the modulation and detection components and not by the transmission channel.

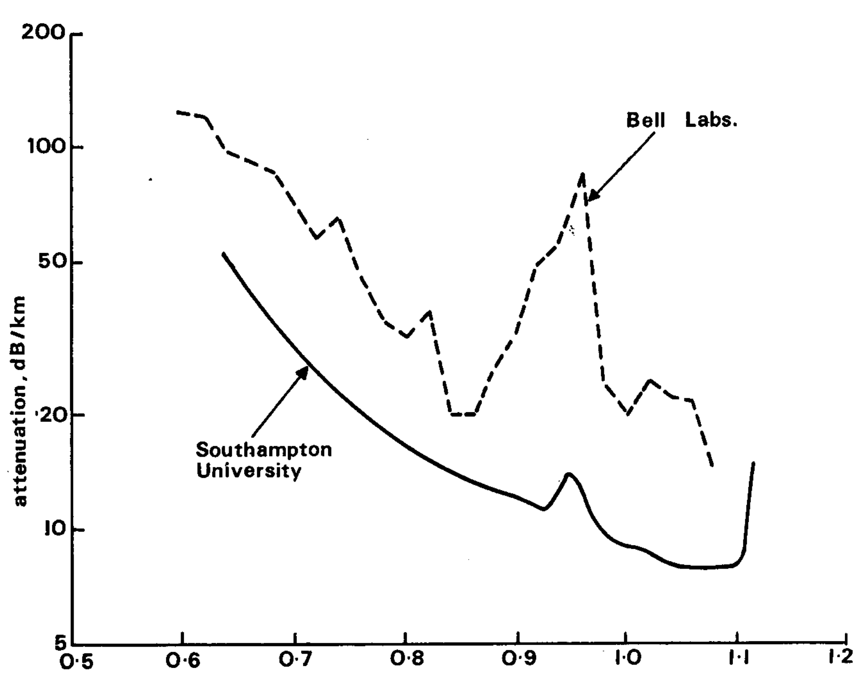
Losses due to reflection at the lens surfaces can be minimised by anti-reflection coatings, while another possibility is to abandon solid lenses and use instead the focusing effect of a radial temperature gradient in a gas. Experimental attenuations in such beam-guiding systems as low as 1 dB/km have been obtained. It is still necessary to prevent all but the smallest temperature gradients occurring in the gas contained in the enclosing pipe which therefore has to be installed underground or thoroughly lagged.

Ground movement and vibration are severe problems which it is proposed to overcome by automatic control of the position and attitude of each lens. Installation and maintenance costs will therefore be very high, but the information-carrying capacity should be large.

A different approach, which was suggested in Britain some six years ago,[5] is to use a guiding structure similar to a waveguide. In a conventional waveguide the energy is propagated down the inside of a hollow conductor, but it is also possible to use a solid rod. In this case, the energy is guided along the outside as a surface wave. Metals are very lossy at optical frequencies, and a low-loss dielectric has to be used. For broadband communication it is essential that only one wave should propagate at a time, and this can be ensured by making the rod diameter comparable with a free-space wavelength.

It transpires that a suitable wavelength is about 1 μm, and a convenient dielectric is glass. It is possible to make glass fibres 1 μm in diameter; but, having drawn them, the difficulty is to find them! Apart from the fragility of the fibres, any supporting structure would cause reflections of the energy, which is largely carried in the space surrounding the fibre. The loss and dispersion would therefore be high.

By cladding the fibre with a material of lower relative permittivity, such as a different glass, a number of advantages are obtained. First, the combined structure is mechanically more robust, and, as long as the cladding is sufficiently thick (say 50 times the light wavelength) for the field amplitude to be extremely small at its outer surface, there is no difficulty in supporting it. Further, if the relative permittivity of the cladding is only slightly less than that of the core, single-mode operation can be achieved with a core diameter of perhaps a few wavelengths, and the manufacturing problems are somewhat easier. The electromagnetic wave is carried partly in the core and



2 Attenuation against wavelength for liquid-filled fibres. The solid line is the Southampton University result obtained for hexachlorobuta-1,3-diene in glass. The broken line was obtained at Bell Labs. with tetrachloroethylene in silica

partly in the cladding, and these should therefore be made of low-loss materials.

Until recently, the best available glass had an attenuation of several hundred decibels per kilometre and a considerable improvement was essential before a useful communication system could be designed. However, there did not seem to be any fundamental reason why this should not be possible. The bandwidth is ultimately limited, by dispersion in the propagating mode and in the bulk material, to several gigahertz over several kilometres. Even with a cladding thickness of 100 wavelengths (i.e. 100 μm) the overall fibre thickness is small (the diameter of a human hair is about 50 μm), so that it is flexible and can negotiate bends with quite a small radius of curvature.

Advantages

The bandwidth is considerably smaller than that of the beam waveguide, but is still large compared with present-day coaxial cables. Indeed, many hundreds of glass fibres could be put into the same cross-section as a coaxial cable, and such spatial multiplexing would produce an enormously increased bandwidth. The resulting fibre bundle is cheap to produce and cheap to install since it could simply be laid in existing ducts in place of the copper cable.

In addition the glass-fibre communication system is more compatible with present-day modulation and detection techniques than the beam-guiding structure. For example, existing avalanche photodiodes have properties close to those ideally required, and great efforts are being made to develop semiconductor-laser sources of sufficiently long life and capable of operating continuously at room temperature. Some form of pulse modulation will almost certainly be used, and the electrical pulses can be applied directly to the diode laser without the necessity for optical time multiplexing.

To have an economical repeater spacing of several kilometres it is essential to reduce the fibre attenuation to less than 20 dB/km. The best existing optical-quality glasses have a bulk transmission loss of about 100 dB/km owing to quite small levels (a few parts in 10^6) of impurities. By reducing the impurity level, it is hoped that the required attenuation can be achieved. Indeed, very pure silica is already available which could be used for the core of a fibre, but no low-loss material of suitably close refractive index (1·457) and mechanical properties is known (the softening point of silica is about 2000 °C compared with about 1000 °C for most glasses).

It has proved possible to produce a single-mode cladded silica fibre with a loss of less than 20 dB/km by doping the core with heavy-metal ions to produce a small change of refractive index. However, there are severe problems with single-mode fibres that arise from the small diameter of the core, namely those of launching efficiently from semiconductor lasers and jointing between adjacent section of fibre. To get two fibre ends flat and permanently aligned, to an accuracy of better than 0·1 μm is no mean problem, as work at the British Post Office Research Station and Standard Telecommunication Laboratories has shown.

Multimode fibres

An alternative approach is being undertaken, as a joint project between the UK Signals Research & Development Establishment and the Department of Electronics at the University of Southampton, to develop low-loss multimode fibres. These fibres have core diameters of 20–100 μm and are easier to manufacture than single-mode fibres. However, because of the large core diameter, they are capable of supporting many modes, and it was expected that the bandwidth would be quite small.

In a thick-core fibre, it is more convenient to visualise energy propagation in terms of rays which travel along the fibre by total internal reflection from the core/cladding interface. As long as the angle to the interface is not greater than that corresponding to the critical angle [given by $\cos^{-1}(n_2/n_1)$ where n_1, n_2 are the refractive indexes of core and cladding, respectively] no energy is coupled into the cladding, at least when the latter is lossless.

If an input beam is launched so as to fill the aperture of the fibre, or if scattering occurs, then the spreading of a transmitted pulse could become comparable with the difference in transmission times of the axial and extreme rays, which, for a typical fibre 1 km long, is 0·5 μs. This is equivalent roughly to a bandwidth of 1 MHz. However, careful measurements made at the University of Southampton have shown that if a narrow beam is launched into a well made glass-core fibre a pulse spreading of as little as 0·3 ns occurs over 50 m with core diameters in the range 50–100 μm.[6,7] If such a low dispersion can be maintained for greater lengths, a bandwidth of 100 MHz over 1 km may be possible. This bandwidth is considerably greater than that currently available from coaxial cables, and the spatial multiplexing which is possible increases the advantage still further.

An additional recent development has been the use of silica-fibre tubes filled with tetrachloroethylene to give attenuations of less than 20 dB/km. Liquid-core fibres were first reported independently by G. J. Ogilvie of CSIRO, Australia, and a group at Bell Telephone Laboratories. Using specially selected silica and highly-purified and filtered tetrachloroethylene, Ogilvie obtained a transmission loss of 17·5 dB/km and Bell Labs. obtained 13·5 dB/km at a wavelength of 1·06 μm, although there is an absorption peak of more than 80 dB/km at 0·96 μm.

An even more recent result,[8] again by the Southampton University team, is the production of liquid-core fibres with a loss of 7 dB/km. A particular virtue of these fibres is that they are made from inexpensive, commercially available materials.

The fibre is drawn from ordinary ME1 glass tubing, which has a bulk loss of approaching 10^4 dB/km. The tube is filled through a filter, under hydrostatic pressures up to 1400 atm, with hexachlorobuta-1,3-diene directly from the bottle, as supplied by British Drug Houses. In view of the unsophisticated nature of the materials used, the low attenuation of 7 dB/km, which is obtained for wavelengths from 1·02 to 1·10 μm with fibres having internal diameters from 40 to 75 μm, is quite remarkable.

While there is a small peak near 0·96 μm, the absorption at this point is still less (13 dB/km) than the lowest attenuation reported by Bell Labs. Indeed the loss is less than 20 dB/km over the range 0·76–1·13 μm. These fibres can therefore be used with both gallium-arsenide injection lasers (fibre loss: 11·5 dB/km) and also neodymium-based lasers (fibre-loss: 7 dB/km) such as the c.w. yttrium–aluminium garnet laser.

Even within the past few months, there have been two further major announcements. First, the Corning Glass Co.[9] have made a multimode version of their silica-based fibre with an attenuation which has a minimum value of 4 dB/km and is below 10 dB/km over a wide range of wavelengths. Secondly, at Southampton,[10] we have measured pulse dispersions corresponding to bandwidths of nearly 1 GHz/km in our liquid-core glass fibres.

Because of the above developments, there is greatly increased interest in multimode fibres since they are cheaper and more readily manufactured than single-mode fibres. In addition, launching and jointing become much easier. Liquid-core fibres are also easy to make and handle, and, although they are not the ideal choice for practical application, they show that low loss and large bandwidths can be achieved.

Considerable progress is being made towards the development of a glass-fibre waveguide suitable for use in optical communication systems. A year or so ago it seemed that the main obstacle to progress was the difficulty in producing a suitable fibre of sufficiently low attenuation. This hurdle has now been overcome, in the laboratory at least, but much work is still needed to provide a laser source with a long operating life.

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