W. A. Gambling and P. J. R. Laybourn

Communicating with light

Today's communications systems are fast becoming overloaded. By using light instead of microwaves or telephone wires an enormously enlarged bandwidth may provide more than enough capacity in the 1980s and beyond

MODERN CIVILIZATION is completely dependent on communications for its existence, and the demand for improved communication facilities of all types is increasing more rapidly than ever. The entertainment aspects of communications such as radio and TV are perhaps the most obvious ones, but the transfer of information by telephone, telegraph, radio and cable between computer and user, reactor and control room, aircraft and radar guidance officer, lunar landing module and Earth or White House and Kremlin is at least as important.

To handle this growing flood of information is taxing the ability and resources of communications engineers the world over. If it were not for the promise of a totally new and very powerful way of transmitting information the position would soon become desperate. As it is, relief—albeit perhaps only temporary, because the information flow growth shows no signs of levelling off—appears to be at hand.

The new communications systems will use beams of light. Some of them will send light along waveguides, probably optical fibres of special glasses or carefully laid pipes either on or within the ground. In most cases the light will have a wavelength in the infrared region and so it will not be visible to human eyes at all. But it will carry information at a rate none of today's methods can approach.

INFORMATION can be passed from one location to another by various means, but electrical methods surpass all others in providing a greater rate of information transfer over longer distances and with greater flexibility. The crudest electrical method of sending information, devised about 130 years ago, involved switching an electric current flowing along a wire on and off to produce sequences of long and short pulses representing letters and numbers in the well-known Morse code. This technique was obviously limited in speed by the rate at which a human operator could manipulate a key, and was unsuitable for speech, music and high speed signals. Later it was found that speech and music could be transmitted by passing the current through a microphone connected in series with the wire. Sound waves impinging on the sensitive diaphragm caused the resistance of the microphone to fluctuate in sympathy with them, in turn producing variations in the current. At the far end of the wire the current, perhaps after amplification en route, passed through the coil of a loudspeaker causing corresponding vibrations in the loudspeaker cone. In this way the original sound waves could be reproduced at a considerable distance.

This is how a simple telephone system works, but it has two big disadvantages. First, only one conversation or signal can be sent along a pair of wires at a time. Secondly, such low frequency fluctuations cannot be efficiently transmitted as radio waves but must be sent along an unbroken wire to their destinations. 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 will contain components, in 'sidebands', having 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.

Such frequencies can be not only passed along a suitable wire system such as a coaxial cable but also transmitted efficiently as radio waves through space. Furthermore, if signals from different sources are allowed to modulate carrier waves of different frequencies, the modulated carriers can be separated by filters at the receiving end, after which the original signals can

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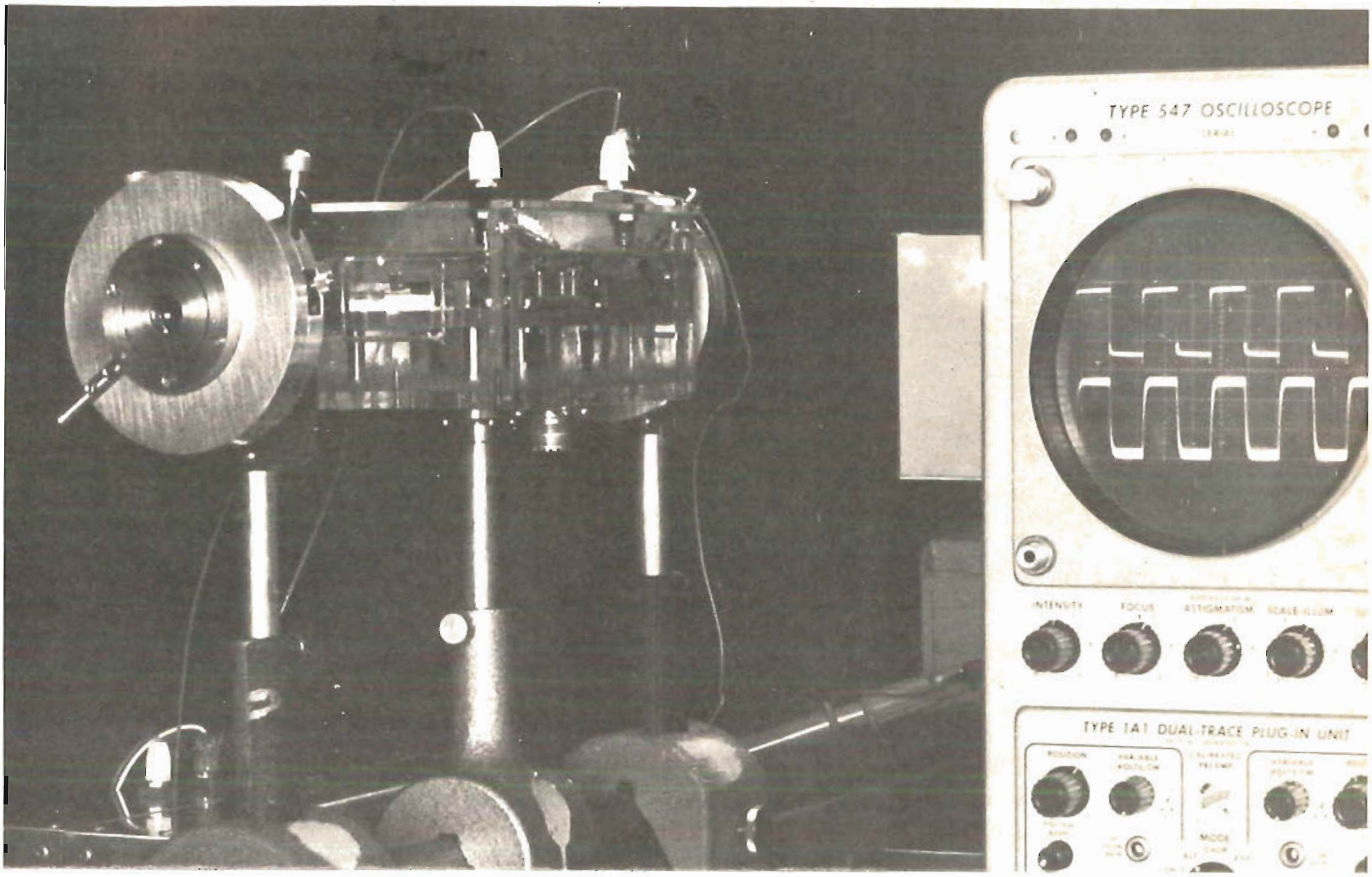


MODULATION of a light beam is demonstrated in the authors' laboratory by impressing a 50 kHz signal on to the beam of light from a laser. On the left the beam can be seen emerging from the second of two balanced electro-optic crystals inside a plastic housing. On the right the oscilloscope indicates the modulating signal (upper trace) and the detected signal (lower trace). In parallel experiments the authors are investigating the propagation of 1 nanosecond (10^{-12} sec) optical pulses along glass fibre guides made in their laboratory

be removed from the carriers and reproduced as before. By this means one pair of wires, or a radio link, can carry many signals simultaneously.

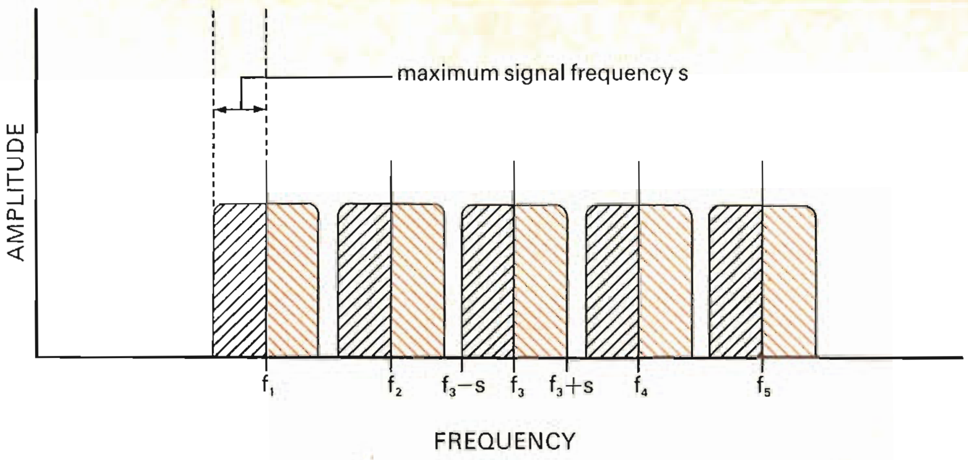
The number of different signals or 'circuits' that can be carried by one channel depends on many factors but, to a first approximation, is proportional to the average carrier frequency used. Thus, increasing the frequency increases the information carrying capacity. Experience shows that, although high frequency high capacity systems cost more than low frequency ones, the cost per circuit is less. It is therefore cheaper to instal a single system with a bandwidth of 100 MHz than ten smaller systems each having a bandwidth of 10 MHz. The highest frequency in commercial use today is in the microwave region at about 10,000 MHz, providing a capacity for some 15,000 telephone or eight TV circuits. Many such microwave links are in operation in all technologically advanced countries. However, more TV and radio circuits are demanded, high speed computer and data links are required and in the UK long distance telephone traffic is doubling every six years. High capacity systems are required capable of carrying many thousands of speech, data and video channels simultaneously, and the pressure for systems operating at even high frequencies is very great.

THE LASER's advent in 1960 therefore provided an exciting and challenging possibility in communications. A laser (see "Practical uses of lasers", *Science Journal,* June 1966) is essentially an electronic oscillator which operates at light frequencies. It differs markedly from other light sources in that it provides all its power at very nearly a single frequency which may be in the region of 5×10^8 MHz—that is 100,000 times higher than those used for microwave communications. Obviously if lasers can be harnessed for use as carrier waves then optical communication systems of enormously high capacity will result; but, before this can be realized, many new techniques will have to be developed.

Basically the mode of operation of a laser is simple. An atom or molecule can take up excess internal energy only in fixed discrete amounts which are characteristic of each atom. This excess energy is released after a short time sometimes in the form of a short burst, or photon, of light having a characteristic frequency. This emission of light usually occurs quite randomly, rather in the nature of radioactive decay. The active portion of a laser consists of a material which emits the excess energy in the form of light, but does so spontaneously only after a comparatively long time interval (comparatively, because this time is normally much less than one second).

Under these conditions an atom can be 'stimulated' to emit its photon by the influence of a similar photon from another atom (the word laser is an acronym for Light Amplification by the Stimulated Emission of Radiation). Rather remarkably the first photon is unaffected by the process and as a result there are two photons in place of the original one. Both may stimulate further photon emissions. As this 'avalanche' process continues, the number of photons builds up very rapidly and, since they act co-operatively and are of the same frequency, the coherent light intensity is also rapidly increased.

In order to construct an oscillator the laser amplifying medium is usually placed between two parallel mirrors so that the light intensity is built up by successive reflections. One mirror is made partially transparent so that an output beam of



FREQUENCY SPECTRUM of a frequency division multiplexed channel shows how, in this case, five carriers having frequencies f_1 to f_5 are each surrounded by sidebands containing components up to the maximum signal frequency s. For greater carrier packing density one of each pair of sidebands (either the ones shaded in colour or shaded in black) may be suppressed. The number of signals which can be carried by each channel is thus given by the ratio of the total channel bandwidth to the frequency space occupied by each signal

light is obtained. The excess energy of the active atoms must be supplied initially and replaced during operation by a pump source. This can be done by passing an electric current through the material, by illuminating it with an intense light source or in other ways depending on the type of laser.

Ideally, the output of a laser is coherent: it consists of a single frequency component having a phase front which is well defined both spatially and temporally. For a Gaussian wave-front the spread of the beam is limited only by very slight outward diffraction to an angle proportional to the wavelength divided by the beam diameter. In practice many factors operate to degrade the output, yet quite straightforward techniques can yield good results. Beam divergence can be held close to the theoretical limit and frequency stability can better one in 10^9.

COMMUNICATION SIGNALS can be impressed on a carrier wave in two main ways. In analogue modulation either the amplitude or the frequency of the carrier is made to change by an amount proportional to the signal. The number of such signals which can be carried on a single channel is approximately equal to the channel bandwidth divided by twice the maximum signal frequency. This spacing of the different signals over adjacent frequency ranges of the communication channel is called frequency-division multiplexing.

In digital or pulse modulation the carrier might be transmitted intermittently in a series of regular pulses having height, width or repetition frequency proportional to the signal amplitude. An important and sophisticated type of digital modulation, gradually coming into use as circuit techniques are improved and microelectronic components become cheaper, is pulse code modulation (PCM). The amplitude of the signal is measured at regular intervals and the measured height expressed as a binary code of zeros and ones. A string of codes representing the signal amplitude at successive instants of time is transformed into carrier pulses, the presence of a pulse indicating a 1 and its absence a 0.

A carrier with PCM has a great advantage over one modulated by one of the analogue methods. After transmission over a great distance the wave will be very weak; it will arrive at the receiver along with atmospherics and noise, and may be distorted or subject to fading. As listeners to foreign radio stations will know, such interference can have a profound effect on the quality and information content of the received signal. With PCM the only task the receiver must perform is to decide at each time interval whether a pulse is present or not. The shape or height of the pulse is immaterial. Thus, providing any interfering noise is less in amplitude than the received signal and is not mistaken for signal pulses, the transmitted signal code can be correctly received, and the original signal perfectly reconstructed at the receiver.

Using pulse-coded signals another scheme to carry multiple signals in a single channel is open to the communications engineer. Two pulse trains having the same repetition frequency may be interleaved; and the resulting double pulse train may be interleaved with a similar one also containing two signals. This time division multiplexing' may be extended to the maximum pulse rate the communications system can handle. In practice, marker groups of pulses must also be inserted, so that the receiver can get in step with the transmitting coder.

Input signals can take many different forms. They can be speech or picture information, or automatic telegraphy such as Telex. Most systems using an electromagnetic carrier wave conform to this pattern, although sometimes in a simplified manner. Sound radio transmissions carry only one signal, but a colour TV system multiplexes (by frequency division) video, colour and sound information (see "Colour television", *Science Journal,* April 1966). Repeaters, such as the local transmitters in the UK Band V television systems, are used to boost a signal en route. With PCM a repeater simply detects when a pulse is present and regenerates a new, undistorted pulse for onward transmission. Optical system components, although carrying out similar tasks, differ greatly from their present day counterparts.

OPTICAL COMMUNICATION calls for a laser source producing either a continuous wave (CW) which can be modulated or a repetitive pulse train for use in some form of pulse modulation system. Although continuously operating gas lasers, principally those containing carbon dioxide, argon or a helium/neon mixture, have been in use for some years they require high voltage power supplies and are generally not robust. Semiconductor lasers, especially those made of gallium arsenide, are small and highly efficient but at present require cooling to 77° K for continuous operation. They may be operated in a pulsed mode at room temperature, but only at a rate too low for most purposes; and their output is not single frequency but covers up to 1000 GHz at high powers. Now neodymium doped, yttrium aluminium garnet single crystal lasers have become available. These give large CW outputs from a compact source and can also be made to produce a train of extremely short pulses, each of 10^{-12} second, at the rate of 10^9 per second.

The method of modulating the carrier beam depends on the type of modulation required and the laser source used. The simplest method is to make the signal vary the laser pumping intensity and thus the amplitude of the output, but this is of practical importance only with semiconductor lasers whose output may be modulated up to 1 GHz by pulsing the pump current. Switching a current of several amperes in a nanosecond or less is not easy and modulation external to the laser may be preferable. For example, in some materials such as gallium arsenide there is a sharp optical absorption band edge, near the laser output wavelength, which can be displaced by an applied electric field. Thus the junction region of a reverse biased gallium arsenide *p-n* diode, where the electric field is large, may be used as an optical switch in the wavelength range over which the absorption band edge may be shifted.

Another possibility is to use the Pöckels effect, which refers to the birefringence produced in certain transparent crystals subjected to an electric field. When a linearly polarized light beam passes through an electro-optic crystal the birefringence induced by the field converts the beam to an elliptically polarized one. A quarter-wave plate in the beam will restore linear polarization at an azimuth angle depending on the electric field and hence on the modulating signal. This polarization modulation may be converted to amplitude modulation by passing the beam through an analyser whose direction of polarization is suitable.

In a digital system a beam deflector may provide a high frequency optical switch. Bragg diffraction from an ultrasonic wave in a medium such as fused silica can transfer a large proportion of the incident laser beam intensity into a diffracted beam, at an angle to the original one. Alternatively electro-optic beam deflectors use birefringence induced by an electric field to vary slightly the refracted angle of a polarized input beam.

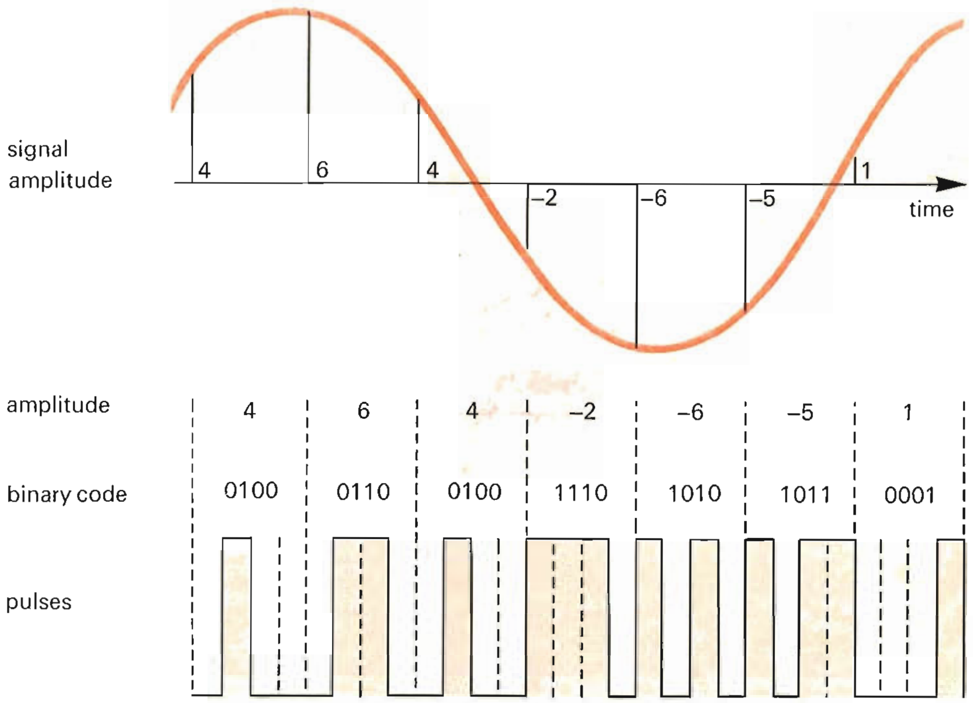
The rate at which information can be modulated on to an optical carrier obviously depends on the speed at which the modulator can operate. All those described so far, and many other modulators, are driven by electrical signals and are unlikely in the near future to produce repetitive pulses much shorter than 10^{-10} second, so that the maximum channel capacity is limited to a bandwidth of roughly 10^{4} MHz. On the other hand, the optical technique of mode locking a laser can easily produce pulses shorter than 10^{-12} second, depending on the fluorescence linewidth of the laser material. Pulse frequency is limited by the length of the laser resonator (between the mirrors) to about 10^{9} per second. But, because the pulses are so short, time-multiplexing can be used to interleave many such pulse trains producing effective pulse rates exceeding 10^{11} per second, far greater than anything currently being achieved. The beauty of this method is that the shaping and producton of the pulses can be done by very fast optical techniques, whilst the modulation of the pulse train before multiplexing can still employ electronic techniques.

PROPAGATION over a distance is the next hurdle to surmount. The laser's intense, narrow and well collimated beam arouses hopes of eventually providing line-of-sight communication over a considerable range. In a manner similar to the microwave chains that have lately been built, laser repeater stations could be positioned on high towers and natural prominences to provide a high capacity trunk communication network. But the atmosphere has unfavourable characteristics which combine to render such an open air system of limited value. Rain, snow, smoke, fog and mist all scatter light to an extent depending on the density and mean size of the obstructing particles and on the wavelength of the carrier beam. In severe weather the loss in signal can be greater than 20 dB per km, so that each kilometre of propagation removes 99 per cent of the signal. The proportion of time during which an atmospheric link would be out of operation would depend on the local weather, although long distance links could be kept in operation by using alternative routes. For domestic and commercial traffic, such as the telephone system, interruption because of weather would be intolerable.

A more subtle objection to atmospheric propagation is the serious effect that very small fluctuations in the density of the atmosphere have on a transmitted laser beam. During the day, the ground and other solid objects heat up in the Sun's radiation, and in turn heat the surrounding atmosphere. The resulting thermal currents and turbulence change the local density and refractive index, and large scale temperature gradients can refract the beam away from its target. Small pockets of warm or cool air speed up or slow down parts of the beam wavefront, and interference of the various out of phase components causes random modulation to be received.

It is therefore unlikely that long distance atmospheric laser communication links will become a reality. On the other hand, over short distances and in inconvenient locations such as building sites and rough country, and where security is required, there are possible applications. Handheld binocular sets have been produced which use the optical system for aiming by eye, with dichroic mirrors to allow one objective to be used as a transmitting telescope for a modulated infrared diode and the other to serve the photodiode receiver.

SPACE COMMUNICATIONS are more promising because outside the Earth's atmosphere diffraction is the only limiting factor and propagation over great distances becomes possible. For given transmitting and receiving apertures the efficiency of transmission increases as the square of the carrier frequency; but the communications engineer is not so concerned with mere signal power as with the signal/noise ratio. At low

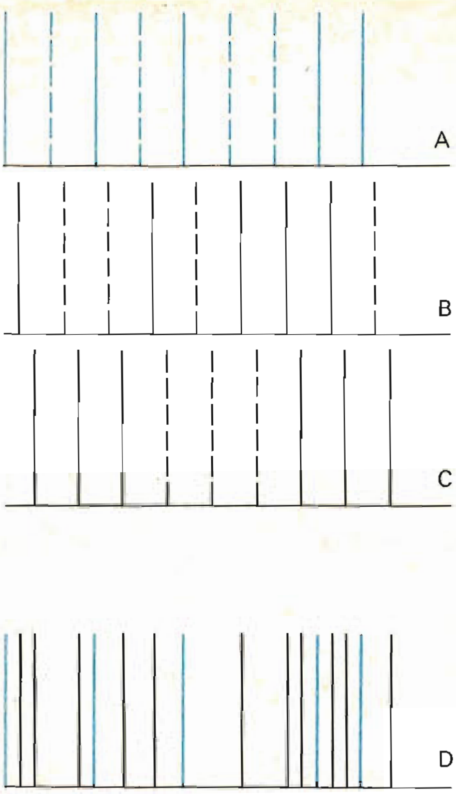


PULSE CODE MODULATION (PCM) begins by measuring the strength of the input signal several times per cycle (in this example the amplitude can be expressed in whole numbers from 7 through zero to −7). The resulting quantities are converted into binary digits and zeros and these, expressed as pulses and gaps respectively, are used to modulate the carrier. A great advantage of PCM is that all the receiver station has to do is decide whether or not a pulse is present; the shape and size of the pulse are of no consequence. As a result it is very unusual for background noise to prevent reconstruction of a perfect output signal

frequencies the limiting noise in a circuit is due to the random motion of electrons in conductors, valves and transistors. At today's microwave frequencies any usable signal contains so many photons that it appears to be continuous; a power level of only 1 mW at a frequency of 10,000 MHz results in some 10^{10} photons being associated with each wave of radiation. In contrast, at light frequencies 1 mW corresponds to only 10 photons per cycle. Thus the signal has an inherent noisiness due to its granularity. But since the photon noise level increases linearly with frequency and the transmission efficiency increases as the square of the frequency, the signal/noise ratio also increases linearly with frequency.

In situations where size and weight are at a premium, such as on an artificial satellite, optical communications may eventually have an important application. An experiment has already been planned by NASA scientists working at the Goddard Space Flight Center in Maryland involving communication between two synchronous, advanced telecommunications satellites and a low altitude satellite. The two synchronous satellites will communicate over 73,000 km using an infrared beam of 10.7 micrometres wavelength, obtained from a 1.2 watt carbon dioxide gas laser. The main 125 mm reflecting telescope is used for both transmission and reception, so that the light will follow the same path on both the outward and return journey.

One satellite will locate the other by transmitting initially without the telescope; the diffracted beam will then be much wider and the second satellite can line up its optical system. The received signal is focused on to an array of four detectors in a square, coupled to piezo-electric controlled compensating mirrors. If the beam goes out of alignment one detector will be illuminated more brightly than the rest, and the compensating mirrors will correct the error. For information reception a separate detector will receive both the incoming signal and a local oscillator signal from a secondary carbon dioxide laser in the receiver. The two signals are mixed at the detector surface and produce a heterodyne signal, in a system analogous to the conventional broadcast band 'superheterodyne' receiver. The carrier will be frequency modulated at up to 100 MHz and may be detected with mercury-cadmium-telluride detectors. On Earth such detectors are inconvenient to use, requiring operation at −170°C, but in a satellite they can be mounted on a heat sink radiating to deep space and thus need no power for cooling. Each transmitter/receiver is designed to have a mass of 34 kg and consume 200 watts.



TIME DIVISION MULTIPLEXING of three modulated pulse trains A, B and C. All have the same frequency but B and C lag A by one third and two thirds of a period, respectively. Zero amplitude pulses (gaps) are indicated by broken lines. When all three trains are transmitted simultaneously the result is train D. Any of the original trains can be extracted from D by taking every third pulse; A can be found by taking the first, fourth (absent) and so on

FOR EARTH COMMUNICATIONS some means of protecting the laser beam from atmosphere fluctuations is desirable and this may be accomplished simply by enclosing the beam in a pipe. As thermal gradients can exist in any gas in the pipe, evacuation of the pipe is to be preferred. As the beam spreads by gradual diffraction it will eventually strike the walls, even if the pipe is optically straight. It might be thought that highly reflecting walls would prevent excessive loss of light; even if this were so, reflections would still introduce the problem of multipath distortion which limits the available bandwidth. The time taken by a ray of light to traverse the length of the pipe in a series of reflections will be greater than the time taken by a direct axial ray. Over a distance of one kilometre a ray at 1° to the axis will have a delay of two nanoseconds. This means that, in a pulse modulated system operating at 500 MHz, each pulse of energy would be spread out over a time determined by the maximum off-axis angle and the system length, and in a distance of one kilometre one pulse would merge with the next.

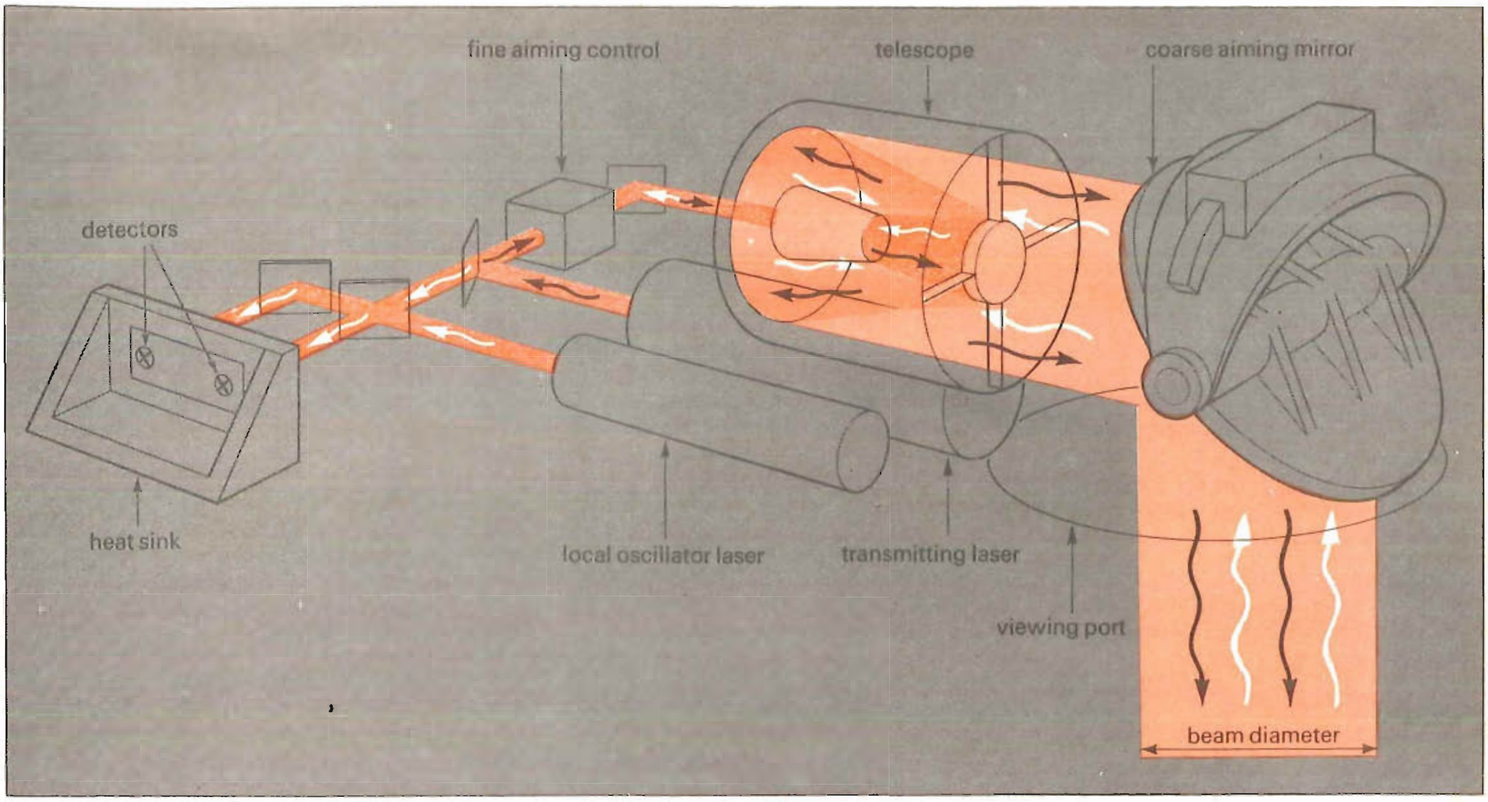
Another way of guiding the beam in a pipe and preventing it from diffracting too widely is periodically to refocus it with weakly converging lenses. Such a system can have an enormous bandwidth because multipath distortion does not occur and dispersion in the lenses is negligible. Loss due to reflection at the lens surfaces may be minimised by anti-reflection coatings. Another possibility is to abandon glass lenses and use the focusing effect of a radial temperature gradient in a gas. Gas lenses are remarkably effective and produce extremely low loss, but they must either be separated from the rest of the evacuated system by glass surfaces, which will reflect light, or the whole system must contain the gas and be protected from thermal gradient troubles by installation underground or extensive lagging. The magnitude of the latter problem can be judged from the fact that a temperature difference of only 10^{-3} °C, across a 10 cm collimated beam over a distance of one kilometre in air at atmospheric pressure is sufficient to displace it by its own diameter.

Displacement of the lenses may be automatically corrected by installing sensing devices at each lens position to correct the attitude of the preceding lens through a servo loop. Lens guide systems for trunk communications have been pioneered by the Bell Telephone Laboratories. Their experimental results indicate that attenuation losses can be reduced to as low as 1 dB/km, but installation and maintenance costs of the systems so far conceived will be very high. Nevertheless, the capacity of such a system would also be very large.

FIBRE OPTICAL COMMUNICATIONS offer yet another possibility. At optical frequencies a metal transmission line structure would be very 'lossy' and only transparent dielectric materials such as glass can be considered.

In a waveguide the microwave energy propagates down the inside of a hollow conductor but it is also possible to use a solid dielectric (or metal) rod in which case the energy is guided along the outside as a 'surface wave'. For broad band communications 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. The energy would be carried mainly in the space surrounding the fibre, and the transmission loss would be small. But for visible light the wavelength is about one micrometre and a fibre of this diameter would be fragile and difficult to support.

By cladding the fibre with a material of lower dielectric constant, such as a different type of glass, a number of advantages are obtained (see "Fibre



SPACE COMMUNICATIONS system proposed for use between two NASA synchronous satellites uses two lasers and a single beam system for transmission and reception. The beam from the transmitter laser is modulated and expanded in a Cassegrain telescope to reduce the diffraction spread of the beam on its journey of many thousands of kilometres through space. The received beam (white arrows) is condensed by the telescope and mixed at the detector with the local oscillator beam

optics", *Science Journal,* September 1965). The combined structure is mechanically more robust and, as long as its cladding is sufficiently thick (say, 50 times the light wavelength) for the wave field to be extremely small at its outer surface, there is no difficulty in supporting it. Furthermore, if the dielectric constant of the cladding is only slightly less than that of the core, single mode operation can be achieved with a core diameter of perhaps four or five wavelengths and the manufacturing problem is somewhat eased. However, the energy is then transmitted mainly in the cladding which absorbs energy and attenuates the signals. Unfortunately, the loss coefficient of the best available glass is equivalent to attenuation of several hundred dB/km and a practical fibre optical communication system calls for a glass with at least an order of magnitude improvement.

The bandwidth of a single mode glass fibre transmission link is governed by mode dispersion, bulk glass dispersion and photon noise. In ensuring single mode operation the effect of several modes travelling at different speeds is eliminated, but there is still the problem that the velocity of propagation of the remaining mode changes with frequency. As a modulated carrier covers a range of frequencies not all components of the signal emerge from the fibre at the same time. If the fibre is too long the components of a pulse become separated in time and the pulse is smeared out. Even in bulk glass the speed depends on the refractive index which, in turn, is a function of wavelength. The magnitude of both these dispersive effects depends upon the refractive indices of the materials used for the fibre core and cladding. On average, the bandwidth is limited to about 5000 MHz over a distance of 10 km.

Photon noise affects the minimum signal that may be successfully decoded at a receiver or repeater station. If the receiver can detect a pulse having ten times the amplitude of the noise then the minimum signal power required at the far end of the fibre is proportional to ten times the frequency multiplied by the bandwidth. The maximum power that can be fed into the fibre is limited by optical breakdown of the glass. Taking a breakdown strength of 500 kW/mm^2 and a core diameter of five micrometres, the signal limit is 10 W. If the fibre attenuation is 10 dB/km and the length 10 km the bandwidth is again limited to about 5000 MHz. Greater attentuation would reduce the bandwidth or require more frequent repeaters. It therefore seems unlikely that in practice the pulse rate will exceed 1000 MHz.

A glass fibre would not need to be optically straight; indeed, such fibres can be wound around one's finger without suffering damage. But they are more fragile than copper wires and must be protected by a suitable covering as are today's telephone lines and co-axial cables. Even though the bandwidth of each fibre may be limited to 1000 MHz, up to 10,000 of them could be bundled into a 10 mm diameter cable giving an enormous channel capacity even with the redundancy needed to allow for breakages. A coating of optically absorbing material should suffice to prevent signals coupling from one fibre to another. A considerable length of 100 micrometre fibre can be drawn (in principle at least!) from a small piece of glass so that, even if glass of the required purity is expensive, the fibre should be reasonably cheap.

The main cost is likely to arise from the light sources, modulators and detectors. For various reasons pulse modulation will almost certainly be required and, while the small size of a semiconductor laser is attractive, its wideband output is not ideal for a single mode, high rate fibre. Suitable diodes capable of operating at room temperature would also need to be developed. Another possibility might be to use a mode locked, solid state laser in which a reasonably high efficiency and long life would be provided by pumping with semiconductor lasers. Up to 20 of the latter could be used, running continuously, so that their wideband output would be no disadvantage. Various wavelengths are available from solid state lasers, and second harmonics can also be generated at up to 100 per cent efficiency. We are investigating a source of this kind at the University of Southampton. By using an external mirror it might be possible to mode lock a semiconductor laser, but the pulse rate would be much too high. Ideally a wavelength should be chosen at which the glass attenuation is a minimum.

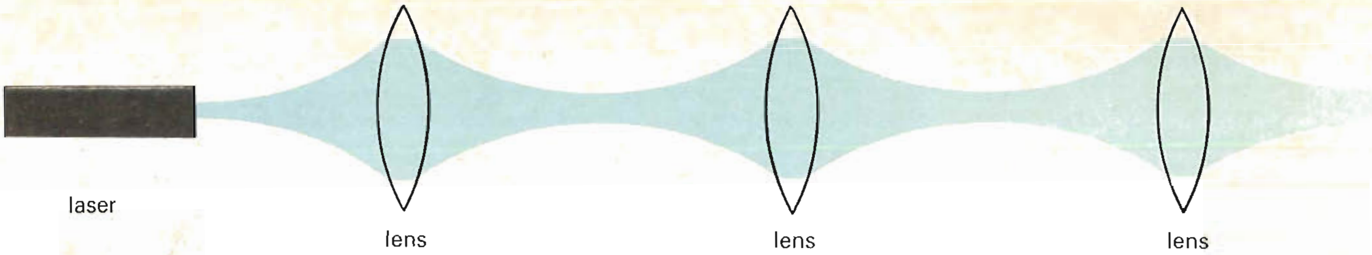
TO SUM UP, it is clear that present efforts in the field of optical communications lie in three distinct directions. In outer space, where diffraction and aiming with the required degree of accuracy are the only limiting factors, communication over vast distances is theoretically possible. Some estimates show that, even with existing techniques, signals could be sent over a distance of ten light years—but, apart from the inconvenient delay in getting a reply, the need is not yet an urgent one! On Earth the beam guiding system offers a huge bandwidth although costs will certainly not be low. An ideal application would be transcontinental trunk routes where the capacity can be fully exploited.

The fibre optical guide (which we might abbreviate to FOG!) promises a more modest bandwidth which still considerably exceeds anything available today. FOGs can be operated in parallel. The main problem which remains to be solved is that of developing fibres which have a suitably low loss at a wavelength where a convenient source is available. Consideration will also have to be given to a host of other topics such as repairing breaks in multi-core cables and the efficient injection of the modulated beam into a core of a few micrometres diameter. For example, how does one find such a small core when it differs from its surroundings only by a refractive index change of a few per cent?

FOG might be ideally suited to the UK with its many highly interconnected urban centres. It is more modest in cost, techniques and bandwidth than the beam waveguide and therefore is more easily realizable. The possibility of using glass fibres originated with Dr K. C. Kao of Standard Telecommunications Laboratories where investigations are continuing. The problem has also been taken up by the Post Office Research Station, while the Signals Research and Development Establishment and the University of Southampton are collaborating in a parallel development of a thick core, low bandwidth system. A fundamental investigation of low loss glasses is being undertaken at the Department of Glass Technology of the University of Sheffield.

The need for greatly increased communications facilities is quite obvious. How often are we prevented from making a long distance telephone call because "all lines are engaged"? Video telephones, which are being introduced in Japan and the US, require 1000 times the frequency space of conventional telephones. The branches of the main banks are connected to a central computer to enable a rapid and up to date check to be kept of all accounts. This service is so valuable that perhaps in the future all offices and factories of most firms may soon be interconnected in the same way thus requiring a considerable increase in the amount of data transmission throughout the country. Already attempts are being made to provide computerized references for research workers, and the logical extension of this would be to commit all academic journals and books to some form of computer store. It would then be possible to do away with most school, college, industrial and public libraries in favour of video links to a relatively few regional centres. The advantages would be considerable.

If the FOG can be successfully developed there are many fascinating possibilities—particularly if it can be made comparable in cost to an ordinary telephone cable, since the meagre bandwidth available in our homes could then be considerably increased. The private citizen could have available a communication capacity exceeding that of any commercial or public enterprise today. He could have direct access to a national or regional data processing or computing centre such as that being set up by the UK Post Office. The computerized libraries of the future could be dialled and consulted from our armchairs and we could receive TV programmes at times convenient to us rather than to the programme directors. A rather less attractive possiblity is that of attending conferences without moving from one's desk; and, as J. R. Pierce of Bell Labs has suggested, our children may not have to commute to work but instead will communicate to work. But these and many other possibilities all depend on our ability to understand, design and produce new and better materials to make communicating with light a practical reality.



PERIODIC REFOCUSSING of a diffracted laser beam is necessary in a tubular guide structure to prevent loss or distortion of signal by reflection from the walls. Here the diffraction is greatly exaggerated; in a practical scheme the weak converging lenses might be 100 metres apart. Glass lenses would reflect part of the signal while gas lenses would either need glass walls or call for a gas filled system. A satisfactory lens technique has yet to be found

FURTHER READING

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