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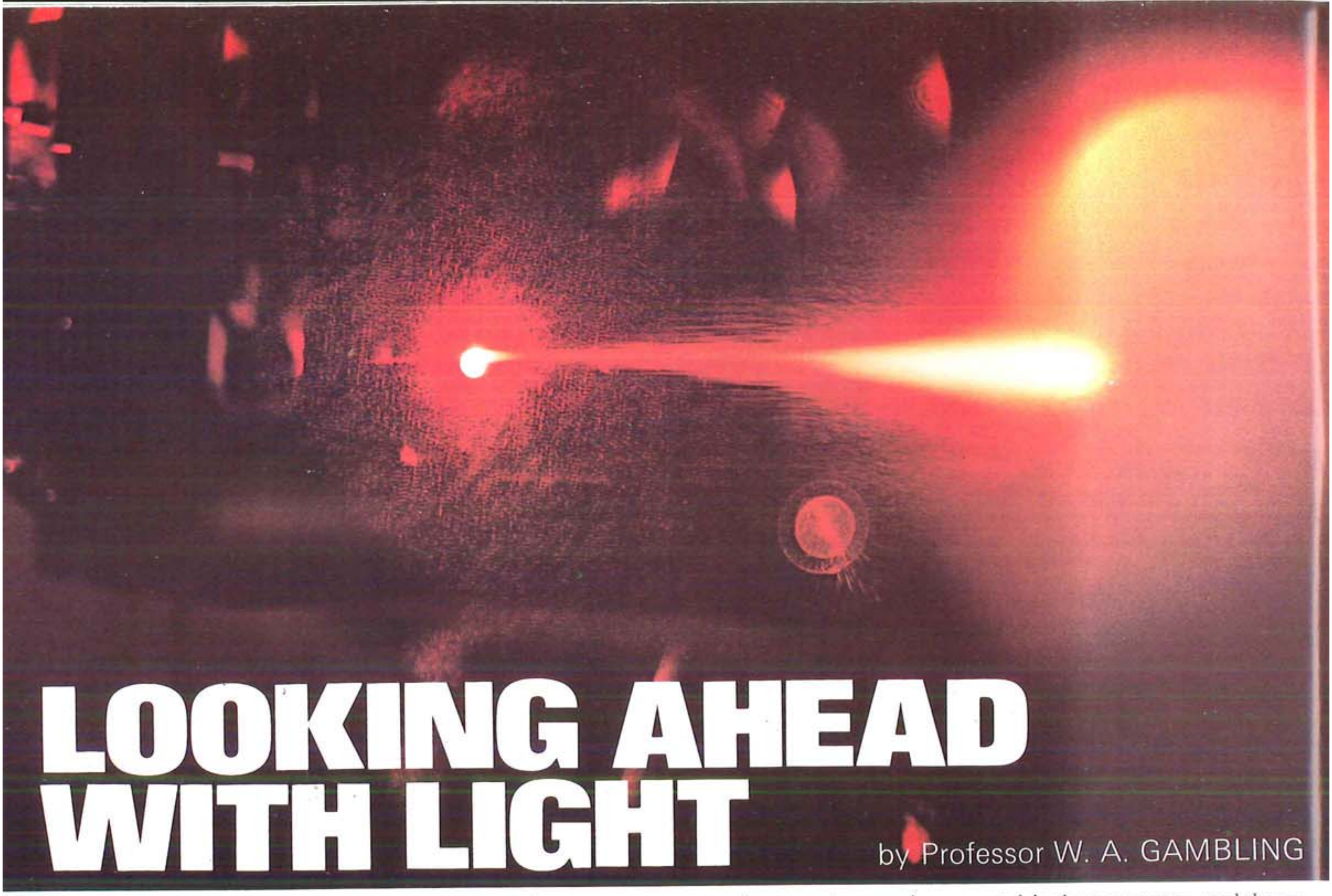

LOOKING AHEAD WITH LIGHT

by Professor W. A. GAMBLING

A beam of light, invisible to the human eye and carrying information at a rate that none of today's methods can approach, could be the communication system of tomorrow. A British expert describes the first steps towards communicating with light

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.

The problem of handling this growing flood of information is taxing the ability and resources of communications engineers the world over. Totally new and very powerful methods of transmitting information are thus being investigated in the hope that a solution will be found before the situation becomes desperate.

Some of the proposed new communications systems involve beams of light. They send light along waveguides, probably optical fibres of special glasses, or along carefully laid pipes either on or under the ground. In most cases the light will have a wavelength in the infra-red 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.

This revolution is coming about through developments in lasers and in the techniques of optical electronics. Because of their high operating frequencies, lasers are potentially communications sources of enormous bandwidth. In addition they can be made to produce an output consisting of a train of pulses. The width of the pulses depends on the laser material. Thus the helium/neon laser can produce 300ps pulses while ruby, neodymium in YAG and glass, and dye lasers can give respectively, 20ps, 5ps, 1ps and <1ps pulses. A completely new time scale has therefore been ushered in due to the fact that optical interaction processes are inherently much faster than electronic.

A 1ps pulse represents a wave train only 0·3mm in length and can be used for high precision radar or high-bit-rate information transmission. Apart from enabling the distance of the moon from the earth to be measured to a precision of a few centimetres, short optical pulses are not yet being widely used but may eventually provide wide bandwidth communication systems.

There are problems of course, and the path of technological progress is not devoid of pitfalls. The first hazard is the fundamental one that at frequencies $>10^{13}$Hz photon noise predominates and increases linearly with frequency and bandwidth. For example, at 10GHz a power level of 1mW corresponds to a flux of 10^{10} photons/cycle whereas a similar power at optical frequencies represents only 10 photons/cycle so that the granular nature of the signal is much more evident. This is one of the penalties to be paid for an increased bandwidth. A second hazard which it transpires can be circumvented is that at present modulators with bandwidths of even a few gigahertz are very difficult to achieve. However since some form of pulse, rather than analogue, modulation will be used, then by forming the pulses by mode locking a laser, a suitable multiplexing arrangement enables relatively slow (100ps) modulators to be used.

A third difficulty lies in finding a suitable transmission channel. Because of turbulence and temperature gradients in the atmosphere point-to-point communication in unshielded systems at optical frequencies is not feasible over any appreciable distance even in clear weather. For example, regions of differing refractive index in a propagating beam can cause it to be deflected or to break up. Since the atmosphere is seldom quiet, the variations occur randomly and quite rapidly.

The magnitude of the problem can be judged from the fact that a collimated beam of 5cm diameter at visible wavelengths is deflected by a transverse temperature gradient of only a few thousandths of a degree, over a distance of 1·5km, through a distance equal to its own diameter.

Light piping

Outside the earth's atmosphere, diffraction is the limiting loss mechanism but for earth

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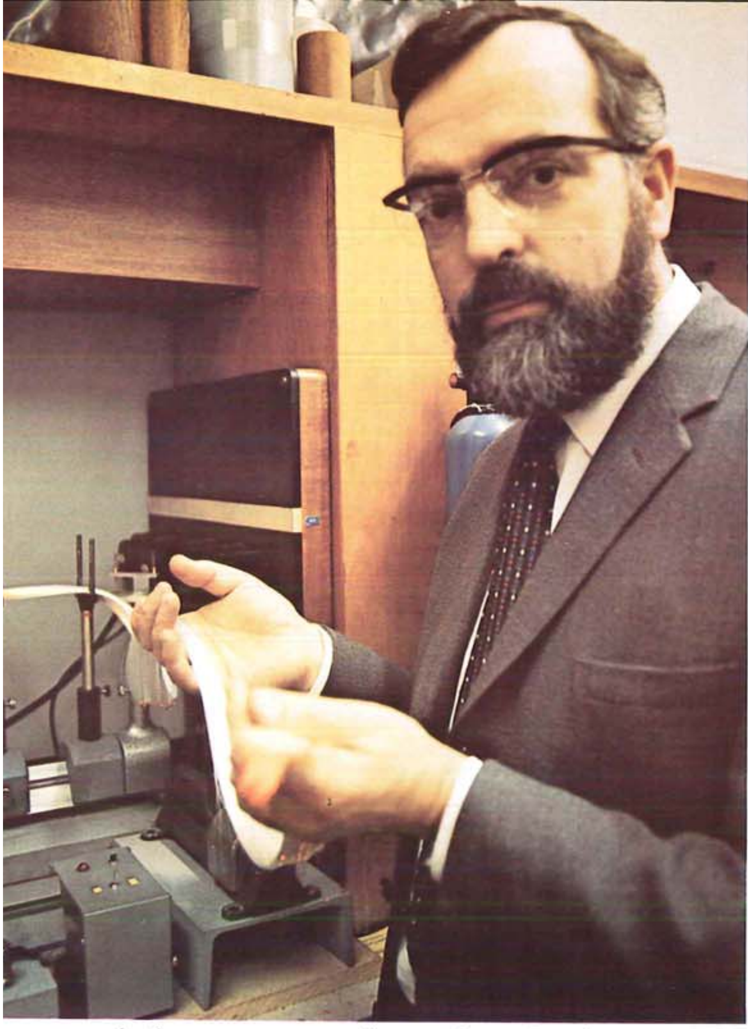
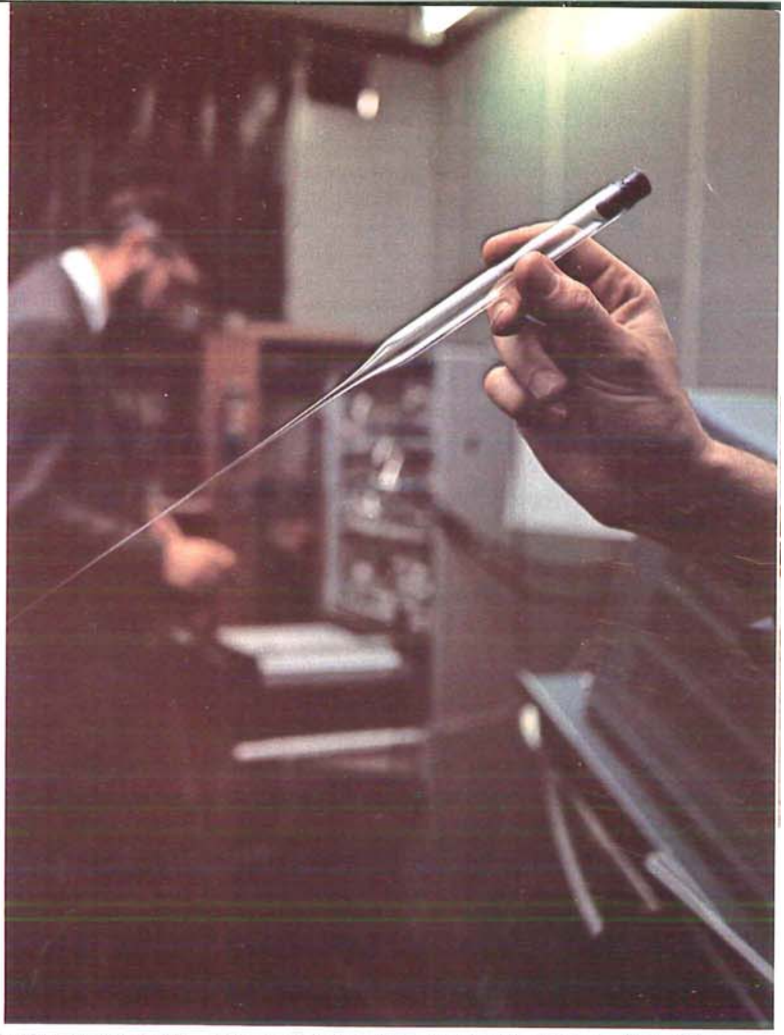




Opposite: *Laser beams like this one may bring about a revolution in communication systems.* Above left: *Although as fine as a human hair, glass fibres can be handled without suffering damage.* Above right: *Drawing a fibre from glass tubing. A considerable length can be drawn from a small piece of glass*

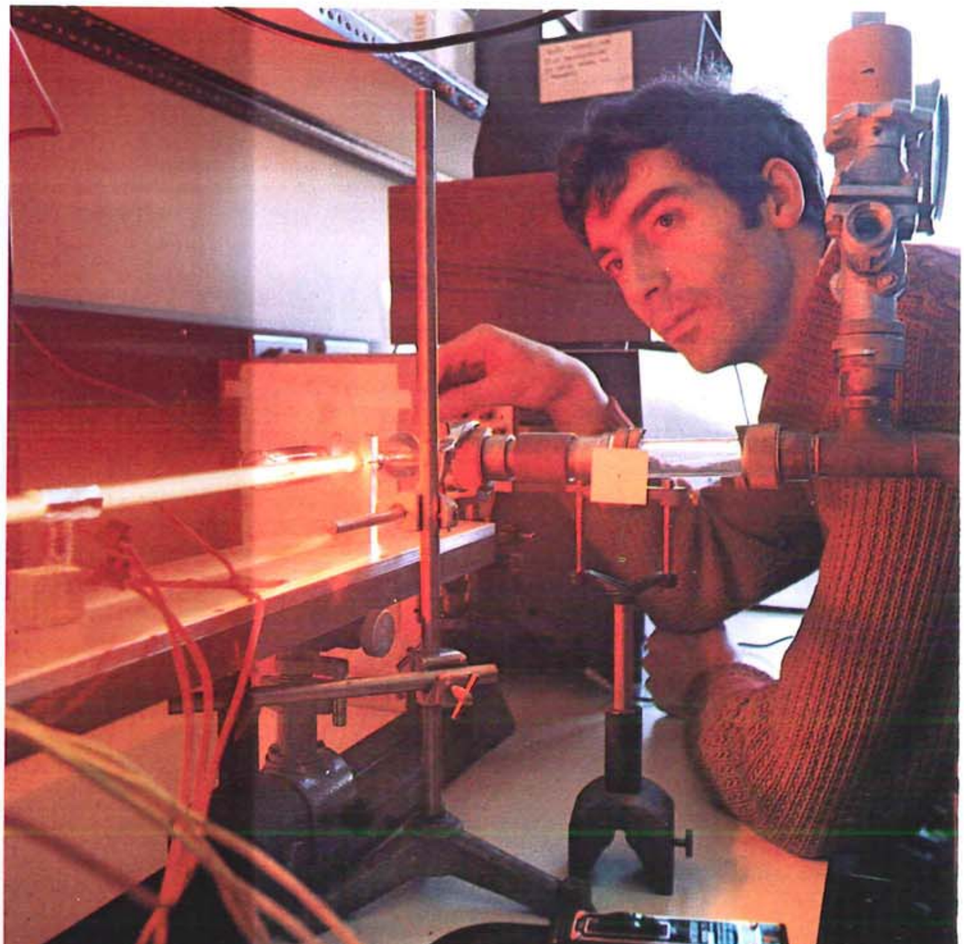
communications some means of protecting the laser beam from atmospheric fluctuations is desirable and this may be accomplished simply by enclosing the beam in a pipe. As thermal gradients can exist in any gas in the pipe, evacuation of the pipe is to be preferred. As the beam spreads by gradual diffraction 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 500MHz, 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 spreading too much is to refocus it periodically with weakly converging lenses. Such a system can have an enormous bandwidth because multipath distortion does not then occur and dispersion in the lenses is negligible. Loss due to reflection at the lens surfaces may be minimised by anti-reflection coatings.

Displacement of the pipe due to earth movements 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

One of the Southampton group experiments with a gas laser



Laboratories and experimental results indicate that attenuation losses can be reduced to as low as 1dB/km. 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. Installation and maintenance costs of the systems so far conceived will be very high but nevertheless the capacity of such a system would also be very large.

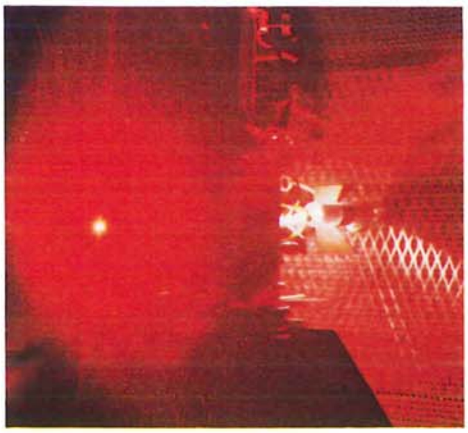
Glass fibre waveguides

Fibre optical communications offer yet another possibility. At optical frequencies any kind of metal transmission line structure would be very 'lossy' and only transparent dielectric materials such as glass can be considered.

In a conventional 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 communication it is desirable 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 then be carried mainly in the space surrounding the fibre and the transmission loss would be small. The same principle applies with optical guided waves but for visible light the wavelength is about one micrometre and a fibre of this diameter would be fragile, almost invisible and difficult to support without causing reflections of the transmitted signal.

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



Top: Professor Gambling demonstrates the transmission of light through the fibres
Centre: An experimental laser showing the straight beam of light
Bottom: Feeding the fibre into a protective tube

Two major factors which are of prime importance in the design of optical fibres for signal transmission, and indeed in any communications channel, are the transmission loss and the bandwidth. As light propagates along a fibre some of it is lost by absorption in the glass and some is scattered out by even very tiny inhomogeneities.

So that the signal is not lost completely it has to be amplified when the power has fallen to a low value and such amplification is carried out repeatedly (cf. the term 'repeater') and at suitable intervals along the fibre. In order to keep the total repeater cost down to an economic value, the transmission loss must be as low as possible and certainly less than 20dB/km (i.e. after a distance of 1km the signal power falls to 1 per cent of its initial value).

Single-mode fibres of this quality, and made of doped silica, have now been produced by the Corning Glass Company in the USA. For various reasons the transmission is best in a fibre at wavelengths between 0·6 and 1·2μm, which is very fortunate as several potentially useful lasers operate within this range.

The components of a modulated carrier cover a spread of frequencies and normally all travel at different velocities—an effect called dispersion—so that over a long length of fibre the components become separated in time and distortion occurs. In a single-mode fibre, the limiting dispersion is that caused by the bulk glass and the particular surface wave (HE_{11}) mode and corresponds to pulse rates, or bandwidths of several gigahertz over several kilometres. However, if a semiconductor laser source is used the spread in its output would limit the overall bandwidth to about 1GHz over 1km or perhaps even less. There are problems with single-mode fibres which arise from the very small diameter (~1μm) of the core. Namely those of launching efficiently from semiconductor lasers and jointing (especially at night in a trench in the rain!) between adjacent sections of fibre. To get two fibre ends flat and aligned to an accuracy of better than 0·1μm is no mean problem.

The carrier source likely to be used with optical fibre transmission lines is the gallium arsenide semiconductor laser operating at 0·9μm. The table shows the values of attenuation so far achieved at this wavelength.

Attenuation dB/km	Type of fibre	Reference
7·0	Doped silica	R. B. Maurer, D.B. Keck Corning Glass Co., U.S.A.
9·3	Liquid-filled glass	D. N. Payne, W.A. Gambling University of Southampton U.K.
17·7	Liquid-filled silica	G. J. Ogilvie, CSIRO Australia
32	Liquid-filled silica	J. Stone, Bell Telephone Labs., U.S.A.

Multimode fibres

An alternative approach was first undertaken in Britain as a joint project between the Signals Research and Development Establishment and the Department of Electronics at the University of Southampton, to develop low-loss multimode fibres. These have core diameters in the region 20 to 100μm and are easier to manufacture than single-mode fibres. However, because of the large core diameter they can support 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 indices 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 length of 1km and a typical fibre, is 0·5μs. This is equivalent roughly to a bandwidth of 1MHz. However, careful measurements made at the University of Southampton have shown that if a narrow beam is properly launched into a well-made glass-core fibre a pulse spreading of as little as 0·3ns occurs over 50m with core diameters in the range 50–100μm.

If such low dispersion can be maintained for greater lengths, a bandwidth exceeding 100MHz over 1km 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.

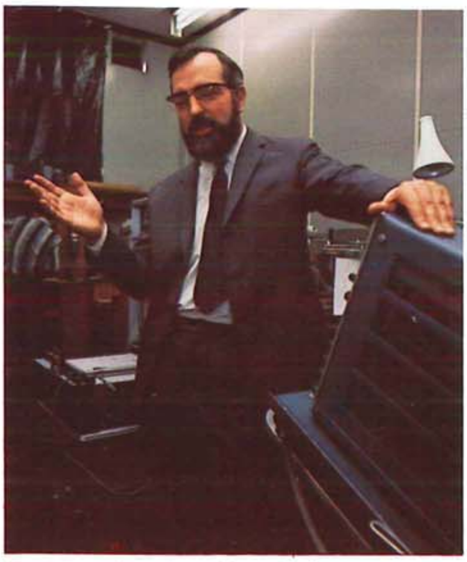
An additional recent development has been the use of silica-fibre tubes filled with tetrachloroethylene to give attenuations of less than 20dB/km. Liquid-core fibres were first reported independently by G. J. Ogilvie of CSIRO, Australia, and Dr. J. Stone at Bell Telephone Laboratories. Using specially-selected silica and highly-purified and filtered tetrachloroethylene, Ogilvie obtained a transmission loss of 17·5dB/km (now 7·5dB/km at 1·09μm) and Stone reported 13·5dB/km at a wavelength of 1·06μm, although there is an absorption peak of more than 80dB/km at 0·96μm.

An even more recent result, again by the Southampton University team, is the production of liquid-core fibres with a loss of 5·8dB/km. A particular virtue of these fibres is that they are made from inexpensive, commercially available materials. The fibre is drawn from ordinary MEI glass tubing, which has a bulk loss of approaching 10^4dB/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 5·8dB/km is quite remarkable.

While there is a small peak near 0·96μm, the absorption at this point is still less (9dB/km) than the lowest attenuation reported by Bell Labs. Indeed the loss is less than 20dB/km over the range 0·72–1·2μm. These fibres can therefore be used with both gallium-arsenide injection lasers (fibre loss: 9dB/km) and also neodymium-based lasers (fibre-loss: 5·8dB/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. has made a multimode version of its silica-based fibre with an attenuation which has a minimum value of 4dB/km and is below 10dB/km over a wide range of wavelengths. Secondly, at Southampton we have measured pulse dispersions corresponding to bandwidths of nearly 1GHz/km in our liquid-core glass fibres.

Because of the above developments, there is now 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. Glass-core fibres have already been produced with losses below 60dB/km and there is no reason in principle why, with glass made from purer raw materials, the loss should not be reduced to well below 20dB/km.



Top: Experimenting with a pulse laser
Centre: Measuring the transmission loss
Bottom: Professor Gambling, leader of the Southampton team, in his laboratory

A glass fibre would not need to be optically straight; indeed, such fibres can be wound round 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 coaxial cables. Even though the bandwidth of each fibre may be limited to 1GHz, up to 10,000 of them could be bundled into a 10mm diameter cable giving an enormous channel capacity even with the redundancy needed to allow for breakages.

A considerable length of 100μm fibre can be drawn (in principle at least) from a small piece of glass, so even if glass of the required purity is expensive, the fibre should be reasonably cheap. Already a live BBC colour television programme in the series "Tomorrow's World" has been transmitted along over 1km of one of the liquid-core fibres produced in my Department and if the full bandwidth can be utilized a single fibre should be capable of carrying 200 television programmes or 100,000 telephone circuits.

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.

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'? And video telephones if they become a commercial proposition require 1000 times the frequency space of conventional telephones. The branches of the main UK 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.

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.

If the fibre-optical guide (which we might abbreviate to 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 would 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 consulted from our armchairs and we could receive television programmes at times convenient to us rather than to the programme directors. A rather less attractive possibility is that of attending conferences, and perhaps even universities, without moving from home 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.