The advent of the laser has opened up many fields of technology. The availability of a powerful and coherent source of controlled light gives the designer a versatile tool in applications ranging from the welding of retinas to high-bit-rate information transmission. In this article, the author reviews the present position and possible future uses of the laser

Industrial applications of lasers

by Prof. W. A. Gambling, D.Sc., Ph.D., F.R.S.A., C.Eng., F.I.E.R.E. F.I.E.E.

ON A SPRING day in 1951, so legend has it, a physicist was sitting on a park bench in Washington, DC, carrying out a process of mental 'doodling', and as a result a new idea evolved to generate and amplify high-frequency electromagnetic waves. At the time, C. H. Townes was concerned with research into magnetic-resonance spectroscopy whereby radiation of a frequency corresponding to the energy difference between two energy levels can be absorbed by an atomic system. The effect, i.e. the absorption, is most noticeable when the number of atoms in the lower energy state greatly exceeds the number of those in the upper energy state. Townes came to what, in the blinding light of hindsight, is the simple and obvious conclusion that if the number of atoms in the upper state could be made to predominate over those in the lower then the absorption would change into amplification. The atomic system in which he thought it might be possible to achieve and maintain this 'population inversion', as it is called, was the ammonia molecule, and his predictions were brilliantly confirmed when, with coworkers, he made the ammonia maser. Thus appeared the first known device depending for its operation on the stimulated emission of radiation, a principle which has since been applied over a wider frequency range than any other. The ammonia and other gas masers proved to be very stable microwave sources, while later developments produced solid-state masers which gave rise to the most sensitive and lowest-noise microwave amplifiers ever known.

Ruby revival

Attention was then turned to the possibility of extending the technique by some five orders of magnitude to optical frequencies—the basic physics was thought to be understood, and all (!) that was required was to find a suitable material, pumping mechanism and experimental configuration. Artificial ruby seemed a likely candidate until theoretical work at Bell Telephone Laboratories indicated that successful operation would not be achieved, and attention shifted to gas media. Great was the surprise, therefore, when Maiman of the Hughes Aircraft Co. announced in 1960 that he had achieved laser operation in ruby, and great was Maiman's surprise when the manuscript which he prepared announcing his remarkable result was rejected by *Physical Review Letters*. A historic 'scoop' of scientific journalism was achieved by the journals *Nature* and *British Communications & Electronics*, which carried the first announcement in the established literature. A few months later in the same year workers at the Bell Telephone Laboratories operated the first helium–neon laser and incidentally performed the first optical-communication experiment with lasers. One of the men involved spoke into one of the mirrors and another, using headphones as part of the detector system, heard him via the output beam.

British expertise

Many thousands of papers and lasing transitions have appeared since then and in addition to gas and solid-state lasers we have liquid, dye and semiconductor devices operating at fixed wavelengths, from 0·7mm to the ultraviolet region of the spectrum. The number of wavelengths at which laser operation has been achieved runs into many thousands, but only a relatively small number of lasers are manufactured on any scale, and some of the main ones, together with their properties, are given in Table 1. Applications are, to some extent, limited by the comparatively few wavelengths easily available, and the thought of having to develop a tailor-made device is a large deterrent, so that the appearance in the past year or so of a number of tunable laser sources is of considerable significance. It is gratifying, therefore, that a considerable degree of expertise in this field exists in the United Kingdom. Thus one of the leading centres for research and especially mode locking in tunable dye lasers for the visible region of the spectrum is at Queen's University, Belfast, while the spin-flip laser, which can be tuned over a wide range in the infrared region of the spectrum, was developed at the Bell Telephone Laboratories and Heriot-Watt University.

More recently the University of Southampton has announced successful operation of a proustite parametric oscillator which has already produced kilowatts of pulsed power and should eventually be tunable over the wavelength range 1·2–9·5 μm. In addition, a downconvertor, where the outputs from a ruby and a

Table 1. Properties of some typical lasers

gas	helium–neon	0·63 μm	1–100 mW	continuous
	argon	0·49, 0·51 μm	1–50 W	continuous
	carbon dioxide	10·6 μm	100 W–10 kW	continuous
	helium–cadmium	0·442 μm	50 mW	continuous
		0·325 μm	15 mW	continuous
	nitrogen	0·337 μm	10 MW	10 ns
solid	neodymium: glass	1·06 μm	10–100000 MW	10 ns
			1–10000 J	10 ms
	neodymium: YAG	1·06 μm	1 W	continuous
			100 MW at 10 pulse/s	
	plus SHG	0·53 μm	1 W	continuous
	ruby	0·694 μm	100–350 MW	*Q* switched
			1 GW	with amplifier
semiconductor	gallium arsenide	0·84–0·9 μm	10 W	100 ns
dye		0·4–0·7 μm	100 mW	continuous
parametric	lithium niobate	0·68–2·4 μm	5 kW	10 ns

Alec Gambling is a professor of electronics at the University of Southampton, with interests in gaseous electronics, microwaves, quantum electronics and optical communication

tunable dye laser are mixed, again in a proustite crystal, produces outputs at a somewhat lower power level in the range 10–12·5 μm and near 5 μm. Work is also proceeding on a tellurium parametric oscillator, which should be tunable over the range 7–25 μm. Tunable dye lasers are already commercially available, and if development and production of the newer types can be carried through successfully we should see an increased application of laser techniques.

Properties of laser light

The difference between laser or 'coherent' light and incoherent light such as is obtained from ordinary light sources is similar to the difference between electrical noise and a sinusoidal signal. It goes without saying that electronic techniques would be in a very primitive state if the only sources available were noise sources, and yet this was just the case with optical electronics before the laser appeared. Before anything like the same developments can take place at optical frequencies as we have come to take for granted at lower frequencies, we must learn to use the new devices and to develop optical components and systems, and significant progress is being made in this direction.

Light rule

The properties of laser light which make it potentially so useful are simple and obvious. First, it can be collimated to a degree limited only by diffraction, whereby the halfangle of spread θ in a system of aperture D is related to the wavelength λ by $\theta \simeq \lambda/D$. Thus, for a helium–neon laser beam of diameter 3 mm, we have $\theta \simeq 0{\cdot}2$ mrad, and a simple and cheap light pencil can be produced which has already found scores of uses in many diverse fields. For example, it is now standard equipment on tunnel-boring machines which can be programmed to keep themselves aligned on the beam, thus obviating tedious and time-consuming surveying techniques. It is used by the Boeing Aircraft Co. to line up the jig for the wing structure in the manufacture of the Jumbo jet with the result that a task which formerly took 12 h can now be done in 20 min. Somewhat unexpectedly a large volume of sales of helium–neon lasers goes to night clubs and discotheques where the bright red beam is shone over walls and ceiling in synchronism with the music to produce the appropriate psychedelic effect! The application of this simple and cheap laser has been unspectacular but widespread.

Focusing

As well as being collimated, a coherent beam can be focused by a lens of focal length f to a spot of diameter $d \simeq f\lambda/D$. Thus, if $f = D$, then $d \simeq \lambda$, and power densities can be achieved which are capable of melting and vaporising any known material, and a wide range of welding, drilling and machining operations are possible. Obviously, common metals are more easily and cheaply worked by conventional techniques, but where these fail, such as with refractory or

'The difference between laser light . . . and ordinary light sources is similar to the difference between electrical noise and a sinusoidal signal'

brittle materials, or where precision, purity and minimum effect on surrounding areas are of prime importance, laser machining offers a potential solution. In fact some of the first applications of lasers were, on the one hand, to the drilling of diamond dies for wire drawing resulting in a great saving in time and hence cost, and on the other hand to welding of detached retinas in eye surgery with considerable lessening of discomfort to the patient and improvement in accuracy.

Photocoagulation of the retina using a Siemens 1in ruby laser and specially developed equipment

With the greatly increasing complexity of microcircuits and the need for more complex designs with closer tolerances, the speed and accuracy of laser machining are becoming more widely appreciated. This facility can be used either in direct machining of the microcircuit itself or in the automatic production of primary patterns for the masks used in their preparation. Thus at Bell Telephone Laboratories, a scanning-laser-beam technique enables complex masks to be cut in 10 min that would require four days by earlier methods. Computer control of the process provides the required flexibility and speed of operation. Direct machining of thin- and thick-film circuits will also become more commercially attractive with increasing circuit complexity.

Interference

Another important property of coherent light is the ability to produce stable interference patterns which can be used in several ways. If a laser beam is split into two components which are reflected from different mirrors and recombined, the position of the peaks of the resulting pattern can be noted on a detector. Movement of one of the mirrors by a distance of half a wavelength produces a pulse in the output from the detector and a simple pulse counter gives the displacement of the mirror, and hence of the object on which it is mounted, to an accuracy of within 0·3 μm with a helium–neon laser. In fact a commercial equipment is available which has a resolution of 10 nm, and an accuracy within 5 parts in 10^7 and measures distances of from 0 to 60 m. It is sufficiently rugged to be used under machine-shop conditions. Systems of this kind are used in calibration of numerically controlled machine tools and co-ordinate-measuring machines and tables for such uses as precision control of microcircuit masks and substrates. Accurate long-term measurements of the movement of land masses for research and for earthquake prediction are also being made.

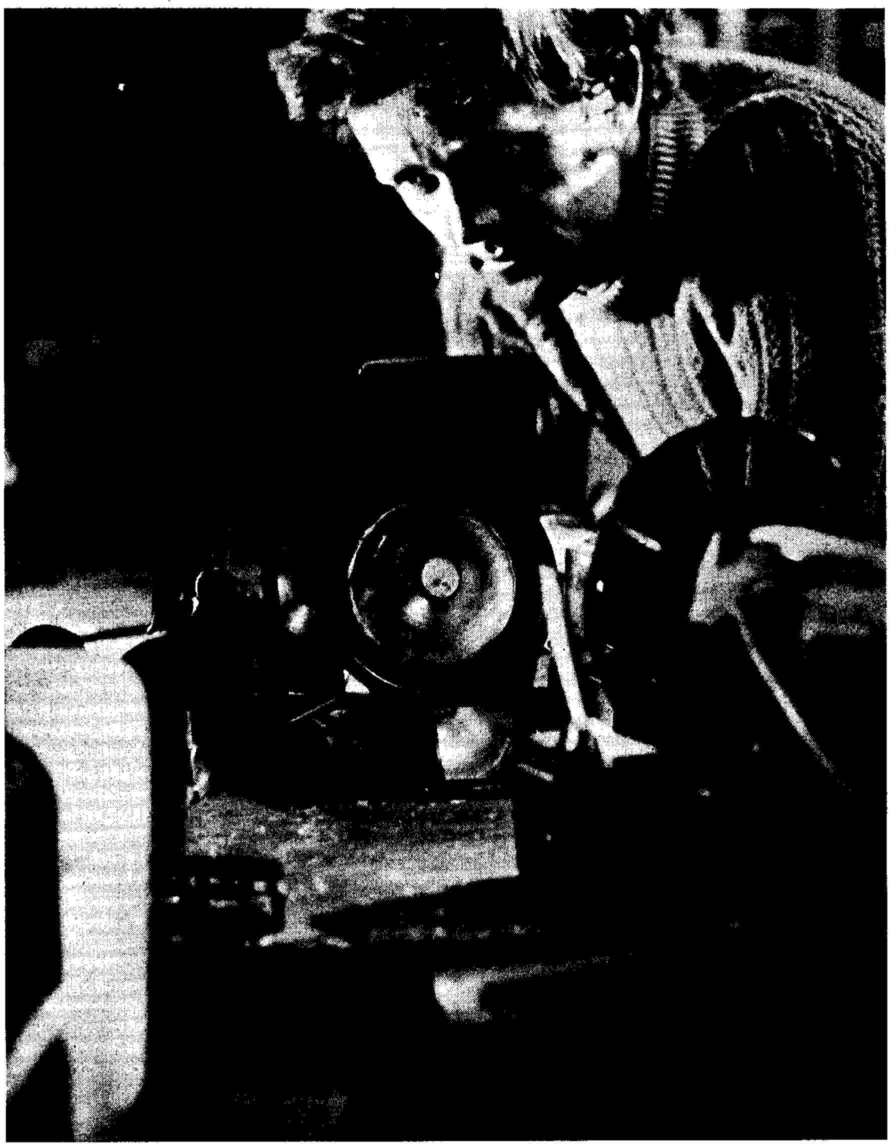
Another consequence of interference has given rise to holography, and while the ability to produce truly 3-dimensional images has not yet been widely used, the technique can record deflections of stationary or high-speed surfaces with about 1 μm resolution. Considerable effort is being directed, at the present time, to the construction of holographic stores for computers. Because a laser beam can be focused to a spot of about 1 μm diameter, one can envisage the recording of information in the form of ones and zeros as spots and lack of spots on a photographic plate. Unfortunately, this type of store would be severely affected by dust, scratches, shrinkage etc. On the other hand, in holographic recording the information is spread in the form of an interference pattern over the whole of the photographic plate and is thus almost immune to imperfections.

A hologram of a few square millimetres area can store about 10^4 bits of information, and thus an array of 100 × 100 such holograms can retain 10^8 bits. Each hologram, when addressed by a laser beam, can be so oriented as to display the image of its spot pattern on a photodiode array. Integrated-circuit processing of the photodiodes and high-speed deflection of the laser beam result in an access time of about 1 μs, and the cost of this random-access semipermanent page store is expected to be less than 0·01 p/bit. Other storage media are also under study in the hope that an addressable memory can be achieved, but it seems likely that a megabit, microsecond store of this type will provide an acceptable compromise between fast but expensive magnetic or semiconductor stores and cheap but slow tape stores.

The coherence of laser light can also provide spatial filtering techniques which in turn can, in principle, be applied to pattern recognition. However, despite the elegance of the method, it has not yet found the range of application initially expected of it, although it has been shown to be capable of rapid automatic inspection of complex integrated-circuit masks.

Communicating with light

A property of lasers which arises rather more indirectly from the coherence of the radiation than those discussed above is the ability to mode lock. Laser resonators are sufficiently large compared with a wavelength that they can be made to oscillate simultaneously in a large number of modes and these modes can be locked together in phase, by various techniques, to produce an output consisting of a train of pulses. The width of the pulses decreases with the number of modes locked, and hence with increase in the linewidth of the laser material. Thus the helium–neon laser can produce 300 ps pulses while ruby, neodymium in YAG and glass, and dye lasers can give, respectively, 20 ps, 5 ps, 1 ps and < 1 ps pulses. A completely new time scale has therefore been ushered in and is due to the fact that optical-interaction processes are inherently much faster than electronic processes. A 1 ps pulse represents a wave train only 0·3 mm 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 high-bandwidth communication systems.



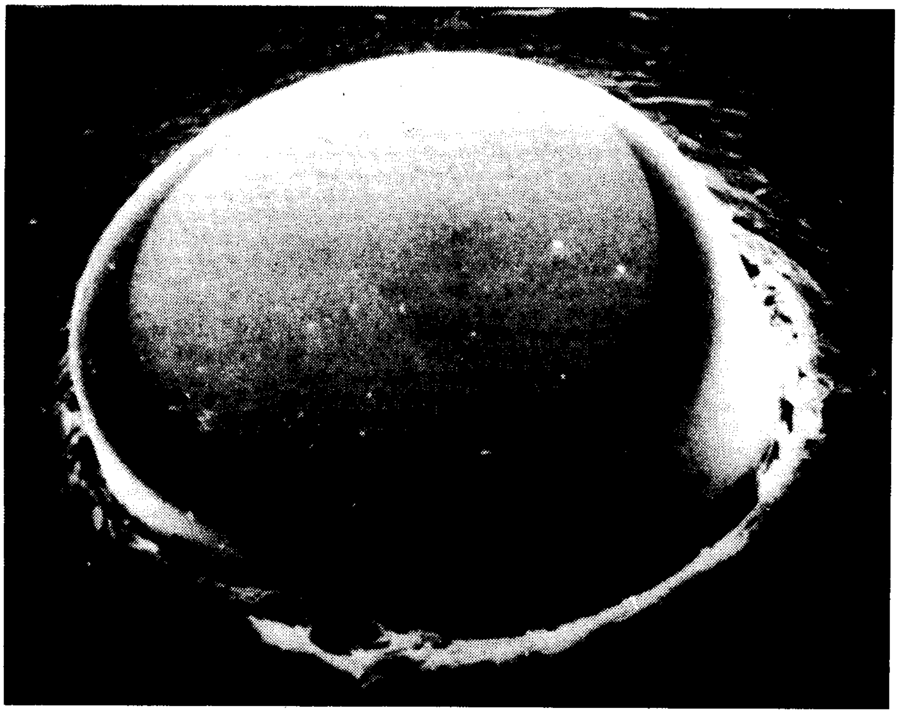
Laser beam being used to check by means of a holographic interference method the accuracy of high-fidelity equipment at H. V. Leak's Bradford research laboratory

'. . . a large volume of sales of helium–neon lasers goes to night clubs and discotheques . . .

Because of their high operating frequencies, lasers are potentially communication sources of enormous bandwidth. There are problems of course, and there is no need to stress that the path of technological progress is not devoid of pitfalls. The first hazard is the fundamental one that, at frequencies above 10^{13} Hz, photon noise predominates and increases linearly with frequency and of course bandwidth. For example, at 10 GHz a power level of 1 mW 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 detoured 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, by forming the pulses by mode locking a laser, a suitable multiplexing arrangement enables relatively slow (100 ps) 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, large regions of differing refractive index in a propagating beam cause it to be deflected and small regions cause a breaking up of the beam. 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 5 cm diameter at visible wavelengths is deflected by a transverse temperature gradient of only a few



Polished end of a multimode glass fibre made at Southampton University; the fibre's central core has a 50μm diameter

thousandths of a degree, over a distance of 1·5km, through a distance equal to its own diameter.

Diffraction difficulties

Outside the Earth's atmosphere, diffraction is the limiting loss mechanism but, for terrestrial applications, the propagating beam must be protected in some way. In one approach, the beam is confined in a hollow pipe, and the diffraction spread of the beam is corrected by a regular sequence of weak-focusing lenses, so that a pipe of reasonable diameter ($\leqslant$10cm) can be used. Reflections with the internal surface must be prevented, as the resulting phase changes cause a large increase in dispersion and reduction in bandwidth. Such a system has a low transmission loss and large bandwidth, but it is expensive and mechanically inflexible. It must either be evacuated or buried underground to prevent unwanted temperature gradients, and slight movements have to be corrected by a complex system controlling the lateral position and attitude of each lens.

Another possibility is to use a transmission-line structure of some kind. At optical frequencies metals are very lossy, and only dielectric materials can be considered. For single-mode propagation, which is essential for broadband communications, a surface wave on a dielectric rod can be used. If the rod diameter is about equal to the wavelength of the carrier, only the HE_{11} mode can propagate, but since at optical wavelengths λ is approximately 1 μm, the rod, or fibre, would be fragile and difficult to support without causing reflections of the electromagnetic field which is carried mainly in the space surrounding the fibre.

By cladding the fibre with a material of lower permittivity a number of advantages are obtained. First, the combined structure is mechanically more robust, and secondly, as long as the cladding is sufficiently thick (say about 50λ) for the surface-wave fields to be extremely small at its outer surface, there is no difficulty in supporting the cladded fibre. Furthermore, if the permittivity of the cladding is only slightly less than that of the core then single-mode operation can be achieved with a core diameter of perhaps four or five wavelengths, so that the manufacturing problem is eased somewhat. However, the surface wave propagates largely in the cladding, and it is essential that a low-loss material is used.

The most convenient material is glass, but the lowest loss achieved in a glass fibre so far is still too high (between 50 and 100dB/km). Quartz fibres having an attenuation of 20dB/km have been made in experimental quantities, so that the problem of making suitable glass fibres seems capable of solution. Work in my own laboratory indicates that even multimode fibres, with core diameters of about 50μm, may be capable of information rates of more than 100Mbit/s over kilometre lengths and 10Gbit/s over 50m, whereas single-mode fibre should be able to carry more than 1Gbit/s over several kilometres. Both types of fibre are flexible and with an overall fibre diameter of less than 100μm several hundred could be carried in a cross-section of less than 1cm^2 providing a much greater overall bandwidth with a high degree of redundancy. Avalanche photodiodes form suitable detectors, but a reliable source has yet to be developed. A c.w. room-temperature diode laser of adequate lifetime would be ideal, and several industrial groups are working on this problem.

Glass-fibre waveguides could find application not only in long-distance communication but also over shorter links where a high data rate is involved or where there is a high level of electrical noise, such as in computer systems or in aircraft. Optical fibres are already capable of helping the electric-power engineer in the measurement of currents in high-voltage transmission lines thus obviating the need for expensive current transformers.

Food for thought

Lasers have not had the widespread spectacular impact which was over-optimistically expected of them in the early 1960s, but they are being increasingly used as individual tools in a wide range of applications. Improvements in performance continue to be achieved, and lasers are even becoming domesticated, following the TEA laser came the edible laser which can be made in the kitchen from ordinary household ingredients—so you can have your laser *and* eat it. However, in addition to the use of the laser as a tool, we are also witnessing the development of optical systems based on laser techniques, in keeping with the inevitable trend in electronics to ever-higher frequencies, speeds and bandwidths. At present, optical systems tend to be large but, in addition to fibre-optical waveguides, appreciable progress has been made in optical integrated-circuit techniques, and already thin-film optical waveguides, modulators and couplers have been produced. With the steady improvement in stability and ruggedness of laser devices, the range of industrial applications will continue to increase, and the miniaturisation of components will introduce the era of optical electronics.

Table 2. Comparison of optical guiding systems

Type of guide	Attenuation dB/km	Bandwidth per channel	Diameter	Flexibility	Cost	Remarks
beam waveguide	1	very large	2–20cm	zero	very high	sensitive to earth movement
reflecting pipe (overmoded)	10–100 (or more, depends on precision)	100MHz	5cm	low	high	performance very dependent on quality of surface
cladded optical fibre (multimode)	20–60	100MHz?	0·1mm	excellent	low	low-loss glass required
cladded optical fibre (single mode)	20–60	more than 1GHz	0·1mm	excellent	low	low-loss glass required