219

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THE LASER AND ITS APPLICATIONS

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Summary

This lecture will seek to separate the science from the popular science fiction image of the laser. Although the laser was invented in 1960 (exactly 25 years ago), laser research is still in the headlines thanks to the Reagan administration's Star Wars Programme. The laser is also the basis of healthy industry. More than 100 companies around the world manufacture lasers, and hundreds more build components, accessories or systems that incorporate lasers. Sales of commercial and military systems reached $4.4 billion last year and sales of manufactured lasers passed $400 million.

Many lasers have found obvious aplications in such areas as medicine, construction and materials yet most of the 1.2 million lasers made last year were low power, comparatively inexpensive types destined to be hidden unnoticed inside boxes. Examples include compact disc audio players, transmitters in optical fibre systems and bar-code readers.

Beginning with the basic properties of atoms and photons the lecture shows how Light Amplification by the Stimulation Emission of Radiation (LASER) can give rise to a highly directional, intense beam of monochromatic coherent light.

The applications discussed are a direct consequence of these special characteristics of laser light. The following areas will be dealt with to a varying degree:

1. Materials processing.
2. Applications in biology and medicine.
3. Optical information processing and recording.
4. Measurement and inspection.
5. Optical communications.
6. Military applications.
7. Applications in physics and chemistry.

In dealing with each heading the relevant materials and properties of light which allow the laser to be thus used will also be discussed.

The case histories of the first two potential mass markets for the laser which appeared in the early seventies: video discs and readers for bar codes will also be included.

Recommended Reading

Revolution in Optics; S. Tolanksy.
Published in Pelican Books 1968.

Colour - Why the World Isn't Grey; Hazel Rossotti.
Penguin Books 1983.

Introduction

In 1960, Theodor H. Maiman demonstrated the world's first laser at the Hughes Research Laboatories in Malibu, California. The experiment was remarkably simple in concept. A synthetic ruby crystal 2cm long and 9mm in diameter was inserted inside a helical flash tube (as used in flash photography) as shown in Figure 1. The ends of the ruby rod had been carefully polished so they were exactly square to the axis and were coated with silver. When a flash was set off in the helical tube a very brief pencil of deep red light emerged from the end of the ruby rod. This was the first successful demonstration of a laser, the first of what has proved to be an impressive series of devices with remarkable and striking properties which have already transformed whole areas of science and technology.

Figure 1

Later we will discuss how the laser works but first let us indicate the features of the laser which have given rise to the intense interest and activity which now surrounds this device.

The laser is a device which produces an intense, highly directional beam of light of a very pure colour. The laser beam also possesses the property of coherence which indicates a certain regularity of the waves in the beam.

Although the description in this form may not seem remarkable, the laser differs from any other light source in all four characteristics mentioned above, and in ways that have quite dramatic impacts.

Consider for example the directional aspect. A typical laser beam may only be 1mm diameter at the point where it leaves the laser and it may spread to only about half a centimeter in diameter at a distance of 30m (see Figure 2). In practically every other light source light emerges in all directions. The familiar filament lamp can be seen from all directions. The projector succeeds in sending out more light in one direction than another but this is achieved by suitable shaping of the filament or by the use of lenses or mirrors. However the source itself - the lamp, or carbon arc -sends its light in all directions. In contrast the intense light from the laser emerges only in the fine pencil-like beam.

Figure 2

Because the laser gives out light into such a narrow beam it appers as an extremely intense source. If we look at a 100-watt lamp filament at a distance of 1ft. the power entering the eye is less than a thousandth of a watt because the light from the lamp streams out more or less uniformly in all directions. If we were to look directly along the beam from a laser (which we never do) then all the radiated power would enter the eye. Thus even a 1 watt laser would appear many thousand times more intense thn the 100 watt lamp (see Figure 3).

Figure 3

Extremely high intensity laser beams may be produced, either as continuous sources or in the form of flashes of very short duration. The most powerful laser flashes will vaporise any known material and have, for example, been used to drill holes in diamond, the hardest known material. An impressive continuous laser is that which uses a tube of carbon dioxide (CO_2), nitrogen and helium. With this device, which produces an invisible, infra-red beam - holes may be drilled though fire bricks - within a matter of seconds.

No less remarkable than the high intensity capability of the laser is that of producing a beam of extemely pure colour. If the light from an ordinary filament lamp is examined in a spectroscope, a continuous colour range is seen from violet through blue, green, orange to red (water vapour acts as a spectroscope for sunlight and so gives rise to the rainbow). The different colours are found to correspond to different wavelengths from about four hundred-thousandths of a centimetre for violet light to seven hundred thousandths for red (Figure 4). Inspection of light from a laser reveals only one single colour i.e. a very definite wavelength, the light is said to be monochromatic. This property provides us with a powerful tool for precision measurement over long distances.

Figure 4

The fourth laser characteristic which distinguishes it from ordinary light sources is coherence. When one looks at the light from an ordinary source the eye receives enormous numbers of waves, coming from myriads of different atoms in the source. Each of the atoms gives out a train of light waves at intervals but a strict state of non co-operation exists amont the atoms, which behave with a rugged individuality. Each sends out its light waves just when the atom thinks fit with no reference to any of its neighbours. In complete contrast the operation of the laser imposes a strict discipline on the behaviour of the atoms which respond by sending out their light waves precisely in step with one another. The chaos is gone and the resultant light wave has a beautiful regularity rising and falling in perfect sequence, for as long as the laser is working (see Figures 5, 6).

In this respect the radiation from the laser shows a close resemblance to the waves which are used in radio communications. Both are coherent. Indeed the laser posesses truly enormous potential for use instead of radio waves in some circumstances.

Figures 5, 6.

How the Laser Works

Atoms can be considered to be miniature solar systems with the nucleus at the centre and electrons orbiting at different distances from the nucleus. The quantum theory predicts that only certain electron orbits are allowed. Each orbit corresponds to a specific energy possessed by the electron and is called an energy level. Normally an atom exists in the "ground state" i.e. all of the electrons of the atom are contained in the lowest available orbits. The atoms is said to be excited if the electrons are shifted to higher energy levels.

In understanding the laser and the applications of laser light we need to know how the transition of an electron from one energy level to another takes place. If we take two energy levels S_1 and S_2 where the energy of S_2 is higher than S_1, then the transition of an electron between these two levels can occur in three ways.

(a) Downwards by the spontaneous emission of light where the energy difference between the two levels is equal to the frequency of the emitted light multiplied by Planck's constant (E_{12} = h x freq) (Figure 7(a)).

(b) Downwards by the stimulated emission of light. This happens when an excited state is kicked into emission by some incident light. The emitted light is the exact replica of the light which stimulated it. (Figure 7(b)).

Figure 7

(c) Upwards by the absorption of light (again E_{12} = h x freq). (Figure 7(c)).

In Figure 8(a) we represent the energy levels of the sodium atom by horizontal lines with the lowest line corresponding to the "ground" state. Possible electron transitions are also indicated while in Figure 8(b) the different light emitted for these different transitions are also indicated.

The basic conditions required for laser action are the same for all types of lasers. Atoms (or, in some cases, molecules) must first be raised to excited energy states from which they subsequently fall to lower energy states, emitting light in the process. It is the special way in which the atoms are stimulated to drop to lower states that characterises lasers.

When an atom is excited, it temporarily occupies a higher energy level. The atom then de-excites either to the lowest energy level available ("ground state") or to some other state below its present level. Although when the de-excitation occurs it is unpredictable, the average time taken by a collection of atoms can be predicted. A laser employs a substance that has an excited state at which a collection of atoms remains for a relatively long time.

When an atom de-excites, it emits light having a certain energy, wavelength, and frequency. The light can be modelled as being a particle (in which case it is called a photon) or as being a wave. If the light emitted by one atom happens to encounter another atom still in the excited state formerly occupied by the first atom, then the passage of the light can force the second atom to de-excite immediately rather than spontaneously at some later time. The light emitted by the second atom then contributes additional light identical to the

Figure 8

light forcing the de-excitation. Because the electric field of the passing light stimulates the emission from the second atom, the de-excitation is called stimulated emission. A light bulb emits light because of spontaneous emission from atoms in its heated filament, whereas a laser emits light because of stimulated emission from its atoms. Both cases are illustrated in Figure 9.

Figure 9

After an atom undergoes stimulated emission, the two light waves (the one forcing the emission and the one resulting from it) are said to be coherent for three reasons. They have (in the terminology of the wave model) the same wavelength, frequency, and energy. They are in step with each other; that is, the peaks of one wave are aligned with the peaks of the other wave. (This situation is depited in Figure 5). They are travelling in the same direction. Because of this coherence, the two light waves add to give a net wave whose intensity is larger than the intensity of the wave whose passage caused the stimulated emission as shown in Figure 10. The goal of a laser is to have such stimulated emission repeated a large number of times. Since all the light waves that are produced are coherent with one another, they add to give a huge wave with a hugh intensity. Lasers are very bright because the de-excitation process results in such an addition of light waves. A light bulb with the same number of emitting atoms is considerably less bright because the waves lack coherence and thus do not add to give a huge wave.

Figure 10

Atoms in a laser can be excited either by absorption of light or by collision. Absorption of light can be accomplished by flooding the laser tube with white light so that the atoms absorb their characteristic wavelengths and are excited to upper energy levels. Eventually the atoms will de-excite by spontaneous emission, and some of the atoms will reach the energy level involved in the laser emission. Pausing there for a relatively long time, they can be stimulated to emit photons. An avalanche of photons can be triggered by a single photon emitted spontaneously by one of these atoms because a photon travelling down the length of the tube will provoke stimulated emission of many other photons that in turn also travel down the tube, stimulating emission of still more photons.

Atoms can also become excited through collision. For example, an electrical discharge can send electrons streaming through a laser tube and crashing into the atoms, thereby exciting them. In some lasers these atoms participate in the stimulated emission; in others they merely transfer their energy to another species of atom that then participates in the stimulated emission. The helium-neon laser is an important example of the latter type. The electrical discharge excites the less massive helium atoms that then excite the more massive neon atoms that, because of their relatively large mass, could not have been efficiently excited directly by the discharge.

Part of the stream of stimulated photons is reflected by mirrors or other reflecting surfaces in the laser. The reflected stream stimulates more photons. The rest of the light, which may be just a tiny fraction of the total light, is allowed to leave, forming the laser beam. The optical arrangement of the laser tube with an external mirror at each end, is called a resonant cavity because the light is built up inside the cavity in much the same way that sound waves can be built up on a guitar string to produce a wave of large amplitude. The overal scheme is depicted in Figure 11.

Figure 11

Laser Applications

Review

Lasers have become important to communications, but not in the way early researchers expected. In the mid-1960's, it was anticipated that laser communications would be carried by evacuated pipes. However, in 1966 Charles Kao and George Hockham of Standard Telecommunications Laboratories suggested that optical fibres might be more suitable. The first fibres with losses low enough for communications were made four years later at the Corning Glass Works. By 1977, the first optical-fibre links were installed in the North American telephone network. This year, worldwide sales of optical-fibre communication equipment will pass the $1 billion mark, although only a small part of that total is lasers.

Semiconductor lasers are almost the ideal light source for high-speed communications through optical fibre over long-distances. These lasers can emit a beam just a few micrometers across - about the same size as the light-carrying cores of new single-mode fibres. Varying the drive current to a semiconductor laser can directly modulate its light output at the high speeds needed - something not possible with other lasers. Long-distance telephone calls in Britain and the United States are increasingly likely to travel part of their route by laser beam. Submarine optical fibres under the Atlantic and Pacific Oceans should be laid by the end of the decade, when they will provide tough competition for transoceanic satellite links.

Lasers have other, quieter uses. For years, high-speed laser printers have churned out vast quantities of junk mail and financial statements. Now smaller, slower versions can be hooked up to personal computers, to combine high resolution with the high speed and ability to "draw" of dot-matrix printers. Elsewhere in the printing industry, lasers expose printing plates, separate colours for full-colour printing, and set type. Metrologists need lasers to measure distance precisely or to count particles.

Other applications are more dramatic and obvious. Sales of systems for medical treatment - particularly eye surgery -are growing more than 30 per cent a year. The increase in sales of systems to shape materials is nearly as rapid. Laser techniques have become standard for such problems as the treatment of diabetic retinopathy (diabetes-induced blindness) and the cutting of titanium sheets. That does not mean that the laser is about to replace the surgical scalpel or general-purpose machine tools, it is just that it can do certain jobs much better.

Military forces have found their own special chores for laser technology. Laser rangefinders and target designators guide weapons to their targets with deadly accuracy. Coded, low-power pulses, from lasers attached to guns, check the accuracy of soldiers' shooting in training exercises. Radars based on infra-red laser beams rather than microwaves are being developed to guide cruise missiles. Pollution detection techniques are also being developed to detect what one observer called "very special pollutants" - nerve gases and other chemical weapons.

Twenty-five years after it was first demonstrated, the laser is far more than a laboratory curiosity. It drills holes in baby bottle nipples and drug capsules, relays telephone calls, prints bank statements and plays music. Yet thanks to highly publicised military programmes, such as the Star Wars effort, the public tends to think of the laser as a deadly weapon from science fiction. It is no wonder that at times many people in the laser industry wish that schemes to build laser weapons would just go away.

Tables I and II summarise the world sales of lasers for last year (1984). Table I lists the different applications and Table II lists the laser types. The main application areas are covered in the following pages.

	1984 Sales (millions $)	Numbers of lasers
Materials processing	83.4	1,700
Agriculture and construction	1.9	23,000
Metrology (includes surveying)	19.5	53,500
Research and development	93.3	20,800
Bar-code reading	4.1	36,500
Printers	28.2	54,800
Other printing equipment	12.0	5,400
Optical disc (audio disc etc.)	10.0	880,000
Diagnostic medical	6.2	30,000
Medical therapy	52.9	7,400
Entertainment and display	2.3	10,000
Technical military	57.3	87,500
Communications	45.0	45,000
Totals	$416.1	1,255,700

Table I World Laser Sales by Application

	1984 sales (millions $)	Numbers sold
Helium-neon (gas)	42.6	212,400
Rare-gas ion	68.6	10,800
Helium-cadmium (gas)	4.9	1,400
Tunable dye (liquid)	23.7	700
Carbon dioxide (gas)	77.9	2,200
Crystalline and glass	118.6	4,500
Semiconductor	66.7	979,300
Excimer (gas)	13.1	400

Table II World Laser Sales by Type

1. Materials Processing

The high intensity available in the focal spot of a high-power (P > 100W) laser beam offers a number of applications in the field of material working and processing, such as welding, cutting, drilling, surface treatment, and alloying. These applications are, at present, the most important industrial applications of lasers. The principal advantages of a laser beam can be summarised as follows: (i) The heating produced by the laser in a given process is usually less than that involved in the corresponding conventional process. It follows that the material distortion is considerably reduced, and also better control can be exercised over the process. (ii) Possibility of working in inaccessible regions. In practice, any region which can be seen (even though it may require some optical system to permit observation) can be processed by a laser. (iii) High velocity of the region being worked and hence high production rates. For instance, welding velocities as high as 10 m/min can be obtained, i.e. about one order of magnitude greater than that obtainable with the best arc welding systems. As another example, the velocity for surface treatment by a laser is, often, greater than that obtainable by induction heating. (iv) Easy automation of the process. For instance, the movement of the laser beam can be achieved by moving the optical focussing system (and this movement can be computer controlled). This also offers the possibility of precision cutting along complicated profiles. (v) Possibilities for producing new metallurgical processes. With the high intensity and easy control of a laser beam, a number of processes which were previously impracticable are now feasible. For instance, due to the high annealing velocity of a laser beam, one can get new types of surface alloys or induce recrystallisation of an amorphous semiconductor surface (laser annealing of semiconductors). (vi) Freedom from wear in the case of a laser tool. This is particularly relevant for laser cutting. Against all these disadvantages, however, one must balance the following disadvantages: (i) high capital and running cost of the laser system; (ii) problems of reliability and reproducibility of the laser beam; (iii) safety problems.

Following this general discussion, we now go on to give a briew description of a few relevant examples. The lasers most widely used for metalworking are either CO_2 lases (with powers which, depending on the type of laser, can vary from ~100W up to ~15kW) or Nd:YAG lasers (with powers usually ranging from 50 to 500W). The CO_2 laser is equally suited to working on metallic or nonmetallic (plastic, ceramic, glass) materials. However, the Nd:YAG laser beam is only appreciably absorbed by metallic materials. The more limited power available from the Nd:YAG laser means that it tends to find use in material-working applications requiring high precision and minimum theral damage (e.g. welding of relays and microelectronic components, drilling of hard materials such as diamond or sapphire). The most interesting applications for medium-power CO_2 laser (100W to 1kW) are perhaps in the area of processing nonmetallic materials. Examples are the cutting and drilling of ceramic material for microelectronics, the cutting of plastic, cloth, wood, leather, etc. Particular mention should also be made of the application of such a laser in the field of electronics, such as for resistor trimming. Some of the most important applications of high-power CO_2 lasers (1-15kW) are perhaps in the automotive industry, e.g. welding of gears and also heat treatment of cylinders.

2. Applications in Biology and Medicine

Lasers are being increasingly used in biological and medical applications. Here the laser can be used either as a diagnostic tool or to produce an irreversible change of the biomolecule, of the cell or of the tissue (laser photobiology and laser surgery).

In biology, the main use of lasers is that of a diagnostic tool. We mention here the following laser techniques: (i) fluorescence induced by ultrashort laser pulses in DNA, in dye-DNA complexes, and in dyes involved in photosynthesis; (ii) resonant Raman scattering as a means of studying biomolecules such as haemoglobin or rhodopsin (the latter being responsible for the mechanism of vision); (iii) photon correlation spectroscopy to obtain information about the structure and the degree of aggregation of various biomolecules; (iv) picosecond flash-photolysis techniques to probe the dynamic behaviour of biomolecules in the excited state. Particular mention should be made of the so-called flow microfluorometers. Here, mammalian cells in suspension are made to pass through a special flow chamber where they are aligned and then pass, one at a time, through the focussed beam of an Ar^+ laser. By suitably placed photodetectors, one can thus measure (i) the light that is scattered from the cell (which gives information on its size); (ii) the fluorescence from a dye which is bound to a specific cell consistituent, e.g. the DNA (this gives information on the amount of that constitutent). The advantage of flow microfluorometry is that it offers the possibility of performing measurements on a large number of cells in a limited time (the cell flow rate is typically 5×10^4 cells/min). This implies a good statistical measurement precision.

In the field of medicine, the predominant use of lasers is for surgery (laser surgery). A few diagnostic applications have also been developed, however (e.g. clinical use of microfluorometers, Doppler velocimetry to measure the blood velocity, laser fluorescence bronchoscope to detect lung tumors in their early phase).

For surgery, the focused laser beam (often a CO_2 laser) is used in place of a conventional (or electric) scalpel. The infra-red beam from the CO_2 laser is strongly absorbed by the water molecules in the tissue and produces a rapid evaporation of these molecules and a consequent cutting of the tissue. The principal advantages of a laser beam scalpel can be summarised as follows: (i) The incision can be made with high precision particularly when the beam is directed by means of a suitable microscope (laser microsurgery). (ii) Possibiity of operating in inaccessible regions. Thus in practice any region of the body which can be observed by means of a suitable optical system (e.g. lenses or mirrors) can be operated on by a laser. (iii) Drastic reduction in haematic losses due to the cauterising action of the laser beam on the blood vessels (up to a vessel diameter of ~0.5mm). (iv) Limited damage to the adjacent tissue (a few tens of micrometers). These advantages must, however, be balanced against the following disadvantages: (i) considerable cost and complexity of a laser surgical unit; (ii) smaller velocity of the laser scalpel; (iii) reliability and safety problems associated with the laser scalpel.

Having made these general comments on laser surgery, we now go on to provide some more details concerning a few of these applications. In ophthalmology the laser has already been in use for several years to treat the detachment of the retina and to cure diabetic retinopathies. In this case the laser beam (usually Ar^+) is focussed on the retina through the lens of the eye. The green beam of the laser is strongly absorbed by the red blood cells and the consequent thermal effect can lead to re-attachment of the retina or coagulation of its vessels. The laser is now finding increasing use in otolaryngology. Use of the laser is particularly attractive in this branch of surgery since it is concerned with organs such as the trachea, pharynx, and the middle ear whose inaccessibility make them difficult to operate on. Often, in this case, the laser is used in conjunction with a micoscope. The laser has also been found useful for surgery within the mouth (e.g. for removal of papillomas or tumours). The principal advantages here are hemostasis, the absence of post-operative edema and pain, and the more rapid recovery of the patient. The laser has also proved its usefulness in treating cases of heavily bleeding lesions in the gastrointestrinal tract. In this case the laser beam (usually Nd:YAG or Ar^+) is directed to the region to be treated by means of a special optical fiber inserted in a conventional gastroscope. The laser also appears promising in gynaecology where it is mostly used in conjunction with a microscope (the colposcope). The considerable reduction of edema and pain is again a noteworthy feature of the laser scalpel. In dermatology lasers are often used for the removal of tatoos and for treating some vascular diseases (e.g. port wine stains).

3. Information Processing and Recording

In this section we describe some laser applications to the reading and writing of information (either in coded or analogue form). Some of these applications fall within the area of high technology, such as optical memories for computers, while others are more consumer oriented, such as bar-code readers and videodiscs.

The bar-code readers read coded information shown on goods to be sold in supermarkets. The characters which identify the product are usually written in a ten bit code in the form of vertical bars of different width and spacing. The scanner consists of a He-Ne laser whose light is focussed on the bar code. A photodetector measures the light reflected from dark and white regions of the bar code. Thus the scanner automatically reads the code and transmits the data to a computer to which the cash registers are linked. The computer recognises the product, provides a printout of its name and price, and also updates the inventory. The use of these scanners has resulted in a considerable reduction of routine cash register operations.

Another consumer-oriented application, or rather, an actual consumer product, is the videodisc (and the audiodisc). A videodisc carries a recorded video program which can then be played back and displayed on a conventional TV set. The optical videodiscs are written by the manufacturer using special scribing equipment and then read by a laser (presently He-Ne in the domestic videodisc reader). A common way of recording involves cutting (along concentric tracks or a spiral track) pits of varying length and spacing. The pits have a depth of $\lambda/4$, where λ is the wavelength of the laser used for the reading process. During reading the laser beam is focussed down so that it falls on one track only (the track width is somewhat smaller than the laser spot size, and the pitch approximately equals the spot size). When a pit falls within the laser spot the reflection is reduced due to the destructive interference between the light reflected from the sides and that reflected from the bottom of the slot. Conversely, the absence of a slot results in a strong reflection. In this way the TV information can be recorded digitally. The principle of the audiodisc is similar. The principal advantages of both laser video and audiodiscs are that a high density of recorded information can be achieved and that the reading process does not require contact with the substrate (hence the absence of wear). The main problem which has so far limited the sale of these systems is the high price, which in part is due to the price of the He-Ne laser. This problem is being overcome by using semi-conductor rather than He-Ne lasers. A dramatic reduction in price is expected for systems using semiconductor lasers.

Another application of lasers to the writing and reading of coded information is that of optical memories for computers. The interest in such memories is again based on the high infor-mation density which can potentially be achieved. Laser tech-niques should in fact be able to provide an information density of $\sim 10^7$ bits/cm^2 since the beam can be focussed to a spot size of the order of the wavelength. The writing technique consists of drilling small holes in an opaque material or in some way changing the transmission or reflection properties of a given substrate by using a laser of sufficient power (usually Ar^+ or He-Ne). This recorded information is then read by a low-power laser, or by the same laser at reduced power. The substrate is often made of photosensitive material and may even be a photo- graphic film. However, none of these substrates can be erased. Erasable memories have been developed, based on the thermo-magnetic ferroeletric, or photochromic effects. Optical memories using the technique of holography (holographic memories) have also been developed. In conclusion, however, while the technical feasibility of optical memories has already been demonstrated, their economical viability appears to be, as yet, rather uncertain.

4. Measurement and Inspection

The properties of directionality, brightness, and monochromaticity makes lasers very useful for a variety of measurements and inspection techniques in industrial process control of machine tools and in civil engineering. We also include in this section geodetic measurements and pollution monitoring.

One of the most common industrial applications of lasers is for alignment purposes. The laser's directionality makes it ideal for establishing a straight reference line for aligning machinery for aircraft construction, and for civil engineering uses such as constructing buildings, bridges, or tunnels. In this field the laser has very largely replaced the optical instruments used previously such as collimators or telescopes. One generally uses a visible He-Ne laser of low power (1-5mW), and alignment is often achieved with the help of solid-state detectors in the form of quadrants. The position of the laser beam on the receiver is determined by the value of photocurrent from each quadrant. Alignment is then dependent on simple electrical measurements, thus avoding the reliance on subjective judgement by the operator (which has often been a source of error in the earlier optical systems). The alignment precision obtainable in practice in a workshop ranges from ~5μm (at a distance of ~5m) to ~25μm (at a distance of ~15m).

Lasers are also used for distance measurements. The technique used depends on the magnitude of the length to be measured. For short distances (up to ~50m) interferometric techniques are used with a frequency-stabilised He-Ne laser as the light source. For intermediate distances (up to ~1km), telemetry techniques involving amplitude modulation of He-Ne or GaAs lasers are used. For greater distances one measures the time of flight of a short light pulse (perhaps a few tens of nanoseconds) emitted by a Nd:YAG or CO_2 laser and reflected by the object.

The interferometric measurements of distance usually rely on the use of a Michelson interferometer. The laser beam is divided by a beam splitter into a measurement beam and a reference beam. The reference beam is reflected by a fixed mirror while the measurement beam is reflected by a mirror fixed to the object being measured. The two reflected beams are then recombined so as to interfere, and their combined amplitude is measured by a detector. When the position of the object is changed along the beam direction by $\lambda/2$, where λ is the laser wavelength, the interference signal will go from a maximum through a minimum and back to a maximum again. A suitable electronic fringe counting system can therefore give information on the displacement of the object. This measurement technique is usually employed in high-precision machine shops and allows length measurements to be made with an accurcy of one part per million. It should be noted that this technique only measures distances relative to a given initial position. The advantage of the technique arises from the fact that it is fast, accurate, and is compatible with automatic control systems.

For greater distances, amplitude-modulation telemetry is used. Here the laser beam (He-Ne or GaAs) is amplitude modulated, and the length is determined from the phase difference between the emitted and return beam. The accuracy is again one part per million (i.e., 1mm over a 1km distance). This technique is used in geodesy and cartography. For distances greater than 1km, the distance is determined from the time of flight of a short laser pulse (10–50ns) emitted by Q-switched ruby or Nd:YAG lasers. These applications are mostly of military interest (laser rangefinders) and will be discussed in a separate section. Among the nonmilitary applications, however, mention should be made of the measurement of the distance between the earth and the moon (with a precision of ~20cm) and the ranging of satellites.

The high degree of monochromaticity makes it possible to use lasers for velocity measurements, for both liquids and solids, by a technique known as Doppler velocimetry. In the case of a flowing liquid, one illuminates the liquid using a laser beam, and the scattered light is then detected. Since the liquid is moving, the frequency of the scattered light is shifted, due to the Doppler effect, to a value slightly different from that of the incident light. This frequency shift is proportional to the velocity. Thus by observing on a detector the beat signal between the scattered and incident light, one can measure the liquid velocity. The same technique can obviously be applied to moving solid objects. It has the advantage of being a noncontact measurement and, due to the high laser monochromaticity, of being very accurate over a wide velocity range (from a few centimetres per second to several hundred meters per second).

Another field in which the laser's properties of directionality and monochromaticity are put to good use is that of ambient measurement of the concentration of various atmospheric pollutants. Conventional techniques require collection of the sample (which is not always easy) and subsequent chemical analysis. These techniques cannot therefore give realtime data and some of them do not lend themselves readily to automatic measurements in fixed locations. The laser technique consists of sending the light of an appropriate laser through the atmospheric region of interest and then detecting the backscattered light after collection by a telescope. The complete system is called an optical radar of LIDAR (from light detection and ranging). The interaction of the laser light with the atmospheric pollutants involves several phenomena, namely, elastic scattering, Raman scattering, fluorescence, and absorption. Each of these phenomena has been used to detect and measure the concentration of a large variety of atmospheric pollutants (smoke, SO_2, NO_2, etc.). The lasers used include ruby, frequency-doubled Nd:YAG, dye lasers, and various medium-infrared lasers.

5. Optical Communications

The possibility of using a laser beam for communications through the atmosphere at first aroused quite a lot of enthusiasm since lasers could in principle offer two important advantages: (i) The first arises from the availability of a large oscillating bandwidth, since the amount of information that can be transmitted on a given carrier wave is proportional to its bandwidth. In going from the microwave region to the optical region the carrier frequency increases by about 10^4, thus allowing the possibility of a much larger oscillating bandwidth. (ii) The second arises from the short wavelength of the radiation. Since a typical laser wavelength is about 10^4 times smaller than a typical microwave wavelength, as a consequence the divergence is 10^4 times smaller for optical waves compared to microwaves. To achieve the same divergence, the antenna of an optical system (mirror to lens) could therefore be much smaller. These two important advantages are, however, nullified by the fact that, under conditions of poor visibility, light beams are strongly attenuated in the atmosphere. The use of lasers for free-space (unguided) communications has therefore only been developed for two particular (although important) cases: (i) Space communicatins between two satellites or between a satellite and a ground station that is located in a region of particularly favourable climatic conditions. The lasers used in this case are either Nd:YAG (with data rates up to 10^9 bit/s) or CO_2 (with data rates up to 3×10^8 bit/s). The CO_2 laser, although having higher efficiency, requires a more complex detection system and has the further disadvantage that its wavelength is ~10 times larger than that of Nd:YAG. (ii) Point-to-point communications over short distances, e.g. data transmission within the same building. In this case semiconductor lasers are the most attractive sources.

The main area of interest in optical communications, however, relies on transmission through optical fibres. Guided propagation of light along fibres is a phenomenon which has been known for many years. However these early optical fibres were used over very short distances, a typical application being in medical instruments for endoscopy. Thus around the end of the 1960's the attenuation of the best optical glasses was ~1000 dB/km. Since then, technological development of both glass and quartz fibres has dramatically improved this figure down to attenuations smaller than 0.5dB/km for quartz (the lower limit being determined by Rayleigh scattering int he fibre medium). These very low attenuations have now established an important future for the use of optical fibres in long-distance communications.

A typical optical fibre transmission system consists of a light source, a suitable optical coupler to inject the light into the fibre, and, at the end of the fibre, a receiver (a photodiode) again coupled to the fibre. Repeaters are placed along the transmission path, with a spacing which may range from 2 to 150 km. The repeaters consist of a receiver and a new emitter. The light source is often a double-heterostructure semiconductor laser. The life of these lasers has recently been improved to ~10^6h. With suitable design of the laser the emission wavelength can be adjusted to fall either at 1.3μm or near 1.6μm, corresponding to two absorption minima in a quartz fiber. Depending on the diameter d of its central core, the fibre may either be of the single-mode type (d≃1μm) or multimode type (d≃50μm). For the transmission rates employed to date (~50 Mbit/s), multimode fibres are commonly used. For higher transmission rates, single-mode fibres are more suitable.

In concluding this section, it is interesting to note that the application of optical fibres to telecommunications is not confined to long-distance (and high cost) systems. For data transmission over shorter distance (e.g., within the same building or on board an airplane or ship) use is made of an incoherent light-emitting diode coupled to a multimode fibre.

6. Military Applications

Military applications of lasers have until recently accounted for the largest share of the laser market as a whole. The most important applications at present are for (i) laser rangefinders, (ii) laser target designators, and (iii) directed-energy weapons.

The laser rangefinder is based on the same principle as that involved in a conventional radar. A short-duration laser pulse (usually of 10-20ns duration) is aimed at the target and the backscattered pulse is monitored by a suitable optical receiver including a photodetector. The range is found by measuring the time of flight of this laser pulse. The main advantages of a laser rangefinder can be summarised as follows: (i) weight, cost, and complexity considerably less than for a conventional radar; (ii) ability to make range measurements even when the target is flying just above the land or sea surface. The main disadvantage is that the laser beam is strongly attenuated by the atmosphere under low-visibility conditions. Several types of laser rangefinders, with ranges up to ~15km, are currently in use: (i) hand-held devices for infantry use (one of the latest models developed in the USA is of pocket size and weighs only 500g, including the batteries); (ii) systems for use on board of tanks; (iii) anti-aircraft ranging systems.

A second military application for lasers is as target designators. The principle is very simple: A laser, placed in a strategic position, illuminates the target. Due to the high laser brightness, the target, when viewed through a narrow band optical filter, will appear as a bright spot. The weapon (which may be a bomb, a rocket, or other explosive device) is equipped with an appropriate sensing system. In its simplest form this could be a lens to image the target onto a quadrant photo-detector which controls the steering system of the weapon and thus guides it onto the target. In this way very high firing accuracy is obtinable (a laser pointing accuracy of ~1m from a distance of 10km appears feasible). The laser is usually Nd:YAG, while CO_2 lasers appear unsuitable owing to the complexity of the photodetectors required (which involve cryogenic temperatures). Target designation may be performed from an airplane, helicopter, or from the ground (e.g., using hand-held target designators).

Considerable effort is now being devoted, both in the USA and USSR, to develop lasers for use as directed-energy weapons. In this case large laser systems are envisaged, with a power perhaps in the megawatt range (for at least a few tens of seconds). An optical system directs the laser beam at the target (airplane, satellite, rocket) with the aim of causing irreversible damage to its sensing equipment or of causing such a damage to its surface that a failure eventually results from flight stresses. Ground-located laser stations appear less promising, owing to the so-called thermal blooming which would occur in the atmosphere. The atmosphere is heated by the beam (due to absorption), and this results in a negative lens which defocusses the beam. This problem can be avoided by having the laser on board an airplane flying at high altitude or in a satellite. Military secrecy about these developments has ensured that the available information on this subject is sparse and fragmentary. It seems, however, that beams with cw power of 5-10 MW (for a few seconds) with pointing optics of 5-10m diameter may be involved. The most promising lasers for this application are chemical lasers. Chemical lasers are particularly interesting for airborne laser stations since the required energy can be stored compactly in the form of chemical energy of suitable reactants.

7. Applications in Physics and Chemistry

The invention of the laser and its subsequent development have depended on fundamental knowledge drawn from the fields of physics and chemistry. It was therefore natural that applications of the laser to physics and chemistry should have been among the first to be considered.

In physics the laser has initiated quite new fields of investigation and has dramatically stimulated some already existing fields. It should also be recognised that the study of laser behaviour and the interaction of laser beams with matter themselves consistute new areas of study within the field of physics. A particularly interesting example of a new area of investigation is that of nonlinear optics. The high intensity of a laser beam makes it possible to observe new phenomena arising from the nonlinear response of matter. We mention in particular the following processes: (i) harmonic generation whereby suitable materials, when excited by a laser beam at frequency f, can produce a new coherent beam at frequency 2f (second harmonic), 3f (third harmonic), etc.; (ii) stimulated-scattering. In this case the incident laser beam at frequency f interacts with a material excitation at frequency f_m (e.g., an acoustic wave) to produce a coherent beam at frequency $f-f_m$. Both harmonic generation and stimulated scattering are used in practice to generate intense coherent beams at new frequencies.

While it is possible with conventional light sources to produce light pulses down to $\sim 10^{-9}$ seconds, lasers are now able to produce pulses down to $\sim 10^{-13}$ ps. This has opened up possibilities for investigating a wide variety of phenomena, based on the new capability of ultrashort time-resolved measurements. Since many important processes in physics, chemistry, and biology have time scales in the picosecond range, this is an exciting new development.

In the field of chemistry, lasers are used both for diagnostic purposes and for producing an irreversible chemical change (laser photochemistry). In the area of diagnostic techniques, particular mention should be made of "resonant Raman scattering" and "coherent antistokes Raman scattering" (CARS). With these techniques it is possible to obtain considerable information on the structure and properties of polyatomic molecules. The CARS technique can also be used to measure the concentration (and temperature) of a molecular species in a given limited spatial region. This capability is being exploited in detailed studies of flame combustion processes and (electrical discharge) plasmas.

Perhaps the most interesting chemical application for lasers (at least potentially so) is the field of photochemistry. It should be borne in mind, however, that owing to the high cost of laser photons, the commercial exploitation of laser photochemistry can only be justified when the value of the end product is very high. Such a case is that of isotope separation (in particular, for uranium and deuterium). The basic idea here is to selectively excite by a laser beam only the wanted isotopic species. This species, once in the excited state, is easily distinguishable and hence separable (perhaps by chemical means) from the unwanted species left in the ground state.

Case Histories

(a) Video Discs

Philips and MCA, an American entertainment conglomerate demonstrated the first laser videodisc players in the early 1970's. They both had the same basic idea: by focussing the red beam from a helium-neon gas laser on to a spot about a micrometer in diameter, they could play back video signals recorded as pits on a rapidly rotating disc. Small pits are vital to record the broad bandwidth of video signals - six megahertz compared to the 20 kilohertz needed for audio. The two firms soon agreed on a standard format which crammed an hour of video onto a side of a disc - a long playing time was considered vital to mass sales.

Visions of a mass market for home videodisc players led Philips to try to persuade other manufacturers to produce hundreds of thousands of helium-neon laser tubes at $15 to $25 apiece. But there were problems: the players' arrival in the shops at the end of 1978 was well behind plan and, at $695, well above the target price of $400. Some of the early players and discs did not work properly. RCA came out with an incompatible laserless videodisc player at a lower price and still another incompatible format was developed in Japan.

The worst news, however, came from the public, which greeted the introduction of the videodisc player with a long yawn. It had met the videocassette recorder first, and liked it.

Pioneer of Japan is still trying valliantly to create a home-entertainment market for videodisc in the United States. The company offers players for as little as $299, and a range of material including movie classics such as Gone With The Wind, cult programmes such as Star Trek, and lots of music videos.

The biggest role for videodiscs seems to be in the commercial world. Videodiscs can be hooked to a computer so that a pupil can be taught by a program with the material on the disc. Similar systems also serve as sales aids, and videodiscs generate images of television quality for arcade games.

Ironically, a spin-off of the videodisc has already become far more successful than the videodisc itself. That is the compact disc player, a digital audio system based on a format jointly developed by Philips and Sony. Pits prerecorded on the reflective disc, which is 12 centimetres in diameter, are played back by an optical head which indludes a laser and a light detector. The recordings are an audiophile's delight. They lack totally the background noise inherent on tape or records, and the discs survive all but the most determined efforts to destroy them.

Compact disc players rely on tiny, semiconductor lasers, rather than the bulkier helium-neon gas lasers still found in some players. Semiconductor lasers produce infra-red beams, unlike the visible, red beams from helium-neon lasers, but that does not matter to an optical player. Semiconductor lasers are compact, long-lived, and cheap (reportedly they can be purchased in bulk in Japan for $5-6 each). Several hundred thousand such inexpensive semiconductor lasers were made last year, and production seems sure to pass the million mark this year.

The compact disc player is the first device to put the laser into the home in large numbers though many buyers may be no more concious of the laser than they are of the diamond tip of a phonograph needle. Prices have dropped from the $1000 range to a few hundred dollars each since Sony introduced the first compact disc player, in March 1983 in Japan. Sony has introduced car and portable compact disc players, and some people have predicted that the phonograph record may be obsolete in five years.

Even before the compact disc player appeared, many companies were working on optical discs to store computer data. They started with 30-centimetre discs, like those used for video, which could store a billion or more bytes for mainframe computers. Now they have moved to the smaller compact disc format, which can hold up to half a billion bytes and seems better suited to personal computers. With current technology, data can be written once, but read back indefinitely. Erasable optical discs are still in the laboratory.

Another variation is just reaching the market, the CD-ROM (compact-disc read-only memory) drive unit, which reads software from prerecorded optical discs. Each disc has enough capacity to store a computer's manuals and instructions as well as its software. Some observers hope that CD-ROM might provide a way around the troublesome problem of software piracy, because software would be stored on a permanent medium which would be separate from the read/write magnetic disks.

(b) Bar Code Readers

It was the Super Market Institute in the US that made laser-reading of bar codes popular in 1973 when it adopted the University Product Code (UPC). A unique UPC symbol was assigned to each product sold in its members' grocery stores. A laser scanner at the cash desk would read the codes, and purchases would be tallied automatically. The original idea was that it would save labour in adding up prices, and by avoiding the need to mark prices on packages.

It looked like a golden opportunity for the laser industry; and within a couple of years a dozen companies had announced plans to make bar-code scanners. Actually, the industry could not have picked a worse time. Food prices were soaring, and shoppers were looking warily at packages to see how much the price had risen since their last visit to the shop. Store managers soon realised that customers would sooner go elsewhere than trust a computer to ring up the right prices, particularly when the right prices were not even on the packages. A few states in the US enacted laws requiring prices to be marked legibly on packages. Laser scanners were installed at a snail's pace, and the number of manufacturers soon dropped to two, IBM and Spectra-Physics.

By about 1980, sales of bar-code scanners finally began to grow quickly. Many shops in the US still mark prices on each package but the scanners are still worthwhile because they save labour at the tills, and they automatically keep stock. (One manufacturer, National Semiconductor, even offers a scanner with speech synthesis that reads the prices out to customers while the shopkeeper silently packs the bags).

Scanners are commonplace in American supermarkets. Ironically, the laser content of the scanners (a red helium-neon laser) is seldom mentioned by the shops. Perhaps they are afraid that customers will think that a laser beam might vaporise them and their purchases.

Bar-code scanning has worked so well that UPC-like symbols have appeared in many other places. American magazines and paperback books have bar codes printed on their covers so that wholesalers can keep track of unsold copies returned to them. Federal Express puts bar codes on the packages it ships overnight across the US. In 1982 the US Department of Defense told suppliers to put bar codes on all packages shipped to it. Several industries followed suit afterwards. One industry source has estimated that by 1990 some 80 per cent of America's gross national product will be tagged, at some stage, with bar codes. The technologg has advanced slower in Britain and Western Europe, but it is gaining acceptance there as well.

Not all bar codes have to be read with a laser, other light sources will work in hand-held wands passed over the printed symbol. Semiconductor lasers are increasingly common, but the difference between their infra-red wavelength and the red output of the helium-neon laser could cause problems if care is not taken in colour printing of bar codes. The laser "sees" an ink the same colour as its beam as being white because both white paper and the coloured ink reflect that light strongly. In the early days of scanners a few companies slipped up by printing bar codes in red ink which was invisible to the helium-neon laser. Of course, it would be much harder for people to see symbols that are highly reflective of infra-red light because the human eye cannot operate at that wavelength.

Concluding Remarks

We have seen that lasers, even 25 years after their discovery, are still full of youthful promise. Many applications are already well established, while others with great potential hold promise for the near future. Probably another ten or twenty years will be needed before the great revolution initiated by the laser can be fully appreciated.

So the laser, which in its early days used to be referred to as a bright solution in search of a problem, can already now be proclaimed as the bright solution to numerous problems in physics, chemistry, biology, medicine, electronics, and engineering.