Chapter 19
Lasers in Industry

19.1 Introduction

In Chapter 10 we discussed the special properties possessed by laser light, namely its extreme directionality, its extreme monochromaticity, and the large intensity associated with some laser systems. In the present chapter, we briefly discuss the various industrial applications of the laser.

The beam coming out of a laser is usually a few millimeters (or more) in diameter and hence, for most material processing applications, one must use focusing elements (like lenses) to increase the intensity of the beam. The beam from a laser has a well-defined wave front, which is either plane or spherical. When such a beam passes through a lens, then according to geometrical optics, the beam should get focused to a point. In actual practice, however, diffraction effects have to be taken into consideration (see Chapter 2), and one can show that if λ is the wavelength of the laser light, a is the radius of the beam, and f is the focal length of the lens, then the incoming beam will get focused into a region of radius (see Fig. 19.1)[1]

$$b \approx \lambda f / a \tag{19.1}$$

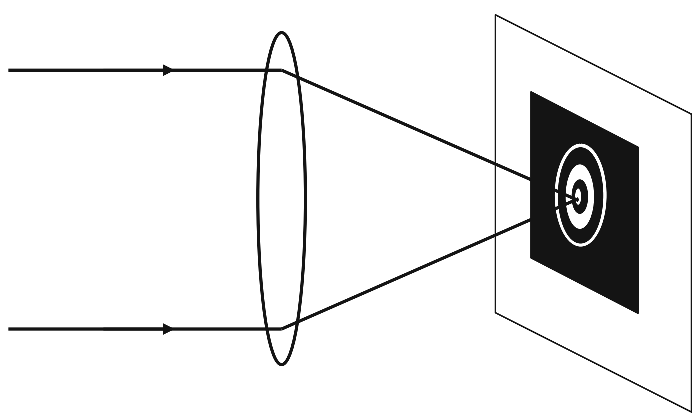

Fig. 19.1 When a plane wave of wavelength λ falls on a lens of radius a, then at the focal plane F of the lens, one obtains an intensity distribution of the type shown in the figure. About 84% of the total energy is confined within a region of radius $\lambda f/a$

[1]Here we have assumed that the aperture of the lens is greater than the width of the beam. If the converse is true, then a would represent the radius of the aperture of the lens.

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As can be seen, the dimension of this region[2] is directly proportional of f and λ (the smaller the value of λ, the smaller the size of the focused spot) and inversely proportional to the radius a. If P represents the power of the laser beam, then the intensity I, obtained at the focused region, would be given as

$$I \approx \frac{P}{\pi b^2} \approx \frac{Pa^2}{\pi \lambda^2 f^2} \tag{19.2}$$

Thus if we focus a 1-W laser beam (with $\lambda = 1.06\ \mu$m and having a beam radius of about 1 cm)[3] by a lens of focal length 2 cm, then the intensity obtained at the focused spot would be given as

$$\begin{aligned} I &\approx \frac{1}{3.14 \times \left(1.06 \times 10^4 \times 2\right)^2} \mathrm{W/cm}^2 \\ &\approx 7 \times 10^6 \mathrm{W/cm}^2 \end{aligned} \tag{19.3}$$

Figure 10.4 shows the spark created in air at the focus of a 3-MW peak power giant pulsed ruby laser. The electric field strengths produced at the focus are of the order of 10^9 V / m. Note here that such large intensities are produced in an extremely small region whose radius is $\sim 2 \times 10^{-6}$ m. Further, as can be seen from Eq. (19.2), the larger the value of a, the greater the intensity; as such, one often uses a beam expander to increase the diameter of the beam; a beam expander usually consists of a set of two convex lenses as shown in Fig. 19.2.

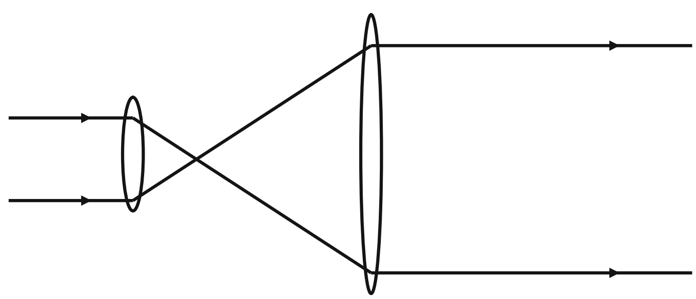

Fig. 19.2 A beam expander consisting of two convex lenses

It may be noted that when one produces such small focused laser spots, the beam has a large divergence, and hence near the focused region, the beam expands again within a very short distance. This distance (which may be defined as the distance over which the intensity of the beam drops to some percentage of that at the focus) defines the depth of focus. Thus, smaller focused spots lead to a smaller depth of

[2] The dimension of the focused region is usually larger than that given by Eq. (19.1) due to the multimode emission of the laser. We are also assuming here that the lenses are aberrationless. In general, aberrations increase the spot dimension, resulting in lower intensities.

[3] The 1.06-μm radiation is emitted from the neodymium-doped YAG or glass laser (see Chapter 11).

focus. This must also be kept in mind while choosing the parameters in a laser processing application.

We now discuss in the next few sections some of the important applications of the laser in industry.

19.2 Applications in Material Processing

Since laser beams have high power and can be focused to very small areas, they can generate very high intensities in the region of focus. The intensity levels at the focus can be adjusted by controlling the power and the focused area of the beam. This property of lasers is used in many industrial applications. The primary lasers used for such applications are the Nd:YAG laser emitting at 1060 nm (infrared) with typical powers of 5 kW, carbon dioxide laser emitting at 10.6 μm (far infrared) with powers of up to 50 kW, excimer lasers emitting at 157–350 nm (ultraviolet range) with powers of up to about 500 W. Depending on the application, both continuous wave and pulsed lasers are used. The applications include welding, cutting, hole drilling, micromachining, marking, photolithography, etc.

19.2.1 Laser Welding

One of the simplest applications is in welding wherein high temperature is required to melt and join materials such as steel. High-power lasers have found many important applications in the area of welding. For example, carbon dioxide lasers emitting a wavelength of 10.6 μm and with a power of 6 kW of power are used in welding of $\frac{1}{4}$-in.-thick stainless steel. Lasers are routinely used in the manufacture of automobiles. Figure 19.3 shows welding of car parts using a laser.

Pulsed ruby lasers have also been used in welding. For example, a pulsed ruby laser beam having an energy of 5 J with pulse duration of about 5 ns was used in

Fig. 19.3 Welding of auto parts by a high-power laser

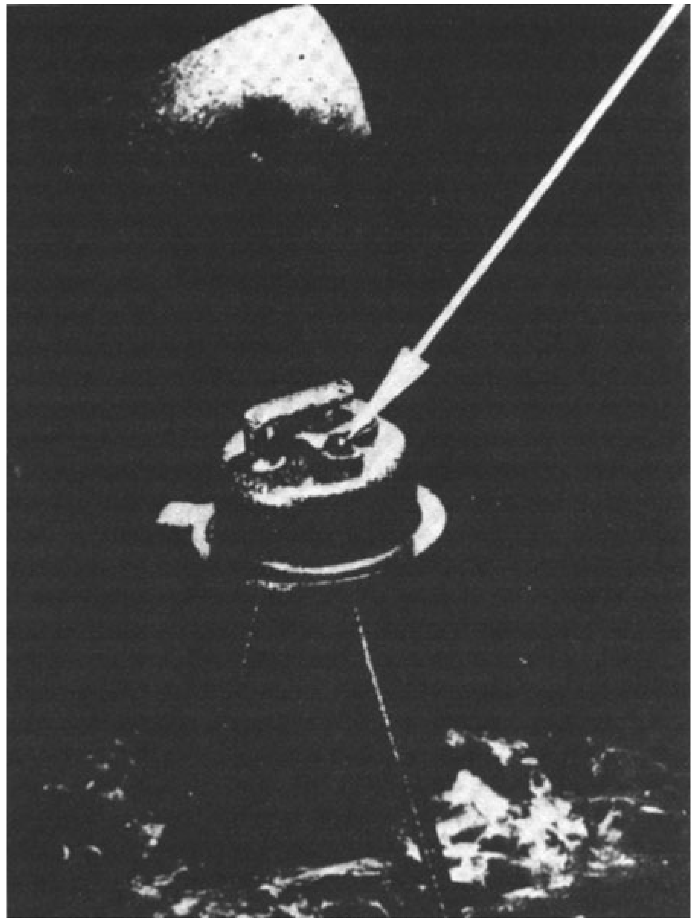

Fig. 19.4 Welding of parts on a transistor; the *arrow* shows the position of the weld. (Adapted from Gagliano et al. (1969))

welding 0.18-mm-thick stainless steel. The weld was made using overlapping spots and the laser was pulsed at a rate of 20 pulses/min. The focused spot was about 1 mm in diameter and the associated power density was $\sim 6 \times 10^5$ W/cm^2.

Laser welding has found important applications in the fields of electronics and microelectronics which require precise welding of very thin wires (as small as 10 μm) or welding of two thin films together. In this field, the laser offers some unique advantages. Thus, because of the extremely short times associated with the laser welding process, welding can be done in regions adjacent to heat-sensitive areas without affecting these elements. Figure 19.4 shows a weld performed with a laser on a transistor unit. Further, welding in otherwise inaccessible areas (like inside a glass envelope) can also be done using a laser beam. Figure 19.5 shows such an example in which a 0.03-in. wire was welded to a 0.01-in.-thick steel tab without breaking the vacuum seal. In laser welding of two wires, one may have an effective weld even without the removal of the insulation.

Laser welds can easily be performed between two dissimilar metals. Thus, a thermocouple may easily be welded to a substrate without much damage to adjacent material. One can indeed simultaneously form the junction and attach the junction to the substrate. This method has been used in attaching measuring probes

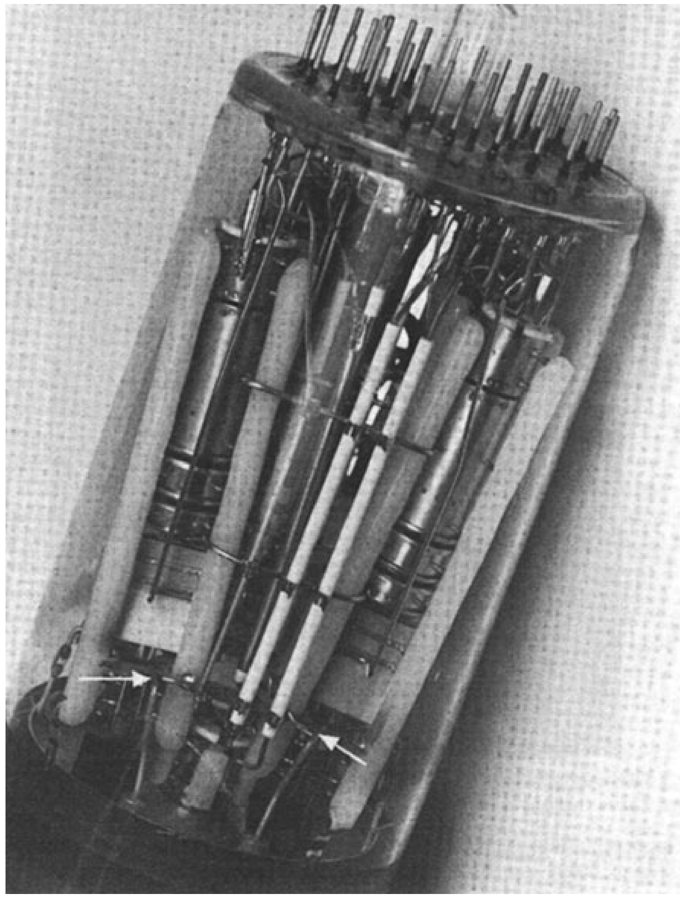

Fig. 19.5 Laser welding in inaccessible areas. The photograph shows the welding of a 0.03-in. wire to a 0.01-in.-thick steel tab inside a vacuum tube without breaking the vacuum seal. The *arrows* point toward the repaired connections. (Adapted from Weaver (1971); photograph courtesy: Dr. Weaver)

to transistors, turbine blades, etc. Laser weld not only achieves welding between dissimilar metals but also allows precise location of the weld.

In welding, material is added to join the two components. Thus the laser power must not be too high to evaporate the material; removal of material leads, in general, to bad welds. Thus the laser used in welding processes must have a high average power rather than high peak power. The neodymium:YAG lasers and carbon dioxide lasers are two important kinds of lasers that find wide-ranging applications in welding.

19.2.2 Hole Drilling

Drilling of holes in various substances is another interesting application of the laser.[4] For example, a laser pulse having a pulse width of about one hundredth of a second and an energy of approximately 0.05 J can burn through a 1-mm-thick steel plate

[4]In the early 1960s, the power of a focused laser beam was measured by the number of razor blades that the beam could burn through simultaneously, the "Gillette" being the unit of measurement of power per blade burnt through.

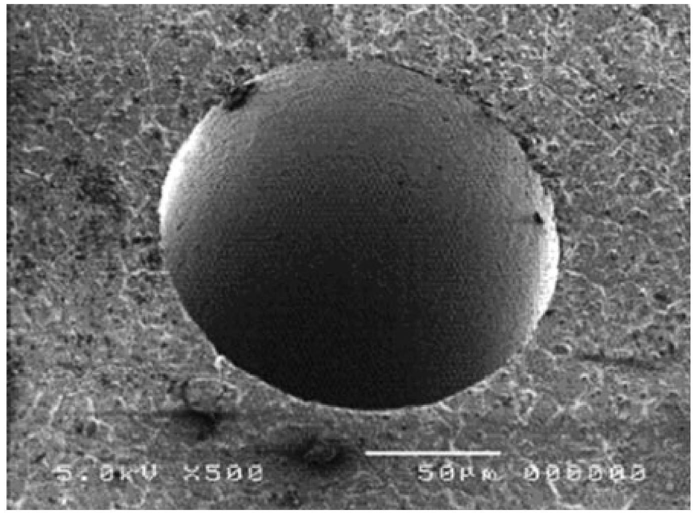

Fig. 19.6 Hole drilled in a 1-mm-thick stainless steel

leaving behind a hole of radius about 0.1 mm. Further, one can use a laser beam for the drilling of diamond dies used for drawing wires. Drilling holes less than about 250 μm in diameter by using metal bits becomes very difficult and is also accompanied by frequent breakage of drill bits. With laser one can easily drill holes as small as 10 μm through the hardest of substances. Figure 19.6 shows a typical laser-drilled hole in a 1-mm-thick stainless steel. The Swiss watch industry in Europe has been using flash-pumped neodymium:YAG laser to drill ruby stones used in timepieces. In addition to the absence of problems like drill breakage, laser hole drilling has the advantage of precise location of the hole.

Figure 19.7 shows drilling through a piece of rock using an Nd:YAG laser emitting at 1.06 μm. Laser drilling can indeed reduce drilling time by more than a factor of 10 and hence reduce cost dramatically in oil exploration applications. Typical drilling speed of 1 cm/s is possible by using different types of lasers.

Due to the extremely small areas to which the laser beams can be focused, they are used in the area of micromachining. Figure 19.8 shows how it is possible to write on a human hair using lasers. Lasers are also being used in the removal of microscopic quantities of material from balance wheels while in motion. They have also been used in trimming resistors to accuracies of 0.1%. Such micromachining processes find widespread use in semiconductor circuit processing. The advantages offered by a system employing lasers for such purposes include the small size of the focused image with a precise control of energy, the absence of any contamination, accuracy of positioning, and ease of automation.

19.2.3 Laser Cutting

Lasers also find application in cutting materials. The most common laser that is used in cutting processes is the carbon dioxide laser due to its high output power.

Fig. 19.7 Drilling through a piece of rock using laser. (Adapted from Ref. http://www.ne.anl.gov/facilities/lal/laser_drilling.html)

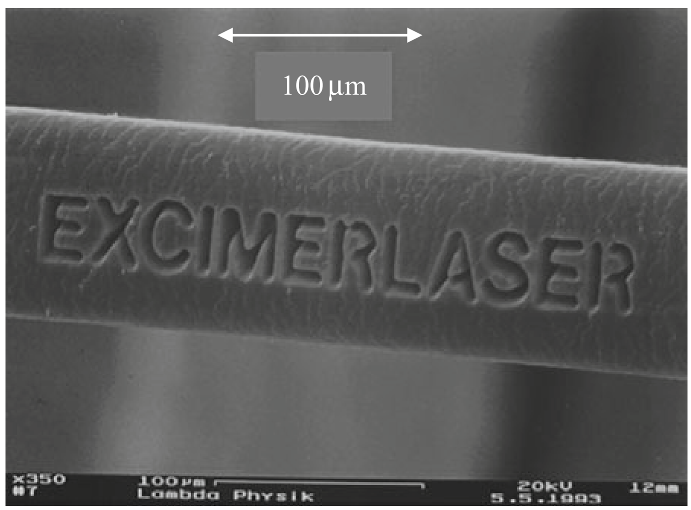

Fig. 19.8 Micromachining in a piece of hair using a laser. (Adapted from Lambda Physik, Germany)

In the cutting process, one essentially removes the materials along the cut. When cuts are obtained using pulsed lasers, then the repetition frequency of the pulse and the motion of the laser across the material are adjusted so that a series of partially overlapping holes are produced. The width of the cut should be as small as possible with due allowance to avoid any rewelding of the cut material. The efficiency of laser cutting can be increased by making use of a gas jet coaxial with the laser (see Fig. 19.9). In some cases one uses a highly reactive gas like oxygen so that when the laser heats up the material, it interacts with the gas and gets burnt. The gas jet also helps in expelling molten materials. Such a method has been used to cut materials like stainless steel, low-carbon steel, and titanium. For example, a 0.13-cm-thick

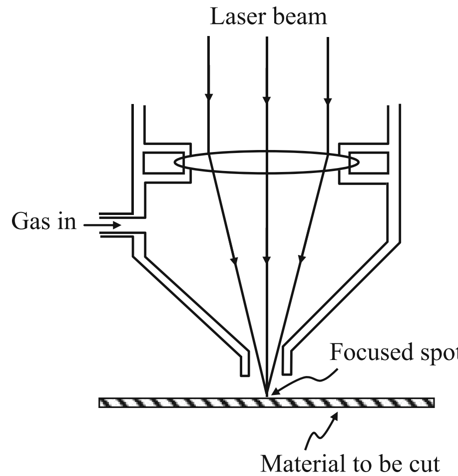

Fig. 19.9 Cutting using a focused laser spot

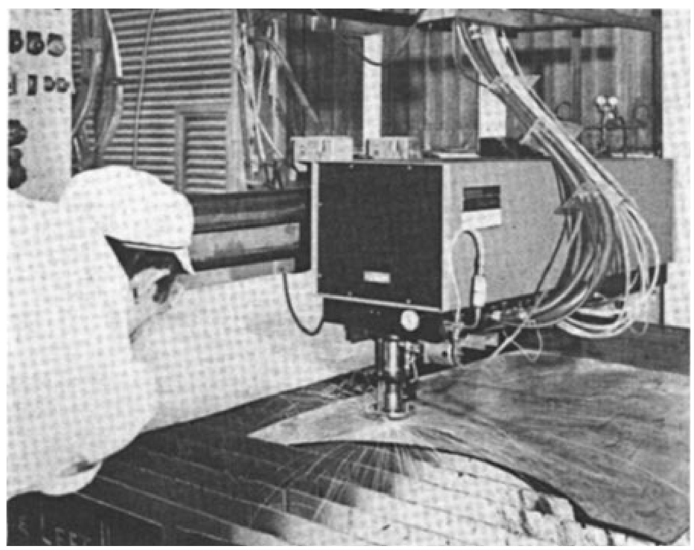

Fig. 19.10 Use of carbon dioxide laser to cut wood. (Photograph courtesy: Ferranti Ltd.)

stainless steel plate was cut at the rate of 0.8 m/min using a 190-W carbon dioxide laser using oxygen jet.

In some methods, one uses inert gasses (like nitrogen or argon) in place of oxygen. Such a gas jet helps in expelling molten materials. Such a technique would be very efficient with materials which absorb most radiation at the laser wavelength. Wood, paper, plastic, etc. have been cut using such a method. A gas jet-assisted CO_2 laser can be used for obtaining parallel cuts of up to 50 mm depth in wood products. At the cut edges, carbonization occurs, but it is usually limited to a small depth (about a few tens of micrometers) of the material. This causes a discoloration only and can be decreased by increasing the cutting speed. Figure 19.10 shows how a carbon dioxide laser is used (with a gas jet) in cutting wood. Laser cutting of stainless steel, nickel alloys, and other metals finds widespread application in the aircraft and automobile industries.

19.2.4 Other Applications

Lasers also find applications in vaporizing materials for subsequent deposition on a substrate. Some unique advantages offered by the laser in such a scheme include the fact that no contamination occurs, some preselected areas of the source material may be evaporated, and the evaporant may be located very close to the substrate.

An interesting application of laser is in the opening of oysters. A laser beam is focused on that point on the shell where the muscle is attached. This results in detachment of the muscle, the opening of the shell, and leaving the raw oyster alive in the half shell (see Fig. 19.11).

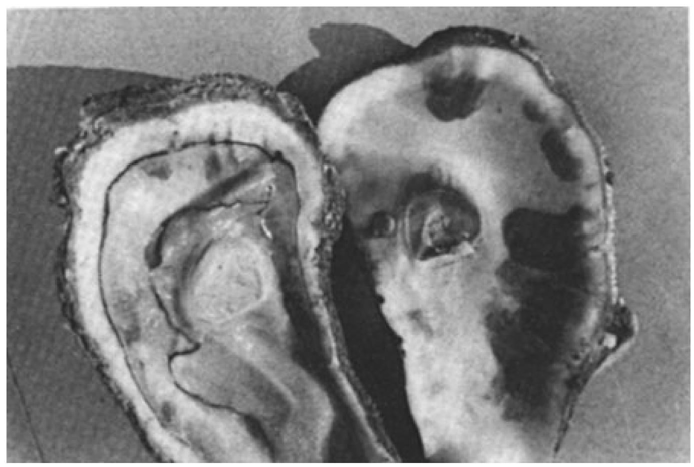

Fig. 19.11 The photograph shows an oyster opened with a CO_2 laser, which neatly detaches adductor muscle from the shell and leaves the raw oyster alive in the half shell. (Photograph courtesy: Professor Gurbax Singh of the University of Maryland)

19.3 Laser Tracking

By tracking we imply either determining the trajectory of a moving object like an aircraft or a rocket, or determining the daily positions of a heavenly object (like the Moon) or an artificial satellite; a nice review on laser tracking systems has been given by Lehr (1974). The basic principle of laser tracking is essentially the same as that used in microwave radar systems. In this technique, one usually measures the time taken to travel to and fro for a sharp laser pulse sent by the observer to be reflected by the object and received back by the observer (see Fig. 19.12); suitably modulated continuous wave (CW) lasers can also be used for tracking.

One of the main advantages of a laser tracking system over a microwave radar system is the fact that not only a laser tracking system has a smaller size but also its cost is usually much less. Further, in many cases one can use a retroreflector on the object; in a retroreflector, the incident and reflected rays are parallel and travel in opposite directions. A cube corner is often used to act as a retroreflector (see Fig. 19.13). For example, on the surface of the moon, or on a satellite, one can have a retroreflector to reflect back the incident radiation. For a laser tracking system, the size of the retroreflector is much smaller than the corresponding microwave reflector

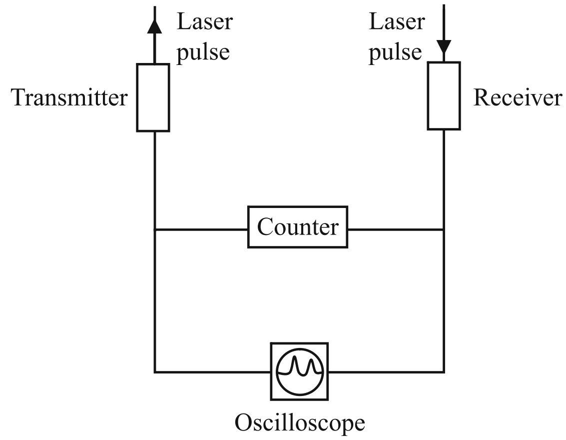

Fig. 19.12 Light detection and ranging (LIDAR)

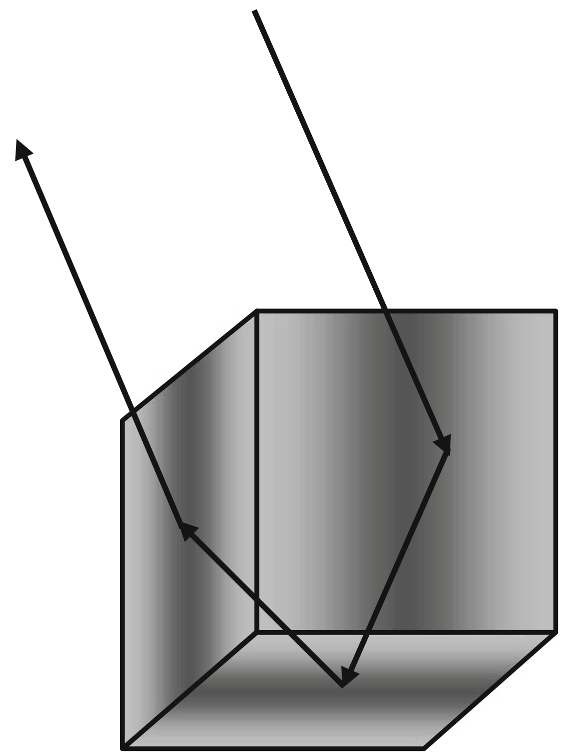

Fig. 19.13 Cube corner as a retroreflector

owing to the smaller wavelength of the optical beam and hence the reflector can be more conveniently mounted in the system involving lasers.

In a microwave radar system, one has to incorporate corrections because of the presence of the ionosphere and also because of the presence of water vapor in the troposphere. These corrections are much easier to incorporate in the case of an optical beam. As compared to a microwave radar system, the laser radar offers much higher spatial resolution.

On the other hand, there are some disadvantages in using a laser tracking system. For example, when fog and snow are present in the atmosphere, it is extremely

Table 19.1 Characteristics of pulsed lasers used in tracking systems

Type	Wavelength (μm)	Efficiency (%)	Energy (J)	Pulse duration (ns)	Pulse repetition rate	Spectral width (nm)
Nd:YAG	1.06	0.1	0.02	10–25	100 s^{-1}	0.5
GaAs	0.9	4	10^{-4}	100	100 s^{-1}	2
Ruby	0.694	0.013	7	3	20 min^{-1}	0.04
Nd:glass	0.530	0.04	20	20	12 h^{-1}	0.9

Source: Adapted from Lehr (1974)

Table 19.2 Typical ranges and velocities

Object	Distance (m)	Angular velocity (arcsec/s)
Moon	3.8×10^8	14.5
Near-Earth satellite	10^6	10^3
Aircraft (DC-10)	2×10^4	500
Rocket (at launch)	5×10^3	10^5

Source: Adapted from Lehr (1974)

difficult to work at optical frequencies. Further, during daytime there is a large background noise. The losses in the transmitter and the receiver are also considerably larger in laser systems.

In Table 19.1 we have tabulated some of the typical lasers that have been used in tracking systems. Typical ranges and velocities of various objects measured by a laser tracking system are tabulated in Table 19.2. One can see that the distance that can be covered range from 5000 m to hundreds of megameters.

The transmitter which is pointed toward the object may simply consist of a beam expander as shown in Fig. 19.2. For tracking a moving object, both the laser and the telescope may be moved. One could alternatively fix the laser and bend the laser beam by means of mirrors. There are other ways of directing the laser beam toward the object; for further details, the reader is referred to the review article by Lehr (1974) and the references therein. The receiver which is also pointed toward the object may consist of a reflector or a combination of mirrors and lenses. The detector may simply be a photomultiplier.

Figure 19.14 gives a block diagram of a laser radar system for tracking of a satellite. A portion of the pulse that is sent is collected and is made to start an electronic counter. The counter stops counting as soon as the reflected pulse is received back. The counter may be directly calibrated in units of distance.

National Aeronautics and Space Administration, USA, had launched an aluminum sphere called the Laser Geodynamic Satellite (LAGEOS) into orbit at an altitude of 5800 km for studying the movements in the Earth's surface, which would be of great help in predicting earthquakes. Figure 19.15 shows the satellite, which is 60 cm in diameter, weighs 411 kg, and has 426 retroreflectors which return the

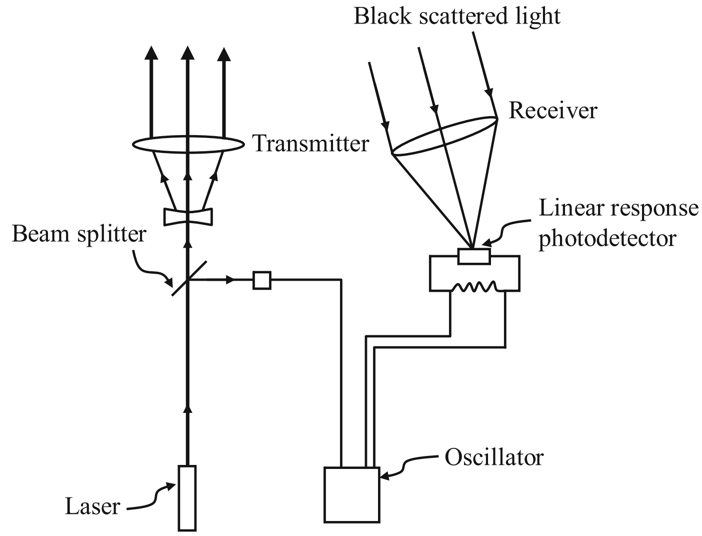

Fig. 19.14 Block diagram of a typical pulsed LIDAR system

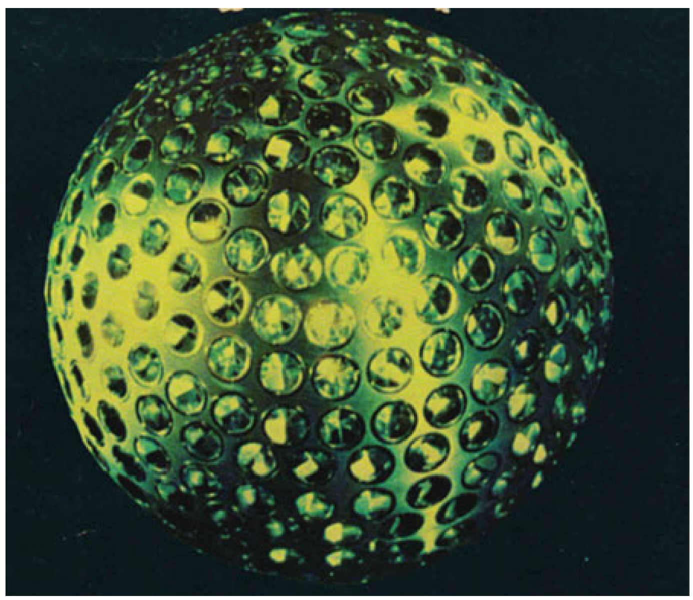

Fig. 19.15 The Laser Geodynamic Satellite (LAGEOS) put into orbit by the National Aeronautics and Space Administration, USA, for measuring minute movements of the Earth's crust, which would be helpful in predicting earthquakes. The satellite is 60 cm in diameter, weighs 411 kg, and is studded with 426 retroreflectors, which return the incident laser pulses to their origin on the surface of the Earth. Minute movements of the Earth's crust are detected by measuring the flight time of a light pulse to the satellite and back. (Photograph courtesy: United States Information Services, New Delhi)

laser pulses exactly back to the point of origin on the Earth. Accurate measurements of the time of flight of laser pulses to the satellite and back should help scientists in measuring minute movements of the Earth's crust. Figure 19.16 shows scientists performing the prelaunch testing of the satellite.

Fig. 19.16 LAGEOS undergoing prelaunch testing in the laboratory. (Photograph courtesy: United States Information Service, New Delhi)

19.4 Lidar

Laser systems have also been used for monitoring the environment. Such systems are called LIDARs (acronym for light detection and ranging) and they essentially study the laser beam scattered from the atmosphere. It may be mentioned that studies of the atmosphere using an optical beam had been carried out even before the advent of the laser; for example, using a searchlight, Hulbert in 1937 studied atmospheric turbidity to a height of 28 km. The arrival of the laser on the scene revolutionized the atmospheric study using coherent laser beams.

Pulses of laser light are sent and the radiation that is scattered by various particles present in the atmosphere is picked up by the receiver. The background sunlight is removed by using filters. This scattered light gives information regarding the particles present in the atmosphere with a sensitivity that is much more than that obtainable from microwave radars.

In Fig. 19.14 we have given a block diagram of a pulsed LIDAR system to study the nature of aerosols present in the atmosphere. One usually measures the time dependence of the intensity of the backscattered laser light using a photodetector. The time variation can be easily converted into the height from which the laser beam has been backscattered. A typical time dependence of the backscattered laser radiance is plotted in Fig. 19.17a which corresponds to an atmosphere which has no aerosols, i.e., the backscattering is by pure molecular gases such as N_2, O_2, and Ar. On the other hand, if the atmosphere contained aerosols, then the time dependence of the backscattered laser radiance would of the form shown in Fig. 19.17b.

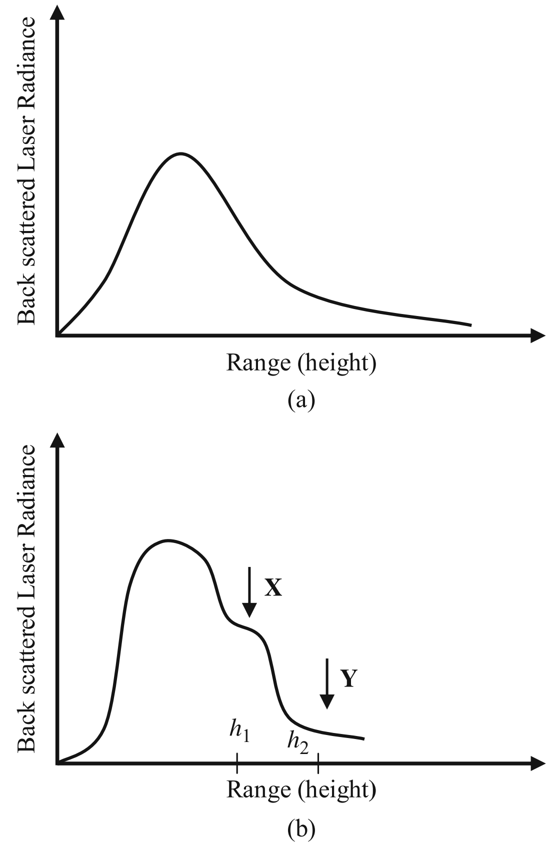

Fig. 19.17 Backscattered radiation from (**a**) a clear atmosphere and (**b**) atmosphere containing aerosols

Note the kinks that appear in the curve at the points marked X and Y; these are due to the fact that between the heights h_1 and h_2 there are aerosols which are responsible for a greater intensity (compared to that for a clear atmosphere) of the backscattered laser light. Thus a curve like that shown in Fig. 19.17b implies a haze which exists between the heights h_1 and h_2. It may be seen that corresponding to the heights h_2 the intensity is roughly the same as that from a pure molecular atmosphere. Thus, beyond the height h_2, one does not expect the presence of any aerosols. With the LIDAR one can also study the concentrations and sizes of various particles present in the atmosphere, which are of extreme importance in pollution studies. Small particles are difficult to detect with the microwave radar; the microwave radar can detect the presence of rain, hail, or snow in the atmosphere. This difference arises essentially due to the larger amount of scattering that occurs at optical wavelengths. In addition, a LIDAR can also be used to study the visibility of the atmosphere, the diffusion of particulate materials (or gases released at a point) in the atmosphere, and also the presence of clouds, fog, etc.; the study of turbulence and winds and the probing of the stratosphere have also been carried out by LIDAR systems. For further details on the use of laser systems for monitoring the environment, the reader is referred to the review article by Hall (1974) and the references therein.

19.5 Lasers in Medicine

Perhaps the most important use of lasers in the field of medicine is in eye surgery. Hundreds of successful eye operations have already been performed using lasers. The tremendous use of the laser in eye surgery is primarily due to the fact that the outer transparent regions of the eye allow light at suitable wavelengths to pass through for subsequent absorption by the tissues at the back of the eye.

As is well known, the eye is roughly spherical and consists of an outer transparent wall called the cornea, which is followed by the iris (which can adjust its opening to control the amount of light entering the eye), and a lens. Between the cornea and the lens is the aqueous humor. The back part of the eye contains the light-sensitive element, namely the retina. Light falling on the eye is focused by the lens on the retina, and the photosensitive pigment-containing cells present in the retina convert the light energy into electrical signals, which are carried by the optic nerve to the brain, resulting in the process of seeing.

As a result of some disease or heavy impact, the retinal layer may get detached from the underlying tissue, creating a partial blindness in the affected area. Earlier, a xenon arc lamp was used for welding together the detached portion of the retina. But the long exposure times of this source required administering anesthesia for safety. Also it cannot be focused sharply. The unique advantages of using a laser beam for welding a detached retina are that since it can be focused to an extremely small spot, precise location of the weld can be made and also the welds are much smaller in size. The spot size of a typical xenon arc beam on the retina when focused by the eye lens is about 500–1000 μm in diameter; this is much larger than the typical diameter (about 50 μm) obtainable using a laser beam. The time involved in laser beam welding is so short that the eye does not need any clamping. Pulses of light from a ruby laser lasting for about 300 μs at levels below 1 J are used for retinal attachment.

Lasers are also expected to be used extensively in the treatment of cancer. In an experiment reported in the USSR, amelanotic melanoma was inculcated from human beings on nine animals. These animals were irradiated with a ruby laser beam and it was reported that within 1 month the tumors completely disappeared. The power associated with the ruby laser beam was about 100 MW with a total energy of about 200 J. Successful skin cancer treatment with lasers has also been reported on human beings.

Lasers can also be used for correction of focusing defects of the eye. In the method referred to as LASIK (*la*ser *i*n *s*itu *k*eratomileusis), the cornea of the eye can be crafted to adjust the curvature so that the focusing by the eye lens takes place on the retina (see Fig. 19.18). This method can correct for eye defects requiring high lens powers and is a very popular technique.

It is impossible to list all the applications of lasers in the field of medicine. Extensive use of lasers is anticipated in surgery, dentistry, and dermatology. For further details and other applications of lasers in medicine, the reader is referred to the recent article by Peng et al. (2008).

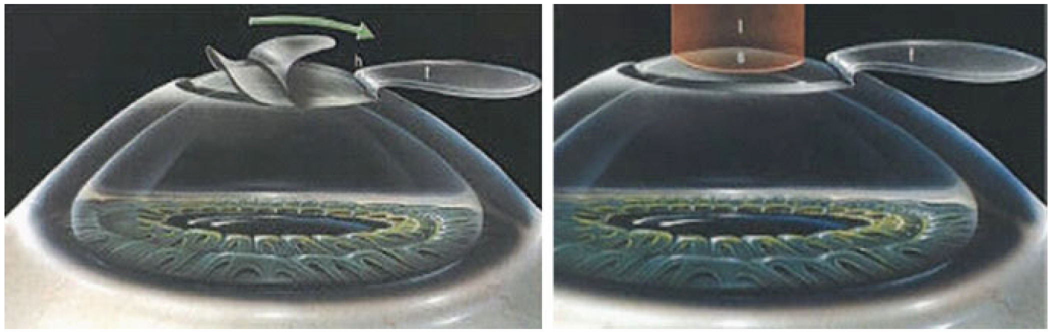

Fig. 19.18 Application of lasers in LASIK

19.6 Precision Length Measurement

The large coherence length and high output intensity coupled with a low divergence enables the laser to find applications in precision length measurements using interferometric techniques. The method essentially consists of dividing the beam from the laser by a beam splitter into two portions and then making them interfere after traversing two different paths (see Fig. 19.19). One of the beams emerging from the beam splitter is reflected by a fixed reflector and the other usually by a retroreflector[5] mounted on the surface whose position is to be monitored. The two reflected beams interfere to produce either constructive or destructive interference. Thus, as the reflecting surface is moved, one would obtain alternatively constructive

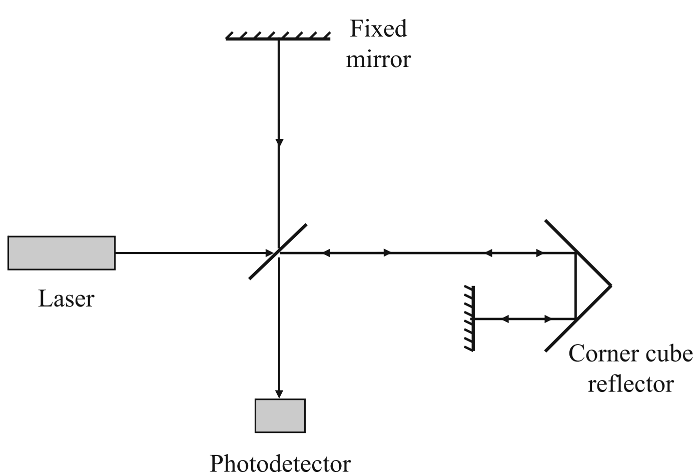

Fig. 19.19 Laser interferometer arrangement for precision length measurements

[5]As mentioned earlier, a retroreflector reflects an incident beam in a direction exactly opposite to that of an incident beam (see Fig. 19.11), and it is characterized by the property that minor misalignments of the moving surface do not cause any significant errors.