NASA SP-5116

LASER TECHNOLOGY

A SURVEY

NASA SP-5116

LASER TECHNOLOGY

A SURVEY

By
Dr. Paul Zilczer

Computer Sciences Corporation
Falls Church, Virginia

Technology Utilization Office 1973
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the Superintendent of Documents
U.S. Government Printing Office Washington, D.C. 20402
Price 50 cents
Stock Number 3300-00537

Foreword

Lasers are extremely powerful new tools. They have been developed in the last few decades and may be used increasingly in industry, medicine and dentistry, communication systems, and many kinds of scientific research. This survey includes both background information for readers unfamiliar with developments to date and suggestions regarding potentialities of lasers that have not yet been fully explored.

It is one of a series of publications about technical and scientific advances in which the National Aeronautical and Space Administration has participated. These surveys have been undertaken as part of its user-oriented Technology Utilization Program. In them, NASA has striven to collect and present the results of aerospace-related work in ways likely to be helpful to persons engaged in other endeavors beneficial to mankind.

References to specific work and to companies using and developing lasers are included for readers who would like to delve more deeply into the subject. It is hoped that this survey will further increase the benefits that are being derived from our country's exploration of space.

Director
Technology Utilization Office

PRECEDING PAGE BLANK NOT FILMED

Contents

CHAPTER 1

Introduction and Summary

A laser beam can burn a hole through a 1/3-cm steel plate, yet it does not contain enough energy to boil an egg. The word "laser" often brings to mind the ray-guns and other fantastic apparatus of outdated science fiction. However, the laser's sometimes spectacular capabilities and its adaptability to new aspects of old technologies relate more to the future than to the past. Laser technology is very much in the present. Practical applications are now in use for industry, government, the military, and research of all kinds; and additional uses are being discovered. This survey provides a background and introduction to the laser of today and suggests applications for tomorrow which may benefit everyone.

The most important attribute of the laser is its ability to amplify. With it, the frequency limit for coherent electronic amplification can be increased ten thousandfold–from 120 to 1 200 000 GHz. The laser is also an oscillator, and has its own built-in antenna. A laser beam is characterized by its coherent light, which is emitted over a very narrow frequency range and can be directed with extremely high precision.

Because of the almost unlimited frequency domain that has been opened for exploitation, communication engineers consider the advent of lasers equivalent to a new technology. This vast quantitative advance has led to corresponding qualitative advances in scientific knowledge and the resulting technologies. An immensely promising field is holography, which is based on the phenomenon of the optical harmonics that are generated when laser light traverses piezoelectric crystals.

BACKGROUND OF LASER DEVELOPMENT

The nature of laser light and how it is produced can be explained through a review of the physical principles involved.

All light is emitted by atoms. The atoms in the filament of an electric bulb absorb energy from electricity and re-emit it in the form of heat and light. Similarly, if electricity is discharged through hydrogen gas, the hydrogen atoms absorb energy from the stream of electrons (cathode rays) and re-emit it in the form of light and other electromagnetic waves.

The way in which an atom absorbs and re-emits energy is governed by the energy level that represents the stable state of each type of atom. When an atom is struck by an electron of energy greater than that of its normal or ground state, it may absorb some of that energy (depending on the energy level and the characteristics of that type of atom) and reach one of several possible excited states.

An atom in an excited state may be compared to a stepped, compressed spring in which energy is stored, whereas an atom in its ground state is like a spring at its natural length.* Whenever an atom jumps from a high energy level to a lower one (as when a stepped, compressed spring is partially released), the energy it loses is given up as a packet of radiation. This radiation consists of electromagnetic waves with a frequency proportional to the difference between the two energy levels. A hydrogen atom emits ultraviolet radiation when it falls from its first excited state to the ground state. Visible light is produced when the atom descends from the second or higher excited state to the first, whereas transitions that end on the second excited state produce infrared radiation.

Although both radio waves and light waves are forms of electromagnetic radiation (differing only in their wavelengths), they are produced in different ways. Light is produced in short bursts, each one called a wave packet or photon. A radio wave is a continuous flow of energy. Although the light from an ordinary light bulb seems to provide steady illumination, it consists of billions of discontinuous photons.

In 1917, Albert Einstein proved in theory a fact of great technological significance. It was known then that an atom in an excited state would eventually decay to a state of lower energy and emit a photon of energy; this continuous process is called spontaneous emission. Einstein showed that emission could be stimulated to occur sooner if the atom in its excited state is struck by an outside photon of exactly the same energy as the photon that is to be emitted. This action causes two photons of the same energy to leave the atom—the original photon and the stimulated one. Einstein also showed that these two photons would leave together and travel in the same direction in phase with each other.

The process that Einstein described is the stimulated emission of radiation; the fact that one photon enters the atom and two photons exit is a basis for amplifying light waves. Until quite recently this possibility aroused little interest because of the seemingly remote chances of controlling the process (which often occurs in less than 1/100 000 000 of a second). Then in 1954, three American scientists, James P. Gordon, H. J. Zeiger, and Charles H. Townes, put the idea to practical use for the first time. They succeeded in amplifying microwaves, which are electromagnetic waves produced by transitions between

---

*The comparison shows that whereas the spring changes from one energy state to another continuously, the atom changes in discrete jumps.

the energy levels of the molecules in the same way that light is produced by atoms. This new amplifying device was called the maser.

In 1958, Townes and Arthur L. Schawlow theorized that stimulated emissions could be used for amplifying light waves as well as microwaves. Two years later Theodore H. Maiman constructed the first "optical maser," a ruby laser. Although several other types have since been developed (as discussed in chapter 2), the ruby laser is described below to illustrate laser operation.

PRINCIPLES OF LASER OPERATION

The heart of the ruby laser is the pink ruby crystal; its chemical composition is aluminum oxide and chromium. Only the chromium ions participate in laser action; aluminum and oxygen are not active.

Figure 1 illustrates a typical ruby laser. The cylindrical ruby crystal is surrounded by a helical lamp (flashtube) that is flashed by discharging a capacitor through it. The operation of this lamp is similar to that of the electronic flash that photographers use except that greater energy is discharged. Both ends of the ruby cylinder are polished flat and parallel. Its diameter may vary between 0.1 and 2 cm, and its length can range from 2 to 23 cm. Silver coating is applied to make one end fully reflective and the other end partially reflective so that some laser light can escape (10 to 25 percent transmission is typical). The degree of reflectivity, which depends on the length of the laser, the intended application, and the excitation (flash) rate, determines the total output obtainable.

Most of the energy entering the flash lamp is dissipated as heat, but a fraction of it is emitted as blue and green radiation in the absorption band of the ruby.

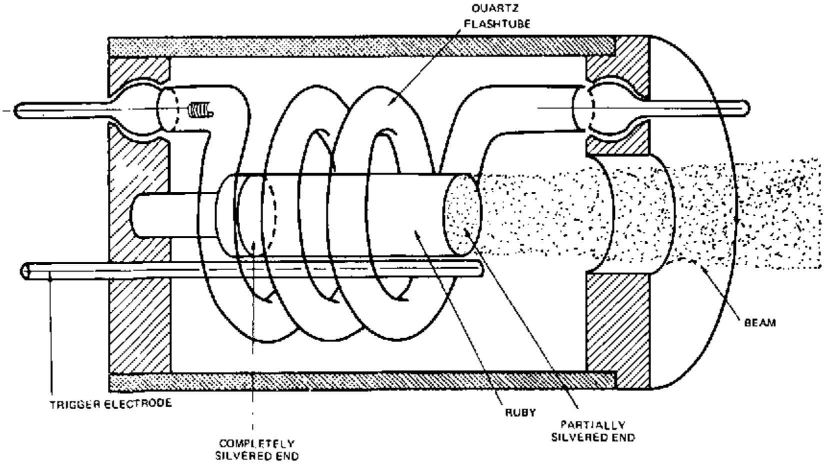

FIGURE 1.–The ruby laser

The ruby absorbs this energy over a broad spectral region and funnels it into a narrow emission line that is determined by the chromium ions. Radiation then emerges coherently through the partially reflecting end of the ruby at a wavelength that is dependent on the temperature. Because efficiency increases at lower temperatures, the ruby is often cooled to cryogenic temperatures to counteract heat generated by the flash lamp.

Operation of the ruby laser requires that the number of chromium atoms (population) in the excited state be greater than the number in the ground state. This is referred to as population inversion because the normal situation is reversed. Supplying energy to achieve population inversion ("pumping") is thus accomplished by the flash lamp.

The ruby laser produces light in pulses, but a continuous laser beam is often more desirable than a series of pulses. Continuous pumping energy is required to maintain a population inversion, which is difficult because of the large amounts of energy pumped into the ruby crystal that cause overheating. Therefore lasers that use other types of active material, with differing energy-level characteristics, have been developed for continuous operation. These are discussed in chapter 2.

CHARACTERISTICS OF LASER LIGHT

The beam from a laser is superior to light from a more conventional source in four respects: intensity, directivity, coherence, and narrowness of bandwidth. These characteristics are not independent because directivity and bandwidth are actually the latitudinal and longitudinal aspects of coherence. However, their practical consequences can be discussed separately.

Intensity

Although the total energy in the pulse from a ruby laser focused by a lens is not very great, it is highly concentrated due to the nature of the stimulated emission process. Each atom is synchronized to add its contribution to the laser beam at precisely the right moment, each photon is in phase with the rest of the beam, and the amplitude of the beam is increased as much as possible.

In a light bulb, the individual atoms produce their energy with random timing. An atom of the tungsten filament is excited by electric heating, decays spontaneously emitting a photon, and then must be re-excited. This may happen almost immediately, or it may take a long time. Meanwhile other atoms are sending out photons in the same way. If the light produced by this process is focused on a steel plate, an irregular stream of photons will hit the plate one after the other not at precisely the same spot but over a relatively large area. The energy is spread over too long a time and too great an area to produce much effect. A laser beam is so narrow and intense that several million photons strike a tiny point on the steel almost instantaneously.

Directivity

Laser beams used in eye operations are focused to spots only 1/10 mm in diameter. Directivity of the laser beam is controlled by the mirrors at the ends of the optical cavity (which in the case of the ruby laser is the ruby crystal itself). A beam can easily originate from a direction not parallel to the crystal axis, and it may trigger off photons from atoms in its path, but eventually it will pass out of the laser system. This may happen before it has reached either of the end mirrors or after one or two reflections; it will be only slightly amplified because it will not have spent enough time in the crystal or cavity. Only when the beam originates parallel with the crystal axis will the mirrors keep it inside the cavity long enough to produce directivity as well as amplification.

Coherence

The term coherence as used here means that the separate light waves in the beam are exactly in step with one another; i.e., they have the same phase. The difference between coherent laser light waves and incoherent light waves that are emitted by a light bulb is shown in figure 2.

Laser light is coherent because stimulated emission always produces a photon that is in phase with the original light beam. The quality of coherence is important because it allows observation of the interference effects that occur when two or more wave trains from different directions overlap and interact.

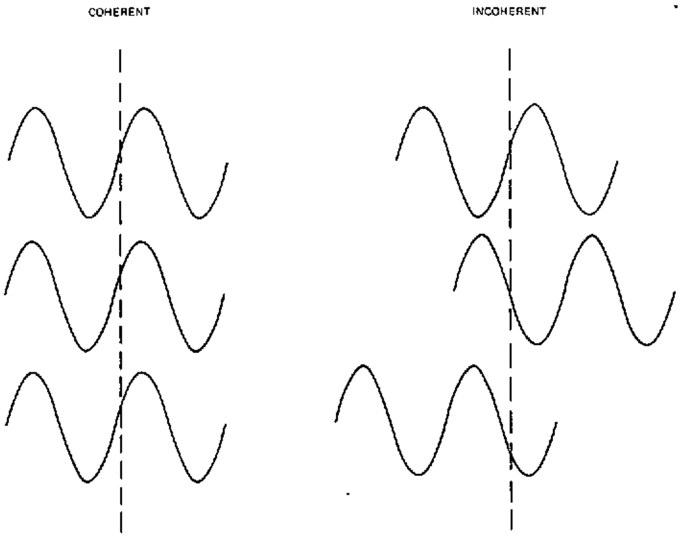

FIGURE 2.–Coherent and incoherent waves

This phenomenon has many technological applications that could not be exploited until the advent of the laser (e.g., holographic interferometry).

Bandwidth

The last characteristic of laser light is its narrow bandwidth. All conventional light sources produce light of more than one wavelength. A hydrogen lamp produces a series of spectral lines which, if closely examined, are not sharp but spread over a band of wavelengths (hence the word bandwidth). This is a function of the energy-level characteristics of hydrogen atoms.

Laser light from certain kinds of lasers is much more uniform in its wavelength content than any other kind of light, and this, too, has significant technological consequences. The narrow spread of wavelengths in the laser beam, like its intensity and coherence, results from the special nature of the generating process. Energy-level characteristics of the chromium atoms in a ruby, for example, cause an incident photon to stimulate another photon of the same wavelength much more readily than one of slightly different wavelength. Thus one wavelength from the band of possible wavelengths is built up to the exclusion of others.

PRACTICAL USES OF LASER LIGHT

The usefulness of the laser can be seen in the variety of its applications. Many applications developed by NASA and others are discussed in chapter 2. In chapter 3 possible future applications and the course that present research is taking are discussed. Typical examples of the areas in which the laser has been used include ranging and altimetry, information transmission, biology and medicine (molecular studies, surgery, and experimental pathology), metallurgy, and the garment industry.

CHAPTER 2

Application of Lasers

The phenomena and characteristics of lasers can be intellectually fascinating and reveal much to the scientist about the structures of atoms and molecules as well as the nature of light. Lasers also offer solutions to problems in production and measurement that reduce costs as well as lead to new knowledge. Laser technology is commercial–today for some fields and in the foreseeable future for others.

In this chapter current laser applications are described in relation to the technologies in which they are used. Two types of applications are omitted: laser holography and optical data processing. These are to be treated in other publications.

LASERS IN METEOROLOGY

Among the first and still major uses of lasers are range finding and altimetry. The representative system described below was developed by the Manned Spacecraft Center for the Apollo Program. In the remainder of this section we will survey laser measuring systems other than ranging.

Range Finding and Altimetry

The laser device illustrated in figures 3 and 4 has been used as a low-altitude aircraft altimeter and terrain contour mapper. Range is determined by measuring the time required for a laser pulse to travel to a target and return. After reflection from the target, a portion of each pulse is collected by a telescope and detected by a photomultiplier. Then a time interval meter measures the elapsed time between transmission and detection, and this time is visually displayed and recorded on magnetic tape for later computer processing.

The range finder was originally developed as an airborne terrain profilometer. By continuously measuring the altitude (above ground level) of an aircraft in level flight, the profile (height and shape of hills and valleys) of the terrain below can be supplied. Up to 1000 range measurements are obtained each second, resulting in a nearly continuous terrain profile when the range finder is flown at a low speed and altitude.

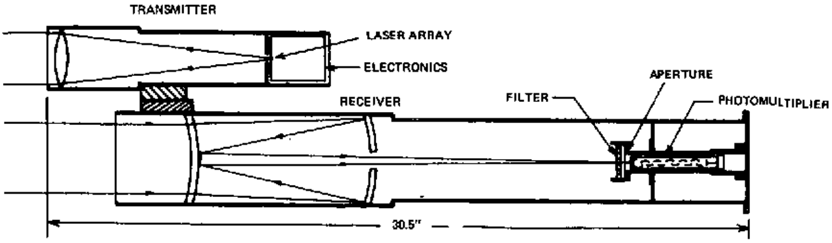

FIGURE 3.–Optical range finder and receiver

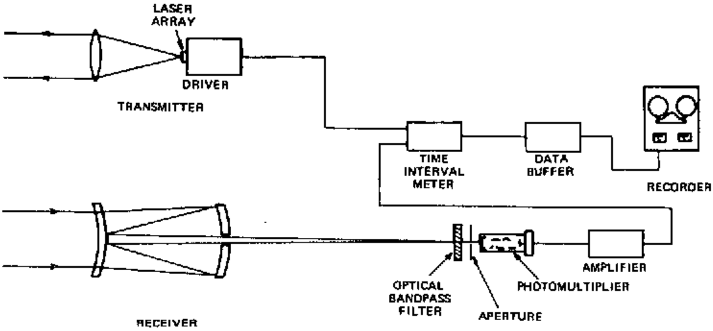

FIGURE 4.–Operation of a range finder system

This system can operate with passive targets, measure the distance to the target with an accuracy of ±30.5 cm (±1 ft), and has a maximum range in bright sunlight of about 76.2 m (250 ft). A 20-element gallium arsenide (semiconductor) laser diode array generates 50 nsec, 140-W pulses at rates up to 1000.

Figures 5 and 6 are profiles of a field of lava rock and a dry lake bed measured during aircraft tests of the range finder at the White Sands Missile Range. They illustrate how well the device operates over surfaces that vary widely in reflectivity. Reflectivity of the lava field was approximately 3 percent, whereas the dry lake bed's reflectivity was greater than 50 percent. Both contours were taken in bright sunlight.

The maximum range of this system (76.2 m) is by no means a present upper limit. A laser range finder on Apollo 15 measured the distance from the spacecraft to the moon–a distance of approximately 111 km (60 n.mi.). Furthermore, a special reflector that was left on the moon by Apollo 15 allowed measurement of the distance from the earth to the moon–more than 370 000 km (200 000 n.mi.).

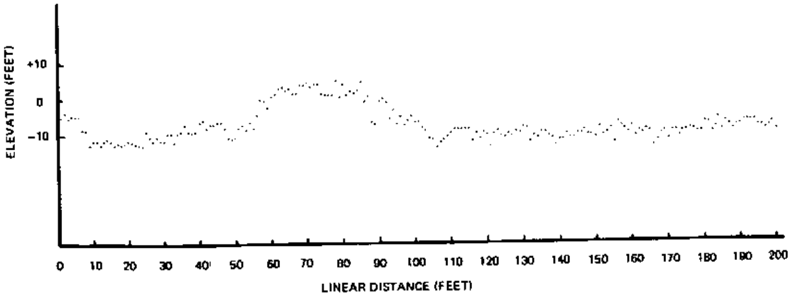

FIGURE 5.–Lava field profile

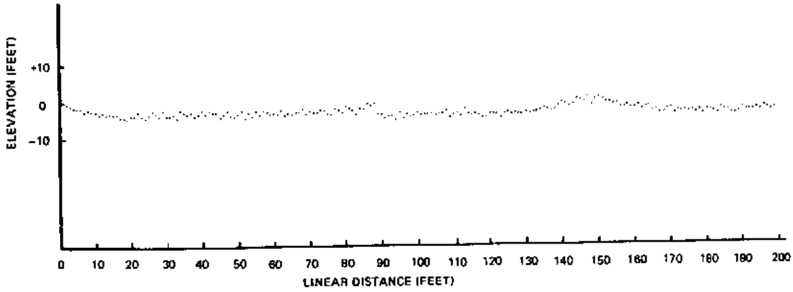

FIGURE 6.–Dry lake bed profile

Laser Doppler Flowmeter

Another meteorological application of lasers is the determination of the motion and relative velocity of fluids by measuring the Doppler shift in the frequency of laser light scattered from the fluid. This measurement is simple and precise; instantaneous velocities can be measured, and no mechanical coupling is required between the flowmeter and the flowing fluid. Velocities as low as 0.01 cm/sec and as high as 1 km/sec have been measured. Figure 7 illustrates a laser Doppler flowmeter developed at Lewis Research Center. Many variations of this system are possible.

The flowmeter works as follows: Light from a helium-neon, continuous-wave, 632.8 n.mi. laser is divided into two beams by beam splitter B. One of the beams passes through the beam splitter to mirror M1 where it is reflected to lens L1. The lens focuses the light to a spot inside the transparent flow chamber where a portion of the beam is scattered from the moving fluid and its frequency is shifted. The light that is scattered through apertures A1 and A2 passes through interference filter F1 to the photomultiplier tube. The other beam is reflected by mirror M2, attenuated by filter F2, and focused by lens

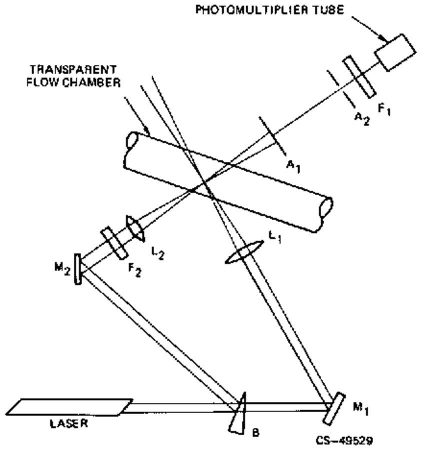

FIGURE 7.–Optical system for fluid velocity measurements

L2 into the flow chamber. This beam passes straight through the flow chamber to the photomultiplier tube and serves as a reference beam. The photomultiplier tube detects, by optical heterodyning, the difference in frequency between the two beams (Doppler shift), and this serves as a measure of the fluid's velocity. The frequency difference can vary from a few hertz to a gigahertz and can be detected and processed with conventional electronics.

Significant advantages of the laser Doppler flowmeter are as follows:

(1) No mechanical device in the moving field is needed;
(2) The fluid flow is undisturbed;
(3) Velocity can be measured at an easily controlled and very small point (about 10 μm long);
(4) No calibration is required;
(5) The method does not require physical contact; and
(6) Measurements in physically inaccessible or hazardous locations are feasible.

Laser Absolute Gravimeter

A new and highly accurate measuring system, the laser absolute gravimeter, was developed at the George C. Marshall Space Flight Center to measure the earth's gravity field.* The gravimeter uses a free-falling mass called a "bird" in a vacuum environment. The distance fallen and the time required for the bird's fall are both determined through use of a laser. From these data gravitational force can be computed.

---

*This system is the invention of Dr. O. K. Hudson at Marshall Space Flight Center. Patent No. 3 500 688 has been assigned to NASA (ref. 1).

Figure 8 shows how the laser gravimeter operates. The laser beam is first projected through a beam splitter. One beam is directed to a mirror in the falling bird from which it is reflected back to the beam splitter; the other beam is directed to a stationary mirror and returned to the beam splitter. The two reflected beams are then combined by the beam splitter and directed to a photodetector that detects interference fringes between the two reflected beams and produces an electronic pulse for each fringe. These pulses are automatically counted and timed by an electronic counter and a high-precision stable oscillator; thus the rate at which the bird falls and the gravitational force are calculated. The free-fall path is 66.9 cm and generates more than 2 million interference fringes.

The light beam originates from a helium-neon, continuous-wave laser that emits radiation at a wavelength of 633 n.mi. This monochromatic light is highly collimated and has a beam divergence of 10 mrad; a collimating lens is also mounted on the laser to decrease further the beam divergence. A polarizing filter can be adjusted for best fringe contrast. The laser unit has a power of 100 μW and can maintain a frequency stability of ±1 kHz per day.

Gas Temperature Measurement by Laser-Raman Scattering

Another application of the laser's unique properties is its use as a remote sensing probe. Some of these applications exploit the laser as an optical radar device (lidar) whose return signal results from the backscattering of laser light by gas molecules. Investigators have used backscattered light from a laser beam

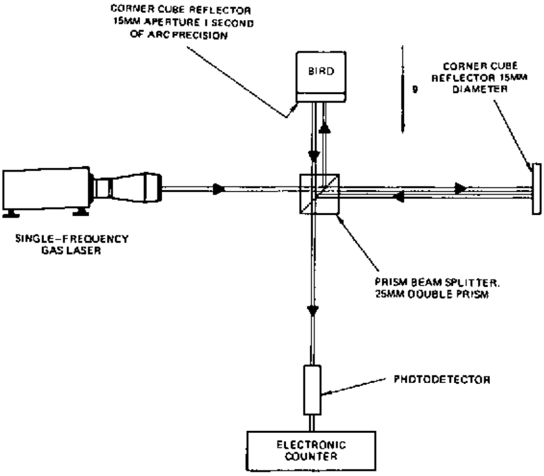

FIGURE 8.–Principle of operation of laser gravimeter

to observe remotely such meteorological variables as aerosol or particulate concentration levels (refs. 2 and 3) in the air.

These experiments suggest that lidar techniques using Raman scattered light could provide additional data on weather parameters. Such a system could remotely measure a local atmospheric temperature by simultaneously monitoring at least two portions of the Raman return signal from a major atmospheric constituent and by examining the ratios of their intensities. The attractive feature of this method is that if the frequencies of the measured Raman signals are relatively close, the effects of all extraneous variables (such as intervening atmospheric phenomena) are essentially eliminated.

An instrument system constructed at Lewis Research Center demonstrated the feasibility of using Raman return in a lidar system for measuring gas temperature (ref. 4). It can measure the Raman spectrum of gaseous nitrogen over a temperature range of 253° to 313° K (–4° to 104° F) at pressures ranging from 506.6 to 5066 N/cm^2 (English). The exciting light source is a continuous-wave, argon-ion laser, tunable to a number of wavelengths by use of an intracavity Littrow prism. For the feasibility demonstration, it was operated at a wavelength of 488 n.mi. and yielded about 200-mW power (fig. 9).

Atmospheric Pollutant Detection by Laser

Two basic laser systems can sense certain molecular constituents in the atmosphere. Both have potential usefulness as monitors of air pollution. One system involves visible or, preferably, ultraviolet radiation that interacts with electronic transitions. The other uses infrared radiation that interacts with internuclear vibration-rotation resonances.

Lidar systems that have been developed so far have used mostly visible or ultraviolet radiation. They are usually confined to observing Raman scattering

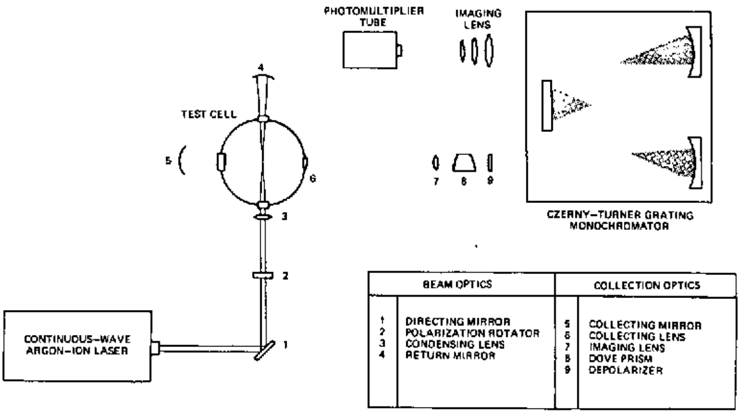

FIGURE 9.–Schematic of Raman spectrophotometer

(a relatively weak interaction effect), although resonant Raman scattering, absorption, or fluorescence could be observed if strong sources of ultraviolet radiation were developed with frequencies matching the strong excitation frequencies of the molecules. This has not yet been accomplished for many of the major pollutant molecules.

Infrared lasers cover a broad region of the spectrum, and many of the laser emissions overlap absorption lines of various molecules (ref. 5). Pollutant molecules could be detected in some substances by noting selective absorption of certain laser lines that pass through a path of interest in a double-ended system, or, in the case of monitoring smokestack effluents, by observing thermal emission lines with a remote heterodyne radiometer. For other applications a single-ended system recording fluorescence from a pulsed infrared laser transmitter would be valuable for remote monitoring, because fluorescence provides a more efficient return signal than Raman scattering. Figure 10 illustrates several of these detection methods.

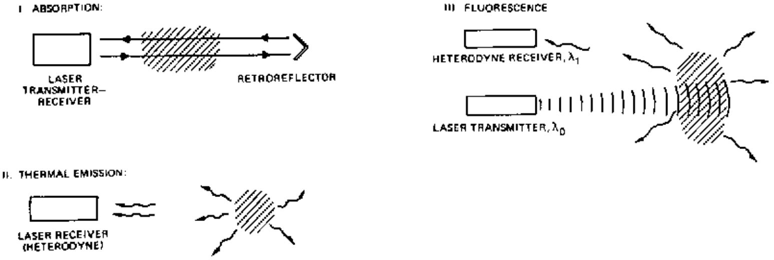

FIGURE 10.–Diagrams of detecting pollutants by absorption, thermal emission and fluorescence, induced by laser beam

A fluorescence system requires high-power lasers to reach suitable sensitivities. Only carbon dioxide and carbon monoxide lasers now offer high enough power output in the infrared to be useful. Both can emit hundreds of different lines in the infrared region where a great number of molecular absorption bands occur, including those of such pollutants as nitric oxide, nitric dioxide, ozone, sulfur dioxide, and carbon monoxide.

The heart of the pollutant monitoring system sketched in figure 11 is the infrared heterodyne radiometer receiver. By widening or narrowing the angular field of view, pollution samples from smokestacks that are several kilometers away can be detected without loss of efficiency. Atmospheric turbulence will reduce the receiver's efficiency; however, receivers operating at a 5-μm wavelength with apertures as large as a meter in diameter have shown very little loss in heterodyne efficiency over a range of kilometers.

Heavy background concentration of a particular pollutant can hamper this receiver's effectiveness in remotely monitoring emissions from a stack. This

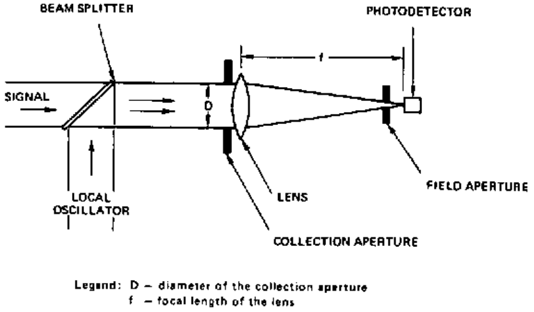

FIGURE 11.–A heterodyne receiver system

occurs largely because of thermal radiation absorption along the path from the stack to the receiver. However, the amount of absorption can be determined if the receiver is first pointed away from the stack toward the background sky.

The type of remote detection system described here requires only a low-power laser, producing a continuous-wave output of only a few milliwatts; it is a relatively simple remote laser sensing system. Infrared lasers can also detect certain hydrocarbons in the atmosphere. Their sensitivities compare favorably with Raman scattering lidar systems that require more laser power. The thermal emission heterodyne radiometer appears useful in remotely monitoring smokestack effluents, whereas a lidar system based on fluorescence could measure ambient atmospheric concentrations and auto exhausts.

Plasma Diagnostics by Laser

Information about plasma composition can be gained through standard emission spectroscopy, if the plasma sample is in a space enclosed by a thermionic diode. Ordinarily these techniques are limited to plasmas in local thermodynamic equilibrium, but the gas laser interferometer offers new possibilities for probing the interelectrode space of the diode. It provides spatial resolution as good as emission spectroscopy and can measure electron density down to 100 billion electrons per square centimeter or lower without relying on the existence of local thermodynamic equilibrium.

The refractive index of the plasma is the parameter that is measured. Not only free electrons but also ground-state and excited-state neutral atoms can contribute to the index; however, application has been generally limited to inert gas plasmas in which the free electrons are the chief contributors to the index at the laser wavelengths used. The index comprises the sum of the individual contributions of the plasma species and can be described in a dispersion equation involving the characteristic absorption frequencies of the atom. The relationship between the plasma refractive index and particle densities for cesium is given in reference 6. Thus particle density may be obtained from the measured value of the refractive index. Such measurements were made by Lewis Research Center by use of an apparatus described in reference 7.

Laser Application in an Electro-Optical Plumb Line

A highly successful application of the laser has been in the precise alignment of large structures, e.g., airframes, accelerators, pipelines, and machinery. Here the laser's properties of straight-line propagation, small divergence, and coherence have come into play.

If it is necessary to lay a base line at a precise angle relative to the local gravitational horizontal, it can be done by mounting a laser in a surveyor's transit and carefully directing the beam relative to the horizontal as defined by the bubble level. However, if a vertical structure must be aligned, the problem grows more complex. One solution is a gimbal-mounted, 90° prism that retroreflects the Fresnel reflections of its input and output faces back to the laser, forming a vertical output laser beam. A simpler and more accurate technique is illustrated in figure 12. Although it shows a planar laser cavity, any standard configuration can be used.

The distinctive feature of this device is the use of mercury as one cavity mirror. Cavity losses are high unless the two mirror planes are closely parallel. Thus only when the output mirror and the mercury surface are parallel will lasing occur; and, in general, this will be along the true gravitational vertical. In its simplest form, then, the azimuthal angle of the optical rail that supports the discharge tube and mirrors can merely be adjusted until an output beam is obtained. This beam will automatically be aligned with local gravitational

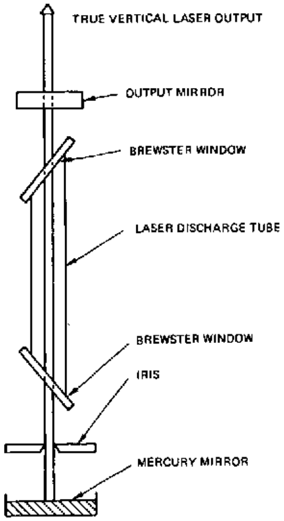

FIGURE 12.–General configuration of a true vertical laser

field lines, except for second-order effects, and hence can be used as an electro plumb line for precise alignment of vertical structures. A simple modification of this basic design would also indicate the levelness of the support on which it rests. Together with a servo system, it could then be used to monitor a stable, horizontal platform.

Although mercury offers many simplifying advantages in this system, its use as a gravitationally sensitive mirror is not always convenient because of problems of vapor-pressure, sensitivity to vibration, and degradation of reflectivity at many of the common, low-grain lasing media wavelengths and at high laser intensities. Figure 13 shows some alternate mirror configurations that are gravitationally sensitive but do not suffer from these disadvantages.

Figure 13(a) illustrates a dielectric mirror floating directly in mercury or other liquid. If the mirror is to be normal to the true vertical, it must be of uniform density with upper and lower surfaces parallel. A more stable arrangement is shown in figure 13(b); figure 13(c) presents still another setup that also damps out mirror oscillations. The latter configuration, used by the Electronic Research Center (ref. 8), comprises a brass conical apex, a hollow plastic midsection, and an aluminized mirror in a 50-percent glycerol-water solution. By choosing a suitable liquid, almost any degree of damping can be achieved with this system.

Measurement of Optical Thickness

In optics it can be important to measure the parallelism, or lack of parallelism, between the opposite surfaces of a transparent object. For example, the

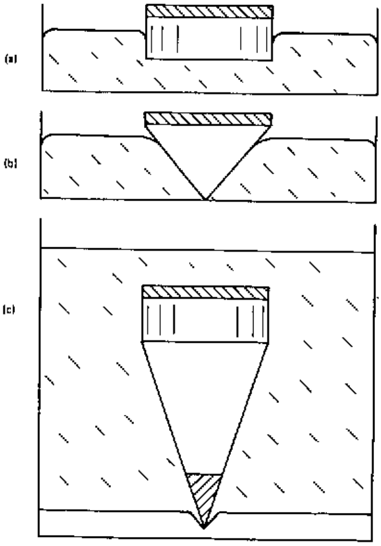

FIGURE 13.–Gravitationally sensitive mirrors that can be used instead of mercury: (a) mirror floating on mercury or other liquid, (b) conical mirror substrate resting on bottom, (c) similar to (b) except vibration damping provided by the surrounding viscous liquid

electro-optic response of optical crystal samples can be determined by measuring how wedge-shaped they are. This kind of parallelism can be measured within ±1/10 μm by use of a collimated monochromatic laser beam to illuminate the object. Reflections of the beam are projected through a field lens, which in effect produces a contour map of the object's thickness. Figure 14 shows a schematic diagram of the apparatus and examples of typical patterns that are observed through the field lens.

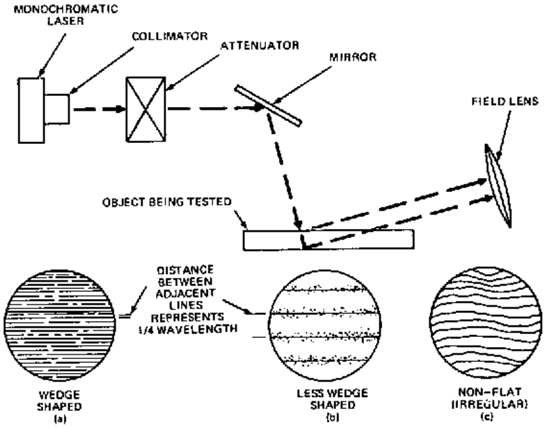

FIGURE 14.–Schematic of optical thickness measurement

Point Coordinate Locator

A computer and an ultraprecision laser-ranging apparatus have been linked in an accurate, easily operated optical measuring system to determine the point coordinates on a photograph. A helium-neon gas, continuous-wave laser provides light for a null-balancing optical system that replaces the conventional drivewire measuring system. No mechanical connection is required between the ranging apparatus and the photograph. The system (fig. 15) consists of a measuring table, a manually positioned cylindrical mirror with centered crosshairs, the laser and associated optics, an electro-optical servo system, and an angular measurement and resonant system.

Ring Lasers

Laser beam coherence is being exploited in the so-called laser gyroscope that detects angular displacement or rotation. Its operation is based on the nature of the laser's optical cavity, which is enclosed between two semitransparent mirrors so that beams leave the laser in opposite directions. The beams travel around a closed optical loop directed by mirrors. One beam moves clockwise and the other counterclockwise (fig. 16), and they are then superimposed on each other.

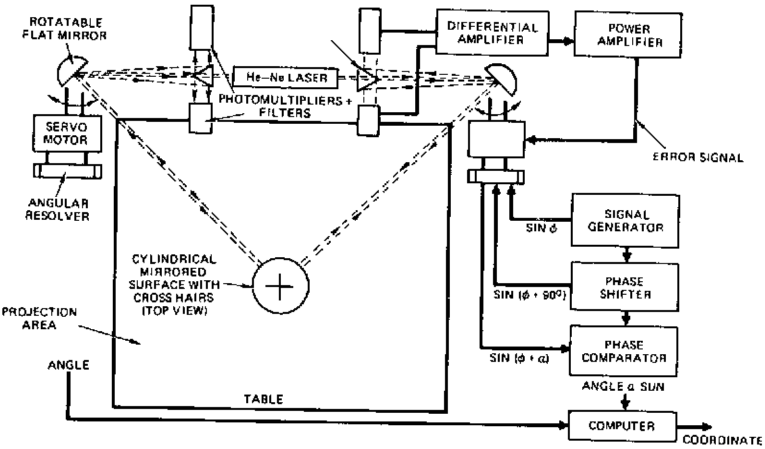

FIGURE 15.–Point coordinate locator

The rotation of the optical loop results–according to the general theory of relativity–in time dilatation for the beam traveling in the direction of rotation and in time contraction for the beam traveling in opposite direction. Consequently, the velocities of propagation for the two beams become:

$$\nu_1 = c - K \text{ and } \nu_2 = c + K$$

where ν_1 is the velocity of the beam traveling in the direction of rotation and ν_2 that of the opposite beam. In these two expressions c is the velocity of light (beams), when the optical loop is at rest and K is a function of the wavelength of the beams, the path length of the loop and the area enclosed by the loop. The beam propagates slower in the direction of loop rotation and faster in the opposite direction. It appears therefore that the beam in the direction of rotation traverses a longer, and the opposite beam a shorter path, than the actual path length of the loop.

This frequency difference can be detected by electronic circuits if the two beams are extracted and allowed to produce a series of interference fringes. This can be done with a combiner prism as shown in figure 16. The fringe pattern moves when the supporting table is turning or rotating, and the number of fringes crossing the detector each second is proportional to the angular velocity of the rotation. Each fringe thus precisely represents an angle through which the supporting table has turned.

The great attraction of laser gyroscopes is their ability to sense extremely high angular velocities. A conventional gyroscope mounted in a vehicle that makes a sudden turn will take several minutes to settle on the new bearing. Laser gyroscopes have no mechanical motors and respond instantly to a sudden turn. They also contain none of the magnetic- and temperature-sensitive elements found in conventional gyroscopes and can be started instantly, as opposed to a 15- to 30-minute startup time for conventional gyroscopes. The laser gyroscope is also much more rugged than the conventional type, and its operation is not affected by the high accelerations encountered during takeoff and maneuver of spacecraft and missiles.

OPTICAL COMMUNICATION SYSTEMS

Laser communication systems are the optical analog of radio systems used for voice and television transmission. Although they are not yet commercially practical because of problems in propagation through the atmosphere, several systems are in the experimental stages. Outside the earth's atmosphere, laser transmission systems are already being successfully tested. A laser radar system can determine the relative position and orientation between two spacecraft in flight. Lasers are also apparently feasible for communicating with satellites from the earth in regions where good visibility usually prevails. This was demonstrated with the NASA satellite GEOS 2.

Information Transmission with Laser Beams

Transmission systems that use laser light are a logical development of radio and microwave systems. In contrast with conventional communications, lasers have the advantages of high directivity and a very wide range of possible bandwidths. This means that large numbers of telephone conversations or a great many television broadcasts can be transmitted and received simultaneously. Although demonstration units have proven the feasibility of this technology, there are problems with practical implementation, especially for terrestrial systems.

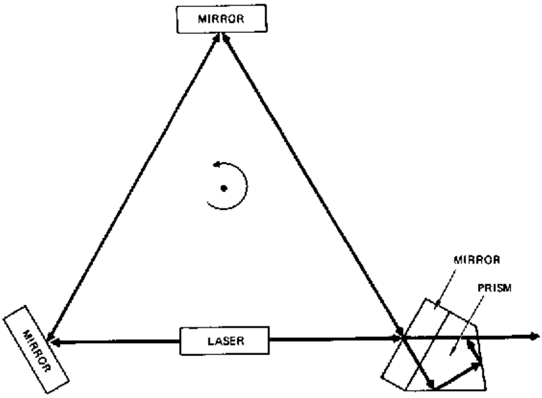

FIGURE 16.–Concept of laser gyroscope

Clouds, fog, rain, and snow interfere with optical transmission through the atmosphere. Laser communications beyond the earth's atmosphere are likely to be perfected first. Figure 17 shows a typical communication system. A laser oscillator generates a single wavelength of constant amplitude. Information in the form of an electrical signal is then superimposed on the laser beam.

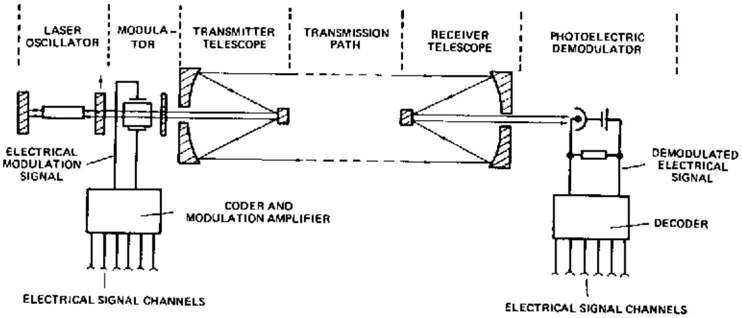

FIGURE 17.–Laser communication system

All the methods of modulation used in electronics are possible, including amplitude, phase, frequency, pulse-amplitude, pulse-phase, and pulse-code modulation. The modulated signal is fed to a telescope (which performs the same function as a radio antenna), or the narrow beam from the oscillator can be transmitted directly. This signal is transmitted to the receiving antenna and is demodulated there in a photoelectric converter.

Laser Radar System

A Scanning Laser Radar (SLR) system to facilitate space vehicle docking, rendezvous and station-keeping operations was developed by International Telephone and Telegraph for the Marshall Space Flight Center. The SLR not only determines the relative position and orientation between two spacecraft but can also provide basic data to the vehicle guidance, navigation, and control systems on slant range between chaser-target vehicles, range-rate, pitch and yaw line-of-sight angle, and so on (fig. 18).

The advantage of laser over microwave radar is its directivity or beamwidth. The beamwidth that is obtainable by any system is directly proportional to the wavelength and is inversely proportional to the antenna aperture. Inasmuch as the optical wavelength is four orders of magnitude smaller than that of the microwave, a significantly smaller antenna size can be used for the same bandwidth.

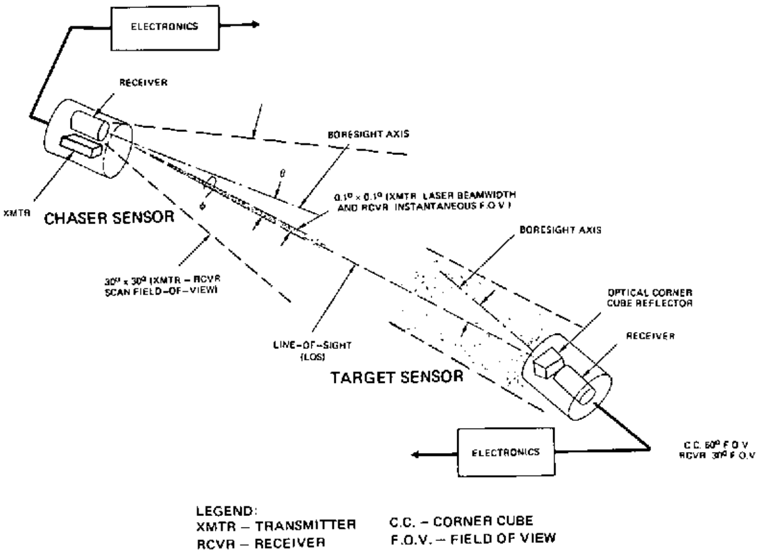

FIGURE 18.–System block diagram scanning laser radar

The major subsystems and associated key components of the SLR are

(1) Laser Transmitter–diffraction-limited, gallium arsenide, semiconductor laser
(2) Beam Steerer–piezoelectric beam deflector and amplifying optics
(3) Receiver Optics–high-speed, narrow-band, refractive receiver optics
(4) Scanning Optical Detector–image dessector
(5) Electronics–high-speed integrated circuits
(6) Cooperative Target–optical corner cube reflector.

The SLR system also has potential as a low-rate optical communications system. With only minor modifications it could transmit at data rates of 5 to 10 kbits/sec. The laser pulses would be pulse-code modulated at the chaser and demodulated at the target. The SLR could thus simultaneously perform the radar and low data rate communication functions (one-way communication from chaser to target). Two-way communication could be achieved if an SLR chaser-type sensor and electronics (transmitter and receiver) were put on both space vehicles.

Electro-Optical Tracking System

Smaller antenna size–the same feature prized in optical radar systems–is the prime improvement in a laser tracking system developed by Sylvania Electronic Systems for Marshall Space Flight Center. It employs a laser with an electronic beam deflector and image dissector to track a space vehicle from lift-off to a maximum slant range of 10 km. In addition to search and acquisition, the system's electronically scanning transmitter and receiver can track rapid movements or accelerations of the target.

Components of the telescope assembly are contained in three aluminum tubes and a small electronics chassis that are supported by a bezel casting mounted directly on the elevation gimbal of a tracking pedestal. The transmitter tube contains the beam deflector, which can electronically steer the laser beam in two dimensions (fig. 19). The system's ultimate accuracy rests with the image dissector contained in the receiver. The telescope in the central tube is a simple Newtonian astronomical unit. Control electronics, system logic circuitry, and power supplies are in an external container not shown in the figure.

Multiple Wavelength Laser Radar

A mobile laser radar system housed in an environmentally controlled van (fig. 20) was used at Langley Research Center to measure dynamic processes taking place in the lower atmosphere (ref. 9). The laser and telescope were aligned parallel and pointed at the zenith through a hatch in the van roof. A ruby laser was used in this experiment with frequency doubler and a 16-in.-diam Newtonian telescope collector (fig. 21). Outputs from a photomultiplier were displayed on dual-beam, dual-trace oscilloscopes and were photographed. The oscillograms were then analyzed by a film reader whose punched-card output was fed to a computer for processing and plotting.

Optical Superheterodyne Receiver

Reception of amplitude-modulated (AM) signals through the atmosphere was made possible by an optical superheterodyne receiver developed by

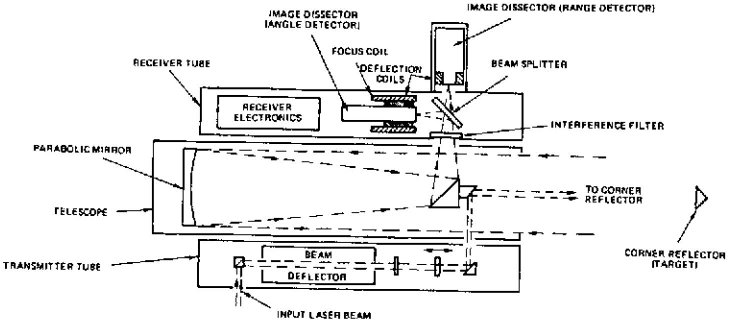

FIGURE 19.–Electro-optical tracking system

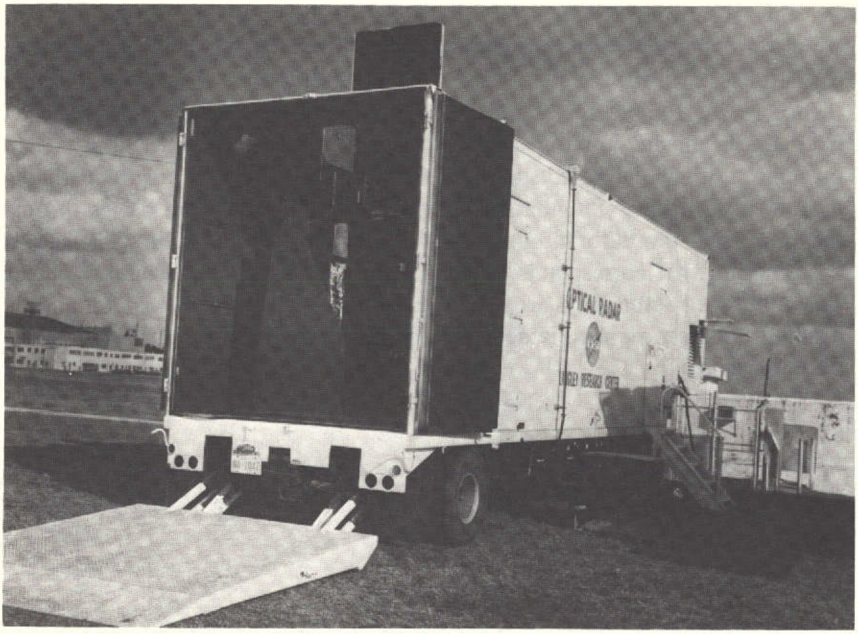

FIGURE 20.–Mobile laser radar van

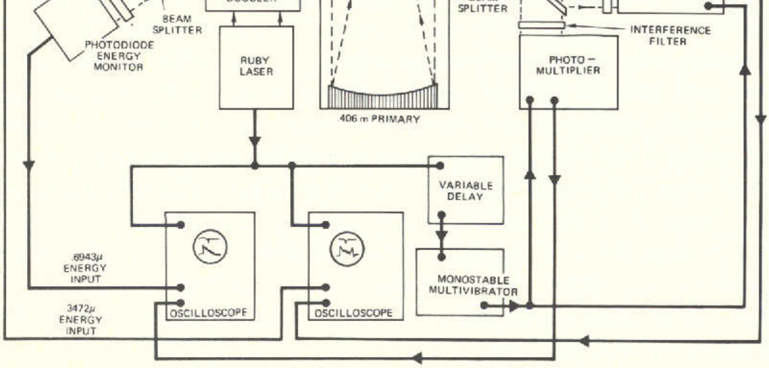

FIGURE 21.–Block diagram of experimental multiple wavelength laser radar

Sylvania Electronic Systems for the Marshall Space Flight Center. A laser coupled to a frequency translator supplies both the incident and the local oscillator signal in the receiver. Laser output is reflected to a beam director and thence to the remote retro-reflector (fig. 22). The return rays are reflected from the beam director to a parabolic mirror and then to a secondary beam-forming mirror which directs the rays through the open center of the parabolic mirror to the adder. Simultaneously the local oscillator beam passes through the frequency translator producing a frequency offset. This beam is focused onto a point that corresponds to the focus produced by the secondary mirror. The collimated return rays are mixed with the local beam at the adder, and the resultant difference beat is detected by the photomultiplier and fed to the output circuitry.

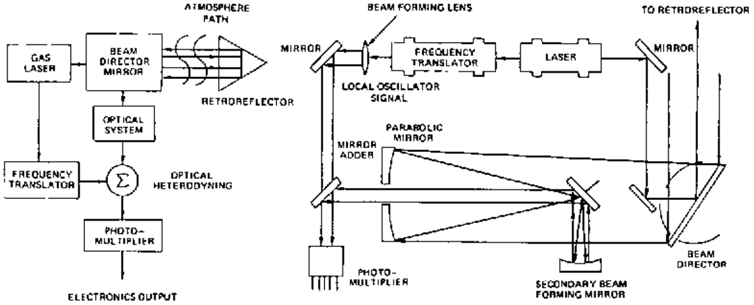

FIGURE 22.–Optical superheterodyne receiver

An Experimental Laser Communication System

Although operation of optical communication systems is quite problematical because of the high attenuation of light waves through the atmosphere, the Marshall Space Flight Center has developed an experimental laser system to study the feasibility of such communication. The system consists of an airborne experimental package and a ground station, which are both equipped with transmitting lasers and receivers to obtain data on uplink and downlink propagation. The ground station uses pulsed laser radar to locate the aircraft and to track it during the course of the experiment. The airborne package is also capable of locating and accurately pointing its laser at the ground station. The optical layout of the ground terminal is shown schematically in figure 23. In addition, acquisition radar comprised of a pulsed argon laser, beam steering optics, and receiving electronics is mounted on and bore-sighted with a 0.6096-m Cassagrainian telescope tube.

The airborne end of this communication link (fig. 24) views the ground station in a steerable mirror which is servo-controlled to point the outgoing beam

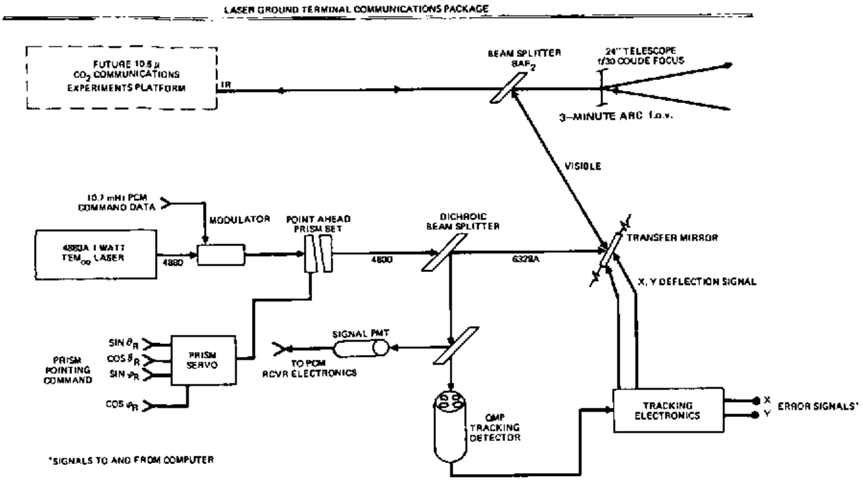

FIGURE 23.–Ground terminal of laser communications system

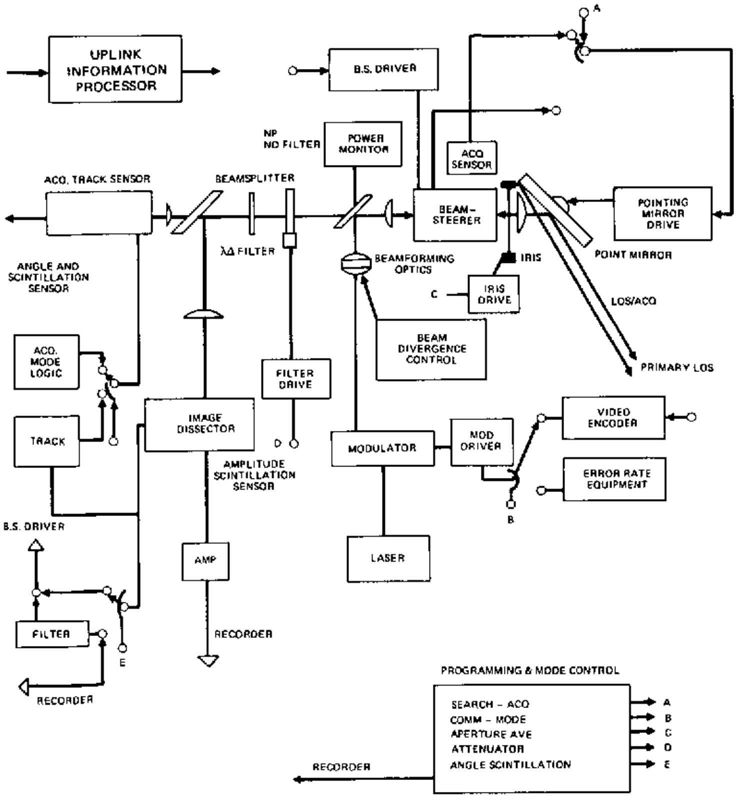

FIGURE 24.–Airborne terminal

in the proper direction. During acquisition the mirror is pointed in the general direction of the ground station. When the ground-based beacon illuminates the aircraft, an acquisition sensor detects the upcoming beam and causes the system to enter a track mode. An image dissector provides tracking information, and a photomultiplier detects upcoming commands and measures scintillation. The airborne transmitter is a helium-neon laser superimposed on the incoming beam by means of a dichroic beamsplitter; the outgoing beam is pulse-code modulated. Operation of the airborne terminal is controlled by signals sent from the ground terminal (ref. 10).

LASERS IN MEDICINE AND BIOLOGICAL SCIENCES

Interest and activities in the development of laser systems applicable to medicine or the biological sciences are quite impressive. Most of this work has been carried on outside NASA, particularly in the medical departments of several universities. The advent of the laser, with its special characteristics, has enabled researchers and medical practitioners to innovate surgical methods (ref. 11) and to conduct fundamental studies of the structure of macromolecules, e.g., amino acids, proteins, and nucleic acids. This section cites a few examples to indicate the trends and the present concentration of efforts in laser technology as a tool in the life sciences.

The laser beam, interacting with living tissue, can be used as a surgical tool in delicate eye operations. By the same token it can also be harmful to inadvertently exposed organs. In the early days of laser research there were some laboratory accidents which caused eye injuries. Scars and bubbles of gas can result from a laser beam's disruption of eye tissue, and cataracts may begin to form when the lens of the eye absorbs energy of the wrong wavelength or when the power is too high. The risk of cornea damage is also present.

One of the most serious aspects of this problem is that damage occurs instantaneously, and the researcher and the victim himself may not be aware that it is happening. The degree of damage depends on the energy density and the length of exposure. Although exposure time may be quite short with a pulsed laser, the energy density is often high. If all the energy from a conventional ruby laser were to enter the eye, its density would be many hundreds of times greater than that used to form scars in detached retina operations, and about 47 000 times as great as exposure to the sun for the same period of time. The most extensive studies on laser radiation damage to living organisms have been conducted at Stanford Research Institute in Menlo Park, California.

Although it is now common practice for anyone working with lasers to wear protective glasses, none the less these are not safe in laboratories in which laser energy is converted to different wavelengths. Thus laser laboratories have enacted rigid safety codes designed to prevent damage to the skin and eyes.

Retinal Coagulation

The retina of the eye is loosely attached to a choroid coat. The retina is of neurodermal origin, whereas the choroid is ectodermal. At the embryo stage these two join and subsequently are held by a thin layer of connective tissue. In adults any number of circumstances, including trauma, can cause separation of the retina from the body of the eye. This leads to a loss of vision because the light cannot be properly focused on the detached retina.

For a number of years, retinas were surgically reattached by use of long needle-like probes to weld the retina to the choroid with a scar (ref. 12). This worked quite well and allowed proper focus to be regained, but it produced one or more blind spots. In the 1950's the xenon photocoagulator was introduced. It produced the same effect through a pulse of intense white light which, when focused by the lens on the retina, resulted in reattachment by coagulated blood in a fashion similar to spot weld. But this method also had disadvantages. The device was very bulky, and its intensity was not high enough or specific enough to allow exposure times shorter than 1 sec. The wide light cone entering the eye sometimes caused damage to undesired sites, and uncertain reactions to white light required "overdoses" to achieve the correct response.

More recently, retinal repair has been accomplished with the high intensity of the laser beam. This method obviates all the disadvantages of the earlier methods. At first ruby lasers were used; then neodymium and finally argon lasers were employed. The value of the argon laser over the xenon photocoagulator is the much smaller size of the spot weld that allows finer "stitching." It is particularly valuable around the fovea—the area of the retina that controls acute vision. Neither anesthesia nor hospitalization is required (ref. 13).

Skin Cosmetic Repair

The destructive effects of lasers have been harnessed for treating some skin disorders. Inasmuch as laser light is preferentially absorbed by pigmented tissue, one of the first experiments was the removal of tattoos. The favorable results led to further study, especially in the cosmetic treatment of angioma (an excessive proliferation of fine blood and lymph vessels in the upper skin layers, which produces a reddish discoloration of the skin). The impact of a laser can occlude the blood vessels and blanch the skin that leads to eventual healing of the impact area and normal skin coloration.

Skin Cancer

Experimental treatment of skin cancers has also been based on laser light's quicker absorption by pigmented tissue. There are differences between normal and cancerous skin cells, and a search has been underway for a dye or pigment that is completely selective for cancer cells. Although the research has not been completely successful, cancer cells can now be stained considerably darker than normal cells. The darker cancer cells then absorb more light energy from the impact of a laser beam and are more severely damaged than normal unstained cells. Two types of cancer treatment with lasers have been practiced. A low-energy beam has been used selectively to disrupt tumor cells. Higher-energy beams are more suited for excising nodules from deeper tissues.

Two problems have arisen with this treatment. First, the plume of debris from laser impact contains viable cancer cells which pose a possible hazard to operating room personnel. Second, the impact drives some of the tumor cells deeper into uninfiltrated tissue, thus spreading the cancer. The first problem has been solved by placing a cone over the laser head to catch the plume from impact. The cone may be attached to a suction device for vacuum cleaner action. The second problem may be overcome by improved techniques.

Bloodless Surgery

Bloodless surgery with a laser scalpel is an outgrowth of the perfection of cobalt and argon ion lasers. The infrared radiation of cobalt and the green argon light interact dramatically with tissue making a "cut" in which vessels scar immediately. These techniques facilitate surgery on organs such as the liver and kidney in which blood loss is a problem. Although the use of high-energy argon lasers is still experimental, it may soon become standard for liver operations, with concurrent use of plastic adhesives to complete closure. Disadvantages of laser surgery are the development of smoke that impairs the surgeon's vision and difficulties that are connected with healing of the charred cut. These may restrict it to certain special conditions.

Transillumination

Transillumination is a technique in which strong light is projected through soft tissues to aid in detecting tumors. The skin is relatively transparent to light and thus lasers may be useful for such examinations. Laser transillumination could allow immediate examination for breast cancer without the potential hazard or delay associated with x-rays.

Neurosurgery

Neurosurgery is another promising area for lasers inasmuch as they can accomplish the precisely controlled cutting that is important in this type of surgery. Transsection and tumor treatment can also benefit from the use of lasers, and bloodless tumor removal may soon be within reach. The possibility of infection after operations on the gray matter of the brain may be reduced if lasers can be used.

Lasers in Dentistry

At the Cincinnati Children's Hospital Research Foundation, doctors have focused a ruby laser beam into tooth cavities and produced extensive destruction of the decayed areas. Laser energy is absorbed by the dark, decayed parts of the tooth but not by the healthy areas. Pulses of about a millisecond are enough to destroy the decayed areas so that there is no overall heating of the tooth and none of the vibration associated with mechanical drills. It seems likely that laser "drilling" can be carried out without anesthetics. Large, deep decayed areas can be drilled out by repeated firings of the laser, and cavities in inaccessible areas of the teeth can be treated by transmitting the laser beam through a flexible glass-fiber rod.

Researchers at Cincinnati and elsewhere are also investigating the use of lasers to prevent tooth decay as well as to correct it. Decay is believed to start in minute cracks on the tooth's enamel which allow decay-forming organisms to spread to the more sensitive inner areas. A laser beam might seal a crack by fusing the enamel on each side. It may also be possible to use new, longer lasting materials for filling teeth; a laser beam can melt highly refractory materials such as porcelain and thus can be used to fill tooth cavities.

A Laser Microscope

A scanning microscope designed at Yale University can be used to study fundamental cell types imbedded in a thick, translucent body, such as a nerve cell buried within the brain. In ordinary microscopy these covering layers obscure and degrade the image of the object that is to be studied.

One recently designed microscope used ordinary light and a perforated rotating disk to scan the optical field (refs. 14 and 15). Although it eliminated unwanted reflections and allowed limited observation of brain cells and similar tissues, the image quality was too low for most biological investigations—only 1/10 000 000 of the light reflected from the source reached the microscope's eyepiece. A new microscope featuring a helium-neon laser light source (ref. 16) not only uses light more efficiently but also allows maximum discrimination between planes of observation (fig. 25).

Experimental Pathology

Experimental pathology and biology often rely on separating or changing one subsystem and studying the behavior of the altered total system. When the interest is cell functions, intercellular entities as small as micrometers may be excluded. One rather crude way to achieve this is to destroy the undesired part. If a microscope is used for observation, an ideal destruction technique is to apply laser pulses through the same microscope. Only optical tools are needed: The highly collimated laser beam can be pinpointed simply by aiming

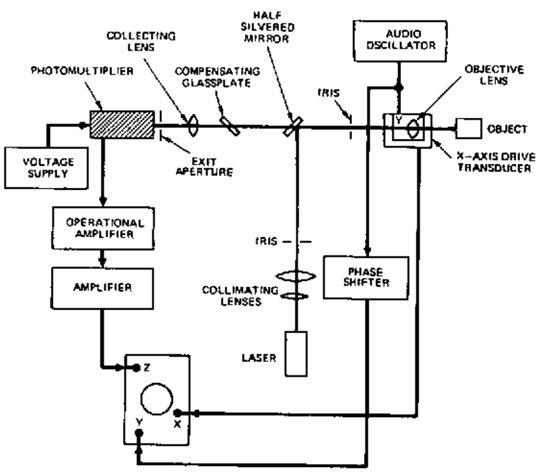

FIGURE 25.–Schematic block diagram of microscope

and can be focused to a spot only one or two wavelengths in diameter. The method is quick, which is a necessity since motion occurs and the response of the biological system must be clearly separable from the impact of initial preparation. The single-wavelength feature of the laser can overcome deficiencies in microscope lenses (ref. 17).

Molecular Studies in Biology

Greater knowledge of molecular structure in cell biology has been gained, thanks to exploitation of the monochromatic property of laser beams in spectroscopy. When monochromatic light energy strikes a molecule, some light is scattered, but part of the initial photon energy can also cause linear or rotational oscillations. This part of the energy is missing in the re-emitted (scattered) photon; hence the re-emitted light has a frequency (wavelength) different from the original frequency. The impinging light can also make excited molecules jump to a lower energy level. These phenomena result in typical Raman lines centered around the original line in the spectrum; the line shifts are characteristic of the molecule's structure.

In normal spectroscopy these line shifts occur in the experimentally difficult infrared region because the energy changes are so minute. The Raman effect lifts the lines up to the more practical visible spectrum, but investigation of Raman lines was difficult until the laser provided a well-collimated light source with sufficiently narrow spectral width and high intensity to excite the samples. Raman studies that use laser techniques are now benefiting both cell biology and quantitative biology when modules must be identified.

Lasers in Cytology

A new method for instantly and positively identifying micro-organisms and tissues is now possible with commercially produced laser instruments. First a sample is cooled to low temperature and irradiated with ultraviolet laser light. Under these circumstances the sample itself produces phosphorescent light whose frequency and decay time are characteristics of the organism. A small computer matches these data with information previously stored and immediately identifies the composition of the sample.

This example illustrates the bright prospects for broadening other areas of knowledge about cell functions through the use of lasers. Development of tunable lasers or lasers with different wavelengths will not only facilitate research on cellular activities but will also yield more information about the mechanism of laser radiation (refs. 18, 19 and 20).

LASERS IN INDUSTRY

It was inevitable that laser light should find application in industry. The reason is simple: lasers have four characteristics that cannot be obtained collectively from any other energy source, namely, monochromaticity, coherence, high intensity, and minute beam divergence. The laser's success in industry, especially in the metalworking industry, has also been greatly assisted by the improvements in reliability and durability of laser sources over the early models.

Metallurgy

Lasers have become practical tools for the metalworking industry because few substances can withstand the energy flux of a high-powered laser beam focused to a density of up to 10 billion W/sq cm. Melting and vaporization are the usual results, even with hard metallic alloys and ceramics. This fact has led to a variety of laser applications, from ordinary welding and machining to highly sophisticated metallurgical experiments. The laser's flexibility is such that it can be accurately focused in diameters ranging from a few hundred micrometers to more than a centimeter, and the rate of penetration for a given material is largely controlled by the level of energy concentration.

The exact mechanism of laser penetration, i.e., drilling is not known; however, metallurgists are studying structural changes that occur in grains and fibers adjacent to laser-drilled holes. A laser beam cannot only cut or drill holes in many materials (especially metals), but can also be used for other types of machining and fabricating where high heat flux in a very small area is needed, such as metal-melting and evaporation in vacuum, microwelding, and cutting.

Microwelding has seemed attractive to industrial physicists. Although the laser beam normally tends to vaporize rather than melt small amounts of metal, melting alone will occur if the material that is to be welded is cooled. Laser action can thus create tiny molten surfaces that can be merged or fused as in ordinary metal welding. Laser techniques have now superseded earlier experiments in the use of electron beams for small precision welds.

Welding, like drilling, is a very old technique, but in the past two decades it has been more refined. New alloys demand special conditions such as inert atmospheres or argon or helium gas around the welding action. High-temperature electric arc and plasma gas torches are now common. Laser micromachining and microwelding are economically sound only when other, more conventional, processes fail. But when electrodes or physical contact are not desired, when the work must be done in air or in a controlled atmosphere rather than in a vacuum, when dissimilar materials are used, or when minute quantities of high-melting-point metals are involved, then the laser technique is often the best or the only solution to the welding problem.

The two sources most suitable for heavy metalworking are the ruby and neodymium lasers, both of which can produce pulses with high enough energies to remove large amounts of material. For most other metalworking applications, the neodymium-yttrium (the rare-earth element neodymium in a host matrix of yttrium aluminum garnet) and the carbon dioxide lasers seem most favorable. The carbon dioxide laser can be employed in a repeated pulse mode, whereas the neodymium-yttrium laser can be used for some applications in continuous operation and for others in a repetitively Q-switched mode.

Q-switched lasers produce high peak powers and have pulse lengths of the order of tens of nanoseconds. They operate by optically isolating the active material from the end mirror of the laser cavity so that the population of excited atoms is allowed to build up to a high level and store a great deal of energy. The laser material is then suddenly opened to the mirror, and the stored energy is released in one rapid pulse rather than over a longer period as is the case in a normally pulsed laser. Q-switching decreases the total energy output but compresses the pulse width so that peak power is much higher. It can be accomplished by inserting a Kerr cell or a bleachable liquid dye cell in the optical cavity between the laser material and the mirror (ref. 21).

The continuous neodymium-yttrium laser offers enough power for continuous seam welding. For spot welding the laser's focusing properties are of most interest. Gas laser beams can be focused to dimensions about the same as the light's wavelength; however, typical values for ruby and neodymium glass laser pulses—the usual tools of spot welding—are about 300 μm with the use of a simple lens. The beam can be shone through an aperture to produce a smaller focal area, at the expense of total energy in the beam, but this does not increase brightness at the focal area.

Welding

Lasers can do welding that is impossible with other methods. Lasers can make repairs inside transparent enclosures (such as vacuum tubes), reattach filaments, restore plate continuity, and fuse grid leads. Laser welding also has been used to attach small insulated wires in electronic assemblies where the advantage is that the laser beam vaporizes the insulation without leaving a residue during the welding process so that the wire does not have to be stripped before welding.

In any laser welding application, heat input to the workpiece is very small compared with other welding processes. This means that the size of the heat-affected area and thermal damage to adjacent parts are held to a minimum. Inasmuch as the heat source is a light beam, direct contact with the metal is not necessary; inaccessible joints can be welded as long as a direct line-of-sight exists. The beam's high-power intensity can be used to make difficult welds between dissimilar metals with high electrical resistivity or between non-conductive materials.

Drilling

Lasers have been used successfully to drill alloys of gold, silver, copper, nickel, iron, aluminum, titanium, molybdenum, tantalum, columbium, zirconium, and tungsten. Nonmetallic materials like diamonds, rubber, plastic, and wood can also be drilled by lasers. Although some of these materials have nearly 98 percent reflectivity at the laser wavelength, high-peak powers can remove substantial amounts of material. Nearly all metals and nonmetals can be drilled when the desired result is a small hole through an area a fraction of an inch thick. If the workpiece is moved while the laser beam is firing, the beam will cut a slot. If the material is only a few mils thick, the slot will penetrate it completely; in thicker materials it will cut a groove.

Machining

The noncontact nature of laser machining is especially suited for taking metal from a moving object. Frequency tuning of quartz crystal resonators is accomplished by selectively vaporizing a thin layer of gold deposited on the crystal. As gold is removed, the resonant frequency of the crystal increases. Lack of mechanical contact permits tuning of the resonant frequency while the crystal is operating in an active electronic circuit.

Another laser application for metal removal is in balancing operations. A dynamic balancing machine detects imbalance and transmits an electronic signal to laser control circuitry. The laser fires at the proper instant, removing metal from heavy spots on the rotor while it is spinning. Repeated shots are fired until sufficient metal has been removed to bring the rotating device into perfect balance. This process can correct imbalance in a component such as an armature, in the construction of a gyro, or in the balance wheel of a timepiece.

Photographic Platemaking

The halftone photographic plates used in printing apply ink to paper from a surface that stands out physically above the background on the plate. In the past, chemical methods were used to eat away the background after the desired areas were coated with an acid-resisting material. Now electronically controlled tools have been used to gouge out the background areas from metal or plastic plates. These tools are driven by signals from a photoelectric cell that scans the picture to be printed. This principle has been advanced with the use of computer-controlled laser pulses to etch the plates in a few seconds–far quicker than conventional methods. When a pulsed laser beam is focused to a point on a metal surface, a fragment of the metal is vaporized leaving behind a small cone-shaped crater. Repeated pulses from the laser beam burn a series of cavities in the plate's surface leaving the untreated areas at a higher level on which to take the ink for printing.

Machine Tool Industry

The distance-measuring capability of the laser has been utilized in precise calibration and verification of measuring tapes and scales. In an industrial system that is now being used the calibration accuracy is 0.000254 mm (0.0001 in.). The laser has also been employed for tool positioning in a numerically controlled machine tool. The final tool position accuracy in one commercially available system is 0.00079 mm, a significant improvement over other systems.

Garment Industry

In the garment industry the laser's potential has been recognized. A computer-driven garment cutter using a laser beam was placed in operation by a manufacturer of men's suits. The laser unit cuts garments one at a time, up to 15 to 20 per hour, to tolerances of a single thread width. Mechanical cutters can match the laser system's speed only by cutting 20 to 25 layers of cloth at a time–a process plagued by inaccuracies and waste of material (ref. 22).

The laser cutting system has four components: a computer that stores patterns and cutting instructions, a laser positioning device, the laser, and a fabric conveyor. A single layer of material is unrolled from a bolt and moves along the conveyor until it is directly under the positioning device. The computer then turns on the laser beam and maneuvers it above the cloth following any complex pattern that is stored in the computer.

CHAPTER 3

Possible Future Developments

NEW PUMPING METHODS

Among the fields in which development and innovation in laser technology can soon be expected are the new methods of pumping. Improved techniques are constantly being sought because flash lamp pumping of solid-state crystal or glass lasers is relatively inefficient. Both Government and industrial laboratories, e.g., the Naval Research Laboratories and North American Aviation Corp., are now working on new chemical pumping techniques which are based on the fact that light and heat generated by certain chemical reactions is intense enough to induce lasing action in selected materials.

The idea of using the radiative energy of a chemical reaction as pumping energy has also triggered another pumping idea: the use of nuclear heat as a direct heat source for a laser (ref. 23). In this scheme, heat from a nuclear fuel is transferred to a cathode, and electrons are emitted thermally into a gas lamp, tube, or diode built to act as the laser itself. The virtue of the nuclear system, as well as with the chemically pumped lasers, is the elimination of an external electrical power supply for pumping action.

The sun has also been suggested as a pumping source, and experiments in this area have been described in many papers and articles. By use of reflected energy from a lightweight parabolic solar concentrator, a proprietary device developed by Electro-Optical Systems, Inc., has produced a continuous-wave output of 25 mW at 300° K (540° F) in ground-level sunlight; in space, sunlight could produce 1 W of continuous wave output. Another suggested method of pumping is the use of exploding wires that will emit brief, sharp bursts of light to trigger laser action in a suitable receiver.

NEW LASER MATERIALS

Probably the most extensive progress in laser development will be made in the selection of new materials for laser emitters. These will be chosen for their versatility, reasonable production cost, stability, and efficiency in producing light amplification. The hope of attaining a wider wavelength coverage is one important stimulus in the search for new materials. Conversion efficiency is another strong motivating force.

There are certain gas lasers in existence that require no external pumping, and further rapid development can be expected. These are the so-called gas dynamic lasers, which use supersonic flow to remove waste energy—the key to high average-power devices. The high-temperature, high-pressure stagnation conditions that are required to achieve such flow also thermally excite the laser medium.

The carbon dioxide gas dynamic laser starts with a volume of the proper carbon dioxide laser mixture at sufficiently high temperature and pressure to ensure significant population of the upper laser level. This population distribution is in thermal equilibrium, so that stimulated emission cannot occur. The gas is then rapidly expanded through a supersonic nozzle within a period shorter than the lifetime of the upper laser level. At the same time, water vapor or helium is added so that the lower laser level cools within a time period comparable to or shorter than the expansion time. The result is that several millimeters downstream from the nozzle a population inversion exists between two levels of carbon dioxide. This gas can be heated by igniting a gas mixture of carbon dioxide and some nitrate in a combustion chamber. The pulsed laser action that results can generate about 20 J of energy at 0.3-sec pulse duration. Further developments will increase this laser energy. Plasma physicists will no doubt give some impetus to research in extremely high peak-power lasers with high-energy content. Such pulses, focused on small solid targets, can produce clean, high-density, high-temperature plasmas.

NEW LASER APPLICATIONS

Although we cannot foresee the development of all new laser applications, we can predict with confidence that laser solutions for many technical problems will be found by laser technologists who are also knowledgeable about the needs of other fields. A good example of this matching of problem to possible solution is a suggestion advanced by the Marshall Space Flight Center to monitor wingtip vortices on airport runways. These vortex wakes can cause unsafe flying conditions for several minutes after an airplane has taken off or landed, and appropriate warnings to other aircraft that use the runway are necessary. Although in time the vortices will decay and move off the runway, uncontrollable variables such as crosswind speed can influence the duration of the vortex hazard.

The proposed solution is a network of laser beams passing over the runway. Lasers and detectors mounted on towers or poles (rigid or telescoping) are positioned along the runway, and the laser beam is directed across the path of the aircraft to photodetectors on the opposite side. A vortex wake passing through one or more of the beams in the net is detected by continuously monitoring the difference between two rms values of the composite signal, one averaged over a much longer time than the other. The path of the beam from the laser to the detector will be a straight line only when the air is undisturbed.

If, during transmission from laser to detector, the beam encounters density gradients, it will be deflected from its undisturbed path, and the magnitude of the deflection can be related to the magnitude of the density gradients encountered. A go/no-go decision for takeoff and landing can then be made from a visual display of the laser beam deflections.

The U.S. Department of Transportation's Systems Center has suggested to the Coast Guard a laser system that would automatically and remotely detect the presence of coastal fog banks. The Coast Guard now uses the so-called videograph backscatter meter as a fog detector, however this detector becomes unreliable in a fog bank that renders the atmosphere inhomogeneous. If the fog bank lingers a few thousand feet off shore, the videograph will indicate good visibility even if the fog bank obscures the view of mariners. The Transportation Systems Center recommended optical backscattering methods for fog bank detection using a laser radar (lidar) system. Optical backscattering correlates well with the extinction coefficient of a distribution of particles, which is the structure of fog banks (refs. 24 and 25). The use of lasers in fog bank detection also indicates its potential for more general uses in meteorology.

Advances can also be expected in making laser systems feasible for long-distance communications. Such systems will almost certainly use pipes of some kind to transmit the beam and obviate attenuation loss through the atmosphere. Electromagnetic waves can be guided through a pipe in several ways. In one, the wave is reflected back and forth between highly reflecting walls, following a zig-zag path about the central line of the tube. The tube can be filled with inert gas and, if the gas and wavelength are suitably chosen, the gas will not attenuate the waves. Losses will occur at each reflection, but these can be reduced by precise manufacture of the reflecting walls. This type of guide has been used for microwave transmission, but transmission of optical waves requires a high degree of refinement.

Future laser systems may be applicable to earthquake prediction measurements. It is known that strain-rate changes occur along a geological fault, causing certain motions of the fault that are followed by quakes in 2 to 18 months. Geodetic laser survey systems could measure the motion of a fault, thus providing a means for predicting earthquakes.

COST AND AVAILABILITY

Nothing has been mentioned about two questions that any potential user will ask—where a laser can be bought and how much it will cost. The cost of a laser is very much a function of its power and whether it is a pulsed laser or a continuous laser. Simple pulsed lasers are now used as experimental tools in school laboratories. They can be bought for less than $100 from several scientific supply houses. More powerful lasers are available from many companies that advertise in trade journals (see the list of journals in the Appendix).

Developing a new laser is a costly, time-consuming process that requires the skills of physicists, metallurgists, chemists, and engineers. However, if a potential application for a laser can be devised, it may not be very costly to purchase one and to develop the ancillary equipment required. Many laser manufacturers assist interested persons in developing new applications; their experience can also help avoid costly false starts. A developer should check to determine whether his application has already been patented. Many applications have been patented, but others are available at no cost from NASA or other Government agencies. Several companies that manufacture lasers keep up-to-date listings of laser patents and may be willing to share this information.

APPENDIX

Information Sources

In addition to the various NASA Centers and the U.S. Department of Transportation Systems Center, the following facilities were used for literature searches and information gathering:

Knowledge Availability Systems Center
University of Pittsburgh
Pittsburgh, Pennsylvania 15213

Library of Congress
Washington, D.C.

Library and Physical Laboratory
University of Maryland
College Park, Maryland

Library and Physics Laboratory
Pennsylvania State University
University Park, Pennsylvania

Library and Physics Faculty
University of Delaware
Newark, Delaware

Laser Laboratory
IBM Federal Systems Division
Gaithersburg, Maryland

Library and Physics Faculty
Columbia University
New York, New York

The Library of Congress is an accessible and extensive source of literature and data search, and consequently, it is recommended to anyone interested in obtaining more detailed information on laser technology.

The following periodicals are used by laser researchers for publication purposes:

American Institute of Aeronautics and Astronautics Journal
American Journal of Physics
Applied Optics
Applied Physics Letters
Bell System Technical Journal
Electronics
Electronics Design
International Business Machines Journal of Research and Development

Institute of Electrical and Electronics Engineers Transactions on Electronics
Journal of Applied Physics
Journal of the Optical Society of America
Journal of Spacecraft and Rockets
Laser Focus
Laser Sphere
Physical Review
Physical Review Letters
Proceedings of Institute of Electrical and Electronics Engineers
Review of Scientific Instruments

Glossary

Brewster window—An aperture through which light can enter into a new medium at an angle to the interface such that

$$\tan \theta_B = \frac{n_b}{n_a}$$

where θ_B is the Brewster angle. n_b and n_a are the indices of refraction of the media a and b, and light enters b from a.

Energy (or work)—That which is exchanged when a force acts through a given distance in the direction of the force. The unit is erg = 1 dyn cm = gr cm^2 sec^2; 1 J = 10^7 erg. One foot-pound is the work done when a force of one poundal acts through a distance of 1 ft.

$$1 \text{ ft-poundal} = 421\ 402 \text{ erg}$$

One electron-volt is the work done when one electronic charge is moved through a potential difference of 1 V.

$$1 \text{ eV} = 1.60199 \times 10^{-12} \text{ erg}$$

Force—That which gives an acceleration of 1 cm/sec^2 to a unit gram of mass; its name is dyne. 1 dyn = g cm sec^{-2} . One newton is a force which gives 1 m/sec^2 acceleration to 1 kg of mass. One newton = 10^5 dyn. One poundal is the force which gives 1 ft/sec^2 acceleration to 1 lb. One poundal = 1.3825 × 10^4 dyn.

Frequency—Rate of oscillation; units: 1 cycle sec^{-1} = 1 Hertz = 1 Hz. One megacycle = 1 megahertz = 10^6 Hz. One gigahertz = 10^9 Hz.

Kerr cell—A cell that contains electrodes immersed in nitrobenzene or other liquid. It shows double refraction in high degree and with short time lag. Used in devices in which light intensity is changed rapidly according to the voltage applied to the electrons.

Laser—Light Amplification by Stimulated Emission of Radiation.

Length—Unit is 1 meter = 1 m; 1 millimeter = 1 mm = 10^{-3} m. One angstrom = 1 Å = 10^{-8} cm = 10^{-10} m. One micrometer = 10^{-6} m; 1 m = 100 cm. One kilometer = 10^3 m; 1 m = 39.37 in.

Maser—Microwave Amplification by Stimulated Emission of Radiation.

Metric System Multiples—Any physical quantity defined and named in the metric system of units can be multiplied by an integral power of 10 to obtain larger or smaller units of the quantity. A prefix to the name of the unit expresses the multiplicity of the basic unit. The table on the next page summarizes this scheme.

Mie scattering—That which is produced by spherical particles without special regard to comparative size of radiation wavelength and particle diameter.

Normal atmosphere—This is defined as the pressure exerted by a vertical column of 76 cm of mercury of density 13.5951 g/cm^3 at a place where the gravitational acceleration is g = 980.665 cm/sec^2.

Multiplier	Prefix	Symbol
10^{12}	tera	t
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

$$
\begin{aligned}
1\ \text{atm} &= 1.013246 \times 10^{6}\ \text{dyn/cm}^2 \\
&= 14.696\ \text{psi} \\
&= 29.291\ \text{in. of Hg at } 32^\circ\ \text{F} \\
1\ \text{mm of Hg} &= 1\ \text{Torr} = 1333.22\ \text{dyn/cm}^2
\end{aligned}
$$

Photon—Light quantum with energy of $h\nu$, where h is Planck's constant, and ν is the frequency of the light.

Plasma—An assembly of ions, electrons, neutral atoms, and molecules in which the motion of the particles is dominated by electromagnetic interaction. The temperature of the collection of these particles is high enough for the ionization level to be above 5 percent.

Power—This is the rate of doing work, units:
$1\ \text{W} = 1\ \text{J/sec} = 10^{7}\ \text{erg sec}^{-1}$;
$1\ \text{hp} = 550\ \text{ft-lb/sec} - 745.7\ \text{W}$;
$1\ \text{ft-lb/min} = 2.2597 \times 10^{-2}\ \text{W}$.

Raman scattering—Raman scattering of light from a gas, liquid, or solid is that scattering in which a shift in wavelength from that of the usually monochromatic radiation occurs. The amount of shift is a function of the scattering particles and wavelengths.

Rayleigh scattering—This is a coherent scattering in which the intensity of the light of wavelength λ, scattered in any direction making an angle θ with the incident light, is directly proportional to $1 + \cos^2 \theta$ and inversely proportional to λ^4. The latter point is noteworthy in that it shows how much greater the scattering of the short wavelengths is. These relations apply when the scattering particles are much smaller than the wavelength of the radiation. Thus the sky is blue because blue light is scattered more than red. The unscattered light is, of course, complementary to blue, i.e., orange or yellow, which explains the "warm" hues of the sunset.

Temperature—1° centigrade is defined as one-hundredth of the temperature interval between freezing point and boiling point of water under one normal atmosphere of pressure. With the size of the degree so defined, temperatures stated as degrees Kelvin

(°K) are measured from absolute zero, and those stated as degrees Celsius (°C) are measured from the triple point (temperature and pressure at which all three states–solid, liquid, gas–may exist simultaneously) of water. The Fahrenheit scale uses degrees in which size is 5/9 the size of the Celsius degree and assigns the value of 32° F to the freezing point of water. Temperatures expressed in Fahrenheit degrees but measured from absolute zero are said to be expressed in degrees Rankine (°R).

Time–Unit is second. 1 microsecond = 10^{-6} sec; 1 nanosecond = 1 ns = 10^{-9} sec.

References

1. Laser Focus, Nov. 1967, pp. 32-35.
2. Collis, R. T. H.: LIDAR: Advances in Geophysics. vol. 13. Academic Press, Inc. 1969, pp. 113-139.
3. Evans, W. E.; and Collis, R. T. H.: Meteorological Applications of Lidar. S.P.I.E.J., vol. 8, Jan. 1970, pp. 38-45.
4. Salzman, J. A.; Masica, W. J.; and Coney, T. A.: Determination of Gas Temperatures from Laser-Raman Scattering. NASA TN D-6336, May 1971.
5. Hinkley, E. D.; and Kelley, P. L: Plys. Rev. Lett., Science, No. 171, 1971, p. 635.
6. Lanchashire, R. B.: Refractive Index-Particle Density Correlation of Nonequilibrium Cesium Plasmas Probed by a Multifrequency Helium-Neon Laser. NASA TN D-5328, July 1969.
7. Lancashire, R. B.: Study of Plasma Diagnostics Using Laser Interferometry with Emphasis on Its Application to Cesium Plasmas. NASA TM-X-1652, Sept. 1968.
8. Billman, K. W.; Leonard, E. T.; and Yaffee, M. A.: True Vertical Laser. Appl. Opt., vol. 10, no. 2, Feb. 1971, pp. 422-425.
9. McCormick, M. P.: Simultaneous Multiple Wavelength Laser Radar Measurements of the Lower Atmosphere. Proceedings of Electro-Optics 1971 International Conference, March 1971.
10. Randall, J. L; Courtenay, St. J.; and Moore, F. B.: High Altitude Aircraft Experiment Test for Visible Laser Optical Communications. NASA-MSFC Astrionics Laboratory Publication, Aug. 1970.
11. Van Pelt, W. F.; Stewart, H. F.; Peterson, R. W.; Roberts, A. M.; and Worst, J. K.: Laser Fundamental Experiments. Radiation Medicine Program, Southwestern Radiological Health Laboratory, Las Vegas, Nevada, May 1970 (U.S. Department of Health, Education, and Welfare).
12. White, H. E.; and Levutim, P.: Floaters in the Eye. Sci. Am., July 1962.
13. Zweng, H. C.; Flocks, M.; Kapany, N. S.; Silvertnist, N.; and Peppers, N. A.: Experimental Laser Photocoagulation. Am. J. Opthalmol., vol. 58, no. 3. 1964, p. 353.
14. Egger, M. D.; and Petrov, M.: Science, no. 157, 1967, p. 305.
15. Petrov, M.; Hadravsky; Egger, M. D.; and Galambos, R.: J. Opt. Soc. Am., vol. 58, 1968, p. 661.
16. Davidovits, P.; and Egger, M. D.: Nature, no. 223, 1969, p. 831.
17. Bessis, M.; Gires, E.; Mayer, G.; and Nomarski, G.: Irradiation des Organities Cellulaires a l' aide d' un laser a rubis. C. R. Acad. Sci. (Paris), no. 255, 1962, p. 1010.
18. Lang, K. R.; Barnes, F. S.; Daniel, J. C.; and Maisel, J. C: Lasers as Tools for Embrology and Cytology. Nature, no. 201, 1964, p. 675.
19. Rounds, D. E.; Olson, R. S.; and Johnson, F. M: The Laser as a Potential Tool for Cell Research. J. Cell Biol., vol. 27, p. 191.
20. Rounds, D. E.; Olson, R. S.; and Johnson, F. M: The Effect of Laser on Cellular Respiration. Zeit, Zellforsch, Mikroskop. Anat., vol. 87, no. 193.
21. Soffer, B. H.: Giant Pulse Laser Operation by a Passive Reversible Bleachable Absorber. J. Appl. Phys., vol. 35, 1964, p. 2551.
22. "Lasers Cut Their Way into Garment Industry." Lasersphere, vol, 1, no. 4, March 22, 1971, p. 1.

23. Johnson. F. N.: A Laser Excited by Nuclear Heat. Nucleonics, vol. 22, Apr. 1964, pp. 57-60.
24. Vogt. H.: Visibility Measurement Using Backscattered Light. J. Atm. Sci., Sept. 1968.
25. Lifstz, J. R.; and Ingrao, H. C.: Two Candidate Systems for Unmanned Fog Bank Detection. Transportation Systems for Department of Transportation, Report DOT-TSC-CG-71-3, June 1971.
26. Keck, P. H; Redmann, J. J.; White, C. E.; and Bowen, D. E.: Pulsations in the Spectrum of Stimulated Emission of Nd in Glass. Applied Optics, vol. 2, 1963, pp. 833-837.
27. Snitzer, E.: Optical Maser Action of Nd^{3+} in a Barium Crown Glass. Phys. Rev. Lett., vol. 7, 1961, pp. 444-446.
28. Snitzer, E.: Neodymium Glass Laser. Quantum Electronics III, Columbia Univ. Press, 1964, pp. 999-1019.
29. Vanyukov, M. P.; Isaenko, V. I.; and Lyubimov, V. V.: Time Variation of the Spectral Composition of the Radiation from an Nd-Activated Glass Laser. Soviet Phys, JETP vol, 17, 1963, pp. 778-779; vol. 44, 1963, pp. 115-1152.
30. Bonch-Bruevich, A. M.; Kariss, Ya. E.; and Feofilov, P. P.: Pulsations in the Spectrum of Stimulated Emission of Nd in Glass. Opt. Spectroscopy, vol. 14, 1963, pp. 438-439; vol. 14, 1963, pp. 824-825.
31. Johnson, L. F.; Boyd, G. D.; and Nassau, K.: Optical Maser Characteristics of Tm^{3+} in $CaWO_4$. Proc. IRE, vol. 50, 1962, pp. 87-88.
32. Kiss, Z. J.; and Duncan, R. C.: Optical Maser Action in CaF_2:Tm^{2+}. Proc. IRE, vol. 50, 1962, pp. 1532-1533.
33. Duncan, R. C., and Kiss, Z. J.: Continuously Operating CaF_2:Tm^2 Optical Maser. Appl. Phys. Lett., vol. 3, 1963, pp. 23-24.
34. Bridges, W. B.: Appl. Phys. Lett., vol. 4, 1964, p. 128.
35. Javan, A.; Bennett, W. R.; and Herriott, D. R.: Phys. Rev. Lett., vol. 6, 1961. p. 106.
36. Patel, C. K. N.: Phys. Rev. Lett., vol. 13, 1964, p. 617.
37. Patel, C. K. N.: Phys. Rev., vol. 136, 1964, p. 1187.
38. Patel, C. K. N.: Appl. Phys. Lett., vol. 7, 1965, p. 15.

Bibliography

Adams, M. J.: Laser Welding. Weld. Inst. Res. Bull., vol. 9, no. 1, 1968.

Angus-Leppan, P. V., ed.: Refraction Effects in Geodesy and Electronic Distance Measurement. Univ. of New South Wales, Kensington, N.S.W., Australia, 1968.

Barrett, J. J.; and Adams, N. J., III: Laser-Excitation Rotation Vibration Raman Scattering in Ultra-Small Gas Samples. J. Opt. Soc. Am., vol. 58, no. 3, Nov. 1968, pp. 311-319.

Bause, K.; Boersch, H.; Herziger, G.; Schaefer, G.; and Selig, W.: Laser Machining. Z. Ang. Phys., vol. 26, p. 195, 1969.

Beaulieu, A. J.: Laser in Metal Industry. Appl. Phys. Lett., vol. 16, 1970, p. 504.

Birnbaum, G.: Optical Masers. Academic Press, Inc., 1964.

Bod, D.; Brasier, R. E.; and Parkes, J.: Welding. Lorer Focus, vol. 5, p. 36.

Boyne, H. S.; Hall, J. L.; Barger, R. L.; Bender, P. L.; Word, J.; Levine, J.; and Foller, J. E.: Laser Applications in the Geosciences. Western Periodicals, 1970, pp. 215-225.

Brotherton, M.: Masers and Lasers. McGraw-Hill Book Co., 1964.

Cohen, M. E.; and Epperson, J. P.: Electron Beam and Laser Beam Technology. Advan. Electron., vol. 4, Academic Press, Inc., 1968, pp. 139-186.

Cool, T. A.; and Shirley, J. A.: Laser for Machining. Appl. Phys. Lett., vol. 14, 1969, p. 70.

Farmer, G.: Communication by Laser. Int. Electron. Device Meeting, Washington D.C., 1970.

Fenster, P.; and Kohn, W. K.: Laser Gyro. Apl. Opt., vol. 7, 1968, p. 2383.

Gardner, F. M.: Phaselock Techniques. John Wiley and Sons, Inc., 1966.

Gerry, E. T.: Welding with Laser. Laser Focus, vol. 6, 1970, p. 27.

Gilmer, R. O.; and Waters, D. M.: A Solid-State System for Measurement of Integrated Refractive Index. ESSA Tech. Rpt. IER 40-ITSA 40, 1967.

Hagon, W. F.: Metal Working with Laser. J. Appl. Phys., vol. 40, 1969, p. 511.

Heavens, O. S.: Optical Masers. Methuen & Co., 1964.

Hutchings, T. J.; Winocur, J.; and Zingery, W. L.: Laser Gyro. 5th Symp. Unconventional Inertial Sensors, 1969, p. 199.

International Association of Geodesy. Electromagnetic Distance Measurement. Hilger & Watts., London, 1967.

Kinsel, T. S.: Laser Communication. Proc. IEEE, vol. 56, 1970, p. 1666.

Klein, H. A.: Masers and Lasers, J. B. Lippincott Co., 1963.

Lee, G.; and Holt, C.: Laser Communication. National Telemetry Conf., 1970.

Lengyel, B. A.: Lasers. Wiley-Interscience, 1971.

Levine, A. K.: Laser Theory Advances. Marcell Delkor, Inc., 1966.

McElroy, J. H.; McAvoy, N.; and Richard, H. L.: A Laser Communication System. Laser Journal, vol. 2, no. 1, 1970.

Melfi, S. H.; Lawrence, J. D., Jr.; and McCormick, M. P.: Observation of Raman Scattering by Water Vapor in the Atmosphere. Appl. Phys. Lett., vol. 15, no. 9, Nov. 1969.

Moitland, A.; and Dunn, M. H.; Laser Physics. North Holland Pub. Co., (Amsterdam), 1969.

Monroe, M. E.: Measurement of Spatial Coherence and Intensity Correlation Function of Atmospherically Distorted Laser Waves. TR 2384-7, Ohio State Univ., 1968.

Ostermoyer, F.: Laser Communication. International Electron. Device Meeting, 1970.

Pratt, W.: Laser Communications. John Wiley and Sons, Inc., 1969.

Ready, J. F.: Effects of High Power Laser Radiation. Academic Press, Inc., 1971.

Rybokov, B. V.; Skulachenko, S. S.; Chumichev, R. F.; and Yudin, I. I.: Optical Gyro. Opt. Spectroscop. (USSR), vol. 25, 1968, p. 317.

Ross, D.: Lasers. Academic Press, Inc., 1971.

Ross, M.: Laser Receivers. John Wiley and Sons, Inc., 1966.

Ross, M.: Laser Applications. Academic Press, Inc., 1971.

Schumacher, B. W.; and Taylor, C. R.: Machining with Laser. 10th Symp. Electron Ion Laser Beam Technol., 1969, p. 271.

Shapiro, S. L.; and Duguary, M. A.: Laser Welding. Phys. Lett. A., vol. 28, 1969, p. 698.

Smith, H. M.: Principles of Holography. John Wiley and Sons, Inc., 1969.

Smith, J. F.: Laser in Industry. Laser Focus, vol. 5, 1969, p. 32.

Steel, W. H.: Interferometry. Cambridge Univ. Press, 1967.

Stroke, G. W.: An Introduction to Coherent Optics and Holography. Academic Press, Inc., 1966.

Thayer, G. D.: Atmospheric Effects on Multiple-Frequency Range Measurements. ESSA Tech. Rpt. IER 56-ITSA 53, 1967.

Tiffany, W. B., Torg, R.; and Foster, J. D.: Laser in Industry. Appl. Phys. Lett., vol. 15, 1962, p. 91.

U.S. GOVERNMENT PRINTING OFFICE: 1973 O—525-862