LASERS--THEORY, TECHNOLOGY, AND APPLICATIONS
Report on a University of Michigan Special Summer Short Course
(May 10-21, 1965)

Wayne L. Frederick

Research Laboratory Division
Office of Testing and Research
Research Project 63 G-124
Research Report No. R-549

Michigan State Highway Department
Lansing, October 1965

LASERS--THEORY, TECHNOLOGY, AND APPLICATIONS
Report on a University of Michigan Special Summer Short Course
(May 10-21, 1965)

The laser course held May 10-21, 1965, at the University of Michigan featured well known lecturers who are presently involved in laser research. Most were University researchers, so the subject matter heavily emphasized theory and mathematical explanations for observed facts. Light waves and atomic systems were dealt with in terms of quantum mechanics, which has led to many recent advances in physics, optics, and electrical engineering, as well as to masers and lasers. This engineering summer conference was of considerable technical value, since in addition to coverage of laser technology, there were reviews of modern thought on quantum mechanics, atomic structure, electrical engineering methods in optics, and mathematics.

This report will attempt to distill the theory to show how such devices work, their physical setups, and the applications of the very narrow, intense beam of light they produce. Before proceeding, definition of a few terms should prove useful:

Maser - an acronym for Microwave Amplification by Stimulated Emission of Radiation.

Laser - an acronym for Light Amplification by Stimulated Emission of Radiation.

Optical Maser - a maser that emits radiation at shorter wavelengths (higher frequency) than the early masers; synonymous with laser since light is emitted instead of microwaves.

Angstrom Unit - (abbreviated Å) a unit of length equal to 10^{-10} meters, used to designate the wavelength of light and for atomic dimensions (3.94×10^{-9} in.).

Micron - (abbreviated μ) a unit of length equal to 10^{-6} meters, often used to designate the wavelength of infrared light (3.94×10^{-5} in.).

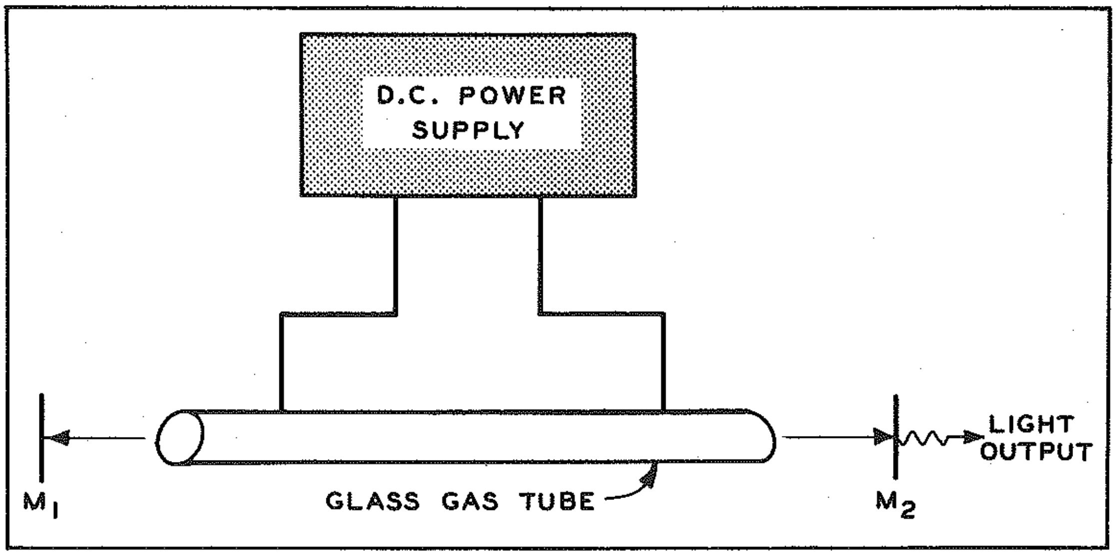


Figure 1. Physical layout of helium-neon gas laser; M_1 and M_2 are mirrors.

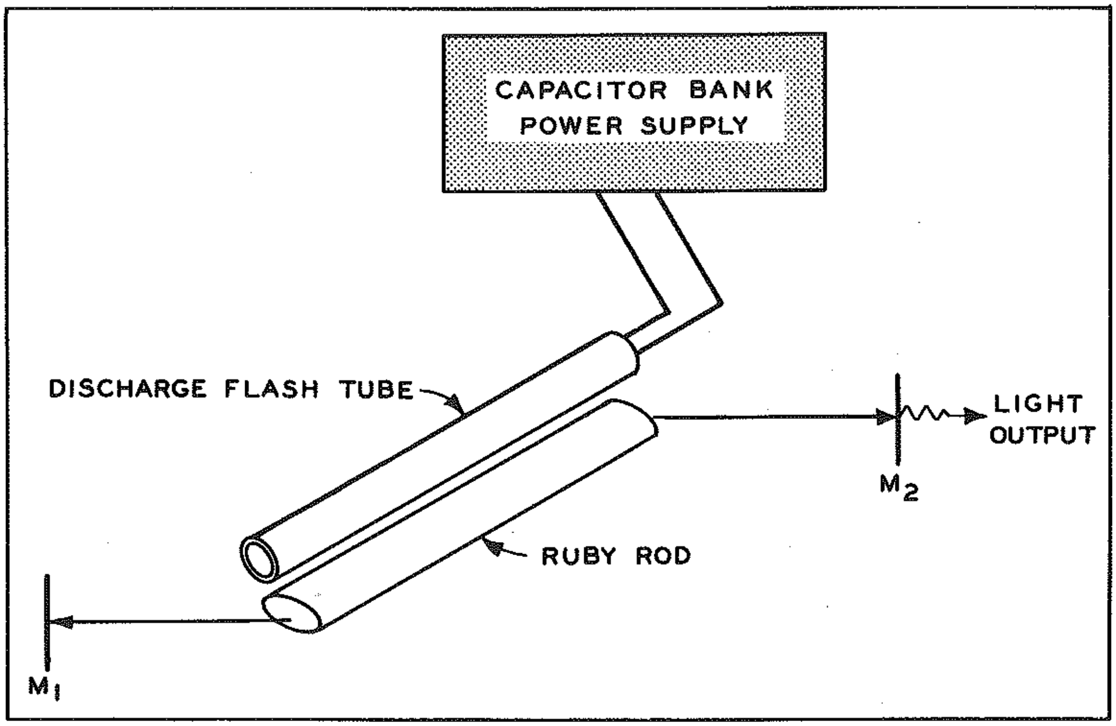


Figure 2. Physical layout of typical impurity laser using a ruby rod.

Laser action is based on energy that can be stored in higher energy levels (excited states) of electrons in certain atoms and semiconductor crystals. It should be noted that electrons in atomic systems can only absorb or give off energy in discrete bundles (photons or quanta) corresponding to the energy difference between energy levels of the particular atoms. Normal atomic systems will not store energy. If an electron is excited (pumped) to a higher energy level farther from the nucleus, it emits a photon of light and returns to its equilibrium energy level within 10^{-9} sec. Some atoms have excited energy levels from which the electron has difficulty in returning to its equilibrium energy level, due to quantum mechanical considerations, and remains trapped at the higher energy level for periods greater than 10^{-6} sec. Laser action can take place only at wavelengths corresponding to the energy difference between such long-lived energy states and the lower energy level that the electron assumes. Thus, nature severely limits the colors of light that lasers will emit.

By applying high pumping power to atomic systems that have suitable long-lived excited states, it is possible to store energy and then to stimulate large numbers of such excited atoms to release energy by emitting light all at once. This stimulation is accomplished by exciting a laser material while it is properly oriented between reflecting surfaces which form an optical cavity. These surfaces are indicated as mirrors M_1 and M_2 in Figs. 1 and 2, and are the cleaved crystal faces in Fig. 3. After excitation the atoms will randomly begin to de-energize by emitting their characteristic light. This light reflects back and forth in the optical cavity between the mirrors and sets up a standing light wave which gains energy on each pass through the laser medium. This standing wave is similar to the standing sounding waves described in discussions of organ pipes, but has a much shorter wavelength and higher frequency. As the energy in the standing wave reaches high enough levels it couples with the energy in the remaining excited atoms and stimulates a sudden release of the stored energy. If sufficient energy can be pumped into the system the laser will emit a continuous beam. If the energy input is pulsed, the laser will emit pulses only when the power level is above the stimulated emission threshold.

General Types of Lasers

Three general types of lasers can be distinguished:

1. Gas lasers (Fig. 1) utilize a gas or mixture of gases as the laser material. The most common gas laser is the helium-neon type, in which neon does the lasing at 6328 Å (red light). The helium aids the

transfer of energy to excited states in neon during the lasing action. The gas tubes range from 0.5 to 1.0 meter in length and are generally less than 10 mm (0.35 in.) in diameter. The ends of the tube are cut at the Brewster angle, which causes transmitted light to be vertically polarized. Reflected light escaping from the system has horizontal polarization. This polarization effect aids the stability of the standing waves in the optical cavity. The reflecting mirrors defining the optical cavity must have a reflectance of at least 98.5 percent or the energy losses will cause quenching of laser action. The gas charge is a 5:1 helium-neon mixture under a very low pressure of about 0.1 mm of mercury. Such lasers have a continuous output power of 3 to 100 milliwatts and an efficiency of up to 0.2 percent of the input power. Power input is accomplished by radio frequency discharge or an electron beam directed down the gas tube.

The argon ion gas laser will provide several watts of power at 4880 Å (blue) and 5145 Å (green) but requires enormous input power. The energy input is increased since the noble gas atom must first be ionized by sufficient energy input to remove an electron from the atom to produce a positive ion. The positive ions then give rise to laser action. Krypton and xenon ion gas lasers have also been operated with very poor performance.

2. Impurity lasers (Fig. 2) are based on a small concentration of certain metal ions in inorganic crystals or certain glass formulations. Ruby, the most common impurity laser material, contains less than 0.1-percent chromium^{+3} ion in aluminum oxide.

Ruby rods range up to 1/2 in. in diameter and 6 in. in length. The larger the rod, the higher the possible power output. The rods may cost $2,000 to $10,000 depending on size and optical quality. The ends of the rod are polished at the Brewster angle. The slanted position of the rod in the optical cavity is necessary since the high refractive index ruby bends the light beam considerably. One of the mirrors is 99^{+}-percent reflecting, while the output mirror is generally 45- to 55-percent reflecting.

In operation, a bank of capacitors is discharged through the flash lamp to give an extremely intense flash of light which excites the laser rod. Several microseconds later several pulses of laser light are emitted which die out in a few hundred microseconds. The highest peak powers are obtained by a process known as "Q-switching." This involves temporary disruption of the buildup of optical power in the cavity so that several small pulses are delayed and emitted as one giant pulse.

Impurity lasers generally operate in a pulsed mode due to the type of pumping power applied and the high power achieved. The discharge flash lamps used for pumping do not operate continuously, and time is required to recharge the capacitor bank power supply between pulses. Also, the laser rod and associated optics cannot stand steady exposure to such high energy levels. Ruined ruby rods and mirrors are routine occurrences for researchers using high-power lasers. Ruby lasers now in existence will deliver peak pulse powers of 1.5×10^9 watts with a pulse length of about 2×10^{-8} sec. The following tabulation indicates the metal ions and host materials for which laser action has been achieved:

Laser Ion	Host Material
Chromium^{+3}	ruby
Nickel^{+2}	magnesium fluoride
Dysprosium^{+2}	calcium fluoride
Samarium^{+2}	strontium fluoride
Thulium^{+2}	barium fluoride
Uranium^{+3}	calcium fluoride
Erbium^{+3}	barium fluoride or glass
Holmium^{+3}	lanthanum fluoride or glass
Neodymium^{+3}	calcium tungstate or glass
Praesodymium^{+3}	calcium or strontium molybdate
Ytterbium^{+3}	glass

Most laser ions are from the rare transition series of metals, which have the unique long-lived excited states necessary for laser action.

3. Injection lasers (Fig. 3) utilize intermetallic compounds of the less known metals which have some of the semi-conductor properties which transistor materials possess. Gallium arsenide (gallium + arsenic), lead selenide (lead + selenium), and indium antimonide (indium + antimony) are examples of injection laser materials. Diodes are prepared from these crystals by "doping" the outer layer with an impurity, which may be one of the metals in the crystal, and cleaving the doped layer from all but one face. This results in a layer of p-type (electron-deficient) material, having holes lacking electrons, on a layer of an n-type (excess electrons) material, or vice versa. The important feature is that there is an

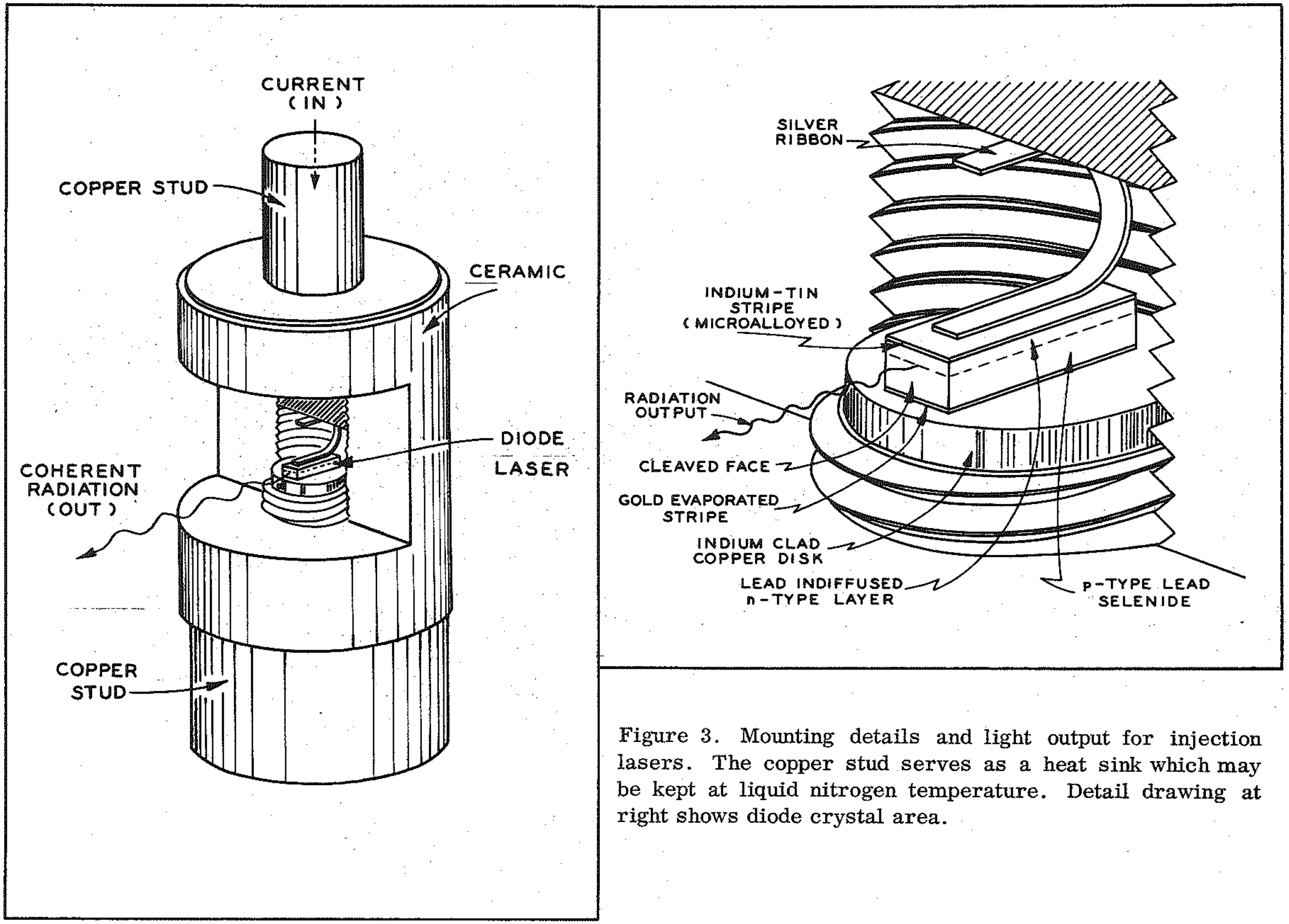


Figure 3. Mounting details and light output for injection lasers. The copper stud serves as a heat sink which may be kept at liquid nitrogen temperature. Detail drawing at right shows diode crystal area.

energy difference between electrons in the two layers. If a bias current of about 2000 amps per sq cm is applied, electrons are pumped to higher energy levels, i.e., holes are injected into the crystal. These electrons and holes can be stimulated to recombine by laser action, with light being emitted in a narrow beam at the p-n interface. The ends of the crystal are polished to serve as reflectors for the optical cavity. Typical crystal dimensions might be 0.02 by 0.01 by 0.01 in., with the longer dimension having the polished faces defining the optical cavity. Injection lasers generally emit in the infrared region of the spectrum in approximately the 1- to 10-μ wavelength range.

Properties of the Laser Beam

Lasers emit a very sharply defined, slowly diverging beam of light which can have very high power. This approximates a point source of light which can be easily detected since it has good intensity. It can be very precisely aimed. The beam consists of monochromatic (single wavelength or color), coherent light which has a wavefront of constant shape. A coherent beam of light will give a strong interference pattern if the beam is split and recombined with an optical path difference. Two different laser beams of the same kind will also form an interference pattern if each one is carefully stabilized at the proper wavelength. This property of coherence is very important to interferometric experiments and for heterodyne detection of laser beams, as described later. Ordinary light gives a very weak and indistinct interference fringe pattern. Even low-power lasers deliver much more power at a given wavelength than light sources previously available. Since only one wavelength is emitted, there is no problem of separating the desired wavelength from other unused wavelengths, as must be done for other light sources.

New Phenomena Observed with Laser Beams

Harmonic Generation. It has been mathematically predicted and experimentally observed that if a powerful laser beam is directed through an anisotropic crystal, such as ammonium dilydrogen phosphate, light is emitted at frequencies which are multiples (harmonics) of the input frequency. About 20 percent of the input power has been observed at double the input frequency. As frequency increases, wavelength decreases and the color of the light shifts toward the ultraviolet region of the spectrum. For example, the neodymium-in-glass laser emits in the infrared, and the second harmonic at half the infrared wavelength is a bright green. Similarly, ruby lasers emit red light and the second harmonic is on the edge of the ultraviolet region--too blue to be detected visually. The experimental setup is shown in Fig. 4.

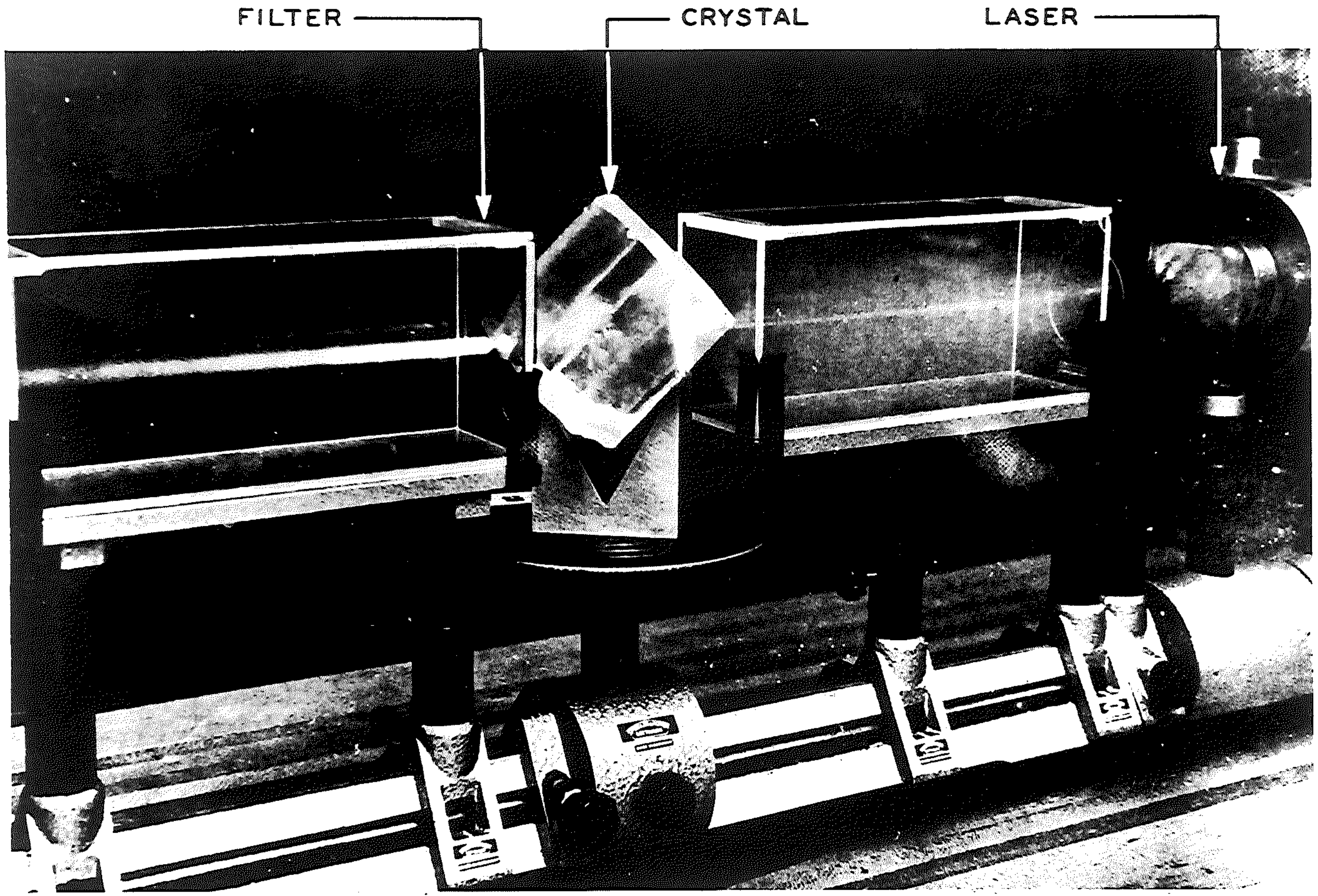


Figure 4. The beam from a powerful pulsed ruby laser (right) focused into a large crystal of ammonium dihydrogen phosphate at the index match angle. A filter was used behind the crystal (left) to remove the laser beam and permit the output second harmonic beam to be photographed. Smoke-filled boxes were used to scatter the beam for visibility.

Anisotropic crystals have a varying index of refraction depending on the direction light travels through the crystal. At very high light levels, photons of light couple to generate harmonics. The effect is greatest when the crystal is positioned at such an angle that the second harmonic refractive index equals the refractive index for the input light. This angular mounting is necessary, since the index of refraction varies with the wavelength of the light passing through the crystal. This effect is extremely interesting technically and has practical application in obtaining laser-like light beams at wavelengths which lasers do not emit.

Raman Laser Action. Raman scattering of light is observed by directing a beam of monochromatic light through a liquid and noting that some of the transmitted light has changed in frequency by $\pm A$, where A is the frequency corresponding to the energy change between two molecular energy levels in the liquid sample. Initially, some of the photons of light strike molecules of the liquid and lose energy equal to A, resulting in transmitted frequency $\omega_\ell - A$. Later, photons of light will strike the excited molecules and gain energy resulting in transmitted frequency $\omega_\ell + A$. Gains and losses of 2A to 3A are possible by continued similar processes. Fig. 5 shows the experimental setup and the spectrum recorded for Raman laser action in benzene.

Ordinary light sources, such as mercury vapor lamps, are so weak that long exposure times are necessary to record $\omega_\ell \pm A$ on film. The high power of a laser beam makes it possible to observe even $\omega_\ell \pm 3A$ in a single pulse. Conversion of up to 50 percent of the initial laser beam energy to the Raman shifted frequency has been noted.

Detectors for Laser Beams

As a result of the considerable interest in using laser beams in communications and optical radar systems, a great deal of work has been done on detection systems to extract information from light beams and prevent interference by daylight or other sources. Three general types of detectors are used:

1. Phototubes and Photomultiplier Tubes.

2. PIN Semiconductor Diodes (Fig. 6), consisting of a layer of p-type semiconductor, an intermediate composition layer, and an n-type semiconductor layer. Light striking the intermediate layer causes current to flow if a bias voltage is applied across the sandwich.

3. Traveling Wave Phototubes (Fig. 7), devices converting the light received into a microwave signal.

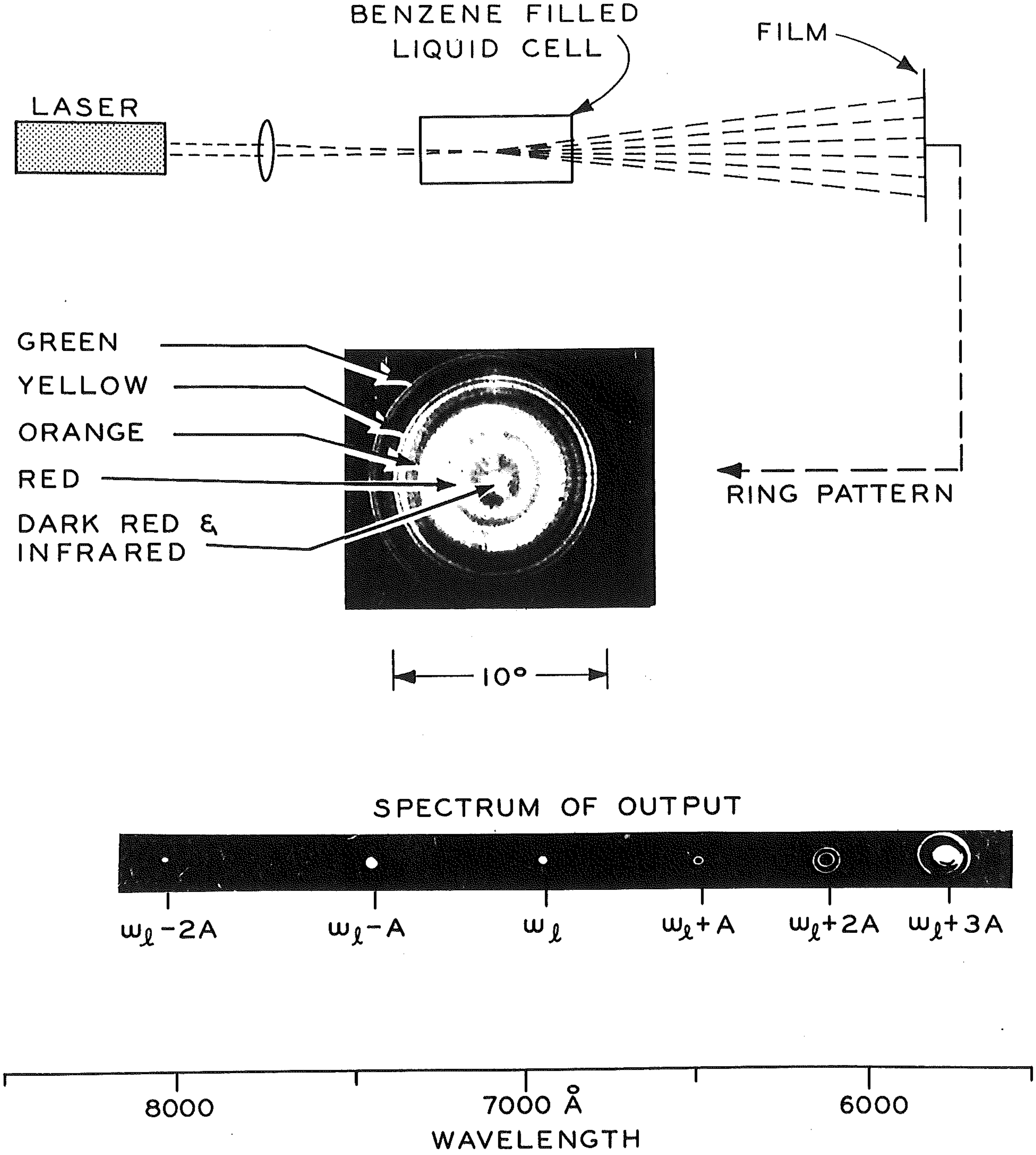


Figure 5. Experimental setup, colored rings, and a spectrum of transmitted light observed when a pulsed laser is focused in benzene. ω_ℓ is the laser frequency and the spots in the spectrum are separated by the frequency A of the molecular energy change for benzene, $\omega_\ell + 3A$ = green ring.

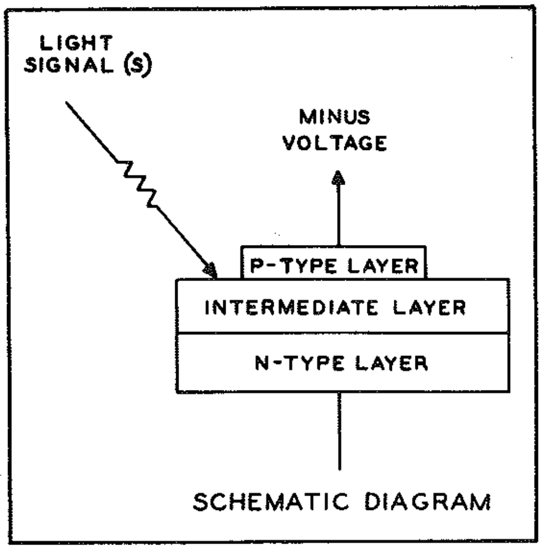


Figure 6 (left). Schematic diagram of a PIN Semiconductor Diode. A light signal, as shown, causes current to flow.

Figure 7 (below). Schematic drawing of a Traveling Wave Phototube (TWP).

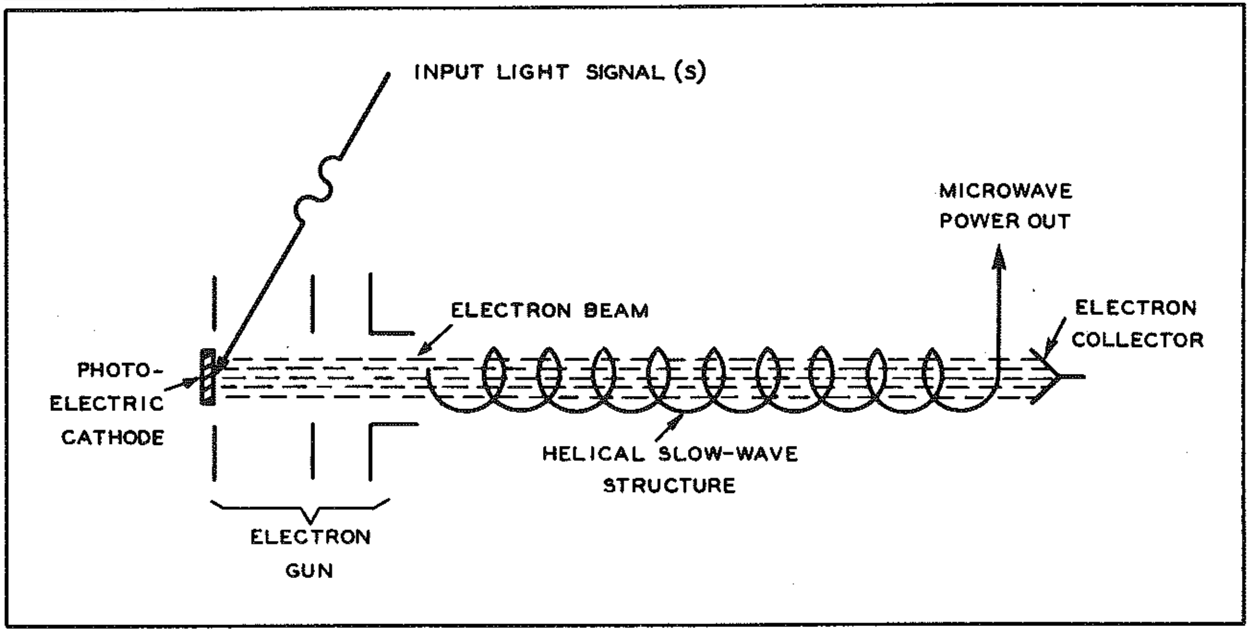
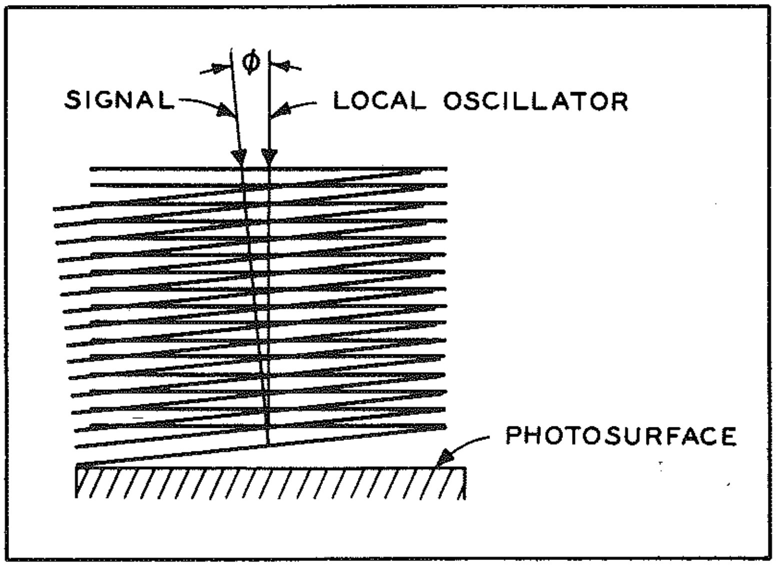


Figure 8 (right). Mixing of two coherent plane waves at a photosensitive surface. The resultant interference pattern generates a difference frequency signal in the photodetector.



These detectors are used in direct (noncoherent) and coherent (heterodyne) modes. In direct detection systems the incoming beam falls on a photosensitive surface and generates a voltage or other signal. Such systems give relatively poor performance since it is difficult to discriminate against background light sources such as daylight.

Coherent or heterodyne detection is possible because laser beams will give interference patterns while other outside sources will not. Thus, it is possible to mix parts of a split laser beam, or two separate stabilized laser beams of the same type, on the surface of a photodetector and create a resultant intermediate frequency (IF) signal from which information can be recovered by conventional electronic methods. All other light sources have no effect since they cannot give an interference pattern (are not coherent with) the laser beam. Fig. 8 shows the interference pattern produced by mixing two light waves on a photodetector surface. The normal beam is analogous to the local oscillator in a conventional radio heterodyne circuit. This type of detection gives excellent discrimination against noise and receives weak signals well.

Uses and Applications of Lasers

The following list of applications of lasers indicates the variety of possible uses:

Distance Measurement
Optical Radar
Optical Testing
Definition of Straight Lines
Micro-Burning and Micro-Etching
Cutting, Drilling, or Welding
Long Distance Communication
Lensless Photography or Holography
Data Processing
Standards of Wavelength and Frequency

Fig. 9 shows a portable battery-powered laser rangefinder for military use. The unit weighs under 25 lb, including batteries. The laser beam and a sighting telescope are mounted in bore sight alignment. A target centered in the sighting scope can be instantly ranged with a single laser pulse to give a digital readout in the scope field. The accuracy is ± 2 to 5 meters with a maximum range of 20 km (over 11 miles) on a clear day. It has been reported that a tank or other vehicle can be ranged if only a radio antenna can be seen above ground obstructions.

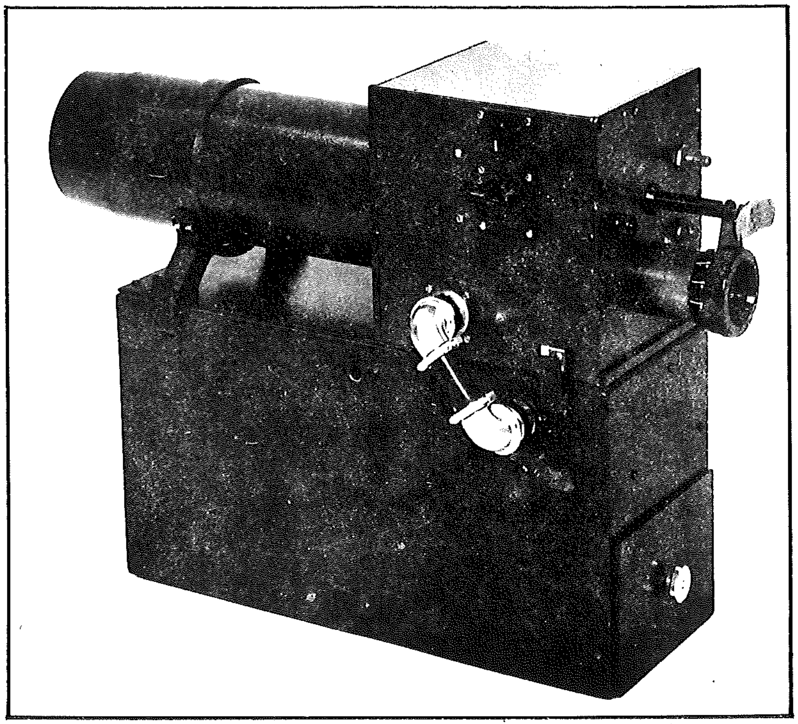
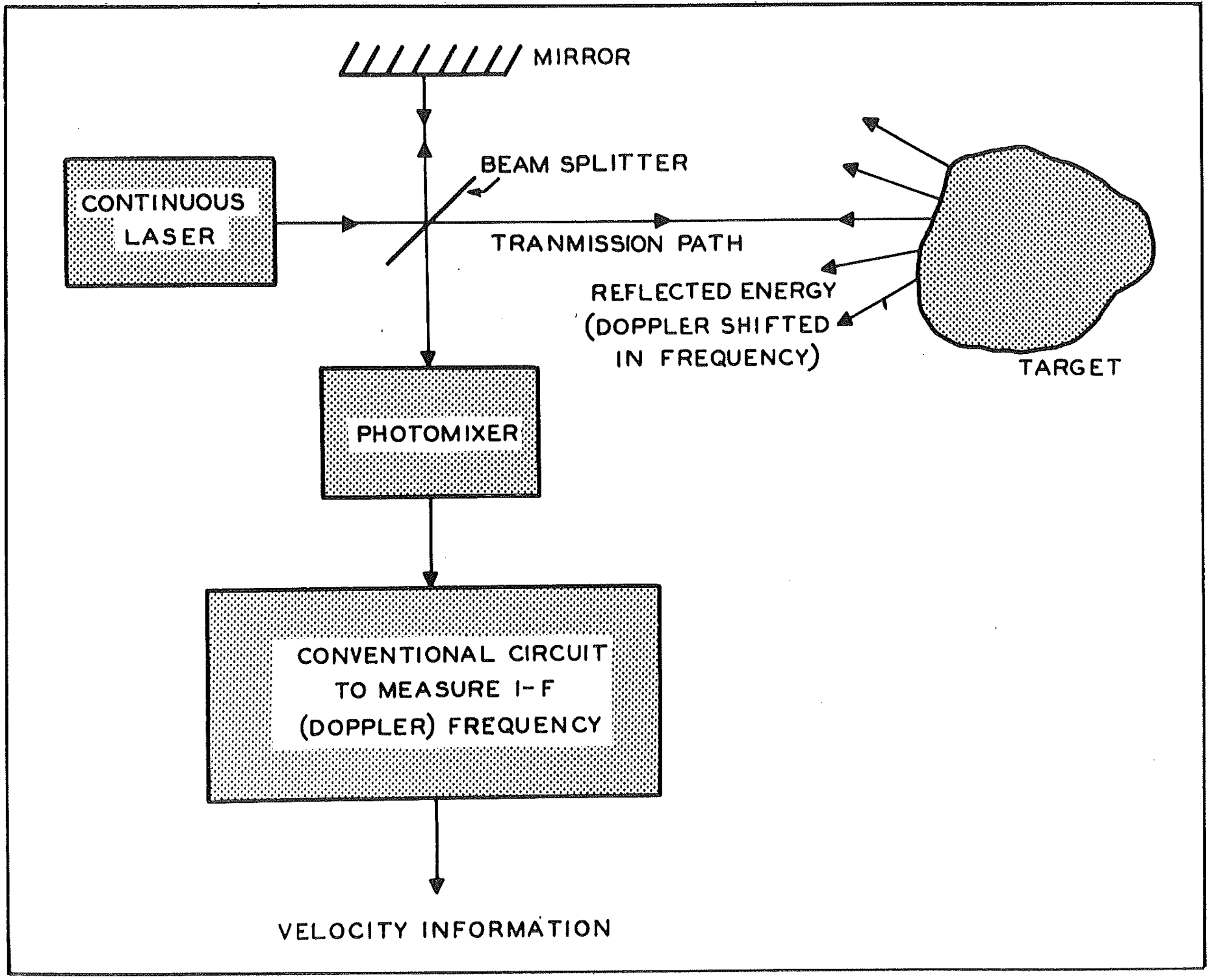


Figure 9 (left). A portable battery-operated military rangefinder.

Figure 10. Schematic of a simple laser radar system using coherent detection.



Larger pulsed-laser systems have been used for optical radar in applications such as tracking aircraft or satellites and determining cloud height. The narrow, precise-pointing laser beam gives more accurate values for azimuth and elevation angle than conventional radar. Continuous lasers and coherent detection systems can also give velocity information by measuring the doppler shift. Fig. 10 shows how such a system is set up.

In the laboratory or machine shop, a laser interferometer equipped with a digital computer readout measures distances up to 100 in. with an accuracy of one part in a million. The interferometer calibrator manufactured by Cutler-Hammer, Inc. is rugged enough to be used under vibration conditions normally encountered in a precision machine shop.

Continuous lasers serve as point sources of light for lining up many optical systems and defining straight lines since the beam is sharply defined and easily visible. Interferometers, collimators, laser mirror systems, grating ruling engines, and photometric light tunnels are examples of systems aligned with the use of lasers.

Lasers have been used medically to weld detached retinas back in place in the eye by causing small spot welds of scar tissue. A microscope has been used in reverse fashion to focus a laser beam to a 1-μ diam spot for micro-cutting and punching of biological specimens for subsequent microscopic study. A higher-power laser has been shown capable of punching a 0.010-in. hole in 0.125-in. thick stainless steel in a single pulse. Calculations indicate this would be an economical production method for punching small holes. Lasers are currently in use for trimming semiconductor crystals during transistor fabrication. Pieces of stainless steel 0.125-in. thick have been neatly laser welded at a linear rate of 1 in. per sec. Fig. 11 shows such a high-power laser mounted on a milling machine stand. The consoles immediately right and left of the laser contain controls, while the cabinet to the far left is the power supply, and the light-colored ventilated cabinet is a heat exchanger which dissipates about 99.95 percent of the input power. Efficiencies of 0.05 percent or less are common for currently used high-power lasers.

The Jarrell-Ash Co., manufacturer of spectroscopic equipment, has applied a laser to analyze a microscopic sample area. The finely focused laser beam vaporizes a selected tiny spot and the vapor plume is then excited to luminescence by an electrical discharge between electrodes just above the sample. The light emitted from the excited vapor is analyzed by a spectrograph in the usual manner. This method was de-

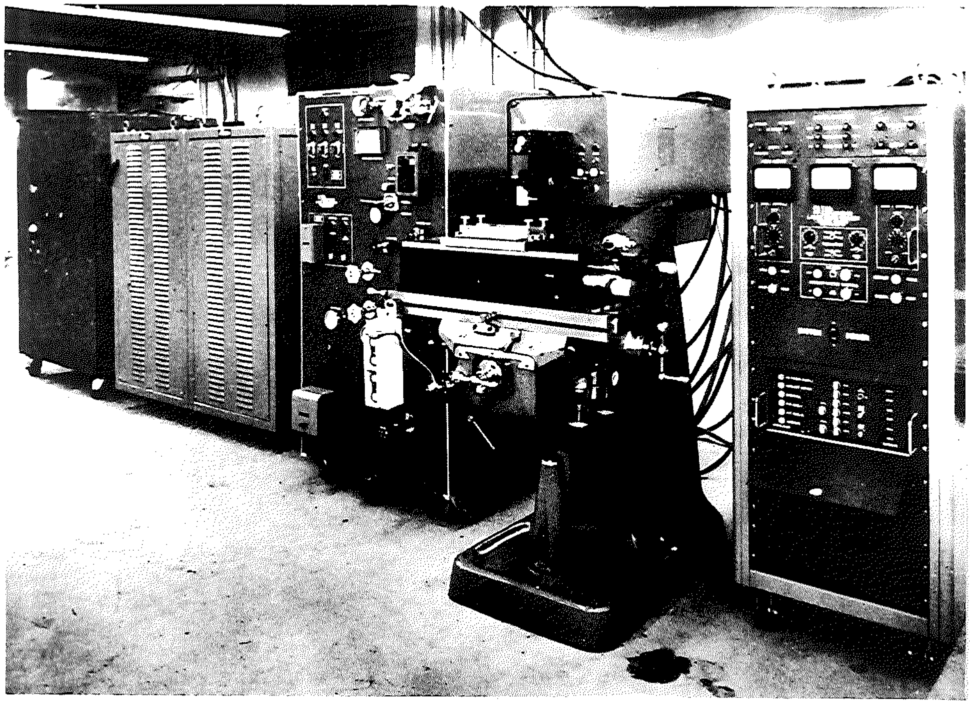


Figure 11. A high-power pulsed laser mounted on a milling machine base to study welding, hole punching, etc. Ventilated console second from left is a heat exchanger which removes wasted energy. Other consoles are for power supply and controls.

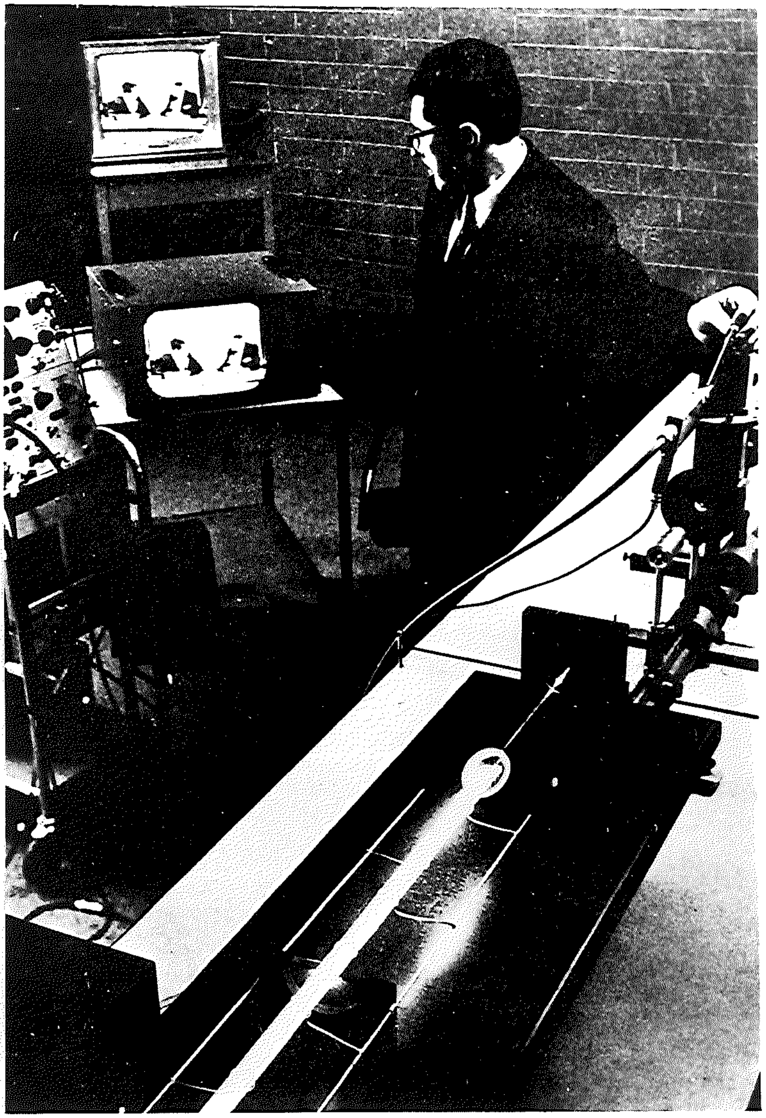


Figure 12. A research worker observes a laser-transmitted television picture (left center) while tuning the system's optical modulator. The helium-neon laser operates in foreground and a conventional television picture is at left rear for comparison.

veloped for direct analysis of impurity inclusions in minerals, metals, ceramics, etc.

There is considerable interest in using lasers in the communications field but the severe technical problems of modulating, detecting, and demodulating light beams on a commercial scale have not yet been overcome. The high frequency of optical radiation offers a potentially enormous band width capability. Fig. 12 shows a laboratory setup which successfully carried a television signal on a laser beam.

A further extremely interesting development made possible by lasers is holography (lensless photography). This is a two-step imaging process which involves recording the diffraction pattern of light scattered or transmitted by an object illuminated by coherent light. In order to retain the necessary phase information of the diffraction pattern, it is mixed with a reference light beam to produce an interference pattern which is recorded on film. Fig. 13 shows the schematic arrangement used in recording holograms. Fig. 14 shows how light waves interact to produce holograms. The active part of the hologram is a series of black and white dots which cannot be seen by the unaided eye. The larger ring systems on the hologram are due to dust particles and do not have any noticeable effect on the final image.

The second step in image formation is to illuminate the hologram with coherent light. It need not be of the same wavelength as the light used to record the hologram but must be coherent. The laser light interacts with the hologram, which is actually a complex diffraction grating, to form a real and a virtual image of the original scene or object. Fig. 15 shows a schematic diagram of the image formation and a photograph of both images of a small screen.

Holograms have several unique properties:

1. Each point on the subject illuminates the entire hologram, so that the film can be cut into smaller pieces each of which will reproduce the entire subject.

2. The images produced are truly three-dimensional. It is necessary to stop down a camera lens to photograph these images to achieve the necessary depth of field. The camera can also be selectively focused on various parts of the image (Fig. 16). An observer viewing this image can change his perspective by moving his head.

3. Since no viewing optics are used, the usual optical limits and distortions do not detract from the sharpness of holographic images.

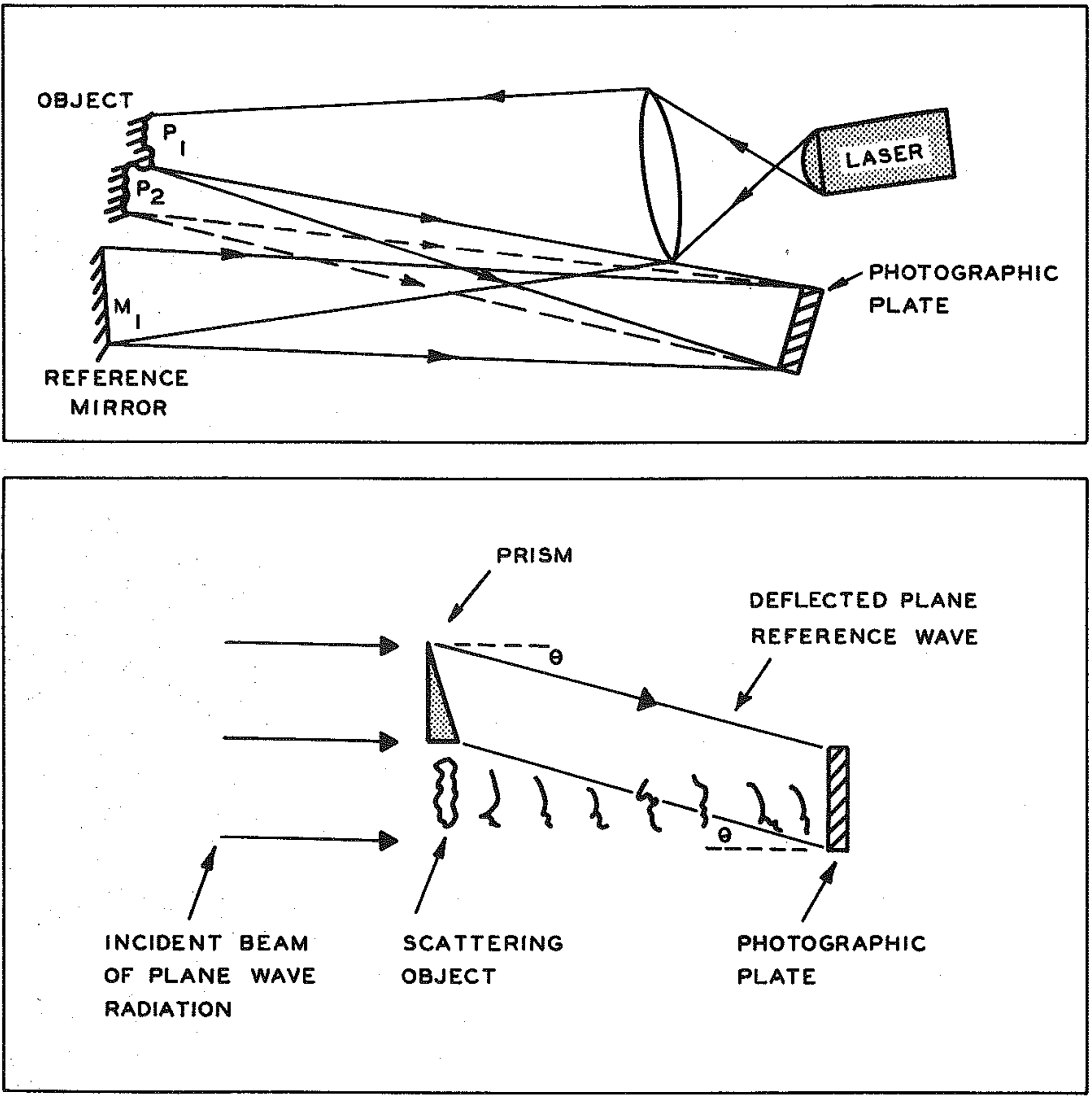


Figure 13. Schematic arrangement to illustrate recording of holograms for opaque objects (top) and transparent objects (bottom).

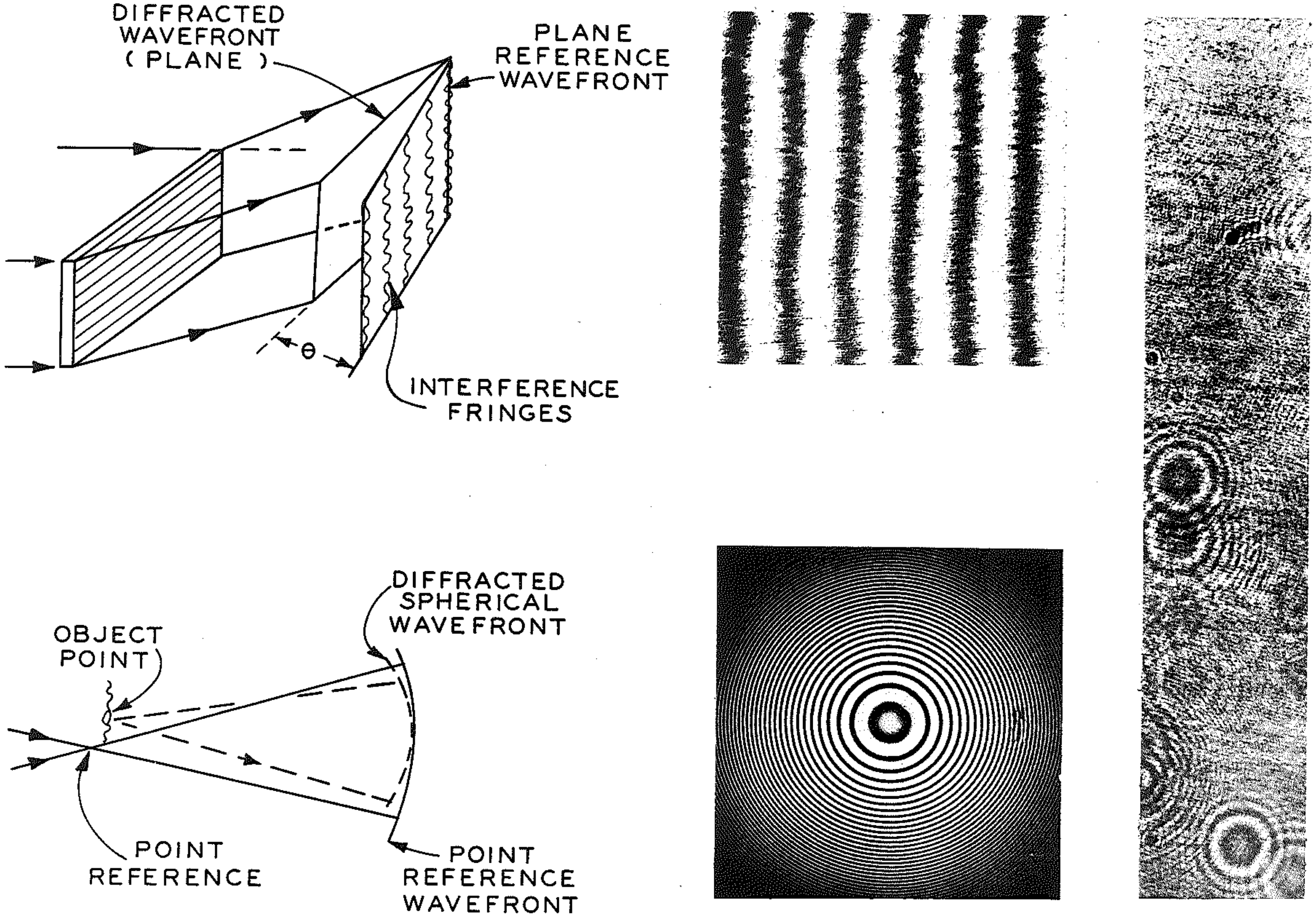


Figure 14. Building blocks for holograms: plane wave interference (upper left) yields line interference patterns (upper center), and spherical wave interference (lower left) yields ring interference patterns (lower center). Combination of the two patterns forms the hologram (right).

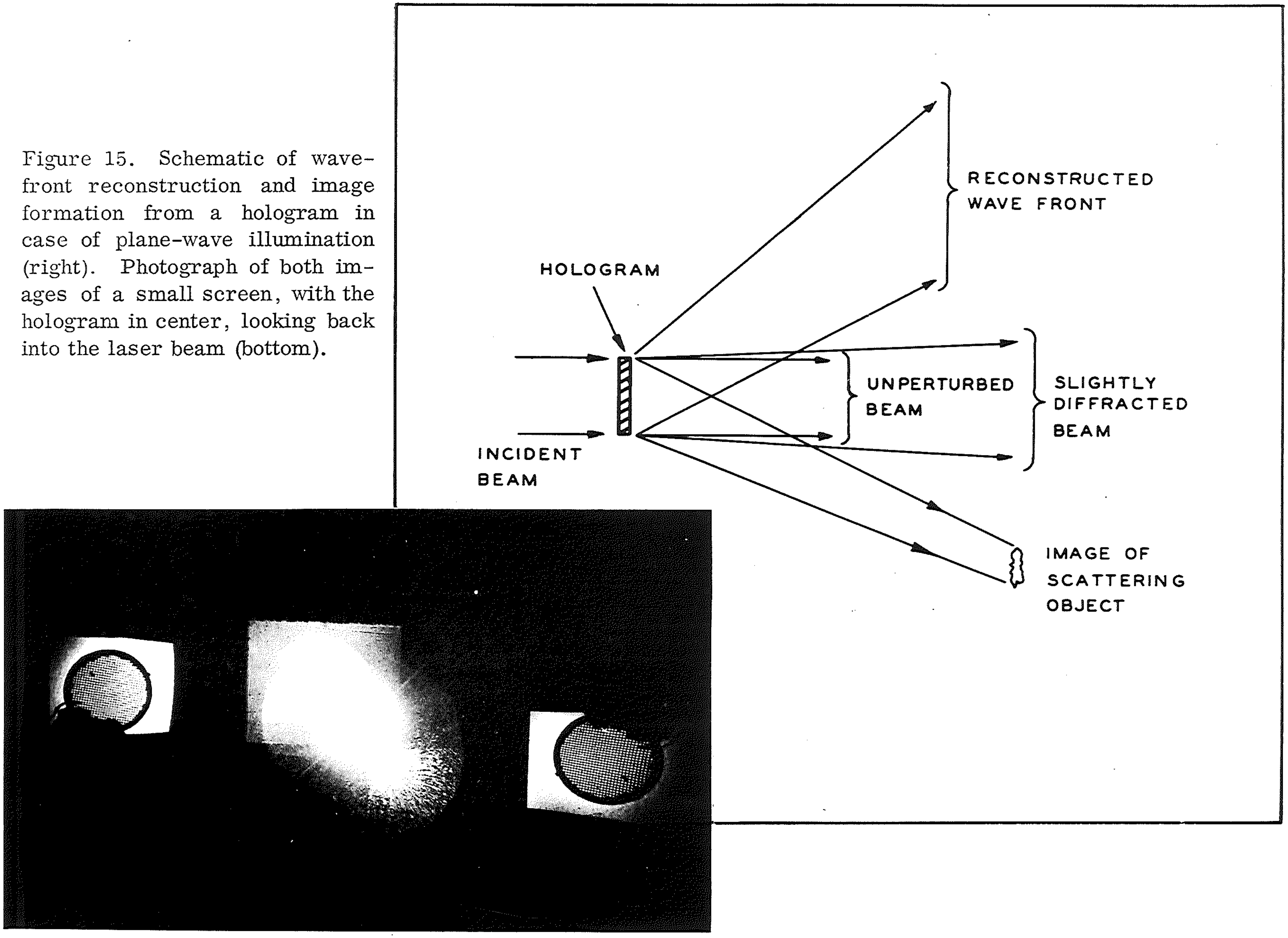
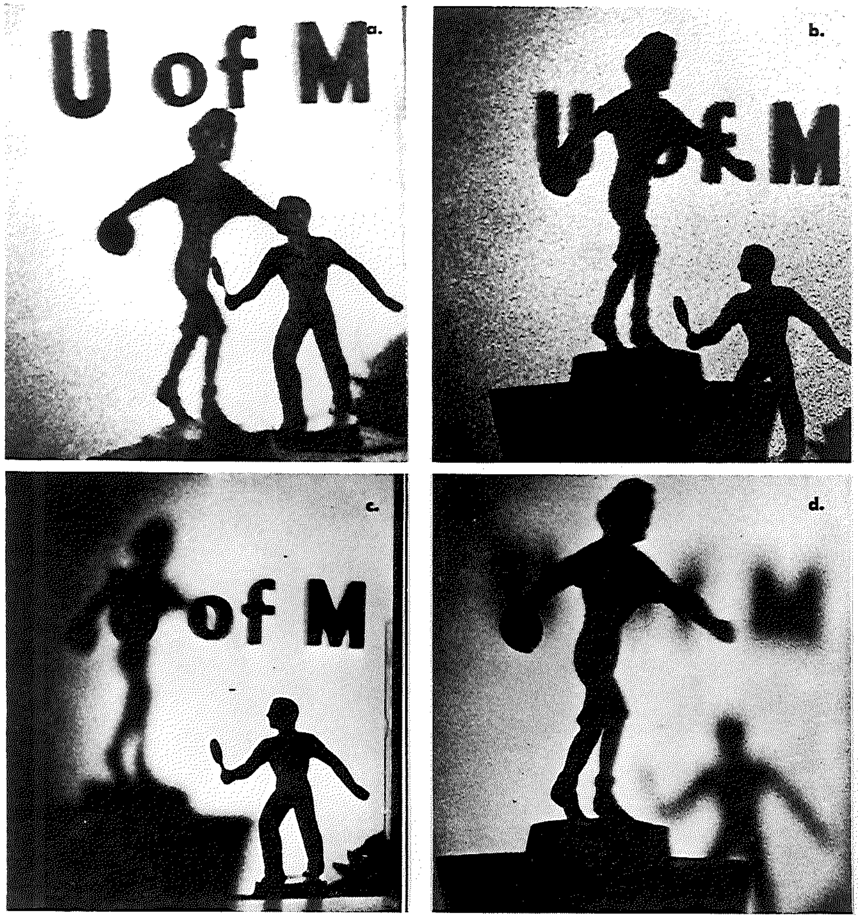


Figure 15. Schematic of wavefront reconstruction and image formation from a hologram in case of plane-wave illumination (right). Photograph of both images of a small screen, with the hologram in center, looking back into the laser beam (bottom).



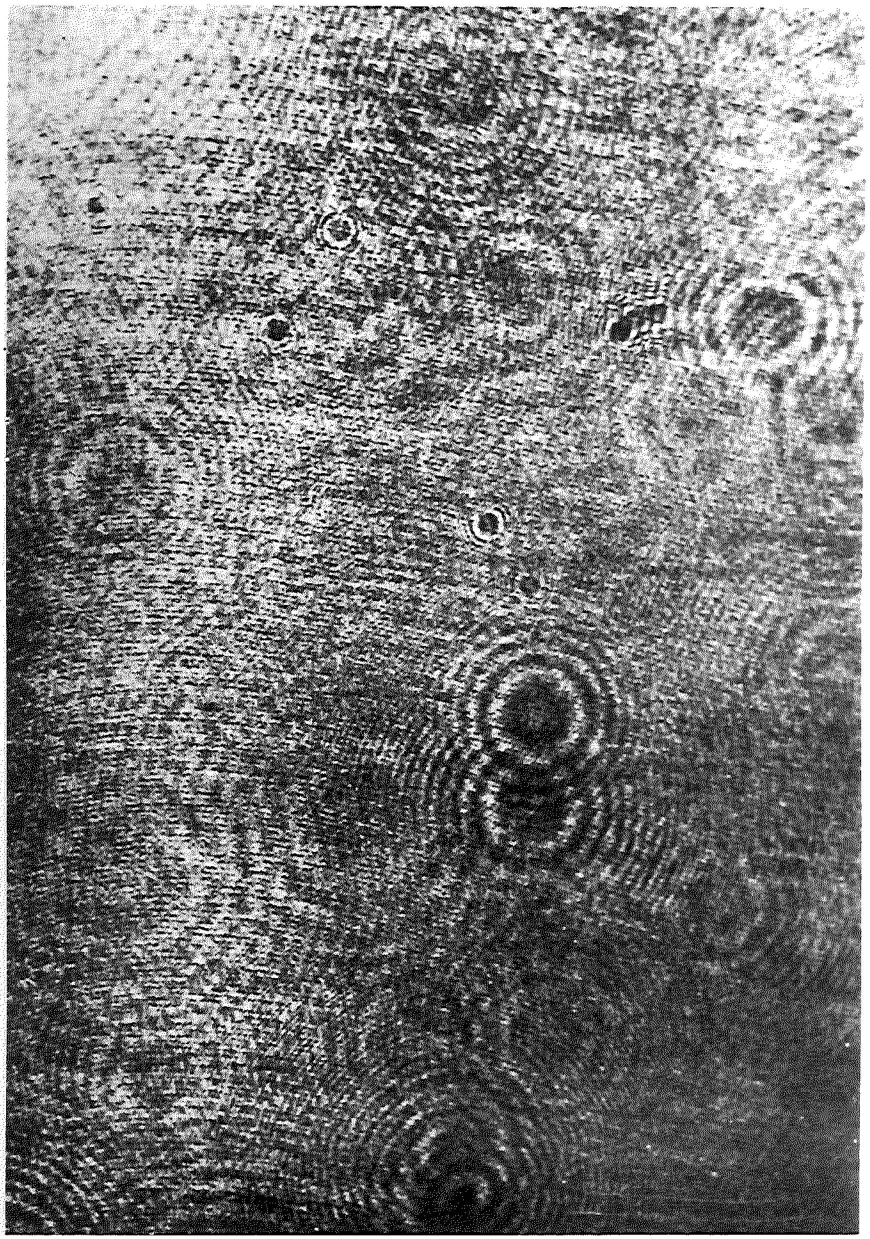


Figure 16. Images of a three-dimensional scene reconstructed from hologram at right. All four images were photographed by a camera looking back through the hologram and so placed as to reveal the three-dimensional nature of the image. The top two photographs were taken at different angles, with small aperture, to show parallax. The lower photos were taken at the same angle, but with large aperture, to show three-dimensional field depth.

4. Extremely large magnifications can be achieved without lenses or other optics. A magnification of one million with a resolution of 1 Å has been predicted. While such magnification could be achieved by optical systems, it would be meaningless because of lack of resolution. If a hologram were recorded using 1 Å wavelength x-rays and illuminated with 6328 Å wavelength laser light, a magnification of 6328 would be achieved. Further magnification is obtained by illuminating the hologram with a diverging beam, causing the image to grow as it travels from the hologram. Such high magnification with excellent resolution would permit direct observation of molecules, atoms, and crystals.

Holograms are now recorded using low-power continuous-output gas lasers. Exposures run from several seconds to several minutes and the object must remain stationary to one-eighth the wavelength of the illuminating light. By using high-power pulsed lasers with a short pulse, life-size scenes with moving objects might be recorded for commercial or military use. Multicolor holography is under study with an eye to future three-dimensional color television.

Since stabilized lasers can be operated for considerable periods at constant wavelength and frequency, they can serve as convenient standards for comparing other wavelengths and frequencies. Standard units of length, such as the meter, can be specified in terms of the wavelength of a stable laser emission. A super-stable frequency also serves as a standard for measuring time.

Data processing by optical means is very promising with laser illumination. A great deal of seismic data on file at various oil companies is being re-evaluated with the aid of "Laser Scan." This is a commerical laser device which filters out noise and interference from slides of seismic data so that the true shape of underground formations is visible. It works by projecting the slide with laser light. Before the image is focused, however, parts of it are filtered out by movable optical wedges in the instrument. It is a trial and error process, with the operator removing various parts of the image until the useful features of the data are apparent. Newsprint pictures have been similarly improved by filtering out the usual dot structure. Improvements of spectroscopic recorder traces and x-ray photographs are expected further applications. Holography can be used in searching data or literature also. For example, if a hologram is taken of a page of text and the image of the page is filtered with a hologram of a word or formula, a white spot will appear in the filtered image to indicate the location of that word or formula in the text.

Highway Applications

Laser technology, as has been described, will find many applications in industries that manufacture highway materials or perform highway construction. Possible Highway Department uses for lasers include the following:

1. A small gas laser, costing about $1300, would be useful for aligning and setting up optical equipment in the Research Laboratory's photometry section.

2. High-power pulsed lasers can melt or vaporize materials, including metals. Possible applications might be found in construction or maintenance where very precise welding or cutting is needed without damage to adjacent areas. Samples of plastics, rubber, etc., might also be flash vaporized for analysis by gas chromatography.

3. A laser beam may be used to vaporize small inclusions of minerals in aggregates, for subsequent emission spectrographic analysis.

4. Laser sources and phototube detectors might be used to replace the infrared systems used in measuring vehicles at the electronic scale near Jackson. These would give sufficient radiant power for easy detection and obviate any difficulties caused by low sensitivity of infrared detectors. The laser beams could be split to cover several detectors so that a laser source would not be needed to replace each infrared source now in use.

5. Traffic control systems may employ lasers to operate systems of traffic signals by bouncing the laser beam to various intersections with mirrors. A recent journal advertisement reports that research is being done on such a system (Fig. 17).

6. Use of the laser beam as a straight line has possibilities in highway construction activities, as in alignment of grade stakes and guides for finish grading and paving machines.

Acknowledgment

Figs. 13, 14, 15, and 16 of this report are reproduced from "An Introduction to Optics of Coherent and Non-Coherent Electromagnetic Radiation," by George W. Stroke, Department of Electrical Engineering, University of Michigan (March 1965).

EAGLE SIGNAL RESEARCH PROJECT #V-5670

Responding to a steady flow of traffic information, the city "master" directs the cycle, split and offset of all major intersections with a finger of light 1/100th of an inch wide—a laser beam! Mirrors bounce it to intersections out of the line of sight. There are no interconnecting wires...no antennas ...intersections and subsystems feed back data. The laser beam works with the speed of light; is "off the line" the balance of the time. Power consumption and maintenance are cut to new standards of economy.

Concepts like these beam-operated signals are already in the minds of the men of Eagle Signal. When your city is ready, wireless interconnect by laser will be available.

Figure 17. Recent advertisement concerning a future application of lasers.