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Research Note

Lasers — A Basic Discussion of Types, Properties, and Principles

C. MARTIN STICKLEY

COMMUNICATION SCIENCES LABORATORY PROJECT 4645

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OFFICE OF AEROSPACE RESEARCH, UNITED STATES AIR FORCE, L. G. HANSCOM FIELD, MASS.

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Abstract

This report describes the basic aspects of a laser. It includes a quantitative discussion of the major properties and the different types of lasers, as well as the basic laser mechanism — stimulated emission. Not included are detailed discussions of items that will be soon outdated. Several applications are presented in order to illustrate the properties of the laser.

Acknowledgments

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Lasers — A Basic Discussion of Types, Properties, and Principles*

1. INTRODUCTION

The laser is the most important new product of technology since the transistor. It results from man's education rather than his ingenuity and inventiveness since it evolved from such basic technical fields as quantum mechanics, microwave spectroscopy, and electromagnetic theory.

The term laser is an acronym for Light Amplification by Stimulated Emission of Radiation. Although true amplification of light has been achieved using a laser, its greatest use has been as an optical oscillator; that is, as a source of coherent radiation in the visible portion of the electromagnetic spectrum. The meaning of the term laser will be probed more extensively later. The concept of the laser, which is a further extension of the principles of the maser (Microwave Amplification by Stimulated Emission of Radiation), was first discussed by Charles Townes and Arthur Schawlow (then of Columbia University and Bell Telephone Laboratories, respectively) in 1958. The first operating laser using ruby as the active material was developed in mid-1960 by Theodore Maiman of Hughes Aircraft Company. Since that time, various types of lasers using different crystals, glasses, gases, and semiconductors have been developed.

The most outstanding properties of the laser are:

(1) Focused power densities in the order of hundreds of millions of watts

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* This paper was written for publication in the Spring 1963 issue of the Air University Quarterly Review.

per cm^2 can be obtained. This property provides a new tool for investigating the interaction of light and matter. Various and diversified applications such as welding, cutting through diamond, medicine, communication systems, and perhaps, radiation weapons are envisioned as products of this property.

(2) The radiation that it produces at optical frequencies is coherent. The quality of coherence in light can be described by the following experiment: Two light beams are allowed to fall on a single piece of film at different times and the intensity, as recorded by the film, will be the sum of the two individual intensities. However, if the two light beams are allowed to fall on a piece of film simultaneously and an intensity pattern is observed that differs from the one obtained when the film was exposed at different times, then the two light beams are said to be partially coherent. If an absolutely dark spot is found in the second pattern, then they are fully coherent. There are advantages in using coherent radiation in a communication system because there are more refined ways of modulation (putting information on it that is to be transmitted) and detection. The amount of information that can be carried is directly proportional to the frequency. Since the frequency of optical radiation is approximately 10^{14} cps as compared to 10^9 cps for the microwave link which is used for coast-to-coast TV transmission, the increase in information that could be carried is immense. In fact, it is so large that it may never be used to its full capability.

(3) The output radiation from the laser is extremely directional in nature. If the laser were to be used in conjunction with a properly designed optical system, the beam spread could be as small as 10^{-6} radians; that is, for every one million feet (about 190 mi) that the beam traveled, its width would increase only one foot. This would make possible a spot size on the moon of 1/4 mi.

These properties, their applications, and the underlying physical phenomena will be discussed further in greater detail.

2. CONSTRUCTION OF A LASER

Many intriguing uses will surely be discovered for the laser because of its simple construction. Unlike masers, electron-beam machines, or other devices, the laser can operate at room temperature and pressure; no low temperature or high vacuum apparatus is required. The construction of the laser used in most research laboratories is the same as that originally devised by Maiman.

The critical element in the laser system is the laser material. Several materials have demonstrated laser action, but the best known material is the ruby. For convenience in the following discussion, the laser material will be referred to as ruby. Aside from the ruby, the primary element in the laser system is the light source which is used to supply energy to the ruby rod. This light source is a high power helical photoflash lamp of the type used in studio photography that is capable of handling megawatts of electrical power on a pulse operation basis.

The ruby rod is coupled to the flashlamp by attaching one end of the ruby rod to the end of a hollow brass tube which serves as a holder and a light pipe for the laser radiation. In order to absorb the maximum amount of light, the unshielded portion of the ruby rod is inserted in the center of the helical flashlamp.

The last step is to provide the large amount of energy to the flashlamp necessary for inducing laser action. Approximately 1800 joules of energy are required for about one thousandth of a second; this is a power flow of 1,800,000 watts which obviously cannot be obtained directly from an a-c line. Therefore, it is necessary to store up this amount of electrical energy in a large capacitor bank and then allow the capacitor to discharge its energy into the lamp.

The elements outlined are the rudiments of most laser systems in which solids such as ruby are used as the active material. A possible variation in this system is in the configuration of the pumping lamp. A helical configuration is very inefficient while a much better design from the viewpoint of increasing over-all efficiency is the use of a straight lamp. If this linear lamp is placed in direct contact with the laser rod and the two are wrapped with silver foil which acts as a reflector, the best over-all efficiency for conversion of stored electrical energy in the capacitor bank to emitted energy from the laser is obtained, and this is of the order of 1 percent.

The simplest laser system ever constructed consisted of a neodymium-in-glass laser rod placed in direct contact with a type AG-1 flashbulb. It was then fired in the same manner as a flashbulb in a camera. This simple system worked because the type of laser material used has a very low threshold energy* at which laser action starts. Of course, the difficulty with this system is that a new AG-1 bulb is needed for every flash; however, it does demonstrate the basic simplicity of a laser.

The large photoflash lamps can be used for many flashes. They are essentially no more than a long tube with electrodes at each end filled with a gas such as xenon. When the capacitors are discharged through the gas, the gas molecules become ionized. When they fall back to their initial and lower energy level, the gas molecules emit light. Although each molecule emits light at one frequency only (at a given instant of time), there are so many molecules radiating at so many different frequencies that the resultant light looks white to the eye. * *

The process for getting energy into a laser rod in order to induce laser action

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* This is so because it is a four-level laser which will be explained in more detail later.

* * White light is composed of a mixture of all colors or frequencies.

is one of absorption by the laser material. Ruby absorbs yellow-green and violet light but does not absorb red light. Since the red light is not absorbed, it is transmitted through the ruby rod and, therefore, ruby appears red to the eye. Other solid laser materials absorb other wavelengths, and consequently, the xenon-filled photoflash lamp is good for general purpose laser pumping since it does emit at all wavelengths.

The typical configuration of a laser rod is that of a right circular cylinder with a length ranging from 1 - 12 in. and a diameter ranging from 1/10 - 3/4 in. For best operation the ends of the rod should be optically polished so that the variations in flatness are no greater than 1/10 of a wavelength (.000003 in.) and they should be parallel to within 4 sec of arc. Other configurations of the ends can be used (such as hemispherical surfaces) but the flat ends are the most common. One end of the rod is then heavily coated with silver so that no light can pass through it, while the other end is coated to allow only a few percent to be transmitted. This few percent constitutes the output of the laser.

At the time of the writing of this report, ruby is the only solid laser material that oscillates at a visible wavelength;* all other solids oscillate in the infrared. Since new laser frequencies are being announced at the rate of two per month, it should not be long before there are other lasers that emit coherent radiation at visible wavelengths.

The second type of laser uses gases as the active medium instead of a solid. The first one of this type was set in operation in late 1960 by Javan, Bennett, and Herriott of the Bell Telephone Laboratories. The basic theory of operation of a gas laser and a solid laser are roughly the same, but the actual performances of the two are considerably different. All gas lasers can be operated continuously since the power requirements are only 40 watts at a radio frequency. The few solid lasers that can be operated continuously require 1000 watts input and therefore must be elaborate in design in order to remove all the heat that is generated. The power outputs of gas lasers (and even the continuous solid lasers) are less than one watt whereas the output power of pulsed solid lasers can be hundreds of thousands of watts for a duration of less than one thousandth of a second.

Gas lasers approach the ideal model of laser operation much closer than do solid lasers. The fact that gas molecules can move around is not of too great importance since their velocities are still slow compared to the velocity of light which is 3×10^{10} cm/sec. Gas molecules are much more widely separated than the ions in a crystal and, consequently, interaction effects are of secondary importance. The gas laser generates frequencies that are much more monochromatic than those emitted from ruby lasers. In fact, the spectral purity (or

* During the proofreading of this report, it was announced by the General Electric Co. that a semiconductor laser had been made to oscillate at about 7100A which is also visible.

monochromaticity) of the radiation from a gas laser is considerably better than the best electronic oscillator. The gas laser oscillates at a frequency of about 3×10^{14} cps and the frequency width of this radiation is about 100 cps. This gives an impurity (by this is meant the spectral width of the radiation divided by the center frequency) of three parts in 10^{13}. A similar figure for the ruby laser is 2.5 parts in 10^{8}. This is not as pure as the gas laser but it is still narrower than the best conventional light source before lasers were invented.

The construction of a gas laser is more difficult than a solid laser system for several reasons. First, the gain per unit length of a wave propagating through the activated gas medium is much less than that for a solid laser. The path length must be comparatively long for a wave to grow sufficiently in amplitude to compensate for the amount lost when it strikes the partial reflector. A typical length is 1/2 - 1 meter whereas for ruby a 1 in. piece is sufficient. This long path length puts very tight tolerance on the alignment of the two mirrors. The second difficulty is that a gas or mixture of gases must be enclosed in a sealed glass tube. Although initially it is easier to set up a solid laser system, there are great variations in operation between similar types of crystals; these problems do not arise in a gas laser.

The systems that are used for pumping a gas laser differ considerably from optical pumping which is used for most solids, because the step of converting electrical energy to optical radiation is eliminated. The one that will be discussed here is that used by Javan to pump the helium-neon laser. This gas laser consists of a mixture of helium and a smaller amount of neon. An electrical discharge is used that excites the helium atoms to a higher energy state. Then these excited helium atoms can transfer all of their energy to the neon atoms via a collision. It is from the excited neon atom that laser action occurs and the mechanism is the same as in solids (this mechanism will be discussed in greater detail later).

Most gas lasers oscillate in the infrared; however, there is one atomic transition in the helium-neon gas laser that permits it to oscillate in the visible wavelength region at 6328A (red). This is the highest frequency laser that is definitely known at the time of the writing of this report.

A third type of laser was announced in November 1962 by R. N. Hall and his colleagues at the General Electric Company. This is a semiconductor device and many of the techniques developed by the semiconductor industry for making transistors and diodes were used in its development. This laser is basically a pn junction diode with mirrors on each end. A 'pn junction' is a junction of two slightly dissimilar semiconductor materials. The actual junction occurs in a very narrow and well-defined region. When a voltage with the correct polarity is applied to the diode, large currents can flow and in the immediate vicinity of the junction, there can be more electrons in an upper energy level than in the valence band (the lower energy level). This is one of the criteria for laser action. The electron then drops down (in energy) to the valence band and gives up this energy difference as a wave or photon. The semiconductor material that was used is gallium arsenide and the wavelength at which it emits coherent radiation is 8420A. * The outstanding feature of this type of laser is that is has an efficiency of 40 percent or greater in the direct conversion of electrical energy to coherent optical energy. This conversion efficiency is approximately forty times greater than solid lasers that are optically pumped. The one drawback at the present time is that they must be cooled to temperatures approximately -300°F or less but it should not be too long before materials are found that do not require cooling.

3. THE LASER MECHANISM

In this section, ruby and its characteristics will be discussed, although it is, in most respects, typical of all optically pumped solid lasers. The part of the following discussion dealing with stimulated emission is characteristic of all types of lasers, whether they be gases, or solids, and whether they are optically or electrically pumped.

The ruby used in conventional lasers consists of a dilute mixture of chromium and aluminum oxides. Pure aluminum oxide, otherwise known as sapphire, is colorless; that is, radiation in all parts of the visible spectrum pass through it unabsorbed. As was mentioned above, ruby gets its red color because the chromium atom in the aluminum oxide absorbs radiation in the yellow-green and violet regions but allows the red and blue to pass through. The chromium atom, because it absorbs a light ray (or photon which is a quantum of light), gains the energy of this photon and is "raised" to a higher energy state. The chromium atom then returns to its lowest energy or original state in two steps. In the first step, the chromium atom collides with the basic crystal lattice structure and in so doing loses about 20 percent of the energy that the absorbed photon imparted to it (if that photon was absorbed in the yellow-green band). It has then arrived at a relatively stable (or metastable) energy state at which it can reside for some three one-thousandths of a second. This is long compared to the elapsed time since the photon was first absorbed. In fact, the time between absorption of the photon and arrival at the metastable energy state is less than one millionth of a second. Its final transition back to its original energy state can occur either spontaneously or

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* The new material that was referred to previously in a footnote is a mixture of gallium arsenide and gallium phosphide. It is predicted that by adjusting the mixture one can obtain an output wavelength of as high as 6200A. In addition, the IBM Corporation has recently announced that they have made a gallium arsenide laser oscillate continuously at a temperature very close to absolute zero (less than -400°F).

it can be forced down. By spontaneously, it is implied that it remains in this metastable state some three one-thousandths of a second on the average and then suddenly, of its own accord, drops down to its original energy state. The energy it loses in making this transition is given up as a wave (or photon) whose frequency 'f' is equal to E/h where E is the energy difference between the two states and h is Planck's constant.

The fact that this chromium atom can also be forced to lose this last amount of energy, E, is the whole heart of the laser action. This process of being forced down is called stimulated emission and is the reverse of the process in which a photon is absorbed between the same two energy levels. During the time in which the chromium atom is sitting in the metastable energy level it can be stimulated to emit a photon if it is struck by an outside photon having precisely the same energy as the one that it would have emitted spontaneously. As a result of stimulated emission, one now has two photons of the same energy, or from the wave view-point, the wave amplitude has been doubled, and the chromium atom is now back at its lowest energy level. The most remarkable feature of this process is that the additional wave that was created is exactly in phase with the wave that stimulated it downward. This in-phase relationship between the stimulating and stimulated waves is responsible for the coherence of the light that is generated. As this wave continues to propagate in the ruby crystal it stimulates other chromium atoms in the metastable state to lose their energy and their energy is all added in phase to the stimulating wave thus producing a wave that is increasing in amplitude.

Since this process can start out in any direction, one must find a way to create a favored direction if it is to be controlled and utilized. Schawlow and Townes, in their now historic paper on the theory of lasers, suggested that this 'active medium'—like ruby—be placed between two highly reflecting, plane, parallel mirrors. Then, a wave that starts out in a direction perpendicular to the plane of these mirrors will be reflected back into the active medium every time it strikes the mirrors. Since some energy of the wave will be lost when it strikes the mirror that is only partially reflecting (this energy that is 'lost' is the output of the laser), the wave will be slightly reduced in amplitude when it starts back through the active medium again. If a wave which has started from any point in the crystal and has undergone reflection at both mirrors arrives back at this point with a greater amplitude than when it first started out, it will continue to build up in amplitude and oscillation will develop. This is another condition for laser action; that is, the gain of the wave in the active medium must be greater than the losses it suffers upon reflection at the ends (plus other losses due to imperfections in the crystal and diffraction).

The laser described above is a 'three-level' laser; one level is the lowest energy state of the chromium atom, the second level is the energy state to which the atom is raised when it absorbs a 'yellow-green' or 'violet' photon, and the third level is the metastable state from which it is stimulated downward. Now consider a photon that is just starting to propagate through the crystal. The probability of it stimulating others downward and starting laser action requires that there be more chromium atoms in the metastable state than there are in the lowest energy state (often called the ground state). Therefore, in order to achieve laser action in the three-level system, more than half of the chromium atoms must be in the metastable level. The number in the absorption level or highest energy level are few since they spend so little time there, and therefore, they are neglected. Now it requires a considerable amount of power to keep at least half of these chromium atoms in this upper energy level; and, if a method could be found to avoid this, it would be exceedingly worthwhile. Since the important point is that the metastable state must have more atoms in it than the state to which they are falling (in energy), then why not insert a normally empty fourth level into the system to which they can fall from the metastable level? If this is done, then only a small part of the total number of excitable atoms must be in the metastable level to get laser action rather than half of them. This results in considerable savings in pump power and makes it possible to operate a four-level laser continuously. Once the excited atom has dropped down to the fourth level from the metastable state, it must then fall down (in energy) very quickly to the ground state to prevent the fourth level from filling up. If it did fill up, laser action would cease immediately after it started. A fast decay rate between the fourth level and the ground state is therefore an additional requirement for this type of a laser. Four-level lasers have been built. In fact, there are more solid lasers that operate in this manner than three-level lasers. It is impossible to convert ruby to this type of operation; rather, new materials must be found that naturally exhibit this type of energy level structure. Although ruby has been made to operate continuously rather than pulsed, all other continuous lasers are four-level systems, since they require so much less power. Lasers of this type will probably become predominant in the future.

4. MAJOR PROPERTIES AND THEIR USES

As mentioned previously, the major features of the laser are: the beam is extremely intense, it is almost completely coherent, it is very directional in nature, and it is very sharp in frequency. Each of these will now be discussed and some indication will be given as to the usefulness of each of these properties.

A. Intensity: This property of the laser beam is probably the best known and the most widely used at this time. To emphasize its extreme intensity, let us compare it with a conventional light source such as the tungsten filament of a light bulb or the sun. These types of light sources emit almost 'white' light; that is, they emit at all of the visible wavelengths such that the superposition of all of this radiation looks white to the eye. It can easily be shown that a light bulb does emit red light by looking at it through a red filter. This allows red light to pass through it but absorbs the other colors or wavelengths. Since it emits red light, the light bulb looks red; if it did not emit red light, one would not be able to see through the filter.

These types of light sources are called blackbody radiators and their radiation can be characterized quantitatively by the blackbody radiation law that was first derived by Max Planck in 1900. This law is essentially a formula for the amount of radiation (power) from a square centimeter of its surface area in a wavelength interval of one angstrom.* The sun, in the red wavelength region, emits approximately 0.7 watt/cm^2/A. Now the ruby laser can emit a thousand watts from a square centimeter (for a very brief period of time) within a wavelength interval of .0001A (this is equivalent to a frequency width of 10 million cps). On a per angstrom basis, it emits 10,000,000 watts/cm^2/A or the laser is some 10^7 times as intense.

One can argue that this is not a fair comparison since the sun emits over a much wider wavelength range than a laser and it also emits in all directions rather than in a well-confined beam. This is a good argument. The biggest difference, though, is the fact that the laser's radiation is coherent whereas sunlight is not. From this point of view, the laser ought to be compared with conventional man-made electronic transmitters which generate coherent radiation. These transmitters can easily produce thousands of watts in a well-directed beam and in a frequency interval smaller than 10 Mc. Why, then, is the laser so good? Its big advantage here is that it emits at optical wavelengths which are some 100,000 times shorter than radio-frequency wavelengths, and the area down to which radiation can be focused is proportional to <u>the square of the wavelength</u>. Hence, if one has a laser beam with a peak power of one million watts and a beam width of 0.5° (one hundredth of a radian), it can be focused to a spot size of .0001 sq cm if a one centimeter focal-length lens is used. This corresponds to a power density of 10^{10} watts/cm^2 This is not achievable with any other type of power source. Thus it becomes relatively easy to drill holes in diamonds and puncture holes in sheet steel.

This, then, will probably be the area where the laser will find its greatest practical application in industry. The laser has the potential to drill holes with diameters not much larger than 1/10,000 in. This is not possible by conventional

* The visible spectrum extends from a wavelength of 7000A which is red light to 4000A which is blue light. One centimeter equals 10,000 microns and one micron equals 10,000A.

means. Holes of this size can be drilled using electron beams which are much more complex than the laser. It has also been shown that the laser is useful as a power source for vacuum evaporation and deposition of a wide range of materials because the laser can be external to the vacuum system and, therefore, will not contaminate it as internal conventional heating sources are prone to do.

The electric field strengths produced in the focused spot are approximately millions of volts per centimeter. These high fields will make possible the production of new nonlinear effects in materials. Some of these have been investigated and frequency doubling and tripling have been observed. It has been reported that a 20 percent conversion efficiency of red light (6943A) to blue light (3472A) has been attained. In the area of medicine, the laser's intensity has been used to reattach a detached retina to the back of the eye. It can also destroy cells in human tissue and there is hope that the laser will kill malignant cells in body tumors.

One of the desired uses of lasers by the Air Force is as a radiation weapon. Since this is a classified subject, little can be said about it here except that the laser is being investigated for this potential application.

B. <u>Coherence:</u> The natural coherence of the laser beam is the distinguishing factor from other optical sources. It is a property of radiation that has always been obtainable at microwave and lower frequencies but never completely obtainable at optical frequencies. One can generate very low intensity light that has a small degree of coherence, but the system for doing it is complex and inefficient and, consequently, it has never been considered practical for use in, for example, a communication system.

The mechanism through which the laser beam becomes coherent was discussed in a previous section, and it is basically due to stimulated emission. A wave propagating through the laser triggers excited atoms to give up their energy, thereby releasing waves that fall precisely in phase with the wave that triggered them. In a sense, all of the waves generated are in step similar to a column of marching airmen. If the airmen were given the command 'Scatter, March,' they would be analogous to incoherent light since they, like the radiating atoms, would be out of step.

The coherence of light is readily demonstrated by performing an experiment first devised in 1806 by Thomas Young. This is the classic double-slit interference experiment. If normal light from a nearby source is allowed to pass through two closely spaced slits and then fall on a distant screen, no structure in the pattern can be seen. But if these two slits are placed in front of a laser, a pattern of alternating bright and dark bands is observed. At the position of a bright band, waves which pass through the different slits arrive in phase and reinforce each other; whereas, at the position of the dark band, half of the waves have traveled an extra half wavelength in distance and arrive out of phase. Consequently, a null is produced. Since normal light is not coherent, the relationship between the different waves which strike the two slits is not fixed as a function of time. If one could make an instantaneous measurement of the light intensity on the screen, an interference pattern could be detected. But the observation is always made over a long period of time during which the patterns produced by the incoherent source have shifted around, and one measures only a smear in intensity-indicating incoherent light.

The primary application of the coherence property of the laser beam is in communications, and this is the strongest interest of the Air Force. Since this application to communication systems also utilizes the other three properties of the laser, it will be discussed at the end of this report.

C. Frequency Sharpness: In order to be absolutely coherent, radiation must be absolutely pure in frequency or perfectly monochromatic. Hence, one cannot separate entirely these two features of the laser radiation, since in the limit of either perfect coherence or purest frequency, one of these implies the other. But since there are some applications of the laser that require only a narrow frequency, they are separated in this discussion.

Although several discrete or well-defined frequencies are usually generated in the firing of a laser, individually they are extremely narrow. This narrowness arises because the internal gain of the laser medium is a function of frequency. Since it has this property, the wave that is propagating through the material with one of these preferred frequencies will grow faster than waves at other frequencies; and, as time progresses, it completely swamps out the waves with a nonpreferred frequency. This procedure of the wave becoming sharper and sharper in frequency as it grows is an extremely regenerative process. As was mentioned previously, the frequency impurity of the gas laser is only three parts in 10^{13}.

The frequency purity of an electronic oscillator is also obtained by a highly regenerative process. In this case, a quartz crystal which is cut to a prescribed shape determines the oscillator frequency and the vacuum tube provides the gain. For the laser, the shape of the rod also determines the frequency of oscillation but the system that provides the gain is built right into the rod rather than being an external element. The best specification for frequency impurity of an electronic oscillator is approximately one part in 10^{10}; hence, the gas laser is obviously superior.

In experiments performed at MIT by A. Javan, the inventor of the gas laser, it was found that the resetability of the gas laser output frequency varied by less than one part in 10^9 when compared with other tries. Since this is a factor of ten better than the present standard of length, it is certain that a gas laser will replace this standard of length in the future. Another astonishing feature of this laser is that it will permit detection of a change in length of less than two parts out of 10^{13}. This corresponds to being able to detect a change of 1.2×10^{-11} cm (the radius of the nucleus of an atom) out of a length of 60 cm.

D. Directivity: The directional nature of the laser radiation is due to both the laser mechanism and to the parallelism of the flat surfaces on each end of the laser rod. The wave propagating in the crystal tends to grow fastest in the direction that has the least loss and this is the direction that is exactly perpendicular to the two end mirrors. Waves that propagate at some other angle soon "walk off" the plates and are lost. Consequently, the output beam is extremely well defined in direction. For the case of the gas laser, the spread of the beam is primarily limited by diffraction effects. Hence, if the size of the end mirror is 1 cm and the wavelength is 10,000A, then λ/d is equal to 10^{-4} radians or about .005°. Observed beam spreads for a ruby laser are considerably greater than this; but, because the output radiation is coherent, the beam spread can be reduced by an external optical system to a point where it, too, is limited by diffraction.

If the 200 in. telescope at Mt. Palomar Observatory could be used as a collimating lens for laser radiation at 10,000A, a beam spread of 10^{-7} radians (or one half second of arc) would result. However, it would be of little value to do this since fluctuations in the atmosphere will deflect the beam by one second of arc. Even more important is that engineers cannot design systems that could point the beam as accurately. This will be the determining factor in which beam width shall be used in a system rather than the laser itself.

An obvious use for the directional properties of the laser beam plus its intensity and coherence is in communication systems; and, as mentioned before, the Air Force has a great interest in this area. An immediate objection from many people is that communication will be limited to times when there is little water vapor between the transmitter and receiver. This is certainly true when one wants to communicate from point-to-point in the atmosphere but it does not hold in outer space where there is nothing to absorb, scatter, or deflect the beam.

Several optical tracking systems are well into the development stage at this time. One of these is PIRT (Precision Infrared Tracking System). It is to be installed at Cape Canaveral, Florida, for precision missile tracking in the range of 0 - 50,000 ft. This is too close for normal radar systems. Another system is being assembled by NASA's Goddard Space Flight Center for optical tracking of a satellite. It will use a high power ruby laser as the transmitter and a highly sensitive photomultiplier as a detector. The laser will be capable of being fired once per second.

The laser will be used best though as an outer-space communication device where there is no atmosphere to disturb the beam. Because of the extreme directionality of the radiation it can be a highly secure system, for the input acceptance angle for laser radiation at a receiver can be made very narrow. Also, an optical communication system is ideal, since antenna sizes can be made much smaller if necessary than the satellite and, once again, because of the low beam spread, very little power is wasted. The transmitter can be made extremely efficient, also, since semiconductor diode lasers have been developed with power conversion efficiencies of greater than 40 percent. Background noise will probably put a limit on the range of these systems, however, and this range is liable to be the diameter of our solar system or some 7×10^9 mi. For this range, a laser pulse energy of 0.1 joule could be detected; but if one would want to communicate with our nearest star, Alpha-Centauri, one would need 10^6 joules in a pulse and this would be exceedingly difficult to obtain.

Although the over-all features of a laser system for communicating in outer space seem good, there are many basic problems yet to be solved that apply to this area as well as others. New frequencies are needed (and this implies new materials), increases in efficiency must be obtained, more efficient modulators must be designed, superheterodyne receivers must be developed, transmitters and receivers must be made tunable, and power outputs must be increased. All of these will appear in the immediate future if continued emphasis is placed on basic research. The Air Force realizes this and it is another area of specific interest as well as the development of laser systems. This is as it should be, for only through basic and applied research will the ultimate potentialities of the laser be realized.

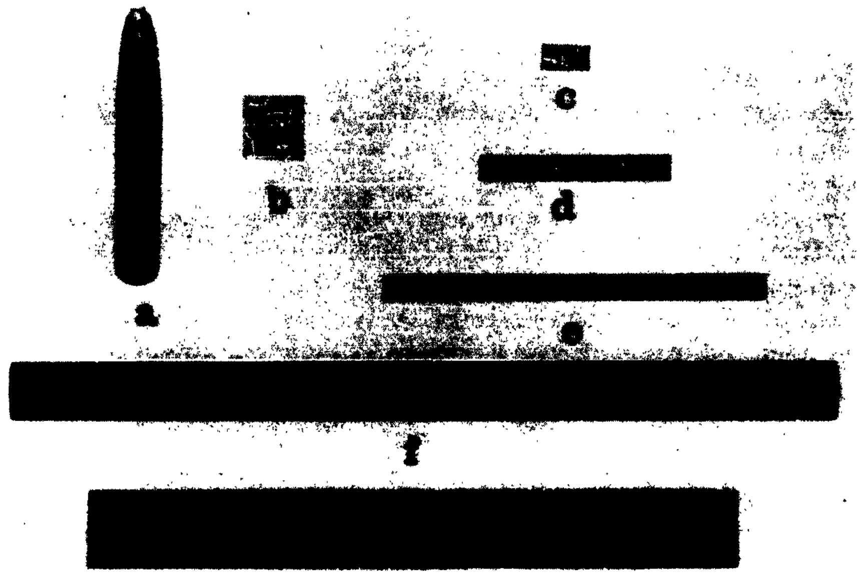


Figure 1. Samples of Ruby Crystals and Laser Rods

This figure illustrates ruby in various forms. Item (a) is a ruby boule as it appears after it is grown and before any optical work is done on it. The clear part at the top of it is a seed crystal of sapphire from which the ruby starts to grow. High quality ruby is an exceedingly difficult material to produce because of its very high melting temperature (about 3700°F). This boule is about 2 3/4 in. long 7/16 in. in diameter and would be suitable for a laser rod 2-1/4 in. long by 1/4 in. in diameter. Item (b) is a square piece of ruby that is 1/4 in. thick. It can be silvered on any two parallel faces and if it is pumped sufficiently hard, laser action can be obtained. Items (c) through (f) are all cylindrical ruby rods. The largest one is about 8-5/8 in. long and is 0.55 in. in diameter and is used in a high power laser system. The smallest one is 1/2 in. long and 1/4 in. in diameter and is useful for generating only one frequency. Longer rods such as (d), 2 in. long, typically generate five frequencies when they are fired at the threshold for laser action.

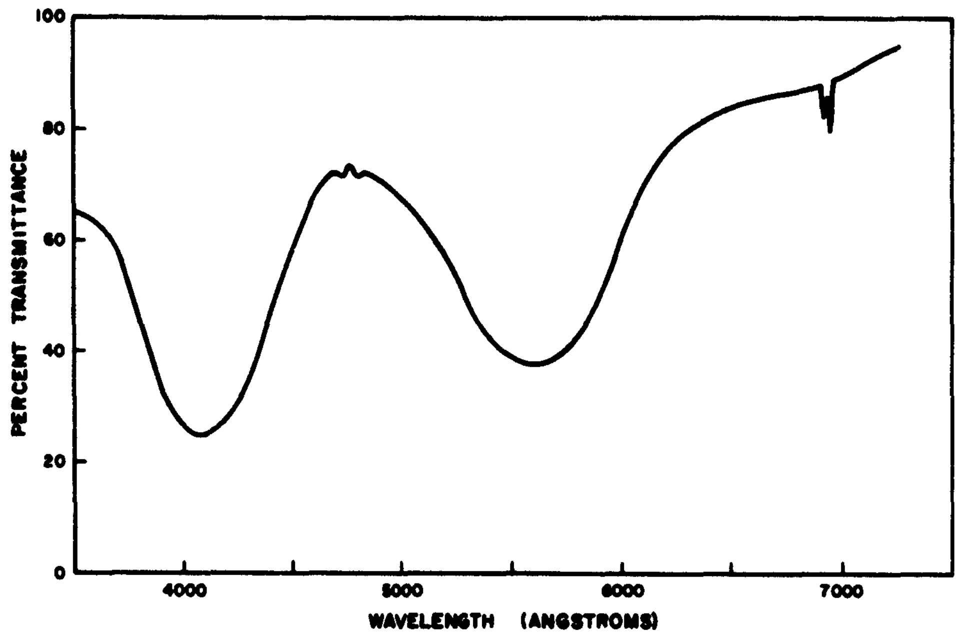


Figure 2: Absorption Curve for Ruby

This figure is a plot of the percentage of the incident light that is transmitted through a thin sample of ruby as a function of the wavelength of the light. The shape of the curve is, therefore, due entirely to absorption in the ruby. The wavelengths of maximum absorption are 4100A and 5600A which in color are violet and yellow-green respectively. These bands are responsible for the color of ruby — since only those colors are absorbed, the resultant light that passes through the crystal looks red to the eye. Since these bands are rather broad, they will absorb approximately 50 percent of white light, and consequently, white light is a reasonably efficient pumping source. The two sharp spectroscopic lines which can be seen at 6929A and 6943A are called the R lines of ruby. The longer wavelength one (the R_1 line at 6943A) is the line from which laser action occurs and is, therefore, designated as the metastable state. Photons which are absorbed in either the violet or yellow-green band lose part of their energy in 'falling down' to the R_1 line; the remainder is then given up to the growing laser beam as it propagates through the ruby rod.

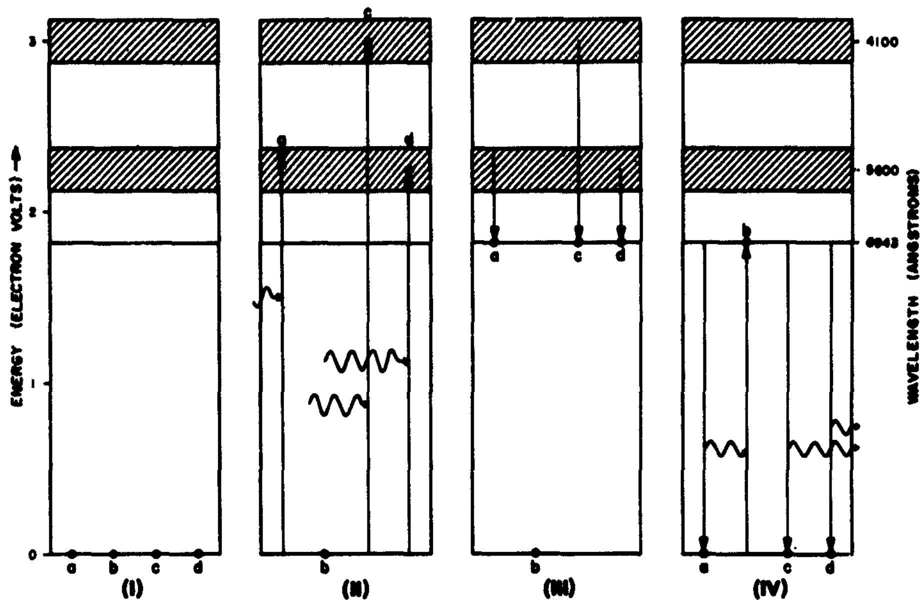


Figure 3. The Laser Mechanism

This figure graphically pictures different aspects of the laser mechanism in ruby. In (I), four atoms are in the ground state (lowest energy level) before the pumping light is turned on. The cross-hatched areas represent the two absorption bands and the sharp line represents the metastable state at 6943A from which laser action occurs. In (II), the flash lamp has been turned on and three photons from it are shown being absorbed by atoms (a), (c) and (d). In (III), these atoms have collided with the crystal lattice and have lost a portion of their energy. This energy that is lost is not radiated in the form of a photon but instead heats up the crystal. When the three atoms lose this energy, they drop down to the R_1 line at 6943A. In (IV), the first thing that occurs is atoms (a) and (c) fall back down to the ground state spontaneously. The photon generated by atom (a) is absorbed through by atom (b) and does not contribute to laser action. The photon released by atom (c), however, stimulates atom (d) to radiate (which is the inverse of absorption). Atom (c) and atom (d) are then in phase and continue to propagate through the crystal. They stimulate other atoms to emit photons and through this process, the laser beam builds up in intensity.

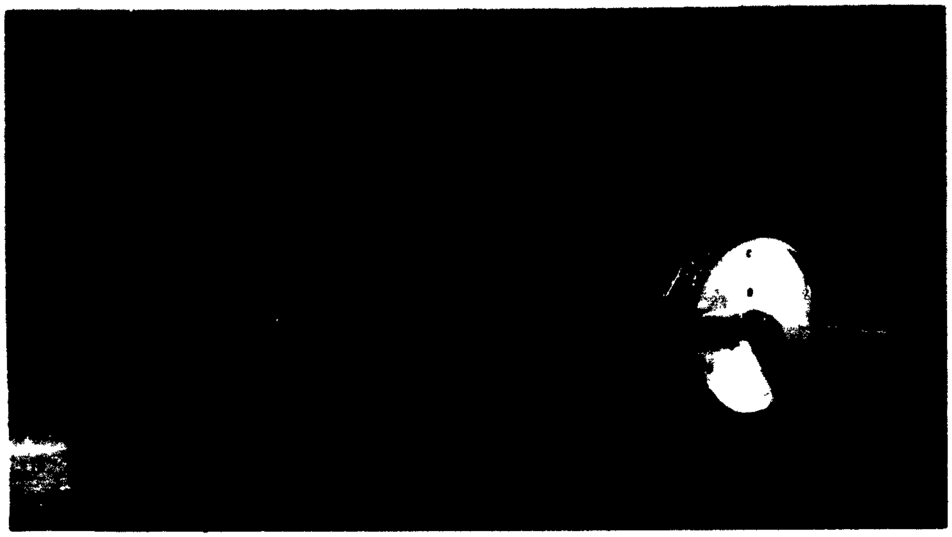


Figure 4. Exploded View of an Optically Pumped Solid Laser

This construction of the laser assembly can be used to optically pump any solid laser except for the semiconductor laser. Its primary element is the helical flash-tube which is inside the large glass envelope. The three small diameter metal rods are used to support the helical lamp and to carry the current from the connectors on the rear plate (on the left) to the lamp. The small aluminum box houses a high voltage pulse transformer. The output of this pulse transformer is carried by the third metal rod to the lamp where it initially ionizes the xenon gas in the helical lamp. This permits the large capacitor band (not shown) which is coupled to the laser through the small connectors to discharge through the lamp and produce the intense white light required to produce laser action. The smaller diameter glass tube on the right slides in through the center of the helix. This tube prevents the high voltages on the lamp electrodes from arcing over to the laser rod. One end of the laser rod is attached to the end of the hollow brass tube (shown on the far right) which serves as a holder for the rod and a light pipe for laser beam only. The large stainless steel can at the top fits around the whole laser assembly to shield personnel from the intense white light of the flashtube.

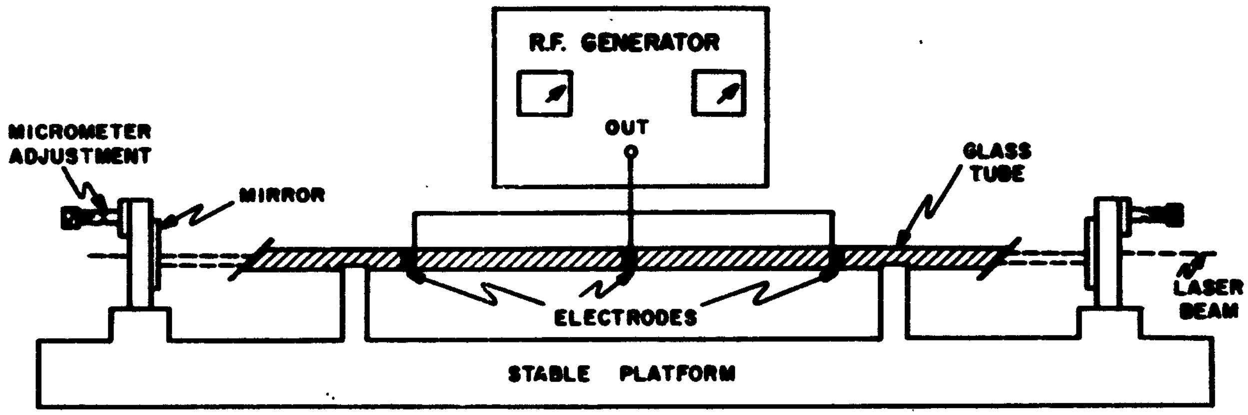


Figure 5. Construction of a Gas Laser

The laser medium for the visible system is a mixture of helium and neon; other gases can be used but their laser frequency is in the infrared. The gas is contained in the glass tube and energy is supplied to it from a radio frequency generator by electrostatic coupling. The typical power requirement is 40 watts at 27 Mc. At each end of the glass tube, a glass plate is mounted at Brewster's angle which prevents a reflection at this surface for a certain polarization of the laser beam. The mirrors are generally mounted externally to the gas laser median, and must have a reflectivity of 99 percent which requires the use of multiple layer dielectric films instead of silver. Micrometer adjustments must be provided for mirror alignment because they must be aligned to within several seconds of arc parallelism. The beam builds up by first making a pass through the gas medium; the mirror then reflects 99 percent of this back into the gas where it is amplified further. The 1 percent that the mirror transmits constitutes the output of the laser.

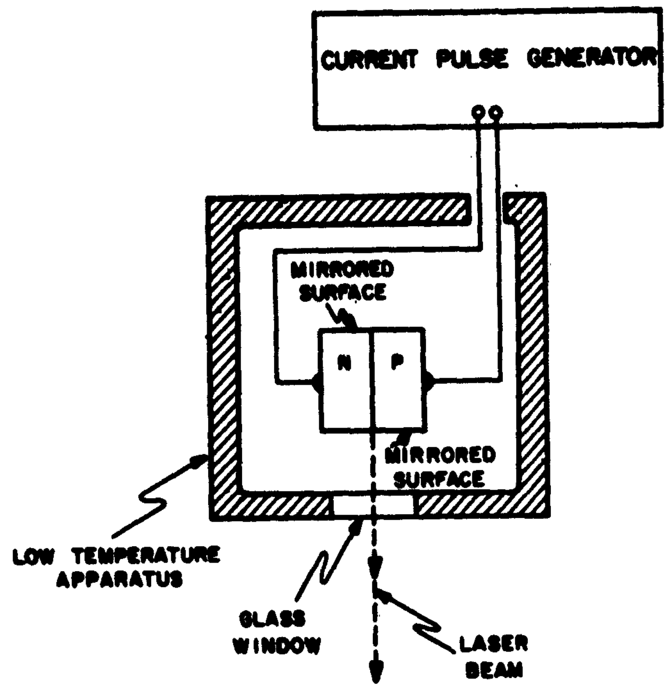


Figure 6: Construction of a Semiconductor Diode Laser

The semiconductor diode laser differs from the other types of lasers in that it is so much more efficient in the conversion of electrical energy to coherent energy at optical frequencies. The present efficiency is 40 percent compared to 1 percent for optically pumped solid lasers and 0.1 percent for gas lasers. The piece of gallium arsenate that is used is shaped like a cube with an edge dimension of about .04 in. The same techniques that have been used to make semiconductor pn junction diodes are used in making this type of laser. Electrical contacts are made to the cube on the two sides that are parallel to the narrow (.0002 in.) junction. Two other surfaces that are perpendicular to the junction and parallel to each other are polished to a high quality optical finish. It must then be immersed in a bath of liquid nitrogen at a temperature of -321°F and must be oriented so that the beam, which travels in the plane of the pn junction, can pass through a window in the low temperature container. In principle, all that is needed for power is a DC battery for the pumping source but it is still necessary to apply only short pulses to it so that it will not overheat.

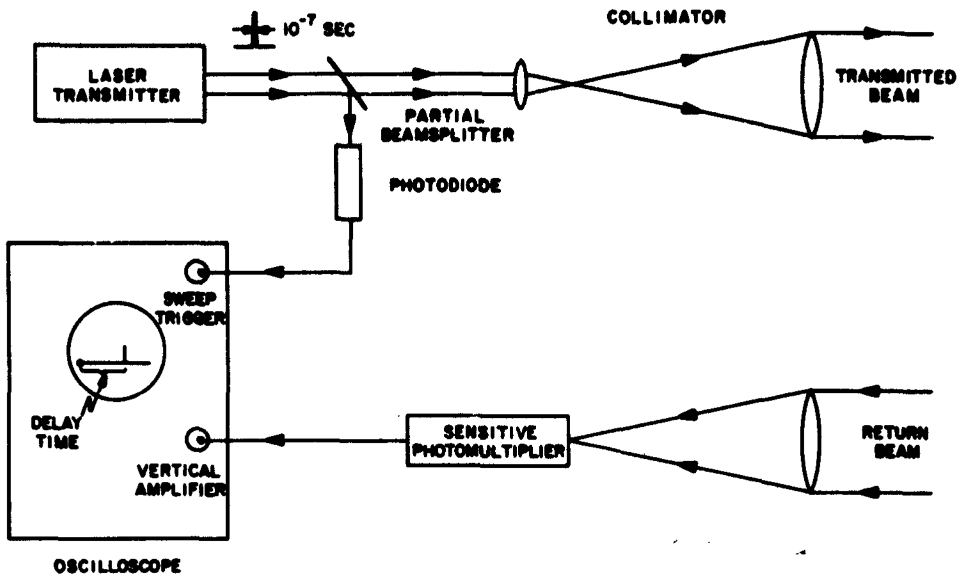
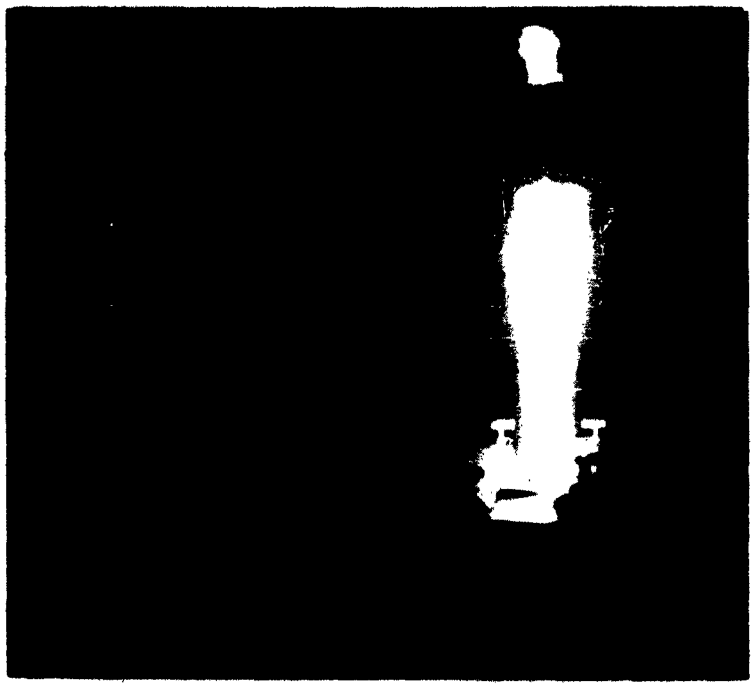


Figure 7: Simplified Laser Radar

This is a schematic drawing of a simple laser radar system. The type of laser that is used can generate a pulse with a duration of one ten millionth of a second and have a peak power of one million watts. If the pulse is this short, then the radar could have a minimum range of 15 meters. When the pulse is generated a small portion of it is picked off by a beam splitter and directed to a photodiode. The output of the photodiode is used to start the sweep of an oscilloscope. The beam is first collimated before it is transmitted to get as narrow an angle as is desired. The return signal comes in through a second optical system. It is detected by a highly sensitive photomultiplier receiver, and this output is then fed to the main amplifier of the same oscilloscope. By knowing the time delay between the initiation of the sweep and the reception of the return signal, one can compute the range of the target. Optical radars are of extreme value since they can work at very close ranges and can have resolutions of the order of a foot or better at 50,000 ft.



F. The Interaction of a High Intensity Laser Beam on Steel

The large luminous glow or flashback is often called the laser plume and presumably represents hot vaporized luminous gases expelled from the metal. The result of the short concentrated pulse is a crater in the steel approximately 1/16 in. in diameter and 1/16 in. deep. Repeated firing can widen and deepen the hole. Deep, narrow holes can be limited, however, by bubble formation in the hole. It is interesting to note that pictures with less contrast are difficult to obtain because of the great intensity of the plume. The length of the plume is about 4 in.

Figure 9. The Same Laser Beam Impinging on an Anesthetized Hamster

Notice that the plume and the interaction are substantially less. The gross effects on the hamster are similar to a minor burn — not unlike that of a cigarette. These studies are continuing but thus far the reduced effects seem to be due to transparency of the tissue to the radiation. The radiation is thus absorbed in a larger volume and results in a smaller temperature rise in that volume and a faster dissipation of the laser pulse energy. Note that the plume comes off the hamster at a 45° angle since the laser beam is striking the surface of the tissue at an angle. The length of the plume in this figure is about 1-1/2 in.

Figures 8 and 9 were supplied through the courtesy of Dr. Richard Seed of Northeastern University and the American Optical Company where these experiments were performed with a neodymium in glass laser.

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