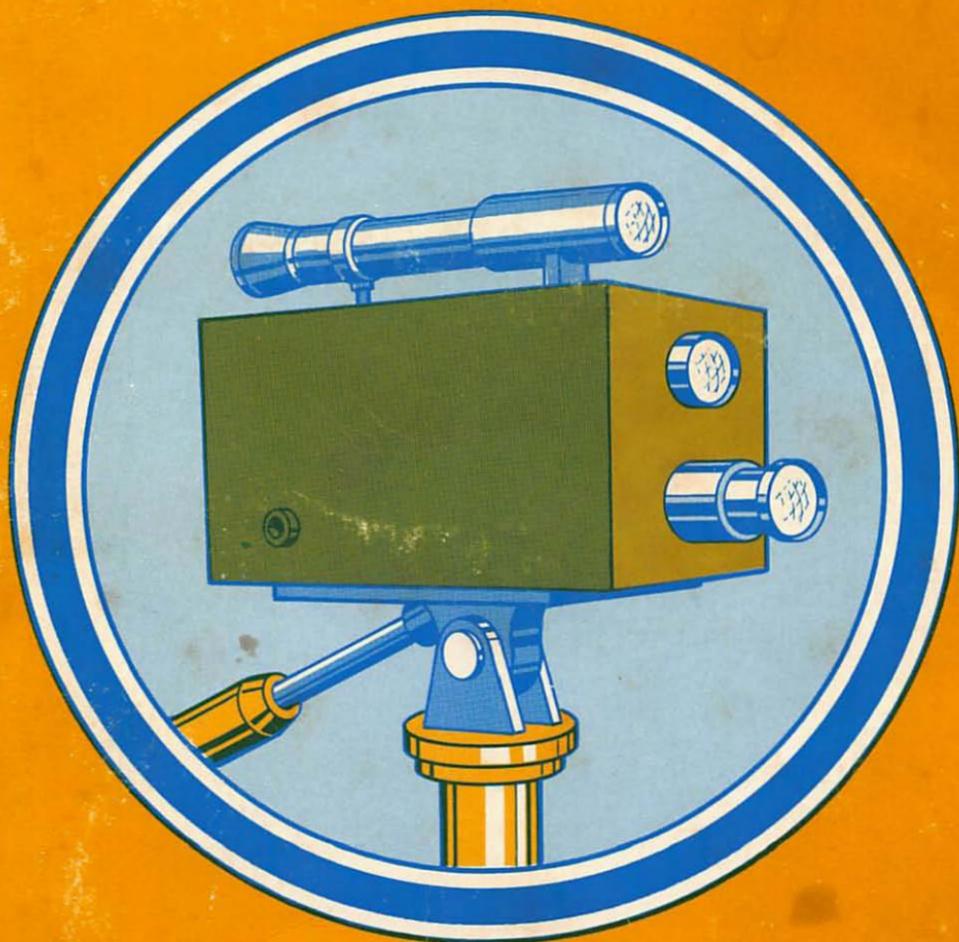


Semiconductor DIODE LASERS

by Ralph W. Campbell and Forrest M. Mims, III



Mark Kaminski

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MAY 25, 1977

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by

Ralph W. Campbell

&

Forrest M. Mims III



**HOWARD W. SAMS & CO., INC.
THE BOBBS-MERRILL CO., INC.**

INDIANAPOLIS • KANSAS CITY • NEW YORK

FIRST EDITION
FIRST PRINTING—1972

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International Standard Book Number: 0-672-20887-3
Library of Congress Catalog Card Number: 77-182873

Preface

The purpose of this book is to provide experimenters and design engineers with a broad introduction to one of the most unique semiconductor devices in electronics—the injection laser. In order to appeal to a wide cross section of readers, the theory of lasers has been greatly simplified. Additionally, numerous circuits for operating and detecting lasers, some never before in print, have been included. The book is rounded out by a wide selection of conventional and infrared photographs and three appendices.

The authors feel that the injection laser offers numerous challenges to ambitious experimenters. The field of radiocommunications, for example, is old and crowded, but practical light-beam communication on a large scale is still years in the future. With the current availability of inexpensive injection lasers, experimenters are presented with the unique opportunity of making important contributions to the state of the art in this vitally important field.

This book could not have been completed without the assistance of many individuals and companies. Sample components and abundant technical information were provided by dozens of firms. Particularly important assistance was provided by Richard S. Myers, Dr. Henry Kressel, Robert Felmlly, Walter Dennen, and Stanley Katz of RCA. Contributions were also provided by Laser Diode Laboratories, United Detector technology, EG&G, Texas Instruments, and Metrol-ogic Instruments. Additional support was furnished by Optical Engineering, Eastman Kodak, Teledyne Crystalonics, and Corion Instruments.

Dr. Izuo Hayashi of Bell Telephone Laboratories provided information and photographs concerning his important work in the development of continuously operating injection lasers. Gary Royster of Hewlett-Packard supplied a high speed HP-180 oscilloscope for use in testing and evaluating many of the circuits included in the text. Dr. Malvern Benjamin of Bionic Instruments contributed information on his work with injection-laser mobility aids for the blind.

Finally, William Gaumer, an optics specialist currently conducting laser research, reviewed portions of the text and supplied numerous helpful suggestions. Duncan Campbell of Santa Barbara Research Center made available supplementary information on the design of laser transceivers. The final manuscript and much of the drafting was typed by Minnie C. Mims. Mabel W. Campbell helped finance and encourage the project. To these many individuals and firms, we both express our gratitude for such generous assistance.

RALPH W. CAMPBELL
FORREST M. MIMS III

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Light, Semiconductors, and Lasers

The laser is one of the most remarkable creations of modern science. First predicted by Drs. Schawlow and Townes in 1958, the first working laser was constructed by Theodore Maiman in 1960. Maiman's first crude laser emitted brief pulses of brilliant red light when a ruby rod with parallel, silvered ends was excited by a powerful flash lamp similar to those used by photographers.

The first laser satisfied the requirements for lasing set forth in the original proposal by Schawlow and Townes: a readily excited fluorescent material of good optical quality, a method for stimulating the material to an excited state, and an optical resonating cavity. Almost all lasers developed since the first have been based on these fundamental requirements.

Soon after Maiman demonstrated his first laser, several other devices were assembled. Most of them used ruby or some other fluorescent crystal, but a major accomplishment occurred a year later at Bell Telephone Laboratories with the development by Ali Javan of the gas laser. Another major step forward occurred with the development of the semiconductor injection laser in 1962.

This and subsequent chapters will discuss the physics, fabrication, and application of the injection laser at some length. But first we shall digress with a discussion on the subject of light, since an understanding of its origin is essential to understanding the injection laser.

LIGHT

Many forms of light are produced by energy transitions of electrons. Basic physics tells us that atoms consist of a central, positively charged region surrounded by a negatively charged cloud of electrons. Normally, an electron must occupy a specific energy level within the cloud. But those electrons near the outer region of the cloud may temporarily be excited to its perimeter by the application of energy from an external source. The energy may take the form of light, heat, a beam of electrons, an electrical current, or even a chemical reaction.

Physicists have developed a special vocabulary to describe the various events that may occur within an atom. For example, the space vacated by an excited electron is called a *hole*. When an electron recombines with a hole, it usually gives off its absorbed energy in the form of either heat or light. When a recombination results in the emission of a *photon*, a packet of electromagnetic energy, the event is referred to as *radiative recombination*. The outermost level that electrons can occupy within the cloud around a nucleus is the *conduction band*. The next highest level, the highest point that unexcited electrons may occupy, is the *valence band*. The region between the two bands is called the *forbidden gap*, as electrons normally pass directly between the two levels, possibly with brief pauses along the way.

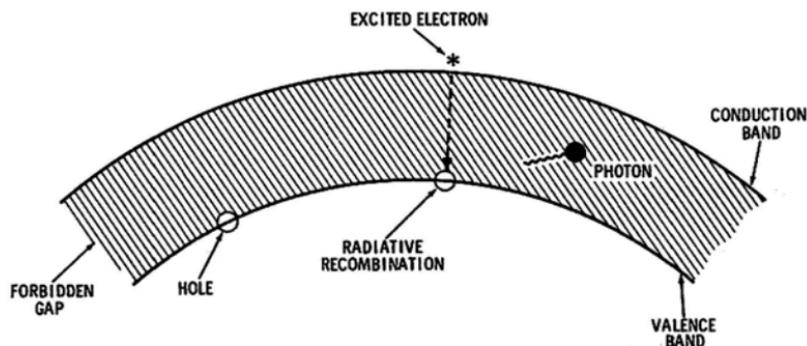


Fig. 1-1. Portion of a hypothetical atom.

Some materials permit transitioning electrons to pause at one or more points in the forbidden gap. These are called *indirect band gap* materials. Materials that do not permit electrons to occupy points in the forbidden gap are said to have a *direct band gap*. A hypothetical atom with several of these terms labeled is shown in Fig. 1-1.

The band gap is important as it is related to the wavelength of an emitted photon by

$$\lambda = \frac{hc}{E} \quad 1.1$$

where,

h is Planck's constant (6.63×10^{-34} joule-seconds),
 c is the velocity of light (3×10^{14} micrometers per second),
 E is the energy in joules that separates the valence and conduction bands.

The equation may be simplified by using electron-volts instead of joules. We then obtain

$$\lambda = \frac{1237 \text{ nanometers}}{E_g \text{ (electron-volts)}} \quad 1.2$$

A material with a band-gap separation of 1.36 electron-volts would then emit photons with a wavelength of 909 nanometers.

The term *nanometer* defines the wavelength of light in relation to the meter (39.37 inches); one nanometer is *one-billionth* of a meter. To better understand the designation of light in terms of wavelength, refer to Fig. 1-2. Note that visible light falls roughly between 400 and 700 nanometers, though as is discussed in a later chapter it is possible for many individuals to see light that has a wavelength of more than 900 nanometers. Fig. 1-2 also shows the relationship to one another of radio waves, ultraviolet, and other divisions of the electromagnetic spectrum.

It is important to note that the band gap is not necessarily a fixed number. Many materials will allow electrons to occupy slightly different levels within the conduction and valence band. Therefore, the wavelength of photons emitted during radiative recombination may be smeared over as much as several tens of nanometers.

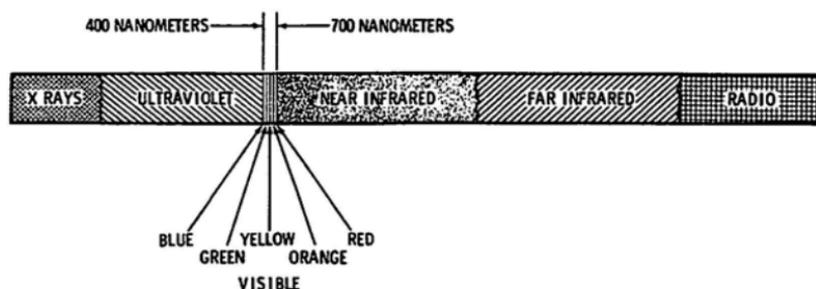


Fig. 1-2. The electromagnetic spectrum.

PRACTICAL LIGHT SOURCES

Now that we know some of the basics of light generation, how is an efficient light emitter fabricated? There are several techniques, and

all of them are based on two fundamental types of light generation: incandescence and luminescence. Both these forms of light generation are vitally important to technology and even to civilization as we know it today.

Incandescence

Perhaps the most common form of lighting device is the *incandescent* lamp. In such a lamp, electrical current is passed through a high-resistance metal filament and as a result large amounts of energy are dissipated in a very small space. The energy takes the form of heat which excites large numbers of electrons to higher than normal energy states. As the electrons move from high to low levels, additional heat and large quantities of photons are emitted. The high level of stimulation results in emission of light at a broad range of wavelengths through the visible and infrared portions of the electromagnetic spectrum. The emissions range from the ultraviolet to the far infrared.

When the supply of electrical current is shut off, the heat contained within the filament continues the excitation process until a point of temperature equilibrium is reached. This decay time means that an incandescent lamp may be modulated at only moderately low frequencies, if at all. Several voice communication systems that utilize an incandescent lamp have been developed through the years, and most of them have used a lamp with as small a filament as possible. The small filament somewhat reduces the decay time and improves the modulation capability.

Incandescent sources are generally very efficient. For example, a typical filament lamp may convert 80% of the current passed through it into photons. Most of the photons are in the infrared, however, and only 5 to 10% are visible.

Incandescent sources have a variety of drawbacks including inefficient visible emission, heat generation, and short lifetime. A particularly important disadvantage is the necessity for a sealed glass bulb to contain the filament and its supports. For these and other reasons, scientists have long searched for other forms of illumination. The mysterious nature of what is popularly called "cold light" has attracted considerable attention.

Luminescence

Light that is not produced as a result of heat is called *luminescence*. Biological luminescence occurs in nature and is represented by the firefly, some types of bacteria, and certain ocean going animals. Some deep-water fish are equipped with spots, stripes, and patterns that luminesce in several colors.

Luminescence that occurs when a beam of electrons (cathode rays) strikes certain materials is called *cathodoluminescence* and is

represented by the phosphor screen of television picture tubes. *Electroluminescence* is the result of an electrical current or discharge and is represented by the *Destriau effect*. Discovered in 1936, the Destriau effect is the emission of light from any of a variety of phosphors sandwiched between conducting electrodes, one of which is usually transparent. Light sources employing this effect are commonly used in household night lights and in aircraft instrument lighting.

Electroluminescence may also occur when current is passed through a wire placed in contact with the surface of certain semiconductors. This effect was first noticed by H. J. Round in 1907. Round touched wires from a source of current to a crystal of naturally occurring silicon carbide (SiC) and noticed flashes of yellow light at the point where the wire made contact with the crystal. A far more efficient form of electroluminescence occurs when a semiconductor with an excess of electrons (n type) is formed directly adjacent to a similar type of semiconductor deficient in electrons (p type). This effect is called either *pn junction* or *injection electroluminescence* and is responsible for light generation in semiconductor light-emitting and laser diodes.

LIGHT-EMITTING DIODES

Since the light-emitting diode (LED) is so closely related to the injection laser, a discussion of its properties and characteristics will be of interest to most readers. Semiconductor diodes are formed by a union of n- and p-type semiconductors. P-type material is formed by adding a substance deficient in electrons, commonly called a *dopant*, to molten silicon, germanium, gallium arsenide, or some other semiconductor. When a crystal is formed from the material, it will then be classed as p-type semiconductor. Since the dopant tends to borrow or accept electrons from the host material, it is called an *acceptor dopant*.

N-type semiconductor material is formed by adding a dopant with an excess of electrons to a molten batch of semiconductor material. In order to maintain equilibrium, the dopant donates electrons to the host material and is therefore called a *donor dopant*. Zinc is a typical acceptor; typical donors are tin, tellurium, and silicon.

Practical pn junctions, that is, unions of p and n semiconductor, are formed by heating a wafer of n-type material in a furnace in the presence of acceptors. The acceptors diffuse into the wafer, forming a p-type region as shown in Fig. 1-3. The border between the p and n regions is, of course, the pn junction.

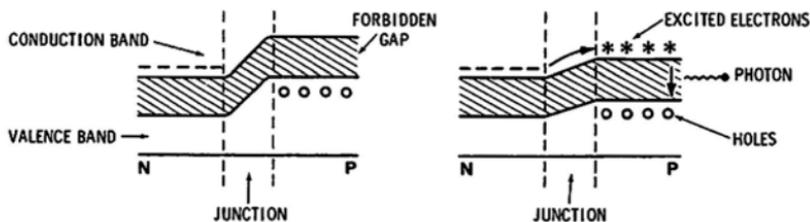
To understand how light is generated at a pn junction, refer to Fig. 1-4A. Here the pn junction is represented by a type of graph called an energy-level diagram. Notice that the conduction and

valence bands on either side of the junction are joined by sloping lines representing the barrier to electron flow formed by a pn junction. The n side of the junction is on the left and the p side is on the right. When electrons are injected into the n side by a source of current, the potential barrier formed by the junction is reduced, Fig. 1-4B, and a current flow takes place from n side to p side across the conduction band.



Fig. 1-3. Pn junction in a semiconductor wafer.

In order to cross the potential barrier at the junction, the electrons on the n side of the diode are first excited up to the conduction band. When they cross over the junction to the p side, they resume equilibrium by falling back to the valence band, in the process giving off, hopefully, a photon of light. Many semiconductor junctions are very inefficient optically so recombination of an electron with a hole on the p side is often accompanied by a phonon (heat).



(A) No electron flow.

(B) Electron flow.

Fig. 1-4. Energy-level diagrams of a pn junction.

Practical LEDs consist of tiny chips of semiconductor that have been given a pn junction and packaged in small blocks of epoxy or standard transistor cans with glass windows on one end. An assortment of both visible and infrared emitting LEDs is shown in Fig. 1-5.

One of the most efficient semiconductors used for LEDs is gallium arsenide (GaAs). Since GaAs has a band gap of 1.37 electron-volts, light from a GaAs pn junction has a wavelength centered at 903 nanometers. By cooling a GaAs LED to the temperature of liquid

nitrogen (-196°C), the wavelength is reduced to about 850 nanometers and light from the diode is visible as a dull red glow.

Visible emission at room temperature can be had from semiconductors with higher band-gap energies. For example, gallium arsenide phosphide (GaAsP) emits a bright red at a peak wavelength of about 630 nanometers (depending on the concentration of phosphorus). Amber and green can be obtained by varying the phosphor content, or by going to gallium phosphide (GaP).

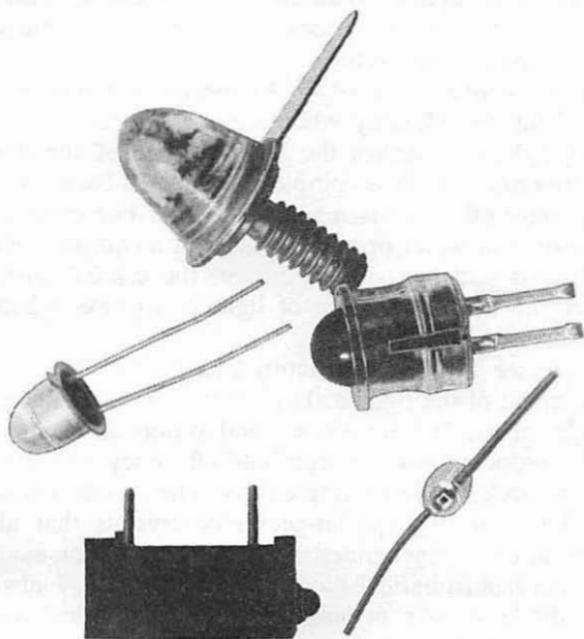


Fig. 1-5. Visible-light and infrared-emitting light-emitting diodes.

The power output of GaAs LEDs is typically several times that of equivalent size visible emitters made of GaAsP and GaP. Up to several milliwatts may be obtained from standard flat diodes, and special geometry structures have produced tens and even hundreds of milliwatts. The method by which specially structured diodes produce increased power output is quite interesting. Like other semiconductor materials, GaAs has the property of bending a beam of infrared light that enters it. The effect, termed refraction, is identical to the bent appearance of objects that are inserted into a container of water. Refraction is caused by the difference between the speed of light in a particular substance and in air. The *refractive index* of a material is given by:

$$n = \frac{c}{V} \quad 1.3$$

where,

c is the velocity of light in air (186,000 miles per second),
 V is the velocity of light in the material whose refractive index is being measured.

The refractive index of air is 1 (1.0003 when compared to the speed of light in a vacuum), while that of liquids, solids, and other denser materials is higher. Diamond has a refractive index of 2.42, and GaAs, with a refractive index of about 3.5, is one of the few materials that exceed this value.

The high refractive index of GaAs means that light generated in an LED is bent considerably when leaving the front surface of the diode. Also, light that strikes the front surface of the diode at less than a certain *critical angle* is completely reflected back into the GaAs. The critical angle effect is often seen in nature. For example, sunlight striking a puddle of water or pane of glass at a certain angle is totally reflected. Prisms and fiber optics exploit the critical angle to either totally reflect an incoming beam of light or to pass a beam around gradual bends.

It is easy to see why a flat-structured LED is inefficient. As shown in Fig. 1-6, much of the light strikes the front surface at less than the critical angle, about 16° for GaAs, and suffers total internal reflection. Besides reducing power output and efficiency, the absorbed light contributes to undesirable heating effects. The problem has been partially solved by forming special-geometry crystals that allow much more of the internally generated light to escape. For example, light emitted by the hemispherical diode shown in Fig. 1-7 always strikes the curved diode surface at less than the 16° critical angle and is therefore permitted to escape from the LED. Some of the light is lost by absorption as it passes through the bulk GaAs material on the way to the surface, but hemispherical emitters are still far more efficient than LEDs constructed with a flat emitting surface.

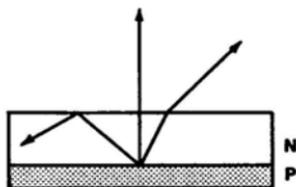


Fig. 1-6. Light emission in a flat light-emitting diode.

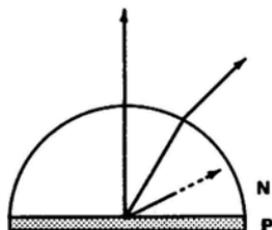


Fig. 1-7. Light emission in a hemispherical light-emitting diode.

Unfortunately, formation of a domed GaAs LED is a time-consuming, costly process. The crystals must be subjected to a precision ultrasonic grinding and polishing process, and seating and soldering the completed crystals on headers so that the p and n regions make contact with their respective electrodes is a difficult alignment procedure. Prices for hemispherical emitters range up to several hundred dollars.

Some manufacturers have exploited the advantages of the hemispherical diode by merely placing a blob of clear epoxy over a standard flat emitter. The flat emitter emits more of its light into the epoxy than into the air because the refractive index of the epoxy is higher than that of air and therefore the critical angle is reduced. Epoxy-coated diodes are still not nearly as efficient as hemispherical emitters, but they are relatively inexpensive and are made quite sturdy by the epoxy coating.

THE INJECTION LASER

The development of the first laser in 1960 stimulated unprecedented interest in the field of electro-optics, and several large research laboratories became involved in research with semiconductor light emitters. The primary goal was to achieve laser action in a semiconductor chip. Such a development promised to greatly simplify the costly construction requirements of crystalline and gaseous lasers.

It should be noted that several physicists predicted laser action in a semiconductor before the actual achievement. It is generally accepted that the first suggestion was by P. Aigrain in a 1958 talk before an international conference on solid-state physics in Brussels. A more formal proposal was put forth by the Soviet academician, N. G. Basov, in a paper published in 1959. Several other papers proposing the semiconductor laser were also published about this time.

Weak light emission from a germanium diode had been noticed as early as 1952. But it wasn't until ten years later that J. I. Pankove of RCA Laboratories reported high-efficiency light generation from a GaAs pn junction. Pankove and other workers found that when GaAs LEDs were pulsed with high current, certain characteristics that might be expected of a laser below threshold became evident. This work indicated that much higher currents than previously thought necessary would be required to reach the lasing threshold in a semiconductor.

Still, the new GaAs data showed that a semiconductor laser might indeed be possible, and several research groups began an intensive campaign in an attempt to fabricate one from GaAs, the best studied material. In the fall of 1962, three of these groups almost simul-

taneously announced the development of lasers made from GaAs. The first was a team headed by R. N. Hall of General Electric. Teams headed by M. I. Nathan of IBM and T. M. Quist at MIT were successful only days later.

The new laser development was first announced in a technical paper in *Physical Review Letters*, November 1, 1962. Entitled "Coherent Light Emission from GaAs Junctions," the paper reported that evidence for coherent radiation from specially fabricated GaAs light-emitting diodes was based upon "the sharply beamed radiation pattern of the emitted light, upon the observation of the threshold current beyond which the intensity of the beam increases abruptly, and upon the pronounced narrowing of the spectral distribution of this beam above threshold."

The paper went on to describe briefly the theory of the injection laser and then discussed the experimental procedures employed by the General Electric researchers in their historic accomplishment. During operation, the cube-shaped diodes (0.4 mm on a side) were immersed in liquid nitrogen and driven by 5- to 20-microsecond current pulses. Spectral measurements were accomplished with a spectrometer and the beam pattern was observed with an infrared image-converter tube. Several photographs showing the beam pattern of one of the first lasers and two curves showing spectral distribution were included in what is now a historical paper in injection laser work.

INJECTION-LASER THEORY

The injection laser is a light-emitting diode with a very flat junction and two end mirrors (Fig. 1-8). The mechanism responsible for the light generation in an injection laser is identical to that of the LED. Electrons from an external power supply are injected into the n side of the junction. The electrons are excited to a higher-than-normal energy state and after crossing the junction they fall into holes, in the process giving off energy in the form of photons and heat.

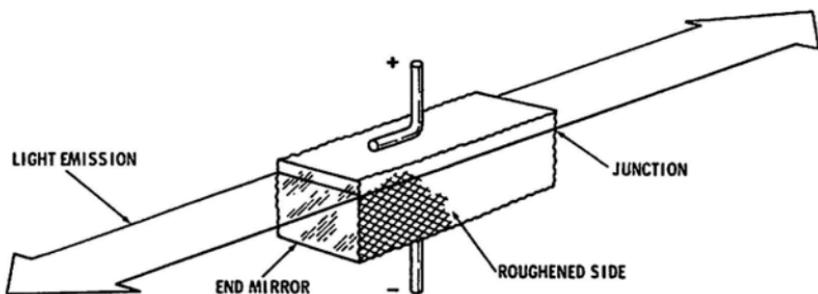


Fig. 1-8. Basic injection laser.

Below a critical point known as the *lasing threshold*, the injection laser emits light spontaneously and randomly like an LED. But if sufficient current is applied to the device, that is, if a very large number of electrons are injected into the crystal, a situation occurs where there are more electrons in an excited than in an unexcited state. This condition is called a *population inversion* and is essential to laser action. A randomly emitted photon can then act to stimulate the emission of a photon from an excited electron. The new photon may do likewise and the process continues in the form of a chain reaction. The process is called *stimulated emission of radiation*. The word "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation.

The importance of the population inversion can be more readily understood if we once again consider light emission in an LED. Since the LED cannot support an inversion of electrons, emitted photons may be absorbed by unexcited electrons (perhaps stimulating them to a higher energy level). When a population inversion is present, photons are more likely to strike excited electrons and stimulate the emission of still more photons. The inversion then sets up a situation where optical gain exceeds optical loss.

Since the injection laser has been given two parallel, facing end mirrors, some of the photons are reflected back into the active region along the junction. There they stimulate still more electrons into emitting photons and an oscillating wave of light is built up along the junction. The process is almost identical in principle to feedback in a resonant electrical circuit. Since the photons are "in step" with each other, the wave of light satisfies the requirement for *phase coherence*.

Some of the theoretical aspects of injection lasers are summarized in Fig. 1-9. Beginning at Fig 1-9A, an injection laser operated below the lasing threshold acts like an LED and emits light randomly. As more current is applied (Fig. 1-9B), a point is suddenly reached where a population inversion exists and more electrons are in an excited than in an unexcited state. Stimulated emission, the key to laser action, occurs in Fig. 1-9C as randomly emitted photons collide with excited electrons in the active region along the junction and cause the emission of additional photons. The new photons are emitted in phase with their progenitors. Finally, in Fig. 1-9D a standing wave of photons is set up between the two end mirrors composing the optically resonant cavity necessary for laser action.

Unlike in most other lasers, the end mirrors of the injection laser are an integral part of the device. The high index of refraction for GaAs discussed earlier may be a disadvantage for LEDs, but it is certainly important to the injection laser. GaAs is a crystal that may be cleaved along certain crystalline planes to produce extremely flat, parallel facets on opposite sides of a chip. These facets have a re-

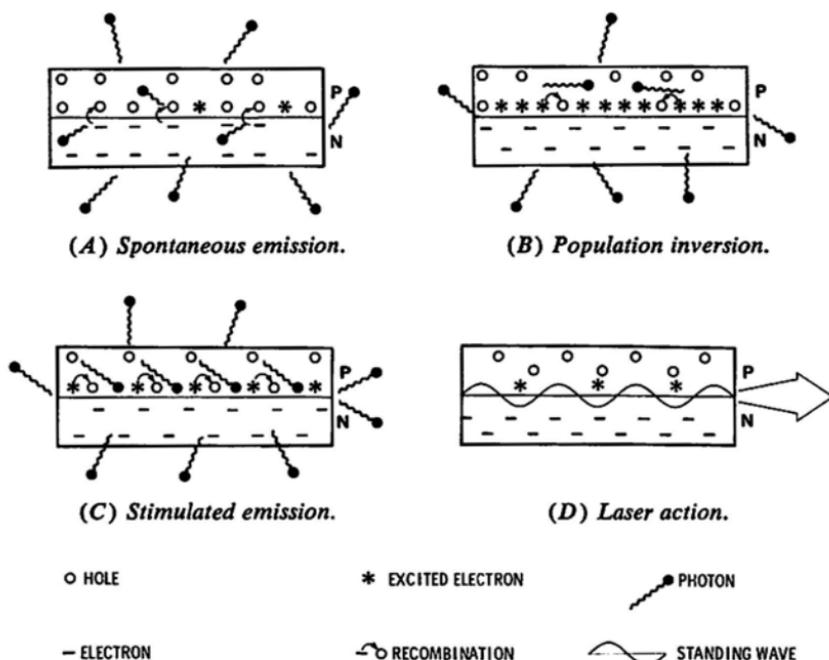


Fig. 1-9. Steps preceding laser action.

flectance of approximately 35% at the GaAs wavelength of 903 nanometers and make excellent end mirrors.

The lasing threshold may be lowered by placing a 100% reflecting mirror over one of the two end facets. The mirror is often a thin film of gold insulated from the junction by a layer of silicon dioxide in order not to cause an electrical short. Light that would have been expelled before from the lasing cavity is then reflected back into the active region, where it contributes to gain by stimulating the emission of additional photons. A practical aspect of using the 100% end mirror is that it is much easier to make use of the total power output of a laser when it exits from only one end of the device. When light is emitted from both ends of a laser, half of it is either redirected in line with the primary beam by means of mirrors or is lost.

OTHER LASERS

This book is about semiconductor lasers, but before moving into Chapter 2 it is entirely appropriate to discuss briefly several other important classes of lasers. There are now a number of excellent books on the subject, but for a very quick glimpse at lasers in general, continue on to the following sections.

Solid Lasers

As was noted at the beginning of this chapter, the first laser was formed of a solid rod of ruby, two end mirrors, and a powerful flash lamp. Whereas the injection laser achieves a population inversion by means of a pn junction, the ruby laser achieves the same electron situation when the flashlamp excites the chromium atoms within the ruby crystal.

Maiman's early laser subsequently evolved to include a family of devices with peak power capabilities ranging up to millions of watts. The brilliant red beam of the ruby laser paved the way for the development of many new laser devices and applications. Experiments in staging two or more lasers and the discovery of Q-switching were first accomplished with the ruby laser.

Q-switching was a particularly important development. In operation, the ruby is allowed to be excited with a flash lamp, as with a conventional ruby laser. Lasing is prevented from occurring, however, because one of the two end mirrors of the laser is either blocked by means of an electro-optical shutter or is slightly misaligned. The absence of one end mirror allows the laser rod to become far more excited than with a conventional laser, and the sudden reappearance of the missing end mirror results in a beam of laser light many times more powerful than when the device is operated in the conventional mode. Since the pulse of light is much briefer than that from a conventional laser, it contains less energy than if Q-switching were not employed. But the very high power resultant from Q-switching produces unique effects when directed against many materials and is therefore of much interest to scientists and researchers. For example, Q-switching lasers have been used to drill tiny holes through extremely hard materials like diamond and other gemstones. The Western Electric Company uses laser drilled diamonds as dies for making very fine diameter wires. The mechanical process of making the holes once took considerable time and was far more costly than the laser drilling technique.

Q-switching is also important to laser radar applications. As with conventional radar, the resolution of a laser radar is largely dependent on the width of the transmitted pulse of light. Q-switching produces pulses as narrow as ten or twenty nanoseconds, equivalent to a resolution of better than ten feet. Besides the uses just mentioned, Q-switched lasers have been used for welding, contouring, and other precision metal-working processes.

Another type of solid laser is formed from a glass rod that has been doped with a small percentage of neodymium, a rare earth. Like the chromium of the ruby laser, the neodymium becomes excited by a burst of flash-lamp light and emits a beam of infrared light.

While neodymium-doped glass lasers have the disadvantage of operating in the infrared portion of the spectrum (1060 nanometers), they are more efficient than their ruby counterparts. Also, there are a number of applications where it is desirable to employ a laser with an invisible infrared beam. The military is particularly interested in neodymium lasers and has spent millions of dollars to develop covert rangefinders and illuminators. A number of press reports have indicated that the military may even be interested in the possibility of developing a blinding weapon with solid-state lasers, and the invisible nature of the neodymium lasers presumably makes them attractive candidates.

There is another type of neodymium laser that has become quite important in recent years. Unlike those that use glass as a host material, this laser employs a crystal of yttrium aluminum garnet, YAG for short. Neodymium doped YAG lasers do not have the peak power capability of glass lasers, but they are more efficient, have a lower lasing threshold, and are more practical for applications requiring miniaturization. The military has developed a number of miniature rangefinders and illuminators employing YAG lasers, and researchers have used small YAG lasers as the first stage of laser chains employing much larger glass laser rods. Because of the advantages just mentioned, this miniature laser will no doubt soon find other uses.

Liquid Lasers

Three major classes of liquid lasers have been developed. The first uses a variety of fluorescent rare earths dissolved in a mixture of solvents designed to be as transparent as possible to the laser beam. The solution of solvent and rare earth is simply poured into a glass tube and excited by a flash lamp. A laser of this type, that uses the rare earth europium, emits a red light.

Another type of liquid laser employs neodymium, the element that has been so successfully applied to solid systems. In operation, the neodymium is dissolved in an acid and placed in a tube like the europium laser. Because of the potency of the acid used to dissolve the neodymium, extreme caution must be exercised with both personnel and equipment.

A third type is the liquid organic dye laser. While the previous two systems are limited to a few output wavelengths, dye lasers emit over the entire visible spectrum and are the most promising of the liquid lasers. Tuning over a variety of wavelengths is accomplished by merely placing a prism or diffraction grating over the laser output aperture and rotating it until the desired wavelength is selected. A variety of dyes have been used, including rhodamine and fluorescein. The former lases in the red portion of the spectrum and the latter in the green.

Liquid lasers have several important advantages over more conventional solid lasers. Chief of these are the ability to use a single laser system with a variety of liquid lasing elements by merely exchanging one for another, and the ability to pump the liquid through the laser and into an external reservoir to assist in cooling. Cooling is a significant problem with all solid lasers intended to be operated at a repetition rate greater than a few pulses a minute. Elaborate cooling systems consist of flowing, chilled water. Other coolants have been designed, and often the cooling system is a significant portion of the total size and cost of the laser. The cooling problem is largely solved with liquid lasers, though a few important technical problems remain to be solved.

Gas Lasers

The invention of the first gas laser closely followed Maiman's accomplishment with ruby. Gas lasers are second only to injection lasers in cost and volume of production, and the family has grown to include devices that cover a spectrum ranging from the ultraviolet to the far infrared. An enormous number of gasses and gas mixtures will lase, and more than one group of happy scientists have been delighted to learn that even some liquor vapors will lase (in the infrared).

The first gas laser used a mixture of helium and neon in a long, slender tube to produce a beam of highly coherent light in the near infrared portion of the spectrum. The gaseous mixture was excited by a radio-frequency generator connected to the tube by means of two electrodes. The beam from this early laser was the most coherent ever obtained and gas lasers still surpass all other lasers for coherence properties.

Many other gaseous lasers have been invented since the Bell Laboratories' accomplishment with their helium-neon device. But the most economical and popular is still the helium-neon system. The gas mixture lases more efficiently in the visible red part of the spectrum than in the infrared, so the laser is widely employed in applications requiring a highly collimated beam of visible light. Uses include precision surveying, alignment of tunnel-digging machines, alignment of other types of lasers, rangefinding, communications, and even laser art. The latter application is particularly unique as the beam, when reflected from vibrating mirrors or metallic foils, creates exceptionally beautiful patterns of scintillating red.

Injection lasers are by far the most economical of all lasers, but, at under one hundred dollars, helium-neon units are second in price contention. Manufacturers offer helium-neon lasers with higher power outputs at higher prices. While the inexpensive units may have a power output of under a milliwatt, thousand-dollar lasers are available with

powers of more than twenty milliwatts. For many experimental applications, however, half a milliwatt is more than adequate, and most persons are quite surprised to see just how bright that much power actually is. One popular application is holography, three-dimensional laser photography, and an inexpensive helium-neon laser is more than adequate for the job.

There are several types of gas lasers that deliver far more power than is available from helium-neon and other earlier gas mixtures. For example a mixture of carbon dioxide, nitrogen, and helium can be used to easily obtain several hundred watts of *continuous* power. Only a few watts of collimated light is sufficient to ignite paper, so one can easily imagine the effect of hundreds of watts. The military has been particularly interested in high-power carbon dioxide lasers for obvious reasons. In the late 1960s both the army and the air force demonstrated continuously operating carbon dioxide lasers with power outputs of several thousand watts. That much power will easily consume wood, most metals, and even the fire bricks used to shield the laser beam from laboratory walls.

More recently, the military has spent millions of dollars developing super-energy lasers that achieve lasing in what literally amounts to the exhaust of a powerful rocket engine. Called gas dynamic lasers, a population inversion is created when the burning exhaust gasses from the rocket pass through a supersonic nozzle and into a cavity with the two end mirrors necessary for laser action. So far, powers in excess of 60,000 watts have been achieved. One report in *Scientific American* magazine predicted that a million watts may eventually be delivered by such lasers!

Research on the gas dynamic laser and advanced lasers that operate with chemical reactions is supported in part by the military with the end objective of developing a Buck Rogers form of ray weapon. Reliable government sources have reported that one eventual goal of these super-power laser weapons is destruction of enemy aircraft and even incoming ICBM warheads.

Interestingly enough, industry has developed several peaceful uses for the new generation of super-power lasers. Applications include large-scale welding, incineration, tunnel excavation, and high-temperature research. Small versions of these big lasers are already in use cutting fabric in a garment factory, and one futuristic application may be the transmission of power over great distances and even through space without the use of transmission lines.

Plastic, Gelatin, and Space Lasers

The variety of lasers is truly unbelievable. Not long ago, scientists at several laboratories amused the press with reports about lasers made from sections of ordinary plastic rulers. The rulers were the type

that fluoresce green or orange, and the lasers were made by simply placing a cut length of ruler adjacent to a flashlamp. External mirrors provided the necessary optical cavity.

More recently, *Laser Focus* magazine reported the first *edible* laser. Several Stanford University scientists, including the famous Dr. Schawlow, added a fluorescein dye to a package of Knox gelatin, mixed "in accordance with the manufacturer's instructions," and set the mixture aside to gel. Intense emission in the green portion of the spectrum was observed when the ultraviolet beam of a nitrogen laser was directed into the gelatin.

The scientists went on to try a rhodamine dye, but first added a small amount of "pink lotion Trend," a dishwashing detergent, to prevent deterioration of the dye. The laser emissions were varied from red to orange by simply adjusting the quantity of the detergent in the gelatin-dye mixture. It was even noted that causing the gel to gently vibrate greatly increased the useful lifetime of the laser.

These rather trivial applications serve to illustrate the enormous flexibility of laser systems. The scale is truly astronomical, for a growing number of scientists are convinced that some of the intense pulsations of energy that occur naturally in the universe are the result*of laser-like processes.

The injection laser, with its tiny size and small power requirement, will no doubt retain an important role in the laser technology of the foreseeable future. The next two chapters describe the fabrication and properties of these tiny lasers, and the remainder of the book is devoted to circuitry and practical applications.

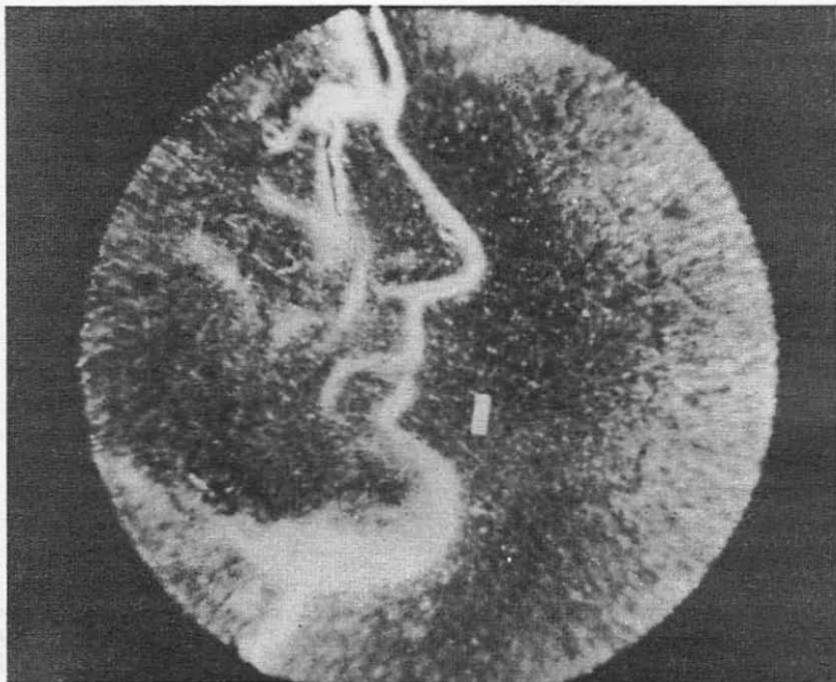
Injection Lasers and Their Properties

Advances in semiconductor technology and crystal growing have resulted in new types of injection lasers that are quite literally tailored to meet required specifications and characteristics. Early injection lasers were not nearly so advanced. This chapter will review the major injection-laser structures and their properties, as well as touch briefly on a few other types of semiconductor lasers.

Before going on, it might be a good idea to look at Fig. 2-1. The tiny chip shown on the penny is a Bell Laboratories double-heterostructure injection laser, the first semiconductor laser to operate continuously at room temperature. Most injection lasers are about this size. When one considers the complex atomic and optical phenomena occurring in such a small device, the technology of these tiny lasers suddenly becomes an exciting subject.

HOMOSTRUCTURE INJECTION LASERS

The first injection lasers were made by diffusing an acceptor such as zinc into wafers of n-type GaAs. The wafers were then cut into small chips with cleaved or polished parallel ends perpendicular to the plane of the junction. A typical diffused homostructure device is shown in Fig. 2-2. Contacts were applied to the chip and enormous current pulses were injected into the n side of the junction in order to achieve lasing. All of the early devices had to be operated at the



Courtesy Bell Telephone Laboratories

Fig. 2-1. Semiconductor laser chip photographed on a Lincoln penny.

temperature of liquid nitrogen (-196°C) in order to permit the removal of heat generated within the diode structure.

The huge current requirement of early diffused lasers, over 100,000 amperes per square centimeter of junction area at room temperature,

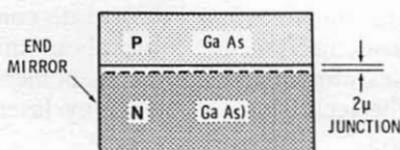


Fig. 2-2. Typical diffused homostructure laser.

was the result of very poor junction formation and inferior GaAs material. This was realized early in the game, and many researchers began work on improving fabrication procedures. As a result, thresholds for lasing in diffused lasers were lowered to the vicinity of $60,000\text{ A/cm}^2$ and practical operation at room temperature became possible. Until Bell Laboratories' historic development of an injection laser that operated continuously at room temperature, uncooled devices had to be operated with very brief pulses of current. With proper

heat sinking, many devices would operate continuously at the temperature of liquid nitrogen (or lower).

The lowering of the lasing threshold was the result of perfecting a relatively flat junction and growing GaAs crystals with fewer imperfections and impurities. Since the active region along the junction may be only a few microns thick, it is obvious why a rough junction might result in a very high lasing threshold. Much of the internally generated light can actually be prevented from leaving the laser by deviations in the flatness of the junction. Crystalline imperfections have a similar effect on internally generated light. Another disadvantage of an imperfect crystal is that stimulated electrons tend to drop back to an unexcited state at crystal dislocations and imperfections. In order for the lasing process to be as efficient as possible, all radiative transitions should take place along the junction and not at random points throughout the crystal.

While a good deal of research was accomplished with diffused homostructure lasers, an important step forward occurred in 1963 with the development by H. Nelson at RCA Laboratories of the liquid epitaxial process for forming laser junctions of a superior nature. Whereas the diffusion process yielded junctions of an unpredictable nature, the epitaxial process produced uniformly flat ones. The epitaxial process will be described in more detail in Chapter 3, but a few comments on it are in order here. In its simplest form, the process consists of wetting a polished wafer of n-type GaAs with molten p-type GaAs at a precise temperature. When the combination is cooled, the molten material, which melts away the first few microns of the wafer, crystallizes onto the substrate wafer, forming a junction as flat as if the wafer had been polished. By varying temperature and time, it is possible to locate the junction at a variety of points within the wafer.

For most efficient operation, both diffused and epitaxial homostructure lasers are baked at high temperature after initial junction formation. The heat treatment greatly increases efficiency. At first it was not known why efficiency was increased by heat treatment, but it was eventually found that the operation caused the junction region to be recessed further into the semiconductor chip in a manner more passive than original junction formation. The result was a gradual change in the index of refraction from the active region to the passive portions of the diode. The refractive variation served to reflect some of the light back into the active region which might otherwise have escaped.

Heat treatment is particularly effective in epitaxial lasers. Since their junctions are generally superior to diffused junctions they already have an important advantage. And since heat treatment moves the active region away from the slight inhomogenities at the interface of the n and p regions, performance is improved still more.

HETEROSTRUCTURE INJECTION LASERS

A significant development in semiconductor lasers occurred in 1968 with the invention by Bell and RCA Laboratories of the single heterostructure (SH) injection laser. Such a structure had been suggested as early as 1963 as a method of strictly containing the light generated in an injection laser to the very thin region along the junction where most of it originates. Both RCA and Bell were studying aluminum arsenide/gallium arsenide alloys [(AlGa)As] for obtaining visible light from injection lasers, so both groups were aware of the metallurgical properties of the material. Since (AlGa)As has a higher index of refraction and higher band gap than GaAs, it was reasoned that forming the p layer from the new material by liquid epitaxy would result in a measure of confinement to the region of active light generation. Fortunately, (AlGa)As and GaAs have very similar crystal structures and the expectations were easily fulfilled by diodes made using the new technique. A typical SH laser is shown in Fig. 2-3. The devices were so much better than epitaxial homostructure lasers that RCA replaced its entire commercial line with the new units. Typical commercial SH devices have room temperature thresholds of 8000 A/cm².

The SH lasers improve performance over homostructure lasers in two ways. First, the slight energy difference between the conduction and valence bands of (AlGa)As and GaAs sets up a potential barrier that serves to confine the stimulated electrons to the very thin region directly adjacent to the junction. Since the electrons can not move back across the junction with ease, most radiative recombinations occur in a controlled region of the device.

Second, since the index of refraction of (AlGa)As is higher than GaAs, most light generated along the junction is prevented from escaping into the light-absorbing p region by being reflected back into the active region. Some light can, of course, still be lost in the n region as photons cross back through the junction, but, nevertheless, the improvement in optical confinement is significant. The index-of-refraction barrier helps to form a one-sided optical waveguide for propagating the recombination radiation along the junction and out of the diode.

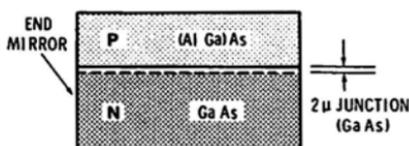


Fig. 2-3. Typical single heterostructure (SH) laser.

DOUBLE-HETEROSTRUCTURE INJECTION LASERS

The performance of SH lasers was so good it was expected that the addition of a second (AlGa)As barrier on the n side of the junction would result in even greater improvement. The first researcher to produce such a double-heterostructure (DH) laser was the Russian scientist, Z. I. Alverov. He reported DH lasers with room temperature thresholds as low as 4300 A/cm^2 . Soon afterward, in the summer of 1970, I. Hayashi and his co-workers at Bell Telephone Laboratories produced DH lasers with room temperature thresholds as low as 1000 A/cm^2 and succeeded in operating an injection laser continuously at room temperature for the first time.

The structure of DH lasers is far more complex than any of the devices discussed so far. The device actually consists of up to five separate layers of semiconductor. A typical DH laser originates from a polished wafer of n-type GaAs. This wafer serves as a mount or substrate for the growth of the various layers of the diode and also provides a material to which electrical contacts may be readily attached. This wafer is passed through a multichambered furnace that holds separate molten solutions of (AlGa)As and GaAs to be epitaxially grown onto the substrate. As the substrate is passed through the furnace, it is allowed to make contact with each of the solutions for a carefully allotted time. The result is shown in Fig. 2-4. The lower layer is the n-type substrate of GaAs. Next is an n layer of (AlGa)As, a p layer of GaAs, a p layer of (AlGa)As, and finally a p layer of GaAs. The last layer is applied to make the attachment of electrical contacts easier. A cross sectional view of a DH laser made with a scanning electron microscope is shown in Fig. 2-5.

In operation, excited electrons cross the pn junction at the intersection of layers 1 and 2 and fall back to the unexcited ground state (valence band) in layer 2, giving off a photon in the process. Those electrons that remain stimulated for some time after entering layer 2 cannot leave the layer, because the energy difference between that

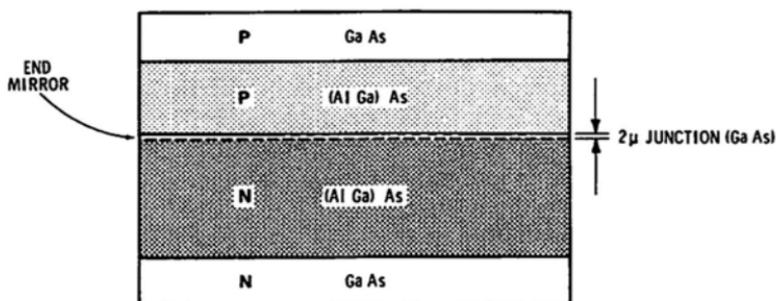
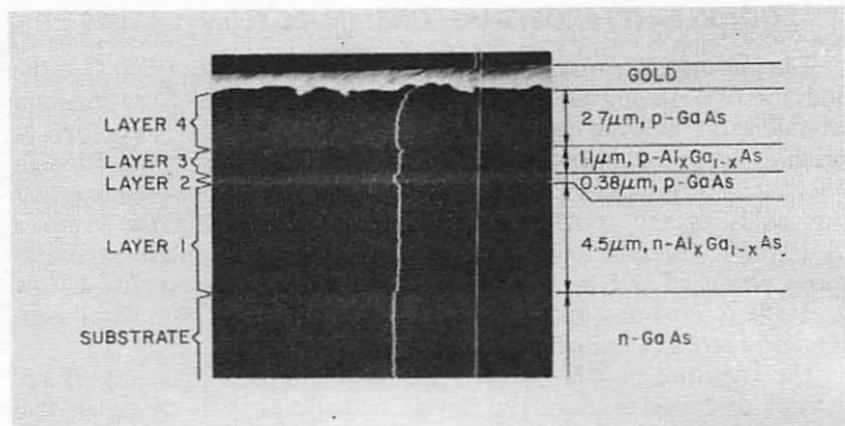


Fig. 2-4. Typical double heterostructure (DH) laser.



Courtesy Bell Telephone Laboratories

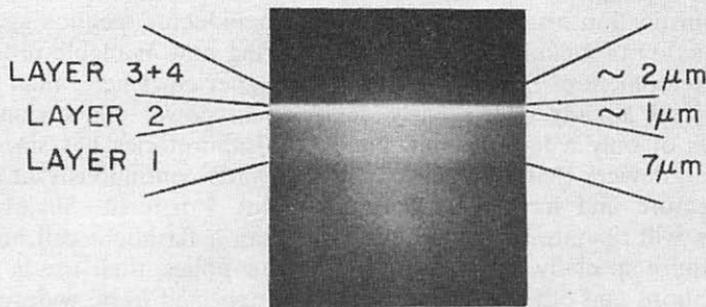
Fig. 2-5. Electron microscope photograph of cross section of a DH laser.

layer and its immediate neighbors, layers 1 and 3, forms a potential difference that forces it to stay in the active region. This confinement of electrons is far better than in SH lasers and helps to explain the extremely low threshold of DH lasers.

The refractive difference between layers 1, 2, and 3 confines almost all of the generated light to the active region. The result is a considerable improvement over the waveguide effect described for SH lasers. Rather than the one-sided waveguide of SH devices, DH lasers have a more efficient double-sided waveguide. Photons that move toward either of the interfaces of the second layer are reflected back into the active region.

A standard fabrication technique in the formation of most types of injection lasers is examination of the junction region through an image-converter microscope while applying a small, subthreshold current to the diode. If the junction appears to radiate light uniformly and in a very flat zone, the wafer from which the sample diode was cut is then cut into many separate lasers. A microphotograph of a DH laser undergoing such an electroluminescence test is shown in Fig. 2-6. Notice that the light generation is confined to a very uniform region, and that it does not extend into either of the adjacent layers. This type of photograph can easily be made on infrared film with the aid of a microscope to enlarge the laser cross section. Another technique is to take the photograph through a microscope that automatically converts the invisible infrared into visible light. The latter technique permits evaluation of the laser sample without the need for an infrared photograph.

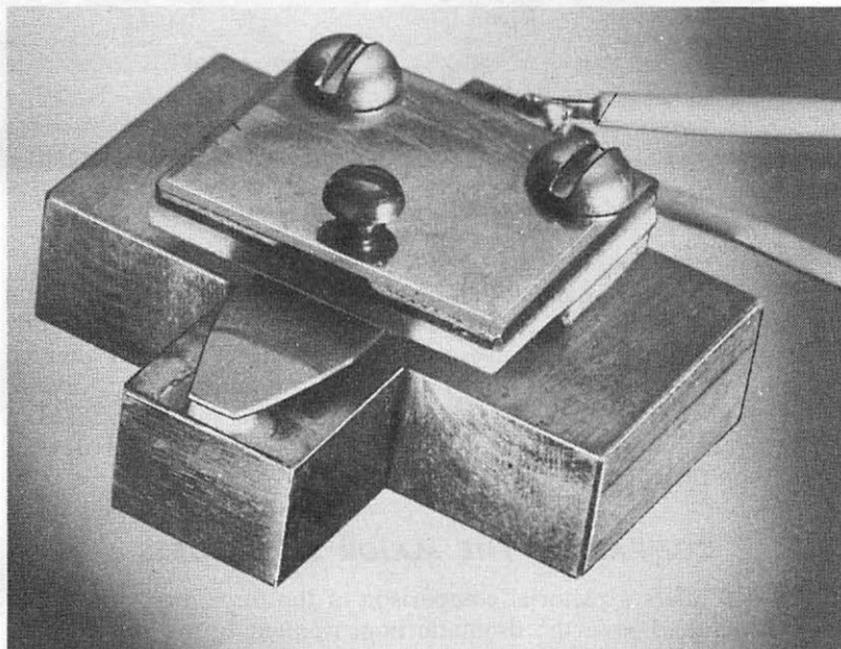
A photograph of one of Bell Laboratories' early DH lasers is shown in Fig. 2-7. The laser is mechanically clamped between the



Courtesy Bell Telephone Laboratories

Fig. 2-6. Microphotograph of electroluminescence test of a DH laser.

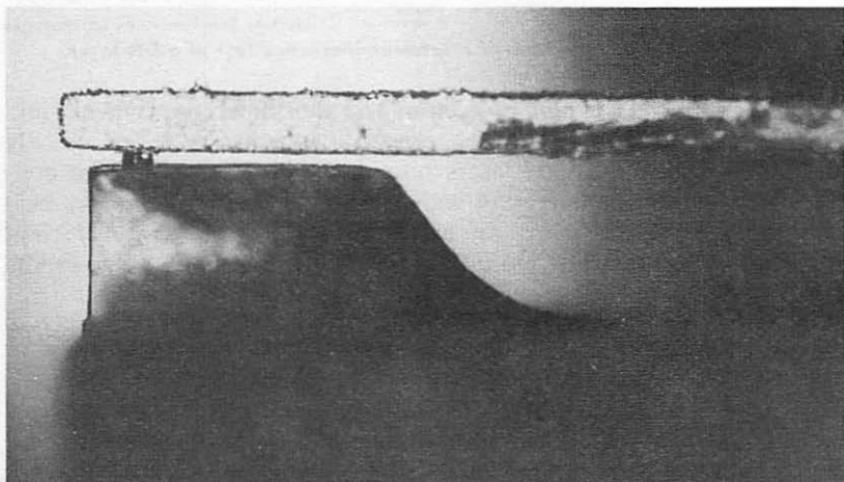
spring-mounted triangular projection and the thick copper heat sink. The holder assembly permits a series of lasers to be tested quickly and efficiently. While DH lasers have been made that operate continuously at room temperature with nothing more than a copper heat sink, this particular laser, an early device, uses a highly efficient diamond heat sink. The close-up photograph in Fig. 2-8 shows the relative size of the tiny laser chip and the diamond heat sink.



Courtesy Bell Telephone Laboratories

Fig. 2-7. DH laser mounted in a test holder.

The development of the DH injection lasers illustrates the level of sophistication attained by modern semiconductor technology. The high quality of metallurgical junction tailoring now available promises the development of DH lasers with much higher efficiencies than those announced already. Bell's early devices had power conversion efficiencies of only a few percent, but RCA Laboratories has since announced devices that emit up to 120 milliwatts continuously at room temperature and have efficiencies of about 7 percent. Since these devices will operate from nothing more than a flashlight cell and do not require specially designed pulse power supplies, their use in communications and other applications can be expected to be widespread.



Courtesy Bell Telephone Laboratories

Fig. 2-8. DH laser clamped between metal tab (top) and large diamond heat sink.

However, it should be noted that because of its very thin active region the peak power of a DH device is considerably less than is currently available from SH lasers. Several researchers have correctly pointed out that while the DH structure represents an important step forward in injection laser technology, applications requiring pulsed infrared of relatively high power are best served by conventional SH devices already on the commercial market.

COMPARING THE MAJOR STRUCTURES

Fig. 2-9 offers a pictorial comparison of the three major injection-laser structures. Note the dramatic improvement in the optical confinement of the DH laser over the others. A summary of the chief characteristics of the three major structures is given in Table 2-1.

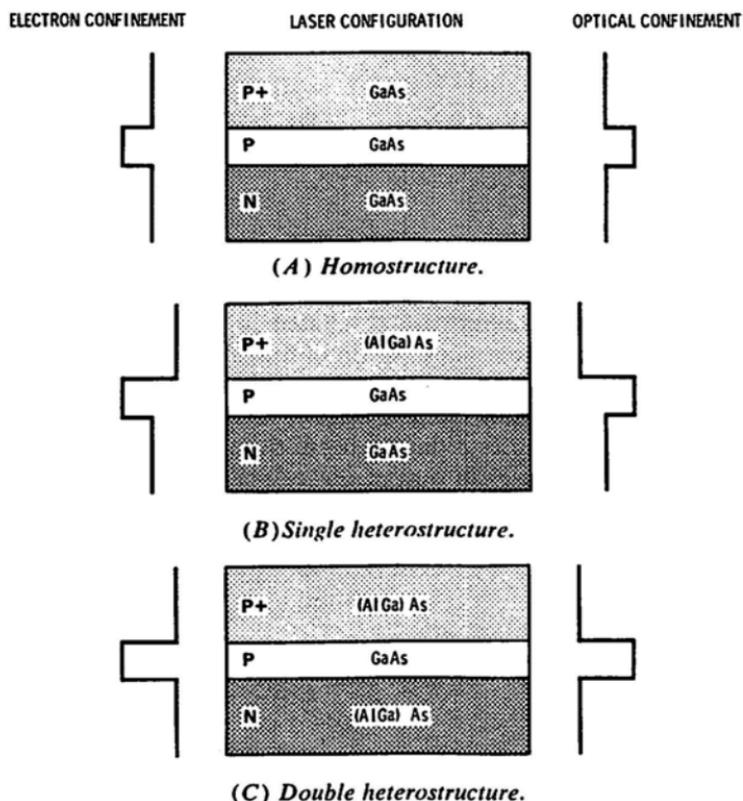


Fig. 2-9. Properties of the three major injection lasers.

Table 2-1. Comparison of the Major Injection Laser Structures

Laser Structure	Threshold (Amperes/cm ²)	Power Efficiency	Lifetime (Hours)	Optical Confinement
Diffused Homostructure	100,000	2 to 3%	100	poor
Epitaxial Homostructure	40,000	2 to 3%	100	poor
Single Heterostructure	8000	10%	1000+	good
Double Heterostructure	2000	10%+	(no data)	fair

OTHER LASER STRUCTURES

Nearly all semiconductor laser work centers on the junction devices described thus far. However there are several other structures and excitation techniques that are of interest. A unique type of junction device is the Large Optical Cavity (LOC) structure. Shown diagrammatically in Fig. 2-10, this laser structure eliminates a major

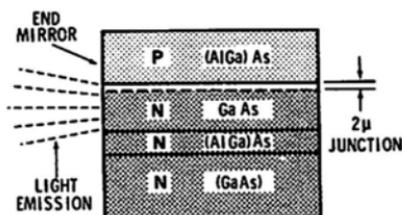


Fig. 2-10. Large optical cavity (LOC) laser.

problem in obtaining narrow beams from semiconductor junction lasers. In operation, photons are generated in the very thin layer of p-type GaAs adjacent to a thick region of low-absorbing n-type GaAs. The optical modes emanating in the thin region spread into the n region and are emitted from a much larger aperture than the slit of the conventional laser. Besides reducing beam divergence, the LOC structure may permit increases in output power per mil of junction width, since power density at the emitting mirror can be quite low in comparison to conventional structures.

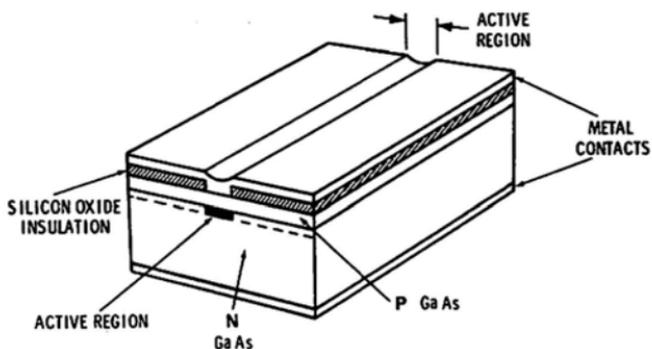


Fig. 2-11. Stripe geometry laser.

A type of junction laser receiving more extensive study than the relatively new LOC structure is the stripe geometry device. Shown in Fig. 2-11, this structure simply consists of any type of conventional junction laser with a very thin contact applied along one side of the chip perpendicular to the end mirrors. The principle of stripe geometry is to limit lasing to a very thin region of the junction and thereby eliminate or suppress unwanted modes. The beam of a stripe geometry laser is generally of very good optical quality. Researchers at Bell Laboratories have obtained Gaussian beams with a quality rarely seen in injection lasers. Stripe geometry DH lasers have demonstrated their superb heat-sinking ability by operating continuously at temperatures exceeding $+70^{\circ}\text{C}$. The high temperature record was set with a diamond-mounted laser, but copper-mounted ones have also operated at relatively high temperature levels.

Some of the most interesting semiconductor lasers are those that are excited by an electron beam instead of an electrical current. Such a laser may be merely a chip of bulk material with no junction. The chip should be of good optical quality and must, of course, have the two end mirrors necessary for laser action. In operation, the chip is mounted so that it can be irradiated by a powerful stream of electrons from an electron gun very similar to those used in television cathode-ray tubes. Early work with electron beam lasers concentrated on GaAs and cadmium sulfide (CdS). The latter material is of interest because the light emissions are bright green and highly visible to the unaided eye. Early experiments used electron guns of very high power and cooled lasers. More recently, RCA has shown that a gun with only moderate output will suffice to produce laser action in CdS at room temperature. The RCA gun consists of a conventional glass envelope with a flat window of glass applied to the target end. A wafer of CdS is applied to the flat window with a small amount of oil or grease. A diagram of such a system is shown in Fig. 2-12.

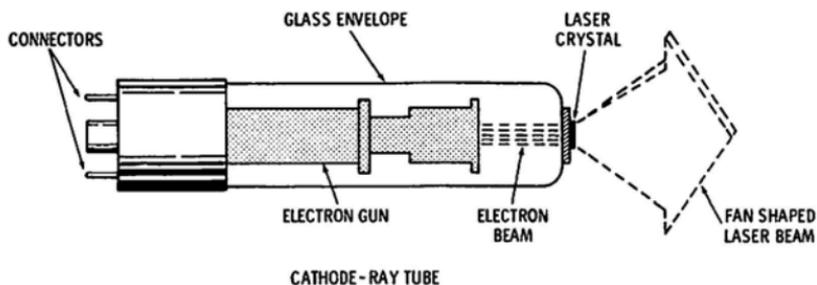


Fig. 2-12. Electron beam pumped semiconductor laser.

Perhaps the Russians are the most active in the field of electron-beam-pumped semiconductor lasers. N. G. Basov has reported that a wafer of GaAs with an area of a square centimeter can theoretically emit up to 200 megawatts peak power when illuminated with a sufficiently intense beam of electrons. These powers are comparable to the capability of some high-power solid (glass and crystal) lasers. These numbers may seem excessively high until it is realized that in 1968, J. L. Brewster achieved 400 kilowatts of peak power from an electron beam pumped CdS laser at room temperature. Also it should be remembered that the total *energy* in a very high power pulse may be quite low. Because of the very brief pulse width of pulsed semiconductor lasers, their output per pulse may contain less energy than the beam of a flashlight over a period of a few seconds.

There are still other types of semiconductor lasers. Basov, his co-workers, and several other researchers have succeeded in achieving laser action in a variety of semiconductors illuminated by the beam

of a ruby laser. More recently, a variety of experiments have succeeded in achieving lasing in small chips of semiconductor illuminated by light from another semiconductor laser (usually an injection laser). Laser action has even been observed in chunks of bulk GaAs with no junction which were connected to an electrical current. A section of the bulk material was given two end mirrors.

We can conclude this section by stating that there are literally dozens of techniques, structures, and methods for obtaining laser action in a semiconductor. As an example of the versatility of semiconductors, both injection lasers and LEDs have been used to excite yttrium aluminum garnet (YAG) crystal lasers. The narrow spectral output of the semiconductor laser results in more efficient operation than with flashlamps and other light sources used to excite YAG lasers. The power limitations of semiconductor lasers do not permit the YAG to deliver the very high power of which it is capable with other forms of less efficient excitation lamps at the present time, but advances in semiconductor technology may modify the current capabilities.

ELECTRICAL PROPERTIES OF INJECTION LASERS

We will resume our consideration of the injection laser with a discussion of some of its properties. In order to understand the electrical and optical characteristics of the injection laser, let us assume that we are working with a typical commercially available device. Since DH lasers are not yet available, the discussion will apply to a room-temperature laser that must be operated with very brief pulses of current. Although one of these pulses, itself, may be only 200 nano-

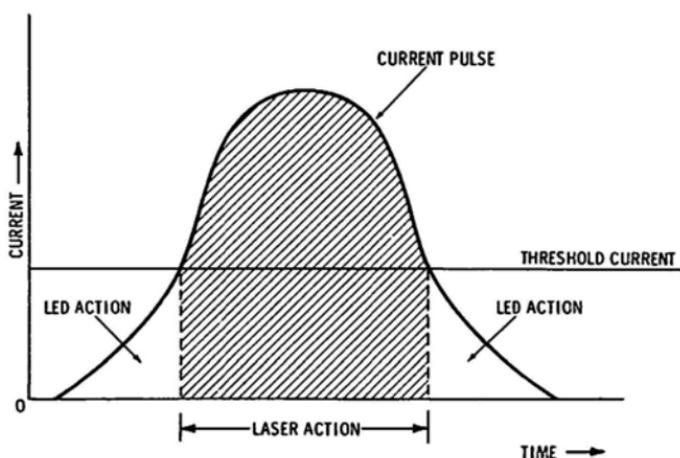
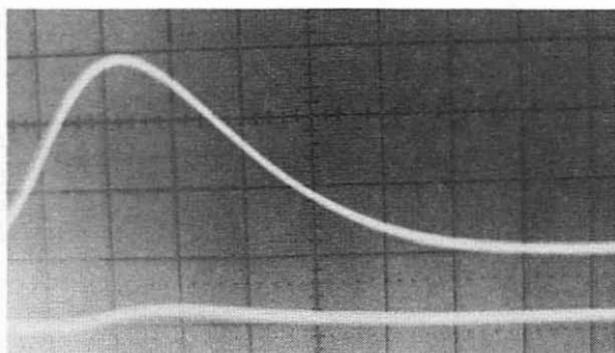
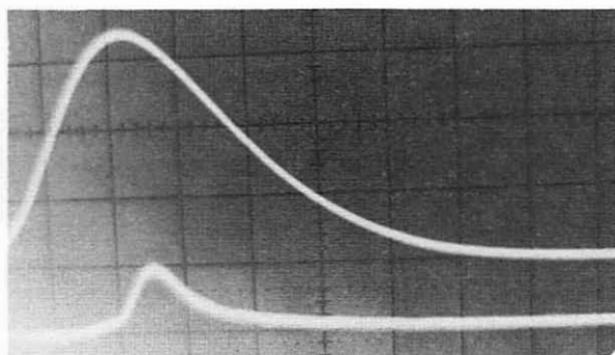


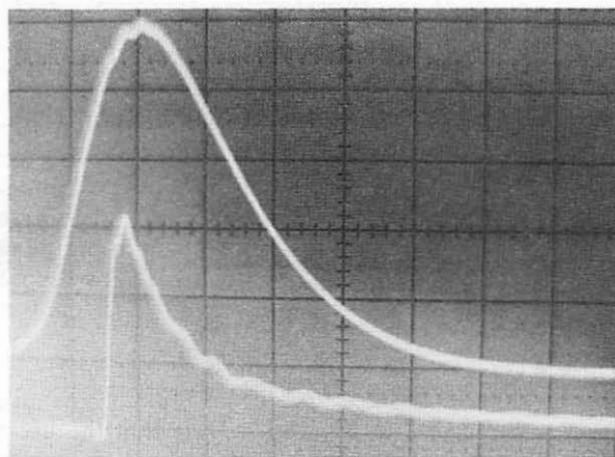
Fig. 2-13. Events of a single laser pulse.



(A) *Just below threshold.*



(B) *Threshold.*



(C) *Well above threshold.*

Fig. 2-14. Laser current (top trace) and laser optical output (lower trace).

seconds in length, we will expand our discussion of it into several paragraphs.

Since it is difficult to obtain current pulses with zero rise and fall times, our laser sample is at first driven with only a small current. Below the lasing threshold current, the laser acts like an LED and emits incoherent light from all portions of the chip not blocked by electrical contacts. As the current increases, the light output increases and the rather wide spectral distribution of the device below threshold (typically 30 nanometers) begins to narrow.

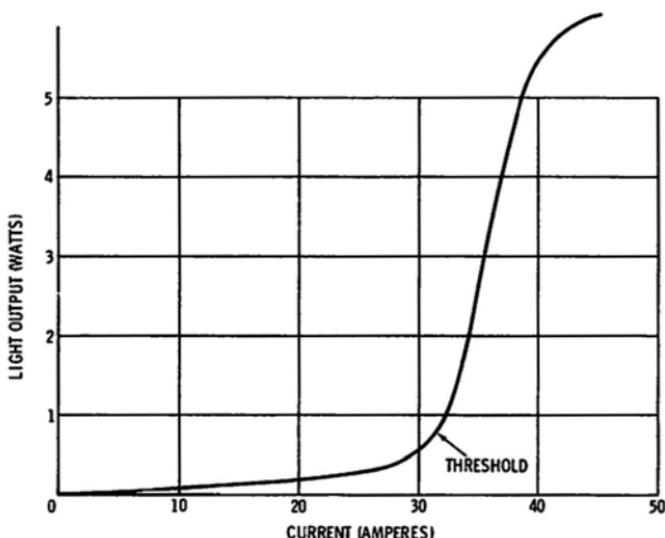


Fig. 2-15. Graph of laser current versus laser optical output.

At the lasing threshold, the spectral output of the device suddenly narrows to a very thin spike that may be only a few tenths of a nanometer in width. Also, the optical power output of the device begins to increase sharply and take on the form of a distinct beam emerging from the chip. Above threshold, the power output continues to increase, but the formerly very narrow spectral distribution widens somewhat. Also, since the current dissipation within the diode causes heating effects, the output wavelength shifts upward as the pulse continues. The wavelength for GaAs varies about 0.25 nanometer per degree Celsius.

As the current pulse begins to fall, the laser output begins to decrease. Below threshold, the laser once again functions as an LED.

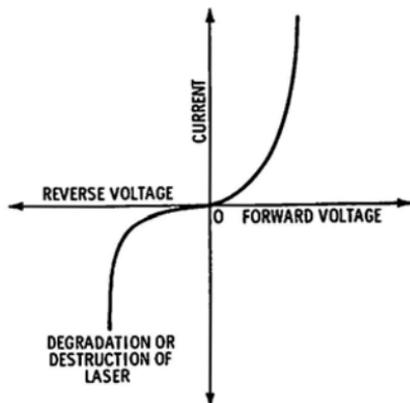
All of this is summarized in Fig. 2-13. Note that the use of a fast rise-time current pulse can improve efficiency by causing the current to reach threshold faster. Besides preventing current waste, heating effects in below-threshold operation are greatly reduced.

The three photos in Fig. 2-14 are oscilloscope traces of a current pulse through an actual laser. The traces also show the optical output of the laser detected by a very fast photodetector. Notice how the optical output increases dramatically above threshold. The application of more current causes a substantial increase in output power.

The same laser used to obtain the photos in Fig. 2-14 furnished data for the graph in Fig. 2-15. This graph vividly illustrates the threshold condition. Notice that at very high current levels the intensity of the laser light begins to fall off. This is a result of device heating. Irreparable damage can be done to a laser if it is operated at excessively high current levels.

The electrical characteristics of a laser diode are similar to those of any conventional diode. Since the resistance of a typical injection laser is about half an ohm, a voltage-versus-current curve shows that current rises rapidly with increasing voltage, as shown in Fig. 2-16. The curve also shows that excessive reverse current can cause destruction of the device.

Fig. 2-16. Voltage characteristics of an injection laser.



OPTICAL PROPERTIES OF INJECTION LASERS

Like all other lasers, the injection laser has such a variety of optical properties that each will be discussed separately. We will begin with the beam itself, then go into a discussion of wavelength, and conclude with some observations on the coherence of injection lasers.

Beam Divergence

While the injection laser does emit a definite beam above threshold, it has far more spread or divergence than the beams of most other lasers. This may be understood better if the light-emitting region of the laser is considered to be a slit. Since the slit has a thickness relatively close to the wavelength of the emitted light, the beam is dif-

fracted outward. The same effect occurs when any light beam is directed through a narrow slit. Since the slit is so much thinner in the plane of the junction (a few microns) than in the width (up to 50 mils), the beam experiences more diffraction or divergence in one dimension than in the other. The result is that the beam from most injection lasers is roughly fan-shaped.

It is interesting to note that early diffused homostructure lasers had far narrower beams than later devices. The reason is that the junctions of these lasers were poorly defined and as a result the light emerged from a slit of relatively large dimensions. Some of these early lasers had beams measuring only $1^\circ \times 5^\circ$.

Epitaxial-grown homostructure lasers have better junctions and therefore beams with more divergence. The same holds for SH lasers. Both of these laser structures have active regions measuring about 2 microns thick and produce beams with half angles of typically 10° to 15° . The extremely thin active region of DH lasers results in beams with even more divergence.

The spread of injection-laser beams is not the problem it may appear to be for applications where a very narrow beam is needed. The emitting region is so very small that collimation by means of external optics is both simple and efficient. A simple lens of comparatively small diameter will reduce the spread of a typical injection laser to a few tenths of a degree.

Filamentary Lasing

The discussion thus far has assumed by omission that the light from an injection laser is emitted uniformly across the plane of the junction. This is not always the case, and many lasers emit light from a series of points along the junction. Since these points are often symmetrical with points along the back face of the laser chip, the light is said to be generated in the form of filaments emanating along the junction. Several theories have been presented to explain filamentary lasing, but it is generally agreed that significant improvements in crystal growing and junction formation will be necessary to completely eliminate the phenomenon.

Filamentary lasing may be observed by means of an image-converter microscope, a microscope in series with an electron tube that converts the invisible infrared from the laser into visible light. A less costly technique is to focus the laser face onto the front surface of an image-converter tube located some distance away. If an image converter is not available, Kodak IR film may be used. The advantage of the image-converter tube is that the lens may be focused while directly viewing the laser face (which appears green through the tube). An infrared photograph made in this manner, showing several filaments or spots, is shown in Fig. 2-17.



Fig. 2-17. Image of light emitted from laser face (the image is the central bar; the other bars result from diffraction in lens used to make the photo).

Beam Patterns

Photographs or diagrams showing light patterns at the junction of an injection laser like the one in Fig. 2-17 are often referred to as "near-field patterns." A better descriptive phrase is *mirror image*, as light from the junction has not yet formed a true near-field pattern. A near-field-pattern photograph would have to be made of the light pattern a few millimeters away from the face of the laser.

The *far-field* pattern of an injection laser is usually a complex arrangement of interference patterns. The beam profile and the pattern of interference varies somewhat with the structure of the laser, as shown by the infrared photographs in Fig. 2-18. The photographs were made by placing strips of infrared-sensitive film a uniform distance away from each of a variety of injection lasers. Exposure times were varied to compensate for the different power outputs of the lasers.

Wavelength

The range of wavelengths over which a light source emits is called a *spectrum*. The spectrum of visible light in relation to infrared, ultraviolet, and other parts of the total electromagnetic spectrum is shown in Fig. 1-2. In the expanded view of the visible spectrum, note the dramatic narrowing of the laser spectrum as compared to that of the LED.

An expanded view of the spectrum of a typical injection laser looks like Fig. 2-19. Each of the spikes in the figure may be several tenths

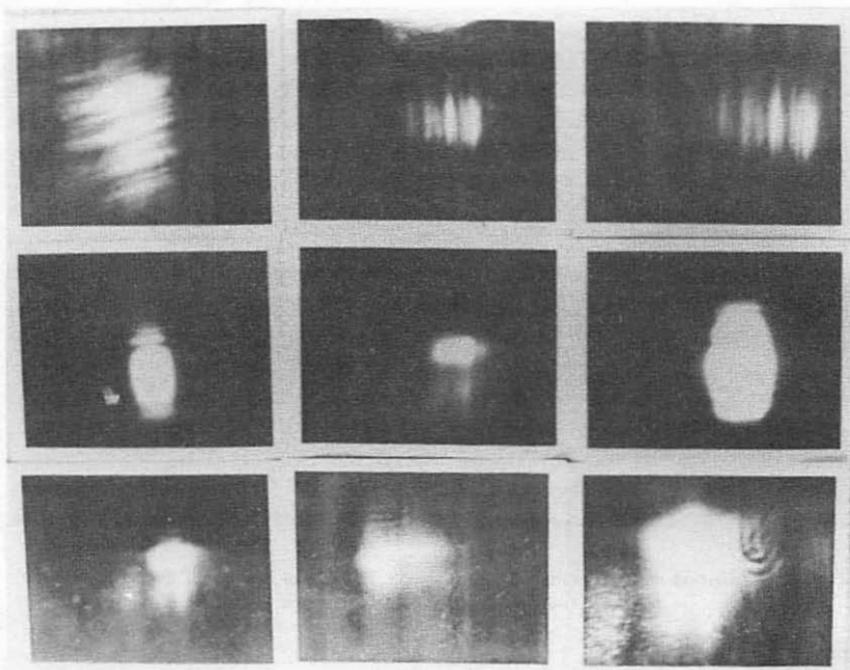


Fig. 2-18. Infrared photos of far-field beam patterns from several injection lasers.

of a nanometer in width. Significantly, each spike may be composed of numerous other spikes of much smaller spectral width. The line width of these spikes may be so small as to be immeasurable with conventional spectrometers, instruments that use a prism or diffraction grating to measure the wavelength of a beam of light.

As mentioned earlier, the wavelength of the injection laser is affected by temperature. At room temperature, a GaAs laser usually emits a wavelength centered at about 905 nanometers. Because of heating effects, the spectrum is shifted slightly upward during the injection current pulse. Since the wavelength is shifted downward at lower temperatures, liquid-nitrogen operation results in an output at about 845 nanometers. Lasers fabricated from other semiconductors show similar temperature effects. Since (AlGa)As and other injection lasers can be made that emit in the near visible at room temperature, cooling causes their radiation to be visible as a cherry red. In fact, it should be noted that radiation from GaAs lasers cooled with liquid nitrogen is visible also. Visible emission from semiconductor lasers will be mentioned again later in the chapter.

The reason injection lasers produce a range of wavelengths is because the high gain of the cavity permits the oscillation of a number of optical frequencies that may be present in the active region. Ideally,

the band gap between the conduction and valence levels would be precisely defined and all emitted photons would be of the same wavelength. Actually, the band gap is not so precise and emitted photons may have a range of wavelengths. Of these, only certain wavelengths will resonate in the laser cavity, and their presence tends to favor the stimulated emission of like photons. The result is a series of regular, closely spaced wavelength spikes.

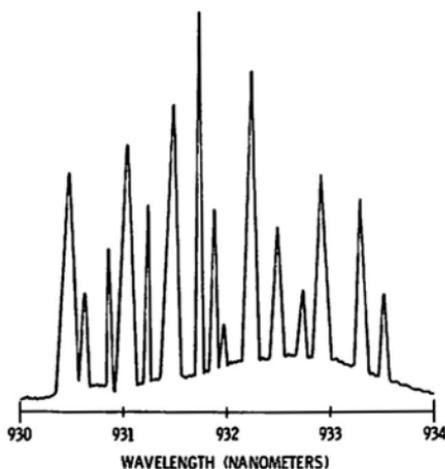


Fig. 2-19. Emission spectrum of a typical injection laser.

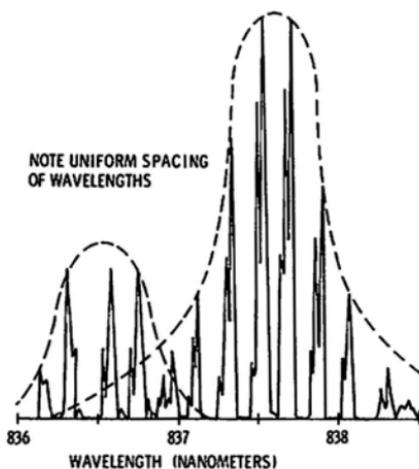


Fig. 2-20. Emission spectrum of a stripe geometry injection laser.

Certain gas lasers achieve a very pure spectral output because of better definition of atomic energy levels and longer cavities that permit fewer modes to oscillate. The cavity of an injection laser can be made more selective by increasing its length-to-width ratio. This has been done by several researchers, notably those in the GaAs Laser Group at Bell Laboratories. The stripe-geometry laser is representative of this type of device, and a spectral distribution from a DH stripe-geometry laser developed at Bell Labs is shown in Fig. 2-20.

Other Characteristics

Injection lasers show a delay and do not emit light immediately after application of a current pulse. The delay may be very brief—a nanosecond or so—but delays of as much as 100 nanoseconds or more have been observed. The effect is related to temperature and impurities in or near the junction.

The delay phenomenon has been explained by the action of what are called *trapping centers*. These traps act to capture excited electrons generated in the active region. When the traps are all occupied, emis-

sion can take place. Since it takes a finite time and a finite number of electrons to saturate the traps, a delay in the onset of lasing results.

A particularly interesting byproduct of the traps is that at the end of a current pulse they suddenly release their captured electrons. The electrons drop back to an unexcited state, releasing photons in the process, and a very brief *Q-switched* pulse of light is emitted from the laser. SH lasers often show this unique form of self Q-switching.

COHERENCE OF INJECTION LASERS

Coherence is a topic that could have been discussed in the previous section, but its importance warrants a separate discussion. Lasers are unique among light sources in that they come closest to producing coherent light. All other light is incoherent, that is many wavelengths are present and the wave fronts are out of phase with one another.

Some lasers, particularly those employing gasses in the lasing medium, produce beams with excellent coherence properties. Unfortunately, the injection laser produces a beam with only moderate coherence. The spectral output is over a range of wavelengths, so time or *temporal coherence* is limited. The effect is due *in part* to the high gain of the injection-laser cavity. High gain and other factors allow numerous modes to propagate in the laser, some being out of phase with the others. Therefore there is only a degree of phase or *spatial coherence*.

What coherence properties the injection laser does possess are not helped by the large divergence of the emitted beam. As evidenced by the complex interference patterns in the far field of a typical unit, there is considerable mixing and smearing of the light as it passes through space.

Though the light emitted from typical injection lasers is at best only quasi-coherent, some of these lasers have been used in applications that normally require a relatively coherent source. One example is *interferometry*. An interferometer is an instrument that has the ability to split and recombine a beam of light so that interference fringes are produced. As shown in Fig. 2-21, the instrument uses two mirrors. A slight movement of one or both of the mirrors will cause the interference fringes to shift, thereby permitting the measurement of extremely small dimensions. The accuracy of an interferometer is limited by the wavelength of light used to produce the fringes.

Fig. 2-22 is a photograph of an interference pattern made by passing the beam of a small helium-neon laser through an interferometer. The laser and interferometer are shown in Fig. 2-23. As one mirror is moved, the central spot in the circular interference pattern shifts from dark to light. The distance (d) the mirror has been moved can be quickly calculated by counting the number of shifts, multiplying by

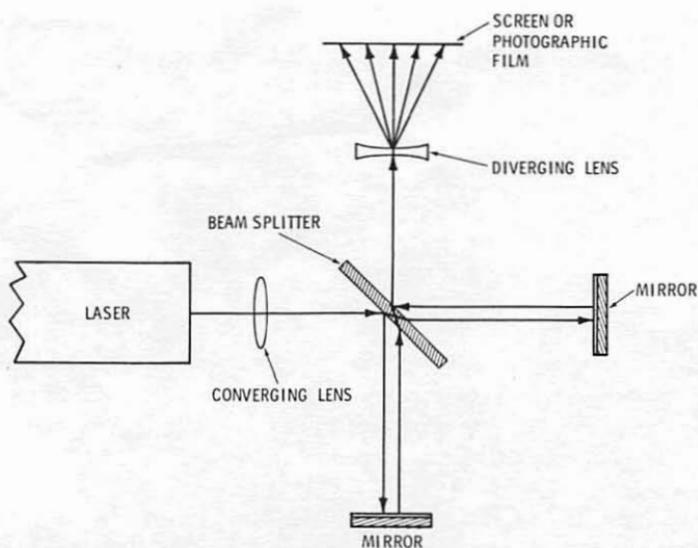


Fig. 2-21. Michelson interferometer.

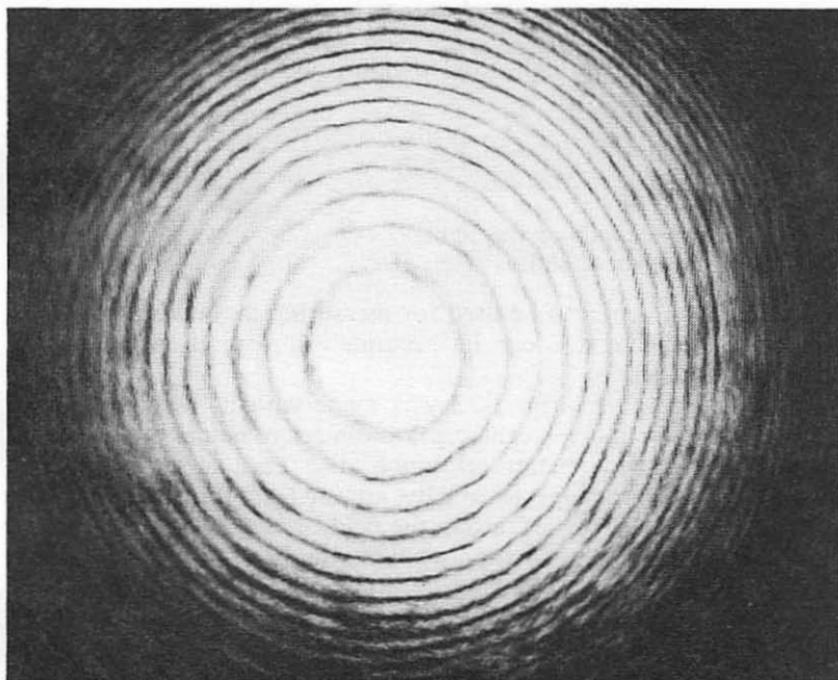


Fig. 2-22. Circular interference pattern produced by a helium-neon laser and a Michelson interferometer.

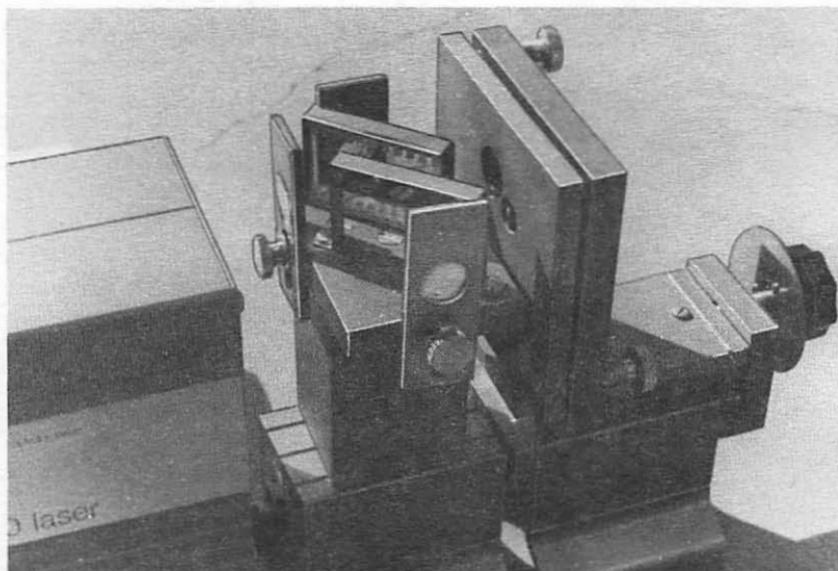


Fig. 2-23. Michelson interferometer and helium-neon laser manufactured by Metrologic Instruments, Inc.

the wavelength of the light, and dividing the product by two. The relationship is expressed as:

$$d = \frac{m\lambda}{2} \quad 2.1$$

where,

- λ is the wavelength of the light,
- m is the number of shifts.

The equation can also be used for measuring the wavelength of an incident light beam if d can be accurately measured as one of the mirrors is moved.

The photograph in Fig. 2-22 was made with a Michelson interferometer. Other more recent types of interferometers are easier to operate and provide better resolution. For ease of operation, the Michelson interferometer is usually adjusted so that parallel bars, rather than circular fringes, are in the field of view. The observer (or an electronic sensor) then simply counts the bars as they move past a reference point.

It should be pointed out that even white light will produce fringes when directed into a high quality interferometer. While the fringes are not as distinct as those produced with monochromatic light (they appear multicolored due to the white light breaking up into its component wavelengths), they are extremely useful in many optical tests.

It is possible to produce excellent interference fringes with some injection lasers. Author Mims has used an RCA TA7606 (now the RCA types 40855-57) and a simple interferometer made from two mirrors and a glass beam splitter inserted into a flat block of clay. The laser had a junction width of 3 mils. Numerous other lasers with wider junctions were tried with poor results. For example, one laser with a 9 mil junction produced poor quality fringes and then only when pointed into the interferometer at an off-axis angle. It is likely that the technique of adjusting the angular alignment of the laser selected a portion of the beam with a more limited number of modes than those in the main portion of the beam.

The production of interference fringes by the TA7606 and not by the other lasers is probably a result of fewer modes operating in the smaller laser. Hence the output radiation is probably both of better spatial and temporal coherence. When driven with high current, fringes from the TA7606 are of poorer quality than those obtained at lower currents. (Best results are had from threshold current to about twice threshold.)

A type of interference exhibited by all injection lasers tested by author Mims (both diffused and epitaxial homostructure and SH units) is shown in Fig. 2-24. Here some of the light from a laser has been caused to strike a mirror at a glancing angle so that it is reflected

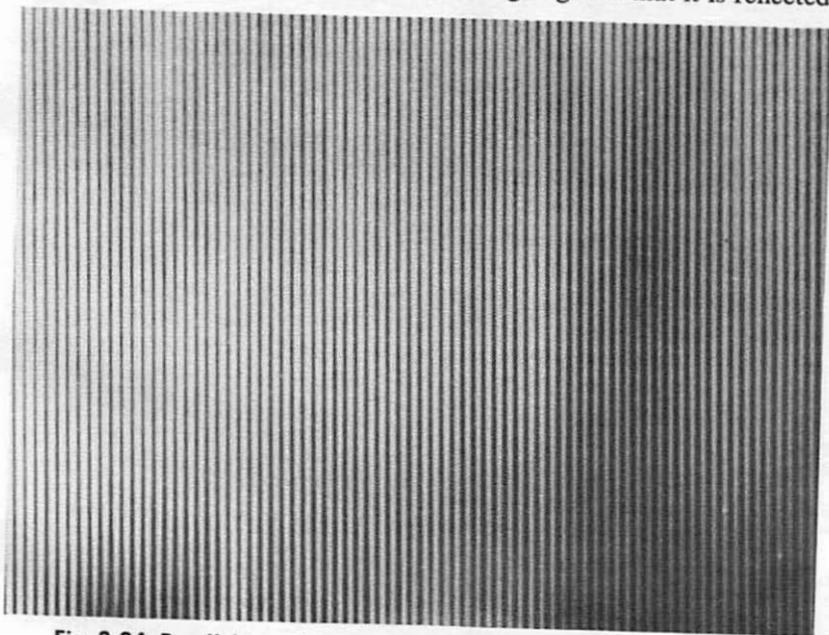
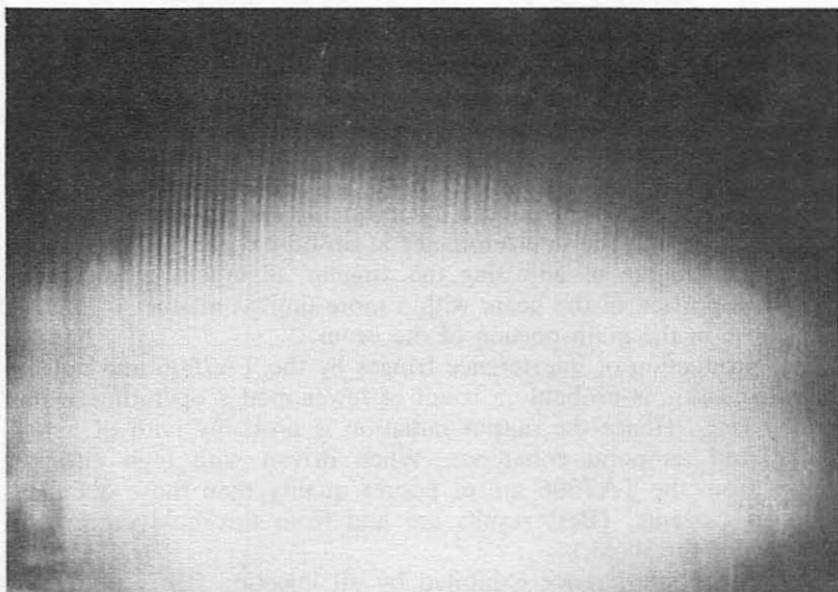
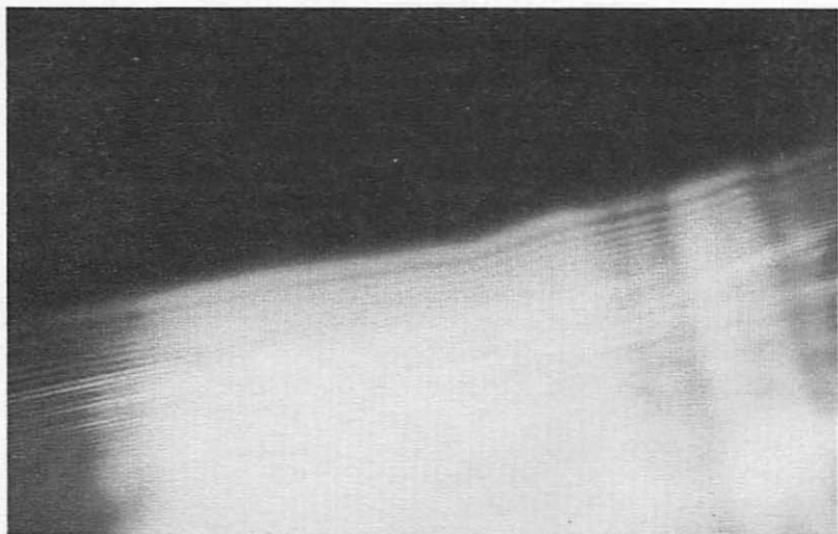


Fig. 2-24. Parallel interference fringes made with GaAs injection laser and a single mirror.



(A) Normal beam pattern.



(B) Interference caused by reflections from heat sink.

Fig. 2-25. Interference resulting from laser chip recessed on heat sink.

back into the main portion of the beam. The light interferes with itself, producing the series of dark and light bands. The bands will be observed from sources with less coherence than necessary for the Michelson interferometer.

It is interesting to note that early injection lasers were mounted on heat sinks in such a manner that a portion of the emitted beam struck the flat surface of the sink a glancing blow and satisfied the requirements for the single-mirror interferometer just described. The far field of these lasers showed the naturally occurring diffraction patterns of the raw beam, as well as the fringes of Fig. 2-24. A pair of photos showing this effect is shown in Fig. 2-25.

It is interesting to note that the use of a single mirror to produce interference was first proposed by Lloyd in 1877. In a classic experiment, Lloyd used a single mirror to form an interference pattern from filtered white light, thus helping to demonstrate the wave nature of light.

VISIBLE INJECTION LASERS

The first injection laser to emit a beam visible to the human eye was fabricated by N. Holonyak, not long after the successful operation of the first GaAs laser. Holonyak's laser, made from gallium arsenide phosphide [Ga(AsP)], emitted a red beam when cooled to the temperature of liquid nitrogen. Ga(AsP) was eventually improved to the point where visible red operation may now be obtained at room temperature.

Since the Ga(AsP) laser is a homostructure device, efficiency is not high, but research aimed at developing heterostructure lasers in this material is currently under way. One suggestion has been to use GaAlAsP.

Reasonably efficient room-temperature-visible red emission from (AlGa)As lasers has been obtained by Dr. Henry Kressel at RCA Laboratories. Kressel has used both the SH and DH technique and has observed room-temperature emission down to 710 nanometers.

An aspect of the subject of "visible" lasers worthy of discussion concerns the definition of *visible* light. Many experimenters have observed that the emission from standard GaAs lasers is visible as a tiny red point of light when viewed straight-on in a darkened room. Since visible light is defined as the range of wavelengths between 380 nanometers (blue) and 760 nanometers (red), by definition GaAs lasers which emit at 905 nanometers are not visible. The reason most individuals can see the radiation from GaAs lasers is that relatively high peak powers are involved. At the temperature of liquid nitrogen, GaAs emits a bright red light, visible at 845 nanometers.

Back to room temperature operation, many observers report that GaAs light emission looks "reddish" rather than red and often the color is described as purple. This off-red appearance is especially noticeable with very high power arrays of these lasers. It is known that GaAs emits a tiny percentage of its light as a second harmonic

in the blue portion of the spectrum. One study of a diode emitting 20 peak watts of infrared detected 10 microwatts of blue. This much light is definitely visible, and a mixture of both it and the dim red from the 905 nanometer radiation might explain the purple appearance of light from a GaAs injection laser.

INJECTION LASER DEGRADATION

While light-emitting diodes may have lifetimes measured in the tens of thousands of hours, injection lasers do not. Early diffused homojunction lasers often had lifetimes of only a few hours or even minutes, but the lower current required to operate epitaxial homojunction lasers increased life to as much as a few hundred hours. SH lasers have significantly longer lifetimes than any of the earlier devices and RCA has accumulated test data showing they may have little degradation after 1000 hours of pulsed operation. Life performance is, of course, not as general as we have described it (some early lasers showed exceptional lifetimes), but it is quite true that improved technology has greatly increased the time over which one can expect to obtain useful light from an injection laser.

There are two major classes of injection-laser degradation: gradual and catastrophic. Gradual degradation occurs over a relatively long period of time and is responsible for the ultimate failure of a device as evidenced by significant reduction in the optical power output. As the name implies, catastrophic degradation is a more massive event.

Gradual Degradation

Under a series of Pentagon contracts let to study the degradation problem, RCA found that the gradual loss of optical power in an injection laser is probably due to the formation of nonradiative recombination centers in the pn junction. Since the formation of these centers may be speeded up by very high current densities, the lower threshold of SH devices is significant in extending their lifetime over other lasers. It is expected that improvements in crystal growing and junction formation technology may contribute to reducing the gradual degradation problem.

Catastrophic Degradation

When an injection laser is operated at a point where optical power density exceeds a certain value, the emitting facets may be physically damaged. This damage often is so severe that the lasing process may no longer take place. And it may occur over a period of only one or two pulses of laser light.

Other solid lasers show a similar effect. The photograph in Fig. 2-26 shows the chipped front surface of a ruby laser rod which has

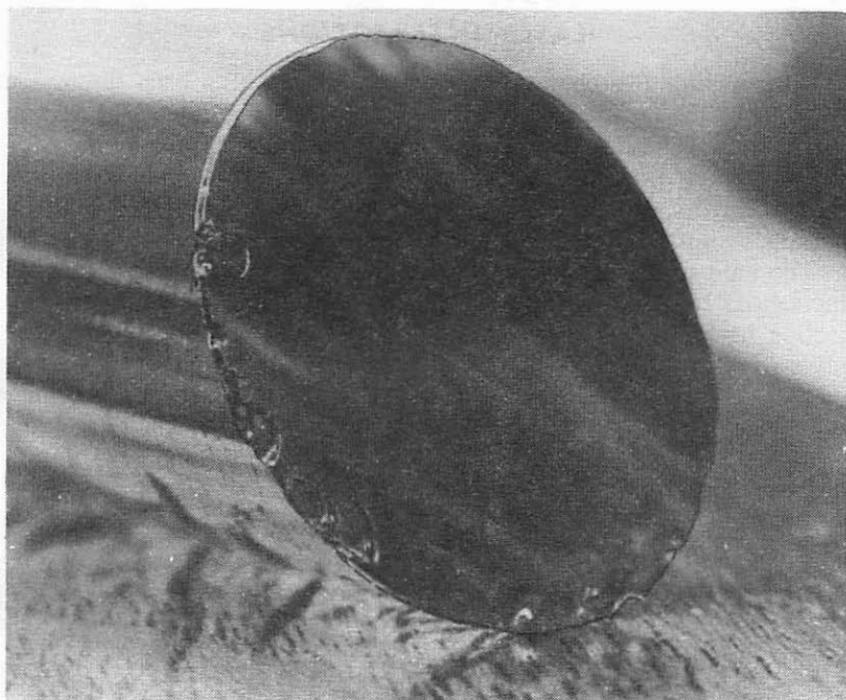


Fig. 2-26. Chips on front face of ruby laser rod caused by high-power optical pulse.

been operated at too high an optical power level. Entire ends of ruby and glass laser rods have been known to literally fly off during a single laser pulse!

The damage mechanism in injection lasers is probably a combination of melting due to absorption of the high optical power levels and fracture due to the generation of acoustical shock waves. Photographs of damaged laser facets have shown both effects. Cracks and fissures from the damage area are usually formed in a row along the junction and are either confined within it or extended several junction widths into the bordering *n* and *p* regions.

So long as injection lasers are operated within ranges that do not exceed the flux density for optical damage, there is no fear of catastrophic degradation. This value is usually a few watts of peak output per mil of junction width. Of course, voltage and current restriction for these lasers should never be exceeded or still another type of catastrophic degradation will occur. Lasers which have been driven with extremely high current pulses often take the appearance of a burnt cinder when observed through a microscope—in the process becoming completely useless for their intended purpose.

LASER INTERACTIONS

We conclude this chapter on a happier note with a brief discussion of some of the unusual effects that occur when one injection laser illuminates another. Lasers are essentially optical amplifiers with positive feedback provided by an optical resonator formed from two facing mirrors. When gain reaches a point where the feedback encourages stimulated emission, oscillation occurs (threshold).

The gain of a laser oscillator may be reduced (and the threshold increased) by reducing the reflectance of the front mirror. In the injection laser this is commonly done by coating one end with a thin layer of silicon oxide. When another laser is placed close to the first so that it illuminates the junction region of the first laser, an amplifier is formed. If the oscillator is operated above its threshold and the amplifier below its threshold, the oscillator will stimulate the amplifier laser into stimulated emission.

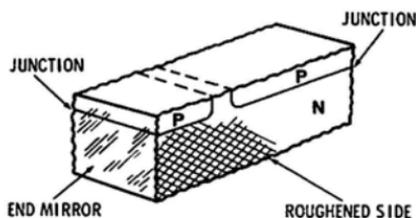


Fig. 2-27. Injection-laser amplifier.

Early injection-laser oscillator-amplifier pairs were made from separate lasers mounted on a common heat sink. But later devices were made in a single chip by integrated circuit techniques. Fig. 2-27 shows such an injection-laser amplifier.

Another interaction occurs when the beam from one laser is caused to impinge on the side of a second laser. The first beam tends to depopulate the excited electrons of the second laser and cause it to stop lasing. It is therefore called a *quenching beam*.

A combination of these two fundamental interaction schemes may be used to design laser switching circuits for use in futuristic optical computers. Potentially such a computer would have an extremely fast operating speed. If the delay effects noticed in many injection lasers can be eliminated, the speed of an optical computer would be limited only by the time to set up a population inversion and by the speed of light itself.

Fabrication and Commercial Devices

The fabrication of the first injection lasers was a delicate combination of materials processing and semiconductor technology. Even poor quality GaAs lasers must be fabricated from materials that are extremely free of contaminants. Besides hindering uniform junction formation, contaminants result in irregular crystal structure.

Though many problems remained to be solved, several manufacturers quickly became involved in attempts to manufacture commercial injection lasers shortly after the success of the first injection lasers. Several novel production shortcuts were developed and evolved, and they contributed greatly to the eventual commercial availability of injection lasers.

CRYSTAL GROWTH

The first step in the production of an injection laser is the growth of a highly pure, uniform crystal of GaAs. The crystal can be grown by several techniques, all of which involve a special form of furnace with precise heating controls. In the Czochralski technique, the crystal is pulled from a molten bath of GaAs by a rod to which is affixed a small seed crystal of GaAs (Fig. 3-1). The seed provides a point for crystal growth to begin and helps to insure that the growth will be uniform and not a mass of randomly oriented crystals.

Czochralski growth is categorized according to the method used to pull the crystal from the melt. Since the melt and the seed-pulling

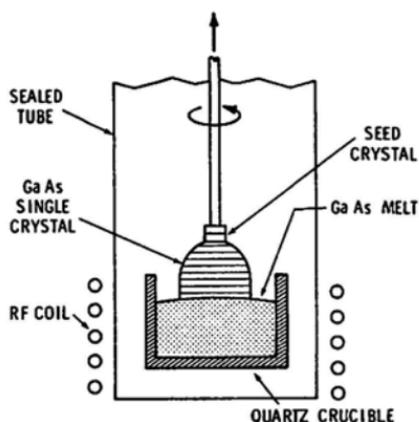


Fig. 3-1. Basic Czochralski crystal growing technique.

assembly must be encapsulated in an inert environment, several unique pulling techniques have been devised. In the magnetic lifting technique, the seed is lifted by a set of movable magnets mounted outside the sealed quartz tube, which is called an ampoule, containing the melt and seed-pulling mechanism. Iron structures inside the ampoule provide the attractive mass for the magnets. Still other magnets impart the rotation to the seed necessary for pulling fine quality Czochralski crystals.

Mechanical lifting techniques employ an exterior motor coupled to the seed by a series of bearings and seals designed to preserve the integrity of the inert atmosphere of the crystal chamber. The disadvantage of direct mechanical pulling is the possibility of contamination through the seals and nonuniform pulling.

Still another technique reduces problems of crystal uniformity and contamination by encapsulating the GaAs melt in a layer of liquid boric oxide. The seed is merely inserted through the liquid layer to the GaAs and pulled back through the layer during crystal growth.

In all the Czochralski techniques, the melt is heated by an external rf induction coil. The GaAs is placed in a quartz crucible located in the bottom of the growing chamber and the chamber is in turn placed in the external induction furnace so that the crucible is located at the point of maximum heating.

Czochralski crystals of GaAs are easily grown and may be observed during growth to check for single crystal formation. (A crystal with perfectly uniform crystalline structure is said to be a single crystal, while a polycrystalline crystal, as the name implies, contains a variety of orientations.) But a disadvantage of the technique is that subtle variations in the pulling conditions often permit thin layers of dopant to congregate within the crystal, thus affecting the semiconductor properties of the material.

The disadvantages of the Czochralski technique are largely corrected by the horizontal Bridgeman method. As applied to the growth

of GaAs, the Bridgeman method makes use of a horizontal furnace assembly and a "boat" for containment of the GaAs melt. As in the Czochralski technique, Bridgeman systems are sealed in an inert atmosphere to prevent contamination and to keep arsenic from diffusing out of the melt. That is where the similarity ends, however, as the Bridgeman method produces a fine quality crystal with the shape of the boat in which it is grown. The boat is slowly pulled through the furnace allowing the melt to pass through a series of controlled temperature gradients. By merely varying the temperature and location of the external rf induction furnace, precise control can be placed over the crystal formation.

It is interesting to note that the problem of contamination limits the choice of furnace and boat materials. Sandblasted quartz is often used, but the GaAs often tends to absorb silicon from the boat during heating. This does not always affect the resultant crystal, and in fact some GaAs LEDs are purposely doped with silicon in order to produce more efficient light emitters. But for precise laser applications where no unwanted contamination is desired, boats of aluminum-nitride, boron-nitride, and aluminum oxide have been used. Graphite is also used for contamination-free growth.

WAFER FORMATION

After a good quality crystal of GaAs has been grown the next step is slicing it into thin wafers. But first it is necessary to determine the characteristics of the crystal. For example, since injection lasers are cleaved along certain crystalline planes to form reflecting end mirrors, the wafers must be cut so that the cleavage planes are properly oriented. The most common method for determining the orientation is with an X-ray technique which produces a type of diffraction pattern on photographic film. Other tests can also be conducted on the crystal before slicing into wafers is begun, and in many cases a close visual examination of the crystal surface will often reveal polycrystalline structure.

The crystal is then mounted to a metal or glass substrate with pitch or wax and sliced into thin wafers by a diamond saw or by other more specialized techniques. The wafers are generally very thin—roughly 0.015 inch (0.38mm). After slicing, they are washed and dried in preparation for junction formation.

JUNCTION FORMATION

There are a variety of techniques for forming junctions in GaAs injection lasers, but the most common methods are zinc diffusion and epitaxial growth.

Zinc Diffusion

One surface of the wafer is lapped and polished and the wafer goes back to a furnace for further heat treatment. In this case, an atmosphere of a dopant material with opposite polarity of the dopant applied to the original crystal is injected into the furnace. For almost all diffused lasers, the dopant at this stage is zinc. The wafer is left in the zinc atmosphere for a period which may range from a few minutes to several hours, depending on temperature (usually 900°C), dopant concentration, and desired junction depth.

The zinc diffuses into all exposed portions of the wafer and when the heating is stopped the boundary of the zinc penetration into the wafer is the junction. Since diffusion generally occurs on both sides of the wafer, one side is lapped down below the zinc penetration region to re-expose the original n-type wafer. The wafer then contains a pn junction and is ready for further processing.

Epitaxial Growth

Very high quality junctions are available with epitaxial growth techniques. The most common form of this technique is liquid phase epitaxy. Here, the freshly sliced wafer is lapped and polished as in the processing for the diffused junction-forming technique. The wafer is then mounted in a graphite boat that contains a quantity of liquid GaAs with a dopant of opposite polarity than that of the original wafer. The boat is tilted to keep the liquid GaAs at one end.

It is then placed in a tilted furnace, as shown in Fig. 3-2, in order to keep the liquid GaAs away from the wafer, and the furnace is heated to about 900°C . When the proper temperature is reached, the furnace is tilted, and the liquid GaAs is permitted to flow over the GaAs wafer. The liquid material immediately begins to crystallize onto the surface of the wafer, thus forming a layer with opposite polarity than that of the wafer itself. The furnace is again tilted after a controlled period of time, and the boat is cooled and removed from the furnace. The result is a junction that is as flat as if the wafer were

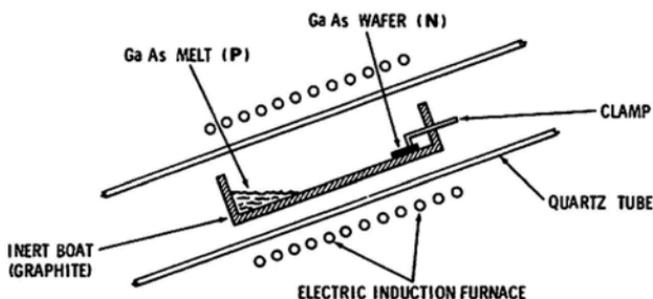


Fig. 3-2. Epitaxial furnace.

polished. The surface of the wafer is again lapped and polished to reduce excess thickness and hence eventual resistance of the final injection lasers.

After junction formation, many injection lasers undergo a period of heat treatment to slightly displace the junction further into the wafer. The displacement usually improves device performance, possibly a result of formation of a type of waveguide. More advanced junction techniques produce far more efficient waveguides and significantly improve performance.

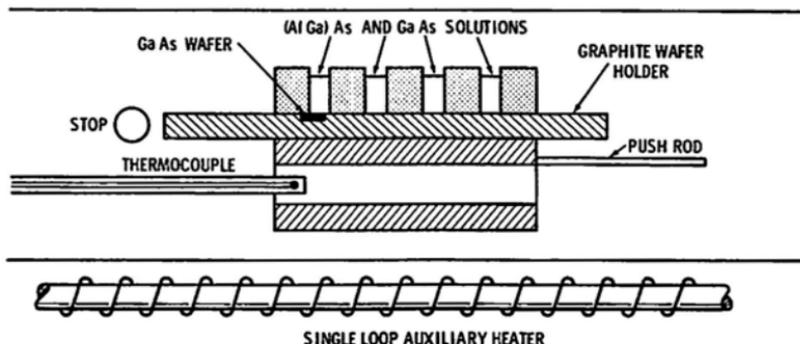


Fig. 3-3. Furnace for producing DH lasers.

Junction formation for these more complex lasers naturally requires more steps than for the basic homojunction device. Formation of a double heterostructure laser is particularly complex, and a specially modified furnace is required for the operation. As shown in Fig. 3-3, the furnace consists of heating elements, four separate melt containers, and a movable wafer holder. The wafer is moved into position under each of the four melt holders for precise periods of time and at precisely controlled temperatures ranging between 800 and 1000 degrees Celsius. Each of the four melts deposits a thin layer of material onto the four by ten millimeter wafer as it passes through the furnace. This superb capability for precision junction tailoring graphically illustrates the superiority of the epitaxial process for formation of complex injection lasers.

METALIZATION

After a wafer has been given a pn junction, it must be metalized on both surfaces. The wafer is usually lapped and polished to remove surface irregularities, and then a thin layer of gold, tin, or other conducting material is applied. Application of the metal, which provides the contact points for the completed lasers, may be accomplished by vacuum deposition or liquid solution techniques.

Metalization is an important step toward improving laser performance. Since series resistance of injection lasers is a cause of inefficiency, good contacting techniques can improve operation by providing low-resistance current paths. Also, metalization greatly eases the problem of attaching final electrical contacts to individual laser chips. Even when lasers are operated by pressure contacts rather than by those soldered or alloyed to the metalization layer, the thin layer of highly conducting material serves to greatly improve both heat sinking and electrical contact.

FORMATION OF SINGLE LASER DIODES

The processing from metalization onward is virtually identical for both diffused and epitaxial lasers and is summarized in Fig. 3-4. First, the wafer is separated into long, thin bars by cleaving, the process of splitting crystals along their natural crystalline planes. Water soluble crystals such as sodium chloride (table salt) and potassium aluminum sulfate (alum) can be cleaved with a light tap on a razor blade placed at an appropriate point on the surface of the crystal. Mica crystals can be cleaved with nothing more than a sharp instrument and a gentle peeling motion. Gallium arsenide wafers are often cleaved with gentle pressure applied to a razor blade, but cleaving is sometimes accomplished by scribing parallel lines spaced an equal distance apart across the wafer with a sharp instrument and then rolling a glass rod over the wafer while it is resting on a soft surface. Gentle pressure applied to the rod will result in the formation of a series of long bars with parallel sides.

The advantage of cleaving GaAs is that the process exposes very flat and parallel surfaces for use as the mirrors necessary for laser action. Early injection lasers and some experimental laboratory devices of the present time were made by polishing the GaAs so as to produce flat and parallel faces. The polishing process is time consum-

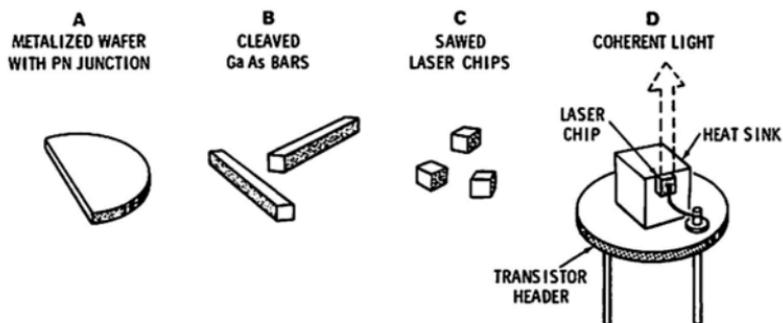


Fig. 3-4. Fabrication of a single-diode laser.

ing and difficult, so almost all practical injection lasers are now given end mirrors by the quick and simple process of cleaving.

After cleaving, the individual bars of GaAs are usually coated on one of the two parallel sides with a layer of silicon monoxide and gold, the former for insulation and the latter for 100% reflection. The laser will operate without the gold mirror, but it is difficult to collect light emerging from both of its ends.

Next, the bars are separated into individual laser "chips," typically from 3 to 50 mils wide. The separation must not be done by cleaving as this will result in four parallel surfaces, a condition that tends to quench laser action. So usually chips are made by sawing, a process that produces roughened sides. Sawing can be done with a diamond saw, but in order to reduce waste a wire saw is often used. The wire saw consists of a very fine tungsten wire in an endless loop configuration which passes through an abrasive slurry and then with carefully controlled pressure over the GaAs bar being separated into chips. Since it takes considerable time to saw a large number of individual laser chips in this manner, saws with as many as 75 wires are sometimes used.

After sawing, individual chips are cleaned and then soldered to the heat sink block of a special header. The chip may be soldered to the block and given a positive electrode at the same time in a very simple operation. A technician orients the header in a jig so that the block faces up and, with fine tweezers and a stereo microscope, places a tiny square of tin on the heat sink. Next come the laser chip, another square of tin, and the wire electrode. A drop of flux aids soldering and holds the tin-chip-tin sandwich together. Then, while observing everything through the microscope, the technician activates a control that applies heat to the jig supporting the header. As soon as the tin begins to melt, the heat is turned off and the laser is ready for installation of a glass windowed protective cap.

Although the fabrication technique just described is similar to that used by most manufacturers, some companies cold-weld metalized chips to copper heat sinks. The process is a simple matter of pressing an indium-plated chip between two similarly plated thin copper strips. The soft indium provides good thermal and electrical contact. Lasers produced in this manner are sometimes difficult to work with, but their excellent heat-sinking characteristics permit higher duty cycles than lasers mounted on conventional headers.

LASER ARRAYS

The availability of individual injection laser diodes soon created a demand for high-power laser arrays, since an array of many individual diodes can deliver far more peak power than a single chip.

Financial assistance for the first injection laser array studies was provided by the National Aeronautics and Space Administration (NASA) and the military. NASA was interested in developing an injection laser array for possible use in space communications, while military scientists were more interested in infrared rangefinders and covert battlefield illuminators.

IBM and General Electric both developed injection laser array technology soon after the invention of the first semiconductor lasers. The work at General Electric centered around linear arrays of ten lasers cut from a single cleaved bar of GaAs. GE first tried sawing the bars into ten separate diodes so that they remained attached to a common substrate. The sawing process was unsuccessful, and the company had better results with a wax and etch technique. The technique consisted of applying a wax grid of parallel lines to a GaAs bar and allowing an acid bath to etch through the material not protected by the wax, thus forming the linear laser array.

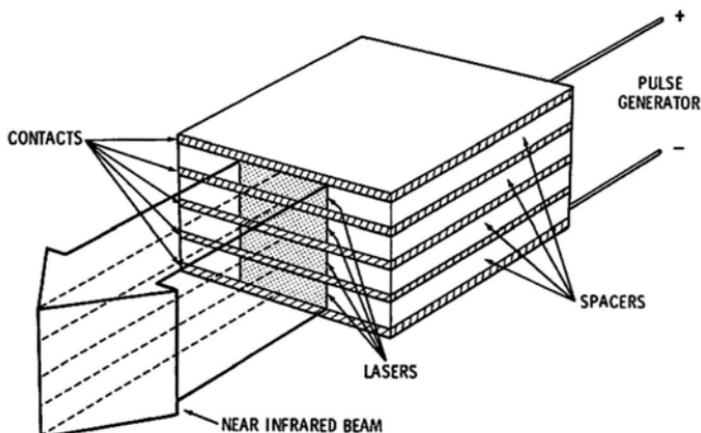


Fig. 3-5. High-power stacked laser array.

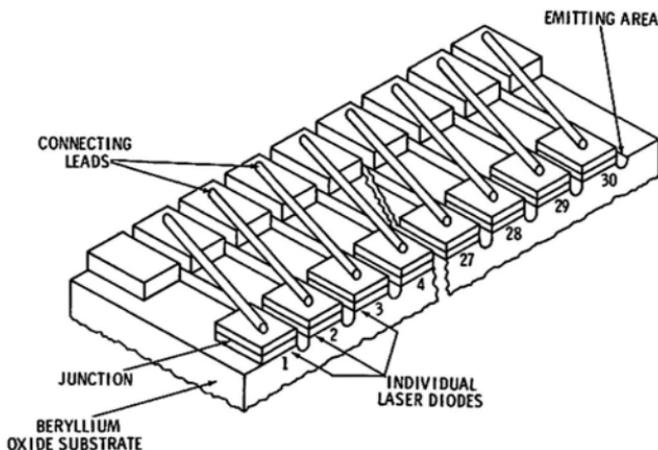
One of IBM's first approaches to an injection laser array was to mount 96 separate chips into a holder with an aperture only 0.3 inch square. When driven with a 300-ampere current pulse, the array delivered approximately 1000 watts of peak power. Since light could be collected from only one side of the array, IBM sought a more efficient type of configuration. The result is shown in Fig. 3-5. The new technique consisted of stacking several very large lasers, thus achieving the same power output as the larger array in a much smaller output area ($0.2'' \times 0.05''$) and permitting light to be collected from each side of the stack. A small output aperture is a great help in narrowing the relatively wide beam of the lasers with an external lens or other optical device.

Assembly of an IBM array is described in more detail later in this chapter. While the technique provides a very compact, small-aperture array, RCA has gone on to perfect arrays using the sawing process abandoned by GE in favor of waxing and etching. RCA's sawing process has resulted in array assemblies delivering up to 40 watts of average power when cooled to the temperature of liquid nitrogen.

Fabrication of an RCA array begins with a cleaved bar of GaAs that has been given an appropriate pn junction. The bar is metalized and mounted on a beryllium oxide (BeO) ceramic block as shown in Fig. 3-6. A contact bar of beryllium-copper (BeCu) is also attached to the BeO block. The entire assembly is coated with an abrasive slurry and placed under a multifilament wire saw so that the BeCu contact bar and the GaAs are simultaneously cut into separate laser cavities and contact points. The wires are allowed to saw into the BeO base in order to electrically isolate the individual lasers and contact points.

After sawing, the slurry is washed from the array and contact wires are affixed. The arrays are wired in series, as shown in Fig. 3-6, by placing tiny interconnect wires from the top of one laser to the contact point directly behind the adjacent laser. All the interconnections are simultaneously alloyed in place by carefully heating the array in a controlled environment. RCA literature does not reveal how the tiny interconnect wires remain in place before alloying, but probably a droplet of flux applied to the top of the contact points and lasers does the job.

Those array strips that meet specification tests are mounted on modularized cold fingers for stacking into larger array assemblies, or are encased in glass-windowed packages much like those used for



Courtesy Radio Corporation of America

Fig. 3-6. Fabrication of RCA laser array.

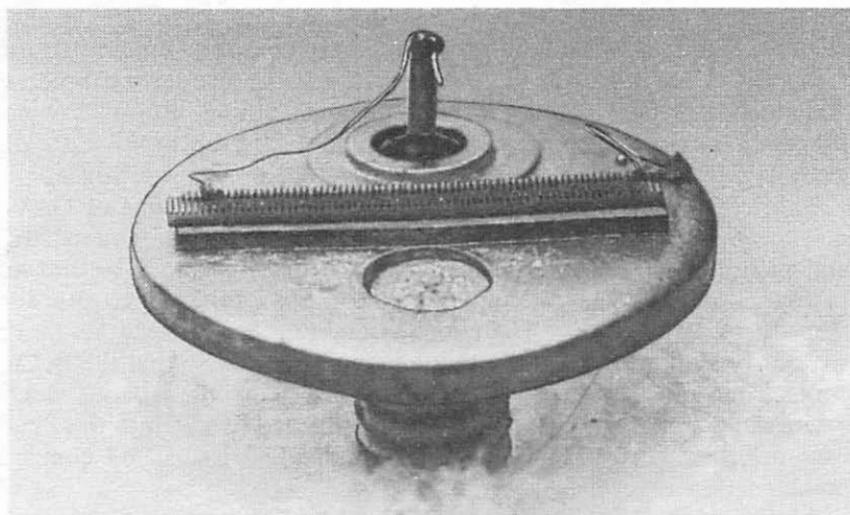


Fig. 3-7. Close-up of a test RCA linear array.

single laser diodes. A close-up view of a completed array strip is shown in Fig. 3-7 and a photograph of a commercial array is shown in Fig. 3-8. The power advantage of an array constructed in this manner is significant. A device not much larger than an ordinary thimble can have a capability of delivering up to 300 watts of peak

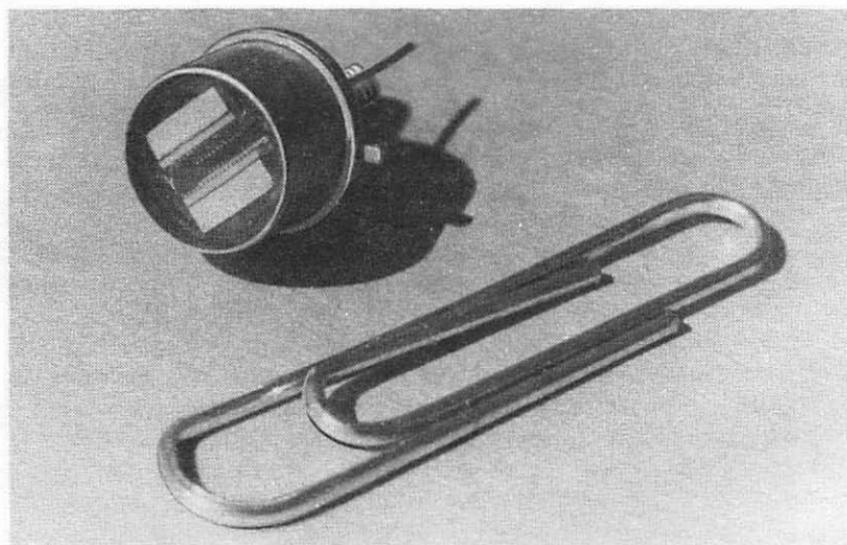


Fig. 3-8. Commercial RCA linear laser array. The lasers are the rows of light-colored blocks.

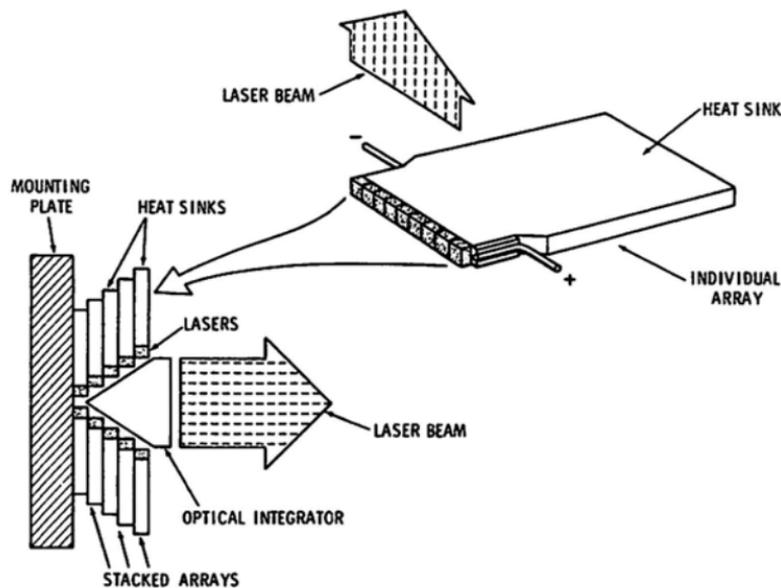


Fig. 3-9. High average power RCA laser array.

power. Collimating the optical output into a narrow beam is more difficult than with the smaller aperture IBM lasers, however, and because of the severe length-to-width ratio of the strip, special lens assemblies must be designed that compensate for the unusual shape of the light-emitting region. Arrays formed from several smaller strip arrays, like the large RCA unit shown in Fig. 3-9, present more difficult optical problems. Since light is emitted over a large area, an optical integrator, a block of transparent quartz, is placed at the optical output of the laser in order to collect as much of the emitted radiation as possible. In this manner, more than 90% of the infrared light can be collected. Since the end of the integrator forms a uniform point of radiation emission, the light can be readily collimated by a relatively simple lens system.

A major drawback of the high-average-power arrays is the need for cooling them to cryogenic temperatures. Liquid nitrogen can be used, but almost all array systems use portable closed-cycle refrigeration units. The refrigerators are relatively compact, but are noisy, a source of vibration, heavy, and expensive. Also, they are subject to mechanical problems. The cooling problem can be eliminated by going to room temperature operation at a significant reduction in average optical power. Laser Diode Laboratories markets two arrays of this type that require no cooling and can be used in conjunction with an infrared viewing device.

As fate would have it, room temperature operation of a conventional GaAs array results in another problem—a reduction in sensitivity

when used in conjunction with the more sensitive infrared viewing systems. These systems respond far better to 850 nanometers than to the 905 nanometers of room temperature lasers made of GaAs. The cycle is completed when one realizes that cooled GaAs emits at the proper wavelength for use with the more sensitive viewing devices while still maintaining a relatively high degree of invisibility to the unaided eye. The wavelength problem has undergone massive study, and RCA has constructed a number of (AlGa)As arrays that emit at the wavelength of cooled GaAs even when operated at room temperature.

As might be expected, high-power arrays are quite expensive. Prices up to \$10,000 are typical for some of the very high power units, and, with such a high price tag, reliability is a major concern. RCA reports that after 1000 hours of operation one of its test arrays showed a decrease in optical output of 22%. That's good for GaAs, but may be of considerable concern to potential users requiring long periods of continuous duty.

FABRICATION OF OTHER SEMICONDUCTOR LASERS

Crystal growing techniques and sectioning of wafers into individual laser chips are relatively standardized procedures. But junction formation and the attachment of chips to heat sinks or headers are rather specialized operations. Some experimental semiconductor lasers are extremely easy to fabricate. In one report that described how to make samples for use in an electron-beam pumped-laser system, GaAs chips were simply cut from wafers and soldered to the end of a notched and polished machine bolt. A razor blade was used to cut the wafer, and the wafer itself was placed in a dish of alcohol to prevent chips from flying about.

Other semiconductor lasers are even easier to fabricate. For example, cadmium sulfide, which can be obtained in the form of thin platelets, is merely diced and the resultant lasers supported by vacuum grease or some other adhering substance. Lasers of cadmium sulfide can be excited by a beam of electrons or light from another laser.

However, some semiconductor lasers are particularly difficult to fabricate. For example, lasers pumped by light from a nearby injection laser must be precisely mounted in order to be efficiently illuminated by the excitation light. The same holds for discrete oscillator-amplifier pairs—two or more lasers operated in series.

Special injection-laser switching devices must be fabricated using integrated circuit techniques in order to place junctions in a variety of locations and planes within the material. In addition to the masking procedures used to form separate junctions, the units must be cleaved at appropriate locations.

COMMERCIAL INJECTION LASERS

Several companies, including Laser Diode Laboratories, RCA, and Texas Instruments, manufacture injection lasers for the commercial market. In addition, there are a number of firms and research laboratories that occasionally produce a limited number of devices for special contracts or proprietary applications. As is relatively common in the semiconductor industry, several companies that at one time manufactured injection lasers are no longer in the business.

Manufacturers currently offer more than fifty different single diodes and arrays. A few are available for less than \$20 and are well suited to the experimenter applications featured in the next chapter. All semiconductor components are high priced when production volume is small, but anticipated large-scale utilization of injection lasers should bring their prices down considerably in coming years.

IBM

In addition to a continuing research program at its huge T. J. Watson Research Center at Yorktown Heights, New York, IBM specializes in custom injection-laser arrays for military applications. The company has constructed arrays intended for use in covert illuminators, aerial reconnaissance systems, and rangefinders.

One of the first companies to produce an injection laser, IBM has devoted considerable effort toward improving the basic homojunction device. By using very large individual laser chips (as much as 50-thousandths of an inch wide) mounted in massive copper heat sinks, IBM manages to obtain very high powers from very compact arrays. Unfortunately, the arrays are plagued by the traditional problem of the relatively inefficient homojunction devices—brief lifetime.

A typical IBM injection laser mounted in a flat, copper heat sink is shown in Fig. 3-10. The H-shaped, double-sided heat sink permits heat from the diode, which is mounted between the central bar of the two H's, to be coupled out to a larger copper block.

The novel package design is admirably suited for high power-density arrays. As many as half a dozen or more lasers can be stacked one upon another and mounted between two copper blocks. A completed IBM laser array mounted within a combination pulse transformer and heat sink is shown in Fig. 3-11. The pulse transformer configuration of the array multiplies the current through the diodes by several times.

An IBM array installed in an illuminator system is shown in Fig. 3-12. The array emits light in two directions, hence the small collection mirror located directly behind the array. The mirror intercepts light that would otherwise be lost and redirects it back out the front of the illuminator along with the primary beam. The array also includes focusing optics and a high-current pulse power supply.

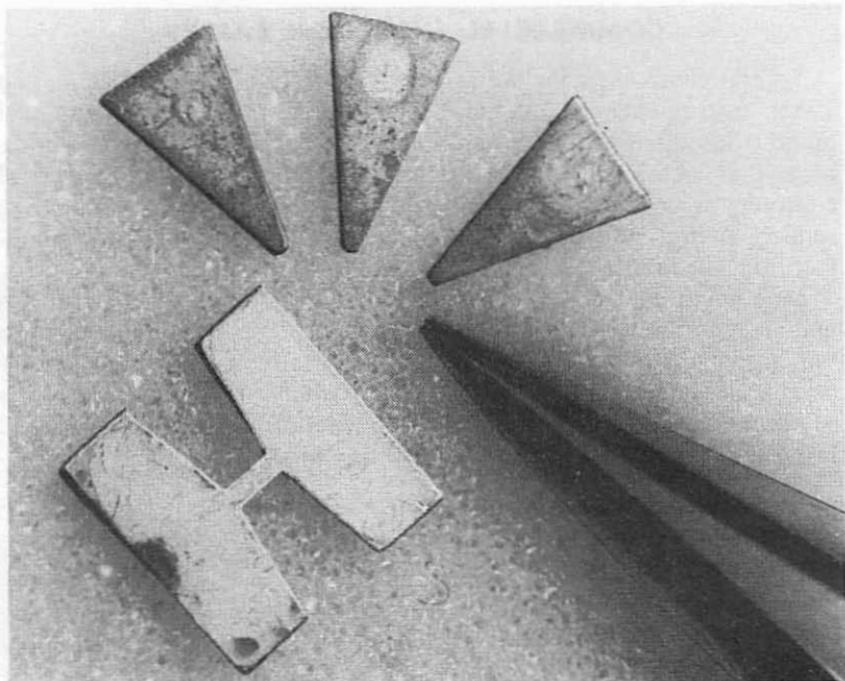


Fig. 3-10. Tweezers dwarf an IBM and three Sperry lasers.

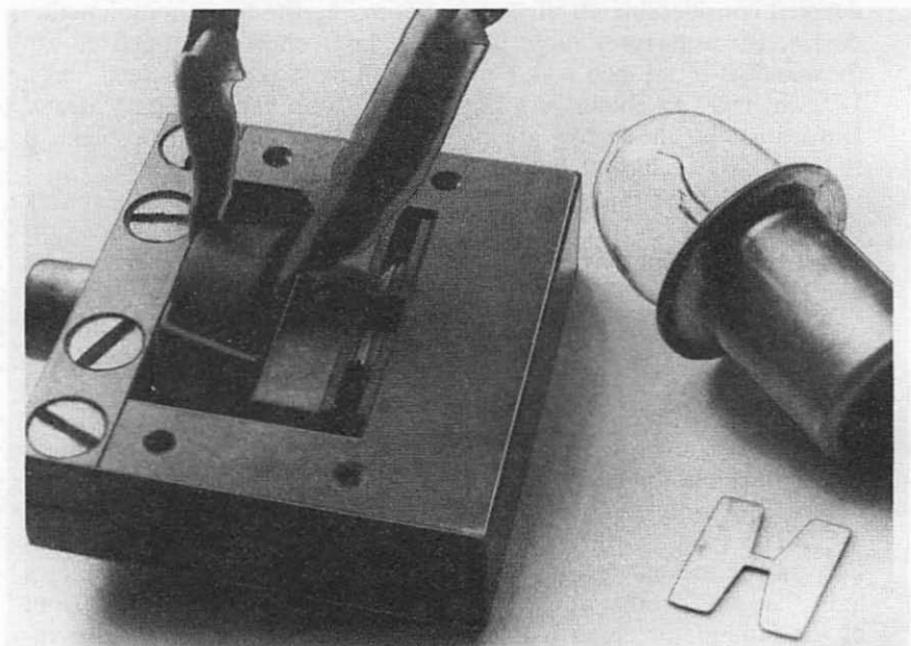


Fig. 3-11. Four IBM lasers stacked and installed in a heat-sink transformer.

A section of another IBM array is shown in Fig. 3-13. In this configuration, light is collected from each end of the laser array and directed toward separate lenses by gold-coated mirrors. Gold is used since it has a very high reflectance at the GaAs wavelength. The particular array shown in Fig. 3-13 is actually only a section of a larger system. The entire device includes four separate arrays and eight pairs of collection mirrors and lenses. A pulsed power supply is also included.

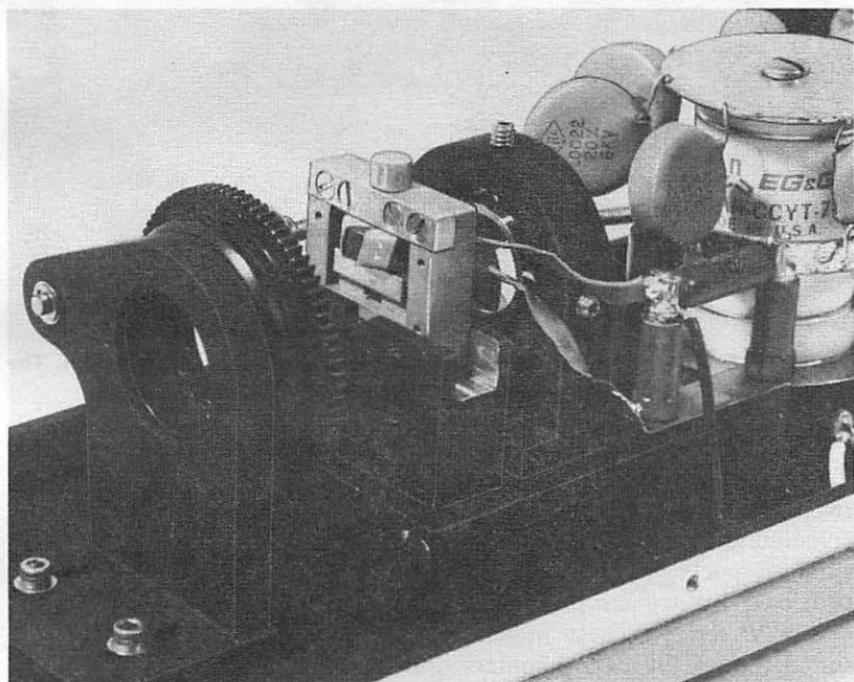


Fig. 3-12. IBM laser array mounted on a portable chassis containing optics and pulse power supply.

While IBM does not presently market injection lasers commercially, the company has made important contributions to the state of the art. In some cases, the contributions directly affect laser products offered by other companies.

Laser Diode Laboratories

A relative newcomer to the injection laser market, Laser Diode Laboratories was started by several engineers formerly from the laser production facility at RCA. Housed in a new facility in Metuchen, New Jersey, the company manufactures both single lasers and arrays. Additionally, the company offers custom fabrication services, covert illumination and viewing system design, and high quality GaAs material.

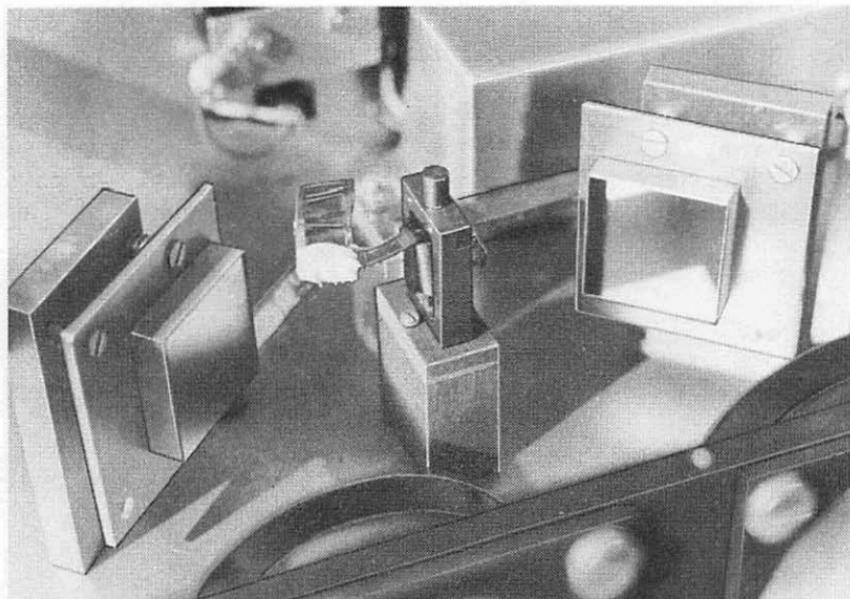


Fig. 3-13. Section of a large IBM illuminator containing four laser arrays. The mirrors permit light to be collected from both sides of the array.

The company's standard single laser package is shown in Fig. 3-14. The laser chip is coaxially located and is protected on both sides by two copper headers used as heat sinks. The headers are individually soldered to the chip and provide a higher degree of heat protection than similarly packaged lasers offered by other companies. The laser chip is protected by a clear plastic dust cover of excellent optical quality.

LD-20 series—These moderately priced lasers are extremely well suited for use by experimenters and design engineers. The lasers in the series are single heterostructure GaAs and emit at a typical wavelength of 900 nanometers. The LD-22 has a typical peak power of 6 watts at 15 amperes, and the LD-23 puts out 12 watts at 30 amperes. More power is available with the LD-24. Both lasers must not be driven at room temperature with a pulse more than 200 nanoseconds wide.

LD-200 series—For high-power applications, these laser arrays are a good choice. The LD-220, for example, has a *minimum* peak power of 200 watts at a drive current of only 40 amperes. Other arrays are available with powers ranging down to 60 watts.

RCA

In addition to individually packaged single heterostructure devices emitting at 905 nanometers, RCA offers a wide variety of arrays, near visible emitting (AlGa)As lasers, and covert illuminator designs.



Fig. 3-14. Assembled and disassembled Laser Diode Laboratories lasers.

RCA's standard package for individual laser chips is shown in Fig. 3-15. While quite sturdy, the package configuration differs from Laser Diode Laboratories design in that the lasing chip is slightly offset from the center of the package. The problem can be easily overcome in most applications, but makes for inconvenience when external optics are to be mounted in the same assembly that holds the laser. Several other package configurations are also offered by the company.

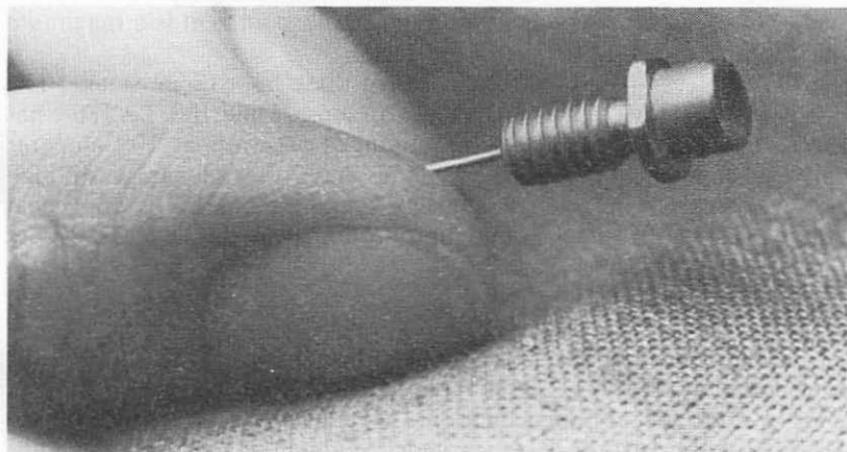


Fig. 3-15. RCA injection laser.

RCA manufactures a complete line of injection-laser arrays. The simplest arrays are laser stacks, which are standard packages containing two or three individual lasers stacked and soldered to one another. More complex arrays are available, ranging in power output from 25 to 300 watts and containing as many as 60 diodes in a strip configuration. A typical array of this type is shown in Fig. 3-8. The company also markets a line of special arrays intended for stacking into super arrays with power outputs of as much as 1850 watts peak and 30 to 40 watts average. Intended for use in covert infrared illumination systems, the huge arrays can be assembled from the separate smaller arrays or, to avoid the inconvenience of assembly, they can be purchased as a single unit.

Like Bell Telephone Laboratories, RCA has fabricated double heterostructure lasers that operate continuously at room temperature. Because of the encouragement the company has received from the military, it is expected that RCA will continue to expand its injection laser line.

40855-40866—This is by far the industry's largest variety of single diode lasers. All are single heterostructure devices (like all RCA lasers), and all have an efficiency of about 3%. Peak power outputs range from just under a watt to 15 watts at drive currents of from 10 to 75 amperes respectively. It should be noted that this line includes some of the lowest threshold currents available (about 4 amperes).

TA7867, TA8127, etc.—The industry's only line of GaAlAs injection lasers, these units emit at a typical wavelength of 850 nanometers. The TA8101, etc., are arrays of up to 48 diodes with a typical peak power of up to 300 watts.

TA7687, etc.—These are GaAs arrays containing up to 60 diodes and emitting up to 300 watts minimum. Driving current is a maximum of 25 amperes for all arrays in the series.

TA7764, etc.—This series consists of three laser diode stacks. The TA7964 and TA7765 each have two chips, while the TA7764 has three. The TA7765 delivers a minimum of 50 watts at 100 amperes forward current. While stacked diodes have the advantage of high power output from a small emitting area, the relatively poor heat sinking resultant from the configuration limits the duty cycle to about 0.02%.

Texas Instruments

The newest company to enter the injection laser market was the first company to market a commercial light-emitting diode. In fact, shortly after the announcement in 1962 of the first semiconductor lasers, Texas Instruments fabricated a number of experimental units on their own.

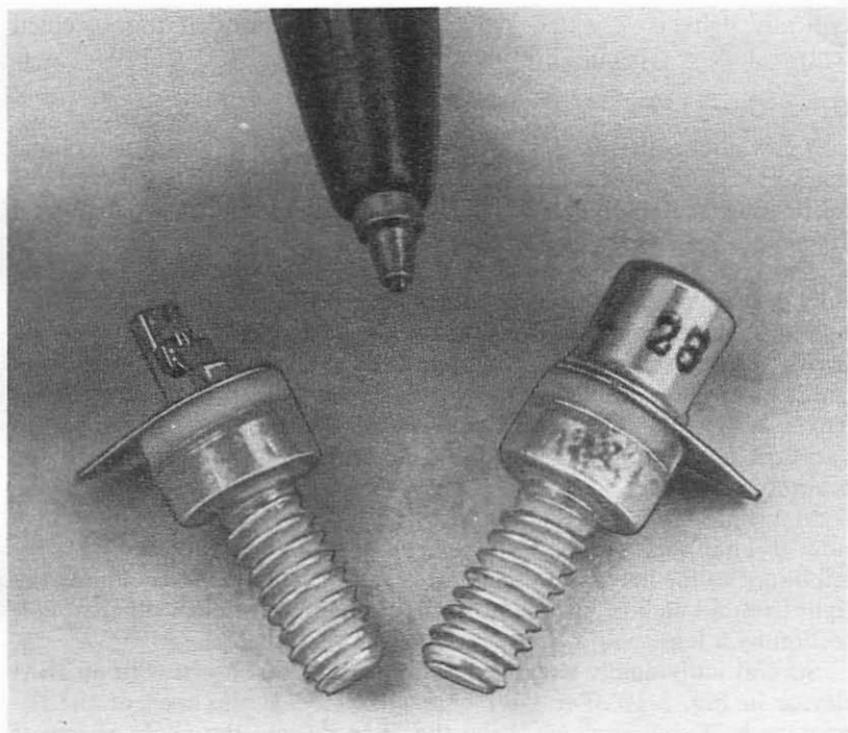


Fig. 3-16. Assembled and disassembled Texas Instruments lasers.

It is interesting to note that at a time when almost all injection laser research is aimed at perfecting heterostructure devices, Texas Instruments offers two lasers with diffused junctions. A typical laser is shown in Fig. 3-16. The package is sturdy and the chip is mounted centrally for ease of optical alignment.

Besides the two diffused lasers, Texas Instruments offers a single heterostructure device. The company is a major producer of light-emitting diodes, and it is logical to assume that if the market develops, their laser line will be expanded accordingly.

TIXL28—A single heterostructure laser, this component is well suited for general experimental applications. The maximum allowable pulse width of 800 nanoseconds is longer than that of any other commercial injection laser. Peak power is typically 7 watts at 25 amperes drive current.

TIXL29—This is one of the few diffused injection lasers on the commercial market. Peak power is typically 6 watts at a drive current of 40 amperes.

TIXL30—Intended for cryogenic operation at -153°C , this is also a diffused laser. At a peak current of only 3.5 amperes, the laser

typically delivers 7 watts. Wavelength of the laser at the specified temperature is typically 860 nanometers.

Other Companies

A few companies market specialized injection lasers for low volume markets. GaAs devices are marketed by Raytheon, and material for fabricating several types of injection lasers is offered by Bell and Howell.

The company whose research laboratory was the first to successfully develop a semiconductor laser, General Electric, offers a complete line of light-emitting diodes, but no longer manufactures injection lasers. For a few years the company did market several commercial units, but the small market apparently failed to justify the effort. Like Texas Instruments, General Electric's LED technology makes for an excellent base upon which to build a future laser product line if the market expands.

Monsanto and Sperry both previously produced lasers but have now discontinued production. Sperry made several interesting contributions to the field, including a fiber optic technique for coupling the light from a batch of lasers into a small area aperture for efficient collection by a lens.

Several individually packaged Sperry lasers are shown with an IBM device in Fig. 3-10. The laser chip is located at the apex of the triangular heat-sink package. Like the IBM design, the package makes for efficient heat sinking and collection of light from both ends of the laser. Lasers that are given a mirrored coating on one end may be mounted so that light is emitted in line with a perpendicular from the triangle base, while uncoated lasers could be mounted so that the emitted light emerges in two beams that are parallel to the base of the triangle.

A Monsanto laser is shown in Fig. 3-7. Besides standard GaAs diffused lasers, Monsanto offered several near-visible emitting GaAsP lasers. It is interesting to note that, like Texas Instruments and General Electric, Monsanto manufactures a broad line of LEDs. The company should be watched closely for a possible re-entry into the injection laser market if a change in conditions should warrant such a development.

Several other companies, including Seed Electronics and Korad, have marketed injection lasers. Seed appears to have left the market and Korad now specializes in high-power solid laser systems. While several universities, research laboratories, and semi-conductor manufacturers have fabricated sample quantities of injection lasers for experimental purposes, it is unlikely that many companies will enter the market until relatively large scale consumer and military markets are created.

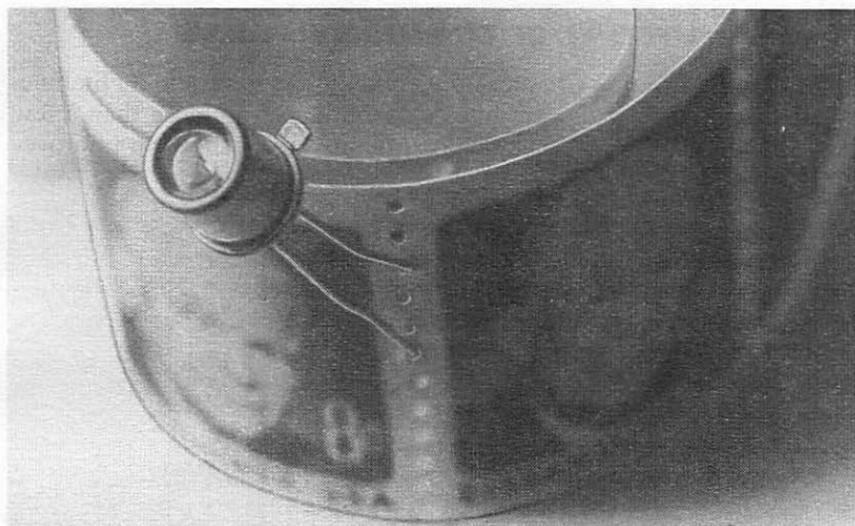


Fig. 3-17. Monsanto laser. Note the light reflecting from front surface of chip.

Laser Specifications

We will conclude this section with some remarks about injection laser specifications. As with most other electronic components, particularly semiconductors, there is often disagreement between industry and user with regard to device specifications. Injection lasers are no exception.

Early commercial lasers rarely met published specifications because of rapid degradation. Also, a good many complaints came from users who had little or no knowledge about pulsing the devices. It was quite common for lasers to be driven with far more than the maximum current ratings allowed and at intolerable duty cycles as well.

Laser specifications of recent years should generally be reasonably accurate. The greatly improved lifetime of single heterostructure devices insures that the manufacturers's quoted specifications will remain accurate considerably longer than they did with homostructure devices.

Still, there are a few erroneous specifications in the industry even today. One diffused laser evaluated for this book refused to lase when driven at the maximum pulse width and current allowed by the data sheet. A letter brought a quick telephone reply from an engineer who pointed out that the data sheet was in error and that the laser would operate if driven at a longer pulse width (because of an exceptionally long delay time). It did.

It is usually good practice to view manufacturers' ratings and specifications carefully. But always be sure to use care when operating the laser, for mistakes on the part of the user are often the cause of complaints about specifications.

LIFETIME OF COMMERCIAL LASERS

As was discussed in Chapter 2, injection lasers have a finite lifetime. While homostructure devices have a useful life of no more than a few hundred hours at best, single heterostructure lasers show an improvement by a factor of ten.

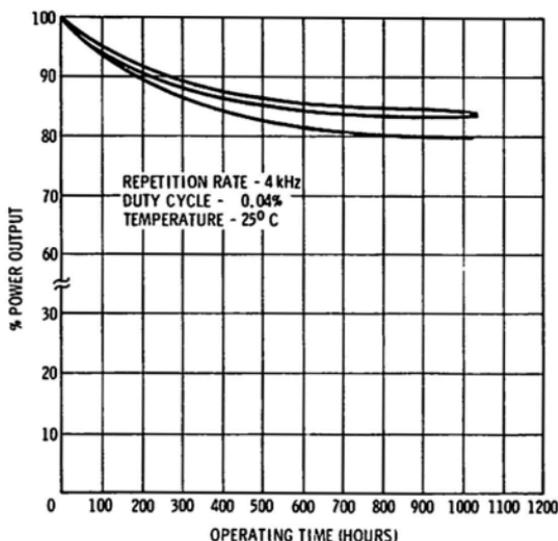


Fig. 3-18. Degradation in a single heterostructure laser.

Some of the most complete lifetime information has been accumulated by RCA under several army and air force contracts. Additionally, the company continually runs life tests on several racks containing dozens of lasers. Viewing an operating test rack through an image converter in order to observe the laser emissions is an eye-catching sight. In the degradation studies, RCA has investigated many aspects of the lifetime problem. Particular attention has been given junction formation and crystal inhomogeneities. The studies have found that high quality GaAs material is essential to the fabrication of lasers with long lifetimes. Other aspects of the studies included the effect of facet coatings, temperature, laser length, pulse width, and optical confinement on damage thresholds. Fig. 3-18 shows the power output of several SH lasers over a period of 1000 hours. At one watt peak output per mil of junction width (i.e., 6 watts peak for a 6 mil wide laser), degradation in output was less than 20%. The lasers were operated at a repetition rate of 4 kilohertz with a 100-nanosecond pulse width, a reasonable duty cycle (0.04%) for many applications.

Pulse Generators, Modulators, and Power Supplies

The double-heterostructure injection laser will lase when connected to an ordinary flashlight cell. But until these devices become commercially available, practical applications are limited to conventional diodes that require very rapid current pulses for room temperature operation. The requirement for a pulse generator is not as serious as it may seem, for conventional lasers operated in a pulsed mode offer considerably higher peak powers than are available from the double-heterostructure device. And furthermore, as we shall soon see, a wide variety of pulse generation techniques are available.

PULSE REQUIREMENTS

As explained in Chapter 3, the injection laser is characterized by the requirement for a minimum operating current, the threshold (I_{th}), for the onset of stimulated emission. Since current below the threshold contributes to diode heating and results in only low-power incoherent emissions, the ideal operating pulse would be square, with zero rise and fall times. Such a pulse would result in a highly efficient operating arrangement.

Unfortunately, the ideal operating pulse is never achieved in practice, but a variety of interesting pulse generators that come close have been developed. Nearly all these generator schemes consist of a voltage

storage element which, as shown in Fig. 4-1, discharges through the laser diode when a fast switching device is activated. When total resistance of the switch and laser diode load is small, very high current pulses are produced.

Capacitors and transmission lines are commonly employed as storage elements. While the transmission line can be designed to provide almost square pulses, the simplicity of the capacitor makes it the usual choice. Selection of a switching device is a more difficult problem. Besides having to withstand very high peak currents, the switch must be capable of switching on within about 50 nanoseconds or less.

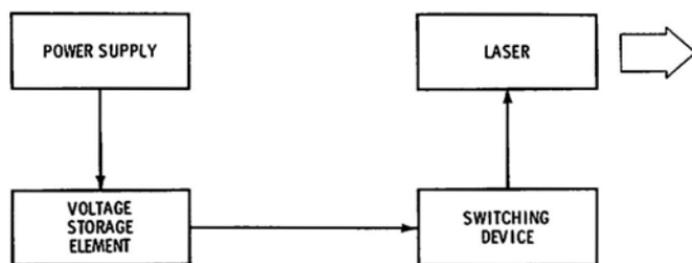


Fig. 4-1. Basic laser pulse generator.

While pulse width and peak current of a pulse generator may be easily calculated in advance of actual circuit assembly, errors may be introduced by inaccurate knowledge of the dynamic characteristics of the switching device. Conventional device specifications are often meaningless when applied to this type of pulse generator. Nevertheless, it is helpful to consider the operation of a hypothetical circuit by a few simple manipulations of Ohm's Law.

If the dynamic resistances of a switching device and laser diode are two ohms and one ohm respectively, and if 30 amperes are required to operate the laser, then according to $E = IR$ the operating voltage of the circuit must equal 90 volts. Pulse width may be approximated by simply multiplying the value in farads of the storage element times the total resistance of the laser and switching device. For example, if the storage element has a value of $.01 \mu\text{F}$, the pulse width would be 30 nanoseconds.

In practice, pulse width may be affected by undesirable stray inductance. For this reason, lead lengths between all components carrying the high current must be kept as short as possible. An alternative arrangement is to employ a carefully designed transmission line. If such a line is used, a laser may be located a foot or more away from its pulser.

In order to observe the pulse shape of a particular laser pulser, a small noninductive resistor or current-monitoring transformer is often

placed in series with the laser diode. A high-speed oscilloscope can then be connected directly across the terminals of the current monitor in order to observe the output characteristics of the pulser. In the case of the small resistor, for example, application of Ohm's Law shows that voltage on the scope equals current in amperes when the resistor has a value of one ohm. Resistors of 1/10 ohm are frequently used in order to reduce current loss.

An ordinary 1/2-watt carbon resistor may have sufficiently low inductance for most applications, but much lower inductance can be obtained by connecting ten resistors in parallel. Fig 4-2 shows a 1/10-ohm monitor made up of a parallel array of ten 1-ohm resistors. The resistors are soldered to two squares of copper foil that have been drilled with appropriately spaced holes.

Since the most carefully designed pulse generator might still produce negative transients or backswing, a fast, computer-grade diode should always be connected across the laser diode as shown in Fig. 4-3. The diode protects the laser by providing a path for the undesirable backswing. The technique is fully effective only if the diode is mounted as close as possible to the laser—and may not be necessary if a good oscilloscope connected across the small current-monitoring resistor in series with the laser diode shows a clean pulse with no negative components.

If a particular laser requires more current than is readily available from a pulse generator, a small transformer with a low turns ratio

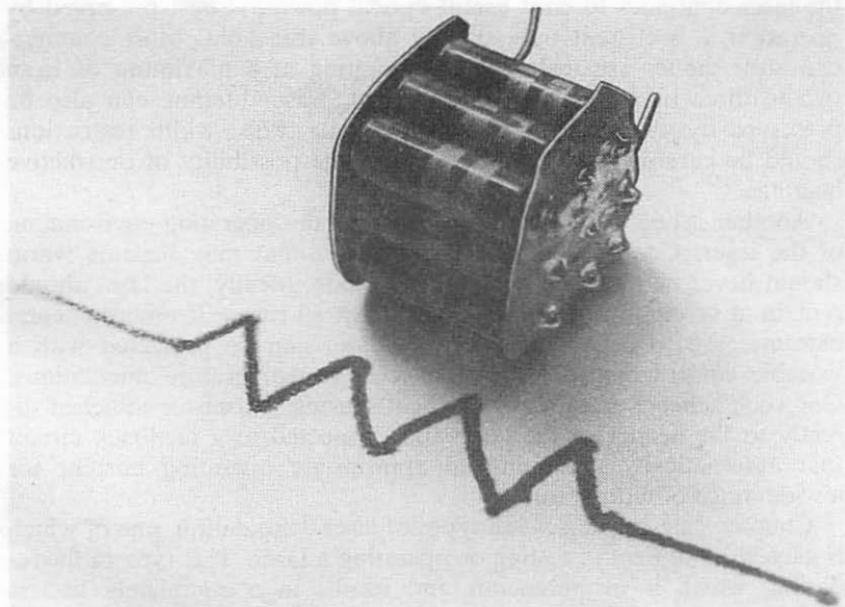


Fig. 4-2. Current monitor made from ten 1-ohm resistors.

may be connected to the laser. An IBM laser array mounted within such a transformer is illustrated in Fig. 3-11. As few commercial transformers are ideally suited for this purpose, custom design and construction may be necessary. Since very small turns ratios are involved (as with the IBM laser array, the transformer mount itself may be the secondary), mechanical considerations are straightforward. But in order to optimize a particular transformer configuration, tests with a dummy load, such as a 1N4004 diode, in place of the laser should be carried out with a high-speed oscilloscope. In this manner, peak current and pulse characteristics can be monitored before operation with the laser itself.

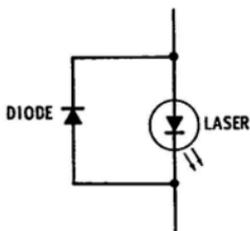


Fig. 4-3. Laser protection diode.

LASER DEGRADATION

The effective lifetime of a laser diode, that is the time for which the laser continues to emit useful optical power, is best preserved by operation at a current only slightly above threshold. Most commercial laser diodes are restricted to operation at a maximum of from two to three times the threshold current. Laser lifetime can also be preserved by operation at a low duty cycle. Pulse-width restrictions should be carefully enforced because of the possibility of destructive heating.

Another aspect of temperature concerns the operating environment of the laser. Components of a laser pulser that may become warm should never be mounted near a laser diode. Ideally, the laser should remain at or close to room temperature at all times. If environmental extremes are to be encountered, the laser can be protected with a variable current control to compensate for temperature fluctuations. One such scheme employs a tiny heat-sensing thermistor attached directly to the header of the laser and connected to a feedback circuit that automatically maintains an appropriate operating current for a wide range of temperatures.

Chapter 2 described several types of laser degradation, one of which is caused by neglect in testing or operating a laser. This type of degradation, which is instantaneous and results in a completely useless device, occurs when maximum specified operating parameters of a

particular laser are exceeded. It may occur when a laser diode is connected to a conventional pulse generator, a direct current source, or even an ohmmeter. In all these cases, the high concentration of heat resultant from continuous operation for only a microsecond or so is generally sufficient to destroy the laser chip and cause it to take on the appearance of a burnt cinder when observed through a microscope.

The remainder of this chapter describes in detail several types of pulse generators that are well suited to the operation of commercial laser diodes at generally specified operating parameters. Application of one or more of these pulse generators to a specific laser requirement will insure optimum performance and lifetime from most commercial laser diodes.

PULSE GENERATORS

A number of interesting pulse generators will fulfill the requirements for operating a laser diode. Several types of generators are specialized and will not be included here. They include mechanical switching devices, mercury-wetted relays, and pressurized spark gaps. The first two devices are capable of producing pulses that are almost square when used with an appropriate transmission line. However, their relative mechanical complexity and limited repetition rate generally make them suitable only for laboratory research. The spark gap, a high-voltage device, is also characterized by a limited repetition rate.

More practical pulse generators are those that use semiconductor or cold-cathode discharge tube switching. A number of these devices, all of them entirely suitable for general purpose experimentation, will be described.

Four-Layer Diode

The simplest semiconductor pulse generator utilizes a four-layer diode as a switching element. Sometimes called the Shockley diode after its inventor, this pnpn device is essentially a silicon controlled rectifier (SCR) without a gate connection. Four-layer diodes normally exhibit very high resistance, but rapidly break down and conduct in the forward direction when exposed to a particular voltage level. This characteristic is called negative resistance. Several semiconductor manufacturers (Motorola, ITT, and American Power Devices) offer these interesting diodes in a wide variety of switching voltages..

The negative-resistance characteristic of the four-layer diode makes it an ideal candidate for a relaxation-oscillator laser pulse generator. Most readers are probably familiar with the relaxation oscillator, as it is the circuit commonly employed to flash small neon lamps, themselves negative-resistance devices. Referring to Fig. 4-4, capacitor C1

is charged through resistor R1 until the switching voltage of the four-layer diode is reached. The diode then switches "on" and discharges the voltage stored in the capacitor through the laser diode. The capacitor again charges to the switching voltage and the process repeats itself continuously. Since the "on" resistance of the four-layer diode is very small (less than an ohm), a high-current pulse is produced.

With the component values shown in Fig. 4-4, an RCA 40856 laser was operated at a repetition rate of up to 20 kHz and more by simply varying the value of the charging resistor. The current pulse had an excellent shape with an extremely fast rise time of less than ten nanoseconds.

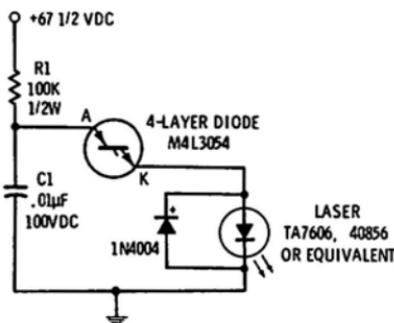


Fig. 4-4. Basic four-layer diode laser pulser.

The circuit, which is adapted from a similar version published in *Electronics* magazine (F. M. Mims, "Relaxation Oscillators Provide Compact Drive for Injection Lasers," July 19, 1971, p. 88), can easily be assembled on a small perforated or etched circuit board. But since there are so few components, the circuit can be wired point-to-point as a self-supporting modulator unit. While the former is quite adequate, the latter is to be preferred as the ultimate means for reducing to an absolute minimum the length of leads carrying the high-current pulse. The small size of the circuit makes it possible to install it in a very compact enclosure. A prototype built into an aluminum cylinder only 4.5" × 0.5" in size, including battery and lens, is shown in Fig. 7-12.

The capacitor and resistor may be commonly available devices with the ratings shown in Fig. 4-4, but the four-layer diode must be checked to verify switching voltage before using the circuit to pulse a laser. This is easily done with a general-purpose oscilloscope and a test jig composed of the basic relaxation-oscillator circuit. The laser diode should not be connected to the test jig; substitute a common diode or connect the four-layer diode directly to ground. With the oscilloscope connected across the capacitor and voltage supplied to the circuit, a modified sawtooth waveform will appear whose amplitude is equivalent to the switching voltage of the four-layer diode under test.

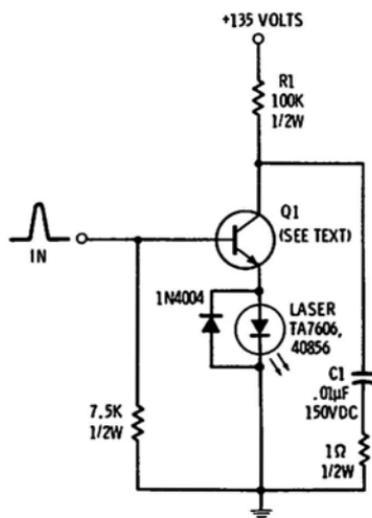
A voltage-calibrated oscilloscope is preferred for this test, but a fairly close approximation of switching voltage can be obtained by connecting the test jig to a source of variable voltage and placing it near an ordinary radio. As the voltage is slowly raised, a point will be reached at which the radio will emit a tone. The tone indicates that the circuit is oscillating and the voltage being applied will be slightly higher than the switching voltage for the four-layer diode under test.

Since four-layer diodes are available with switching voltages of from 8 to 200 volts, the basic circuit shown in Fig. 4-4 may be used to produce a range of pulse amplitudes. When a 40856 laser is being operated, a four-layer diode with a switching voltage of about 18 to 22 volts will produce up to ten amperes, the maximum current with which the laser can be pulsed. While increased capacitance will provide a wider current pulse and increase the average power from the laser, care must be exercised to insure that the duty cycle of the laser and the average current rating of the four-layer diode are not exceeded.

Avalanche Transistor

While the four-layer diode provides the simplest laser pulse generator, the most economical generator employs an avalanche transistor as a switching device. Besides low cost, the avalanche transistor approach offers the advantage of higher peak current. A basic circuit employing such a transistor is shown in Fig. 4-5. In operation, C1 charges through R1 to a maximum voltage slightly below the breakdown voltage (BV_{cex}) of Q1. An external pulse applied to the base of Q1 triggers Q1 into breakdown, and the voltage stored in C1 discharges through Q1, R3, and the laser diode.

Fig. 4-5. Basic avalanche-transistor laser pulser.



Voltage V_{cc} should be 10 or 15 volts below BV_{cex} for Q1. The value of R1 should be such that current through Q1 does not result in self-avalanching. Protection from self-avalanching is assured if

$$R1 > \frac{V_{cc}}{I_h} \quad 4.1$$

where,

I_h is the holding current of Q1.

The circuit can be triggered by a relatively fast pulse with an amplitude of several volts from a conventional pulse generator. Another technique is to employ another avalanche transistor in a simple relaxation oscillator. While such an oscillator is ideal for triggering the basic pulse generator, it is also well suited to driving laser diodes itself.

Single Transistor Relaxation Oscillator

A simple relaxation oscillator employing an avalanche transistor is shown in Fig. 4-6. Operation of the circuit is unchanged from the four-layer diode pulse generator described above. C1 charges through R1 until the breakdown voltage of Q1 is reached. R2 provides base bias to Q1. When Q1 switches "on", the voltage stored in C1 discharges through Q1, the laser diode, and R3. R3 serves as a current monitor and may be omitted from the circuit if the peak current rating of the laser diode is not exceeded.

Several semiconductor manufacturers market avalanche transistors that are especially designed for high-current, fast-rise-time pulsers. As these transistors are available at fairly high breakdown voltages, their use is desirable in laser pulsers operating lasers that require as much as 20 amperes for proper operation. But these special avalanche transistors are relatively costly and it is possible to obtain good performance from many common silicon npn switching transistors operated in an avalanche mode. Since the pulse generator shown in Fig. 4-6 can be

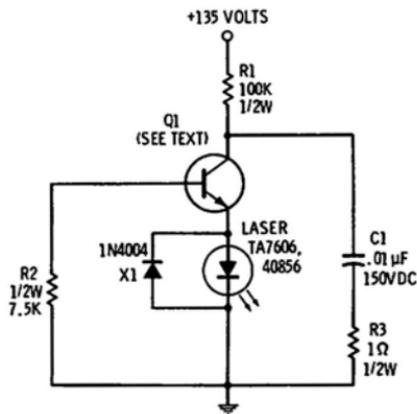


Fig. 4-6. Avalanche-transistor relaxation-oscillator pulse generator.

quickly constructed for only a few dollars with such a transistor, it is highly recommended as a first project laser pulser.

The pulse generator can be assembled on a small perforated circuit board using point-to-point wiring, but an etched circuit board is to be preferred for ease of construction and optimum performance. Whatever technique is used, keep all leads carrying the high current as short as possible. Also, mount Q1, C1, R3, and X1 flush with the circuit board. The laser diode should be mounted directly to the board, as shown in Fig. 4-7.

Literally dozens of transistor types will operate in the circuit. In order to control peak current through the laser diode, a transistor must be selected for proper BV_{cex} using a procedure identical to that described for the four-layer diode. Besides a test jig and oscilloscope, a batch of common npn silicon switching transistors will be required. The amplitude of the sawtooth wave that appears when the oscilloscope is connected across C1 is equivalent to the BV_{cex} of the transistor under test. The graph of peak current for a range of BV_{cex} in Fig. 4-8 permits the circuit to be matched to a variety of commercially available lasers by the procedure presented for the four-layer-diode pulse generator. If several lasers are to be used with the pulser, it is a good idea to keep several selected transistors on hand in small coin envelopes. Since the individual BV_{cex} can be marked on each envelope, transistors can be rapidly switched from circuit to circuit.

A completed version of the pulser is shown in Fig. 4-9. The original unit was featured in *Popular Electronics* magazine (October 1971)

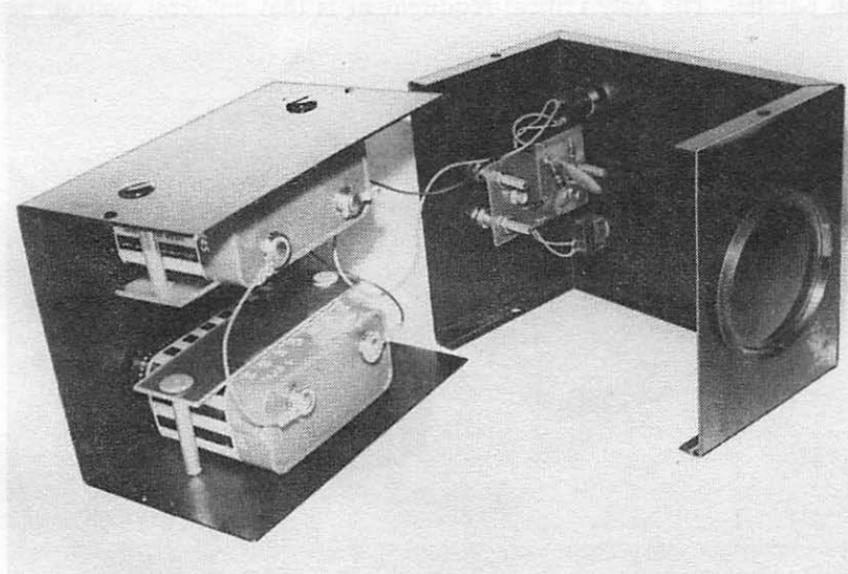


Fig. 4-7. Internal view of *Popular Electronic's* laser.

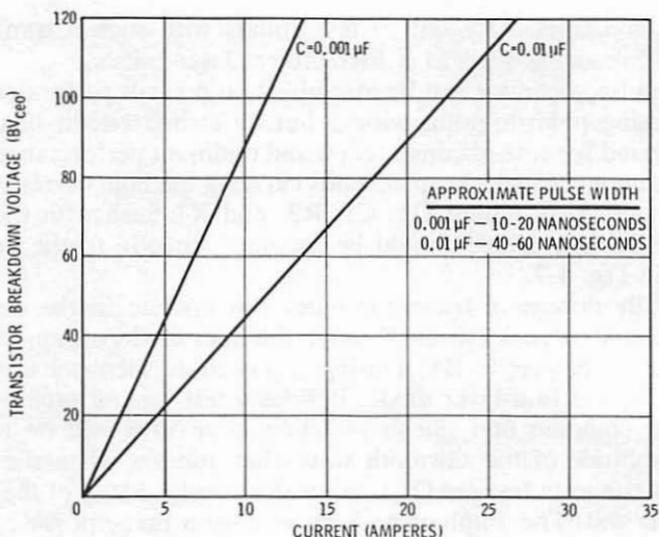


Fig. 4-8. Peak current versus avalanche breakdown voltage.

and operated an RCA TA7606 laser at a repetition rate of about 300 Hz. Peak current through the laser was 10 amperes and pulse width, as shown in Fig. 4-10, was about 50 nanoseconds.

Parallel Operation of Avalanche Transistors

If more current is needed, two or more transistors may be operated in parallel. The only critical requirement is that collector voltage be

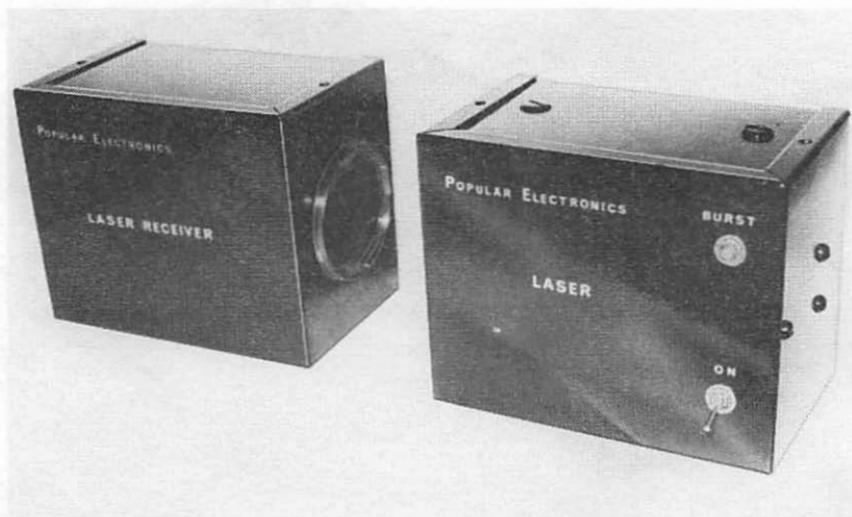


Fig. 4-9. Popular Electronic's laser and receiver.

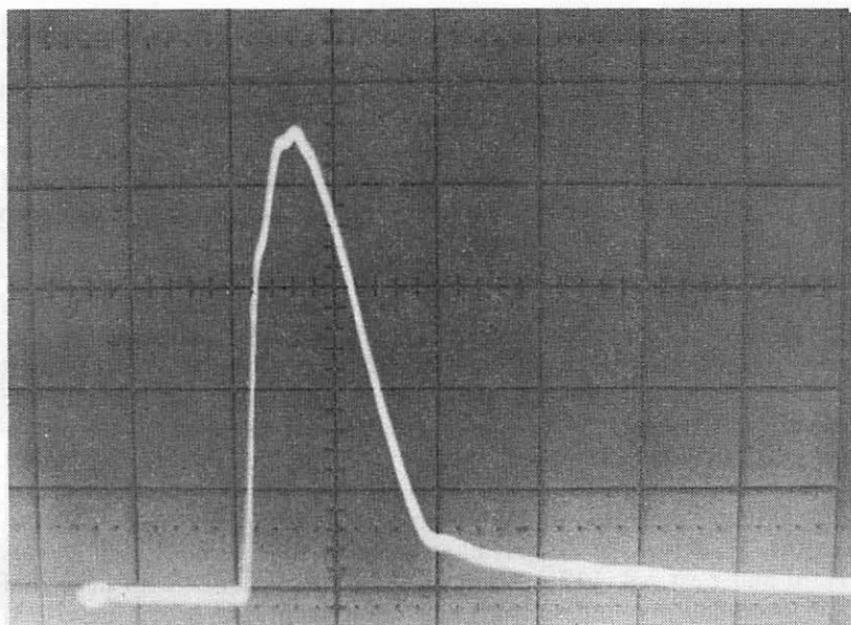
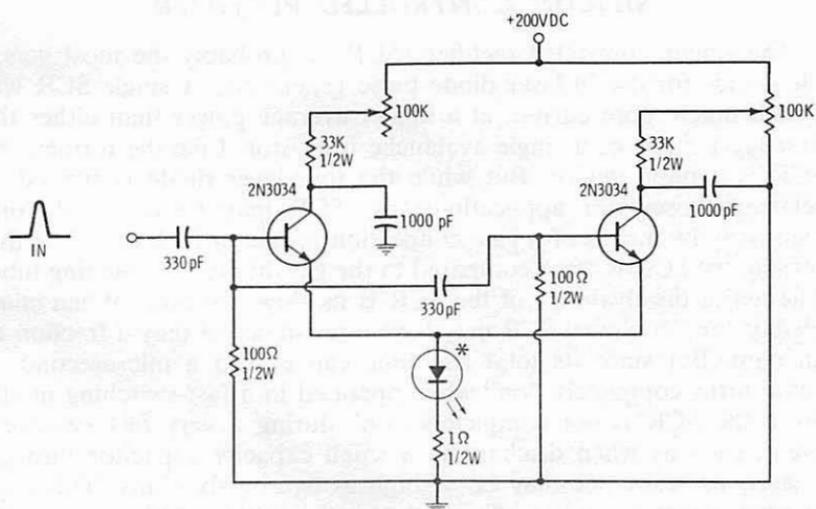


Fig. 4-10. Current pulse produced by avalanche-transistor pulse generator (2 amperes/vertical division; 50 nanoseconds/horizontal division).



* USE LASER CAPABLE OF OPERATING WITH 30-AMPERE PULSE (WIDTH IS LESS THAN 50 NANoseconds)

Courtesy Electronic Design

Fig. 4-11. Laser pulser using parallel avalanche transistors.

independently adjustable for each transistor to insure coincidental switching.

A circuit employing two avalanche transistors in parallel is shown in Fig. 4-11. The operation is essentially the same as the single transistor circuits we have just discussed—a capacitor is discharged through the laser diode load. The circuit will not go into oscillation by itself but requires a small input pulse to trigger the two transistors into avalanche.

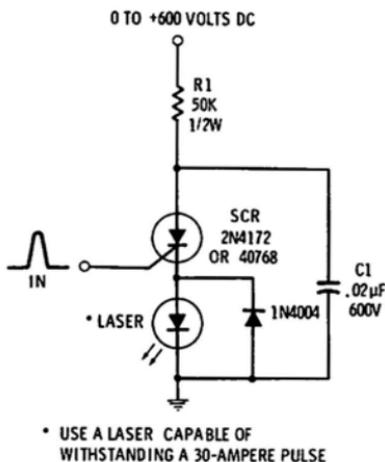
Although all the avalanche transistor circuits just described operated quite well with selected silicon switching transistors, use of a standard avalanche transistor can greatly increase peak current. For example, the 2N3507 avalanche transistor has a typical BV_{cex} of about 140 volts and will produce up to 40 amperes when operated in the circuit shown in Fig. 4-6. Higher currents are made available by selecting 2N3507s with higher than average BV_{cex} . An interesting report describing the operation of four 2N3507s in parallel to produce nearly 200 amperes appeared in the November 14, 1966 edition of *Electronics* (H. E. Brown, et al. "Avalanche Transistors Drive Laser Diodes Hard and Fast," p. 137). A single 200-ampere pulser with laser and lens occupied a volume of only one cubic inch! The article described an array of three pulsers and lasers for use in an experimental optical ranging application.

SILICON CONTROLLED RECTIFIER

The silicon controlled rectifier (SCR) is probably the most versatile device for use in laser diode pulse generators. A single SCR will switch much more current at a higher average power than either the four-layer diode or a single avalanche transistor. Like the former, the SCR is a pnpn device. But while the four-layer diode is limited to relaxation oscillator applications, the SCR may be triggered "on" externally by means of a gate connection to one of its layers. For this reason, the SCR is often compared to the gas thyatron switching tube. The major disadvantage of the SCR is its slow rise time. When completely "on," a typical SCR may have a resistance of only a fraction of an ohm. But since its total rise time can exceed a microsecond, it never turns completely "on" when operated in a fast-switching mode. Since the SCR is not completely "on" during a very fast switching event, such as when discharging a small capacity capacitor through a laser, its resistance may be as high as five or six ohms. This high resistance reduces pulser efficiency, stretches pulse width, and greatly increases the amount of voltage needed to obtain a laser-operating current. While four-layer diode and avalanche transistor pulsers will operate from as little as 50 volts, typical SCR pulsers require more than 200 volts.

A simple SCR pulser is shown schematically in Fig. 4-12. In operation, C1 is charged through R1 and discharged through the SCR and the laser diode when a positive pulse is impressed on the gate of the SCR. With the component values shown, the circuit will produce a peak current of about 30 amperes in a 200-nanosecond pulse. The power-supply adjustment permits peak current to be adjusted for the individual laser used in the circuit.

Fig. 4-12. Basic SCR laser pulse generator.



Many types of pulse generators, commercial or otherwise, may be used to supply the trigger pulse to the SCR gate. The only requirement is that the pulse have a relatively fast rise time and a minimum amplitude of at least five volts.

Not all SCRs will operate properly in a laser pulser circuit. While the SCR may switch "on" in a particular circuit, its operating parameters may be far too slow for safely pulsing current through the laser. Furthermore, it may not be capable of withstanding the rapid current surges of a laser pulser circuit.

A few semiconductor manufacturers make SCRs especially designed for injection laser pulsers. RCA manufactures the 40768, an SCR designed, according to the company, to provide long and trouble-free service in laser pulsers. The 40768 will switch currents of up to 75 amperes. Unfortunately, the device is relatively expensive, and good performance may be obtained with less costly SCRs. Both the Motorola 2N4172 and the RCA 40553 are economical and recommended for use in SCR pulser circuits.

An excellent booklet on SCR laser pulsers is available from RCA. Entitled "Solid-State Pulse Power Supplies for RCA GaAs Injection Lasers," it describes a variety of practical pulser circuits. To obtain a copy of the booklet, try an RCA distributor or write RCA, Solid

Unijunction-Transistor SCR Trigger Circuit

A unijunction-transistor relaxation oscillator suitable as a trigger for the basic SCR pulse generator is shown in Fig. 4-13. The oscillator consumes little power, is inherently stable, and can be assembled for a relatively low cost. The oscillator period T may be calculated from the equation

$$T = \frac{1}{RC \ln(1/1-\eta)} \quad 4.2$$

where the intrinsic standoff ratio η has a value between 0.51 and 0.82. In actual practice, both $R1$ and $C1$ are often made variable for convenient adjustment of T .

Although the unijunction oscillator will easily operate at a repetition rate of several thousand Hz, the RC time constant of the basic SCR circuit limits the maximum operating rate to several hundred Hz. The pulse generator may be operated at a higher duty cycle, but, since the SCR charging capacitor will be incompletely charged when the SCR is turned "on," peak current may be significantly less.

It might appear that the circuit can be made to operate at a higher duty cycle and still preserve peak current by simply reducing the value of $R1$ in the basic SCR pulser. But this is unacceptable since there might then be sufficient current through $R1$ to keep the SCR on after a single pulse has been applied to its gate. Besides the possibility of overheating the SCR, the laser diode might be damaged. An interesting solution to this repetition rate limitation will be described shortly, but first a few more SCR switching techniques will be presented.

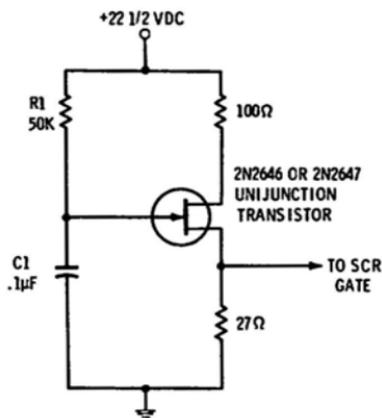


Fig. 4-13. Unijunction-transistor oscillator.

Four-Layer Diode SCR Trigger Circuit

Since the switching speed of an SCR is in part dependent on the rise time of the pulse applied to the gate, much faster switching can be achieved with a four-layer-diode relaxation oscillator than with the unijunction technique. The laser diode pulse generator shown in Fig. 4-4 will serve this purpose admirably and is shown connected to a basic SCR pulse generator in Fig. 4-14. Adjustment of R1 will vary the repetition rate of the pulser. The four-layer diode oscillator alone will operate at a repetition rate of many kilohertz, but, like the unijunction technique, the complete pulser is limited to a maximum rate of only a few hundred hertz.

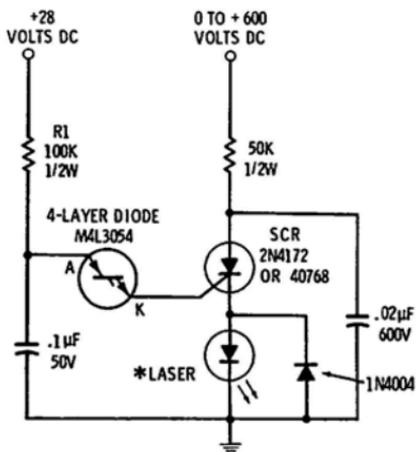


Fig. 4-14. Four-layer diode trigger for SCR pulse generator.

R1 - VARY TO ADJUST REPETITION RATE
* USE A LASER CAPABLE OF WITHSTANDING
A 30-AMPERE PULSE

Diac SCR Trigger Circuit

A *diac* is a three layer pnp device. Unlike the transistor, also a three-layer component, the diac has only two terminal connections. When a voltage applied across the device reaches a certain point, the diac avalanches and turns "on." In this respect, the operation of a diac is identical to that of a four-layer diode. But unlike the four-layer diode, the diac can be switched on without regard to the polarity of the switching voltage. For this reason, it is an important semiconductor for alternating current applications.

The diac is easier to manufacture than the four-layer diode and is, therefore, relatively inexpensive. While typical four-layer diodes cost more than several dollars each, a diac can be purchased for less than 50¢.

A diac relaxation oscillator connected to a basic SCR pulser is shown in Fig. 4-15. The low cost of the diac makes this pulser the

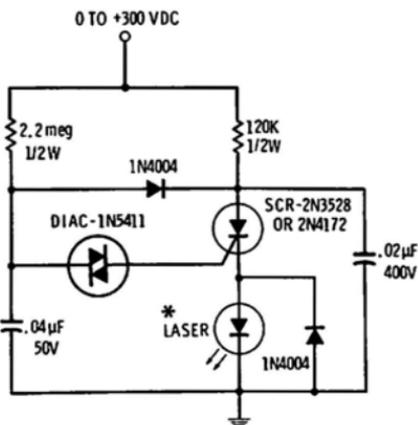


Fig. 4-15. Diac trigger for SCR pulse generator.

* USE A LASER CAPABLE OF WITHSTANDING A 30-AMPERE PULSE (TA-2628 OR EQUIVALENT)

most economical of all those which employ an SCR. As with the previous circuits, the diac SCR pulser can be assembled in less than an hour on a small perforated board. Remember to keep leads carrying the high current as short as possible.

SCR Fast Charging Circuit

The performance of the two SCR pulser techniques just described can be improved dramatically with the addition of a simple transistor speed-up network. An explanation of this circuit, shown in Fig. 4-16, has been provided by R. A. Hunt: "Transistor Q2 reduces the RC time constant by supplying a low-resistance path through which the capacitor can charge up to the applied voltage. When the SCR, Q1, is triggered, C1 discharges, and the resulting voltage drop across the diode reverse-biases the base-to-emitter junction of Q2, leaving only

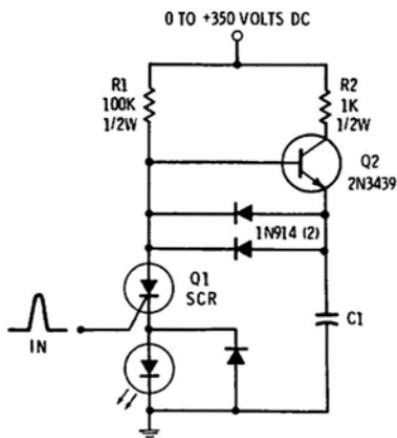


Fig. 4-16. Fast charging circuit for SCR laser pulse generator.

R1 between the SCR and the power supply. Since R1 satisfies equation 1, the SCR shuts 'off' when C1 has discharged.

"At this point, Q2 turns 'on' because there is no longer enough voltage across the diode to keep it 'off,' and C1 can charge up very rapidly through the R2 and Q2. Adding Q2 increases the maximum repetition rate of the circuit from 100 Hz to 10kHz." ("Laser Diodes Need High-Current Drivers," *Electronic Design*, Sept. 20, 1970, p. 50. Used with permission.)

TWO GENERAL-PURPOSE SCR PULSE GENERATORS

The fast charging circuit just described makes for a highly functional, general-purpose pulse generator when used in conjunction with a unijunction or four-layer-diode trigger source. An assembled unit using a unijunction trigger is shown in Fig. 4-17. The pulse repetition rate is continuously adjustable from 1 Hz to 10 kHz. Peak current, which may be adjusted downward by decreasing input voltage, is about 30 amperes. Pulse width at half current points is 150 nano-seconds.

The unit may be readily duplicated using point-to-point wiring. Component values are shown in the circuit diagram presented in Fig. 4-18, and a close-up view of the suggested parts layout is shown in Fig. 4-19. Parts layout is actually unimportant so long as the leads carrying the high current are kept as short as possible.

The prototype pulse generator described here is intended for tests with a variety of lasers. But since the long clip lead for the connec-

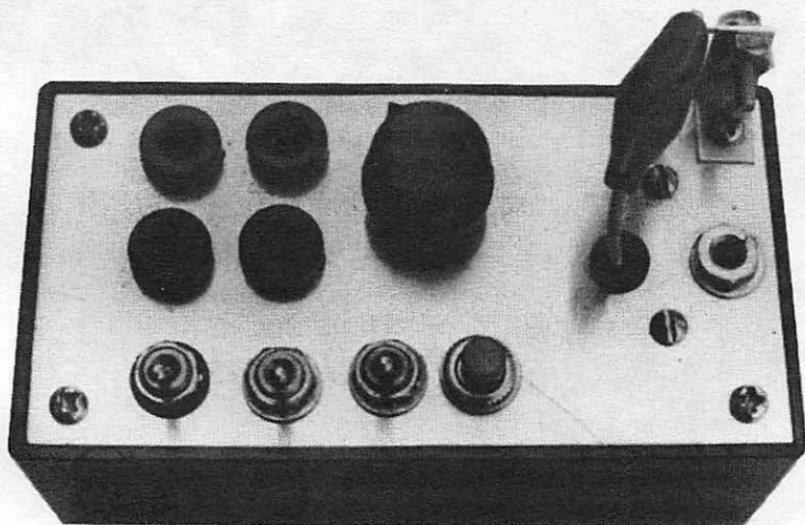


Fig. 4-17. General-purpose SCR laser pulse generator.

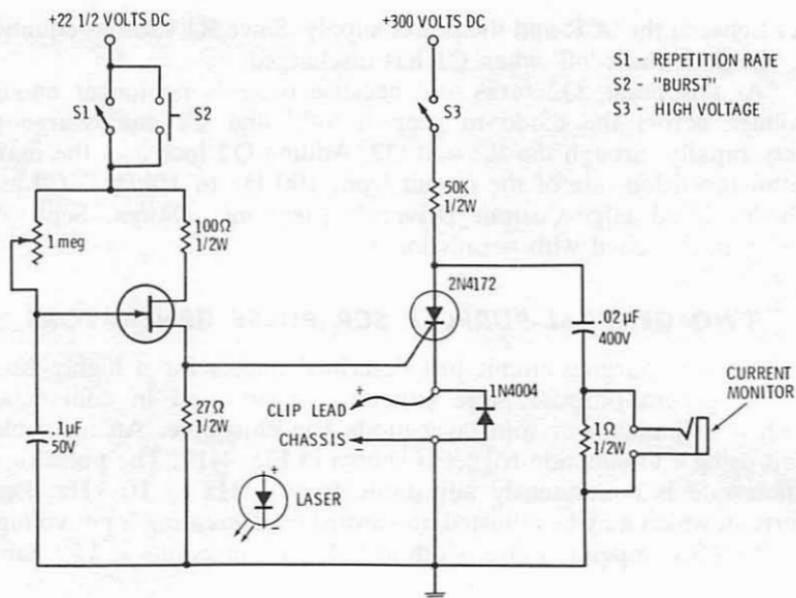


Fig. 4-18. Circuit of general-purpose SCR laser pulse generator.

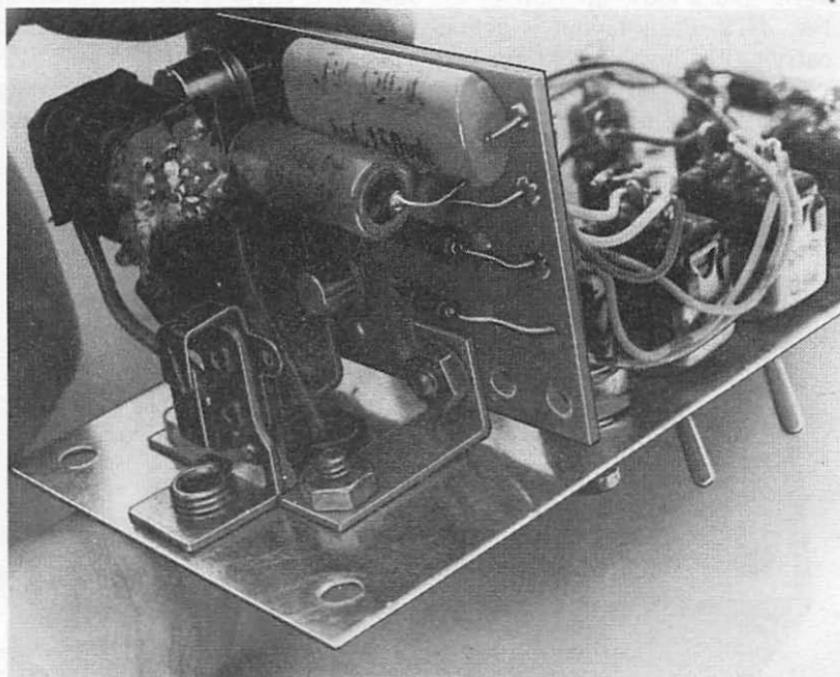


Fig. 4-19. Internal view of general-purpose pulse generator.

tion to the laser anode may introduce undesirable negative transients, it should be eliminated in favor of direct connection in cases where only a single laser is to be operated.

A somewhat more sophisticated SCR pulser makes use of an additional transistor to provide a variable current control. The circuit for the unit is shown in Fig. 4-20. Like the previous pulser, parts layout is noncritical and the photograph in Fig. 4-19 can serve as a guide.

Unlike the previous pulser, this unit accepts a variety of lasers by means of a standard miniature phone jack. Lasers to be operated by the pulser are simply soldered to a matching plug and inserted into the jack. For more permanent applications, a laser can be soldered directly into the circuit. The assembled pulser is shown in Fig. 4-21.

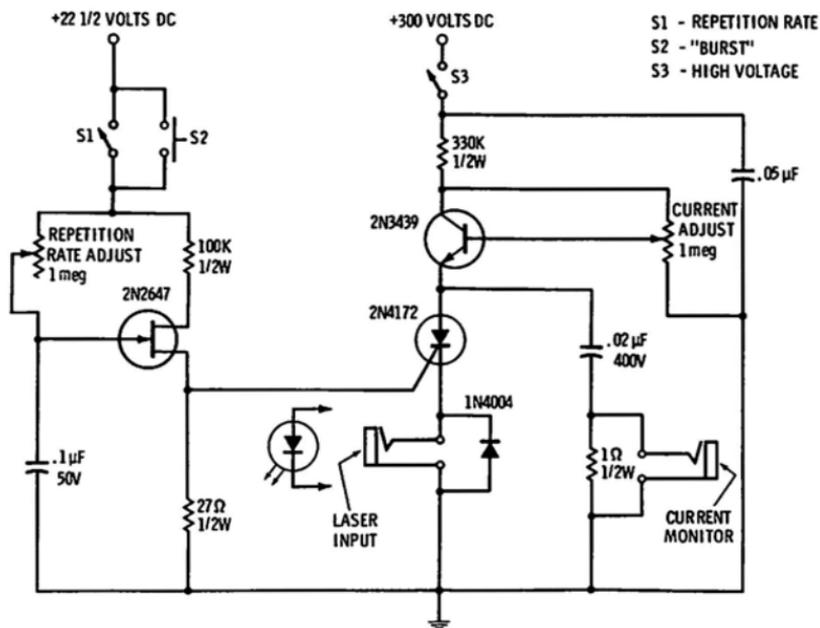


Fig. 4-20. General-purpose laser pulse generator with current adjustment.

As with any injection laser pulser, it is wise to include a current-monitoring resistor in the assembled SCR pulse generators. Both versions just described include current monitors, and access to them is provided by the small phone jacks visible on their front panels in the photographs. While most experimenters will not have an oscilloscope fast enough to accurately display the current pulse, inclusion of the current monitor will enable the pulser to be calibrated with a borrowed oscilloscope. Most universities and research laboratories and many good radio-television repair shops will have an oscilloscope with the required 15 to 20 MHz frequency response and will often

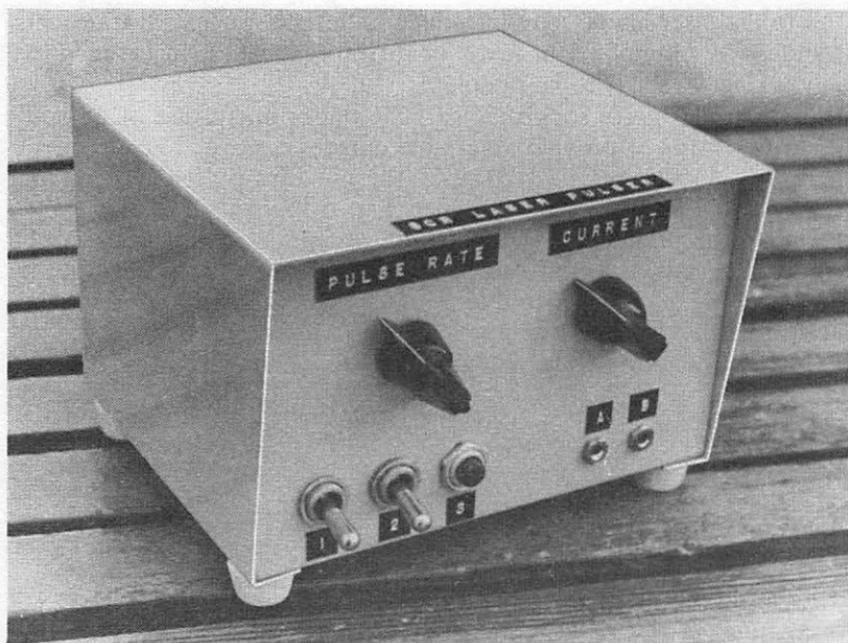


Fig. 4-21. General-purpose laser pulse generator.

honor a courteous request to use the scope for an hour or so to calibrate a laser pulser.

Calibrate a pulser by noting current for a variety of positions of the current-adjustment-control potentiometer. Check to see if increasing the repetition rate of the pulser reduces the current value; often it will, and the calibration should then be made for a variety of currents *and* repetition rates. Carefully note the calibration data in a notebook for future reference. Also, check the voltage of the power supply and record it next to the calibration data. The calibration will only be valid, in many cases, if the power supply voltage is kept unchanged.

Remember that, from Ohm's Law, peak current equals volts shown on the oscilloscope when the current monitor is a one-ohm resistor. If a 1/10-ohm resistor is used, current equals ten times the scope voltage. Besides measuring current of the pulser, be sure to check the pulse shape and make sure that it is approximately 100 or 200 nanoseconds wide at the center points. The pulse width should never exceed 200 nanoseconds for most injection lasers (an exception is the Texas Instruments' laser).

Often it will be possible to use the calibrated pulse generator to cross-calibrate an oscilloscope that is inadequate to properly respond to the brief current pulses. Use a voltage calibrated scope and, with

the pulser set to known currents, record the amplitude of the current pulse in the notebook. If it is possible to perform such a cross-calibration (and it will not always be possible), use of the pulse generator will be more flexible as its current can be checked when power-supply voltage drops. Remember, though, that a cross-calibrated scope provides information that is only approximate. For applications where the precise value of current needs to be measured, use a high-speed scope.

OTHER SCR PULSE GENERATORS

It should be obvious by now that there can be numerous variations on the basic SCR pulse-generator concept. An excellent general-purpose pulser is shown in Fig. 4-22. The simplicity of this 500-pulses-per-second laser transmitter makes it an ideal candidate for long range optical communications experiments. Indeed, the assembled version shown in Fig. 4-23 was used in conjunction with a sensitive receiver circuit in a test that resulted in a communications range of 2.4 miles during heavy rain. The tests, which were accomplished by author Campbell, were conducted during daylight.

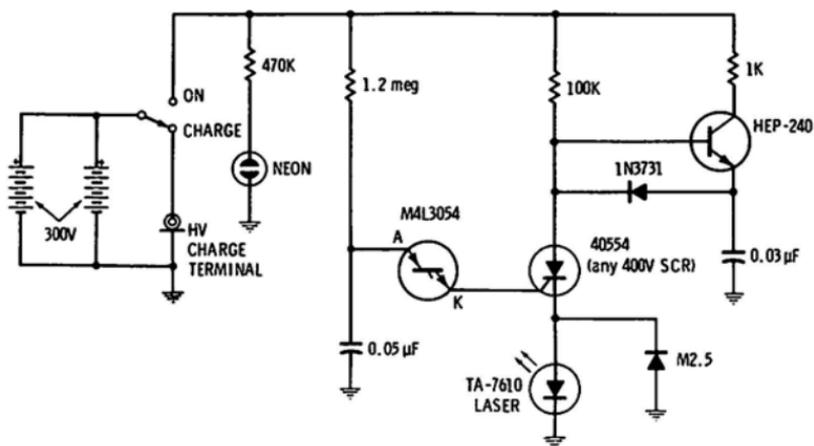


Fig. 4-22. 500-Hz general-purpose laser pulser.

THYRATRON DRIVERS

Some of the larger laser diodes require very high currents for proper operation. The RCA TA7705 and TA7787, for example, will radiate 50 and 65 watts respectively when driven at a peak current of 250 amperes. That is a lot of current—but the very high optical output from a single point source (which, as we shall discuss in a

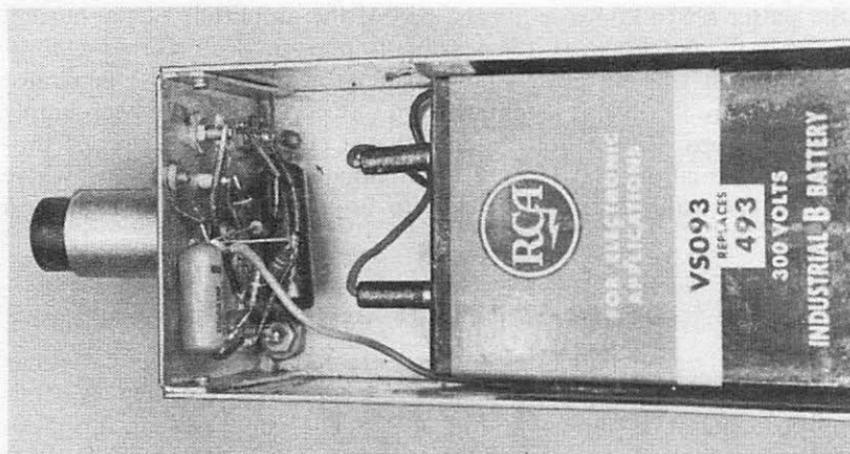


Fig. 4-23. Internal view of 500-Hz laser pulser.

later chapter, is important for beam collimation with external optics) is highly desirable for many injection laser applications. An arrangement of parallel avalanche transistors can be used to obtain this much current, but a much simpler method employs a miniature cold cathode thyatron called the krytron (made by EG&G Inc., 160 Brookline Ave., Boston, Massachusetts 02215). These sturdy, peanut-size tubes are no more difficult to operate than most semiconductors and are capable of switching currents of up to 2000 amperes with rise times comparable to avalanche transistors.

A simple circuit employing a krytron in a relaxation oscillator is shown in Fig. 4-24. Operation of the oscillator is virtually identical to the avalanche-transistor oscillators described earlier. R2 provides

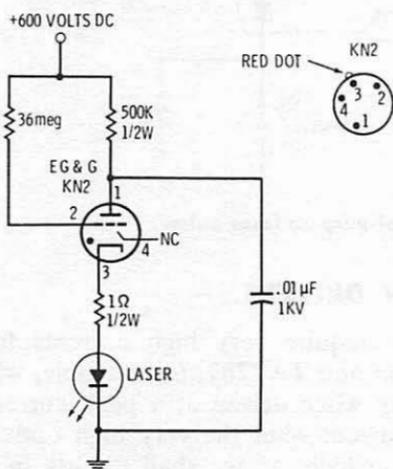


Fig. 4-24. High-current krytron laser pulse generator.

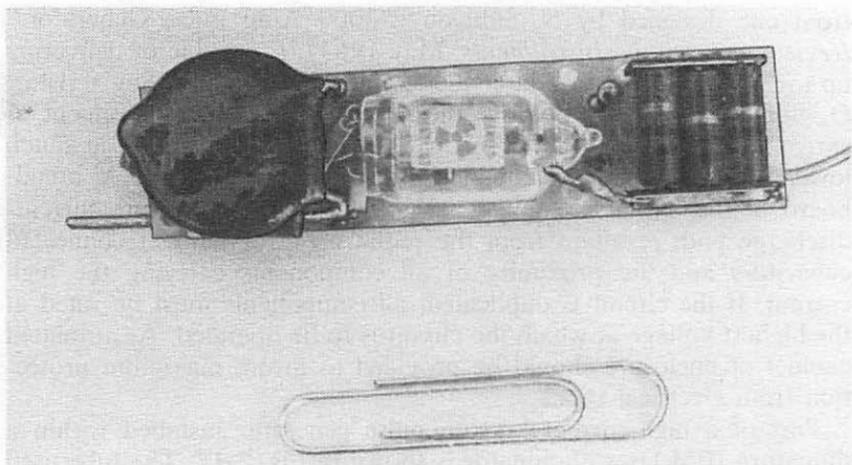


Fig. 4-25. Miniature version of a krytron pulse generator.

sufficient bias voltage to maintain an ionized region in the krytron. The circuit requires an operating voltage of at least 500 volts, with higher voltages producing a faster repetition rate. As can be seen in Fig. 4-25, the circuit can be made quite small. With the values shown in Fig. 4-24, the circuit will produce 100-nanosecond pulses of about 75 amperes at a repetition rate of about 100 Hz. The circuit is adapted from a similar version published elsewhere. (See W. Koechner, "Extremely Small and Simple Pulse Generator for Injection Lasers," *Review of Scientific Instruments*, January 1967, p. 17).

Much higher currents are possible by operating the krytron in an externally triggered mode. The circuit shown in Fig. 4-26, adapted

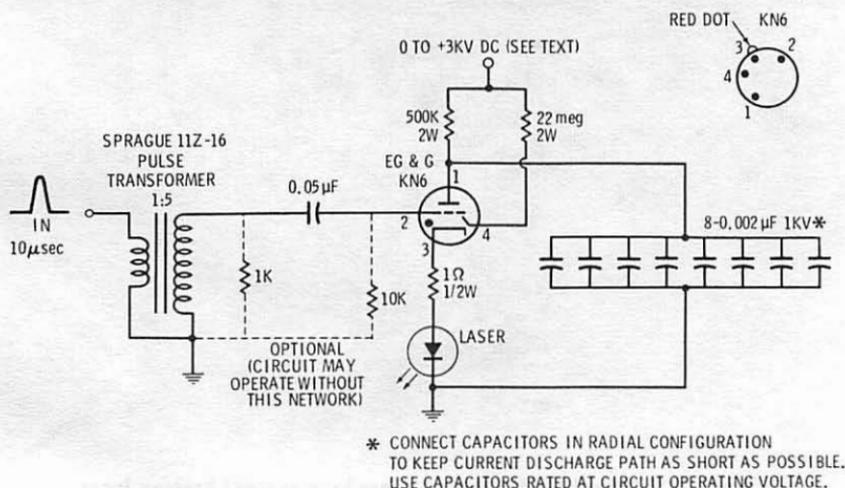


Fig. 4-26. Very high current krytron laser pulse generator.

from one designed by N. Sullivan ("2000 Amp Pulse Generator," *Review of Scientific Instruments*, May 1964), is capable of delivering up to 2200 amperes to a laser diode and current-monitoring resistor. Originally developed to satisfy the very high current requirement of early injection lasers, the circuit can be tailored to operate at much lower levels by merely adjusting the operating voltage. A breadboard of the circuit is shown in Fig. 4-27. Note the short current-discharge path resultant from the radial array of parallel connected capacitors and the proximity of all components carrying the high current. If the circuit is duplicated, all components must be rated at the highest voltage at which the circuit is to be operated. An insulated cabinet or enclosure should be provided to insure maximum protection from electrical shock.

Part of a high-current krytron pulse generator installed within a miniature IBM laser illuminator is shown in Fig. 3-12. The tube used in this pulser is encased in a ceramic material and has a higher current capability than the glass-packaged tubes employed in the circuits described here. When studying Fig. 3-12, note the radial arrangement of capacitors, the one-ohm current-monitoring resistor, and the low inductance copper foil strips connecting the laser array to the pulse generators.

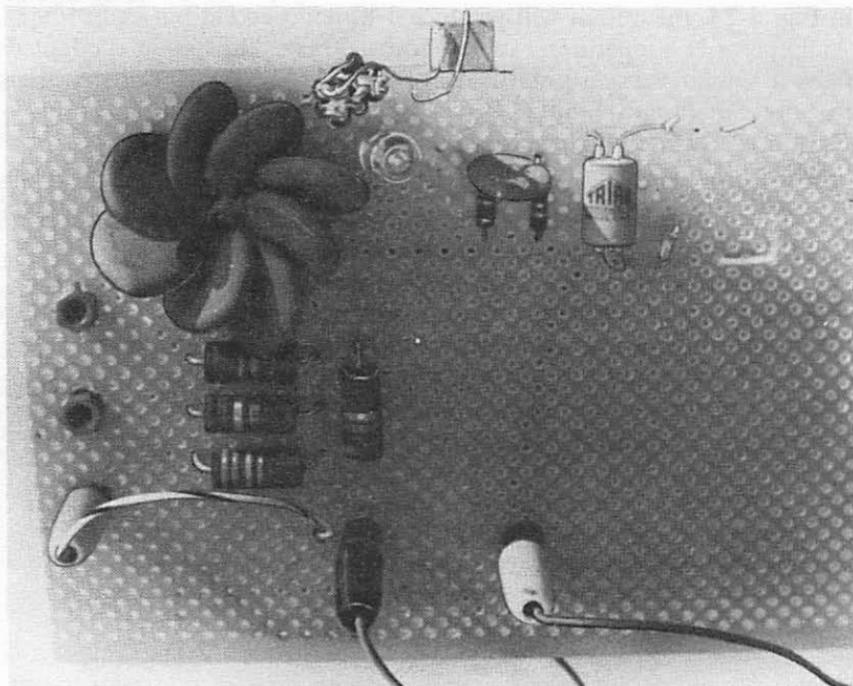


Fig. 4-27. Breadboard version of very high current krytron laser pulse generator.

TRANSISTOR DRIVER FOR CRYOGENIC OPERATION

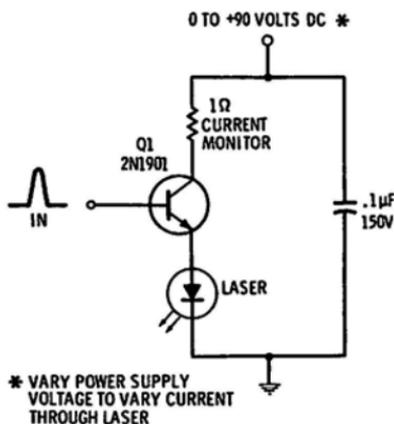
Several important advantages occur from operating injection lasers at cryogenic temperatures. When cooled to the temperature of liquid nitrogen (-196°C), for example, the driving requirements for almost any commercial laser are greatly relaxed. Pulse widths may be as wide as two microseconds and, since threshold is dependent on temperature, driving current need only be a few amperes. Peak power output is reduced, but average power is greater because of the higher duty cycle ratings.

As will be seen in the chapter on laser detectors and receivers, the wider pulse width permissible with cryogenically operated lasers significantly eases detector requirements. Since many experiments will benefit from the lower wavelength (closer to the visible red) and high duty cycle of cryogenic operation, the circuit shown in Fig. 4-28 is presented as a general guideline.

Operation of the circuit is fundamental: Q1, a 40-watt power transistor, is turned on for fixed intervals by positive pulses from an external pulse generator. The pulse specifications are such that lead dress is not nearly so critical as in the room-temperature drivers discussed earlier. Since the pulse characteristics of the circuit will be closely dependent on those of the pulse generator, a one- or two-microsecond pulse of several volts amplitude should be used. Since laser diodes cooled to the temperature of liquid nitrogen may be operated at a duty cycle of typically 2%, 2 μsec pulses permit a pulse repetition rate of up to 10 kHz. If a suitable commercial pulse generator for operating the circuit shown in Fig. 4-28 is not available, an astable multivibrator can be used to supply the necessary trigger pulses.

Liquid nitrogen is available from many of the commercial outlets that market welding oxygen. An uncovered vacuum bottle will hold

Fig. 4-28. Pulse generator for cryogenic laser operation.



of the cylinder. A 3.5" length of 1.5" copper tubing was inserted through holes formed directly opposite each other just above the Dewar's bottom and soldered to its walls. The completed Dewar was leak tested with a penetrating solvent such as acetone, since liquid nitrogen provided a false indication of leaks due to the condensation of oxygen from the air onto the Dewar walls.

The original assembly used an RCA TA7610 laser, but any laser mounted within a coaxial stud package can be employed. The stud package insures optimum heat removal from the laser chip. The detail drawing in Fig. 4-30 shows how the laser is mounted in a cold head which fits within the copper tube of the Dewar flask. The plastic extension connected to the laser cold head protects the electrical leads of the laser and provides a convenient method for removal of the cold head.

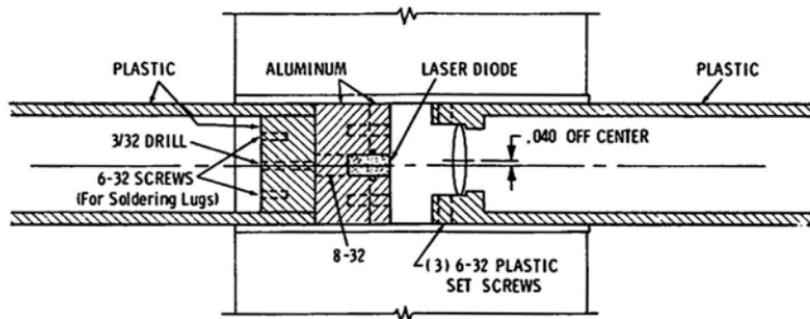


Fig. 4-30. Mounting assembly for cooled injection laser.

The laser beam is collimated by a small $f/1$ lens mounted in a teflon tube that fits into the copper tube. Since water vapor in the air tends to condense upon and frost-over cryogenically cooled surfaces, gaseous dry nitrogen or dry air should be directed into the space between laser and lens and then out over the external face of the lens. The completed assembly is housed in a box made of wood. A block of insulating material is placed over the exposed top of the Dewar flask to reduce evaporation when it is filled with liquid nitrogen. The pulser circuitry is mounted to one side of the box.

In operation, the cryogenically cooled TA7610 laser produced an 845-nanometer beam that was easily seen by the unaided eye. The cherry-red beam could be easily focused without the need for image-conversion devices.

A wide variety of cooling techniques are possible, and certainly the reader will be able to come up with designs suitable for specific applications. For example, the assembly just described could easily be modified to operate with a vacuum bottle. The cold head could

then be mounted upon a large copper bar inserted into the liquid nitrogen. Or, if the single-wall Dewar is preferred, stainless steel can be replaced with copper, brass, aluminum, or any of a number of metals. The essential requirement for cryogenic operation is that the operating parameters of the laser must never be exceeded. Particular care must be paid to coupling between the liquid-nitrogen coolant and the laser itself. Also, the laser must never be operated when the liquid nitrogen has evaporated.

DRIVING LASER ARRAYS

As discussed in Chapter 3, a wide variety of laser arrays are commercially available. Since arrays are capable of peak optical powers in excess of 100 watts, they are important sources of infrared illumination. Also arrays are potentially useful in very high power optical communication systems.

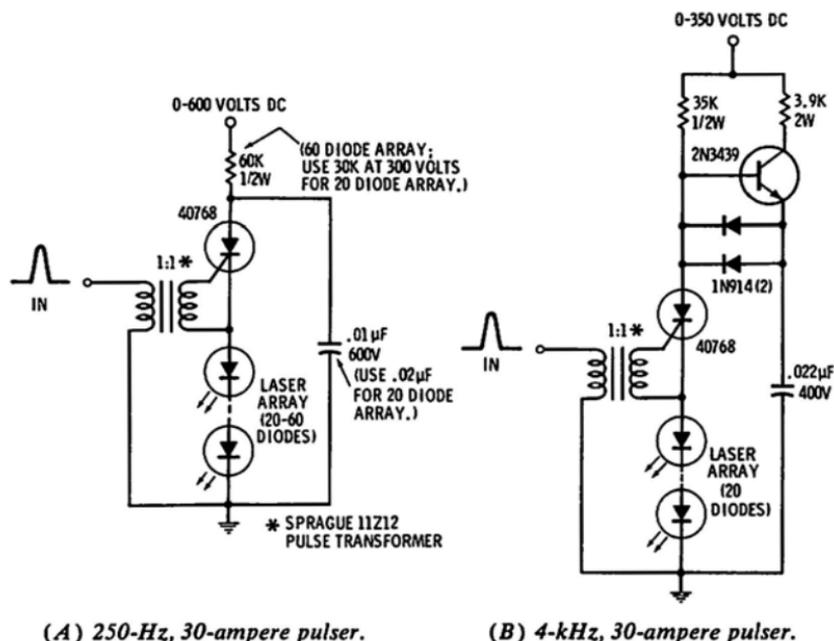


Fig. 4-31. Pulse generators for laser arrays.

Richard S. Myers of RCA has designed several pulse generators suitable for driving commercial laser arrays requiring a peak current of up to 40 amperes. From Chapter 3, the current required by a series-connected array is the same as that of a single diode within the array. But because of the increased resistance, the voltage require-

ment is considerably higher. Additionally, arrays have somewhat higher inductance than single diodes due to the relatively lengthy current path resultant from diode to diode connections.

Some of Myer's driving circuits are shown in Fig. 4-31. All of the circuits use an SCR switch. The 11Z12 transformers (Sprague) impedance match the laser array load to the trigger source T. The four-layer diode or unijunction trigger circuits used throughout this chapter may be used as a trigger.

COMMERCIAL PULSE GENERATORS

Until recently only highly specialized commercially available pulse generators were capable of operating laser diodes within required specifications. But now several companies offer small pulse generators especially designed for driving laser diodes.

Laser Diode Laboratories manufactures a line of pulse generators suitable for driving both single laser diodes and arrays. The units are encapsulated in sturdy miniature enclosures equipped with appropriate electrical connections and mounting holes. Although the generators contain internal clocks operating at 500 Hz, faster repetition rates may be obtained by means of external triggering.

Pulse generators are also available from Washington Technological Associates, Inc. Only 0.6" x 0.6" x 2.5" in size, the units are more compact than the LDL devices. Operating voltage is also lower, but since peak current is less and an internal clock is not provided, the prospective buyer is advised to consult data sheets available from the manufacturer for more complete information.

Laser pulsers are also manufactured by Lad Electro Systems, Inc., Advanced Kinetics, Inc., and Pulse Engineering, Inc.

MODULATORS FOR VOICE COMMUNICATIONS

While any of the pulse generators described so far are well suited to coded tone communications, much more interesting results will be had with a voice-modulated system.

Amplitude Modulation

The double-heterostructure laser diodes, capable of being operated continuously at room temperature, can be voice modulated with only a simple amplitude modulation driver circuit such as the one shown in Fig. 4-32. The circuit was originally designed for driving noncoherent light-emitting diodes, but it should operate quite well with continuous laser diodes. Current through the laser or LED may be adjusted by connecting a voltmeter across R2 and adjusting R1. Current will equal one-tenth the voltage across R2.

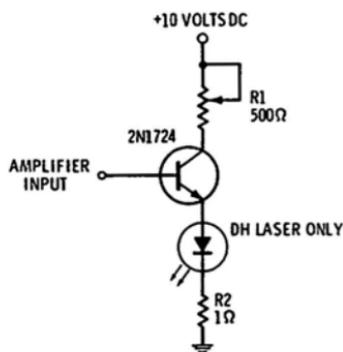


Fig. 4-32. A-m modulator for light-emitting diode or DH laser.

Pulse Modulation

Since laser diodes that operate continuously at room temperature are not likely to be commercially available for some time, optical communications systems employing conventional laser diodes must make use of various types of pulse modulation (pm) techniques. While the circuitry required for pm is certainly more complex than that for simple a-m, the high signal-to-noise ratio offered by pm is a significant advantage. Furthermore, conventional laser diodes have considerably higher peak power capabilities than do the new continuously operated lasers.

One of the simplest pm techniques is pulse frequency modulation (pfm), but pulse position (ppm) and pulse width modulation (pwm) have also been employed as communications techniques. Pulse amplitude modulation (pam) is another possibility, but it suffers from the same disadvantage as a-m while requiring circuitry as complex as that of any of the other pm techniques.

Since none of these techniques depend on amplitude of signal strength at the receiver for information communication, very high quality transmissions can be obtained. Receiver sensitivity is restricted only by logic thresholds within the receiver and the ever-present noise of a-m receivers is eliminated entirely. Atmospheric conditions tend to play havoc with optical a-m communication links, but not so with most of the pm schemes. While maximum range capability might be reduced somewhat by weather or atmospheric turbulence, transmission quality remains uniform at any range. All these points make a convincing case for applying conventional laser diodes to optical communication links.

Pulse Frequency Modulator

The simplest pm technique is pulse frequency modulation (pfm). A block diagram of a simple pfm technique is shown in Fig. 4-33. Audio signals from the microphone are amplified and passed on to a modulator that controls the charging time of a laser diode pulse

generator. The frequency of the optical pulse train is therefore a direct function of the variations in the audio signal. Optical pfm receivers will be described in detail in Chapter 5. Suffice it to say here that the receiving system detects the optical pulses, amplifies them, and feeds them into a single-shot multivibrator. If the signals are of sufficient amplitude to trigger the multivibrator, they are in effect stretched to a standard amplitude and width that is independent of the strength of the received beam. The pulses are then passed through a low-pass filter to a speaker.

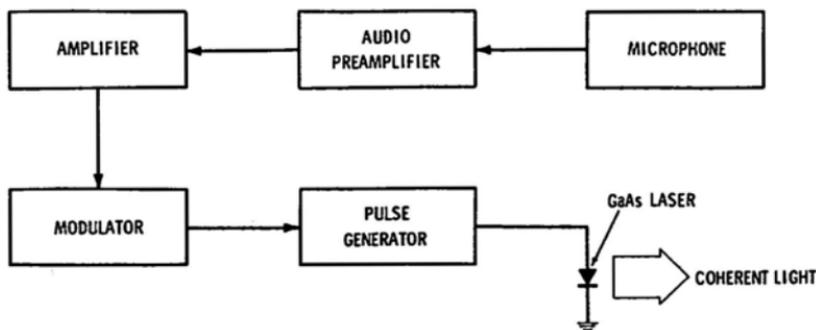


Fig. 4-33. Simplified pfm laser communications transmitter.

The circuit diagram in Fig. 4-34 is a practical realization of the basic block diagram. In operation, Q1 modulates the frequency of the relaxation oscillator formed by four-layer diode Q2 at a rate proportional to the amplitude of the audio input. Since Q2 fires SCR Q3, the laser output is pulse-frequency modulated. Transistors Q4 and Q5 provide a fast charging circuit for the SCR pulser and permit a modulation rate of 8 kHz.

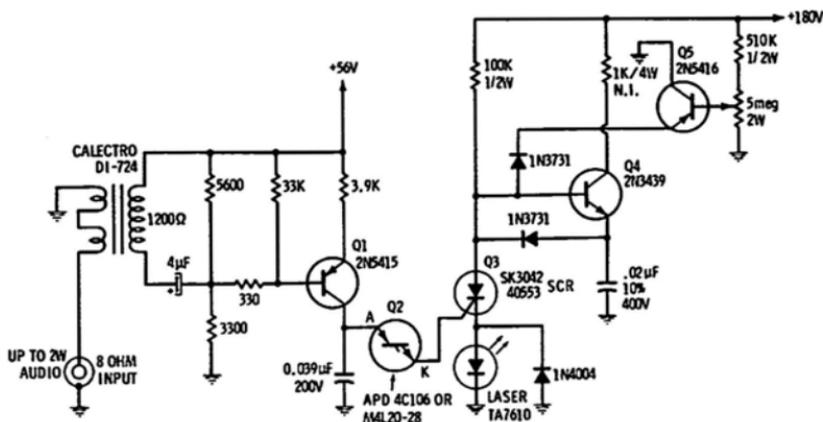


Fig. 4-34. Pfm laser transmitter used to transmit voice signal 3.5 miles.



Fig. 4-35. Exterior view of pfm voice transmitter.

An assembled version of this pfm laser communicator is shown in Fig. 4-35. Using this transmitter in conjunction with a receiver system described in Chapter 5, author Campbell achieved one-way voice communication over a range of 3.5 miles.

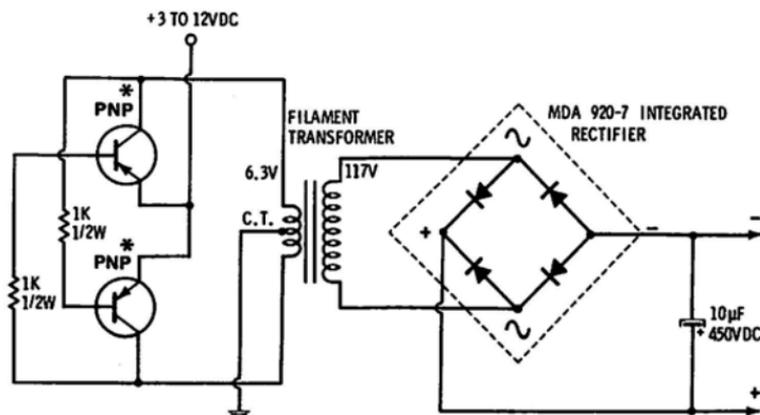
Power Supplies

Since the current requirement for most of the pulse generator and modulator circuits described in this chapter is low, several types of power supplies may be employed. The most economical supply is the line-operated variety, but for portability, batteries and small dc-dc converters are often used.

Whatever type of power supply is employed, safety should be a foremost consideration. Even a harmless looking high-voltage battery can deliver a sturdy electrical shock. All leads carrying high voltage should be well insulated and separated from areas with sharp edges or other projections that may penetrate or compromise the insulation.

Batteries

The simplest of all power supplies is the battery. Most major battery manufacturers market these self-contained power supplies with outputs of up to 500 volts. The higher-voltage batteries were originally



* FOR LOW CURRENT OPERATION, USE ANY COMMON PNP TRANSISTORS. FOR HIGH CURRENT OPERATION, USE PNP POWER TRANSISTORS SUCH AS HEP232 (MOTOROLA) OR 2N3614.

Fig. 4-36. Dc to dc converter power supply for laser pulse generator.

designed for Geiger counters and photoflash equipment and are ideal for powering laser pulse generators and modulators. Avalanche transistor pulsers will operate quite well when powered by two series-connected 67.5-volt batteries, but SCR pulsers require up to 300 volts.

Though batteries are the simplest power supply, their cost as a function of energy output is high. A typical 300-volt unit, for example, costs nearly \$9.00. Nevertheless, for applications where portability is a must, the battery is an excellent power supply.

DC-DC Converters

The converter is an electronic circuit capable of increasing or decreasing an input voltage as a function of current. A dc-dc converter that increases the small voltage from a few dry cells to several hundred volts makes an extremely useful laser pulse generator power supply. If transistorized circuitry is employed, the dc-dc converter is even more compact than high-voltage dry batteries. An additional advantage over high-voltage dry batteries is that since ordinary dry cells can be used to power the converter, its operating expense is small.

There are numerous converter designs, but one of the most common is the blocking oscillator. Shown schematically in Fig. 4-36, the blocking oscillator impresses a pulsating low voltage onto the primary of a high-turns-ratio transformer. The high voltage appearing at the secondary is rectified, filtered, and passed on to the laser pulser. With the values shown in Fig. 4-36, the converter will deliver about 300 volts from two 1.5-volt dry cells. The output voltage may be altered by varying the input voltage from 3 to 12 volts. For high-power applications, the transistors must be mounted on heat sinks. But for

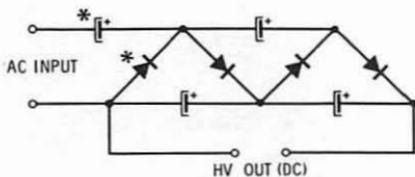


Fig. 4-37. Half-wave voltage-quadrupler circuit.

* NOTE:
EACH CAPACITOR MUST BE RATED AT A VOLTAGE GREATER THAN THE INPUT VOLTAGE. EACH RECTIFIER MUST BE RATED AT TWICE THE INPUT VOLTAGE. ANY SIZE CAPACITOR WILL OPERATE IN THE CIRCUIT, THOUGH REGULATION IS IMPROVED WITH LARGER VALUES.

very low power applications, ordinary plastic-case transistors will suffice.

When powering a laser pulser with the converter, output voltage should be checked with a voltmeter to protect the pulser from possible overvoltage. Too much voltage applied to many of the pulsers described in this chapter will result in possible destructive self-switching and possible permanent damage to the switching device and laser.

A variation of the basic blocking-oscillator circuit employs a voltage multiplier to provide an even higher voltage at the output. A typical multiplier circuit is shown in Fig. 4-37. As can be seen from Fig. 4-38, a converter-voltage multiplier can be made quite small. The converter shown there can deliver several hundred volts under load when powered by a tiny 1.3-volt mercury cell. The circuit was developed by author Mims to enable a miniature laser-diode tracking beacon to be launched in a small rocket.

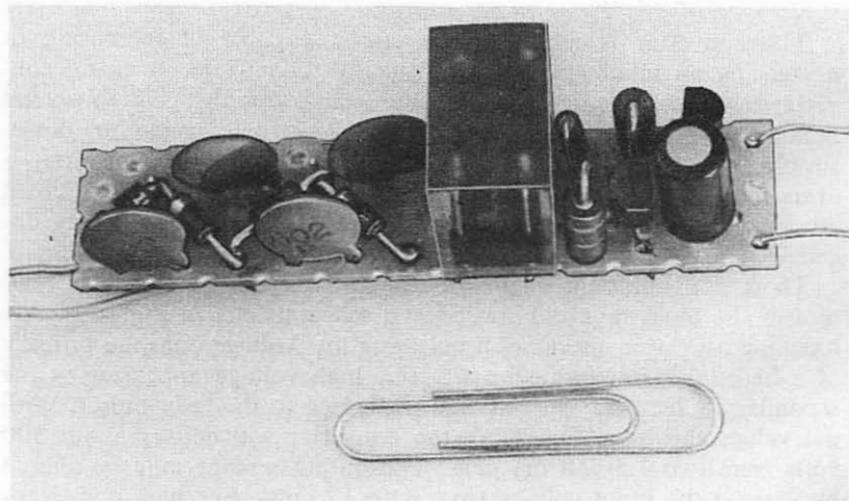
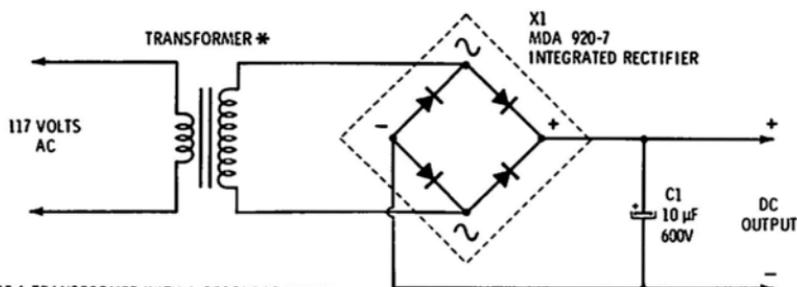


Fig. 4-38. Miniature high-voltage power supply.



* USE A TRANSFORMER WITH A SECONDARY WHICH PRODUCES APPROXIMATELY THE DESIRED OUTPUT VOLTAGE. FOR EXAMPLE, A 117V TO 240V TRANSFORMER WILL GIVE A DC OUTPUT OF APPROXIMATELY 240V.

Fig. 4-39. Basic line-operated power supply.

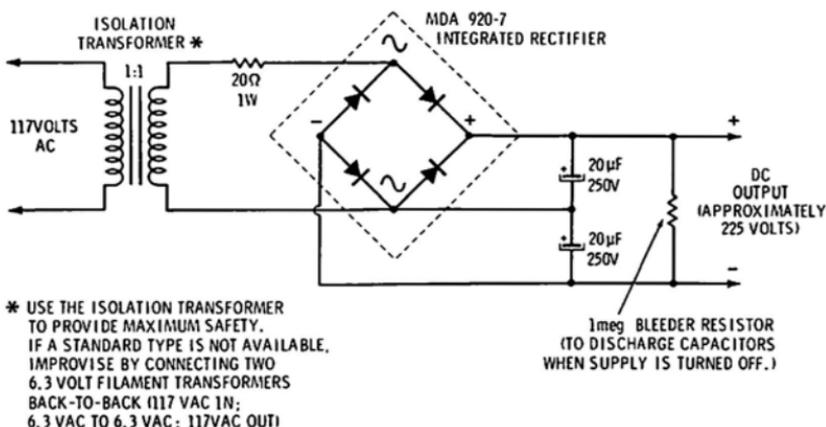
Line Supplies

Several types of line power supplies may be used to operate laser pulsers. All can be constructed for relatively low cost and are by far the least expensive to operate.

A simple transformer line-operated supply is shown in Fig. 4-39. Many types of transformers will work in the circuit; the main requirement is that the transformer chosen be rated at the maximum voltage required by the laser pulser. Rectification is provided by diode bridge X1, and C1 serves as a filter.

A type of line-powered supply that uses a voltage multiplier is shown in Fig. 4-40. The 1:1 transformer provides isolation from the ac line and MUST be used to preclude shock hazards.

There are many additional circuit possibilities for line-operated power supplies. Many of them will provide variable-voltage output,



* USE THE ISOLATION TRANSFORMER TO PROVIDE MAXIMUM SAFETY. IF A STANDARD TYPE IS NOT AVAILABLE, IMPROVISE BY CONNECTING TWO 6.3 VOLT FILAMENT TRANSFORMERS BACK-TO-BACK (117 VAC 1N; 6.3 VAC TO 6.3 VAC; 117VAC OUT)

1meg BLEEDER RESISTOR (TO DISCHARGE CAPACITORS WHEN SUPPLY IS TURNED OFF.)

Fig. 4-40. Line-operated voltage-multiplier power supply.

an important consideration for adjusting peak laser current. The reader is advised to consult one or more of the many technical books on the subject for additional information. If it is not desirable to construct a power supply, literally dozens of types are on the commercial market.

Detectors and Receivers

Some form of infrared detection system is required for nearly all injection laser applications. Fortunately, a variety of electronic components suitable for detecting the near infrared beam of these lasers is available. As with other electronic components, each type has relative advantages and disadvantages, and the experimenter and design engineer will be forced to make a number of trade-offs when choosing a detector. The most common trade-offs concern response time and sensitivity, but there are others as well and several of the more important ones will be discussed later in the chapter.

This chapter includes a section on receivers—that is, the combination of a specific detector with an electronic amplifying or processing circuit. While the information on detectors will prove informative, the section on receivers is more practical, as it contains several tested circuits that can be put to good use by the laser experimenter.

DETECTORS

Light-detection technology has come a long way since early experiments with liquid-electrolyte light-sensitive cells. Manufacturers now offer a wide range of commercial detector types ranging from the slow but sensitive photoresistive cells to the extremely fast, highly sensitive silicon avalanche detectors. The middle ground is covered by a variety of phototransistors, photodiodes, light-sensing electron tubes, solar cells, and other components. In the latter category are the

image-converter tubes, electron tubes capable of converting invisible infrared into visible light. Since they have a special application in injection laser work, they will be discussed along with several other specialized infrared detectors in Chapter 6.

Not all detectors have sufficiently fast response times to be practical for efficient use with pulsed injection lasers. And other types do not respond well to near infrared, the most common wavelength of these lasers. The former category includes phototransistors, solar cells, and some photodiodes. These detectors all have high sensitivity at near infrared wavelengths, but their slow response time limits their use with injection lasers to bench work and other applications where very short detection ranges can be tolerated. They are best used with light-emitting diodes and continuously operating double-heterostructure lasers operated at frequencies below about 5 MHz.

Those detectors that have a response time sufficiently fast to respond to the 100- or 200-nanosecond pulse of a conventional injection laser include Schottky barrier photodiodes, certain diffused photodiodes, light-sensitive field-effect transistors, and photomultiplier tubes. A specialized and costly detector that is admirably suited for injection laser applications requiring extremely fast response time and sensitivity is the avalanche photodiode.

PHOTOMULTIPLIER TUBES

One of the fastest and most sensitive light detectors available, the photomultiplier tube is a member of a class of detectors designed around vacuum-tube technology. The family continues to grow and now includes a large variety of highly specialized photomultipliers, image tubes, vacuum photodiodes, and other specialized light-detection devices. The photograph in Fig. 5-1 shows an assortment of these glass-and metal-enclosed detectors.

Operation of a photomultiplier can best be understood by explaining the operating principles of the basic phototube. In its simplest form, a phototube consists of a pair of electrodes encased in a glass envelope similar in appearance to a standard electron tube. One of the electrodes is coated with a layer of *photoemissive* material. When struck by light, the material, usually a compound containing either sodium, cesium, or potassium, emits electrons. If the photoemissive electrode is made negative with respect to the remaining electrode, a small current will then flow. The emission of electrons by a photoemissive material is called the photoelectric effect.

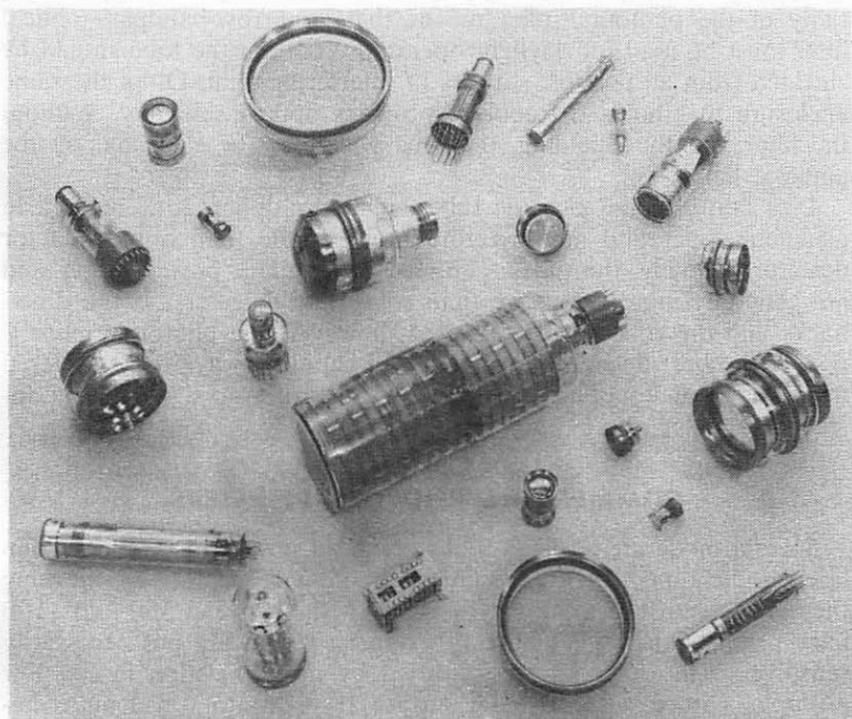
The photomultiplier greatly increases the sensitivity of the basic phototube by adding a series of electrodes called *dynodes*. The dynodes (there may be ten or more) are precisely oriented within the tube so that electrons emitted from the first strike the second, cause

the emission of additional electrons, and so forth. In short, a very low light level causes a relatively large number of electrons to flow through the tube by means of a type of chain reaction. The result is an output photocurrent hundreds of thousands of times greater than that originally initiated by the incoming light signal.

As in the phototube, the dynodes of the photomultiplier must be separated by voltage differences in order to permit an electron flow. Since each step must have a potential difference of as much as 150 volts over the last, the tube may require an operating voltage of more than 1500 volts.

The voltage is usually applied to the tube by a miniature, high-voltage, low-current power supply. A voltage divider formed from a chain of resistors, often soldered directly to the tube socket, directs the appropriate voltage level to each of the dynodes. A circuit diagram for a typical photomultiplier voltage divider is shown in Fig. 5-2.

Often the front surface of the photomultiplier and other photo-sensitive electron devices is the primary photoemissive material. The material, metallic and therefore shiny in appearance, can be easily seen on several of the tubes shown in Fig. 5-1.



Courtesy ITT Electron Tube Div.

Fig. 5-1. Assortment of photoemissive light detectors.

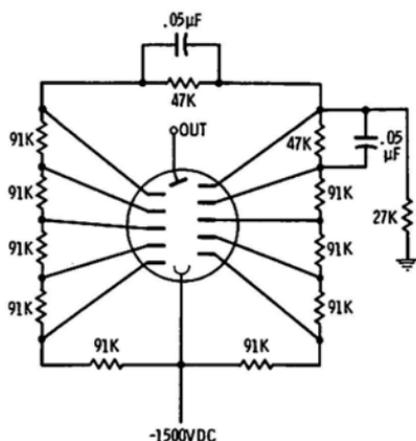


Fig. 5-2. Typical photomultiplier voltage-divider circuit.

There are a number of factors that should be considered when choosing a photomultiplier over other types of detectors. First, for optimum operation the tube should be cooled. Cooling with dry ice, liquid nitrogen, or other commonly used coolants significantly reduces tube noise and therefore increases sensitivity. The high sensitivity of the photomultiplier means that a narrow-bandpass optical filter must be used for daylight operation and that the tube should be shielded from all possible sources of interfering light. Often the same enclosure that holds the coolant provides optical shielding. Without the filter and the shielding, the tube will likely be saturated by the ambient light level.

Like conventional electron tubes, photomultipliers are enclosed in glass envelopes and are therefore more fragile than semiconductor detectors. Finally, the tubes require a high-voltage power supply and are generally more expensive than solid-state detectors. If the drawbacks and the cost can be tolerated, however, the photomultiplier is one of the best detectors available and should always be considered for sophisticated applications involving low-power signals from injection lasers.

COMMERCIAL PHOTOMULTIPLIERS

Several moderately priced tubes are good possibilities for injection laser applications. They have an S-1 photoemissive surface, meaning they are sensitive to the range of wavelengths between 300 and 1100 nanometers. Other tubes have other surfaces and are not necessarily sensitive to the near infrared emitted by most injection lasers. For example, a tube with an S-11 surface responds to wavelengths between 350 and 650 nanometers while an S-20 tube responds to the wavelengths from 300 to 900 nanometers. A graph portraying the

sensitivity of several surfaces as a function of wavelength is shown in Fig. 5-3.

A tube that can be obtained new from most major electronics suppliers for about \$115 and surplus for about \$95 is the 7102, but finding a surplus dealer who stocks the tube can prove difficult. The 7102, manufactured by RCA, has excellent response at the 905-nanometer wavelength of most injection lasers and has a sensitivity of 420 milliamperes per milliwatt of incident light. This is roughly a thousand times better than typical silicon detectors.

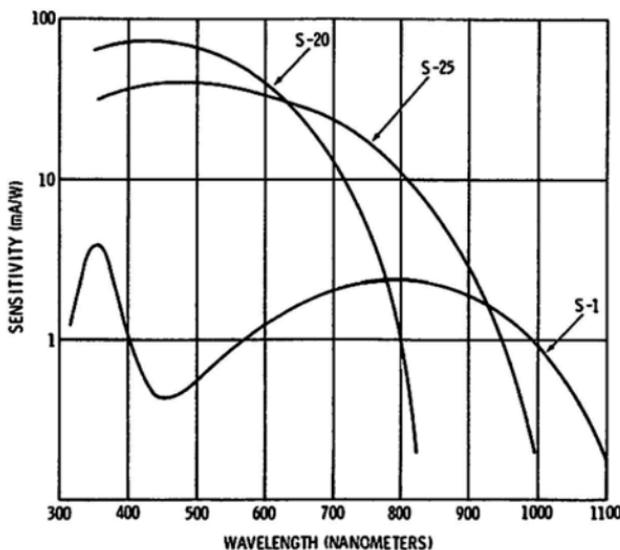


Fig. 5-3. Sensitivity curves of some infrared photoemissive surfaces.

Another tube is the Hamamatsu TV Company's R406. Available from Kinsho-Mataichi Corporation, the R406 has excellent sensitivity to near infrared.

Other photomultipliers are manufactured by ITT, DuMont, Varian, General Electric, and at least thirty additional companies. Many manufacturers are represented in the catalogs of major electronic parts suppliers, but for detailed information, specifications, and applications material, a quick letter to the manufacturer is recommended.

SILICON DETECTORS

As was noted earlier, not all silicon detectors have sufficiently fast response times to efficiently detect the very rapid pulses from a conventional injection laser. Nevertheless, most silicon detectors can be used in at least some injection laser applications, so a variety of both fast and slow detectors will be described.

SOLAR CELLS

With the specified application of converting sunlight into electricity, most experimenters don't think of the solar cell as a conventional detector. Actually, solar cells make good large-area, low-cost, near-infrared detectors. They can be used to efficiently detect the relatively low frequency modulation of audio signals transmitted by a light-emitting diode, but their slow response time limits their use in injection-laser applications to bench work, or to other uses where the optical signal level is very high. The large-area solar cell, shown with a variety of other silicon photodetectors in Fig. 5-4, has a rise time of about 20 microseconds.

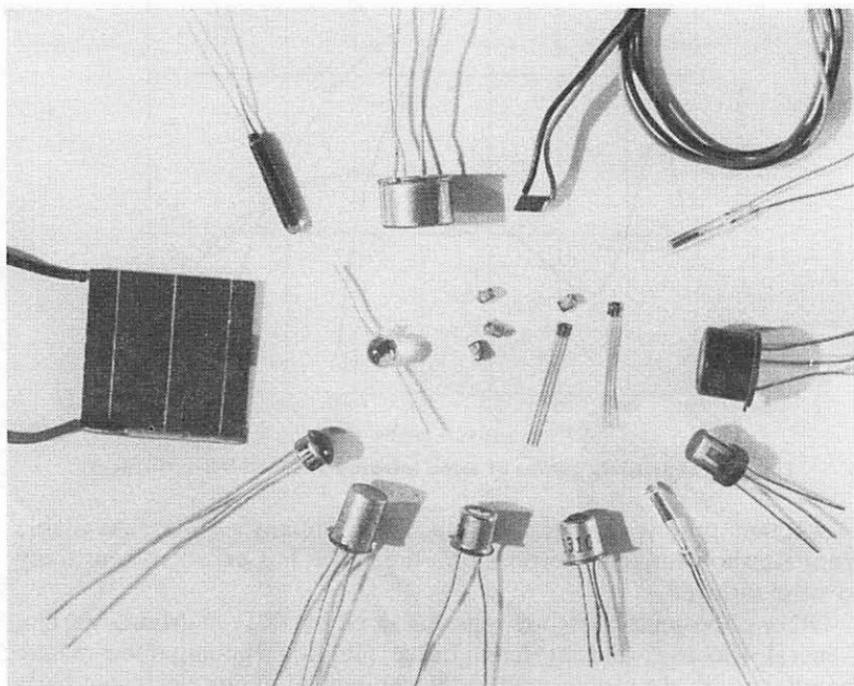


Fig. 5-4. Assortment of silicon solar cells, phototransistors, and photodiodes.

A particularly interesting application for a solar cell detector is a miniature injection laser interferometer. This subject is discussed in considerable detail in Chapter 2, and a few more applications are mentioned in Chapter 7.

A disadvantage of the solar cell is that it is susceptible to saturation from sunlight or artificial light sources. For this reason, it must be shielded from direct illumination by these sources by some form of baffle or infrared filter.

PHOTOTRANSISTORS

A wide variety of phototransistors is available to both the experimenter and the design engineer. While many of these devices have excellent spectral sensitivity to near infrared, response times are too slow for efficient use with injection lasers. Typical rise times are several microseconds, far short of the total pulse width of a few hundred nanoseconds of conventional injection lasers.

Nevertheless, the phototransistor can be used in short range applications with injection lasers when the optical signal is high. Furthermore, an interesting circuit arrangement permits the response time of many phototransistors to be speeded up considerably, and makes them more attractive candidates for laser applications.

FIELD-EFFECT PHOTOTRANSISTORS

Ordinary bipolar transistors will often operate as phototransistors when their protective packaging is removed. Indeed, a major problem with early plastic encased transistors was their sensitivity to variations in ambient light. Field-effect transistors (FETs) often show the same effect. Teledyne Crystallonics has developed and marketed a line of specially fabricated FETs that are designed specifically for light-sensing applications. Called Fotofets, the light sensitive FETs are packaged in glass-windowed containers like conventional phototransistors.

The chief advantage of the Fotofet over bipolar phototransistors in laser applications is its very fast response time. Typical Fotofets have a rise time of 30 nanoseconds and a fall time only slightly longer. Another important advantage they have over bipolar phototransistors is their very high gain. A typical phototransistor will exhibit a gain of a few hundred when exposed to an optical pulse, whereas the Fotofet may produce a gain of several million. The gain of the phototransistor is reduced at high light levels, but the Fotofet retains a relatively uniform response over large variations in the incoming optical signal.

An example will serve to illustrate the very high gain that can be achieved with a Fotofet. If a tungsten filament lamp illuminates an FF102 Fotofet with one footcandle, a light-generated gate current of 40 nanoamperes will flow through a one-megohm gate resistor. According to Ohm's Law, the voltage appearing across the gate resistor will be 40 millivolts. Since the Fotofet has a transconductance of typically 1000 micromhos, the light-generated drain current is 40 microamps. This corresponds to a current gain of 1000.

The external circuitry technique used to speed up the response of a bipolar phototransistor can be used with the Fotofet for similar

results. A sample circuit is shown in Fig. 5-5. By clamping the drain of the Fotofet to ac ground, its normal capacitance of about 180 pF is reduced to an effective value of about 15 pF. The lowered capacitance increases the high-frequency response of the Fotofet by from ten to fifty times, thus greatly improving its response to injection laser pulses.

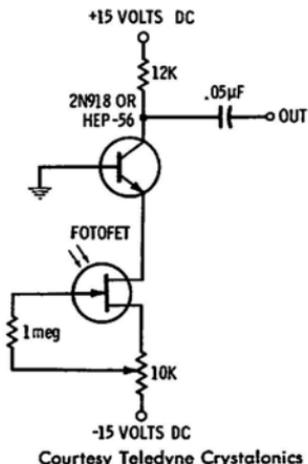


Fig. 5-5. Transistor speed-up circuit for Fotofet infrared detector.

PIN PHOTODIODES

Several photodiodes have been developed that employ an intrinsic semiconductor layer between the p and n regions to improve response time and sensitivity over that of conventional pn photodiodes. Schottky barrier photodiodes consist of a silicon die topped by an undoped depletion region (the intrinsic layer). The p region of the diode is formed by oxidizing a thin layer at the top of the depletion region. Electrical contact is made by means of a thin film of gold applied to the front surface of the p material. An aluminium coating at the base of the n region, the original silicon die, forms the other contact of the diode.

The gold film that serves as the top contact of the diode has a high reflectivity at the near infrared wavelength of most injection lasers. The film may reflect as much as 30% of the photons striking the surface, thus significantly altering the spectral response of the diode. The problem is eliminated by diffused PIN photodiodes. These diodes do not have the gold electrode and are therefore immune to the reflection problem. Their response peaks more closely to the near infrared output of most injection lasers and the response time is quite fast.

The response time of both Schottky barrier and diffused PIN photodiodes is dependent on the diode capacitance, series resistance, and the value of the external load resistor. Response time is RC dependent,

so it is advantageous to have both R and C as low as possible. Large-surface-area photodiodes are available that obviate the need for external optics to collect the incoming beam, but their large size means increased capacitance and slower response time. Smaller diodes must usually be coupled with an external lens, but their small capacitance means optimum response time. More on detector trade-offs appears later in this chapter.

Schottky barrier and n on p photodiodes suffer from noise problems caused by current leakage across the surface of the device. The leakage may occur even when the detector is in the dark. The problem is partially eliminated by fabrication of a *guard ring* around the active region of the diode. The guard ring, an annulus of diffused silicon separated by a thin ring of insulating silicon from the active region, is biased with the same potential as the active region. Surface-current leakage is then shunted through the guard ring instead of through the load resistor and out through the amplifier circuit as undesirable noise. The guard-ring method of reducing noise is considered to be one of the most important technological advances in silicon detectors.

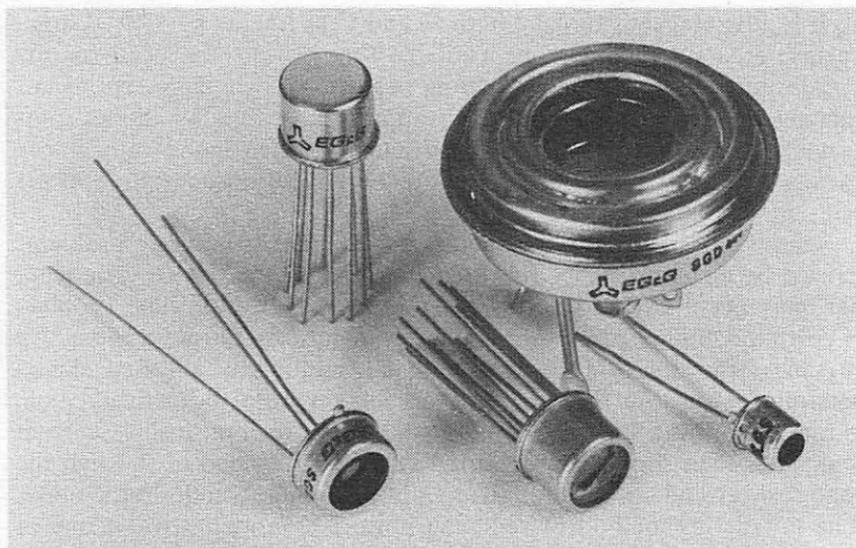
While Schottky barrier and n on p diffused PIN photodiodes benefit from the guard ring, p on n diffused photodiodes have negligible surface leakage and therefore do not employ guard rings. Fortunately, many detection applications do not require the highest sensitivity of a diode, and if the signal is significantly greater than the leakage current, the guard ring can be left unconnected when present.

COMMERCIAL PIN PHOTODIODES

There are a number of good quality PIN photodiodes available at prices well below those of photomultipliers. EG&G, Inc. manufactures several PIN diodes at prices ranging from about \$15 to more than \$100. The SGD-040, a low cost diode, is well suited for most experimenter applications and is featured in one of the circuits described later in this chapter. Several EG&G PIN diffused photodiodes are shown in Fig. 5-6.

United Detector Technology, like EG&G, a leader in PIN photodiode fabrication, offers one of the most complete lines of the detectors. One of their diodes, the PIN-3D, sells for less than \$10 and is ideal for many experimenter applications. A PIN-3D is shown in Fig. 5-7. Another United Detector Technology diode of interest is the PIN-10. This large area Schottky barrier photodiode is used in some of the circuits presented later in this chapter. Fig. 5-8 is a photograph of the PIN-10.

Other PIN photodiodes are manufactured by Monsanto, Motorola, Hewlett-Packard, and several other semiconductor companies. Many of these diodes have less sensitivity than those just described, but



Courtesy EG&G

Fig. 5-6. Several EG&G high-speed silicon photodiodes.

their low price makes them attractive contenders for applications requiring high signal level. The characteristics of several of these low cost PIN diodes are compared with those of the more sensitive diodes made by EG&G and United Detector Technology in Table 5-1.

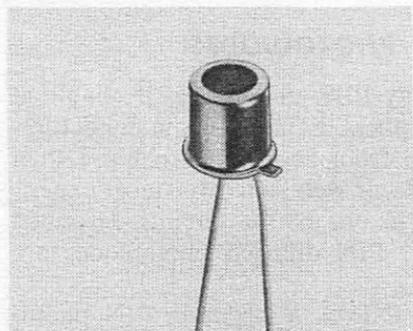


Fig. 5-7. PIN 3-D photodiode.

Courtesy United Detector Technology

AVALANCHE PHOTODIODES

One of the most promising developments in semiconductor detector technology is the avalanche photodiode. Similar in construction to a standard diffused photodiode, the avalanche photodiode is operated at a precise voltage just below the avalanche breakdown point. Special fabrication techniques permit some diodes to be operated at more than 1800 volts before breakdown occurs, thus providing maximum pos-

sible gain. With the diode biased to within a few millivolts of avalanche, an incoming optical signal of sufficient magnitude will cause the diode to switch "on" and deliver a voltage pulse.

Fig. 5-8. PIN 10-D photodiode.



Courtesy United Detector Technology

The sensitivity of the diode compares favorably with photomultipliers, and its rise time is equally good. Because of its temperature sensitivity (a result of tiny fluctuations of avalanche voltage with

Table 5-1. Comparison of Several PIN Photodetectors

Photodetector	Sensitivity ($\mu\text{A}/\mu\text{W}$)	Rise Time (nanoseconds)	Dark Current (nanoamperes)	Capacitance (picofarads)
EG&G				
SGD-040	0.5	3	3	2
SGD-100	0.5	4	10	7
UDT				
PIN-3D	0.4	5	20	6
PIN-10D	0.4	5	500	250
PIN-10	0.35	10	500	130
Motorola				
MRD-500	0.0012	1	2	4
Monsanto				
MD-2	0.004	0.5	200	8

temperature), special-purpose high-voltage power supplies must be used to provide the highly regulated voltage required for proper operation. The high voltage that most of these devices require makes biasing tricky, but the diode is such a significant advance in solid-state-detector technology that it rightly deserves the label "solid-state photomultiplier" applied by one of its manufacturers.

COMMERCIAL AVALANCHE PHOTODIODES

Several semiconductor manufacturers fabricate a variety of avalanche photodiodes. Texas Instruments offers both individual diodes and diodes combined with a special power supply module. Prices are currently above several hundred dollars for most types, and more detailed information can be obtained by writing the company.

General Electric's Space Technology Division sells several types of avalanche photodiodes. One, the Laser Eye Receiver, is supplied with a self-contained power supply and amplifier module and is capable of detecting less than 3 nanowatts of near-infrared light. Since a typical GaAs laser emits at least several watts (peak power), it is easy to see why the avalanche photodiode makes an excellent detector for long range laser communications systems. Complete information on the Laser Eye is available by writing the company.

EG&G is also a manufacturer of avalanche photodiodes. Their AV-102 has an avalanche voltage of about 12 volts and therefore has less internal gain than high-voltage units. The diode is considerably less costly than more sensitive units, however.

PHOTODETECTOR TRADE-OFFS

Before beginning the section on laser receivers, some of the major trade-offs that must be considered when choosing a detector will be reviewed. The foremost considerations are response time and sensitivity. A fast response time is essential for efficient detection of a pulse from an injection laser. Even slow detectors will respond to an injection laser pulse, but, as Fig. 5-9 shows, only a tiny amount of the laser pulse will be detected.

Sensitivity is usually closely related to response time. Photomultiplier tubes and avalanche photodiodes are exceptions, but generally the more sensitive the detector, the slower its response time. An inter-

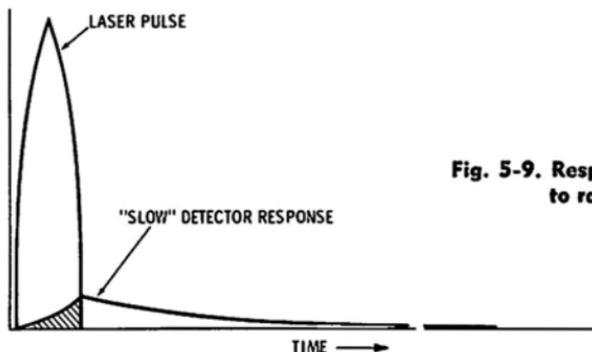
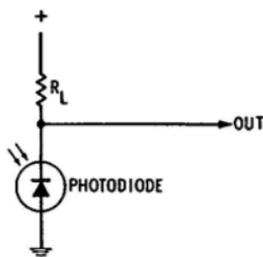


Fig. 5-9. Response of "slow" detector to rapid laser pulse.

esting interaction between sensitivity and response time occurs in the selection of a load resistor. Fig. 5-10 shows a typical photodiode circuit, R_L being the load resistor across which the light-generated current must flow. If R_L is large in value, a very small current will produce a comparatively large voltage. For example, a light-generated current of 2 microamps will appear as 2 volts across a 1-megohm load resistor. On the other hand, the same current will appear as only 100 microvolts across a 50-ohm load resistor.

Fig. 5-10. Basic photodiode circuit.



For very sensitive detection applications, the choice seems obvious—use a high resistance load. But if the optical signal is modulated at a high frequency, choice of a detector is limited by the RC factor. The resistance of R_L multiplied by the capacitance of the photodiode produces a time constant that can significantly alter the ability of a detector to detect high frequencies.

Fig. 5-11 is a graph of sensitivity vs load resistance for a detector circuit using an EG&G SGD-040 PIN detector. The graph clearly shows that an optimum value for R_L can be chosen by setting up a test jig into which a variety of resistors can be inserted and monitoring the output of the circuit with an oscilloscope. In this case, the input pulse was square, with a width of 17.5 microseconds. For the much briefer pulses emitted by injection lasers, a new curve can be

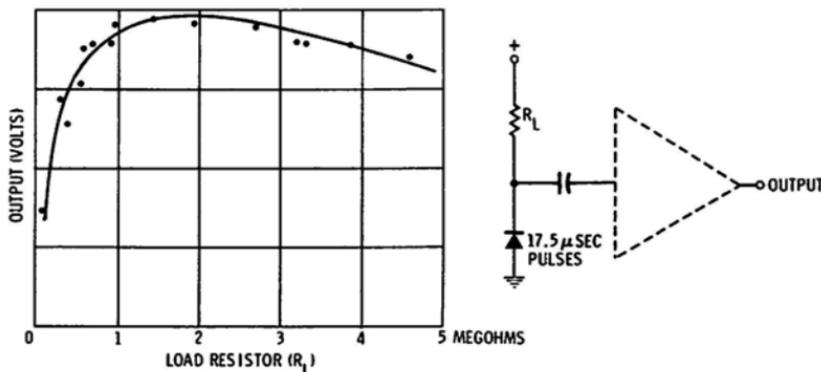


Fig. 5-11. Sensitivity versus photodiode load resistor.

generated. Because of the RC factor, a curve made with a 100- or 200-nanosecond pulse would push the curve to the left, meaning that a reduced value for R_L is necessary for optimum detection.

Since PIN detectors are relatively inexpensive and operate well in injection laser applications, they have predominated in this brief discussion of detector trade-offs. There are several other trade-offs that affect PIN photodiodes as well as all other light detectors, and they are summarized in Table 5-2. Some of the parameters include spectral response, sensitivity, and response time.

Table 5-2. Laser Detector Trade-Offs

Detector	Peak Spectral Response (nanometers)	Sensitivity (mA/mW/cm ²)	Response Time (nanoseconds)	Dark Current (nanoamperes)
Solar Cell	820	0.25	20	—
Phototransistor	800	0.8	3	25
Fotofet	950	10.0	0.05	1
PIN Photodiode	900	0.5	0.005	2

RECEIVERS

Once a detector has been chosen for a particular injection laser application, a circuit for amplifying or processing its signals must be selected. The short pulse width of injection lasers places special limitations on the detector circuitry, as we have already seen in the case of the load resistor. There is little sense in employing a very fast (and perhaps costly) detector if the amplifier and processing circuit cannot respond efficiently to very rapid pulses.

While an audio-modulated LED or double heterostructure laser can be detected by a receiver circuit with a very low frequency response, an injection laser receiver must have a response of at least one megahertz and preferably ten. For some limited applications and bench tests, low frequency receiving systems will operate satisfactorily.

TWO "SLOW" RECEIVERS

Pulses from an injection laser only 50 nanoseconds in width can actually be detected with nothing more than a single silicon solar cell and a transistor-radio earphone. The arrangement is certainly not the most sensitive type of receiver, but it makes an excellent device for quickly checking the operation of a laser setup. The low cost of this type of receiver should particularly appear to the budget-conscious experimenter. Since the solar cell tends to integrate the laser pulses,

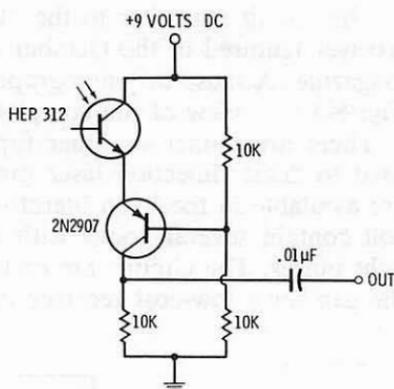


Fig. 5-12. Basic photodiode circuit.

they are stretched and may be easily amplified by a standard transistor amplifier. The audio-frequency amplifiers sold by most electronics parts dealers for less than five dollars are excellent for this purpose. The use of an amplifier will significantly improve the utilization of a solar-cell detector.

A type of receiver somewhat more sophisticated than the solar-cell version just described can be made with a phototransistor. A simple circuit for a phototransistor receiver is shown in Fig. 5-12. The circuit can be used as is, but much better results will be had if several stages of transistor amplification are added.



Fig. 5-13. Internal view of phototransistor laser receiver.

The circuit is similar to the "front end" of a phototransistor-laser receiver featured in the October 1971 edition of *Popular Electronics* magazine. A close-up photograph of the receiver circuit is shown in Fig. 5-13. A view of the completed receiver is provided in Fig. 4-9.

There are numerous other types of "slow" receivers that can be used to detect injection laser pulses at close ranges. Many of them are available in the open literature, and any reasonably good library will contain several books with at least a few circuits for detecting light pulses. The circuits are certainly not optimum, but they will fill the gap for a low-cost receiver operated relatively close to the laser.

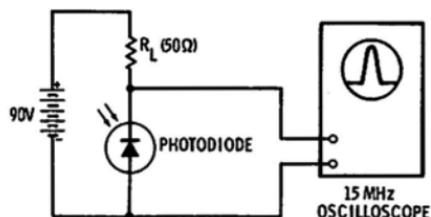


Fig. 5-14. Basic "fast" laser receiver.

A BASIC "FAST" RECEIVER

For accurately displaying on a wide-band oscilloscope the pulse shape of an injection laser, a simple circuit consisting of nothing more than a PIN photodiode, a load resistor, and a 90-volt battery can be used. The circuit arrangement is shown in Fig. 5-14. In operation, a suitable oscilloscope will display the laser pulse with an amplitude proportional to its strength when the scope is connected across the load resistor. Recall from the previous discussion on load resistors that the pulse will be displayed more accurately if the value of R_L is kept low.

While the circuit itself is quite simple and can be quickly assembled for less than ten dollars, proper operation requires an oscilloscope with a frequency response of 15 or 20 megahertz. An oscilloscope with this type of response can be purchased for a few hundred dollars, but the experimenter without one will be hard pressed to fully exploit the circuit. One possibility is to borrow a wide-band scope from a university or a television repair shop.

FOTOFET LASER RECEIVER

A relatively sophisticated laser receiver circuit can be assembled with the inclusion of a Fotofet detector. A circuit for such a receiver is shown in Fig. 5-15. In operation, the speed-up transistor Q-2 increases the response capability of Fotofet Q1, enabling it to more efficiently detect brief laser pulses. The signal appearing across load

portable use, it is best to mount the final assembly in a sturdy enclosure. The Fotofet can be mounted to the outside of the enclosure as in Fig. 5-17 or mounted inside and coupled to the outside by means of a small hole or lens assembly. A lens will do much for improving the range capability of the unit. Chapter 6 discusses external optics for both receivers and transmitters at length.

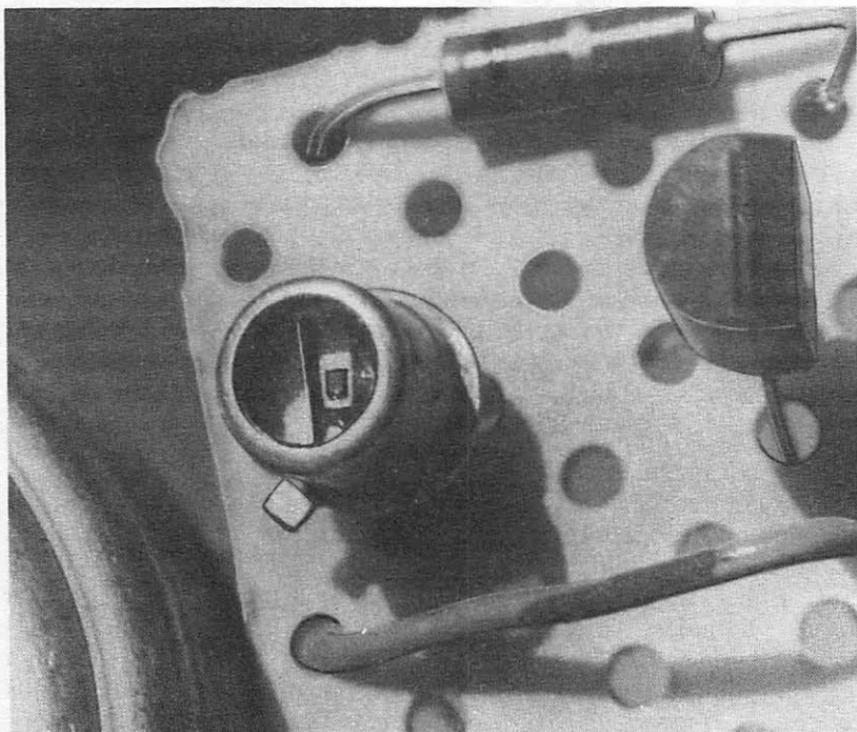


Fig. 5-16. Close-up of Fotofet detector.

PHOTODIODE LASER RECEIVER

A PIN photodiode and a single integrated amplifier can be used to detect pulses from a 10-watt injection laser at a range of about half a mile. This figure was obtained by author Campbell, using a well-collimated laser and a PIN-10 photodiode from United Detector Technology. No lens was used with the large-surface-area detector.

The circuit for the receiver is shown in Fig. 5-18. In operation, a FET source follower acts as a high-frequency impedance converter in coupling the light-generated signal from detector to amplifier. The PIN-10 detector was biased with 45 volts in the original receiver, but less voltage can be used if decreased sensitivity can be tolerated. As with the previous receiver circuit, R_L can be adjusted for maximum

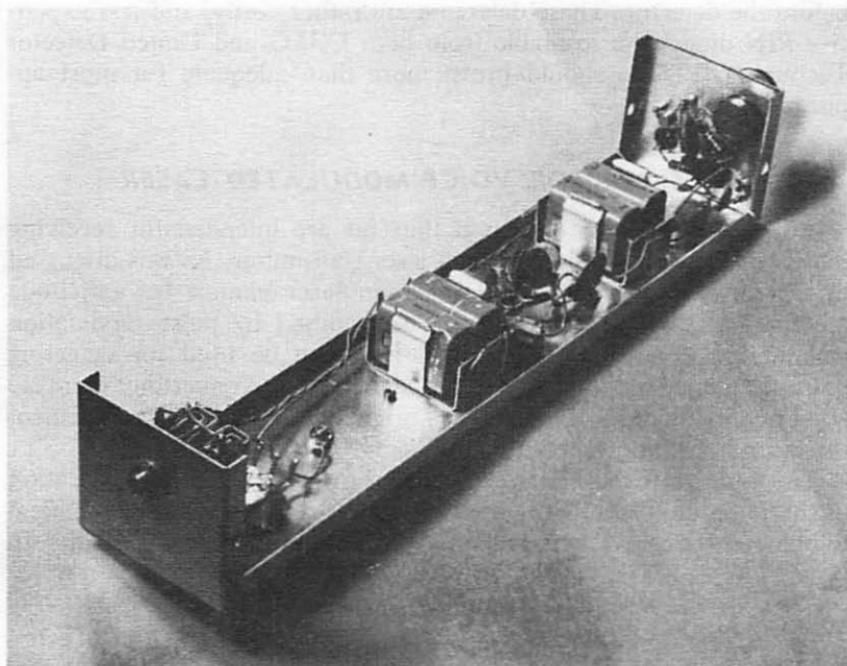


Fig. 5-17. View of Fotofet receiver.

sensitivity. Also, a variety of detectors can be used with the circuit. For example, a PIN-6LC, also a United Detector Technology product, received the laser signal at 2.4 miles when a lens was placed

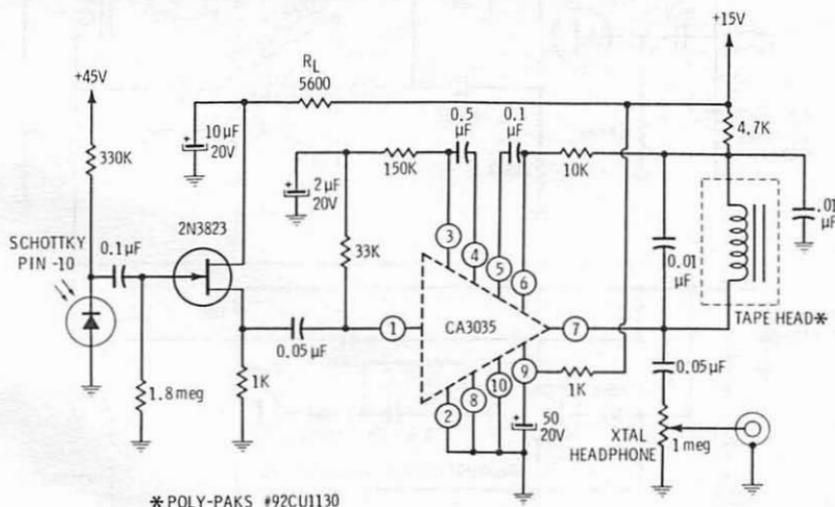


Fig. 5-18. PIN photodiode laser receiver.

before the detector. These detectors are rather costly, and less expensive PIN diodes are available from both EG&G and United Detector Technology. These should prove more than adequate for most applications.

RECEIVER FOR VOICE-MODULATED LASER

All of the receivers discussed thus far are intended for receiving pulse or tone transmissions from a laser transmitter. As was discussed in Chapter 4, a conventional injection laser cannot be amplitude modulated, and voice can only be transmitted by pulse modulation techniques. The receiver described here can be used for detecting pulse-frequency-modulated (pfm) signals and converting them to good quality audio. The circuit was originally designed to complement the laser transmitter shown in Fig. 4-34.

The circuit for the laser receiver is shown in Fig. 5-19. Operation of the photodiode and integrated circuit portions is virtually identical to that of the previous receiver. The circuit is given the ability to

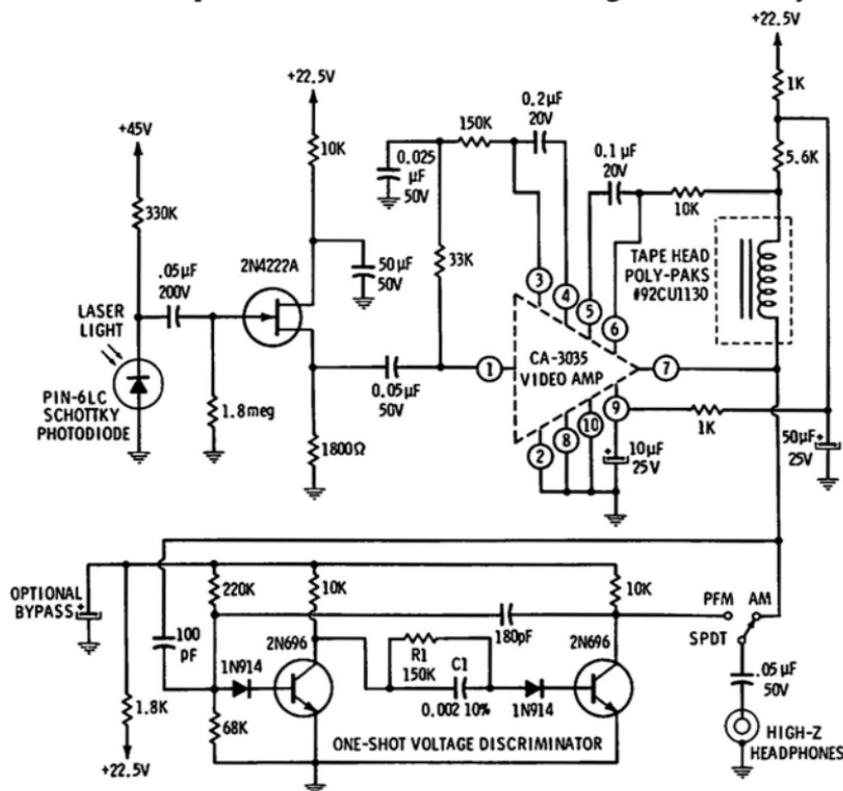


Fig. 5-19. Am/fm laser receiver for voice communications.

demodulate pulsed fm signals by a simple monostable multivibrator connected to the output of the integrated amplifier. The circuit for the multivibrator was adapted from a similar receiver design presented in Part Two of the General Electric Solid State Lamps Manual ("Optical-Electrical Receiver," p 37).

When the amplifier sends a pulse to the multivibrator, it turns on for several milliseconds if the pulse is of sufficient amplitude. The circuit is adjusted so that the trigger point is higher than most random noise signals and those that do get through cause little problem. The multivibrator can be switched out of the circuit for receiving tone transmissions by an "AM-PFM" switch.

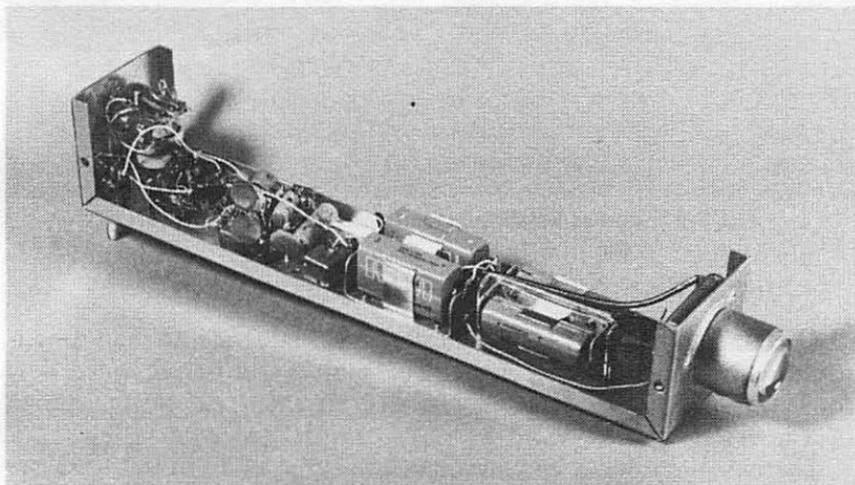


Fig. 5-20. Internal view of assembled am/fm voice laser receiver.

Some experimentation with the values of R1 and C1 in the multivibrator may be needed for optimum operation. The original receiver used values of 150,000 ohms and 0.002 μ F respectively, but slightly different values may operate better in other versions of the circuit. In order to check the suitability of R1 and C1, the following procedure can be used. Merely aim the laser transmitter at the detector of the receiver and listen to the audio signal as various values of R1 and C1 are substituted into the circuit. Choose values that provide the best quality reception.

Note the lens mount placed ahead of the detector in Fig. 5-20, an internal view of the receiver. A photograph of the external view of the receiver and a voice modulated laser transmitter is shown in Fig. 5-21. Using this equipment, author Campbell succeeded in transmitting and receiving voice communications at a distance of approximately 3.5 miles.



Fig. 5-21. Author Ralph Campbell operating laser transceiver.

INTEGRATED CIRCUITS FOR LASER RECEIVERS

Thus far nothing has been said about the integrated circuit amplifiers used in these laser receivers. The subject will be presented now for the benefit of those readers who wish to undertake custom design of a laser receiver.

The CA-3035 linear amplifier has been used in all of the receivers that provide amplification for the detected signal. The CA-3035 is actually an array of three separate amplifiers within a single IC package, and the receiver circuits connect them in series in order to achieve maximum possible gain. Since one of the three amplifiers has a maximum frequency response of only half a megahertz, the CA-3035 does not provide optimum efficiency in injection laser applications. Nevertheless, it works well, as the 3.5-mile communication range achieved with one of the receivers clearly attests.

Somewhat better results can be obtained with integrated amplifiers having higher frequency response than the CA-3035. A circuit using such an amplifier, the CA-3011, is shown in Fig. 5-22. The CA-3011 amplifies signals from an SGD-040 photodiode, though, as with the other receiver circuits in this chapter, a variety of photodiodes will operate in the circuit. When operated at 9 volts, the circuit draws about 20 milliamperes, not much more than the current drawn by a typical transistor radio.

When 40-nanosecond pulses from an injection laser are directed toward the photodiode, the IC will exhibit a gain of about 1000. The

single stage of transistor amplification that precedes the IC exhibits a gain of about 5. The gain is certainly adequate for many laser applications, and a wider laser pulse and additional amplification should provide even further improvement.

Like the CA-3035, the CA-3011 is very economical; both ICs can be purchased for only a few dollars each. The CA-3011, however, is designed specifically to amplify signals having a frequency in excess of 10 MHz, a significant improvement over the frequency response of the CA-3035. While the CA-3011 does not have the gain of the CA-3035, it can be used in conjunction with another CA-3011 or another high-frequency IC to provide high-gain amplification.

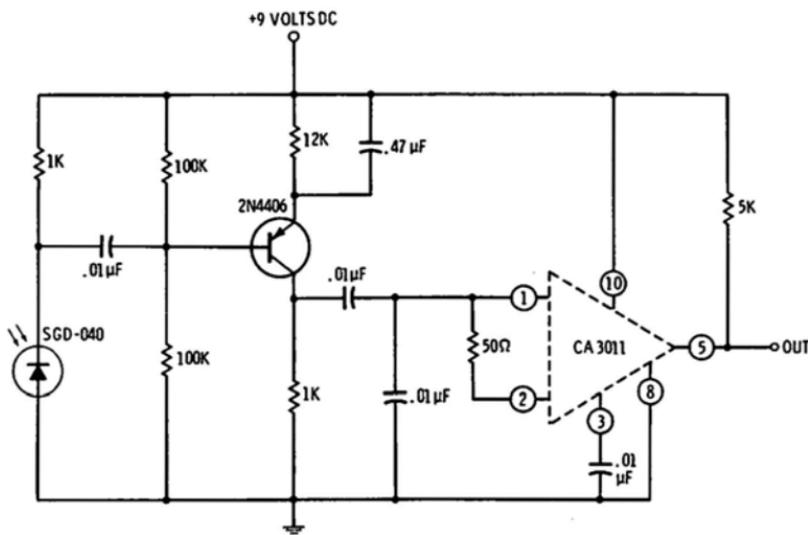


Fig. 5-22. Laser receiver using high-frequency integrated circuit.

RCA manufactures both the CA-3011 and CA-3035, as well as a variety of other linear IC amplifiers well suited to injection laser applications. "Linear Integrated Circuits," an RCA publication available from major electronic parts suppliers, includes an excellent survey of the company's inexpensive high-frequency IC amplifiers and a number of practical circuits. The experimenter who wishes to design his own laser receiver will find a good deal of helpful information on high-frequency, low-cost amplifiers in the book.

COMMERCIAL RECEIVERS

There are a variety of interesting receivers well-suited to injection laser applications and research. Two commercial receivers are the Micro Instrumentation and Telemetry Systems injection-laser re-

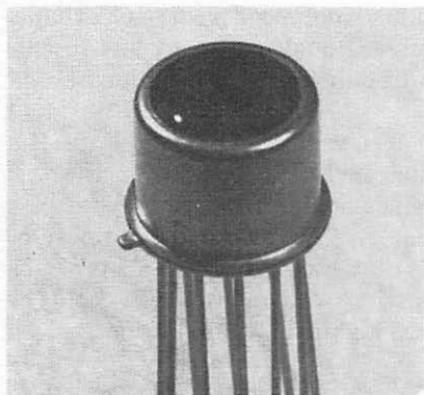


Fig. 5-23. HAD-1000 integrated-circuit operational amplifier.

Courtesy EG&G

ceiver kit and the General Electric Laser Eye receiver. The former is economical, but has limited sensitivity, while the latter, which uses an avalanche photodiode, can detect less than 3 nanowatts of near infrared, but is quite costly.



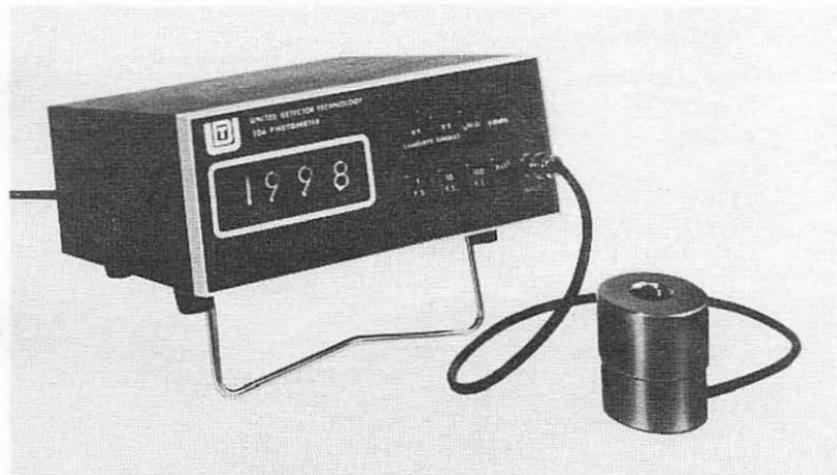
Courtesy EG&G

Fig. 5-24. EG&G radiometer system for precision light measurement.

A receiver that combines 10-nanowatt sensitivity with the ability to detect a 7-nanosecond pulse is the Metrologic Instruments Model 60-244 Photodetector. Housed in a compact enclosure complete with high-frequency (50-MHz) amplifier, the Model 60-244 sells for less than a hundred dollars.

Another compact laser receiver is manufactured by Steller Instrument Northwest, Inc. At nearly \$500, the receiver is costly, but its miniature size and internal battery compartment make it a useful instrument in many applications.

Both EG&G and United Detector Technology manufacture special IC amplifiers with self-contained photodiodes. Fig. 5-23 shows the HAD-1000 Operational Amplifier, an EG&G integrated circuit. It is similar in appearance to the HAD-130, also an EG&G IC, and to the United Detector Technology UDT-400.



Courtesy United Detector Technology

Fig. 5-25. Digital light detector.

None of these amplifier-photodiodes have optimum frequency response for injection laser applications. However, they will respond to brief pulses, though inefficiently, and may be used in applications requiring low sensitivity. They should prove quite useful with light-emitting diodes and double-heterostructure injection lasers modulated at frequencies below a megahertz. Prices are currently above a hundred dollars, so use of the ICs will be limited to specialized applications until volume production results in a cost drop.

Besides IC photodiode receivers, both United Detector Technology and EG&G manufacture specialized laboratory instruments for the precision measurement of laser pulses. The photograph in Fig. 5-24 shows an EG&G Radiometer and Radiometer Indicator Unit along

with a laser beam sampler. The units are intended for laboratory laser research. A somewhat more economical laser sampler is the United Detector Technology Photometer. The unit, shown in Fig. 5-25, includes a detector head and a digital readout. Switches permit light intensity readings to be easily selected.

Optics and Viewing Devices

The near-infrared light emitted by most injection lasers is like visible light in that it can be focused, reflected, and filtered by a variety of common optical components like those in Fig. 6-1. External optics are extremely important in many injection laser applications, particularly communications and optical radar (ranging). Merely placing a lens in front of the detector of a receiver can increase the reception range by a factor of five, ten, or even a hundred. And properly aligning a lens used to collimate a laser beam can mean equally significant range improvements.

Besides optics, this chapter describes several types of highly specialized detectors left over from Chapter 5—near-infrared viewing devices. Often called *image converters*, these specialized detectors are most often used in aligning external optics and for that reason were reserved for this section of the book.

LENSES

The most important optical device for injection laser applications is the lens. With but a single, simple lens costing less than a dollar, the 20° infrared beam emerging from a typical injection laser can be reduced to a divergence of but a few tenths of a degree. The resultant beam narrowing is very important to increasing the range of laser communicators and rangefinders.

Similarly, a lens may be employed to collect a good deal more infrared than would normally be received on the bare surface of a detector. A lens with a diameter of 2 centimeters (2.54 centimeters equals 1 inch) will gather 100 times more light than a bare detector with a diameter of 0.2 centimeter. This example should convincingly demonstrate the advantage of using lenses in injection laser applications.

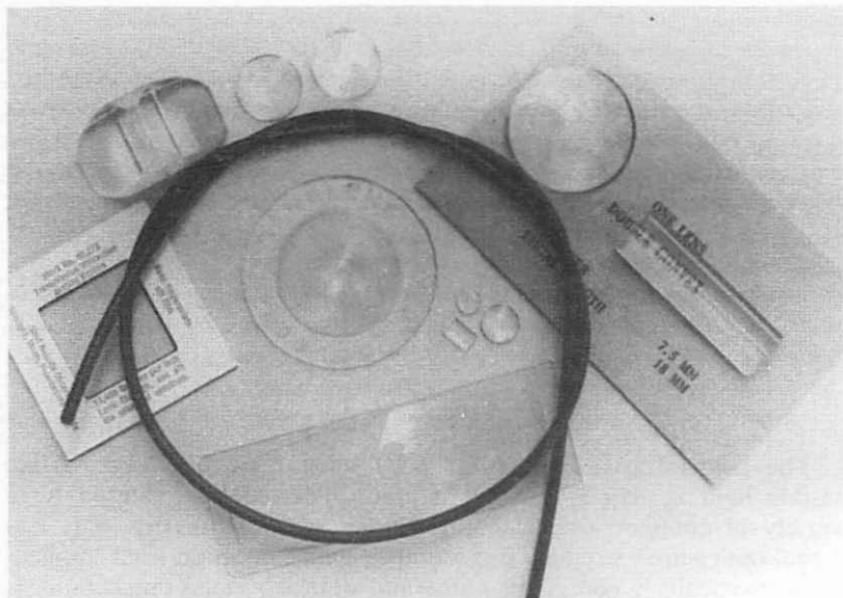


Fig. 6-1. Fresnel, circular, and cylinder lenses, together with fiber optics light guide and a diffraction grating.

Because light from an injection laser is nearly monochromatic, simple lenses will perform well in most applications. For optimum beam collimation, however, compound lenses should be used. They will reduce the divergence that can result from even the very narrow spectral width (a few tenths of a nanometer) exhibited by these lasers.

Another type of simple lens that is very useful is the cylinder lens. This type of lens, as the name implies, is a section of a cylinder rather than a sphere. Since it is curved in only one dimension, the lens magnifies or focuses in only one plane. Therefore, it has the ability to project a fan-shaped beam, particularly when used with a small source of light, such as the injection laser. The military has employed arrays of cylinder lenses and lasers in experimental aerial reconnaissance systems that sweep the ground below an aircraft with a very narrow, intense beam of infrared.

Choosing a Lens

Choosing a lens for collimating a laser beam is a relatively simple procedure, particularly since the light emerges from such a tiny point and optimum collimation occurs when a light source is placed directly at the focal point of a lens. When matching conventional light sources with a lens system, several trade-offs must be considered for optimum results. For example, the relatively large size of the source means that a lens of long focal length must be used to obtain good collimation. Yet a long focal length means that a large-diameter lens must be used to collect sufficient light for the intended application.

No such problem exists with the injection laser. Since its light is emitted from a point source in the form of a distinct beam, all of it can be collected and collimated by a small-diameter lens placed a few centimeters from the laser. A simple equation can be used to predict the approximate divergence that will be produced by a particular lens and laser:

$$\theta = \frac{d}{f} \quad 6.1$$

where,

- θ is the beam divergence in radians,
- d is the width of the laser junction,
- f is the focal length of the lens.

(Radians can be converted to degrees by multiplying the angle expressed in radians by 57.3.)

Accuracy of the equation can be quickly checked with a simple experiment. If a lens with a focal length of 0.6" is used to collimate a laser with a 0.003" wide junction, the equation predicts a divergence of 0.005 radians (0.287°). A test with an actual laser and lens was conducted and the divergence was found to be 0.0048 radians, the slight difference being due to the difference in focal length caused by the infrared light of the laser (the focal length was measured with visible light).

Various manufacturers specify different beam divergences for their lasers. Therefore, they also specify different lens requirements. The only important requirement is the f number, the focal length divided by the diameter of the lens. A small f number means that most of the laser light will be collected by the lens. RCA specifies an $f/1$ lens for optimum light collection with its lasers, while Texas Instruments maintains that an $f/2.8$ lens will collect 90% of the light emerging from its lasers. The difference is mainly due to slight variations in laser beam divergence, and the two f numbers provide a good spread from which to choose a lens. For applications requiring the utmost in collimation, the higher f number is the better choice, while most

general applications will be adequately served with practically any lens within the $f/1$ to $f/2.8$ range.

It should be noted that *positive* lenses must be used to collimate laser beams. Either plano-convex or double convex lenses, the type used in magnifiers and eyepieces, may be employed.

Lens Alignment

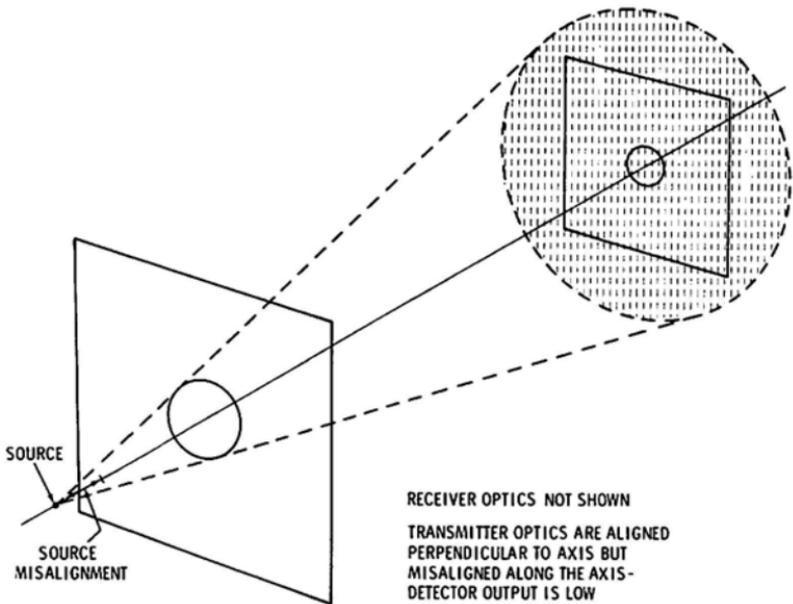
Often a lens can be accurately aligned by sight without the need for an infrared viewing device. The simplest technique is to align the lens so that when viewed straight-on the laser chip is magnified to the point where its blurred image fills the lens. (CAUTION. Do *not* view a laser straight-on when it is operating.) Better collimation can be achieved with an infrared viewing device, however, as the lens can be adjusted until the desired spot size appears on a sheet of white paper several feet from the laser.

An intentional error in focusing a lens can be advantageous in many applications. A perfectly focused injection laser will produce a rectangular pattern representative of the shape of the light-emitting junction (see Fig. 2-18), while a mere few thousandths of an inch displacement of laser chip from focal point will produce a circular pattern.

Angular misalignments are disadvantageous, since they cause some of the laser light to be projected at an angle from the primary beam. For this reason, the laser should be aligned so that the chip is perfectly centered when viewed through the lens. This procedure poses no problem with lasers that have a perfectly centered chip, since both lens and laser can be mechanically aligned within the same holder assembly. Lasers with an offset chip, however, pose a special problem as they must be provided with a similarly offset holder.

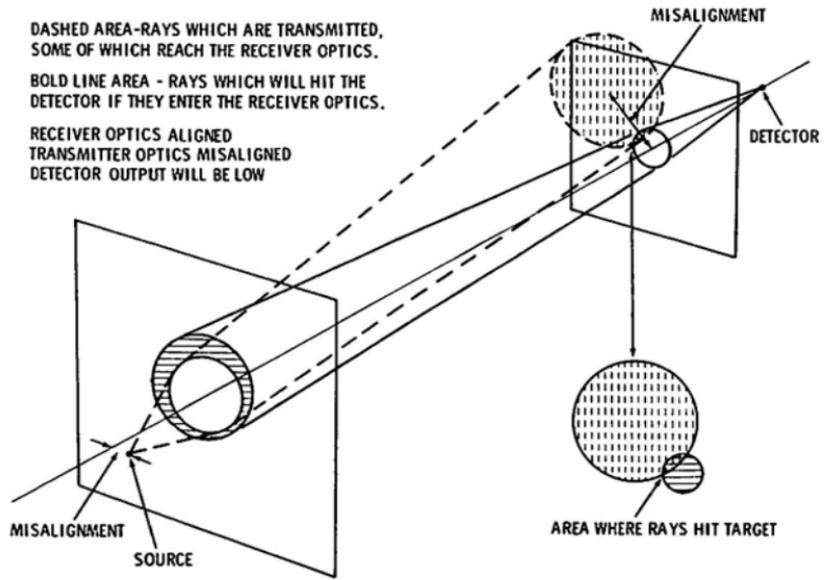
Alignment is particularly important to optical communication links. While the very narrow beam of a collimated laser makes for a totally secret, jam-proof communications system, slight misalignments can make detection by the intended receiver difficult, if not impossible. Several examples of misalignment are summarized in Figs. 6-2, 6-3, and 6-4. In Fig. 6-2, the laser is mounted too far behind the focal point of the lens, thus resulting in a very wide, conical beam with low power density at the receiver. While the wide beam eases the problem of aligning laser with receiver, the low signal strength at the receiver significantly reduces maximum range capability.

Fig. 6-3 shows the result of a slight lateral misalignment of laser chip with respect to lens focal point. In this case, the transmitter lens may appear to be in alignment with the receiver, but the laser beam is actually projected at an angle and only a small portion of it strikes the receiver aperture. Of course, the transmitter itself can be slightly misaligned to allow for the laser focusing error, but then the function



Courtesy Richard S. Myers, RCA

Fig. 6-2. Lens alignment: laser behind lens focal point.



Courtesy Richard S. Myers, RCA

Fig. 6-3. Lens alignment: laser laterally displaced from focal point.

of any optical sighting devices used to visually align transmitter with receiver will be defeated and final alignment will be much more difficult.

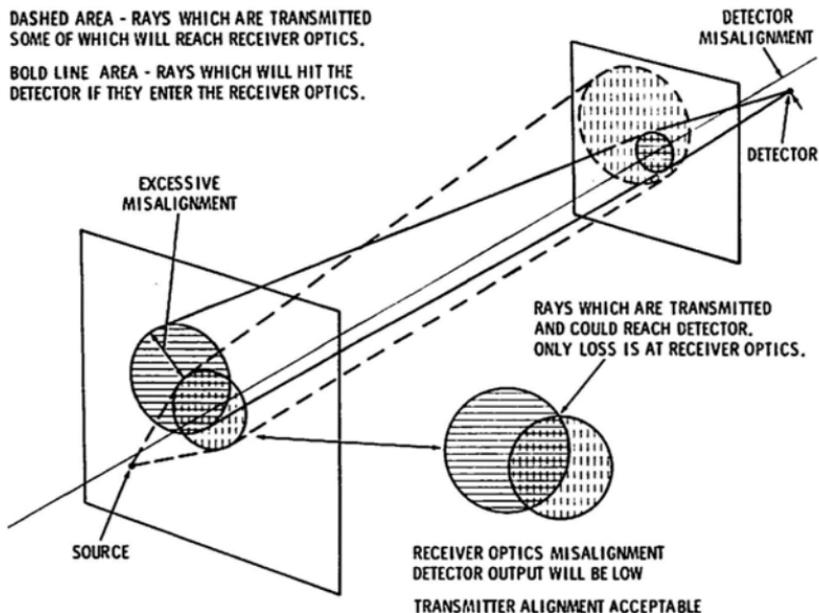
In Fig. 6-4, the transmitter and its lens are properly aligned, but the receiver and its detector are not. We then have the same optical alignment situation as in the previous example. The receiver detector can be aligned visually by merely centering and focusing until its active area fills the lens aperture. Since detectors are much larger than laser chips, the procedure is quite easily accomplished.

Finally, in Fig. 6-5, both laser and detector are aligned relatively well, and the receiver intercepts a maximum amount of laser light. Besides permitting high signal strength at the receiver, good alignment makes possible rapid establishment of communications with only simple sights mounted on both transmitter and receiver. For very long range communications, telescopic sights are very useful. Fig. 6-6 shows a laser transmitter with a small optical telescope for rapid sighting of the receiver at long ranges. The sight must be boresighted with the laser (note the optical assembly of the laser in the photograph), sometimes a tedious process. The sight can save many hours of time which would otherwise be wasted in attempting to set up a communications link.

One relatively quick and simple method to boresight a laser transmitter sight is to set up laser and receiver so that they are separated

DASHED AREA - RAYS WHICH ARE TRANSMITTED SOME OF WHICH WILL REACH RECEIVER OPTICS.

BOLD LINE AREA - RAYS WHICH WILL HIT THE DETECTOR IF THEY ENTER THE RECEIVER OPTICS.

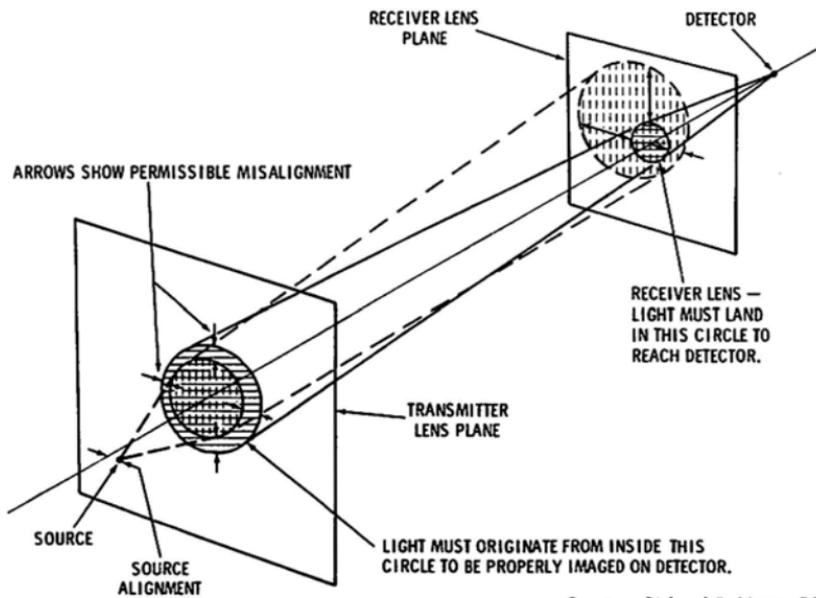


Courtesy Richard S. Myers, RCA

Fig. 6-4. Lens alignment: receiver detector misaligned.

by a hundred feet or so, hand-align the laser so that maximum signal is received at the receiver, and carefully fasten the sight so that it is aimed directly at the receiver. Remember that the sight alignment will only be as good as the laser lens alignment. An offset laser collimation lens will project an off-axis beam and any rotation of the lens will destroy alignment of the optical sight.

This section on lens alignment is graphically summarized by the two infrared photographs in Fig. 6-7A and B. In A, a slight misalignment of the laser and the focal point results in a poor beam pattern with a good deal of the light being projected at an angle from the primary beam. In B, a relatively good alignment has been obtained, and a circular pattern is projected. The photographs were made with a GaAs injection laser, a small, double-convex lens, and infrared film, using techniques described later in this chapter.



Courtesy Richard S. Myers, RCA

Fig. 6-5. Good lens alignment.

INFRARED FILTERS

Since the detector of most light-beam communication and range-finder receivers will respond to a wide variety of interfering wavelengths of light, an infrared filter should be employed to select only the desired wavelength. Because of its broadband spectral characteristics and intensity, sunlight is a particularly strong source of optical interference. While many receivers will operate quite well during darkness with no filter, daylight operation may be all but impossible.



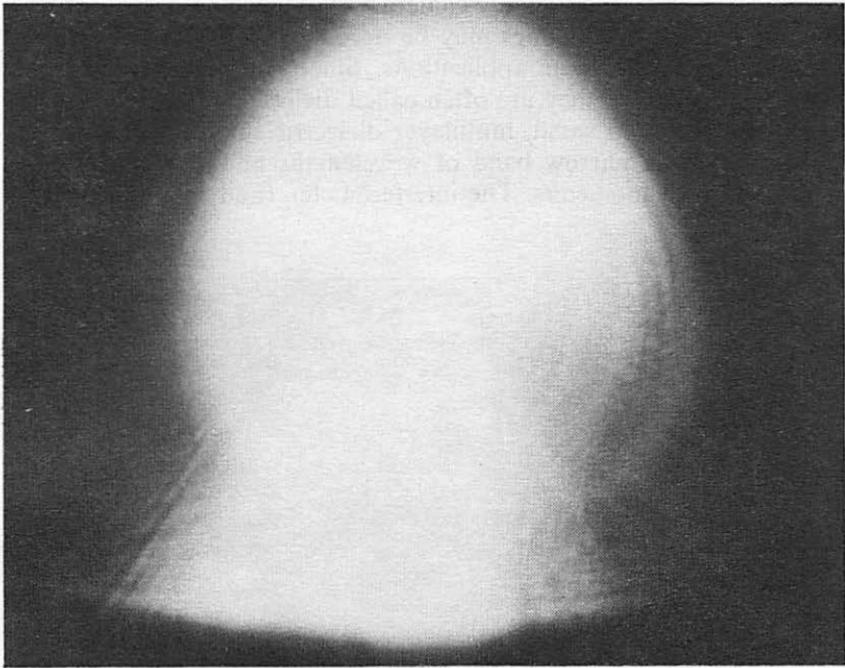
Fig. 6-6. Laser transmitter and bore-sighted telescope.

There are a variety of infrared filters that will significantly improve the optical noise rejection of a receiver. Some are purely optical, while others are mechanical. Using either type or a combination of both will significantly enhance receiver capabilities in the presence of an interfering optical source.

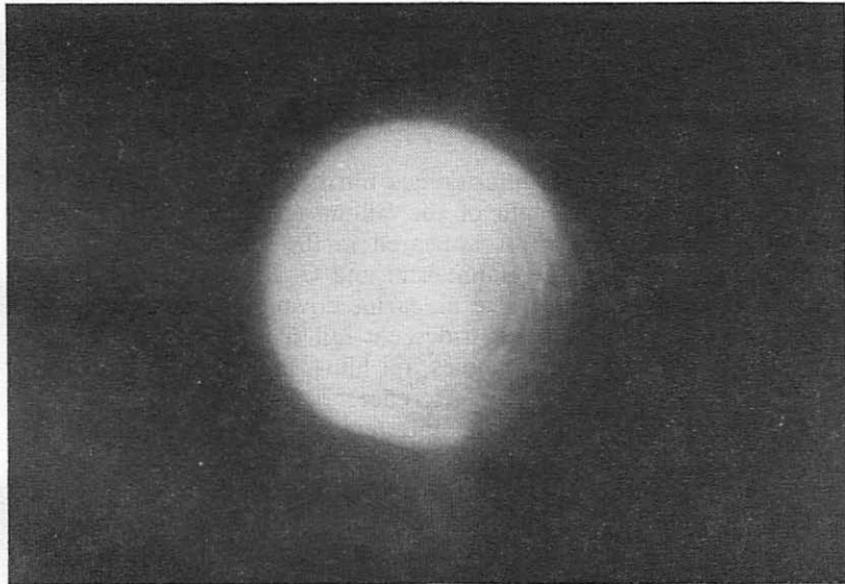
Narrow-Band Optical Filters

The ideal optical filter would pass only the desired wavelength and reject all others. The interference filter comes closest to meeting this difficult requirement.

An interference filter usually consists of a very flat circle or square of glass upon which have been deposited several alternating layers of materials with different indexes of refraction. By varying the thickness of the layers, their refractive indexes, and their number, it is possible to use optical interference to make mirrors and filters that reflect or transmit very narrow wavelengths of light. The most common (and the simplest) example of the interference filter is the antireflection



(A) Laser slightly misaligned with respect to focal point of collimating lens.



(B) Laser in relatively good alignment with focal point of lens.

Fig. 6-7. Infrared photos of lens alignment.

coating applied to good quality camera and binocular lenses. More advanced interference coatings may be dozens of layers thick and used in special purpose laser applications. Since interference filters are usually nonmetallic, they are often called dielectric filters.

Fig. 6-8 shows a small, multilayer dielectric interference filter designed to pass a narrow band of wavelengths at the primary GaAs region of 905 nanometers. The interferometer (and the laser) shown

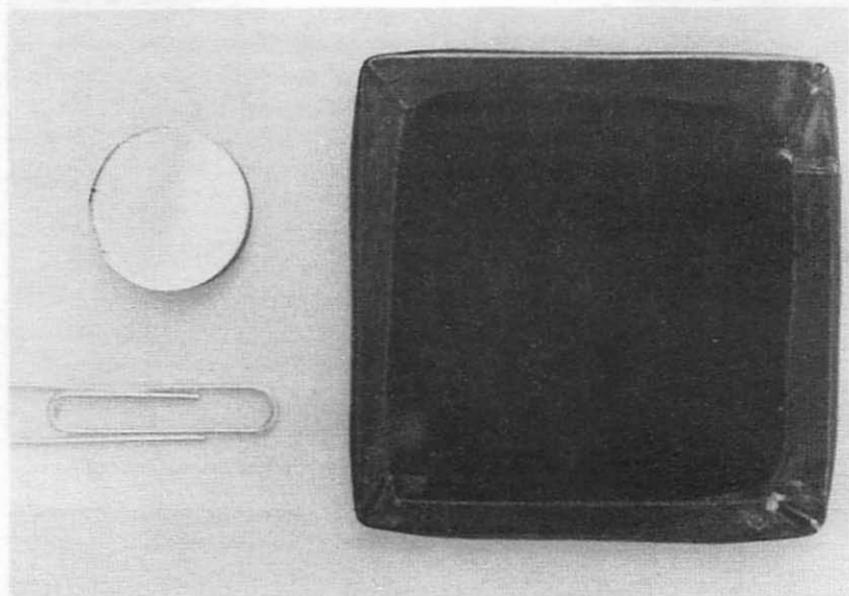


Fig. 6-8. Infrared interference filter (circular) and absorption filter.

in Fig. 2-24 uses several interference mirrors designed to reflect the 632.8-nanometer wavelength of the helium-neon laser. An excellent article on interference filters appeared in the December 1970 issue of *Scientific American* (P. Baumeister and G. Pincus, "Optical Interference Coatings," p 59). The magazine cover featured a portion of a peacock's brightly colored, iridescent tail feather, a representative example, along with soap bubbles, oil films, and mother of pearl, of naturally occurring thin-film interference.

The major drawback of the interference filter is cost—the one shown in Fig. 6-5 sells for about \$35 surplus. However, the high cost can be well justified by the reduction in noise from interfering optical sources, particularly sunlight. At sea level, sunlight can irradiate the earth's surface with up to 100 watts per square meter, and a narrow bandpass interference filter can reduce the amount of solar background power reaching a detector to a maximum of a few nanowatts. In this manner, the detector is not overloaded or saturated and the dc compo-

ment of the small amount of light that does get through is blocked by capacitive coupling between receiver stages.

Installation of an interference filter in front of a detector is a simple mechanical problem. If a lens is used, the filter should be mounted in front of the lens since its operation will be less efficient if nonparallel rays of light are passed through it.

Broad-Band Optical Filters

A filter that is both less efficient and less costly than the interference filter is the broad-band type. Usually made of plastic or glass coated with light-absorbing material, these simple absorption filters are available in a wide variety of configurations. Since they generally absorb a good deal of the desired wavelength as well as the undesired ones, they are not nearly as desirable as interference filters. However, where low cost is an important consideration, they should be used in lieu of no filter at all.

Like the interference filters, installation should pose no special problems. Since this type of filter is unaffected by nonparallel light, it can be placed either behind or in front of a lens.

Other Filters

Simple baffles and light shields can make important contributions in reducing external light. In a simple receiver using a large-area solar cell for a detector, a baffle made from a small piece of aluminum "honey comb" for use in aircraft rejected enough sunlight to make limited operation in sunlight possible. The baffle was coated with lampblack to eliminate internal reflections.

Ordinary cardboard tubing or aluminum foil make good temporary light shields. Foil can be glued to plastic lens tubes and used permanently. For optimum results, light scattering and reflection can be reduced to a minimum by applying a coat of dull black paint to the inside of a light shield.

FIBER OPTICS

A specialized optical component that can be very useful in certain injection laser applications is a fiber optics light guide. As the name implies, these guides are composed of thin strands of plastic or glass that have the ability to transmit light from one end to the other with little loss along the way. The principle of light conduction through a transparent fiber is identical to the concept of total internal reflection discussed in Chapter 1—the air to fiber interface results in the light beam being reflected back into the fiber rather than escaping into the air. Some fibers are clad with a plastic or glass coating with an index of refraction different from that of the primary fiber. In these fibers,

internal reflection takes place at the junction of the core with the cladding. An interesting photograph showing light emerging from one end of a fiber optics bundle is shown in Fig. 6-9; sunlight enters the opposite end of the bent fibers and emerges practically unaffected by its trip through a foot of plastic.

Single optical fibers have been used to couple light from a single laser diode to a collection point filled with other fibers from as many as scores of lasers. The process significantly reduces the source size of a laser array and permits collimation with but a simple lens. Bundles of fibers have also been used in communications experiments and in monitors. In the latter case, a few strands are placed near the laser in a laser transmitter and are used to couple a tiny amount of the light output to a power-monitoring photodiode.

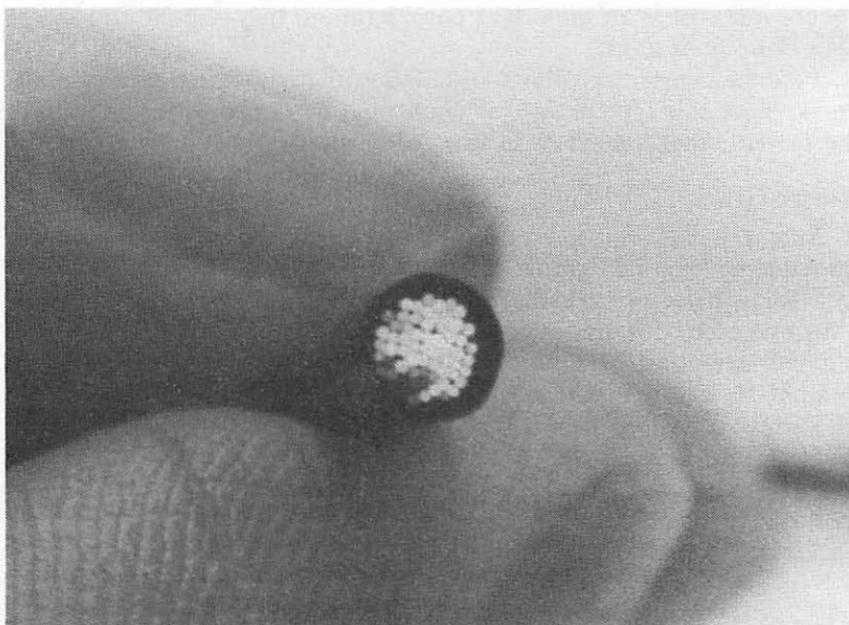


Fig. 6-9. Light emerging from fiber optics bundle.

OTHER OPTICAL COMPONENTS

A number of other common optical components can prove useful in injection laser applications. Mirrors can be used to reflect collimated or raw laser beams to places otherwise inaccessible. Ordinary dime-store mirrors should prove adequate for many applications, but for precision work front-surface mirrors should be used. (A front- or first-surface mirror is one that is silvered on an exposed, uncovered side.)

Beam splitters, thin squares or circles of glass, are useful when one wishes to sample a small portion of a laser beam. For instance, as with the example given for fiber optics, it may be necessary to monitor the output of an injection laser transmitter in a particular application. A small beam splitter placed directly in the path of the laser beam will reflect a small percentage of the light onto a monitoring photodiode, while permitting the remainder to pass unobstructed.

Beam splitters may be purchased as specially fabricated optical components, but for most applications a glass microscope slide or cover glass will do very well. Besides being inexpensive, they are easy to obtain.

Another very useful optical component is the retro-reflector or corner cube. Retro-reflectors are optical components that have the unique ability to reflect a beam of incident light directly back to its source and are particularly useful in laser range-finding applications.

Operation of a retro-reflector is based on the familiar principle of total internal reflection. The reflector is actually a specialized prism having the shape of a corner of a cube. Light entering the face of the corner strikes one of the sides, is reflected to one of the other sides, and is reflected back out in a line parallel with the original ray. If the prism is cut and ground with a great deal of precision, such as the retro-reflectors placed on the moon by the Apollo astronauts, the beam will be returned to its source even along very lengthy paths.

Besides precision measurements of the distance from earth to moon, retro-reflectors are very useful in earthbound ranging and intrusion alarm systems. A mirror would work in both cases, but the alignment procedure would be practically insurmountable. Since a retro-reflector returns light to its source, even if the beam strikes it at an off-axis angle, it is a far more versatile device.

High quality retro-reflectors are very expensive. However, ordinary automobile and highway safety reflectors make excellent substitutes. These reflectors are actually made by molding a large number of miniature corner cubes into a single sheet of plastic. The clear ones used to mark highways are particularly good for injection laser applications.

Still another optical component that can prove useful is the parabolic reflector. The small types used in flashlights can often be used to collect light for a receiver detector by mounting the detector in the central hole through which the flashlight bulb was originally mounted. Parabolic reflectors are particularly useful for large-area detectors such as solar cells. A very efficient receiver system can be made by actually converting a flashlight into an enclosure and using its reflector to mount one or two solar cells in a back-to-back configuration. Plastic encased units, such as the Burgess "Dolphin" lantern, are particularly easy to use in this manner.

MOUNTING OPTICAL COMPONENTS

A few comments have already been made on this subject, but a more detailed discussion is needed. The lens, the most common optical component, is often the most difficult to mount. Several techniques, however, can be used to make the procedure rather simple. One is to simply glue the lens to its mounting with clear cement. Silicone sealants are particularly good for this purpose, since their flexibility tends to absorb shocks that can disengage a lens from a more conventional cement. Good second choices are white glue and butyl acetate household cement.

Lenses can also be mounted with rubber O rings or grommets. Simply slip the lens into a tube and place O rings on either side. Sometimes set screws made of nylon will work fine if a recessed seat can be made in the lens tube. The lens is placed against the seat and set screws are placed at several points just above it.

Whatever technique is used to mount the lens, an adjustable holder will greatly simplify focusing. This is particularly true of laser assemblies, as very subtle focusing adjustments have a significant effect on beam collimation. Simple adjustable holders can be made by telescoping lengths of plastic tubing available from plastic wholesalers, electronic parts suppliers, and hobby shops. Thin walled brass and aluminum tubing is also good for this purpose. Adjustments can be maintained by using tightly fitting tubes or set screws. Also, the use of two short lengths of tubing inside the main tube can greatly facilitate lens mounting.

The ideal way to mount lenses is with threaded holders. Anyone with access to a small lathe should be able to make such holders with little trouble, and sometimes surplus equipment can be salvaged for very useful holder assemblies. An example of the latter is the pocket dosimeters about the size of a fountain pen used to measure radiation. The units have a lens in one end that is ideal for mounting in either a special holder or in the original assembly. The holder is threaded and makes for a very sturdy mounting. In fact, it is possible to assemble an entire laser pulser in the tube of the dosimeter.

COMMERCIAL SOURCES FOR OPTICS

Some optical components can be obtained locally—magnifying lenses, mirrors, and reflectors, for example. Much better choices are available from companies that deal largely in specialized scientific and experimental apparatus. One of these is Edmund Scientific (600 Edscorp Building, Barrington, New Jersey 08007). The company sells a large variety of lenses, mirrors, fiber optics, reflectors, prisms, and other components. In addition to a large assortment of simple and

compound convex lenses, well-suited for laser collimation, the company offers a variety of surplus 8-mm motion picture projection lenses. Since these multielement lens assemblies are mounted in metal holders with spiral focusing threads, they make excellent laser collimation lenses. Many of the laser transmitters described in this book use an $f/1.6$ lens of this type obtained from Edmund Scientific.

Other companies that sell optical components include B&F Enterprises (P.O. Box 44, Hathorne, Massachusetts 01937) and John Meshna, Jr. (P.O. Box 62, E. Lynn, Massachusetts 01904). Most of the companies offer complete catalogs of their optical components, either free or for a small charge. For special-purpose applications where very high quality components are a must, those who can afford the cost should check with one of the major optical equipment manufacturers. Names and addresses for a dozen or so companies can be found in any edition of *Laser Focus*, *Optical Spectra*, *Advanced Optics*, or other optical publications.

While many common optical components are best purchased from distributors such as Edmund Scientific, bargains in good quality interference filters can sometimes be obtained from the manufacturers themselves. Many of the economical optics distributors sell infrared absorption filters (which should be used on receivers when interference types are not available), but their selection of 905-nanometer interference filters is usually very limited or nonexistent. Manufacturers such as Corion Instrument Co. (23 Fox Road, Waltham, Massachusetts 02154) issue listings of stock interference filters by size and wavelength and at reasonable prices, when one considers the high quality of the components.

VIEWING DEVICES

As might be expected, the ability to see the invisible infrared light from an injection laser greatly simplifies optical alignment. In fact, an infrared conversion device is quite handy for checking the lasing threshold, studying beam parameters, and setting up communications links. There are several methods for converting infrared into visible light and some of them are discussed in the remainder of this chapter.

INFRARED-SENSITIVE PHOSPHOR SCREENS

The simplest infrared viewing device is a screen coated with a special infrared-sensitive phosphor. In operation, the phosphor is sensitized or primed by exposing it to light from the sun or to any bright artificial light. When exposed to near-infrared, the screen will glow orange wherever struck by the invisible light. If the infrared is left on one spot for half a minute or so, the screen will become "discharged"

at that particular point and general illumination of the entire screen will reveal a dark shadow with the same shape as the beam outline.

Infrared-sensitive screens are very convenient to use. In aligning a lens system, for example, the screen can easily be used to see when good collimation has been achieved. If power density of the infrared beam is sufficiently high, the screens can even be used in aligning communication and intrusion alarm systems. The main disadvantage of the screens is their poor sensitivity. The phosphor is strongly energy dependent, and its orange emission is very weak for all but the most powerful infrared lasers. Also, the physical size of the phosphor crystals that make up a screen cause poor resolution and make observation of details in a laser beam impossible.

Their disadvantages notwithstanding, infrared phosphor screens are important and useful viewing devices, and the experimenter will be well advised to obtain one. They have an indefinite lifetime, require no source of power, and are compact in size.

A particularly handy type of phosphor screen is manufactured by the Eastman Kodak Company. Available in sizes ranging from 2" x 3" to 20" x 24", the phosphors are coated on either paper or a clear

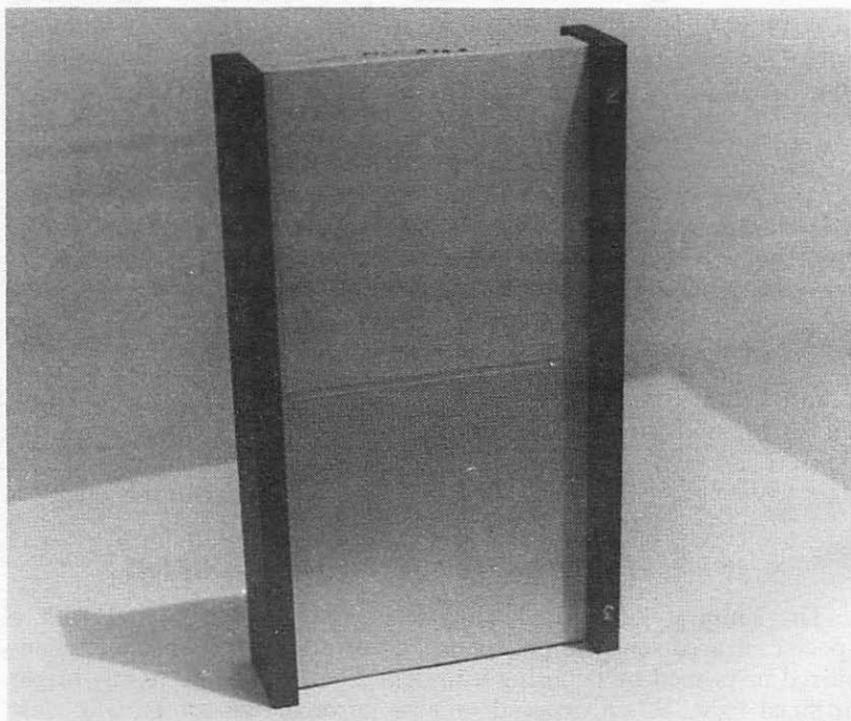


Fig. 6-10. Infrared-sensitive phosphor screen manufactured by Optical Engineering.

base, and laminated between two layers of Kodacel transparent plastic. Prices range from \$25 for a small card to several hundred dollars for the larger sheets. The manufacturer explains that the high price for a relatively uncomplicated looking device is due to a lengthy and complex chemical process for manufacturing the phosphor itself.

Kodak has some interesting literature containing more details about their phosphor screens. Activation and excitation wavelengths are discussed in detail as is the procedure for photographing the infrared stimulated orange patterns. To obtain the literature, write the company and request Kodak Pamphlets U-70 ("Kodak IR Phosphor") and U-76 ("Photographing Phosphor Displays of Laser Patterns").

Fig. 6-10 shows an IR Display Plate manufactured by Optical Engineering, Inc. The infrared viewer is made in the form of an erect aluminum frame coated with three separate infrared-sensitive screens. The various surfaces respond to continuously operated and pulsed neodymium doped YAG, and glass and GaAs injection lasers. Like the Kodak phosphor screen, the plate surfaces are activated by exposure to sunlight or artificial light before being used with an infrared laser.

In tests with several injection lasers, the IR Display Plate proved somewhat less sensitive than the Kodak screen. But its sturdy construction and the variety of infrared sensitive coatings give it several advantages.

INFRARED IMAGE-CONVERTER TUBES

By far the most efficient and useful infrared viewing device is the image-converter tube. When connected to a high-voltage power supply and equipped with two or more lenses for focusing and imaging, this close relative of the photomultiplier tube becomes a useful device indeed.

Fig. 6-11 shows the outline of a typical image-converter tube. In operation, infrared light striking the front window of the tube causes

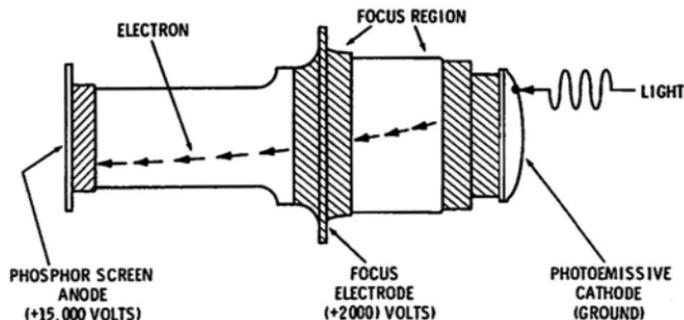


Fig. 6-11. Outline drawing of a typical image-converter tube.

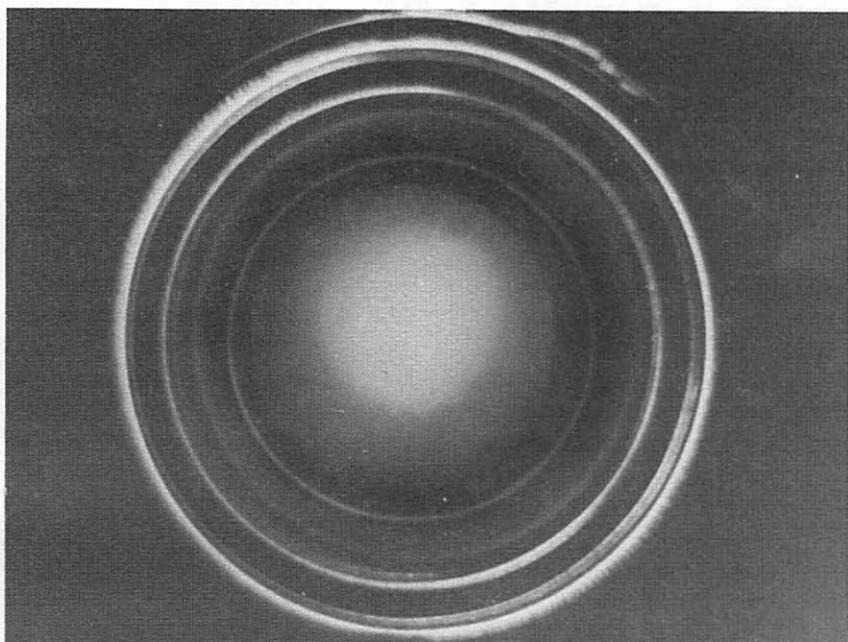
electrons to be emitted from a photoemissive surface similar to those used in photomultipliers. The electrons are accelerated and directed toward a phosphor screen at the rear of the tube by a high-voltage electric field, where they cause the screen to glow in much the same way that a cathode-ray tube operates. The image on the phosphor screen is generally enlarged by an eyepiece lens, and another lens assembly permits images to be focused onto the front surface of the tube. Often a centrally located electrode, which is biased at a high voltage, helps to focus the electron beam before it strikes the phosphor screen.

Image-converter tubes, several of which are shown in Fig. 6-12, are for more sensitive than infrared-sensitive phosphor screens. Also, their resolution of up to 50 lines per millimeter far exceeds the 5 lines of typical phosphor screens. S-1 surfaces respond well to infrared emission of most GaAs lasers, and the green-yellow color of the phosphor screen is pleasant to the eye.

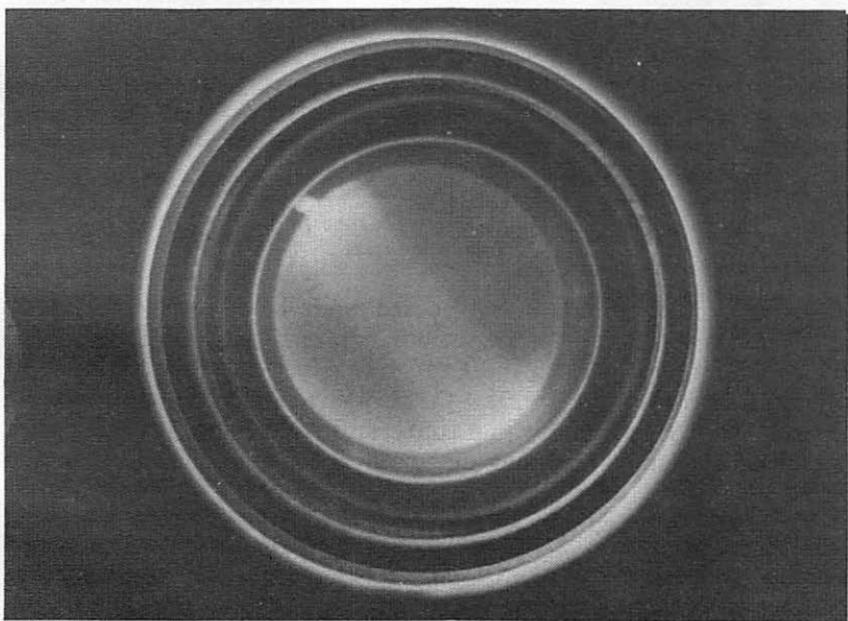
A bare image-converter tube with no lenses is an excellent tool for studying the very fine beam structure of most injection lasers. As shown by the pair of photographs in Fig. 6-13, the lasing threshold can be readily observed with only the bare tube and its power supply. In Fig. 6-13A, the laser is operated just below threshold, and its randomly emitted light fills the screen with a circular pattern. Just



Fig. 6-12. Several image-converter tubes and a miniature high-voltage (12 kV) power supply.



(A) Just below threshold the beam is broad and poorly defined.



(B) Above threshold a definite beam appears.

Fig. 6-13. Laser threshold as seen with an image-converter tube.

above threshold (Fig. 6-13B), the laser emits a distinct fan-shaped beam that appears as a rectangle on the screen. The resolution is actually much better than that shown in the figure, since photographic reproduction contributes major losses.

With lenses, the image converter can be used to quickly align the most difficult laser collimation lenses. A sample view through a focused converter is shown in Fig. 6-14. The bright spot comes from



Fig. 6-14. Using an image-converter tube to aid in focusing an injection laser.

an injection laser that is being focused while being viewed for maximum intensity with the tube. Collimation can also be accomplished by pointing the beam at a sheet of white paper and focusing the lens while viewing the spot size. But the former technique, that of looking directly into a laser beam with a converter tube, is more versatile, since it can be used over very long distances in order to achieve optimum results.

The chief disadvantages of the image converter are its expense and the need for a high-voltage power supply. A minor disadvantage for close-in work is the necessity of holding the converter while looking through the eyepiece, and in some circumstances it is more convenient to hold a small infrared phosphor screen and merely glance at it to study the beam pattern.

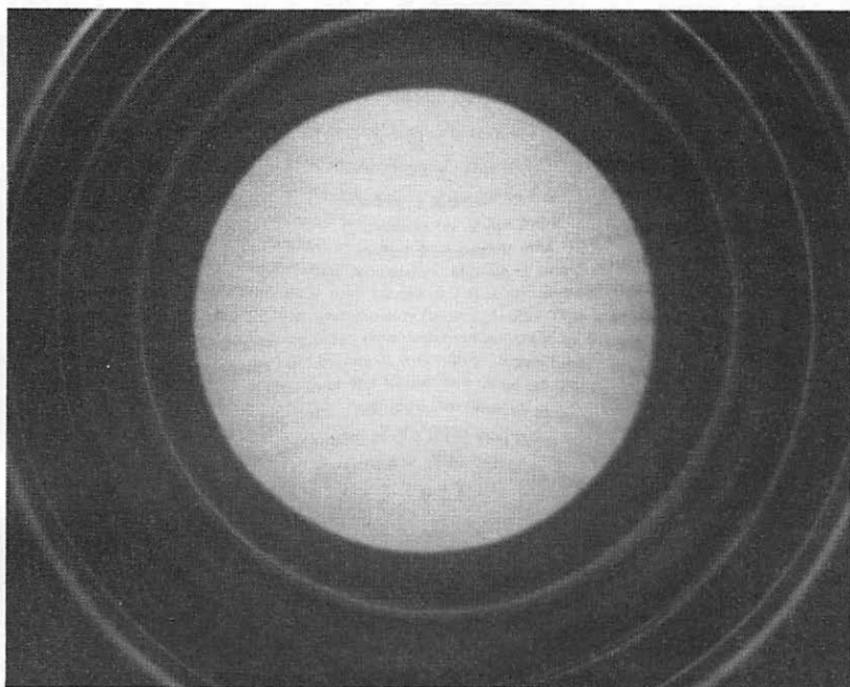


Fig. 6-15. Pincushion distortion in an image-converter tube.

Another problem is the tendency for the tubes to exhibit a pincushion effect, defocusing the image around the outer perimeter of the screen. This effect, shown in Fig. 6-15, is partially alleviated by external optics in the eyepiece.

Image-Converter Assembly

Though commercial infrared converters are expensive, the experimenter can assemble one from surplus components for a relatively small cash outlay. A variety of surplus image tubes are available from optics and electronics parts dealers, and, if desired, the tubes can be purchased new. A photograph of a very simple image-converter system is shown in Fig. 6-16. The unit consists of a high-voltage power supply and a surplus image tube manufactured by the Gramophone Co., Ltd. in England during World War II. The tube requires about 3500 volts for proper operation, a potential relatively easy to obtain by means of a power transformer and a voltage doubler. The circuit for the unit is shown in Fig. 6-17.

The tube is a type CV-148 available from John Meshna, Jr. (P.O. Box 62, E. Lynn, Massachusetts 01904). While a particular transformer is specified in the circuit diagram, many discarded oscilloscope and television power-supply transformers may work equally well. The

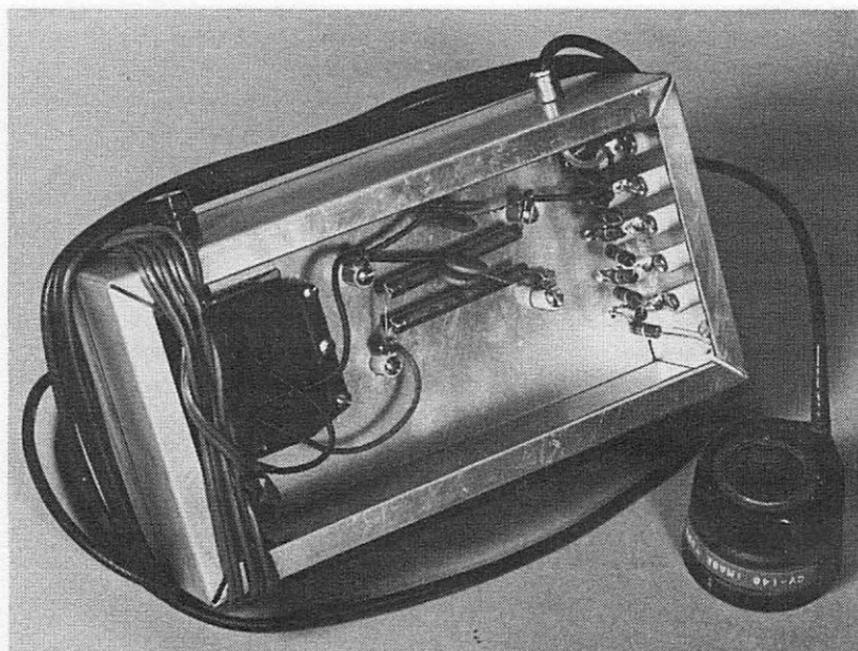


Fig. 6-16. Easily constructed power supply for an image-converter tube.

tube in the original unit was potted in clear casting resin to preclude electrical shock. When duplicating the unit, equal protection must be provided in order to prevent a dangerous electrical shock. In lieu of casting the tube in plastic, it can be mounted in a plastic cylinder or other insulating tube. Be sure to use adequate protection at all high-voltage points as well.

More recent image tubes require considerably more voltage than the CV-148. Several companies sell the RCA 6032 for about \$10, a tube that requires about 15 to 20 kilovolts. The tube also has a focusing electrode that must be connected to several thousand volts. This much voltage is much more difficult to generate than the 3500 volts required for the CV-148. Flyback transformers from discarded television sets and even automobile ignition coils can be used to obtain the voltage, if connected to a simple transistor multivibrator. High-voltage rectifiers must be used to convert the pulsating voltage into dc, and a voltage multiplier circuit is an even better solution. Besides regulating the output voltage from the transformer or coil, the multiplier steps up the output voltage several times, depending on the number of stages it contains.

A circuit for a high-voltage power supply suitable for operating the 6032 is shown in Fig. 6-15. The circuit has been built and tested, but is by no means optimum. For one thing, the ignition coil used to ob-

tain the high voltage is not the most efficient type of transformer to use in the circuit. But the circuit is inexpensive and easily assembled by even those inexperienced in electronics.

Like the CV-148 power supply, particular care must be exercised with all leads carrying the high voltage. The tube itself must be mounted in a sturdy, insulated tube and its wire leads must be well insulated. Use only high-voltage cable for all leads carrying tube operating voltages. While the power supply does not generate sufficiently high current for a fatal shock, coming in contact with the leads carrying the high voltage can be a rather unpleasant experience. This is particularly true when the possibility of dropping the image tube during a shock is considered.

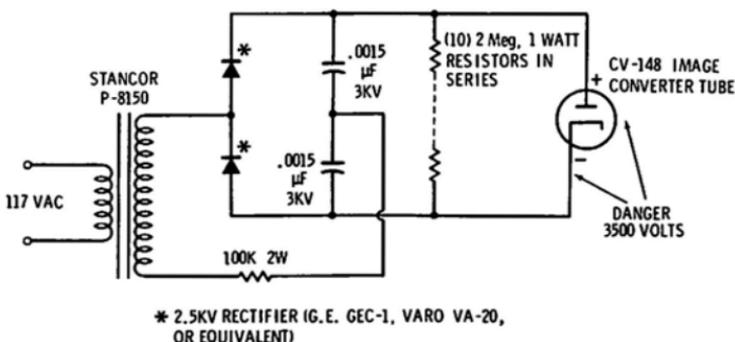


Fig. 6-17. Line-operated image-converter power supply.

Construction of the power supply is rather straightforward where the high voltage is not involved. In fact, the oscillator can be mounted some distance from the coil.

Use care, however, when mounting the voltage doubler and divider circuits. An excellent way to insure adequate insulation and protection is to mount these circuits in a sturdy plastic box. A single high-voltage cable can then be connected from coil to box and another cable connected from box to image tube. The box itself can be fastened or cemented inside the enclosure housing the coil and oscillator.

The potentiometer used to adjust the focus voltage of the tube should be equipped with a thick plastic knob to further preclude shock possibilities. Also, the diodes used in the voltage doubler should be high-voltage units, such as the ones specified in Fig. 6-18, as diodes with less than the specified voltage rating will be destroyed. Fig. 6-19 shows two high-voltage diodes similar to those specified.

To operate the circuit with the image tube, first adjust the power-supply voltage to the oscillator until at least 16, and no more than 20, kilovolts appears across the high-voltage output. If the minimum high voltage cannot be obtained without overheating the transistors in the

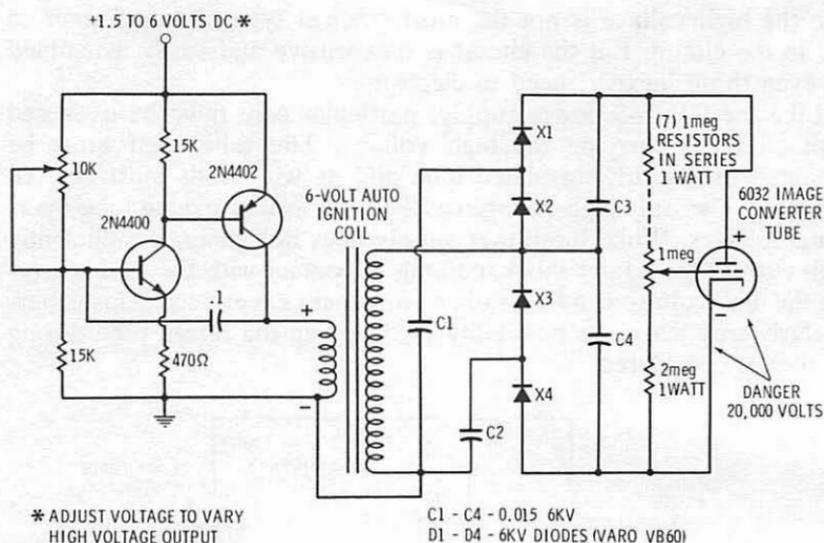


Fig. 6-18. Battery-powered image-converter power supply.

oscillator, it may be necessary to add another voltage-doubler stage in series with the first.

When the proper voltage is obtained, adjust the focusing potentiometer until clear images are produced on the phosphor screen of the tube. Remember that an objective lens must be used to focus images



Fig. 6-19. Two high-voltage rectifier diodes (ball-point pen included for scale).

on the front photoemissive surface of the tube. Otherwise only blurred patterns of green will be seen. Make sure that the lens, which should be at least the diameter of the tube and have a focal length of several inches (use a single or double convex), is separated from the image tube in order to prevent the possibility of electrical shock during focusing. The best way to do this is by mounting the lens in a plastic tube that telescopes over the tube containing the image tube itself.

IMAGE CONVERTER SAFETY PROCEDURES

Throughout this section, a number of high-voltage safety procedures have been recommended to eliminate possibilities of electrical shock. Often the poor regulation and low current of the two power supplies described here will result in only a harmless shock, but variations or slight modifications to the circuits may produce conditions that will permit a dangerous electrical shock. **CAUTION:** Insulate all high-voltage terminals and wires with appropriate insulation to prevent electrical shock. Use safe handling procedures at all times and instruct others who use the image converter about correct handling.

Recently another safety consideration has been mentioned with regard to image-converter tubes. Studies by health physicists have shown that some image-converter tubes, like some color-television tubes, emit small quantities of X rays. Many tubes now carry the following label: "X-RAY WARNING. This tube in operation produces X rays that can constitute a health hazard unless the tube is adequately shielded for radiation." Shielding can be in the form of lead foil or other metal material carefully wrapped around the plastic tube carrying the image tube. Lead foil can often be purchased in small quantities locally. (Do not use aluminum foil as its shielding properties are minimal.) Be sure to keep the metal shield insulated from the high voltage.

The application of a foil shield, while possibly not absolutely necessary, will result in an additional benefit. Stray electrical fields often distort the image on image-converter tubes by interfering with the passage of electrons from photoemissive surface to phosphor screen. The shield, which must be demagnetized if made of steel or iron, will significantly reduce this undesirable effect.

Additional information on both electrical safety and X-ray precautions can be found in data sheets on specific tubes. Often the data sheets include helpful installation and mounting hints as well.

COMMERCIAL IMAGE CONVERTERS

Surplus image tubes can be purchased from most of the surplus optical distributors already mentioned in this chapter. New tubes can be

purchased directly from manufacturers (such as RCA, Varo, ITT, Sylvania, and many others) and electronics parts distributors.

For those who are financially able, it is possible to purchase several types of factory-assembled image converters. Prices begin at more than several hundred dollars, but quality is always very high.

Fig. 6-20 shows a typical commercial image converter in use. Besides being excellent for viewing the infrared emissions from GaAs lasers, the converters can be used to detect crop diseases, alterations and forgeries of documents, and various skin and vein disorders. The converter shown here was manufactured by Varo, Inc.

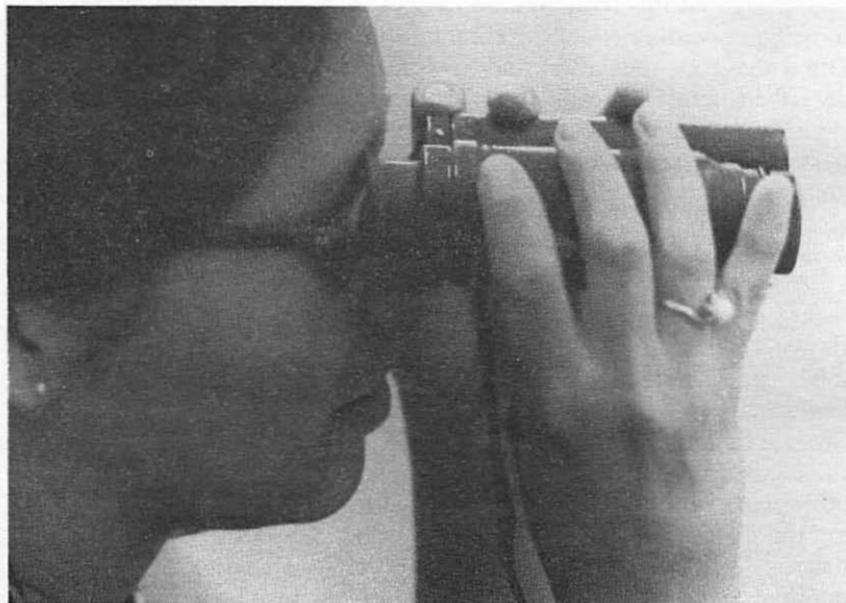


Fig. 6-20. Commercial infrared image converter.

Another commercial infrared viewer is manufactured by FJW Industries. Their Model Mod 4 is shown in Fig. 6-21. Other converters are made by Electrophysics Corp. and Old Delft Corporation of America. The manufacturers will forward literature about their products upon written request.

Specialized infrared image *intensifiers*, a multistage version of the standard image tube, are manufactured by several companies, including Varo, ITT, and RCA, for use by the military and law enforcement agencies. These extremely sensitive viewing devices will permit a night scene to be viewed with only the presence of starlight or sky glow, hence the popular name "Starlight Scope." The tubes are currently very costly, typically selling for a thousand dollars or more, and require operating voltages of as much as 30,000 volts.

Fig. 6-21. Find-R-Scope infrared image converter.



Courtesy FJW Industries

INFRARED PHOTOGRAPHY

A third form of infrared viewing device is infrared photography. While there are inconvenient aspects of using film to study or view infrared patterns produced by a GaAs laser, the technique does offer significant advantages. For example, infrared film far exceeds the resolution of the previous two image-conversion techniques described in this chapter. Also, photography provides a permanent record that may be studied at one's convenience, perhaps many hours after completion of an experiment or alignment of a communicator lens system.

Several types of infrared-sensitive film are available commercially. Kodak manufactures the most extensive line, and Polaroid offers a roll film that fits many of its cameras. Two types of Kodak infrared film, IR 135 and Ektachrome IR Aero 8443, are shown in Fig. 6-22. The IR 135, a black-and-white film, is inexpensive and was used to make many of the infrared photographs in this book. The infrared Ektachrome is a color film that converts the infrared from GaAs lasers into a red-tinted color. Both types of films can be developed using standard processing techniques.

The Kodak and Polaroid films each have relative advantages and disadvantages. While the IR 135, used for most of the photographs in this book, has an ASA of about 20, the Polaroid film (type 413) is rated at about 800. Whereas one or two pulses from an injection laser will more than adequately expose the Polaroid film, many hundreds of pulses may be needed to produce an equivalent result with the Kodak product. Better results might be obtained with Kodak High-

Speed Infrared Film, as it is given an ASA rating of about 200. Also, spectral sensitivity curves show that this film is somewhat more responsive to near infrared than is IR 135.

Additionally, the Polaroid film is more convenient to use, and the results are available almost immediately. On the other hand, the Kodak film provides a negative from which large size prints can be made. Unlike the Polaroid film, Kodak IR 135 and infrared Ektachrome are available at many photography shops in most cities.



Fig. 6-22. Black and white and color infrared film.

There are several ways to make infrared photographs of injection-laser beam patterns. In one technique, the beam is caused to illuminate a white surface, a camera is focused on the surface, and the film is exposed. A problem with this technique is that the camera focus will have to be altered from that obtained with visible light, since the infrared has a longer wavelength. The lens must be adjusted so that it is somewhat more distant from the film than when used with visible light.

A technique that eliminates the need for focusing adjustments and produces excellent results is to directly illuminate the infrared sensitive film with laser radiation. This can be done by loading a camera in the standard manner and removing the lens. The film is then ex-

posed to infrared by directing the laser beam into the camera and snapping the shutter as when making a normal photograph.

If the camera does not have a focal-plane shutter, a piece of dark, soft foam plastic can be held over the lens opening between exposures. If a camera lens is not removable, a light-tight film holder can be made of wood and used to accomplish the photography.

Exposure times will vary according to the type of laser, its wavelength, and its *energy* output. Like the other image conversion techniques described in this chapter, film exposure is energy dependent. Therefore, operation of a laser at a high pulse-repetition rate during the exposure will result in more rapid exposure. During actual exposure of the film, the camera must be held perfectly still (the same holds for the laser) and the room must be completely darkened. All of the infrared film photographs in this book were made by projecting the laser beam directly onto the film without the use of a camera lens.

At times it may be desired to photograph the beam emerging from an injection laser assembly; this can be done with the use of infrared film. The trick here is to obtain correct focus and proper exposure time. As with the other photographic techniques described in this section, a number of different exposures should be made at slightly different exposure times and focus adjustments.

The technique of photographing a piece of equipment containing an operating laser can produce startling results with the infrared Ektachrome film. For optimum results, try exposing the film in the presence of no light to record the infrared, and then allow a blue or other single colored light (do not use red, as this is the color produced by the laser) to strike the equipment for a few tenths of a second. Many trial exposures may have to be made in order to obtain good results. But the photograph will be well worth the effort.

Applications

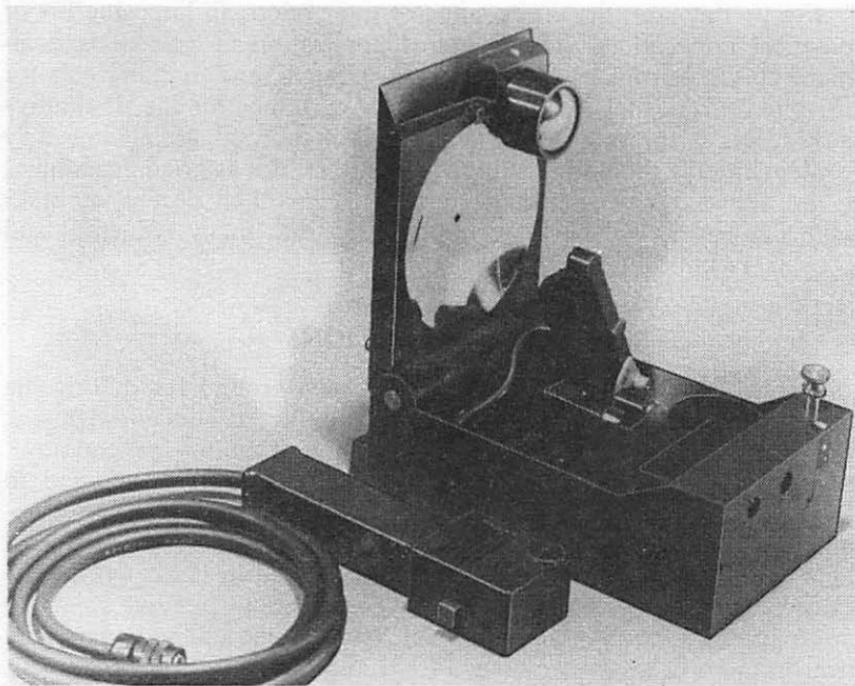
For its tiny size, the semiconductor laser offers an imposing list of practical applications. The foremost application at present is communications, but intrusion alarms, rangefinders, and mobility aids for the blind are not far behind. The major customer for the diminutive little lasers is the military—a single GaAs infrared illuminator may contain literally thousands of individual lasers. But as pricing continues to be adjusted downward, the injection laser, like dozens of other semiconductors, will begin to find its way into many industrial and consumer applications.

COMMUNICATIONS

Optical communications has actually been around for quite some time, particularly when one considers the reflected sunlight signaling techniques of many early civilizations. In the last century, several novel techniques for voice-modulating a gas flame were devised, and in World War II the Germans perfected a battlefield light-beam communicator. The first significant demonstration of a semiconductor light emitter in an optical communicator occurred in 1962, when MIT staged a demonstration from the MIT campus to a point some 30 miles distant. Clearly intelligible voice was transmitted by a collimated near-infrared beam from a cooled LED and detected by a cooled photomultiplier tube mounted in the focal point of a surplus army searchlight.

The injection laser was invented shortly after the MIT demonstration and communications experiments with it soon began. Both IBM and RCA proposed satellite-to-ground voice communicators employing injection lasers and an RCA unit was actually flown on one of the flights of Gemini 7. Unfortunately, the experiment was unsuccessful in that signals were not received on the ground. But the chances of success were considerably reduced by the necessity for aiming the unit toward the ground receiver station by hand.

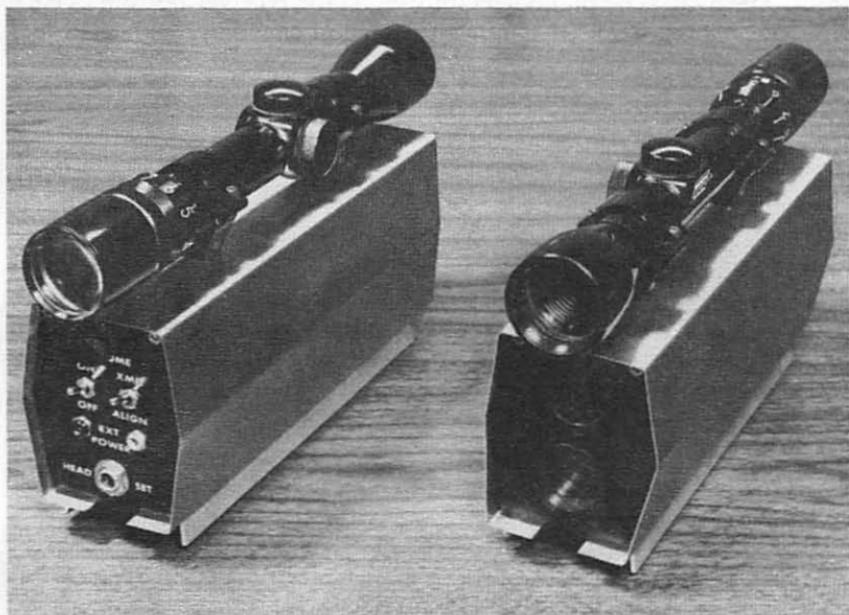
RCA went on to develop several experimental injection-laser transceivers for the military. The unit shown in Fig. 7-1 uses two lasers and will operate for several hours when connected to a small battery-operated power supply. The lasers and their lenses are located rather inconspicuously in the base of the transceiver, while the large parabolic reflector serves to collect signals transmitted from another unit and focus them onto a silicon photodiode. The photodiode mount, which also contains amplification and signal-processing circuitry, folds down when the transceiver is not in use. The top portion of the unit containing the reflector also folds down, thus making an extremely compact and portable optical communicator presumably well-suited to military applications.



Courtesy Radio Corporation of America

Fig. 7-1. Miniature laser transceiver.

Recently, a number of other companies have assembled and demonstrated laser voice transceivers, and the Navy has purchased several such communicators from Holobeam, Inc. The Holobeam transceiver, which was featured on the cover of *Electronics* magazine (March 16, 1970), can be mounted on a helmet assembly or tripod, and is intended for high-fidelity audio transmission from ship-to-ship, ship-to-shore, and at construction sites.



Courtesy Santa Barbara Research Center

Fig. 7-2. Commercial laser transceivers for voice communications.

Holobeam's transceivers contain several novel features, a particularly interesting one being that the peak current through the laser is regulated by a temperature-sensing thermistor feedback circuit. No lenses are used on the detectors of the receivers. Rather, large-area photodiodes are employed with only narrow-band interference filters, in order to reduce alignment problems between communicators. A lens with a focal length of about 5 centimeters (1.9") is used to project a beam with a divergence of about 300 milliradians (17.2°) from the laser. The rather wide beam spread of the transmitter gives a communications range of only 250 feet, but narrowing the divergence to 1 milliradian will give a range of ten miles.

The Santa Barbara Research Center has also developed a commercial injection-laser transceiver. Using a single injection laser emitting two watts of peak power into a 5-mr (0.3°) beam, the 5.5-pound communicator has a range of up to 6 miles and is powered by re-

chargeable batteries. Other versions are available that permit voice transmission at ranges exceeding 10 miles.

Fig. 7-2 shows a pair of the laser transceivers and the sighting scopes that permit rapid alignment over very long distances. During alignment (Fig. 7-3), the laser transmits a series of tone bursts as a marker signal. The operators each zero in on their partner's transmitter, lock their tripods in a fixed position, and begin communications. The avalanche photodetector used in the receiver portion of each transceiver provides a 64-nanowatt detection capability with a 30 to 1 signal-to-noise ratio.



Courtesy Santa Barbara Research Center

Fig. 7-3. Alignment of a laser transceiver.

The laser transceiver described here has definite practical applications, but more wide-spread use will probably await the development of telephone communications systems that use fiber optics or other optical guides that permit more than line of sight communications. In the meantime, the companies mentioned, and others as well, will no doubt continue to announce new types of injection-laser transceivers well suited for specific applications.

RANGEFINDERS

In addition to communicators, the military is also actively developing several types of injection-laser rangefinders. The devices permit

the distance to a distant target or terrain feature to be measured by simply pointing a compact instrument toward it. The rangefinder transmits a brief laser pulse that is reflected from the objects of interest and returned to a sensitive receiver in the instrument. An electronic clock measures the round trip time of the pulse, divides by two, multiplies the result by the speed of light, and indicates the range to the object on a digital read-out.

The military and several corporations have developed a variety of rangefinders that employ ruby, glass, or YAG lasers. But these systems are costly and relatively large and bulky compared to those that use injection lasers. While the former class of rangefinders outperforms the latter, injection-laser units have a definite advantage in applications requiring range measurements of a few kilometers or less.

A block diagram of a typical injection-laser rangefinder is shown in Fig. 7-4. In operation, the clock controls the number of laser pulses per second to be transmitted, triggers the laser, and resets the counter between pulses. The counter is activated by a signal from a photodiode located near the laser. A small beam splitter in the space between the laser and its lens reflects a small portion of the transmitted pulse to the photodiode. The counter is stopped when the return signal is received by the primary detector of the unit.

The small size potential of injection-laser rangefinders makes them useful as miniature bomb fuses. The fuses are quite small and attach to the nose of a conventional bomb like a standard impact fuse. The advantage of the laser fuse is that the bomb can be exploded at a preset altitude above the ground, thus causing wider damage than that resulting from an impact explosion.

A highly advanced type of laser bomb fuse is being developed by IBM with financial support from the Air Force Weapons Laboratory

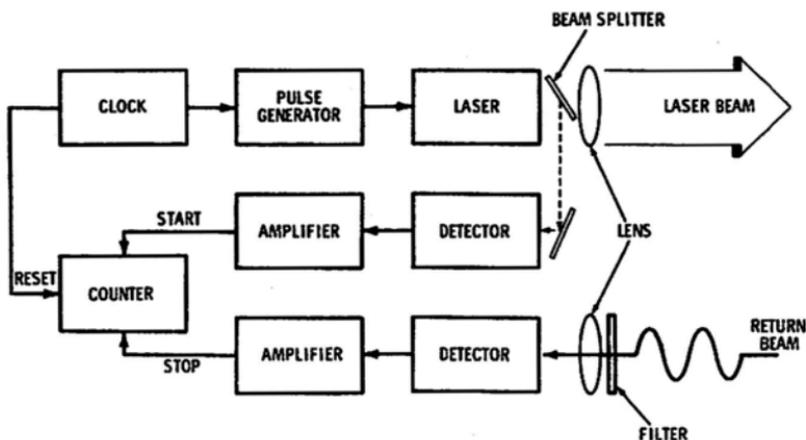
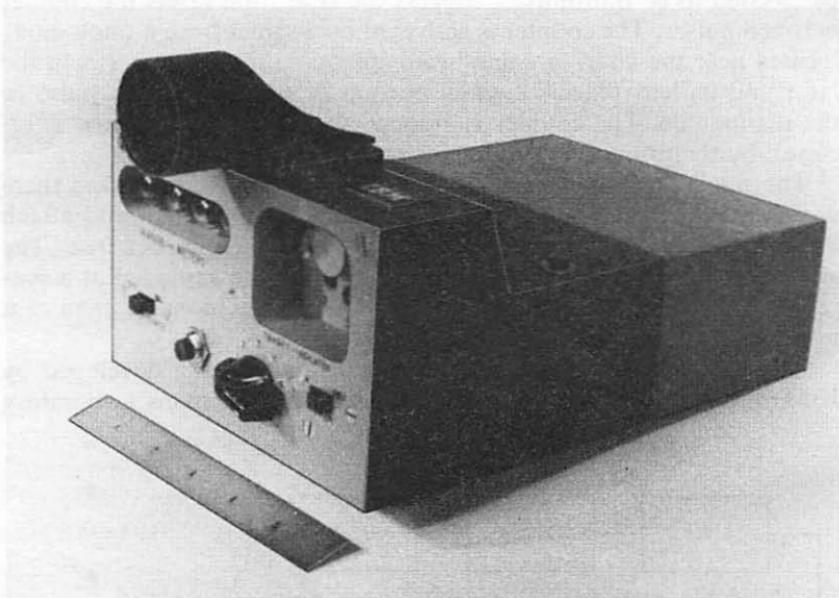


Fig. 7-4. Block diagram of a laser rangefinder.

in New Mexico. This fuse is intended to be operated from very high altitudes during the re-entry phase of an incoming missile warhead. A photograph of one of the prototype units is shown in Fig. 7-5.

An important result of military rangefinder and fusing research is the development of miniature injection laser altimeters well-suited for use in light aircraft. The Raytheon Company, under an Air Force contract, has developed a rangefinder with a range of 2000 feet in darkness against a target with a diffuse reflectance of only about 10%. The unit is very compact and has been both air and ground tested. The rangefinder is not nearly as effective in bright sunlight as in darkness—range is cut back to 270 feet for the 10% target. But since most ground and man-made materials reflect considerably more than 10% at the GaAs wavelength, the test results are conservative. Resolution of the rangefinder is sufficiently good to permit mapping the cross-section of a stand of bleachers from a low-flying aircraft.



Courtesy Air Force Weapons Laboratory

Fig. 7-5. An IBM laser rangefinder.

INTRUSION ALARMS

A rise in the national level of crime has made the manufacture of electronic intrusion alarms a big business. Both injection lasers and LEDs are finding increasing use in this field because their beams are not detected by normal vision. A sturdy commercial unit (Fig. 7-6) using an injection laser is manufactured by Optical Controls Inc.

Fig. 7-6. Injection-laser intrusion alarm.



Courtesy Optical Controls, Inc.

Called the Optogard, the unit can cover a 1000 foot perimeter with a signal level sufficiently high to permit operation through fog, rain, and snow. An interference filter at the detector permits operation in daylight. The pulsed operation necessary for the injection laser permits the use of a coding technique and helps to greatly reduce false alarms from falling leaves and other natural objects that may briefly interrupt the beam.

RCA has developed a number of experimental injection-laser intrusion alarms for the military. Like the Optogard, the units are self-contained and have ranges of up to 1000 feet. One particularly compact system uses a separate transmitter and receiver, each approximately the size of a cigarette package, and has a range in excess of 100 yards.

As the cost of injection lasers continues to drop and as technological advances result in lifetime improvements, it can be expected that many more manufacturers will market injection-laser intrusion alarms.

ILLUMINATION

The military's interest in covert, infrared illumination and viewing systems has resulted in millions of dollars in research and development contracts being granted to some of the manufacturers of injection lasers. By combining many individual diodes into large arrays, relatively compact, covert illuminators can be assembled. In operation,

the typical illuminator sends out a 1kHz pulsed beam with an average power of from several watts to more than 30 watts. An image-converter tube is used to view the illuminated scene.

Some illumination-viewing systems are gated. That is, they have an electronic circuit to switch the image converter on and off at precise intervals so that the unit will respond only to infrared reflected from objects at a certain fixed distance from the system. The advantage of gated viewing is that scenes can be viewed through fog, haze, smoke, and rain.

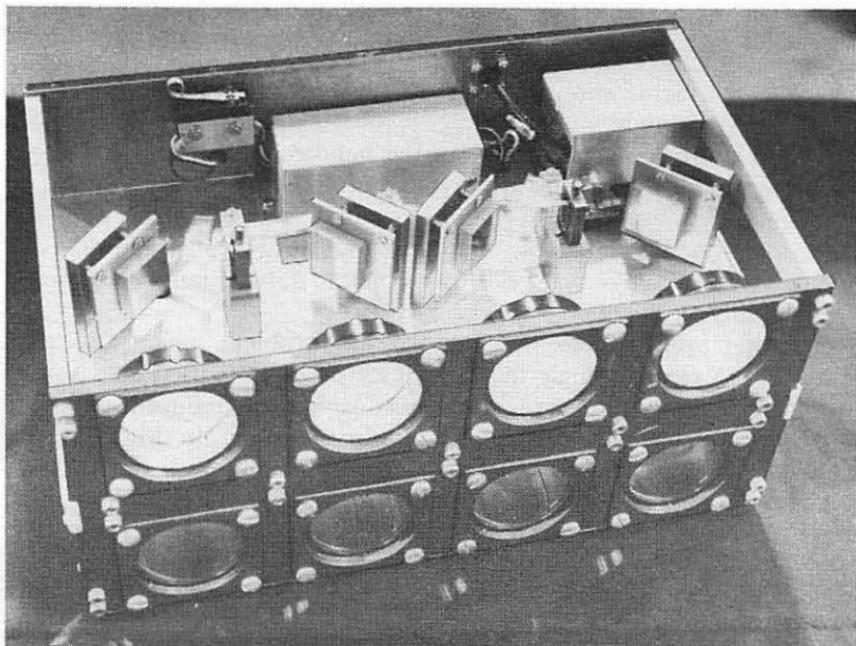
The military is interested in covert illuminators for both battlefield and airborne applications. In the latter case, the Army and Air Force have contracted for a variety of injection laser arrays that can be used to illuminate the ground from altitudes of several thousand feet and higher. More recently, civilian police forces have expressed interest in GaAs illuminators, as they can be quite helpful in locating concealed suspects. Even the U.S. Forest Service is considering using illuminator-viewing systems employing injection lasers to aid in viewing scenes through the dense smoke encountered in forest fires.

Laser Diode Laboratories and RCA both make a variety of gated illuminator-viewing systems. The Laser Diode Laboratories' Model GV10 has a peak power of 1000 watts and an average power of 1 watt. The viewing device is a three-stage image intensifier similar to the Starlight Scope. The entire unit weighs about 120 pounds. The company also manufactures several types of GaAs illuminators without the viewing device attachment. The LS410, for example, projects one watt average power into an 8-milliradian beam.

A laser illuminator made by IBM for the Air Force is shown in Fig. 7-7. The top cover of the illuminator has been removed to show two of the laser arrays. The unit has a peak power capability of 3000 watts, and the total divergence of all 8 lenses is only 10 milliradians.

RCA manufactures many types of illuminator-viewing systems for use by the military. One of their devices is handheld and has been studied for possible use by police agencies. Several excellent papers describing RCA work in illumination and viewing are found in *RCA Lasers*.

The subject of "covert" injection-laser illuminators once again brings up the subject of human eye response to near-infrared. (See the discussion on this subject in Chapter 2.) Some GaAs illuminators are operated at the temperature of liquid nitrogen to lower their wavelength, thus making their beam more visible with conventional image converters. At the same time, the beam becomes visible as a cherry red glow to observers directly in its path and is therefore not covert in the strictest meaning of the term. Even uncooled GaAs laser illuminators emit a beam that is somewhat visible, but not nearly so much so as cooled illuminators. Though GaAs illuminators can emit



Courtesy Air Force Weapons Laboratory

Fig. 7-7. 3000-watt IBM injection-laser illuminator (top removed).

a slightly visible beam, they are still the best infrared source for use in covert applications, as their portability and low power requirement are unsurpassed by other light sources.

MOBILITY AIDS FOR THE BLIND

Ironically, it is the laser that is rumored to be a candidate for use as a military blinding weapon and it is the laser that also can be used to give new mobility to the blind. A number of electronic mobility aids have been designed and tested in the past thirty years, but most of them use light sources that are inefficient and require considerable power for proper operation.

The invention of the light-emitting diode and the injection laser greatly changed the picture for optical mobility aids. Bionic Instruments, Inc., a company that has been conducting research in this important field since 1952 under auspices of the Veterans Administration, has developed a series of injection-laser mobility aids. Their more sophisticated device, the laser typhlocane, consists of three separate injection laser transmitters and receivers mounted on a conventional long cane. Beams from the transmitters are aimed down, outward, and up in order to detect, respectively, drop-offs, straight-ahead obstacles, and overhangs. In operation, the blind operator grasps the can by

the handle, thus making contact with a tiny vibration generator called a tactile stimulator. When an obstacle is detected by the straight-ahead channel, the tactile stimulator signals the operator and he then alters his path accordingly.

A miniature sound generator in the handle of the cane provides a warning tone for drop-offs and overhangs. The tone is set so as to be loud enough to warn the user but not so loud as to attract the attention of passers-by. Rechargeable batteries and sturdy construction make the cane an attractive prospect for helping to solve a number of pressing mobility problems.

Another approach to the mobility aid problem makes use of a handheld device. A single injection laser or LED is used as a source of infrared and, therefore, cost is considerably reduced over the multiple systems designed by Bionic Instruments. In Fig. 7-8, Le Quang Manh, a blind Vietnamese student, is being given instructions on the use of such an aid. Though he spoke no English and had never operated a transistor radio, young Manh learned how to expertly operate the aid in only a few test sessions (Fig. 7-9). In a series of such tests conducted with a crude prototype device using a GaAs light-emitting diode, more than 20 blind Vietnamese students in Saigon learned to use the aid effectively.

A more sophisticated, simplified, mobility aid is shown in Fig. 7-10. This device can operate with either a laser or LED illuminator and



U.S. Air Force photo

Fig. 7-8. A blind Vietnamese is instructed in the use of a mobility aid by author Forrest Mims.



Fig. 7-9. Le Quang Manh uses a mobility aid.

can provide range information by means of a lens tube that is rotated with a small plunger. By rotating the transmitter lens tube so that its beam intercepts both an obstacle and field of view of the receiver, crude range information can be obtained by merely noting the position of the plunger. The principle is called triangulation ranging and is the most simple of all ranging concepts.

An interesting possibility is to use the injection laser in an eyeglass-mounted mobility aid. Here the entire aid would be installed in the frames of a special pair of glasses much like similarly mounted hearing aids.

While the single illuminator-laser mobility aids do not provide as much information about obstacles as the laser cane, they are more economical and have a definite application in areas where the blind user is somewhat familiar with his environment. It is expected that the injection laser will continue to make valuable contributions in this important area of medical electronics.

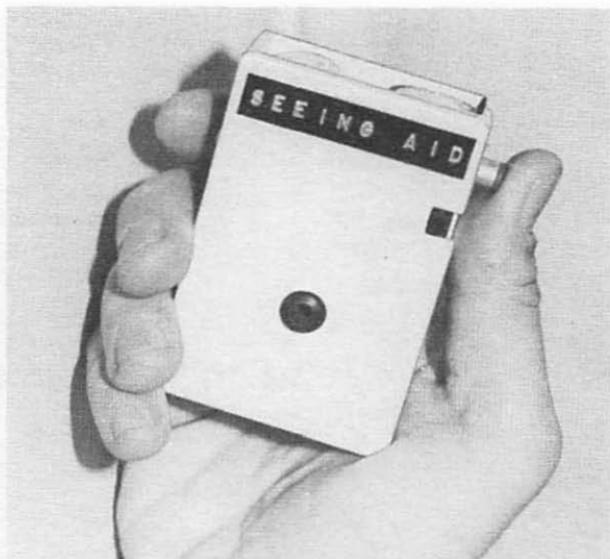


Fig. 7-10. Mobility aid that uses either a light-emitting diode or an injection laser.

HOLOGRAPHY

One of the most exciting developments in laser technology is holography—laser photography. Holograms are photographic representations of the interference patterns that result when a coherent beam of light strikes an object and is reflected toward a photographic plate and mixed with another beam of coherent light. Until the development of the laser, holography was limited to crude efforts with highly filtered and purified white light. Unfortunately, the filtering process greatly reduced the light intensity and exposures had to be quite lengthy. Also, the size of the object being recorded holographically was greatly limited.

The laser provided holography researchers with an ideal source of coherent light, and now holograms are made in a large variety of sizes and of a large number of objects. Tire companies use holography to study invisible defects in their products. Other practical applications include data storage, precision fabrication of mechanical objects, and wind tunnel studies.

Conventional injection lasers do not have the coherence necessary for production of good quality holograms. However, RCA has used injection lasers to read out holograms made with other types of lasers.

A very simple type of hologram can be made by placing a thin wire between an injection laser and a strip of infrared film. The resulting image, as shown by Fig. 7-11, consists of a central dark space

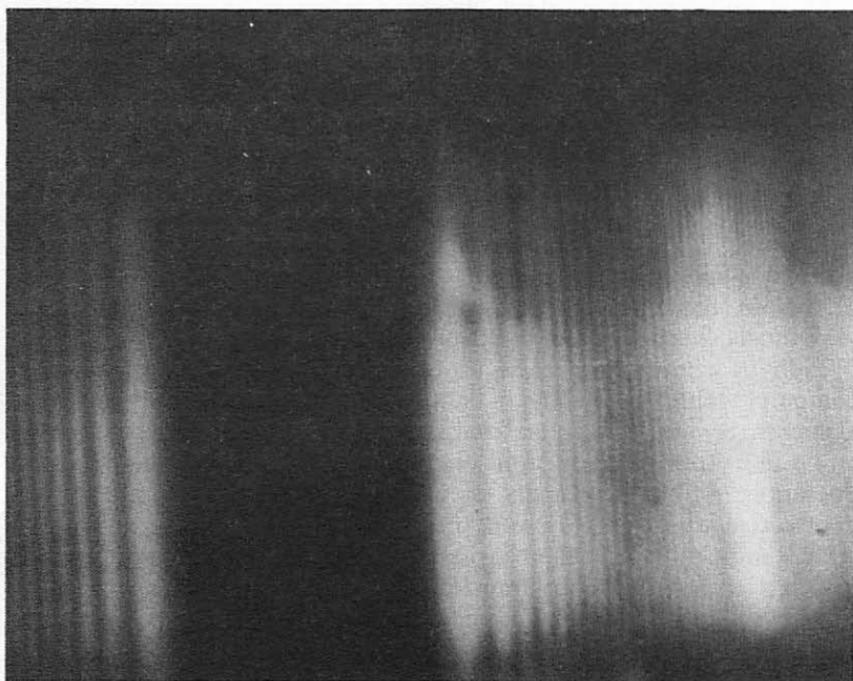


Fig. 7-11. Diffraction pattern produced by small-diameter wire and an injection laser.

(the shadow of the wire) bordered by interference fringes. A similar hologram can be made of a tiny sphere. One of the infrared photographs in Fig. 3-19 shows an inadvertant hologram made of a dust particle on the protective glass window of the laser. The hologram is characterized by a series of concentric rings surrounding a central dark space.

The parallel bars that are produced by the Lloyd's mirror technique described in Chapter 2 and shown in Fig. 2-25 are a type of hologram. If the photographic film is placed very close to the laser when making the hologram, very fine, closely spaced bars are produced that can serve as a diffraction grating; an optical device that can be used like a prism to break up a light beam into its component wavelengths.

INTERFEROMETRY

Though conventional injection lasers do not have sufficient coherence for the production of good holograms, they can be used in some types of interferometers. This interesting field is discussed in more detail in Chapter 2. The advantages of injection lasers over other types of lasers are their small size and limited power-supply requirement.

A complete injection laser interferometer with laser power supply can be made about the size of a deck of playing cards. Applications for such a device range from vibration detection and measurement of very small distances to ultraprecise weighing.

OPTICAL COMPUTERS

Chapter 3 briefly discusses some of the unique properties of injection lasers that make possible certain switching operations. As the state of the art continues to progress, it is possible that injection lasers may indeed become practical computer elements.

Perhaps a more immediate use of injection lasers (and LEDs) in computer technology will be in data transfer between various computer elements. Several computers that depend on the infrared beam from an LED to transmit data from one building to another are already in operation. At the University of Colorado, such a system transmits data across a range of more than a mile.

The military and several large companies have expressed interest in this technique of data transfer, and several companies have designed systems that are more complex than those currently in operation.

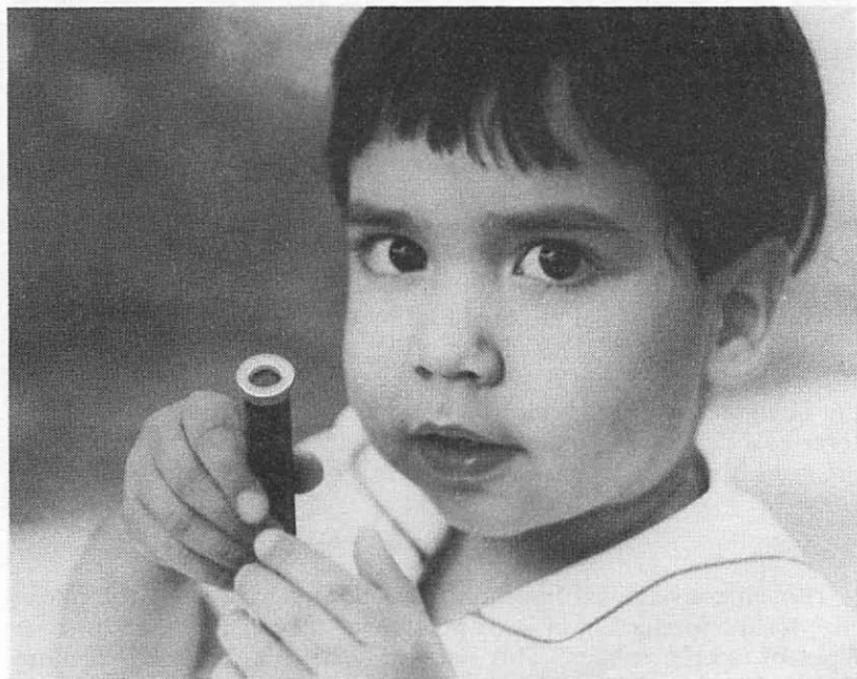


Fig. 7-12. Miniature injection-laser unit includes both collimating lens and batteries.

LASER PUMP SOURCE

One of the most novel applications of the injection laser is as a pump source for other lasers. IBM, McDonnell Douglas, and Texas Instruments have used injection diodes to stimulate small YAG laser rods. The advantage of the injection diode over the conventional light sources (flashlamps and incandescent lamps) used to stimulate YAG lasers is that a narrow band of light centered at one of the YAG absorption regions is available. Therefore, the light is more efficiently utilized by the YAG in the lasing process, and little is wasted in heating. NASA and the military have both expressed interest in injection-laser-pumped YAG lasers for space communications. Research funding is limited, but the future of this interesting form of laser looks promising.

OTHER APPLICATIONS

It is likely that other uses will be found for the injection laser. Perhaps new data-processing techniques will enable more efficient utilization of the limited coherence of these lasers. Or perhaps the eventual availability of commercial continuously operating injection lasers may open up markets and applications not yet foreseen. Whatever the application, the tiny size of injection lasers and their power supplies (Fig. 7-12) will certainly enhance their standing as efficient and powerful sources of near-infrared light.

Laser Safety

The electrical hazards of laser power-supply equipment are well known. But because of the difficulty, variability, and expense of biological experiments to measure the precise quantity of laser radiation required to produce a retinal lesion, ocular damage levels are not precisely defined.

As a general guideline, the Air Force School of Aerospace Medicine lists the maximum permissible energy to enter the eye from a ruby laser (694.3 nanometers) with a 100-nanosecond pulse width as 0.75 microjoule. For a neodymium doped laser (1060 nanometers), the permissible energy level is 45 microjoules. Injection laser safety levels fall somewhere between these numbers.

The large difference in safe exposure limits between ruby and neodymium results from absorption of infrared in the vitreous humor of the eye and imperfect focusing of infrared wavelengths. Furthermore, since the beam from an injection laser broadens significantly, it would be difficult to receive even the 0.75 microjoule level without placing the laser directly adjacent to the eye.

In the case of a well-collimated GaAs laser beam, more energy can enter the eye. Therefore, to avoid any possibility of ocular injury, always follow these simple safety rules:

1. Treat the injection laser as any other bright light source and do not look directly into its beam.

2. Do not allow collimated light from an injection laser to strike mirrors or other shiny surfaces.
3. Warn assistants and onlookers when preparing to conduct a test or experiment with an injection laser.

For additional information on the subject of laser safety, obtain a copy of "Laser Fundamentals and Experiments" (written by Bureau of Radiological Health, Department of Health, Education, and Welfare, and available for \$1.25 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402).

Range Equations

Those who wish to design laser ranging devices or to more accurately analyze the performance of communications systems or intrusion alarms will want to consider the equations presented here. The equations are important for several reasons. In a communications system, for example, if only a limited range is needed, alignment will be greatly eased if beam divergence can be broadened so that signal power density at the receiver is the minimum required to efficiently detect the signal. In this manner, reception of the transmitted signal is simplified, and capabilities of the communication system are significantly enhanced.

To calculate the maximum range of an optical communicator, the following equation is used:

$$R = \sqrt{\frac{P_o A_r \tau_o \tau_a}{P_{th} \theta^2}} \quad \text{B.1}$$

where,

- P_o is peak power of the laser,
- P_{th} is threshold power of the receiver system,
- A_r is area of the receiver lens,
- τ_o is transmissivity of the receiver optics,
- τ_a is transmissivity of the atmosphere,
- θ is the beam divergence of the laser in radians.

(From W. J. Hannan, "Application of Injection Lasers to Communication and Radar Systems," *RCA Lasers*.) For ranges shorter than a

few thousand feet on clear days, transmissivity of the atmosphere can be considered as unity (1). A good number to use for lens transmissivity is 0.9.

Several equations can apply in the case of a laser rangefinder. For example, the target against which a rangefinder is to operate will generally be classified as a diffuse reflector, since it will tend to scatter light incident upon it in all directions. Sometimes the target is specular, that is a mirror or corner cube that reflects the incident beam back toward its source in a narrow beam. Several other conditions may also apply. For example, the beam may be larger or smaller than the target which it strikes.

Where the target is diffusely reflecting and larger than the beam:

$$R = \sqrt{\frac{P_o A_r \rho \tau_o}{P_{th} \pi}} \quad \text{B.2}$$

where

ρ is the reflectance of the target.

Where the target is diffuse and smaller than the beam:

$$R = \sqrt[4]{\frac{P_o A_T A_r \rho \tau_o}{P_{th} \pi \theta}} \quad \text{B.3}$$

where,

A_r is the area of the target.

It is interesting to compare the equations with experimental results. In a series of tests with both laser and light-emitting diodes in a mobility aid for use by the blind, experimental results were consistently within 5 to 10% of calculated results. Some of the test materials with known reflectances at the 904-nanometer wavelength of GaAs lasers may be of interest to readers planning to conduct similar tests:

white paper	94%
concrete block	39%
unpainted plywood	92%
asphalt paving	5%

The use of retroreflectors greatly increases range capabilities of an injection laser rangefinder. For example, the optical gain of a good grade glass corner reflector may be 5,000,000,000 times that of a perfect diffuse reflector! Typically, injection laser radars "see" corner reflectors at ranges measured in kilometers even though range for diffuse targets may be measured in hundreds of meters.

Comprehensive analysis of injection laser rangefinders, and communicators involves consideration of many more factors and equations. Signal-to-noise ratio is but one area which should be considered.

While the equations presented here will work well in many limited applications, the reader desiring to go further is advised to obtain a copy of the *Electro-Optics Handbook* (RCA, Defense Electronic Products, Box 588, Burlington, Massachusetts 01801). Additional information can be obtained in *RCA Lasers* and a paper by B. S. Goldstein and G. F. Dalrymple ("Gallium Arsenide Injection Laser Radar," *Proceedings of the IEEE*, Vol. 5, No. 2, February 1967, p. 181).

Addresses of Manufacturers

A number of manufacturers and suppliers are mentioned at various places in the text. The following addresses are offered for the convenience of our readers and are assumed to be correct at the time of printing. However, addresses do sometimes change with time so no guarantee of accuracy is made.

Advanced Kinetics, Inc.
1231 Victoria Street,
Costa Mesa, Calif. 92627

B & F Enterprises,
P.O. Box 44,
Hathorne, Mass. 01937

Bionic Instruments, Inc.,
221 Rock Hill Road,
Bala Cynwyd, Pa. 19004

Corion Instrument Co.,
23 Fox Road,
Waltham, Mass. 02154

Eastman Kodak Co.,
Rochester, New York 14650

Edmund Scientific Co.,
600 Edscorp Bldg.,
Barrington, New Jersey 08007

EG & G, Inc.,
160 Brookline Ave.,
Boston, Mass. 02215

Electrophysics Corp.,
48 Spruce Street,
Nutley, New Jersey 07110

FJW Industries,
215 E. Prospect Ave.,
Mt. Prospect, Ill. 60056

General Electric, Space Technology
Products,
P.O. Box 8439,
Philadelphia, Pa. 19101

John Meshna, Jr.,
P.O. Box 62,
E. Lynn, Mass. 01904

Kinsho-Mataichi Corporation,
80 Pine Street,
New York, N.Y.

Lad Electro-Systems, Inc.,
7 Commercial Street,
Hicksville, N.Y. 11801

Laser Diode Laboratories,
205 Forrest Street,
Metuchin, New Jersey 08841

Metrologic Instruments, Inc.,
143 Harding Ave.,
Bellmawr, New Jersey 08030

Old Delft Corporation of America,
2735 Dorr Ave.,
Fairfax, Va. 22030

Optical Engineering, Inc.,
11550 Western Ave.,
Stanton, Calif. 90680

Pulse Engineering, Inc.,
560 Robert Ave.,
Santa Clara, Calif. 95050

Radio Corporation of America,
Solid State Division,
Somerville, New Jersey 08876

Stellar Instrument Northwest, Inc.,
11459 S.E. 266th Street,
Kent, Wash. 98031

Teledyne Crystalonics,
147 Sherman Street,
Cambridge, Mass. 02140

T. J. Watson Research Center,
Yorktown Heights, N. Y.

Texas Instruments Semiconductor
Components Division,
P.O. Box 5012,
Dallas, Texas 75222

United Detector Technology,
1732 21st Street,
Santa Monica, Calif. 90404

Varo Inc., Optical Division,
5574 N. Northwest Highway,
Chicago, Ill. 60630

Washington Technological Associates,
Inc.,
979 Olins Ave.,
Rockville, Md. 20852

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SEMICONDUCTOR DIODE LASERS

The first laser was a ruby rod, stimulated by the intense light from an electronic flash lamp. Since then a number of materials have been used as lasers, including liquids, gases, and plastics, and various means of stimulation have been used, including other lasers.

The semiconductor diode laser, although less powerful than some of the lasers mentioned, is considered quite an advance because of its small size and inexpensive construction, and because it is easily stimulated by simple electronic circuits. The authors point out that half a milliwatt of output is more than adequate for many experimental applications.

Chapter 1 of the book discusses the history and development of the laser with some attention to light-generating devices in general, and light generation by semiconductors particularly, since the LED might be considered the direct ancestor of the semiconductor laser. The theory of lasing action is explained. The need for cooling in some lasers is discussed.

The next two chapters describe the fabrication and electrical properties of the injection laser. Coherence, the most important aspect of laser light, is explained.

The remaining chapters of the book are devoted to circuitry and practical applications. Circuitry includes pulse generators, modulators, power supplies, detectors, and receivers. Optical systems and viewing devices are described. The last chapter covers several of the many applications already a reality and suggests others to come.

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Ralph W. Campbell studied for three years at the University of Kentucky, followed with three years at the Capitol Institute of Technology, graduating with an Associate Degree. A Navy veteran, Campbell also graduated from the U.S. Naval Electronics School at Great Lakes, Illinois.

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