SEMICONDUCTOR LASERS

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The Naval Training Device Center is currently conducting in-house research into the applicability of Semiconductor Lasers to training devices. This paper presents the gallium-arsenide injection laser, methods of pulsing this diode laser, and the collimation of its beam. Eye safety and methods of receiving or detecting the output will also be covered.

Semiconductor lasers, unlike other lasers, convert electrical energy directly into optical energy. They are small in physical size, low in cost, simple in construction and the laser diodes output can be easily modulated, by modulating the input current to the diode. (Figure 1.)

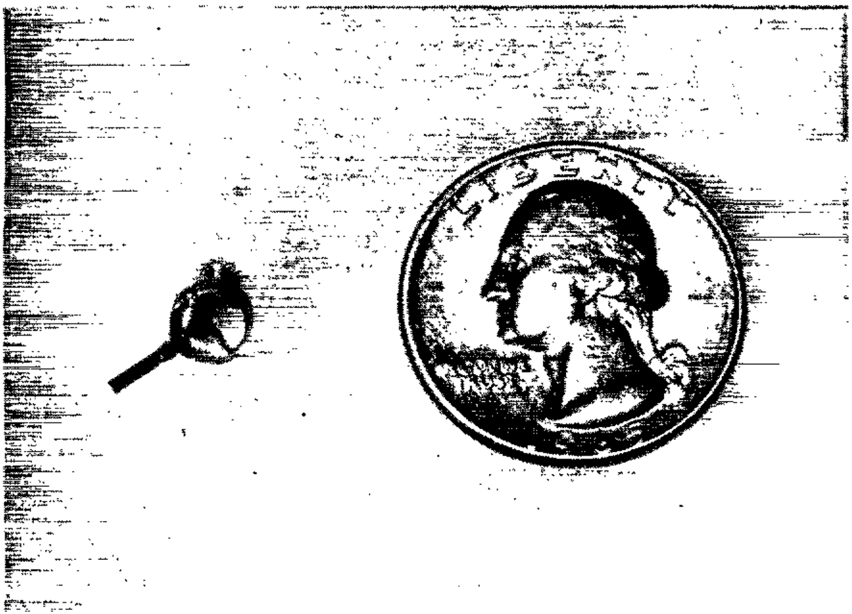

Figure 1. Laser Injection Diode

The gallium-arsenide, GaAs, injection laser diode is basically a planar p-n junction in a single crystal of GaAs. The p-n junction is formed by diffusing an acceptor element such as zinc (zn) into an oriented wafer of n-type GaAs. To obtain lasing, the holes and electrons in the p-n junction are brought in close proximity by injection of carriers by a narrow high current pulse. Within a few nsec, (the life time of the carrier), they recombine and radiate in the infrared region (near 9000A at 25° C). Optical gain occurs only in a layer about $2\,\mu$ thick at the p-n junction (see figure 2). Therefore, great care is taken to make the junction planar so that the lasing threshold current is low. A Fabry-Perot cavity is formed by two parallel

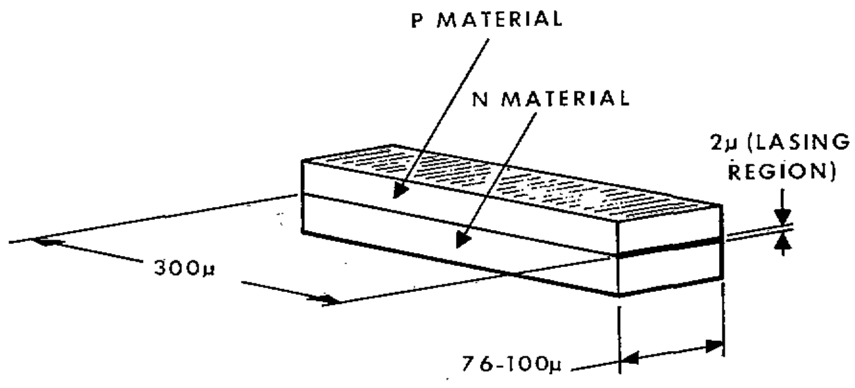

Figure 2. Schematic Representation of a Laser Diode

sides of the conductor chip. The cavity is typically near 100μ, parallel to the junction. The stimulation is amplified on the axis of the Fabry-Perot cavity. The cavity formed by the Fabry-Perot is approximately 330 wavelengths or 300μ long. A schematic representation of a diode laser is shown in figure 2. GaAs cleaves easily along certain crystal planes. These planes are used to form a Fabry-Perot cavity by orienting the GaAs wafer so the cleavage planes will be perpendicular to the plane of the junction.

The faces of the cleaved planes have a reflectivity of approximately 35% without any reflective coating. Silvering the end faces can reduce the threshold current required for lasing to take place. The sides of the cavity are sometimes sawed so as to suppress all but the Fabry-Perot modes propagating between the end-faces.

The magnitude of the radiated output is a function of the forward current through the diode. The pulse length is typically 200 nsec (max) and the maximum prf at 25° C is currently 1000 Hz. The wavelength is typically near 9000 A with a spectral half width at the 50% point of about 40 A. The power efficiency or power radiated per unit input is 10%. Most other lasers such as gas lasers and solid state lasers only have efficiencies of less than 1%. The 10% efficiency is obtained using the new heterostructure diode which consists of three distinct layers: n-type GaAs, p-type GaAs, and p-type gallium-aluminum-arsenide. Recombination occurs in the immediate vicinity of the GaAs p-type region. The heterojunction formed at the interface of the p-type GaAs and p-type gallium-aluminum-arsenide serves to confine the injected electrons and also reduce the absorption. As a result, the threshold is reduced by a factor of 2 to 3 and power efficiency is increased by a factor of 2 to 6.

In a laser, stimulated emission is achieved by means of an electron or hole population inversion. A population inversion occurs when an upper energy level has a greater probability of being occupied by electrons or holes than does a lower level. Under these circumstances the electrons or holes are said to be inverted. The new distribution of charges no longer represents the lower energy state. When this occurs, the probability of a photon-induced downward transition will exceed the probability of an upward transition, leading to a net stimulated emission. The electrons then recombine radiatively with the holes by dropping from the conduction band to empty states in the valence band. For each electron transition, light in the form of a photon of energy, $h\nu$ is emitted (h = Plank's constant and ν = frequency).

In the semiconductor injection diode laser, population inversion is produced by injecting electrons directly into p-type materials or holes into n-type material. The injection of charges to achieve lasing threshold is accomplished by a narrow current pulse approximately 150 to 200 nsec for conventional injection lasers. The dynamic forward resistance of a diode is typically 0.2 ohms.

In order to get stimulated emission or obtain laser action there must be in addition to population inversion, sufficient gain present to overcome the optical losses. The principle loss mechanisms of this semiconductor laser are: the bulk losses due to free-carrier absorption; diffraction of light out of the active region; and surface losses due to imperfect reflections at the Fabry-Perot surfaces, which may be formed by cleaving the crystal. Other items affecting the lasing threshold are the thickness of the region over which a population inversion will exist and the temperature. Threshold current density has a dependence on temperature of approximately T^3.

The energy vs distance diagram shown in figure 3 is a method of representing conditions necessary for lasing. In the unbiased case the Fermi level is continuous across the junction. When a forward bias is applied, the barrier restricting the flow of electrons and holes is reduced. In this forward biased condition electrons are injected into the p-side and holes into the n-side; this results in a population inversion between the conduction and valence-band levels. The separation in energy is less than the separation of the quasi-Fermi levels for electrons and holes. A transition, shown in figure 3 results in the emission of a photon of energy $h\nu$.

Laser diode output is known to degrade over a period when a laser diode is operated at the high current-density levels as required at 25° C. This type of degradation is known as noncatastrophic degradation.

Failure can also occur due to catastrophic failure over a few pulses. The catastrophic mode of failure is the result of mechanical damage of the material facets and has been shown to be related to the optical flux density rather than the current density in the p-n junction.

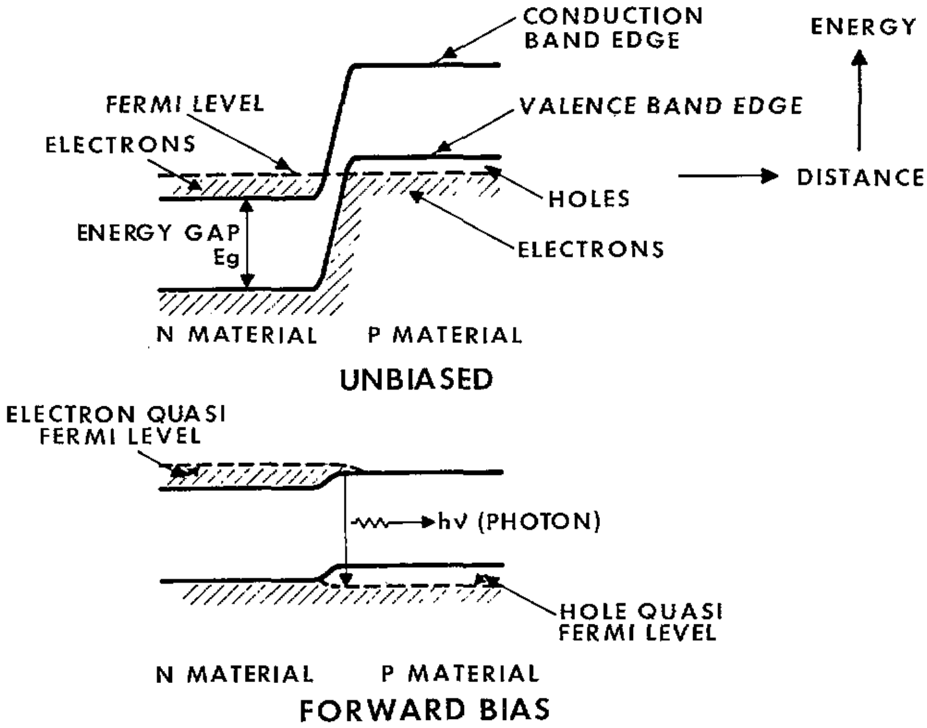

Figure 3. Energy vs Distance

Many manufacturers guarantee their diodes for 1000 hours of operation at 25° C. With the recent reduction in threshold current and the improvements in the GaAs materials the life of the diode should increase greatly. The new diodes announced early in 1969 feature low threshold current and increased junction uniformity. Using this process the threshold currents are reduced to 50%. Since experimenters have found that degradation varies superlinearly with current, the life of the diodes should be increased significantly above 1000 hours due to the reduced current necessary to achieve lasing. Further improvement may also eventually allow cw operation at room temperature.

Studies are underway to understand the physical mechanisms responsible for the gradual degradation. Some researchers believe the degradation is caused when carriers recombine nonradiatively, causing thermal spikes. The thermal spikes displace a zinc dopant atom from a substitutional site into an interstitial site causing the degradation. The degradation process is therefore due to bulk effects involving fundamental material changes in the diode with the dominant factor being the gradual reduction in the internal radiative quantum efficiency and optical loss in the junction region. The rate of this gradual degradation has also been found to depend on the initial uniformity of the near-field pattern of the laser.

A diode laser which emits nonuniformly degrades up to an order of magnitude faster than a laser which emits uniformly along the planes of the p-n junction. It is possible that the laser's material nonuniformity causes higher local current densities than in a uniform laser. The nonuniformity of the near-field patterns indicates the presence of a structural flaw which may cause the formation of nonradiative centers.

When the degradation process begins, the near-field emission patterns become nonuniform. Also, the pulse-to-pulse output varies up to 15% about the mean-power output. This is caused by part of the p-n junction "turning-on" randomly and not emitting during each current pulse.

It is believed that better materials and methods of manufacture, which reduces the threshold current, will increase the life of the diodes.

A typical modulator to provide the high current pulses required for laser diode operation is shown in figure 4.

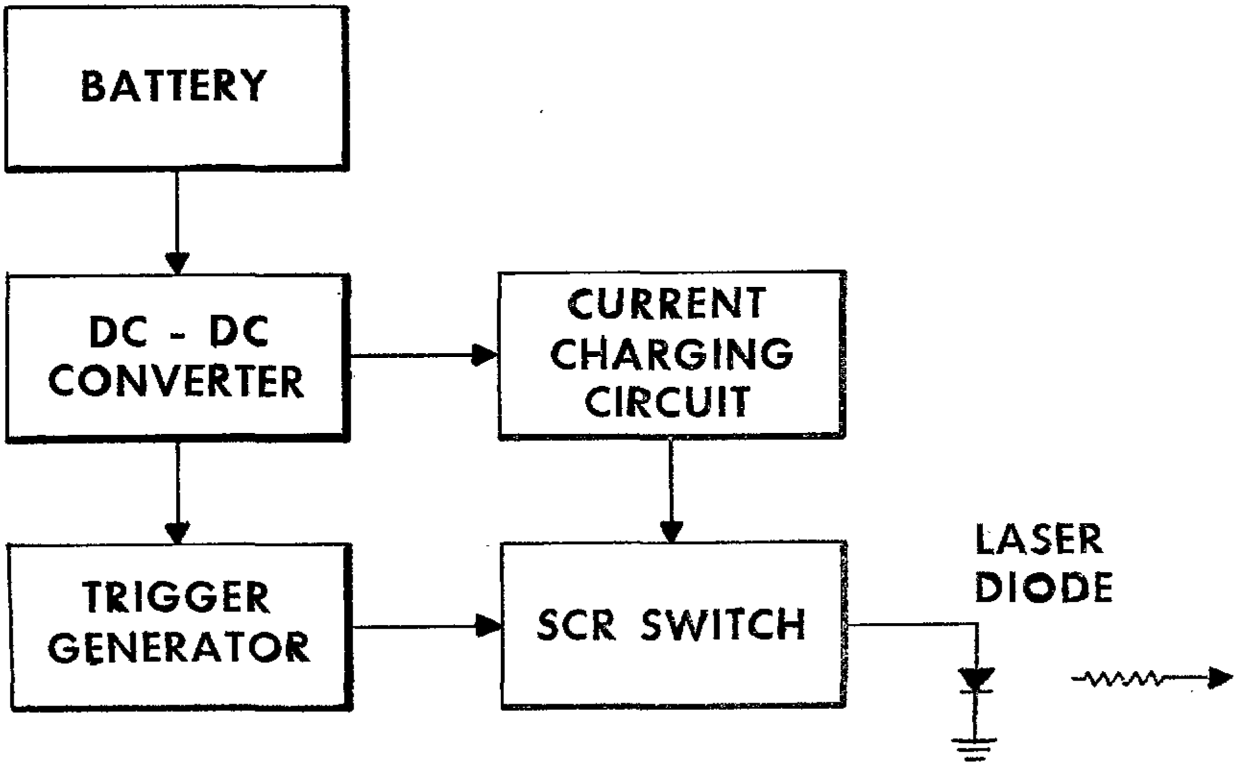

Figure 4. Modulator

To obtain optimum operation a GaAs laser must be pulsed with as near a perfect square wave as possible. Such a pulse produces the minimum rise time characteristic necessary not to overheat the junction. If the rise time of zero could be achieved the diode would change immediately to its lasing state and no junction heating would occur prior to lasing.

The applied pulse must also have minimum negative overshoot. If the diode is reversed biased an excessive current flows in the negative direction and the diode will be destroyed. Lead lengths to the laser diode must be very short (under 2 inches) to prevent this voltage from being applied. Maximum pulse width that can be applied to the diode is limited, and is a function of room temperature. At 25° C the maximum pulse applied is typically 200 nanoseconds in length.

The present maximum pulse repetition frequency is about 5,000 Hz for commercially available laser diodes. This limitation on PRF is due to the Joule heating of the junction. At excessive PRF's the efficiency of the diode laser decreases.

Components for a design to obtain the above cited characteristics must have high speed and current handling capabilities.

The modulation pulses can be obtained by discharging a capacitor through the low impedance laser diode (0.2 ohms) to create a current pulse. The rise time of the pulse is essentially determined by the response time of the SCR switch controlling the capacitor discharge. A current charging circuit is utilized to charge the capacitor.

In most lasing gallium-arsenide diodes the beam half angles at 25° C is between 15° to 25°. Figure 5 shows the laser beam geometry. The emitting area in the lasing diode is a function of the semiconductor chip size parallel to the p-n junction and the carrier diffusion lengths perpendicular to the junction. This area which is nominally 2 x 100μ, is represented by a heavy black line between the p and n materials shown in figure 5.

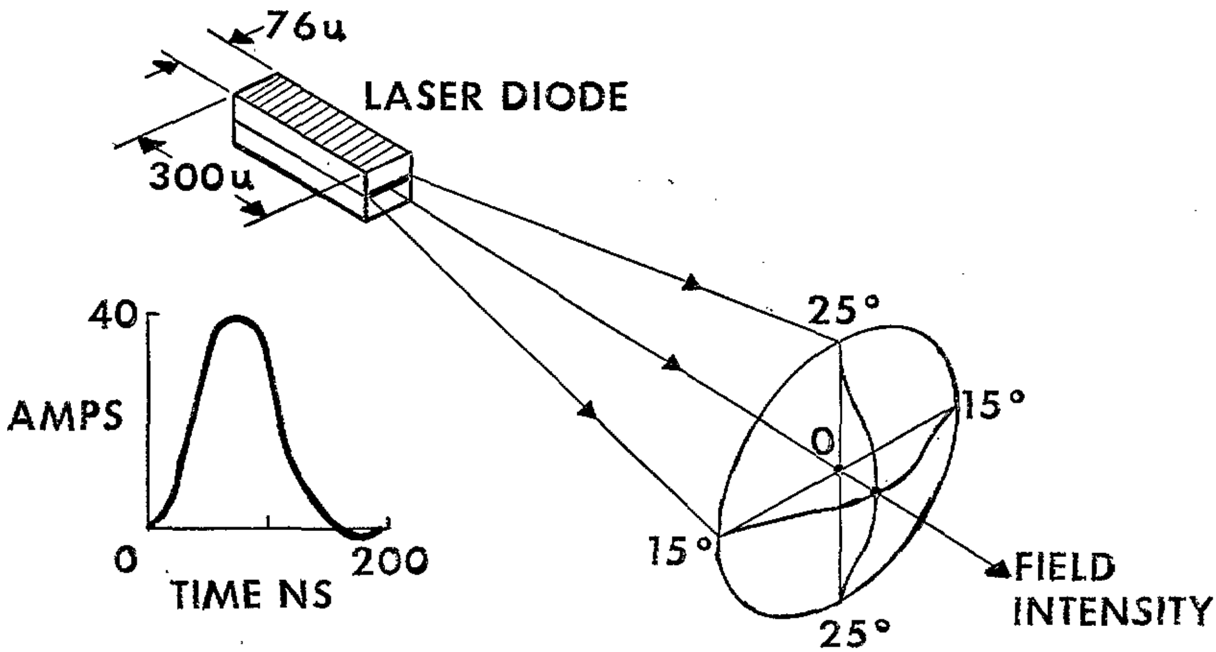

Figure 5. Laser Beam Geometry

The beam angles originate primarily from diffraction of the radiation at the rectangularly shaped emitting area. For a rectangularly shaped p-n junction $\left[\frac{\sin x}{x}\right]^2$ diffraction pattern will result.

The injection laser diode can be collimated by a simple single convex lens. By changing the position of the laser diode relative to the focal plane of the lens the beam shape can be adjusted from a rectangular to a circular beam. The size of the beam is also changed.

To collect the maximum power radiated by the diode the f-number, $\frac{\text{focal length}}{\text{diameter}}$, of the lens must be chosen such that the maximum power will be intercepted by the lens. A lens of f-number 1.5 is sufficient to collect most of the power from commercial room temperature GaAs lasers.

A silicon diffused photodiode may be used as a detector in a receiver. The diode detector is reversed biased so current will flow under the period of illumination. Detector current is caused by incident photons raising electrons in the detector material from non-conducting to conducting states, where they contribute to the current flow.

The diode is essentially a current generator. An EGG, SGD-100A diode was selected as the detector in our experiments. The laser output has a nominal 200 nanosecond pulse width, therefore, a detector with a large bandwidth is required. The selected detector has a rise time of four nanoseconds, and a bandwidth of 100 MHz. The relative spectral response of the detector is shown in figure 6.

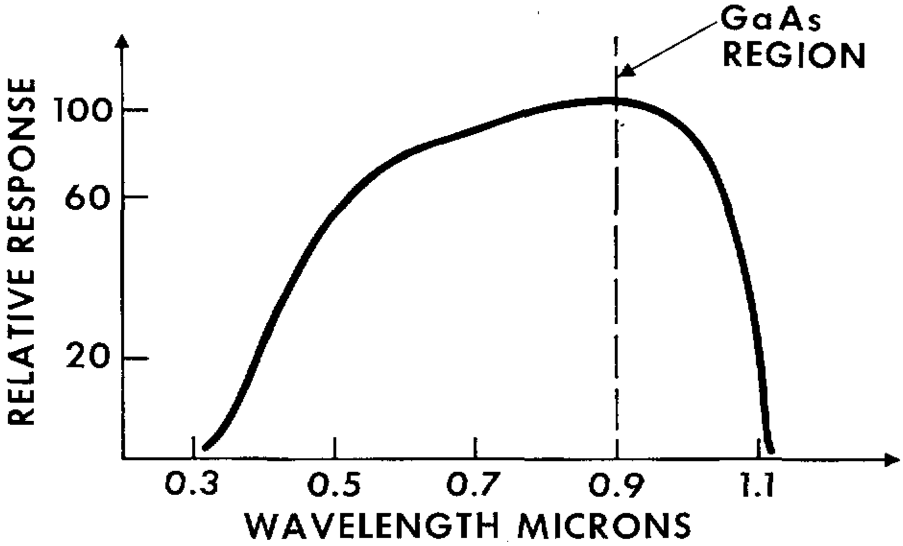

Figure 6. Spectral Response of Detector

It can be seen from figure 6 that the peak spectral response occurs at near 0.9 microns, so an excellent spectral match occurs. The detector has a sensitivity of approximately 0.5 μA / μW at 0.9 microns.

A schematic representation of a typical receiver is shown in figure 7.

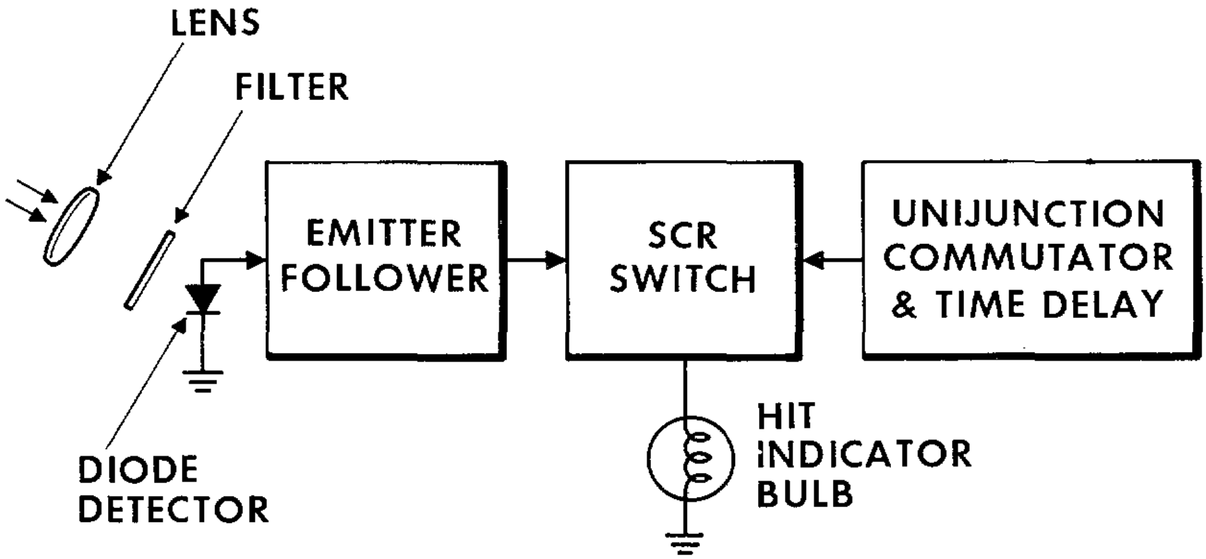

Figure 7. Schematic Representation of the Receiver

The detector signal is fed to an emitter follower which is used as an impedance matching device. The output of the emitter follower is used to turn on a silicon controlled rectifier which acts as a switch to turn on the signal indicator light bulb by effectively providing a ground for the bulb.

Bandpass filters can be utilized to improve the S/N ratio and allow operation in an outdoor environment.

Lasers can cause irreparable damage to the cornea or retina of the eye. For example, laser energy entering the eye can be focused by the lens to an extremely high energy density. The resultant temperature can be so great that a permanent burn-spot may occur on the retina. This can cause partial or total blindness. For this reason, safety precautions must be taken when transmitting laser energy to be safe for direct-viewing by the human eye into the collimating lens.

The threshold for a non-Q-switched laser with pulse widths of 1 nsec to 0.1 sec and a prf less than 10 has been determined. This threshold is based on biological damage at the retina of the eye. Levels of damage were established from experimental work on animals for radiation at 6943 A. (Reference 10.)

Table 1. Laser Safety Levels

pulse length - 1 nsec to 0.1 sec
prf < 10

Daylight 3-mm pupil	5.0×10^{-7} (j/cm^2)
Laboratory 5-mm pupil	2.0×10^{-7} (j/cm^2)
Night 7-mm pupil	1.0×10^{-7} (j/cm^2)

However, the damage threshold value must be adjusted for the room temperature injection laser diode radiation of 9050 A, as shown in figure 8.

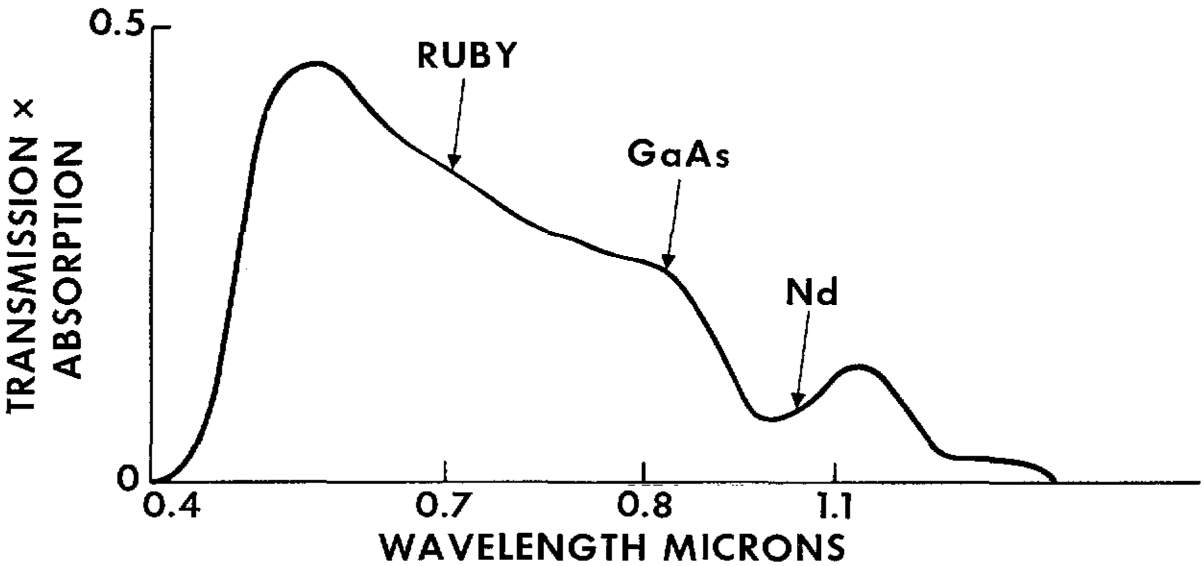

Figure 8. Non-Q-Switched Laser Safety Levels

As can be seen from figure 8, the values in Table 1 can be reduced even further for GaAs lasers. The basic formula to calculate j/cm^2 for safety determination is:

$$\text{j/cm}^2 = \frac{\text{Watts peak power x pulse width (50\% pts)}}{\text{Area of GaAs Laser Beam}}$$

Let us consider the safety of a system which has the following characteristics:

Laser Power - 4 w peak power at lens surface
Pulse Length - 100 nsec

f number 1.0 lens - 3 cm in diameter and a 3-cm focal length

$$j/cm^2 = \frac{4 \times 100 \times 10^{-9}}{\pi (1.5)^2} \quad \frac{400 \times 10^{-9}}{7} \quad 5.6 \times 10^{-8} \text{ joules}/cm^2$$

This number (0.56×10^{-7} is less than 1.0×10^{-7} j/cm^2 (see figure 8,) for the worst case condition. From this example, it can be seen that if the 4-w peak-power laser is limited to emitting less than 10 pulses in any 1 sec interval, it may be considered safe when viewed directly into the collimating lens. A safety analysis must be performed on each system prior to usage.

The miniature laser diode system provides a small lightweight, relatively inexpensive and safe solution to applications that require a pulse output, like a weapon fire simulator and communications system. All that is required is a properly designed pulsing circuitry and a simple lens to satisfy the transmitter needs. However, the method of pulsing the diode was found to be extremely important. If the diode is improperly pulsed, its low impedance and fast fall time can combine to cause high reverse voltages that can degrade or destroy it. The length of the leads to the diode is critical to prevent destructive ringing in the input current.

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