EXPLORING LASER LIGHT

by T. Kallard

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Laboratory Exercises and
Lecture Demonstrations
Performed With Low-Power
Helium-Neon Gas Lasers

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DEDICATED TO
THE MEMORY OF MY PARENTS

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PREFACE

The purposes of this book are, first, to describe some of the most recent experiments in optics, and second, to point out possibly fresh and simplified ways of performing some of the older ones. It is by no means a comprehensive manual of all the known optics experiments but rather a selective one. It does, nevertheless, explore a wide and far ranging variety of optical bypaths, and thus offers the reader the choice of following those which interest him most.

For example: the emergence of lasers. Many optics experiments used to be difficult to perform with ordinary light sources. With lasers this is no longer so. And when lasers were combined with large-screen closed circuit television, many old and difficult optics demonstrations became easier to do and able to be viewed by a large audience. The low-power, continuous wave helium-neon gas laser is now one of the most dependable tools of the serious experimenter in optics.

The He-Ne laser has also earned a place as an aid to the science educator. It can be used at all levels in education - in the basic high-school physics laboratory as well as in the most complex of university installations. This book explores the properties of the He-Ne lasers and applies them to experiments in optics for use in lecture demonstrations, teaching laboratories and home study experimentation. It will suggest and point the way rather than offering the reader a cookbook type manual. Relevant formulas are presented to refresh the memory and, where appropriate, numerical values for parameters are given. Schematic drawings are used profusely to further help the experimenter.

The problem of cost has not been overlooked. The experiments to be found here were designed to keep the cost of required apparatus at a minimum. Many components are available as surplus items and the experiments were selected on a qualitative basis, this in order to expose the reader to the largest number of optical principles and techniques in the space available. It is hoped this presentation will whet the reader's appetite and tempt him to delve more deeply into textbooks and journals for further study.

The "References" and the literature suggested "For Further Reading" make it easier for the reader to pursue any of the topics covered here in greater detail. Review and tutorial articles are often included in the references. Relevant books are listed at the end of this volume in the extensive Bibliography. Author, title, publisher and year of publication are given.

If this book proves useful, similar volumes will be compiled as new experiments are devised and new developments emerge. Comments and suggestions from readers are welcome and should be addressed to the publisher. Contributors of new experiments will receive full credit if their work is incorporated in later editions.

The author thanks the many people who gave advice, help and information in the preparation of this book. Especially does he wish to thank the manufacturers who so generously furnished equipment, raw materials, data and illustrations.

T. KALLARD

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INTRODUCTION

What is a laser?

The term "laser" is an acronym for "Light Amplification by Stimulated Emission of Radiation." Thus, the laser is a device which produces and amplifies light. The mechanism which accomplishes the stimulated emission was postulated by Einstein in 1917. Lasers may generate energy in the ultra-violet, visible, or infrared spectrum. The first continuously operating (c.w. - continuous wave) helium-neon laser was reported in February 1961 by Javan, Bennett and Herriott of the Bell Telephone Laboratories. Helium-neon lasers produce an intense, coherent, visible light beam of wavelength 6328 A (Angstroms), or, expressed in another unit of length: 632.8 nm (nanometers). All exercises and lecture demonstrations contained in this book utilize low-power c.w. He-Ne (helium-neon) lasers.

How does the He-Ne gas laser operate?

Without delving into the mathematics and quantum theory involved in the operation of a laser, the simplest way to describe the device is to compare it with an electronic r.f. oscillator.

An electronic oscillator (Fig. 1) has four main parts: (1) amplifier, (2) resonant feedback network, (3) output coupling port, (4) power source. The corresponding parts of a laser are shown in Fig. 2. Here the amplifier is a glass tube which contains a gaseous mixture of helium and neon, with neon as the active lasing material. When the laser's power supply (the "pump") delivers enough energy to cause continuous glow discharge in the gas tube (much the same as a neon sign is pumped by an electrical discharge), the neon atoms are elevated to a higher energy state by colliding with the helium atoms. When the neon atoms drop back to their lower energy state, they give up energy at certain wavelength: in this example the wavelength is 632.8 nm, in the red portion of the visible spectrum. The light output will be random and scattered equally in all directions. Some of this light is

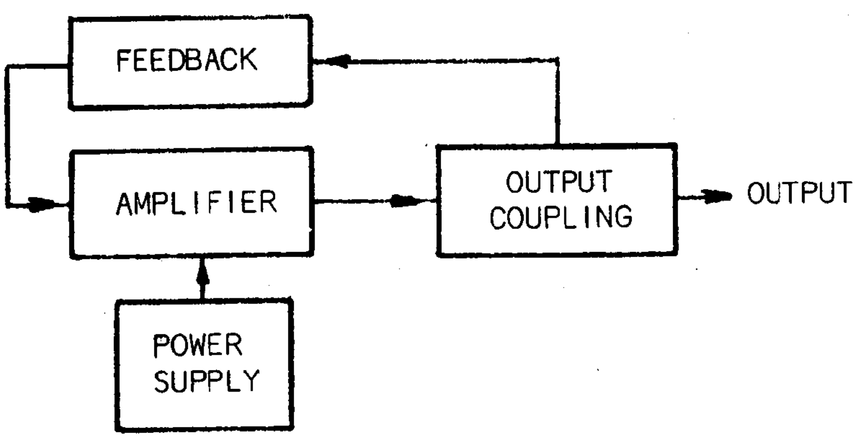

Fig. 1

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lost through the side walls of the glass tube, but the portion that travels down the center of the tube strikes other excited neon atoms creating more light energy of the same wavelength.

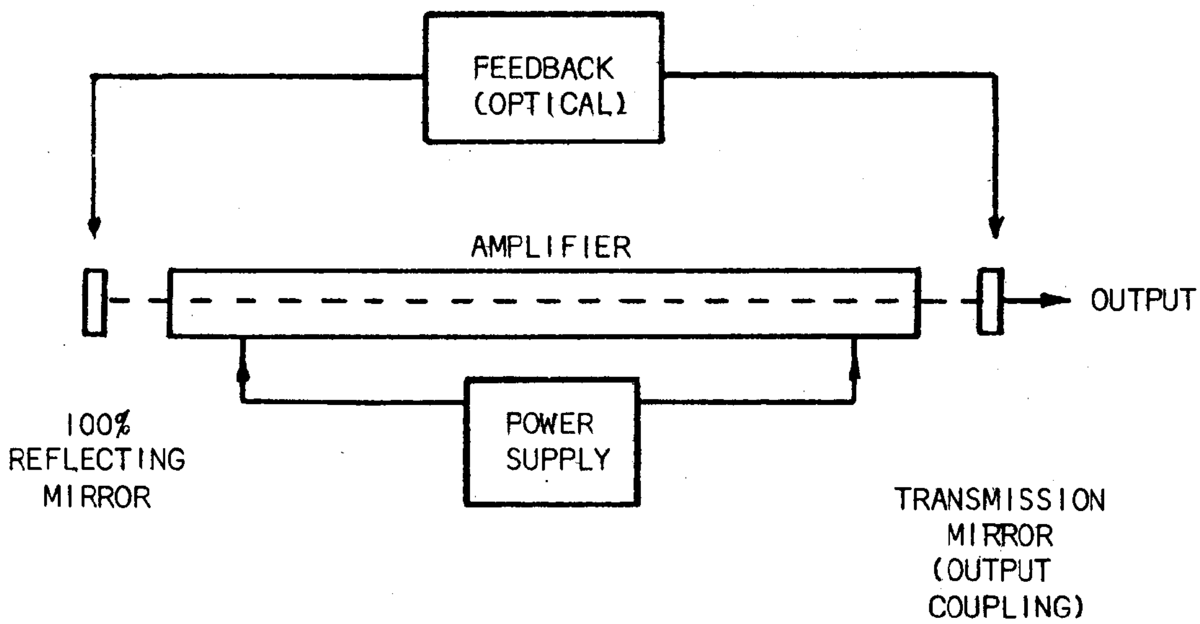

Fig. 2

The laser tube is placed in an optical cavity formed by two highly reflective mirrors positioned to face each other along a central axis. The mirrors reflect the initial beam which, as it bounces back and forth, eventually builds up enough energy to emerge through whichever mirror has the least reflectivity. This escaping light constitutes the highly directional beam of the laser. Since in the He-Ne laser, light amplification is only 1.02 on each pass of the beam from one mirror to the other, all losses must be kept below 2%. The so-called transmission mirror is coated to allow less than 1% of the generated light to escape. Thus, the beam emitted is less than 1/100th as intense as the beam between the mirrors.

Since the laser tube and the mirrors form an optical resonant cavity, the optical path length between successive reflections at a mirror must be of an integral number of wavelengths to produce reinforcement of the wave. Perfect alignment of the mirrors produces a beam which has an irradiance distribution that decreases smoothly from the center to the edge of the beam; the flux density pattern is ideally Gaussian over the beam's cross-section. This pattern, - a single disk area, - produces a single spot of light. It is designated "single mode," "uniphase," or TEM_{OO} mode. The last from Transverse Electric and Magnetic.

The TEM_{OO} mode has a number of properties which make it the most desirable mode in which to operate. The TEM_{OO} beam's angular divergence is smallest and can be focused down to the smallest sized spot. Furthermore, the TEM_{OO} (uniphase!) mode does not suffer any phase shifts or reversals across the beam as do higher order modes. It is completely spatially coherent. This is an important consideration in interferometric applications and holography.

Properties of laser light.

Laser light is quite different from light normally encountered. It has four unique characteristics that make the device a useful tool: (1) it is highly directional, (2) coherent, (3) very bright, and (4) monochromatic.

1) The directionality of the laser light is because only the light on the axis between the mirrors can escape from the laser. The beam emerges inherently well collimated and highly directional, and thus useful for applications where high concentration of light in a given direction is important.

2) The coherence of laser light in time and space is the one previously unobtainable property that makes it such an important source of light. Only light whose multiples of half a wavelength fit exactly between the mirrors is allowed to escape from the laser. Thus, standing waves are established between the mirrors, and each light particle is in step with the others. Since the light produced by the laser can be thought of as a wave oscillating some 10^{14} times a second, for such a wave to be coherent two conditions must be fulfilled: 1) It must be very nearly a single frequency (the spread in frequency or linewidth must be small). If this condition is fulfilled, the light is said to have temporal coherence, and 2) the wavefront must have a shape which remains constant in time. (A wavefront is defined to be the surface formed by points of equal phase. A point source of light emits a spherical wavefront. A perfectly collimated beam of light has a plane wavefront.) If this second condition holds, the light is said to be spatially coherent.

3) Intensity and monochromaticity go hand in hand. Since the laser builds up energy of only one frequency, all its power per interval of wavelength is much greater than the power available from other sources, this is simply because of its greater monochromaticity.

4) Monochromaticity (single coloredness) is the result of the narrow pass band of the amplifier plus the selectivity of the resonant feedback mirrors. For example, the wavelength of the red light emitted by a He-Ne laser is 632.8 nm. It is possible to limit the wavelength spread to a small band, say from 1 nm to 10 nm and produce light of high chromatic purity. Such light is called roughly "monochromatic" light, meaning light of a single color. If we refer to monochromatic light of 633 nm, it means a small band of wavelengths around 633 nm.

The anatomy of a He-Ne gas laser.

A) The Plasma Tube.

The plasma tube is a long capillary tube, two millimeters in diameter, surrounded by a hermetically sealed outer tube, one inch in diameter. The laser action which produces the beam occurs in the central capillary tube as the high voltage D.C. is applied to a mixture of gases, approximately 85% helium and 15% neon, at a pressure of about 1/300 of an atmosphere. As the electric energy is applied, the electrons of each atom respond by changing their orbits from the normal ground level configuration to the larger and more complex orbits associated with higher energy levels. After a short time in the energized state, the electrons spontaneously revert to their original conditions and the characteristic spectra of both helium and neon gases may be observed as each of the atoms radiates its recently acquired energy. This produces the characteristic blue light of helium gas and the familiar red glow of neon which may be observed in the laser tube. IMPORTANT NOTE: Do not look into the laser! Hold a piece of thin paper in the beam path near the exit window of the laser to observe the colors.

Although neon radiates several different wavelengths of light as its electrons fall from higher energy levels to the ground state, one of the strongest radiations in the visible light range (632.8 nm) is produced when the orbital electrons fall from the $3S_2$ to the $2P_4$ level. When one of the neon atoms undergoes this particular transition, a photon of light travels down the laser tube and other energized neon electrons along its path are stimulated to undergo the same transition. This frequency action produces additional radiations of the same frequency. The phenomenon is called stimulated emission or radiation. The stimulated emission results in a combined wave of increasing amplitude. Upon reaching the end of the laser tube, the wave encounters a mirror which sends it back through the tube to stimulate more energized neon atoms and increase its amplitude by a factor of 1.02 with each pass. With a flar mirror at each end of the laser tube, perfectly aligned waves of high amplitude are generated in a very short time.

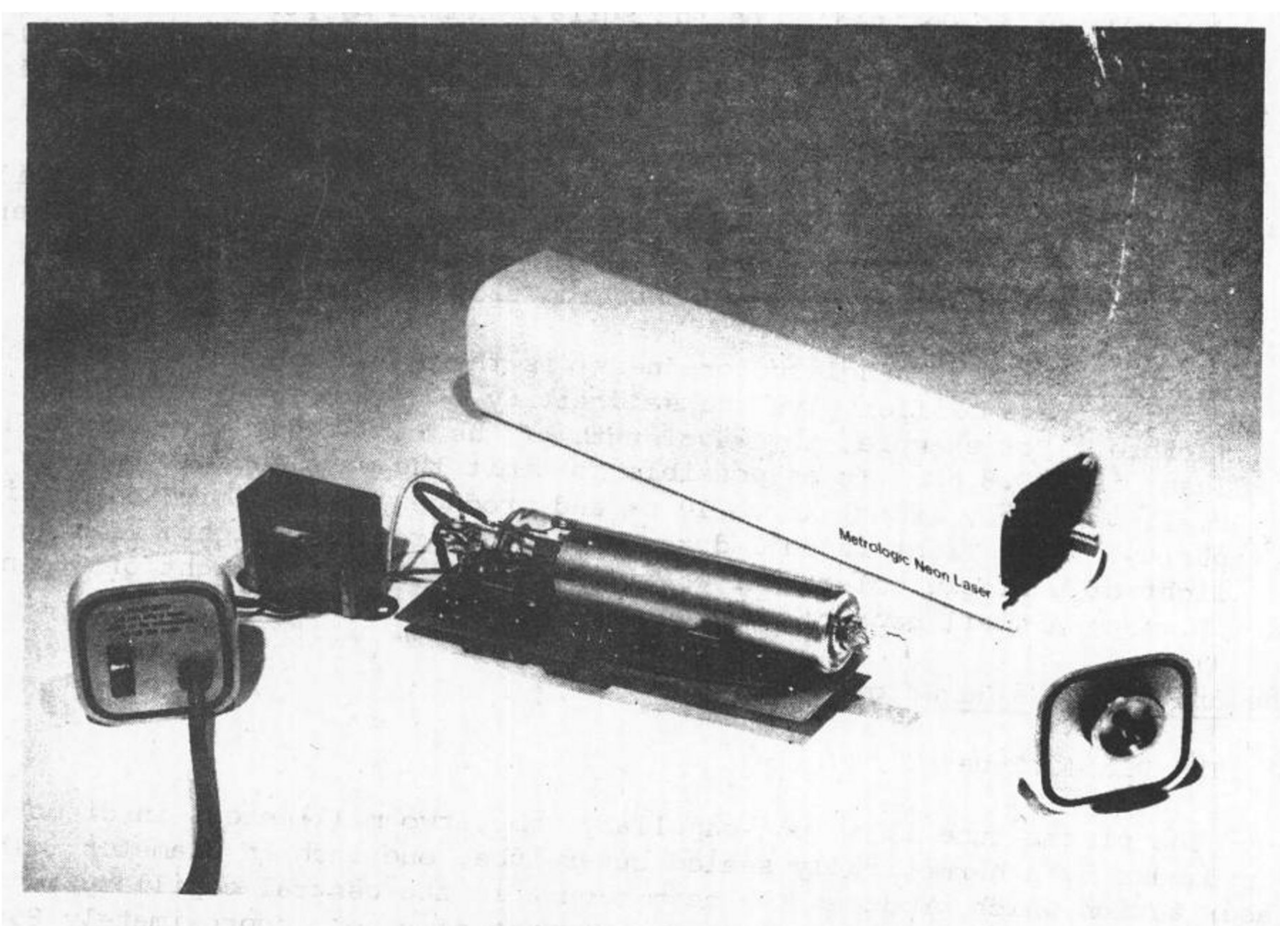

Fig. 3. Exploded view of laser

These waves are coherent in time because only those waves with an integral number of half wavelengths from mirror to mirror can sustain oscillation.

The situation is similar to the standing waves in a jump rope.

To produce an external laser beam, the mirror at the front of the laser tube is a partial reflector which reflects 99% of the light and transmits approximately 1%. The mirror at the back end of the laser tube has a higher reflectivity and reflects about 99.9% of the light while transmitting less than 0.1%.

During the manufacturing process, the coatings of the two mirrors are carefully adjusted so that the laser will resonate at 632.8 nm emission at the expense of other radiations produced by the neon gas.

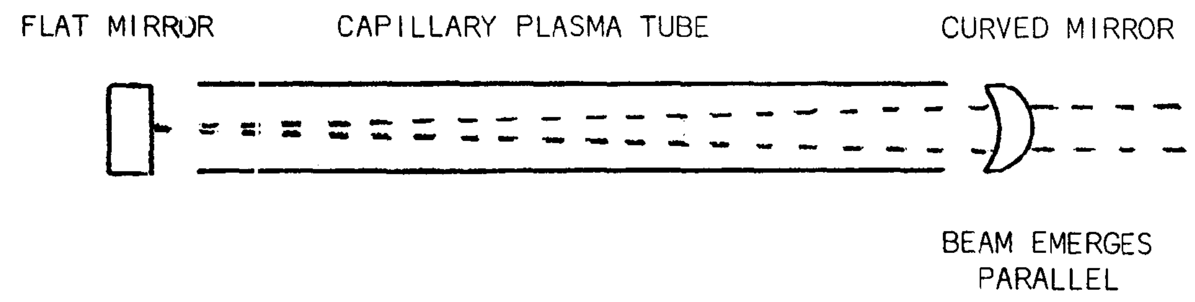

Fig. 4. The capillary plasma tube

A "semi-confocal" mirror arrangement is used in the plasma tube (Fig. 4). This consists of a flat mirror at the back of the laser tube and a concave mirror at the end where the beam emerges. Although a greater power output could be obtained with a flat mirror (or a long radius curved mirror) at each end of the laser tube, flat mirrors are very difficult to align; it is even more difficult to maintain their alignment when the laser is subjected to minor mechanical stresses during operation. With the semi-confocal arrangement, some power is sacrificed but the laser is so stable it can withstand the rough vibration and stress which occurs in a typical student laboratory. Furthermore, the curvature of the mirror at the output end of the laser tube is calculated so it will focus the laser beam at approximately the plane of the distant flat mirror. This curve/flat arrangement produces a laser beam which is cone shaped between the mirrors, the point being at the flat end, and diverging at the curved end. To compensate for this divergence, an additional converging lens surface is placed on the laser output mirror to produce a beam whose edges are very close to parallel.

Because of the internal geometry of individual laser tubes, it is found that the beam tends to vibrate more strongly in a particular plane than at any other possibilities. That is, the beam tends to be elliptically polarized. It is also observed that there is sometimes a secondary beam, polarized at right angles to the favored direction of vibration. In a short laser tube, one will find that the output beam is polarized at a given instant and that this plane of polarization appears to shift between two favored directions at right angles to each other in a somewhat unpredicatble manner. This interesting effect may be observed by passing the laser beam through a polarizing filter and observing the changes in beam intensity.

The capillary tube in which the laser action occurs is surrounded by a second tube about one inch in diameter. This outer tube has two purposes:

1) It supports the inner capillary and the two end mirrors in a rigid permanent alignment, 2) it provides a large reservoir for the neon gas which replenishes the supply in the laser cavity as it is slowly absorbed by the cathode during laser operation.

Helium gas is included in the laser because it has been found to enhance the output of the neon gas by a factor as high as 200x. As the helium atoms are energized by the high voltage direct current, they collide with nearby neon atoms in a most efficient energy transfer process. Although it has been found that the neon gas alone will provide lasing action, the output is about 200 times as great when helium and neon are mixed in proportions of about 6 to 1 (i.e., about 85% helium and 15% neon).

B) The D.C. Power Supply

The D.C. power supply receives 110 volts A.C. from the linecord and produces a D.C. voltage of 2000 volts. To do this, a transformer steps up the 110 volts to 630 volts A.C. with peak-to-peak voltage excursions of about 1000 volts positive and 1000 volts negative. Solid state rectifiers act upon the positive and negative excursions of the transformer output separately to produce two independent outputs of 1000 volts. These voltages are then added in series using a voltage doubler circuit to produce a combined output of approximately 2000 volts. This is reduced to the required 1100 volts with the aid of a string of ballast resistors. To start the initial laser action and ionize the gas in the tube, a separate circuit provides a pulse of about 2000 volts which is automatically removed when the laser action starts.

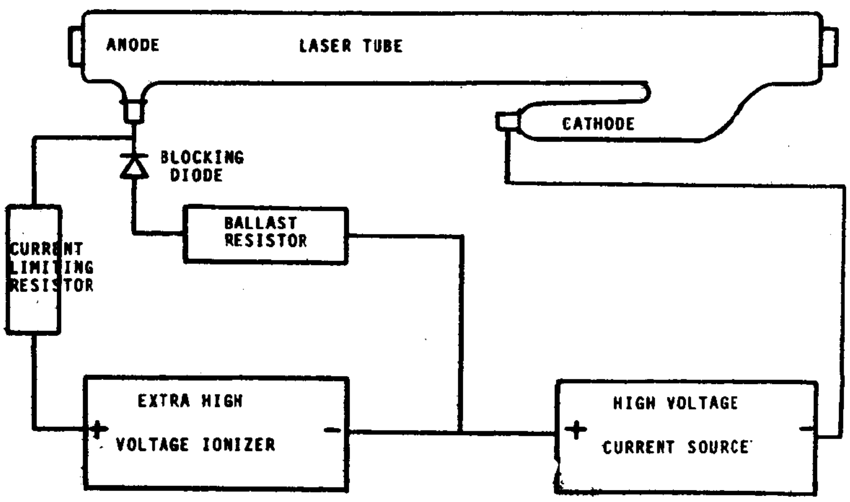

Fig. 5. Gas laser power supply

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H. Weichel, Am J Phys v44 p839 (Sep '76)

Laser Safety

Powerful pulsed lasers are used for welding and, also, are capable of drilling holes in metal. High-power lasers are used in surgery, in resistor trimming, in non-destructive testing, and even in static and dynamic art exhibits. More and more graduate research is performed with high-power lasers in the 10^2 - 10^{12} W/cm^2 range. Therefore, it is essential that all persons who are exposed to laser hazards be informed on the subject of laser safety.

All exercises and lecture demonstrations described in this book can be performed with lasers whose output falls in the 1-5 mW range. A recent study concludes that with ordinary caution even the highest power lasers in this range (1-5 mW) are safe. Over 90% of the exercises described for the student laboratory, from elementary school science to undergraduate physics level, can be performed with low-power helium-neon gas lasers in the 0.5-1.0 mW range. The Metrologic ML-669 modulatable student laser used in most exercises covered in these pages has a nominal 0.8 mW visible output which places the device within the Class II category, as defined by the Department of Health, Education and Welfare for laser safety. To insure absolute safety, however, the following precautions and safety procedures are recommended:

1) Treat all laser beams with great respect.

2) Never look into the laser window (even when turned off) or stare into the beam (on axis) with either the naked eye or through binoculars or a telescope at a distance.

3) Do not rely on sunglasses as eye-protecting devices.

4) Never point the laser beam near anyone else's eyes.

5) Cover all windows to protect passers-by.

6) Never leave lasers unattended while activated. If not in use, disconnect A.C. power cable.

7) Room illumination in the work area should be as high as is practicable to keep the eye pupil small and reduce the possibility of retinal damage due to accidental exposure.

8) Remove all superfluous and highly reflective objects from the beam's path. These include rings, watches, metallic watchbands, shiny tools, glassware, etc.

9) Beware of electrical hazards: Ungrounded frames or chassis' and inadequately insulated power cables. Adequate grounding should be provided for the laser case and the laser should never be operated without a protective cover.

10) Never attempt any adjustments to the laser plasma tube or associated electronics with the laser plugged in. First, disconnect the power

cable and then discharge capacitors. Lethal current levels at high voltage is present inside the laser chassis.

11) While operating outdoors (laser communications, speed of light experiments, etc.) do not point the laser at passers-by and do not track vehicular or airborne traffic with the laser beam.

12) Do not operate the laser in rain, snow, fog or heavy dust. Potentially dangerous, uncontrolled specular reflections can result.

References:

Lloyd, L.B., Popular Electronics p41 (Dec '69)
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Federal Register v40 n148 Pt. II (31 Jly '75)

Care and Maintenance of Equipment

The following suggestions for routine care of the equipment will help to prolong its useful life:

1) To save the plasme tube, the laser should be shut off and disconnected when not in use.

2) To prevent dust from entering the laser housing, the laser should be stored in a dry room and covered with plastic or other suitable covering.

3) If possible, all chemicals should be kept in a separate store-room, away from the laser and its accessories.

4) Before and after each use wipe smudges and fingerprints from lenses, prisms and other accessories with a soft cloth, or, preferably with a good quality lens tissue.

5) After each use, wrap lenses, prisms, glass plates, filters and all fragile accessories in lens paper or soft tissue and place them in individually marked envelopes or boxes. In this way they may be easily located and safely stored.

6) Never use solvents to clean plastic parts, polarizing and color filters, photographic films such as holograms, diffraction grating replicas and similar items.