# Applications of the Laser

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Published by:

CRC PRESS

CRC Press, Inc., 18901 Cranwood Parkway, Cleveland, Ohio 44128
Formerly The Chemical Rubber Co.

International Standard Book Number 0-87819-028-17

Library of Congress Card Number 73-89461

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Prior to his present appointment, Dr. Goldman was an intern and resident in medicine and later dermatology at the Cincinnati General Hospital. He was also a fellow in dermatology at Dermatologische Klinik, University of Zurich.

Dr. Goldman has filled appointments as co-chairman of First Conference on the Laser, New York Academy of Science, 1965, chairman of Second Conference on the Laser, New York Academy of Science, 1970, and chairman of the Gordon Conference on Lasers. He is also a member of the American National Standards Committee Z-136-Standard for the Safe Use of Lasers and is currently chairman of the Subcommittee on Lasers of the AAMI (Association for the Advancement of Medical Instrumentations).

He is the author of 3 books and has published over 75 articles on lasers.

# FOREWORD

As Director of a Laser Laboratory for more than 11 years, it is obvious that I should be aware of the impacts of the laser. This is actually literally true because I have been aware of more than a thousand purposeful impacts on my own skin as part of the long continued and pioneering studies on laser safety as regards chronic exposure. In spite of the fact that I have written some little books on laser medicine and biology, mostly inadequate, I still felt that it was necessary to try to assemble mostly superficially, what the laser has actually done, what are its current needs, and what are some of its dreams for the future. My own special fields of interest and work have been in laser safety, biology and medicine, laser biomedical engineering, law and order, social conscience of laser research, now, unfortunately, becoming but a trite phrase, and finally, most curiously, laser art and music. Unfortunately, at the last moment and without my wishes, it was not possible to be restricted to these themes. So, much to the horror of the expertise, who in spite of their protective glasses, will see red as I scan, superficially again, many fields of laser applications in order to complete this review. Courage and, of course, information have been furnished, fortunately, by associates and friends in laser technology. These have been accompanied at times by expressions of real sympathy.

In order to do this, I have been helped by many people. Chiefly, of course, is the staff at the Laser Laboratory, present and past. The Directing Physicist of the Laser Laboratory, R. J. Rockwell, Jr., M.Sc., has looked over my shoulder for a number of years and has helped to restrain the unwarranted enthusiasm and unmeasured work of biologists and physicians in the Laser Laboratory. Many studies have been done together with him. Ronald Dreffer and John Johnson, technicians in the Laser Laboratory, have labored long hours with the experiments and with tender care of many patients.

The Office Manager of the Department, Billie Wilson, and her associate, Yvonne Wing, have done countless hours of extra work in this new field of laser technology to assist me in assembling the vast amount of data. Esther Giermann, as current secretary of the Laser Laboratory, has accepted the extra burden of preparation and help for this work. Pati Kelley, recently introduced to laser technology, has gone through mountains of literature. In addition to her preparation of excellent slides, Marilyn Franzen, Director of Laser Histology and Histochemistry, has ventured into many strange fields, including laser photography in the preparation of visual educational aids to help in this monstrous task and in the exhibits from the Laser Laboratory.

Patty Smith, our photographer, has had large responsibilities in all phases of this laser work, has spent long hours assembling these pictures, and has developed some interesting techniques for laser photography as an art. Ron Dreffer is also a real pioneer in the development of laser art. I am also grateful to our summer students for teaching us, as teaching is also one of the functions of the Laser Laboratory. Summer students are young and full of enthusiasm and thrilled by the challenges of the laser, very unlike the givers of grants. They are good answers to those scientists who have fears and anxieties about working with the new technology. To those who have promised little or much and not come through, I do understand, for, again, this is a new technology. It is difficult to give up someone's things or even to loan some of one's precious darlings. However, as maturity continues in this new field, such insecurities, anxieties, and fears will no longer continue. All interested in laser technology have a certain responsibility to do and to teach.

My friends throughout the laser field in this country and abroad have given valuable services. They include Arthur Schawlow, Professor of Physics at Stanford and truly a "father" of the laser, who has stimulated all of us at the Laser Laboratory to go far beyond our antiquated instrumentation; Don Rounds in biology; Fred Brech in laser instrumentation, especially the microprobe; George Wilkening, Charles Powell, and Wordie Parr in safety; Bill Ham, Chris Zweng, and Fran L'Esperance, all in ophthalmology; and Dick Honey for offering to help in the current difficult field of attempts of standardization of laser biomedical instrumentation. First names are used purposely to show the personal interest that they have taken in our past and current studies.

In Germany, Gunther Nath, Fritz Hillenkamp, and Ernest Weidilich; in Russia, Nicholai Gamaleja;

in Japan, our former Research Associate in Laser Surgery at the Laser Laboratory, Kumio Hishimoto, and in Czechoslovakia, Zdenek Naprstek, our laser surgeon, have all helped to show the international need for laser cooperation and work.

Altogether, then, we all are trying to introduce the laser to this brave new world and to open new paths for much better, more effective, and more controlled uses of laser technology. This will be mostly for the good of man in a world made much smaller and more cooperative by the laser.

Leon Goldman, M.D.
Cincinnati, Ohio

# INTRODUCTION

A current review of application of lasers would be out of date as soon as it is written. Yet, it is necessary to show some of the directions the laser can take now and what it may take in the future. This work will present an informal, oftimes superficial view of the applications of many laser systems primarily to stimulate interest, imagination, and desire. There are many excellent volumes and journals on lasers and on specific areas of information for laser applications and for laser expertise.

The background for this is a laser laboratory with more than 11 years of detailed activity. The goals were and continue to be studies of the basic reactions of lasers in living tissues, the development of laser safety programs, and the responsibility and obligation to teach laser safety, research, and the development of the biomedical applications of the laser. Therefore, in this laboratory or laser center, one must know about applications. A staff of many disciplines helps to guide the interested but unlearned amateur through the laser field.

Perhaps, as stated previously and repeatedly, some of the material to the expertise may appear to be too superficial, inadequate, or even with the sources of information, inaccurate.

For those not familiar with lasers, there will be a review of lasers and some remarks on the fascinating new developments in such systems that do affect applications now and in the future. Wave guides to transmit lasers to make them more flexible, the important aspects of measurements to be measured and to measure, chemistry, bits of botany, and holography will be given. The vast expanse of communications, especially through the development of the new and important hybrid discipline of electrooptics will be reviewed. The military and law and order programs show their applications; all initiate the study of actual applications. Then follow metalworking, construction, pollution, and a number of miscellaneous techniques. There will be, we hope, a critical review of safety programs so necessary for the proper development of laser technology. Then follows the story of the applications in biology, medicine, dentistry, photography, art, and music. Many of the applications cross to other fields. To stimulate the youth to be interested in science, there are brief remarks about the social conscience in laser and, finally, the dreams of the future.

Details will certainly have to be added sometimes by some critics and some details may be revised, as in all fields of development. If interest is stimulated to venture into the lasers, to examine the references, or with reason to object, then its purpose is fulfilled. The reviewer will agree that this is to interest and communicate, not to develop expertise.

To the annoyance or maybe just puzzlement of some, the increased emphasis of certain phases of technology may be disturbing. The repeated detailed emphasis on laser safety, its philosophies, its goals, and its confusions should not be disturbing to anyone. Safety cannot be overemphasized and laser safety programs are to be reviewed often.

Above all, the ancient cliché of all the laser technology should be repeated again and again and again, "If you don't need the laser don't use it." If you cannot tell, then with proper controls, try it, you'll like it.

# TABLE OF CONTENTS

Chapter 1

# AN INTRODUCTION TO LASERS AND LASER SYSTEMS

It is not well known or perhaps even appreciated that the laser was born in 1917 when Einstein in his great publication, "Zur Quantum Theorie der Strahlung," established the concepts of stimulated emission, stimulated absorption, and spontaneous emission. It was not until 1953, however, after the development of the maser, microwave amplification by stimulated emission of radiation, that Basov and Prokhorov, in Russia, and Townes and Weber, in the U.S., developed the concept of the laser, light amplification by stimulated emission of radiation. The first ruby laser was shown to the public on July 7, 1960, by Maiman of Hughes Aircraft. Since that time, tremendous strides have been made in this new darling of modern-age physics.

There is much literature available on lasers and laser physics. Only a brief review will be given here.

Laser physics includes such basic phases as population inversion, energy levels, and stimulated emission. From population inversion, the fundamental characteristics of laser light are produced:

1. Monochromatic light
2. Coherent light
3. Parallel beams of light
4. Polarized light
5. High intensity
6. Electromagnetic field strengths.

As indicated, this book will not go into the detailed background, perhaps even for what Jones[8] calls "lasers for the masses." The interested reader is referred to the books listed in the references.

It is quite proper that a brief review of laser systems be given by Rockwell, the Directing Physicist of the Laser Laboratory. This is taken from his detailed presentation to the Health Physicist Meeting with Wordie Parr as Chairman (Electronic Product Radiation and The Health Physicist BRH/DEP 70-26) in 1970.

### Characteristics of Laser Systems

"*Fundamental Aspects of Laser Devices.* The list of substances which can produce laser emission is comprised of an impressive number of different solids, liquids, gases, and junction diodes. There are, however, several features which are common to the configuration of all types of lasers, namely:

1. *The Laser Media.* – This is the substance, either solid, liquid, gas, or junction between two dissimilar metals, which is capable (because of its atomic and/or molecular makeup) of sustaining stimulated emission.
2. *The Source of Excitation Energy.* – In order to generate a laser beam a redistribution is required in the number of atoms which normally exist in certain atomic energy levels of the laser media. This requires an external source of excitation energy often called the "pump" energy.
3. *A Fabry-Perot Interferometer.* – This device is a pair of mirrors which are aligned plane-parallel to one another. In the case of the laser, one mirror is placed at each end of the laser media. Usually, one mirror is a total reflector, the other a partial reflector (i.e., it allows part of the laser beam which is generated within the active media to pass outside the interferometer).

In the most general manner, the following describes how a laser operates: Excitation energy is vigorously supplied to the active media to produce the specific condition called a population inversion. In this condition, more atoms of the laser media are in a specific excited-state energy level than in the lowest "ground-state" level. This condition is contrary to the normal population of states of a system in thermal equilibrium. One manner for an atom in an excited state to release excess energy is by the spontaneous emission of light in discrete units called photons. The unique feature of a laser device lies in the fact that because of the population inversion the energy release may be accomplished by the process known as *stimulated emission.* In this case a photon released by one excited atom will cause (stimulate) an excited atom it may encounter in its path also to release a photon of excess energy. The result of this interaction is the combination of two photons with identical coherence properties (phase relationships) so that they add completely together to produce a beam of twice the intensity. As the beam progresses through the excited laser media, its amplitude will be rapidly increased while its coherence properties remain unaltered. Upon reaching the total reflection mirror the beam direction is completely reversed, thus allowing another pass through the excited laser media so that the beam may be further amplified. Upon reaching the partial reflecting mirror, a portion of the beam escapes. This escaping portion is the active emission from the laser. The process will continue for as long as sufficient pump energy is supplied to the laser media.

## TYPICAL LASER CHARACTERISTICS

| Laser Media | Predominant Wavelengths (nanometers) | Active Media | Common Method of Operation | Continuous Power (w) | Peak Power (megawatts) | Beam Divergence (milliradians) |
|---|---|---|---|---|---|---|
| Ruby | 694.3 | Solid | Pulsed | 1.0 | 1–1,000 | 0.5–20 |
| Neodymium-glass | 1,060 | Solid | Pulsed | | 1–500 | 0.5–20 |
| Neodymium-YAG | 1,060 | Solid | CW | 1–100 | 1–10 | 0.5–10 |
| Helium-neon | 632.8<br>1,150<br>3,390 | Gas | CW | 0.001–0.100 | | 0.1–1.0 |
| Argon ion | 476.5<br>488.0<br>514.5 | Gas | CW | 1–20 | $10^{-4}$ | 1.0–3.0 |
| Krypton ion | 647.1<br>568.2<br>520.8<br>476.2 | Gas | CW | 0.5–2.0 | | 1.0–3.0 |
| Helium-Cadmium | 325.0<br>441.6 | Metal Vapor | CW | 0.015<br>0.05 | | 0.5 |
| Neon ion | 332.4 | Gas | CW | 0.250 | | 1.0–3.0 |
| Neon-pulsed E field | 504.1 | Gas | Quasi-CW | .003 | $10^{-2}$ | Rectangular beam 2 x 30 |
| Carbon dioxide | 10,600 | Gas | CW | 10–5,000 | $10^{-2}$ | 1.0–5.0 |
| Nitrogen-pulsed E field | 337.1 | Gas | Quasi-CW | 0.100 | $10^{-2}$–$10^{-1}$ | Rectangular beam 2 x 30 |
| Gallium-arsenide | 840.0 | Semiconductor | Quasi-CW | 1–20 | | Rectangular beam 1–10 |

The following sections will review the most important laser devices in use today. Special emphasis will be placed upon the variations possible in the outputs which these devices may produce.

*Pulsed Laser Devices.* Lasers which use a solid-state media are generally operated in a pulsed mode. The most common solids used are ruby crystals and neodymium-doped glass and neodymium-doped crystals such as Yttrium Aluminum Garnet (YAG). In the present state of the art, the pulse envelope is generated in one of the following manners:

1. A millisecond or multi-millisecond pulse envelope comprised of many random pulse spikes of submicrosecond duration.
2. A single multinanosecond high power pulse.
3. A single nanosecond or sub-nanosecond high power pulse.
4. A train of evenly spaced ultrashort, sub-nanosecond pulses.
5. A single ultrashort, picosecond pulse.

The distinction of the type of pulses becomes exceedingly important in the evaluation of the interaction phenomenon of pulsed laser radiation, where the rate of energy delivery is the critical factor. The following will review the most common variations in pulse characteristics produced by commercially available laser systems:

1. *Normal Mode Operation.* – The pulse envelope from a long pulse or so-called "normal mode" solid-state laser will appear, when viewed photoelectrically, as a series of random "spikes." Although this sporadic spiking behavior is not completely understood, it is believed to be a consequence of interaction which occurs between the excited ions in the active laser media and regions of strong electromagnetic fields of the laser beam *inside* the media. This produces a sporadic de-population of the excited ions, which are observed as random pulsations during the laser burst. Each spike has a duration of 300 to 400 nanoseconds and the average spacing between spikes is in the order of a few microseconds. Recent reports have shown that each spike may consist of a large number of even shorter pulses which may last from three to ten picoseconds ($10^{-12}$ seconds).

Ruby or neodymium laser-systems derive the excitation energy from xenon arc flashlamps that are usually placed in a highly reflecting housing so as to actually focus the lamp emission onto the laser rod. The pulse of the normal mode laser output is, in the first approximation, about equal to the length of time that the xenon flashlamp is excited; providing, of course, that the emission from the lamp is sufficient to sustain a population inversion in the laser media. The duration of the current pulse in the lamp is determined by the time-constant of the inductance-capacitance (IC) network which drives the flashlamp circuit.

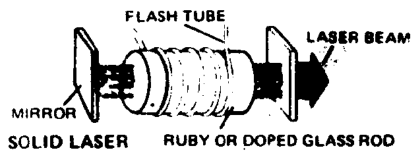
There are methods to stretch the pulse-length in normal mode operation. The most common is to use additional inductance-capacitance sections which will serve to increase the pulse-length monotomically; with

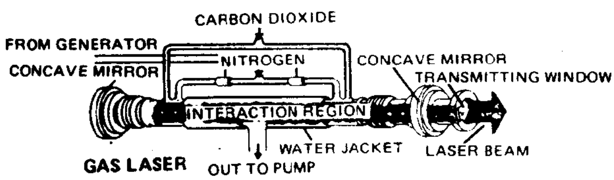
## WAYS TO MAKE A LASER

**Solids, liquids, or gases will all work.**

Take a big block of energy. It can be in any form the light of a flash tube, the energy of a radio generator, an electrical current, or an electron beam. Shoot this energy through a substance that contains a tiny amount of another kind of atom. If you have selected the right atoms and made your machine the right shape, you will be forced to work in unison and to radiate in unison. Out of the substance will come a beam of laser light. Here are some examples

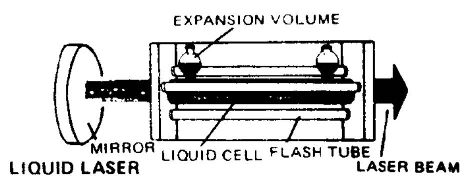
The solid laser employs a cylinder of ruby or even of glass. The energy comes from a flash tube. Mirrors at each end shoot the light back and forth. Impurities built into the ruby or glass are the source of the electrons that get sorted. When these electrons radiate, a beam of laser light emerges.

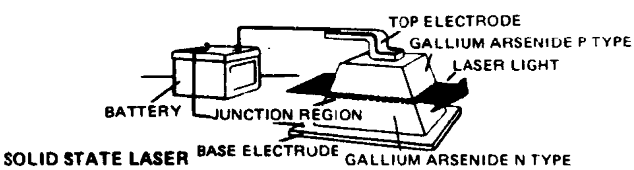



The gas laser operates much like the solid laser. The $CO_2$-$N_2$ laser is one example. Carbon dioxide fills a tube; nitrogen is the impurity. A high-frequency radio wave from a generator supplies the power. The nitrogen electrons are sorted and end up emitting a typical laser light. The helium-neon laser is another widely used type.

The liquid laser looks much like the gas laser. This one gets energy from flash tubes. The liquids can be an alcohol mixture or, more usually, exotic substances such as trivalent neodymium in selenium oxychloride.




The solid-state laser uses the same material that transistors are made of. These, like the previous lasers, require a specific trace of impurity atoms to furnish electrons. The P-type and N-type of materials control the way the electrons flow. A wrong-way heavy current makes the junction light up.

FIGURE 1-1. Ways to make a laser. (Xerox Education Publications.)

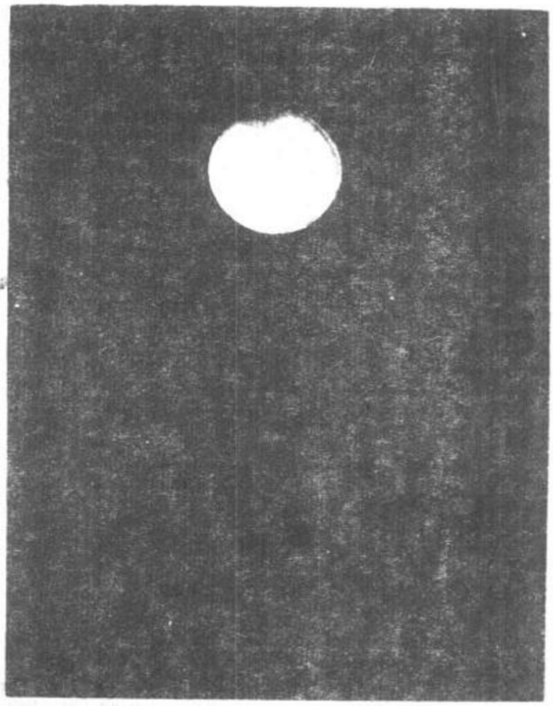


**FIGURE 1-2.** Oscillator amplifier Q-switched ruby laser* **impact showing** target 1.8 cm, 8 J, 25 nsec, and 300 m$\mu$. **(Murakami, Oak Ridge** National Laboratories.)

**this** technique, normal mode laser pulses have been **stretched** to 30 msec for some laser welding applications.

**2.** ***Q-Switched Operations.*** – Pulsed laser operation is **also possible** in a second mode of operation. In 1961 **McClung** and Hellwarth announced the technique known **as** "Q-Switching." The term "Q" is a carry over from the **radio** wave and microwave terminology, and it relates to **the so-called** "quality factor" of a resonating system. A **"low Q"** would refer to a system that would not easily **support** oscillation; thus, to switch (or spoil) from a low **to a high** Q (viz., Q-Switching) means to change rapidly **from a** condition in which the laser cannot lase to a **condition in which** it will. The mechanics of Q-spoiling **usually incorporate** some form of electro-optical or **electromechanical** shutter between the mirrors of the laser **cavity.** Recent reports, however, indicate that Q-Switching **can be** accomplished also by a simple misalignment of the **Fabry-Perot** mirrors. The effect of Q-spoiling is to force **the laser** to operate in a condition of maximum gain. This **occurs** because the overpopulation in the metastable state **will be** larger than in the case of normal mode laser action **due** to the fact that no stimulated de-population can occur in the low Q cavity. When the "switch is thrown," so to speak, de-population by stimulated emission will **rapidly** occur, causing the emission of an intense giant **pulse**, or train of two or three pulses, each lasting from **ten** to 50 nanoseconds. The result of such short bursts of **light** is the production of enormous peak-power outputs. **With** this method it is possible to produce instantaneous **light levels** exceeding 100 million watts in a single burst of **light.**

Because of the desire for even high peak powers, the damage threshold was soon reached for most solid state laser materials and investigations immediately began on amplifier devices into which a Q-Switched laser pulse could be passed so as to experience still further amplification without damage to the system. This oscillator-amplifier concept is one in which a Q-Switched pulse from the first laser (the oscillator) is passed into a second (larger diameter) laser system (the amplifier). Consequently, the amplifier section will receive signals substantially below the damage levels of the active laser media. With single amplifier system, peak pulse powers up to 500 megawatts are easily achieved using ruby and neodymium-glass lasers. Systems are now available which employ three or four amplifiers and produce hundreds of gigawatts ($10^9$) per pulse.

3. *Time Variable Reflectivity.* – The concept of controlling Q-Switched laser outputs with a time-variable reflectivity (TVR) was first introduced by Vuylsteke in 1963, with his pulse-transmission-mode (PTM) Q-Switched laser. In this device, the Fabry-Pérot mirrors were both initially 100% reflective then, at the proper time, one mirror is changed to maximum transmission to allow the laser pulse circulating in the cavity to escape. This basic concept has been used in both neodymium and ruby lasers to generate giant pulses in a range from 0.1 to 10 nanoseconds.

The technique of TVR is accomplished with the Kerr electro-optic effect. This phenomena is observed in both liquids (nitrobenzene) and solids (potassium dihydrogen phosphate: KDP) which are placed in a large electric field. Under these conditions, the material is changed into a double refracting media. Consequently, a linearly polarized light wave passing through the media will be changed into a circular, elliptical, or orthagonally linearly polarized beam depending upon the degree of retardation imposed.

The Kerr effect device most commonly used with pulsed lasers is called a Pockel's Cell; and usually employ the crystal KDP as the media. In this case, application of a large electric field (in the direction of propagation) will change a linearly polarized laser beam into a circular polarization. Upon reflection from a 100% reflector the sense of circular polarization is reversed, thus, when the beam re-enters the Pockel's Cell it is changed back into a linear polarization, but the direction of the electric field vector will be orthagonal to the original beam polarization. Consequently, insertion of a polarization sensitive prism inside the resonant cavity of the laser (viz: a calcite prism or Glan-Thompson prism) will allow the laser pulse to be reflected out of the cavity from the side.

The principal advantage of TVR switching is that the energy of the output pulse is independent of the cavity gain characteristics and the duration of the output pulse is solely dependent on the separation between the resonator mirrors. The laser pulse length is equivalent to the time for the pulse to make a round-trip circuit in the cavity. Consequently, laser pulses which last only 2 to 5 nanoseconds are easily generated (without loss of pulse energy) from standard Q-Switched ruby lasers which would normally produce pulses which are 10 nanoseconds or longer. In this manner, the peak power of the pulse is increased by at least a factor of five over standard Q- Switched systems.

4. *Mode-Locked Laser Systems.* – A laser device is a resonant oscillator of electromagnetic waves. Consequently, it can support standing wave patterns in a manner somewhat analogous to the resonance of an organ pipe. The laser "standing waves" are produced when an integral number of half-wavelengths exactly fit into the separation between the mirrors of the Fabry-Pérot cavity. In all lasers this spacing is many, many orders of magnitude larger than one laser wavelength, thus, there are many slightly different standing wave frequencies which can fit within the narrow linewidth of a laser source. This gives rise to many distinct spectral components or longitudinal "cavity modes" each with individual amplitude, frequency, and phase characteristics. In the event that the phases of these different frequency modes are synchronized in some manner (e.g.: the phases of the different longitudinal modes become "locked together") the different modes will then interfere with one another to generate a beat effect. The result will be a laser output which is observed as regularly spaced, periodic intensity pulsations.

Mode locking is usually accomplished by inserting an ultrafast intensity dependent "switch," such as a bleachable dye, inside the resonant laser cavity (i.e.: between the mirrors). The overall system operation may be explained as follows: The active laser media serves as a light amplifier, the resonance of the Fabry-Pérot Etalon and the natural line width of the laser act as a selective frequency filter. The time for the laser beam to travel the cavity length twice will serve as an optical delay line. The bleachable dye is sometimes referred to as the "expandor element," meaning that it serves as a non-linear absorber, since it provides less loss for a high intensity signal than a low level signal.

Thus, a pulse circulating intra-cavity will be amplified only if it has sufficient intensity to cause the dye to momentarily bleach to transparency. The dye also serves to produce optimum mode coupling, provided its relaxation time is shorter than the time for a pulse to make round trip in the cavity. Since many of these dyes may be "switched" in less than $10^{-13}$ seconds, it becomes theoretically possible to produce individual laser pulses in this time range. The individual pulses which are contained in the pulse train of a mode locked laser are "ultrashort" picosecond ($10^{-12}$ seconds) pulses. The separation between successive pulses is that of a round trip of the beam between the Fabry-Pérot mirrors.

5. *Ultrashort Pulses.* – In 1967, Bell Telephone Laboratory scientists, Duguay, Shapiro, and Rentzepis, discovered that picosecond duration pulses may actually be present in the output from many standard solid-state Q-Switched lasers. Because these pulses are of such a brief duration, it is almost impossible (prior to the unique measurement techniques such as they devised) to individually observe these pulses; although it was suspected that they did exist. Since most solid-state lasers do have a definite width to the spectral line (or, in other terms, many cavity modes) it is possible by mode-locking techniques to generate very short duration intensity pulsations. The broader the spectral width of the laser line, the more harmonic components that will occur in the interference phenomena, and thus, the shorter will be the duration of the beats which occur. As a result, the amplitude or the peak power will increase as the width of the pulse decreases. The neodymium-glass laser is of particular interest in the generation of mode locked pulses because of its quite broad (100-200 Å) bandwidth. This would theoretically allow for the generation of subpicosecond high peak power laser pulses.

Special techniques can be used to isolate an individual ultrashort pulse. The importance of such pulse widths lies in the peak power of the pulse. For example, using a neodymium-glass oscillator-amplifier laser system, peak powers of 30-40 gigawatts ($10^9$ W) in a pulse width of 10-15 psec have been observed.

Scientists at the United Aircraft Research Laboratories recently observed an ultrashort laser pulse of only 0.4 picosecond duration. A neodymium-glass laser was used which was simultaneously mode locked and Q-Switched by a saturable absorber. Although it had been known for some time that the theoretical limit of the pulse width from a neodymium mode locked laser would be in the order of about one-third of a picosecond, pulse widths previously observed were usually in the order of 4 to 10 picoseconds. This discrepancy between measured and the theoretical pulse length suggested the existence of an amplitude or carrier wave modulation in the pulses themselves. The experiments confirmed this fact and showed that most of the measured spectral content of the pulse was due to an almost linear relation between the frequency of the carrier wave and the laser wavelength. The modulation was about one per cent larger at the beginning of the pulse than at the end. As a result, the pulses could be compressed to a length approaching the reciprocal of the bandwidth by passing them through a dispersing system which also had a linear relation between time and wavelength. In this manner, ultrashort pulses were compressed into a range of 0.4 X $10^{-12}$ seconds, near the theoretical limit.

Thus, it is seen that there is an enormous variation in pulse durations generated from the many available laser systems. The spread in time of the overall pulse envelope from the normal mode pulse to the single ultrashort pulse may be as great as $10^{10}$. The specification of such pulse characteristics is extremely important, especially in any critical evaluation of the interaction phenomenon of laser energy.

6. *Wavelength Variation With Pulsed Lasers.* – The advent of Q-Switched laser systems with their associated enormous electromagnetic fields, also introduced the more common use of frequency shifting with two non-linear techniques; namely, second harmonic generation (SHG) and Stimulated Raman Scattering. The non-linear polarization field induced in non-centrosymmetric crystals such as quartz, potassium Dihydrogen phosphate (KDP), and Barium Sodium Niobate can actually generate harmonic components of the fundamental laser frequency. In this manner, high power pulses in the ultraviolet spectrum may be produced: 347 nM with the ruby laser and 265 nM using two frequency doubling crystals and a Q- Switched neodymium laser.

Commercial systems are also available which employ

**Stimulated Raman Scattering** to produce additional wavelengths. In one such system, (Geoscience Instruments) produces three Stokes (longer wavelength) and four Anti-Stokes (shorter wavelength) shifts. Using the ruby laser as the source, the available wavelengths are 432 nM, 492 nM, 577 nM, 694 nM, 871 nM, 1167 nM, and 1768 nM. It is evident that by combining both SHG and Raman shifting techniques together, one may achieve laser frequencies in almost any desired region of the spectrum with a single laser source.

*Continuous and Quasi-Continuous Wave Laser.* Simulated emission is possible when the necessary condition of population inversion is met in the active media. Although there are, in general, many competitive processes which may limit continuous laser operation (e.g., heating of the media, "self-quenching" effects, etc.), it is often possible to achieve continuous or high repetition-rate operation with many materials that have heretofore been considered as only "pulsed" laser media. The limiting factors are (1) the low efficiency of converting pump energy into laser emission, (2) retention of heat by the laser media, and (3) degradation of the components used for continuous optical "pumping." This does not mean, however, that the same levels of power as achieved instantaneously in the pulsed operation will be achieved in CW operation. The rapid de-population and subsequent high power achieved,

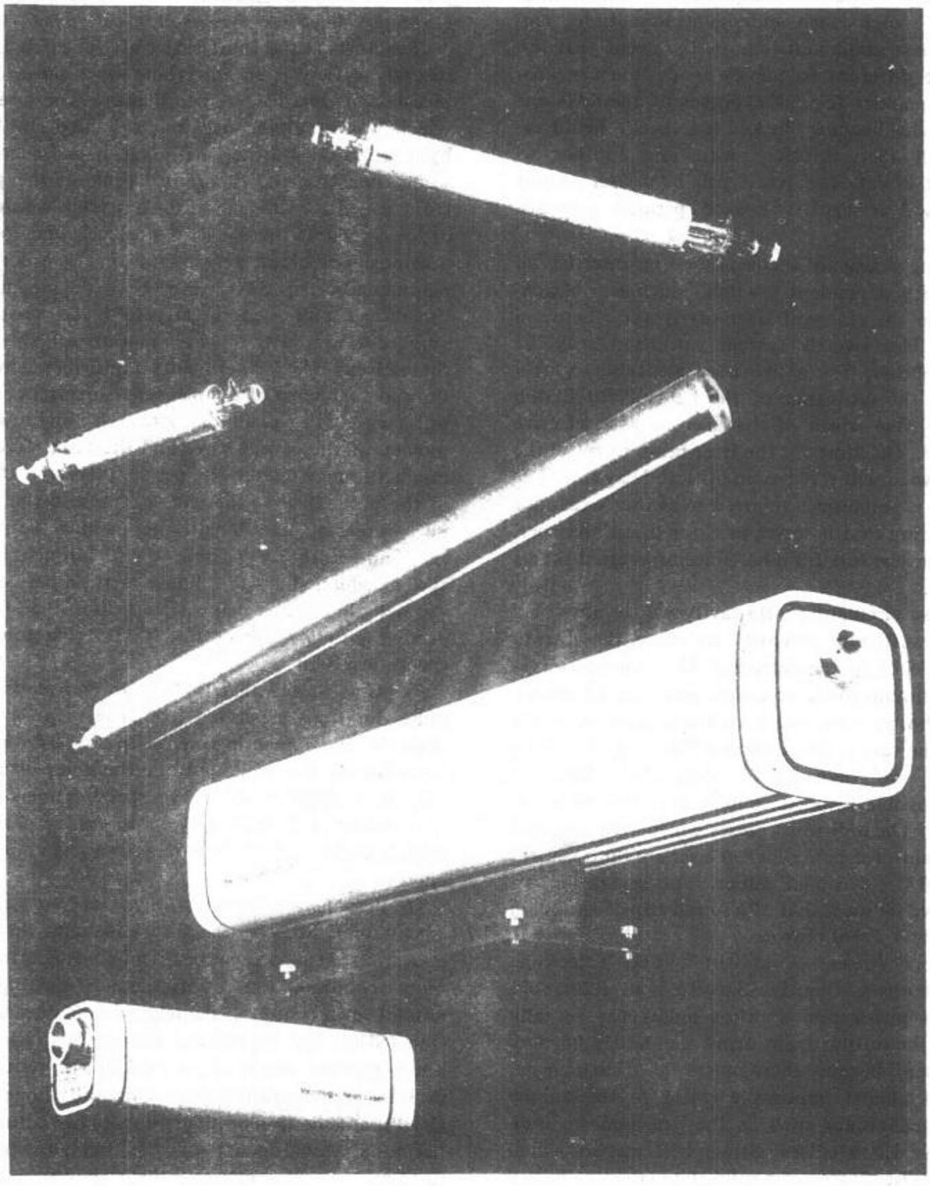


FIGURE 1-3. Some practical CW lasers. A. Top: aluminum cathode coaxial tube, 35 cm and 25 cm long table. B. Next: laser in a stainless steel housing for rugged use. C. helium-cadium laser. D. Below: low cost helium-neon laser. (Metrologic Instruments, Inc.)

for example, in a normal mode ruby laser will produce instantaneous power levels in the multikilowatt range, whereas the quasi-continuous, 60 pulse per second (pps), operation of a ruby crystal will only reach a few watts – even in the most ideal system.

The most successful medias for pure continuous wave operation have been gases (or gaseous mixtures) and the many diode lasers. The media for quasi-continuous lasers include most of the solids common in pulsed operation as well as many gases.

The first CW system was the helium-neon gas mixture. Although its first successful operation was at an infrared wavelength of 1150 nM, the helium-neon (He-Ne) laser is most well known operating at the red (632.8 nanometers) transition. The earlier He-Ne lasers were excited by radio frequency (RF) discharge. In this case, the He atoms were excited from the ground state by the RF field. This energy excess is coupled to an unexcited neon atom by a collisional process with the net result of an inversion in the neon atom population, thus allowing laser action to begin. The more recent He-Ne gas laser designs have used direct current excitation. Power levels available from the low efficiency He-Ne laser ranges from a fraction of a milliwatt to about 75 milliwatts in the largest available systems. The He-Ne laser is noted for its high-frequency stability and single-mode operation.

The family of ion lasers (argon, krypton, xenon, and neon) provides a source for over 35 different laser frequencies, ranging from the near ultraviolet (neon at 332.4 nM) to the near-infrared (krypton at 799.3 nM). It is possible to mix the gases, for example, argon and krypton in which lasing may occur simultaneously at ten different wavelengths, ranging from the violet through the red spectral region. Such an output is truly a "white light" laser. Reference to table will review the most important wavelengths available from the family of ion lasers.

There are many other gases which can generate laser emission. The carbon dioxide laser is the most efficient, and consequently, the most powerful of all CW laser devices. Continuous powers have been reported above 1,000 w at the infrared 10,600 nm wavelength. Nitrogen

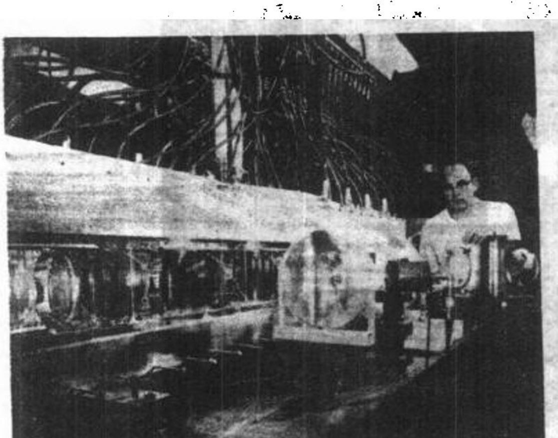


FIGURE 1-4. Nd glass laser, long path disc. A/O. (TRW Instruments.)

gas may be operated in a rapid-pulse or quasi-continuous manner. The beam is emitted in a continuous train of 8-10 nanosecond pulses of kilowatt power levels at pulse repetition rates of 100 pps, producing a maximum average power level of about 100 mw at the ultraviolet 337.1 nm wavelength. Neon gas, operated with same transverse field method, produces green pulses of 3-5 nsec duration for an average power of 3 mW at 100 pps.

Recent development of a metal vapor laser has been successful using Helium and Cadmium, which is placed into vapor distribution by a cataphoresis technique. This laser produces emission at either a dark blue (441.6 nm) or an ultraviolet (325 nm) wavelength at maximum powers of 50 mW and 15 mW, respectively.

One of the most promising laser sources of the day uses a neodymium-doped crystal yttrium-aluminum-garnet (commonly called YAG). This device is optically pumped either by special tungsten or krypton flashlamps and is capable of CW outputs approaching 50 w at the 1,060 nm wavelength. The recent emergence to popularity of the YAG laser has been made possible by better growth techniques of the YAG crystals. Sufficient crystal lengths can now be obtained to provide for high CW power levels.

Most of the diode lasers are also operated on a continuous wave basis. The most common diode device uses a gallium-arsenide junction which emits a fan-shaped infrared beam at 840 nm.

Normal mode and Q-Switched solid-state lasers are often designed for a high repetition-rate operation. Usually, the specific parameters of operation are dictated by the application. For example, normal mode ruby lasers operating 1 pps at 150 joules per pulse are used in high-speed dynamic balancing metal removal applications. As the repetition rate increases, the allowable exit energy per pulse necessarily decreases. Systems are in operation, for example, which produce ten joules per pulse at a repetition rate of 4 pps. A similar ruby, operated in the Q-Switched mode, could produce a one megawatt per pulse at a rate up to ten pulses per minute.

a. *Frequency Expansion Using Non-Linear Techniques.* Methods of converting high-power CW outputs into new frequencies with harmonic generation techniques have also been most successful. Probably the most significant development has been the high power continuous frequency doubling from the neodymium-YAG laser, using the crystal: Barium Sodium Niobate ($Ba_2NaNb_5O_{15}$), commonly referred to as the "Banana Crystal." Continuous powers of 1 watt at the green frequency doubled wavelength of 530 nM have been obtained using an intracavity doubling crystal.

A further expansion of output frequencies is available if the output of the CW frequency doubled YAG-Nd laser is directed into a parametric oscillator. This device also uses "Banana Crystals" which, when temperature-controlled in a range from 97 to 103°C, will allow a tunable output in a range from 980 to 1160 nM. Using 300 nW of 530 nM input power, such a parametric oscillator can produce up to

3 mW at selected wavelengths in the range from 980 to 1160 nM. Smith and Geusic of Bell Telephone Laboratories indicate that proper choice of oscillator mirror reflectances in a parametric oscillator could allow the tunable range to cover a range from 650 to 4,000 nM.

b. *Emergence of Tunable, Liquid and Diode Lasers.* The first multi-wavelength liquid laser was introduced in 1966 by Sorokin, and his associates at IBM. The device, using three different organic dyes, was capable of producing red, green, and yellow laser emission. The key development in this system was the excitation by an ultrafast pulse of incoherent "pumping" light. Previous liquid laser systems required excitation using very short laser pulses. Sorokin's studies had shown that lasing of organic dyes required a very fast optical pumping pulse (300 nsec. rise). Consequently, a special flashlamp system was used which delivered pulses of 400 nsec. duration at repetition rates of 1 pps. Power outputs in his early system were 1 mW/pulse with 0.2 joules/pulse.

Sorokin's early data had shown that the principal central wavelength of organic dye lasers is a function of the dye concentration. This was quantitatively shown by Schaefer, Schmidt, and Voltze, using a 5 MW 10 nsec. Q-Switched ruby laser to optically pump a DTTC – Bromide dye solution. Variation in concentration from $10^{-5}$ to $10^{-3}$ mol/liter produced a change from 805 to 865 nM in the principal laser wavelength. The output was also found to be dependent upon the cavity "Q"; with shorter wavelengths characteristic of a low "Q" cavity.

Several techniques have recently been demonstrated which provide a unique "tunable" control of the dye laser output frequency. One such system is the movable piston concept devised by Kagan (IBM). Movement of the piston actually changes the length of the lasing media, and, since the emission from a nonuniformly pumped dye laser is also dependent upon path length, a lower frequency will be produced. The longer path length serves as a passive absorber of pump energy, thus, changing the ratio of emitting to absorbing molecules. As a result, there will be an upshift in wavelength due to the decreased absorption in the organic molecules at the longer wavelengths.

Soffer and McFarland (Korad), proposed a diffraction grating resonating cavity to obtain spectral narrowing and tunability. Using dyes in the xanthene and carbocyanine families, a 40 nM shift was obtained in rhodamine 6G pumped by a frequency doubled ruby laser (347 nM in 10 nsec. @ 10 MW/cm²). Variation in the inclination of the grating served to selectively produce high cavity gain at a given wavelength. Additionally, a significant narrowing is obtained (approximately: 0.06 nM) in contrast to the 5-6 nM spectral width of normal dye lasers. Tunable organic lasers have also been controlled simply by changing the temperature of the dye media. Schappert has shown that an

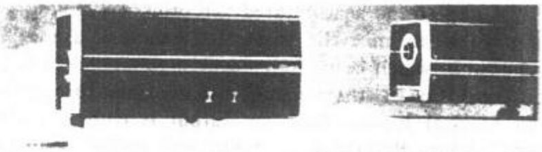


FIGURE 1-5. CW tunable laser. (Chromatix.)

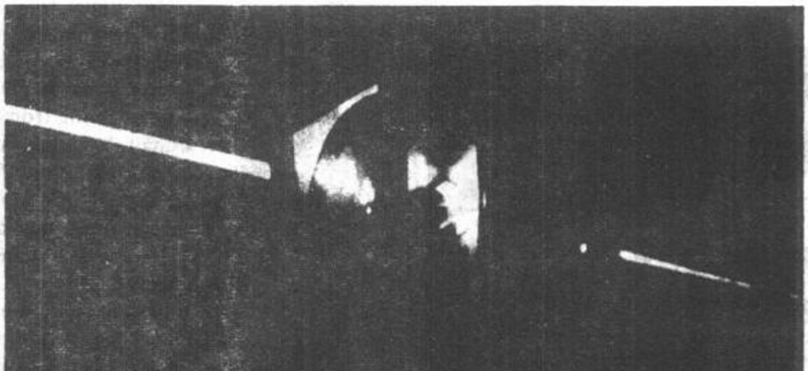


FIGURE 1-6. Ultraviolet laser. (American Optical Corp.)

FIGURE 1-7. Semiconductor laser 0.015 x .003 in. small battery powered at room temperature. (Hayashi, Panish, Foy, Sumski, Bell Telephone Lab.)

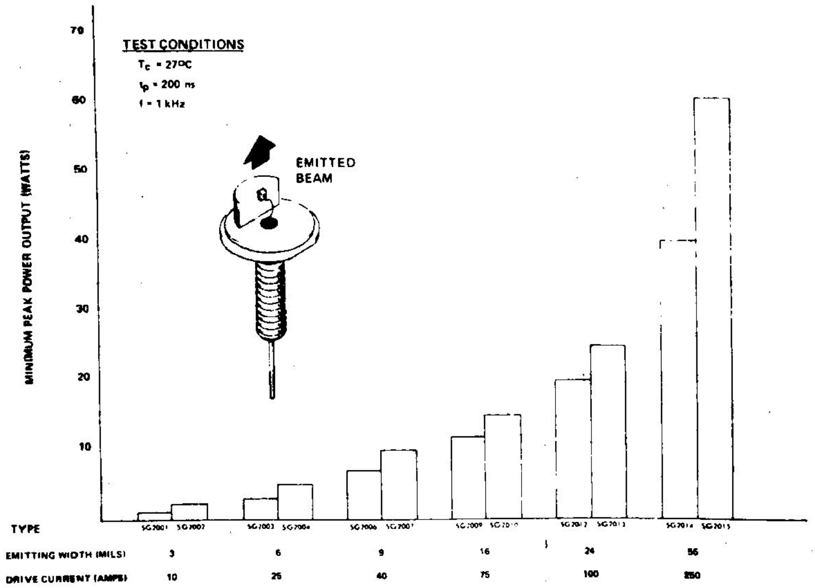



FIGURE 1-8. Peak-power output of various commercial single heterojunction laser diodes. (From Glicksman, R., *Opt. Spectra,* 6, 7, 1972. With permission.)