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H4.SMR/540-15

Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

Solid State Lasers

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SOLID STATE LASERS

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1. INTRODUCTION

Not all lasers using a solid as active medium are referred as solid state lasers. Historically this nomenclature is applied to lasers made by a solid, usually a crystal or a glass with some doping, having the upper laser level optically pumped by a suitable light source.

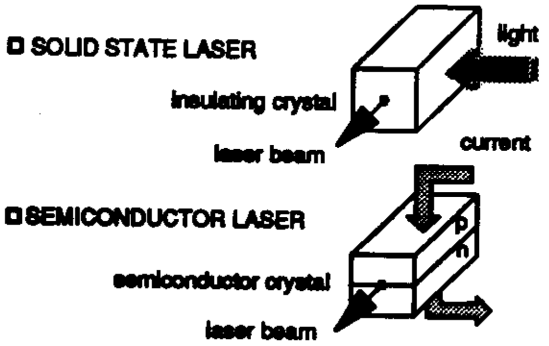


Fig. 1. Definition of Solid State Laser

There is a second class of lasers using a solid as active medium, which are becoming more and more important. They use a semiconductor crystal, usually with one or more junctions, and pumping is achieved by injecting a current in the crystal, where is conducted by the appropriate carriers, electrons or holes (fig. 1). One must be sure to avoid confusion between those two classes of lasers, especially now, when semiconductor lasers are often used as pump sources for solid state lasers, and the result is a compact, monolithic, all solid state system.

A Solid State Laser (SSL), in the first meaning, was the first laser to be operated, in 1960 by Maiman. He obtained laser action in a ruby crystal (Cr^{+3}:Al_2O_3), excited by a pulsed flashlamp. Today SSLs are still one of the most important classes of lasers, both in industrial applications, where the only competitor in average power is the CO_2 laser, as well as in medical applications where the possibility to transport the laser beam by a thin optical fiber opens the possibility of easy internal surgery.

On the scientific side the interest is kept high by the continuous discovery of new crystals. After the discovery of tunable SSLs the spectroscopy applications are increasing, also in those fields covered up to now by dye lasers.

2. MATERIALS FOR SOLID STATE LASERS

In general materials for laser operation must posses sharp fluorescent lines, strong absorption bands, and reasonably high quantum efficiency for the fluorescent transition of interest. These characteristics are often shown by solids (crystals or glass) which incorporate in a small amounts elements in which optical transitions can occur between states of inner, incomplete electron shells. Thus the transition metals, the rare earth (lanthanide) series, and the actinide series are of interest in this connection.

The sharp fluorescence lines in the spectra of crystals doped with these elements result from the fact that the electrons involved in transitions in the optical regime are shielded by the outer shells from the surrounding crystals lattice. The corresponding transitions are similar to those of the free ions. In addition to a sharp fluorescence emission line, a laser material suitable for optical pumping should possess broad-band pump transitions since, except for laser pumped systems, usually broad-band light sources, i.e., incandescent lamps, cw arc lamps, or flashlamps are used as pump sources for pumping SSLs.

The three principal elements leading to gain in a laser are:

- The host material with its macroscopic mechanical, thermal and optical properties, and its microscopic lattice properties.
- The active ions with their distinctive charge states and free-ion electronic configurations.
- The optical pump source with its particular geometry, spectral irradiance, and duration.

These elements are interactive and must be selected self-consistently to achieve a given system performance.

In the following we consider the properties of the most common host materials and active ions used in SSLs.

2.1. Host materials

Solid-state host materials may be broadly grouped into crystalline solids and glasses. The host must have good optical, mechanical and thermal properties to withstand the severe operating conditions of practical lasers. Desirable properties include hardness, chemical inertness, absence of internal strain and refractive index variation, resistance to radiation-induced color centers, and ease of fabrication.

Several interactions between the host crystal and the active ion restrict the number of useful material combinations. These include size disparity, valence, and spectroscopic properties. Ideally the size and valence of the additive ion should match that of the host ion it replaces.

In selecting a crystal suitable for a laser ion host one must consider the following key criteria:

1) The crystal must possess favorable optical properties. Variations in the index of refraction lead to inhomogeneous propagation of light through the crystal with consequent poor beam quality.

2) The crystal must possess a set of mechanical and thermal properties that will permit repetitively pulsed operation without suffering excessive stress under the operational thermal load.

3) The crystal must have lattice sites that can accept the dopant ions and that have local crystal fields of symmetry and strength needed to induce the desired spectroscopic properties. In general, ions placed in a crystal host must achieve high radiative lifetime with cross sections near 10^{-20} cm^2.

4) It must be possible to scale the growth of the impurity-doped crystal, while maintaining high optical quality and high yield. It appears that the greatest prospect for successful growth scaling is for crystals that melt congruently at temperatures below 1300 °C. This relatively low melting temperature permits the use of a wide variety of crucible materials and growth techniques.

Two main classes of host materials are used in SSL: glasses and crystals.

Glasses

Glasses form an important class of host materials for some of the rare earths, particularly Nd^{3+}. The outstanding practical advantage compared to crystalline materials is the tremendous size capability for high-energy applications. Rods up to 1 m in length and over 10 cm in diameter and disks up to 90 cm in diameter and several cm in thickness are currently available. The optical quality can be excellent, and beam divergence approaching the diffraction limit can be achieved.

Glass, of course, is easily fabricated and takes a good optical finish. Laser ions placed in glass generally show a larger fluorescent line-width than in crystals as a result of the lack of a unique and well-defined crystalline surrounding for the individual active atom. Therefore, the laser threshold for glass lasers have been found to run higher than their crystalline counterparts. Also, glass has a much lower thermal conductivity than most crystalline hosts. The latter factor leads to thermally induced birefringence and optical distortion in glass laser rods when they are operated at high average powers. For these reasons glass media are used mainly for low repetition rate, high energy, lasers systems.

In addition to the Nd:glass another important glass laser medium is Er:glass. Glass doped with erbium is of special importance, because its radiation of 1.55 μm does not penetrate the lens of the human eye, and therefore cannot destroy the retina. Because of the three-level behavior of erbium and the small absorption of pump light by Er^{3+}, multiple doping with neodymium and ytterbium is necessary to obtain satisfactory system efficiency.

Crystals

A large number of crystalline host materials have been investigated since the discovery of the ruby laser. Crystalline laser hosts generally offer as advantages, over glasses, their higher thermal conductivity, narrower fluorescence line-widths, and, in many cases, greater hardness. For all these reasons they are used for high average power, CW or repetitively pulsed, lasers. However, the optical quality and doping homogeneity of crystalline hosts are often poorer, and the absorption lines are generally narrower. Here we will review briefly only the two crystals mainly used as laser hosts.

Sapphire. The first laser material to be discovered (ruby laser) employed sapphire as a host. The Al_2O_3 (sapphire) host is hard, with high thermal conductivity, and transition metals can readily be incorporated subtitutionally for the Al. The Al site is too small for rare earths, and it is not possible to incorporate appreciable concentrations of these impurities into sapphire. Besides ruby, still used today, Ti-doped sapphire has gained significance as a tunable-laser material.

Garnets. Some of the most useful laser hosts are the synthetic garnets: yttrium aluminum, $Y_3Al_5O_{12}$ (YAG), gadolinium gallium garnet, $Gd_3Ga_5O_{12}$ (GGG), and gadolinium scandium gallium garnet $Gd_3Sc_2G_{a3}O_{12}$ (GSGG). These garnets have many properties that are desirable in a laser host material. They are stable, hard, optically isotropic, and have good thermal conductivities, which permits laser operation at high average power levels.

In particular, yttrium aluminum garnet doped with neodymium (Nd:YAG) has achieved a position of dominance among solid-state laser materials. YAG is a very hard, isotropic crystal, which can be grown and fabricated in a manner that yields rods of high optical quality. At the present time, it is the best commercially available crystalline laser host for Nd^{3+}, offering low threshold and high gain.

2.2 Active ions

Introduction

Before proceeding to a discussion of the active laser ions, we will review briefly the nomenclature of atomic energy levels.

Different energy states of electrons are expressed by different quantum numbers. The electrons in an atom are characterized by a principal quantum number n, an orbital angular momentum l, the orientation of the angular momentum vector m, and a spin quantum number s. A tradition from the early days of line-series allocation has established the following method of designating individual electronic orbits: a number followed by a letter symbolizes the principal quantum number n and the angular number l, respectively. The letters s,p,d,f stand for l=0,1,2,3, respectively. For example a $3d$ electron is in an orbit with n=3 and l=2.

To designate an atomic energy term one uses by convention capital letters with a system of subscripts and superscripts. The symbol characterizing the term is of the form $^{2S+1}L_J$, where the resultant orbital quantum numbers L=0,1,2,3,4 are expressed by the capital letters S,P,D,F,G,H. A superscript to the left of the letter indicates the value ($2S$+1), i.e., the multiplicity of the term due to possible orientation of the resultant spin S. Thus a one-electron system (S= 1/2) has a multiplicity 2. L and S can combine to various resultant J, indicated by a subscript to the right of the letter. Thus the symbol $^2P_{3/2}$ shows an energy level with an orbital quantum number L=1, a resultant spin of S=1/2, and a total angular momentum of J=3/2. The complete term description must include the configuration of the excited electron which precedes the letter symbol. Thus the ground state of Li has the symbol $2s\,^2S_{1/2}$.

When an atom contains many electrons, the electrons that form a closed shell may be disregarded and the energy differences associated with transitions in the atom may be calculated by considering only the electrons outside the closed shell.

In describing the state of a multielectron atom, the orbital angular momenta and the spin angular momenta are added separately. The sum of the orbital angular momenta are designated by the letter L, and the total spin is characterized by S. The total angular momentum J of the atom may then be obtained by vector addition of L and S. The collection of energy states with common values of J,L, and S is called a term.

The most important ions used in crystal doping for SSLs can be divided into two main classes: transition metal ions and rare earth ions. Here follows a qualitative description of their most prominent features.

Transition Metals Ions

The most important members of the transition metal family are Cr^{3+} and Ti^{3+}. The former was the first to show laser action, using Sapphire as host crystal (ruby: Cr^{3+}:Al_2O_3). Now is still interesting for its tunability in some crystal (Alexandrite) and its broad absorption bands, making it useful as co-dopant to increase absorption efficiency of other ions.

Titanium is mainly interesting because using sapphire as host it shows a very broad, tunable, emission range, making it very useful for spectroscopic applications.

Rare Earth Ions

The rare earth ions are natural candidates to serve as active ions in solid-state laser materials because they exhibit a wealth of sharp fluorescent transitions representing almost every region of the visible and near-infrared portions of the electromagnetic spectrum.

It is a characteristic of these lines that they may be very sharp, even in the presence of the strong local fields of crystals, as a result of the shielding effect of the outer electrons. The outermost electrons of these ions form a complete rare gas shell, which is the xenon shell with two *5s* and six *5p* electrons. This shell is optically inactive. Next inside the xenon shell is the *4f* shell, which is filled successively in passing from one element to the next. Trivalent cerium, Ce^{3+}, has one *4f* electron, and trivalent ytterbium, Yb^{3+}, has 13. As long as the *4f* shell is not completely filled with 14 electrons, a number of *4f* levels are unoccupied, and electrons already present in the *4f* shell can be raised by light absorption into these empty levels. The sharp lines observed in rare earth absorption and emission spectra are ascribed to these transitions, and the sharpness of the lines is explained by the fact that the electrons making the transition lie inside the xenon shell and thus interact only weakly with outside ions.

All the above mentioned rare hearts ions, and many others, have shown laser action in many different crystals. By far the most important one is the Nd^{3+}, used as dopant for many crystals as well as in glasses. Here follows the main properties of Nd^{3+} and Er^{3+}, which is growing in interest for its eye safe emission wavelength.

Neodymium. Nd^{3+} was the first of the trivalent rare earth ions to be used in a laser, and it remains by far the most important element in this group. Stimulated emission has been obtained with this ion incorporated in at least 40 different host materials, and a higher power level has been obtained from Nd lasers than from any other four-level material. The principal host materials are YAG and glass. In these hosts stimulated emission is obtained at a number of frequencies within three different groups of transitions centered at 0.9, 1.06, and 1.35 µm. Radiation at these wavelengths result from $^4F_{3/2}$ to $^4I_{9/2}$, $^4I_{11/2}$, $^4I_{13/2}$ transitions, respectively.

Erbium. Numerous studies of the absorption and fluorescence properties of erbium in various host materials have been conducted to determine its potential as an active laser ion. Laser oscillation was observed most frequently in the wavelength region 1.53 to 1.66 µm arising from transitions between the $^4I_{13/2}$ state and the $^4I_{15/2}$ ground state Er^{3+}. Stimulated emission in the vicinity of 1.6 µm is of interest, because the eye is less subject to retinal damage by laser radiation at these wavelengths due to the greatly reduced transmissivity of the ocular media.

2.3 Specific laser crystals

Among the lot of crystals used as SSLs active media, a few have gained great prominence. The first is ruby (Cr^{3+} in sapphire), both for historical reasons (it was the first laser to be operated) as well as for some unique properties. Next cames the Nd^{3+}:YAG and all the others Nd based materials, being by far the most used SSL material. More recently a new class of materials has grown in interest: the tunable vibronic laser crystals, mainly represented by Alexandrite and Ti:sapphire. Here follows a survey of the main properties of this most used materials.

Ruby

The ruby laser, although a three-level system, still remains in use today for certain applications. From an application point of view, ruby is attractive because its output lies in the visible range, in contrast to most rare earth four-level lasers, whose outputs are in the near-infrared region. Photodetectors and photographic emulsions are much more sensitive at the ruby wavelength than in the infrared. Spectroscopically, ruby possesses an unusually favorable combination of a relatively narrow line-width, a long fluorescent lifetime, a high quantum efficiency, and broad and well-located pump absorption bands which make unusually efficient use of the pump radiation emitted by available flashlamps.

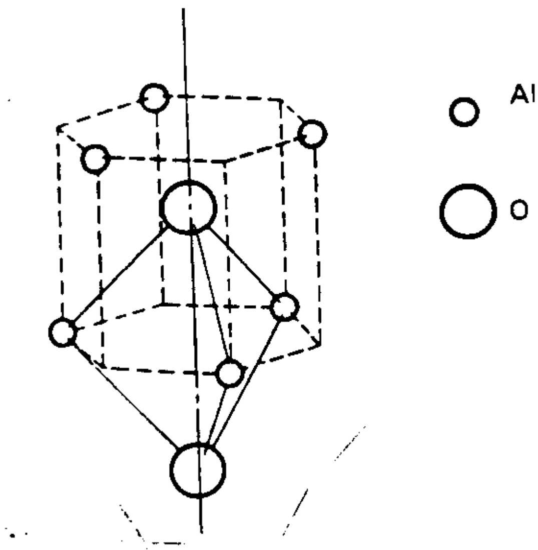


Fig. 2 Structure of sapphire

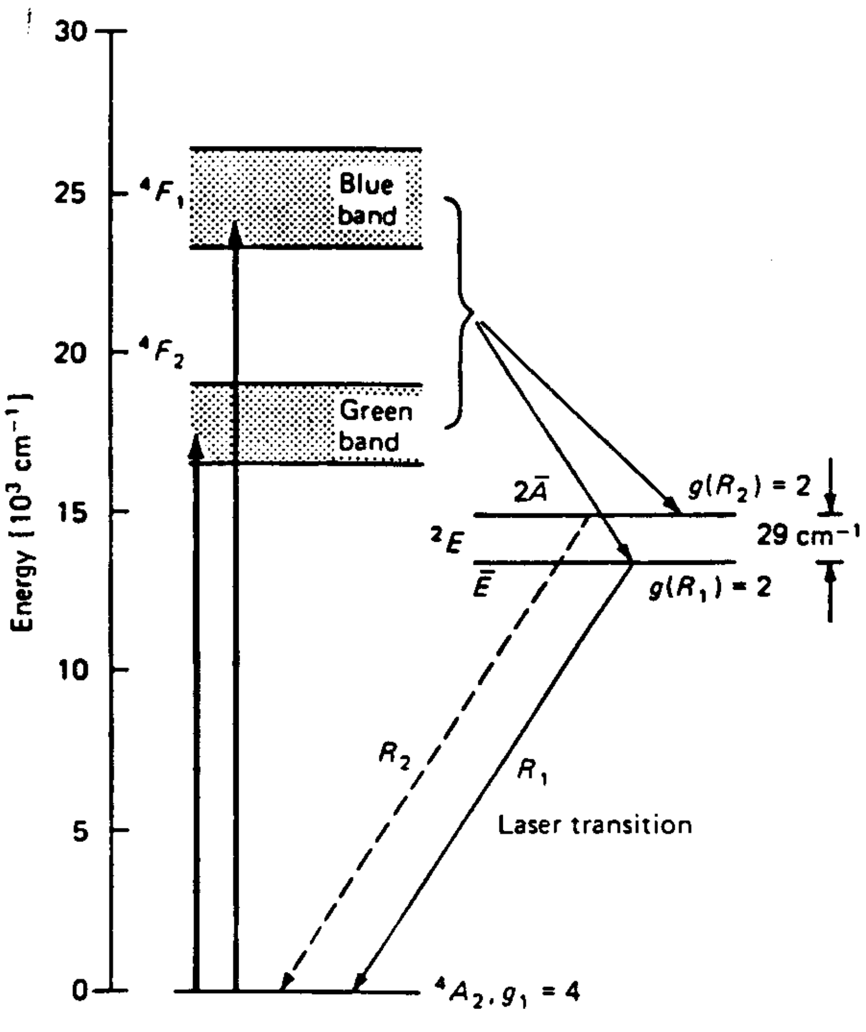


Fig. 3 Energy levels of ruby

Ruby chemically consists of sapphire (Al_2O_3) in which a small percentage of the Al^{3+} has been replaced by Cr^{3+}. This is done by adding small amounts of Cr_2O_3 to the melt of highly purified Al_2O_3. The pure single host crystal is uniaxial and possesses a rhombohedral or hexagonal unit cell, as shown in fig. 2. The crystal has an axis of symmetry, the so-called c axis, which forms the major diagonal of the unit cell. Since the crystal is uniaxial, it has two indices of refraction, the ordinary ray having the E vector perpendicular to the c (optic) axis, and the extraordinary ray having the E vector parallel to the c axis.

As a laser host crystal, sapphire has many desirable physical and chemical properties. The crystal is a refractory material, hard and durable. It has a good thermal conductivity, is chemically stable, and is capable of being grown to very high quality, grown by the Czochralski method. In this procedure the solid crystal is slowly pulled from a liquid melt by initiation of growth on high-quality seed material. Iridium crucibles and rf heating are used to contain the melt and control the melt temperature, respectively. The crystal boules can be grown in the 0°, 60°, or 90° configuration, where the term refers to the angle between the growth axis and the crystallographic c axis. For laser grade ruby the 60° type is commonly used.

Ruby can be grown in relatively large boules with high optical quality. The boules are cut into smaller cylindrical sections. Core-free cylindrical rods can be obtained up to 30 cm in length and 2.5 cm in diameter. Typical commercially available rods with flat ends are fabricated to the following specifications: ends flat to $\lambda/10$, ends parallel to ± 4 arc seconds, perpendicularity to rod axis to ± 5 minutes, rod axis parallel to growth axis (0, 60, 90) to ± 5.

Common rod geometries may be plane parallel, wedged surfaces, Brewster angle, or prismatic. The best way to inspect a laser rod is by means of an interferometer, such as a Twyman-Green. Optical inhomogeneities, strain, distortion, etc., will show up as fringes. Scattering centers or regions of high defects in a laser rod are revealed by illuminating the crystal from the side with a He-Ne gas laser.

Nd:materials

From the large number of Nd:doped materials only few have gained prominence. Nd:YAG, because of its high gain and good thermal and mechanical properties, is by far the most important solid-state laser for scientific, medical, industrial and military applications. Nd:glass is important for laser fusion drivers because it can be produced in large sizes. Very recently, Nd:Cr:GSGG has received considerable attention because of the good spectral match between the flashlamp emission and the absorption of the Cr ions. An efficient energy transfer between the Cr and Nd ions results in a highly efficient Nd:laser. Nd:YLF is a good candidate for certain specialized applications, because the output is polarized, and the crystal exhibits lower thermal birefringence. Nd:YLF has a higher energy storage capability (due to its lower gain coefficient) compared to Nd:YAG and its output wavelength matches that of phosphate Nd:glass, therefore mode-locked and Q-switched Nd:YLF lasers have become the standard oscillators for large glass lasers employed in fusion research.

Nd:YAG

The Nd:YAG laser is by far the most commonly used type of solid-state laser. Neodymium-doped yttrium aluminum garnet (Nd:YAG) possesses a combination of properties uniquely favorable for laser operation. The YAG host is hard, of good optical quality and has a high thermal conductivity. Furthermore, the cubic structure of YAG favors a narrow fluorescent line-width, which results in high gain and low threshold for laser operation. In Nd:YAG, trivalent neodymium substitutes for trivalent yttrium, so charge compensation is not required.

Improving both the quality of the material and pumping technique so that available cw power outputs rose from the fractional watt level initially obtained to several hundred watts from a single laser rod. On the other hand, in single-crystal Nd:YAG fiber lasers, threshold was achieved with absorbed pump powers as small as 1 mW. Today, more than twenty years after its first operation, the Nd:YAG laser has emerged as the most versatile solid-state system in existence.

In addition to the very favorable spectral (fig. 4) and lasing characteristics displayed by Nd:YAG, the host lattice is noteworthy for it's unusually attractive blend of physical, chemical, and mechanical properties. The YAG structure is stable from the lowest temperatures up to the melting point, and no transformations have been reported in the solid phase. The strength and hardness of YAG are lower than ruby but still high enough so that normal fabrication procedures do not produce any serious breakage problems.

Pure $Y_3Al_5O_{12}$ is a colorless, optically isotropic crystal which possesses a cubic structure characteristic of garnets. In Nd:YAG about 1% of Y^{3+} is substituted by Nd^{3+}. The radii of the two rare earth ions differ by about 3%. Therefore, with the addition of large amounts of neodymium, strained crystals are obtained, indicating that either the solubility limit of neodymium is exceeded or that the lattice of YAG is seriously distorted by the inclusion of neodymium.

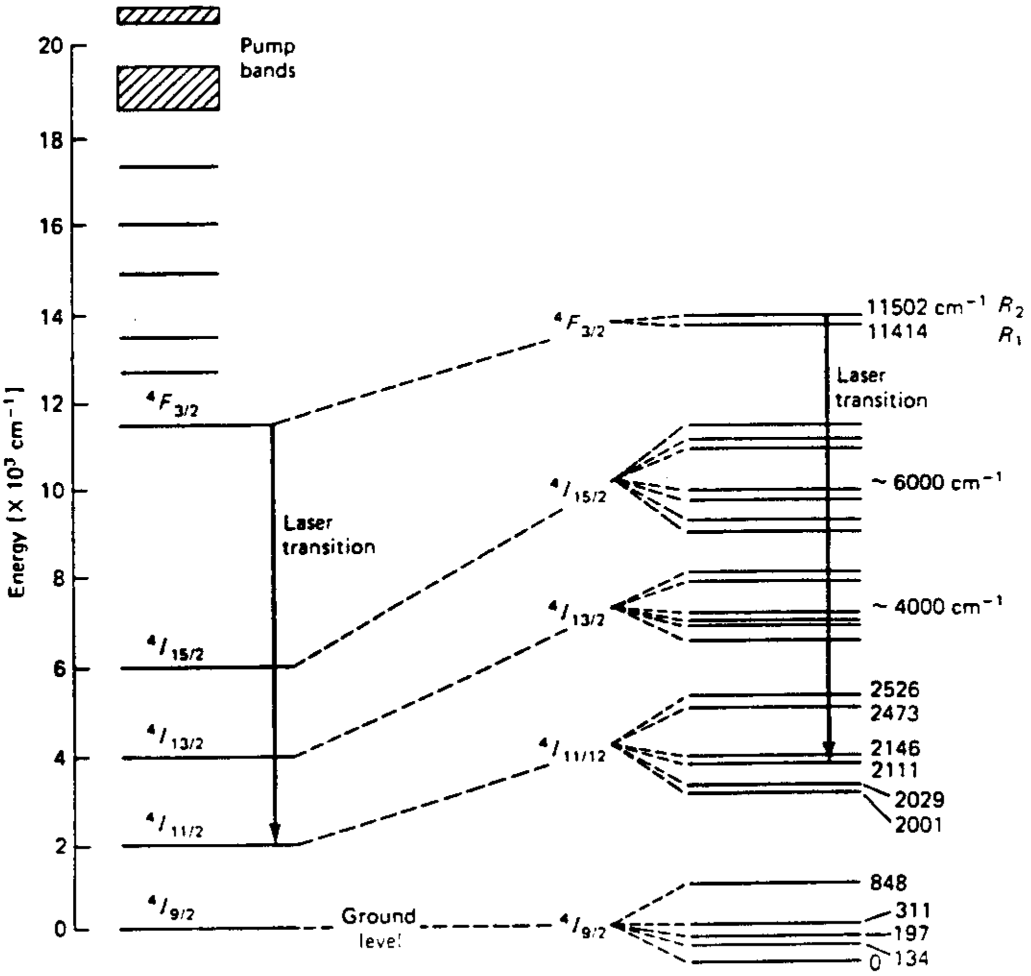


Fig. 4. Energy levels of Nd:YAG

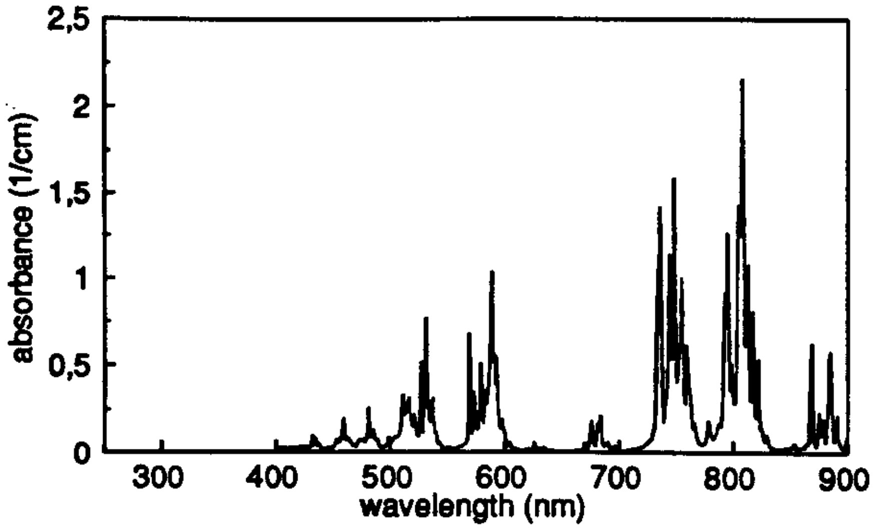


Fig. 5. Absorption of Nd:YAG

Commercially available laser crystals are grown exclusively by the Czochralski method. The high manufacturing costs of Nd:YAG are mainly caused by the very slow growth rate of Nd:YAG, which is of the order of 0.5 mm/h. Typical boules of 10 to 15 cm in length require a growth run of several weeks. However, all Nd:YAG crystals grown by Czochralski techniques show a bright core running along the length of the crystal. The cores originate from the presence of facets on the growth interface which have a different distribution coefficient for neodymium than the surrounding growth surface. This means, of course, that, in order to provide rods of a given diameter, the crystal must be grown with a diameter that is somewhat more than twice as large. The boules are processed by quartering into sections. At the present time, rods can be fabricated with maximum diameters of about 10 mm and lengths up to 150 mm. The optical quality of such rods is normally quite good and comparable to the best quality of Czochralski ruby or optical glass. For example, 6 mm by 100 mm rods cut from the outer sections of 20 mm by 150 mm boules typically may show only 1 to 2 fringes in a Twyman-Green interferometer.

Neodymium concentration by atom percent in YAG has been limited to 1.0 to 1.5%. Higher doping levels tend to shorten the fluorescent lifetime, broaden the line-width, and cause strain in the crystal, resulting in poor optical quality. In specifying Nd:YAG rods, the emphasis is on size, dimensional tolerance, doping level, and passive optical tests of rod quality.

In a particular application the performance of a Nd:YAG laser can be somewhat improved by the choice of the optimum Nd concentration. As a general guideline, it can be said that a high doping concentration (approximately 1.2%) is desirable for Q-switch operation because this will lead to high energy storage. For cw operation, a low doping concentration (0.6 to 0.8%) is usually chosen to obtain good beam quality.

It is worth noting that in contrast to a liquid or a glass, a crystal host is not amenable to uniform dopant concentration. This problem arises as a result of the crystal-growth mechanism. In the substitution of the larger Nd^{3+} for a Y^{3+} in $Y_3Al_5O_{12}$, the neodymium is preferentially retained in the melt. The increase in concentration of Nd from the seed to terminus of a 20-cm long boule is about 20 to 25%. For a laser rod 3 to 8 cm long, this end-to-end variation may be 0.05 to 0.10 % of Nd_2O_3 by weight.

Nd:Glass

There are several characteristics which distinguish glass form other solid-state laser host materials. Its properties are isotropic. It can be doped at very high concentrations with excellent uniformity, and it can be made in large pieces of diffraction-limited optical quality.

In addition, glass lasers have been made, in a variety of shapes and sizes, from fibers a few micrometers wide supporting only a single dielectric waveguide mode, to rods 2 m long and 7.5 cm in diameter and disks up to 90 cm in diameter and 5 cm thick.

There is a wide variety of Nd-doped laser glasses depending on the compositions of the glass network former and the network-modifying ions. Among various laser glasses only silicates and phosphates are commercially available at present with sufficient optical, mechanical and chemical properties.

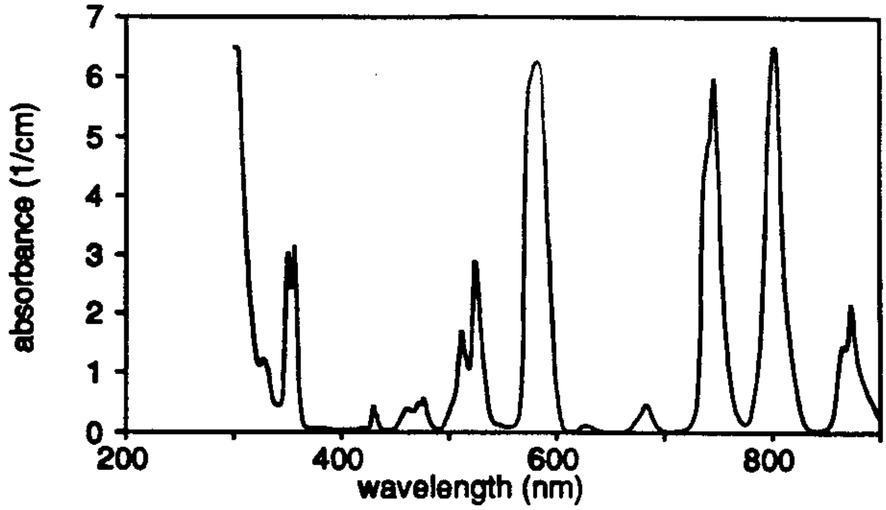


Fig. 6. Absorption of Nd:Glass

There are two important differences between glass and crystal lasers. First, the thermal conductivity of glass is considerably lower than that of most crystal hosts. Second, the emission and absorption lines of ions in glasses are inherently broader than in crystals, as shown by the comparison of fig. 5 with fig. 6. A wider line increases the laser threshold value of amplification. Nevertheless, this broadening has an advantage. A broader line offers the possibility of obtaining and amplifying shorter light pulses, and, in addition, it permits the storage of larger amounts of energy in the amplifying medium for the same linear amplification coefficient. Thus, glass and crystalline lasers complement each other. For continuous or very high repetition-rate operation, crystalline lasers provide higher gain and greater thermal conductivity. Glasses are more suitable for high-energy pulsed operation because of their large size, flexibility in their physical parameters, and the broadened fluorescent line.

Unlike many crystals, the concentration of the active ions can be very high in glass. The practical limit is determined by the fact that the fluorescence lifetime and, therefore the efficiency of stimulated emission, decreases with higher concentrations. In silicate glass, this decrease becomes noticeable at a concentration of 5% Nd_2O_3.

The main constituents of glasses are nonmetal oxides, such as SiO_2, B_2O_3, and P_2O_5. Different metal oxides alter the structure in various ways and make it possible to obtain a large variety of properties. The components are mixed before melting, with the laser activators also added to the batch. The mixture is heated in a heat-resistant crucible. The principal laser glass manufacturers use either platinum or ceramic crucibles, clay pots, or ceramic continuous tanks to contain the melt. When the melt has reached a high viscosity it is cast into a mold. Finally, the glass in the mold is placed into an annealing furnace where it is very slowly cooled down.

Glass laser rods are fabricated in a large variety of sizes. Typical rod sizes are between 10 and 50 cm in length, with diameters from 1 to 3 cm. However, rods up to 1 m in length and 10 cm in diameter are commercially available. Standard rod end configurations are the same as those mentioned for ruby and Nd:YAG rods.

Nd,Cr:GSGG

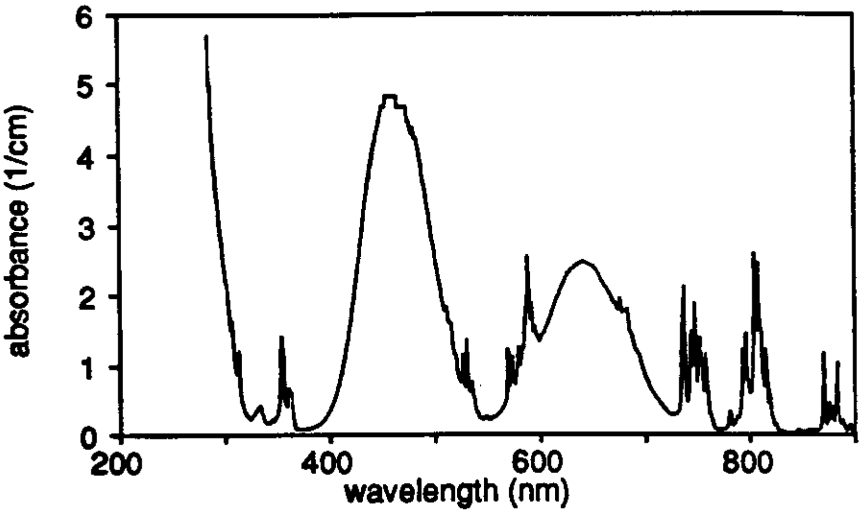


Fig. 7. Absorption of Nd,Cr:GSGG

Soon after the invention of the Nd:YAG laser attempts were made to increase the efficiency of transferring radiation from the pump source to the laser crystal using a second dopant called a "sensitizer". A particularly attractive sensitizer is Cr^{3+} because the broad absorption bands of chromium can efficiently absorb light throughout the whole visible region of the spectrum. Experiments performed in several laboratories showed, with flashlamp-pumped operation, nearly a factor-of-three improvement in slope efficiency for the doubly doped garnet compared to a Nd:YAG crystal.

The higher pump efficiency of Nd,Cr:GSGG does not automatically translate into better system performance because Nd,Cr:GSGG does exhibit much stronger thermal focusing and stress birefringence, compared to Nd:YAG. The absorption efficiency and the heat-deposition rate for the Nd,Cr:GSGG rod is almost three times those of Nd:YAG, a consequence of the broad red and blue absorption bands of the Cr^{3+} sensitizer. As a consequence, thermal focusing power as a function of lamp input power is several times larger in Nd,Cr:GSGG than in Nd:YAG. Therefore, if beam brightness is the criteria, rather than output energy, some of the advantage of GSGG is offset, particularly at high average powers.

The explanation for the high efficiency of co-doped GSGG follows from Fig. 7 which shows the absorption spectrum of this material, comparing it with Fig. 5. Two high-intensity Cr^{3+} absorption bands having maxima at 450 and 640 nm covering an appreciable part of the visible region, and narrow Nd lines can be observed (see also Fig 8).

Vibronic lasers

Tunability of the emission in solid-state lasers is achieved when the stimulated emission of photons is intimately coupled to the emission of vibrational quanta (phonons) in a crystal lattice. In these "vibronic" lasers, the total energy of the lasing transition is fixed, but can be partitioned between photons and phonons in a continuous fashion. The result is broad wavelength tunability of the laser output. In other words, the existence of tunable solid-state lasers is due to the subtle interplay between the Coulomb field of the lasing ion, the crystal field of the host lattice, and electron-phonon coupling permitting broad-band absorption and emission. Therefore, the gain in vibronic lasers depends on transitions between coupled vibrational and electronic states; that is, a phonon is either emitted or absorbed with each electronic transition.

The best known, and most used, vibronic laser media are, up to now, the Alexandrite and Ti:sapphire.

Alexandrite

Alexandrite ($Cr^{3+}:BeAl_2O_4$) is the best-characterized commercially-developed vibronic laser. Alexandrite is the common name for chromium-doped chrysoberyl, with four units of $BeAl_2O_4$ forming an orthorhombic structure.

The crystal is grown in large boules by Czochralski method much like ruby and YAG. The main problem is handling the very toxic Be oxide. For this reason the process for growing Alexandrite is patented and only 2 supplier currently exist in the world, one in USA and the other in China. In any case laser rods up to 1 cm in diameter and 10 cm long with a nominal 2-fringe total optical distortion are commercially available. The chromium concentration of alexandrite is expressed in terms of the percentage of aluminum ions in the crystal which have been replaced by chromium ions. The Cr^{3+} dopant concentration, occupying the Al^{3+} sites, can be as high as 0.4 atomic percent and still yield crystals of good optical quality. A concentration of 0.1 atomic percent represents 3.51×10^{19} chromium ions per cubic centimeter.

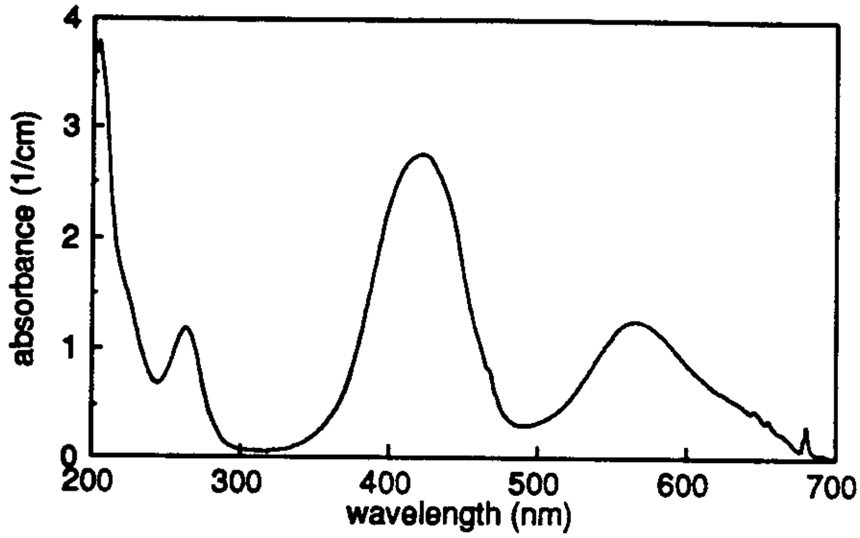


Fig. 8. Absorption of Alexandrite

Alexandrite shows the typical absorption spectrum of Cr doped materials (Fig. 8). It is optically and mechanically similar to ruby, and possesses many of the physical and chemical properties of a good laser host. Hardness, strength, chemical stability and high thermal conductivity (two-thirds that of ruby and twice that of YAG) enables alexandrite rods to be pumped at high average powers without thermal fracture. Alexandrite has a thermal fracture limit which is 60% that of ruby and five times higher than YAG. Surface damage tests using focussed 750 nm radiation indicate that alexandrite is at least as damage resistant as ruby.

The development of the alexandrite laser has reached maturity after nearly 10 years of efforts. Its current high average-power performance is 100 W if operated at 100 Hz. Overall efficiency is close to 0.5%. Tunability over the range of approximately 700 to 818 nm has been demonstrated with tuning accomplished in a manner similar to dye lasers: a combination of etalons and birefringent filters. With these standards spectral control devices 0.5 cm^{-1} line-widths and tunability over 150 nm has been achieved. Alexandrite has been lased in pulsed and cw modes; it has been Q-switched and mode-locked.

A rod 10 cm long and 0.63 cm in diameter, when lased in a stable resonator, yields over 5 J long-pulsed, and as much as 2 J with pulse duration less than 30 ns when Q-switched. The reason for such high output energies is that alexandrite is a low-gain medium, $g=0.04\ cm^{-1} - 0.1 cm^{-1}$ at room temperature.

Commercially available alexandrite lasers feature continuous, automatic tuning and a minimum 100 mJ of Q-switched output with 0.2 nm band-width over the wavelength range from 730-780 nm.

Because of alexandrite's physical strength and thermal properties, cw operation is possible at room temperature. The bulk of the experimentation to date has been with cw xenon arc lamps. CW operation with arc lamp pumping has proved difficult to achieve, yet output powers of up to 40 W with good transverse-mode quality are now being generated. CW lasers were also acousto-optically Q-switched at rates greater than 10 kHz, with peak powers as high as 300 W and pulsewidth of 1 µs.

Ti:sapphire

The Ti:Al_2O_3 laser is one of the more promising tunable solid-state systems, combining a broad tuning range (800 nm peak, 300 nm band-width) with a relatively large gain cross-section (50% of Nd:YAG's value at its peak).

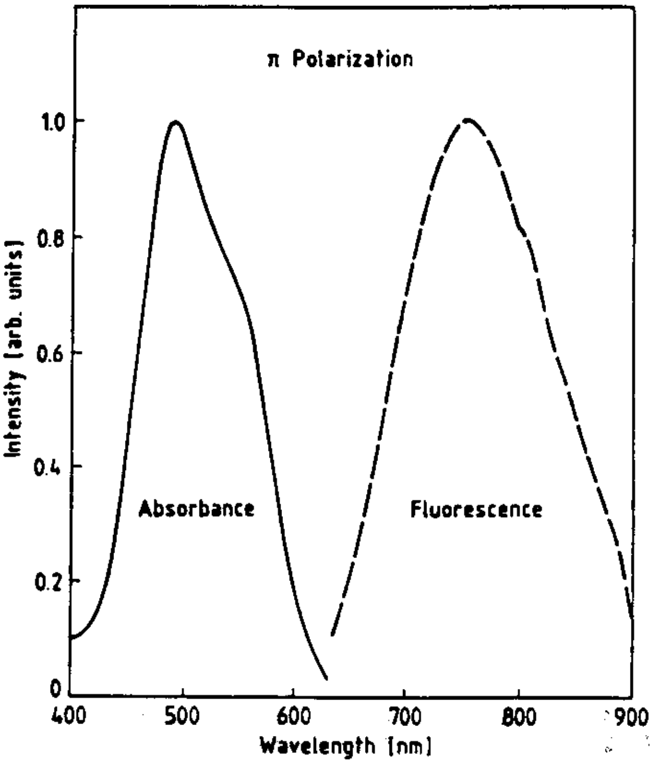


Fig. 9. Spectra of Ti:sapphire

One of the greatest advantages is the material properties of the sapphire host itself, namely very high thermal conductivity, exceptional chemical inertness and mechanical rigidity. Titanium sapphire is presently available from commercial vendors in sizes of 3.5 cm diameter by 15 cm long and, due to the well-developed growth technology for sapphire, of good optical quality. The absorption and fluorescence spectra for Ti:Al_2O_3 are shown in Fig. 9. The broad, widely separated absorption and fluorescence bands are caused by the strong coupling between the ion and host lattice, and are the key to broadly tunable laser operation.

Development of the Ti:Al_2O_3 laser has been confined mainly to laser pumping because of the material's short (3.2 µs) spontaneous-emission life-time. Flash-lamp pumping of Titanium sapphire gives hard technological problems in terms of flash-lamps lifetime, due to the short pulse duration needed for driving this crystal above threshold. Only recently the development of special flash-lamp allowed the constructions of Ti:Al_2O_3 laser with high average power and reasonable flash-lamps lifetime, in excess of 1 millions shots.

3. PUMPING SOURCES

Many different light sources have been used for the optical excitation of SSLs. They can be divided into two broad classes (fig. 10): the standard incoherent sources and the coherent sources, namely other lasers.

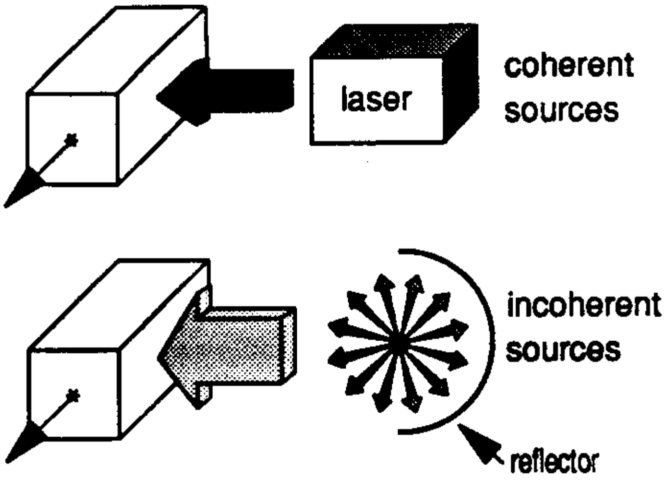


Fig. 10. Pumping sources

The incoherent sources are by far the most used up to now, because of their lower cost and easier availability. The maximum average power available from lamp pumped solid state lasers is also order of magnitude higher than that available from laser pumped systems. This situation is now evolving, because of the recent availability of relatively high power semiconductor lasers, but their high cost limit the average power level in the watt range, at least up to now.

Lamp pumped systems, on the other hand, are already commercially available in the KW range, with several project in progress to extend the average power above this limit.

The incoherent light sources used for SSLs pumping:

- **noble-gas arc and flash lamps.** They are the most commons sources, and cames in many different shapes and technology, according to the application of the laser.
- **metal vapor arc lamps**, different from the previous ones because of the narrow emission spectrum, which sometimes leads to a higher overall efficiency. Drawbacks are the low power capabilities and the CW operation only.
- **filament lamps**, made by the same tungsten halogen technology used for illumination, so they are very cheap and the power supply is very simple. Their problems are the limited available average power, the CW operation only, and the low transfer efficiency, due to the broad-band, blackbody, emission spectrum. They are then limited to low power, inexpensive Nd:YAG systems.
- **sun.** There are several examples of SSLs pumped by the solar radiation, using mirrors to collect the light on the crystal. Of course, they depend on the availability of the sources, but they are very interesting for example for space application. In some cases, for example using a Nd,Cr:GSGG crystal, the overall efficiency compete with that of photovoltaic solar cells.
- **chemical reactions.** These are mainly single shot devices, because the chemicals used for the reaction must be replaced after each shot. The most common of these sources is the flash-bulb, similar to that used in old photographic flash-lights.
- **light emitting diodes.** LEDs are in concept similar to diode lasers, but their broader emission bands and, especially, their wide emission angle give a lower coupling efficiency.

Here follows more details of noble-gas arc and flash lamps.

3.1 Arc and flashlamps

Flashlamps are gas discharge devices, usually filled with xenon or krypton, designed to produce pulsed radiation.

Unlike flashlamps, which produce pulsed radiation, arc lamps are basically the same gas discharge devices, but designed and optimized to produce continuous radiation.

The most common shape of both flash and arc lamps is linear. Other shapes are available from lamps manufactures, as the helical lamps used for the older Ruby lasers, or U-shaped and point lamps.

Linear lamps, as in fig. 11, are now preferred for laser pumping since they are much easier to cool, by means of a coaxial water flow confined by a transparent tube. In addition a cylindrical emitter can be more easily coupled to a laser rod.

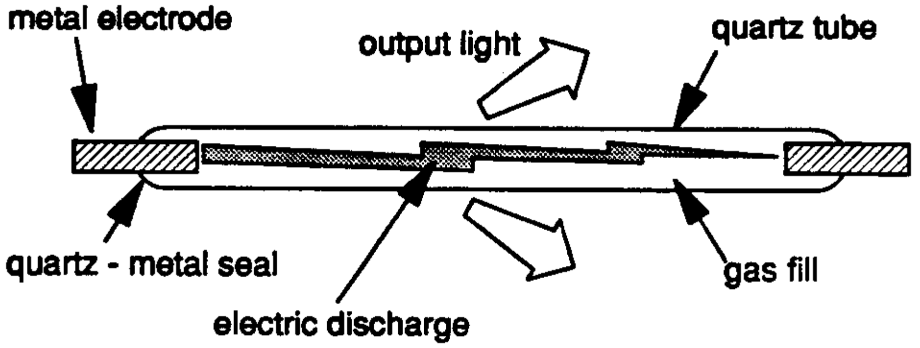


Fig 11. Linear arc lamp

A linear or flash lamp is basically very simple. A quartz tube is ended by two metal electrodes and filled with a rare gas (krypton or xenon) at a pressure from 4 bar (for CW arc lamps) to about 0.5 bar (for short pulse arc lamps).

Radiation from flashlamps and arc lamps is made up of both line and continuum components. The line radiation corresponds to discrete transitions between the bound energy states of the gas atoms and ions (bound-bound transitions). This radiation is strongly dominant in D.C. arc lamps. Since several emission lines of krypton coincide with absorption lines of Nd:YAG, krypton arc lamps are used for CW YAG lasers.

Lines are clearly present also in pulsed discharges at low power density values. The continuum is made up primarily of recombination radiation from gas ions capturing electrons into bound states (free-bound transitions) and of bremsstrahlung radiation from electrons accelerated during collisions with ions (free-free transitions). It is present but very weak in D.C. krypton arc lamps.

In flashlamps. however, the continuum is responsible for a large percentage of total output and dominates the lamp radiation characteristics at high values of power density, often almost completely masking any line radiation that remains. Since in these conditions the conversion efficiency increases with the atomic weight of the gas, xenon is mainly used in short pulses flashlamps, also for YAG pumping.

The actual spectral distribution of the emitted light depends in complex ways on electron and ion densities and temperatures; these parameters in turn are difficult to measure and a true lamp optimization can be made only on the laser itself.

Electrical characteristics

In characterizing the electrical behavior of tubular rare gas flashlamps and arc lamps it is convenient to deal with four distinct operating regimes separately. The first regime is triggering and initial arc formation. This is followed by a second; the regime of unconfined discharge. The third is the low current density, wall stabilized regime, and the fourth regime is that of the wall stabilized plasma at high current.

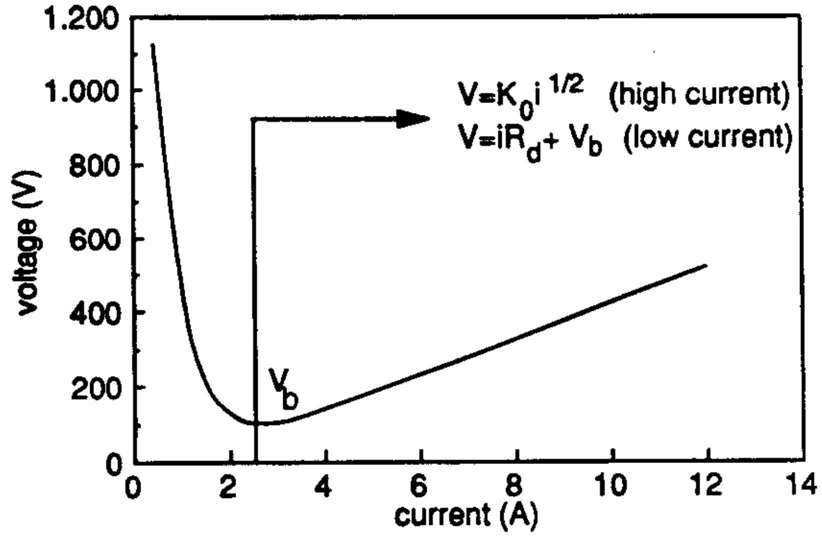


Fig. 12. Electrical Characteristic of arc lamps

A typical voltage-current characteristic of an arc lamp, after triggering, is shown in fig. 12. The characteristic of a flashlamp is similar, except that the actual values of voltage and current may be different. Fig. 12 shows clearly the regime of unconfined discharge, with negative impedance characteristic and the wall stabilized regime, with positive impedance.

In solid state laser lamps, the initial bias voltage V_0 across the tube is usually much lower than the voltage required to break down the gas, which lies in the range of 15 to 24 KV. The majority of lamps incorporated into these systems use either series or external triggering. Each of these methods of triggering has its advantages. External triggering provides greater design flexibility since the secondary winding of the transformer is not in the main discharge circuit. Transformers used for external triggering are less expensive and smaller than those used for series triggering. However, series triggering offers better reliability than external triggering.

Guidelines for selecting triggering voltage values, and the energy to be discharged by the trigger devices are usually given by the lamps manufacturers. However quantitative requirements for reliable triggering are difficult to precisely specify. Each lamp type has its own characteristic trigger curve, and, in addition, even with the most stringent manufacturing procedures, different lamps of the same type will give slightly different trigger curves.

Another trigger consideration is the length of time required for the streamer to form. This is in the neighborhood of 60 ns per centimeter of arc length. If the trigger pulse length is too short for the streamer to form, then triggering will be erratic even if the energy discharged into the trigger circuit is very high.

After undergoing triggering, a lamp is operating in the regime of unconfined discharge when most of the characteristics of the arc are not influenced by the existence of the wall of the lamp envelope. Either of the following conditions exists:

a) the lamp arc is undergoing rapid expansion while approaching equilibrium during start-up,

b) the lamp is in a steady state condition at currents in the region of negative slope on its voltage/current characteristic curve.

Arc lamps

For a CW arc lamp the main power supply leads the lamp from the conditions from a) to b), and then stabilizes the current in the positive voltage/current characteristic region, where the lamp is usually operated.

The low current density, wall stabilized regime is arbitrary defined as a steady state operating condition in an arc lamp where the ratio of current to crossectional area of the lamp bore is in the 30 to 200 amperes per square centimeter range. In this regime a krypton arc lamp is operating in the region of positive resistance on its voltage/current specification curve. The entire useful lifetime of the lamp is spent in this operating range.

In the range of interest for full power operation of these lamps, the curves can be described by the following formula:

$$C= i\, r_d + V_b$$

where:

$V=$ lamp voltage drop in volts per cm of arc length

$i=$ lamp current in amperes

$r_d=$ differential impedance in ohms per cm of arc length

$V_b=$base voltage in volts per cm of arc length.

The differential impedance rd and base voltage V_b are complicated functions of bore diameter and the cold fill and operating gas pressures in the lamp. However, once the lamp bore diameter and operating current are chosen, the lamp voltage at that current becomes dependent only upon the operating pressure of the gas after the lamp has achieved thermal equilibrium.

Pulsed flashlamps

In practice the high current wall-stabilized regime is only encountered in pulsed discharges because of the high current and power densities it encompasses. This regime is arbitrarily defined as a range of operation in a pulsed light source where the arc is stabilized by the inside wall of the lamp envelope. The arc is either expanding at a rate that is determined by its proximity to the envelope wall or expansion has ceased. The electrical behavior of flashlamp discharges is presented in the following discussion.

Flashlamps can be operated with the main capacitor directly connected to the lamps electrodes, with or without a current limiting inductance. In this case the lamp itself act as electrical switch after triggering, This is used only for low repetition rates, because it leads to high electrode erosion and short lamp lifetime.

The majority of pulsed solid state lasers incorporate flashlamp driving circuits designed to maintain a steady state of partial ionization in the lamp during the time between flashes. This important technique is called "simmer mode" operation. It usually involves establishing and maintaining a low current D.C. arc between the lamp electrodes.

The value of steady state simmer current in a flashlamp should be chosen between 25 milliamperes and several amperes. Simmer currents at the high end of this range require more massive simmer power supplies and dissipate more power but lead to higher electrical stability and less difficulty with regard to problems during recovery. Simmer currents at the low end of this range require relatively high simmer power supply open circuit voltages and are frequently troubled by instabilities due to "hopping" of the simmer arc at the point of attachment on the tip of the lamp cathode.

The time dependent functional relationship between voltage and current in a flash discharge in the high current regime can be represented by the formula:

$$V(t) = \pm K_0(t)\,[i(t)]^{1/2}$$

where:

$V(t)$ = voltage across lamp at time t (volts)

$i(t)$ = current through lamp at time t (amperes)

$K_0(t)$ = arc impedance parameter at time t ([ohm-ampere]$^{1/2}$).

The sign is chosen to be the same as the sign of i.
Flashlamp driving circuits for solid state laser systems often consist of a single mesh low resistance RLC circuits with capacitor charge voltages in the range of 500-2000 V and pulse widths from 50 µs to a few ms. In designing pulse forming networks the trigger circuit components can usually be ignored.

The complete time dependent current function for a flashlamp operating in such a circuit is obtained by using computer methods to solve a system of two rather complicated second order differential equations, as functions of a damping parameter α.

For delivery to the lamp of the highest values of instantaneous power at all times during the discharge, and therefore for highest circuit efficiency, the current pulse should be critically damped. This occurs when α has a value of approximately 0.8.

The equations most commonly used for the design of single section flashlamp circuits are listed below:

$$2E_0 = V_0^2\,C$$

$$T = (LC)^{1/2}$$

$$C^3 = 2E_0\,\alpha^4\,T^2/K_0^4$$

In a critically damped discharge, 3T is equal to the time from pulse initiation until the time near the end of the pulse when the current has fallen to 20 percent of its peak value. In a critically damped current pulse, the product 3T is often referred to as the pulse length. The design steps using the above equations are:

A) knowing the desired energy input, pulse length, and choosing a lamp K_0, C is found from the last equation for values of α ofinterest.

B) L is then determined from the second equation and V_0 is determined from the first one.

Lamps cooling

Since almost 50% of the lamp input power is dissipated as heat, the lamp body needs cooling. For small power systems, namely, low energy, low repetition rate pulsed lasers, static or forced gas cooling can be used. And order of magnitude increase in the power handling capability of a given lamp can be however achieved with liquid cooling.

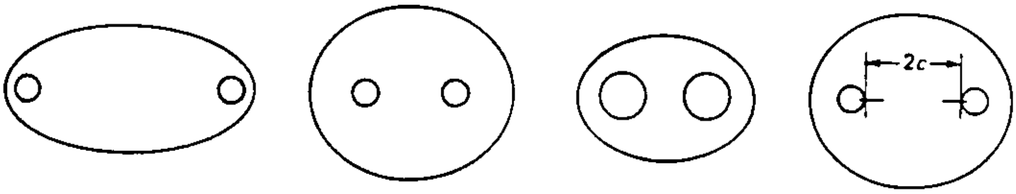
Although liquid cooling of flashlamps and D.C. krypton arc lamps is occasionally performed using coolants other than water, deionized purified water continues to be the most popular liquid coolant. The purity of the water must be high to prevent the etching of quartz and the attachment of dark deposits to the outside surface of the lamp envelope.

In systems where electrical connections and coolant are in contact with one another, the water must be deionized to prevent the shorting or weakening of the starting pulse and to minimize erosion of electrical contacts due to electrolysis. Water resistivity greater than 0.2 megohms is highly recommended. All cooling system component materials should be plastic, stainless steel, or nickel plated metal.

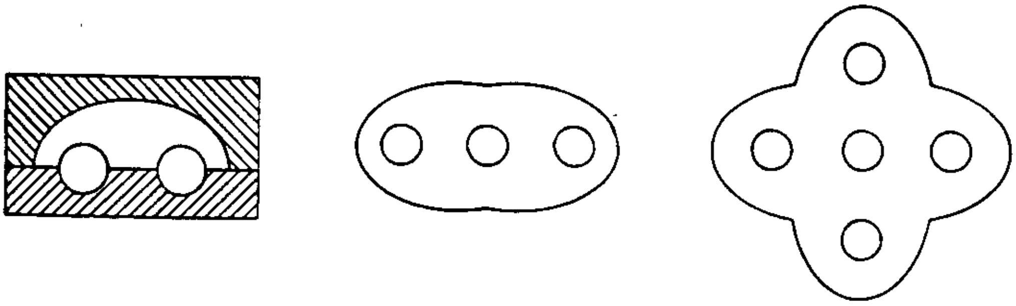
The flow velocity of the coolant around the flashlamp must be high enough to be in the turbulent flow regime, where the heat exchange between the lamp walls and the liquid is maximum. This means, for the most common geometries, water flow in excess of 10 l/min, for each lamp.

3.2 PUMPING CAVITIES

Since lamps, and most other incoherent sources, emit light diffusely in any directions, an optical system is used to collect the light onto the laser active medium. This usually takes the form of a reflector surrounding the lamps and the laser crystal (fig. 13).



(a) Single ellipse with large eccentricity (b) Small eccentricity (c) Closed coupled (d) Exfocal



(e) Semi ellipse (f) Double ellipse (g) Multi elliptical cavity

Fig. 13 Pumping cavities

The most widely used pump cavity is a highly reflective elliptical cylinder with the laser rod and pump lamp at each focus. The elliptic configuration is based on the geometrical theorem that rays originating from one focus of an ellipse are reflected into the other focus. Therefore an elliptical cylinder transfers energy from a linear source placed at one focal line to a linear absorber placed along the second focal line. The elliptical cylinder is closed by two plane-parallel and highly reflecting end plates. This makes the cylinder optically infinitely long.

A single elliptical cylinder can have a cross section with a large or small eccentricity. In the former case, the laser rod and lamp are separated by a fairly large distance, in the second case they are close together. If the elliptical cylinder closely surrounds the lamp and rod, then one speaks of a close-coupled elliptical geometry. This geometry usually results in the most efficient cavity. This cavity has the further advantage that it minimizes the weight and size of the laser heads.

Such reflectors are made machining solid metal blocks, usually brass or aluminum. The reflective surface is then optical grade polished and coated with a suitable reflective film. For Nd:YAG or Nd:glass laser best coating is electroplated gold, which has a good reflectivity on the main absorption bands of Nd (fig. 14). For crystals requiring blue or ultraviolet pumping (as ruby or Ti:sapphire) vacuum evaporated aluminum is often used, since it gives higher reflectivity than gold at wavelengths shorter than 500 nm (fig. 14).

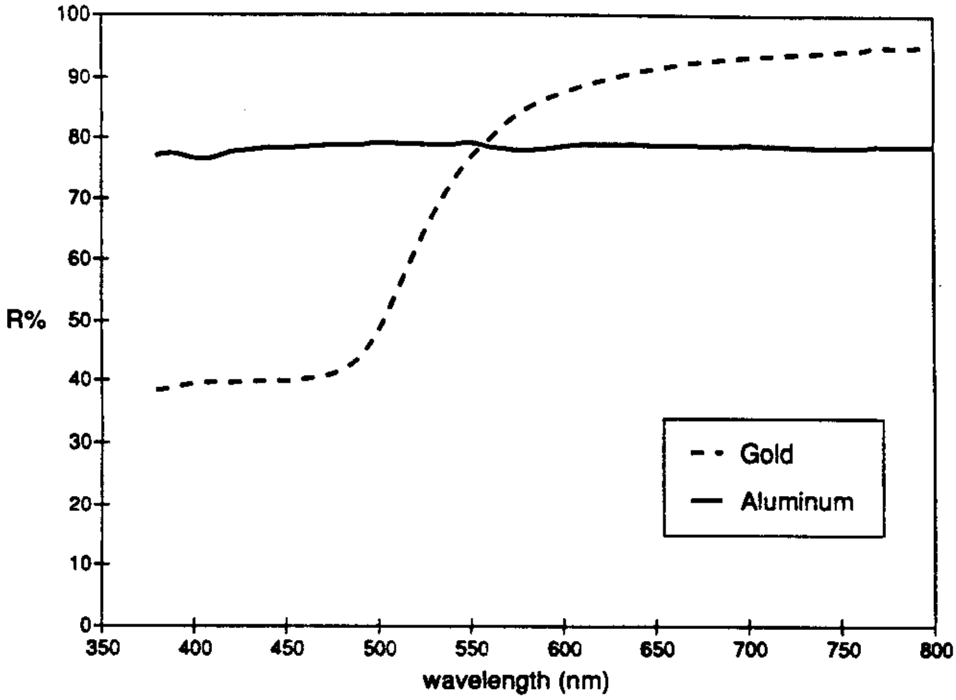


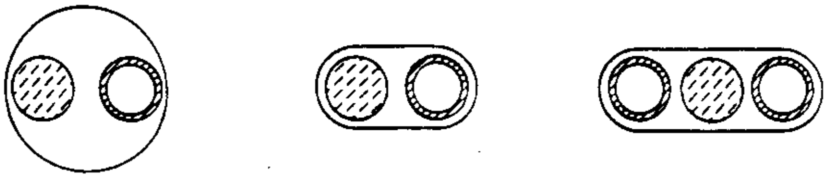
Fig. 14 Specular reflectance of Gold and Aluminum

Silver (electroplated or vacuum evaporated) has higher reflectivity than aluminum, but it rapidly tarnishes, greatly reducing reflectivity, when exposed to air and moisture. Silvered reflectors must be then protected with a transparent coating.

The other possible technology is the close-coupled, non focusing, pump cavity, where the lamp and rod are placed as close together as possible, and a reflector closely surrounds them. The reflector can be circular or oval in cross section (fig.15).

The advantage of this pump cavity is fabrication simplicity; however, this design has a number of disadvantages: nonuniform pumping of the rod cross section and difficulties in providing adequate cooling of the rod, flashlamp, and reflector.

Multi-lamp close-coupled cavities provide a higher degree of pumping uniformity in the laser rod than single-lamp designs, at the expenses of a lower efficiency.



(a) Circular cylinder (b) Single-lamp close-wrap (c) Douple-lamp close-wrap

(d) Four-lamp close-wrap configuration (e) Close-coupled multiple coaxial

Fig. 15 Close-coupled diffusive cavities

Very important for the efficiency is the proper choice of the reflecting material. Very high reflectivity can be achieved with white powders, as Magnesium oxide or Barium oxide (fig 16). The powder must be contained in quartz tubes, because any attempt of sticking together the powder grains, dramatically reduces the reflectivity. The limitation of this technology is then given by the low thermal conductivity of the powder, making it suitable only for low power lasers.

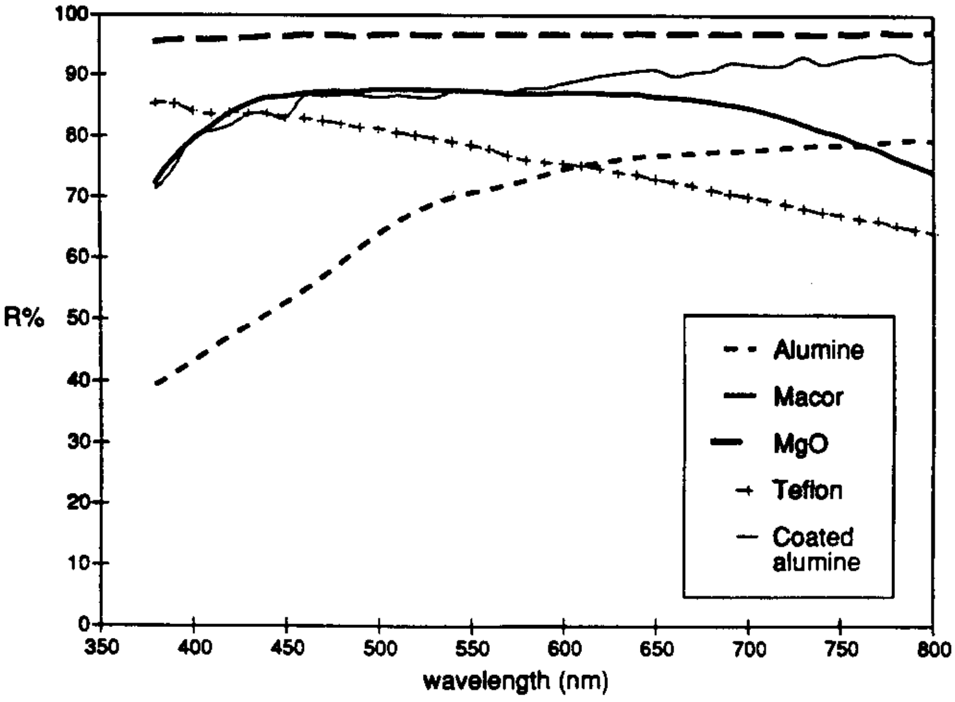


Fig. 16 Diffuse reflectance of materials used in laser cavities

The most rugged reflectors are made of solid ceramic blocks. Many high power industrial laser systems, where reliability is very important, use this kind of cavity. Using a good ceramic material this kind of cavity can be nearly as efficient as a metallic coated elliptical one. Good reflectivity is achieved by high purity alumina. The reflectivity can be enhanced (fig. 16) by a vitreous transparent glaze, which also protect the ceramics from ageing effects of lamps UV radiation and of cooling water. The glaze technology is however proprietary of few companies, mainly suppliers of laser companies. Good reflectors of this kind can be than obtained only as spare parts of commercial lasers.

A close-coupled reflector often used in laboratory setups of low-repetition-rate pulsed lasers is simply made by a silver or aluminum foil wrapped around the flash lamp and laser rod. The efficiency of this closely wrapped cavity is found to be about as high as when a gold plated elliptical cylinder is used.

3.3 THERMAL EFFECTS IN LASER RODS

Since all high average power solid state lasers are pumped by broad-band flash or arc lamps thermal effects dominate their operating characteristics. Typically, 5-10% of the power from the exciting flash-lamps is converted to heat within the host material (fig. 17).

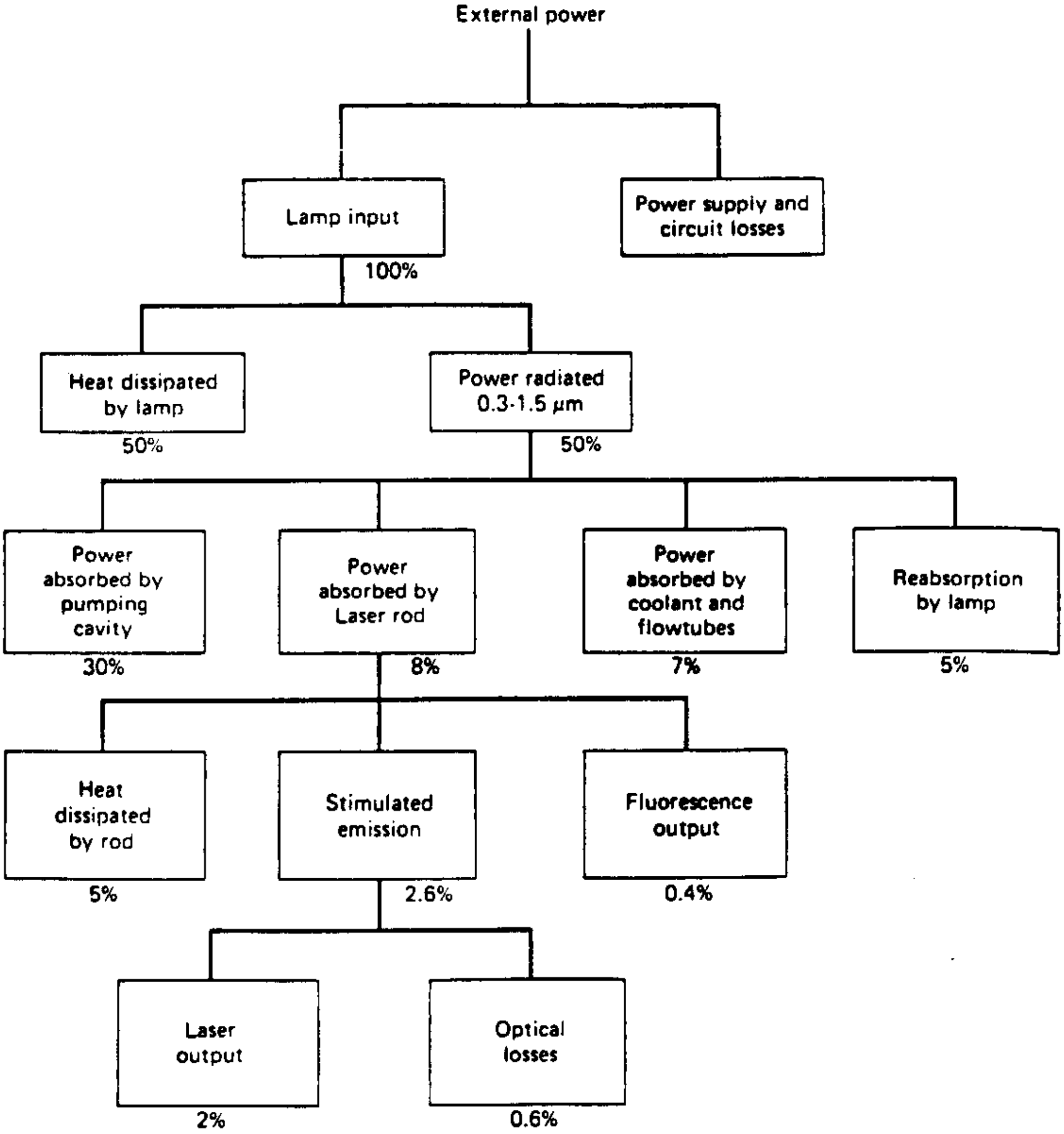


Fig. 17 Heat transfer in a Nd:YAG laser

This heating is due to:

- lost energy when ions decay from the pump bands to the upper laser level
- non-radiative decay of a fraction of the ions in the upper laser level
- direct excitation of the host material by the broadband flash-lamp light.

The heat is removed by cooling the barrel of the laser rod. This leads to the development of a near parabolic temperature profile in the material. The temperature distribution takes between a few seconds (Nd:YAG) and a minute or so (Nd:glass) to stabilize. The resulting temperature gradients in an operating laser influence optical behavior via two mechanisms:

- they lead to variations in refractive index causing lensing and wavefront distortion,
- they produce variations of stress within the body of the material inducing birefringence via the photoelastic effect.

At very high flash-lamp powers the induced stress can lead to rupture of the laser rod.

Thermal lens effect

In most rod systems, the pump light absorption and the heat deposition is close to uniform within the material volume. Under uniform continuous (CW) pumping and cooling conditions, the temperature distribution that results is near parabolic with a magnitude depending on the thermal conductivity of the material and the heat input.

Under pulsed operation, a similar distribution results if (as is usual) the interpulse period is short compared with the material thermal relaxation time.

To first order, the induced lens power resulting from the temperature gradients is spherical and given by:

$$1/f = QL/2K * dn/dT$$

where:

L is the pumped length of the laser rod,
K is the material thermal conductivity,
Q the heat absorbed/unit length,
dn/dT the change in refractive index with temperature.

For Nd:YAG, the last parameter is approx $7.3 * 10^{-6}$ /C. For example a high average power Nd:YAG laser, capable of about 400 W of laser output, under a typical flash-lamp pumping condition of approx 10 KW, with a 150 x 9.6 mm YAG crystal, has an induced lens power of approx 2 diopters.

Since lens power increases with Q, smaller rods providing the same output suffer from higher induced lens power.

Thermal stress effects

The stress induced by temperature differences is most severe at the rod barrel surface where the temperature gradient is greatest. The resulting difference between radial and tangential refractive indices, caused by the stress, leads to beam depolarization.

This is not usually a major problem in industrial lasers which are predominantly fixed-Q and unpolarized. The effect is commonly the cause of severe loss of power in high average power systems which are Q-switched and where the beam is polarized.

For all high average power, high brightness, systems the depolarization effect degrades beam divergence. The onset of significant depolarization has a relatively low threshold. A halfwave retardation occurs at the edge of a pumped rod for an absorbed power of approx 50 W in Nd:YAG and only approx 10 W in Nd:Glass.

Fracture of a laser rod occurs when the stresses (maximum at the barrel wall) exceed the material rupture strength. The absorbed power at which this occurs scales with rod length and is dependent on a number of materials parameters.

For Nd:YAG and Nd:Glass, the absorbed power limits are approximately 145 and 20 W cm^{-1}, respectively. Since small surface imperfections and inclusions can significantly modify stress at the rod barrel, it is usual to operate at a flash-lamp pumping level that will give absorbed heat below this limit.

Compensation of thermal effects

There are some possible techniques that may be used to help compensate for thermal effects in laser rods. Several of these methods can be incorporated within a resonator design.

Birefringence problems can be reduced in crystals by selection of the orientation of the crystal axes relative to the cylindrical axis.

In commercially grown YAG the rod axis is along the (111) direction; however, it has been shown that the (001) direction would be preferable for lower losses if the heat dissipation of the rod is less that approximately 50 W. (Losses become independent of axis orientation for powers in excess of 50 W). Unfortunately, cutting the (001) type rod from a (111) grown boule of Nd:YAG is limiting on size and wasteful on material.

Compensation of thermal focussing has been accomplished in many ways, for example, by grinding the ends of the rod to form a negative lens, by insertion of a negative lens close to the rod, and by including the rod focal length in the resonator design procedure when choosing suitable cavity mirrors. It should be noted that each of these passive schemes only provides compensation at one (selected) average pump power. However many applications require a broad variation of the output power and more complicated adaptive resonator should be used (adaptive mirrors, phase conjugation, etc.).

3.4 SEMICONDUCTOR LASER PUMPING

The most promising alternative to flash-lamp pumping of solid-state lasers, in order to avoid the above mentioned problems, has always been the diode laser. Throughout the last twenty years numerous laboratory devices have been assembled which incorporated single diode lasers, small laser-diode arrays or LED's for pumping of Nd:YAG, Nd:glass and a host of other Nd lasers. The low power output, low packaging density, and extremely high cost of diode lasers prevented any serious applications for laser pumping in the past.

The reason for the continued interest in this area stems from the potential dramatic increase in system efficiency and component lifetime, and reduction of thermal load of the solid-state laser material. The latter will not only reduce thermo-optic effects and therefore lead to better beam quality, but will also enable an increase in pulse repetition frequency. The attractive operating parameters combined with the low-voltage operation and the compactness of an all solid-state laser system have a potential high payoff.

The high pumping efficiency compared to flashlamps stems from the good spectral match between the laser-diode emission and the Nd absorption bands. Actually, flashlamps have a higher radiation output to electrical input efficiency (70%) compared to laser diodes (25-50%), however, only a very small fraction of the blackbody spectrum is usefully absorbed by the various Nd bands.

A concomitant advantage derived from the spectral match between the diode-laser emission and the long-wavelength Nd absorption-band is a reduction in the amount of heat which is deposited in the laser material. In addition, system lifetime and reliability will be higher in laser-diode-pumped solid-state lasers compared to flashlamps-based systems. Laser-diode arrays have exhibited lifetimes on the order of 19,000 h in cw operation and 10^9 shots in the pulsed mode. Flashlamp life is on the order of 10^7 shots, and about 200 h for cw operation. In addition, the high pump flux combined with a substantial UV content in lamp-pumped systems causes material degradation in the pump cavity and in the coolant, which lead to systems degradation and contribute to maintenance requirements. Such problems are virtually eliminated with laser-diode-pump sources. The absence of high-voltage pulses, high temperatures and UV radiation encountered with arc lamps lead to much more benign operating features of laser-diode-pumped systems.

Coupling Geometries

In contrast to flashlamps or filament lamps, the emission from laser diodes is highly directional, therefore requiring different pump configurations. Arrangements for transferring pump radiation from laser diode arrays to the solid-state laser material will be discussed below.

We have to distinguish between optical system employed for end-pumping of a laser crystal, side-pumping of a cylindrical rod, and side-pumping of a rectangular slab.

End-pumping configurations.

The focused end-pumping configuration, if properly designed to provide matching of the pump light distribution and resonator mode, is the most efficient pump-radiation transfer scheme. Since the pump beam from the diode array is collinear with the optical resonator, the overlap between the pumped volume and the TEM_{00} mode can be very high. In addition, the coupling efficiency into the rod is high and the absorption length can be as long as the crystal.

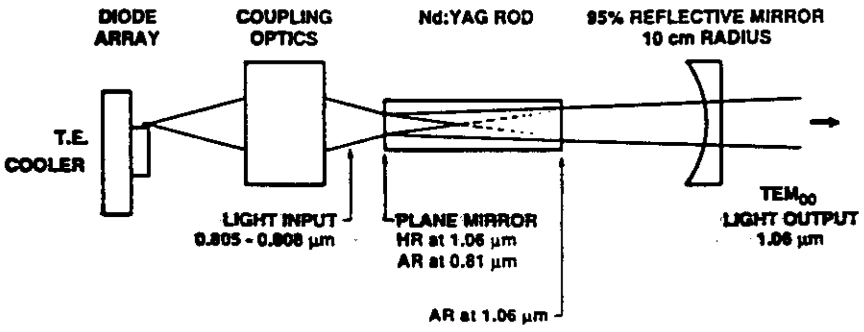


Fig. 18. End pumping geometry

In its most basic form, end pumping involves (fig. 18) a collimating lens with a large numerical aperture in order to collect radiation from a large cone angle, and a focusing lens to produce a small diameter spot inside the laser crystal. Since the radiation lobe emitted from a diode array has a high degree of astigmatism, one can introduce prisms or cylindrical optics to transform the beam into a circular shape.

The purpose of the coupling optics is to shape the radiation distribution from the diode array such that the pumping volume coincides with the laser's TEM_{00} mode. Radiation from the laser diode array diverges approximately 40 degrees in the plane perpendicular to the active layer. The radiation is collected by a lens. After passing through a pair of anamorphic prisms, the radiation is focused in the rod by a lens. The resulting divergence inside the Nd:YAG rod is about 6 degrees.

In the most common geometry, a plano-concave configuration is chosen, with one planar rod surface, high-reflection coated at 1.06 μm and antireflection coated at 0.81 μm, to allow the pump light to enter the rod. The intracavity rod surface is antireflection coated at 1.06 μm and an output radius mirror can be placed outside the rod, or direct coated on the rod itself.

End-pumping of a miniature Nd:YAG laser with laser diode arrays is an attractive means of obtaining efficient cw lasers. However, at present, the end-pump scheme is useful only for low-power lasers because the pump area is very small. In order to achieve a somewhat higher output power, two sources can be polarization-coupled to double the pump power available, or a double-ended pumping arrangement can be employed.

Side pumping

In this configuration, the diode arrays are placed along the length of the laser rod and pumped perpendicularly to the direction of propagation of the laser resonator mode. As more power is required, more diode arrays can be added along and around the laser rod. There are three practical approaches to couple the radiation emitted by the diode lasers to the rod:

a) direct coupling;

b) with optics between source and absorber;

c) fiber-optics coupling.

The direct coupling option does not allow for variations other than the placement of the diode lasers around the rod. Fiber-optics coupling is very impractical for a large number of diode lasers. Optical coupling can be achieved by using imaging optics such as lenses or elliptical and parabolic mirrors, or by non-imaging optics such as reflective or refractive flux concentrators.

The side-pump geometry is not as efficient as the end-pump design, however, it permits scaling of the laser to large power levels. As a matter of fact, the side-pump geometries are normally result of a small absorption length, low pumping density, and wasted pump energy due to resonator-mode and pump-distribution mismatch. Large lasers require large rod diameters, thus increasing the pump efficiency; they also require densely packaged, high-power diode arrays which provide gains over the whole cross section of the rod at sufficient intensity to permit the use of unstable resonators. All these factors contribute to a more efficient utilization of the pump radiation, as compared to small systems.

The side-pump geometry is very suitable slab laser pumping. Side-pumped-slab lasers are usually pumped by 2-D arrays or densely-packed linear arrays. In a slab laser, the face of the crystal and the emitting surface of the laser diodes are in close proximity, and no optics is employed.

The slab can be pumped from one face only. In this case the opposite face is bonded to a copper heat sink containing a reflective coating to return unused pump radiation back into the slab for a second pass. An antireflection coating on the pump face is used to reduce coupling losses (the diode array is not in contact with the YAG). Liquid cooling is employed to remove heat from the YAG and diode heat sink.