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The Potential of High-Average-Power Solid State Lasers

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The Potential of High-Average-Power Solid State Lasers

Abstract

We discuss the possibility of extending solid state laser technology to high average power and of improving the efficiency of such lasers sufficiently to make them reasonable candidates for a number of demanding applications. A variety of new design concepts, materials, and techniques have emerged over the past decade that, collectively, suggest that the traditional technical limitations on power (a few hundred watts or less) and efficiency (less than 1%) can be removed. The core idea is configuring the laser medium in relatively thin, large-area plates, rather than using the traditional low-aspect-ratio rods or blocks. This presents a large surface area for cooling, and assures that deposited heat is relatively close to a cooled surface. It also minimizes the laser volume distorted by edge effects. The feasibility of such configurations is supported by recent developments in materials, fabrication processes, and optical pumps. Two types of lasers can, in principle, utilize this sheet-like gain configuration in such a way that phase and gain profiles are uniformly sampled and, to first order, yield high-quality (undistorted) beams. The zig-zag laser does this with a single plate, and should be capable of power levels up to several kilowatts. The disk laser is designed around a large number of plates, and should be capable of scaling to arbitrarily high power levels.

Introduction

The first laser was a solid state laser, demonstrated by T. Maiman in 1960¹ using a cylindrical ruby crystal rod pumped by a xenon flashlamp. In 1961, additional crystalline² and glassy³ solid state laser materials were discovered, in which the neodymium ion (Nd^{3+}) served as the active constituent. These early discoveries immediately caught the attention of military technologists, and prompted the conceptualization and assessment of a wide range of military applications based on powerful solid state lasers. Low-energy, low-average-power tactical applications such as range finding and target designation were rapidly and successfully developed in the 1960s, based initially on ruby and later on Nd:YAG (yttrium-aluminum-garnet) and Nd:glass laser materials.⁴ Scaling the pulsed energy of solid state lasers into the kilojoule range at millisecond pulse durations proved relatively straightforward.⁵⁻⁷ Single-pulse efficiencies as high as 7 to 9% have been reported^{6,8} for this "free-running" pulse regime.

However, scaling to high average power was judged to be very difficult if not impossible, especially if high efficiency and high output beam quality were both to be maintained.

To alleviate the power-limiting problem of waste heat removal, two novel geometries for the solid state laser material and its associated cooling were proposed in the late 1960s: the face-pumped "zig-zag" configuration by General Electric,¹⁰ and the "axial-gradient" configuration by Autometrics Division of Rockwell^{11,12} and by American Optical Corporation.^{13,14} The zig-zag device concept was developed by GE under Air Force support, and by the mid-1970s had been scaled into the hundred-watt range of cw average power^{15,16} using Nd:YAG as the laser medium and to tens of watts of average power in the repped-pulse mode using Nd:glass. More recently, Byer's group at Stanford has also joined in developing Nd:glass and Nd:YAG zig-zag laser technology.^{17,18}

Support for advancing solid state laser technology to very high powers was suspended in 1964, following the discovery of the carbon dioxide (CO_2) gas laser, of which high-power versions were developed in the mid to late 1960s. The concept of scaling a gas laser to high average power by convectively removing waste heat from the laser cavity was demonstrated by AVCO with the CO_2 gas-dynamic laser in 1965.¹⁹ Emphasis on high average power shifted to deuterium fluoride (DF), another flow-cooled gas laser medium with shorter wavelength ($3.8 \mu\text{m}$), in the early 1970s.

Although development of high-average-power solid state lasers languished during the past two decades, vigorous development of high-energy single-pulse Nd:glass laser systems has taken place, particularly in connection with inertial fusion research.²⁰⁻²³ Basic plasma-physics considerations, coupled with computer simulations carried out in the 1960s, indicated that efficient implosion of fusion targets is facilitated by short-wavelength radiation as a driver. In the early 1970s, the Nd:glass laser operating at a wave-

length of 1060 nm ($1.06 \mu\text{m}$) was the shortest wavelength laser with energy and peak-power scaling potential. At the Lawrence Livermore National Laboratory (LLNL), a two-pronged laser R&D strategy was adopted in the early 1970s: (1) develop Nd:glass laser systems (fitted with harmonic frequency converters, if necessary) as a sequence of experimentally flexible, single-shot target irradiation facilities; and (2) in parallel, develop entirely new, short-wavelength lasers having the efficiency, average power, and cost potential necessary to support power-generating applications of inertial fusion.²⁴

Figure 1 shows the growth in peak power and on-target pulse energy achieved over the past decade by Nd:glass laser systems at LLNL. The Shiva laser was the "technological fulcrum" for the entire development enterprise portrayed in Fig. 1. To achieve the performance goals set for this system, it was necessary to develop greatly improved laser glasses,²⁴ high-damage-threshold optical components,²⁵ and techniques for propagating intense optical beams while maintaining

Fig. 1. Energy, peak power, and pulse width capabilities of Nd:glass laser systems constructed and operated at LLNL during the past decade. The Nova system is capable of operating at 1050, 525, and 350 nm; the others operate only at 1060 nm.

high beam quality.²⁶ To conduct fusion experiments at wavelengths shorter than the 1060-nm fundamental wavelength of Nd:glass, nonlinear up-conversion technologies were developed for beam diameters up to 74 cm. This required the growth of large-aperture (27-cm) KDP crystals,²⁷ the development of diamond-turning fabrication techniques,²⁸ and the construction of a crystal array.²⁸ These efforts were so successful that it is now technically assured that laser system outputs can be scaled into the multimegajoule energy range and the 500-TW peak power range.²¹

We centered our research on short-wavelength advanced laser systems for fusion applications on gas laser media, because of their potential for high-average-power operation and because of the poor efficiency and average-power performance that had been demonstrated by Nd:glass and other solid state lasers by the mid-1970s. Between 1974 and 1979, a variety of energy-storage and steady-state gas lasers were conceptualized, developed, and assessed for use in fusion applications.^{21,29} The KrF excimer laser (fitted with one of several forms of pulse compression) proved to be the best of the systems investigated. However, after further study, the KrF laser in its present conceptual form was judged to be marginal in efficiency ($\leq 6\%$), extremely complex optically because of the need for pulse-width compression, and several times too expensive for use in the end applications of inertial fusion.

While continuing to seek a breakout from these limitations on KrF (excimer) systems, a re-examination of the potential of solid state lasers to achieve the efficiency and average power needed for fusion applications was carried out at LLNL. New design concepts and recent developments in materials and techniques provided a focus for that re-examination. Our conclusion³⁰ was that proper design and material selections would permit unconstrained scaling of average power, while maintaining high beam quality; and, further, that with careful conservation of pump energy through a variety of techniques, efficiencies of over 10% should be possible at high power and radiance. The critical elements of design for high average power and good efficiency are the following:

1. Thermal management—assuring that all deposited energy is adequately close to a coolable free surface. For hosts with low thermal conductivity, such as glass, this requires that the

doped material be configured in thin layers. Crystals, with higher conductivity, can be made thicker.

2. Thermal gradient control—assuring that the thermal gradients constitute a uniform, parallel field at a fixed angle to the beam propagation direction, so as to minimize optical distortion. Size is an important factor here: gradients near edges are difficult to control, and a large ratio of clear surface area to edge-affected area is needed. Thus large size, which naturally favors higher-power designs, also favors beam quality.

3. Pump energy utilization—assuring the efficient capture of pump radiation by the laser medium. This requires careful attention to the pumping configuration and to the pump spectrum (as convolved with the laser pump bands), and sufficient areal density of the active species (ions per unit area) to absorb most of the pump radiation that enters the laser medium.

4. Efficient extraction—assuring that the available population inversion is optimally converted to laser output. The key factors here are (1) filling most of the pumped volume with extracting radiation at several times the saturation fluence; and (2) matching the pump duration to the excited-state lifetime.

These necessary design factors are poorly realized in traditional solid state lasers; although specific lasers have embodied one or two factors at a time, they have never been brought together in combination. A broad variety of technical advances, which have occurred over the past decade, can be exploited in the effort to implement all of these critical factors simultaneously.

It appears that thermal management techniques similar to those described in items (1) and (2) above can also be applied to nonlinear optical converter structures, to permit their use at high average power. Combining such converters with the solid state lasers described here would provide high-power sources, with high efficiency and good beam quality, from the near ultraviolet to the mid-infrared.

We begin this article with a brief survey of potential applications of a solid state laser technology improved in efficiency and unconstrained in average power, and then describe the ideas and analyses upon which our projections of the scaling of solid state lasers to high power and efficiency rest.

Possible Applications of High-Power Solid State Lasers

Solid state lasers have been employed in a wide variety of low-power industrial, military, and medical applications. Technical limitations have excluded them from use or consideration in moderate- to high-power applications, which therefore have been developed or conceptualized around gas lasers of various sorts. If the restrictions on average power could be removed, and the efficiency improved, solid state lasers have intrinsic features that would make them attractive candidates for many of these more demanding applications. They are operationally benign, requiring no toxic, exotic or explosive materials and generating no hazardous radiation or chemical by-products; and they minimally stress logistics in applications requiring mobility, since their primary consumable is electricity, or the fuel to generate electricity. With respect to technical qualities, solid state lasers are exceptionally flexible in terms of wavelength and waveform and can be specialized to meet widely divergent system requirements. The following is a brief description of several areas in which an improved solid state laser technology might find application.

X-Ray Lithography

Lithography for submicron-scale circuit fabrication is a rapidly growing interest, as integrated circuits advance to greater density. Electron beams, ion beams, and x-rays all have demonstrated capability for submicron lithography, but practical combinations of feature size and throughput are yet to be achieved. Electron and ion beams are superior in terms of minimum feature size, but x-rays have the potential for achieving both adequate feature size and throughput that would make them the choice for production systems. Several types of x-ray sources have been used experimentally and are being developed for production purposes—bremsstrahlung sources, which use the most conventional technology, but which have the least potential for small feature size and high throughput; synchrotron sources, which may be technically ideal, but which are large and expensive; and laser-driven-plasma sources, which are promising in terms of size, cost, and efficiency, but which require higher average laser power to achieve useful throughput. The laser requirements for efficient x-ray generation are short pulse width (about 1 ns), short wave-

length (near IR to near UV); modest pulse energy (1 to 10 J); and a prf determined by the desired throughput. Average powers of about 100 W (5 to 10 W of usable x-ray power) would be useful in an early production context,³¹ and one to several kilowatts would probably be desirable later. Solid state lasers, based on advanced technology, should meet these requirements well, and excimer lasers will also compete for the role.

Laser Fusion

Laser-driven inertial confinement fusion is one of several approaches to controlled fusion energy for commercial power that are under active development in the U.S. and in several other nations. The projected laser requirements for commercial fusion power are³² short wavelength (less than 0.5 μm); short pulse width (about 10 ns); tailored pulse shape; efficiency of 10% or better; pulse energy of several megajoules; prf of several pulses per second; and cost less than a few hundred dollars per joule. No current laser technology can be projected to meet all of these requirements, but the quest for a suitable solution was the source of many of the ideas for advanced solid state lasers that are described in this paper. If these ideas prove out, solid state lasers will be a strong contender for the fusion-driven role.

Laser Isotope Separation

Laser isotope separation (LIS) has progressed to the point at which the first applications, nuclear fuel enrichment, are approaching production-scale implementation. Other applications are at the stage of preliminary evaluation. It appears that LIS is more cost effective than alternative isotope separation technologies for heavy atoms, for which the fractional difference in mass between isotopes is small. The competition between atomic vapor processes (AVLIS), which require short wavelengths, and molecular processes, which require long wavelengths as well, have thus far favored the atomic processes. The laser requirements to support LIS generally and flexibly are wavelength tunability (between 0.25 and 4 μm); precise wavelength control (to about 10⁻⁶ wave numbers); high peak power and sufficient average power for the production rate desired (for

typical applications examined so far, the power requirements have ranged from kilowatts to megawatts).

The current AVLIS radiation sources are tunable dye lasers pumped by copper-vapor lasers.²³ This technology is applicable to processes based on green to near-IR, but would require an additional harmonic-generation step to reach the shorter wavelengths. Solid state lasers were evaluated in the late 1970s for use in the LLNL AVLIS process for uranium enrichment,²³ but were passed over in favor of copper-vapor lasers. Advances in solid state technology, such as those described in this paper, could render such lasers relevant for future LIS applications.

Materials Fabrication and Processing

Lasers are being used for cutting, drilling, welding, and heat-treating operations on metals, and, as relevant, on wood, plastics, ceramics, fabrics, rubber, semiconductors, and paper. Despite early resistance by the usually conservative manufacturing community, these applications have grown, and they constitute the largest market area for production lasers and laser systems. The current market is roughly split between CO₂ and neodymium lasers, with cw CO₂ lasers the only entry for applications between 400 W (the upper limit on neodymium) and 25 kW (the upper limit for CO₂ lasers engineered for a manufacturing environment). Below 400 W neodymium is the major entry, but CO₂ competes in that range also, and a variety of other laser types are reaching sufficient maturity to enter the market. On the high-power side, experiments have been extended up to 100 kW (see Ref. 32), but commercial interest is largely below 25 kW. It appears that for some time

the advances in laser fabrication will be in the form of cost reduction, improved reliability, and expansion in the existing marketplace.

It is unclear whether solid state lasers in the 1- to 10-kW range would be an important factor in the fabrication industries. Waveform flexibility could be useful in optimizing the processes, but CO₂ offers such flexibility also, and it has not been exploited at the higher power levels, at which cw beams have been used exclusively. The shorter wavelengths of solid state lasers could couple more efficiently to metals, particularly high-reflectivity metals, and would have markedly different penetration depths in non-metallic materials. The utility of these differences is unassessed.

Military Applications

Military applications of low-power lasers have been realized and deployed, most notably range finders and designators using neodymium lasers. Medium and high-power applications are still in the future and are paced by the availability of suitable laser technology. Unbounding the average power and increasing the efficiency of solid state lasers will put them in contention for these applications. Compactness, for compatibility with military vehicles, is an additional requirement, and at medium to high power all laser concepts have been deficient in this respect. The laser heads in solid state lasers should be comparatively small, but the power supplies and cooling equipment will determine the size of the systems, and it remains to be seen whether solid state lasers will be superior to other lasers in this critical aspect.

Operation at High Average Power

For the high-average power solid state lasers of interest to us, we impose three design criteria that must be simultaneously fulfilled: (1) the laser must be efficient; (2) the laser beam quality must be near diffraction-limited; and (3) the beam quality must be independent of the operating point. In the past, the average power output of solid state lasers was limited by two failure modes, which appear in succession as the power loading is increased: (1) the beam quality decreases rapidly with the buildup of thermal gradients in the laser medium; and (2) the laser material fractures when the thermal gradients are high enough. Since good beam quality is required for a great many laser applications, the first failure mode determines the maximum average output power. Limiting the growth of thermal gradients and minimizing the effect of the gradients on the phase front are the major techniques for achieving high average power while preserving beam quality. Constraining the magnitude of thermal gradients is primarily a heat-transfer problem. Limiting the impact of thermal gradients on the phase front of an extraction beam can be approached intrinsically, by contriving geometries for which the gradients are equally sampled by the full wave front, or extrinsically, through the use of beam-cleanup elements external to the laser medium (adaptive optics, phase conjugators, or Raman converters). The approach to be described here emphasizes intrinsic control. It may be possible to achieve adequate beam quality with intrinsic control alone; if not, the remaining corrective burden can be borne by extrinsic elements.

For almost all combinations of pump sources and solid state laser media, it is not possible to saturate the pump bands and thereby deposit pump energy in the laser volume uniformly. A Lambert's law (exponential) absorption of the pump radiation will determine the pump-energy profile in the material, rather than bleaching waves driven by pump radiation. Efficient absorption of the pump radiation thus implies a rather nonuniform energy deposition in the laser medium. This is shown in Fig. 2 for the case of xenon flashlamps pumping Nd:glass; the phenomenon is qualitatively similar in most pump source-laser medium combinations. Figure 2 shows the relative pumping efficiency of a slab of laser material as a function of the number of ions per unit area with which the pump light interacts in traversing the thickness of a slab (we will refer to this parameter as the areal density or optical depth). Figure 2 also

shows the corresponding energy-deposition (or gain) profiles for the slab pumped on both of their lateral surfaces. The relatively uniform deposition profile (curve A) is only achievable at low pump utilization efficiency (point A). Efficient use of the pump irradiation (point C) is only achieved with a concomitant nonuniform energy deposition profile (curve C).

The usual realization of a solid state laser is to configure the medium as a right-circular cylinder that is pumped and cooled through its lateral surface. For this geometry the gain and thermal gradients are radial, and perpendicular to the optical propagation direction along the cylinder axis; this arrangement can achieve high pump efficiency only at the price of gain and beam nonuniformity [Fig. 3(a)]. However, if the laser medium is configured as a face-pumped, face-cooled plate, and if the optical propagation direction is chosen so that each ray of the beam experiences the same integral of gain and phase shift along its path through the medium, then no amplitude or phase distortion results; high pump efficiency is then consistent with high beam quality even at high average power [Fig. 3(b)].

The conduction of heat through a solid is governed by the heat-diffusion equation. The solution to this equation for plates or rods with volume heat deposition and surface cooling leads to thermal gradients that are linear combinations of parabolic or Bessel functions, respectively. These temperature gradients, apart from their physical distortions of the entrance or exit faces of the laser medium, can lead to substantial aberration of the optical beam if

$$\frac{ds}{dT} = (n-1)\alpha + \frac{dn}{dT} \neq 0, \quad (1)$$

where s is the optical path length, T is the temperature, n is the index of refraction, and α is the coefficient of thermal expansion. The case of a rod with a positive ds/dT is shown in Fig. 4(a). Again, if the laser medium is configured as a plate and the optical propagation direction is chosen so that the integral of s along the ray path in the medium is identical for all rays in the beam, then no beam distortion occurs [Fig. 4(b)].

A major problem with high-average-power solid state lasers is induced birefringence in thermally stressed media. In many amplifier or oscillator designs, birefringence is the limiting parameter for system performance. If the laser medium

Fig. 2. Relative pumping efficiency of a slab of laser medium vs Nd^{3+} areal density (or optical depth), showing the correlation with the nonuniformity of pump energy deposition in the slab.

is unconstrained, linear thermal gradients ($d^2T/dx_i^2 = 0$) do not produce stress. However, it is a natural result of the heat-diffusion equation that, for volume thermal deposition and surface heat removal, thermal gradients in the direction of heat transport are not linear ($d^2T/dx_i^2 \neq 0$), and a stress results. Since the photo-elastic coefficients of materials are rarely zero, a stress on the medium will in general reduce the optical symmetry of the medium, producing or modifying existing birefringence. Thus under stress an isotropic material can become uniaxial or biaxial, and lower-symmetry materials can be further reduced in symmetry (e.g., uniaxial to biaxial) or can have their principal symmetry axes rotated. The condition for stable propagation (no scattering into the orthogonal polarization) of a plane-polarized wave is easily described, using the optical indicatrix to represent

the optic and symmetry characteristics of the material.³³ The plane perpendicular to the direction of propagation cuts the indicatrix ellipsoid, producing an ellipse (in general). The two stable polarization directions for that particular propagation direction are along the major and minor axes of the ellipse. Thus there are two general requirements for stable propagation of a polarized wave in a medium: the polarization must lie along the major or minor axis of the ellipse described, and the principal axes of the optical indicatrix must not rotate with position in the medium, or with temperature.

The now-familiar case of an isotropic cylindrical rod with a radial thermal gradient is shown in Fig. 5(a). In this case the stress is in the azimuthal or θ direction, so that the orientation of the principal axes of the resulting uniaxial optical

(a) Rod amplifier

(b) Disk amplifier

Fig. 3. Effect of spatially nonuniform pump energy deposition on laser output beam quality. (a) In rod amplifiers, spatially nonuniform power deposition produces a radial gradient in the gain. The beam propagates perpendicular to this gradient, leading to a distortion in the beam. (b) In disk amplifiers, the beam propagates parallel to the gradient, and is not distorted.

indicatrix with respect to the beam polarization is different at each θ . This results in the familiar rings-and-cross pattern obtained with crossed polarizers, as shown in Fig. 5(a).

If the laser medium is configured as a plate cooled on its faces, however, a much more favorable condition exists. For a plate whose lateral extent is large compared with its thickness, a thermal

gradient in the $x_3(z)$ direction (across the thin dimension of the plate) will give rise to a plane stress only. (This condition, known as Saint-Venant's principle, states that the change of stress direction necessary to satisfy the boundary conditions on a free plate affects a region only one to two plate thicknesses in from the edge.) An isotropic plate becomes uniaxial under plane stress. The

Fig. 4. Effect of spatially nonuniform temperature distribution on laser output beam quality. (a) In rod amplifiers, a radial temperature gradient generates a radial gradient in the index of refraction, which causes focusing or defocusing of the output beam. (b) In disk amplifiers the beam propagates parallel to the temperature gradient, and no focusing occurs.

(a) Rod amplifier

(b) Disk amplifier

magnitude and sign of the plane stress vary with x_3 through the plate, but the planar nature of the stress is unchanged. Thus various plane layers of the plate can be viewed as positive or negative uniaxial, depending on the sign of the plane stress (usually compression in the interior and tension near the surface). The important point is that the principal axes of the indicatrix do not rotate with

position in the plate, so that a properly polarized wave can propagate without depolarization, as shown in Fig. 5(b).

Since only a few of the laser materials of interest will be isotropic, it is interesting to inquire as to the generality of our conclusion that propagation is stable in plates with plane stress. Figure 6 shows the 6×6 photo-elastic matrices for

(a) Rod amplifier

(b) Disk amplifier

Fig. 5. Effect of spatially nonuniform temperature distribution on laser beam polarization. (a) In rod amplifiers, thermally induced stress produces birefringence that depolarizes the beam. This depolarization can be observed, using a crossed polarizer, as the familiar rings-and-cross interference pattern. (b) In disk amplifiers, the stress birefringence associated with an axial temperature gradient does not depolarize the beam if the polarization vector lies along a principal direction of the index indicatrix.

all 32 crystal classes.³³ The optical indicatrix of a stressed medium is represented by the product of the photo elastic matrix and a 1×6 column matrix representing the stress.³³ By convention, rotation of the optical indicatrix is represented by non-zero values in element positions 4 through 6 of the product (column) matrix, and plane stress is represented as a column matrix in which zeros appear in element positions 4 through 6. Thus, from symmetry considerations alone, we can see that no rotation of the optical indicatrix will occur under plane stress for those crystal classes in which the lower left and upper right quadrants of the photo-elastic matrix contain only zero values. (This is true for all orientations of crystal axes relative to the coordinate axes defined by the orthogonal edges of a rectangular parallelepiped plate; only the magnitudes of the principal indices of refraction under plane stress will depend on the orientation of body-edge and crystal axes.)

Figure 6 shows that 16 of the 32 crystal classes meet this criterion: all cubic and orthorhombic crystals, hexagonal crystals of classes $\bar{6}m2$, $6mm$, 622 , and $6/mmm$, and tetragonal crystals of classes $4mm$, $\bar{4}2m$, 422 , and $4/mmm$. Crystals of an additional 12 classes can be utilized in plane-stress situations provided that their crystal axes are properly oriented with respect to the edges of the fabricated crystal plate. In these cases, the optical indicatrix will rotate under plane stress, but it can be made to rotate about that principal axis that leaves the other principal axes parallel to the electric field of the extraction beam. The crystal classes meeting this criterion are those with zero entries in two of the three rows of the lower left quadrant and two of the three columns of the upper right quadrant: that is, the hexagonal classes 6 , $\bar{6}$, and $6/m$, the trigonal classes $3m$, 32 , and $\bar{3}m$, the tetragonal classes 4 , $\bar{4}$, and $4/m$, and all of the monoclinic classes. Thus, apparently

Fig. 6. The photo-elastic matrices for the 32 crystal classes, from Ref. 33. No rotation of the optical indicatrix occurs under plane stress if the lower left and upper right quadrants of the photo-elastic matrix contain only zero values. The optical indicatrix will rotate, but can be made to rotate about that principal axis that leaves the other principal axes parallel to the electric field of the extraction beam, if there are zero entries in two of the three rows of the lower left quadrant and two of the three columns of the upper right quadrant.

(a) Zig-zag

(b) Flow-cooled disk

Fig. 7. Geometries suitable for high-average-power operation. (a) In the zig-zag geometry, the gain medium is pumped through the broad face of a slab, and the energy is extracted with a beam that enters through one end of the slab, makes multiple bounces by total internal reflection, and exits the other end. (b) In the disk geometry, the gain medium is pumped through the broad faces of the disk, and the extraction beam enters and exits through the same faces. The disk is normally oriented at Brewster's angle with respect to the extraction beam in order to minimize Fresnel loss.

only crystals of four classes (both of the triclinic classes, and the trigonal classes 3 and $\bar{3}$) are ruled out on symmetry considerations alone. Even in these latter cases, it may be possible to find particular orientational cuts for particular values of the photo-elastic coefficients that will allow stable propagation. Thus, it appears that almost all crystalline materials can be used in flat-plate configurations in which planar stress in the useful region can be maintained.

Two laser geometries readily adapt themselves to the use of laser media in the form of

plates. They are the zig-zag¹⁰ geometry shown in Fig. 7(a), and the flow-cooled-disk³⁴ geometry shown in Fig. 7(b). In both of these geometries, the plate is both pumped and cooled symmetrically through its large lateral faces, and the optical propagation directions are correct with regard to gain gradients, thermal gradients, and stable propagation of a polarized wave. Note, however, that in the zig-zag geometry, the extraction beam enters and exits through plate edges, where the plane-stress approximation is not valid. Thus the thermal gradients in this region must be tailored,

at considerable effort, to control depolarization.¹⁸ In the flow-cooled disk, it is easy to keep the extraction beam one or two plate thicknesses from the plate edges, so depolarization should be negligible in the disk geometry.

It is important to prevent faces of the plate from distorting out of plane while operating, because that will lead to focusing or higher-order beam aberrations. Figure 8 illustrates this point. If the plate surfaces are cooled to equal temperatures and the energy deposition is not symmetrical, then the plate will bend, producing focusing or higher-order aberrations. Partial compensation of asymmetrical energy deposition can be achieved by asymmetrical cooling, but such compensation is operating-point dependent and thus unsatisfactory by our initial criterion. Operating point independence can only be achieved by a combination of symmetrical cooling and symmetrical energy deposition, such that³⁵

$$\int_{-t/2}^{+t/2} z \Delta T(z) dz = 0, \quad (2)$$

and $T_1 = T_2$ [$\Delta T(z)$ is defined in Fig. 9].

As a practical matter, materials with coefficients of thermal expansion of $10^{-5}/^{\circ}\text{C}$ will require symmetrization to a few percent. It is this requirement of symmetrical thermal deposition

and symmetrical cooling that rules out the active mirror amplifier configuration³⁶ for use in high-average-power applications. However, the configuration is useful for very low repetition rate applications.³⁷

Since we have observed that flow-cooled plates offer an excellent geometry for a solid state laser medium operated at high average power, it is appropriate to determine the power-handling capability of such plates. If the two large faces of the plate are held at constant temperature by coolant flow (Fig. 9), and if the energy deposition is uniform throughout the volume of the plate, then the temperature profile is just³⁸

$$\Delta T(z) = \Delta T_0 \left(1 - \frac{4z^2}{t^2} \right), \quad (3)$$

where t is the plate thickness and z is the distance measured normal to the plate, with $z = 0$ at the midplane; the midplane temperature rise, ΔT_0 , is given by

$$\Delta T_0 = \frac{P_v t^2}{8\kappa}, \quad (4)$$

where P_v is the thermal power deposited per unit volume and κ is the thermal conductivity. This

Fig. 8. Uniform energy deposition and uniform cooling are the keys to minimizing optical distortions and to allowing operation over a wide range of output powers. (a) Asymmetrical energy deposition leads to lensing. (b) This lensing can be compensated for by adjusting the cooling rate, but this solution is sensitive to operating point.

Fig. 9. Geometry and temperature profiles for a disk amplifier with symmetrical energy deposition within the disk and identical cooling on each face.

temperature profile results in the center of the plate being in compression, while the surface is in tensile stress (this is so for materials with positive thermal expansion coefficients; some materials have negative coefficients, in which case the surface stresses in compression and the midplane stresses in tension). Since brittle materials fail first in tension, the tensile stress at the surface is what most concerns us. It is easy to show that the peak tensile stress occurs at the surface, and that it is given by³⁸

$$\sigma_T = \frac{2\alpha\Delta T_0 E}{3(1-\nu)} \quad (5)$$

where α is the coefficient of thermal expansion, E is Young's modulus, and ν is Poisson's ratio.

In most laser applications, long life is desirable; thus the thermal load operating point should be set so that σ_T is a small fraction of the material's tensile yield stress, S_T . Writing the ratio of the thermally induced stress, σ_T , to the tensile yield stress as

$$b = \frac{\sigma_T}{S_T}, \quad (6)$$

and combining Eqs. (4) and (5), we have

$$P_v = \frac{12K_T b}{t^2}, \quad (7)$$

where R_T is the thermal shock parameter, defined as

$$R_T = \frac{(1-\nu)KS_T}{\alpha E}. \quad (8)$$

Equation (7) expresses the thermal power that can be dissipated per unit volume in an arbitrary material with thermal shock parameter R_T . (The assumption of uniform thermal deposition is the worst case. If the energy deposition profile is like curve C of Fig. 2, then the average P_v will be somewhat higher than in the uniform-deposition case, since the effective thermal-transport distance is reduced. The actual value must be calculated from the actual shape of the thermal deposition profile. Model calculations³⁹ show that the average P_v is usually increased by at most 20% over the uniform-deposition case.) For long-life operation of a brittle material under stress, the value of b should be held below 0.2 or 0.3 (see Ref. 12). For the examples in this paper, we use the conservative value $b = 0.2$. As will be seen, very high average powers are achievable without even approaching material rupture.

There are three approaches to achieving high power-handling capability in solid plates. First, one can choose materials with low thermal expansion coefficients, such as low-expansion glasses, glass-ceramics, or crystals with low or negative coefficients. Second, one can choose ordered media, such as crystalline materials, that exhibit high thermal conductivities. While these two strategies are equivalent from the point of view of thermally induced stress, they are not equivalent from the viewpoint of the laser-ion physics. The approach to a high R_T value through low coefficients of

thermal expansion will yield a much higher ΔT_0 for a given average P_v than will the same R_T value achieved by high thermal conductivity. The higher midplane temperature may lead to thermal population of the terminal laser levels and to reduced gain (as for the Nd^{3+} ion) or it may lead to increased quenching of excited-state populations. Table I shows mechanical and thermal properties of a representative group of solids. R_T values run from 43 to 10^4 W/m at room temperature. A number of laser plate design examples, given later, indicate that R_T values in the range of 300 to

1500 W/m yield quite functional designs for high-average-power lasers.

From Eq. (7), we see that the third approach to high power per plate is to employ very low values of the plate thickness, t . (Since P_v scales as $1/t^2$, the total power per plate increases as $1/t$.) Although considerations of mechanical stability argue against the use of very thin plates, this limitation can be circumvented by the use of composite plates, as shown in Fig. 10. Composite plates are straightforward to produce in glass, for which it is easy to match thermal expansion coefficients

Fig. 10. The poor structural rigidity of thin, highly doped disks can be improved by using composite disks in which only the surface layers are gain media, and the core provides mechanical rigidity. The thermal characteristics of the two materials must be matched to minimize stresses at the boundaries.

Table I. Properties of optical materials. The thermal-shock parameter $R_T = S_T(1 - \nu)/\alpha E$ is a figure of merit for the selection of materials suitable for operation at high average power.

Material	n	Poisson's ratio ν	κ (W/m°C)	α ($10^{-6}/^\circ\text{C}$)	E (kg/mm ²)	S_T (kg/mm ²)	R_T (W/m)
Glasses							
ED-2	1.56	0.24	1.35	8.0	190	~10	140
LG-750	1.53	0.26	0.62	11.4	5 150	5.5	43
Q-100	1.56	0.24	0.82	9.6	7 150	6.5	59
Fused SiO_2	1.45	0.17	1.38	0.55	7 190	5.0	1 450
Zerodur	1.54	0.24	1.64	0.12	9 060	9.3	10 600
Crystals							
Al_2O_3	1.76	0.27	42	~5.0	35 230	~55	10 000
MgO	1.67	0.18	59	11.0	25 450	37	5 000
YAG	1.81	—	13	7.8	31 725	~20	~790
GSGG	1.92	~0.15	~8	7.8	21 000	~17	~700
BeAl_2O_4	1.73	—	23	~6.5	44 550	~60	~3 570
MgF_2	1.38	0.27	21	~10.0	17 625	~5.4	~470
LiYF_4	1.45	0.33	6	~10.0	7 650	~3.4	~180

between the active and non-active media. In crystalline media, such composites might be bonded by epitaxial growth or by solid state diffusion. The use of composite plates, either singly, or multiply in a single disk position (Fig. 11), effectively re-

moves the thermal design constraints with low- R_T materials. Note, however, that if multiple plates are used in a single disk position, it will be necessary to choose the doping-thickness product of each layer properly to assure the symmetrical

(a) Single disk

(b) Multiple disks

Fig. 11. Flow-cooled disk lasers can be constructed with single or multiple composite disks.

thermal deposition necessary to prevent warping of the plate. The effective use of thin layers of active media in single composite plates requires high active-ion doping density if efficient absorption of a spectrally broad pump source is to be achieved. In this connection, laser materials that exhibit low concentration quenching of the active ion are desirable. Figure 12 shows the concentration-quenching behavior of a variety of neodymium-containing materials. Clearly, it is possible to develop materials with very low concentration quenching, at least when Nd^{3+} is the active ion.

Since flow-cooled plates can handle high average thermal power deposition if properly cooled, we next examine flow-cooling and its impact on overall laser efficiency. The analyses^{34,40} of flow cooling plates of a laser medium have been recently recast⁴¹ to more clearly exhibit the salient characteristics of the design problem. Figure 13 shows R_p , defined as

$$R_p \equiv \frac{\text{pumping power}}{\text{thermal power removed}}, \quad (9)$$

as a function of ΔT_{bf} the boundary layer temperature rise. (It is assumed that the pressure drop across the heat exchanger and piping is equal to the pressure drop across the plates.) In the figure, R_p is given for a variety of flow-channel thicknesses and for a range of values of $P_e t$ of a single plate. It should be noted that R_p scales as $1/p^2$, where p is the pressure of the helium coolant used for this example. This strong pressure dependence

provides a very useful design variable. Figure 14 relates ΔT_{bf} to the rate of increase of gas-flow temperature with distance x across the plates, dT_g/dx . With these two graphs, the designs are easily evaluated.

A study of Figs. 13 and 14 shows that (in general) $\Delta T_{bf} > \Delta T_p$; further, we note that dT_g/dx usually falls in the range 0.1 to 1°C/cm. Thus the thermal conductivity of the solid is not the limiting feature of the heat transport. The boundary layer dominates the problem, as is usual with convective heat transport problems. The figures also show that heat can be removed at the rate of 40 kW/m² by helium at 1 atm with approximately 4 kW of pumping power, or that 100 kW/m² can be removed with helium at 3 atm with 10 kW of pumping power. Thus it appears that solid state laser media are no more limited for average power capability than are gaseous media!

In designing a high-average-power solid state laser there are, of course, design constraints other than thermal constraints. For example, if the medium is to be used in an energy-storage mode, the well-known parasitic-loss constraints⁴² developed for large solid state fusion lasers must be applied. Thus the product of the plate-averaged gain coefficient $\bar{\alpha}$, the index of refraction n , and the length L^* of a plate determines the inversion loss rate enhanced by amplified spontaneous emission (ASE). An $\bar{\alpha} n L^*$ product of 3 will reduce the peak storage efficiency of an amplifier by 10%. Thus a relation exists between the energy storage density, the stimulated-emission cross section, and the dimensions of a plate. In developing plate design

Fig. 12. Fluorescence lifetime vs Nd^{3+} ion concentration for several laser glasses and crystals. Laser hosts that will accept a large neodymium doping while maintaining fluorescence lifetime have an advantage for high-average-power operation.

Fig. 13. Design curves for disk amplifiers, showing the ratio of cooling system pumping power and the thermal power removed, R_p , vs the temperature drop ΔT_{bl} across the boundary layer.

Fig. 14. Design curves for disk amplifiers, showing the relationship between the temperature rise across the boundary layer and the temperature rise along the direction of the gas flow.

examples for solid state lasers, we have chosen to address operation in the energy-storage mode (for example, Q-switched operation) with simultaneous application of the thermal constraint with $b = 0.2$ and the ASE constraint at $\bar{\alpha} n l^* = 3$. In addition, we have chosen the plate length

$$l^* = w(n^2 + 1)^{1/2}, \quad (10)$$

which is consistent with the active region of a Brewster's-angle flow-cooled disk and yet is not an unrealistic choice for the active region of a zig-zag laser. In this design chart, we have made use of the fact that for known optically pumped lasers, the ratio, χ , of the deposited thermal energy to the available optical energy (both per unit volume) is 0.5 to 2.0. For simplicity we have chosen $\chi = 1$ for numerical examples; this value is typical of well-designed flashlamp-pumped systems. In addition, we have set the ratio of plate thickness to plate width equal to 0.1. With these assumptions, we can represent the design options by the graph shown in Fig. 15. On the ordinate, the relevant host parameters (index of refraction n

and thermal shock parameter, R_T) are collected. The saturation parameter of the laser transition, $S = h\nu/\sigma_{12}$, is plotted along the abscissa.

Tables 2, 3, and 4 show a series of plate design examples that follow from Fig. 15. Table 2 shows how high-average-power single or multiple composite plates can be designed using a material (such as Nd:glass) with a low thermal-shock parameter. In these examples an amplifier is composed of 12 disks or 12 disk positions, which results in a small-signal gain of ~ 10 . By using composite plates, it is straightforward to obtain ≥ 650 kW from a 40×72 cm aperture. Note that with a material with this low cross section, repetition rates are not high.

Table 3 shows what might be done with a low-cross-section, high-thermal-shock-parameter material such as alexandrite.⁴³ In this case, low-repetition rate, high-power performance is obtained without resort to composite plates.

As a final example, Table 4 shows what might be done with a material of high stimulated-emission cross section and a moderate thermal-shock parameter, such as gadolinium scandium

Fig. 15. Design curves showing the relationship between the thermal shock parameter, R_T (weighted by the index of refraction), and the saturation parameter for the laser medium, for various values of fw , the product of repetition rate and plate width, and nEf^2 , the product of the refractive index, the energy per plate, and the square of the repetition rate. The loci for several laser media are indicated.

Table 2. Representative design parameters and power outputs for Nd:glass using monolithic and composite plates. A thermal-shock parameter of 100 W/m and a saturation parameter of 6 J/cm² (typical of laser glasses) has been used; the stress has been limited to 20% of the yield stress ($b = 0.2$).

Plate dimensions (active area) (cm)	Active region	Amplifier type	Coolant	Heat removal (W/cm ²)	Rep rate (Hz)	Power per plate position (kW)	No. of positions	Total power (kW)
40 × 72 × 4	Monolithic 10 ²¹ ions/cm ²	Flow- cooled disk	He	0.3	0.8	1.6	12	19
40 × 72 × 4	1 composite plate (2 0.5-cm layers) 10 ²¹ ions/cm ²	Flow- cooled disk	He	1.2	3.2	6.4	12	77
40 × 72	3 composite plates (6 1.67-mm layers) 10 ²¹ ions/cm ²	Flow- cooled disk	He	3.6	30	56	12	677

Table 3. Representative design parameters and power outputs for a low-cross-section laser medium with high thermal-shock parameters, such as alexandrite (BeAl₂O₄:Cr). In this case, high-power performance is obtained at low repetition rates without the use of composite plates.

Plate dimensions (active area) (cm)	Amplifier type	Coolant	Heat removal (W/cm ²)	Rep rate (Hz)	Power per plate (kW)	No. of plates	Total power (kW)
10 × 20 × 2	Zig-zag	H ₂ O	10	11	5.0	1	5.0
40 × 80 × 4	Flow- cooled disk	He	5.2	11	40	12	480

Table 4. Representative design parameters and power outputs for a high-cross-section laser medium with moderate thermal-shock parameters, such as GSGG:Cr:Nd. In this case, high average power is obtained at moderately high repetition rates.

Plate dimensions (active area) (cm)	Amplifier type	Coolant	Heat removal (W/cm ²)	Rep rate (Hz)	Power per plate (kW)	No. of plates	Total power (kW)
5 × 10.9 × 1	Zig-zag	H ₂ O	8.2	90	0.9	1	0.9
10 × 21.8 × 2	Flow- cooled disk	He	4.1	45	1.8	12	21

gallium garnet (GSGG), co-doped with trivalent chromium and neodymium.⁴⁴ In this case, operation at both high repetition rates and high average power is achieved. The examples of Tables 2 through 4 serve only to indicate the range of possibilities.

Having demonstrated that properly configured solids can handle high average power gracefully, we now address the problems of pump sources and the design of *efficient* high-average-power lasers.

Pump Sources

Selecting the optical pump source is a critical step in the development of a high-efficiency, high-power solid state laser operating in the visible or near-infrared. A review of the radiative properties of potentially useful optical sources leads us to conclude that at least three types of

pump sources should be developed for use in the near future:

1. Broadband rare-gas-filled flashlamps.
2. High-density arrays of semiconductor laser diodes.
3. Electron-beam-pumped epitaxial phosphors.

The relevant parameters of these three types of pump sources are summarized in Fig. 16, and are described in more detail below.

Rare-Gas-Filled Flashlamps

Rare-gas-filled flashlamps are probably the most efficient electrically driven light source known: for example, xenon flashlamps show efficiencies of $75 \pm 5\%$ under a variety of operating conditions.⁴⁵ The major disadvantages of flashlamps are that the output radiation is emitted into about 10 steradians, and that the emission takes place over a wavelength band of 0.2 to $2\ \mu\text{m}$ (see Fig. 16). The wide angular spread of the emission makes the optical design of the pump cavity subtle and difficult, while the broad wavelength spread is rarely matched by the absorption bands of the active laser ion, so that the overall transfer efficiency is low.

The performance limits of xenon flashlamps are usually specified by their single-shot explosion energy E_x , defined as

$$E_x = 2 \times 10^4 L_d D \tau^{1/2} \quad \text{joule}, \quad (11)$$

where L_d and D are, respectively, the discharge length and bore diameter, in centimeters, and τ is $(LC)^{1/2}$ for the critically damped single-mesh discharge circuit⁴⁶ (approximately 1/3 of the full pulse duration), in seconds. The lifetime (expressed as a number of shots, N) of a flashlamp with a fused-quartz envelope and with energy input E can usually be represented as

$$N = \left(\frac{E_x}{E} \right)^\beta, \quad (12)$$

where β usually ranges from 8 to 10. For $E \geq 0.25E_x$, the lifetime is determined by envelope failure. For

Fig. 16. Spectral output and electrical and optical characteristics of three possible laser pumping sources: xenon flashlamps, electron-beam epitaxial phosphors, and GaAs semiconductor diode arrays. (A high-intensity ZnS:Ag phosphor has not yet been demonstrated.)

$E < 0.25E_v$, the lifetime is more often limited by electrode degradation. For $E < 0.1E_v$, lifetimes of $>10^8$ shots have been observed at high repetition rates, and achieving 10^9 -shot lifetimes appears to be technologically straightforward.

The average-power capability of flashlamps is limited by heat transport through the envelope. Almost all of the heat input to the wall ($25 \pm 5\%$ of the input) is deposited on the inner surface, while cooling is from the outer surface. Neglecting envelope curvature, the ratio of the thermally induced stress to the tensile yield stress is

$$\frac{\sigma_T}{S_T} = \frac{\alpha E I P_A}{(1 - \nu) \kappa S_T} \quad (13)$$

where P_A is the thermal power deposited per unit area of inside surface. The power that can be dissipated is just

$$P_A = \frac{2(1 - \nu) \kappa S_T b}{\alpha E t} = \frac{2R_T b}{t} \quad (14)$$

Figure 17 shows $P_A(t)$ as given by Eq. (14) for fused-silica and crystalline sapphire envelopes. Comparison of these power loadings with the examples of Tables 2 to 4 indicates that flashlamps can easily pump neodymium in glassy or crystalline hosts to the average power levels required for most applications presently envisioned. However, the pump conditions required for the alexandrite material may not be achievable.

Fig. 17. Maximum thermal power deposited per unit area at the inside surface of a flashlamp for fused silica and sapphire at two wall temperatures.

Semiconductor Arrays

The efficiency and output power of GaAs injection-laser diodes have increased greatly in recent years, particularly through use of the "large optical cavity" (LOC) heterojunction laser diode structure described by Kressel et al.⁴⁷: room-temperature power conversion efficiency of 25% with a single-facet output power of >1 W at 913 nm has been achieved. More recently, RCA has announced⁴⁸ a GaAs LOC diode with a room-temperature efficiency of 35%. Taken alone, these developments have implications for a wide variety of low-power applications. However, when coupled with the recent development of diode arrays with high packing densities, important implications also arise for medium- and high-power applications. Using improved diode-wafer growth techniques (liquid-phase epitaxy, or LPE; metal-oxide chemical vapor deposition, or MOCVD; and molecular-beam epitaxy, or MBE), it is now possible to fabricate linear (bar) arrays of high-performance GaAs diodes capable of being operated in parallel electrically and of delivering high instantaneous output powers.⁴⁹ Figure 18 shows a multi-stripe diode bar array produced by Scifres et al. at Xerox.^{50a} It is anticipated^{50b} that bar arrays can be stacked mechanically to form a two-dimensional array allowing for the generation of instantaneous output power densities of ~ 1 kW/cm² [see Fig. 16(c)]. Figure 19 shows a schematic of such a two-dimensional array and the associated electrical and optical parameters

Fig. 18. Construction details of a GaAs multi-stripe diode array (after Scifres et al., Ref. 50a).

Drive parameters (1-cm² array)

Array voltage, V_A	132 V
Bar/array current, I	30 A (300 K)
	15 A (250 K)
Bar voltage, V_B	2 V
Peak power, P_{in}^p	4000 W (300 K)
	2000 W (250 K)

Array output parameters

Wavelength, λ	800–860 nm
Width, $\Delta\lambda$	≤ 10 nm
τ_{pump}	≤ 10 ms
Duty factor	< 0.1
Fluence	1–10 J/cm ²

Fig. 19. Electrical and geometrical parameters of an array of GaAs lasers (projected, based on Ref. 50b).

that can be anticipated with further development. Current array-cooling technology allows the removal of ~ 50 W/cm² of average thermal power at room temperature. Thus the operating duty factor of the present array must be < 0.05 . It is anticipated that this thermal dissipation limit will be raised significantly with advanced micro-cooling techniques, perhaps to a few hundred watts per square centimeter. Even more recently, researchers at Lincoln Laboratory⁵¹ have directly produced a two-dimensional array of diodes using litho-

graphic and regrowth techniques, without resort to mechanical stacking. When this technique is fully developed, diode packing densities of 10^4 /cm² are anticipated, corresponding to instantaneous output power densities of 2 kW/cm². Efficiencies of $\sim 30\%$ have been observed at room temperature, and $\sim 50\%$ efficiency can be anticipated at low operating temperatures ($\sim 100^\circ\text{C}$ or so). Since the radiation emitted by these diode arrays typically lies in a spectral bandwidth of a few nanometers, their spectral intensity is very high

[Fig. 16(c)]. Accordingly, they may be used to pump spectrally narrow features of impurity ions in solids and yet maintain high coupling and high overall efficiency.

E-Beam-Pumped Epitaxial Phosphors

Phosphors excited by electron beams ("e-beams") are well known from their use in conventional cathode ray tubes (CRTs). These phosphors are made from inorganic crystalline powders attached to glass substrates with organic binders. The crystallites are doped with impurity ions that give rise to the colors with which they phosphoresce. For example, Fig. 16(b) shows the distribution of light emitted from a zinc sulfide:silver phosphor (type 1310, P-222). This phosphor emits a more compact band of light than a xenon flashlamp, with a spectral half-width of 1000 cm^{-1} . When excited by an e-beam at a current density characteristic of CRT use ($\sim 10\text{ }\mu\text{A/cm}^2$), this

phosphor can convert over 20% of the incident e-beam energy into light.⁵² However, as the excitation current density exceeds 20 mA/cm^2 , the output light intensity begins to roll off,⁵³ as shown in Fig. 20. This behavior is thought to be due mostly to thermal quenching of the luminescent center as the local temperature in the phosphor particles rises at high excitation density. Researchers at Philips reasoned that phosphors made in the form of epitaxial films on transparent substrates with high thermal conductivity would overcome this heating phenomenon, and would thus be free of thermal quenching. Indeed, these researchers have recently reported⁵⁴ that a cerium-doped YAG epitaxial phosphor layer, deposited on an undoped YAG substrate, exhibits light output proportional to excitation current density up to at least 1 A/cm^2 , with an efficiency of 7%. Research and development of high-efficiency ultraviolet and blue phosphors in epitaxial form are warranted as pump sources for energy storage lasers radiating directly in the visible.

Materials

We have seen that the potential applications for high-average-power solid state lasers call for a wide range of operating characteristics (pulse energy, pulse duration, prf, minimum efficiency, wavelength, radiance, etc.). As we broadly consider how to render solid state lasers relevant to

these applications, we need to ask, "What are the laser material characteristics (laser and bulk material parameters) that will allow an optimum laser system to be constructed for any given application?" While a complex laser-system model is needed for each application in order to determine

Fig. 20. Output power (and corresponding photomultiplier response) vs current density for a ZnS:Ag phosphor pumped by an electron beam (after Einstein, Ref. 53).

a complete quantitative answer to this question, our laser system experience indicates that the effective stimulated-emission cross section of the laser transition, σ_L , tends to drive the optimum design solution strongly.

The stimulated-emission cross section of the laser transition determines the maximum stored energy density E_d achievable in a laser plate, consistent with the constraint imposed by amplified spontaneous emission. Calculations⁵⁵ and design experience³² both show that the product of the plate-averaged small-signal gain coefficient, $\bar{\alpha} = \sigma_L \Delta N$, and the effective dimension of the plate, $n\ell^*$, should be constrained to a value less than 3 (that is, $\bar{\alpha}n\ell^* = \sigma_L \Delta N n\ell^* \leq 3$) in an energy-storage laser. Here ΔN is the plate-averaged population inversion density, and $E_d = h\nu \Delta N$.

In addition to determining the energy stored in a plate, σ_L also determines how much fluence, Γ_{out} , must be passed through an amplifier in order to extract the stored energy efficiently. By way of example, Fig. 21 shows plots of the single-, double-, and six-pass extraction efficiencies of an amplifier (with a small-signal gain of 3 and a passive transmission coefficient of 0.9) as a function

of Γ_{out}/S . Here S is the effective saturation parameter for a homogeneously saturating four-level laser scheme, $S = h\nu/\sigma_L$. The figure shows that the maximum extraction efficiency is independent of the number of passes and that the output fluence required for maximum extraction efficiency decreases with the number of passes.⁵⁶ Thus, for maximum extraction efficiency, the output fluence of a single-pass amplifier should be about twice the saturation fluence, and the output fluence of a double-pass amplifier should be about equal to the saturation fluence. Increasing the number of passes beyond two only slowly reduces the optimum output fluence (0.7 times the saturation fluence for six passes), but it introduces considerable optical complexity. Thus for practical few-pass extraction configurations, we can write

$$\Gamma_{out} = (1 \text{ to } 2)S. \quad (15)$$

If a repetitively pulsed laser is to operate damage-free for a large number of shots, limited experience^{57,58} indicates that its output fluence should be less than 40% of the single-shot damage fluence, Γ_{damage} , of the gain medium for the

Fig. 21. Single-, double-, and six-pass extraction efficiencies of an amplifier vs Γ_{out}/S . Maximum extraction efficiency is independent of the number of passes; output fluence required for maximum extraction efficiency decreases with the number of passes.

pulse duration involved. Using this criterion, Eq. (15), and the relationship $S = hc/\lambda\sigma_L$, we can write the following constraint, which determines the minimum allowable stimulated-emission cross section:

$$\sigma_L \text{ (in } 10^{-19} \text{ cm}^2) \geq \frac{(5 \text{ to } 10)}{\Gamma_{\text{damage}} \text{ (J/cm}^2\text{)}}. \quad (16)$$

If a laser is required to deliver high-peak-power pulses as well as high average power, it is also necessary to consider carefully the nonlinear optical properties of the gain material. The degree to which a laser beam self-focuses as it passes through a solid state amplifier is quantified by the so-called B -integral,³⁰ which specifies the phase delay between the center and the edge of the beam. Using computations reported earlier,³⁰ we can relate the B -integral for a single-pass saturating amplifier to the saturation fluence (or, equivalently, to the stimulated-emission cross section, since $S = h\nu/\sigma_L$), the stored energy density E_d , the pulse duration τ_L , and the linear and nonlinear indices of refraction, n and n_2 . Figure 22 shows the maximum allowed values of the quantities $n_2(n^2 + 1)^{1/2}$ and $E_d n(n^2 + 1)^{1/2}$ as functions of σ_L (or of S), for various plate widths. Table 5 gives linear and nonlinear index data for a number of glasses and crystals. In general, materials contain-

ing fluorine anions have lower nonlinear refractive indices than those containing oxygen anions. For this reason, fluoride-based materials are candidates for use in lasers requiring high-peak-power output pulses (e.g., inertial fusion). However, the data in Table 1 indicate that, in general, fluoride-based crystals have lower thermal-shock parameter values than oxide-based crystals, potentially compromising their use in lasers that must deliver high average power as well as high peak power.

In general, laser systems intended for use in applications requiring high energy per pulse and low pulse repetition rates must utilize gain materials with relatively low stimulated-emission cross sections (e.g., a few $\times 10^{-20}$ cm²). Alternatively, high-cross-section materials (e.g., $> 3 \times 10^{-19}$ cm²) are appropriate for use in laser systems addressing applications requiring low-energy pulses at high pulse repetition rates. Some representative designs of laser plates relevant to distinctly different applications are illustrated in Fig. 23. Each of the three larger points shown specifies a saturation fluence (or, equivalently, a stimulated-emission cross section) and a minimum value of the thermal shock parameter required to carry the average power dissipated in the plate. Of course, materials with thermal shock parameters higher than the minimum indicated may also be used

Fig. 22. Maximum allowed values of $n_2(n^2 + 1)^{1/2}$ and $E_d n(n^2 + 1)^{1/2}$, as functions of σ_L (or S), for various plate widths.

Table 5. Refractive indices and dispersion of crystals and glasses.

Material	n_D (588 nm)	Dispersion, ν	n_2 (1060 nm) (10^{13} esu)	n_2/n (10^{13} esu)
Crystals				
GGG ($Gd_2Ga_2O_7$)	1.934	—	(8.0)*	(4.0)
YAG ($Y_3Al_5O_{12}$)	1.835	51	3.20	1.73
Al_2O_3	1.768	72	1.10	0.60
$BeAl_2O_4$	1.740	73	0.80	0.48
MgO	1.74	55	2.80	1.60
$MgAl_2O_4$	1.68	61	2.10	1.20
$LaMgAl_{11}O_{19}$	1.792(e)	58	(2.8)	(1.6)
	1.784(o)	60	(2.6)	(1.5)
MgF_2	1.378	104	0.30	0.22
$LiYF_4$	1.457	90	0.60	0.41
LiF	1.392	99	0.35	0.25
NaF	1.326	85	0.43	0.32
CaF_2	1.434	95	0.65	0.45
SrF_2	1.438	92	0.60	0.42
BaF_2	1.475	82	1.0	0.68
CdF_2	1.576	61	1.44	0.91
LaF_3	1.602	83	1.49	0.93
Glasses^b				
ED-2 (S)	1.561	56	1.41	0.90
LG-750 (P)	1.516	68	1.08	0.71
LHG-10 (FP)	1.454	90	0.58	0.40
BT28 (FB)	1.335	100	0.31	0.23

* ( ) = estimated value.

^b S = silicate, P = phosphate, FP = fluorophosphate, FB = fluoroberyllate.

Fig. 23. Design curves for high-average-power lasers, showing the parameter regimes for various applications. Vertical bars show that materials with thermal shock parameters higher than the minimum indicated may also be used. Width of bars indicates range within which assumed saturation fluence could be varied without great reduction in plate performance.

(this is shown by the vertical bar extending above the design point). Additionally, the saturation fluence assumed for each of these examples could be varied several-fold without precipitous reduction in plate performance (this is indicated by the lateral breadth of the bar centered on the design point).

The first design relates to a MW-class inertial fusion reactor driver operating at 2 Hz and using a gain material with a saturation parameter of 10^5 J/m² (10 J/cm²), which corresponds to a stimulated-emission cross section of 2×10^{-20} cm² at a wavelength of 1000 nm. The laser is constrained to operate at a prf-width product of 0.6 Hz·m, implying a plate width of 0.3 m. For a material with $n = 1.5$, the thermal shock parameter must exceed 260 W/m. The plate is capable of delivering about 3.3 kW, and lies on the 10^4 W·Hz operating line of Fig. 23. From Fig. 22 and the data just given, we note that the maximum allowed value for n_2 is 1.7×10^{-13} esu, and that the maximum stored energy density is 0.37 J/cm³.

The second reference design relates to laser systems that might be used in materials processing applications being addressed by presently available solid state lasers. The design point represents a 1060-nm pump laser delivering 250 W in a single plate (2.5 J/pulse at 100 Hz) operating on the line $nPf = 4 \times 10^4$ W·Hz. For a laser gain material with an effective saturation parameter of about 4 kJ/m² (0.4 J/cm²), which corresponds to an effective stimulated-emission cross section of 5×10^{-19} cm², the plate operates at $fw = 6$ Hz·m, implying a plate width of 0.06 m. The gain material can have a relatively low thermal shock parameter of >100 W/m, for a material with $n = 1.6$.

The third design is that of a 3-kW (30 J/pulse, 100 Hz), 1060-nm pump laser that might be used to drive an x-ray source for submicron lithographic applications requiring high throughput. This laser operates on the line $nPf = 5 \times 10^5$ W·Hz, using a gain material with a saturation parameter of 10 kJ/m² (1 J/cm²) and an index of refraction of $n = 1.6$. It therefore operates on the $fw = 13$ Hz·m line, implying a plate width of 0.13 m. The gain material must have a thermal shock parameter >550 W/m for plate design and $n_2 \leq 3 \times 10^{-12}$ esu for a 10-ns pulse.

From these examples, we see that the stimulated-emission cross section of a gain material strongly influences the design and performance of a laser. From the literature, it is known that impurity-doped solid state materials offer a very wide range of stimulated-emission cross sec-

tions (from 10^{-21} to 10^{-18} cm²). We have also seen from Table 1 that solid state host materials exhibit an extremely wide range of thermal shock parameters (from tens to thousands of watts/meter). Thus, the opportunity exists to tailor solid state gain media to the application, and to realize considerably higher performance levels than previously envisioned.

To identify and develop solid state lasers optimized for specific applications, we must treat the laser as a system comprising three subsystems: the pump source, the laser impurity ion, and the solid host material. We have already seen that three types of pump sources appear to be relevant to efficient energy-storage lasers operating in the near-UV to near-IR spectral region: flashlamps, e-beam-excited epitaxial phosphors, and semiconductor diode arrays. Because of their diverse spectral radiance properties (shown in Fig. 16), one must select laser impurity ions that exhibit energy-level structures capable of tight spectral coupling to these sources. Figure 24(a) shows a classical four-level laser scheme in which a single activator (laser) ion provides both broad absorption pump bands and a narrow-band laser transition terminating on a thermally empty level. This scheme is suitable for use with either flashlamp or phosphor pump sources. The major limitation of such a scheme is the possibility of excited-state absorption at the pump and laser wavelengths [dashed transitions in Fig. 24(j)].

Excited-state absorption is avoided in the scheme shown in Fig. 24(b). Here a sensitizer ion provides efficient broad-band pump absorption and transfer of excitation energy to the activator ion, which is free of energy levels that could lead to excited state absorption at either the pump or laser wavelengths. An example of this scheme is the material discussed earlier, GSGG doped with chromium (Cr³⁺) as the sensitizer ion and neodymium (Nd³⁺) as the activator ion (see Table 4). Figure 25 shows the cross section of the broad absorption bands of Cr³⁺ in GSGG, and Fig. 26 shows the cross sections of the fine-featured absorption bands of Nd³⁺ in GSGG; Fig. 27 shows the spectral absorbance of co-doped Cr:Nd:GSGG. Spectroscopic measurements⁴⁴ indicate that energy absorbed by the chromium ions is efficiently transferred to the neodymium ions when the concentration of neodymium ions is $\leq 2 \times 10^{20}$ ions/cm³. A visual impression of the degree to which a broadband (flashlamp) source can pump singly doped (Nd) and co-doped (Cr:Nd) materials is given by Figs. 28 and 29. Figure 28 shows the spectral transmission of Nd:GSGG for

Fig. 24. Four-level laser schemes with varying spectral bandwidths for pumping. In (a) the laser ion itself provides a broadband absorption. In (b), a sensitizer ion provides a broadband absorption followed by transfer to the laser ion. Schemes (a) and (b) are suitable for use with broadband pumping sources. In (c) and (d) the absorption bands are narrow, and narrowband pumps are required.

areal densities of 2, 10, and 30×10^{20} ions/cm². Figure 29 shows the spectral transmission of Cr:Nd:GSGG for the same three areal densities (with respect to Nd ions) and with a fixed chromium areal density of 4×10^{20} ions/cm². These data are used below to calculate the excitation efficiency of these materials pumped with xenon flashlamps.

The energy-level schemes of Figs. 24(c) and 24(d) are appropriate for use with narrow-band semiconductor diode array pump sources. Figure 24(c) shows a classical four-level laser scheme in which the pump excites a level lying just above the upper laser level. The narrow-band laser transition terminates on a level thermally unoccupied at ambient temperature. (An example of this scheme is a Nd³⁺ activator ion pumped with GaAs semiconductor diode arrays; see Fig. 26.) The scheme shown in Fig. 24(d) involves

pumping between the ground crystal-field-split (Stark) level and an excited Stark level of a higher-lying electronic state. Stimulated emission takes place between the lowest metastable Stark level and an excited Stark level of the ground state. The amount of pump energy transformed into lattice heat is an absolute minimum in this scheme, so it provides an exceptionally high utilization of pump energy and permits relatively high pulse-repetition rates. (An example of this scheme is an Yb³⁺ activator pumped with a GaAs semiconductor diode array.)

Once the activator ion and the character of its "free-ion" electronic states are selected, the static and dynamic influences of a host medium on these states can be estimated using phenomenological models. Generally speaking, substitution of impurity ions in highly symmetric lattice sites will preserve selection rules that forbid certain

Fig. 25. Absorption cross section of Cr³⁺ in GSGG.

Fig. 26. Absorption cross section of neodymium in GSGG.

Fig. 27. Spectral absorbance of GSGG co-doped with chromium and neodymium. The broad absorption bands at 0.48 and 0.64 μm are due to Cr^{3+} .

Fig. 28. Absorption of a slab of neodymium-doped GSGG, for neodymium optical depths of (a) $2 \times 10^{20}/\text{cm}^2$, (b) $10 \times 10^{20}/\text{cm}^2$, and (c) $30 \times 10^{20}/\text{cm}^2$.

Fig. 29. Absorption through a slab of GSGG co-doped with neodymium and chromium, for neodymium areal densities of (a) $2 \times 10^{20}/\text{cm}^2$, (b) $10 \times 10^{20}/\text{cm}^2$, and (c) $30 \times 10^{20}/\text{cm}^2$, and a fixed chromium areal density of 4×10^{20} ions/ cm^2 . Note the increased absorption compared to Fig. 28 arising from the addition of the chromium.

transitions among levels of the free ion, thus providing for metastable upper laser energy levels in the solid state. By selecting crystal forms with lower site symmetries (particularly forms lacking inversion symmetry), one can substantially increase radiative transition probabilities to provide higher stimulated-emission cross sections. At the same time, crystals formed with various anions (oxygen, fluorine, etc.) surrounding the activator

ion generally exhibit a wide range of multiphonon nonradiative relaxation rates. Although only a finite number of crystals are formally possible (compared to an infinite number of possible glass compositions), the actual number of crystals of potential interest is extremely large. This is illustrated in Tables 6 and 7, which list some interesting simple cubic and uniaxial crystals based on fluorine and oxygen anions. Note that, for each

Table 6. Some types of fluorine-based crystals potentially useful as laser hosts.

Type ^a	Symmetry	Example
M ^I F ₂	cubic	CaF ₂
	tetragonal	MgF ₂
M ^{III} F ₃	hexagonal	LaF ₃
M ^I M ^{II} F ₃	cubic	KMgF ₃
	tetragonal	NaZnF ₃
M ^I M ^{III} F ₄	cubic	NaYF ₄
	tetragonal	LiYF ₄
	hexagonal	β-KLaF ₄
M ₂ M ^{II} F ₄	cubic	K ₂ CaF ₄
	tetragonal	K ₂ MgF ₄
M ^{II} M ^{III} M ^{III} F ₁₀	cubic	BaCaY ₂ F ₁₀
M ₃ M ^I M ₂ M ^{III} F ₁₂	cubic	Na ₃ Li ₃ Al ₂ F ₁₂
M ^{II} M ₂ M ^{III} F ₁₂	cubic	CaMg ₂ Al ₂ F ₁₂
M ₃ M ₂ M ^{III} F ₁₂	cubic	Mg ₃ Al ₂ F ₁₂
M ^I M ^{II} M ^{III} F ₆	cubic	NaCaYF ₆
M ^I M ₂ M ^{III} F ₆	cubic	K ₂ NaAlF ₆

^a M^I = Li, Na, K, Rb, Cs, Tl, Ag.

M^{II} = Be, Mg, Ca, Sr, Ba, Mn, Zn, Cd.

M^{III} = Al, Ga, Sc, Y, La.

type of crystal listed, the cation metals M^I, M^{II}, and M^{III} may be any of the several alkali, alkaline-earth, and transition-metal ions shown at the bottom of each table. Each metal ion will have different effects on the radiative and nonradiative transition rates among energy levels of the activator ion. If we include biaxial crystals as well as cubic and uniaxial crystals, there is a large number of potentially usable crystals. To identify laser-ion/host-material combinations optimized for specific applications, we have recently begun an effort in which doped crystals are rapidly and inexpensively synthesized and screened (spectroscopically and physically). By roughly ranking their utility, we can select crystals for more complete characterization and assessment. From this reduced set, we will select materials to be grown in useful size and quality for the intended applications.

For applications calling for average power output significantly in excess of ~100 W and/or pulse energies significantly in excess of ~10 J from a single crystal aperture, it will be necessary to grow properly doped crystals considerably larger than those associated with solid state lasers

Table 7. Some types of oxygen-based crystals potentially useful as laser hosts.

Type ^a	Symmetry	Example
M ^{II} O	cubic	MgO
M ^I M ^{III} O ₂	tetragonal	NaGdO ₂
M ₂ ^{II} O ₃	hexagonal	Al ₂ O ₃
M ^{II} M ^{IV} O ₃	cubic	SrTiO ₃
	tetragonal	BaTiO ₃
M ^I M ^V O ₃	hexagonal	LiTaO ₃
M ^I M ^{III} O ₄	tetragonal	NaGdO ₄
M ^{II} M ₂ ^{III} O ₄	cubic	MgAl ₂ O ₄
M ₂ ^{III} M ^{III} M ^V O ₆	cubic	Ba ₂ GdTaO ₆
M ₃ ^{III} M ₂ ^{III} M ₃ ^{III} O ₁₂	cubic	Gd ₃ Ga ₂ Sc ₃ O ₁₂

^a M^I = Li, Na, K, Rb, Cs.

M^{II} = Mg, Ca, Sr, Ba.

M^{III} = Al, Ga, Sc, Y, Gd, etc.

M^{IV} = Ti, Zr.

M^V = Ta, Nb.

in the past. Fortunately, there have been significant developments in the scaled growth of high optical quality crystals in recent years. Soviet workers have developed large crystal growth facilities and techniques capable of yielding alkaline-earth fluoride crystals⁵⁹ up to 60 cm in aperture and alkali halide crystals⁶⁰ up to 45 cm in aperture. The demand for dislocation-free bubble memory substrate materials has led to the growth of gadolinium gallium garnet (GGG) single crystals up to 13 cm in diameter and up to 25 cm in length, using the Czochralski growth technique.⁶¹ Figure 30 shows a production boule of GGG grown by Material Progress of Santa Rosa, Calif., measuring 8 cm in aperture and 25 cm in length. Exploratory growth experiments on the related crystal GSGG suggest that it grows as well as GGG under similar conditions. High-quality GSGG crystals of modest size (3 cm diameter and 10 cm length) have already been grown, and efforts to scale crystal size are in progress at several industrial companies. It appears likely that single-crystal plates of Nd:Cr:GSGG, each capable of delivering over a kilowatt of average power, should be possible.

Using the "heat exchanger method" (HEM) of crystal growth,⁶² high-quality single crystals of sapphire (Al_2O_3) have been grown by Crystal Systems of Salem, Massachusetts, with apertures up to 30 cm in diameter for use as optical windows of extremely high mechanical and thermal strength. Figure 31 shows an as-grown boule and several fabricated crystals of HEM-grown sapphire. Re-

cently, exploratory HEM growth of chromium-doped sapphire (ruby), titanium-doped sapphire, and cobalt-doped magnesium fluoride (MgF_2) crystals has been undertaken for laser applications.⁶³ Thus it appears to us that the prospect is good for the growth of selected laser crystals in sizes, and of a quality, relevant to the average power levels of interest in this paper.

Fig. 30. Production boule of gadolinium gallium garnet (GGG) of 8-cm aperture and 25-cm length (Materials Progress, Inc., Santa Rosa, Calif.).

Fig. 31. HEM-grown sapphire boule and fabricated plates of sapphire up to 30 cm diameter (Crystal Systems, Salem, Mass.).

Efficiency Considerations

To assess the efficiency potential of rare-gas flashlamps pumping various solid state laser materials, it is necessary to know the absorption spectrum and thickness of the laser media and the output spectra of the flashlamps at a variety of operating points. We have developed a model of the xenon flashlamp that provides a reasonable approximation of its output spectra between 0.2 and 1.8 μm , which includes most of the output from the xenon plasma. By applying the model, and by direct comparison with experiment, we observe that the pumping efficiency of an active ion such as neodymium, which has absorption bands throughout a wide region, depends only weakly on flashlamp operating point. Thus the calculation of the absorption efficiency of the media for flashlamp output is relatively straightforward.

Figures 32, 33, and 34 show the results of such calculations for Nd:glass, Nd:GSGG, and Nd:Cr:GSGG, whose absorption spectra are shown in Figs. 35, 25, and 26, respectively. In each of Figs. 32 to 34, the upper curve represents the fraction of the total energy output of the xenon flashlamp that is absorbed by passing the radiation once through a medium as a function of the areal density of the medium. The lower curve represents the fraction of the flashlamp's total output energy that is potentially available as 1.06- μm

photons. [Thus in the lower curve the quantum energy defect (the photon energy loss in the conversion, expressed as the ratio $\lambda_{\text{em}}/\lambda_{\text{abs}}$) between emission and absorption has been taken into account.]

To see how to use this information, first consider a piece of Nd:GSGG 6 mm thick and doped with 2×10^{20} Nd^{3+} ions/ cm^3 ; these values are similar to those found in a range finder or target designator using Nd:YAG. Table 8 shows this case along the first row. The fraction absorbed at 1.2×10^{20} ions/ cm^2 is 0.11. The average quantum defect (the ratio of values in the lower and upper curves in Fig. 33) is 0.59. The product of these two factors and the flashlamp radiative efficiency yields an instantaneous pumping efficiency of the metastable state of 0.048, or 4.8%, as shown in column 4. This is the proper estimate for the case in which *all* of the flashlamp output radiation passes *once* through 6 mm of laser medium. The situation in a pump cavity is somewhat more complicated.

The second example in Table 8 is Nd:glass at 10^{21} ions/ cm^3 , the design point chosen for the Nd:glass amplifiers in Table 2. In this case a maximum pumping efficiency of the metastable level of 15.6% of the flashlamp input power is achievable.

Fig. 32. Fraction of flashlamp output energy between 0.22 and 1.8 μm absorbed in Nd:glass, and energy fraction available as Nd^{3+} excited state, vs Nd^{3+} areal density (optical depth).

Fig. 33. Fraction of flashlamp output energy absorbed and fraction available as Nd^{3+} excited state, for Nd:GSGG. Points marked A and B represent areal densities used for calculations in the text.

Fig. 34. Fraction of flashlamp output energy absorbed and available for Nd:Cr:GSGG vs Cr^{3+} areal density, showing the improvement in efficiency achieved by co-doping with Cr^{3+} . The neodymium doping corresponds to case B in Fig. 33.

Fig. 35. Absorption cross section for Nd:glass.

Table 8. Potential efficiency of several representative flashlamp-pumped laser systems, showing the effect of optical feedback.

	Flashlamp radiative efficiency (1)	Fraction absorbed (2)	Average quantum defect (3)	No feedback		Full optical feedback	
				Instantaneous pump efficiency (4)	Peak storage efficiency (5)	Instantaneous pump efficiency (6)	Peak storage efficiency (7)
Nd:GSGG							
1.2×10^{20} ions/cm ²	0.75	0.11	0.59	0.048	0.019-0.034	0.14	0.1-0.10
Nd:glass							
10^{21} ions/cm ²	0.75	0.34	0.62	0.16	0.062-0.110	0.31	0.13-0.23
Nd:Cr:GSGG							
2×10^{20} Nd/cm ³ 2×10^{20} Cr/cm ³							
1 cm thick	0.75	0.42	0.54	0.17	0.067-0.11	0.30	0.12-0.21
2 cm thick	0.75	0.48	0.54	0.20	0.077-0.14	0.32	0.13-0.22

In the last two cases we calculate the pump efficiencies for Nd:Cr:GSGG, in which it is necessary to model the kinetics of the Cr-to-Nd energy transfer. We wrote a computer code to do this, relying on the energy-transfer data of Zharikov et al.⁴⁴ to determine the microscopic rates. Because transfer rates depend on concentration, it is necessary to state both the thickness and ion concentration; this has been done in Fig. 34 and in Table 8. For Nd and Cr ion densities of 2×10^{20} ions/cm³,

the pump efficiencies for 1- and 2-cm-thick plates are 16.8% and 19.4%, respectively. Thus high overall efficiencies should be achievable, at least in principle. These pump efficiencies of the metastable state are the appropriate data to use in considering the maximum efficiencies attainable for a free-running oscillator or an amplifier. However, if the oscillator or amplifier is used in the energy-storage mode, then the peak storage efficiency will be about 40 to 70% of the value shown in

column 4 of Table 8. These efficiency ranges are shown in column 5.

In principle, it should be possible to capture the unabsorbed pump radiation and use it to increase the overall pump efficiency. One way to do this would be to allow the flashlamp to absorb the unused radiation, thus reducing the required electrical input. Under typical operating conditions ($\tau > 100 \mu\text{s}$) the plasma is in local thermodynamic equilibrium throughout most of the discharge period. Thus, absorbed optical energy should heat the emitting/absorbing xenon plasma, with effects equivalent to electrical-energy deposition. While this fact has been widely recognized, either implicitly or explicitly,⁶⁴ only in the USSR have detailed experimental and theoretical studies of the process been carried out.⁶⁵ These studies indicate that the flashlamp can be used as an energy converter and that the only significant difference between electrical heating and optical heating may be the resulting plasma-temperature profile. Thus, it is probably safe to assume that absorbed optical radiation will be converted to emitted optical radiation with about the same overall efficiency as obtains in the conversion of deposited electrical energy to optical radiation. As mentioned earlier, the flashlamp itself can convert electrical energy to optical energy with a very high efficiency ($\sim 75\%$).

The energy-flow diagram in Fig. 36 shows how such a process might work. By equating the total (optical plus electrical) energy input to the total energy output, one can easily show that the

ratio of the pump efficiencies with and without optical feedback is just

$$\frac{\eta_{\text{feedback}}}{\eta} = \frac{1}{1 - \epsilon}, \quad (17)$$

where ϵ is the radiative efficiency of the flashlamp and p is the fraction of total flashlamp radiative output reabsorbed by the flashlamp plasma. To simplify the remainder of the discussion and to extend its technical validity, we assume that all optical input to the flashlamp allows a corresponding reduction of electrical input, so that the flashlamp operating point remains approximately constant. The data of columns 4 and 5 of Table 8 can be modified by Eq. (17) to yield the maximum possible pumping efficiencies for free-running and storage modes, as shown in columns 6 and 7 respectively.

The implementation of optical feedback is by no means trivial. Photons must be rigorously conserved to ensure that the only energy sinks are the active ions and the flashlamp inefficiency (i.e., wall losses). This is much more difficult than realizing low-loss resonators for a laser, because a pumping cavity must be developed that has low loss over an extremely wide wavelength interval, as well as over all angles of incidence from 0 to 90° . By contrast, a laser resonator must usually be low-loss only over a narrow wavelength interval and at just one angle of incidence. The problem of obtaining a low-loss pump cavity is further complicated by the necessity of propagating the laser

Fig. 36. Flow of electrical and optical energy in a xenon flashlamp.

beam in and out of the cavity, while not allowing the pump energy to escape. Amplifiers must therefore have high length-to-diameter ratios to minimize the solid angle subtended by the input and output ports at the pump sources.

In summary, it is clear that the combination of xenon flashlamps and existing laser media is potentially capable of very high efficiency. However, truly efficient optically pumped solid state lasers can be developed only if the design accords as much importance to pump photons as to laser photons.

The efficiency potential of semiconductor-array-pumped solid state lasers is next considered in terms of a specific example: a GaAs-diode array emitting at 805 nm and pumping Nd:YAG. We take the efficiency of an array to be 30% (this is possible now at reduced diode life; it will may be possible with extended life in the future). The diode array is a half-plane radiator with a surface intensity commensurate with the pumping intensity desired at the surface of the Nd:YAG laser material. Thus we can envision a pumping geometry in which the diode-array output directly illuminates the broad surfaces of the YAG plate without suffering loss by reflection from intervening mirrored surfaces. [Even if it proved desirable to utilize intervening mirrored surfaces, a very high transport efficiency (>99%) should be possible because the array output radiation is typically confined to a spectral band a few nm wide in a region of the spectrum where exceptionally high-efficiency, wide-angle dielectric reflectors can be fabricated.] Thus we assume an overall transport

efficiency of 95%. Because of the spectral narrowness of the pump radiation, laser materials with relatively narrow pump-band absorption features, such as Nd:YAG, can readily absorb 90% of the pump radiation entering the material. In this example, the quantum energy defect is $805/1060 = 0.76$, so that the efficiency of pumping the metastable level of the Nd:YAG may approach $(0.3)(0.95)(0.90)(0.76) = 0.19$. The device efficiency will be lower than this because of spontaneous decay during pumping (in the energy-storage mode), and incomplete extraction of available stored energy. Typical values for these efficiency factors are 0.5 to 0.7, and 0.65, respectively, so that the estimated device efficiency is 6 to 9% in the energy-storage mode. Somewhat higher efficiencies can be expected for the free-running mode, in which the effects of spontaneous decay during pumping are minimized.

It is difficult to estimate the potential efficiencies of solid state lasers pumped with e-beam-excited epitaxial phosphors, since at least one complete phosphor/laser-ion/host combination would have to be defined. Since such a combination has not yet been defined, we can offer only some general observations. Like semiconductor arrays, phosphors are half-plane radiators emitting in a compact spectral region. Thus radiation-transport and deposition efficiencies for phosphors may be about as high as for semiconductor arrays. Allowing for spontaneous decay and fill factors, it is reasonable to expect an overall efficiency of $\geq 5\%$ in an energy-storage laser emitting directly in the mid-visible spectral range.

Wavelength Diversity and Agility

Given the successful development of high-quality, repetitively pulsed solid state lasers operating in the near infrared, efficient shifting of the output energy to other spectral regions becomes technically plausible using nonlinear conversion techniques. For example, using the 1060-nm fundamental radiation from neodymium-based solid state lasers, one can efficiently generate the second harmonic at 530 nm by frequency doubling (called second-harmonic generation, or SHG), the third harmonic at 353 nm by frequency doubling and mixing with the fundamental ("THG"), and the fourth harmonic at 265 nm by frequency doubling twice ("4HG"). Further wavelength diversity can be achieved by using the harmonic wavelength sources as pumps to drive tunable optical parametric oscillators, Raman oscillators, and

other laser media. Each of these processes has been demonstrated on a single-pulse basis with high conversion efficiency; concepts for preserving high conversion efficiency at high average power are discussed below.

Harmonic generation was first demonstrated by Franken et al.⁶⁶ shortly after the demonstration of the ruby laser. Giordmaine⁶⁷ demonstrated how to make harmonic conversion efficient with the clever technique of phase matching in birefringent crystals. GW/cm² beams of 1060-nm radiation have since been converted with 50 to 90% efficiency to the second, third, and fourth harmonics using KH₂PO₄ (potassium dihydrogen phosphate, or KDP) and crystalline isomorphs as nonlinear materials. Figure 37 shows the crystal

Second-harmonic generation (SHG) — type II

Fig. 37. Crystal and electric vector orientations for Type II harmonic generation in KDP. Extraordinary axis, e ; ordinary axis, o .

orientation for Type II harmonic generation in KDP at 1050 nm. Both the 1ω and 2ω input beams are linearly polarized. Analysis and experiments show that conversion efficiencies of $>80\%$ can be achieved only for a limited range of beam intensities or for beams of low divergence angle ($\Delta\theta < 100 \mu\text{rad}$). Figure 38(a) shows the so-called quadrature approach to second-harmonic generation. Both crystals are cut for Type II phase matching; however, the optical axes are arranged so that the planes containing the laser beam propagation vector and the crystal optical axes are orthogonal. The incident fundamental plane wave is polarized at 45° to the k - z planes of both crystals, allowing phase matching for both. The second-harmonic waves generated in both crystals are orthogonal, so that conversion efficiencies are independent of each other. The overall output is thus the simple sum of the output from each crystal, and the conversion efficiency is then just

$$\eta = \eta_1 + \eta_2(1 - \eta_1). \quad (18)$$

The great advantage of the quadrature scheme is that it allows efficient harmonic generation over an extremely wide intensity range.³⁰ The quadrature system in KDP has another interesting

feature, shown in Fig. 38(b): the two crystals are also in the basic orientation for Type II-Type II third-harmonic generation. A rotation of the crystal set by 10° around the beam-propagation axis and a tilt of 4.4 mrad to the phase-matching angle for $1\omega + 2\omega$ mixing are all that is required for third-harmonic generation. This SHG-THG system is now being implemented on the Nova laser system⁶⁰ at LLNL.

To generate SHG and THG wavelength output in the Nova laser, 74-cm-diam harmonic-conversion crystal assemblies have been developed. Fortunately, KDP crystal is rather easily grown from water solution, and the scale-up of crystal size has proceeded rapidly, up to boules $30 \times 30 \times 64 \text{ cm}$. From crystals this large, we can fabricate the 27-cm-square plates shown in Fig. 39. It turns out that plates of this size are the largest that can be effectively utilized with GW/cm^2 beams, because of the onset of transverse Raman scattering in the plate.

To cover the entire 74-cm aperture of the laser beam, we developed the multicrystal array. This array technology is made possible by extremely precise diamond-point machining and by precision measurement of the KDP crystal orientation, which ensures that the phase-matching

(a) Quadrature SHG

(b) Cascade THG

Fig. 38. Crystal and electric vector orientations (a) for "quadrature" second-harmonic generation in KDP; and (b) for cascade third-harmonic generation in KDP. Extraordinary axis, e; ordinary axis, o.

Fig. 39. Large KDP crystal plates fabricated using a diamond-point machining technique.

direction and the surface normal are coincident to within $30 \mu\text{rad}$. The diamond-point machining produces such a fine finish that no subsequent grinding or polishing is required. Figure 40 shows a completed fluid-index-matched doubling array of 74-cm aperture that has been installed and op-

erated in the two-beam Novette laser system. Figure 41 shows the measured and theoretical values of the doubling efficiency for this array vs input beam intensity. Efficiencies of $>75\%$ are observed at the nominal operating point of 1 to 2 GW/cm^2 .

Fig. 40. An array of frequency-doubling crystals (total aperture >74 cm) operational in the Novette laser system.

Fig. 41. SHG conversion efficiency of the Novette monolithic array vs first-harmonic intensity.

To simplify the array design, and to avoid the slight but cumulative optical damage of the index matching fluid, we have recently developed a low-temperature sol-gel chemical deposition technique for applying a high-damage-threshold anti-reflection (AR) coating to KDP crystals. Ar-

rays using this coating are now being deployed in the Nova laser system.

Given the high single-pulse conversion efficiency demonstrated, the question arises as to how to maintain this performance at high average power. When a nonlinear optical crystal heats up,

the optimum phase-matching angle changes, reducing the harmonic conversion efficiency. The full width at half maximum of the conversion efficiency/temperature curve is typically from a few to tens of degrees Celsius. Thus, the temperature must be held constant to within about one-tenth of this value, or 1 to 5°C. In analogy with the concept of a transverse-flow-cooled laser plate described earlier, Fig. 42 shows a simple method for accomplishing heat removal and temperature control in a high-average-power harmonic generator assembly. Thin plates of nonlinear crystal are arranged parallel to one another using precision spacers, and cooling gas is flowed across the plate faces to control temperature gradients. Construction of such an array presumes the availability of high-damage-threshold AR coatings, such as those described above for KDP crystals. (The sol-gel deposition technique developed for coating KDP should be widely applicable to other soft, water-sensitive crystals.) When the nonlinear optical crystal is sectioned into several parallel plates, as in Fig. 42, strict attention must be paid to

maintaining very close parallelism, and the phase-matching angle of the individual plates must be coincident with the surface normal to within 30 to 50 μrad (if KDP-type materials are used). These requirements can be relaxed significantly if ninety-degree phase-matchable materials are used. In addition to precision fabrication and assembly, consideration must also be given to assuring that a proper phase relationship exists between the 1ω and 2ω waves reaching each successive crystal plate, since the cooling gas introduces a phase shift $\Delta\psi$ given by

$$\Delta\psi = \frac{2\pi}{\lambda_2} (n_{2\omega} - n_{\omega})\delta, \quad (19)$$

where $n_{2\omega}$ and n_{ω} are the indices of refraction of the coolant gas and δ is the total path length of gas between the crystals. If we assume that $\Delta\psi < \pi/10$ will result in no loss of harmonic conversion efficiency, then we require

$$\delta \leq \frac{\lambda_1}{40 \Delta n}. \quad (20)$$

Fig. 42. Conceptual design of a high-average-power harmonic generator using transverse-flow cooling.

Table 9 shows the maximum value of δ thus defined for a variety of coolant gases. Clearly, air is a rather marginal coolant if more than one coolant channel is required. On the other hand, 1-atm helium places almost no restriction on the design of the harmonic generation assembly. The allowable temperature rise is calculated as was done previously for solid state laser plates, with a power loading of $P_v = I_{av}\gamma$, where I_{av} is the average optical power passed through the crystal and γ is the optical-loss coefficient. Figure 43 shows I_{av} vs crystal thickness for various nonlinear crystalline materials. Clearly, very high specific and total average powers are attainable through the use of the plate-array concept. For example, a single 1-cm-thick, 27×27 cm plate of KD*P could provide up to 20 kW of average power at 530 nm.

The high efficiency and high power-handling capability anticipated for harmonic generators has important implications for the future development of fusion laser drivers. The optimum operating wavelength range for a fusion reactor (350 to 500 nm) results from a competition between im-

Table 9. Coolant gases for high-average-power harmonic conversion.

Coolant gas at 1 atm (273 K)	Total path length, δ (cm), for $\Delta\psi = \pi/10$
Air	0.68
Argon	5.59
Neon	6.20
Helium	11.60

proved pellet performance and lowered optical-damage thresholds of materials and components as wavelength is decreased. Recent fusion experiments⁶⁹ indicate that most of the pellet performance improvement anticipated relative to 1000 nm is realized in the 350 to 500 nm region; at the same time, as Fig. 44 suggests,^{70,71} high optical-damage thresholds are maintained for wavelengths down to 500 nm and then begin to decrease rapidly at shorter wavelengths. The prospect for significantly improving damage thresholds in the ultraviolet is greatly diminished

Fig. 43. Calculated specific average power throughput of a flow-cooled harmonic generator vs crystal thickness, for KDP, KD*P, and CD*A nonlinear crystal materials. The deuterated crystals KD*P and CD*A (cesium deuterium arsenate) give better performance.

Fig. 44. (a) Damage thresholds of various oxide and fluoride half-wave films, vs wavelength for pulse durations of 12 to 15 ns. Data after Walker et al., Ref. 70. (b) Laser damage thresholds of zirconia/silica high-reflectivity coatings at 1064, 527, and 355 nm for pulse durations of 0.6 to 1 ns. Data after Rainer et al., Ref. 71.

by the paucity of materials that are transparent at one-half the operating wavelength (required to avoid deleterious two-photon absorption processes). To obviate these excessively low damage thresholds and to achieve adequate system lifetime and cost, a KrF excimer laser operating at a fundamental wavelength of 249 nm may have to be shifted to a longer output wavelength, for which the damage thresholds are considerably higher. On the other hand, the prospect for developing a sufficiently powerful and efficient solid state laser radiating directly within the optimum 350 to 500 nm band is remote, because of the lack of adequate pump sources and metastable laser ions. However, a near-infrared pump laser (which we have seen can be very efficient using xenon flashlamps), driving second- or third-harmonic generators, appears to be a very plausible approach to attaining the efficiency, wavelength, and power required for an optimum fusion laser driver.

Once high-radiance, fixed-wavelength, high-average-power sources exist in the near-UV and in the visible, additional wavelength diversity throughout these regions can be obtained with any of several wavelength-shifting techniques. For applications requiring visible radiation, the concept of driving optical parametric oscillators (or amplifiers) is particularly appealing. In the parametric process, pump energy at wavelength λ_p is converted into a signal wave at wavelength λ_s and an idler wave at wavelength λ_i , where $1/\lambda_p = 1/\lambda_s + 1/\lambda_i$ is required by conservation of photon energy. This process is not intrinsically dissipative, so the efficiency of conversion of pump energy to energy at the two longer wavelengths can be very high. If the application can utilize the pair-wise generated photons lying in contiguous spectral bands, effective conversion efficiencies of over 90% may be realized. Some years ago, Yarborough and Massey⁷² demonstrated the generation of tunable light over the spectral region from 420 to 730 nm using an ammonium dihydrogen phosphate (ADP) parametric crystal, pumped by the fourth harmonic of an Nd:YAG laser. A conversion efficiency of >25% was obtained in an

unsaturated amplifier. Wavelength selection was achieved using both temperature and angle tuning of the phase-matching condition. In principle, scaling to high average power can be accomplished using the same flow-cooling concept described above for high-average-power harmonic generation.

Wavelength diversity can also be addressed on a discrete-wavelength basis by utilizing efficient stimulated Raman scattering⁷³ driven by high-radiance harmonic sources. Here the process is dissipative, the output photon suffering a Stokes shift corresponding to the energy of the vibration involved in the scattering. Raman scattering in gases, liquids, or solids may be utilized, depending on the desired wavelength coverage and the power requirements.

A third process for shifting the wavelength of high-performance harmonic sources is that of laser pumping of other (tunable) laser media, such as liquid dyes or various solid state lasers, a technique called linear down-conversion. Energy conversion efficiencies of >50% have been achieved in the LLNL Laser Isotope Separation Program using high-average-power copper-vapor lasers to pump liquid dyes. Because the chemical destruction of dye molecules proceeds at a very low rate in laser pumping (compared to the rate induced by broadband flashlamp pumping), only a modest dye inventory is required for extended high-average-power operation. Solid state analogs to the dye molecule have come under increasing study recently [e.g., phonon-terminated laser transitions⁷⁴ typified by $\text{Cr}^{3+}:\text{BeAl}_2\text{O}_4$ (Ref. 43) and $\text{Ti}^{3+}:\text{Al}_2\text{O}_3$ (Ref. 75), and a variety of color-center lasers⁷⁶]. Alternatively, one could pump a solid state laser medium containing an impurity ion with an absorption feature that matches the wavelength of the harmonic pump source (e.g., the third harmonic of Nd:glass or Nd:YAG pumping the thulium ion in various solids,⁷⁷ producing coherent emission at ~455 nm). High average power from laser-pumped solid state lasers can be obtained just as in the case of flow-cooled laser plates.

Summary

Several basic characteristics make solid state lasers highly attractive for high-average-power applications—they are operationally benign, logistically unobtrusive, and potentially very flexi-

ble in their wavelength and pulse width—but the exploitation of these characteristics has been truncated in the past by severe technical limitations on average power and by low efficiency. A variety of

new design concepts, new components, and new materials have emerged over the last decade, all suggesting that the limits on average power can be removed and that the efficiency can be considerably increased. Such a development could greatly expand the use of solid state lasers. Those concepts, components, and materials have been described in this paper.

The key factors in high-average-power operation are controlling thermal gradients in the laser medium and configuring the laser in such a way that thermal gradients do not generate phase distortions. Plate geometries of the laser medium, as contrasted with the traditional rod geometries, are required for both of these reasons. Two configurations appear to be useful—the zig-zag configuration for average powers up to several kilowatts, and the disk configuration above that. The plates should have high aspect ratio, to minimize edge effects; the doped material should be physically thin, for rapid heat diffusion to the surface, and optically thick, for efficient use of pump radiation. Zig-zag lasers are effectively constrained to a single plate, and their average power scales with plate area; disk lasers can employ many plates in sequence, constrained only by surface and volume scattering losses; average power in such lasers scales as the product of plate area and number of plates. If necessary for mechanical strength, thin plates can be replaced by thicker plates, with the doping in thin surface layers; the center and outer sections must be optically and thermally matched. The area per plate is ultimately limited by transverse amplified spontaneous emission, and segmentation with absorbing strips is required to design for areas above that limit.

Conclusions

Based on the material presented in this article, we can draw six salient conclusions:

First, using properly configured gain-medium and flow-cooling assemblies, solid state lasers can be built to deliver average power and radiance as high as those of known gas lasers.

Second, by rigorously applying the pump-photon utilization techniques described, laser efficiencies of over 10% should be achievable at high average power and radiance.

Third, high-average-power, high-radiance solid state systems operating throughout the visible and near infrared can be achieved using non-

The average laser power that can be extracted per unit plate area is constrained by the rate at which heat can be removed from that area. For flashlamp pumping, the rate of heat generation is typically 1 to 2 times the extractable laser power; for diode array pumping it is typically half of the extractable laser power. Disk lasers cooled by flowing helium gas could yield several to tens of watts per square centimeter of disk surface without excessive temperature rise.

Wavelength shifting can be accomplished through harmonic generation and with Raman and dye-laser converters, all of which have been developed to high efficiency. Efficient optical parametric oscillators are also possible in principle, but have not received much development effort. Solid wavelength converters, such as harmonic generators and optical parametric oscillators, would exploit the concept of multiple, thin, gas-cooled disks for thermal control at high average power. Fluid converters, such as dyes and Raman converters, would flow the fluid through a heat exchanger for thermal control.

In addition to the traditional flashlamps, semiconductor diode arrays and e-beam-pumped epitaxial phosphors are candidates for pumping solid state lasers. While neither of these newcomers is likely to match or exceed the efficiency with which flashlamps produce pump radiation, semiconductors offer a superior spectral match to the narrow pump bands of certain ions and provide some relief on thermal load, and the e-beam-pumped phosphors may be useful in pumping solid state lasers radiating in the visible.

linear converter assemblies configured to carry average power loadings.

Fourth, the use of crystalline laser media will increase specific average power capability by an order of magnitude over that of Nd:glass. Recent advances in the growth of large crystals of high optical quality underwrite the prospect for development of high-average-power crystal-based solid state lasers.

Fifth, new laser ions and crystalline host materials, developed in concert with new pumping sources, offer the prospect of realizing several new classes of high-performance solid state lasers.

Sixth, the full realization of the potential of solid state lasers will be achieved only through a broadly based, well-integrated, and well-balanced R&D effort that spans the disciplines of laser system

design, quantum electronics, materials science, and the engineering sciences (thermomechanics, optics, and pulse power).

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References

1. T. H. Maiman, "Stimulated Optical Radiation in Ruby," *Nature* **187**, 493-494 (1960).
2. L. F. Johnson and K. Nassau, "Infrared Fluorescence and Stimulated Emission on Nd^{+3} in CaWO_4 ," *Proc. IRE* **49**, 1704-1706 (1961).
3. E. Snitzer, "Optical Maser Action of Nd^{+3} in a Barium Crown Glass," *Phys. Rev. Lett.* **7**, 444-446 (1961).
4. M. L. Stith, "Laser Ranging," in *Laser Handbook*, vol. 2, pp. 1745-1804 (North Holland Publishing Company, Amsterdam, 1972), F. T. Arecchi and E. O. Schulz-Dubois, Eds.
5. C. G. Young and E. Snitzer, "Glass Laser Technology," *Laser Focus* **3**(12), 21-29 (December 1967).
6. R. W. Beck, "Predicting the Output of Glass Laser Materials," *Laser Focus* **5**(11), 42-44 (June 1969).
7. V. A. Batanov, I. A. Bufetov, S. B. Gusev, B. V. Ershov, P. I. Kolisnichenko, A. N. Malkov, Yu. P. Pimenov, and V. B. Federov, "Millisecond Neodymium Glass Laser Characterized by a High Output Energy and a High Directionality of Radiation," *Sov. J. Quantum Electron.* **4**, 853-856 (1975).
8. A. A. Mak, V. A. Fromzel', A. A. Shcherbakov, V. M. Volynkin, V. E. Gavrilov, V. A. Gerasimov, V. M. Gradov, V. I. Zhil'tsov, G. I. Kromskii, A. G. Murzin, and L. K. Sukhareva, "The Effect of the Properties of a 'Light Boiler' on Laser Efficiency," *Sov. J. Opt. Technology* **50**, 62-63 (1983).
9. J. C. Almasi and W. S. Martin, *Face-Pumped Face-Cooled Laser Device*, U.S. Patent 3,631,362 (December, 1971).
10. W. S. Martin and J. P. Chernoch, *Multiple Internal Reflection Face-Pumped Laser*, U.S. Patent 3,633,126 (January, 1972).
11. E. Matovich, "Development of an Axial Gradient Laser," Final Report, Contract F29601-68-C-0039, Air Force Special Weapons Center, Kirtland Air Force Base, NM, Autonetics Division of Rockwell (1968).
12. E. Matovich, "The Axial Gradient Laser," *Proc. of the Fourth DOD Conference on Laser Technology*, San Diego, Jan. 6-8, 1970, vol. 1, pp. 311-362 (Infrared Information and Analysis Center, P.O. Box 8618, Ann Arbor, MI, 1970).
13. W. F. Hagen, C. G. Young, D. W. Cuff, and J. E. Keefe, "Segmented Nd Glass Lasers," *Proc. of the Fourth DOD Conference on Laser Technology*, San Diego, Jan. 6-8, 1970, vol. 1, pp. 363-377 (1970).
14. W. F. Hagen, J. E. Keefe, and C. G. Young, "Segmented Nd:Glass Laser," American Optical Corporation, Sturbridge, MA, Technical Report AFAL-TR-71-303 (February, 1972).
15. G. J. Hulme and W. B. Jones, "Total Internal Reflection Face Pumped Laser: Concept and Design Consideration," *SPIE* **69**, 38-44 (1975).
16. W. B. Jones, "The Slab Geometry Laser," *Laser Focus/Electro-Optics* **19**(9), 107-114 (September, 1983).
17. J. M. Eggleston, T. J. Kane, J. Unternahrer, and R. L. Byer, "Slab-Geometry Nd:Glass Laser Performance Studies," *Optics Letters* **7**, 405-407 (1982).
18. T. J. Kane, R. C. Eckardt, and R. L. Byer, "Reduced Thermal Focusing and Birefringence in Zig-Zag Slab Geometry Crystalline Lasers," *IEEE J. Quantum Electron.* **QE-19**, 1351-1354 (1983).
19. E. T. Gerry, "Gasdynamic Lasers," *SPIE Journal* **9**, 61-70 (1971).

20. A. Bettinger, L. Jacob, C. Meunier, and J. Pezot, "Uniform Energy Density at the Output of High Power Glass Lasers," *Digest of Technical Papers, 1973 Conference on Laser Engineering and Applications (CLEA)*, Washington, DC, pp. 93-94 (IEEE, New York, NY, June, 1973).
21. J. E. Swain, R. E. Kidder, K. Pettipiece, F. Rainer, E. D. Baird, and B. Loth, "Large Aperture Glass Disk Laser System," *J. Appl. Phys.* **40**, 3973-3977 (1969).
22. J. M. McMahon, J. L. Emmett, J. F. Holzrichter, and J. B. Trenholme, "A Glass Disk Laser Amplifier," *IEEE J. Quantum Electron.* **QE-9**, 992-999 (1973).
23. J. L. Emmett, W. F. Krupke, and J. I. Davis, "Laser R&D at the Lawrence Livermore National Laboratory for Fusion and Isotope Separation Applications," *IEEE J. Quantum Electron.* **QE-20**, 591-602 (1984).
24. M. J. Weber, "Fluorescence and Glass Lasers," *J. Noncrystalline Solids* **47**, 117-133 (1982).
25. W. H. Lowdermilk and D. Milam, "Laser-Induced Surface and Coating Damage," *IEEE J. Quantum Electron.* **QE-17**, 1888-1903 (1981).
26. J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, "Suppression of Self-Focusing Through Low-Pass Spatial Filtering and Relay Imaging," *Appl. Opt.* **17**, 2053-2057 (1978).
27. Cleveland Crystals, Cleveland, Ohio, and Interactive Radiation, Northvale, New Jersey, developed large-aperture crystals under contract to Lawrence Livermore National Laboratory. See *Final Report on Quality of 100 mm ϕ KD*P Crystals*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-15399 (1981).
28. J. E. Murray, P. C. Baker, J. B. Bryan, B. C. Johnson, S. E. Mayo, S. Warshaw, and B. W. Woods, "Orientation and Finishing of KDP Array Segments for Large-Aperture Harmonic Generators," *J. Opt. Soc. Amer.* **71**, 1629 (1981).
29. W. F. Krupke, "Advanced Lasers for Fusion Applications," *Proc. International Conference on Lasers 1978*, San Diego, California, August, 1978, pp. 24-30 (STS Press, McLean, VA, 1979).
30. J. L. Emmett, W. F. Krupke, and J. B. Trenholme, "Future Development of High Power Solid State Laser Systems," *Sov. J. Quantum Electron.* **13**, 1-23 (1983).
31. R. L. Byer, K. Kuhn, M. Reed, J. Trail, "Progress in High Peak and Average Power Lasers for Soft X-Ray Production," *Proceedings of SPIE*, vol. 448, p. 2 (October 19-20, 1983), *X-Ray Lithography and Applications of Soft X-Rays to Technology*, A. D. Wilson, Ed.
32. C. M. Banas, "High Power Laser Welding—1978," *Opt. Eng.* **17**(3), 210-216 (1978).
33. J. F. Nye, *Physical Properties of Crystals* (Oxford University Press, London, 1957).
34. J. L. Emmett, J. F. Holzrichter, J. B. Trenholme, and W. F. Krupke, "High Efficiency, High Rep Rate Glass Lasers," Lawrence Livermore National Laboratory, Livermore, Calif., Laser Program Internal Memorandum (August, 1977).
35. H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, 2nd ed. (Oxford, Clarendon Press, 1959).
36. J. M. Soures, "Design Criteria for High Power Laser Systems," *Proc. SPIE* **61**, 68-72 (1975).
37. J. A. Abate et al., "Active Mirror: a Large-Aperture Medium-Repetition Rate Nd:glass Amplifier," *Appl. Optics* **20**, 351-361 (1981).
38. S. Timoshenko and J. N. Goodier, *Theory of Elasticity* (McGraw-Hill, New York, 1951), p. 400.
39. J. B. Trenholme, "Temperature and Stress in a Pumped Glass Slab," *1982 Laser Program Annual Report*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-82 (1983), pp. 7-112 to 7-114.
40. R. F. Bourque, "A Step-by-Step Approach to Convective Cooling of Laser Disc Amplifiers," General Atomic Company, San Diego, Calif., Final Report, GA-A15336, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-15047 (April, 1979).
41. M. W. Taylor, "Cooling Considerations for High Average-Power Solid-State Amplifiers," Lawrence Livermore National Laboratory, Livermore, Calif., Internal Memorandum MWI 84-1 (August, 1984).
42. J. A. Glaze, S. Guch, and J. B. Trenholme, "Parasitic Suppression in Large Aperture Nd:Glass Disk Laser Amplifiers," *Appl. Optics* **13**, 2808-2811 (1974).
43. J. C. Walling, O. G. Peterson, H. P. Jensen, R. C. Morris, and E. W. O'Dell, "Tunable Alexandrite Lasers," *IEEE J. Quantum Electronics* **QE-16**, 1302-1315 (1980).
44. E. V. Zharikov, N. N. Bichay, V. V. Laptev, A. A. Malyutin, V. G. Ostroumov, P. P. Pashurin, A. S. Pimenov, V. A. Smirnov, and I. A. Shcherbakov, "Spectral, Luminescence, and Lasing Properties of Gadolinium Scandium Gallium Garnet Crystals Activated with Neodymium and Chromium Ions," *Sov. J. Quantum Electronics* **13**, 82-85 (1983).

45. L. P. Bradley and H. T. Powell, "Flashlamp Characterization," *1982 Laser Program Annual Report*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-82 (1983), pp. 7-6 to 7-15.
46. J. P. Markiewicz and J. L. Emmett, "Design of Flashlamp Driving Circuits," *IEEE J. Quantum Electron.* **QE-2**, 707-711 (1966).
47. H. Kressel, H. F. Lockwood, and F. Z. Hawrylo, "Large-Optical-Cavity (AlGa)As-GaAs Heterojunction Laser Diode: Threshold and Efficiency," *J. Appl. Phys.* **43**, 561-567 (1972).
48. "Industry Briefs," *Photonics Spectra* **18**(1), 34 (January, 1984).
49. R. R. Rice, McDonnell-Douglas Astronautics, St. Louis, MO, private communication (1983).
50. (a) D. R. Scifres, R. D. Burnham, and W. Streifer, "High Power Coupled Multiple Stripe Well Injection Lasers," *Appl. Phys. Lett.* **41**, 118-120 (1982); (b) D. R. Scifres, Spectradiode, Mountain View, Calif., private communication (March, 1984).
51. I. Melngailis, Lincoln Laboratory, Cambridge, MA, presentation at Lincoln Laboratory, "DARPA Study on Optical Imaging Radars," March, 1984.
52. J. D. Kingsley and G. W. Ludwig, "The Efficiency of Cathode Ray Phosphors," *J. Electrochem. Soc.: Solid State Science* **117**, 353-359 (1970).
53. P. A. Einstein, "The Light Output of Some Phosphors Excited with Electrons of High Current Density," *Br. J. Appl. Phys.* **8**, 190-194 (1957).
54. J. M. Robertson and M. W. van Tol, "Epitaxially Grown Monocrystalline Garnet Cathode Ray Tube Phosphor Screens," *Appl. Phys. Lett.* **37**, 471-472 (1980).
55. J. B. Trenholme, "Fluorescence Amplification and Parasitic Oscillation Limitations in Disc Lasers," Naval Research Laboratory, Washington, D.C., NRL Memorandum Report 2480 (1972).
56. W. F. Hagen and J. B. Trenholme, "Multipass-Systems Analysis," *1981 Laser Program Annual Report*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-50021-81 (1982), pp. 7-49 to 7-56.
57. B. G. Gorshkov, Yu. K. Danileiko, V. N. Nikolaev, and A. V. Sidorin, "Effects of Multiple Interaction in Laser Damage to Optical Materials," *Sov. J. Quantum Electron.* **13**, 388-391 (1983).
58. L. D. Merkle, M. Bass, and R. T. Swimm, "Multiple Pulse Laser Induced Bulk Damage in Crystalline and Fused Quartz at 1.064 and 0.532 μm ," *Opt. Engineering* **22**, 405-410 (1983).
59. V. A. Sokolov, E. A. Simun, and A. N. Sinev, "Large Calcium and Barium Fluoride Crystals," *Sov. J. Opt. Technol.* **46**, 279-281 (1979).
60. V. I. Gorilevsky, V. A. Nemenov, V. G. Protsenko, A. V. Radkevich, and L. G. Eidelman, "Automated Pulling of Large Alkali Halide Single Crystals," *J. Crystal Growth* **52**, 509-513 (1981).
61. C. D. Brandle, "Growth of 3" Diameter $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ Crystals," *J. Appl. Phys.* **49**, 1855-1858 (1978).
62. D. Viechnicki and F. Schmid, "Growth of Large Monocrystals of Al_2O_3 by a Gradient Furnace Technique," *J. Crystal Growth* **11**, 345-347 (1971).
63. F. Schmid and C. P. Khattak, "Large Crystal Sapphire Optics," *Laser Focus/Electro-Optics* **19**(9), 147-152 (September, 1983).
64. J. G. Edwards, "Some Factors Affecting the Pumping Efficiency of Optically Pumped Lasers," *Appl. Opt.* **6**, 837-843 (1967).
65. Yu. G. Basov, "Influence of Reflected Radiation on a Pulsed Xenon Discharge in Quartz Tubes," *J. Appl. Spectrosc.* **35**, 943-953 (1981).
66. P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich, "Generation of Optical Harmonics," *Phys. Rev. Lett.* **7**, 118-119 (1961).
67. J. A. Giordmaine, "Mixing of Light Beams in Crystals," *Phys. Rev. Lett.* **8**, 19-20 (1962).
68. W. W. Simmons and R. O. Godwin, "Nova Laser Fusion Facility—Design, Engineering, and Assembly Overview," *Nucl. Technol./Fusion* **4**, 8-24 (1983).
69. R. E. Turner, E. M. Campbell, W. C. Mead, F. Ze, C. Max, D. W. Phillion, P. Lee, B. Pruett, G. Tirsell, and B. F. Lasinski, *ARGUS Laser Plasma Experiments at 1060, 530, and 350 nm*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-86911 (1982).
70. T. W. Walker, A. H. Guenther, C. G. Fry, and P. Nielson, "Pulsed Damage Thresholds of Fluoride and Oxide Thin Films from 260 to 1060 nm," in *Laser Induced Damage in Optical Materials Proceedings 1979*, National Bureau of Standards, Washington, D.C., NBS Special Publication 568 (1979), pp. 405-416.
71. F. Rainer, C. L. Vercimak, D. Milam, C. K. Carniglia, and T. Tuttle Hart, *Measurements of the Dependence of Damage Thresholds on Laser Wavelength, Pulse Duration, and Film Thickness*, Lawrence Livermore National Laboratory, Livermore, Calif., UCRL-89864 (1984).

72. J. M. Yarborough and G. A. Massey, "Efficient High-Gain Parametric Generation in ADP Continuously Tunable Across the Visible Spectrum," *Appl. Phys. Lett.* **18**, 438-440 (1971).
73. A. Penzkofer, A. Laubereau, and W. Kaiser, "High Intensity Raman Interactions," *Prog. Quant. Electr.* **6**, 55-140 (1979).
74. L. F. Johnson, R. E. Dietz, and H. J. Guggenheim, "Optical Maser Oscillation from Ni^{2+} in MgF_2 Involving Simultaneous Emission of Phonons," *Phys. Rev. Letters* **11**, 318-320 (1963).
75. P. F. Moulton, "A New Solid State Tunable Laser," Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, Solid State Research Report No. 3, pp. 15-21 (1982).
76. L. F. Mollenauer and D. H. Olsen, "Broadly Tunable Lasers Using Color Centers," *J. Appl. Phys.* **46**, 3109-3118 (1975).
77. E. P. Chicklis, R. C. Folweiler, T. M. Pollak, and J. Baer, "High Power Laser and Materials Investigation," Department of Energy, Defense Programs, Report No. DOE/DP/40054-1 (June, 1980), pp. 7-36.