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(54) **LASER CONTAINING A SLURRY**

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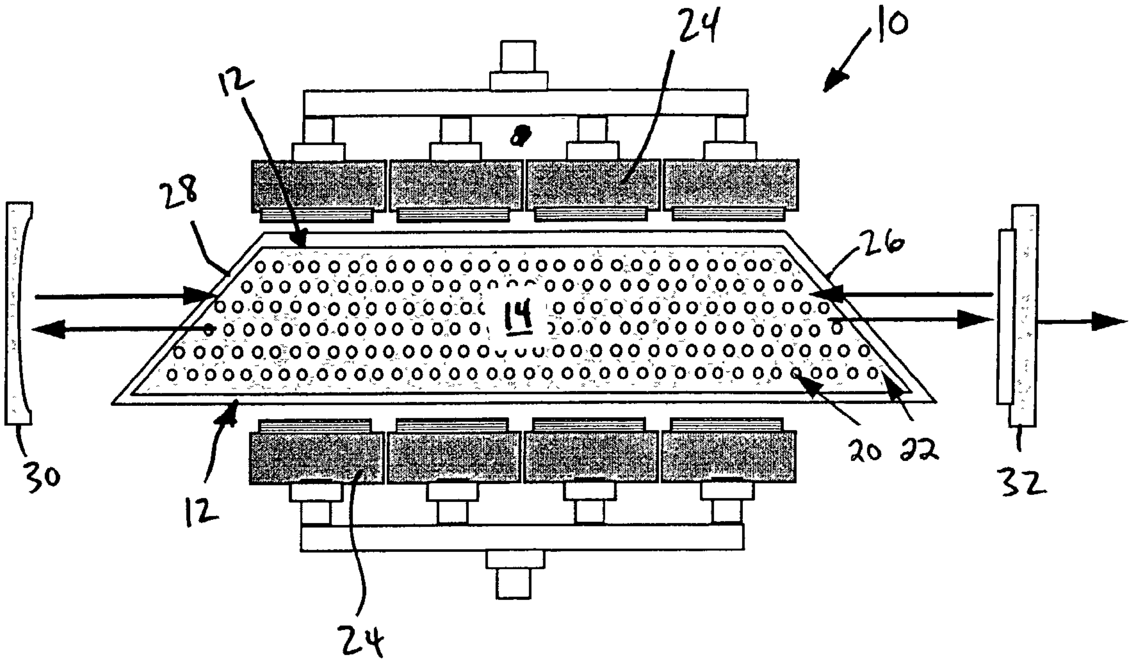
(57) **ABSTRACT**

A laser device and methods of lasing, the laser device comprising a chamber containing a volume formed therein and a gain medium within the volume. The gain medium comprises solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions. In a variation, the gain medium is flowed through the volume, cooled externally of the volume and then flowed back through volume. In preferred form, the solid state portions are either naturally suspended within the fluid or are suspended by flow within the fluid. Thus, laser devices are provided in which the laser and the coolant are homogenized into a single gain medium exhibiting thermal properties of a liquid laser but with solid state gain material in order to produce high energy and high average power.



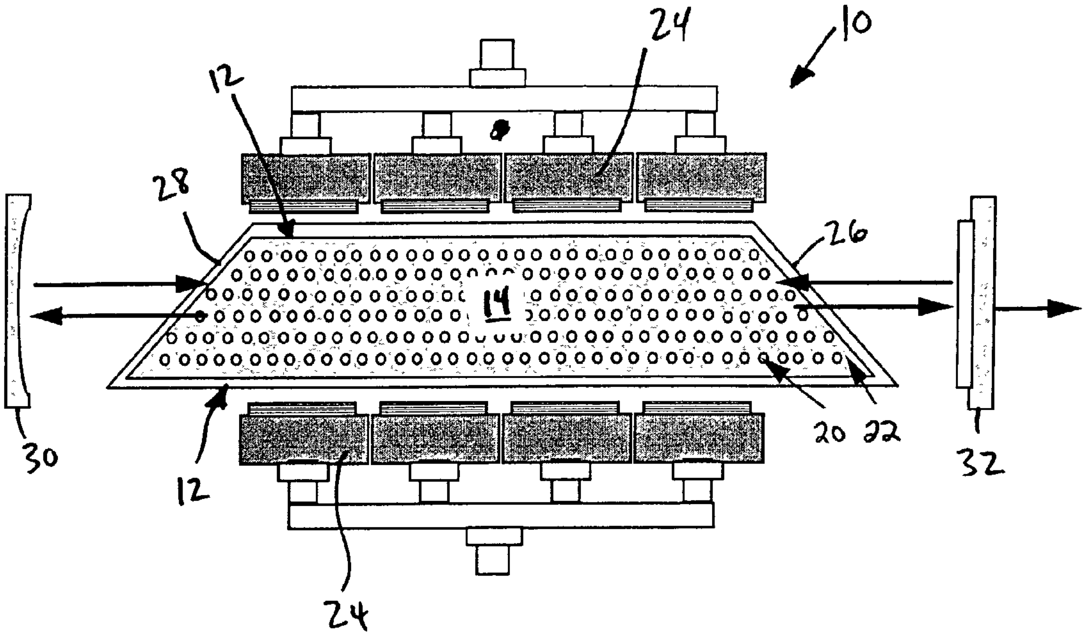


FIGURE 1

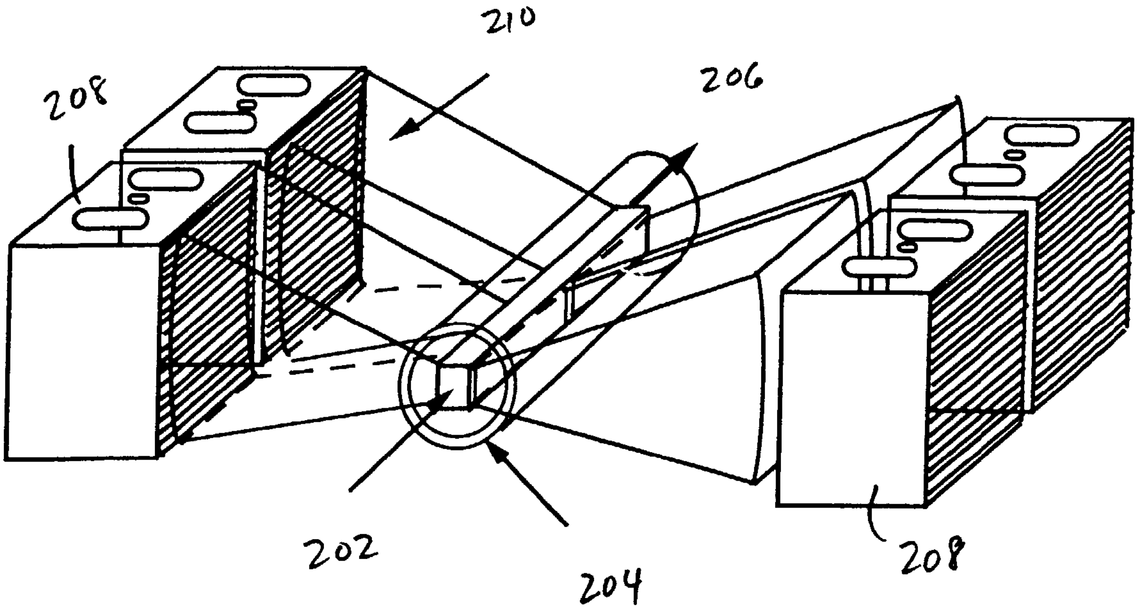


FIGURE 2

PRIOR ART

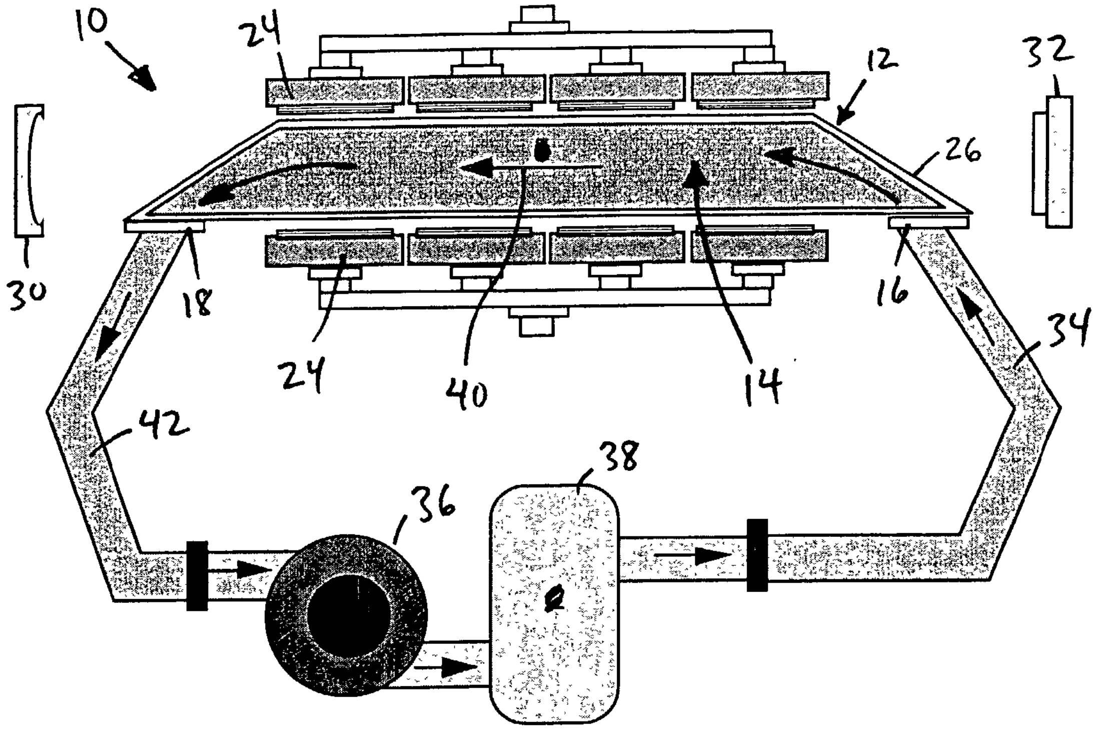


FIGURE 3

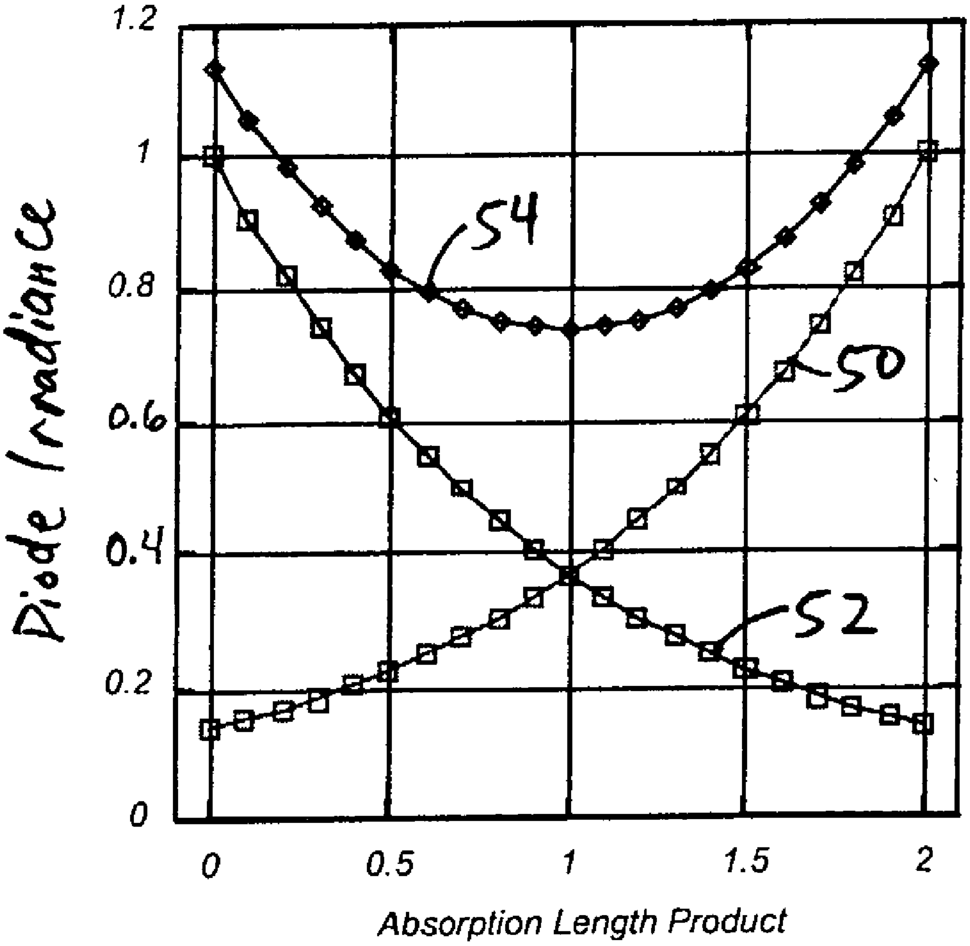

1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Absorption Length Product
Diode Irradiance
54
50
52

FIGURE 4

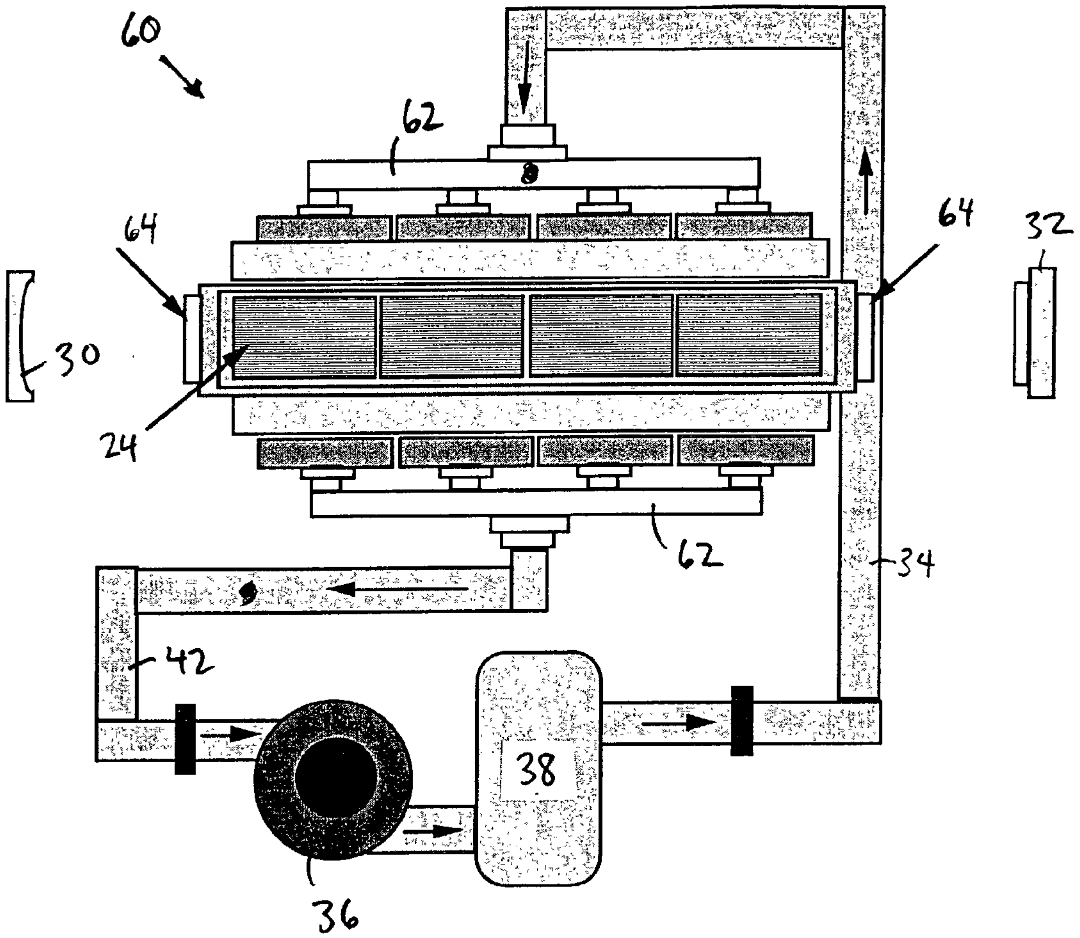


FIGURE 5

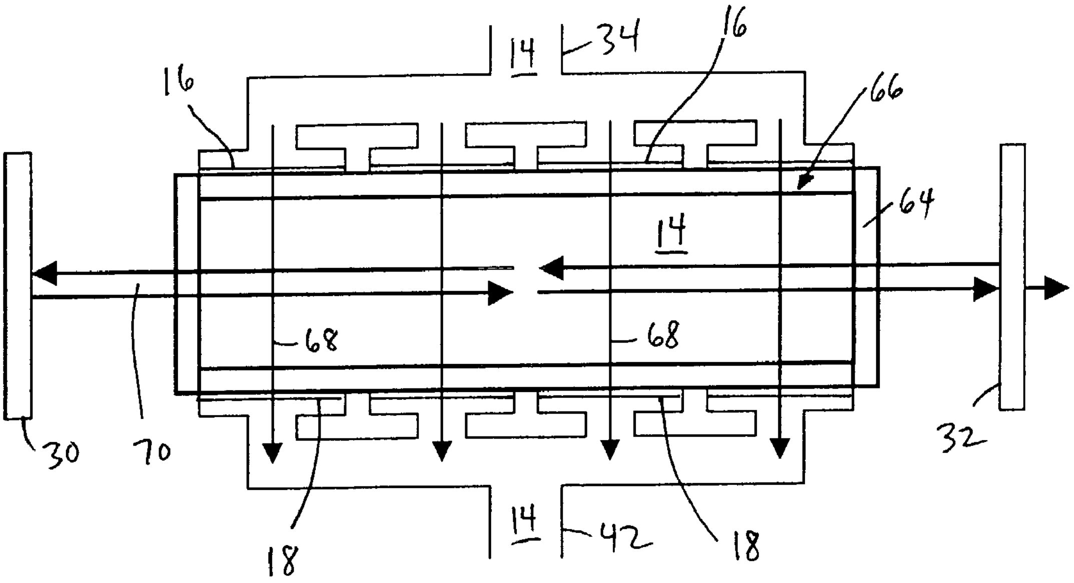


FIGURE 6

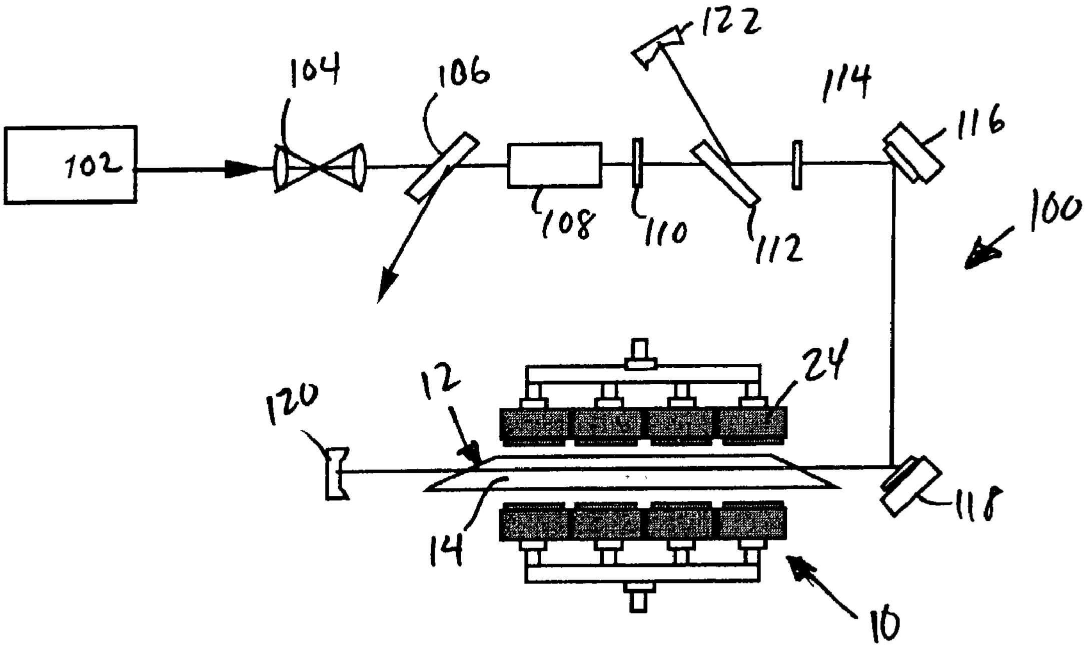


FIGURE 7

LASER CONTAINING A SLURRY

[**0001**] This application claims priority to the following applications: U.S. Provisional Application No. 60/332,085, filed Nov. 21, 2001, entitled LASER CONTAINING A SLURRY; and U.S. Provisional Application No. 60/401,411, filed Aug. 6, 2002, entitled LASER CONTAINING A DISTRIBUTED GAIN MEDIUM, the entire disclosures of both applications incorporated herein by reference.

BACKGROUND OF THE INVENTION

[**0002**] 1. Field of the Invention

[**0003**] The present invention relates to the field of laser systems, and more specifically, it relates to laser systems in which the gain medium is diode-pumped.

[**0004**] 2. Background

[**0005**] Lasers have been produced from a variety of materials and in all phases: liquid, gas, plasma and solid-state. Liquid lasers most commonly contain of a gain medium of organic dye salts such as derivatives of Rhodamine or fluorescein which are dissolved in solvents such as methanol or water. The gain medium is excited by light produced typically by flashlamps or another laser. The pump source must produce radiation in the absorption band of the dye and is typically in the range of 300 to 560 nm depending upon the specific dye being used. These dye lasers exhibit gain across a broad region of the visible to near infrared spectrum. The high gain cross section and broad tunability make these lasers attractive for a number of uses. On the other hand, these dye lasers exhibit a very short upper-state lifetime and low saturation fluence which makes them unsuitable for high energy applications. Furthermore, the absorption bands of these dyes do not overlap with the emission bands of high power semiconductor diode lasers (typically 780 to 980 nm) and are therefore not amenable to pumping with currently available laser diodes.

[**0006**] There have been various attempts at achieving inorganic liquid lasers composed of rare earth salts dissolved in various solvents. The challenge in these systems has been the tendency of the lasing ion (e.g., Nd^{3+}) to undergo radiationless decay from the upper laser level in most liquid solutions. This de-excitation is due to the high energy vibrations of bonds involving light atoms such as hydrogen. By eliminating the presence of any light atoms, this quenching can be reduced to the point where lasing can be achieved. For example, this quenching has been used to achieve lasing in Neodymium Selenium Oxychloride

[**0007**] A significant challenge with such liquid lasers is the extremely corrosive nature of the solvents which requires special handling both the preparation and use of the laser medium. When initially developed, these systems were initially pumped by flashlamps. By using recently developed laser diode arrays as pump sources, the pump light can match the absorption spectrum thereby enabling a resurgence of interest in this type of liquid laser.

[**0008**] Solid-state lasers contain a gain medium which is comprised of a lasing ion contained in a crystal or amorphous matrix. The most common lasing species are based on rare-earth elements such as neodymium, erbium, ytterbium, etc. The laser properties (e.g., absorption and emission cross-section, upper-state lifetime, etc.) of the gain medium are determined by the interaction of the local crystal field with the field of the ion itself. This interaction determines the specific energy levels of the ion and their width. For example, the neodymium ion exhibits a series of narrow absorption lines centered around 808 nm and a series of strong emission lines around 1064 nm when bound in the common crystal matrix, yttrium aluminum garnet (YAG). This laser medium is formed when a small amount of neodymium replaces the yttrium ion in the garnet crystal matrix resulting in neodymium-doped YAG (Nd:YAG). By placing the neodymium in other crystal hosts, different laser properties can be obtained. For example, neodymium dissolved in phosphate glass will produce a series of broad absorption bands extending from 500 to over 900 nm and tens of nanometers in width. Gain is exhibited across a broad band centered at 1054 nm. Unlike dye lasers, these solid-state lasers exhibit a long upper-state lifetime and a high saturation fluence which enables high energy output. In addition, their absorption bands in to 800 to over 950 nm range make them ideal for excitation by the emission from semiconductor laser diodes based on gallium arsenide (e.g., AlGaAs, InGaAs, etc).

[**0009**] Solid-state lasers are formed by growing the crystal (or melting the glass) and then cutting and polishing the crystal into the desired shape. Large scale single-pulse systems with the solid-state media in the shape of disks have been developed for laser-driven inertial confinement fusion research with disks over 40 cm in diameter. These systems produce very high pulse energy (approximately 15 kJ) but disadvantageously, have low average power (less than 1 W). High average power systems containing either Nd:YAG or Yb:YAG as the gain medium and pumped by laser diodes have been developed at the kilowatt level. A typical diode-pumped solid-state laser is shown in **FIG. 2**. The solid state laser **200** includes a laser rod **202** surrounded by a flow tube **204** (sheath) which directs a coolant fluid flow **206** across the laser rod **202** and prevents contact of the laser rod **202** with diode pump sources **208**. Pump radiation is produced by the diode arrays **208** which may be coupled into the laser rod **202** by a refracting means **210** (e.g., lenses) or other reflecting means. The coolant fluid removes heat from the laser rod **202** through convection by flowing the fluid **206** over the surface of the laser rod **202**. Heat is conducted through the laser rod to the surface. This conduction establishes a large temperature gradient between the center of the rod and the surface. This gradient causes stress within the material which results in beam distortion and eventually catastrophic failure of the crystal. As a result, the average power available from solid-state lasers is limited by the ability to remove heat from the medium.

[**0010**] A class of solid-state lasers which contained the solid material immersed in a fluid were developed in the 1970's and 1980's. These so called "immersion lasers" were flashlamp-pumped and had the solid-state laser material shaped into various forms. For example, as described in U.S. Pat. No. 3,735,282 issued to Gans, a pulsed laser is described which is composed of a segmented Nd:Glass rod immersed in a liquid which is index matched at the emission wavelength. The liquid consists of brominated acyclic hydrocarbon mixed with acyclic alcohol. The segmented rod is immersed in a thermostatically controlled housing surrounded by a helical arc lamp containing xenon or krypton. Gans focuses on a particular type of index matching fluid containing OH and bromine groups to prevent ultraviolet hydrolysis of the index matching fluid.

[0011] A similar laser architecture can be found in U.S. Pat. No. 3,602,836 issued to Young, which teaches the use of a segmented laser rod immersed in a coolant fluid. Young focuses on meniscus-shaped segments of zero lens power spaced apart a sufficient distance to permit free passage of sufficient coolant. In U.S. Pat. No. 3,621,456 issued to Young, the use of parallel discs is described containing reflective surfaces. In U.S. Pat. No. 3,487,330, issued to Gudmundsen, a laser arrangement is described in which a flashlamp is enclosed by segmented laser material. In such a system, the coolant flow would be directed inwardly across the segmented laser materials so that the unheated coolant first crosses the laser material and then cools the lamp. Additionally, Gudmundsen also describes that the flashlamp is placed adjacent to the segment laser material. Gudmundsen primarily focuses on various coolant flow geometries for cooling the laser media and the flashlamp.

[0012] A packed bed laser composed of solid state glass lasing elements was described in U.S. Pat. No. 4,803,439 issued to Ryan, et al. Ryan et al. teach the use of lasing beads or elements which are packed within a laser cavity to be in contiguous contact with each other. The laser elements are to be of the order of 1 cubic millimeter in volume to facilitate the packing of the glass lasing elements contiguously into the laser amplifier cavity. A cooling fluid is pumped through and in between the lasing beads which are packed within the laser cavity such that they are fixed in space within the cavity. Additionally, a phase conjugate mirror is required to cancel the optical distortions associated with the lasing medium.

[0013] All of these solid-state laser systems including the so called immersion lasers are limited in average power output by heat removal from the gain media. The difference between the energy of the pump photon and the emission photon is referred to as the quantum defect and left in the crystal as heat. For example, Nd:YAG is pumped by laser diode radiation at 808 nm (photon energy=1.53 eV) and emits laser radiation at 1064 nm (1.17 eV), the quantum defect of 0.36 eV appears as heat within the medium following lasing. This heat must be removed or will terminate lasing by thermally populating the lower laser level (e.g., Yb:YAG) or eventually resulting in catastrophic failure of the laser crystal by thermal stresses associated with the temperature gradient across the crystal. Severe beam distortion and depolarization resulting from the temperature dependence of the refractive index and stress birefringence occur far below the limit of thermal stress induced fracture. Heat is removed by flowing a coolant across the laser material, for example, as shown in **FIG. 2**. The diode-pumped solid state laser assembly **200** shown in **FIG. 2** is representative of current state of the art side-pumped laser systems. Alternate heat removal methods designed to address the problem of thermal stress and beam distortion have led to a variety of laser designs, such as thin-disk and zig-zag slab solid state lasers.

[0014] What is needed is a laser device in which the advantages of a solid-state gain medium (e.g., diode-pumping, high power density, etc) can be realized but which is not limited in average power output by thermal stress.

SUMMARY OF THE INVENTION

[0015] The present invention advantageously addresses the needs above as well as other needs by providing a laser device which addresses the thermal limitations in solid state lasers by homogenizing the laser and coolant into a single gain medium. Such a laser is not limited by thermal stress or other thermal effects in the solid-state gain medium.

[0016] In one embodiment, the invention may be characterized as a laser device comprising: a chamber containing a volume formed therein; and a gain medium within the volume, the gain medium comprising solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions.

[0017] In another embodiment, the invention may be characterized as a method of lasing, and a means for accomplishing the method, the method comprising the steps of: providing a chamber having a volume formed therein and containing a gain medium, the gain medium comprising solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions; and directing optical pump radiation through the chamber into the volume; directing a laser emission through the chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The above and other aspects, features and advantages of the present invention will be more apparent from the following more particular description thereof, presented in conjunction with the following drawings.

[0019] **FIG. 1** is a laser device in accordance with one embodiment of the present invention including a gain medium is comprised of rare-earth doped solid-state particles distributed throughout an index matched fluid which is flowed through a laser chamber. The gain region is pumped by semiconductor diode arrays emitting in the absorption band of the rare-earth ion in the solid-state host. Flow of the fluid containing the particles is along the laser axis.

[0020] **FIG. 2** is a diode-pumped, solid-state laser gain assembly representative of the current art, including a laser rod surrounded by a flow tube which direct coolant flow across the laser rod and prevents contact with a diode pump source. Pump radiation is produced by the diode arrays of the diode pump source which may be coupled into the laser rod by refracting (e.g., lenses) or reflecting means.

[0021] **FIG. 3** is a system view showing a representative flow system associated with the laser device shown in **FIG. 1**.

[0022] **FIG. 4** is a plot of diode irradiance vs. absorption length of the product illustrating the distribution of diode pump radiation for a rectilinear parallelepiped laser chamber pumped on two opposing faces according to one embodiment of the invention. The abscissa is the product of the absorption coefficient and the transverse length, $\alpha_a L$.

[0023] **FIG. 5** is a laser in accordance with another embodiment of the present invention including a gain medium comprised of rare-earth doped solid-state particles distributed throughout a substantially index matched fluid which is flowed through the laser chamber. The gain region between the mirrors is pumped by diode arrays. Flow of the fluid containing the particles is transverse to the laser axis

[**0024**] **FIG. 6** is an enlarged view of the laser chamber of the laser device of **FIG. 5** illustrating the flow of the gain medium.

[**0025**] **FIG. 7** illustrates an example of one embodiment of the current invention used as a four-pass amplifier.

DETAILED DESCRIPTION OF THE INVENTION

[**0026**] It is an objective of several embodiments of the present invention to provide a diode-pumped laser in which the average power of the laser is not limited by thermal stress or other thermal effects in the solid-state gain medium.

[**0027**] It is an objective of several embodiments of the present invention to provide a diode-pumped laser which may be operated continuously or pulsed.

[**0028**] It is also an objective of several embodiments of the present invention to provide a laser in which the solid-state gain medium is distributed throughout the coolant and in intimate contact with it.

[**0029**] A laser in accordance with several embodiments of the invention can be used either as the gain medium for a laser oscillator or as an amplifier.

[**0030**] As described previously, there are a multitude of geometries for diode-pumped solid-state lasers. These configurations all utilize a solid-state gain medium which has been configured as a rod, slab, or disk and heat is removed from the gain medium either by conduction to a thermal reservoir or by convection to a coolant flowing over the surface. In both cases, temperature gradients cause stress within the gain medium resulting in beam distortion and eventually catastrophic failure of the laser if the average power is not limited. It is an objective of several embodiments of the present invention to provide a diode-pumped laser architecture with a large gain aperture which enables both side or end-pumping architectures and achieves high extraction efficiency and higher average power operation than can be achieved from current state-of the art side-pumped or end-pumped laser rods or slabs.

[**0031**] According to one embodiment, the solid-state laser medium is immersed in a liquid coolant which is approximately matched in refractive index to the solid-state laser medium. Such a system is homogeneous to the electromagnetic wave and enables the use of a solid-state laser gain medium which has a dimension sufficiently small that heat is rapidly conducted out of the solid-state element into the liquid coolant.

[**0032**] Referring to **FIGS. 1 and 3**, a laser device **10** is illustrated which includes a chamber **12** having a volume formed therein. A gain medium **14** is flowed through the volume (also referred to as a lasing region) of the chamber. In one embodiment, the gain medium **14** flows into the volume via an inlet **16** and out of the volume via an outlet **18** of the chamber **12**. According to one embodiment, the gain medium **14** comprises particles **20** (referred to generically as portions **20**) of solid-state gain medium such as rare-earth (e.g., neodymium) doped glass, yttrium-aluminum garnet or other laser host which are distributed within a substantially index-matched fluid **22**. The fluid **22** serves as the coolant for the laser gain medium. The particles **20** may be any shape, however, spheroids are the preferred embodiment in order to minimize erosion of the piping and laser windows. In one embodiment, the particles **20** are sized such that they can be suspended within the liquid medium creating a slurry. Herein, the term slurry refers to the system comprised of particles **20** within a fluid **22**, e.g., suspended within the fluid **22**. The term is specifically used to include particles whose size is sufficiently small that they are naturally suspended in the fluid **22** in the absence of flow (e.g., also known as a colloid) and particles which are suspended within the fluid **22** by the action of buoyancy and flow. The solid state particles **20** are excited by pump radiation from arrays of semiconductor laser diodes **24**. The diode pump radiation is introduced from the sides of the laser chamber **12**.

[**0033**] Advantageously, a laser device is provided in which the gain medium **14** contains solid state material but exhibits thermal properties similar to a pure liquid. This is in contrast to known liquid lasers, since the gain medium **14** contains solid state material. This is further in contrast to known solid state lasers since the solid state particles are effectively homogenous with the flowing index-matched cooling fluid **22**. For example, the solid state particles **20** actually flow with the fluid **22**, as opposed to the fluid flowing over or about solid state material. This results in a laser device capable of high energy and high average power which is generally not limited by heat removal from the solid state material. Since the laser device is generally not limited by heat removal, the laser device may be operated in either a pulsed manner or continuously.

[**0034**] According to one embodiment, the laser chamber **12** is composed of transparent optical material such as fused silica, borosilicate glass or sapphire and may take on a variety of geometries, such as a rectilinear parallelepiped. For example, the laser chamber **12** includes walls having a thickness and forming the laser chamber with the volume therein. Diode produced pump radiation passes through one or more walls of the laser chamber **12**. The ends **26** and **28** of the laser chamber **12** are composed of transparent optical material and preferably oriented at an angle to permit the slurry of solid state particles **20** and fluid **22** to easily flow into the chamber **12**. Depending on the embodiment, the laser device of **FIGS. 1 and 3** can be used either as a laser oscillator or as an amplifier. The chamber **12** containing the gain medium is placed within a cavity composed of a high reflector **30** and an output coupler **32** (also referred to as a partially transmitting mirror **32**) when the invention is configured as a laser oscillator. It is noted that in other embodiments, the laser chamber **12** comprises a cylindrically shaped structure having end walls and through which the mixture of solid state particles **20** and index matched fluid **22** is flowed, e.g., where the inlet and outlet are formed in the sides of the cylindrical chamber.

[**0035**] As illustrated in **FIG. 1**, the slurry, which includes the solid state particles **20** within the fluid **22**, is flowed in the direction substantially parallel to the axis of the laser emission (the emission illustrated as arrows in **FIG. 1**). Thus, the laser emission passes through the slurry. Radiation from laser diode arrays **24** at a wavelength tuned to the absorption band of the solid-state medium enters through a window on the side wall of the laser chamber **12** containing the flowing slurry. In preferred embodiments, the fluid **22** is selected such that it exhibits low absorption at both the absorption and emission wavelength of the solid-state gain medium (e.g., for Nd:glass λ_a 803 nm and λ_{em} 1054 nm). The radiation from the pump diodes **24** is absorbed within the solid-state particles **20** which are suspended within the fluid. In order to be suspended within the fluid **22**, the particles **20** should be sufficiently small that the distribution of particles **20** within the fluid can be made approximately uniform while the gain medium resides within the region where laser action is required, i.e., resides within the volume within the chamber **12**. In the case of very small particles, they can be naturally suspended without flow by a combination of surface tension, buoyancy and Brownian motion.

[0036] Larger particles **20** may require flow to achieve suspension. The buoyant force on the particle is determined by its size and density according to $F_B=(4\pi R^3/3)[\rho_{solid}-\rho_{liquid}]g$ where R=particle radius, g is the gravitational constant ($g=9.8$ m/sec^2), ρ_{solid} is the density of the solid state particle and ρ_{liquid} is the density of the fluid **22**. The buoyant force should be balanced by the force associated with bulk flow for the length of time that the particles are within the lasing region. The flow requirements to establish uniform slurries have been the subject of extensive research in chemical engineering and many correlations exist. A correlation applicable to one embodiment of the present invention is that originally developed by Spells, et al for describing the flow velocity, u, necessary to suspend a slurry of sand in water flowing in a horizontal pipe. According to one embodiment, when the particle size is less than approximately 1 mm, the required velocity is obtained by solving,

$$\left(\frac{u^2}{2\,gR_S}\right)\frac{\rho_L}{(\rho_S-\rho_L)}=0.0251\left(\frac{\rho_m uD}{\mu_L}\right)^{0.775}$$

[0037] where

[0038] u=flow velocity

[0039] ρ_s=Density of solid particle

[0040] ρ_L=Density of liquid

[0041] ρ_m=Density of slurry (mixture of the solid particle and the liquid)

[0042] D=Diameter of pipe

[0043] R_s=Radius of solid particle

[0044] In preferred embodiments, the particles **20** are sized to be less than 1 mm, more preferably less than 1 μm. For example, particles **20** are preferably sized between 10 nm and 2 mm in diameter.

[0045] In addition to exhibiting negligible absorption, in this embodiment, the fluid **22** is approximately index matched to that of the solid-state medium (solid state particles **20**). This is required in order that the losses resulting from Mie scattering are sufficiently small to not significantly effect the efficiency of the laser or the net single-pass gain. There are index matching fluids available within the laser community. While commercially available index matching fluids may be used, simple mixing of miscible fluids: one with an index above that of the particle **20** and one below can be used. In one embodiment, the fluids are mixed in the ratio determined by

$$n_1x+n_2(1-x)=n_p$$

[0046] where

[0047] n_1=refractive index of fluid **1**

[0048] n2=refractive index of fluid **2**

[0049] np=refractive index of the solid particle

[0050] x=mixing fraction

[0051] For this fluid mixture, the density is given by, $L=1x+2(1-x)$. An example would be the mixture of carbon tetrachloride and carbon disulfide to provide an index matched fluid **22** for the suspension of neodymium-doped phosphate glass as the solid state particles **20**. Carbon disulfide has a refractive index at 1054 nm of 1.62 and carbon tetrachloride has an index of 1.45 while the Nd-doped phosphate glass LHG-5 has a refractive index of 1.531. By mixing carbon disulfide and carbon tetrachloride with 47.65% CS2, an index matched slurry can be obtained.

[0052] In the embodiment shown in **FIG. 3**, the fluid **22** containing particles **20** of the solid-state gain medium (the slurry/colloid) is pumped into the laser chamber **12** through a pipe **34** coupled to the chamber inlet **16**. The fluid pump **36** is a common slurry pump with seals designed for compatibility with the index matching fluid **22**. The gain medium (i.e., a slurry including particles **20** within the fluid **22**) flows from the pump **36** into a heat exchanger **38** where the fluid is cooled back to its starting temperature. The heat exchanger **38** is most commonly a tube type exchanger where heated fluid is cooled by conduction through one or a series of tubes which are, in turn, cooled by a secondary fluid. The secondary cooling fluid is most commonly water or air. Following the heat exchanger **38**, the gain medium **14** flows into the laser chamber **12** through the inlet **16** via the pipe **34**. In this embodiment, the inlet **16** and the pipe **34** are configured to introduce the slurry into the laser chamber **12** at a shallow angle relative to the window forming one end **26** of the chamber so as not to create turbulent eddies against the window. Additionally, the slurry enters the laser chamber and flows in a direction substantially parallel to the axis of laser emission, the direction of flow indicated in **FIG. 3** as arrow **40**. It is noted that in other embodiments, the pipe **34** may be configured to flow the slurry across or transverse to the laser axis depending on the location of the inlet **16** and outlet **18**, such as illustrated in **FIG. 5**. The minimum flow velocity set by the pump **36** is that required to achieve an approximately uniform suspension of the solid particles **20** within the fluid **22**. The slurry now flows along the laser axis and is directed back out of the laser chamber **12** through outlet **18** by striking the second window forming another end **28** of the chamber **12**. The slurry then flows through pipe **42** back to the pump **36** and heat exchanger **38**. Thus, the shape of the ends **26** and **28** and the orientation of the pipes **34** and **42** into the inlet **16** and the outlet **18** assist in directing the fluid flow through the chamber **12** without introducing eddies or other turbulence. While within the volume forming the laser cavity or lasing region, the gain medium **14** is excited by radiation from the diode arrays **24**. As a result of this excitation, the temperature of the gain medium **14** increases. The mixture of solid state particles **20** within the fluid **22** then returns back to the pump **36** completing the flow cycle.

[**0053**] An enlargement of the laser chamber **12** is shown in **FIG. 1**. A laser cavity is formed on one end by a high reflector **30** which is a multilayer dielectric coated mirror designed to be a high reflector at the laser emission wavelength. In alternate embodiments, this mirror can be comprised of a metallic or semiconductor reflector which may or may not contain a dielectric coating. As described above, the gain medium **14** is comprised of the slurry containing solid-state particles **20** in the index matched fluid **22** which is bounded on both ends **26** and **28** of the chamber **12** by an optical window (where the ends **26** and **28** of the chamber for the windows). In one embodiment, Fresnel losses off of this surface may be minimized by orienting this window at Brewster's angle, i.e., the ends **26** and **28** are oriented at Brewster's angle relative to the axis of laser emission. At this angle, light which is polarized in the plane of the window passes through with no reflection at the surface even when the surface is uncoated. In the preferred embodiment, the window is of laser grade quality and is made from either fused silica, sapphire or borosilicate glass. The slurry is also directed along the laser axis by the optical windows formed in ends **26** and **28**. At the other end of the cavity is the output coupler **32**. The output coupler **32** is a partially reflecting mirror which transmits some of the incident laser radiation. In the preferred embodiment, the mirror of the output coupler **32** is comprised of a multilayer dielectric coating deposited on a fused silica substrate and designed to transmit 10 to 80% of the incident laser radiation. The optimum transmission and geometry of this mirror will be determined by the single-pass gain within the cavity which is a function of the available pump power from the diodes, the concentration of lasing ion (e.g., neodymium) and the length of the gain region and overall cavity design requirements which are well known in the art. The gain medium **14** is excited by pump radiation from diode arrays **24** arranged on the side of the gain region. The diode arrays are designed to emit in the absorption band of the solid-state particles **20** (e.g., near 800 nm for neodymium). The pump radiation from the diode arrays **24** passes through the sides of the chamber **12** which is formed from either fused silica, borosilicate glass or other optical materials known in the art.

[**0054**] As mentioned previously, in one embodiment, the particle **20** size is determined by that which enables a uniform suspension of the solid state particles **20** within the fluid **22**. However, to complete the design, the concentration of particles is specified. In this embodiment, the concentration should not be large enough to cause a distortion of the flow within the volume of the laser chamber **12**, heat exchanger **38** or pump **36**. Particle concentrations corresponding to a volume fraction less than approximately 30% have been shown to work well. Further determination of the particle concentration is determined by laser dynamics. First, in the side-pumped embodiment shown in **FIG. 1**, the concentration of solid state particles **20** within the fluid **22** must be sufficiently high to absorb the majority of pump radiation from the diodes **24**. Accordingly, the diameter of the volume of the chamber **12** may be adjusted such that approximately 90% of the diode light is absorbed. According to one embodiment, this requirement can be written as exp[−a D] 0.08, where D is the effective diameter of the volume or gain region and a is the effective absorption coefficient for pump radiation. When pumped from both sides, the pump light within the volume will have the approximate distribution as shown in **FIG. 4**. In **FIG. 4**, curve **50** is the normalized diode irradiance vs absorption length for diode pump radiation entering through one side of the laser chamber **12** shaped as a rectilinear parallelepiped, while curve **52** is the diode irradiance vs absorption length for diode pump radiation entering through an opposite side of the laser chamber **12**. Curve **54** represents the summation of curves **50** and **52** indicating the absorption of diode pump radiation through a cross section of the laser chamber **12**. The effective absorption coefficient, α_a is given by

$$\alpha_a = N_o \sigma_a V_s$$

[**0055**] where

[**0056**] N_o=Concentration of absorbing ions in the solid-particle

[**0057**] σ_a=Absorption cross section

[**0058**] V_s=Volume fraction of solid particles

[**0059**] For example, LG-760 Nd:Phosphate laser glass doped at 5 wt % has a neodymium concentration of 4.65×10^{20} ions/cm^3 and an effective absorption cross section over the 803 nm band of 2.4×10^{-20} cm^2. Hence, each individual particle would exhibit an absorption coefficient of 11 cm^1. In a slurry with a volume fraction of 5% occupied by the solid particles, the effective absorption coefficient of the slurry would then be, α_a=0.56 cm^{-1}. Hence, in order to achieve 90% absorption of the pump radiation, the diameter of the gain region would be approximately 3.6 cm.

[**0060**] The effective small-signal gain coefficient, α_e, is similarly given by,

$$\alpha_e = N \sigma_e V_s$$

[**0061**] where σ_a is the emission cross section and N is the concentration of ions within the solid particle which have been excited by the pump radiation. Since the particles are much smaller than the absorption length, the ion concentration which is excited is approximately, $N=\alpha_a \phi_p(x,y,z)\tau_p$ where $\Phi_p(x,y,z)$ is the local photon flux from the pump diodes at the point (x,y,z) within the laser chamber **12** (see **FIG. 4**) and τ_p is the duration of the pump light. This approximation of $N=\alpha_a \phi_p(x,y,z)\ \tau_p$ is applicable for pulsed diode pumping and neglects any spontaneous emission during the pump duration. The pump irradiance available from current state of the art diode arrays is approximately 500 W/cm^2. This corresponds to a photon flux, ϕ_p, at the output of the diodes of 2×10^{21} photons/cm^2-sec. With a diode pulse of τ_p=400 microseconds and assuming a uniformly pumped gain region, the excited state density within the solid-particle is $N=\alpha_a \phi_p(x,y,z)\ \tau_p = 11\ \text{cm}^{-1} \times (2 \times 10^{21}$ photons/cm^2-sec)$\times 4 \times 10^8$ sec$=9 \times 10^{18}$ ions/cm^3. Continuing with LG-760, as the example, the emission cross section is 4.2×10^{-20} cm^2. Again with 5% Nd-doping and a volume fraction of solids equal to 5%, the effective gain coefficient for the slurry is α_e=0.019 cm^{-1}. The small signal gain, G_o is given by, $G_o=\text{Exp}[\alpha_e L]$, where L is the length of the pumped region of the laser chamber. Satisfactory laser performance is achieved with a small signal gain of approximately 1.5. Hence, the pumped length required for this example is approximately 21 cm.

[**0062**] In the embodiments illustrated in **FIGS. 1, 3** and **5**, the laser chamber **12** was pumped from two sides at 500 W/cm^2. Since the width and length of the laser chamber **12** are set by absorption and gain, respectively, the only variable dimension in this embodiment is the height. In principle, any height could be used when pumping from the two sides. However, diffraction of the beam is minimized when the aspect ratio of the aperture is approximately 1:1. Hence, in preferred embodiments, good laser performance with minimal divergence would be obtained when the height is approximately equal to the width. For our present example, the height would therefore be 3.6 cm. The total diode power would then be approximately 38 kW from each side. Current state of the art diode arrays **24** contain 1 cm long bars placed on a 1.7 mm pitch. With 2 mm between the bars, we would have two blocks of diode arrays **24**, each of which is 10 bars long and 21 bars high on each side of the laser chamber **12**. The total number of bars on each side is then 420. To achieve 38 kW pump, will require each bar to operate at 90 W for the duration of the pump pulse. This value is achievable with current state of the art gallium arsenide based diode bars.

[0063] No conventional solid-state laser could operate at this level of average diode pump power and size. Laser operation would cease rapidly as the temperature increased in the absence of cooling. The laser material would have to be cooled by a fluid flowing over its surface, such as illustrated in the conventional liquid cooled rod of **FIG. 2**. Even with cooling such as illustrated in **FIG. 2**, conventional solid-state laser materials would fracture due to thermal stress resulting from the large temperature gradient which would be established between the center region of the solid state laser material and the cooled surface. According to several embodiments of the invention, this problem is solved by sizing the solid-state laser particles **20** sufficiently small that the temperature gradient established between the center of the particle **20** and its surface is small. Furthermore, the temperature of the particle **20** is readily controlled by simply controlling the temperature of the fluid **22** by conventional heat exchanger technology which is well known in the art. Additionally, since the slurry flows through the chamber **12**, individual particles **20** are exposed to the pump radiation for less time since they flow out of the chamber and are cooled, in contrast to known solid state lasers in which the solid state gain medium is fixed in location and the cooling fluid is flowed the stationary gain medium.

[0064] These features are quantified by calculating the temperature distribution inside a spherical particle. For a spherical particle **20** suspended in a cooling fluid **22** and moving with the fluid, the steady-state temperature distribution inside the sphere is given by,

$$T(r) - T_f = \frac{q''' R^2}{6k_s}\left[1 - \left(\frac{r}{R}\right)^2 + \frac{2k_S}{k_f}\right]$$

[0065] where k_s and k_f are the thermal conductivities of the solid laser medium and the fluid, respectively. Outside the sphere, the temperature distribution is given by,

$$T(r) - T_f = \frac{q''' R^2}{3k_f}\left[\frac{r}{R}\right]$$

[0066] The temperature at the solid-liquid interface is represented by $T(R)=T_s$ and the radius of the spherical particle is R. Heat generation, $q'''(W/cm^3)$ occurs throughout the sphere at a rate given by,

$$q'''=I_{pump}\alpha_a\delta$$

[0067] where I_{pump} is the irradiance of the pump radiation, α_a is the absorption coefficient described earlier and δ is known as the quantum defect. The quantum defect is the difference in energy between the absorption and emission bands of the laser medium. For Neodymium, photons absorbed near 803 nm have an energy of 1.54 eV and the emission near 1060 nm have an energy of 1.17 eV, quantum defect, δ(1.54 eV−1.17 eV)/1.54 eV=24%. In other words for every photon absorbed from the pump, at least 0.37 eV is left in the solid-state material as heat. For a pump flux of $I_{pump}=500\ W/cm^2$ (see distribution in **FIG. 4**) and the absorption coefficient described earlier ($\alpha_a=11\ cm^{-1}$), we will have heat generated inside the sphere at a rate of $q'''=1320\ W/cm^3$.

[0068] The significance of several embodiments of the present invention lie in the dependency of the temperature on the square of the dimension of the solid-state laser media (i.e., each solid state particle **20**). The thermal conductivity of carbon tetrachloride is 0.1 W/m ° C. while that of LG-760 Nd:Phosphate laser glass is 0.67 W/m ° C. From the above equations, we see that the temperature difference between the center of the sphere and the surface, $\Delta T=T(0)-T(R)=q'''R^2/6\ k_s$ is negligible (much less than 1° C.) for a 10 micron diameter sphere and pumped as described previously. Note that a conventional rod with a diameter of the order of 1 cm pumped under the same conditions would exhibit a characteristic thermal difference between the center and the edge of several thousand degrees with catastrophic failure occurring much earlier.

[0069] It is also noted that in one embodiment, in order to optimize heat removal from the individual solid state particles **20** within the fluid **22**, the individual particles **20** should be suspended within the fluid **22** such that individual solid state particles do not contact each other, or if adjacent particles **20** do contact they only briefly contact and are not held in contiguous contact within the fluid **22**. This provides the most surface area for the individual particles **20** contacting the cooling fluid **22** and insures conduction of heat to the fluid and not to adjacent particles. Particles in constant or even near constant contact with each other would defeat the advantage of several embodiments of the current invention.

[0070] As such, according to several embodiments, the flowing slurry-like gain medium provides a laser device that can operate at high average power and is not limited by thermal gradients. This is due in part to the relative size of the solid state particles as mixed within the flowing index matched fluid. The substantially index matched fluid **22** is preferably such that the fluid has very low absorption at the relevant laser emission wavelength and the relevant optical pump source wavelength; thus, the majority of the pump radiation is absorbed by the solid state particles **20**. Since the laser device is generally not limited by thermal gradients in the solid state material, the laser device may be operated in a pulsed manner or in a more continuous manner. For example, a laser device in accordance with several embodiments of the invention may be operated continuously for very long periods of time, e.g., periods of time greater than 1 second. That is, the optical pump radiation from the semiconductor diode array is continuously pumped into the gain medium **14** for a duration of at least the time desired for laser output. This output time is limited only by the ability to supply pump power to the gain medium and remove heat from the fluid in the heat exchanger.

[**0071**] It is noted that in alternative embodiments, the gain medium **14** including the solid state particles **20** suspended within the fluid **22** flows within the volume of the chamber **12**, but not necessarily into the chamber, through the chamber and then exits the chamber. For example, in such an alternative embodiment, the chamber **12** does not include and inlet and an outlet for the gain medium to flow there through. In this embodiment, the gain medium **14** may simply flow from one end of the chamber to another end of the chamber, or is flowed or circulated within the chamber. Conventional heat sinks of other heat removal devices could be used to remove the heat through convection. In another alternative embodiment, the gain medium including the solid state particles **20** suspended within the fluid **22** does not flow within the volume of the chamber **12**. For example, the fluid is generally static within the chamber, heat being removed by conventional heat sinks or other heat removal convection devices.

[**0072**] Another embodiment of a laser device **60** according to the present invention is shown in **FIGS. 5 and 6** in which the mixture of solid state particles **20** and fluid **22** flow through a manifold **62** and across the laser axis. Here, the laser gain medium **14** is again composed of particles **20** suspended in a refractive index-matched fluid **22**. The laser fluid (particles suspended in fluid) is pumped into the laser chamber **66** through a manifold **62** located on the side of the laser chamber **66**. The purpose of the manifold **62** is to distribute the fluid **22** and solid state particles **20** uniformly throughout the volume within the laser chamber **66** and maintain a uniform flow velocity and pressure. As shown in **FIG. 6**, the particles **20** and fluid **22** flow across (e.g., transverse to) the laser axis instead of along (or parallel to) it as shown in **FIGS. 1 and 3**; however, it is noted that individual particles **20** are not illustrated in **FIG. 6**, but appear as those illustrated in **FIG. 1**. The direction of the gain medium or slurry flow is indicated by arrows **68** while the laser axis is along arrows **70**. In one embodiment, the slurry flows vertically from top to bottom through the laser chamber **66**. The fluid pump **36** is a common centrifugal pump with seals designed for compatibility with the index matching fluid. In this embodiment, the laser chamber **66** (also referred to as the laser head) is composed of the manifold **62**, windows (not shown) to allow entry of the pump radiation, and end caps **64** which are transparent to the laser radiation. Thus, in this embodiment, the laser chamber **66** generally defines a rectangular parallelpiped lasing region or volume formed therein; however, it is understood that the chamber itself and its volume may take on other known geometries, such as cylindrical. It is noted that the end caps **64** are oriented normal to the axis of the incident laser beam; however, it is understood that the end caps may be oriented other than normal with respect to the path of the laser emission, e.g., at Brewster's angle.

[**0073**] The fluid **22** flows from the manifold **62** forming the laser chamber **66** through the pump **36** and into a heat exchanger **38** via pipe **42** where the fluid is cooled back to its starting temperature. The heat exchanger **38** is most commonly a tube type exchanger where the hot fluid is cooled by conduction through one or a series of tubes, which are, in turn, cooled by a secondary fluid. The secondary cooling fluid is most commonly water or air. Following the heat exchanger, the fluid flows back to the laser chamber **66** via pipe **34** and into the chamber via the manifold **62**. In this embodiment, the inlet **16** (of **FIG. 3**) for fluid flow into the chamber is formed as a plurality of openings or inlets **16** as provided by the manifold **62**. Likewise, the outlet **18** (of **FIG. 3**) for fluid flow out of the chamber is formed as a plurality of openings or outlets **18** as provided by the manifold **62**

[**0074**] As best illustrated in **FIG. 5**, the solid laser material **20** is excited by radiation from the diode arrays **24**. As a result of this excitation, energy is stored in the upper laser level. Like the embodiments described previously, the gain medium **14** appears as homogeneous to the electromagnetic wave since the coolant fluid **22** is in intimate contact with the solid-state particles **20** and is index matched to it. Laser oscillation occurs between the high reflector **30** and the output coupler **32**. The output coupler **32** is a partially transparent mirror which is commonly composed of dielectric layers alternating in refractive index. The high reflector **30** is also well known in the art and is typically a multilayer dielectric coated mirror. Metallic mirrors can also be used. In addition, a deformable mirror can be used in the location of the high reflector. When coupled with a wavefront sensor, such a mirror can be used to compensate for any distortion in the laser chamber resulting from flow of the fluid or temperature gradients.

[**0075**] In this embodiment, as best illustrated in **FIG. 6**, the flow of the slurry of solid state particles **20** and fluid **22** flows across the laser axis rather than along it as in the embodiments of **FIGS. 1 and 3**. Thus, depending on the dimensions of the laser chamber **66**, the distance traveled by the slurry within the laser chamber **66** of **FIGS. 5 and 6** may be less than the distance traveled by the slurry within the laser chamber **12** of **FIG. 1**. Accordingly, since a portion of the slurry is within the laser chamber **66** for less time, it is subjected to less heating across the flow path through the lasing region or volume of the laser chamber **66**. Thus, in some embodiments, the configuration of **FIGS. 5 and 6** is preferred since less heat is added into particular particles **20** within a portion of the slurry, possibly increasing the available laser average power output.

[**0076**] In addition to the laser materials shown in Table 1, the performance of erbium and ytterbium-doped laser materials have been evaluated for use in several embodiments of the current invention. The design concepts described previously would enable anyone of ordinary skill in the art to produce a laser utilizing a solid-state laser material distributed in a substantially index matched coolant fluid as the gain medium.

TABLE 1

Material characteristics

		Nd:YLF		
	Nd:YAG	σ	π	Nd:Glass-LG-760
Nd density (at 1 at. %)	1.38×10^{20} cm^{-3}	1.38×10^{20}		0.93×10^{20}
Upper state lifetime	230 μs	520 μs		360 μs
Lower state lifetime	<200 ps	10 ns		
Thermal cond. (W/cm-K)	.14	.06		.006
Laser wavelength (nm)	1064.1	1053	1047	1053.5
Index of refraction	1.82	1.4481	1.4704	1.508
Emission cross section	2.8×10^{-19} cm^2	1.2×10^{-19}	1.8×10^{-19}	$4.2 \times 10^{-20\text{ cm2}}$
Absorp cross section	2.9×10^{-20} cm^2	2.2×10^{-20}	6.5×10^{-20}	2.4×10^{-20}
Absorption peak	808 nm	797 nm	792 nm	808 nm
Absorp. coef(1 at. %)	4 cm^{-1}	3 cm^{-1}	9 cm^{-1}	2.2 cm^{-1}

[0077] Referring next to **FIG. 7**, an example how an embodiment of a laser device in accordance with the invention can be used in a four-pass amplifier. Here, the beam emerges from an oscillator **102** producing a pulsed output. The beam passes through an expanding telescope **104** to adjust the beam size to approximate that of the aperture of the gain medium. The pulse then passes through a thin film polarizer **106** oriented to pass P-polarization. The pulse then passes through a Faraday Rotator **108** which rotates the polarization by 45 degrees. A half-waveplate or 45 degree quartz rotator **110** cancels the rotation of the Faraday rotator orienting the beam back at P-polarization for passage through the second thin-film polarizer **112**. The beam then passes through a quarter-waveplate **114** oriented to provide circular polarization at the output. The beam is then directed to (e.g., via mirrors **116** and **118**) and then passes through the laser chamber **12** of a laser device **10** according to an embodiment of the present invention whereby it undergoes amplification. After the first-pass of amplification, the beam strikes a mirror **120** which directs it back through the gain medium **14** for a second pass. The second pass through the quarter-waveplate **114** converts the circularly polarized beam to linearly polarized in the S plane (vertical). The now S-polarized beam reflects off the thin film polarizer **112** towards another mirror **122**. This mirror reflects the beam back through the waveplate and amplifier combination. The beam strikes the first mirror **120** a second time and passes a fourth time through the amplifiers. Passage through the quarter-waveplate **114** this time produces a linearly-polarized beam in the P (horizontal) plane which passes through thin-film polarizer **112**. The beam then encounters the half-waveplate **110** which rotates the plane of polarization by 45 degrees. Passage through the Faraday rotator in the backwards direction rotates the polarization by an additional 45 degrees in the direction produced by the waveplate **110**. The Faraday rotator/waveplate combination serves to rotate the plane of polarization by 90 degrees when the beam is travelling backwards toward the oscillator. The now S-polarized beam then reflects off of thin-film polarizer **106** and is directed out of the laser system. This is one of many possible uses of an embodiment of the present invention in a multipass amplifier. Similar uses of other embodiments of the invention as a single-pass amplifier, inside a regenerative amplifier design or as the gain medium in an oscillator cavity are not intended to be precluded by this example.

[0078] Changes and modifications in the specifically described embodiments can be implemented without departing from the scope of the invention, which is intended to be limited only by the scope of the appended claims.

What is claimed is:

1. A laser device comprising:

a chamber containing a volume formed therein; and

a gain medium within the volume, the gain medium comprising solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions.

2. The laser device of claim 1 wherein the gain medium flows within the volume.

3. The laser device of claim 2 wherein the gain medium flows through the volume.

4. The laser device of claim 2 wherein the solid state portions are suspended by flow within the fluid.

5. The laser device of claim 2 wherein the solid state portions are naturally suspended within the fluid in the absence of flow.

6. The laser device of claim 2 wherein the chamber further comprises an inlet and an outlet, the gain medium flowing in the inlet, through the volume and out the outlet.

7. The laser device of claim 6 wherein the inlet and the outlet are sized to be larger than individual ones of the solid state portions, such that the gain medium can flow through the inlet and the outlet.

8. The laser device of claim 6 further comprising a heat exchanger coupled to the inlet and outlet, the gain medium exiting the outlet passing through the heat exchanger and cooled then flowed through the inlet.

9. The laser device of claim 6 wherein the gain medium is flowed through the chamber in a direction substantially parallel to an axis of a laser emission.

10. The laser device of claim 6 wherein the gain medium is flowed through the chamber in a direction substantially transverse to an axis of a laser emission.

11. The laser device of claim 1 wherein the solid state portions have at least one dimension in a range between 10 nanometers and 2 millimeters.

12. The laser device of claim 1 further comprising a diode pump source, wherein optical pump radiation is continuously pumped into the gain medium by the diode pump source for a duration of at least a time desired for laser output.

13. The laser device of claim 1 wherein individual solid state portions do not contact each other.

14. The laser device of claim 1 wherein the chamber includes one or more faces adapted to transmit optical pump radiation therethrough to enter the gain medium.

15. The laser device of claim 1 further comprising semiconductor laser diodes for providing optical pump radiation to the chamber.

16. The laser device of claim 1 in which ends of the chamber are comprised of material which is transparent to a laser emission wavelength.

17. The laser device of claim 1 in which ends of the chamber are comprised of material which is transparent to a laser emission wavelength and oriented at Brewster's angle with respect to an axis of the laser emission wavelength.

18. The laser device of claim 1 in which ends of the chamber are comprised of material which is transparent to a laser emission wavelength and which are coated to provide reflectance at the laser emission wavelength, the coating being applied on a surface of a window which does not contact the gain medium.

19. A method of lasing comprising:

providing a chamber having a volume formed therein and containing a gain medium, the gain medium comprising solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions;

directing optical pump radiation through the chamber into the volume; and

directing a laser emission through the chamber.

20. The method of claim 19 further comprising:

flowing the gain medium within the volume.

21. The method of claim 20 wherein the flowing the gain medium step comprises:

flowing the gain medium through the volume.

22. The method of claim 21 further comprising:

cooling a portion of the gain medium flowing out of the chamber and flowing the portion back into the chamber.

23. The method of claim 20 wherein the flowing the gain medium step comprises:

flowing the gain medium such that the solid state portions are suspended by flow within the fluid.

24. The method of claim 20 wherein the flowing the gain medium step comprises:

flowing the gain medium, wherein the solid state portions are naturally suspended within the fluid in the absence of flow.

25. The method of claim 20 wherein the flowing the gain medium step comprises:

flowing the gain medium into the volume via an inlet of the chamber, through the volume and out of the volume via an outlet of the chamber.

26. The method of claim 25 further comprising:

cooling a portion of the gain medium flowing out of the chamber by flowing the portion of the gain medium through a heat exchanger and flowing the portion of the gain medium back into the chamber.

27. The method of claim 25 wherein the flowing the gain medium step comprises:

flowing the gain medium through the volume in a direction substantially parallel to an axis of the laser emission.

28. The method of claim 25 wherein the flowing the gain medium step comprises:

flowing the gain medium through the volume in a direction substantially transverse to an axis of the laser emission.

29. The method of claim 20 wherein the flowing the gain medium step comprises:

flowing the gain medium, the gain medium comprising the solid-state portions suspended within the fluid, the solid state portions have at least one dimension in a range between 10 nanometers and 2 millimeters;

wherein the directing the optical pump radiation step comprises:

continuously directing the optical pump radiation through the chamber into the volume for a duration of at least a time duration of the directing the laser emission through the chamber step.

30. The method of claim 19 wherein the providing step comprises:

providing the chamber having the volume formed therein and containing the gain medium, the gain medium comprising the solid-state portions containing the active laser ion, wherein individual solid state portions do not contact each other within the fluid.

31. A laser device comprising:

means for providing a chamber having a volume formed therein and containing a gain medium, the gain medium comprising solid-state portions containing active laser ion suspended within a fluid which exhibits a refractive index which is substantially similar to that of the solid-state portions;

means for directing optical pump radiation through the chamber into the volume; and

means for directing a laser emission through the chamber.

32. The device of claim 31 further comprising:

means for flowing the gain medium within the volume.

33. The device of claim 32 wherein the means for flowing the gain medium comprise:

means for flowing the gain medium through the volume.

34. The device of claim 33 further comprising:

means for cooling a portion of the gain medium flowing out of the chamber and flowing the portion back into the chamber.

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