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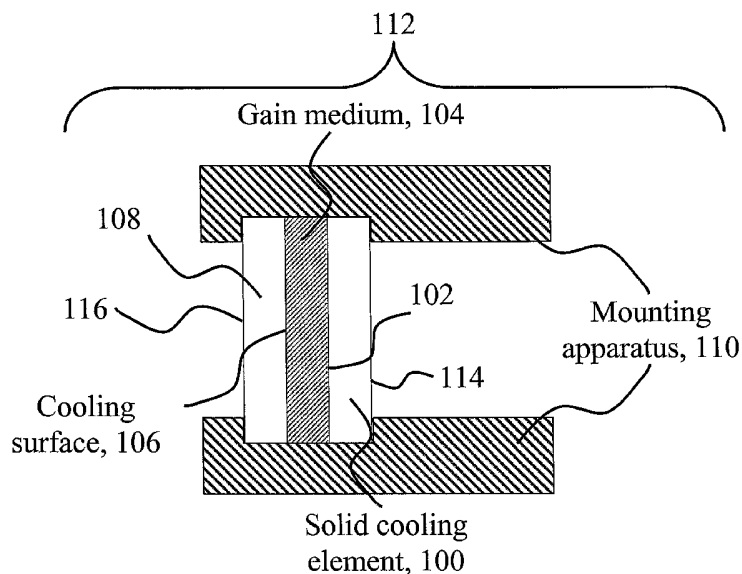
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(54) Title: HIGH THERMAL-CONDUCTIVITY MATERIALS FOR A COOLED LASER GAIN ASSEMBLY



(57) Abstract: The present application discloses an optical system having high thermal-conductivity materials for a cooled laser gain assembly. More specifically, the optical system includes at least one pump source outputting a pump energy, at least one gain medium optically coupled to the pump source and configured to output a laser beam, the gain medium having at least one cooling surface, at least one cooling element in thermal contact with cooling surface, and a mounting apparatus configured to hold the cooling element in thermal contact with the gain medium.

HIGH THERMAL-CONDUCTIVITY MATERIALS FOR A COOLED LASER GAIN ASSEMBLY

BACKGROUND

Generally, the output power available from diode-pumped, solid-state lasers is limited by several factors, including the thermal and mechanical properties of the gain medium. However, often the methods used to mount and cool a gain medium places further restrictions on the performance of the system. For example, thermo-optical effects may lead to a degradation of the output beam quality and a loss in output power, which results from the formation of a thermally induced lens in the gain medium. The thermally induced lens may result from the combination of the effects caused by the temperature dependence of the refractive index, often referred to as a "bulk thermal lens," and from the deformation of the surface due to the thermal expansion of the material, often referred to as a "bulge."

In response, a number of techniques to mitigate these effects have been developed. For example, one technique commonly used to mitigate the effects of the bulk thermal lens incorporates a "one-dimensional (1-D) cooling" geometry. In this configuration, heat is extracted from the gain medium such that the thermal gradients are longitudinal with respect to the laser beam. US Patent Number 3,631,362, discloses a system utilizing the one-dimensional (1-D) cooling geometry. Further, Matthews and Marshall in OSA TOPS Vol. 50, page 138, 2001 applied the one-dimensional (1-D) cooling geometry technique to Nd:YVO₄ laser rods to achieve reduced thermal lensing.

In contrast, US Patent No. 5,363,391 disclosed a system wherein longitudinal cooling was used to improve to the performance of nonlinear crystal used in laser systems. Additionally, the system disclosed in US Patent No. 5,363,391 further disclosed that it may be advantageous to have a narrow gas-filled gap between the material to be cooled and the heat conducting media to prevent damage to the optical surfaces of the cooled material.

While these various geometries addressed some problems associated with generation of thermal-induced lens formation within a gain medium, a number of shortcomings of these architectures were discovered. For example, one disadvantage

is often higher than if it were cooled transversely. High temperatures can lead to many undesirable effects such as stress buildup and even fracture of the gain material or of the bonds to other materials. In addition, other potential undesirable effects due to higher temperatures include, without limitation, a reduction in efficiency of the laser, a decrease of the upper-state lifetime of the laser transition, and a reduction in thermal conductivity of materials leading to the formation of ever-increasing temperatures within the device.

There is, therefore, an ongoing need for efficiently cooled high power solid-state lasers that have a weak thermally induced lens, a small temperature rise in the laser gain medium, possess simplified dielectric coatings with good thermal conductivity and reduced thermally induced stress, all of which are achieved using contacting techniques that do not require heating joined materials to high temperature.

SUMMARY

The present application is directed to an optical system and includes at least one pump source outputting a pump energy, at least one gain medium optically coupled to the pump source and configured to output a laser beam, the gain medium having at least one cooling surface, at least one cooling element in thermal contact with cooling surface, and a mounting apparatus configured to hold the cooling element in thermal contact with the gain medium.

In an alternate embodiment, the present application is directed to an optical system and includes a pump source, a gain medium optically coupled to the pump source, a solid cooling element in physical contact with a cooling surface of the gain medium, and joined using a low temperature contacting technique, and a mounting apparatus that holds the solid cooling element in thermal contact with the gain medium.

Other features and advantages of the embodiments of the optical systems disclosed herein will become apparent from a consideration of the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of optical systems incorporating high thermal-conductivity materials for a cooled laser gain assembly will be explained in more detail by way of the accompanying drawings, wherein:

FIG. 1 shows a schematic diagram of an embodiment of an optical system having a gain medium, cooling elements and a mounting apparatus;

FIG. 2 (a) shows a schematic diagram of an embodiment of an optical system having a pump source, a coupling apparatus, and a gain assembly, wherein the optical system is configured as a laser oscillator;

FIG. 2 (b) shows a schematic diagram of an embodiment of an optical system having a pump source, a coupling apparatus, and a gain assembly, wherein the optical system is configured as an amplifier;

FIG. 3(a) shows a schematic diagram illustrating the location of one or more thin-film coatings that can be utilized with the embodiment of the an optical system shown in FIG. 1 when used in a double-pass configuration with material having indices of refraction that are similar;

FIG. 3(b) shows a schematic diagram illustrating the location of one or more thin-film coatings that can be utilized with the embodiment of FIG. 1 when used in a double-pass configuration with material having indices of refraction that are not similar;

FIG. 3(c) is a schematic diagram illustrating the location of thin-film coatings that can be utilized with the embodiment of FIG. 1 when used in a single-pass configuration with material having indices of refraction that are similar;

FIG. 3(d) is a schematic diagram illustrating the location of thin-film coatings that can be utilized with the embodiment of FIG. 1 when used in a single-pass configuration with material having indices of refraction that are not similar; and

FIG. 4 illustrates the calculated temperature distribution within a gain assembly for: (a) a single cooling element; and (b) two cooling elements.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 shows an embodiment of a single crystal diamond for a cooled laser gain assembly. As shown, the gain assembly 112 includes at least a first cooling element 100 and a cooling surface 102 of gain medium 104. In one embodiment, the first cooling element 100 is in contact with the cooling surface 102 of the gain medium 104. In an alternate embodiment, the first cooling element 100 may be positioned proximate to but not in contact with the cooling surface 102 of the gain medium 104. As such, the first cooling element 100 may be positioned in thermal contact with the cooling surface 102 of the gain medium 104. Optionally, any number of cooling elements may be included in the gain assembly 112. Further, any number of cooling surfaces 102 may be formed on or in communication with any number of gain mediums 104. For example, as shown in FIG. 1 two cooling surfaces 102 and 106, and two cooling elements 100 and 108 may be provided.

Heat flow through the gain medium 104 may be substantially one-dimensional, in a direction substantially normal to the cooling surfaces 102 and 106. Optionally, heat flowing through the gain medium 104 and/or at least one of the cooling elements 100, 108 may be substantially multi-dimensional and/or transverse to the cooling surfaces 102 and 106. In the illustrated embodiment, the cooling elements 100 and 108 are solid. Optionally, the at least one of the cooling elements 100 and 108 need not be solid. The at least one surface of the gain medium 104 and/or the cooling elements 100 and 108, may include one or more thin-film coatings. For example, the thin-film coating may provide the desired optical properties at the interfaces.

The cooling elements 100 and 108 may be held in contact with gain medium 104 at surfaces 102 and 106 by a low temperature contacting technique. Further, any number of contacting techniques may be used to ensure the cooling elements 100 and 108 are held in contact with the gain medium 104. For example, the cooling elements 100 and 108 may be held in contact with gain medium 104 at surfaces 102 and 106 using Surface Activated Bonding (SAB). Any variety of SAB processes may be used to couple the cooling elements 100, 108 to the surfaces 102, 106 of the gain medium 104.

For example, in one embodiment contaminants may be removed from the surfaces of the cooling elements 100, 108 and the surfaces 102, 106 of the gain medium 104 using an activation process, such as Argon etching. In the alternative, various chemical and/or chemical-mechanical polishing techniques, wet and dry, or dry-only chemical activation processes may be used to activate the surfaces of the cooling elements 100, 108 and the surfaces 102, 106 of the gain medium 104. Following the activation, strong bonds may be formed by contacting the activated surfaces of the cooling elements 100, 108 to the activated surfaces 102, 106 of the gain medium 104. Optionally, one or more mechanical clamping devices may be used to ensure the cooling elements 100, 108 remain in contact with the surfaces 102, 106 of the gain medium 104. Those skilled in the art will appreciate that the activation process and/or bonding process may be performed at any temperature.

Optionally, an alternate SAB process may be used to couple the cooling elements 100, 108 to the surfaces 102, 106 of the gain medium 104. For example, the surfaces of the cooling elements 100, 108 and the surfaces 102, 106 of the gain medium 104 may be activated using a B_2H_6 plasma etching and the activated surfaces may be exposed to a HF solution immediately before bonding. Thereafter, the activated surfaces of the cooling elements 100, 108 and the activated surfaces 102, 106 of the gain medium 104 may be brought in contact. In one embodiment, the bonded surfaces may be annealed under low vacuum at a temperature higher than room temperature. For example, the temperature may be above room temperature but below about 300°C. In an alternate embodiment, the bond may be formed at room temperature.

In another embodiment, thin-film coatings applied to the surfaces of the cooling elements 100, 108 and/or the surfaces 102, 106 of the gain medium 104, may be used to provide Surface Activated Bonding. For example, a thin-film coating may be applied on each of the surfaces 102, 106 of solid cooling element 114 and gain medium 104. Thereafter, the cooling elements 100, 108 may brought in contact with the coated surfaces 102, 106 of the gain medium 104. Optionally, the cooling elements 100, 108 may be brought in contact with the coated surfaces 102, 106 of the gain medium 104 under vacuum while in the coating chamber. In another embodiment, the surfaces could

be brought together soon after the chamber was opened. This process could also be applied to cooling surfaces 106 of solid cooling element 108 and gain medium 104. In an alternate embodiment, the cooling elements 100 and 108 may be held in contact with gain medium 104 at surfaces 102 and 106 using a mounting apparatus 110 to apply opposing forces to the cooling elements 100 and 108 in a direction substantially normal to the cooling surfaces 102 and 106. Thus, the mounting apparatus 110 holds the cooling elements 100 and 108 to gain medium 104. As stated above, optionally, the cooling elements need not be held in contact with the gain medium 104 but rather may be positioned sufficiently proximate to the surface 102 and 106 to permit heat extraction from an area of interest.

The cooling elements 100 and 108 may be manufactured from any variety of materials. For example, in one embodiment at least one of the cooling elements 100 and 108 may be manufactured from a single-crystal CVD diamond. Alternate materials include, without limitation, IIA natural diamond, CVD diamond, silicon carbide, single-crystal silicon carbide, optical quality single-crystal silicon carbide, sapphire, copper, copper-tungsten, materials having a thermal conductivity $> 100 \text{ Wm}^{-1}\text{K}^{-1}$, materials having a thermal conductivity $> 1000 \text{ Wm}^{-1}\text{K}^{-1}$ and the like. In addition to the thermal characteristics, at least one of the cooling elements 100 and 108 may be manufactured from a material having desirable optical qualities. For example, at least one of the cooling elements 100 and 108 may have a high transmission at a laser wavelength. Optionally, at least a portion of one of the cooling elements 100 and 108 may have a high transmission at the pump wavelength. In an alternate embodiment, at least a portion of one of the cooling elements 100 and 108 may be formed from a material substantially free of birefringence. For example, at least the area of the cooling elements 100 and 108 through which a laser beam passes may be manufactured from a material such as sapphire or a single crystal birefringent material having an optical axis substantially parallel to the direction the laser beam traverse therethrough, thereby minimizing the birefringent effects. Similarly, at least a portion of one of the cooling elements 100 and 108 may be formed from a material substantially free of scattering effects. As stated above, optionally the cooling elements 100 and 108 need not be in contact with the gain medium 104.

Referring again to FIG. 1, in one embodiment the cooling elements 100 and 108 are joined to or positioned sufficiently proximate to the gain medium 104 at surfaces 102 and 106 such that the gain medium 104 is in thermal contact with the cooling elements 100 and 108, thereby permitting heat to be removed from the gain medium 104. As shown in FIG. 1, the mounting apparatus 110 may be configured to provide additional structural stability to gain medium 104 and/or the cooling elements 100 and 108. In various embodiments, the gain medium 104 is positioned between the cooling elements 100 and 108 such that the cooling surfaces 102 and 106 of the gain material 104 are in physical contact with the cooling elements 100 and 108. Optionally, at least one surface of gain medium 104 and/or the cooling elements 100 and 108 that are in contact with the gain medium 104 may include a sufficiently small surface roughness, thereby providing good thermal and physical contact. For example, in one embodiment the surface roughness will be less than about 50 nm Ra. In an alternate embodiment, the surface roughness may be from about .5 nm Ra to about 50 nm Ra. In an alternate embodiment, the surface roughness is less than about 5 nm Ra. Optionally, the surface roughness may be greater than about 50 nm Ra.

In one embodiment, at least one surface of the gain medium 104 and/or the cooling elements 100 and 108 are in contact with the gain medium 104 and may include a sufficiently flat surface thereby providing good thermal and physical contact over a substantial portion of the surface thereof. For example, in one embodiment the surface of at least one of the gain medium 104 and/or the cooling elements 100 and 108 will include surface irregularities less than about one wavelength of light. Exemplary wavelengths include, for example, about 632nm. In another embodiment, the surface of at least one of the gain medium 104 and/or the cooling elements 100 and 108 will include surface irregularities less than about one-tenth of a wavelength. In still another embodiment, the surface of at least one of the gain medium 104 and/or the cooling elements 100 and 108 will include surface irregularities less than about one-twentieth of a wavelength. In short, the surface of at least one of the gain medium 104 and/or the cooling elements 100 and 108 may include any number and/or size of surface irregularities.

The gain medium 104 may include a thin disk gain medium. For example, the thin disk gain medium may be configured having substantially one-dimensional heat flow. As such, the thin disk gain medium includes one transverse and/or longitudinal dimension, the thickness, much smaller than the other two transverse dimensions. For example, a thin disk might have a diameter of about a few millimeters and a thickness of only about a fraction of a millimeter. The thinness of the disk will ensure that the heat-flow will be substantially 1-dimensional. Optionally, the gain medium 104 may be manufactured from a variety of materials, including, without limitation, Nd:YVO₄, Nd:YAG, Nd:YLF, Yb:YAG, Yb:KGW, Yb:KYW, apatite-structure crystals, stoichiometric gain materials, stoichiometric Yb³⁺ gain materials including KYbW or YbAG, Ti:Al₂O₃, semiconductor materials, and the like.

Alternatively, the gain medium 104 may include a bulk gain medium. For example, the bulk gain medium 104 may be configured to permit substantially one-dimensional heat flow or substantially multi-dimensional heat flow. As such, the bulk gain medium 104 may include one dimension substantially large than other dimensions thereof. For example, in one embodiment the thickness of the bulk gain medium 104 may be similar to or larger than the thickness and/or length thereof. In one illustrative embodiment, the bulk gain medium 104 might have a thickness of about a few tens of millimeters and transverse dimensions of about a few millimeters. More specifically, the thickness of the bulk gain medium 104 may range from about 10 millimeters to about 90 millimeters while the transverse dimensions of the bulk gain medium 104 may range from about 1 millimeter to about 9.9 millimeters. As such, the cooling elements 100 and 108 may be configured to provide cooling from the ends of the bulk gain media 104.

Referring again to FIG. 1, a cooling medium may be provided to cool the cooling elements 100 and 108 using a variety of cooling methods that include, without limitation, direct liquid cooling, convective cooling, both convective and conductive cooling, and the like. Examples of cooling media include, but are not limited to, air, water, ethylene glycol, copper, copper tungsten, and the like. In one embodiment, the cooling element 100 is cooled using water as the cooling medium. Optionally, the water may be in direct contact with surface 114 of the cooling element 100. The cooling element 108 may also be cooled with at least one cooling medium described above. For example, the cooling media may be in contact with the surface 116 of the cooling element 108. In one

embodiment, the cooling medium in contact with the cooling surface 116 is air. In another embodiment, the cooling elements 100 and 108 are cooled by contacting cooling media over an area near the periphery of the cooling elements.

FIGS. 2(a) and 2(b) show an embodiment of an optical system. As shown, the optical system 200 includes a gain assembly 202, substantially similar to the gain assembly 112 shown in FIG. 1, and a pump source 204. The gain assembly 202 may be optically coupled to the pump source 204 by a coupling apparatus 206. FIG. 2(a) shows an embodiment of the optical system 200 configured as a laser. As shown, a high reflector 208 and output coupler 210 are provided to form a resonator. Optionally, any number or type of additional optical elements may also be provided within the resonator. The laser may be configured to be Q-switched, mode-locked, and the like. As shown in FIG. 2(b), the optical system 200 may be configured to as an amplifier.

In one embodiment, the gain media may comprise a semiconductor device. More specifically, the optical system 200 may be configured as a semiconductor laser or amplifier. For example, the semiconductor laser or amplifier could be configured as an edge emitting semiconductor laser or amplifier. As such, the semiconductor laser or amplifier may include mirrors 208 and 210, which are formed by the facets of the semiconductor device. As such, the index and/or gain guiding properties may be provided by the semiconductor device. Optionally, the mirrors 208 and 210 may also be configured to form a distributed feedback structure as part of the semiconductor device. In an alternate embodiment, the semiconductor device may be configured as a surface emitting semiconductor laser or amplifier. As such, the mirrors 208 and 210 may comprise thin-film structures which may be included as part of the semiconductor device.

Any number and/or variety of pump sources 204 may be utilized with the optical system. For example and without limitation, fiber coupled diode bars and diode stacks may be used as a pump source 204. Optionally, any number and type of alternate devices may be used as a pump source, including, without limitation, non-diode lasers and non-laser pump devices. Exemplary non-laser pump devices include electric power supplies configured to provide electric pump energy thereto. Further, any number and/or variety of coupling apparatus 206 including, but not limited to lenses, non-imaging

concentrators such as lens ducts or hollow funnels and the like may be used with the optical system.

Optionally, thin film coatings may be applied to at least one surface of the gain assembly 112 and/or the cooling elements 100 and 108. Exemplary thin-film coatings can include, without limitation, multi-layer dielectric coatings, anti-reflective (AR) coatings, high reflective (HR) coatings, dichroic coatings, dielectric coatings, metallic coatings, combinations of at least one of a set of coatings selected from: AR-coatings, HR-coatings, dichroic coatings, dielectric coatings, metallic coatings, and the like. AR coatings may be configured to reduce optical loss when adjacent materials have substantially different refractive indices. HR coatings may be configured to provide a double pass through the gain assembly. As stated above, the thin-film coatings may be used to provide the Surface Activated Bonding by depositing a coating on the surfaces of gain medium 104 and/or the cooling elements 100 and 108 and then bringing the surfaces into contact.

FIG. 3(a) shows an embodiment of a cooled laser gain assembly. As shown, at least one thin-film coating 300 may be provided between the gain medium 302 and the cooling element 304. Optionally, the thin film coating 300 may be highly reflecting at least one of the laser wavelength and/or the pump wavelength. In an alternate embodiment, at least one thin-film coating 308 can also be provided on the surface of the cooling element 306 not in contact with gain medium 302. The thin-film coating 308 may include an anti-reflection coating for at least one of the laser wavelength and/or the pump wavelength. As such, the gain assembly may be used in a double-pass configuration. In one embodiment, the indices of refraction of gain medium 302 and the cooling element 306 are sufficiently close in value that a thin-film coating is not required between the gain medium 302 and the cooling element 306.

FIG. 3(b) shows an alternate embodiment of a cooled laser gain assembly. As shown, the gain assembly 314 is configured in a double-pass configuration wherein a thin-film coating 312 is provided between the cooling element 318 and gain medium 314. Optionally, a thin-film coating 310 may also be provided between the cooling element 316 and gain medium 314. Further, a thin-film coating 320 may be provided on at least one surface of the cooling element 318 not in contact with gain medium 314. The thin-film coatings 312 and 320 may comprise anti-reflection coatings for at least

one of the laser wavelength and/or the pump wavelength. Similarly, the thin-film coating 310 may be highly reflecting for at least one of the laser wavelength and/or the pump wavelength.

FIG. 3(c) shows an alternate embodiment of a cooled laser gain assembly. As shown, the gain assembly is configured in a single-pass configuration. Optionally, thin-film coatings 330 and 332 may be provided on at least one surface of the cooling elements 334 and 336 not in contact with gain medium 338. The thin-film coatings 330 and 332 may comprise anti-reflection coatings for the laser wavelength and/or possibly anti-reflecting or highly reflecting coatings for the pump wavelength. The indices of refraction of the gain medium 338 and the cooling elements 334 and 336 may be sufficiently close in value that a thin-film coating is not required between them.

FIG. 3(d) shows an alternate embodiment of a cooled laser gain assembly. As shown, one or more thin-film coatings 340 and 342 may be provided between the cooling elements 344 and 346 and the gain medium 348. Optionally, the thin-film coatings 350 and 352 may also be provided on at least one surface of the cooling elements 344 and 346 not in contact with gain medium 348. In this embodiment thin-film coatings 340, 342, 350, and 352 may comprise anti-reflection thin-film coatings for the laser wavelength, and/or one or more anti-reflection or high-reflection thin-film coatings for the pump wavelength. In the illustrated embodiment, the gain assembly is configured as a single pass configuration. Optionally, alternate gain assembly configurations may be used with any of the previous disclosed embodiments.

Referring again to FIGS. 1, 2(a) and 2(b), it may be desirable to remove heat from the gain medium 104 of the optical system 200 as efficiently as possible. As such, the thermal conductivity of any material positioned between the gain medium 104 and the cooling medium may have as high a thermal conductivity as possible. Further, the cooling medium may be positioned proximate to locations of increased heat deposition and/or increased temperature. For example, FIGS. 4(a) shows the temperature distribution in a thin disk gain medium 400 attached to a copper cooling-element 402. As shown, the pump light enters from the bottom. As such, the cooling surface 404 of gain medium 400 is the surface that is furthest away from the region where most of the heat is deposited. Copper, has a thermal conductivity of less than $400 \text{ Wm}^{-1}\text{K}^{-1}$. The maximum temperature rise in the gain medium 400 is calculated to be about 100°C . In

contrast, FIG. 4(b) shows a device having a cooling element 410 made from a material having a thermal conductivity of greater than $1800 \text{ Wm}^{-1}\text{K}^{-1}$, such as CVD-diamond, and the like. In addition, cooling elements 410 and 412 are in contact with both surfaces 414 and 416 of the thin disk gain medium 418. As such, heat can be efficiently removed directly from the region where it is deposited. As shown in FIG. 4(b), the maximum temperature rise is much less than the device shown in FIG. 4(a).

Optionally, any combination of the previously disclosed embodiments may be used to form a single crystal diamond for a cooled laser gain assembly. For example, in one embodiment, an undoped optically transparent material may be applied to doped disk material to effectuate heat dissipation therefrom. In an alternate embodiment, undoped materials used herein may be optimized to include predetermined thermal characteristics, optical characteristics, or both. For example, United States Pat. No. 10/678,596, filed on October 3, 2003, the content of which are incorporated by reference in its entirety herein, describes several diamond laser gain assemblies which may incorporate a single crystal diamond for a cooled laser gain assembly. Alternatively, single-crystal silicon carbide and/or sapphire materials may be used.

Referring again to FIG. 1, in one embodiment the materials forming the cooling elements 100 and 108 may have a high thermal conductivity while simultaneously having thermal expansion coefficients that are close in value to those of gain medium 104. Optionally, using a low temperature contacting technique such as Surface Activated Bonding will reduce the likelihood that the gain material will fracture or bulge as a result of changes in temperature. Furthermore, the thermal resistance across the interfaces 102 and 106 between the cooling elements 100 and 108 and gain medium 104 may be reduced. As a result, the heat may be efficiently extracted from gain medium 104, thereby permitting much higher pump power levels to be used than has previously been possible.

The present application further discloses a method of removing heat from gain medium 104 of optical system 200. In one embodiment, the cooling elements 100 and 108 are in physical contact with cooling surfaces 102 and 106 of gain medium 104. Optionally, the cooling elements 100 and 108 may be in thermal contact with the cooling surfaces 102 and 106 of the gain medium 104 but not be in physical contact therewith. Gain medium 104 is then cooled, thereby reducing a bulge formed thereon. Further, the

gain medium 104 may also be cooled to a lower temperature than previously obtainable. Also, the gain medium 104 may also be cooled to reduce thermal lens in gain media 104. In addition, the gain medium 104 may also be cooled without causing a fracture of the gain material, and the like.

The foregoing description of various embodiments of an optical system having high thermal-conductivity materials included therein is not intended to be exhaustive or to limit the invention to the precise forms disclosed.

What is claimed is:

1. An optical system, comprising:
 - at least one pump source outputting a pump energy;
 - at least one gain medium optically coupled to the pump source and configured to output a laser beam, the gain medium having at least one cooling surface;
 - at least one cooling element in thermal contact with cooling surface; and
 - a mounting apparatus configured to hold the cooling element in thermal contact with the gain medium.
2. The device of claim 1 wherein the optical system comprises a laser.
3. The device of claim 1 wherein the optical system comprises an amplifier.
4. The device of claim 1 wherein the pump device comprises at least one fiber coupled laser diode bar.
5. The device of claim 1 wherein the pump device comprises at least one laser diode stack.
6. The device of claim 1 wherein the pump device comprises at least one source of electrical power.
7. The device of claim 1 wherein the gain medium comprises a thin disk gain medium.
8. The device of claim 1 wherein the gain medium comprise a semiconductor device.
9. The device of claim 1 wherein the gain medium comprises a bulk gain medium having a thickness of about 10mm to about 90 mm and a transverse dimension of about 1mm to about 9.9mm.

10. The device of claim 1 wherein the cooling element comprises a single crystal, natural diamond.
11. The device of claim 1 wherein the cooling element comprises a CVD diamond.
12. The device of claim 1 wherein the cooling element comprises a single-crystal silicon carbide.
13. The device of claim 1 wherein the cooling element comprises sapphire.
14. The device of claim 1 wherein the cooling element comprises natural diamond.
15. The device of claim 1 wherein the cooling element comprises single-crystal CVD diamond.
16. The device of claim 1 wherein the cooling element comprises CVD diamond.
17. The device of claim 1 wherein the cooling element comprises single-crystal silicon carbide.
18. The device of claim 1 wherein the cooling element is substantially free of birefringence.
19. The device of claim 1 wherein an area of the cooling element is configured to be substantially free of birefringence wherein a pump beam and output beam pass.
20. The device of claim 1 wherein at least one cooling elements is coupled to the gain medium using surface activated bonding.
21. The device of claim 1 wherein at least one of the cooling elements is coupled to the gain medium using at least one mounting apparatus configured to apply opposing forces to the cooling elements in a direction substantially normal to cooling surfaces on the cooling elements.
22. The system of claim 1 wherein the temperature is kept below about 300°C.
23. An optical system, comprising:

a pump source;
a gain medium optically coupled to the pump source;
a solid cooling element in physical contact with a cooling surface of the gain medium, and joined using a low temperature contacting technique; and
a mounting apparatus that holds the solid cooling element in thermal contact with the gain medium.

24. The system of claim 23 wherein the low temperature contacting technique comprises surface activated bonding.

25. The system of claim 23 wherein the mounting apparatus is configured to apply one or more forces to the solid cooling elements in a direction substantially normal to the cooling surfaces.

26. The system of claim 23, wherein the optical system is a laser.

27. The system of claim 26 further comprising a Q-switched laser.

28. The system of claim 26 further comprising a mode-locked laser.

29. The system of claim 23 wherein the optical system comprises an optical amplifier.

30. The system of claim 23 wherein the gain medium comprises a thin disk gain medium.

31. The system of claim 30, wherein the thin disk gain medium has a ratio of cross-section to thickness that is greater than 10.

32. The system of claim 23 wherein one or both of the solid cooling-elements are transparent at least one of the laser wavelength and the pump wavelength.

33. The system of claim 23, wherein at least one cooling element has a thermal conductivity $> 100 \text{ Wm}^{-1}\text{K}^{-1}$.

34. The device of claim 23 wherein the cooling element comprises sapphire.

35. The device of claim 23 wherein the cooling element comprises natural diamond.

36. The device of claim 23 wherein the cooling element comprises single-crystal CVD diamond.

37. The device of claim 23 wherein the cooling element comprises CVD diamond.

38. The device of claim 23 wherein the cooling element comprises single-crystal silicon carbide.
39. The device of claim 23 wherein the cooling element is substantially free of birefringence.
40. The device of claim 23 wherein the gain medium comprises a thin disk gain medium.
41. The device of claim 23 wherein the gain medium comprise a semiconductor device.
42. The device of claim 23 wherein the gain medium comprises a bulk gain medium having a thickness of about 10mm to about 90 mm and a transverse dimension of about 1mm to about 9.9mm.
43. The system of claim 23, wherein the gain medium is Nd:YVO₄.
44. The system of claim 23, wherein the gain medium is a Yb-doped crystal.
45. The system of claim 44, wherein the Yb-doped crystal is Yb:YAG.
46. The system of claim 44, wherein the Yb-doped crystal is Yb:KGW.
47. The system of claim 44, wherein the Yb-doped crystal is Yb:KYW.
48. The system of claim 23, wherein the gain medium is an apatite-structure crystal.
49. The system of claim 23, wherein the gain medium is a stoichiometric gain material.
50. The system of claim 50, wherein the gain medium is a stoichiometric Yb³⁺ gain material.
51. The system of claim 23, wherein the gain medium is a semiconductor.

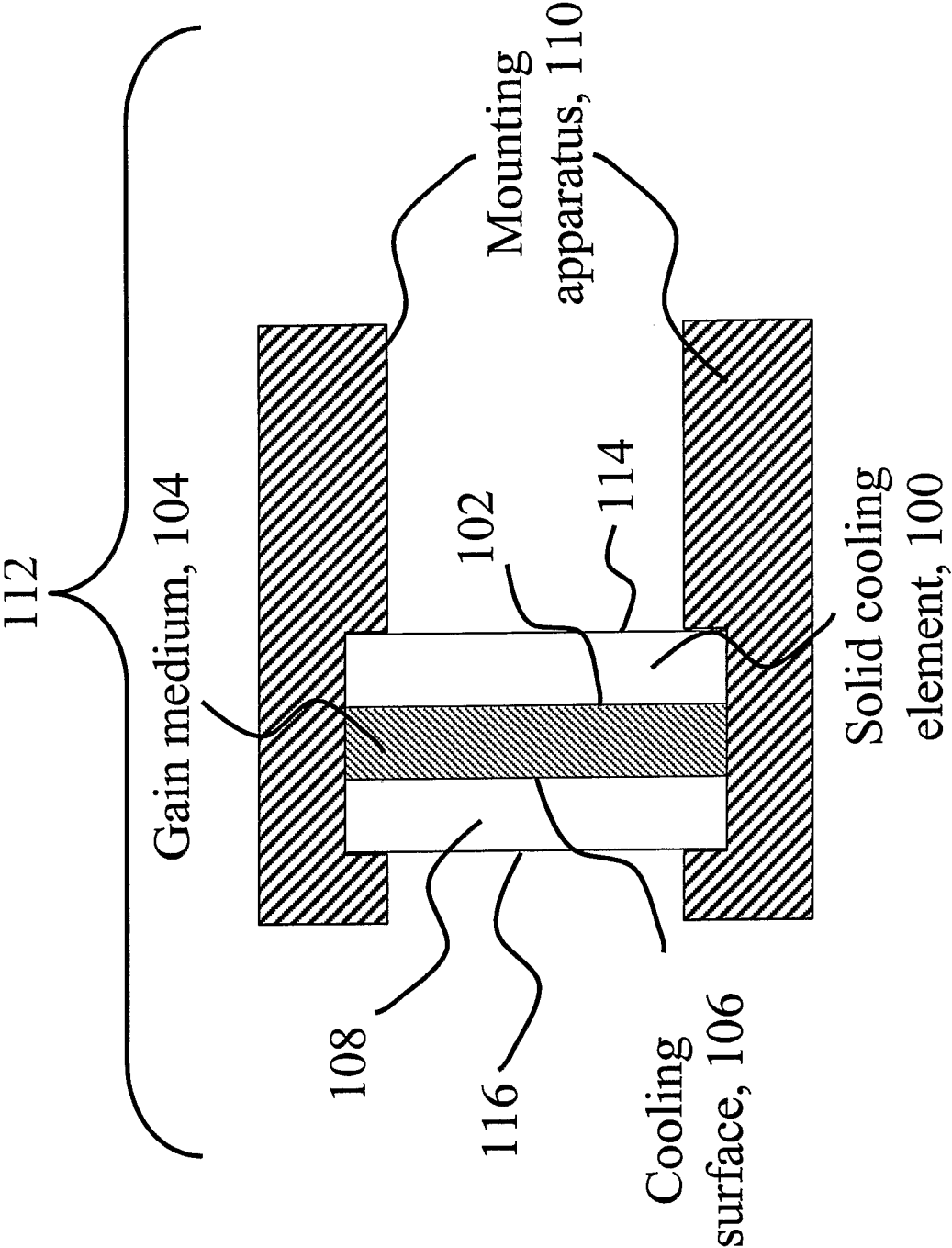


Figure 1

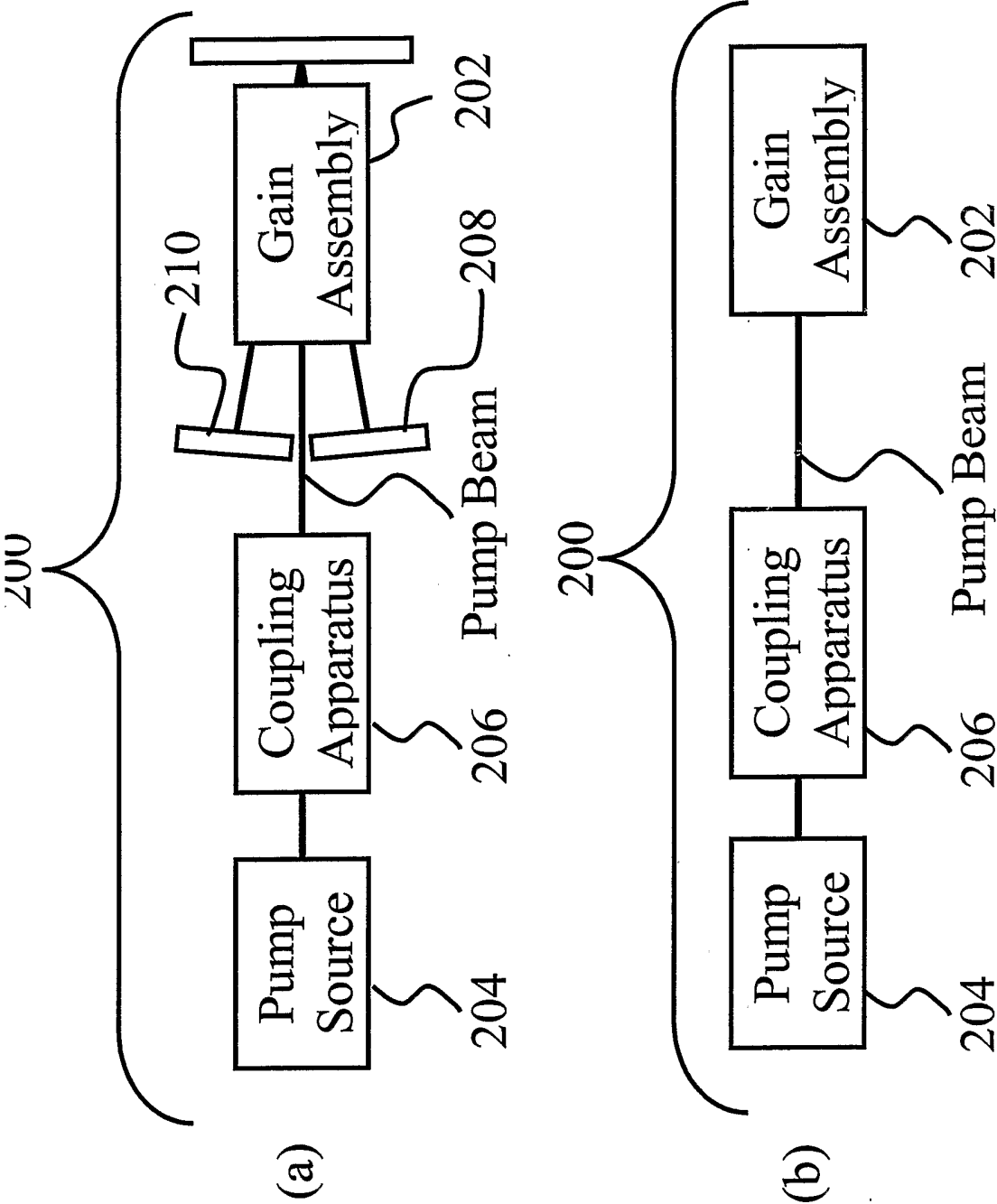


Figure 2

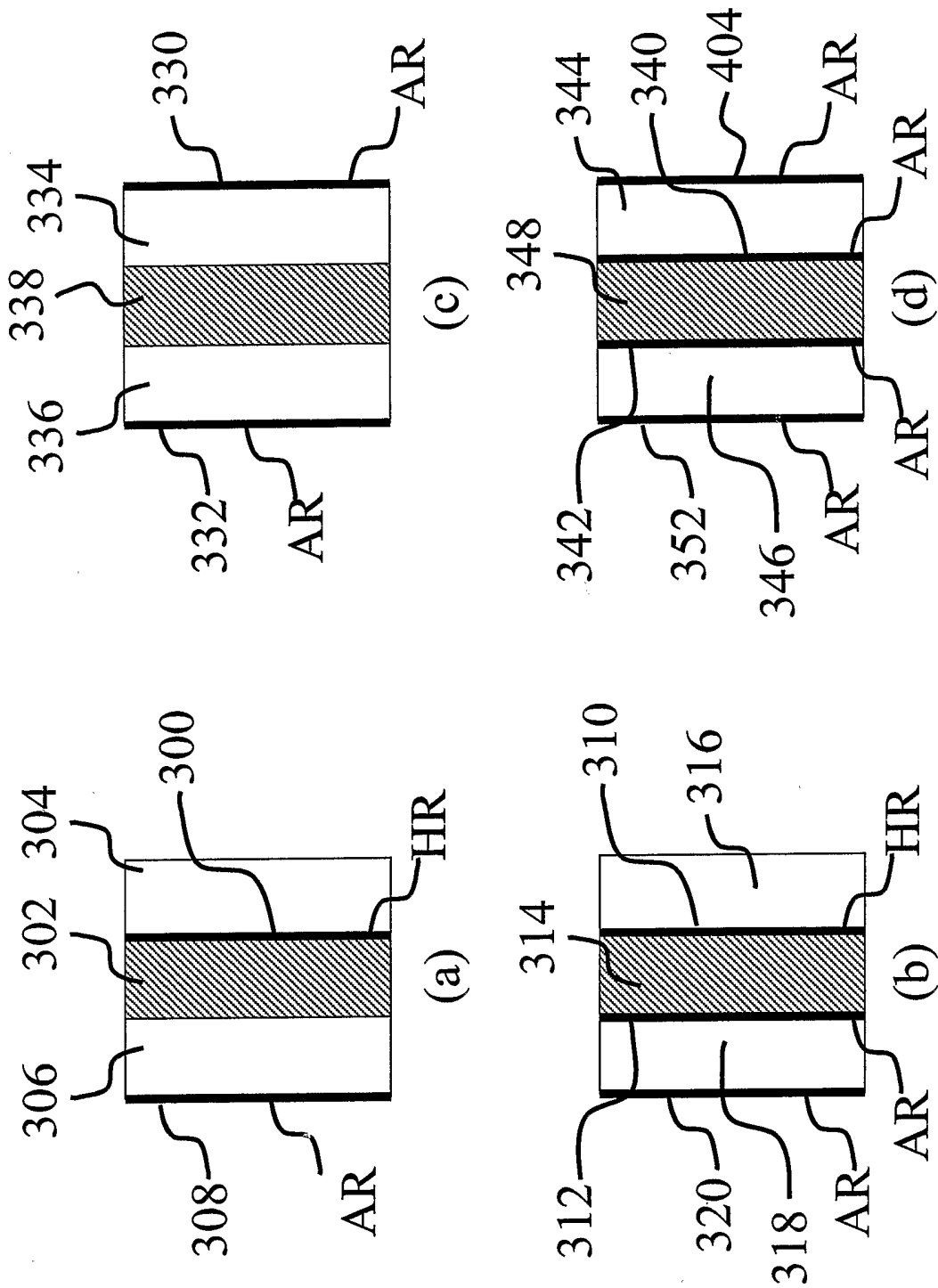


Figure 3

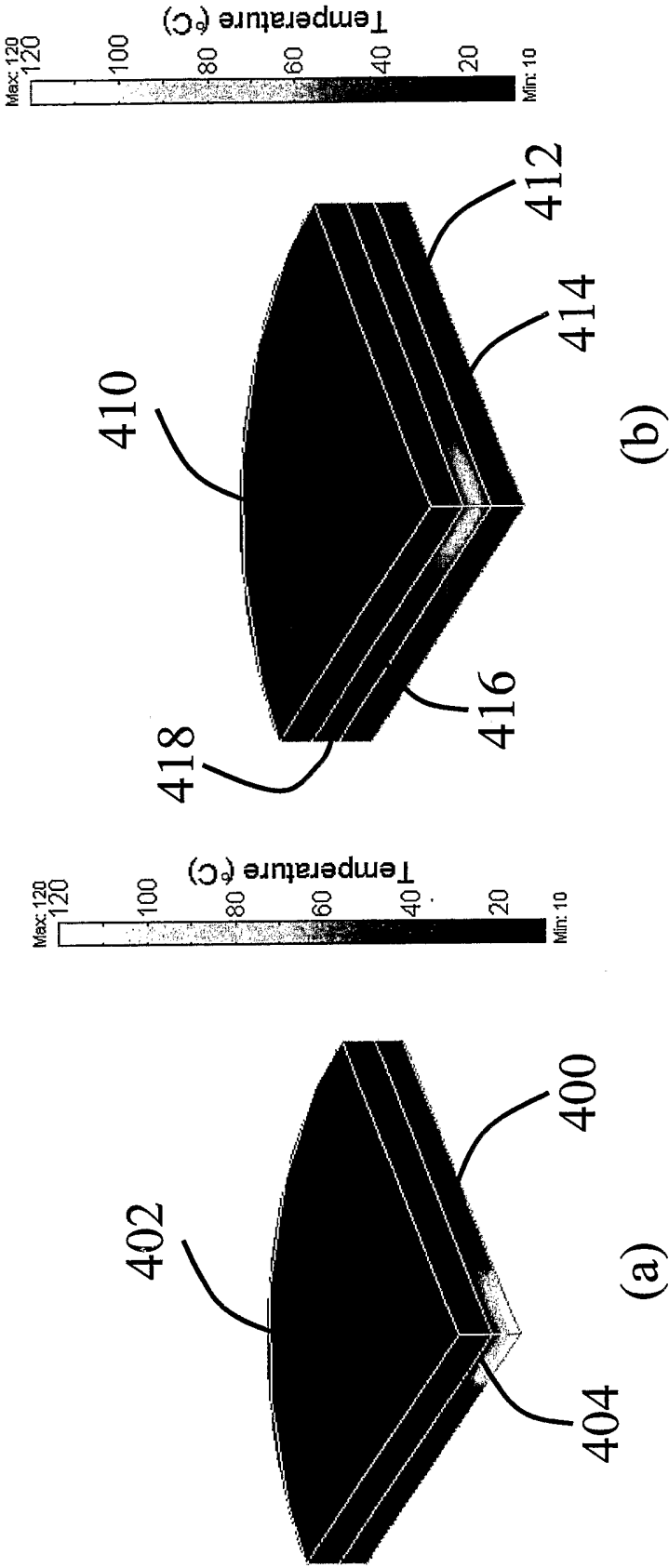


Figure 4