

IMPROVEMENTS RELATING TO SOLID-STATE LASERS /**FIELD OF THE INVENTION:**

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The present invention relates to the field of solid-state lasers and is concerned particularly with diode-pumped lasers.

BACKGROUND OF THE INVENTION:

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Currently, many applications, such as mechanical processing, non-linear optics etc., need an efficient and reliable laser device having relatively high energy or power. In such applications and the like, laser diode pumped Nd: YAG lasers are prominently used.

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Compared to the conventional flashlamps, laser diodes form efficient pumping sources. Moreover, laser-diode pumps also possess the advantages of having lower heat generation, longer utility lifetime and physical compactness. A variety of laser diodes, including laser-diode arrays can be and have been used as pumping sources for solid-state lasers.

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For many laser applications, it is desirable to produce small size, low cost yet high performance solid-state lasers. Therefore, the resonator/pump configuration is a key feature of laser design and performance. Laser-diode pumped laser design configurations have hitherto been categorized into two types, i.e. the end-and side-pump methods.

A diagram showing the principle of operation of a conventional end-pumped solid-state laser system is shown in Fig. 1 of the accompanying drawings. In such a system, the pumping laser radiation from the laser diode 1 is focused and delivered into the laser medium 2 through the coupling optics 3 and the reflective mirrors 4 and 5. In such an end pumping scheme, the pump volume can be matched to the desired TEM₀₀ mode volume for improving pumping efficiency. However, end pumping schemes limit the amount of pumping energy that can be used, thereby limiting the power of the laser, because of two reasons: 1. the power densities in the pump region of the laser medium become too high and the heat produced cannot be removed effectively (thermal effects in the pump region have been addressed in Satoshi Yamaguchi et al., *"Efficient Nd: YAG laser End-Pumped by a 1 cm Aperture Laser-Diode Bar with a GRIN Lens Array Coupling"*, IEEE. *Journal of Quantum Electronics*, Vol. 28, No. 4, April, 1992, P. 1101-1105); and 2. owing to high power or energy densities, laser damage in the laser gain medium is easily caused by the focused pump laser (see Sheldon B. Hutchison et al., *"Advances of 3-10 Watt Average Power Diode Pumped Laser"*, SPIE Vol. 1865(1993), P.16-72).

A diagram showing the principle of operation of a side pump scheme with coupling optics is shown in Fig. 2A (see Hans Bruesselbach et al, *"69-W-average Yb: YAG laser"*, *Optics Letters*, Vol. 21, No. 7, April 1, 1996, P.480-482) where the same reference numerals are used as for Fig 1. In such laser-diode pump, the pumping laser radiation from the laser diode 1 is coupled into the laser medium 2 by the coupling optics 3 in a direction perpendicular to the axis of the laser medium 2.

A direct side pump scheme is shown in Fig. 2B (see Frank Hanson et al., "*Laser diode side pumping of neodymium laser rods*", *Applied Optics*, Vol. 27, No. 1, 1 January, 1988, P. 80-83; H. Ajer et al., "*Efficient diode-laser side-pumped TEM00-mode Nd: YAG laser*", *Optics Letters*, Vol. 17, No. 24, December 15, 1992, P. 1785-1787). In such laser diode pump, the pumping laser radiation from the laser diode 1 emits into the laser medium 2 directly. After entering the laser medium 2, the pumping laser radiation from the laser diode 1 can be multi-reflected by a reflective film 6 into the laser medium 2 for increasing the pumping energy or power. However, the geometric matching between the laser mode and the pump volume are not as good for the Fig. 2B arrangement as the two types of laser diode pumping schemes described previously with reference to Figs. 1 and 2A.

In the above described side pumping schemes, although higher pumping energy or power can be delivered into the laser medium, the optical coupling efficiency between the pumping volume and the laser TEM00 mode is poor. Thus, such schemes do not provide mode matching and are therefore inefficient.

There exists another scheme, shown in Fig. 2C, which was proposed by H. Zbinden et al. ("*Diode-pumped Nd: YAG laser with parabolic pump cavity*", *OSA Proceedings on Advanced Solid-State Lasers*, 1993, Vol. 15, P.32-35), whereby a focusing reflector is designed to increase the optical coupling efficiency between the pump volume and the laser TEM00 mode. In this system the pumping laser radiation from the laser diodes 10 and 11 is first reflected by the mirror arrays 12 and 13 to be parallel and then is focused by the spherical reflective surface 14 onto the laser medium 15, and the portion of the pumping laser radiation that is not absorbed in a first pass

through the laser medium 15 is reflected at the parabolic reflective surface 16 for a second pass. However, this focusing reflector arrangement is not only complicated in design and bulky in size, but also requires higher fabrication cost.

5 **OBJECTS AND SUMMARY OF THE INVENTION:**

Accordingly, it is the principal object of the present invention to overcome or at least substantially reduce the abovementioned problems of the conventional end- and side-pumping schemes.

10 According to the present invention in its broadest aspect a laser pumping configuration is proposed which combines the advantages of both the end and the side pumping schemes, ie a pumping configuration whereby a portion of the pumping energy is delivered axially into the laser medium so that the pump volume can be matched to the desired TEM00 mode volume so as to optimize pumping efficiency, and a portion of the pumping energy is delivered laterally so as to allow more energy to be
15 delivered into the laser medium without giving rise to laser damage of the laser medium.

Hereinafter described is an exemplary embodiment of the present invention which employs a configuration whereby the laser medium is housed within a semi-cylindrical casing. The pumping laser source, which can either be a laser diode or a
20 laser-diode array, is positioned at the back end of the casing. The inner wall of the casing is reflective to reflect light from the pumping source and deliver the reflected light into the laser medium to increase the pumping efficiency. Also, the pumping laser source is positioned so as to optimize the pumping efficiency and is not necessarily

axially aligned with the laser medium. In the described embodiment, for example, the pumping laser source is positioned off-centered relative to the laser medium to optimize the optical coupling or pumping efficiency. Using such a configuration, a portion of the pumping energy falls on one end of the laser medium, and the rest of the pumping energy is delivered to the laser medium laterally by reflection from the inner reflective wall of the casing. In this manner, efficient geometric matching between the TEM00 laser mode and the pump volume can be obtained using a laser pump of higher energy without causing laser damage to the pumping end of the laser medium. Such a pumping configuration will hereinafter be referred to as a semi-end-side (SES) pumping technique.

The need for a focusing lens to focus the pumping radiation onto the pumped end of the laser medium can be eliminated by fabricating a curvature on the pumped end of the laser medium and coating it to be totally reflective for the laser radiation generated within said laser medium. Furthermore, whilst the described embodiment provides for efficient mode-matched pumping by housing the laser medium inside a semi-cylindrical casing whose inner wall constitutes a reflector, other shaped casings such as cylindrical or another geometrical shape could possibly be used.

The SES pumping technique of the present invention combines the advantages of both the conventional end pumping and side pumping schemes, namely good geometric matching between the laser mode and the pump volume, and high pumping efficiency. The present invention thereby allows the use of pumping lasers of higher power or energy which in turn yield higher laser output energy or power without causing laser damage to the gain medium. In short, the present invention provides a

means of constructing laser-diode pumped solid-state lasers that are efficient, low cost, compact and high power.

The above and other features of the present invention are set forth in the appended claims and, together with advantages thereof, will become apparent to those
5 possessed of appropriate skills upon reading the following detailed description of the preferred embodiment in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS:

Fig. 1 illustrates a schematic diagram of a conventional end pumped system;

10 Fig. 2A illustrates a schematic diagram of a conventional side pumped system employing coupling optics;

Fig. 2B illustrates a schematic diagram of a conventional direct side pumped system;

15 Fig. 2C illustrates a schematic diagram of a conventional side pumped system employing focusing reflectors;

Figs. 3A and 3B illustrate a basic schematic diagram of an embodiment of the present invention in cross-sectional and end elevation views respectfully.

Figs. 4A-F illustrate cross-sectional views of the pumping radiation distribution at different longitudinal positions of an SES pumped laser rod; and

20 Fig. 5 illustrates a SES-pumped free lasing laser, such as a YAG laser.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Hereinafter described is an exemplary embodiment of the invention which comprises a solid-state laser pumped by a laser diode or a laser-diode array and having
5 a SES-pump module providing effective coupling of higher energy or power from the laser diode to the laser medium. The embodiment utilizes a laser medium, e.g. a YAG rod, with one of its ends fabricated with a curvature which focuses a portion of the pumping laser radiation from the pumping laser source into the laser medium. The curvature replaces the focus lens or optics in the conventional end pumping
10 configuration, and it is coated so that it also acts as a reflector for the laser radiation generated within the laser medium. This solid-state laser embodying the present invention optimizes geometric matching between the TEM00 mode and the pump region in the laser medium by using an optional output mirror forming the laser cavity.

A schematic diagram of a SES-pump module solid-state laser embodying the
15 present invention is shown in Fig. 3. A pumping laser source 31, which can be one or more separate laser diodes or a laser-diode array comprising a plurality of laser diodes or even a plurality of such arrays, emits pumping radiation 37 into the SES-pump module which consists of a semi-cylindrical reflector 36, a front cover 35 and a back cover 38. The laser medium 33 is affixed to and held in place by the front cover 35 of
20 the SES-pump module by adhesive 34 or by means of a gasket ring formed of rubber or indium for example. In this particular embodiment, as shown in Fig. 3A, the laser medium 33 is positioned 3.5 mm above the laser source 31 in the direction perpendicular to the axis of the laser medium 33, and 5 mm away from the laser source

31. The end of the laser medium 33 facing the pumping laser source 31 is fabricated as a convex structure 32 which acts as a lens for focusing the pumping radiation falling onto the curvature area 32 into the laser medium 33. The other end 39 of the laser medium 33 is made flat and is coated to be anti-reflective for the laser radiation
 5 generated by the laser medium 33. The curved end 32 is coated so as to be a reflector for the laser radiation generated by the laser medium 33 but anti-reflective for the pumping laser radiation 37 from the pumping laser source 31.

In accordance with the present invention, a portion of the pumping radiation 37 is focused by the curved end 32 of the laser medium 33 and the radiation is absorbed by
 10 the laser medium 33. The rest of the pumping radiation 37 from the pumping laser source 31 is absorbed by the laser medium 33 through its side surfaces after having been reflected by the inner wall 40 of the SES-pump module.

Cross-sectional views of the pumping radiation distribution in the SES-pumped laser medium 33, simulated by using ray tracing, are shown in Figs. 4(A)-(F), which
 15 correspond to locations spaced 5mm, 10mm, 15mm, 20mm, 25mm and 30mm from the emitting surface of the pumping laser source 31, respectively. These Figures show that the laser power is mainly concentrated in the middle of the laser medium.

A SES-pumped free lasing solid-state laser based on the present invention is shown in Fig. 5. The laser light generated by the laser medium 33 is coupled by an
 20 output mirror 41 of the laser cavity to provide an output laser beam 42. By inserting a Q-switch between the output mirror 41 and the laser medium 33, the free lasing laser can be further developed into a Q-switched laser.

The SES pumping technique of the present invention combines the advantages of the end and side pumping solid-state laser schemes, i.e. efficient geometric matching between the laser TEM00 mode and the pump volume, high coupling efficiency of pumping radiation into the laser medium and ability to use a higher energy or power
5 pumping source without causing laser damage to the laser medium. The details of the design and implementation described above are merely illustrative of the invention and it is to be understood that various changes in such details may occur to those skilled in the art without departure from the scope of the invention as set forth in the appended claims.

**CLAIMS**

1. A diode-pumped solid-state laser wherein the arrangement is such that a portion of the pumping radiation is delivered to one end of an elongate solid-state laser medium and a portion is delivered to side surfaces of the laser medium.
- 5 2. The laser of claim 1 wherein said one end of the laser medium is formed to facilitate the entry of pumping laser radiation into said laser medium.
3. The laser of claim 2 wherein said one end of the laser medium is formed with a
10 convex curvature.
4. The laser of claim 2 or 3 wherein a coating is formed on said one end of the laser medium, said coating being reflective in respect of laser radiation generated by said laser medium and transmissive in respect of the pumping radiation.
- 15 5. The laser of any preceding claim wherein the laser pumping source is a laser diode or a plurality of separate laser diodes.
6. The laser of any of claims 1 to 4 wherein the laser pumping source is a laser-
20 diode array or a plurality of separate laser-diode arrays.

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7. The laser of any preceding claim comprising a casing locating a laser pumping source with respect to said laser medium, internal surfaces of said casing being reflective with respect to the pumping radiation.
- 5 8. The laser of claim 7 wherein the laser pumping source is so positioned with respect to the laser medium in said casing as to optimize the pumping efficiency of the laser medium by the pumping source.
9. The laser of claim 7 or 8 wherein the casing is semi-cylindrical with front and
10 back ends locating the laser medium and the laser pumping source respectively.
10. The laser of claim 7 or 8 wherein the casing is cylindrical with front and back ends locating the laser medium and the laser pumping source respectively.
- 15 11. The laser of claim 7 or 8 wherein the casing is non-cylindrical with front and back ends locating the laser medium and the laser pumping source respectively.
12. The laser of claim 9 or 10 or 11 wherein one or other on both of the front and back end surfaces is/are flat.
- 20 13. The laser of any of claims 9 to 12 wherein the laser medium is affixed to and held in place by the front cover of the casing by means of adhesive and/or by means of a gasket ring.

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14. The laser of claim 13 wherein the gasket ring is made of rubber.
15. The laser of claim 13 wherein the gasket ring is made of indium.
- 5 16. The laser of any preceding claim wherein the laser medium is in the form of a rod.
17. The laser of claim 16 wherein the laser medium is a YAG rod.
- 10 18. The laser of any preceding claim wherein the pumped volume of the laser is matched to the TEM00 mode of the laser medium.
- 15 19. The laser of any preceding claim further including an output mirror for collimating the output laser radiation.
- 20 20. The laser device of any preceding claim comprising a free lasing laser device further developed into a Q-switched laser.
- 20 21. A mode-matched diode-pumped solid-state laser, comprising:
a SES-pump module including
a laser pumping source,
a laser medium, and

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a casing including a front cover and a back cover, and wherein the inner wall of said casing and said front and back covers form a reflector in respect of the pumping radiation.

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IMPROVEMENTS RELATING TO SOLID-STATE LASERS**ABSTRACT OF THE DISCLOSURE:**

5 A diode-pumped solid state laser is disclosed in which a portion of the energy
from the pumping laser diode is directly absorbed by one end of the laser medium, e.g.
a YAG rod, and the rest of the pumping radiation is absorbed through the side surfaces
of said laser medium after reflection from the reflective inner walls of a shaped casing.
The arrangement combines the advantages of conventional end- and side-pumping
10 schemes for the construction of a laser-diode pumped single-mode laser.
(Fig. 3A)

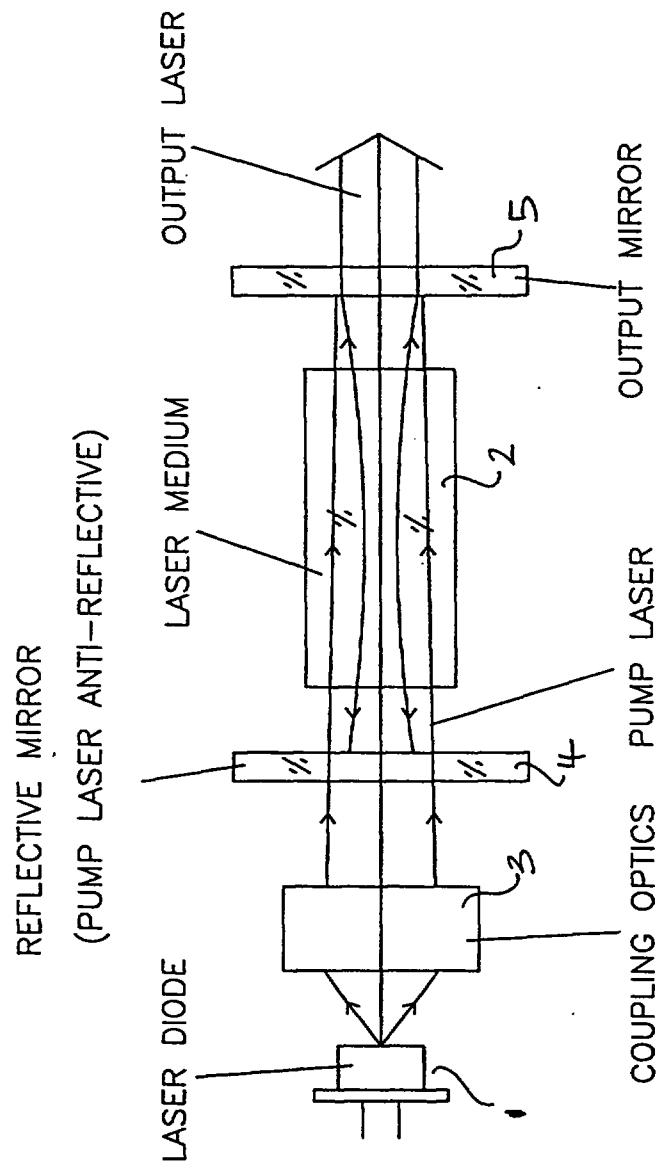


Fig. 1

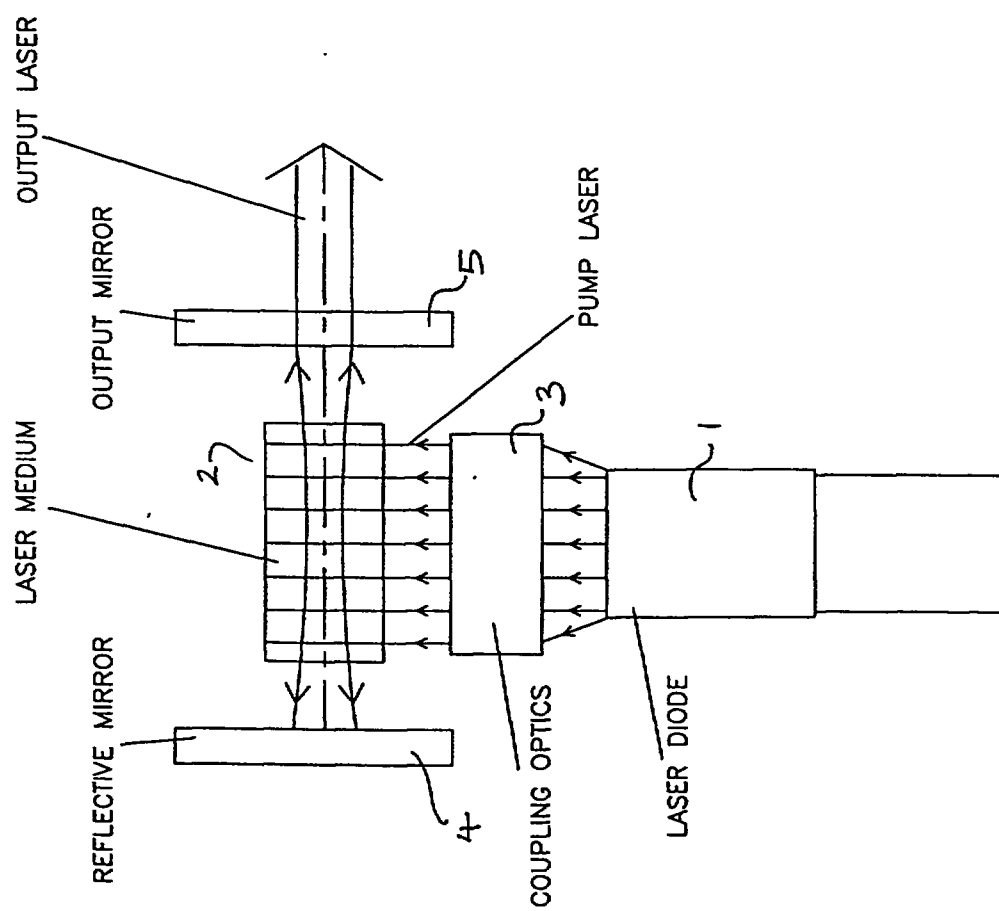


Fig. 2A

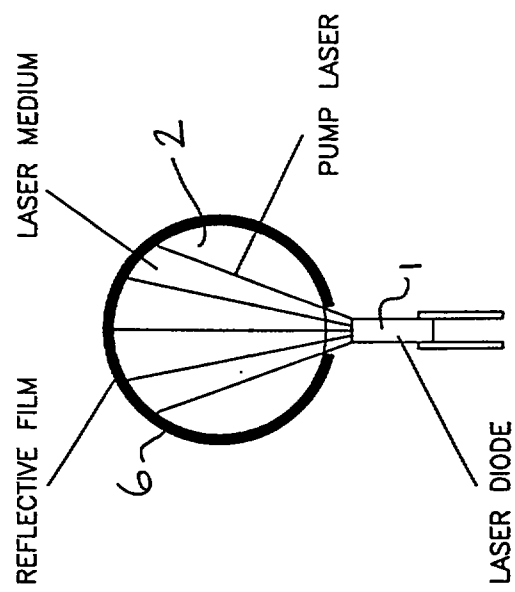


Fig. 2B

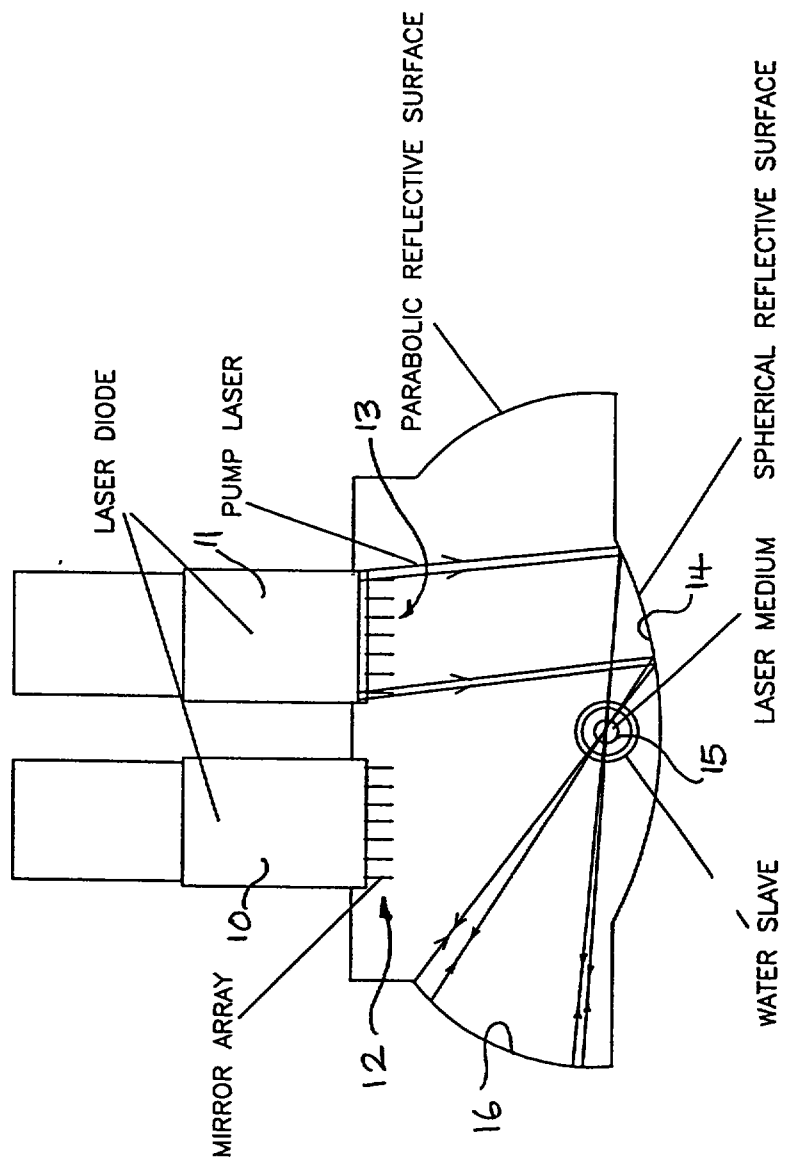


Fig. 2C

Fig. 3A

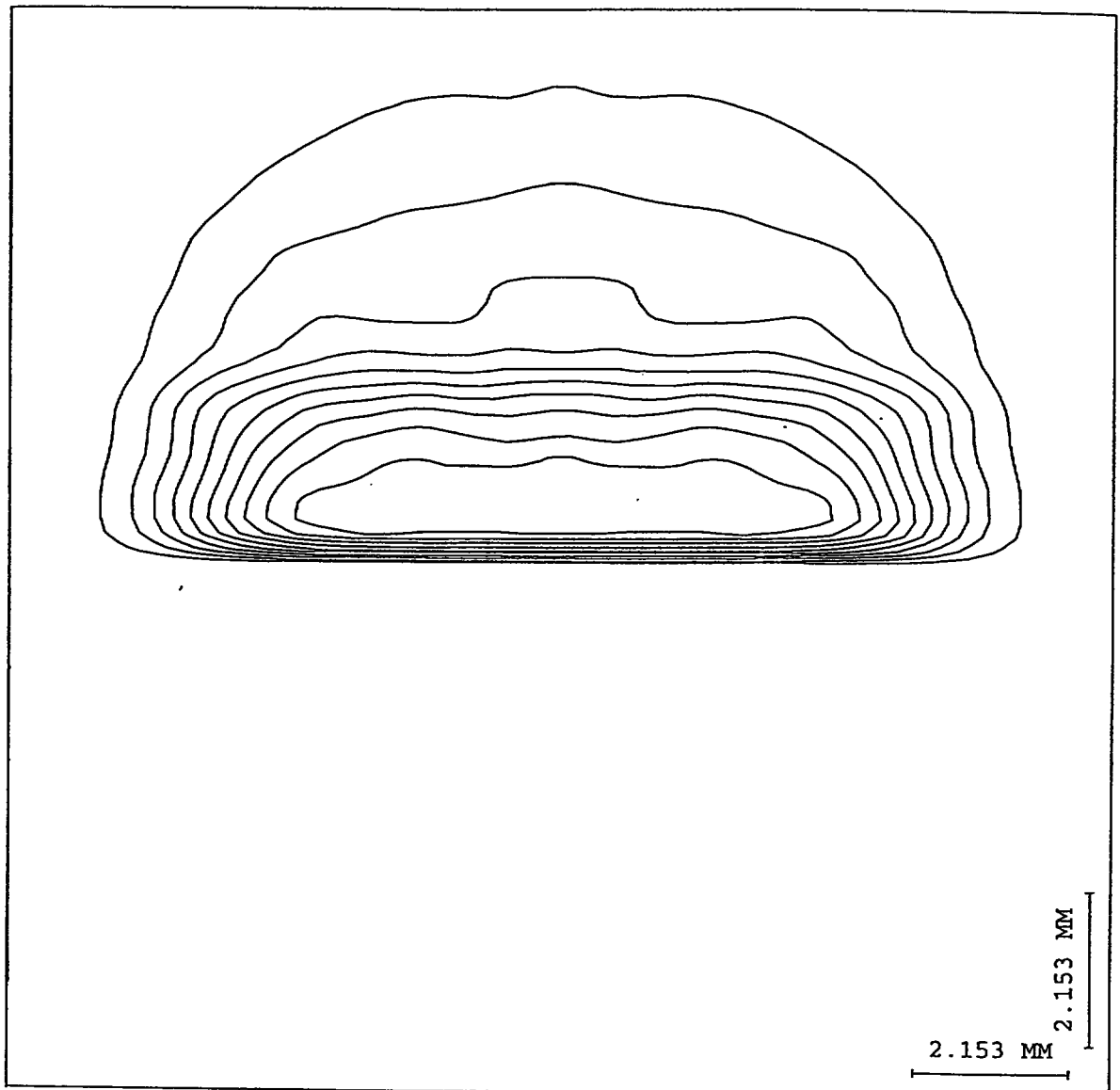


Fig. 4A

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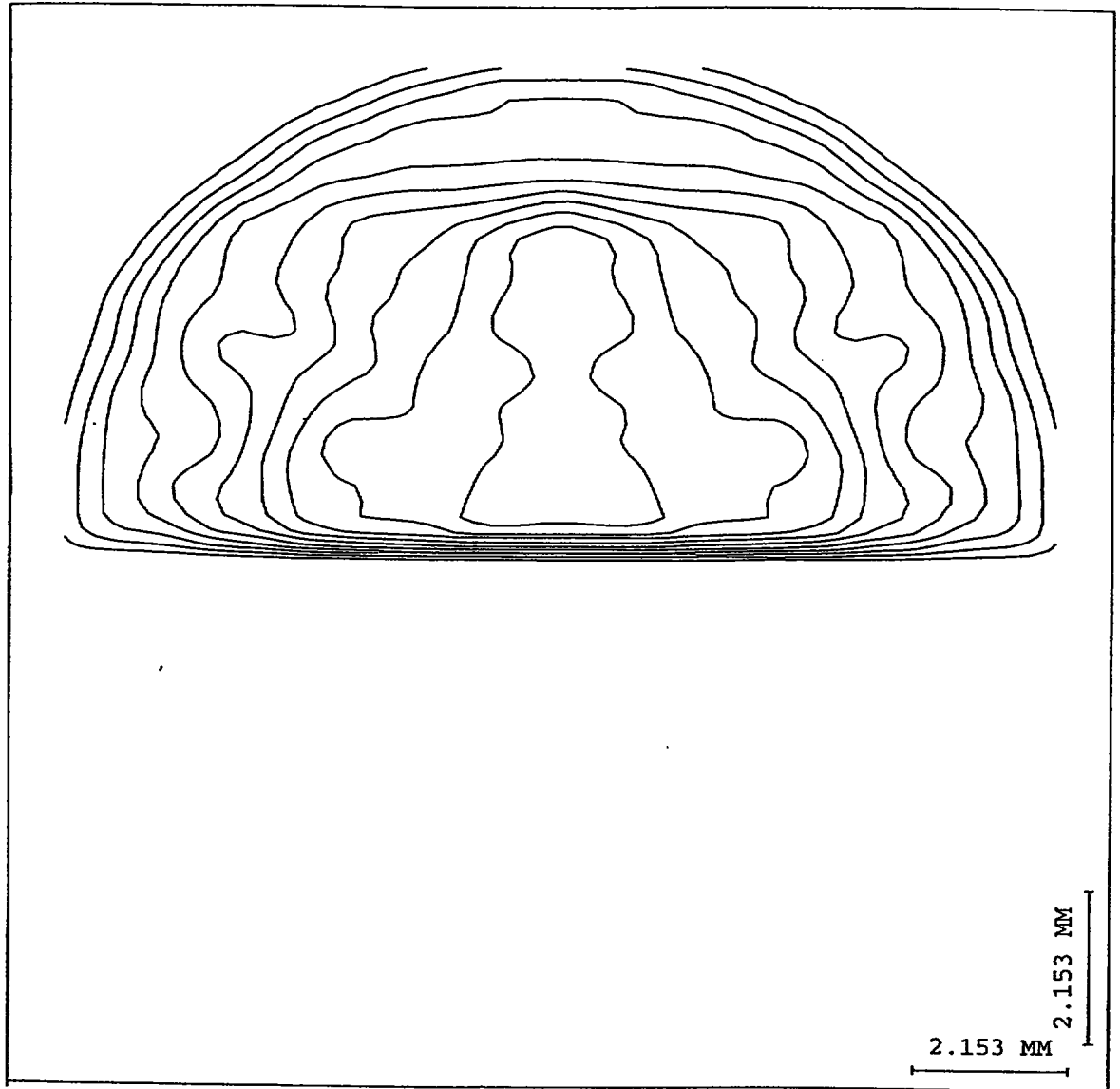


Fig. 4B

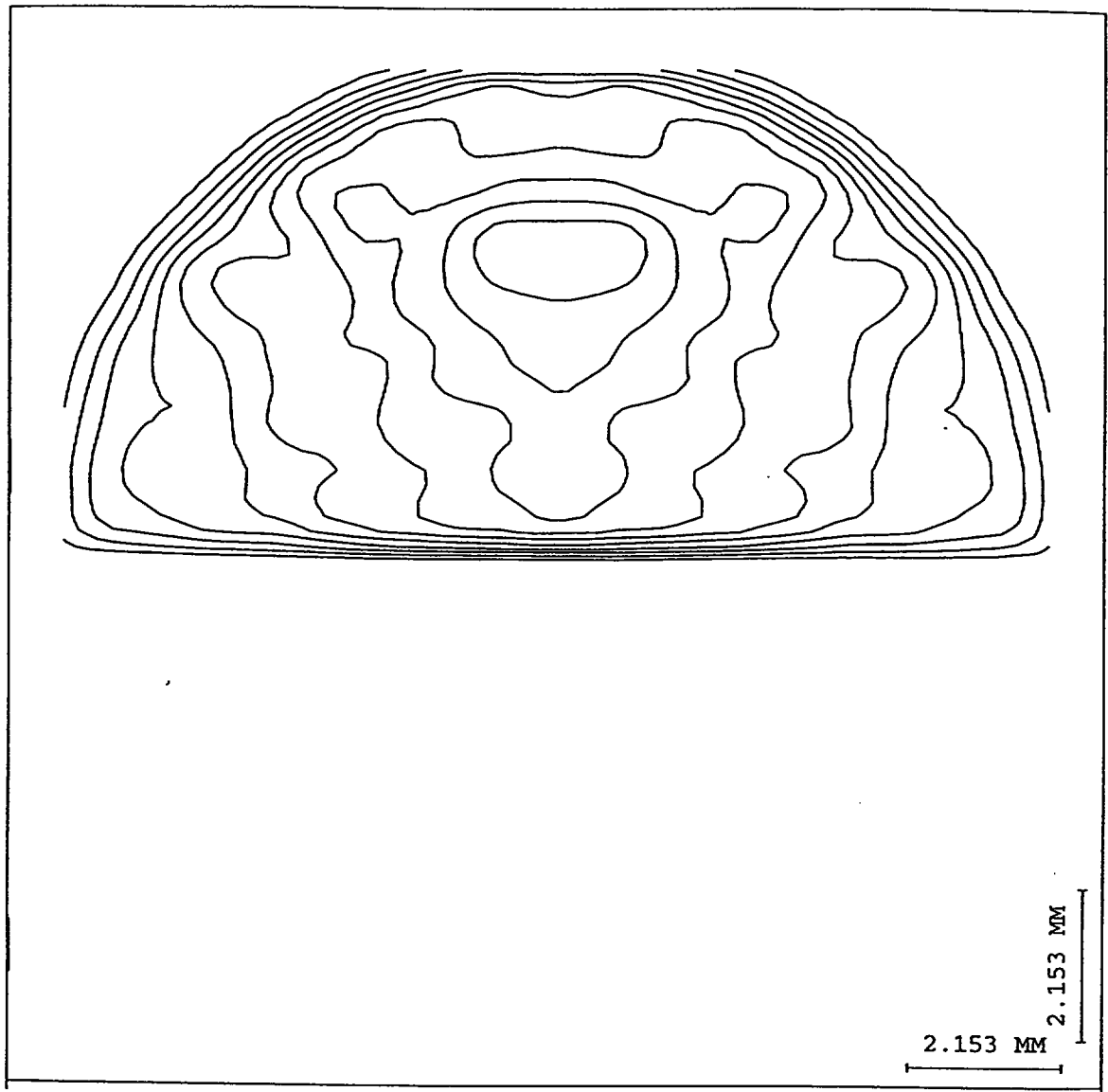


Fig. 4C

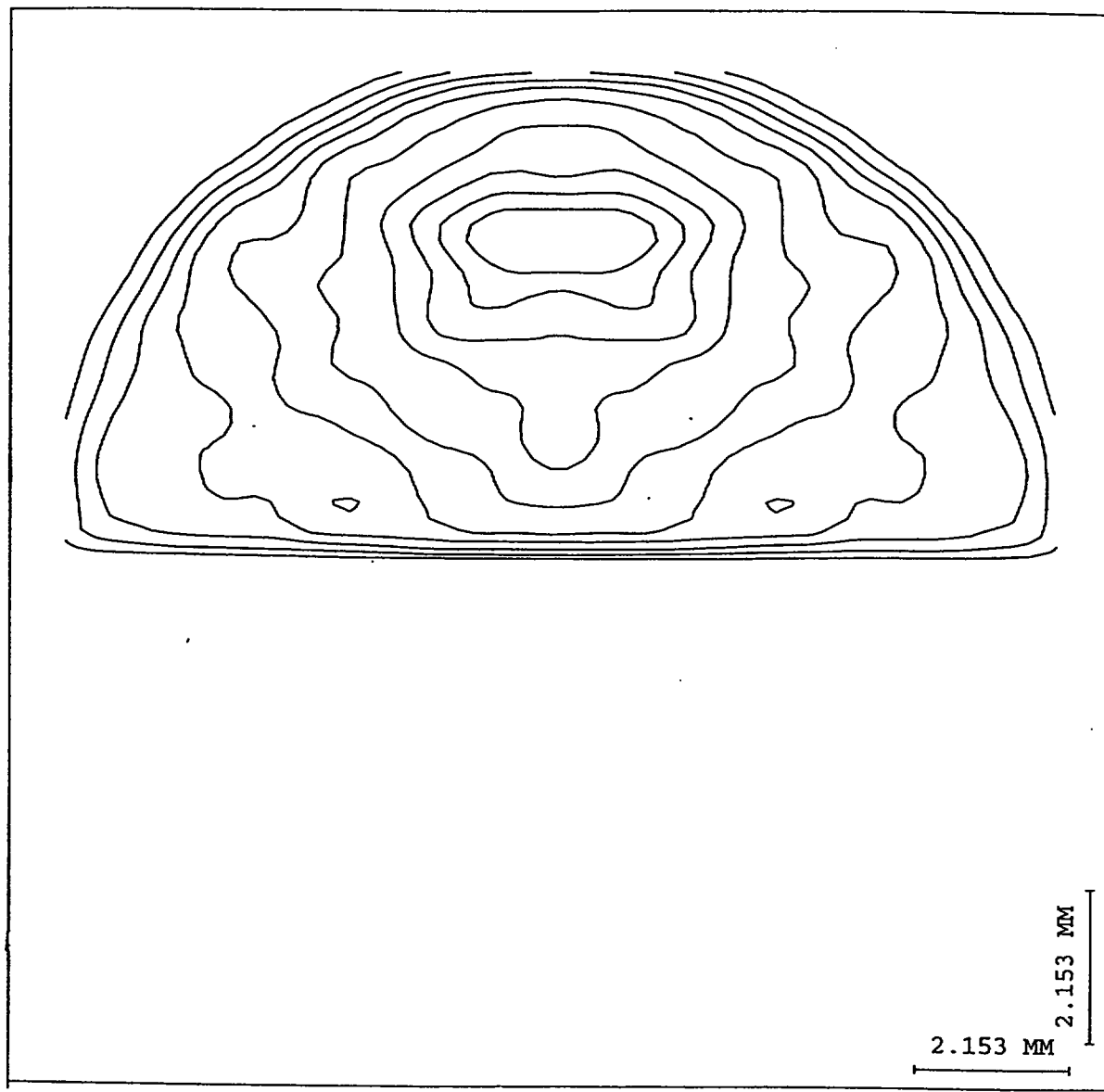


Fig. 4D

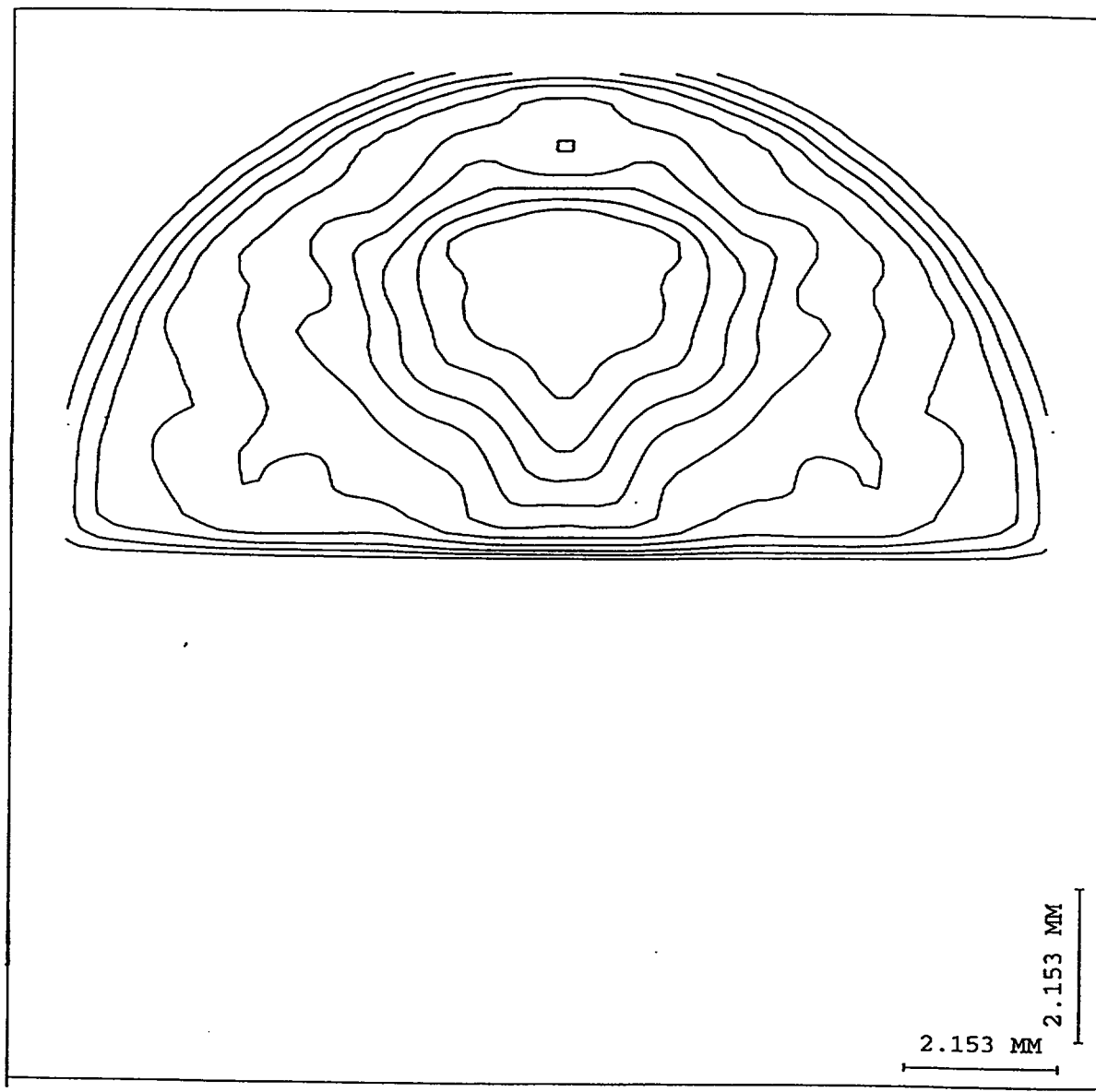


Fig. 4E

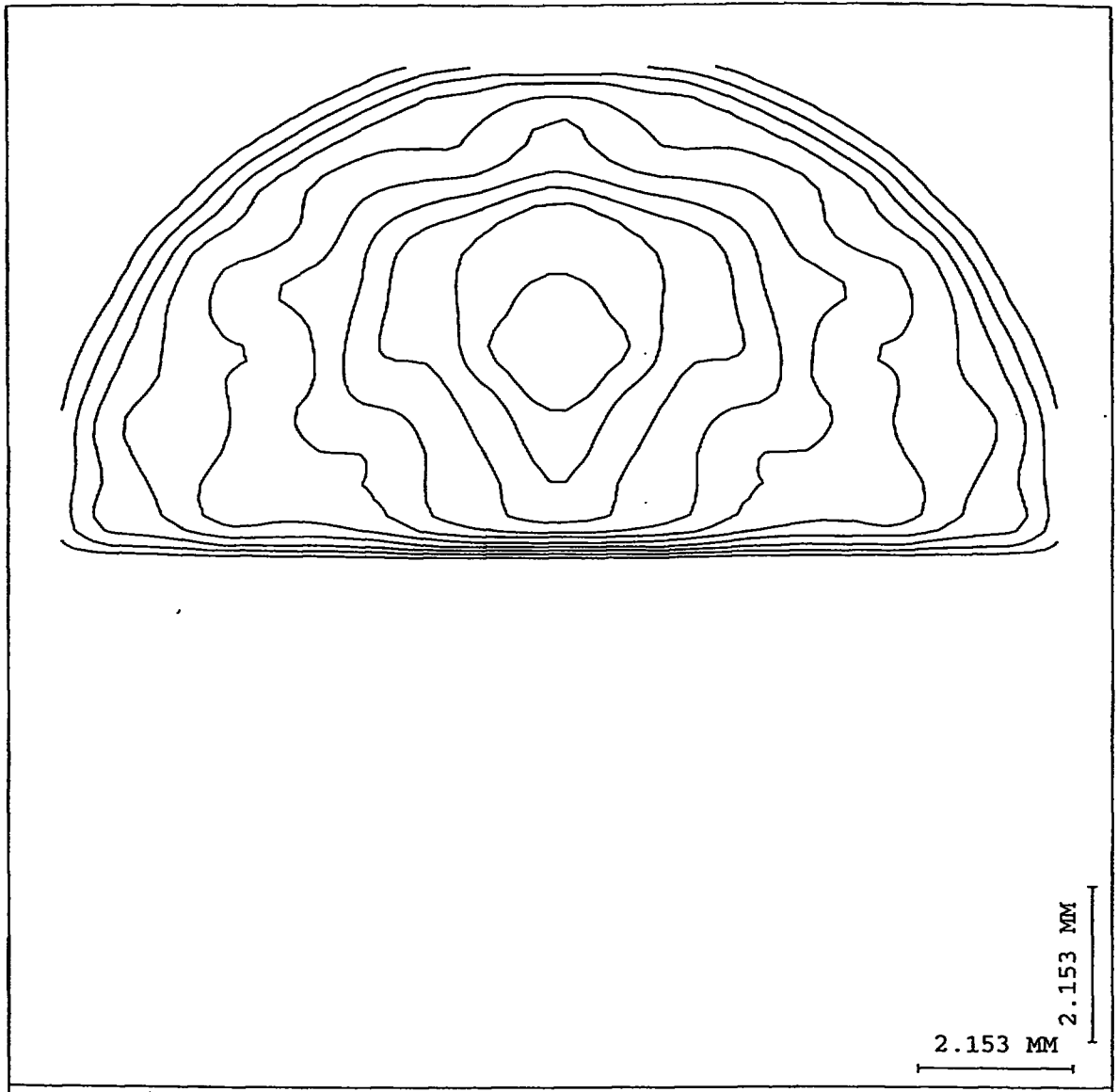


Fig. 4F

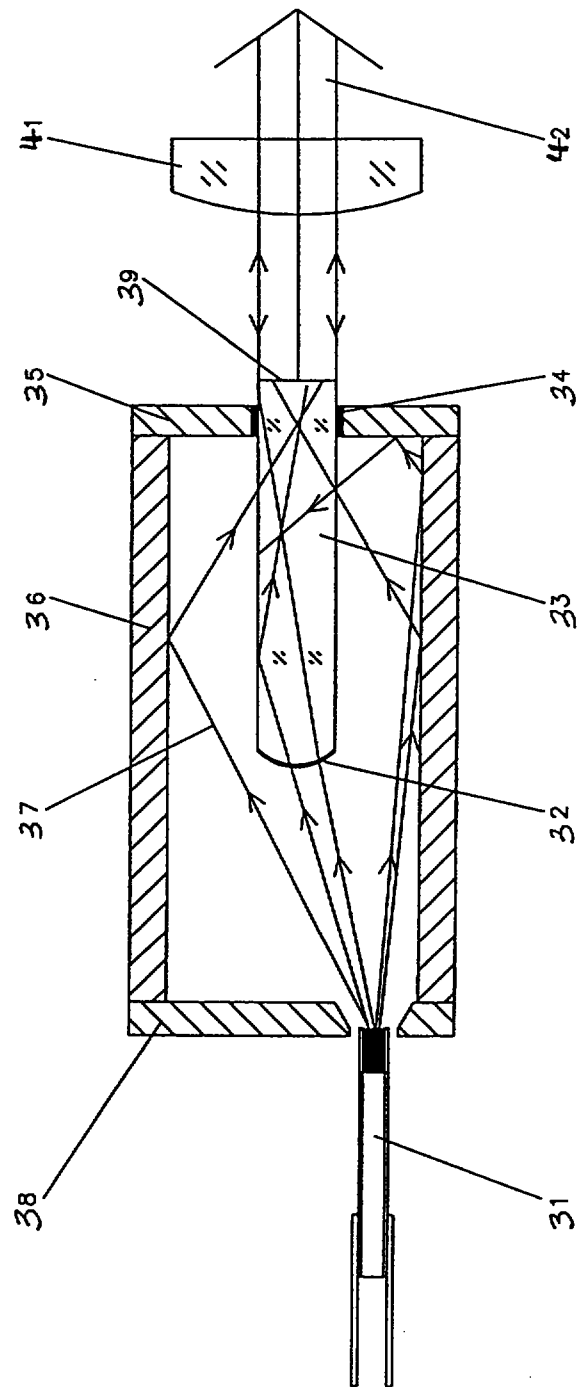
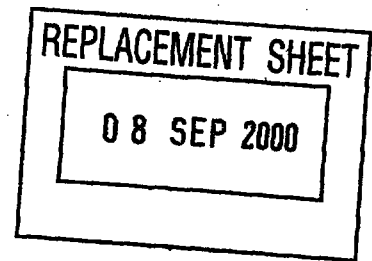


Fig. 5

**CLAIMS**

1. A diode-pumped solid-state laser wherein the arrangement is such that a portion of the pumping radiation is delivered to one end of an elongate solid-state laser medium (33) and a portion is delivered to side surfaces of the laser medium (33), and the laser comprising a casing locating a laser pumping source (31) with respect to said laser medium (33), internal surfaces (40) of said casing being reflective with respect to the pumping radiation.

2. The laser of claim 1 wherein said one end of the laser medium is formed to facilitate the entry of pumping laser radiation into said laser medium (33).

3. The laser of claim 2 wherein said one end of the laser medium is formed with a convex curvature (32).

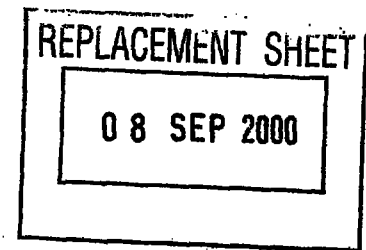
4. The laser of claim 2 or 3 wherein a coating is formed on said one end of the laser medium (33), said coating being reflective in respect of laser radiation generated by said laser medium (33) and transmissive in respect of the pumping radiation.

5. The laser of any preceding claim wherein the laser pumping source (31) is a laser diode or a plurality of separate laser diodes.

6. The laser of any of claims 1 to 4 wherein the laser pumping source (31) is a laser-diode array or a plurality of separate laser-diode arrays.

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7. The laser of claim 1 wherein the laser pumping source (31) is so positioned with respect to the laser medium (33) in said casing as to optimize the pumping efficiency of the laser medium (33) by the pumping source (31).

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8. The laser of claim 1 or 7 wherein the casing is semi-cylindrical with front and back ends locating the laser medium (33) and the laser pumping source (31) respectively.

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9. The laser of claim 1 or 7 wherein the casing is cylindrical with front and back ends locating the laser medium (33) and the laser pumping source (31) respectively.

10. The laser of claim 1 or 7 wherein the casing is non-cylindrical with front and back ends locating the laser medium (33) and the laser pumping source (31) respectively.

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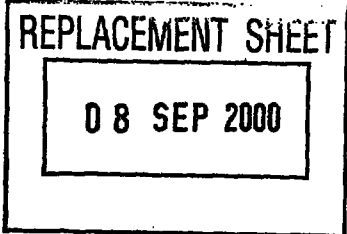
11. The laser of claim 8 or 9 or 10 wherein one or other on both of the front and back end surfaces is/are flat.

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12. The laser of any of claims 9 to 11 wherein the laser medium (33) is affixed to and held in place by the front cover (35) of the casing by means of adhesive (34) and/or by means of a gasket ring.

13. The laser of claim 12 wherein the gasket ring is made of rubber.

14. The laser of claim 12 wherein the gasket ring is made of indium.



15. The laser of any preceding claim wherein the laser medium (33) is in the form of a rod.

5 16. The laser of claim 15 wherein the laser medium (33) is a YAG rod.

17. The laser of any preceding claim wherein the pumped volume of the laser is matched to the TEM00 mode of the laser medium.

10 18. The laser of any preceding claim further including an output mirror (41) for collimating the output laser radiation.

19. The laser device of any preceding claim comprising a free lasing laser device further developed into a Q-switched laser.

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20. A mode-matched diode-pumped solid-state laser, comprising:

a SES-pump module including

a laser pumping source (31),

a laser medium (33), and

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a casing including a front cover (35) and a back cover (38), and wherein the inner wall (40) of said casing and said front and back covers (35, 38) form a reflector in respect of the pumping radiation.