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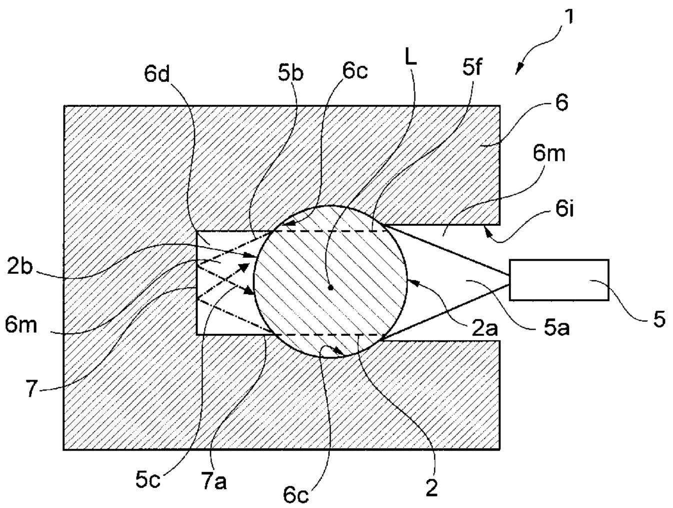

Fig. 2

(57) Abstract: A monolithic, side pumped solid-state laser (1) comprising a laser resonator structure (3) comprised of a laser gain medium (2) having a longitudinal axis (L), wherein the laser resonator structure (3) comprises end faces (4) forming a linear optical path resonant cavity there between, at least one of the end faces (4) comprising at least partially reflecting laser mirrors (4a, 4b) in particular deposited thereon, the laser gain medium (2) comprising a side face (2a) for receiving pump light (5a) of a pump source (5), wherein the pump light (5a) is generated by a diode laser (5), and comprising a conductive cooler (6) comprising contact faces (6c) contacting the laser gain medium (2), and comprising a reflector (7) arranged opposite to the side face (2a) with respect to the longitudinal axis (L), wherein the laser gain medium (2) is a low gain material.

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MONOLITHIC, SIDE PUMPED SOLID-STATE LASER AND METHOD FOR OPERATING THE SAME

FIELD OF THE INVENTION

This invention relates to a monolithic, side-pumped solid-state laser comprising the features of claim 1. The invention further relates to a method for operating a monolithic, side pumped solid-state laser comprising the features of claim 22.

BACKGROUND OF THE INVENTION

Diode pumped lasers have grown in usefulness, particularly in industrial, medical and military applications. Diode pumped lasers are particularly useful, because diode pumps are power efficient, all solid-state and long lived. These result in laser systems that are lighter, more efficient and typically not water cooled, as compared to similar flash lamp pumped solid-state lasers.

In general, end-pumped or side pumped solid-state laser configurations are known. Q-switched lasers or monolithic lasers are configurations such as those described in U.S. Pat. Nos. 5,394,413; 5,381,431; 5,495,494; 5,651,023 and 6,373,864 B1. Disadvantages of such designs are, inter alia, limitations regarding the maximal pulse energy. In addition Q-switched lasers are able to only produce pulses of very short duration.

U.S. Pat. Nos. 6,219,361 B1 and 6,377,593 B1 describe side pumped designs, where the beam path takes an internal zig-zag path, such design lengthening the pulse duration and increases manufacturing difficulty and cost.

In diode side-pumped geometries, the gain media is typically either a rod or a slab. Slab geometries have typically been used in conductively cooled laser systems with one side of the slab attached to a thermal heat sink, and with the opposing face used for the introduction of pump light. Side pumped slabs can employ various techniques such as utilizing a so called "zig-zag" optical path, as for example disclosed in US 2007/0060917, Fig. 2b. Zig-zag slabs, however, are difficult to fabricate owing to tight optical tolerances and are therefore more difficult to produce in large quantities than straight through slab embodiments, and are therefore more expensive to produce.

Document WO2004/034523 discloses a monolithic, side pumped, passively Q-switched and not water cooled solid-state laser that includes a laser resonator structure, and that includes a laser gain medium having an output face bonded to a passive Q-switch. The gain medium has a side face for receiving pump light. The pump light is generated by a diode laser array. One disadvantage of this solid-state laser is that the average power is limited. Another disadvantage of this solid-state laser is that thermal effects arise during operation. In addition Q-switched lasers are able to only produce pulses of very short duration.

Document US 2007/0060917 discloses in Fig. 1b and 2a a MIR (mid-infrared) diode side pumped solid-state laser that includes a laser resonator structure were gain switched pulse can be emitted (Fig. 5c). One disadvantage of this solid-state laser is that the power of the generated laser light is limited and low.

Document US 6,366,596 B1 discloses a diode side pumped OPO laser that generates, inter alia, MIR (mid-infrared) radiation. Although the wavelength can be tuned in a wide range in the MIR wavelength region, the disadvantage of such lasers is the short pulse duration in the one and two digit nanosecond region with high power densities (intensities) or if the laser pulse lengths are in the microsecond region the laser pulse intensity is very low. In addition such lasers are complex, require optical elements with various optical coatings, and are thus very expensive. Another disadvantage is that such lasers are not robust against shock and vibration, and that the large number of critical components increases the likelihood of a system failure.

Documents US 5,642,370; US 5,643,252; US 5,868,731; US 5,908,416; US 5,947,957; US 6,251,102 B1 and US 6,395,000 B1 disclose side pumped solid state lasers working in the mid-infrared wavelength region. In general such solid-state lasers are used for biological tissue ablation. Some of these lasers are battery powered and so called self contained, delivering single laser pulses followed by a few seconds charge time of the capacitors in the high voltage power supply.

It is therefore an object of the present invention to provide a side-pumped solid-state laser device for generating high power laser light pulses. It is a further object of the present invention to provide an inexpensive, robust and reliable laser device. It is a further object of the present invention to provide a high performance operating laser device, in particular to provide laser light having high pulse energy and/or high power and in particular allowing high pulse repetition rate in a broad working range. It is a further object of the present invention to provide a laser device suitable to be used in the medical field, in particular with a wavelength in the mid- infrared (MIR) range of between 1700 nm to 3200 nm, and/or in particular suitable for treating, cutting or ablating biological tissue.

SUMMARY OF THE INVENTION

This problem is solved with a monolithic, side pumped solid-state laser comprising the features of claim 1. Dependent claims 2 to 21 disclose optional features. The problem is further solved with a method for operating a monolithic, side pumped solid-state laser comprising the features of claim 22, with dependent claims 23 to 24 disclosing optional features.

The problem is in particular solved with a monolithic, side pumped solid-state laser comprising a laser resonator structure comprised of a laser gain medium having a longitudinal axis L, wherein the laser resonator structure comprises end faces forming a linear optical path resonant cavity there between, at least one of the end faces comprising at least partially reflecting coatings deposited thereon, the laser gain medium comprising a side face for receiving pump light of a pump source, wherein the pump light is generated by a diode laser, and comprising a conductive cooler comprising contact faces contacting the laser gain medium, and comprising a reflector arranged opposite to the side face with respect to the longitudinal axis L.

The problem is further in particular solved with a monolithic, side pumped solid-state laser comprising a laser resonator structure comprised of a laser gain medium having a longitudinal axis L, wherein the laser resonator structure comprises end faces forming a linear optical path resonant cavity there between, at least one of the end faces comprising at least partially reflecting laser mirrors in particular deposited thereon, the laser gain medium comprising a side face for receiving pump light of a pump source, wherein the pump light is generated by a diode laser, and comprising a conductive cooler comprising contact faces contacting the laser gain medium, and comprising a reflector arranged opposite to the side face with respect to the longitudinal axis L, wherein the laser gain medium is in particular a low gain material.

The problem is further in particular solved with a method for operating a monolithic, side pumped solid-state laser comprising a laser resonator structure comprised of a laser gain medium having a longitudinal axis L, wherein pump light is fed through a side face into the laser gain medium, wherein part of the pump light is exiting the laser gain medium at an opposite side face as an exiting pump light, and wherein the exiting pump light is reflected such that a reflected pump light is reentering the laser gain medium at the opposite side face.

The diode side pumped solid-state laser disclosed in Document US 2007/0060917 generates low quality laser light respectively of low intensity. On the other hand, it has been found out that the laser light needs a certain level of intensity to highly efficient ablate biological tissue. It is further known that diode side pumped solid-state lasers emit less pulse energy than flash lamp pumped solid-state lasers. The monolithic, side pumped solid-

state laser according to the invention uses several technical features to improve the intensity of the laser light. First of all a laser gain medium having a cross sectional area of less than 7,5 mm^2 is used. If the laser gain medium has the shape of a rod, with a circular or elliptical cross section, this means that the rod has a diameter of less or equal 3 mm, preferably less or equal 2 mm. The advantage of a rod having such a small diameter respectively having such a small cross sectional area is the fact that less pump power is required to achieve a certain power density inside the laser gain medium. Only by using a rod with such a small cross sectional area it is possible to create sufficient power density, whereby the pump light is generated by a semiconductor laser. Assuming the laser rod would have a diameter of 4 mm, then the cross sectional area would increase to about 12,5 mm^2, which is about double the cross sectional area of the 3mm rod. The 4 mm rod needs about two times the pump power to achieve the same power density than the 3 mm rod. It is therefore a very important advantage to limit the cross sectional area of the laser gain medium to less than 7,5 mm^2. In a preferred embodiment the diode laser pump power within the laser active medium is between 20 and 500 W/mm^3.
In a preferred embodiment the intra cavity laser intensity (within the laser active medium) is between 5 kW/cm^2 and 10 MW/cm^2 and more preferably between 10 and 100 kW/cm^2.

A further advantageous measure to increase the intensity within the laser gain medium is to use an output coupler that has a reflectivity in the range of between 92,5% to 99%. A further advantageous measure to increase the intensity within the laser gain medium is to reduce cavity losses. It is a disadvantage of solid state lasers such as disclosed in document US 2007/0060917 that the use of a discrete laser cavity causes optical losses through media transitions from the laser gain medium to air and from air to the laser mirrors due to reflection and absorption losses of laser light on these transitions. Since the used laser media are low gain laser materials, these additional losses prevent such known laser systems from efficient operation. Another disadvantage of laser cavities especially working in the mid infrared (MIR) wavelength region of 1700 nm to 3200 nm is that dust or humid air between the laser gain medium and the laser mirrors strongly reduce efficiency of the laser system or almost stop the laser cavity from emitting laser light due to the strong water absorption of the emitted laser light. This causes additional losses and further reduces intensity within the laser gain medium.

A further advantageous measure to optimise the laser output beam quality is to symmetrically cool the laser active gain medium. Due to the fact that the laser gain medium in WO2004/034523 is not cooled symmetrically, the beam profile is not homogeneous and therefore the beam parameter product M2 is bad which leads to poor focusability. The symmetrical cooling of the laser active gain medium according to the invention therefore leads to a homogeneous beam profile.

A further advantage of the solid-state laser according to the invention is, that the manufacturing costs are low and that little maintenance is required. This strongly improves market acceptance. This advantage is achieved by reducing the number of needed optical elements and/or the number of adjustable optical elements or laser cavities. Especially adjustable optical elements or laser cavities in hand held or movable laser based medical and non medical devices have been the cause for market failure and expensive product callbacks or at least high maintenance costs. A solid state laser according to the invention is highly shock and vibration proof as well as stable even after quick changes of environment conditions like e.g. temperature, humidity. Laser designs produced according to conventional methods suffer from robustness and usually self-disadjust. In addition a decrease in laser output power might occur, caused by temperature, mechanical stress (shock, vibration), dust on optics and so on. Such devices have to be repaired, optics have to be cleaned and laser cavities have to be realigned on a regularly basis which causes high maintenance costs.

A further advantage of the solid-state laser according to the invention is that the design can be highly miniaturized due to the highly efficient and also short laser cavity. This allows implementing the solid-state laser in device parts which in the past could not include a high power solid-state laser. One example would be the implementation of a mid infrared solid-state laser with e.g. up to 5 W in a so called self contained or handheld wireless device such as disclosed in US 7,118,563. Today only a diode laser in the near infrared (780 – 1400 nm) can be used in such devices. One advantage of the invention is, that battery powered self contained devices can now be provided with mid-infrared solid-state lasers. In addition, such devices can also be light weighted, e.g. less than 1 kg. Other new devices comprising a laser may be build which are smaller and less power consuming. It could be even thought about a device consisting of (i) a table top part containing a power supply, a cooling unit and eventually a control unit, and (ii) a hand held unit containing the solid-state laser, eventually beam shaping optics, beam deflection means and maybe also a control unit. The hand held unit could be detachable for maintenance reasons and could be sent within a small light weight package to the device manufacturer. Before shipping the device to the manufacturer the device owner can inform him and could be provided with a temporary hand held unit prior to sending back his hand held unit via ordinary mail for service reasons. No more expensive travelling of service personal is necessary and no more expensive shipping of heavy devices is needed any more. All these advantageous lead to a very economic product and satisfied customers.

In a further advantageous embodiment the pump light is guided such that there is an about homogenous distribution of the pump light in the laser gain medium 2. Most advantageously this is achieved by a pump light reflector arranged opposite to the side face with respect to the longitudinal axis of the laser gain medium. This arrangement allows the pump light entering the laser gain medium from the side face to cross the laser gain medium, to exit the laser gain medium, and being reflected by the pump light reflector, so that the reflected light again enters the laser gain medium. This embodiment creates a homogenous light distribution within the laser gain medium. The advantage of such a homogenous light distribution is that it results in a much better laser mode compared to conventional systems.

This laser mode can have a beam parameter product M2 between 1 and 25 which is the key to a very well focusable laser beam.

A further advantage of the small cross sectional area of the laser gain medium is that the laser beam can be focused to a smaller diameter. Known flash lamp pumped lasers or diode pumped lasers with laser gain media cross sectional areas allow the laser beam to be focused to 300 to 500 µm. The laser gain media used in the solid-state laser according to the invention allows the laser beam to be focused to about 100 to 250 µm. This allows increasing the intensity of the laser beam in the focus.

A further advantage of the solid-state laser according to the invention is that the laser beam with such a small cross sectional area can now be transmitted high efficiently through thin and thus inexpensive light fibres. A further advantage of the invention is, that the transmission of the laser beam into the fiber is more efficient because the better the laser beam quality the more efficient the incoupling into the fiber which is equivalent to reduced losses.

A further advantage of the solid-state laser according to the invention is that they do not comprise adjustable optical elements such as for example laser mirrors or flash lamps. The solid-state laser according to the invention is therefore robust against disadjustment caused by shock events, vibration or disadjustment over time caused by thermal effects. A further advantage is that the solid state laser overcomes the loss of power over time, which is typical for flash lamps.

A further advantage of the solid-state laser according to the invention is that the maintenance expenses are low. Because of the laws and regulations for laser based medical devices, a change in optical output power is allowed only within small ranges. Known solid-state lasers therefore required expensive maintenance on a periodical basis or required complex control mechanisms to fulfil such laws and regulations.

In a preferred embodiment the present invention provides a laser device suitable to generate laser light to be used in the medical field, in particular suitable for treating, cutting or ablating biological tissue including hard tissue. Background information regarding laser devices and treating or ablating biological tissue are disclose in the following patent applications, all of them incorporated by reference: WO2006/111526, WO2006/111200, WO2006/111199, WO2006/111429 and WO2008/049903. In a preferred embodiment the laser device according to the invention is used for treating, cutting or ablating biological tissue including hard tissue. It has been found out that most advantageous biological tissue ablation is achieved with laser pulses having a pulse length of between 1 μs and 15 μs and having an intensity of between 10^3 W/mm^2 and 10^8 W/mm^2. Such laser pulses allow a highly efficient ablation of biological tissue, with reduced destruction, for example reduced thermal damage like e.g. denaturation, coagulation, carbonization of the adjacent biological tissue. It has been found out that a certain level of intensity is necessary to efficiently ablate biological tissue and that a certain level of intensity is even more important than high pulse energy. It has been found out that a pulse of high pulse energy, whereby the high pulse energy is achieved by a pulse of long duration, is much less efficient than a pulse having a certain intensity of between 10^3 to 10^6 W/mm^2 for e.g. soft tissue and 10^5 to 10^8 W/mm^2 for hard tissue. Therefore generating laser light having an intensity of between 10^3 W/mm^2 and 10^8 W/mm^2 is most preferred for ablating or cutting biological tissue, whereby the pulse length of the laser light most preferably is in the range of between 1 μs and 15 μs, and less preferably is in the range of between 15 μs and 200 μs. Pulses shorter than 1 μs e.g. produced by Q-Switched lasers or OPO lasers destroy tissue in a mechanical manner through shock waves, tearing cells apart from their natural bond. To achieve an intensity of the laser light of between 10^3 W/mm^2 and 10^8 W/mm^2 on the target such as the biological tissue, the size of the laser light hitting the target may be shaped using beamshaping, in particular by using lenses.

According to one aspect of the invention, a solid state laser and an apparatus comprising the solid state laser is disclosed, suitable for cutting or ablating biological tissue. The solid state laser comprises an optical cavity; a gain medium disposed within the optical cavity; a semiconductor laser optically aligned to light pump the gain medium to generate laser light, wherein the generated laser light has a wavelength and an intensity suitable for cutting and ablating biological tissue.

In accordance with one aspect of the present invention, a method of cutting or ablating biological tissue including hard tissue is disclosed, comprising the steps of providing a gain medium, a semiconductor laser, and an optical cavity; placing the gain medium and the semiconductor laser within the optical cavity so that the semiconductor laser is optically aligned to pump the gain medium; activating the semiconductor laser to optically pump the gain medium and generate laser light; and directing the laser light onto the biological tissue such as soft, medium hard or hard tissue to cut or ablate the biological tissue.

In one embodiment at least one of pulse width, pulse shape, repetition rate, pulse intensity and pulse energy of the laser beam can be modulated, which allows to modulate the characteristics of individual cuts or pores created in the biological tissue as well as the ablated depth of biological tissue per pulse.

The laser for treating or ablating biological tissue having a wavelength between 1700 nm and 3200 nm. Most preferred a wavelength of about 2950 nm is used because this is a major local maximum in the water absorption spectrum in the MIR (mid infrared) range.

A solid-state laser according to the invention preferably generates a laser beam having a diameter between 0,5 mm to 2,5 mm, and more preferably having a diameter between 0,5 mm and 1 mm.

Such a solid-state laser preferably has a pulse temporal width between 1 µs and 500 µs, in particular between 1 µs and 200 µs, and most preferably between 1 µs and 15 µs.

Such a solid-state laser has a laser pulse energy between 0,1 mJ and 100 J, in particular between 1 mJ and 5 J.

Such a solid-state laser being able to be focused to a spot, having an intensity of the laser radiation between 1 W/mm^2 and 10^8 W/mm^2, in particular between 10^3 W/mm^2 and 10^7 W/mm^2.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention can be better understood and its advantages appreciated by those skilled in the art by referencing to the accompanying drawings. Although the drawings illustrate certain details of certain embodiments, the invention disclosed herein is not limited to only the embodiments so illustrated.

Fig. 1	depicts a diagram of a monolithic, side-pumped solid state laser;
Fig. 1a, 1b, 1c	depicts embodiments of the end faces of the laser gain medium;
Fig. 1d, 1e	depicts embodiments of laser cavities including a q-switch;
Fig. 2	depicts a symmetrically cooled solid state laser with direct pump light incoupling;
Fig. 2a	depicts another symmetrically cooled solid state laser with direct pump light incoupling;
Fig. 3	depicts a symmetrically cooled solid state laser with indirect pump light incoupling;
Fig. 4	depicts a radial symmetrically and liquid cooled laser;
Fig. 5	depicts a symmetrically cooled solid state laser with direct pump light incoupling comprising two pump lights;
Fig. 6	depicts a cross-sectional view of an example of an arrangement of the laser rod in a heat-sink;
Fig. 7	depicts a cross-sectional view of a further example of an arrangement of the laser rod in a heat-sink;
Fig. 8	depicts schematically the path of the laser beam of the arrangement according to figure 2 or 7;

Fig. 9	depicts schematically the whole path of the laser beam of the arrangement according to figure 2 or 7;
Fig. 10	depicts the energy density of the emitted laser beam;
Fig. 11a	depicts average optical output power as a function of current of the diode laser or semiconductor laser;
Fig. 11b	depicts average optical output power as a function of repetition rate;
Fig. 12	depicts the energy density of an emitted laser beam, the laser rod being liquid cooled;
Fig. 13	depicts the energy density of a further emitted laser beam
Fig. 14	depicts a cross-sectional view of a heat-sunk side-pumped solid-state laser along the line B-B of figure 15;
Fig. 15	depicts a cross-sectional view of the laser according to figure 14 along the line A-A;
Fig. 16	depicts a diagram of a semi-monolithic, side-pumped solid state laser;
Fig. 17	depicts a time diagram of the current driving the pumping semiconductor laser and of the emitted laser light;
Fig. 18	depicts another time diagram of the current driving the pumping semiconductor laser and of the emitted laser light;
Fig. 19	depicts another time diagram of the current driving the pumping semiconductor laser and of the emitted laser light to operate the laser in CW-mode;
Fig. 20	depicts the absorption coefficient of Er:YAG material in function of the wavelength;
Fig. 21	depicts a monolithic solid state laser followed by lenses;
Fig. 22	depicts a monolithic solid state laser followed by a fibre.

DETAILED DESCRIPTION

Reference will now be made in detail to particular embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same or similar reference numbers are used in the drawings and the description to refer to the same or like parts. It should be noted that the drawings are in simplified form and are not to precise scale. In reference to the disclosure herein, for purposes of convenience and clarity only, directional terms, such as, top, bottom, left, right, up, down, over, above, below, beneath, rear, and front, are used with respect to the accompanying drawings. Such directional terms should not be construed to limit the scope of the invention in any manner.

As used herein the term conductive cooler or cooler means including but not limited to a heat energy transport medium (e.g. liquids, gases, solid materials), a heat spreader (e.g. metals such as copper, gold, aluminum or many more or alloys thereof; ceramics such as Beryllium oxide, Aluminum nitride, Aluminum oxide, Zirconium oxide or many more; crystalline materials such as diamond, sapphire, silicon carbide) or a heat energy storing buffer element. A liquid heat energy transport medium may in particular be a circulating, moving or still standing liquid that is at least partially transparent for the pump light. The liquid heat energy transport medium may for example be water, water-glycol mixtures, ethanol or other heat transfer fluids like e.g. the Solvay Solexis Galden™ HT200. Galden™ is a trademark of Solvay Solexis Inc. Another type of conductive cooler could be a thermally conducting liquid like liquid metals and liquid metal alloys, for example gallium or liquid metal alloy or mixtures or for example a liquid metal alloy called galinstan® that can be purchased from Geratherm, Germany and which is less corrosive than pure gallium. Yet another type of conductive cooler could be a thermally conducting foil made of graphite, indium or other metals, which could be even used to solder the crystals to the cooler.

As used herein the term reflector means including but not limited to surfaces that fully or partially or diffuse reflect or back scatter light. A full reflecting surface can be a polished metal surface coated with e.g. gold, silver, platinum or even a dielectric coating. Another full reflecting surface could be made of a crystalline material that is coated with a dielectric coating like an optical laser mirror. A partially reflective or diffuse reflector can be a rough surface or a partially pump light transparent material that can diffuse and reflect light such as e.g. a sand blown gold coated metal surface that scatters the light back more than directly reflects the light back. Another type of reflector could be a ceramic material that partially absorbs the light but reflects most of the light in a scattered way than in a reflective way. Another type of reflector can be made of a kind of plastic material that is called Spectralon®. Another type of reflector could be a thermally conducting liquid like liquid metals and liquid metal alloys, for example gallium or a liquid metal alloy called galinstan® that can be purchased from Geratherm, Germany and which is less corrosive than pure gallium. Yet another type of reflector could be a reflective foil made of indium or other metals, which could be even used to solder the crystals to the cooler.

As used herein the term mirror or laser mirror means including but not limited to surfaces or substrates the fully or partially reflect light. Such a substrate can be a polished piece of metal or crystalline material (e.g. YAG, sapphire, fused silica, ...) where the at least partially reflecting surface is established with a metal coating (e.g. of gold, silver, platinum) or a dielectric coating.

Another laser mirror with an at least partially reflecting surface could be made of a substrate from crystalline material that is coated with a dielectric coating. The substrate can then be diffusion bonded onto the laser crystal, which is kind of an atomic level, usually not separable component bonding or joining technique.

The laser mirror can also be made of a metallic or dielectric coating directly onto a laser active material. This laser mirror at least partially reflects the desired emission wavelength of the laser active material. A laser mirror is called high reflector (HR) if the reflectivity is about 99% and above. A laser mirror is called output coupler (OC) if the reflectivity is below 99% or the other way around, more than 1% of the laser light leaves the cavity. Optical coatings, in particular dielectric coatings are deposited in multiple layers by PVD (physical vapour deposition) or CVD (chemical vapour deposition) techniques. In particular PVD is widely used for optical coating layers whereas the technologies differ between EBS or EBC (electron beam sputtering or electron beam coating), magnetron sputtering, IBS (ion beam sputtering), IAP (ion assisted plating), IP or RLVIP (Ion plating or Reactive

Low Voltage Ion Plating), MBE (molecular beam epitaxy), MOCVD (metal organic chemical vapor deposition), MOVPE (metal organic chemical vapor phase epitaxy), and many others. The coatings shall not contain materials (like e.g. OH-bonds) that well absorbe laser light with wavelengths between 1700 and 3200 nm. Another cause of damage to a mirror is the absorption of laser light in the layers of such a mirror. Therefore it is advantageous to use low absorbing layer materials in the desired wavelength range. Preferably such a layer material has an absorption of less than 2% per layer, in particular less than 0.5% per layer, and, most preferably less than 0.1% per layer. The coatings shall therefore not be made of materials that well absorbe laser light with wavelengths between 1700 and 3200 nm. The main difference between the coating processes is the deposition energy. If the deposited materials have a low energy at least one coating layer can contain microvoids or pores. The voids create lower packing density (the ratio of the volume of the solids in the layer to the layer's total volume) that results in less dense layers. Typical layer packing densities for less dense layers are in the range of 0.75 to less than 0.9. Less dense layers are less stable environmentally and when the layer is exposed to humidity, the microvoids eventually fill up with water. Laser wavelengths in the mid infrared are strongly absorbed by water and therefore the water in the microvoids can vaporize and damage the layer, respectively the laser mirror. Therefore only laser mirrors consisting of layers with a packing density of greater than 0.90 or even greater than 0.99 should preferably be used in laser systems in the MIR (mid infrared). Such high density layers may be achieved using IBS (ion beam sputtering), IAP (ion assisted plating) techniques to deposit the coating layers. In a most preferred embodiment the deposited materials have a very high energy leading to packing densities greater than 1.05 or 1.10. Such very high density layers which are also called overdense layers may be achieved using IP (Ion plating), RLVIP (Reactive Low Voltage Ion Plating) or MBE (molecular beam epitaxy) techniques to deposit the coating layers.

As used herein dense layer refers to a layer with a packing density of greater than 0.9, preferably greater than 0.95 and more preferably greater than 0.99. Most preferably dense layers have a packing density of greater than 1.05 or 1.1.

As used herein semiconductor laser or diode lasers or laser diodes refers to, including but not limited to, laser diodes, laser diode arrays, VCSELs (vertical cavity surface emitting laser), VECSELs (vertical external cavity surface emitting laser), lead salt lasers, quantum dot lasers, quantum well lasers, quantum cascade lasers, semiconductor ring lasers, hybrid silicon lasers.

As used herein the term "low gain material" or "low gain laser active material" refers to gain materials / laser active materials / laser active media / laser gain media with a stimulated emission cross section equal or less than that of Er:YAG namely <= $3{,}0 * 10^{-20}$ cm^2. Examples are, including but not limited to:

- Er:YAG (Erbium doped YAG laser crystal host) ... $2{,}6\sim3{,}0 * 10^{-20}$ cm^2
- Er:YSGG (Erbium doped YSGG laser crystal host) ... $6{,}5 * 10^{-21}$ cm^2
- Er:YLF (Erbium doped YLF laser crystal host) ... $12{,}5 * 10^{-21}$ cm^2
- Cr,Er:YSGG (Chromium-Erbium doped YSGG) ... $5{,}2 * 10^{-21}$ cm^2
- Ho:YAG (Holmium doped YAG laser crystal host) ...$1{,}2 * 10^{-20}$ cm^2
- Ho:YLF (Holmium doped YLF laser crystal host) ... $1{,}47 * 10^{-20}$ cm^2
- CTH:YAG or Cr:Tm:Ho:YAG (Chromium-Thulium-Holmium doped YAG laser crystal host) ... $7 * 10^{-21}$ cm^2
- Ho:Tm:Er:YLF (Holmium-Thulium-Erbium doped YLF laser crystal host) ... $1{,}8 * 10^{-21}$ cm^2
- Tm:YAG (Thulium doped YAG laser crystal host) ... $1{,}5\sim2{,}5 * 10^{-21}$ cm^2
- Tm:YAP (Thulium doped YAP laser crystal host) ... $5{,}0\sim6{,}0 * 10^{-21}$ cm^2
- Ho:Tm:YAG (Holmium-Thulium doped YAG laser crystal host) ... $9 * 10^{-21}$ cm^2
- Tm:Ho:YLF (Holmium-Thulium doped YLF laser crystal host) ... $5 * 10^{-21}$ cm^2

Relevant laser crystal host materials are e.g.

- YAG (yttrium aluminium garnet)
- YSAG (yttrium scandium aluminium garnet)
- YSGG (yttrium scandium gallium garnet)
- YGG (yttrium gallium garnet)

- GdVO (Gadolinium Vanadate)
- GGG (gadolinium gallium garnet)
- GSAG (gadolinium scandium aluminium garnet)
- GSGG (gadolinium scandium gallium garnet)
- LLGG (lanthanum lutetium gallium garnet)
- YAP (yttrium aluminium perovskite)
- YLF (yttrium lithium fluoride)
- BYF (Barium Yttrium Fluoride)
- Ceramic host crystals like YAG, Lu_2O_3, Sc_2O_3 and Y_2O_3

Figure 1 illustrates a monolithic, side pumped solid-state laser 1 as used with an embodiment of this invention. The basic laser architecture is intentionally made simple. The laser 1 includes a laser gain medium 2, preferably an Er:YAG. The laser resonator 3 is formed by the end faces 4 of the monolithic block structure, with a high reflector (HR) laser mirror 4a deposited directly on the gain medium 2 and an output coupler (OC) laser mirror 4b deposited directly on the opposite end on the gain medium 2. The output coupler 4b has most preferably a reflectivity in the range of between 92,5 % and 99 %, which means that about 1 % to 7,5% of the laser light is leaving the gain medium 2 through the output coupler 4b. The gain medium 2 is side pumped on a pump face 2a by a pump source 5. The pump source 5 comprises a least one semiconductor laser, preferably a diode laser array emitting a light beam 5a. The laser resonator 3 having a diameter of less or equal 3 mm, and therefore having a cross section area of about less than 7.5 mm^2.

The side pumped solid-state laser 1 disclosed in figure 1 is a plano-plano resonator, also called flat-flat resonator which means that the end faces are orthogonal to the optical axis L with an angle deviation of equal or less than 0,05° with respect to 90° to the optical axis L, comprising a high reflectivity laser mirror 4a and an outcoupling, partially transmitting laser mirror 4b, the outcoupling laser mirror 4b having a transmission of between 1% and 7,5%. For certain applications intracavity elements 11, such as an electro-optic or acousto-optic cell for Q-switching, or an etalon for wavelength tuning can be introduced between the laser rod and the laser mirror. A saturable absorber or a bleachable absorber or SESAM might be suitable for Q-switching also. The saturable absorber can act as a transmissive or a reflective element. The saturable absorber could be made of one of the herein mentioned host materials and can be doped for example with rare earth elements. The saturable absorber could also be diffusion bonded directly onto the laser active gain material. The laser 1 can emit energy in, for example, one of the following modes of operation: CW, gain switched obtained by quasi-CW operation of the pump diode laser, or pulsed modus which means pump modulation. Figure 1 discloses a gain medium 2 with plane end faces 4 covered by a plane reflectivity laser mirror 4a and an outcoupling laser mirror 4b. In a further advantageous embodiment at least one end face 4 may have a convex, a concave, an aspherical convex or an aspherical concave shape or even a flat surface with an angle, so called wedge, between 89,7° – 90,3° with respect to the optical axis L (laser output axis) to compensate very little asymmetry or thermal lensing problems, so that the reflectivity laser mirror 4a and the outcoupling laser mirror 4b deposited directly on the end face 4 adopt the shape of the respective end face 4. Such laser mirrors 4a, 4b on both ends of the laser resonator 3 allow a beam shaping or allow adjustment of a thermal lens. Due to very short laser cavities a use of a convex or concave end face requires high precision in laser gain material manufacturing. One of the important properties with such curved end faces is the need of a centricity of equal or less than 3 minutes of angle with respect to the optical axis L. The laser gain medium 2 consists most preferably of a low gain laser active material.

The solid state laser 1 disclosed in figure 1 also comprises a cooling, which is not shown in detail. Examples of cooling arrangements are for example disclosed in figures 2 to 7.

The embodiment disclosed in figure 1 has the advantage that the small diameter of the circular laser gain medium of less or equal 3 mm, respectively of the cross section area of about less than 7,5 mm^2 allows a more or less homogenous high intensity of the pump light 5a of the pump source 5 within the laser gain medium 2, so that a homogenous high

intensity of laser light is generated within the laser gain medium 2. In addition the relatively high reflectivity of the output coupler 4a in the range of between 92,5 % and 99 % allows efficient generation of an output laser beam B of high intensity. In addition providing both end faces 4 with a reflective coating 4a, 4b reduces the loss of laser light at the end faces 4, which also contributes to a laser beam B of high intensity. All measures in combination allow building a diode side pumped solid-state laser being able to emit a high quality laser beam, which can be focused to an intensity in the range of about 1 W/mm^2 and 10^8 W/mm^2. The solid-state laser 1 according to the invention therefore shows high efficiency, so that moderate pump power of the pump source 5 is sufficient to create a laser beam B with desired power and quality.
In figure 1 the cross section of the laser gain medium 2 is of circular shape. The cross section of the laser gain medium 2 may have other shapes, such as rectangular, triangle, polygonal or square.

Figure 1a illustrates the laser gain medium 2 in detail, and shows the end face 4 on the right side covered by a polished metal block or surface 4c bonded onto the end face 4 and thereby forming the high reflecting (HR) laser mirror 4a. The left end face 4 is coated by a substrate 4d such as a metallic layer or a semiconductor layer, thereby forming an output coupler (OC) laser mirror 4b.
Figure 1b shows another embodiment of a laser gain medium 2 in detail with laser mirrors 4a and 4b, the laser mirrors 4a and 4b comprising a crystalline structure 4e coated by a substrate 4d such as a metallic layer or a semiconductor layer. The crystalline structure 4e is bonded onto the end faces 4. The crystalline structure 4e can act as stress reducing elements to improve lasing stability and decrease thermal lensing effects which contributes to high laser stability over a wide working range. The crystalline structure 4e can also contribute to more stable optical coatings than optical coatings which are deposited directly onto the crystal and then often get damaged through thermal overload.
Figure 1c shows another embodiment of an laser gain medium 2 in detail with laser mirrors 4a and 4b consisting of a substrate 4d such as a metallic

layer or a semiconductor layer coated onto the end faces 4. Such laser mirrors 4a and 4b are attached to the end face 4 of the laser gain medium 2, thereby forming a high reflecting laser mirror 4b respectively a laser mirror 4a to at least partially reflect the laser light B. Figure 1d shows an embodiment including a q-switch or a saturable absorber 11. Figure 1e shows a further embodiment including a q-switch or a saturable absorber 11. In the embodiments according to figures 1d and 1e, the q-switch 11 could also be arranged between the laser active medium 2 and the output coupler (OC). Combinations of the embodiments disclosed in figures 1 to 1e are of course also possible.

Figure 2 illustrates an advantageous embodiment of a monolithic, side pumped solid-state laser 1 comprising a laser crystal or gain medium 2 thermal conductively connected with a conductive cooler 6. The conductive cooler 6 is also holding the gain medium 2. A pump source 5 is arranged on the side of the gain medium 2. A reflector 7 is arranged at the opposite side of the pump source 5. In addition to the reflector 7 also the conductive cooler faces 6c might comprise reflective characteristics, for example by an appropriate coating, so that the cooler faces 6c could be used as reflectors also. The pump light 5a of the pump source 5 enters the gain medium 2 at a side face 2a and leaves the gain medium 2 at an opposite side face 2b. Depending on the absorption of the laser beam 5a in the gain medium 2, an exit beam 5b, which means the fraction of the laser beam 5a not being absorbed within the gain medium 2, exits the gain medium 2, whereby the not absorbed/remaining pump light 5b hits the reflector 7 and is at least partially reflected causing a reflected laser beam 5c, which enters the gain medium 2. Depending on optical properties of the gain medium 2 and the pump source 5 which is a diode laser, the laser beam 5f might traverse the gain medium 2 in parallel direction or also in another direction. Figure 2 discloses a direct pump light incoupling of the laser beam 5a into the laser crystal 2. The pump light emitted by the diode laser 5 is guided trough a slit 6e to the crystal 2. The slit 6e could also be filled with a pump light transparent material like e.g. YAG (yttrium aluminum garnet) or sapphire and thus facilitate more homogeneous and symmetric thermal heat transport which finally stabilizes the solid state laser additionally. This embodiment discloses a symmetrically cooled solid state laser gain medium 2 in that the laser crystal 2 is symmetrically arranged and held in the cooler 6. In the most preferred embodiment the monolithic, side pumped solid-state laser 1 comprising a laser resonator composite structure 3 comprised of a laser gain medium 2 having a longitudinal axis L, wherein the laser comprising a conductive cooler 6 comprising contact faces 6c contacting the laser gain medium 2, whereby the contact faces 6c are most preferably symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2. Most preferred this embodiment allows cooling the laser gain medium 2 such that there is a symmetric cooling with respect to the longitudinal axis L. One purpose of the conductive cooler 6 is to transport the heat from the laser gain medium 2 to a heat sink which is not shown. The heat sink might for example be the outer surface of the conductive cooler 6. The conductive cooler 6 may also be connected with an additional cooler such as a thermo electric cooler and/or a forced air cooled heat sink, or a thermo electric cooler and/or a water cooling system not shown in figure 2. The conductive cooler 6 consists of a material suitable for transporting heat, most preferably the conductive cooler 6 is made of metal such as copper or ceramics or of a crystalline material or another material herein referred to as suitable for a reflector. As disclosed in figure 2 the conductive cooler 6 comprises a cooler cavity 6d arranged beside the laser gain medium 2 and arrange opposite to a side face 2a. The pump light 5a entering the laser gain medium 2 through the side face 2a. The reflector 7 is arranged in the cooler cavity 6d, which also means that the reflector 7 may be a reflecting surface of at least one side wall of the cooler cavity 6d, whereby the side wall may also be coated with a reflective coating. Further measures may be taken to improve the heat transfer from the gain medium 2 to the conductive cooler 6 by applying a thermal compound between the gain medium 2 and the conductive cooler 6, such as a thermal heat sink paste, or a liquid metal such as gallium, or a mixture of a liquid metal comprising one or more particles of a solid metal.

The symmetric heat transfer is essential for a monolithic laser resonator structure 3 operating over a wide range of pump light 5a power. A laser crystal 2 with the space 6d replaced by the contact face 6c gets unstable with high pump light 5a powers and the laser resonator structure 3 stops to generate laser radiation. The symmetric heat transfer in the embodiment illustrated in figure 2 results in a symmetric thermal lens, which does not destabilize the laser resonator structure 3 and allows generating laser radiation over a wide range of pump light 5a powers. It is also possible to compensate an asymmetric heat transfer, respectively thermal lens, by angled end faces 4, but this limits the efficient operation of the laser resonator structure to just one specific pump light 5a power.

Figure 2a illustrates another advantageous embodiment of a monolithic, side pumped solid-state laser 1 comprising a laser crystal or gain medium 2 thermal conductively connected with a conductive cooler 6. Laser 1 comprising a reflector 7 arranged opposite to the side face 2a with respect to the longitudinal axis L and the reflector 7 being arranged just beside the laser gain medium 2 or the reflector 7 being arranged just on the laser gain medium 2.

Figure 3 illustrates a further embodiment of a monolithic, side pumped solid-state laser 1 comprising a laser crystal or gain medium 2 thermal conductively connected with the conductive cooler 6. A pump source 5 is arranged on the side of the gain medium 2. In contrast to the embodiment according to figure 2, the embodiment according to figure 3 discloses an indirect pump light incoupling of the laser beam 5a into the laser crystal 2, in that, as disclosed in figure 3, at least part of the laser beam 5a is reflected on the inner surface 6i of the cooler 6 before entering the gain medium 2. The inner surface 6i is the surface of the gap of the cooler 6 leading from the diode laser 5 to the laser gain medium 2. The advantage of the longer pathway for the pump light 5 is a better mixing /diffusing of the pump light 5 and a more homogeneous pumping of the gain medium, the crystal 2. The pathway is also of advantage for using different diode lasers 5 having different emission angles which means one can use diode lasers with high or with low brightness. The exemplary embodiment disclosed in figure 3 is symmetric with respect to plain C. The width of the inner gap 6m of the cooler 6 may for example vary, as disclosed in figure 3 or may for example have the same width, as disclosed in figure 2.

Thermal management and temperature control of the conductive cooler 6 are most advantageously provided by air cooling with the possibility of also using thermo-electric cooling but also water cooling might be suitable.

Figure 4 illustrates a further embodiment of a monolithic, side pumped solid-state laser 1 comprising a laser crystal or gain medium 2 thermal conductively connected with a cooler 6. The gain medium 2 is in longitudinal direction L surrounded by a fluid, in particular water or water containing cooling fluid which is flowing in between the outer crystal surface 2c and a tubular member 6b of the cooler 6, the tubular member 6b being concentrically arranged with respect to the longitudinal axis L. In the example disclosed three pump sources 5 are spaced apart by 120 ° with respect to the longitudinal axis L of the gain medium 2, and are arranged along the side of the gain medium 2. Three corresponding reflectors 7, each arranged at the opposite side of the respective pump source 5, are arranged such that the pump light 5a of the pump source 5 enters the gain medium 2, and an exiting, not absorbed/remaining pump light 5b, which is the portion of the pump light 5a leaving the gain medium 2 opposite to the side face 2a, exits the gain medium 2, whereby the exiting pump light 5b hits the reflector 7 and is at least partially reflected by the reflector 7, forming a reflected exit pump light 5c, a least part of which enters the gain medium 2 again. Figure 4 discloses a direct pump light incoupling of the pump light 5a into the laser active medium 2. This embodiment discloses a symmetrically cooled gain medium 2 in that the laser crystal 2 is symmetrically arranged and held in the cooler 6, which comprises a tubular member 6b concentrically arranged with respect to the laser active medium 2, the outer tubular member 6b and the surface 2c of the laser crystal 2 delimiting a volume the fluid cooling medium can flow through. The cooler 6 could also be built as a solid, hollow tubular member surrounding the gain medium 2 and preferably being in direct contact with the gain medium 2. Such a solid cooler 6 can for example be built of metal such a copper. The embodiment disclosed is symmetrically with respect to the longitudinal axis L, whereby the elements reflector 7 and pump source 5 are arranged at a respective angle of 120°, but any other symmetrical angle distribution of the arrangement may be useful.

Figure 5 illustrates a laser 1 of similar design than the embodiment shown in figure 2 but comprising two diode lasers 5 spaces apart by 90° with respect to the longitudinal axis L. The laser 1 comprising a conductive cooler 6 comprising contact faces 6c contacting the laser gain medium 2, whereby the contact faces 6c are symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2. The contact faces 6c could also be used as reflectors, as well as the walls 7, 7a of the cooler cavity 6d, in particular the side walls 7a.

Figure 6 illustrates another laser 1 of similar design than the embodiment shown in figure 2. The laser 1 comprising a conductive cooler 6 comprising contact faces 6c contacting the laser gain medium 2, whereby the contact faces 6c are symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2. The conductive cooler 6 comprising an upper part 6h and two lower parts 6g, whereby the laser gain medium 2 is clamped between the upper part 6h and the two lower parts 6g. The conductive cooler 6 comprises a slit 6e allowing the light of the diode laser 5 to enter the laser gain medium 2. Opposite to the slit 6e the conductive cooler 6 comprises a cooler cavity 6d so that the contact faces 6c are symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2. The cooler cavity 6d comprises a reflector 7 to reflect the light exiting the laser gain medium 2. Also the side walls 7a of the cooler cavity 6d could be used as a reflector.

Figure 7 illustrates another laser 1 of similar design than the embodiment shown in figure 2. The laser 1 comprising a thermally conductive cooler 6, for example a metallic cooler 6, and a heat conductive substance 6k thermally connecting the laser gain medium 2 with the cooler 6, so that a heat flow 6f occurs between the laser gain medium 2 and the cooler 6 when light of the diode laser 5 is emitted into the laser gain medium 2 and heating the laser gain medium 2. The contact faces 6c of the gain medium 2 with the heat conductive substance 6k are symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2.

Figure 10 shows schematically the energy distribution respectively the signal intensity in x- and y-direction of a laser beam B emitted by the laser gain medium 2 of the laser 1 disclosed in figure 7. The symmetrical heat flow 6f causes the elliptical energy density. One advantage of the embodiment according to the invention is that most preferably there is a symmetrical temperature distribution in the laser gain medium 2, similar to the energy distribution disclosed in figure 10. Most preferably the temperature distribution stays symmetrically or about symmetrically in a wide range of power inputted by the diode laser 5 into the laser gain medium 2. This effect is achieved by cooling the laser gain medium 2 symmetrically with respect to the longitudinal axis L. This arrangement allows reducing thermal aberrations during operation of the laser. The symmetric cooling geometry according to the invention avoids uncompensated thermal gradients which normally result in lensing, stress induced birefringence and other optical aberrations. The laser 1 according to the invention doesn't show this effect due to the symmetric cooling geometry. Most advantageously high-power, quasi-cw diode arrays 5 are used for side pumping the laser gain medium 2, for generating high peak-power pulses in the pulse energy regime of millijoules to Joules. The laser gain medium 2 is typically either a rod or a slab. The laser 1 according to the invention may be operated in a wide energy range with little thermal aberrations during operation. Therefore no means are necessary for compensation of thermal aberration, leading to an inexpensive, reliable laser device that may provide high-power laser light.

A further measure to provide a high performance operating laser device 1, in particular to achieve high intensity, high pulse energy and high pulse repetition rate, is disclosed with the following exemplary embodiment shown in figures 7 to 9. Figure 7 shows a cross-sectional view of a laser device 1 comprising a laser rod 2 arranged in the cooler 6. The contact faces 6c of the gain medium 2 with the heat conductive substance 6k are symmetrically arranged with respect to the longitudinal axis L of the laser gain medium 2. Laser 1 is a monolithic solid state laser 1, comprising a laser resonator structure 3 as disclosed in figure 1, with a laser high reflector 4a on one end face of the laser rod 2, and with an output coupler 4b on the other end face of the laser rod 2. The laser rod 2 material includes e.g. Er:YAG. The laser rod 2 may for example have a diameter of 1 mm or 1,4 mm or 2 mm. The diode laser array 5 having a wavelength in the range of 760 nm to 815 nm or 955 nm to 985 nm. Figure 20 shows the absorption coefficient of Er:YAG material in function of the wavelength. It is known to select the wavelength of the diode laser array 5 such that it corresponds to the maximum absorption of the laser active material 2. One additional aspect of the invention is that it has been found out that such a selection of the wavelength has the disadvantage that the pumping light of the diode laser array 5 is highly absorbed by the laser rod 2. This leads to the effect that the pumping light is already absorbed in the area of the side face 2a in the laser rod 2, so that only a reduced amount of pump light may enter the center of the laser rod 2, where most of the electrons should be activated. To overcome this effect it has been found out to select the main wavelength of the diode lasers 5 such that a reduced absorption occurs in the laser rod 2. Based on figure 20 this may be achieved by selecting the main wavelength of the diode laser 5 such that the main wavelength is shifted relative to a peak absorption of the laser gain medium 2, the main wavelength of the diode laser 5 might even be selected at a low or even a minimal absorption coefficient of the laser gain medium 2. Depending on the used low gain laser active material the deviation from the selected pump light wavelength to the pump light absorption peak can vary. For example the wavelength of the diode laser 5 may be shifted up to 15 nm and preferably up to 10 nm relative to the peak absorption line of the laser gain medium 2, which for example using Er:YAG is about 964 nm, the average center of a high absorption region. In addition the pumping light of the diode lasers 5 is advantageously guided as disclosed in figure 7 to 9, to preferably achieve a uniformly illuminating of the laser gain medium 2 with the light of the diode laser 5.

The path of the pumping laser light 5 is schematically shown in figures 7 and 8 in that the diode laser 5 emits pump light 5a which enters the laser gain medium 2, and which partially traverses the laser gain medium 2, and leaves the laser gain medium 2 as exiting pump light 5b. The wavelength of the pumping semiconductor laser is for example in the range of between 760 nm and 985 nm. The exiting pump light 5b being reflected at the reflector 7 of the cooler cavity 6d and being back scattered as reflected pump light 5c that enters again into the laser gain medium 2, which max partially traverses the laser gain medium 2 and which may even leave the laser gain medium 2 as a reflected exiting pump light 5d.

For example 100% of the total emitted energy of the diode laser 5 may enter the laser gain medium 2, 64% of the total emitted energy being absorbed in the laser gain medium 2, and 36% of the total emitted energy leaving the laser gain medium 2 as exiting pump light 5b. The exiting pump light 5b being reflected at the reflector 7 and around 36% of the total emitted energy enters the laser gain medium 2 in form of the reflected pump light 5c, and about 10% of the total emitted energy leaving the laser gain medium 2 as reflected exiting pump light 5d.

As disclosed in figure 8 the diode laser 5 and the reflector 7 are most preferably arranged in such a way with respect to the longitudinal axis L that there is equal distance D1, D2 between the longitudinal axis L and each of the diode laser 5 and the reflector 7. In other words, in a preferred embodiment, the length of the optical path between the pump source 5 and the longitudinal axis L is the same or about the same as the length of the optical path between the longitudinal axis L and the reflector 7. Figure 9 discloses the path of the light of the diode laser 5 more clearly, such that the path of the reflected pump light 5c is shown for illustration purpose on the right side of the reflector 7 entering the laser gain medium 2 and leaving the laser gain medium 2 as exiting pump light 5d. The pump light 5a emitted by the diode laser 5 is entering the laser gain medium 2, and part of the pump light 5a is exiting the laser gain medium 2 as exiting pump light 5b. The exiting pump light 5b is reflected at the reflector 7, so that the reflected pump light 5c again enters the laser gain medium 2, and part of the reflected pump light 5c is exiting the laser gain medium 2 as reflected exiting pump light 5d. One advantage of the beam path of the pumping light disclosed in figures 8 and 9 is that the laser gain medium 2 is preferably homogenously or about homogenously illuminated. One advantage of this kind of illumination of the laser gain medium 2 is that it allows achieving high power density and preferably also a good beam profile very similar to a Gaussian intensity distribution.

In the most preferred embodiment the wavelength of the pump source 5, which means the diode laser 5, is selected such with respect to properties of the laser gain medium 2, that between 30% to 70%, more preferably between about 50% to 65% of the pump light 5a is absorbed by the laser gain medium 2 and the rest exiting the laser gain medium 2 as exiting pump light 5b. Such a wavelength ensures that the gain medium 2 is homogenously illuminated. Most preferably the wavelength of the pump source 5 is selected in the range of between 955 nm to 985 nm, wherein the wavelength of the pump source 5 depends on doping material used, so that diode lasers 5 emitting in the wavelength required can be manufactured. If the gain medium 2 would comprise Holmium or Thulium, most preferably the wavelength of the pump source 5 is selected in the range of between 760 nm to 815 nm.

Most advantageously the contact area 6c and therefore also the heat flow 6f from the laser gain medium 2 to the cooler 6 is symmetrically with respect of the longitudinal axis L, as disclosed in figure 7, so that the light path 5a, 5b, 5c, 5d as disclosed in figures 7 to 9 leads to the effect that the laser gain medium 2 is the hottest in the center, along the longitudinal axis L. This embodiment has the advantage that it is able to provide a high pulse energy and high power, and that temperature effects due to the warming up of the laser gain medium 2 are minimal. This embodiment has the additional advantage that it allows a high repetition rate, because the temperature effect due to the warming up of the laser gain medium 2 is small, and due to the effect that there is efficient cooling of the laser gain medium 2.

Figure 11a shows the laser power, which is the average optical output power, as a function of the current through the diode laser 5 for different pulse repetition frequencies and for different pulse lengths. Two solid-state lasers 1 of identical construction are shown operated at 500 Hz with pulse lengths of 100 µs. Two solid-state lasers 1 of identical construction are shown operated at 250 Hz with pulse lengths of 200 µs. Two solid-state lasers 1 of identical construction are shown operated at 500 Hz with pulse lengths of 200 µs. Figure 11a also shows that the two solid state lasers of identical construction have only small variations, which means that the variation of the solid state lasers according to the invention having identical construction is small.

The solid state laser 1 according to the invention creates relatively high laser power, which is the average optical output power, over a wide repetition rate, as disclosed in figure 11b. The solid state laser 1 may be operated from about 100 Hz to 1000 Hz or more, as disclosed in figure 11b.

The effect of the inventive measures described above can be seen in the laser mode profiles disclosed in figures 12 and 13, showing the energy density of a laser beam B in a plane with directions x and y. Figure 12 shows the energy density of an emitted laser beam B, the laser rod 2 being water cooled. Figure 13 shows the energy density of an emitted laser beam B, the laser rod 2 being cooled by an arrangement according to figure 2. The effect of the efficient cooling is preferably that a low repetition rate and a low thermal loading as well as a high repetition rate and higher thermal loading doesn't distort the quality of the laser beam B. The laser gain medium 2 is most preferably of cylindrical shape or elliptical-cylindrical shape. The elliptical-cylindrical shape has the advantage that it is able to equalize a distortion of the laser beam caused by a conductive cooler 6 such as the coolers 6 disclosed for example in figures 2, 2a, 3 or 5 to 7, so that a laser beam B having an energy density of about the one disclosed in figure 12 may be achieved.

The embodiment according to figures 7 to 9 has, by way of example, been described with a laser crystal 2 comprising an Er:YAG laser rod. All embodiments disclosed in figures 1 to 16 may comprise laser rods of other suitable materials to achieve the same or similar effects as decribed in figures 7 to 9. Most preferably the laser gain medium 2 is a low gain material such as Er:YAG, Er:YSGG, Ho:YAG or Ho:Tm:YAG.

Figure 14 shows a cross-sectional view of a side-pumped solid-state laser 1. The laser 1 comprising a laser gain medium 2 fixed between a lower part 6g and an upper part 6h of a cooler 6. The laser 1 also comprising a base plate 6l. An array of diode lasers 5 are arranged along the laser gain medium 2 for pumping the same. The array of semiconductor lasers 5 is fixed on a plate 6n such as a printed circuit board. As disclosed in figure 14 the laser gain medium 2 has most preferably free ends 2d which are not arranged within the cooler 6, whereby the length of the free ends 2d in direction of the longitudinal axis L is preferably about 1 mm. The free ends 2d act as stress reducing elements to improve lasing stability and decrease thermal lensing effects which leads in turn to high laser stability over a wide working range. Most preferably, all embodiments disclosed in figures 2, 2a, 3, 5, 6 and 7 comprise such free ends 2d as disclosed in figure 14, the free end having a length of preferably about 1 mm. Figure 15 shows another cross-sectional view A-A of the embodiment according to figure 14 showing the laser gain medium 2, which has the shape of a rod, and which is fixed between the lower and upper part 6g, 6h of the cooler 6.The pump source 5, a diode laser array, is arranged beside the laser gain medium 2.

Figure 16 shows a laser resonator structure 3 comprising a laser gain medium 2, a pump source 5, an output coupler 4b and a spaced appart laser high reflector 4a. Such an embodiment might be necessary if the totally reflecting laser mirror 4a disclosed in figure 1a, which is arranged on one of the end faces of the main medium 2, becomes too hot because of high intracavity power, so that instead of the reflecting laser mirror 4a arranged on the one of the end faces, a spaced apart reflecting laser mirror 4a is used.

Figure 17 shows the pump light 5 (lower curve) and the emitted laser beam B (upper curve) versus time. The pump light 5 pumps the laser gain medium 2 up to the laser gain medium 2 emits a laser beam B. In the example disclosed the pump light 5 is stopped as soon as the laser gain medium 2 emits the laser beam B, which leads to very short laser pulses of between 1 to 5 μs pulse length. Longer pulses can be achieved by prolonging the pump light 5 so that the laser gain medium 2 is pumped during a longer period of time, which leads to longer pulses of the laser beam B. Figure 18 shows the pump light 5 (lower curve) and the emitted laser beam B (upper curve) versus time over longer period of time. The pump light 5 may, for example, be regularly emitted, as disclosed in figure 18, so that a laser pulse B is regularly emitted. Figure 19 shows another time diagram of the current respectively the pump light 5 (lower curve) driving the pumping diode 5 and of the emitted laser light to operate the laser in CW-mode (continuous wave mode).

Figure 21 shows a side view of the monolithic solid state laser 1, where the laser beam B is spread and focused by lenses 8a, 8b, to focus the laser beam B onto a target 10. Figure 22 shows a side view of the monolithic solid state laser 1, where the laser beam B is expanded and focused by lenses 8a, 8b, to focus the laser beam B into an optical fiber 9. In a preferred embodiment the optical fiber 9 has a diameter in the range of 100 μm to 250 μm, most preferably of less or equal 200 μm, and the laser beam B entering into the optical fiber 9 has in a preferred embodiment a diameter of less or equal 100 μm. At the exit or following the exit end of the optical fiber 9 an additional lens may be arranged. The laser gain medium 2 according to the invention having a cross sectional area of less than 7,5 mm^2 has the advantage that the exiting laser beam B may be focused to a diameter of less or equal 100 μm. Known laser gain medium 2 have a diameter of 3,5 mm or even more, which causes the problem that the laser beam B of such laser gain mediums 2 can only be focused to a diameter of about 400 μm, which doesn't allow creating a laser beam of high intensity. In addition optical fibers 9 having a diameter in the range of 300 µm to 500 µm were required. The solid-state laser 1 according to the invention therefore has the advantage that a laser beam B of high intensity may be emitted, and because of the small diameter of the beam, a small optical fiber 9 having a diameter of for example less or equal 200 µm may be used. Therefore a laser beam B of relatively high intensity may pass the optical fiber 9.

In a preferred embodiment the laser 1 according to the invention having a wavelength in particular between 1700 nm and 3200 nm. Most preferred a wavelength of about 2950 nm is used because this is a major local maximum in the water absorption spectrum in the MIR (mid-infrared) range. There is another water absorption peak in the ultra violet range but this wavelength is not save for treating or ablating life tissue. Most preferably, the gain medium 2 may comprise an Erbium-doped crystalline laser rod for generating laser light in a range between 2,73 and 2,95 µm. The laser light can be generated in the TEM00 mode and strongly focused to overcome thermal effects. Temporal pulse width control can be used to attain a uniform temporal pulse pattern. The diode or semiconductor laser light pump 5 can comprise a diode array, and the diode array can be optically aligned to side pump the gain medium.
The diode side pumped Erbium doped crystalline laser gain medium 2 may emit at wavelengths between 2,73 and 2,95 µm. The pumping may be accomplished by e.g. InGaAs diode lasers configured as bars or arrays emitting at between 955 to 985 nm, and can be delivered in either a CW (continuous wave) or a QCW (quasi-continuous wave) mode of operation, at power levels that may begin at 40 W peak power. With an optimized output coupling, the light-to-light efficiency can be at least 10% and can reach a magnitude up to 35%. One of the embodiments of this invention is that these efficiency magnitudes are higher than those which may have been previously attained, owing to the inventive design which seeks to minimize thermal effects and intracavity losses and to optimize the beam path of the pump light to enable high energy pulses or CW operation of the laser.

In a further preferred embodiment the laser 1 according to the invention having a wavelength in particular between 1675 nm and 2100 nm, whereby the gain medium 2 comprises a Holmium-doped and/or a Thulium doped crystalline laser rod for generating laser light in a range between 1,67 and 2,1 μm. The laser light can be generated in the TEM00 mode to overcome thermal effects. Temporal pulse width control can be used to attain a uniform temporal pulse pattern. The diode side pumped Holmium-doped and/or a Thulium doped crystalline laser gain medium 2 may emit at wavelengths between 1,67 and 2,1 μm. The pumping may be accomplished by e.g. AlGaAs diode lasers configured as bars or arrays emitting at between 760 to 815 nm or by e.g. GaSb laser diodes emitting at between 1600 to 2050 nm, and can be delivered in either a CW (continuous wave) or a QCW (quasi-continuous wave) mode of operation, at power levels that may begin at 20 W peak power. With an optimized output coupling, the light-to-light efficiency can be at least 10% and can reach a magnitude up to 85%.

A suitable optical gain material 2 may include the following crystals: $Er:LiYF_4$ (Er:YLF) emitting at 1,73 μm on the $Er^{3+4}I_{13/2} \Rightarrow {}^4I_{15/2}$ transition; $Er:LiYF_4$ emitting at 2,80 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:Y_3Sc_2GasO_{12}$ (Er:YSGG) emitting at 2,79 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:Gd_3Sc_2GasO_{12}$ (Er:GSGG) emitting at 2,8 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:Gd_3GasO_{12}$ (Er:GGG) emitting at 2,82 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er,Tm:Y_3Al_5O_{12}$ (TE:YAG) emitting at 2,69 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:KYF_4$ emitting at 2,81 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; Ho, $Yb:KYF_4$ emitting at 2,84 μm on the $Ho^{3+5}I_6{}^5I_7$ transition; $Er:Y_3Al_5O_{12}$ (Er:YAG) emitting at 2,94 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:Y_3AlO_3$ (Er:YALO) emitting at 2,71 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:KGd(WO_{4s}$ (Er:KGW) emitting at 2,8 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:KY(WO4_s$ (Er:KYW); $Er:Al_3O_3$ emitting on $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:Lu_3O_3$ emitting at emitting at 2,7 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:CaF_2$ emitting at 2,75-2,85 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Cr,Tm,Er:Y_3Al_5O_{12}$ (CTE:YAG) emitting at 2,7 μm on the $Er^{3+4}I_{11/2} \Rightarrow {}^4I_{13/2}$ transition; $Er:BaLu_2F_8$ emitting at 2,8 μm on the

Er^{3+} $^4I_{11/2}$⇨$^4I_{13/2}$ transition; Er:BaY_2F_8 (Er:BYF) emitting at 2,7 μm on the Er^{3+} $^4I_{11/2}$⇨$^4I_{13/2}$ transition; and Cr:ZnSe emitting at 2-3 μm.

CTH:YAG or Cr:Tm:Ho:YAG emitting at 2080 nm, 2097 nm and 2130 nm

Ho:YAG emitting at 2097 nm

Ho:YLF emitting from1850 to 2075 nm

Ho:Tm:YAG emitting from 2091 to 2097 nm

Tm:YAG emitting at 2013 nm

Tm:Cr:YAG emitting at 2017 nm

Tm:YLF emitting from 1675 to 2050 nm

Tm:YAP emitting from 1965 to 2020 nm

Tm:Lu:YAG emitting at 2020 nm

Another embodiment of the side diode pumped erbium lasers and Tm, Ho, Yb:KYF_4 laser is that when operated in pulses, the pulsed format is highly repetitive in time and intensity. This performance can for example facilitate precise and predictable cutting, and can improve cutting efficiency. In dental and medical applications, this feature is consistent with less heat or thermal denaturation of the tissue, which can provide for quicker healing.

This invention is not limited to Er doped, Ho doped or Tm doped low gain laser active materials, but also high gain laser active materials may be used, such as Nd:YVO_4, Nd:YAG, Er:Glass, and many others. In the case of using a high gain laser active material the advantage of the invention is the very good robustness against disadjustment caused by shock events, vibration and disadjustment over time due to thermal effects.

Due to their efficient interaction with biological tissue and water, the laser according to the invention is for example useful as surgical instruments, in the areas of, for example, tissue surgery, tissue cutting, tissue ablation, dental surgery, orthopedic surgery, bone cutting and soft tissue surfacing.

Claims

1. A monolithic, side pumped solid-state laser (1) comprising a laser resonator structure (3) comprised of a laser gain medium (2) having a longitudinal axis (L), wherein the laser resonator structure (3) comprises end faces (4) forming a linear optical path resonant cavity there between, at least one of the end faces (4) comprising at least partially reflecting laser mirrors (4a, 4b) in particular deposited thereon, the laser gain medium (2) comprising a side face (2a) for receiving pump light (5a) of a pump source (5), wherein the pump light (5a) is generated by a diode laser (5), and comprising a conductive cooler (6) comprising contact faces (6c) contacting the laser gain medium (2), and comprising a reflector (7) arranged opposite to the side face (2a) with respect to the longitudinal axis (L), wherein the laser gain medium (2) is a low gain material.

2. The solid-state laser (1) according to claim 1, wherein the laser gain medium (2) having a cross sectional area of less than 7,5 mm^2.

3. The solid-state laser (1) according to claim 2, wherein the contact faces (6c) are symmetrically arranged with respect to the longitudinal axis (L) of the laser gain medium (2).

4. The solid-state laser (1) according to claim 3, wherein the conductive cooler (6) comprising a cooler cavity (6d) arranged beside the laser gain medium (2) and arranged opposite to the side face (2a), wherein the pump light reflector (7) is arranged in the cooler cavity (6d).

5. The solid-state laser (1) according to claim 4, wherein the diode laser (5) and the reflector (7) are arranged in such a way with respect to the longitudinal axis (L) that there is equal distance (D1, D2) between the longitudinal axis (L) and each of the diode laser (5) and the reflector (7), so that the length of the optical path between the pump source (5) and the longitudinal axis (L) is the same or about the same as the length of the optical path between the longitudinal axis (L) and the reflector (7).

6. The solid-state laser (1) according to one of claims 2 to 5, wherein both end faces (4) comprise a laser mirror (4a,4b), wherein one of the laser mirrors is a high reflecting laser mirror (4a), in particular having a reflectivity of 99% to 100%, and wherein the other laser mirror (4b) is an output coupler.

7. The solid state laser (1) according to one of claims 2 to 6, wherein the laser resonator structure (3) emits a wavelength in the range of 1700 nm to 3200 nm.

8. The solid state laser (1) according to claim 7, wherein the output coupler (4b) has a reflectivity in the range of between 92,5% and 99%.

9. The solid-state laser (1) according to one of the preceding claims, wherein the laser gain medium (2) has free ends (2d) which are not arranged within the cooler (6), whereby the length of the free ends (2d) in direction of the longitudinal axis L is preferably about 2 mm and most preferably about 1 mm.

10. The solid-state laser (1) according to one of the preceding claims, wherein the laser gain medium (2) comprises a rare-earth-doped YAG or YSGG or YLF crystal host, with neodymium, ytterbium, erbium, thulium, chromium and/or holmium doping.

11. The solid-state laser (1) according to one of the preceding claims, wherein the wavelength of the diode laser (5) is selected such that the main wavelength of the diode laser (5) is shifted relative to an absorption peak region of the laser gain medium (2).

12. The solid-state laser (1) according to one of the preceding claims, wherein the conductive cooler (6) comprising contact faces (6c) contacting the laser gain medium (2) and also holding the laser gain medium (2), the conductive cooler (6) consisting of metal, ceramics or a crystalline material.

13. The solid-state laser (1) according to claim 12, comprising two contact faces (6), wherein the contact faces (6c) are symmetrically

arranged with respect to the longitudinal axis (L) of the laser gain medium (2), opposite to each other.

14. The solid-state laser (1) according to one of claims 1 to 11, wherein the conductive cooler (6) comprising an outer tubular member (6b) concentrically arranged with respect to the longitudinal axis (L), the outer surface (2c) of the laser gain medium (2) and the outer tubular member (6b) defining an internal space (6a) for a cooling fluid.

15. The solid-state laser (1) according to one of the preceding claims, comprising at least two pump sources (5) spaced apart in circumferential direction with respect to the longitudinal axis (L), and further comprising a corresponding pump light reflector (7) arranged opposite to the side face (2a) with respect to the longitudinal axis (L).

16. The solid-state laser (1) according to one of the preceding claims, comprising a lens (8a,8b) and comprising an optical fiber (9) having a diameter between 100 µm and 250 µm, wherein the lens (8a,8b) is arranged to focus a laser beam (B) of the solid-state laser (1) into the optical fiber (9).

17. The solid-state laser (1) according to one of the preceding claims, wherein the laser gain medium (2) is of cylindrical shape or elliptical-cylindrical shape.

18. The solid-state laser (1) according to one of the preceding claims, wherein at least the partially reflecting laser mirror (4a,4b) is deposited on the end face (4) of the laser gain medium (3), wherein the layer deposited thereon has a packing density of greater than 0.9, preferably greater than 0.95 and most preferably greater than 0.99.

19. The solid-state laser (1) according to one of the preceding claims, wherein the pump source (5) having a wavelengths between 955 to 985 nm.

20. The solid-state laser (1) according to one of claims 1 to 18, wherein the pump source (5) having a wavelengths between 760 to 815 nm.

21. The solid-state laser (1) according to one of claims 1 to 18, wherein the pump source (5) having a wavelength between 1600 to 2050 nm.

22. A method for operating a monolithic, side pumped solid-state laser (1) comprising a laser resonator structure (3) comprised of a laser gain medium (2) having a longitudinal axis (L), wherein pump light (5a) is fed through a side face (2a) into the laser gain medium (2), wherein part of the pump light (5a) is exiting the laser gain medium (2) at an opposite side face (2b) as an exiting pump light (5b), and wherein the exiting pump light (5b) is reflected such that a reflected pump light (5c) is reentering the laser gain medium (2) at the opposite side face (2b).

23. A method for operating the solid-state laser (1) according to claim 22, wherein the laser gain medium (2) is cooled symmetrically with respect to the longitudinal axis (L) of the laser gain medium (2), so receive in the laser gain medium (2) with respect to the longitudinal axis (L) a symmetrical thermal distribution.

24. A method for operating the solid-state laser (1) according to one of claims 22 and 23, wherein the main wavelength of the pump light (5a) is shifted relative to an absorption peak region of the laser gain medium (2).

25. Use of a solid-state laser (1) according to one of claims 1 to 21 for treating or ablating biological tissue.

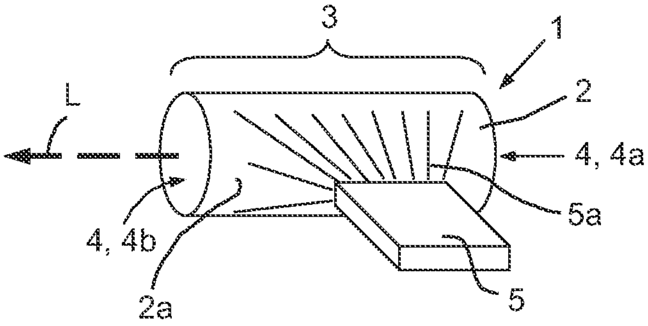

Figure 1

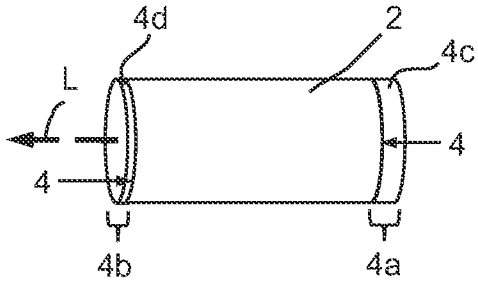

Figure 1a

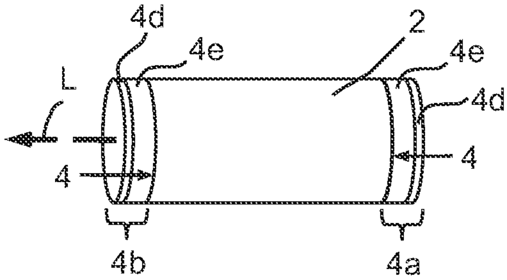

Figure 1b

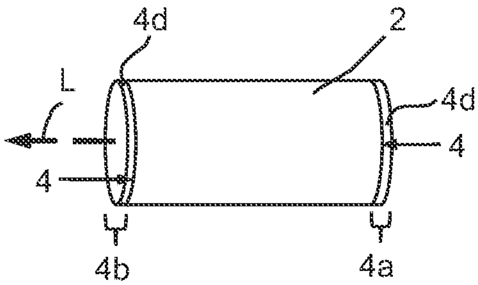

Figure 1c

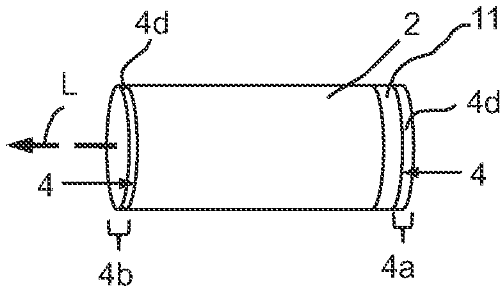

Figure 1d

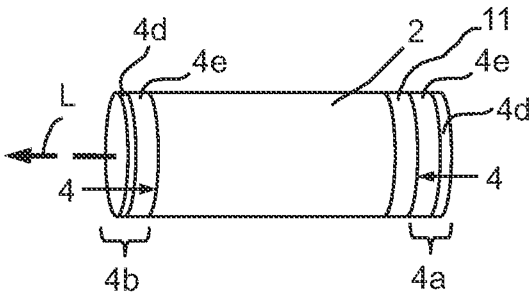

Figure 1e

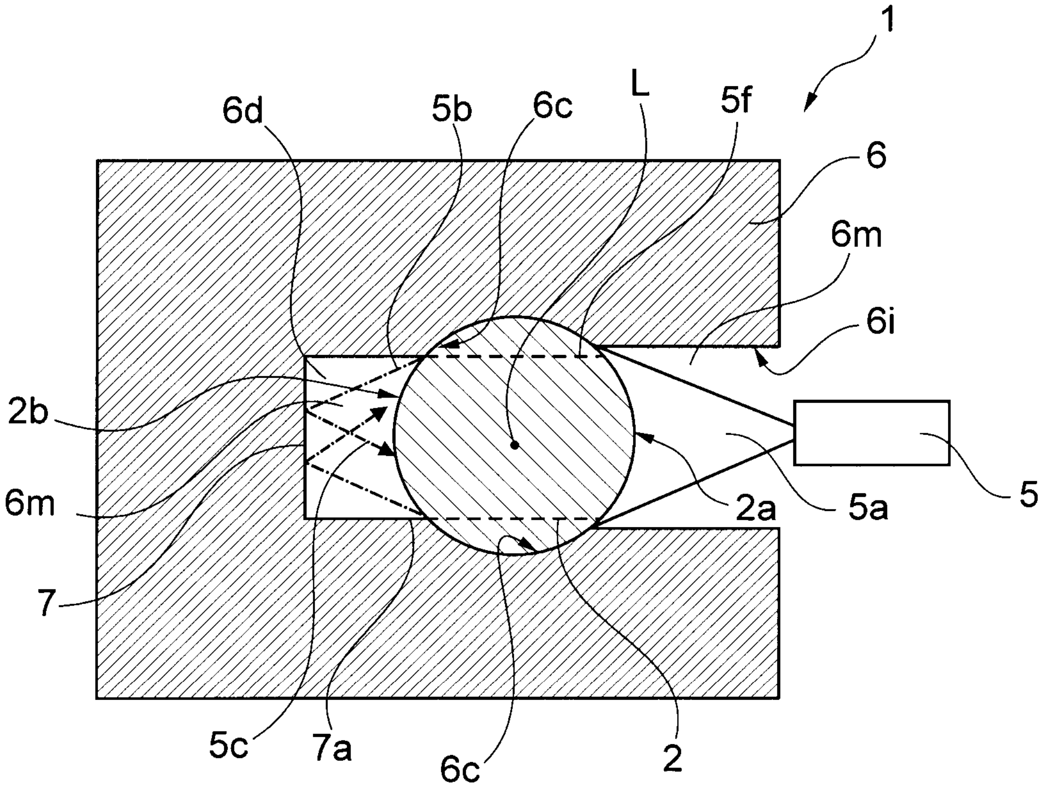
1
6d
5b
6c
L
5f
6
6m
6i
2b
6m
7
5
5a
2a
5c
7a
6c
2

Fig. 2

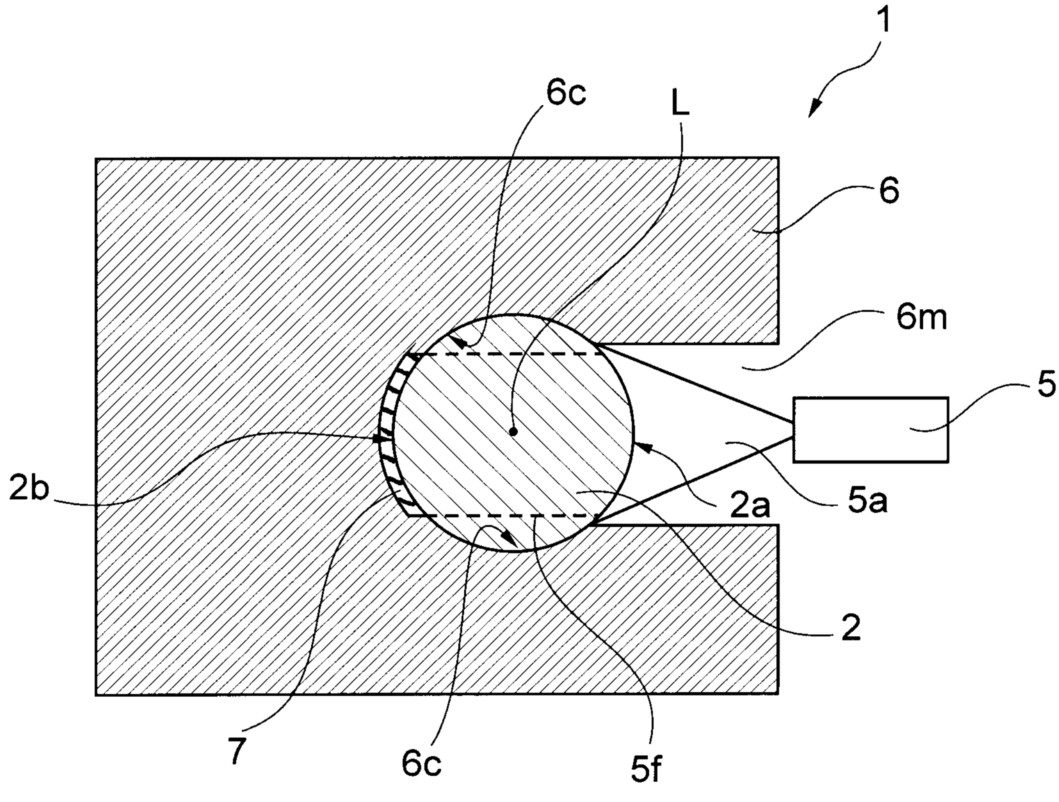
1
6c
L
6
6m
5
2b
2a
5a
2
7
6c
5f

Fig. 2a

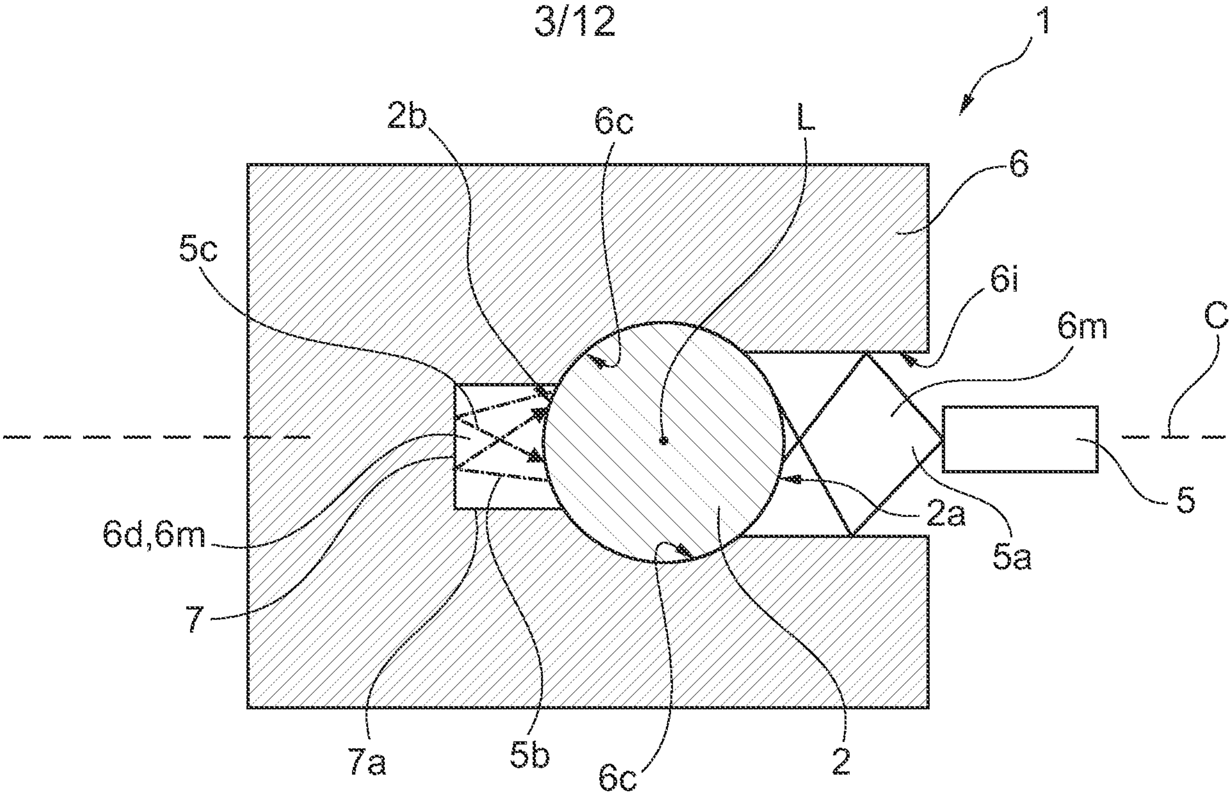
1
2b
6c
L
6
5c
6i
6m
C
2a
5
5a
6d,6m
7
7a
5b
6c
2

Fig. 3

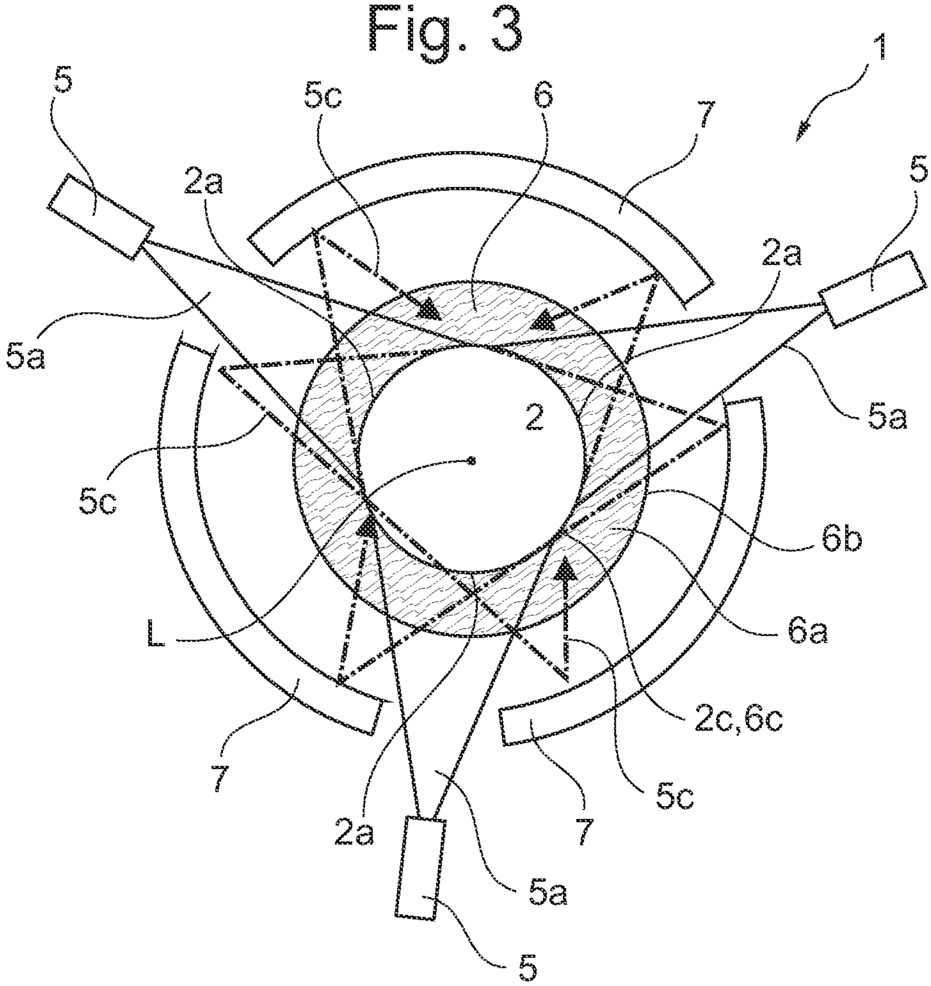
1
5
5c
6
7
2a
5
2a
5a
5a
2
5c
6b
L
6a
2c,6c
7
5c
7
2a
5a
5

Fig. 4

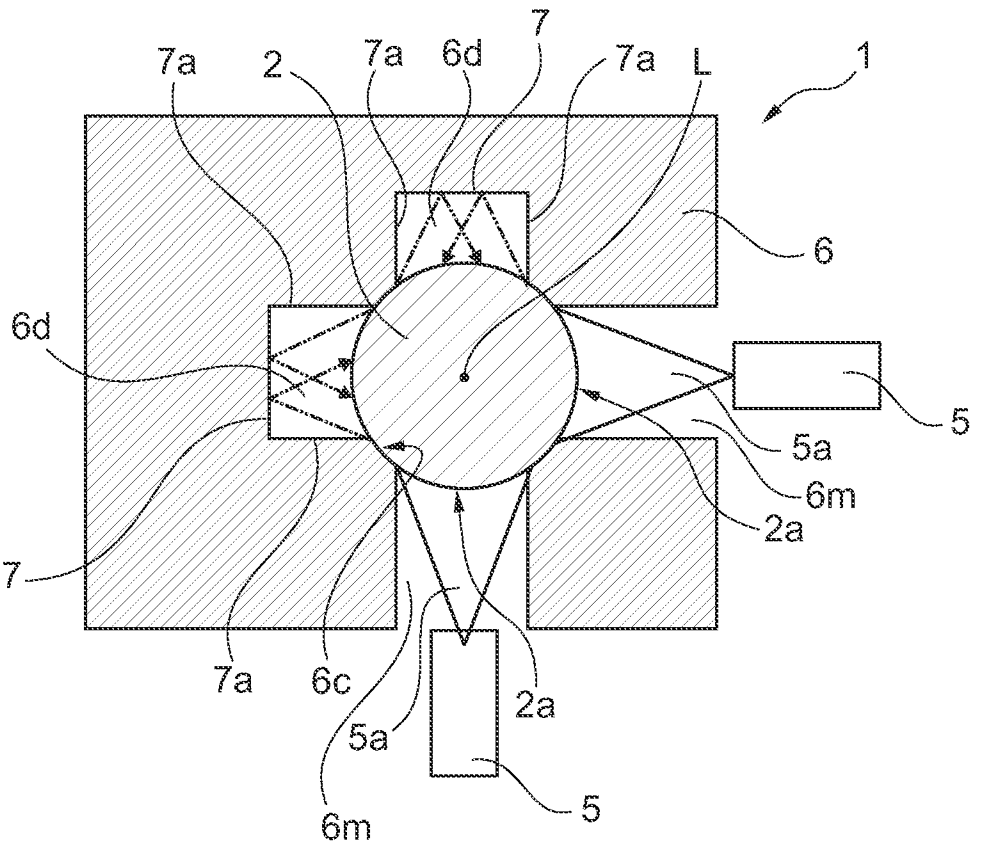
7a
2
7a
6d
7
7a
L
1
6
6d
5
5a
6m
2a
7
7a
6c
5a
2a
5
6m

Fig. 5

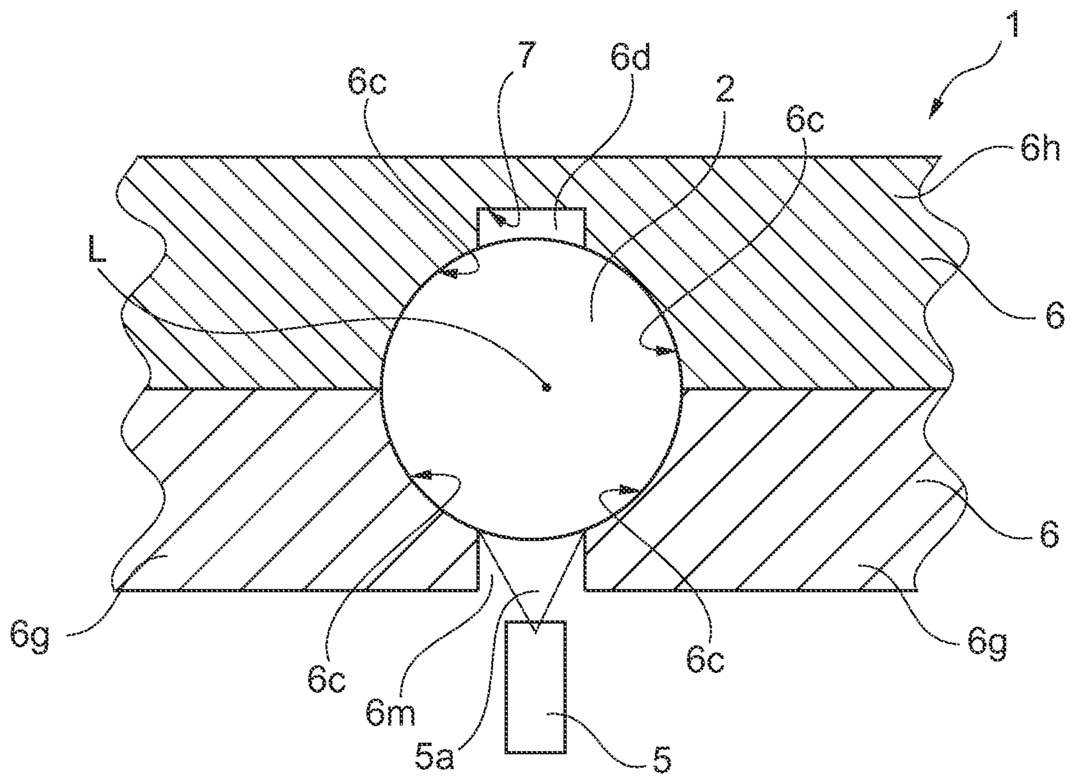
1
7
6d
6c
2
6c
6h
L
6
6
6g
6c
6m
5a
5
6c
6g

Fig. 6

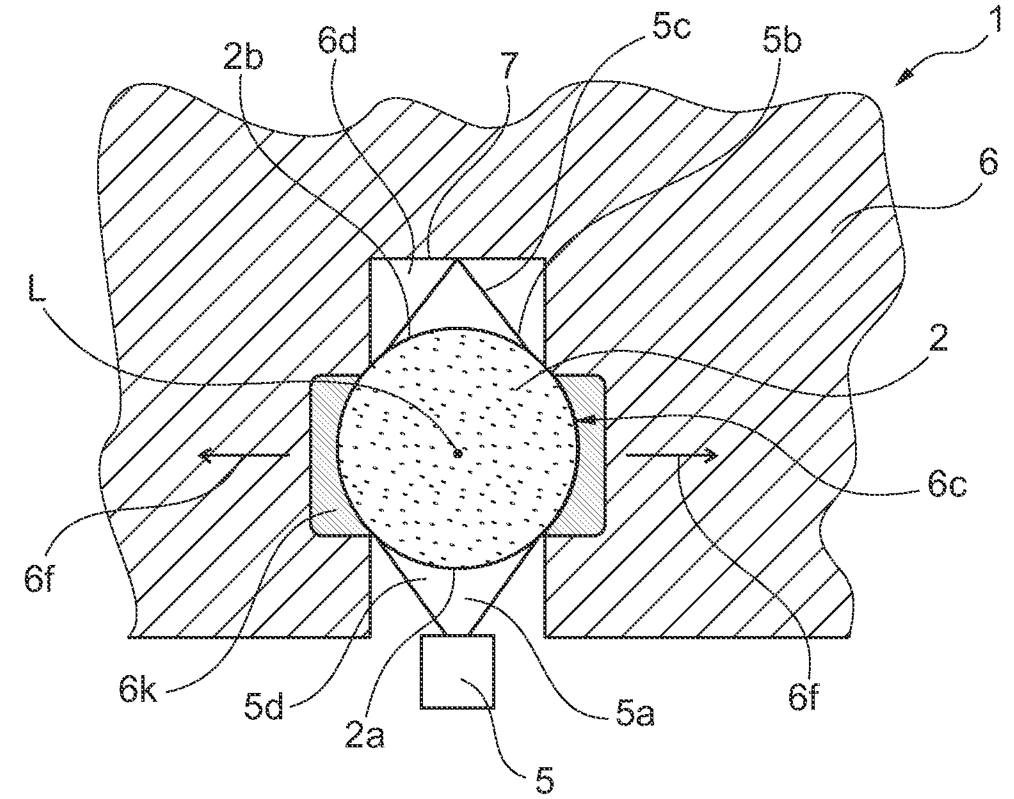

Fig. 7

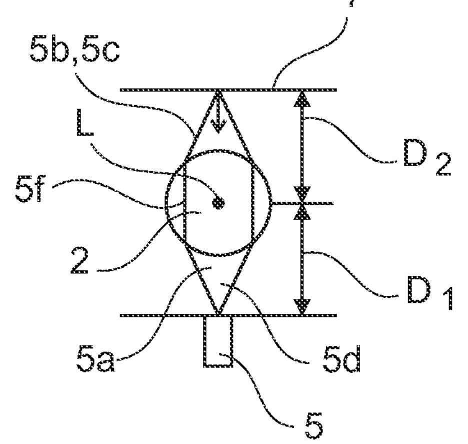

Fig. 8

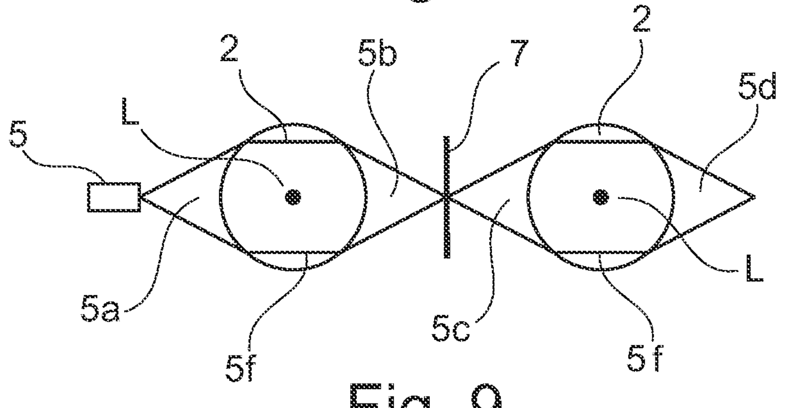

Fig. 9

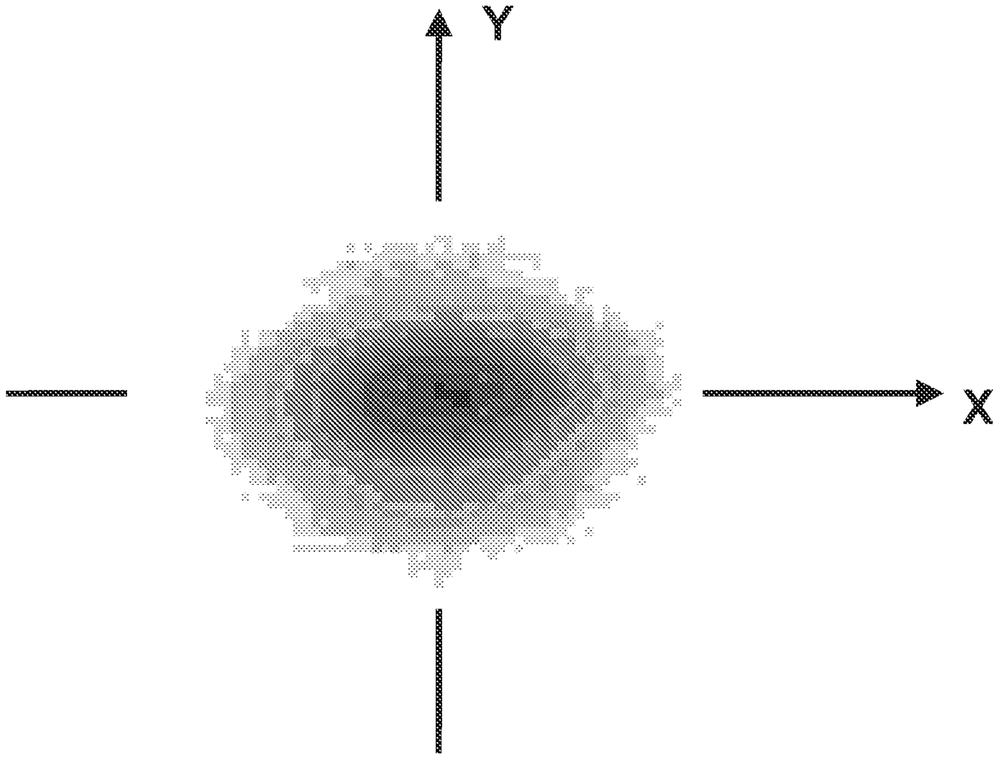

Figure 10

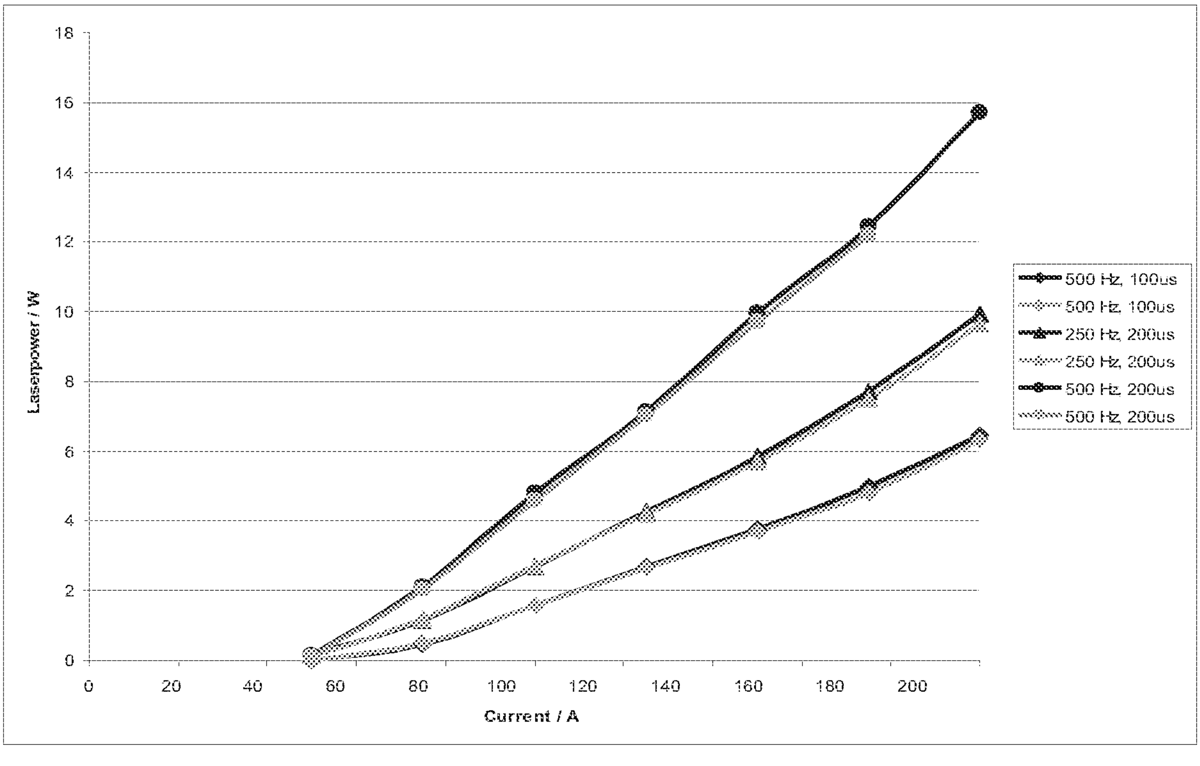

Figure 11a

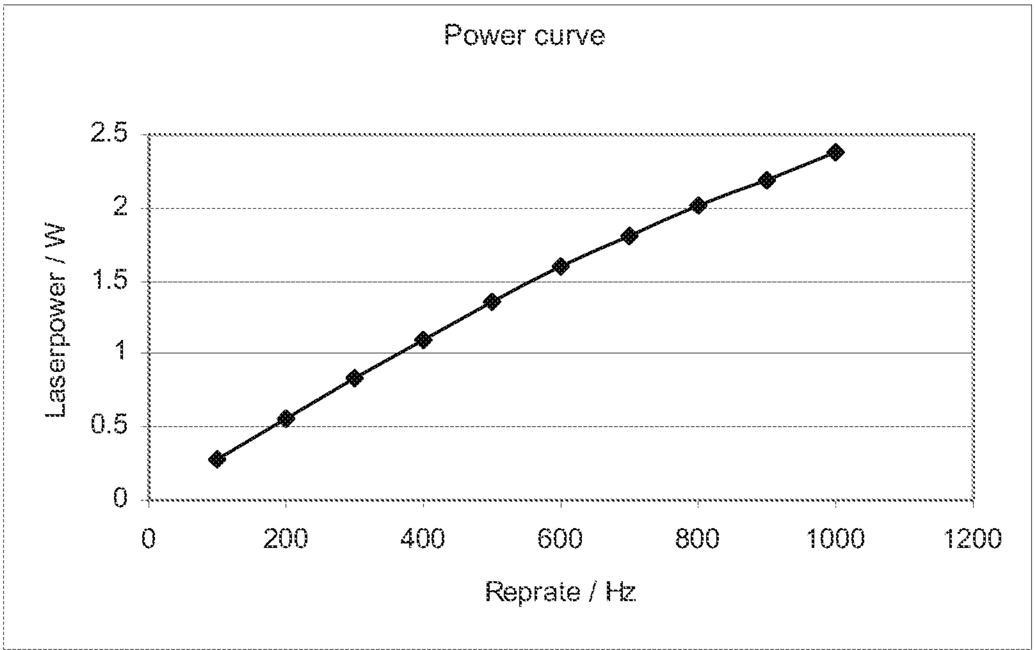
Power curve
Laserpower / W
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
1200
Reprate / Hz

Figure 11b

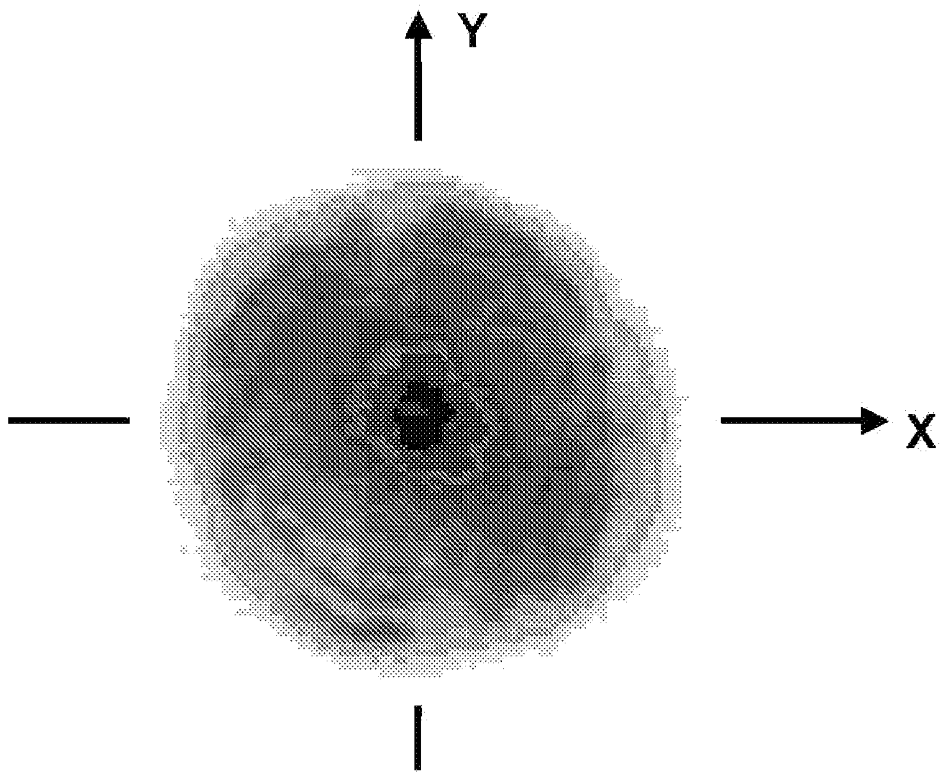

Figure 12

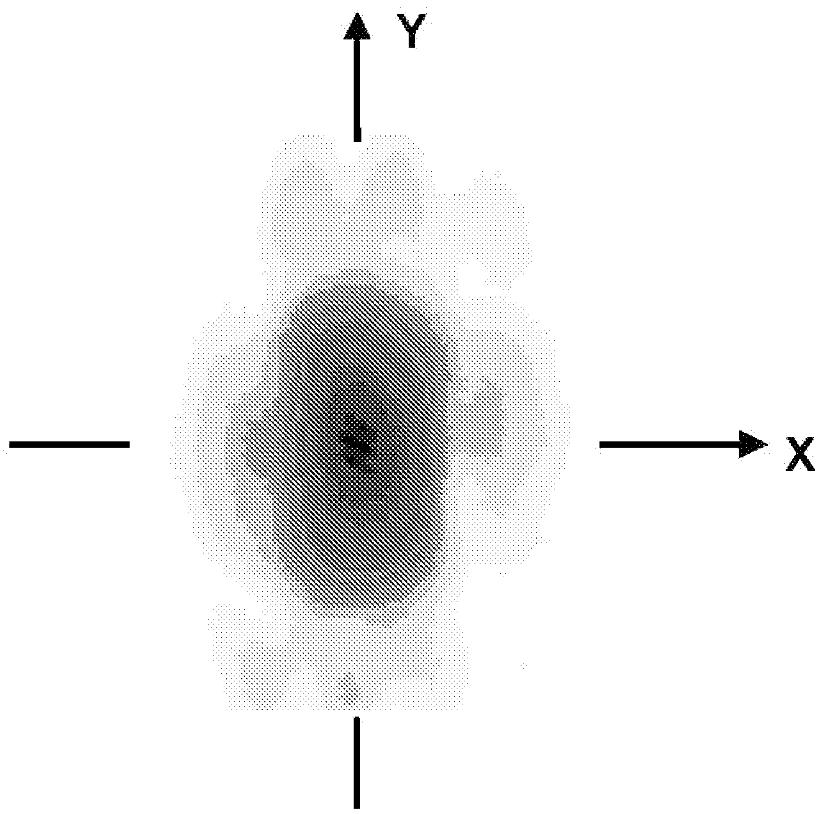

Figure 13

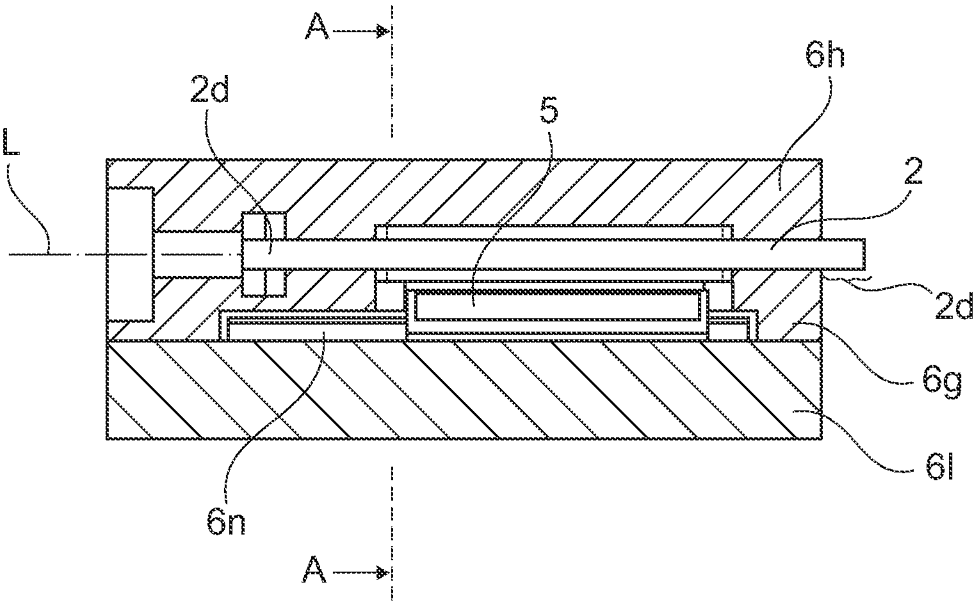

Fig. 14

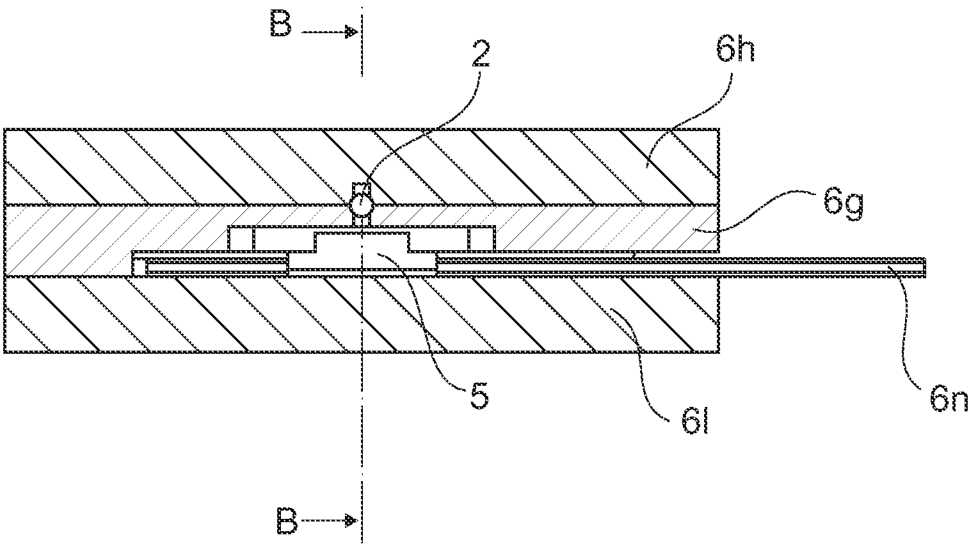

Fig. 15

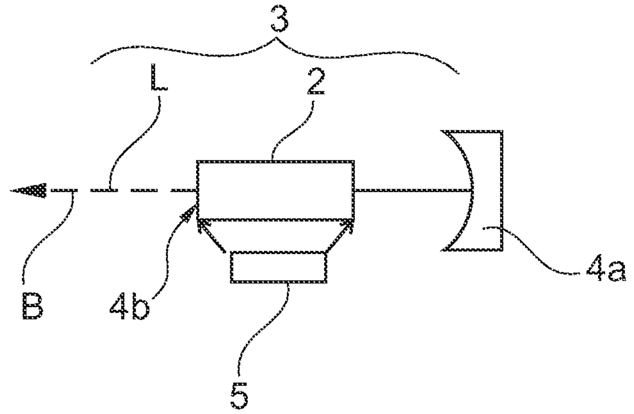

Fig. 16

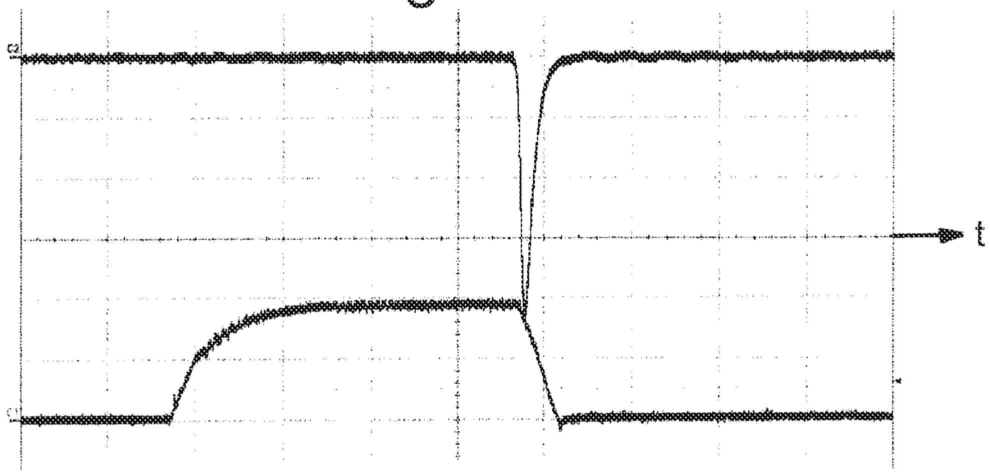

Figure 17

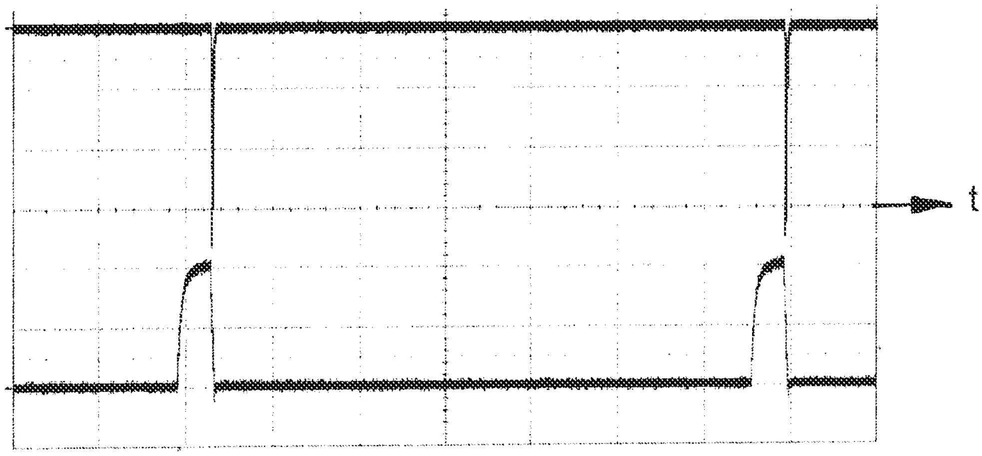

Figure 18

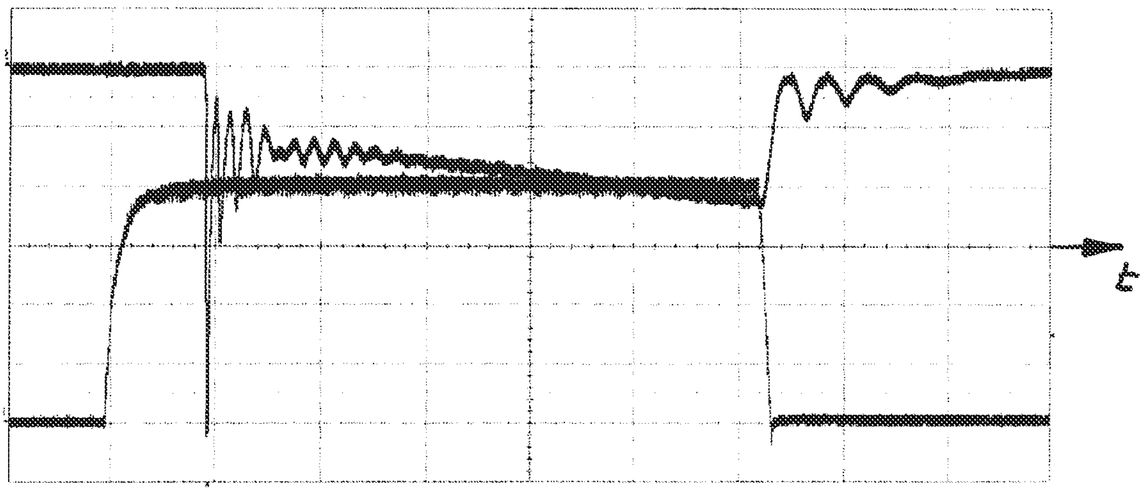

Figure 19

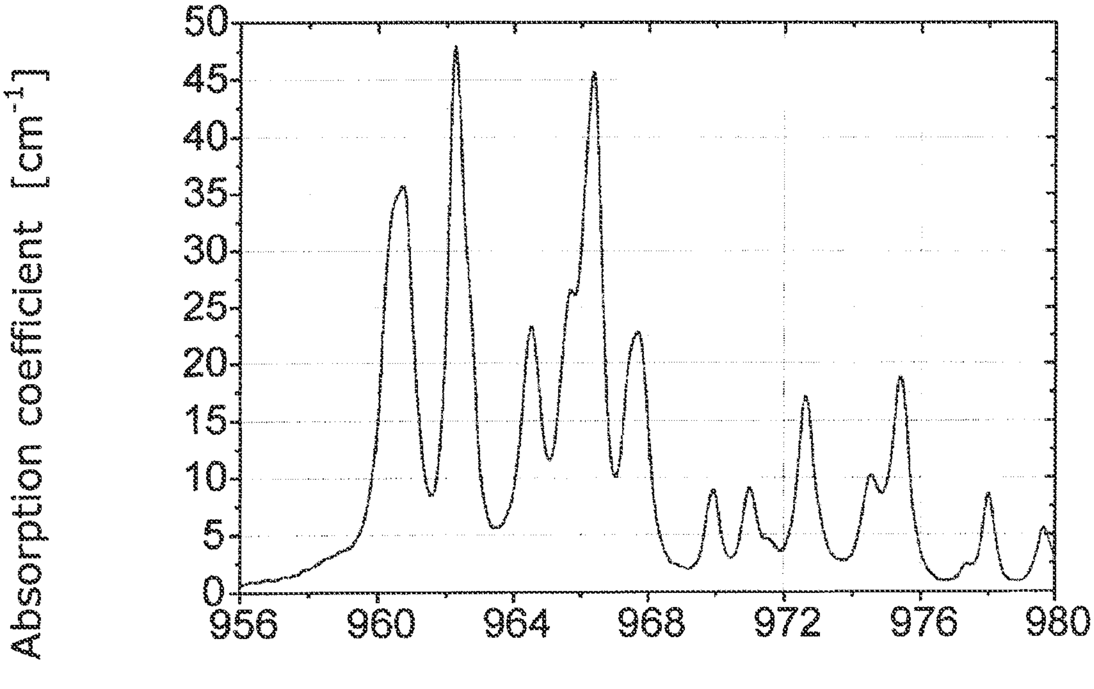

Figure 20

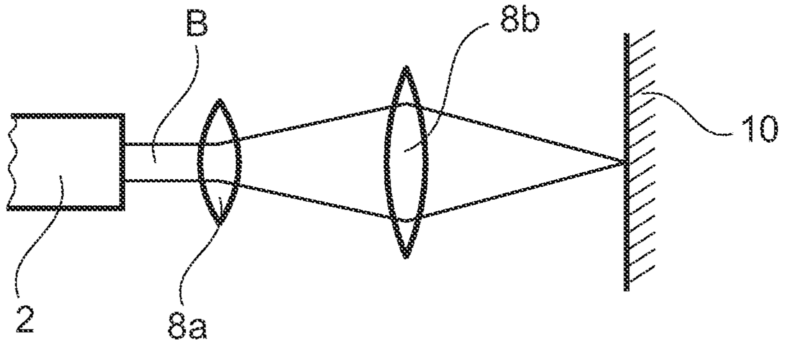

Fig. 21

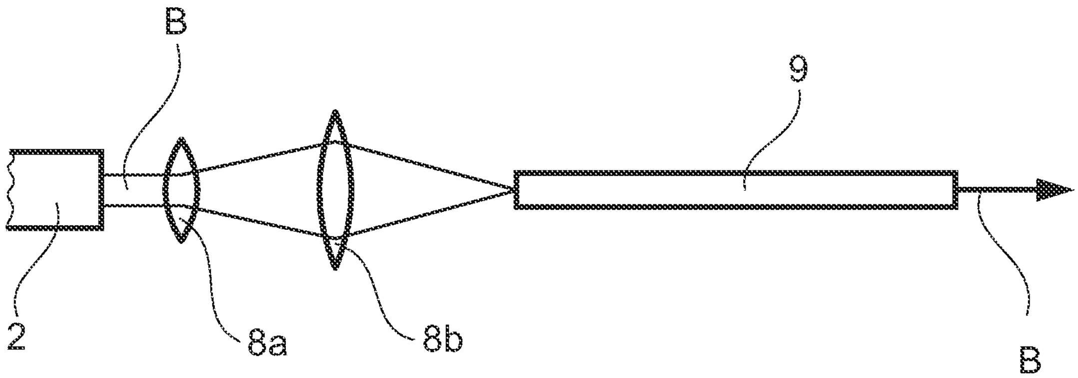

Fig. 22

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2010/051825

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01S3/0941 H01S3/06 H01S3/042
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, COMPENDEX, INSPEC, IBM-TDB, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FR 2 670 623 A1 (EUROP AGENCE SPATIALE [FR]) 19 June 1992 (1992-06-19)	1,15,22
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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
28 April 2010	10/05/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Fax: (+31–70) 340–3016	Gnugesser, Hermann

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