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End-pumping system for a diode pumped solid state laser and solid state laser.

(57)

The present invention relates to an end-pumped system for efficiently pumping a laser active medium. The system comprises a laser diode stack emitting an optical beam, equipped with a fast axis collimator that defocuses the fast axis of the optical beam. A lens duct with a tapered shape and flat input and output surfaces is coupled to the diode stack. The input side of the lens duct covers the entire area of the diode stack, preventing pump beam escape through total internal reflection on its side surfaces. The system further includes a laser active medium, coupled to the output side of the lens duct. The invention enables precise control of pump beam divergence angles and can incorporate various materials for the lens duct, including borosilicate crown glass, fused silica, calcium fluoride, zinc selenide, germanium, undoped YAG, polymethyl methacrylate, or sapphire. Applications of the system include solid-state lasers and its utilization as a part of laser amplifiers and oscillators, offering enhanced performance and efficiency in laser technologies.

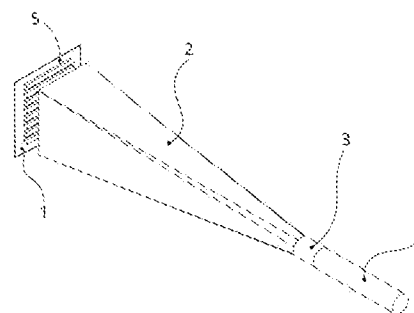


Fig. 1

End-pumping system for a diode pumped solid state laser and solid state laserTechnical field

[001] The present invention relates to a laser system. In particular, the present invention relates to a diode pumped solid state laser. Even more particularly, the present invention relates to an end-pumping system for the diode pumped solid state laser.

Background art

[002] A well-known method for pumping solid-state lasers is using laser diode stacks. Laser diode stacks offer several advantages over alternative pumping techniques, including high efficiency, compactness, and direct electrical-to-optical conversion. A laser diode stack may consist of multiple laser diode bars which have linear array. Each laser diode in the stack emits high-intensity light that matches the absorption spectrum of the gain medium. The emitted light is typically focused onto the gain medium using optics such as lenses or fiber-optic coupling.

[003] Laser diode stacks often require additional optics for the beam collimation and shaping to match the specific requirements of the solid-state laser system. The primary function of the collimator is to convert the diverging output beam from the laser diode stack into a collimated beam with minimal divergence, which serves as an input coupling for active medium. This is achieved by utilizing optical elements such as lenses or lens systems that effectively converge the beam to a parallel configuration. Different collimator designs can be employed for diode stack applications. Multi-lens collimators employ multiple lens elements arranged in a specific configuration to achieve higher collimation performance, better control over aberrations, and improved beam quality.

[004] In laser diode technology, the fast axis and slow axis refer to the two perpendicular planes of emission from a laser diode stack. These axes are determined by the structure and properties of the diode and play a crucial role in beam quality and divergence characteristics. The fast axis is the plane of maximum divergence. The beam emitted along the fast axis has a wider divergence and requires collimation to achieve a desired beam profile. The slow axis is the plane of minimum divergence. The beam emitted along the slow axis has a narrower divergence compared to the fast axis and may require minimal collimation or shaping.

- [005]** WO 0120731 discloses a lens duct used to deliver pump light into a laser gain LU505737 medium. The laser beam is propagating through the intermediate beam extractor which can be implemented as part of the gain element, part of the lens duct or a separate component entirely. The laser duct is pumped by a diode array, also known as the diode stack. Such a configuration, however, does not provide homogenized beam.
- [006]** US5936984A discloses an end-pumped Yb:YAG laser. The end-pumped laser comprises a lasing rod bonded to two undoped end caps. The laser rod is pumped with a diode bar stack. The light exiting each individual diode bar is initially conditioned with a cylindrical microlens. The microlens allows the diode light to emerge with a far field l/e divergence of approximately 10 mrad and 150 mrad in the fast and slow axis directions, respectively. The pump input surface is coated with a multilayer, dichroic coating for a high reflectance at 1030 nm and a high transmission at 941 nm allowing this end of the composite structure to perform as an efficient reflector for the laser cavity. Through total internal reflections down the barrel of the rod, the pump light becomes well homogenized with approximately 75% of the received pump light being absorbed on the first pass. The laser cavity described above was also Q-switched using an acoustooptic Q-switch. However, as shown bellow, the homogeneity is not sufficient.
- [007]** US6160934A discloses a hollow lens ducts having a small hole located in the lens to allow optical access to the end of the laser rod or slab at which the lens duct is located. This configuration provides optical access to the end of the laser rod or slab, such that pump geometries are enabled in which the rod or slab may be pumped at both ends. However, the present solution requires a birefringence compensator, therefore the solution is not cost effective.
- [008]** US5307430A discloses a lens duct suitable for solid state laser system. The lens duct condenses and intensifies light using a combination of front surface lensing and reflective waveguiding. The lens duct is utilized in the diode pumped laser oscillator. The lens duct includes an input side, an output side, and interconnecting sides or surfaces. Input side is curved or lens-shaped and coated with an antireflective material for more efficient transmission of light into the lensing duct. Output side is a flat configuration and includes an antireflective coating indicated. The other sides are flat and configured so as to form a taper down from the width of input side to the width of output side and are not coated as light is prevented from escaping by total internal reflection at these surfaces as it travels towards output end. The sides or surfaces

perform a waveguide function in channelling the light from end. However, as it will be shown bellow, it's curved input side is not optimal for coupling in a pump beam from a laser diode stack. LU505737

Summary of the invention

- [009]** With respect to the above-mentioned drawbacks, the object of the present invention is to provide an end-pumping system for directly diode pumped solid state laser.
- [010]** A further object of the present invention is to provide a homogenized pump spot for solid state laser pumped by laser diode stack, wherein the active medium is preferably a laser rod. Therefore, another object of the present invention is to achieve a top-hat output profile.
- [011]** A further object of the present invention is to provide a couple in the pump beam to the laser without a need to provide any further homogenizing device.
- [012]** A further object of the present invention is to manufacture the laser system at low manufacturing cost as possible.
- [013]** In a first aspect of the present invention and meeting the above-mentioned objectives, an end pumped system for pumping a laser active medium is provided. The system for pumping a laser active medium is defined by claim 1. The end-pumped system for pumping a laser active medium comprises a laser diode stack. The laser diode stack is coupled to a collimator. The diode stack is emitting an optical beam toward the side of the collimator. The system further comprises a lens duct. The lens duct comprises an input side. The input side serves for coupling in the collimated optical beam from the collimator of the diode stack into the lens duct. The lens duct further comprises a body, through which the collimated optical light is propagating to an output side. The output side is opposite to the input side. The output side serves for coupling out the optical beam from the lens duct. Both sides, the input side and the output side, are flat. Flat sides are advantageous in coupling in/out the diode lights into/from the lens duct. The lens duct is tapered away from the input side to an output side, which means that input side has larger cross section than the output side. The input side is effectively covering the whole part of the diode stack so that full optical beam emission from the diode stack is coupled into the lens duct. The system further comprises a laser active medium coupled to the output side of the lens duct. The present invention is characterized by the collimator, which is a fast axis collimator. The fast axis collimator is configured to emit the optical beam toward the lens duct, wherein the

optical beam is defocused in its fast axis. An incident angle Θ_{in} of the optical beam LU505737 coupled into the lens duct is within the range defined by equation

$$\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out}.$$

[014] In the equation, l_{in} is transverse distance of an edge of the input side. l_{out} is transverse distance of an edge of the output side. Θ_{out} is a output angle of the optical beam outputting the lens duct. The output angle Θ_{out} is defined by inequation

$$\theta_{out} \leq \frac{n_2}{n_1} \sin(\pi - \sin^{-1}\left(\frac{n_1}{n_2}\right) + \theta_{tp})$$

[015] for effective coupled in of the beam into a laser active medium, wherein n_1 is a refractive index of the surrounding area; n_2 is a refractive index associated with the material properties of the lens duct; and θ_{tp} is a taper angle of the lens duct.

[016] The present invention meets the above-mentioned objectives. Furthermore, the laser system including the system for pumping a laser active medium according to the present invention can be air-cooled, which is a further advantage of the present invention.

[017] A laser diode stack can include a plurality of diode bars, which are arranged in the form of a diode stack. The diode stack is provided with a fast axis collimator, which are directly optically coupled to the diode stack. Fast axis collimator can be optically coupled to the laser diode stack via mechanical mountings attached to the laser diode stack and holding a plurality of micro-optical components serving as the fast axis collimator. The position of the fast axis collimator, with respect to lens duct, can be configured so that the optical beam is positively defocused. The positive defocus refers to the intentional adjustment or positioning of the fast axis collimator so that the optical beam, in the fast axis direction, converges after the passing fast axis collimator and diverges slightly before or at entry into the lens duct. In another embodiment, the position of fast axis collimator, with respect to lens duct, can be configured so that the optical beam is negatively defocused. Negative defocus is characterized in the position of focal plane of the fast axis collimator, which is located in front of the intended or desired object plane. In negative defocus, light rays from a point source converge before reaching the image plane.

[018] Furthermore, the incident angle Θ_{in} of the optical beam coupled into the lens duct is carefully controlled within a specified range. This control is governed by the equation

$\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out}$, where l_{in} represents the transverse distance of an edge of the input side, l_{out} corresponds to the transverse distance of an edge of the output side, and θ_{out} denotes the output angle of the optical beam upon exiting the lens duct. The output angle θ_{out} is defined within specific limits, optimizing the behaviour of the optical beam within the laser system. This configuration contributes to the efficacy and precision of the laser pumping process, thereby enhancing the overall functionality of the end-pumped system. LU505737

- [019]** In a preferred embodiment, the laser diode stack comprises a plurality of laser diode bars. Each laser diode bar comprises a plurality of laser diode. Each laser diode bar is preferably provided with a bar of fast axis collimator, therefore the number of fast axis collimator and equals to the number of laser diode bars.
- [020]** In an embodiment, the laser stack is square shaped; and wherein the lens duct is configured to defocus the pump beam so that the optical beam fast axis divergence angle is substantially the same as slow axis divergence angle.
- [021]** In a preferred embodiment, to minimize leakage of the optical beam, the lens duct is preferably designed within the critical angle. Therefore, the material of lens duct is configured for total internal reflection of the optical beam, which is propagating inside the lens duct. Total internal reflection occurs when light traveling through a medium encounters an interface with another medium with a lower refractive index at an angle greater than the critical angle. This phenomenon causes all of the incident light to be reflected back into the lens duct. Preferably, the system is air cooled. Therefore, the skilled person can consider air, having refractive index of approximately 1.0003, the following materials as the material which can provide total internal reflection at the air-interface. Certain types of glass, such as high-index glass or optical glass with a high refractive index, can exhibit total internal reflection. Examples includes N-BK7 is a borosilicate crown glass with relatively low refractive index and good optical properties in the visible and near-infrared wavelength range. Another example is fused silica, also known as quartz, is a high-purity glass with excellent transmission properties across a wide wavelength range, including ultraviolet (UV), visible, and near-infrared (NIR). It is suitable for high-power laser applications due to its excellent thermal stability and low coefficient of thermal expansion. Another material providing total internal reflection suitable for construction of duct lens can be calcium fluoride, which is a crystalline material with high transparency in the ultraviolet (UV) to infrared (IR) range. Another material providing total internal reflection suitable for construction of

duct lens can be zinc selenide, which is a transparent material used for lenses in the mid-infrared (IR) range. Another material providing total internal reflection suitable for construction of duct lens can be germanium, which is a high refractive index material with good transmission in the mid-infrared (IR) range. Another material providing total internal reflection suitable for construction of duct lens can be acrylic, also known as polymethyl methacrylate (PMMA), which is a transparent thermoplastic material with a relatively high refractive index (approximately 1.49). Another material providing total internal reflection suitable for construction of duct lens can be sapphire, which is a single crystal form of aluminium oxide (Al_2O_3) and possesses a high refractive index (approximately 1.77).

- [022]** The shape of the laser active media used with laser ducts can vary depending on the specific laser system. In a preferred embodiment, the shape of the active media can be a laser rod, such as a cylindrically shaped laser rod, wherein laser active media can be made from materials such as Yb:YAG, Nd:YVO₄, Nd:YLF, Nd:YAG or Er:YAG. The rod shape allows for efficient absorption of pump energy and uniform distribution of the laser beam. In another embodiment, the shape of the active medium is a laser slab, which is rectangular-shaped laser active media. They can be made from materials like Nd:YAG or Yb:YAG. Slabs provide a large surface area for thermal management and can handle high power densities. In another embodiment, the shape of the active media can be a laser disk, which is flat, usually circular-shaped laser active media. They can be made of materials like Yb:YAG or Nd:YAG and offer high thermal conductivity and efficient cooling. The disk shape allows efficient pumping and extraction of laser energy.
- [023]** The shape of the lens duct is adapted in such a way that its input side, which serves for coupling in the pump beam from the laser diode stack to the laser duct, covers the entire emitting surface of the laser diode stack. The lens duct is tapered away from the input side so that its output side is tailored to the shape of the active medium mentioned above.
- [024]** In a preferred embodiment, the system further comprises an un-doped crystal or glass rod positioned between the laser duct and the active medium.
- [025]** In a preferred embodiment, the system encompasses an active medium or an un-doped crystal or glass rod. Notably, the active medium or rod features a dichroic coating on one side designed for coupling in an optical beam from the lens duct. The specific configuration of the dichroic coating facilitates the transmission of the optical

beam at an excitation wavelength, such as of 800 nm for Nd:YAG or 940 nm for Yb:YAG, and/or the reflection of the optical beam at the lasing wavelength, such as of 1064 nm for YAG or 1030 for Yb:YAG.

[026] In another preferred embodiment, the input side of the laser duct is square or polygonal; cylindrical or rounder and output side of the laser duct is circular; or square; or polygonal, in particular hexagonal or octagonal.

[027] Another object of the present invention is a solid state laser pumped by a diode stack. The solid state laser comprises the end-pumped system according to anyone of the above-mentioned embodiment.

Brief description of the drawings

Fig. 1 is an illustration of an end-pumped system for solid state laser.

Fig. 2 is a side illustration of the end-pumped system for solid state laser according to Fig. 1 showing pump beam propagation through the lens duct from the side view.

Fig. 3 is a top illustration of the end-pumped system for solid state laser according to Fig. 1 showing pump beam propagation through the lens duct from the top view.

Fig. 4 shows details on the parameters of lens duct and input and output beam.

Fig. 5 shows more details on the parameters of lens duct and input and output beam.

Fig. 6 is an illustration of the lens duct with details on input side and output side.

Fig. 7 is an illustration of six alternative embodiments of the lens ducts having different shapes.

Fig. 8 is an illustration of positively defocused fast axis collimation from top view.

Fig. 9 is an illustration of positively defocused fast axis collimation from side view.

Fig. 10 is an illustration of negatively focused fast axis collimation from top view.

Fig. 11 is an illustration of a system according to the present invention suitable for solid state laser.

Fig. 12 is an illustration of an alternative system according to the present invention suitable for solid state laser.

Fig. 13 illustrates a non-claimed embodiment, which serves for experimental comparison with LU505737 the present invention.

Fig. 14 illustrates a transversal laser beam profile coupled out from the embodiment according to Fig. 12.

Fig. 15 illustrates a non-claimed embodiment, which serves for experimental comparison with the present invention.

Fig. 16 illustrates longitudinal profile of the laser beam coupled out from the embodiment according to Fig. 15.

Fig. 17 illustrates transversal profile of the laser beam coupled out from the embodiment according to Fig. 15.

Fig. 18 illustrates a longitudinal profile of the laser beam coupled out from the embodiment according to the present invention depicted in Fig. 11.

Fig. 19 illustrates a transversal profile of the laser beam coupled out from the embodiment according to the present invention depicted in Fig. 11.

Fig. 20 illustrates a transversal profile of the laser beam coupled out from the embodiment according to the present invention depicted in Fig. 12 in free-running regime.

Detailed description

[028] FIG. 1 is an illustration of a part of end-pumped Q switched Nd:YAG solid state laser with energy per pulse about 60 mJ at repetition rate 50 Hz, power is about 3 W, and length of the pulse is <10 ns and emitted wavelength at 1064 nm. The laser system according to the present invention is suitable for laser induced breakdown spectroscopy, whereas the whole laser system can be air-cooled.

[029] In particular, Fig. 1 illustrates an embodiment for pumping a laser active medium, which in this particular example is a laser rod 4. The laser rod 4 is pumped by laser diode stack. The laser rod is preferably provided with an undoped crystal or glass rod 3, which can be fabricated from the lasing medium, such as undoped YAG. The laser rod 4 is pumped with a diode stack 1. The laser diode stack comprises a plurality of diode bars. Each diode bar comprises a plurality of laser diode emitting a pump beam. The diode bar is coupled to a fast axis collimator 5. The light exiting diode stack is initially conditioned with the fast axis collimator 5. The fast axis collimator comprises

a plurality of micro lenses. The number of microlenses equals to the number of the diode bar. The micro lenses are in the form of aspheric micro-hemicylindrical lens. In **Fig. 1**, the fast axis collimator **5** plays a pivotal role in the optical beam management within the system. Notably, the fast axis collimator **5** is positioned to defocus the fast axis of the optical beam, enhancing the efficiency and stability of the laser pumping process. This is achieved by ensuring that the lens duct **2** is positioned external to the focal plane of the fast axis collimator **5**. The arrangement introduces a deliberate defocusing effect on the fast axis, contributing to improved performance and control over the optical beam. To further optimize the incident angle Θ_{in} of the optical beam entering the lens duct **2**, a specific range is defined by the equation $\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out}$. Here, l_{in} represents the transverse distance of an edge of the input side **21** of the lens duct, and l_{out} corresponds to the transverse distance of an edge of the output side **22**. The output angle Θ_{out} of the optical beam upon exiting the lens duct **2** is also subject to control within predefined limits. This regulation ensures that the optical beam is directed with precision, and the output angle Θ_{out} is defined by

$$\theta_{out} \leq \frac{n_2}{n_1} \sin(\pi - \sin^{-1}(\frac{n_1}{n_2}) + \theta_{tp})$$

wherein n_1 is a refractive index of the surrounding area; n_2 is a refractive index associated with the material properties of the lens duct **2**; and θ_{tp} is a taper angle of the lens duct **2**. Setting the Θ_{out} is contributing to the overall efficacy and reliability of the laser system. This embodiment highlights a unique configuration where the fast axis collimator **5** collaborates with the lens duct **2** in a manner that strategically defocuses the fast axis of the optical beam, combined with precise control over the incident and output angles. This results in an optimized laser pumping system with improved performance characteristics and enhanced functionality. The diode stack **1** and the fast axis collimator **5** are forming a single unit configured for emitting the collimated pump beam. The final laser beam can be coupled out from the laser rod for further processing or can be a part of laser resonator.

[030] The pump beam emitted from the diode stack **1** is focussed in front or inside the lens duct **2** in order to end-pump the laser rod **4**. The defocusation is provided by the position of the fast axis collimator **5** with respect to the lens duct **2**, which is configured for positive defocus **53** of the pump beam emitted from the diode stack **1**.

[031] Typically, lens duct **2** is formed of a transparent material for the pumping wavelength, such as fused silica, although it can be made of another material such as YAG. The lens duct is made of material, which is capable to provide total internal reflection as it

is shown in **Fig. 2**. **Fig. 2** illustrates a side view and **Fig. 3** illustrates a top view of the system according to one embodiment of the present invention. The laser diode stack **1** emits a diverging pump beam in the direction of the lens duct **2**. Before entering the lens duct **2**, the pump beam propagates through the fast axis collimator **5**. The position of the fast axis collimator **5** and the lens duct **2** are configured so that the lens duct **2** lies outside the focal plane of the fast axis collimator **5** for diverging the pump beam in the fast axis direction, resulting in a positively defocused pump beam. This positively defocused pump beam is then coupled into the lens duct **2**. Inside the lens duct **2**, the pump beam propagates by repeating internal total reflection, as indicated by the lines inside the laser duct **2** in the **Fig. 2**. In particular, lines **51** represent the defocused pump beam, while lines **52** represent the pump beam that has been totally reflected from the sides of the lens duct **2** as it propagated through. The pump beam continues to propagate and is coupled out of the lens duct **2** at the output side **22**. Immediately after exiting the lens duct **2**, the pump beam preferably enters the undoped rod and then proceeds to the laser rod **4**, which serves as the active medium. By employing the system according to the present invention as illustrated in **Fig. 2**, efficient homogenization of the pump beam can be achieved, leading to improved laser beam output.

[032] **Fig. 3** shows a top view on the laser duct schematically provided with the input and output sides **21** and **22**. The input side **21** of the lens duct **2** is preferably coated with antireflective coatings.

[033] **Fig. 4** shows the side view of the lens duct **2** with clear indications of an input angle θ_{in} and an output angle θ_{out} , the parameters for controlling the trajectory of the optical beam within the system. The input angle θ_{in} is intricately linked to the output angle θ_{out} through a relationship defined by the lengths of input sides and output side edges: l_{in} , representing the transverse distance of an edge of the input side **21** of the lens duct, and l_{out} , corresponding to the transverse distance of an edge of the output side **22**. This relationship is precisely characterized by the equation $\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out}$. The interdependence of these parameters ensures a controlled and optimized flow of the optical beam through the lens duct, contributing to the overall efficiency of the laser pumping process. In addition to these geometric considerations, **Fig. 4** also introduces a refractive index, denoted as n_2 , associated with the material properties of the lens duct. This refractive index is a critical factor influencing the behaviour of the optical beam as it traverses through the lens duct. The specific value of n_2 preferably contributes to the determination of the output angle θ_{out} and plays a

significant role in achieving the desired optical characteristics within the laser system. LU505737
In particular, the link between n_2 and θ_{out} is defined as follows:

$$\theta'_{out} = \sin^{-1} \left(\frac{n_1}{n_2} \sin(\theta_{out}) \right)$$

[034] where n_1 is a refractive index of the surrounding area, such as $n_1 = 1$ for air. θ'_{out} is an output angle in the lens duct. The placement of the lens duct **2** in **Fig. 4** is such that it interacts with other components of the laser system, ensuring that the fast axis collimator **5** is appropriately positioned external to the focal plane. The arrangement collectively optimizes the defocusing effect on the fast axis of the optical beam, enhancing the system's overall performance.

[035] **Fig. 5** further discloses limitations to the output angle θ_{out} defined by the following (in)equalities:

$$\theta'_{out} = \sin^{-1} \left(\frac{n_1}{n_2} \sin \theta_{out} \right); \text{and}$$

$$\theta_a = \pi - \theta'_{out} + \theta_{tp} ; \text{wherein}$$

θ_{tp} is a taper angle of lens duct **2** as schematically shown in **Fig. 5**; and wherein

$$\theta_c = \sin^{-1} \left(\frac{n_1}{n_2} \right).$$

When $\theta_a \geq \theta_c$, the invention is provides an advantage of no leakage loss.

[036] Therefore, considering all of the above-mentioned condition, the limitation to the output angle θ_{out} is:

$$\theta_{out} \leq \frac{n_2}{n_1} \sin(\pi - \sin^{-1} \left(\frac{n_1}{n_2} \right) + \theta_{tp}) .$$

[037] **Fig. 6** is an isometric view of the lens duct shown in **Figs. 1 – 3**.

[038] **Fig. 7** represents six examples of the embodiment of the laser duct **2** shape. These six embodiments have different geometries of surface on input side **21** and output side **22** and therefore, different shapes, however, it shall be visible to a skilled person in the art that common features are bigger surface at input side **21** and smaller side at the output side **22** of the laser duct **2** and shape of the lens duct **2** is tapered away. The following description will be presented from right to left and from top to bottom. In one exemplary embodiment, the lens duct **2** features two circular surfaces for input and output side **21** and **22** of the pump beam emitted from a diode stack **1**. Therefore,

it takes the form of a truncated cone where the beam enters through the larger surface **21** and exits through the smaller surface **22**. Another embodiment comprises a square shape, which then narrows down to an octagonal output cross-section. The shape of the lens duct **2** gradually tapers. Another embodiment features a skewed square cross-section in the plane, preferably inclined at an angle. The lens duct **2** is narrowed from the square input side **21** suitable for laser diode stack **1** as shown in the other embodiment to the optional undoped glass rod **3** or directly to the laser rod **4**, exhibiting a hexagonal shape. The following embodiment displays a hexagonal input surface **21** and a trapezoidal output surface **22**, with the lens duct **2** tapered from the larger surface to the smaller one. In the next embodiment, a rounded square surface **21** and a circular surface **22** is provided. Another embodiment showcases square inputs **21** and outputs **22**, which can be advantageous in case of laser slab active medium or laser disk. By employing various geometries and shapes in the lens duct, the present invention provides flexibility and adaptability to suit different laser systems and applications. In the context of the preferred embodiment depicted in **Fig. 4**, when the lens duct **2** features a circular cross-section, the length of the edge on the input or output side **22** corresponds to the diameter of the lens duct. Specifically, in the case of a circular geometry, the transverse distance represented by l_{in} on the input side **21** and l_{out} on the output side **22** equates to the diameter of the lens duct.

[039] **Fig. 8** illustrates positive defocus of the pump beam, in its fast axis, emitted from a laser diode stack **1** illustrated from the top view. The positive defocus provided by the fast axis collimator **5** is characterized by that a plane **53** of focus points is in front of the input side of the lens duct **2**. Therefore, the pump beam is entering the lens duct **2** already defocused with slightly diverging beam.

[040] **Fig. 9** illustrates a side view on the laser diode stack **1** from **Fig. 8** provided with the fast axis collimator. As illustrated on **Fig. 9**, there is no change in the propagation of the beam.

[041] **Fig. 10** illustrates a negative defocus of the pump beam, in its fast axis, emitted from a laser diode stack **1**. This embodiment is characterized by the negative defocusation of the pump beam. The negative defocusation is characterized in that a focus plane is behind the input side of the lens duct **2**. Therefore, the focus plane is in the material of lens duct.

[042] **Fig. 11** illustrates an example of a free running mode laser cavity of the above illustrated configuration which has been operated in a Q-switched mode. The pump

source is a diode stack **1**, in **Fig. 10** illustrates the diode stack **1** mounted in a suitable mechanical mountings. According to the present invention, the laser diode stack **1** is provided with fast axis collimator **5**. LU505737

- [043]** Radiation from pump source **1** passes through the fast axis collimator **5** and lens duct **2** and is homogenized by lens duct **2** prior to passing into the active medium **3**. In one configuration of this embodiment, input surface of the laser rod **4** is coated with a dichroic coating.
- [044]** Through total internal reflections down the body of the lens duct **2**, the pump light becomes well homogenized of the received pump light being absorbed on the first pass. Lens duct **2** is preferably fabricated from a single piece of material. However, it may be fabricated from several pieces of material and bonded together using the low scatter optical bonding process known to a skilled person in the art.
- [045]** In this preferred embodiment, laser rod **4** is bonded using a low scatter, optical bonding technique to undoped glass rod **3**. Laser rod **4** may be comprised solely of lasing material, or it may be a composite rod. For example, a laser rod **4** may have a lasing medium with a square cross-section surrounded by an undoped cladding layer. Although this invention is not limited to a specific lasing material, the preferred host lattice materials are yttrium aluminium garnet (e.g., YAG), gadolinium gallium garnet (e.g., GGG), gadolinium scandium gallium garnet (e.g., GSGG), yttrium vanadate, lithium yttrium tetrafluoride (YLF), sapphire and phosphate laser glass. Suitable dopants for the lasing medium include Ti, Cu, Co, Ni, Cr, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb. The pump source is selected based on the absorption characteristics of the selected lasing material.
- [046]** Preferably, the portion of undoped glass rod **3** may have the same dimensions as the laser rod **4** while the distal portions of the end-caps may have an expanded cross-section. The present embodiment finds frequent application in the input configuration of a composite rod, wherein a gradual taper plays a crucial role in facilitating the effective coupling of pump radiation into the lasing medium through total internal reflection.
- [047]** The invention is equally applicable to a lasing medium with any cross section, such as square or rectangular cross-section used in laser discs or laser slabs. Typically in this configuration the large side surfaces are precision polished to enable beam propagation by total internal reflection. These lasers may be end-pumped or side-

pumped through their polished sides. The lens duct **2** can be optically coupled to the LU505737 end of the laser rod **4** or to the undoped glass **3** serving as an interface.

[048] Referring to **Fig. 12**, the present embodiment exemplifies a Q-Switch mode cavity. The laser diode stack **1**, which is securely held mountings. The laser diode stack **1** serves as the pump source for the laser active medium **4**. The laser diode stack **1** emits a pump beam towards the fast axis collimator **5** which effectively defocus the laser diode output, i.e. the pumping beam, in the fast-axis direction. The optical beam then progresses through the laser duct **2** is providing, if the embodiment is in its positive defocusation, homogeneous spatial distribution of pump laser at end surface of lens duct. Alternatively, the negative defocused beam propagating through the laser duct **2** is also providing homogeneous spatial distribution of pump laser at end surface of lens duct **2**. As the beam traverses the laser duct **2**, it undergoes a process of homogenization, resulting in a more uniform intensity profile. Advantageously, the homogenized beam continues its journey through the undoped glass rod **3**. This component is specifically included to exploit its favourable characteristics, such as low refractive index, which facilitates the subsequent processes within the laser system. The undoped glass rod **3** further contributes to coupling of the pump radiation into the active medium **4**. Upon entering the active medium **4** the beam interacts with the lasing material and initiates the generation of a homogeneous optical beam. The active medium, carefully selected for its desired properties, ensures the production of a laser beam with a top hat beam profile, characterized by a uniform intensity across the cross-sectional area. To further control and manipulate the laser beam, the invention incorporates additional components downstream. The beam is directed towards the Polarizing Beam Splitter **6**, which separates the laser beam based on its polarization state. From there, the beam proceeds through a quarter-wave plate **7** and a Pockels cell **8** which enable active modulation and polarization control. Finally, the laser beam reaches the Output Coupler **9**, which serves as the output of the laser system providing top hat homogenized laser beam **10**. The Output Coupler **9** can be a mirror selectively reflecting a portion of the intracavity laser beam **10** while allowing the remaining portion to exit the system, resulting in the desired output characteristics.

[049] The inventors have conducted series of experiments and simulation to compare the state of the art result with the present invention.

[050] **Fig. 13** depicts an unclaimed embodiment used for comparing the output of the laser beam **10** according to the present invention with the prior art. **Fig. 13** schematically illustrates the device comprising a laser diode stack **1** that emits a pump beam. The

pump beam is collimated by a set of cylindrical micro lenses **11**. This collimated pump beam is then directed towards a group of lenses **12** where it is focused into the active medium **4**. LU505737

- [051] **Fig. 14** represents the transverse profile of the laser beam obtained by the inventors using the unclaimed embodiment shown in **Fig. 13**. The obtained transverse profile of the laser beam, as depicted in **Fig. 14**, serves as a representation of the beam's intensity distribution across the transverse plane. This experimental data demonstrates the heterogeneity of the beam profile since there are visible peaks within the transversal cross section.
- [052] Another unclaimed embodiment is illustrated in **Fig. 15**, which follows a similar configuration to the previous example. **Fig. 15** depicts a laser diode stack **1**, a cylindrical lens **12**, and a lens duct **2**. The optical beam passes through these components in a similar manner as described in the previous case.
- [053] **Fig. 16** represents the longitudinal profile of the laser beam obtained from this unclaimed embodiment. This profile provides information about the intensity distribution of the beam along its propagation direction.
- [054] **Fig. 17**, on the other hand, shows the transverse profile of the laser beam, which presents the intensity distribution across the transverse plane. As observed from the measurements, both beam profiles exhibit a heterogeneous nature, indicating variations in intensity across the beam's cross-section.
- [055] In this experiment, the unclaimed embodiment was employed to investigate and analyse the output characteristics of the laser beam **10**. However, the obtained longitudinal and transverse beam profiles reveal an undesired heterogeneity, indicating deviations in the beam's intensity distribution.
- [056] Inventors further conducted the measurement with the embodiment shown in **Fig. 11** and **Fig. 12**.
- [057] **Fig. 18** shows the longitudinal profile of the laser beam coupled out from the claimed embodiment illustrated in **Fig. 11**, while **Fig. 19** represents the corresponding transverse profile. From these figures, the beam's homogeneity is apparent, displaying a beam profile.

[058] Fig. 20 displays the transverse profile of the laser beam for the embodiment depicted LU505737 in Fig. 11. Comparing the results from the prior art and the present invention, a skilled person can recognize improvement in pump beam homogeneity.

[059] Accordingly, disclosure of the preferred embodiment of the invention is intended to be illustrative, but not limiting, of the scope of the invention which is set forth in the following claims.

1. An end-pumped system for pumping a laser active medium (4) comprising
 - a laser diode stack (1) emitting an optical beam, wherein the laser diode stack (1) is provided with a collimator;
 - a lens duct (2) having an input side (21) and an output side (22), wherein surface of input side (21) and surface of output side (22) are flat; and wherein the lens duct is tapered away from the input side (21) to the output side (22); and wherein
 - the input side (21) of the lens duct (2) covers whole area of the diode stack (1), wherein the lens duct (2) is coupled to the input side (21); and wherein the system further comprising
 - a laser active medium (4), wherein an active media (4) input is coupled to the lens duct's (2) output side (22) **characterized in that**
 - the collimator is a fast axis collimator (5); and wherein
 - an incident angle Θ_{in} of the optical beam coupled into the lens duct (2) is within the range defined by equation

$$\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out},$$

wherein l_{in} is transverse distance of an edge of the input side (21), and l_{out} is transverse distance of an edge of the output side (22), and Θ_{out} is a output angle of the optical beam outputting the lens duct (2), wherein the output angle Θ_{out} is defined by inequation

$$\theta_{out} \leq \frac{n_2}{n_1} \sin(\pi - \sin^{-1}(\frac{n_1}{n_2}) + \theta_{tp}),$$

wherein n_1 is a refractive index of the surrounding area; n_2 is a refractive index associated with the material properties of the lens duct (2); and θ_{tp} is a taper angle of the lens duct (2).

2. The system according to claim 1, wherein the laser diode stack (1) is square shaped; fast axis divergence angle of the optical beam is substantially the same as slow axis divergence angle.

3. The system according to claim anyone of the previous claims, the optical beam in its fast axis is positively defocused.
4. The system according to claim 1 or 2, wherein the optical beam in its fast axis is negatively defocused.
5. The system according to claim anyone of the previous claims, wherein the lens duct (2) is having side surfaces preventing escaping the pump beam (51 and 52) from the lens duct (2) sides by total internal reflection.
6. The system according to claim anyone of the previous claims, wherein the laser diode stack comprises a plurality of laser bars comprising a plurality of laser diodes emitting the optical beam, wherein each laser bar is equipped with a bar of fast axis collimator.
7. The system according to anyone of the previous claims further comprising an un-doped crystal or glass rod positioned between the laser duct and the active medium.
8. The system according to claim 7, wherein the un-doped crystal of glass rod is attached to the active medium.
9. The system according to claim anyone of the previous claims, wherein the lens duct comprises an antireflective coating on input side (21) and/or output side (22).
10. The system according to claim anyone of the previous claims, wherein the active medium or the un-doped crystal or glass rod comprises a dichroic coating on a side for coupling in the optical beam from the lens duct, wherein the dichroic coating is configured to transmit the optical beam having an excitation wavelength and/or reflect the optical beam having the lasing wavelength.
11. The system according to claim anyone of the previous claims, wherein the material of the lens duct (2) is glass, in particular borosilicate crown glass, fused silica; or calcium fluoride; or zinc selenide; or germanium; or undoped YAG; or polymethyl methacrylate; or sapphire.
12. The system according to anyone of the previous claims, wherein the input side of the laser duct is square or polygonal; cylindrical or rounder and output side of the laser duct is circular; or square; or polygonal, in particular hexagonal; octagonal.
13. A solid state laser pumped by a diode stack comprising the end-pumped system according to anyone of the preceding claims.

14. Use of the system according to anyone of the claims 1 – 12 as a part of laser amplifier. LU505737

15. Use of the system according to anyone of the claims 1 – 12 as a part of laser oscillator.

1. Ein endgepumptes System zum Pumpen eines laseraktiven Mediums (4) umfassend

einen Laserdiodenstapel (1), der einen optischen Strahl emittiert, wobei der Laserdiodenstapel (1) mit einem Kollimator versehen ist;

einen Linsenkanal (2) mit einer Eingangsseite (21) und einer Ausgangsseite (22), wobei die Oberfläche der Eingangsseite (21) und die Oberfläche der Ausgangsseite (22) flach sind; und wobei der Linsenkanal von der Eingangsseite (21) zur Ausgangsseite (22) verjüngt ist; und wobei

die Eingangsseite (21) des Linsenkanals (2) die gesamte Fläche des Diodenstapels (1) abdeckt, wobei der Linsenkanal (2) mit der Eingangsseite (21) gekoppelt ist; und wobei das System ferner umfasst

ein laseraktives Medium (4), wobei ein Eingang des aktiven Mediums (4) mit der Ausgangsseite (22) des Linsenkanals (2) verbunden ist, dadurch gekennzeichnet, dass

der Kollimator ein Kollimator der schnellen Achse (5) ist; und wobei

ein Einfallswinkel Θ_{in} des in den Linsenkanal (2) eingekoppelten optischen Strahls innerhalb des Bereichs liegt, der durch die Gleichung definiert ist

$$\theta_{in} = \frac{l_{out}}{l_{in}} \theta_{out}$$

wobei l_{in} der Querabstand eines Rands der Eingangsseite (21) ist und l_{out} der Querabstand eines Rands der Ausgangsseite (22) ist, und Θ_{out} ist ein Ausgangswinkel des optischen Strahls, der den Linsenkanal (2) verlässt, wobei der Ausgangswinkel Θ_{out} durch die Ungleichung definiert ist

$$\theta_{out} \leq \frac{n_2}{n_1} \sin(\pi - \sin^{-1}\left(\frac{n_1}{n_2}\right) + \theta_{tp})$$

wobei n_1 ein Brechungsindex der Umgebung ist; n_2 ein Brechungsindex, der mit den Materialeigenschaften des Linsenkanals (2) verbunden ist; und θ_{tp} ein Verjüngungswinkel des Linsenkanals (2) ist.

2. Das System gemäß Anspruch 1, wobei der Laserdiodenstapel (1) quadratisch geformt ist; der Divergenzwinkel des optischen Strahls in seiner schnellen Achse im Wesentlichen gleich dem Divergenzwinkel in seiner langsamen Achse ist.
3. Das System gemäß einem der vorherigen Ansprüche, wobei der optische Strahl in seiner schnellen Achse positiv defokussiert ist.
4. Das System gemäß Anspruch 1 oder 2, wobei der optische Strahl in seiner schnellen Achse negativ defokussiert ist.
5. Das System gemäß einem der vorherigen Ansprüche, wobei der Linsenkanal (2) Seitenflächen aufweist, die das Entweichen des Pumpstrahls (51 und 52) von den Seiten des Linsenkanals (2) durch total interne Reflexion verhindern.
6. Das System gemäß einem der vorherigen Ansprüche, wobei der Laserdiodenstapel eine Vielzahl von Laserstäben umfasst, die eine Vielzahl von Laserdioden emittieren, wobei jeder Laserstab mit einem Kollimator der schnellen Achse ausgestattet ist.
7. Das System gemäß einem der vorherigen Ansprüche, ferner umfassend einen undotierten Kristall- oder Glasstab, der zwischen dem Laserkanal und dem aktiven Medium positioniert ist.
8. Das System gemäß Anspruch 7, wobei der undotierte Kristall- oder Glasstab mit dem aktiven Medium verbunden ist.
9. Das System gemäß einem der vorherigen Ansprüche, wobei der Linsenkanal an der Eingangsseite (21) und/oder Ausgangsseite (22) eine Antireflexbeschichtung aufweist.
10. Das System gemäß einem der vorherigen Ansprüche, wobei das aktive Medium oder der undotierte Kristall- oder Glasstab eine dichroitische Beschichtung aufweist, die auf einer Seite für das Einkoppeln des optischen Strahls aus dem Linsenkanal positioniert ist, wobei die dichroitische Beschichtung konfiguriert ist, den optischen Strahl mit einer Anregungswellenlänge zu übertragen und/oder den optischen Strahl mit der Laserschwingungswellenlänge zu reflektieren.
11. Das System gemäß einem der vorherigen Ansprüche, wobei das Material des Linsenkanals (2) Glas ist, insbesondere Borosilikat-Kronglas, geschmolzenes Siliziumdioxid; oder Calciumfluorid; oder Zinkselenid; oder Germanium; oder undotiertes YAG; oder Polymethylmethacrylat; oder Saphir.
12. Das System gemäß einem der vorherigen Ansprüche, wobei die Eingangsseite des Laserkanals quadratisch oder polygonal; zylindrisch oder abgerundet ist und die Ausgangsseite des Laserkanals kreisförmig; oder quadratisch; oder polygonal, insbesondere hexagonal; oktagon ist.

13. Ein Festkörperlaser, der von einem Diodenstapel gepumpt wird, der das endgepumpte System gemäß einem der vorhergehenden Ansprüche umfasst. LU505737
14. Verwendung des Systems gemäß einem der Ansprüche 1–12 als Teil eines Laser-Verstärkers.
15. Verwendung des Systems gemäß einem der Ansprüche 1–12 als Teil eines Laser-Oszillators.

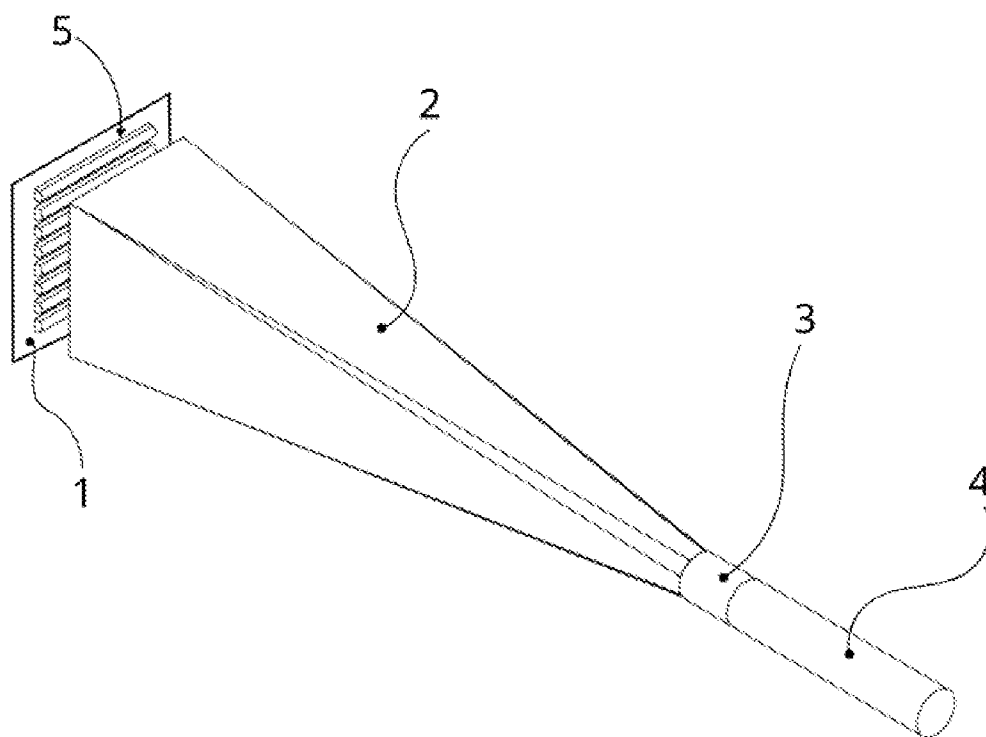


Fig. 1

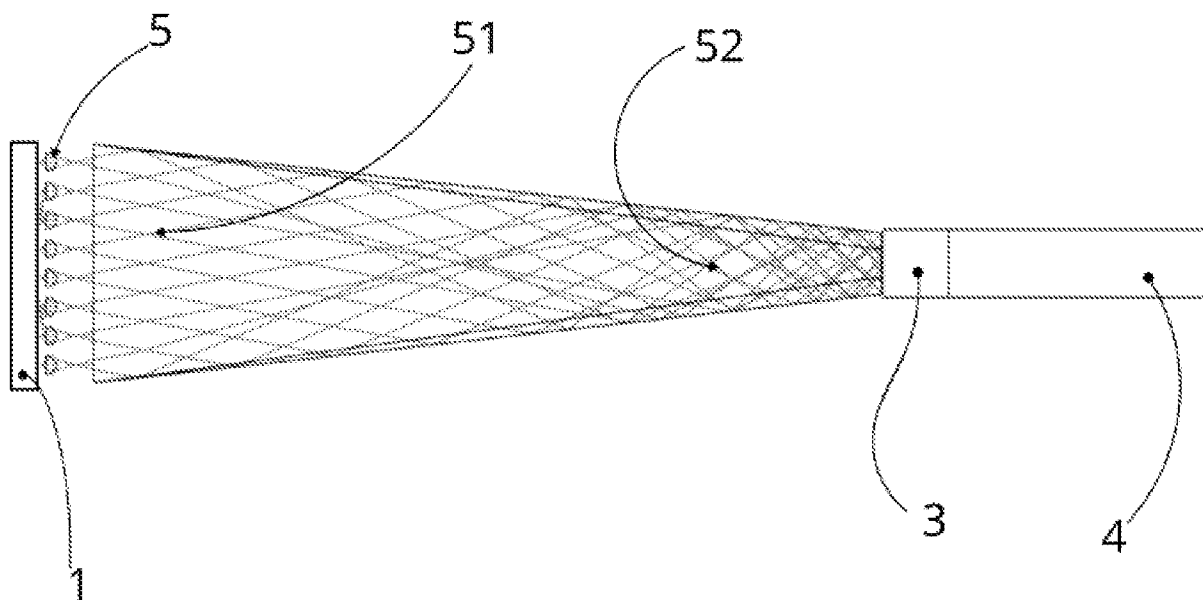


Fig. 2

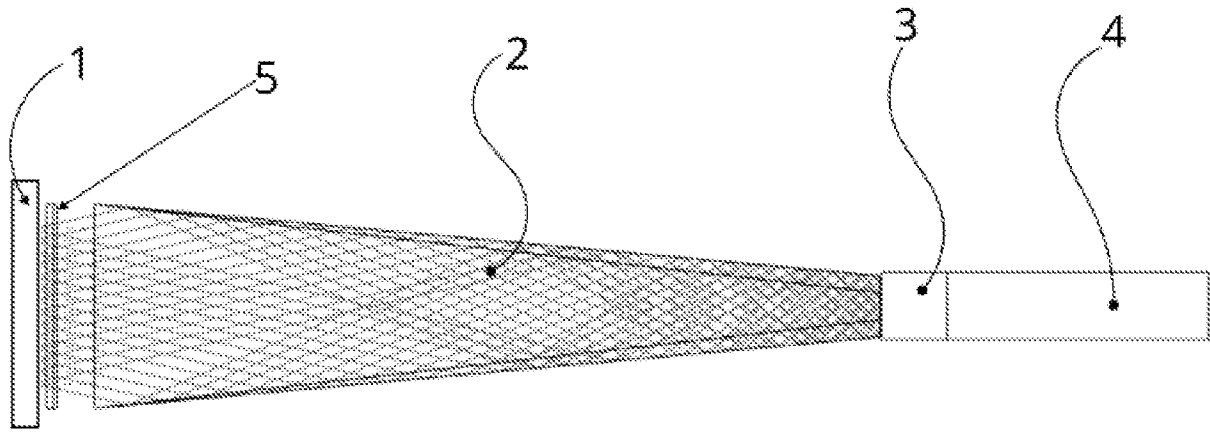


Fig. 3

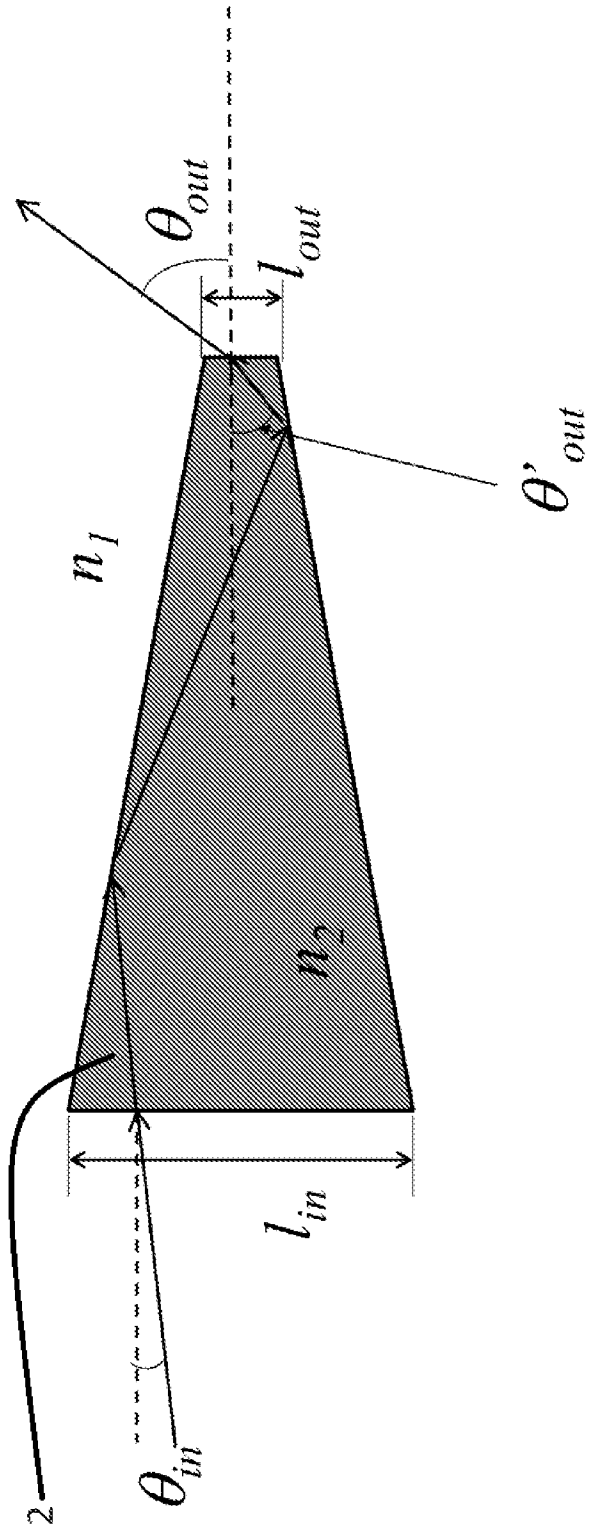


Fig. 4

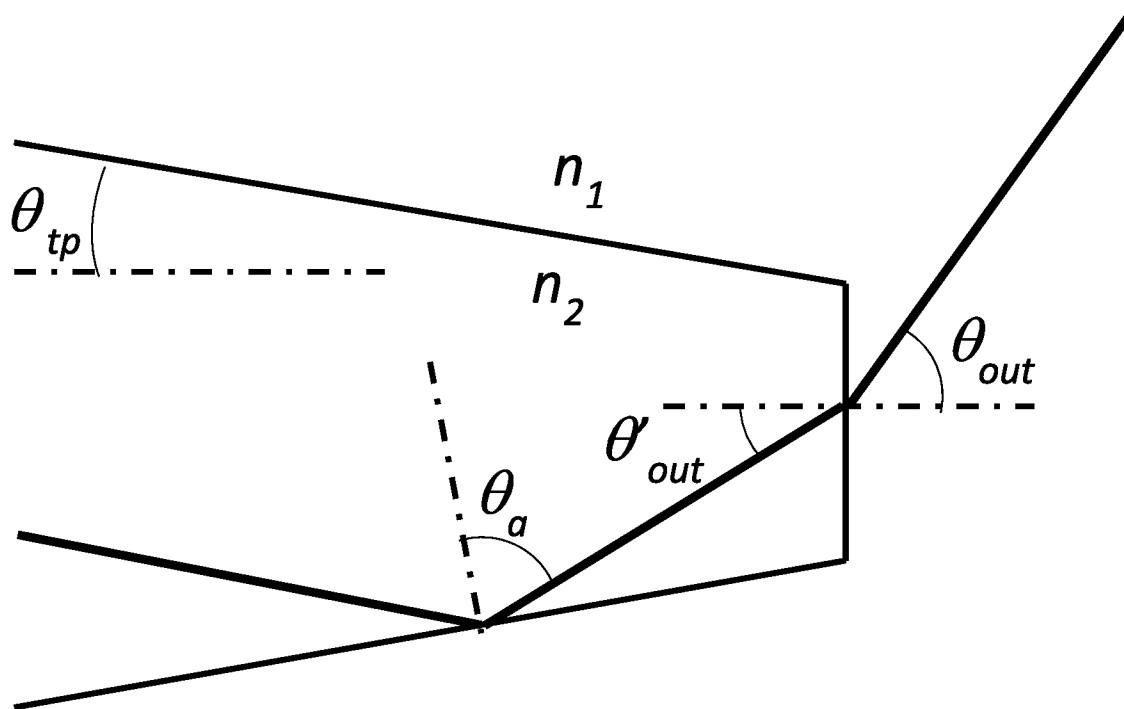


Fig. 5

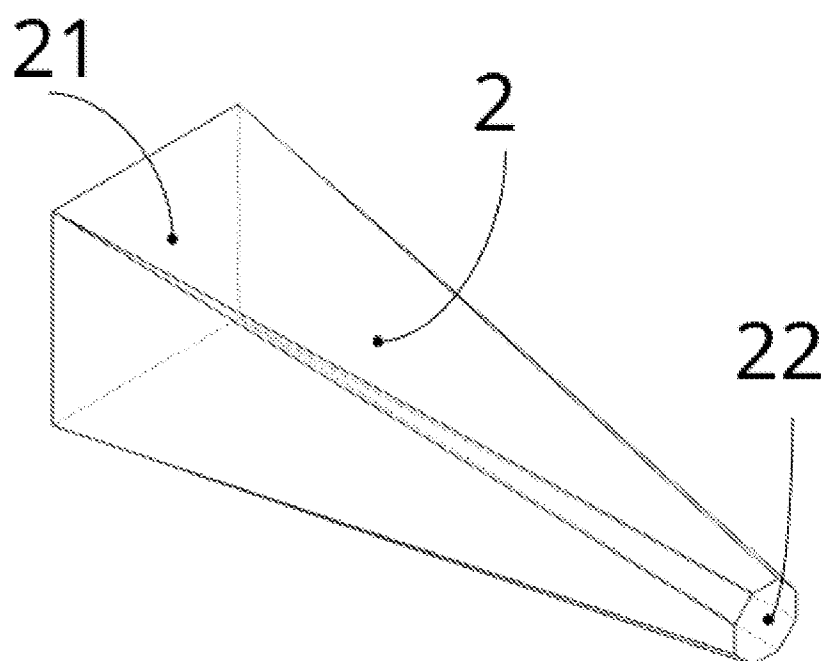


Fig. 6

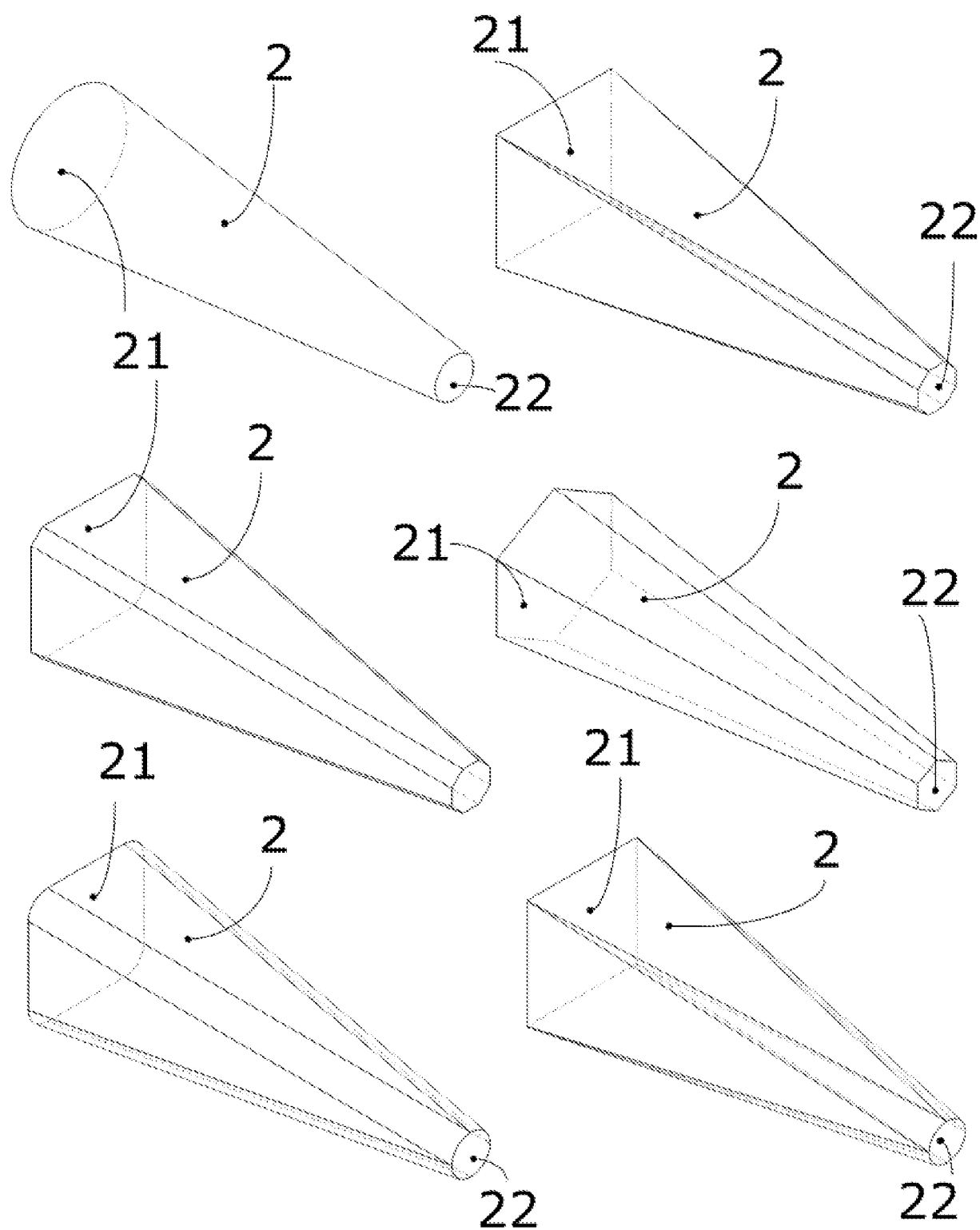


Fig. 7

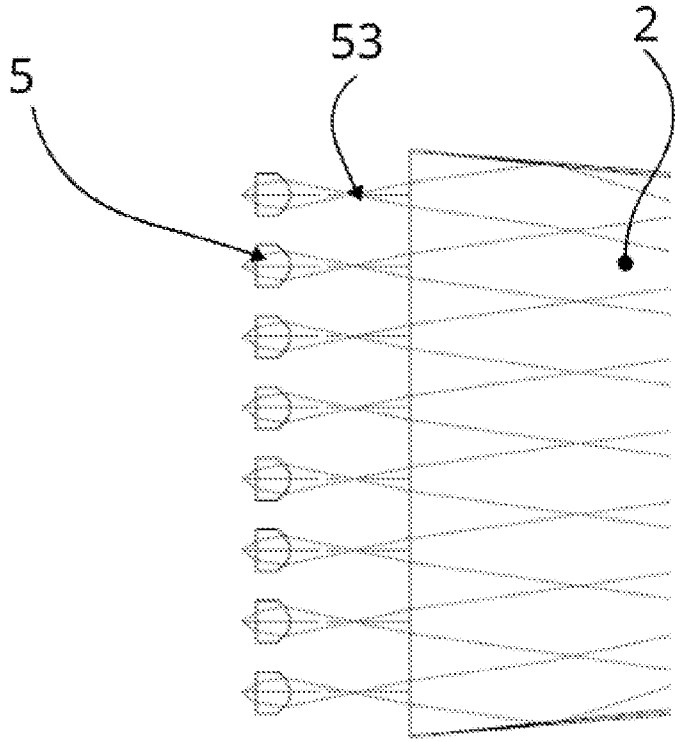


Fig. 8

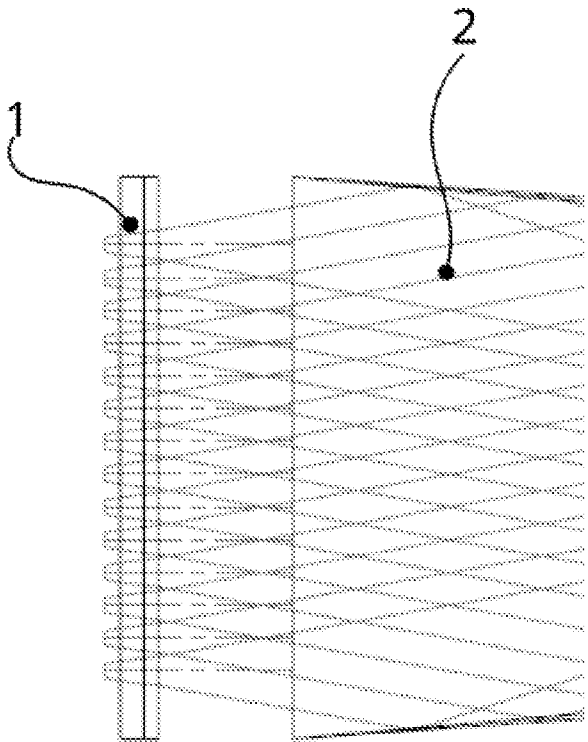


Fig. 9

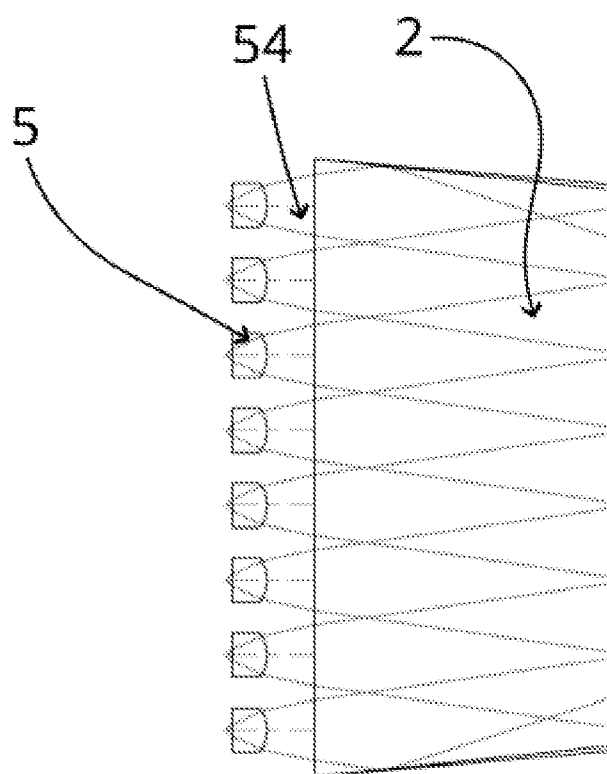


Fig. 10

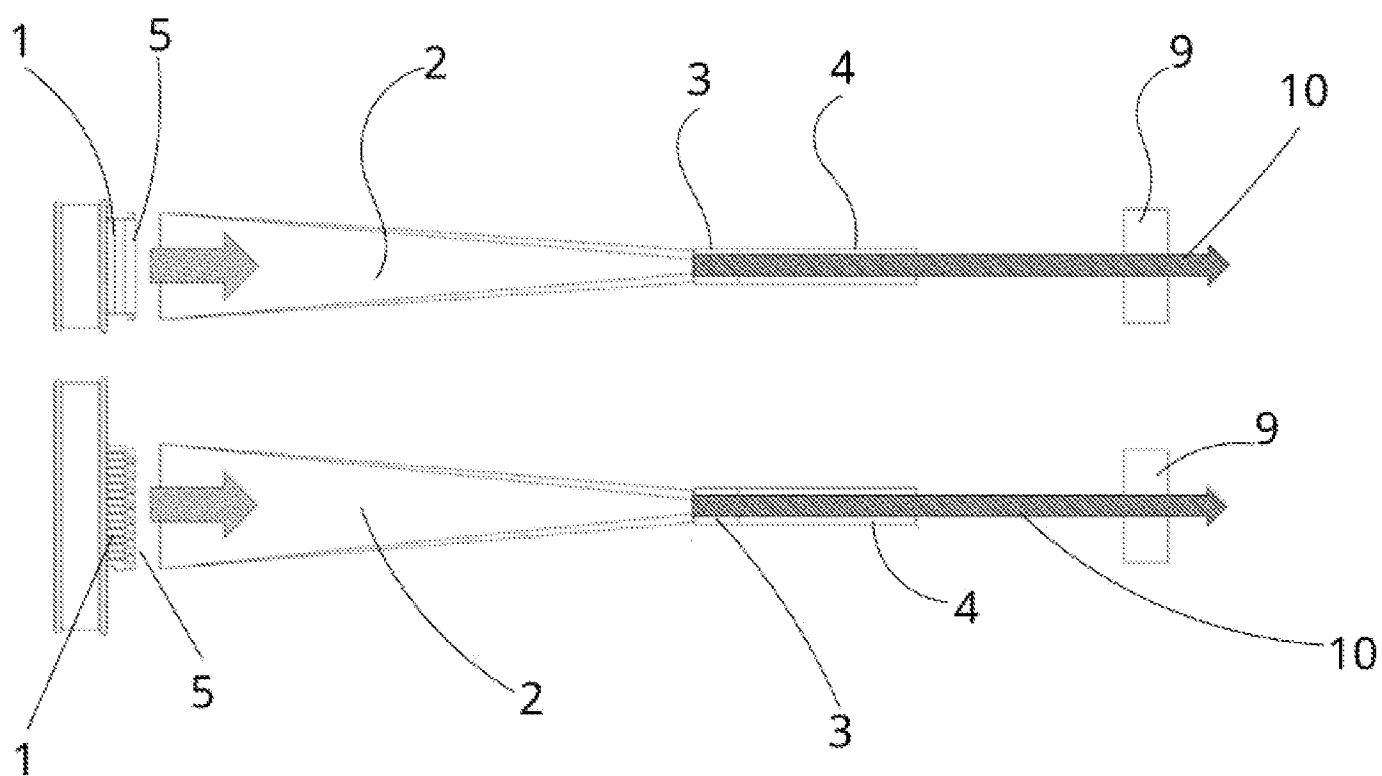


Fig. 11

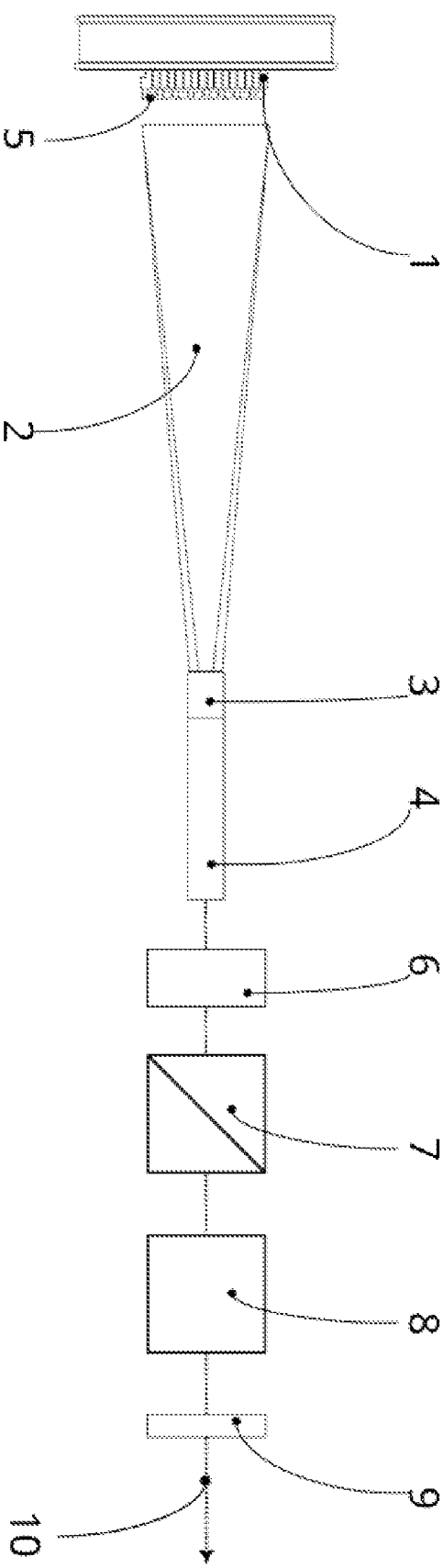


Fig. 12

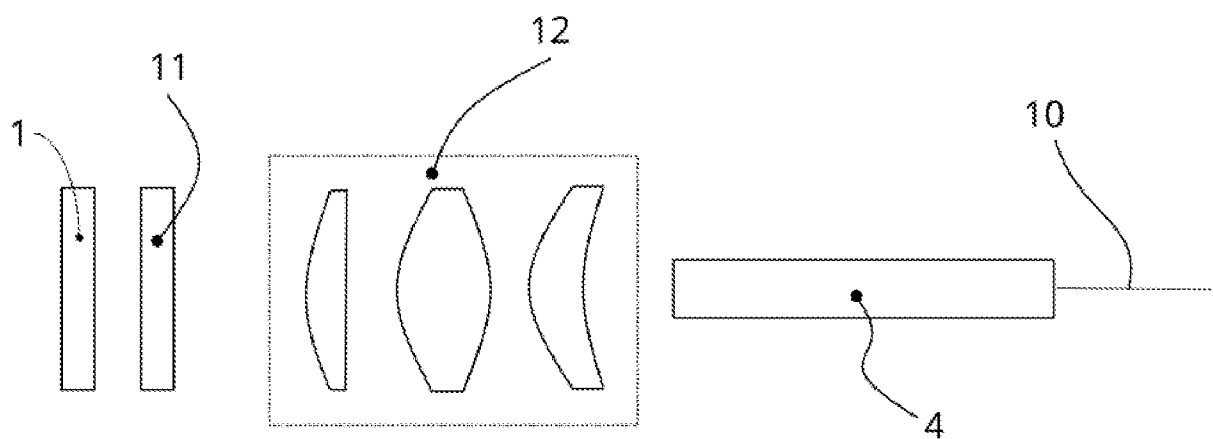


Fig. 13 (NOT CLAIMED)

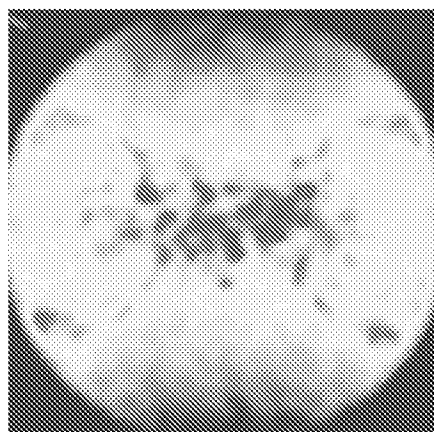


Fig. 14 (NOT CLAIMED)

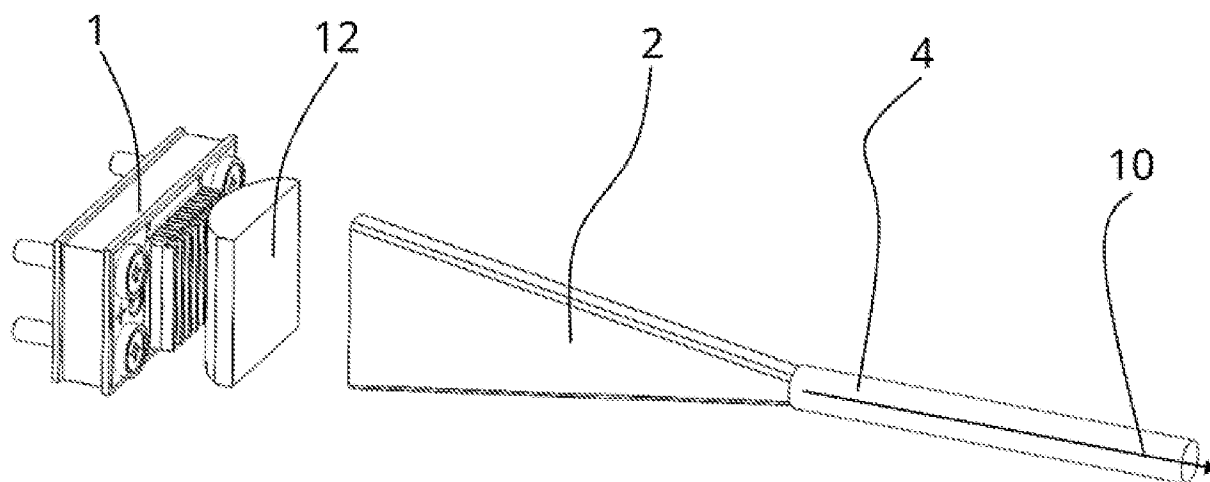


Fig. 15 (NOT CLAIMED)

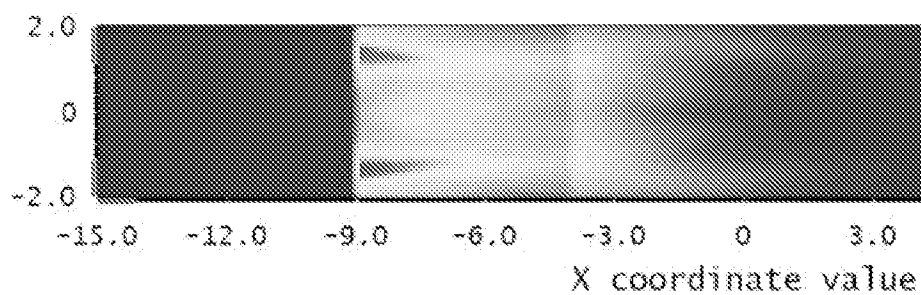


Fig. 16 (NOT CLAIMED)

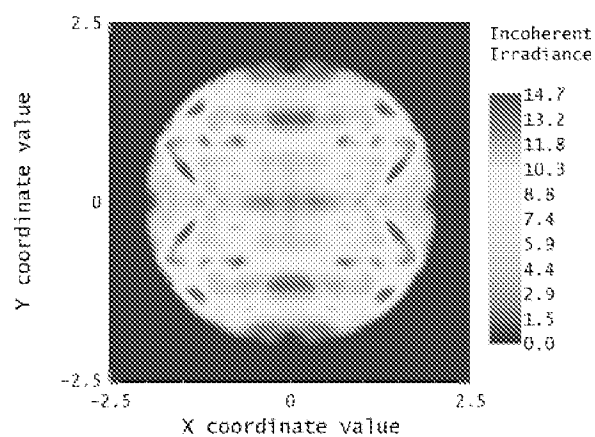


Fig. 17 (NOT CLAIMED)

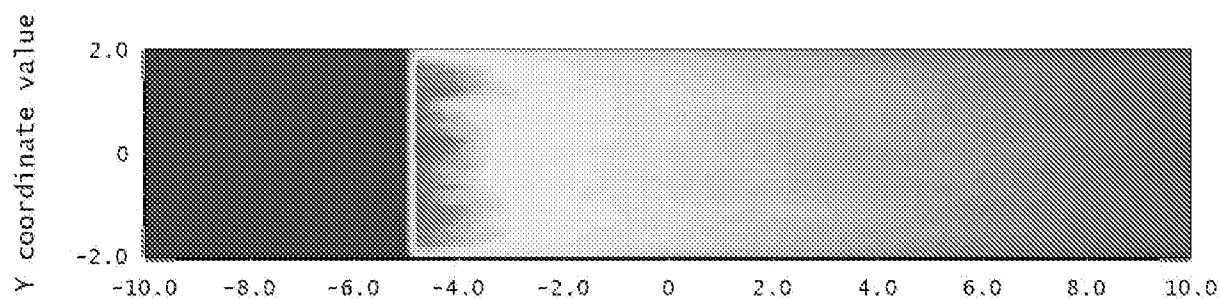


Fig. 18

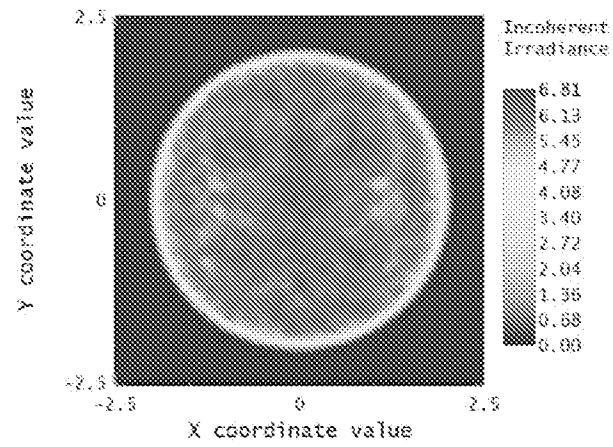


Fig. 19

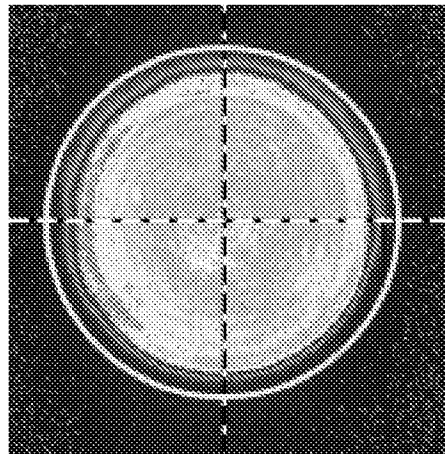


Fig. 20