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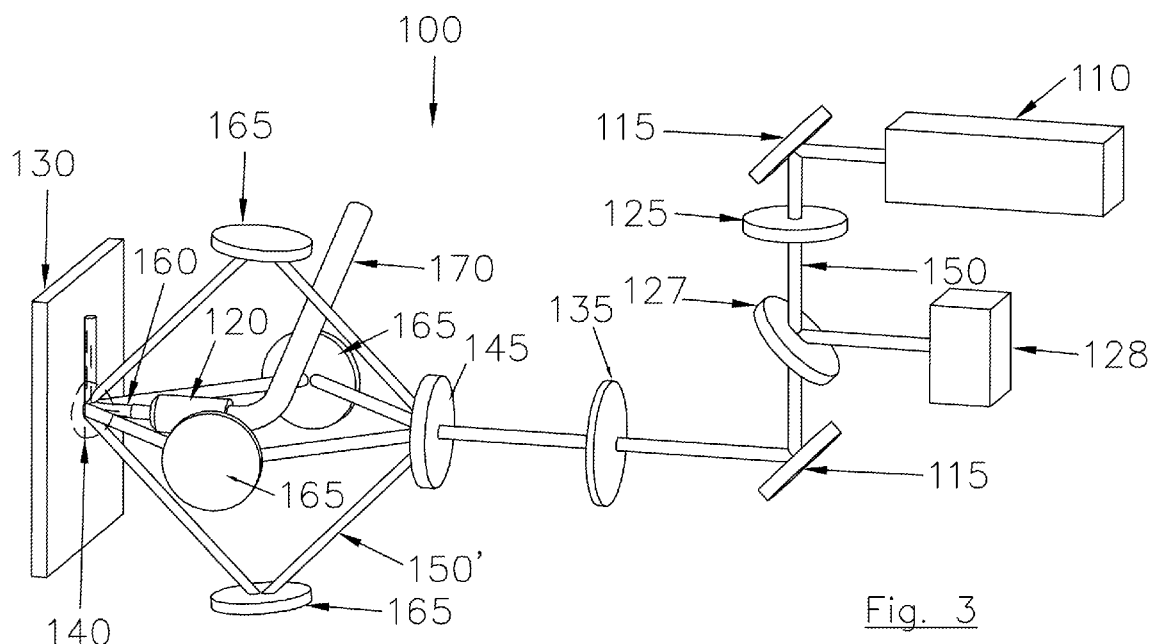


Fig. 3

(57) **Abstract:** The present invention relates to an apparatus (100) for additive manufacturing of a three-dimensional glass object. The apparatus comprises a stage (130) for supporting the glass object, a laser beam source (110) for providing a primary laser beam (150), a printer head (102), and means for relative movement of the printer head (102) and the stage (130), wherein the printer head (102) comprises at least one glass filament feeding nozzle (120) for feeding a glass filament (160) towards a location of deposit (140) in order to form the glass object, and an optical beam path unit configured for directing the laser beam (150) from the laser beam source (110) to the location of deposit (140) for heating the glass filament (160). The apparatus is characterized in that the optical beam path unit comprises a beam splitter (145) in order to divide the primary laser beam (150) into at least three partial laser beams (150'), wherein the optical beam path unit is configured for directing each of the at least three partial laser beams (150') from the beam splitter (145) to the location of deposit (140), and a feed-back control unit comprising means for monitoring a process parameter that is representative for the temperature at the location of deposit (140) and means for controlling the power of the primary laser beam (150) in order to adjust

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the temperature at the location of deposit (140) towards a predetermined level.

APPARATUS FOR ADDITIVE MANUFACTURING

Technical field of the Invention

The present invention relates generally to the field of additive manufacturing. In particular,
5 the present invention relates to an apparatus for additive manufacturing for forming three-dimensional component/objects from a feedstock of glass material onto a stage. The term "stage" as used herein comprises any element/body/support onto which the glass object may be printed directly or indirectly.

The present invention relates especially to an apparatus for additive manufacturing of a
10 three-dimensional glass object, wherein the apparatus comprises a stage for supporting the printed glass object, a laser beam source for providing a primary laser beam, a printer head, and means for relative movement of the printer head and the stage. The printer head comprises at least one glass filament feeding nozzle for feeding a glass filament towards a location of deposit in order to form the glass object, and an optical beam path unit configured for directing the laser
15 beam from the laser beam source to the location of deposit for heating/melting the glass filament.

Background of the Invention

In glass three-dimensional printing or glass additive manufacturing, the existing
20 technologies include (1) hot glass extruding from a furnace, (2) glass rods deposition, (3) stereolithography/ink-jetting with glass-polymer mixed solution, and (4) glass filament deposition.

Technology (1). In US10464305B2 and US10266442B2 a large crucible is used to pour out liquid glass onto a build plate/stage in a predetermined geometry using translation stages. The drawback of this method is the risk of nozzle damage by the molten glass and is therefore limited
25 to multicomponent silicate glasses such as soda-lime glass or borosilicate glass having a lower melting temperature. The layer thickness is about 10 mm, thus this technique is only applicable in large size printing with relatively poor resolution. The energy consumption is the highest among all the existing technologies.

Technology (2). In US2020/0070415A1 and WO2020/167470A1 continuous filament
30 feeding for glass 3D printing. The printing uses glass rods larger than 1 mm in diameter as raw material. Feeding rods are fed through a printing head and deposited on a substrate. Unable to print glass at temperature higher than 1700 °C, limits material selection. The problem with this system is the risk of nozzle damage by molten glass, the printing volume is limited by the glass rod volume, the gaps between fed rods lead to inhomogeneous print quality and the setup is
35 considered to be of high mechanical complexity.

Technology (3). In US2020/0039868A1, WO2017/214179A1 and WO2020/118157A1 glass powder is mixed with liquid polymer. In the printing process, firstly a 3D green body is created by means of a polymer 3D printer. The green body is then subjected to a de-binding process that

results in a porous body of pure glass. The porous body is sintered to finally form a “dense” glass object. The glass content in the original mixture is low. Therefore, the technique can only create models commonly smaller than 10 mm because of the large volume shrinkage. Thereto, the entire process takes several days and an energy intensive furnace is required for de-binding and sintering. The printing quality is poor due to the uneven shrinkage during sintering.

(4) Laser based melting of thin glass filaments or optical fibers have also been used for glass 3D printing, see [J. M. Hostetler et al., FIBER-FED PRINTING OF FREE-FORM FREE-STANDING GLASS STRUCTURES, Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International, 994-1002] and [T. Grabe, et al., Additive Manufacturing of fused silica using coaxial laser glass deposition, experiment, simulation and discussion, Proc. SPIE 11677, Laser 3D Manufacturing VIII, 116770Z (8 March 2021)]. Using a laser, non-contact heating is achieved meaning that no glass melt is in contact with the walls of a crucible, thereby avoiding crucible corrosion and contamination of the glass melt. Here the silica glass fiber/filament is continuously fed into a location of deposit, or hot-zone, having temperatures sufficient to soften the glass. For silica glass (quartz- or fused-silica) temperatures in the range 1800 to 2000 °C is required.

However, in [J. M. Hostetler et. al.] only one laser beam is used to soften/melt the glass filament. Such asymmetric heating significantly limits the directional printing capability. Thereto inhomogeneous temperature gradient in the molten glass filament can result in high residual stress in the printed object that may lead to material failures and interruption of the printing process. This technique uses bare glass filament printing, which means that before the printing/deposit of the glass filament any coating needs to be removed/stripped from the glass filament. Stripping off the coating can be performed using mechanical or chemical means (e.g. using sulfuric acid, dichloromethane, etc.) before the glass filament is fed into the hot-zone/location of deposit. However, such approach causes the glass filament to be left unprotected during the last stage of the printing process, i.e. during the mechanical feeding of the glass filament into the hot-zone. Stripping the coating may further weaken the mechanical strength of the glass filament, this is not an ideal solution as filament breakage during printing will cause major interruption of the printing process. Using chemical means is not preferred due to risks involved when using strong acid (sulfuric acid) or dichloromethane (carcinogenic). The stripping process also limits the total length of the printable glass filament, i.e. maximum mechanical stripping is less than a few meters, maximum chemical stripping is usually less than 50 meters, which severely limits the continuity and capability (volume) of the 3D printing process.

In [T. Grabe, et. al.] one primary laser beam is split into four sub laser beams that are directed to the hot-zone from different directions. However, the quality of the sub laser beams is poor as they are not uniform Gaussian laser beams as the primary laser beam. Thereby, the inhomogeneous heating problem still exists. According to this method, coated glass filament is used. The coating is burnt off from the glass filament near the hot-zone, i.e. the hot-zone itself can be used to remove the coating. A problem with said method with commonly used fiber

coatings is that it may cause unwanted combustion by-products, thereby more likely to leave residues affecting the purity of the printed object. Another issue is that the coating can ignite and start to burn off long lengths of filament even after the heat source is turned off. Therefore, process gas is needed to suppress coating combustion. To burn off the coating, excessive energy is needed which cause massive glass vaporization during printing.

Glass vaporization is very common and hard to eliminate during laser-based 3D glass printing. The vaporization creates unwanted fume silica particles which will attach to surrounding surfaces, such as nozzles and mirrors. The existence of fume silica particles raises the risk of optics contamination and damage in the system. The control of vaporization rate, i.e. temperature at the location of deposit, and the control of process fumes are critical.

Thus, there is still a great need within the field of additive manufacturing to provide an additive manufacturing method/apparatus for printing glass objects, wherein a stable/correct temperature at the entire location of deposit (hot zone) is obtained in order to obtain printed glass objects without detrimental defects, and wherein the apparatus is not limited to any specific printing direction regarding the relative movement of the stage and the printer head.

Object of the Invention

The present invention aims at obviating the aforementioned disadvantages and failing of previously known methods/apparatus for additive manufacturing of three-dimensional glass objects, and at providing an improved apparatus. A primary object of the present invention is to provide an improved apparatus for additive manufacturing of three-dimensional glass objects of the initially defined type that ensure stable/correct temperature at the entire location of deposit (hot-zone) in order to obtain printed glass objects without detrimental defects.

It is another object of the present invention to provide an improved apparatus for additive manufacturing of three-dimensional glass objects that has no limitation to any specific printing direction regarding the relative/mutual movement of the stage and the printer head.

Summary of the Invention

According to the invention at least the primary object is attained by means of the initially defined apparatus having the features defined in the independent claim. Preferred embodiments of the present invention are further defined in the dependent claims.

According to the present invention, the optical beam path unit comprises a beam splitter in order to divide the primary laser beam into at least three partial laser beams, wherein the optical beam path unit is configured for directing each of the at least three partial laser beams from the beam splitter to the location of deposit, and comprises a feed-back control unit comprising means for monitoring a process parameter that is representative for the temperature at the location of deposit and means for controlling the power of the primary laser beam in order to adjust the temperature at the location of deposit towards a predetermined level.

Thus, the present invention is based on the insight of the inventors that a stable/correct temperature at the entire location of deposit (hot-zone) is the single most important factor to be able to obtain printed glass objects without detrimental defects. Thereto the present invention is based on the insight of the inventors that a stable/correct temperature is dependent on at least, the power of the primary laser beam, the direction of incidence of the laser beam, and the location of the focal point of the laser beam in relation to the location of deposit.

One direct advantage of having the primary laser beam divided into at least three partial laser beams is that the multiple laser beams may be provided symmetrically around the glass filament (location of deposit) which provides an even temperature, decreased melting/softening time and also increased heating efficiency.

According to various embodiments of the present invention, said process parameter representative for the temperature at the location of deposit is constituted by the power of the primary laser beam upstream the beam splitter in the printer head. Thereby it is easy to have a clear relationship between the measured power of the primary laser beam and the control of the power of the primary laser beam generated in the laser beam source.

According to various embodiments of the present invention, the means for monitoring the process parameter constituted by the power of the primary laser beam comprises a beam tap configured for separating a predetermined sample of the primary laser beam towards a detector/power meter. Thereby the power of the non-redirectioned part of the primary laser beam is determined using simple mathematics, wherein the power of the primary laser beam is proportional to the temperature at the location of deposit.

According to various embodiments of the present invention, the optical beam path unit comprises means for providing circular polarization to the primary laser beam upstream the beam splitter. Thereby the laser beam source used may be of less expensive and complicated nature, i.e. any negative effect originating from possible unstable polarization of the laser beam source is decreased/removed.

According to various embodiments of the present invention, the optical beam path unit comprises a pyramid mirror located downstream the beam splitter in order to diverge the at least three partial laser beams from each other. According to various embodiments, the optical beam path unit comprises for each partial laser beam one or more secondary beam steering mirror(s) configured for directing the partial laser beam towards the location of deposit. Thereby, the length of the beam paths may be decreased and thereby any negative effect coming from possible unstable wavelength of the primary laser beam are decreased/removed.

Further advantages with and features of the invention will be apparent from the other dependent claims as well as from the following detailed description of preferred embodiments.

Brief description of the drawings

A more complete understanding of the abovementioned and other features and advantages of the present invention will be apparent from the following detailed description of preferred embodiments in conjunction with the appended drawings, wherein:

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- Fig. 1 is a schematic illustration of a PRIOR ART apparatus for additive manufacturing of three-dimensional glass objects,
- Fig. 2 is a schematic illustration of an inventive apparatus for additive manufacturing of three-dimensional glass objects,
- 10 Fig. 3 is a schematic perspective side view of an inventive apparatus according to a first example embodiment, disclosing the inside of the printer head,
- Fig. 4 is a schematic perspective side view of an inventive apparatus according to a second example embodiment, disclosing the inside of the printer head,
- Fig. 5 is a schematic perspective side view of an inventive apparatus according to a variant
- 15 of the first example embodiment, disclosing the inside of the printer head,
- Fig. 6 is a schematic perspective side view of an inventive apparatus according to a third example embodiment, disclosing the inside of the printer head,
- Fig. 7 is a schematic perspective side view of an inventive apparatus according to a variant of the third example embodiment, disclosing the inside of the printer head,
- 20 Fig. 8 is a schematic side view of a glass filament and a filament feeding nozzle, and
- Figs. 9a-9c are schematic illustrations of various example embodiments of a glass filament.

Detailed description of preferred embodiments of the invention

The invention herein refers to the field of additive manufacturing (AM) of three-

25 dimensional glass objects using a digital/computer model, i.e. a component/object geometry is built by fusing glass filaments/fibers that are melted layer-by-layer or in batches of layers using an energy source such as a laser beam through either selective melting or simple scanning of the printed profile following the fusion process.

Reference is initially made to figure 1, disclosing a prior art apparatus for additive

30 manufacturing of three-dimensional glass objects. The apparatus comprises a stage 130, a laser beam source 110 providing a laser beam 150 and a glass filament feeding nozzle 120 providing a glass filament 160 having a coating 169 to a location of deposit 140, wherein the filament feeding nozzle 120 is part of or constitutes a printer head. The glass filament feeding nozzle 120 and the stage 130 are configured for relative/mutual movement in order to apply a layer/string of glass

35 material to the glass object at the location of deposit 140, also called the hot-zone. The glass filament 160 may be fed to the glass filament feeding nozzle 120 via a tube 170. This is also applicable to the invention.

Reference is now made to figure 2, disclosing a schematic illustration of the inventive apparatus for additive manufacturing of three-dimensional glass objects, wherein the apparatus is generally designated 100. The apparatus 100 comprises a stage 130 for supporting the glass object, a laser beam source 110 for providing a primary laser beam 150 and a printer head 102.

5 The term stage 130 as used herein comprises any element/body/support onto which the glass object may be printed directly or indirectly, for instance via a build plate/object connected to the stage 130. Thus, a build plate/object may be connected to the stage 130 wherein the glass object is printed on the build plate/object and still considered supported by the stage 130. The build plate/stage may be made of any material, e.g. the same material as the final three-dimensional
10 glass component/object, a ceramic material or any other metallic material which is different from the material of said three-dimensional glass object/component. Hereinbelow the use of the term stage 130 shall be understood as also comprising build plate, component, object, etc., if nothing else is mentioned.

The printer head 102 and/or the stage 130 may be mounted on a robot, such as an
15 articulated robot with one or more rotary joints, a cartesian robot having linear axes, a cylindrical robot having one rotary axis and two linear axes, or a combination thereof. Thus, the apparatus 100 comprises means for relative/mutual movement of the printer head 102 and the stage 130, i.e. a motorized support. Thereby, one or both of the printer head 102 and said stage 130 may be displaceable in a direction perpendicular to a surface of said stage 130, or to a predetermined
20 geometrical plane, in order to allow for additive manufacturing of the three-dimensional glass component/object and for keeping a distance between the printer head 102 and a top surface of the stage or component/object to which a new layer is to be attached at a constant distance, i.e. for every new applied layer the stage 130 may be moved backwards (away from the printer head 102) a distance corresponding to the thickness of new applied layer or the printer head 102 may
25 be moved away from the stage 130 with a distance corresponding to the thickness of new applied layer or a combination of movement of said stage 130 and said printer head 102 in order to keep the distance between the printer head 102 and a top surface of the stage or component/object to which a new layer is to be attached constant.

A control unit may control the relative movement of said printer head 102 in relation to
30 the stage 130. The printer head 102 may be configured to move in a plane essentially in parallel and relative to said stage 130 so that said printer head 102 covers a predetermined area of said stage 130. The stage may be arranged in a vertical direction, or any other direction. The relative movement may be that said stage 130 is fixed and said printer head 102 is moving in said plane. In an alternative embodiment the stage 130 is moving while said printer head 102 is fixed for
35 covering the full stage 130. In yet an alternative embodiment both the stage 130 and said printer head 102 is movable in said plane for allowing said printer head 102 to cover the full area of said stage 130. The printer head 102 and/or the stage 130 are preferably also tiltable in relation to

each other, in order to be able to print new layers that are not necessarily parallel to the other layers.

The laser beam source 110 may be directly mounted to the printer head 102, i.e. connected as one unit, or may be separated from the printer head 102. According to various
5 embodiments wherein the laser beam source 110 is separated from the printer head 102, the apparatus 100 may comprise free space optics to direct the primary laser beam 150 from the laser beam source 110 to the printer head 102, i.e. naked laser beam, or may comprise opto-mechanical directing means, i.e. unexposed laser beam, or may comprise glass fiber/laser guide directing means, i.e. flexible fiber, or combinations thereof. The printer head 102 may print in any
10 direction, i.e. vertical, horizontal, from above, from below, tilted at any degree, etc., and the stage 130 may be oriented in any direction.

Reference is now made to figure 3, disclosing a first example embodiment of the inventive apparatus 100 for additive manufacturing of three-dimensional glass objects. The housing of the printer head 102 is removed. The printer head 102 comprises a glass filament feeding nozzle 120,
15 configured to feed and direct the glass filament 160 towards the location of deposit 140, also known as hot-zone. The glass filament 160 may be fed to the filament feeding nozzle 120 via a flexible tube 170. The laser beam source 110 may be a CO₂-laser, CO-laser, Nd:YAG laser, fiber laser, excimer laser, nitrogen laser, or the like. The laser beam 150 is continuous or pulsed or combination thereof. The laser beam 150 softens or melts the glass filament 160 at the location of
20 deposit 140 in vicinity to the stage 130 or component/object onto which said glass filament 160 is to be attached.

By providing the stage 130 in a vertical direction as disclosed in figure 3, it is ensured that any fumes from e.g. combustion by-products of coating material or vaporized/molten glass (fume silica particles due to overheating) moves upwards rather than towards the inside of the printer
25 head 102. This is beneficial as such fumes otherwise could damage the printer head 102 optics and glass filament feeder nozzle 120, requiring frequent cleaning or part-replacement. Also, by said vertical arrangement of said stage 130 the relative movement of the printer head 102 and said stage 130 may be performed so that any fumes and gaseous material exiting from said hot-zone is configured to be out of the optical path of the laser beam and thereby improving the
30 performance of the additive manufacturing apparatus 100. The present invention is not limited to vertical orientation of the stage 130.

During additive manufacturing the glass filament, i.e. the feedstock material, is fused/deposited onto the stage 130 or object. The filament feeding nozzle 120 locally deposits the glass filament along a predefined path, provided from a sliced computer model. The filament
35 feeding nozzle 120 may pre-heat the glass filament before it leaves the nozzle 120 on its way towards the stage 130. The filament feeding nozzle 120 may be adapted to the size and shape of the glass filament, but may also be configured to be able to feed different glass filaments having different dimensions/diameters. Thus, a gap may be present between the glass filament 160 and

the glass filament feeding nozzle 120, wherein fume silica particles must not enter such gap. In figure 3 only one glass filament 160 is fed to the stage 130, but according to various example embodiments, multiple glass filaments 160 having the same of different shapes and/or material compositions/colors may be fed sequentially through the single filament feeding nozzle 120 in order to perform multi-material deposition. In figure 3 only one filament feeding nozzle 120 is used, but according to various example embodiments multiple filament feeding nozzles may be used located beside each other, more or less oriented in parallel to each other, such that the glass filaments 160 are directed to the same location of deposit 140. According to various example embodiments multiple strings of glass filament 160 may be provided to the stage 130 simultaneously in order to provide a three-dimensional glass component of different materials/colors. Different layers of the three-dimensional component may comprise different materials and/or different positions within a single layer may comprise different materials, i.e. a multi-material deposition may be made within a layer and/or in different layers.

Figure 3 disclose a schematic side view of an example embodiment of an additive manufacturing apparatus 100 according to the present invention which is configured to manufacture three-dimensional glass objects. Said apparatus 100 comprises the stage 130, the laser source 110 and the printer head 102 having the filament feeding nozzle 120. Thereto the printer head 102 comprises an optical beam path unit configured for directing the laser beam 150 from the laser beam source 110 to the location of deposit (hot-zone) 140 for heating the glass filament 160 and the area of the stage 130 or object that the glass filament 160 shall attach/adhere to. The optical beam path unit may be based on techniques using reflection and/or transmission optics.

The optical beam path unit comprises a beam splitter 145 in order to divide the primary laser beam 150 into at least three partial laser beams 150'. The optical beam path unit is configured for directing each of the at least three partial laser beams 150' from the beam splitter 145 to the location of deposit 140. Figure 3 disclose use of four partial laser beams 150'. The at least three partial laser beams 150' are used to heat the glass filament 160 at the location of deposit 140 by directing the at least three partial laser beams 150' on the location of deposit 140. The laser beam source 110 may be operating in a wavelength region where the glass filaments 160 have high optical absorption, which when irradiated by said laser beam 150 results in melting/softening of the glass filament 160.

Thus, the beam splitter 145 is used to be able to have multiple partial laser beams 150' directed towards the location of deposit 140 from different directions and thereby obtaining an even temperature in the entire location of deposit (hot-zone) 140, independent on the direction of the relative movement of the printer head 102 and the stage 130.

The glass filament feeding nozzle 120 is configured for feeding the glass filament 160 in a direction perpendicular to a geometrical plane, wherein the geometrical plane is preferably the plane onto which the layer being printed, wherein each of the at least three partial laser beams

150' has an angle of incidence in the range 30-60 degrees in relation to said geometrical plane, preferably in the range 40-50 degrees and most preferably about 45 degrees. The optical beam path unit is configured to direct the partial laser beams 150' towards the location of deposit 140. Said geometrical plane is usually parallel to the stage 130. The geometrical plane may be spherical or non-flat.

Silica and silica-based glass filament have a strong absorption at wavelengths above 2.2 μm . Irradiating a glass filament 160 using a CO₂-laser (typically operating in the 9.2-10.6 μm wavelength region) or a CO-laser (operating at 5.5 μm wavelength region) results in strong absorption of radiation leading to subsequent heating of the glass filament 160. A CO₂-laser operating at a wavelength of 10.6 μm may be used. At this wavelength silica glass is opaque, resulting in efficient heating. The absorption depth is approximately 2 μm to 40 μm and is efficient for heating glass filaments 160 having a diameter in the area 100-300 μm . For larger glass filaments the shallow penetration depth at 10.6 μm makes it difficult to heat rapidly without causing significant vaporization. Using a CO-laser operating at 5.5 μm is more suitable for glass filaments larger than approximately 0.5 mm. The penetration depth at 5.5 μm is much larger (100's of μm) resulting in more efficient energy deposition into the glass filament 160.

The optical beam path unit also comprises a feed-back control unit comprising means for monitoring a process parameter that is representative for the temperature at the location of deposit 140 and means for controlling the power of the primary laser beam 150 in order to adjust the temperature at the location of deposit 140 towards a predetermined level. The temperature at the location of deposit 140 determines the viscosity of the glass material that is deposited and has great impact on the printing result. For long-duration printing the temperature has to be well controlled over time in order to provide a high-quality printed glass object.

The predetermined temperature level may be different along a single layer of the glass object, may be different for different layers of the glass object, or a combination thereof. The predetermined temperature level is for instance dependent on the printing speed, glass filament feeding speed, the type of material at the location of deposit, i.e. stage, build plate, glass object, etc., the width and/or thickness of the previous layer/layers of the object, glass filament cut-off, etc. Thus, if the process parameter indicates that the temperature is too low the power of the primary laser beam 150 is increased by controlling the laser beam source 110, and vice versa. The temperature at the location of deposit 140 is proportional to the power of the primary laser beam 150.

The means for monitoring a process parameter that is representative for the temperature at the location of deposit 140, may be constituted by equipment configured to monitor black body radiation at the location of deposit 140, i.e. temperature measurement at the location of deposit 140 or adjacent the location of deposit 140, using a camera, thermal imager, pyrometer, spectral/intensity measurement of the radiation, etc., i.e. other form of in-situ non-contact temperature monitoring/measurement at the location of deposit 140.

The means for monitoring a process parameter that is representative for the temperature at the location of deposit 140, may be constituted by equipment having laser-based/ interferometric temperature measuring technique, i.e. temperature measurement at the location of deposit 140 or adjacent the location of deposit 140 using the filament itself as a Fabry-Perot type, Mach-Zehnder type interferometer, etc., i.e. other form of in-situ non-contact temperature monitoring/measurement at the location of deposit 140.

The means for monitoring a process parameter that is representative for the temperature at the location of deposit 140, may be constituted by equipment configured to separate a small sample from the laser beam to a detector/power meter and evaluate the sample, i.e. measure the power of the sample and thereby being able to determine the total power of the primary laser beam which is proportional to the temperature at the location of deposit 140. This separation of a small sample from the laser beam may be performed upstream or downstream the beam splitter 145. Examples of such means will be described in more detail hereinbelow.

The means for monitoring a process parameter that is representative for the temperature at the location of deposit 140, may be constituted by equipment based on geometrical imaging technique, i.e. the shape of the glass object and/or the shape of the glass filament at and/or near the location of deposit 140 will be different depending on the temperature at the location of deposit 140. A too high temperature, i.e. too low viscosity of the glass material, will result in poor adhesion, and a too low temperature, i.e. too high viscosity of the glass material, will result in glass filament breakage. Thus, this technique is based on the actual viscosity of the glass at the location of deposit 140, which is proportional to the temperature at the location of deposit 140.

The optical beam path unit may comprise one or more primary beam steering mirror 115 located between the laser beam source 110 and the beam splitter 145 and configured to direct the primary laser beam 150 from the laser beam source 110 to the beam splitter 145.

The optical beam path unit may comprise a focusing lens 135 located upstream the beam splitter 145 in order to focus the primary laser beam 150, i.e. control the diameter of the primary laser beam 150 and thereby the size of the hot-zone, in order to fit different diameter of the glass filament 160, and in order to compensate for beam pointing instability of the laser beam source 110. The focusing lens 135 may be fixed in relation to the beam splitter 145, or may be displaceable back and forth in relation to the beam splitter 145 in order to adjust the focus of the primary laser beam 150, i.e. adjust the diameter of the primary laser beam 150 and adjust the diameter of the at least three partial laser beams 150' and thereby adjust the size and intensity of the hot-zone, in order to modify the heating dynamics of the apparatus 100. The focusing lens 135 may be mounted on a computer controlled motorized translation stage.

According to various embodiments the apparatus 100 may comprise a focusing lens for each partial laser beam 150', i.e. downstream the beam splitter 145, in order to be able to compensate for any instability of the beam splitter 145, such as wavelength instability of the laser beam and beam pointing instability of the laser beam source 110.

When using one or more focusing lens 135 in the optical beam path unit, the power of the primary laser beam 150 may be changed since the focusing lens may be used to adjust/control the laser intensity at the location of deposit in order to achieve suitable temperature at the location of deposit.

5 The optical beam path unit may comprise means for providing circular polarization to the primary laser beam 150 upstream the beam splitter 145, in order to obtain a stable circularly polarized primary laser beam 150. A quarter-wave plate 125 may be used to generate a circularly polarized primary laser beam 150, and preferably a linear polarization unit 126 (disclosed in figure 7) is located between the laser beam source 110 and the quarter-wave plate 125 in order to have
10 best output from the quarter-wave plate 125 independently on the polarization stability of the laser beam source 110. A circularly polarized primary laser beam 150 may also be obtained using a reflective phase retarder 129 (disclosed in figure 4) instead of the quarter-wave plate 125, for instance instead of one of the primary beam steering mirrors 115. When using a reflective phase retarder 129 the direction of the linear polarization of the primary laser beam 150 has to be
15 inclined 45 degrees to the plane of incidence.

According to various embodiments, the beam splitter 145 is configured to provide uniform partial laser beams 150' having circular/near circular polarization in order to obtain even and stable temperature in the entire location of deposit 140.

Circular/near circular polarization of the laser is preferred since it is preferred to have
20 identical partial laser beams 150' downstream the beam splitter 145. If the laser beam is not circularly polarized the different partial laser beams 150' will obtain different polarization depending on the incident angle/direction and the different partial laser beams 150' will have different heating efficiency and thereby result in uneven temperature at the location of deposit.

The beam splitter 145 may be constituted by a diffractive optical element (DOE)
25 configured to divide the primary laser beam 150 into at least three, but preferably four, partial laser beams 150', wherein each partial laser beam 150' are uniform, i.e. has the same characteristics as the primary laser beam 150. Using a circularly polarized beam primary laser beam 150 ensures that the partial laser beams 150' are identical/uniform, as the DOE 145 may have polarization dependency, and thereby even and stable temperature at the location of
30 deposit is achieved.

The optical beam path unit comprise one or more secondary beam steering mirror 165 for each partial laser beam 150', in order to direct each partial laser beam 150' from the beam splitter 145 to the location of deposit 140, wherein all the partial laser beams 150' impinge at the glass filament 160 but from different directions. Each of the partial laser beams 150' should have
35 the same beam path length in order to obtain even temperature at the location of deposit 140.

The inventors have realized/discovered the importance of removing instability/variation of the wavelength of the primary laser beam 150, since instability/variation of the wavelength will provide a change in beam alignment and thereby a change in position of the hot zone and uneven

temperature at the location of deposit 140. The inventors have also realized/discovered that the diffraction angle, i.e. angle between incoming primary laser beam 150 and outgoing partial laser beam 150' at the beam splitter 145, shall be as small as possible in order to have a small as possible negative effect on the location of the focal point of the partial laser beams 150' originating from instable/varying wavelength.

More precisely, each DOE 145 has a predetermined grating frequency/density, and the greater value of the grating frequency/density the diffraction angle variation will increase more rapidly for a specific variation in laser beam wavelength. Increased diffraction angle variation entails that the location of the focal point is unstable/travels in the axial direction and thereby the temperature is unstable at the location of deposit 140.

The primary laser beam 150 naturally has varying wavelength when generated. Thereto, the change in power of the laser beam source 110, in order to obtain different preset/predetermined temperatures at the location of deposit 140 or due to feedback information confirming incorrect temperature at the location of deposit 140, will have influence on the construction of the laser beam source 110. Thus, changing equilibrium temperatures of the laser beam source 110 entails that the dimensions of the laser cavity in the laser beam source 110 will change and thereby varying wavelength of the primary laser beam 150.

According to various embodiments, see the schematic example embodiments of figures 3-7, the glass filament feeding nozzle 120 is located surrounded by the beam paths of the partial laser beams 150', i.e. surrounded by the secondary beam steering mirrors 165. In order to be able to obtain an angle of incidence in the range 30-60 degrees, and at the same time have room for the glass filament feeding nozzle 120 between the secondary beam steering mirrors 165, and thereto have a small diffraction angle, the beam path length of the partial laser beam 150' has to become relatively long (see figure 5). The longer beam path the more displacement of the focal point due to wavelength variations of the primary laser beam 150.

Thus, in such embodiments as disclosed in figure 5 the DOE 145 may be chosen to generate a small diffraction angle equal to or less than 15 degrees, preferably equal to or less than 10 degrees and most preferably equal to or less than 5 degrees, in order to have small/acceptable variations/travel of the location of the focal point.

According to various embodiments, see the schematic example embodiments of figures 6 and 7, the optical beam path unit may comprise a pyramid mirror 155 located downstream the beam splitter 145 in order to diverge/redirect the at least three partial laser beams 150' from each other more rapidly than in the figure 5 embodiment. The secondary beam steering mirrors 165 are located downstream the pyramid mirror 155. Thanks to the pyramid mirror 155 the beam path of the partial laser beams 150' are distinctly decreased, i.e. much more compact design of the printer head 102 compared to a setup without the pyramid mirror 155. Thus, the use of a pyramid mirror 155 downstream the beam splitter 145 increase the stability of the location of the focal point thanks to the shortened beam path of the partial laser beams 150'.

Thus, in such embodiments as disclosed in figures 6 and 7 the DOE 145 may be chosen to generate a larger diffraction angle, i.e. equal to or less than 45 degrees, preferably equal to or less than 30 degrees and most preferably equal to or less than 20 degrees, and still have small/acceptable variations/travel of the location of the focal point.

5 It shall be pointed out that when using a laser beam source 110 that comprises sophisticated wavelength stabilization means, such as embodiments as disclosed in figures 3 and 4 the DOE 145 may be chosen to generate a diffraction angle equal to or less than 80 degrees, thereby the use of a pyramid mirror is not necessary.

10 Examples of the means for process parameter monitoring of the feed-back control unit that is based on separation of a small sample of the laser beam will now be described in more detail, and with reference to figures 3-7.

The means for process parameter monitoring may comprise a beam tap 127 located upstream the beam splitter/DOE 145. The beam tap 127 separates a predetermined sample, for instance in the range 1-10%, of the primary laser beam 150. The beam tap 127 directs the
15 separated sample to a detector 128, such as a power meter, wherein a control unit compares the measured power of the primary laser beam 150 with a reference value. Any deviation is used to adjust/control the power of the primary laser beam 150 originating from the laser beam source 110. The beam tap 127 may have polarization dependency and different polarization will be tapped off in different amount, which will result in errors in power reading, i.e. the same total
20 power of the primary laser beam 150 will result in different power reading depending on the stability of the polarization of the primary laser beam 150. According to various embodiments of the apparatus 100 having a quarter-wave plate 125 in combination with the linear polarization means (see figure 7), the beam tap 127 may be located upstream the quarter-wave plate 125 and downstream the linear polarization means 126. According to embodiments of the apparatus 100
25 having a phase retarded mirror 129 (figure 4) or a quarter-wave plate 125 (figures 3 and 5-7), the beam tap 127 is located downstream the phase retarded mirror 129/quarter wave plate 125 and upstream the beam splitter/DOE 145. When using a quarter-wave plate 125 or a phase retarded mirror 129 in order to obtain a circularly polarized laser beam, one will also achieve blocking of laser reflection directed back into the laser beam source 110 from downstream the quarter-wave
30 plate 125 or phase retarded mirror 129. A shutter (not disclosed) may be used to turn on/off the primary laser beam 150 adjacent the entrance of the printer head 102. When OFF (closed) the entire primary laser beam 150 is directed to a beam dump which may then be used as a detector/power meter. When ON (open) the entire primary laser beam 150 enters the printer head 102.

35 It shall be pointed out that separation of a sample of the laser beam may alternatively be performed downstream the beam splitter/DOE 145, i.e. a sample of the laser beam originating from the beam splitter/DOE 145 is directed to a detector/power meter.

According to various embodiments of the apparatus 100, the printer head 102 comprises a gas purging arrangement configured for removing deposits, i.e. fume silica particles and combustion by-products, from the area comprising the location of deposit 140 and the glass filament feeding nozzle 120. The gas purging arrangement is configured to generate a gas/air flow in the area of the glass filament feeding nozzle 120. According to one example embodiment the gas/air flow is fed into the printer head 102 housing in order to obtain over pressure therein, wherein the gas/air flow then leaves the printer head 102 housing around the filament feeding nozzle 120.

This is to ensure that any fumes from combustion by-products of the coating material 169 or vaporized/molten glass (fume silica particles due to overheating) does not move towards the glass filament feeding nozzle 120 or other parts/optics of the printer head 102 or linger/remain at the location of deposit 140. Otherwise, such fumes could damage the printer head optics and filament feeding nozzle 120, requiring frequent cleaning or replacement of parts, and have negative effect on the printed glass object. In figure 3 the printing is performed with the glass filament fed towards the stage 130 in a horizontal direction. This is beneficial as the fumes automatically will leave the area of the glass filament feeding nozzle 120 and the location of deposit 140. However, using suitable gas purging the printer head 102 can be placed in any direction (upwards, downwards, sideways, etc.).

Reference is now made to figures 8 and 9a-9c.

Bare glass filaments possess poor mechanical properties, and thus are susceptible to breakage. In order for mechanical and chemical protection of the glass filament during storage and handling, a protective coating is required. The protective coating can be applied during filament fabrication, using for instance a fiber draw tower used to produce optical fibers. A furnace heats the preform (large version of filament in both shape and composition). The softened glass is then pulled using a capstan in combination with a diameter gauge for the correct filament dimensions. As the filament is being pulled, the preform is fed further into the furnace. Typically, a coating resin may be introduced into a coating cup, which the filament is passing through. The coating may then be subsequently cured, either thermally or using for instance UV lamps, prior to winding the filament onto storage and transport spools. Curing temperatures for polyimide coatings on optical fibers may typically be performed in the temperature range of about 100 to 400 °C.

Polyimide coated optical fibers can survive operating temperatures of around 300 °C, and are commonly used for higher-temperature (sensing) applications. Here coating thickness of 10 to 15 µm is typically used. Thicker coatings can be applied by repeating the coating procedure, adding multiple layers of the coating but still obtaining only one coating.

For glass filaments the coating thickness should be as thin as possible, while ensuring sufficient mechanical and chemical protection of the fiber. The filaments we have evaluated that gave good results have a single layer polyimide coating thickness of approximately 5 µm.

Suitable outer diameters of glass filaments are in the range 100 μm to 500 μm . The diameter has a large impact on the mechanical properties of the filament with increased diameter resulting in more stiff filaments. The translation of the printer head and glass filament relative to the printed object/stage during printing, results in a lateral force on the filament. A deviation of the filament position depends on viscosity and surface tension of the liquid glass in the hot-zone, as well as printing speed. A schematic of a feeding nozzle 120 and fed glass filament 160 is shown in figure 6. Using a stiffer filament, the distance between the filament feeding nozzle 120 and the stage 130 can be increased. L is the distance between the glass filament feeding nozzle 120 and the stage 130. The glass filament diameter, filament feeding nozzle 120 design, and the distance between the glass filament feeding nozzle 120 and the stage 130 therefore has a large effect on the print accuracy/quality. A large glass filament 160 diameter and short distance between the glass filament feeding nozzle 120 and the stage 130 will reduce the glass filament deflection/deviation during printing. If the distance L is too short the filament feeding nozzle 120 can be damaged by the temperature at the hot-zone. Theoretically, under the same processing conditions the glass filament having a diameter of about 200 μm deflects only one quarter to that of the glass filament having a diameter of about 125 μm . Using a glass filament having a diameter of 200 μm and a distance L equal to or less than 5 mm, the deflection/deviation will be parts of μm and can be considered negligible.

In glass 3D printing, the glass filament is continuously fed to a hot-zone having a temperature in the range 1800 to 2200 $^{\circ}\text{C}$, when printing fused silica/fused quartz glass. Other types of glass, e.g. soft glass, requires much lower temperatures. One common method is to feed pure glass filament. However, since most of the glass filament are produced having a coating, removal of the coating is required to produce pure glass filament prior to printing/deposit. Stripping off the coating can be performed using mechanical or chemical means (e.g., using sulfuric acid, dichloromethane). As the glass filament may become brittle without coating and stripping the coating may further weaken the mechanical strength of the filament, this brings extra risks as filament breakage during printing which will cause major interruptions of the printing process.

Another approach is to directly feed the coated glass filament from the glass filament feeding nozzle 120. With protective coating 169, the printable filament length is extended to kilometers. However, as glass filaments 160 are commonly coated using flammable polymers, e.g. acrylics, this approach can cause an open flame on the filament due to the high printing temperature, leading to the printing failure and likely destruction of the 3D printer. Besides, standard coating has a thickness at about 50 μm , which is considered too "thick" for glass 3D printing. Direct burning of such "thick" coating is not an ideal solution as it may produce more combustion by-products, be more likely to leave residues affecting the purity of the print, and it is not energy efficient.

Our approach is to produce the glass filament with a thin flame retardant and self-extinguishing single coating. The thin coating has a thickness in the range 1 to 50 μm . As the hot-zone is heated to very high temperatures, using CO_2 -laser beams, the coating will start to burn near the hot-zone, i.e. the hot-zone itself can be used to remove the coating. While the coating is flame retardant, the risk of open flame is eliminated. Once the laser beam source 110 and glass filament feeding are turned off, the combustion of the coating will stop. A thin coating will be easily burnt off. Besides increasing efficiency and reducing environmental impact, it will also reduce the production of combustion by-products. The ideal coating may have a non-toxic chemical composition to further reduce toxic fumes produced during combustion e.g. should not contain halogens.

Figures 9a-9c disclose three different types of glass filaments 160 with one protective coating 169, which may be used in the additive manufacturing apparatus 100.

Figure 9a discloses a single composition (rod/fiber filament), where the composition (type of glass) can be high purity silica glass, e.g. fused silica, fused quartz, (used for printing high purity transparent glass). These materials have low thermal expansion coefficient. i.e. does not need heated print plate and post thermal annealing is not always necessary. Silica glass filament can be co-doped with GeO_2 , Al_2O_3 , B_2O_3 , or F, or combinations of these. Multifilament printing (together with silica glass filament) can be used to create 3D prints with designed shape and refractive index structure. Example can be fabrication of optical fiber preforms or different optical components. Silica glass doped with rare earth oxides, of e.g., Er, Yb, Er/Yb in combination with additional dopants (e.g., GeO_2 , Al_2O_3 , B_2O_3 , F). These filaments can be used to create 3D prints of active laser material. Silicates, boro-silicates, alumino-boro silicates and soda-Lime glass present low(er) cost materials of standard type. Due to higher thermal expansion coefficients these may require heated printing plate and post thermal annealing to alleviate stress.

Figure 9b discloses a glass filament 160 with a central air hole 162, i.e. a capillary structure. These capillary filaments can be used to print different types of glass/air structures. If pressure control is applied to the inner section of the capillary filament, active contraction/expansion of the filament during printing is possible. The volume of said air hole 162 may be between 10-70% of a volume of said glass content in said glass filament 160. The air hole 162 may be centered or non-centered in said glass filament 160. In various example embodiments said glass filament 160 may be provided with a plurality of air holes.

Figure 9c discloses a glass filament 160 consisting of silica-based composition containing a central core structure 160' of a refractive index modifying dopant, e.g., GeO_2 , Al_2O_3 , B_2O_3 , F. These core/cladding filaments, which function as optical waveguides, can be used to print optical circuits on different types of glass substrates for use in telecommunication, sensing or biomedical applications. Other core materials, besides glass based, include semiconductor and alloys, e.g. silicon, germanium etc.

Feasible modifications of the Invention

The invention is not limited only to the embodiments described above and shown in the drawings, which primarily have an illustrative and exemplifying purpose. This patent application is intended to cover all adjustments and variants of the preferred embodiments described herein, thus the present invention is defined by the wording of the appended claims and the equivalents thereof. Thus, the equipment may be modified in all kinds of ways within the scope of the appended claims.

Throughout this specification and the claims which follows, unless the context requires otherwise, the word “comprise”, and variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or steps or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

Claims

1. Apparatus (100) for additive manufacturing of a three-dimensional glass object comprising:

- a stage (130) for supporting the glass object,
- a laser beam source (110) for providing a primary laser beam (150),
- a printer head (102), and
- means for relative movement of the printer head (102) and the stage (130),

wherein the printer head (102) comprises:

- at least one glass filament feeding nozzle (120) for feeding a glass filament (160) towards a location of deposit (140) in order to form the glass object, and
- an optical beam path unit configured for directing the laser beam (150) from the laser beam source (110) to the location of deposit (140) for heating the glass filament (160),

characterized in that the optical beam path unit comprises:

- a beam splitter (145) in order to divide the primary laser beam (150) into at least three partial laser beams (150'), wherein the optical beam path unit is configured for directing each of the at least three partial laser beams (150') from the beam splitter (145) to the location of deposit (140), and
- a feed-back control unit comprising means for monitoring a process parameter that is representative for the temperature at the location of deposit (140) and means for controlling the power of the primary laser beam (150) in order to adjust the temperature at the location of deposit (140) towards a predetermined level.

2. The apparatus (100) according to claim 1, wherein said process parameter is constituted by the power of the primary laser beam (150) upstream the beam splitter (145) in the printer head (102).

3. The apparatus (100) according to claim 2, wherein means for monitoring the process parameter constituted by the power of the primary laser beam (150) comprises a beam tap (127) configured for separating a predetermined sample of the primary laser beam (150) towards a detector (128).

4. The apparatus (100) according to any preceding claim, wherein the optical beam path unit comprises means for providing circular polarization to the primary laser beam (150) upstream the beam splitter (145).

5. The apparatus (100) according to any preceding claim, wherein the optical beam path unit comprises a pyramid mirror (155) located downstream the beam splitter (145) in order to diverge the at least three partial laser beams (150') from each other.

6. The apparatus (100) according to any preceding claim, wherein the optical beam path unit comprises for each partial laser beam (150') one or more secondary beam steering mirror (165) configured for directing the partial laser beam (150') towards the location of deposit (140).

5 7. The apparatus (100) according to claim 6, wherein the glass filament feeding nozzle (120) is located surrounded by the secondary beam steering mirrors (165).

8. The apparatus (100) according to any preceding claim, wherein the glass filament feeding nozzle (120) is configured for feeding the glass filament (160) in a direction perpendicular to a geometrical plane, wherein each of the at least three partial laser beams (150') has an angle of incidence equal to 30-60 degrees in relation to said geometrical plane.

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9. The apparatus (100) according to any preceding claim, wherein the optical beam path unit comprises a focusing lens (135) located upstream the beam splitter (145) in order to adjust the primary laser beam (150).

15

10. The apparatus according to claim 9, wherein the focusing lens (135) is displaceable back and forth in relation to the beam splitter (145) in order to adjust the diameter of the primary laser beam (150).

20

11. The apparatus (100) according to any preceding claim, wherein the printer head (102) comprises a gas purging arrangement configured for removing deposits from the area comprising the location of deposit (140) and the glass filament feeding nozzle (120).

25 12. The apparatus (100) according to claim 1, wherein said process parameter is constituted by the temperature at the location of deposit (140).

13. The apparatus (100) according to claim 12, wherein means for monitoring the process parameter constituted by the temperature at the location of deposit (140) comprises a thermal imager/camera.

30

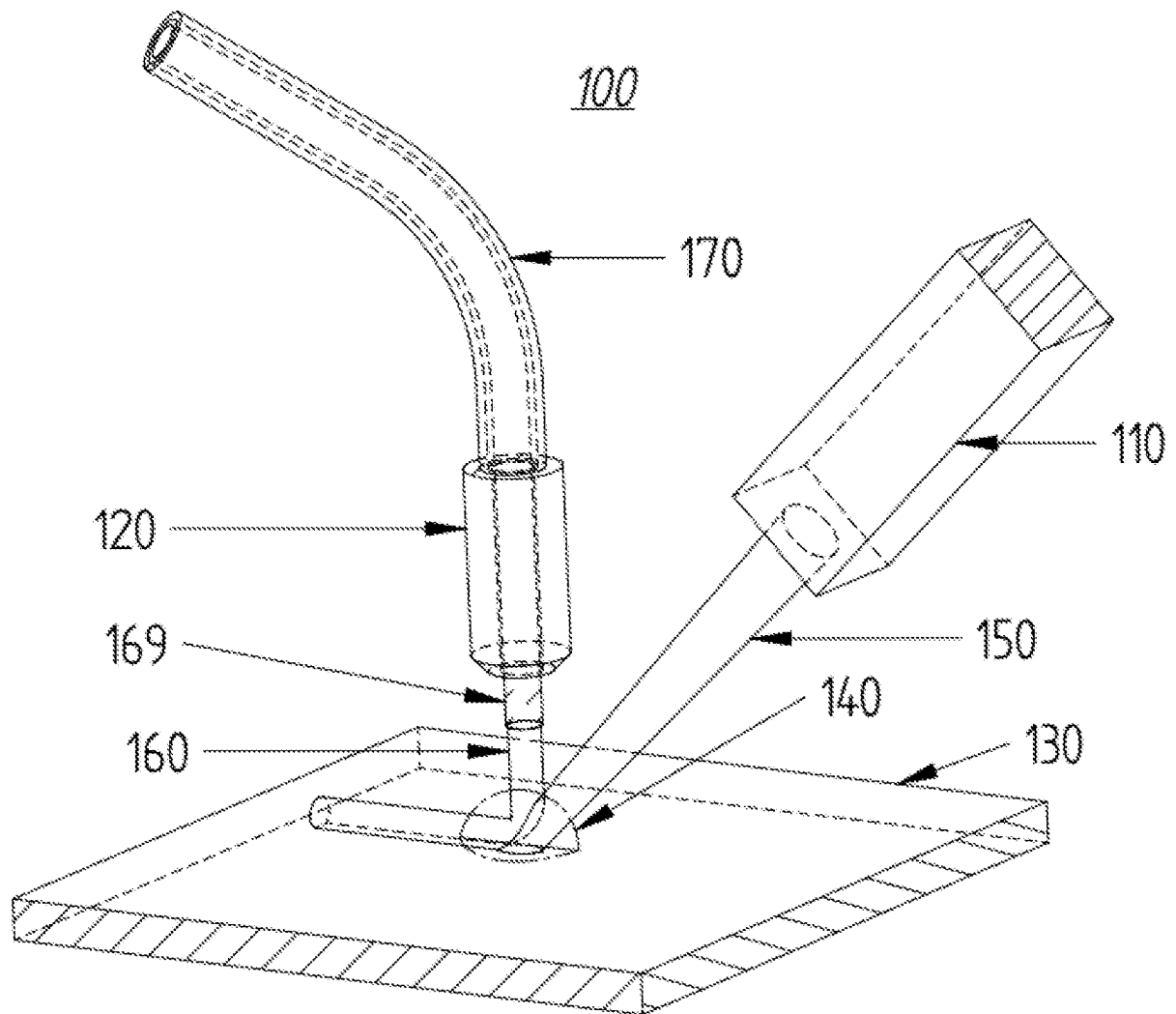


Fig. 1
PRIOR ART

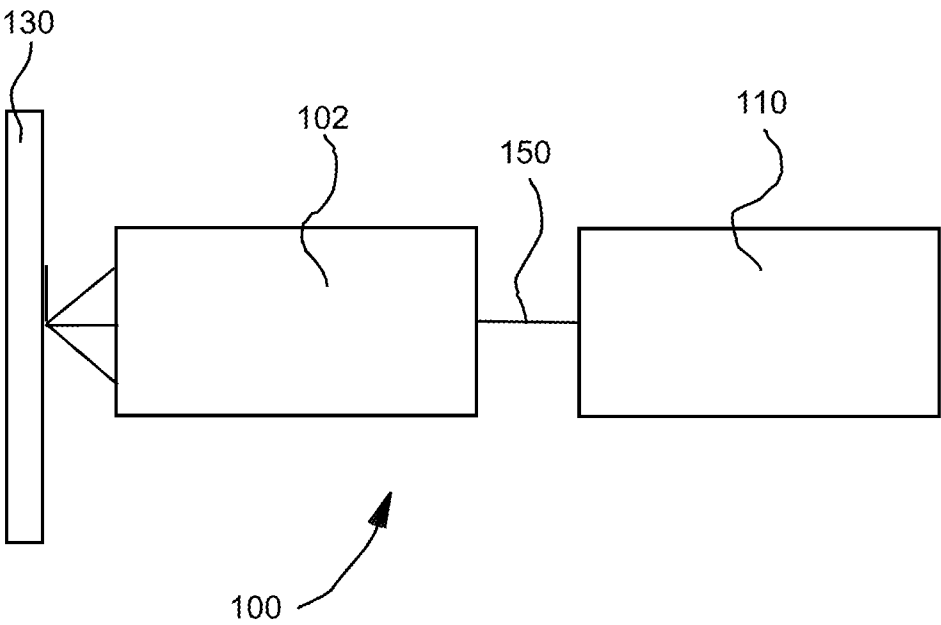


Fig. 2

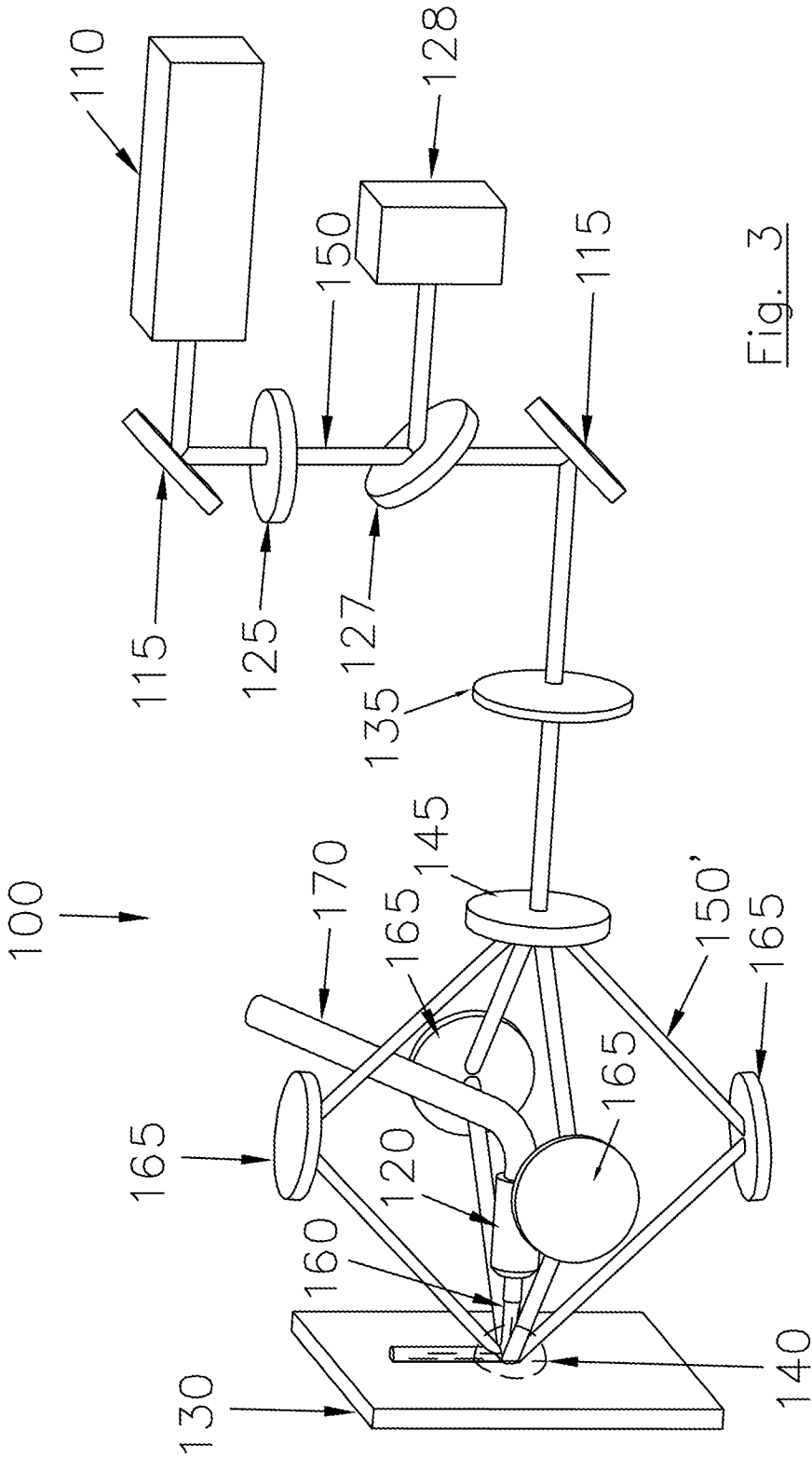


Fig. 3

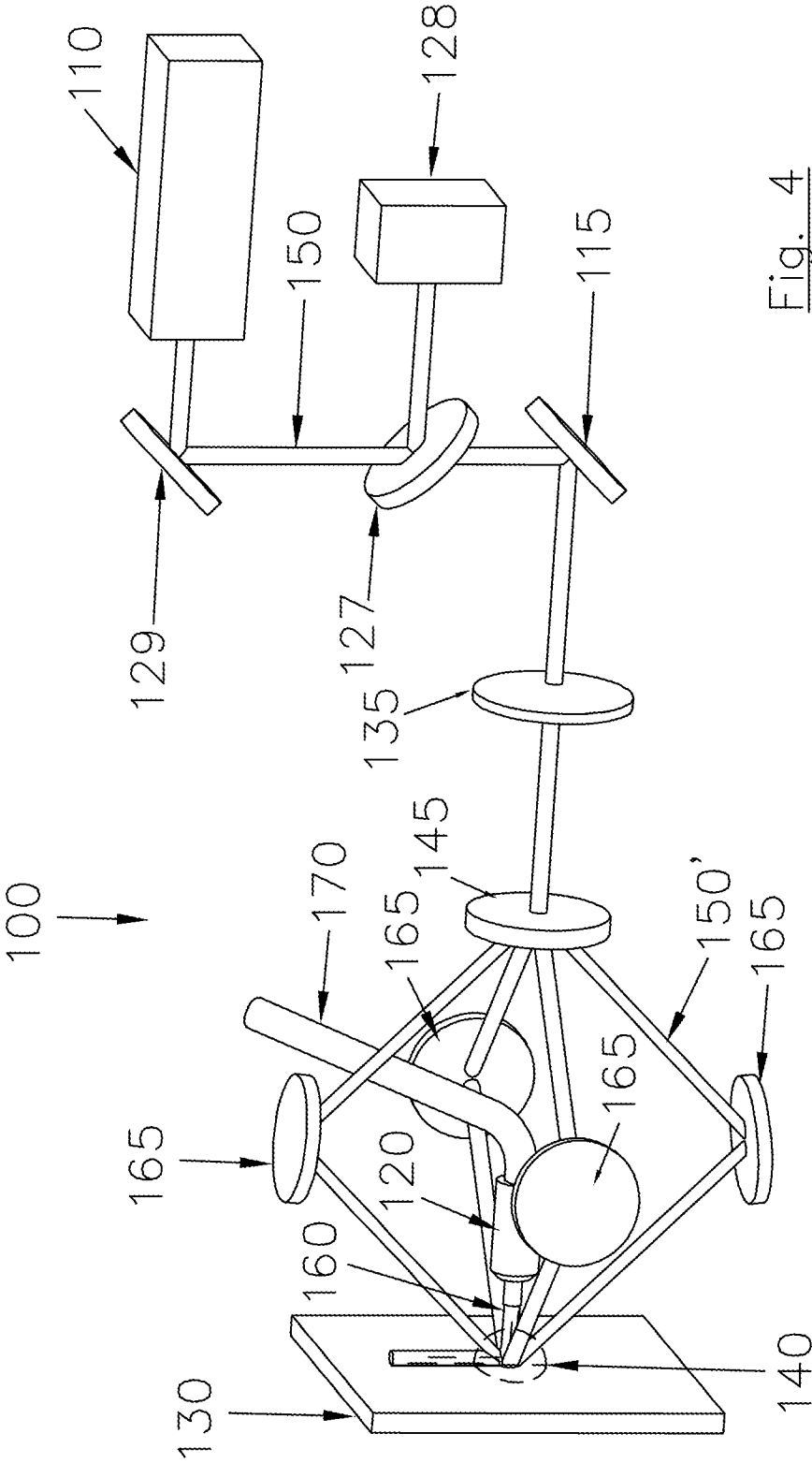


Fig. 4

100

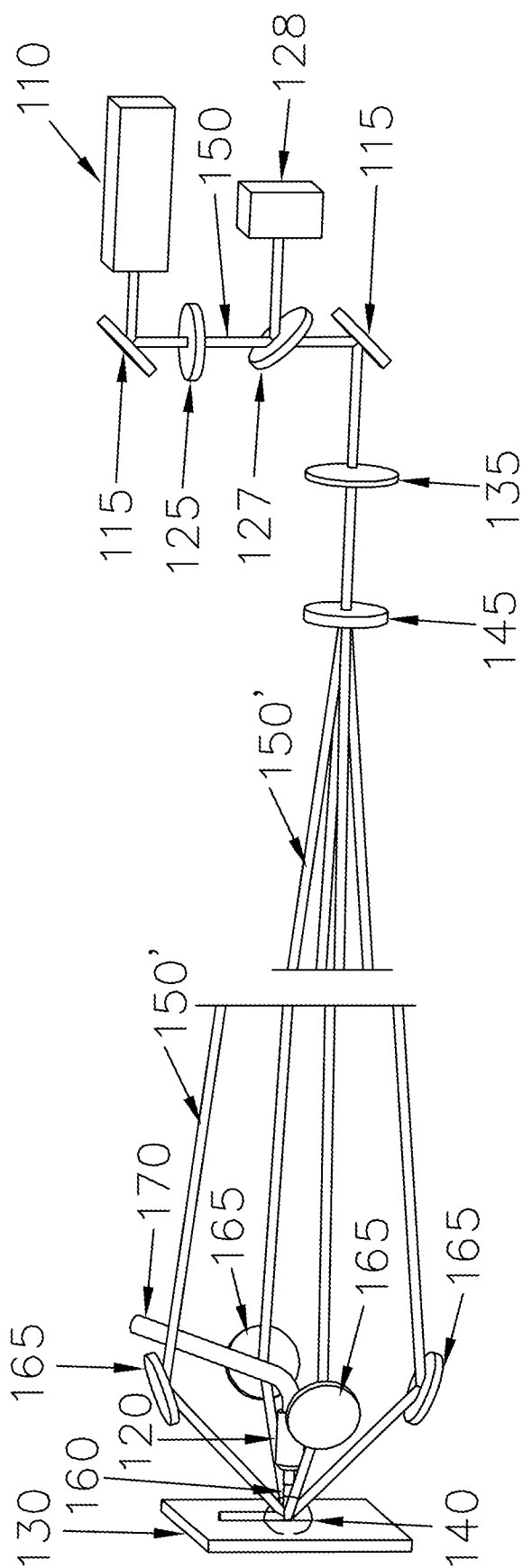


Fig. 5

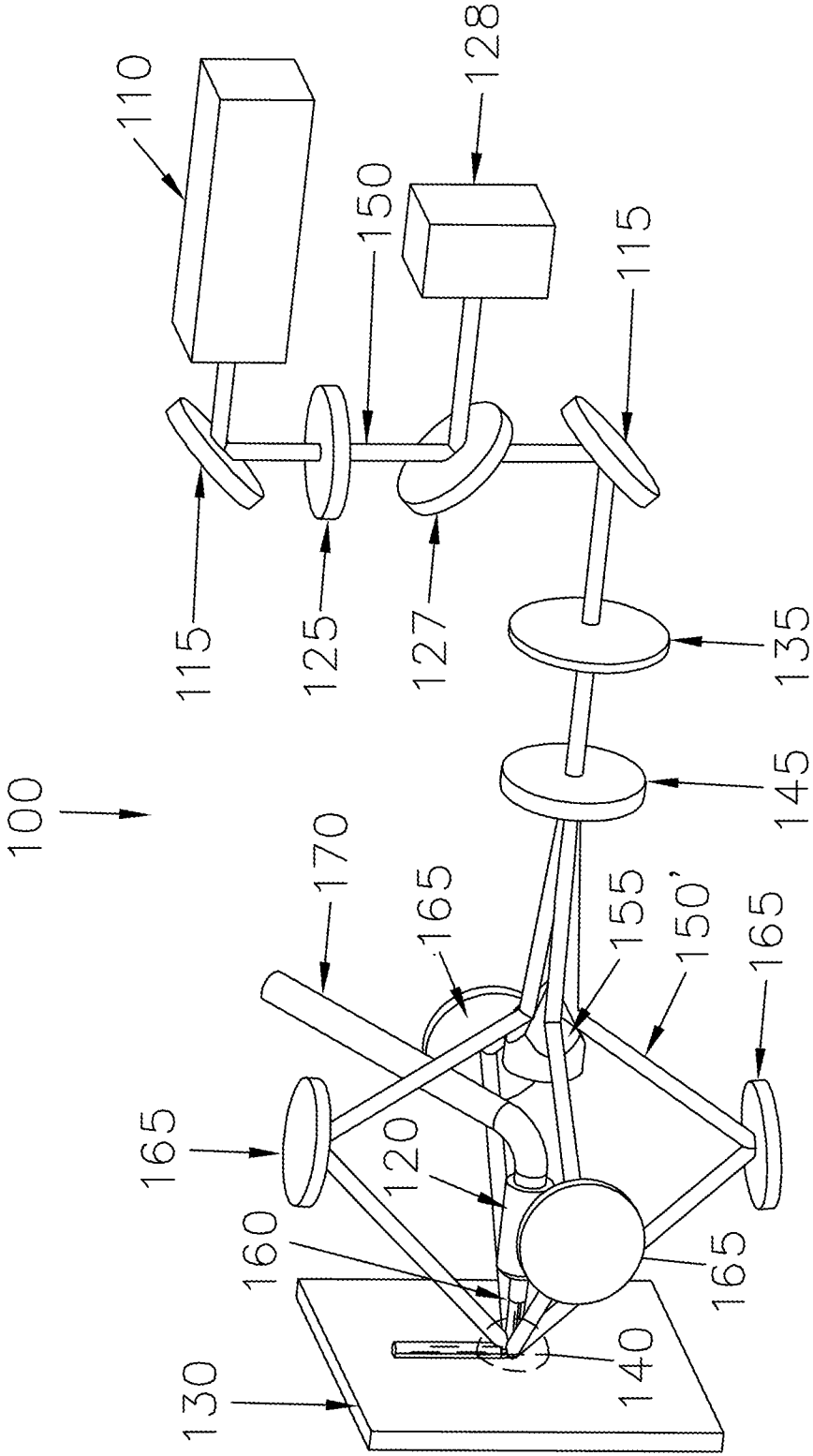


Fig. 6

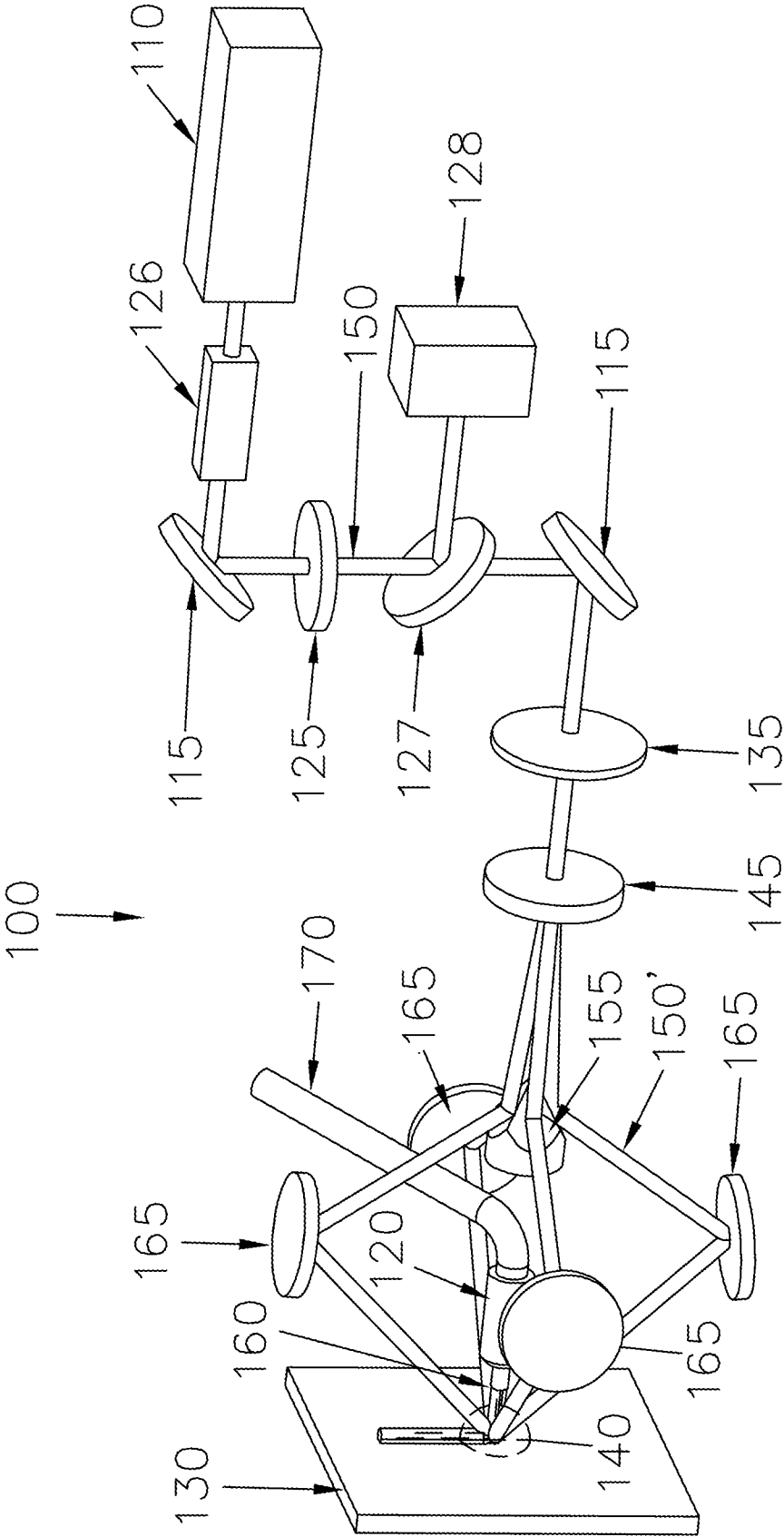


Fig. 7

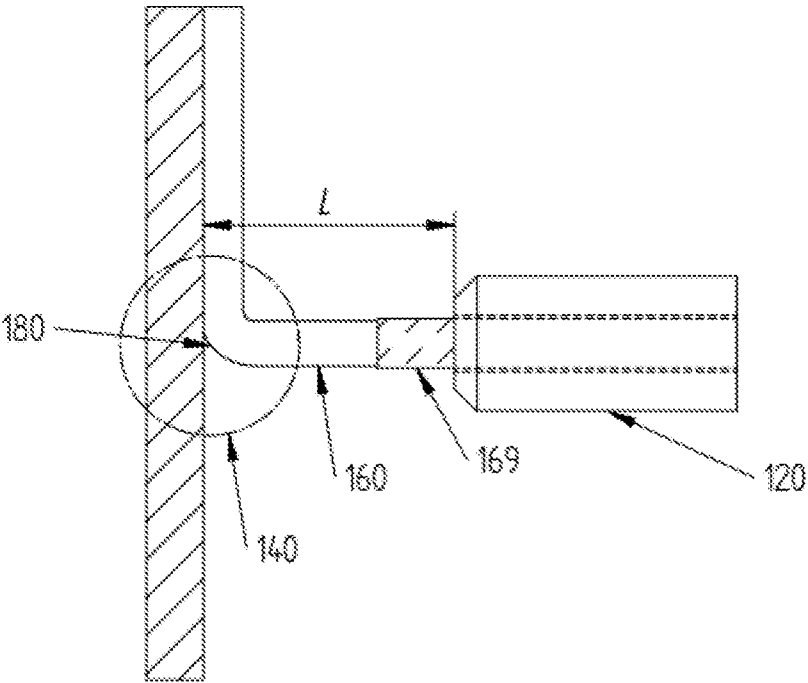


Fig. 8

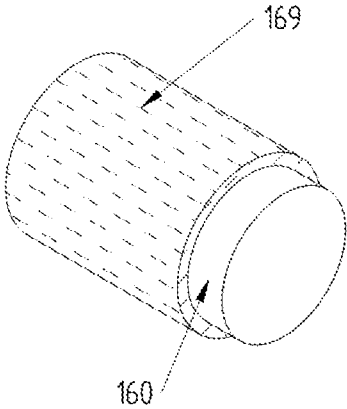


Fig. 9a

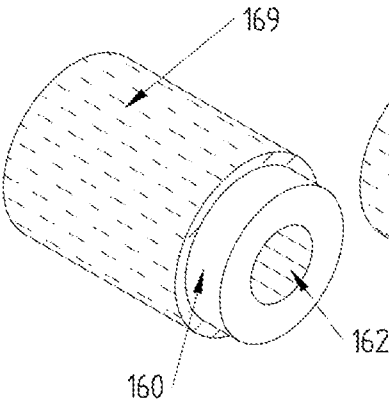


Fig. 9b

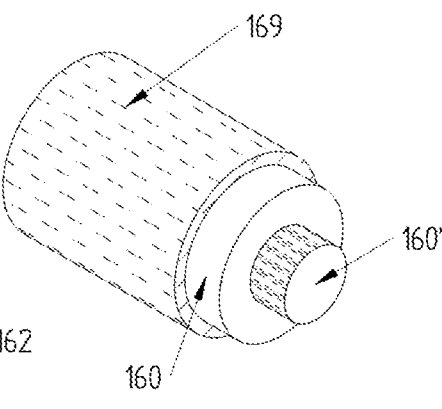


Fig. 9c

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2023/050027

A. CLASSIFICATION OF SUBJECT MATTER		
IPC: see extra sheet		
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)		
IPC: B29C, B33Y, C03B, G02B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
SE, DK, FI, NO classes as above		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
EPO-Internal, PAJ, WPI data, BIOSIS, CHEM ABS Data, COMPENDEX, EMBASE, INSPEC, MEDLINE, IPRally		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 20190352210 A1 (DREWNOWSKI CHRISTOPHER WILLIAM ET AL), 21 November 2019 (2019-11-21); paragraphs [0002]-[0003], [0010]-[0011], [0028]-[0032], [0044], [0053], [0058]-[0069], [0084]; figures 1,3-4; claims 1,7-9,10,17-19	1-13
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D, Y	Grabe T. et al., 'Additive manufacturing of fused silica using coaxial laser glass deposition: Experiment, simulation, and discussion', In: Proceedings of SPIE - The International Society for Optical Engineering - Laser 3D Manufacturing VIII, March 6-11 2021, Vol. 11677, pp. 1-12; figures 1-2; pp. 3, first paragraph; pp. 3, section 2.2; pp 5, Table 1	1-13
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents:		
"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	
"D" document cited by the applicant in the international application	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	
"E" earlier application or patent but published on or after the international filing date		
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art	
"O" document referring to an oral disclosure, use, exhibition or other means		
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family	
Date of the actual completion of the international search	Date of mailing of the international search report	
02-08-2023	03-08-2023	
Name and mailing address of the ISA/SE Patent- och registreringsverket Box 5055 S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Authorized officer Elina Staaf Telephone No. + 46 8 782 28 00	

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2023/050027

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Lusquinos F. et al., 'Bioceramic 3D Implants Produced by Laser Assisted Additive Manufacturing', In: Proceedings of the 8th International Conference on Photonic Technologies LANE 2014, Physics Procedia, Vol. 56, pp. 309-316; pp. 312, first paragraph --	4
Y	Oriekhov T. 'Hybrid fiber preform fabrication using CO laser heating', Dissertation, Defense 25 May 2022, KTH Royal Institute of Technology, School of Engineering Sciences, Department of Applied Physics; Section 6.1; pp. 53; Fig. 6.1(a) --	1-13
Y	Liu C. et al., 'Investigation of glass bonding and multi-layer deposition during filament-based glass 3D printing', Frontiers in Materials, August 2022, Vol. 9, pp 1-10; figure 1; pp. 03, column 1, first paragraph; pp. 09, column 1, second paragraph --	1-13
Y	Liu C. et al., 'Rapid Fabrication of Silica Microlens Arrays via Glass 3D Printing', 3D printing and additive manufacturing, October 2022, https://doi.org/10.1089/3dp.2022.0112 , pp 1-7; figure 1A; pp. 2, column 2, final paragraph - pp. 3, column 1, second paragraph --	1-13
A	US 20200156310 A1 (SHAH PAREN ET AL), 21 May 2020 (2020-05-21); paragraphs [0004]-[0017], [0052]-[0055], [0059]; figures 2-3; claims 56-62, 72-73 --	1-13
A	WO 2020131400 A1 (CORNING INC), 25 June 2020 (2020-06-25); paragraphs [0126], [0167]-[0185]; figures 11-13 --	1-13
A	DE 102018109131 A1 (SCHOTT AG), 17 October 2019 (2019-10-17); whole document --	1-13
A	US 6143378 A (HARWELL LANE D ET AL), 7 November 2000 (2000-11-07); whole document --	1-13
A	US 20160230283 A1 (TSELIAKHOVICH DMITRIY ET AL), 11 August 2016 (2016-08-11); paragraph [0023] --	1-13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2023/050027

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E	WO 2023285340 A1 (FOKINE MICHAEL ET AL), 19 January 2023 (2023-01-19); whole document -- -----	1-12

Continuation of: second sheet

International Patent Classification (IPC)

B29C 64/118 (2017.01)

B29C 64/245 (2017.01)

B29C 64/268 (2017.01)

B33Y 10/00 (2015.01)

B33Y 30/00 (2015.01)

G02B 27/09 (2006.01)

B29C 64/209 (2017.01)

B33Y 50/00 (2015.01)

C03B 19/02 (2006.01)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SE2023/050027

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US	20200156310 A1	21/05/2020	US	11338502 B2	24/05/2022
			WO	2018217650 A1	29/11/2018
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