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(54) **OPTICAL REFRIGERATOR**

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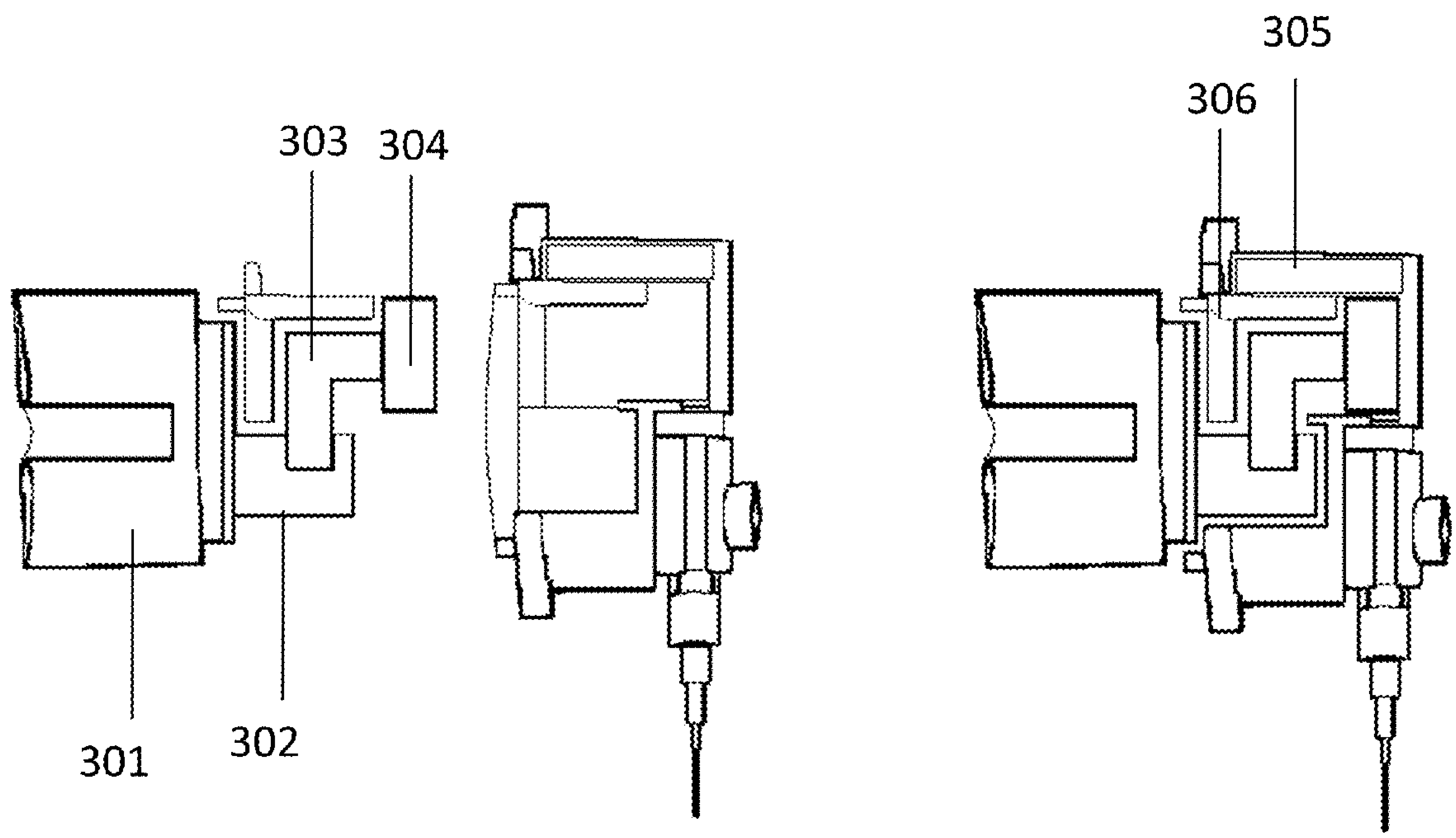
USPC **62/3.1**

(57) **ABSTRACT**

An optical refrigerator comprises a laser source, a cooling crystal, a cavity for enhancing the absorption of the laser light in the cooling crystal, a thermal link which connects a cold finger to the cooling crystal and prevents the fluorescence from heating the cold finger, an absorbing chamber to remove the fluorescence and eliminate the waste heat, an a mechanical support that keeps the cooling crystal properly aligned with the laser beam and minimizes heat leakage.



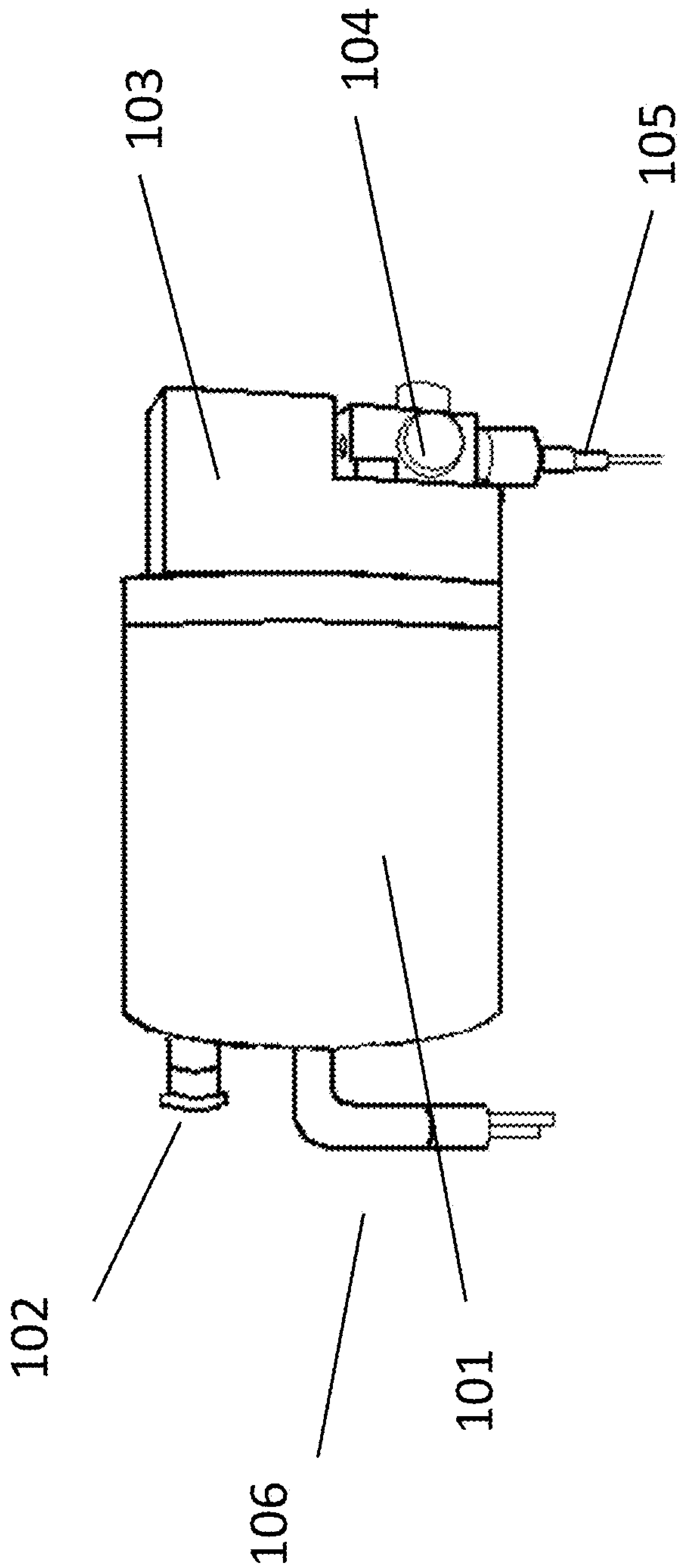


FIG. 1

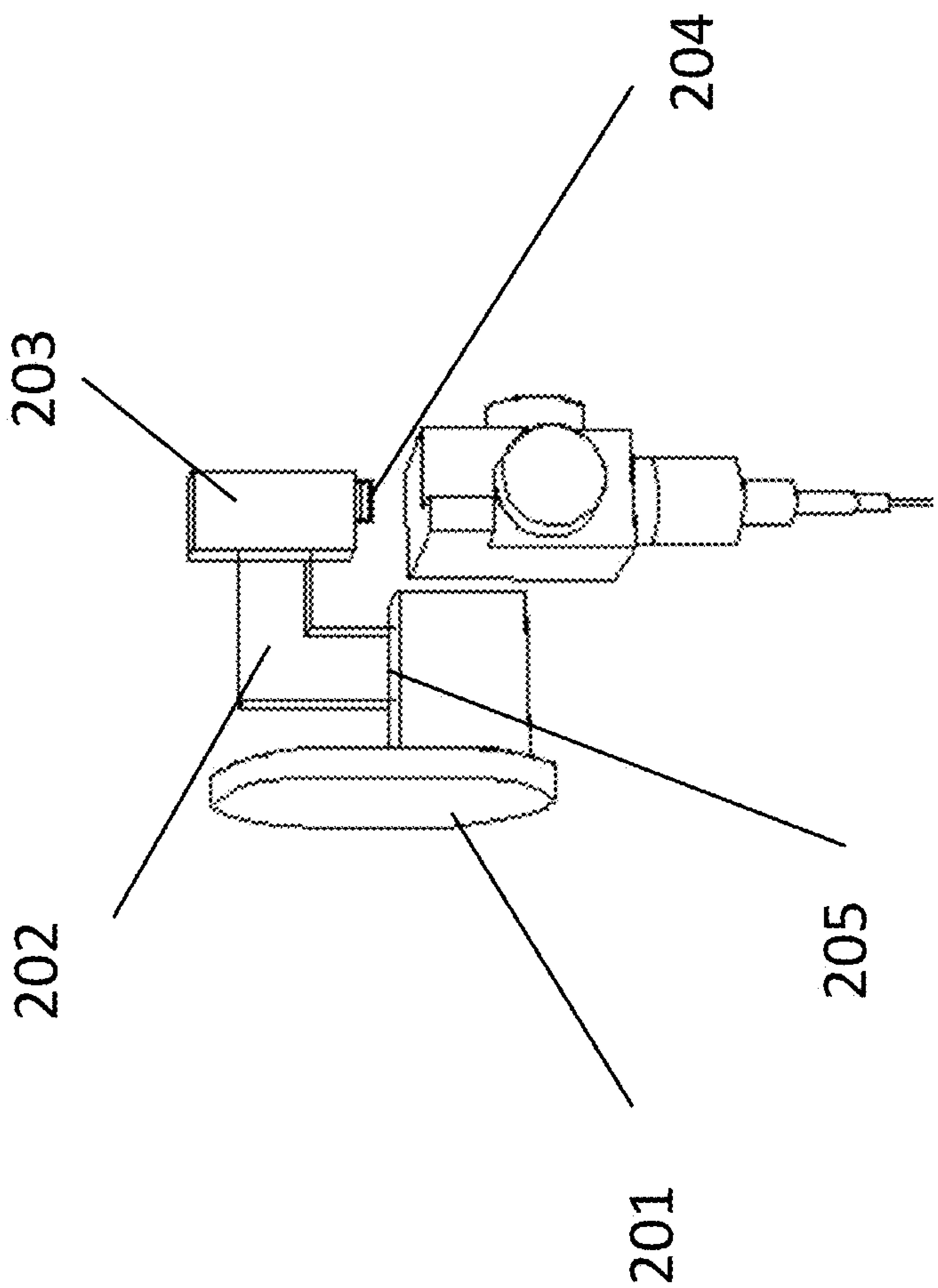


FIG. 2

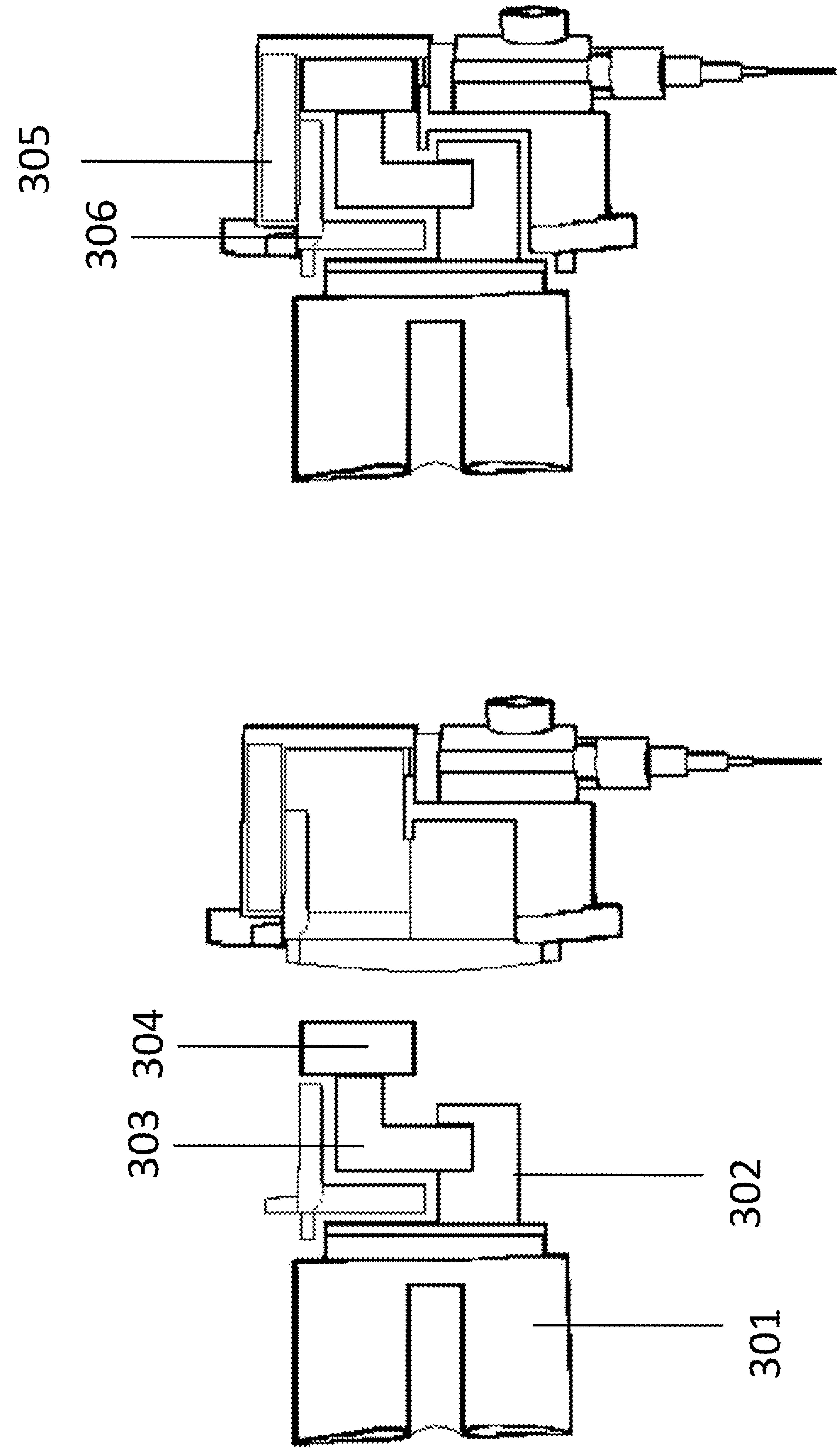


FIG. 3

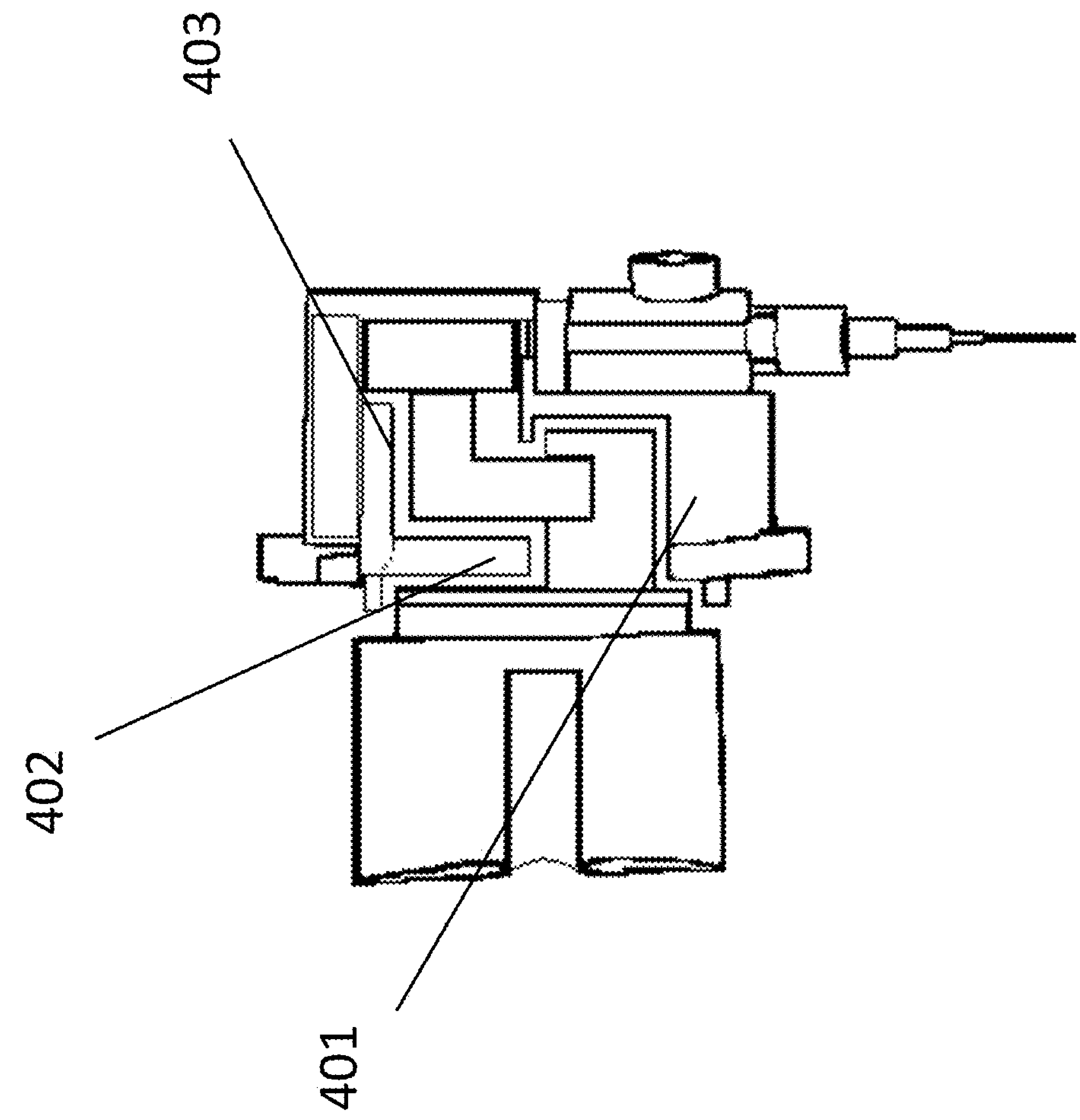


FIG. 4

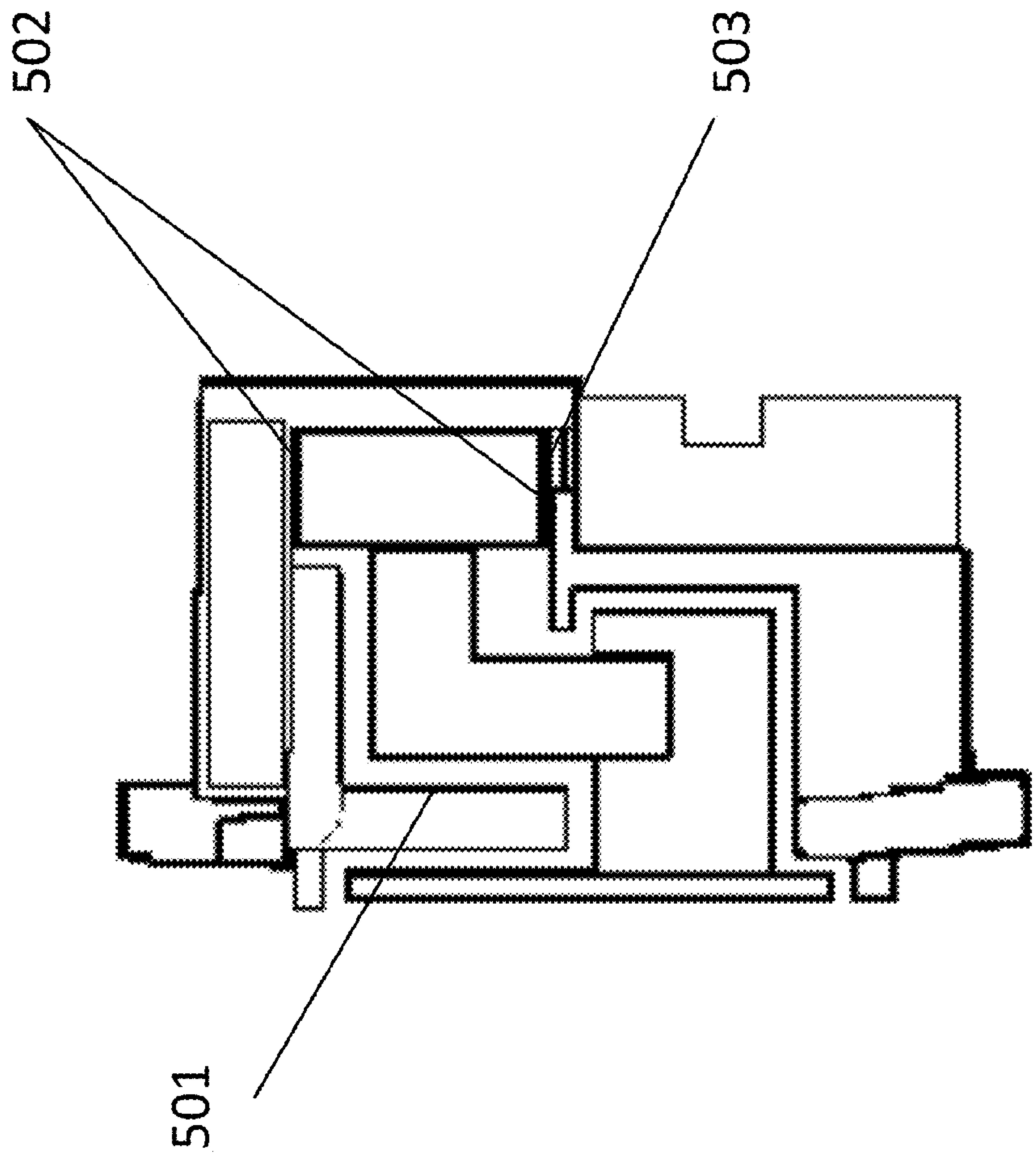


FIG. 5

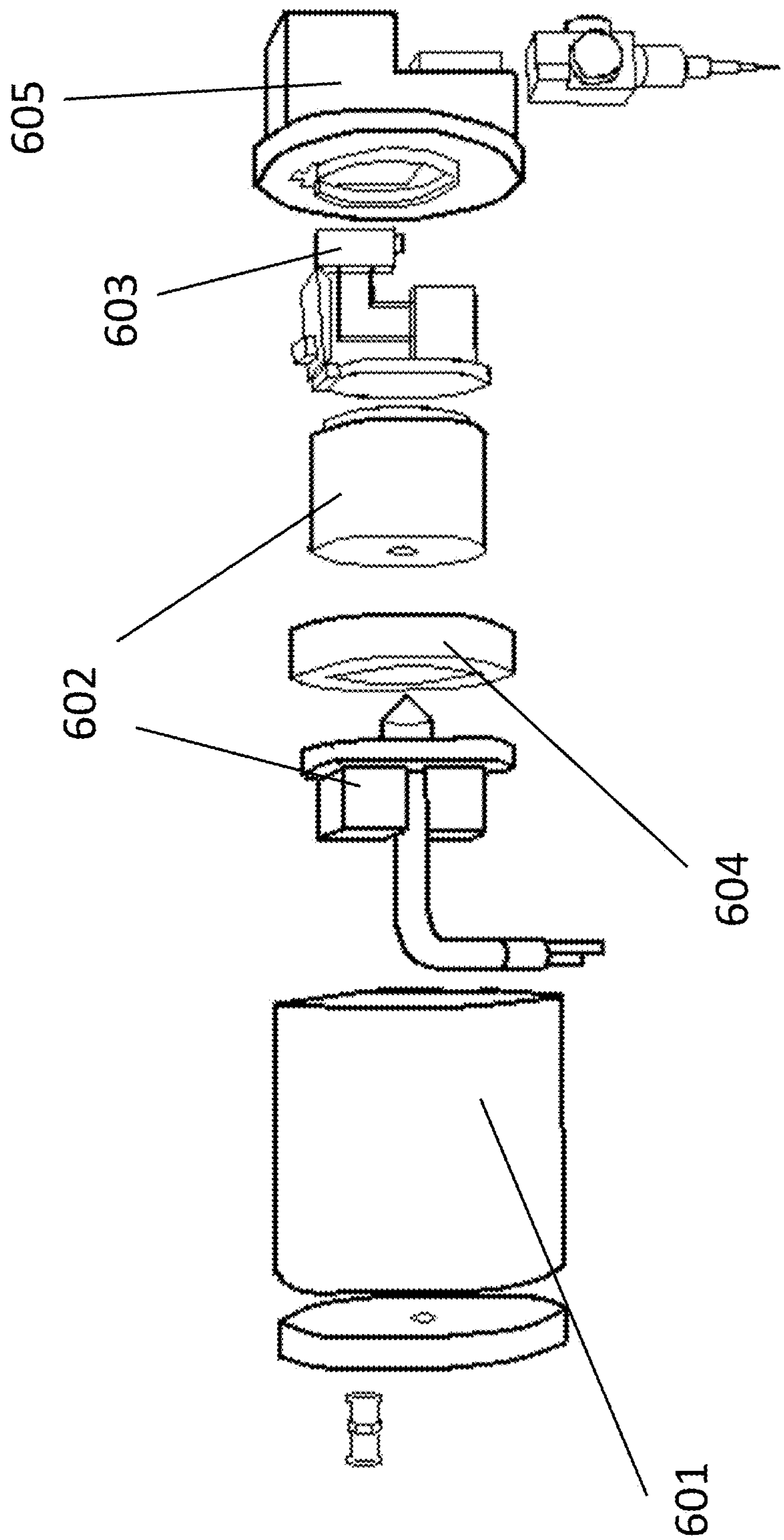


FIG. 6

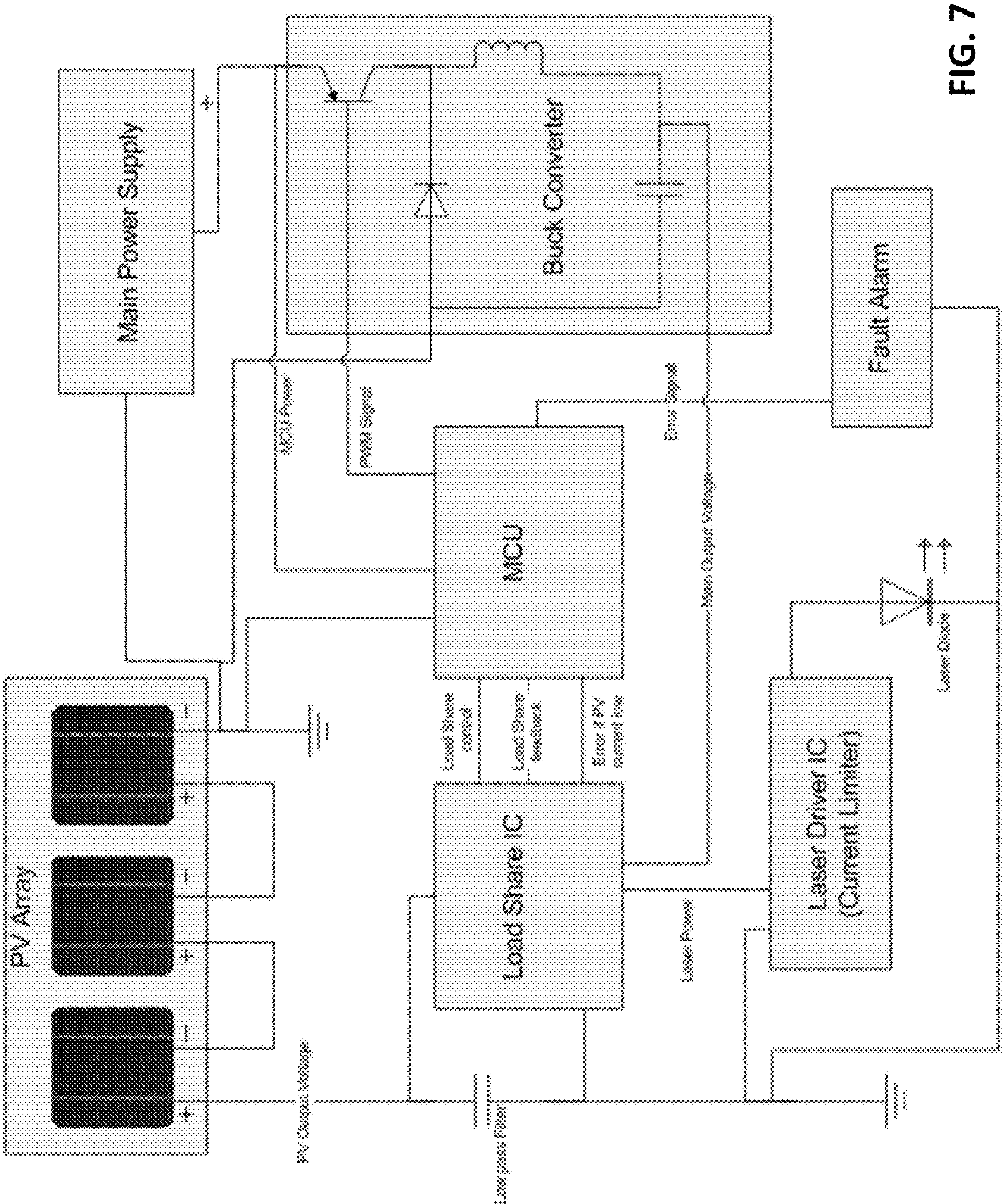

Main Power Supply
Buck Converter
MCU
PV Array
Load Share IC
Laser Driver IC
(Current Limiter)
Fault Alarm
MCU Power
PWM Signal
Error Signal
Main Output Voltage
Laser Power
Laser Diode
PV Output Voltage

FIG. 7

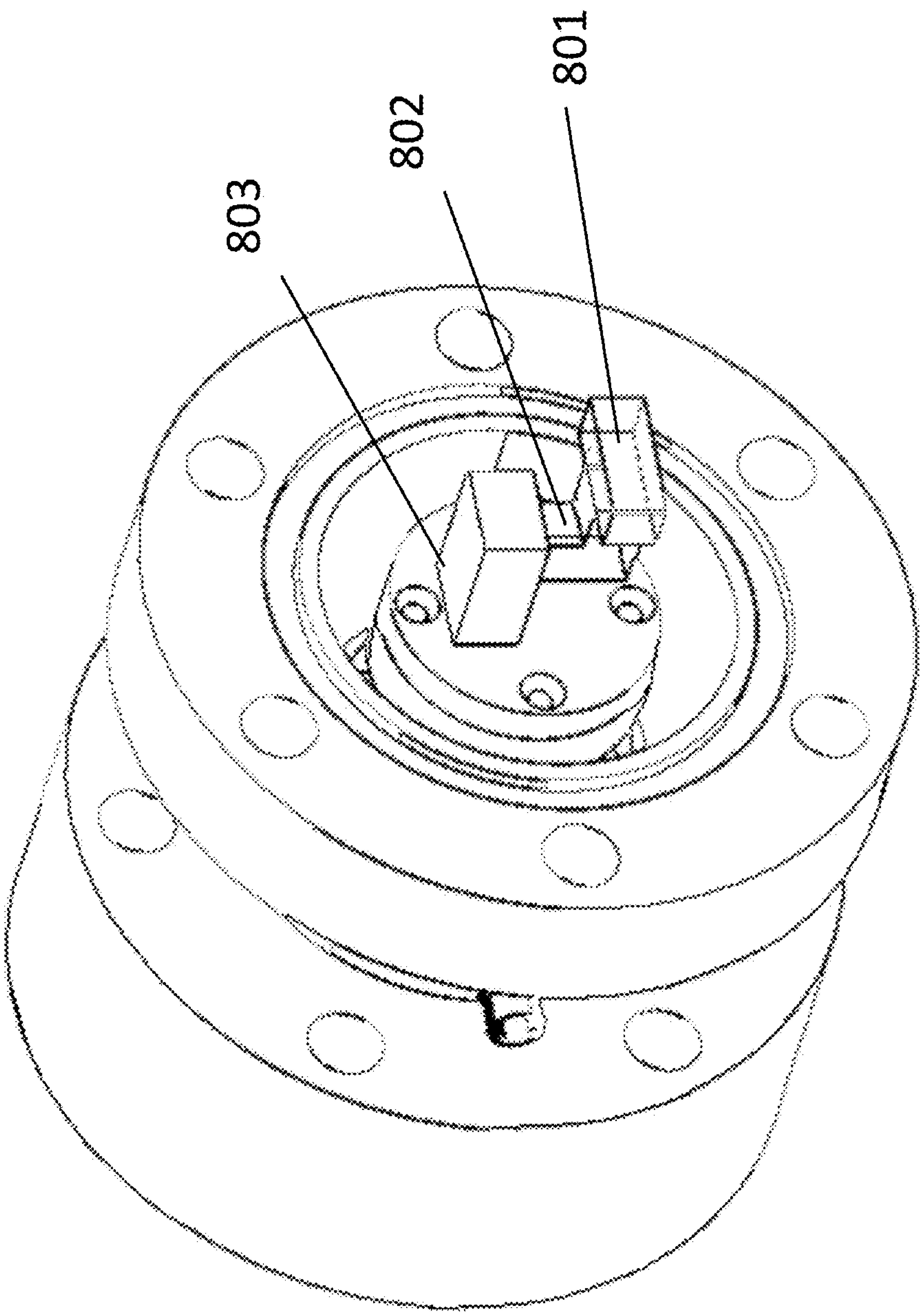


FIG. 8

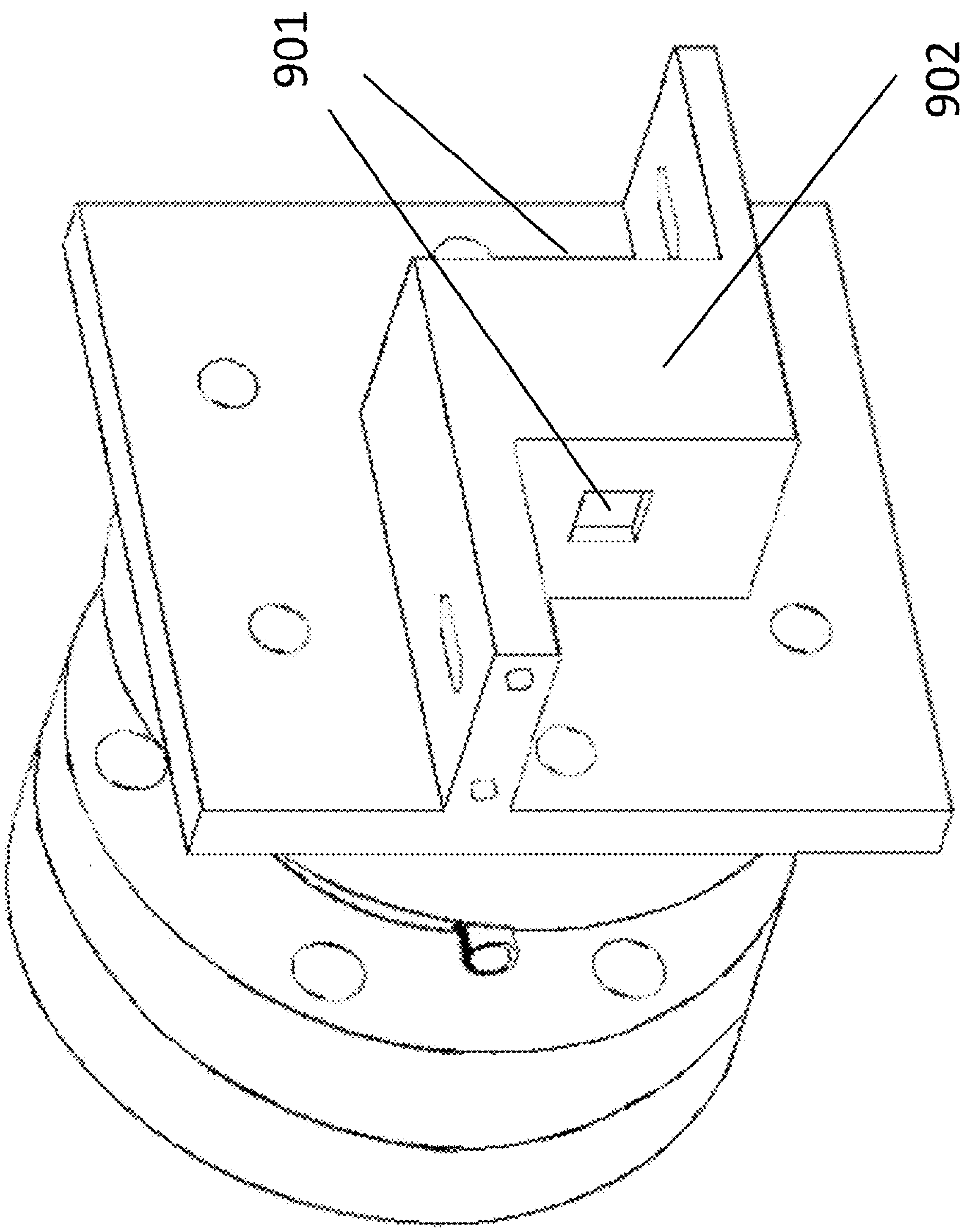


FIG. 9

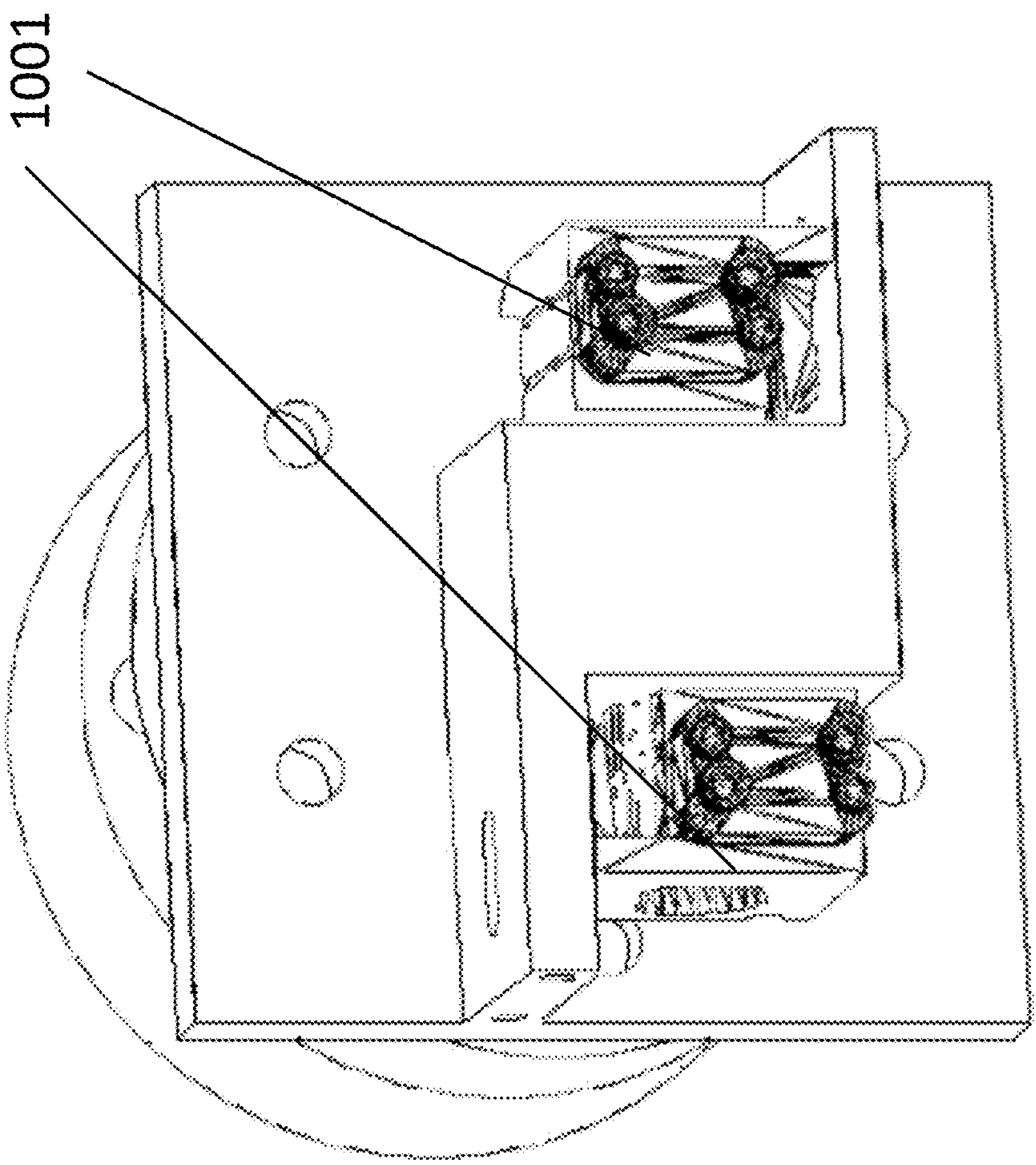


FIG. 10

OPTICAL REFRIGERATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. provisional 61/877,892, filed Sep. 13, 2013, which is incorporated herein by reference.

BACKGROUND

[0002] This invention was made with Government support under Contract FA9550-13-C-0006 awarded by USAF, AFRL. The Government has certain rights in the invention.

[0003] Epstein et al. (U.S. Pat. No. 5,447,032) teaches the physical basis of optical refrigeration. Cooling is achieved by anti-Stokes fluorescence in which the cooling material absorbs nearly monochromatic laser light and subsequently fluoresces producing light of a higher average frequency. Edwards et al. (U.S. Pat. No. 6,041,610) teaches how the efficiency of optical refrigeration could be enhanced by employing reflectivity tuned dielectric mirrors and by extracting electrical power using photovoltaic cells. The review paper by Seletskiy, et al., (2012) and the book *Optical Refrigeration: Science and Applications of Laser Cooling of Solids* (2009) by Epstein and Sheik-Bahae describe recent scientific developments related to optical refrigeration. Each of the foregoing references is incorporated herein by reference.

[0004] The following references can aid in understanding the present invention: "Fluorescent Refrigeration" Epstein, R. I., Edwards, B. C., Buchwald, M. I. & Gosnell, T. R., 1995, U.S. Pat. No. 5,447,032.

[0005] "Optical Refrigerator Using Reflectivity Tuned Dielectric Mirrors" Edwards, B. C., Buchwald, M. I. & Epstein, R. I., 2000, U.S. Pat. No. 6,041,610.

[0006] "*Cryogenic Optical Refrigeration*" Seletskiy, D. V., Hehlen, M. P., Epstein, R. I., Sheik-Bahae, M., *Advances in Optics and Photonics,* 4, 78-107, 2012.

[0007] *Optical Refrigeration: Science and Applications of Laser Cooling of Solids,* 2009, (Wiley-VCH, Weinheim) editors R. I. Epstein & M. Sheik-Bahae.

[0008] "A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity", Kessler et al. *Nature Photonics,* 6, 687. 2012. Each of the foregoing references is incorporated herein by reference.

SUMMARY OF THE INVENTION

[0009] An optical refrigerator comprises a laser source, a cooling crystal, a cavity for enhancing the absorption of the laser light in the cooling crystal, a thermal link which connects a cold finger to the cooling crystal and prevents the fluorescence from heating the cold finger, an absorbing chamber to remove the fluorescence and eliminate the waste heat, and a mechanical support that keeps the cooling crystal properly aligned with the laser beam and minimizes heat leakage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a schematic illustration of an optical refrigerator connected to a cold device that it is cooling.

[0011] FIG. **2** is a schematic illustration of components of an example optical refrigerator.

[0012] FIG. **3** is a schematic illustration of an example connection between an optical refrigerator and a device being cooled. The left panel shows how the components can be assembled and the right panel is a cross-section of the assembled unit.

[0013] FIG. **4** is a schematic illustration of how the radiation and heat flow can be managed in an optical refrigerator.

[0014] FIG. **5** is a cross-section view of a housing with cooling crystal and heat spreader.

[0015] FIG. **6** is an exploded view of an example optical refrigerator and a device being cooled.

[0016] FIG. **7** is a schematic for an example circuit that uses waste fluorescence light to generate electrical power for driving a pump laser.

[0017] FIG. **8** is schematic illustration of the interior of an optical refrigerator that contains an optical cavity that uses mirrors outside the vacuum chamber.

[0018] FIG. **9** is schematic illustration of the vacuum chamber with sapphire windows sealed in the camber walls. These windows are part of the optical cavity.

[0019] FIG. **10** is schematic illustration of the mirror mounts of an optical refrigerator that has an optical cavity that uses mirrors outside the vacuum chamber.

DESCRIPTION OF THE INVENTION

[0020] The present invention provides practical optical refrigerators, and for the application of optical refrigeration to several technologies. An optical refrigerator according to the present invention can comprise several important components: a cooling element, an optical cavity, a means of directing light into the optical cavity, a cooling chamber, a means of removing heat from the chamber walls, a thermal link, and a heat spreader. The various components can be implemented in various ways, and combined in various ways, as described herein and as will be apparent to those skilled in the art by examination of the present disclosure.

[0021] The cooling element cools when it absorbs nearly monochromatic light (typically from a laser). The light absorption excites atoms to a higher energy level. Heat is produced if the excitation decays non-radiatively by producing thermal vibrations called phonons. It can be advantageous in the present invention to select crystals that decay mostly radiatively with very little heat production. Typically a cooling element is a solid with a broad ground state and a broad first excited state. The frequency of the pump light is chosen such that it excites the cooling element from near the top of the ground state to near the bottom of the excited state. The excitations thermalize before radiatively de-exciting and emitting light of higher average frequency than the pump light; this is anti-Stoke luminescence. Typical cooing elements are transparent solids that are doped with rare-earth ions that provide the energy levels described above.

[0022] The optical cavity holds or intensifies the light so that it can be efficiently absorbed by the cooling element. A pair of opposing mirrors that reflect the light back and forth can form a cavity. A cavity can be formed by having light trapped in a cooling element by total internal reflection.

[0023] The means of directing the laser light into the optical cavity can be of various forms known to those skilled in the art. As examples, this can comprise a pinhole in one mirror, resonant coupling through one of the mirrors of the cavity, or a cut facet on a corner of the cooling element.

[0024] The cooling chamber typically surrounds the cooling element. This chamber provides a vacuum, which is needed for cryogenic cooling. The interior surfaces of the cooling chamber absorb the waste fluorescence from the cooling element and convert it to heat in the walls. For space-born applications, the vacuum chamber is not needed. For some applications, the waste fluorescence can be expelled from the cooling cavity without being converted into heat. To improve the efficiency of an optical refrigerator, the chamber walls can be lined with photovoltaic cells to extract electrical power from the waste fluorescence.

[0025] The means of removing heat from the chamber walls can be of various forms as known to those skilled in the art. As examples, the chamber can be thermally connected to a larger unit that acts as a heat sink. The connection can be by copper braid or a heat pipe. The chamber, the heat sink, or both can be fitted with thermal fins to enhance heat removal.

[0026] The thermal link provides a good thermal connection to the heat spreader, while limiting the amount of light that reaches the heat spreader. The thermal link can be constructed from a material that has low absorption to the fluorescence and has a high thermal conductivity. The thermal link is shaped so that most of the light that enters it escapes through its sides and is absorbed by the walls of the chamber. Effective shapes for thermal links include L-shaped with one right angle bend, shapes with two or more right angle bends, and tapered trapezoidal solids. Generally, one or more sharp bends can be suitable, where a "sharp bend" contemplates angles of 90 degrees, or angles of 88 to 92 degrees, or angles of 80 to 100 degrees, or angles of 70 to 120 degrees.

[0027] The heat spreader can be considered as analogous to a cold finger in a conventional cryogenic refrigerator. The heat spreader provides a thermal connection between the thermal link and the load that is being cooled by the optical refrigerator.

[0028] This present invention contemplates several embodiments for each of the above components as well as other important features of optical refrigerators and their applications.

[0029] FIG. **1** is a schematic illustration of an optical refrigerator connected to a cold device that it is cooling. The refrigerator comprises a vacuum chamber **101** and vacuum pump connection **102**. An electric feed **106** for the device being cooled, a chamber **103** for optical refrigerator, a mechanism **104** for steering a laser light beam, and an optical fiber **105** for pump laser light. The figure illustrates a vacuum chamber for the device being cooled, in communication with a chamber for optical refrigeration. An electrical feed or connection for the device being cooled enters the vacuum chamber from the left in the figure. A connection for a vacuum chamber pump is also depicted at the left of the vacuum chamber in the figure. The vacuum chamber can be configured to accept such connections as are required for the device and application, and at such locations as fit the desired operating environment.

[0030] The chamber for optical refrigeration is in communication with a mechanism for steering a laser light beam, which accepts light from an optical fiber for transmitting the pump laser light. In some embodiments, light from a laser can be focused into the cooling cavity without the need of an optical fiber.

[0031] FIG. **2** is a schematic illustration of components of an example optical refrigerator. The refrigerator comprises a heat spreader **201** bound to the device being cooled, a thermal link **202** that prevent most of the light from reaching the heat spreader, a metal mirror **205**, a cooling crystal **203**, and a lens, e.g., a sapphire lens **204**, that is heat-sunk to the optical refrigerator chamber. The heat spreader can be placed in thermal communication with the device to be cooled, for example by physical bonding or contact. The metal mirror reflects fluorescence away from cold surfaces. The thermal link prevents most of the light from reaching the heat spreader. The cooling element, which can be a rare-earth-doped crystal, loses heat as it absorbs the pump radiation. The lens, for example a sapphire lens, which can be heat sunk to the optical refrigerator chamber so that it does not heat up, focuses the light into the cooling element; it is not in contact with the cooling crystal. In this example embodiment, the cooling element has mirrors deposited on both ends to form an optical cavity. Pump laser light enters this cavity through a pinhole in one of the mirrors.

[0032] In operation, a pump laser generates light that reaches the optical refrigerator through an optical fiber. Light from the fiber is focused into the cooling element cavity. The cooling element absorbs the light and then fluoresces, thereby removing heat from the cooling element. The cooling element removes heat from the load via the heat sink and the thermal link. The waste fluorescent light is absorbed on the chamber walls and removed by the means described above.

[0033] FIG. **3** is a schematic illustration of an example connection between an optical refrigerator and a device being cooled. The left panel shows how the components can be assembled and the right panel is a cross-section of the assembled unit. The cold elements, which included the load being cooled **301**, the heat spreader **302**, the thermal link **303** and the cooling element **304**, are all in effective thermal contact with each other. The warm elements, which include the chamber **305** and the baffles **306** that absorb the fluorescence, are similarly in good thermal contact with each other. The cold elements and the warm elements are separated by vacuum gaps to minimize heat transfer between the warm elements and the cold elements. In FIG. **3** the chamber covers the cold element and connects with the warm baffles and extracts heat from them.

[0034] FIG. **4** is a schematic illustration of how the radiation and heat flow can be managed in an optical refrigerator. The housing **401** is heat sunk. Sharp corners **402** on the baffles prevent fluorescence from reaching the cold finger. The interior **403** of the housing is coated with material that absorbs fluorescence while limiting emission of thermal radiation. The interior of the housing can be coated with a spectrally selective absorption material that absorbs fluorescence while limiting the emission of thermal radiation. The housing can comprise a material with a high thermal conductivity, for example materials such as copper, aluminum or silver. The selective coating can be a commercial coating such as Maxorb, which is bound to the inner surface of the chamber with adhesives. Alternative coatings include anodized nickel, or tarnished copper or silver. These coatings can be formed directly on the surfaces by electroplating and chemical processing. Sharp corners near the interface of the thermal link and the heat sink can prevent fluorescence from reaching the load being cooled. The housing can be heat sunk by the methods described above.

[0035] FIG. **5** is a cross-section view of a housing with cooling crystal and heat spreader. The surface area of the inside of the optical refrigerator **501** can be minimized to lower radiative heat load. The ends of the cooling crystal **502** can have a special multilayer dielectric mirror coating that provides high reflectivity and generates very little heat. Ion beam sputtering is sometimes used to make high reflectivity mirrors. These two mirrors create a cavity that traps light in the cooling element until it is absorbed. A pinhole in the side of the mirror **503** facing the fiber optic provides access for the laser light to enter the cooling element.

[0036] FIG. **6** is an exploded view of an example optical refrigerator and a device being cooled. A vacuum chamber **601** for a device being cooled **602** mounts with connections for vacuum line and as required by the device. A device being cooled mounts within the vacuum chamber, for example using a mechanical support. A cooling element **603** mounts with an optical refrigerator **605** chamber, which is in thermal communication with the device being cooled. The mechanical support **604** is schematically shown as a disk of low-thermal-conductivity material. Better thermal isolation can be achieved with a spiral-shaped mechanical support or other shape that has a long path for heat transfer and thereby limits the heat leakage.

[0037] FIG. **7** is a schematic for an example circuit that uses waste fluorescence light to generate electrical power for driving a pump laser. The photovoltaic array (PV array) can be mounted on the inside walls of the cooling chamber. The PV array converts some of the energy of the fluorescence into electrical power. The other elements shown in FIG. **7** are electronic components that can be located remotely from the cooler. The buck converter, the microcontroller unit (MCU) and the load share integrated circuit (IC) add the electrical power from the PV array to that of the main power supply to power the laser driver IC. Adding the power from the PV array to the main power supply lessens the power needed to drive the laser and thereby increases the overall efficiency of the optical refrigerator.

[0038] FIGS. **8**, **9** and **10** are schematic illustrations of an example embodiment of an optical refrigerator in which the optical cavity employs mirrors that are outside the vacuum chamber. This embodiment has the advantage that the optical cavity mirrors can be readily adjusted to improve the refrigerator's performance. A second advantage is that any heating that occurs in the mirrors will not impact the cold parts of the optical refrigerator.

[0039] FIG. **8** is an illustration of the cooling element **801**, the thermal link **802** and the heat spreader **803** of this example embodiment. In this example embodiment, the cooling element does not have high reflectivity mirrors on its ends. The end surfaces of the cooling element can be coated with anti-reflection coatings.

[0040] FIG. **9** is an illustration of how the vacuum chamber fits over the cold components. The laser light enters the vacuum chamber **902** through windows **901** that are heat sunk to the vacuum chamber. These windows can comprise sapphire or some other transparent material with a high thermal conductivity.

[0041] FIG. **10** illustrates how the external mirrors can be mounted using mirror mounts **1001**. One of the mirrors has a pinhole in it through which laser light enters the optical cavity.

EXAMPLE APPLICATIONS AND EMBODIMENTS

[0042] The present invention can be combined with high-purity germanium (HPGe) gamma ray spectrometers. These devices need to be cooled to near **100** K to provide high-energy-resolution gamma ray spectra. Additionally, they perform best when they are not subject to vibrations or microphonics. Optical refrigeration is ideal since generates no vibrations. Additionally, the low mass and compactness of optical refrigeration is advantageous for hand-held HPGe units.

[0043] The present invention can also be used in connection with high-temperature superconductor (HTS) devices have to be cooled to near 100 K to function. These devices include computer memories and processors and high-sensitivity magnetometers. The latter can be used for geological and medical applications. Optical refrigerators can cool HTS devices with the advantages of compactness, no moving parts, no vibrations, high reliability, good efficiency, no electromagnetic interference and no sensitivity to the presence of high magnetic fields.

[0044] The present invention can be used in combination with cryogenic refrigerators in pre-cooling of cryogenic refrigerators. Some refrigerators work best if they are pre-cooled; i.e., if the load they are cooling is much colder than room temperature. Refrigerators of this sort include those based on the Joule-Thomson effect (JT coolers). Since JT coolers produce few vibrations, it is advantageous to pre-cool them with vibration-free optical refrigerators.

[0045] The present invention can be used in combination with some conventional electronics that perform better when cooled. For example, low-noise amplifiers (LNA) produce less noise when cooled. Using low-mass optical refrigerators to cool LNA can be advantageous for rapidly moving antennas, where mass is critical in some applications.

[0046] Optical refrigerators according to the present invention can be used in combination with and to cool infrared cameras and detectors for terrestrial and space borne applications. The compactness, lack of vibrations, reliability and good efficiencies of the optical refrigerators make this application attractive.

[0047] Optical refrigerators according to the present invention can be used in combination with and to cool HPGe-based Compton cameras. The compactness and superior energy resolution of the HPGe spectrometers would make these devices more accurate and practical for medical and other imagining.

[0048] Optical refrigerators according to the present invention can be used in combination with and to cool ultra-stable frequency standards of the type developed by Kessler et al. 2012. These standards use cavities made of single silicon crystals cooled to 124 K. Since it is important that no vibrations degrade the cavity, optical refrigerators can be well-suited for cooling these cavities.

[0049] The present invention contemplates cooling crystals or cooling elements that comprise a transparent host material doped with a rare earth ion. Suitable cooling materials include the following:

[0050] (a) $Y\ Li\ F_4$ host crystal doped with Yb^{3+} ions; written as Yb^{3+}:$Y\ Li\ F_4$

[0051] (b) Yb^{3+}:$Ba\ Y_2\ F_8$

[0052] (c) Yb^{3+}:$La\ Cl_3$

[0053] (d) Yb^{3+}:$La\ Cl_3$

[0054] (e) Yb^{3+}:$K\ Pb_2\ Cl_5$

[0055] (f) Yb^{3+}:$La\ Br_3$

[0056] (g) Tm^{3+}:$Y\ Li\ F_4$

[0057] (h) Tm^{3+}:$Ba\ Y_2\ F_8$

[0058] (i) Tm^{3+}:$La\ Cl_3$

[0059] (j) Tm^{3+}:$La\ Cl_3$

[0060] (k) Tm^{3+}:$K\ Pb_2\ Cl_5$

[0061] (I) Tm^{3+}:$La\ Br_3$

[0062] (m) Ho^{3+}:$Y\ Li\ F_4$

[0063] (n) Ho^{3+}:$Ba Y_2 F_8$

[0064] (o) Ho^{3+}:$La Cl_3$

[0065] (p) Ho^{3+}:$La Cl_3$

[0066] (q) Ho^{3+}:$K Pb_2Cl_5$

[0067] (r) Ho^{3+}:$La Br_3$

[0068] (s) Dy^{3+}:$La Cl_3$

[0069] (t) Dy^{3+}:$K Pb_2 Cl_5$ (u) Dy^{3+}:$La Br_3$

[0070] Optical refrigerators according to the present invention can comprise several embodiments of an optical cavity that include the following:

[0071] A cavity formed by coating two ends of the cooling element with highly reflecting mirrors tuned at the wavelength of the pump monochromatic light. One of the mirrors has a pinhole, and the pump light enters the cavity through this pinhole.

[0072] A cavity formed by two highly reflecting mirrors. The cooling element is placed between the two mirrors. One of the mirrors has a pinhole, and the pump light enters the cavity through this pinhole.

[0073] Same as above with the addition that the mirrors are placed outside the vacuum cooling chamber, allowing them to be adjusted. The light enters the cooling chamber through windows in the chamber walls. The windows are heat-sunk to the chamber walls to keep them from heating up.

[0074] The cooling sample and windows in (b) and/or (c) are coated with anti-reflective coatings to minimize reflections.

[0075] The cooling sample and windows in (b) and/or (c) are oriented at the Brewster angle to minimize reflections.

[0076] A cavity formed by exploiting total-internal reflection from the surfaces of the cooling crystal. The pump light can enter the cooling crystal through a small prism mounted on one face. The light rays hit the interior surfaces of the cooling element at angles relative to normal incidence that are large compared to that for required for total internal reflection. The light is repeatedly reflected until it is absorbed or escapes through surface defects.

[0077] Structures and configurations for directing the laser light into the optical cavity in example embodiments of the present invention can include laser light that is brought to the optical refrigerator with an optical fiber and a lens system directs it through a pinhole in one of the cavity mirrors or a surface-mounted prism. This mirror can comprise either the one deposited on the cooling element or an external mirror, depending on the cavity design.

[0078] Example embodiments of the present invention can comprise a cooling chamber that surrounds the cooling element that has one or more of the following features:

[0079] The cooling chamber can be made of a material with a high thermal conductivity such as copper, aluminum or silver.

[0080] The interior surface of the chamber is prepared in such a way that it has selective absorption and emission properties as follows: It has high absorption for light at the wavelength of the fluorescent radiation, and it has a low absorption at the wavelengths corresponding the Planck blackbody radiation at the chamber temperature.

[0081] The selective coating can be created by coating the inside of the chamber with silver, which is then strongly tarnished with silver sulfide, Ag_2S.

[0082] Other useful selective coatings include the commercial coating Maxorb and anodize nickel.

[0083] Example embodiments of the present invention can comprise a thermal link fabricated from a highly transparent solid with high thermal conductivity. Examples include (a) A thermal link made of sapphire; (b) A thermal link with a sharp bend or kink; (c) A thermal link with two or more sharp bends or kinks; (d) A tapered thermal link; (e) Absorbing baffles surrounding the thermal link to remove the fluorescent radiation.

[0084] Example embodiments of the present invention can comprise a heat spreader that thermally connects the thermal link to load to be cooled. Examples include (a) Highly reflecting coating on the heat spreader to limit heating by the fluorescence; (b) Absorbing baffles near the interface of the thermal link and the heat spreader to limit the fluorescence hitting the heat spreader; (c) A means of connecting the heat spreader to the load to be cooled; (c) A means of connecting the heat spreader to the thermal link.

[0085] Example embodiments of the present invention can comprise a system of photovoltaic cells and the associated circuitry for higher-efficiency optical refrigerators.

[0086] The present invention has been described in connection with various example embodiments. It will be understood that the above description is merely illustrative of the applications of the principles of the present invention, the scope of which is to be determined by the claims viewed in light of the specification. Other variants and modifications of the invention will be apparent to those skilled in the art.

What is claimed is:

1. An optical refrigerator, comprising:

(a) a laser source;

(b) a cooling crystal configured to receive light from the laser source;

(c) a cavity configured to enhance the absorption of the laser light in the cooling crystal;

(d) a cold finger configured to accept heat from an object to be cooled by the optical refrigerator;

(d) a thermal link mounted with the cooling crystal and in thermal communication with the cold finger and configured to discourage fluorescence from the cooling crystal from heating the cold finger;

(e) an absorbing chamber mounted to receive fluorescence light from the cooling crystal;

(f) a mechanical support configured to maintain the cooling crystal in optical alignment with the laser source.

2. An optical refrigerator as in claim **1**, wherein the thermal link comprises an element with two or more sharp bends.

3. An optical refrigerator as in claim **1**, wherein the mechanical support has a spiral shape.

4. An optical refrigerator as in claim **1**, wherein the absorbing chamber is coated with a spectrally selective coating.

5. An optical refrigerator as in claim **4**, wherein the spectrally selective coating is tarnished silver.

6. An optical refrigerator as in claim **1**, wherein the cavity comprises a plurality of mirrors, each of which is configured to reflect light onto at least one other mirror in the plurality of mirrors.

7. An optical refrigerator as in claim **6**, wherein at least one of the mirrors has a pinhole therethrough configured to accept light into the cavity.

8. An optical refrigerator as in claim **1**, wherein the absorbing chamber comprises one or more photovoltaic cells mounted with the chamber such that fluorescence light impinges on the one or more photovoltaic cells.

9. An optical refrigerator as in claim **1**, further comprising a heat sink in thermal communication with the absorption chamber.

10. An optical refrigerator as in claim **1**, wherein the thermal link comprises a material having low absorption of fluorescence and high thermal conductivity.

11. An optical refrigerator as in claim **1**, wherein the thermal link is configured such that light entering the thermal link escapes through the sides of the thermal link.

12. An optical refrigerator as in claim **1**, wherein the cooling crystal comprises a transparent host material doped with a rare earth ion.

13. An optical refrigerator as in claim **1**, wherein the absorption chamber has an interior surface with high absorption for light at the wavelength of the fluorescent radiation of the cooling crystal, and low absorption at the wavelengths corresponding to the Planck blackbody radiation at the chamber temperature.

14. An optical refrigerator as in claim **4**, wherein the spectrally selective coating is anodized nickel.

15. An optical refrigerator as in claim **1**, wherein the thermal link comprises sapphire.

16. An optical refrigerator as in claim **1**, wherein the thermal link comprises baffles connected to the absorbing chamber and coated with a selective absorbing coating.

17. An optical refrigerator as in claim **1**, wherein the cavity is defined by surfaces of the cooling crystal configured to achieve substantially total internal reflection.

18. An optical refrigerator as in claim **1**, wherein the thermal link comprises a highly reflective mirror at one end.

* * * * *