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FUCHIMUKAI et al.(10) **Pub. No.: US 2020/0136339 A1**(43) **Pub. Date: Apr. 30, 2020**(54) **WAVELENGTH CONVERTER**(52) **U.S. Cl.**CPC **H01S 3/109** (2013.01); **H01S 3/06758**
(2013.01); **H01S 3/027** (2013.01)(71) Applicant: **Gigaphoton Inc.**, Tochigi (JP)(72) Inventors: **Atsushi FUCHIMUKAI**, Oyama-shi
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(57)

ABSTRACT

A wavelength converter including: A. a crystal holder configured to hold a nonlinear crystal configured to convert a wavelength of a laser beam incident thereon and output the wavelength-converted laser beam; B. a first container configured to accommodate the crystal holder and include a light incident window so provided as to intersect an optical path of the laser beam incident on the nonlinear crystal and a light exiting window so provided as to intersect the optical path of the laser beam having exited out of the nonlinear crystal; C. a second container configured to accommodate the first container; D. a position adjusting mechanism configured to adjust at least a position of the first container; and E. an isolation mechanism configured to spatially isolate the light incident window and the light exiting window from the position adjusting mechanism.

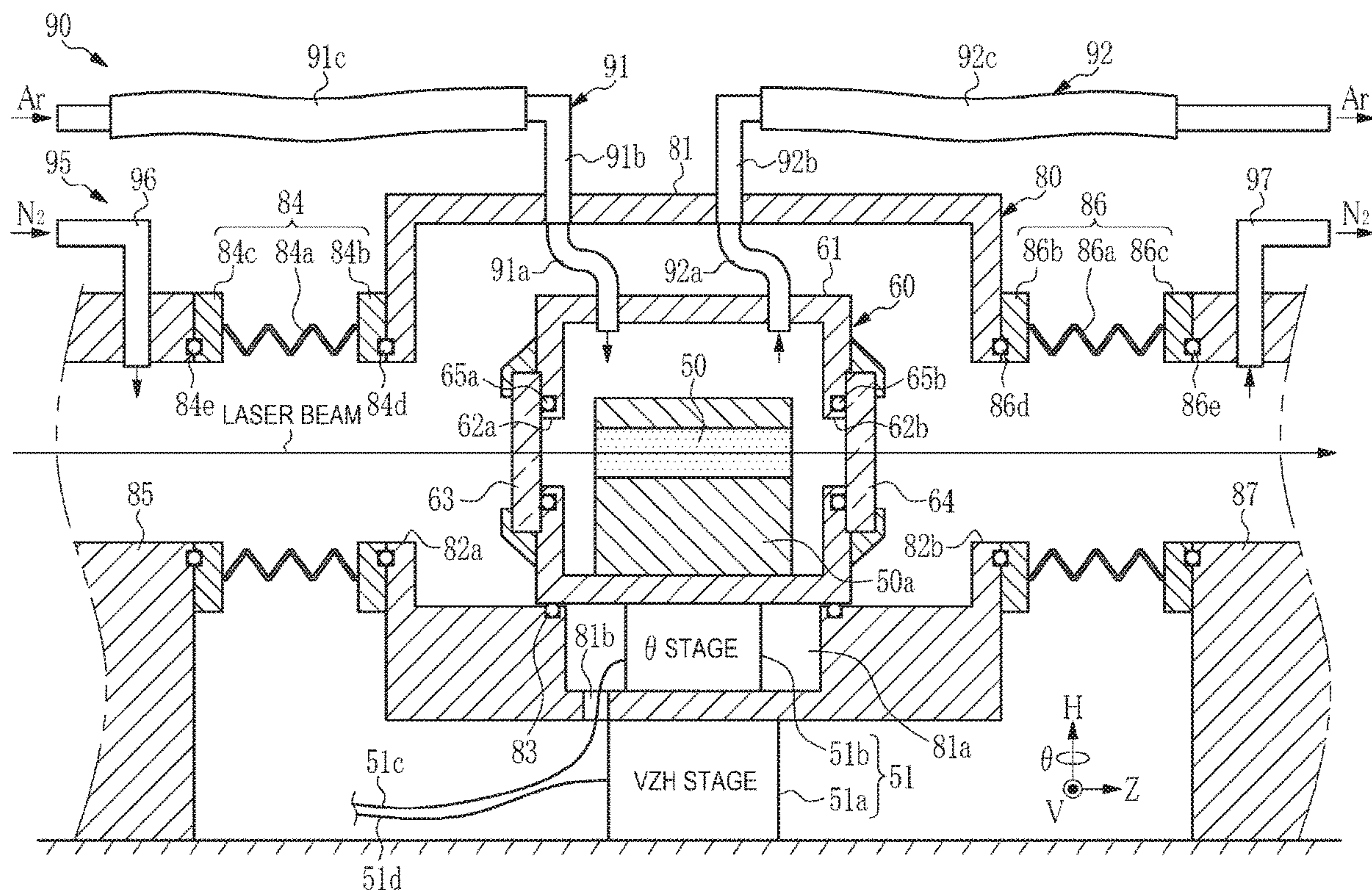
(73) Assignee: **Gigaphoton Inc.**, Tochigi (JP)(21) Appl. No.: **16/731,408**(22) Filed: **Dec. 31, 2019****Related U.S. Application Data**(63) Continuation of application No. PCT/JP2017/
029922, filed on Aug. 22, 2017.**Publication Classification**(51) **Int. Cl.****H01S 3/109** (2006.01)**H01S 3/02** (2006.01)

FIG. 1

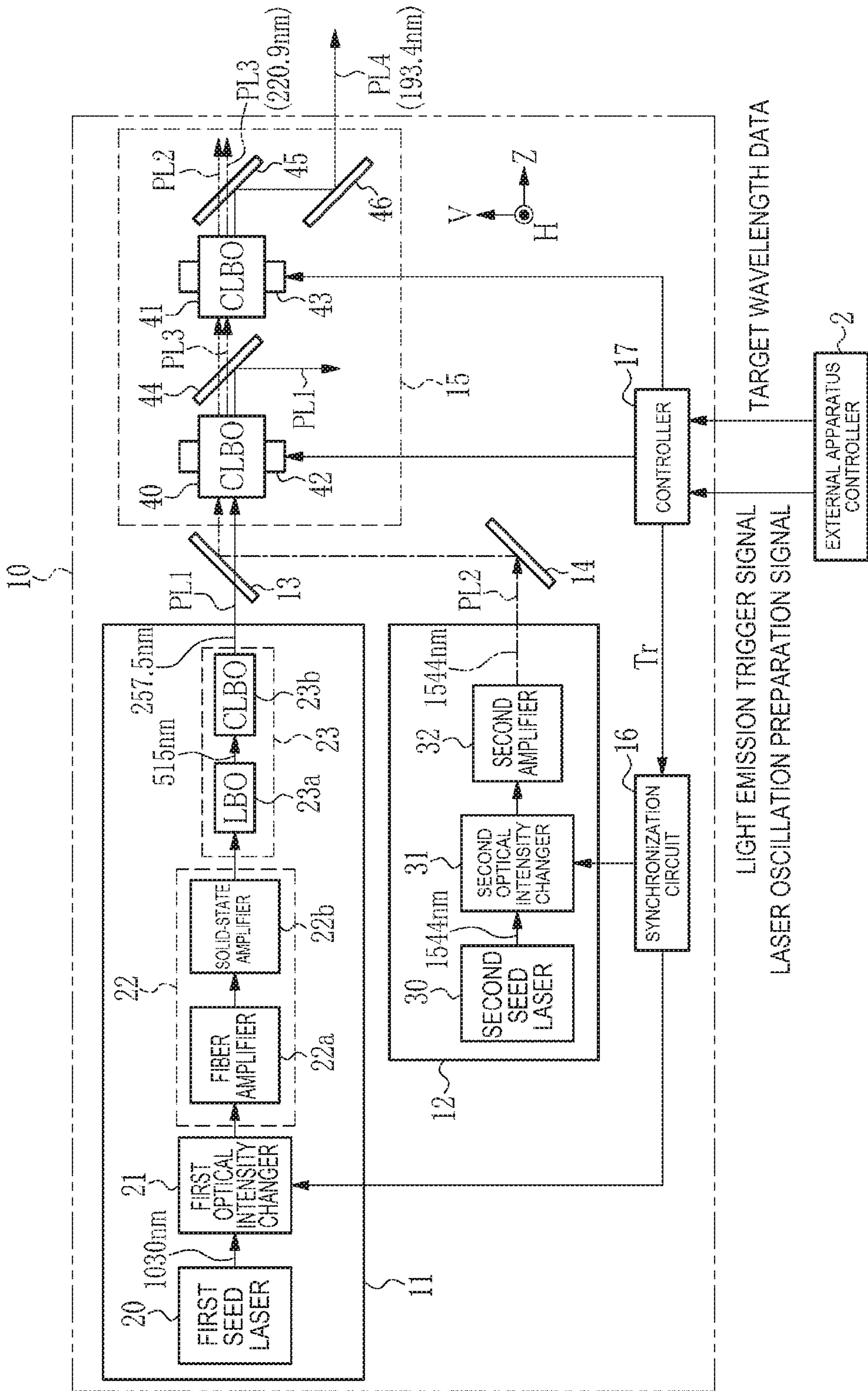


FIG. 2

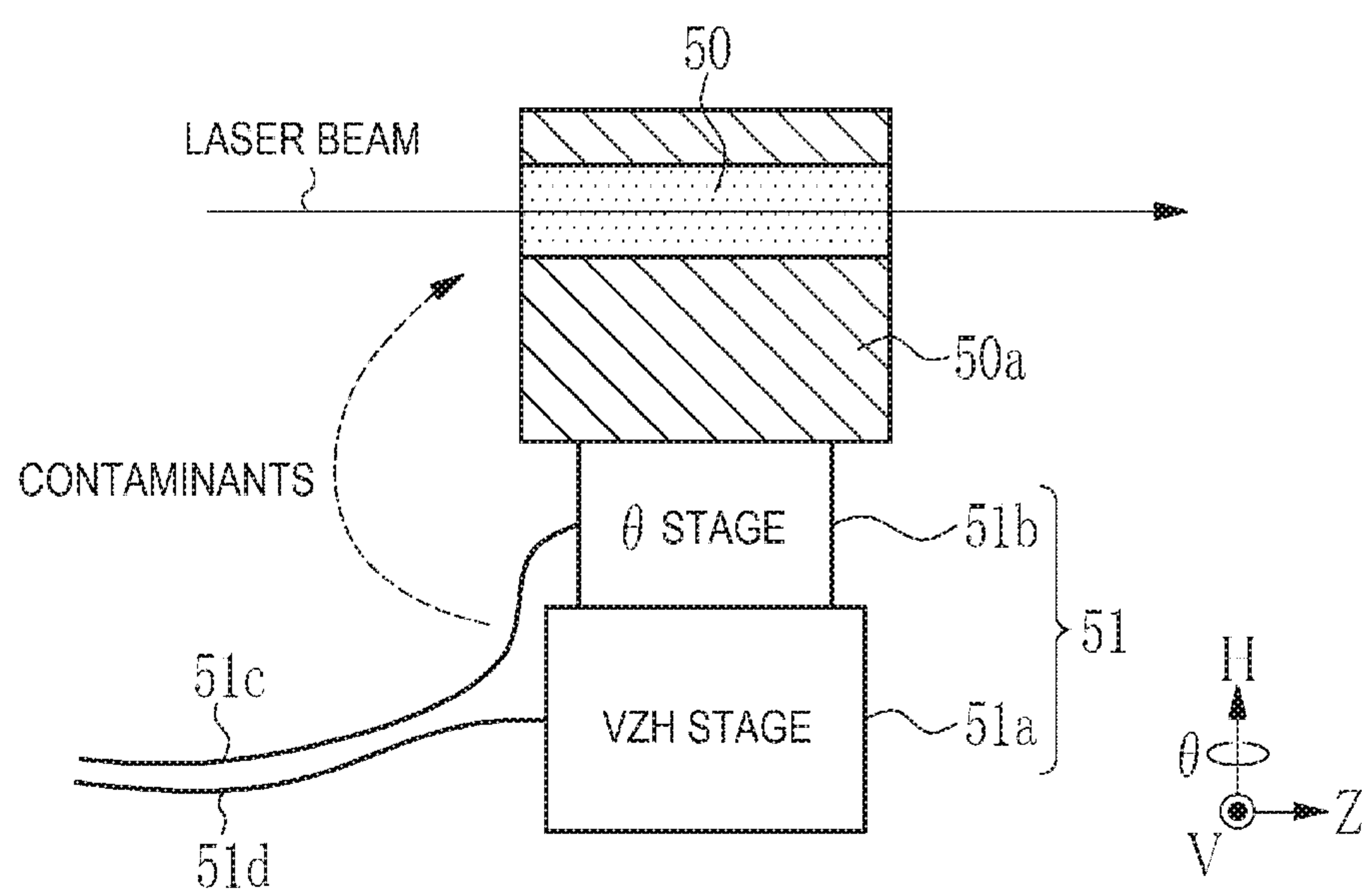
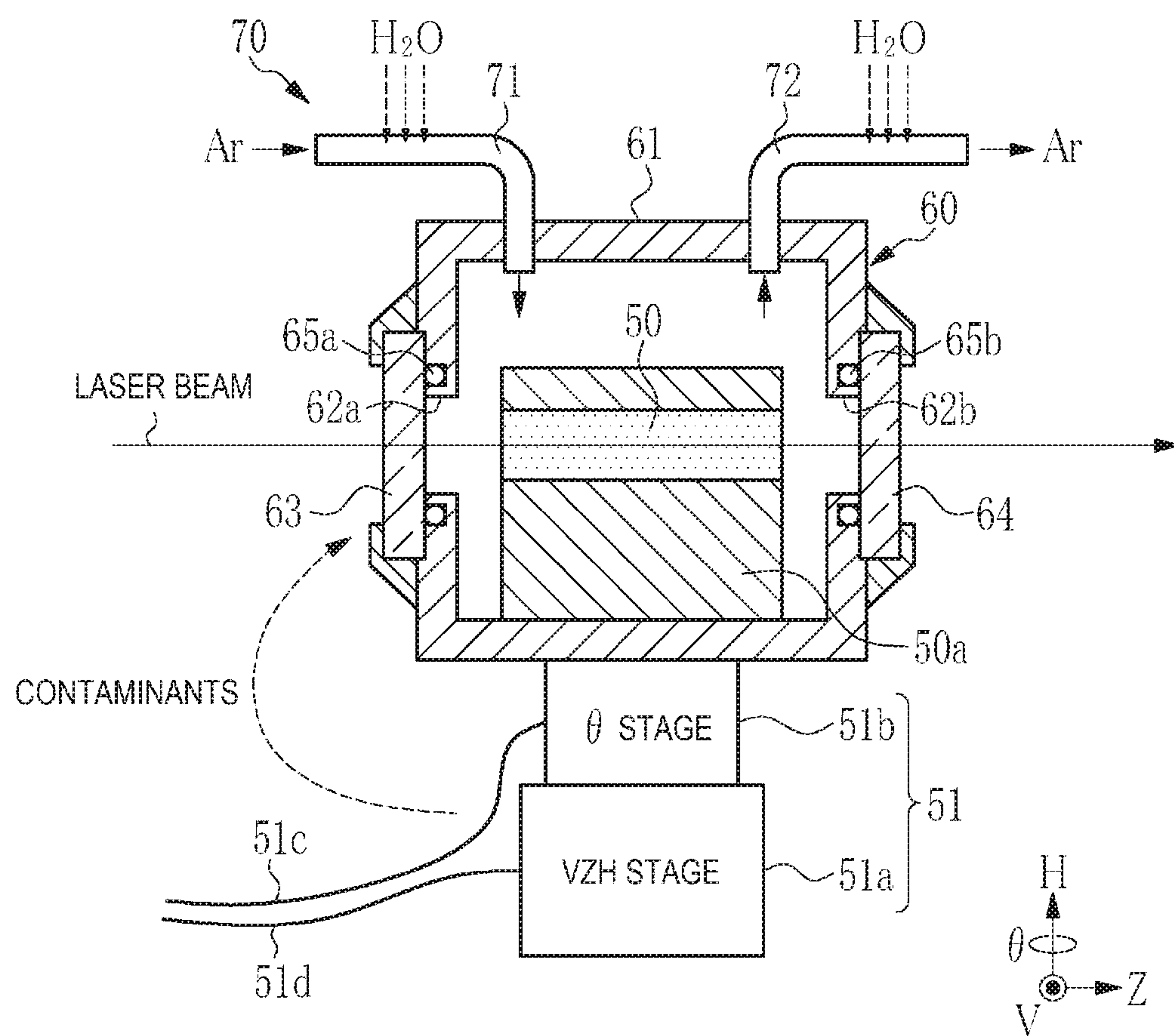


FIG. 3



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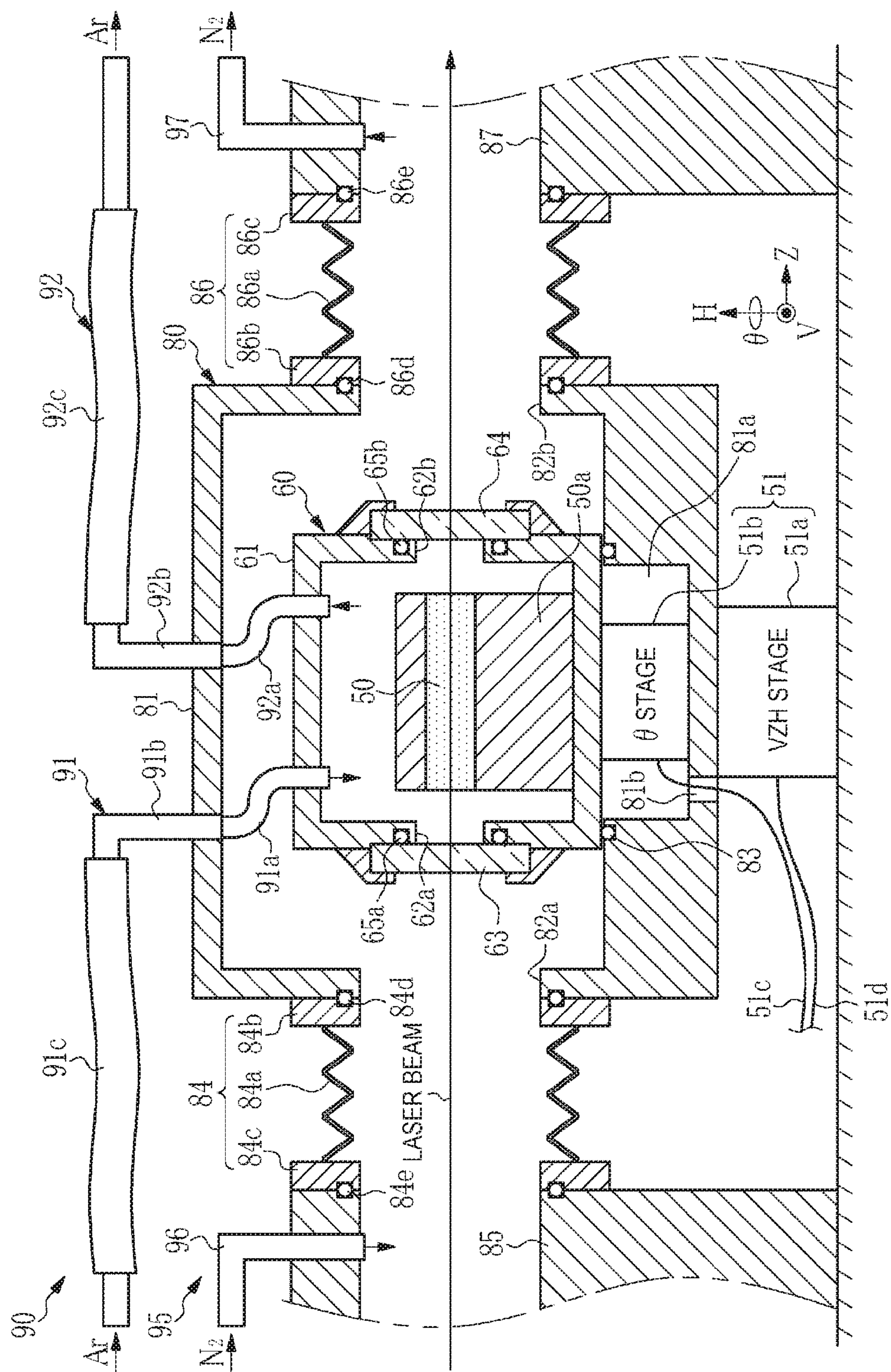
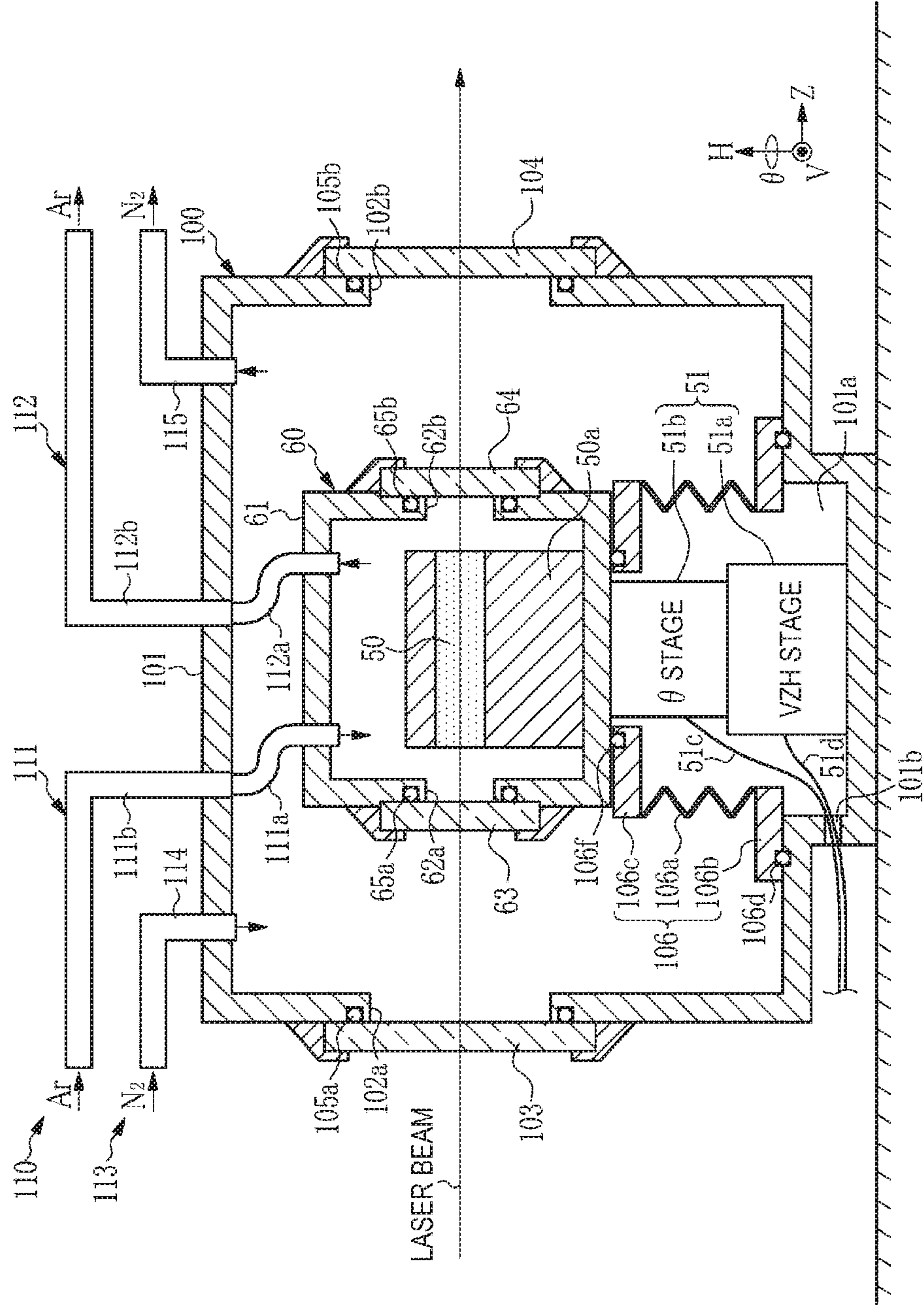


FIG. 5



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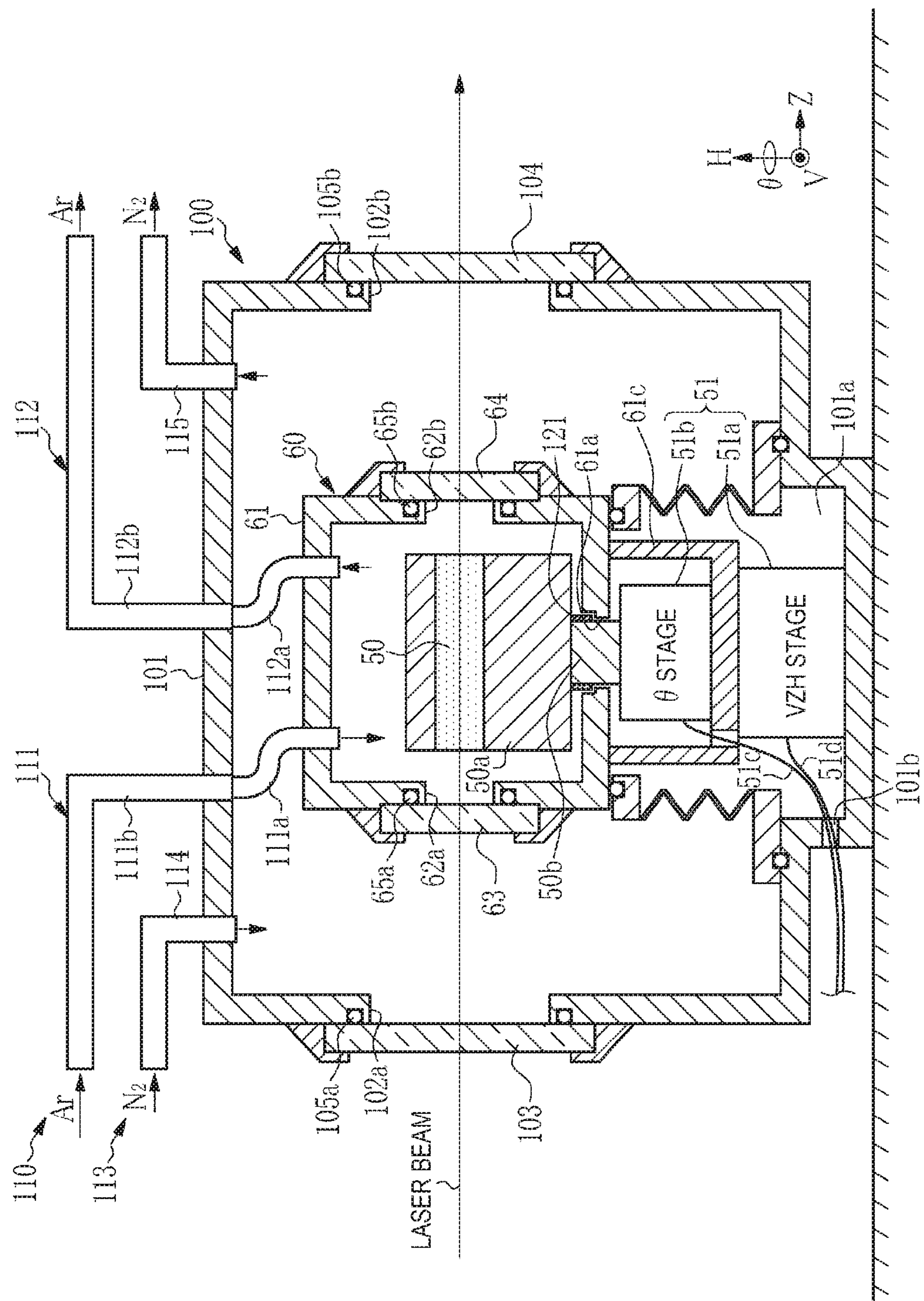


FIG. 8

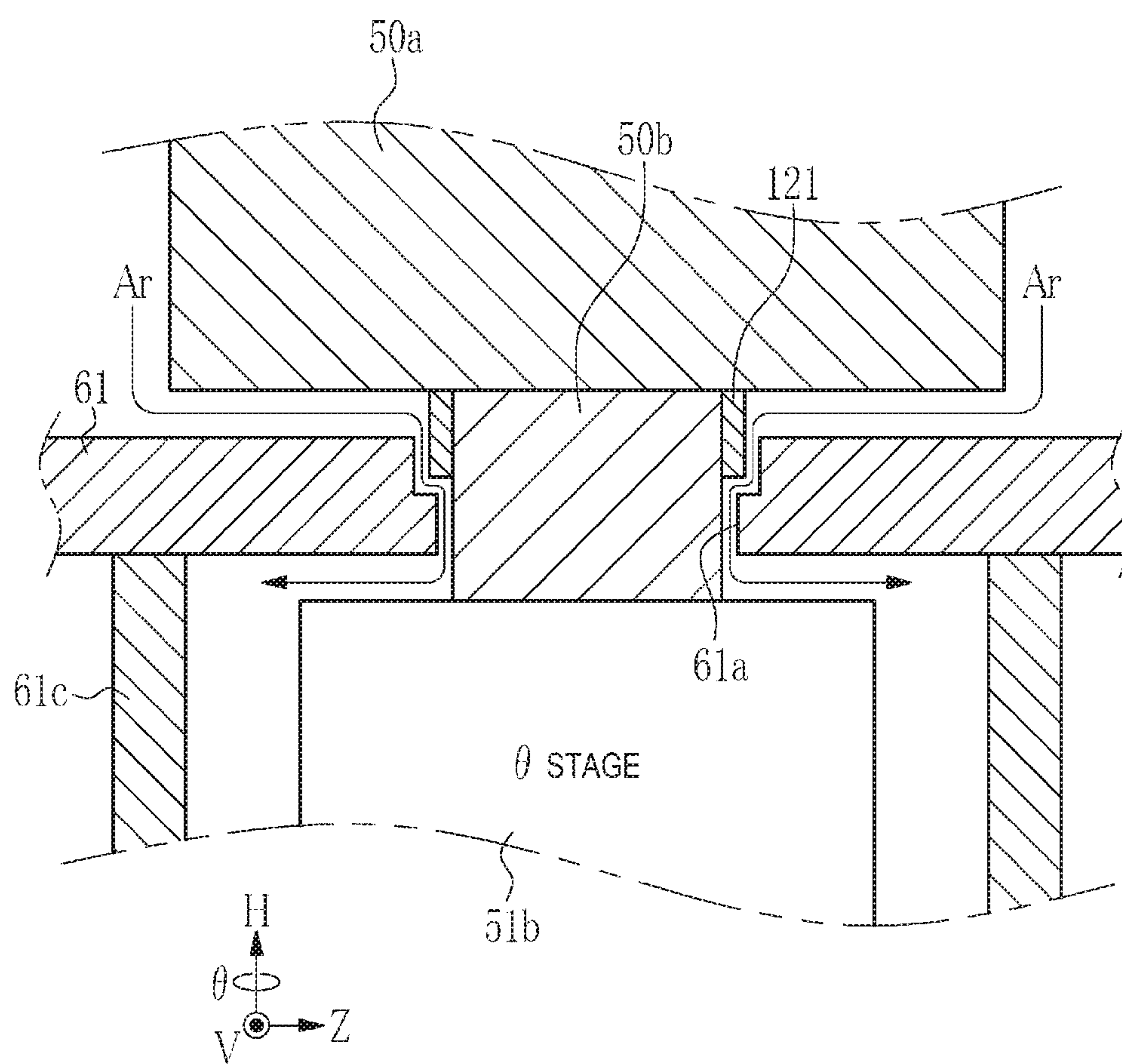


FIG. 9

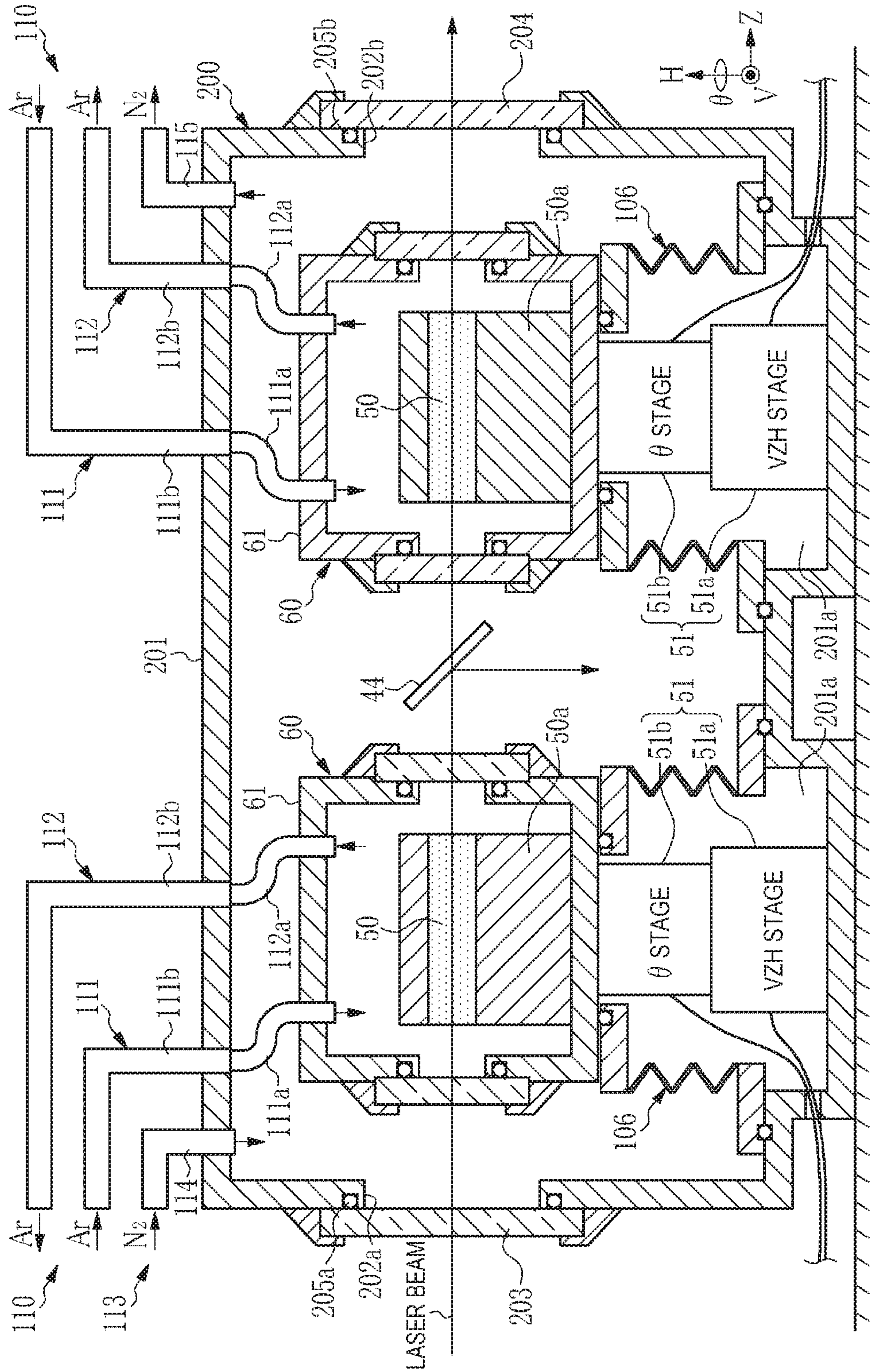


FIG. 10

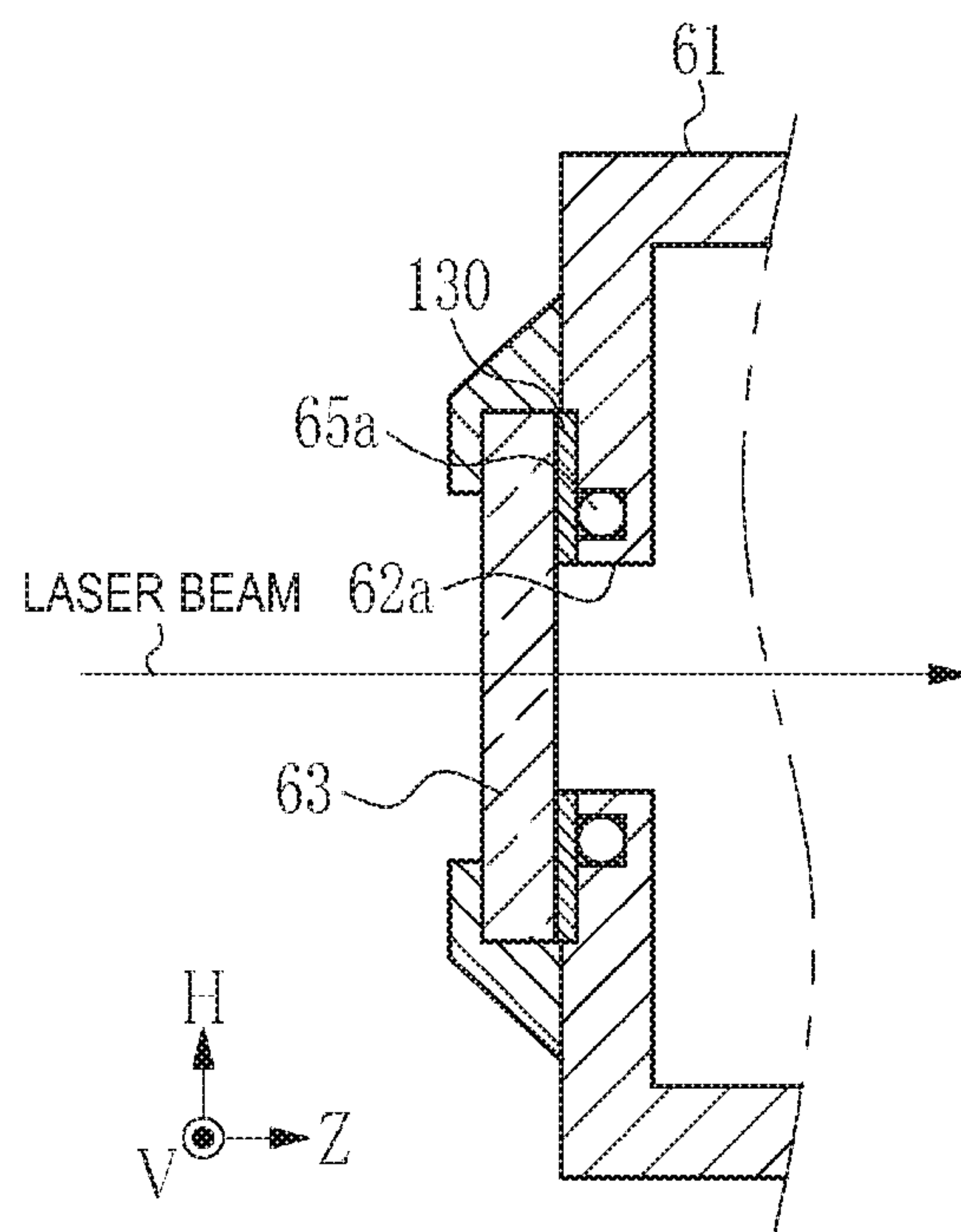
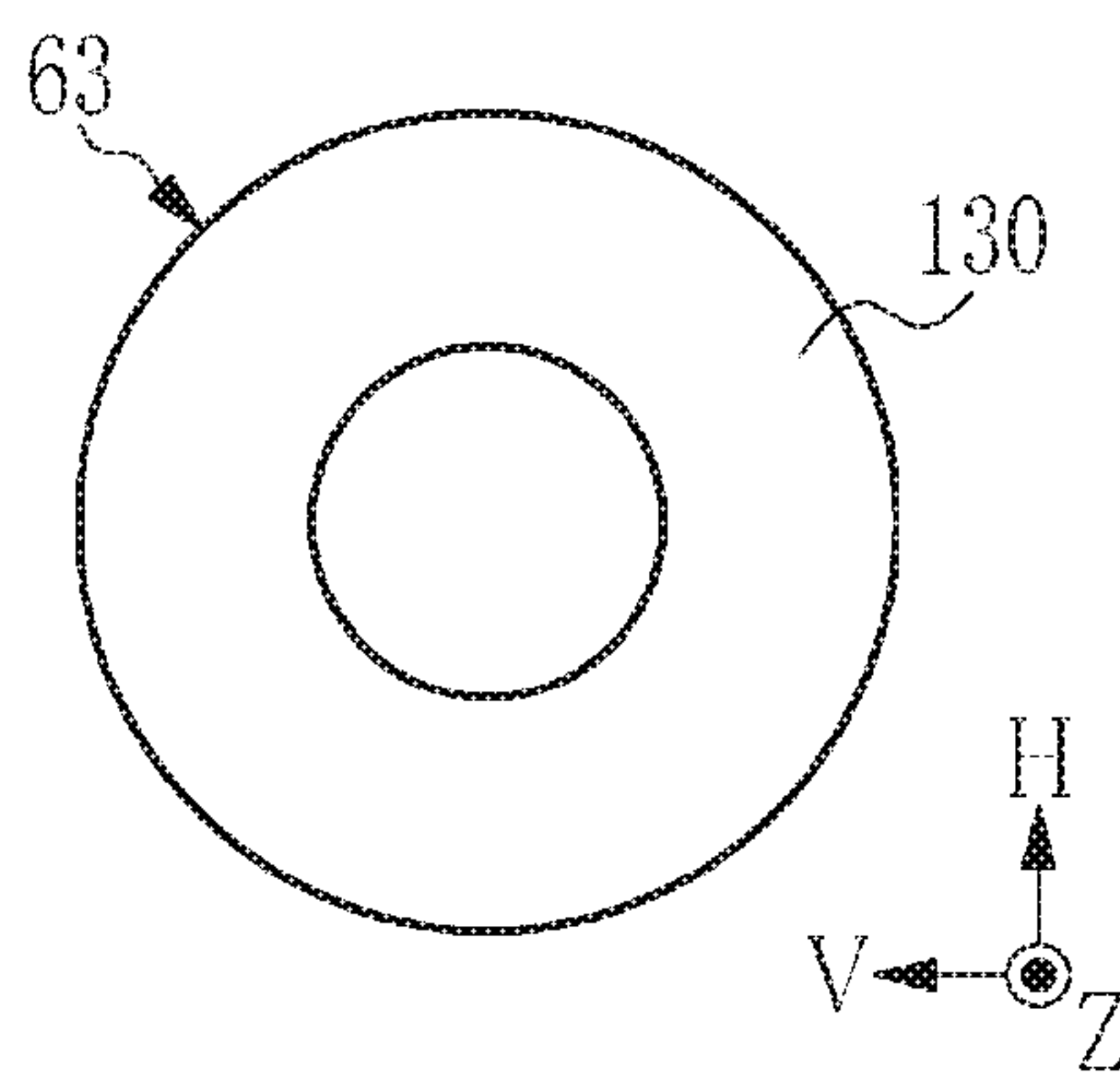


FIG. 11



WAVELENGTH CONVERTER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation application of International Application No. PCT/JP2017/029922 filed on Aug. 22, 2017. The content of the application is incorporated herein by reference in its entirety.

BACKGROUND

1. Technical Field

[0002] The present disclosure relates to a wavelength converter used in a laser apparatus.

2. Related Art

[0003] A semiconductor exposure apparatus is required to improve the resolution as a semiconductor integrated circuit is increasingly miniaturized and highly integrated. A semiconductor exposure apparatus is hereinafter simply referred to as an “exposure apparatus.” To improve the resolution of an exposure apparatus, reduction in the wavelength of the light emitted from a light source for exposure is underway. A gas laser apparatus is used as the light source for exposure in place of a mercury lamp in related art. At present, a KrF excimer laser apparatus configured to emit ultraviolet light having a wavelength of 248 nm or an ArF excimer laser apparatus configured to emit ultraviolet light having a wavelength of 193.4 nm is used as a laser apparatus for exposure.

[0004] As a current exposure technology, liquid-immersion exposure, in which the gap between the exposure lens of the exposure apparatus and a wafer is filled with a liquid, has been put into use. In the liquid-immersion exposure, since the refractive index of the gap changes, the apparent wavelength of the light from the light source for exposure shortens. In the liquid-immersion exposure using an ArF excimer laser apparatus as the light source for exposure, the wafer is irradiated with ultraviolet light having a wavelength of 134 nm in water. The technology described above is called ArF liquid-immersion exposure. The ArF liquid-immersion exposure is also called ArF liquid-immersion lithography.

[0005] Since KrF and ArF excimer laser apparatuses each have a wide spectral linewidth ranging from about 350 to 400 pm in spontaneous oscillation, the chromatic aberrations occur in association with the laser beam (ultraviolet light) projected with the size thereof reduced onto the wafer via the projection lens of the exposure apparatus, resulting in a decrease in the resolution of the projection lens. To avoid the decrease in the resolution, the spectral linewidth of the laser beam emitted from the gas laser apparatus needs to be narrow enough to make the chromatic aberrations negligible. A line narrowing module including a line narrowing element is therefore provided in the laser resonator of the gas laser apparatus. The line narrowing module narrows the spectral linewidth. For example, the line narrowing element may be an etalon or a grating. A laser apparatus having a narrowed spectral linewidth described above is referred to as a narrowed-linewidth laser apparatus.

[0006] Some laser apparatus for exposure apparatus each use a solid-state laser apparatus from the viewpoint of

energy conservation. The solid-state laser apparatus includes a semiconductor laser, a nonlinear crystal, and other components.

CITATION LIST

Patent Literature

[PTL 1] JP-A-2001-296570

[PTL 2] JP-T-2011-507305

[PTL 3] JP-A-2000-347234

[PTL 4] JP-A-2010-128119

[PTL 5] JP-A-2011-211234

SUMMARY

[0007] A wavelength converter according to a viewpoint of the present disclosure includes the following:

[0008] A. a crystal holder that holds a nonlinear crystal configured to convert a wavelength of a laser beam incident thereon and output the wavelength-converted laser beam;

[0009] B. a first container configured to accommodate the crystal holder and include a light incident window so provided as to intersect an optical path of the laser beam incident on the nonlinear crystal and a light exiting window so provided as to intersect the optical path of the laser beam having exited out of the nonlinear crystal;

[0010] C. a second container configured to accommodate the first container; D. a position adjusting mechanism configured to adjust at least a position of the first container; and

[0011] E. an isolation mechanism configured to spatially isolate the light incident window and the light exiting window from the position adjusting mechanism.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Embodiments of the present disclosure will be described below only by way of example with reference to the accompanying drawings.

[0013] FIG. 1 schematically shows the configuration of a solid-state laser system according to Comparative Example.

[0014] FIG. 2 shows the configuration of a position adjusting mechanism.

[0015] FIG. 3 describes problems with the solid-state laser system according to Comparative Example.

[0016] FIG. 4 shows the configuration of a wavelength converter according to a first embodiment.

[0017] FIG. 5 shows the configuration of a wavelength converter according to a second embodiment.

[0018] FIG. 6 shows the configuration of a wavelength converter according to a third embodiment.

[0019] FIG. 7 shows a variation of the wavelength converter according to the third embodiment.

[0020] FIG. 8 is an enlarged view of a rotational shaft and therearound.

[0021] FIG. 9 shows the configuration of a wavelength converter according to a fourth embodiment.

[0022] FIG. 10 is a cross-sectional view of a light incident window on which a shielding film is provided.

[0023] FIG. 11 is a front view of the light incident window on which the shielding film is provided.

DETAILED DESCRIPTION

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[0025] 6. Various variations

[0026] Embodiments of the present disclosure will be described below in detail with reference to the drawings. The embodiments described below show some examples of the present disclosure and are not intended to limit the contents of the present disclosure. Further, all configurations and operations described in the embodiments are not necessarily essential as configurations and operations in the present disclosure. The same component has the same reference character, and no redundant description of the same component will be made.

1. Comparative Example

[0027] 1.1 Configuration**[0028]** 1.1.1 Overall Configuration

[0029] FIG. 1 schematically shows the configuration of a solid-state laser system 10 according to Comparative Example. In FIG. 1, the solid-state laser system 10 includes a first solid-state laser apparatus 11, a second solid-state laser apparatus 12, a dichroic mirror 13, a high-reflectance mirror 14, a wavelength conversion system 15, a synchronization circuit 16, and a controller 17.

[0030] The first solid-state laser apparatus 11 includes a first seed laser 20, a first optical intensity changer 21, a first amplifier 22, and a wavelength converter 23. The first amplifier 22 includes a fiber amplifier 22a, a solid-state amplifier 22b, and a CW-excitation semiconductor laser that is not shown. The wavelength converter 23 includes an LBO (LiB_3O_5) crystal 23a and a CLBO ($\text{CsLiB}_6\text{O}_{10}$) crystal 23b. The LBO crystal 23a and the CLBO crystal 23b are each a nonlinear crystal.

[0031] The first seed laser 20 outputs a single-longitudinal-mode CW or pulsed beam having a wavelength of about 1030 nm as a first seed beam. For example, the first seed laser 20 is a distributed feedback semiconductor laser. The first optical intensity changer 21 includes a semiconductor device on which the first seed beam is incident from the first seed laser 20. The first optical intensity changer 21 converts the first seed light into a laser beam having a predetermined pulse width by causing a current controller that is not shown to apply pulsed current to the semiconductor device. The first seed beam converted by the first optical intensity changer 21 is hereinafter referred to as a first seed pulsed beam.

[0032] The fiber amplifier 22a is formed of a plurality of quartz fibers to which Yb is doped and which are connected to each other for multi-stage amplification. The solid-state amplifier 22b is a YAG crystal to which Yb is doped. The fiber amplifier 22a and the solid-state amplifier 22b are optically excited with CW excitation beam inputted from the CW-excitation semiconductor laser that is not shown. The first amplifier 22 amplifies the first seed pulsed beam incident from the first optical intensity changer 21.

[0033] The wavelength converter 23 converts the first seed pulsed beam amplified by the first amplifier 22 into a harmonic beam and outputs the harmonic beam as a first pulsed laser beam PL1. Specifically, the wavelength converter 23, which includes the LBO crystal 23a and the CLBO crystal 23b, produces a fourth harmonic beam having a wavelength of about 257.5 nm from the first seed pulsed beam and outputs the fourth harmonic beam as the first pulsed laser beam PL1.

[0034] The second solid-state laser apparatus 12 includes a second seed laser 30, a second optical intensity changer 31, and a second amplifier 32. The second amplifier 32 includes an Er fiber amplifier that is not shown and is formed of a plurality of quartz fibers to which Er and Yb are doped and which are connected to each other for multi-stage amplification, and the second amplifier 32 further includes a CW-excitation semiconductor laser that is not shown.

[0035] The second seed laser 30 outputs a single-longitudinal-mode CW or pulsed beam having a wavelength of about 1554 nm as a second seed beam. For example, the second seed laser 30 is a distributed feedback semiconductor laser. The second optical intensity changer 31 includes a semiconductor device on which the second seed beam is incident from the second seed laser 30. The second optical intensity changer 31 converts the second seed light into a laser beam having a predetermined pulse width by causing a current controller that is not shown to apply pulsed current to the semiconductor device. The second seed beam converted by the second optical intensity changer 31 is hereinafter referred to as a second seed pulsed beam.

[0036] The Er fiber amplifier provided in the second amplifier 32 is optically excited with CW excitation beam inputted from the CW-excitation semiconductor laser that is

not shown. The second amplifier **32** amplifies the second seed pulsed beam incident from the second optical intensity changer **31**. The second amplifier **32** outputs the amplified second seed pulsed beam as a second pulsed laser beam PL2.

[0037] The dichroic mirror **13** is so disposed as to receive the first pulsed laser beam PL1 outputted from the first solid-state laser apparatus **11**. The high-reflectance mirror **14** is so disposed as to reflect the second pulsed laser beam PL2 outputted from the second solid-state laser apparatus **12** at high reflectance and cause the second pulsed laser beam PL2 reflected at high reflectance to be incident on the dichroic mirror **13**.

[0038] The dichroic mirror **13** is coated with a film which transmits the first pulsed laser beam PL1 having the wavelength of about 257.5 nm at high transmittance and reflects the second pulsed laser beam PL2 having the wavelength of about 1554 nm at high reflectance. The dichroic mirror **13** is so disposed that the optical path axis of the first pulsed laser beam PL1 that the dichroic mirror **13** has transmitted at high transmittance coincides with the optical path axis of the second pulsed laser beam PL2 that the dichroic mirror **13** has reflected at high reflectance.

[0039] The wavelength conversion system **15** includes a first CLBO crystal **40**, a second CLBO crystal **41**, a first position adjusting mechanism **42**, a second position adjusting mechanism **43**, a first dichroic mirror **44**, a second dichroic mirror **45**, and a high-reflectance mirror **46**. The first CLBO crystal **40** and the second CLBO crystal **41** are each a nonlinear crystal.

[0040] The first CLBO crystal **40**, the first dichroic mirror **44**, the second CLBO crystal **41**, and the second dichroic mirror **45** are arranged in the presented order along the optical paths of the first pulsed laser beam PL1 and the second pulsed laser beam PL2. The first pulsed laser beam PL1 and the second pulsed laser beam PL2 are incident on the first CLBO crystal **40**.

[0041] The first CLBO crystal **40** superimposes the first pulsed laser beam PL1 and the second pulsed laser beam PL2 on each other into a third pulsed laser beam PL3 having a wavelength of about 220.9 nm corresponding to the sum frequency of the wavelength of about 257.5 nm and the wavelength of about 1554 nm. The first pulsed laser beam PL1 and the second pulsed laser beam PL2 pass through the first CLBO crystal **40**.

[0042] The first dichroic mirror **44** is coated with a film which reflects the first pulsed laser beam PL1 at high reflectance and transmits the second pulsed laser beam PL2 and the third pulsed laser beam PL3 at high transmittance. The second pulsed laser beam PL2 and the third pulsed laser beam PL3 that the first dichroic mirror **44** has transmitted at high transmittance are incident on the second CLBO crystal **41**.

[0043] The second CLBO crystal **41** superimposes the second pulsed laser beam PL2 and the third pulsed laser beam PL3 on each other into a fourth pulsed laser beam PL4 having a wavelength of about 193.4 nm corresponding to the sum frequency of the wavelength of about 1554 nm and the wavelength of about 220.9 nm. The second pulsed laser beam PL2 and the third pulsed laser beam PL3 pass through the second CLBO crystal **41**.

[0044] The second dichroic mirror **45** is coated with a film which reflects the fourth pulsed laser beam PL4 at high reflectance and transmits the second pulsed laser beam PL2 and the third pulsed laser beam PL3 at high transmittance.

The high-reflectance mirror **46** is so disposed as to reflect at high reflectance the fourth pulsed laser beam PL4 that the second dichroic mirror **45** has reflected at high reflectance and outputs the reflected fourth pulsed laser beam PL4 from the wavelength conversion system **15**.

[0045] The first position adjusting mechanism **42** adjusts the position of the first CLBO crystal **40**. Specifically, the first position adjusting mechanism **42** linearly drives the first CLBO crystal **40** in the directions along axes V and H and rotationally drives the first CLBO crystal **40** in a direction θ , which is the rotational direction around the axis H. The axes H, V, and Z are perpendicular to one another. The axis-Z direction is the direction along the optical path axes of the first pulsed laser beam PL1 and the second pulsed laser beam PL2 that enter the wavelength conversion system **15**. For example, the axis-H direction is the vertical direction.

[0046] The second position adjusting mechanism **43** adjusts the position of the second CLBO crystal **41**. The configuration of the second position adjusting mechanism **43** is the same as the configuration of the first position adjusting mechanism **42**. The second position adjusting mechanism **43** linearly drives the second CLBO crystal **41** in the axis-V and axis-H directions and rotationally drives the second CLBO crystal **41** in the direction θ .

[0047] The controller **17** is electrically connected to the first position adjusting mechanism **42** and the second position adjusting mechanism **43** and controls the driving operation performed by the first position adjusting mechanism **42** and the second position adjusting mechanism **43**. The controller **17** is also electrically connected to the synchronization circuit **16**. The synchronization circuit **16** is electrically connected to the first optical intensity changer **21** and the second optical intensity changer **31**. The synchronization circuit **16** controls the first optical intensity changer **21** and the second optical intensity changer **31** based on a trigger signal Tr inputted from the controller **17** to synchronize the timings at which the first seed pulsed beam and the second seed pulsed beam are generated with each other. The controller **17** is further electrically connected to the first seed laser **20**, the second seed laser **30**, the CW-excitation semiconductor laser provided in the first amplifier **22**, and the CW-excitation semiconductor laser provided in the second amplifier **32** via signal lines that are not shown.

[0048] The controller **17** receives a laser oscillation preparation signal, a light emission trigger signal, and target wavelength data from an external apparatus controller **2** provided in an exposure apparatus that is not shown and controls the first position adjusting mechanism **42**, the second position adjusting mechanism **43**, the synchronization circuit **16**, the first seed laser **20**, the second seed laser **30**, and other components.

[0049] 1.1.2 Configurations of position adjusting mechanisms

[0050] The configurations of the first position adjusting mechanism **42** and the second position adjusting mechanism **43** will next be described. FIG. 2 shows a position adjusting mechanism **51** used as the first position adjusting mechanism **42** or the second position adjusting mechanism **43** described above. A nonlinear crystal **50** is detachably held by a crystal holder **50a**. The position adjusting mechanism **51** adjusts the position of the crystal holder **50a**. The nonlinear crystal **50** is the first CLBO crystal **40** or the second CLBO crystal **41**.

[0051] The position adjusting mechanism **51** includes a VZH stage **51a** as a linear driver and a θ stage **51b** as a rotational driver. The θ stage **51b** is placed on the VZH stage **51a**. The crystal holder **50a** is placed on the θ stage **51b**. The VZH stage **51a** can linearly move the crystal holder **50a** in the axis-V, axis-Z, and axis-H directions to change the position of the nonlinear crystal **50** with respect to the laser beam. The θ stage **51b** can rotate the crystal holder **50a** in the direction θ around the axis H to change the angle of incidence of the laser beam incident on the nonlinear crystal **50**.

[0052] The VZH stage **51a** and the θ stage **51b** are each formed, for example, of a stepper motor that is not shown. A wiring line **51c** and a wiring line **51d** are connected to the VZH stage **51a** and the θ stage **51b**, respectively. The VZH stage **51a** and the θ stage **51b** are driven via the wiring line **51c** and the wiring line **51d**, respectively.

[0053] 1.2 Operation

[0054] The operation of the solid-state laser system **10** according to Comparative Example will next be described. Upon reception of the laser oscillation preparation signal from the external apparatus controller **2**, the controller **17** causes the first seed laser **20**, the second seed laser **30**, and the CW-excitation semiconductor lasers provided in the first amplifier **22** and the second amplifier **32** to start oscillating.

[0055] The first seed beam is thus outputted from the first seed laser **20** and inputted to the first optical intensity changer **21**. Before a control signal that will be described later is inputted to the first optical intensity changer **21**, the first optical intensity changer **21** suppresses the amplification of the first seed beam. Similarly, the second seed beam is thus outputted from the second seed laser **30** and inputted to the second optical intensity changer **31**. Before a control signal that will be described later is inputted to the second optical intensity changer **31**, the second optical intensity changer **31** suppresses the amplification of the second seed beam. The first amplifier **22** and the second amplifier **32** are optically excited with the CW excitation beams inputted from the CW-excitation semiconductor lasers that are not shown.

[0056] Upon reception of the light emission trigger signal from the external apparatus controller **2**, the controller **17** transmits the trigger signal Tr to the synchronization circuit **16**. Upon reception of the trigger signal Tr, the synchronization circuit **16** transmits control signals to the first optical intensity changer **21** and the second optical intensity changer **31**. Upon reception of the control signal, the first optical intensity changer **21** amplifies the first seed beam only for a predetermined period to generate a first seed pulsed beam having a predetermined pulse width and causes the generated first seed pulsed beam to enter the first amplifier **22**. Similarly, upon reception of the control signal, the second optical intensity changer **31** amplifies the second seed beam only for a predetermined period to generate a second seed pulsed beam having a predetermined pulse width and causes the generated second seed pulsed beam to enter the second amplifier **32**.

[0057] Having entered the first amplifier **22** and the second amplifier **32**, the first seed pulsed beam and the second seed pulsed beam are amplified based on stimulated emission. The first seed pulsed beam amplified by the first amplifier **22** enters the wavelength converter **23**. The first seed pulsed beam having entered the wavelength converter **23** is converted into a fourth harmonic beam, which is outputted as

the first pulsed laser beam PL1 from the first solid-state laser apparatus **11**. On the other hand, the second seed pulsed beam amplified by the second amplifier **32** is outputted as the second pulsed laser beam PL2 from the second solid-state laser apparatus **12**.

[0058] The first pulsed laser beam PL1 outputted from the first solid-state laser apparatus **11** passes through the dichroic mirror **13** at high transmittance and enters the wavelength conversion system **15**. The second pulsed laser beam PL2 outputted from the second solid-state laser apparatus **12** is reflected off the high-reflectance mirror **14** at high reflectance, is reflected off the dichroic mirror **13** at high reflectance, and enters the wavelength conversion system **15**.

[0059] The synchronization circuit **16** adjusts the timings at which the control signals described above are inputted to the first optical intensity changer **21** and the second optical intensity changer **31** in such a way that the first pulsed laser beam PL1 and the second pulsed laser beam PL2 having entered the wavelength conversion system **15** enter the first CLBO crystal **40** substantially at the same time.

[0060] The first pulsed laser beam PL1 and the second pulsed laser beam PL2 are superimposed on each other in the first CLBO crystal **40** into the third pulsed laser beam PL3, which is a beam having a frequency equal to the sum of the frequency of the first pulsed laser beam PL1 and the frequency of the second pulsed laser beam PL2. The first pulsed laser beam PL1 having passed through the first CLBO crystal **40** is reflected off the first dichroic mirror **44** at high reflectance. The second pulsed laser beam PL2 having passed through the first CLBO crystal **40** and the third pulsed laser beam PL3 pass through the first dichroic mirror **44** at high transmittance and enter the second CLBO crystal **41**.

[0061] The second pulsed laser beam PL2 and the third pulsed laser beam PL3 are superimposed on each other in the second CLBO crystal **41** into the fourth pulsed laser beam PL4, which is a beam having a frequency equal to the sum of the frequency of the second pulsed laser beam PL2 and the frequency of the third pulsed laser beam PL3. The second pulsed laser beam PL2 and the third pulsed laser beam PL3 having passed through the second CLBO crystal **41** pass through the second dichroic mirror **45** at high transmittance. On the other hand, the fourth pulsed laser beam PL4 is reflected off the second dichroic mirror **45** at high reflectance, further reflected off the high-reflectance mirror **46** at high reflectance, and outputted from the wavelength conversion system **15**.

[0062] The fourth pulsed laser beam PL4 outputted from the wavelength conversion system **15** is outputted from the solid-state laser system **10**, amplified by an ArF excimer amplifier that is not shown, then inputted to the exposure apparatus that is not shown, and used as exposure light.

[0063] The controller **17** transmits the trigger signal Tr to the synchronization circuit **16** whenever the controller **17** receives the light emission trigger signal from the external apparatus controller **2**. The fourth pulsed laser beam PL4 is thus repeatedly outputted from the solid-state laser system **10**.

[0064] The controller **17** counts the number of actions of receiving the light emission trigger signal from the external apparatus controller **2** and causes the first position adjusting mechanism **42** and the second position adjusting mechanism **43** to operate whenever the count, that is, the number of

shots reaches a predetermined number to linearly drive the CLBO crystals in the directions perpendicular to the directions along the optical path axes of the laser beams. Specifically, the controller 17 moves the first CLBO crystal 40 and the second CLBO crystal 41 by a predetermined distance in at least one of the axis-V and axis-H directions. The reason for this is to reduce damage of the first CLBO crystal 40 and the second CLBO crystal 41 resulting from a situation in which the ultraviolet pulsed laser beams keep being incident on a specific portion of each of the CLBO crystals and a situation in which the ultraviolet beams having undergone the wavelength conversion keep being generated. The crystal life of each of the first CLBO crystal 40 and the second CLBO crystal 41 can thus be prolonged.

[0065] The controller 17 changes the oscillation wavelength of the first seed laser 20 or the second seed laser 30 in accordance with the target wavelength data received from the external apparatus controller 2. Further, the controller 17 causes the first position adjusting mechanism 42 and the second position adjusting mechanism 43 to operate to rotate the CLBO crystals in the direction θ in accordance with the target wavelength data. Specifically, the controller 17 causes the first CLBO crystal 40 and the second CLBO crystal 41 to rotate in the direction θ in such a way that the angles of incidence of the laser beams incident on the first CLBO crystal 40 and the second CLBO crystal 41 are equal to phase matching angles corresponding to target wavelengths. As a result, even when the target wavelengths are changed, the angles of incidence of the laser beams always coincide with the phase matching angles, whereby the first CLBO crystal 40 and the second CLBO crystal 41 generate intensive sum-frequency beams.

[0066] 1.3 Problems

[0067] The position adjusting mechanism 51 includes a driver, such as the stepper motor, as described above. The driver, such as the stepper motor, includes mechanical components, such as a gear, and therefore, a lubricant containing an organic substance, such as oil, is applied to the mechanical components to reduce friction therebetween. The nonlinear crystal 50 could therefore be contaminated when the organic substance contained in the lubricant is emitted in the form of outgas and the ultraviolet pulsed laser beams optically decompose the outgas.

[0068] Specifically, the outgas emitted from the driver in the position adjusting mechanism 51 is optically decomposed by the ultraviolet pulsed laser beams, and the decomposed outgas could adhere as contaminants to the surface of the nonlinear crystal 50. When the nonlinear crystal 50 is irradiated with the laser beams with the contaminants adhering to the surface of the nonlinear crystal 50, the transmittance of the laser beams decreases, and the surface of the crystal is damaged, undesirably resulting in a decrease in operational performance of the solid-state laser system 10.

[0069] To prevent the contamination of the nonlinear crystal 50, it is conceivable to accommodate the nonlinear crystal 50 in a container and purge the container with a purge gas. Specifically, for example, the crystal holder 50a that holds the nonlinear crystal 50 is accommodated in a container 60, and the interior of the container 60 is purged by a purge mechanism 70, as shown in FIG. 3. In this case, the crystal holder 50a is fixed inside the container 60. The container 60 includes a container body 61, a light incident window 63, and light exiting window 64.

[0070] The container body 61 is made of aluminum or stainless steel (SUS). The container body 61 has a light-incident-side opening 62a so formed as to intersect the optical path of the laser beam incident on the nonlinear crystal 50. The container body 61 further has a light-exiting-side opening 62b so formed as to intersect the optical path of the laser beam that exits out of the nonlinear crystal 50. The light incident window 63 is so bonded to the container body 61 via an O ring 65a as to close the light-incident-side opening 62a. The light exiting window 64 is so bonded to the container body 61 via an O ring 65b as to close the light-exiting-side opening 62b.

[0071] An O ring is an annular seal member having a substantially circular cross-sectional shape. A resin ring made of Teflon (registered trademark), rubber or the like or a ceramic ring is used as the O ring. The configuration and material of each O ring described in the present specification are the same as the configuration and material described above.

[0072] The light incident window 63 and the light exiting window 64 are each formed of a substrate made of calcium fluoride (CaF_2) crystal or synthetic quartz, the two surfaces of which are coated with reflection suppressing films that are not shown. The light incident window 63 transmits the laser beam to cause the laser beam to be incident on the nonlinear crystal 50. The light exiting window 64 transmits the laser beam having exited out of the nonlinear crystal 50.

[0073] The purge mechanism 70 includes a gas introducing pipe 71, through which the purge gas is introduced into the container body 61, and a gas discharging pipe 72, through which the purge gas is discharged from the interior of the container body 61. The gas introducing pipe 71 is connected to a gas tank that is not shown. The gas discharging pipe 72 discharges the purge gas into the atmosphere. The gas discharging pipe 72 may be connected to a duct that is not shown but communicates with the atmosphere. The purge gas is a gas that hardly reacts with the CLBO crystal as the nonlinear crystal and is, for example, argon (Ar) gas. The purge gas is introduced into the container body 61 and discharged therefrom at a substantially fixed flow rate. Nitrogen (N_2) gas, which highly reacts with the CLBO crystal, cannot be used as the purge gas.

[0074] The container 60 is placed on the position adjusting mechanism 51, which linearly drives the container 60 in the axis-V, axis-Z, and axis-H directions and rotates the container 60 in the direction θ . The gas introducing pipe 71 and the gas discharging pipe 72 are each formed of a flexible duct to allow the movement of the container 60. It is preferable to use a resin tube as the flexible duct. It is further preferable that the resin tube emits only a small amount of outgas. For example, a fluorine-based resin tube made of Teflon (registered trademark) or the like is used as the flexible duct.

[0075] As described above, accommodating the nonlinear crystal 50 in the container 60 allows suppression of contamination of the nonlinear crystal 50 but has a possibility of contamination of the light incident window 63 and the light exiting window 64. Contaminants that adhere to the light incident window 63 and the light exiting window 64 could lower the transparency of the windows so that the transmittance of the laser beam undesirably decreases. Even a configuration in which the entire container 60 is purged with nitrogen gas or the like cannot prevent contamination of the

light incident window **63** and the light exiting window **64** resulting from the outgas emitted from the position adjusting mechanism **51**.

[0076] Further, a fluorine-based resin tube that forms each of the gas introducing pipe **71** and the gas discharging pipe **72** could undesirably transmit water. The nonlinear crystal **50**, such as a CLBO crystal, has deliquescency. Therefore, when water penetrates through the gas introducing pipe **71** or the gas discharging pipe **72** into the container **60**, the nonlinear crystal **50** could absorb the water, which causes erosion to occur and progress, resulting in a decrease in crystal life. In a case where the gas introducing pipe **71** and the gas discharging pipe **72** are each formed of a metal duct configured to allow no water penetration, it is difficult to adjust the position of the nonlinear crystal **50** because the metal duct has low flexibility.

2. First Embodiment

[0077] A solid-state laser apparatus according to a first embodiment of the present disclosure will next be described. The solid-state laser apparatus according to the first embodiment has the same configuration as the configuration of the solid-state laser apparatus according to Comparative Example shown in FIG. 1 except that the wavelength converters in the two solid-state laser apparatuses have different configurations. In the following description, substantially the same portions as the components of the solid-state laser apparatus according to Comparative Example shown in FIG. 1 have the same reference characters and will not be described as appropriate.

[0078] 2.1 Configuration

[0079] FIG. 4 shows the configuration of the wavelength converter according to the first embodiment. The wavelength converter according to the first embodiment includes the crystal holder **50a**, which holds the nonlinear crystal **50**, the position adjusting mechanism **51**, a first container **60**, and a second container **80**. The first container **60** has the same configuration as that of the container **60** according to Comparative Example and accommodates the crystal holder **50a** that holds the nonlinear crystal **50**. For example, the crystal holder **50a** is made of copper.

[0080] The second container **80** includes a container body **81**, a light-incident-side opening **82a**, and a light-exiting-side opening **82b**. The container body **81** is made of aluminum or SUS. The light-incident-side opening **82a** is so provided as to intersect the optical path of the laser beam incident on the light incident window **63** of the first container **60**. The light-exiting-side opening **82b** is so provided as to intersect the optical path of the laser beam that exits through the light exiting window **64** of the first container **60**.

[0081] The position adjusting mechanism **51** includes the VZH stage **51a** and the θ stage **51b**, as in Comparative Example. A recess **81a** is formed in the bottom of the container body **81**. The θ stage **51b** is accommodated in the recess **81a**. The first container **60** is placed on the θ stage **51b**. The θ stage **51b** rotates the container body **61** in the direction θ . The first container **60** is so disposed as to cover the recess **81a**. A through hole **81b** is formed in the bottom surface of the recess **81a**. The wiring line **51c** described above is inserted through the through hole **81b**.

[0082] The recess **81a** has a circular shape when viewed in the axis-H direction. An O ring **83** as an isolation mechanism is disposed in a portion of the upper end of the recess **81a** that is the portion with which the bottom of the first

container **60** is in contact. The O ring **83**, which is in contact with the bottom of the first container **60** and the upper end of the recess **81a**, spatially isolates the light incident window **63** and the light exiting window **64** of the first container **60** from the position adjusting mechanism **51**. The O ring **83** may be a low-airtightness O ring that does not prevent the θ stage **51b** from rotating the first container **60**.

[0083] The second container **80** is placed on the VZH stage **51a**. The VZH stage **51a** moves the second container **80** in the axis-V, axis-Z, and axis-H directions.

[0084] A first bellows **84** is connected to a circumferential portion of the light-incident-side opening **82a** of the second container **80**. The first bellows **84** includes a bellows body **84a**, a first flange **84b**, and a second flange **84c**. The first flange **84b** is provided at one end of the bellows body **84a** and fixed to the circumferential portion of the light-incident-side opening **82a**. An O ring **84d** is provided between the first flange **84b** and the circumferential portion of the light-incident-side opening **82a**. The second flange **84c** is provided at the other end of the bellows body **84a** and connected to a first optical path pipe **85**. An O ring **84e** is provided between the second flange **84c** and the first optical path pipe **85**.

[0085] A second bellows **86** is connected to a circumferential portion of the light-exiting-side opening **82b** of the second container **80**. The second bellows **86** includes a bellows body **86a**, a first flange **86b**, and a second flange **86c**. The first flange **86b** is provided at one end of the bellows body **86a** and fixed to the circumferential portion of the light-exiting-side opening **82b**. An O ring **86d** is provided between the first flange **86b** and the circumferential portion of the light-exiting-side opening **82b**. The second flange **86c** is provided at the other end of the bellows body **86a** and connected to a second optical path pipe **87**. An O ring **86e** is provided between the second flange **86c** and the second optical path pipe **87**.

[0086] The first optical path pipe **85** and the second optical path pipe **87** are disposed as in an immobile manner. The first optical path pipe **85** and the second optical path pipe **87** cover the optical path of the laser beam, and an optical element, such as a dichroic mirror, is disposed in each of the two optical path pipes. The first bellows **84** and the second bellows **86** extend and contract or deform in such a way that the bellows allow the VZH stage **51a** to move the second container **80**.

[0087] The wavelength converter according to the first embodiment further includes a first purge mechanism **90** for purging the interior of the first container **60**. The first purge mechanism **90** includes a gas introducing pipe **91**, through which the purge gas is introduced into the first container **60**, and a gas discharging pipe **92**, through which the purge gas is discharged from the interior of the first container **60**. The gas introducing pipe **91** and the gas discharging pipe **92** pass through the second container **80** and are connected to the first container **60**.

[0088] The gas introducing pipe **91** includes a first flexible introduction pipe **91a**, a fixed duct **91b**, and a second flexible introduction pipe **91c**. The first flexible introduction pipe **91a** is connected to the container body **61** of the first container **60** and the container body **81** of the second container **80** and located therebetween and communicates with the interior of the container body **61**. For example, the first flexible introduction pipe **91a** is formed of a fluorine-based resin tube made of Teflon (registered trademark) or the

like. The fixed duct **91b** is a highly rigid duct. The fixed duct **91b** has one end so connected to the container body **81** of the second container **80** that the fixed duct **91b** communicates with the first flexible introduction pipe **91a**. The second flexible introduction pipe **91c** is so connected to the other end of the fixed duct **91b** that the second flexible introduction pipe **91c** communicates with the fixed duct **91b**. The fixed duct **91b** and the second flexible introduction pipe **91a** are made of a metal material that allows no water penetration, such as SUS. That is, a portion of the gas introducing pipe **91** that is the portion outside the second container **80** is made of a material that allows no water penetration.

[0089] The gas discharging pipe **92** includes a first flexible discharge pipe **92a**, a fixed duct **92b**, and a second flexible discharge pipe **92c**. The first flexible discharge pipe **92a** is connected to the container body **61** of the first container **60** and the container body **81** of the second container **80** and located therebetween and communicates with the interior of the container body **61**. For example, the first flexible discharge pipe **92a** is formed of a fluorine-based resin tube made of Teflon (registered trademark) or the like. The fixed duct **92b** is a highly rigid duct. The fixed duct **92b** has one end so connected to the container body **81** of the second container **80** that the fixed duct **92b** communicates with the first flexible discharge pipe **92a**. The second flexible discharge pipe **92c** is so connected to the other end of the fixed duct **92b** that the second flexible discharge pipe **92c** communicates with the fixed duct **92b**. The fixed duct **92b** and the second flexible discharge pipe **92a** are made of a metal material that allows no water penetration, such as SUS. That is, a portion of the gas discharging pipe **92** that is the portion outside the second container **80** is made of a material that allows no water penetration.

[0090] The flexibility of the first flexible introduction pipe **91a** and the first flexible discharge pipe **92a** allow the θ stage **51b** to rotate the first container **60**. The flexibility of the second flexible introduction pipe **91c** and the second flexible discharge pipe **92c** allow the VZH stage **51a** to move the second container **80**.

[0091] The gas introducing pipe **91** is connected to a gas tank that is not shown and introduces a first purge gas into the container body **61** at a substantially fixed flow rate. The gas discharging pipe **92** discharges the first purge gas from the container body **61** into the atmosphere. The first purge gas is preferably argon gas, which hardly reacts with the CLBO crystal as the nonlinear crystal **50**. The first purge gas can instead be helium (He) gas, neon (Ne) gas, or hydrogen (H_2) gas.

[0092] The wavelength converter according to the first embodiment further includes a second purge mechanism **95** for purging the interior of the second container **80**. The second purge mechanism **95** includes a gas introducing pipe **96** and a gas discharging pipe **97**. The gas introducing pipe **96** is connected to the first optical path pipe **85** and communicates with the interior of the first optical path pipe **85**. The gas discharging pipe **97** is connected to the second optical path pipe **87** and communicates with the interior of the second optical path pipe **87**.

[0093] The gas introducing pipe **96** is connected to a gas tank that is not shown and introduces nitrogen gas as a second purge gas into the first optical path pipe **85** at a substantially fixed flow rate. The second purge gas introduced into the first optical path pipe **85** is introduced into the second container **80** via the first bellows **84**. The gas

discharging pipe **97** discharges the second purge gas from the interior of the second container **80** into the atmosphere via the second bellows **86** and the second optical path pipe **87**. The second purge gas can instead be argon gas, helium gas, or hydrogen gas.

[0094] 2.2 Operation

[0095] The position of the nonlinear crystal **50** is adjusted with respect to the laser beam by driving the VZH stage **51a** and the θ stage **51b** provided in the position adjusting mechanism **51**. Driving the θ stage **51b** to rotate the first container **60** allows adjustment of the position of the nonlinear crystal **50** in the direction θ . Further, driving the VZH stage **51a** to move the second container **80** allows adjustment of the position of the nonlinear crystal **50** in the axis-V, axis-Z, and axis-H directions.

[0096] The flexibility of the first flexible introduction pipe **91a** and the first flexible discharge pipe **92a** allows the rotation of the first container **60**. The flexibility of the first bellows **84**, the second bellows **86**, the second flexible introduction pipe **91c**, and the second flexible discharge pipe **92c** allows the movement of the second container **80**.

[0097] 2.3 Effects

[0098] According to the first embodiment, the light incident window **63** and the light exiting window **64** of the first container **60** are spatially isolated from the position adjusting mechanism **51** via the O ring **83** as the isolation mechanism. The contamination resulting from the outgas emitted from the position adjusting mechanism **51** is thus suppressed, whereby a decrease in transparency of the light incident window **63** and the light exiting window **64** due to contamination thereof can be suppressed.

[0099] In the first embodiment, in which the first container **60** is accommodated in the second container **80** and the second container **80** is purged with a gas containing no water, water penetration through the first flexible introduction pipe **91a** and first flexible discharge pipe **92a** is suppressed. Entry of water into the first container **60** is therefore suppressed, whereby a decrease in the crystal life of the nonlinear crystal **50** is suppressed.

[0100] Further, in the first embodiment, in which portions of the gas introducing pipe **91** and the gas discharging pipe **92** that are the portions outside the second container **80** are made of a material that allows no water penetration, entry of water into the first container **60** is further suppressed, whereby a decrease in the crystal life of the nonlinear crystal **50** is further suppressed.

[0101] In the first embodiment, in which only the first container **60** is placed on the θ stage **51b**, the load required to rotate the nonlinear crystal **50** is smaller than in a case where the first container **60** and the second container **80** are placed on the θ stage **51b**. The θ stage **51b** therefore allows a minute change in the angle of incidence of the laser beam incident on the nonlinear crystal **50** with small force.

3. Second Embodiment

[0102] A solid-state laser apparatus according to a second embodiment of the present disclosure has the same configuration as the configuration of the solid-state laser apparatus according to the first embodiment except that the wavelength converters in the two solid-state laser apparatuses have different configurations.

[0103] 3.1 Configuration

[0104] FIG. **5** shows the configuration of the wavelength converter according to the second embodiment. The wave-

length converter according to the second embodiment includes the crystal holder **50a**, which holds the nonlinear crystal **50**, the position adjusting mechanism **51**, the first container **60**, and a second container **100**. The first container **60** has the same configuration as that of the container **60** according to Comparative Example and the first embodiment and accommodates the crystal holder **50a** that holds the nonlinear crystal **50**.

[0105] The second container **100** includes a container body **101**, a light incident window **103**, and a light exiting window **104**. The container body **101** accommodates the first container **60** and the position adjusting mechanism **51**. The container body **101** has a light-incident-side opening **102a** so formed as to intersect the optical path of the laser beam incident on the nonlinear crystal **50**. The container body **101** further has a light-exiting-side opening **102b** so formed as to intersect the optical path of the laser beam that exits out of the nonlinear crystal **50**. The light incident window **103** is so bonded to the container body **101** via an O ring **105a** as to close the light-incident-side opening **102a**. The light exiting window **104** is so bonded to the container body **101** via an O ring **105b** as to close the light-exiting-side opening **102b**. In the present embodiment, the second container **100** is disposed in an immobile manner.

[0106] The light incident window **103** and the light exiting window **104** are each formed of a substrate made of CaF_2 crystal or synthetic quartz, the two surfaces of which are coated with reflection suppressing films that are not shown. The light incident window **103** transmits the laser beam to cause the laser beam to be incident on the light incident window **63** of the first container **60**. The light exiting window **104** transmits the laser beam having exited through the light exiting window **64** of the first container **60**.

[0107] The position adjusting mechanism **51** includes the VZH stage **51a** and the θ stage **51b**. A recess **101a** is formed in the bottom of the container body **101**. The VZH stage **51a** is placed at the bottom of the recess **101a**. The θ stage **51b** is placed on the VZH stage **51a**. The first container **60** is placed on the θ stage **51b**. The θ stage **51b** rotates the container body **61** in the direction θ . A through hole **101b**, through which the wiring lines **51c** and **51d** described above are inserted, is formed in the recess **101a**.

[0108] A bellows **106** is disposed between a circumferential portion of the recess **101a** of the second container **100** and the bottom surface of the container body **61** of the first container **60**. The bellows **106** includes a bellows body **106a**, a first flange **106b**, and a second flange **106c**. The first flange **106b** is provided at one end of the bellows body **106a** and fixed to the circumferential portion of the recess **101a**. An O ring **106d** is provided between the first flange **106b** and the circumferential portion of the recess **101a**. The second flange **106c** is provided at the other end of the bellows body **106a** and connected to the bottom surface of the first container **60**. An O ring **106f** is provided between the second flange **106c** and the bottom surface of the first container **60**.

[0109] The bellows **106** covers the circumference of the position adjusting mechanism **51**. The O ring **106f** may be a low-airtightness O ring configured not to prevent the θ stage **51b** from rotating the first container **60** and the VZH stage **51a** from moving the first container **60** in the axis-V and axis-Z directions. The bellows **106** extends and contracts to allow the VZH stage **51a** to move the first container **60** in the axis-H direction.

[0110] In the present embodiment, the bellows **106** and the O rings **106d** and **106f** function as an isolation mechanism configured to spatially isolate the light incident window **63** and the light exiting window **64** of the first container **60** from the position adjusting mechanism **51**.

[0111] The wavelength converter according to the present embodiment further includes a first purge mechanism **110** for purging the interior of the first container **60**. The first purge mechanism **110** includes a gas introducing pipe **111**, through which the first purge gas is introduced into the first container **60**, and a gas discharging pipe **112**, through which the first purge gas is discharged from the interior of the first container **60**. The gas introducing pipe **111** and the gas discharging pipe **112** pass through the second container **100** and are connected to the first container **60**.

[0112] The gas introducing pipe **111** includes a flexible introduction pipe **111a** and a fixed duct **111b**. The flexible introduction pipe **111a** is connected to the container body **61** of the first container **60** and the container body **101** of the second container **100** and located therebetween and communicates with the interior of the container body **61**. For example, the flexible introduction pipe **111a** is formed of a fluorine-based resin tube made of Teflon (registered trademark) or the like. The fixed duct **111b** is a highly rigid duct. The fixed duct **111b** has one end so connected to the container body **101** of the second container **100** that the fixed duct **111b** communicates with the flexible introduction pipe **111a**. The fixed duct **111b** is made of a metal material that allows no water penetration, such as SUS.

[0113] The gas discharging pipe **112** includes a flexible discharge pipe **112a** and a fixed duct **112b**. The flexible discharge pipe **112a** is connected to the container body **61** of the first container **60** and the container body **101** of the second container **100** and located therebetween and communicates with the interior of the container body **61**. For example, the flexible discharge pipe **112a** is formed of a fluorine-based resin tube made of Teflon (registered trademark) or the like. The fixed duct **112b** is a highly rigid duct. The fixed duct **112b** has one end so connected to the container body **101** of the second container **100** that the fixed duct **112b** communicates with the flexible discharge pipe **112a**. The fixed duct **112b** is made of a metal material that allows no water penetration, such as SUS.

[0114] The flexibility of the flexible introduction pipe **111a** and the flexible discharge pipe **112a** allow the θ stage **51b** to rotate the first container **60** and the VZH stage **51a** to move the first container **60** in the axis-V, axis-Z, axis-H directions.

[0115] The gas introducing pipe **111** is connected to a gas tank that is not shown and introduces the first purge gas described above into the container body **61** at a substantially fixed flow rate. The gas discharging pipe **112** discharges the first purge gas from the container body **61** into the atmosphere.

[0116] The wavelength converter according to the present embodiment further includes a second purge mechanism **113** for purging the interior of the second container **100**. The second purge mechanism **113** includes a gas introducing pipe **114** and a gas discharging pipe **115**. The gas introducing pipe **114** and the gas discharging pipe **115** each have one end connected to the container body **101** of the second container **100** and communicate with the interior of the container body **101**. The gas introducing pipe **114** and the gas discharging

pipe **115** are each a highly rigid fixed duct and made of a metal material that allows no water penetration, such as SUS.

[0117] The gas introducing pipe **114** is connected to a gas tank that is not shown and introduces the second purge gas described above into the second container **100** at a substantially fixed flow rate. The gas discharging pipe **115** discharges the second purge gas from the second container **100** into the atmosphere.

[0118] 3.2 Operation

[0119] The position of the nonlinear crystal **50** is adjusted with respect to the laser beam by driving the VZH stage **51a** and the θ stage **51b** provided in the position adjusting mechanism **51**. Driving the θ stage **51b** to rotate the first container **60** allows adjustment of the position of the nonlinear crystal **50** in the direction θ . Further, driving the VZH stage **51a** to move the θ stage **51b** and the first container **60** allows adjustment of the position of the nonlinear crystal **50** in the axis-V, axis-Z, and axis-H directions. The flexible introduction pipe **111a** and the flexible discharge pipe **112a** allow the rotation and movement of the first container **60**.

[0120] 3.3 Effects

[0121] According to the present embodiment, the light incident window **63** and the light exiting window **64** of the first container **60** are spatially isolated from the position adjusting mechanism **51** via the bellows **106** and the O rings **106d** and **106f** as the isolation mechanism. The contamination resulting from the outgas emitted from the position adjusting mechanism **51** is thus suppressed, whereby a decrease in transparency of the light incident window **63** and the light exiting window **64** due to contamination thereof can be suppressed.

[0122] In the present embodiment, in which the first container **60** is accommodated in the second container **100** and the second container **100** is purged with a gas containing no water, water penetration through the flexible introduction pipe **111a** and flexible discharge pipe **112a**, which are connected to the first container **60** and the second container **100** and located therebetween, is suppressed. Entry of water into the first container **60** is therefore suppressed, whereby a decrease in the crystal life of the nonlinear crystal **50** is suppressed.

[0123] Further, in the present embodiment, in which portions of the gas introducing pipe **111** and the gas discharging pipe **112** that are the portions outside the second container **100** are made of a material that allows no water penetration, entry of water into the first container **60** is further suppressed, whereby a decrease in the crystal life of the nonlinear crystal **50** is further suppressed.

[0124] In the present embodiment, in which the second container **100** is not moved by the position adjusting mechanism **51** but is disposed in an immobile manner, the first bellows **84** or the second bellows **86** shown in the first embodiment is not required. Further, in the present embodiment, in which the second container **100** is sealed, the maintenance of the wavelength converter can be separately performed. The configuration described above minimizes a portion of the wavelength converter that is the portion exposed to the air at the time of the maintenance of the wavelength converter, whereby the period required for re-purging the second container **100** after the maintenance can be shortened.

[0125] In the present embodiment, the first optical path pipe **85** and the second optical path pipe **87** described above

may be connected to the light-incident-side opening **102a** and the light-exiting-side opening **102b**, respectively. In this case, the light incident window **103** or the light exiting window **104** may not be provided.

4. Third Embodiment

[0126] A solid-state laser apparatus according to a third embodiment of the present disclosure has the same configuration as the configuration of the solid-state laser apparatus according to the first embodiment except that the wavelength converters in the two solid-state laser apparatuses have different configurations.

[0127] 4.1 Configuration

[0128] FIG. **6** shows the configuration of the wavelength converter according to the third embodiment. The wavelength converter according to the third embodiment includes the crystal holder **50a**, which holds the nonlinear crystal **50**, the position adjusting mechanism **51**, the first container **60**, and the second container **100**. The second container **100** has the same configuration as that of the second container **100** according to the second embodiment.

[0129] The first container **60** has the same configuration as that of the first container **60** according to the second embodiment except that a through hole **61a** is provided in the bottom of the container body **61**. A rotational shaft **50b** is connected to the bottom of the crystal holder **50a**. The rotational shaft **50b** is inserted through the through hole **61a**. The lower end of the rotational shaft **50b** is connected to the θ stage **51b**. For example, the rotational shaft **50b** is made of copper. In the present embodiment, the θ stage **51b** rotates the crystal holder **50a** via the rotational shaft **50b**.

[0130] An O ring **120** is disposed between the inner wall of the through hole **61a** and the rotational shaft **50b**. The O ring **120** may be a low-airtightness O ring configured not to prevent the θ stage **51b** from rotating the first container **60**.

[0131] A holder **61c** is provided at the bottom of the container body **61**. The holder **61c** has a box-like shape that opens upward, and the upper end of the holder **61c** is connected to the bottom of the container body **61**. The holder **61c** accommodates and holds the θ stage **51b**. A through hole **61d**, through which the wiring lines **51c** is inserted, is so formed in the holder **61c**. The holder **61c** is placed on the VZH stage **51a**.

[0132] The bellows **106** is disposed between the circumferential portion of the recess **101a** of the second container **100** and the bottom surface of the container body **61** of the first container **60**, as in the second embodiment. The bellows **106** has the same configuration as that in the second embodiment. The bellows **106** covers the circumference of the position adjusting mechanism **51** and the holder **61c**. In the present embodiment, the O ring **106f** may be a low-airtightness O ring configured not to prevent the VZH stage **51a** from moving the first container **60** in the axis-V and axis-Z directions. The bellows **106** extends and contracts to allow the VZH stage **51a** to move the first container **60** in the axis-H direction.

[0133] In the present embodiment, the bellows **106** and the O rings **106d** and **106f** function as an isolation mechanism configured to spatially isolate the light incident window **63** and the light exiting window **64** of the first container **60** from the position adjusting mechanism **51**.

[0134] The wavelength converter according to the present embodiment further includes the first purge mechanism **110** for purging the interior of the first container **60** and the

second purge mechanism **113** for purging the interior of the second container **100**. The first purge mechanism **110** and the second purge mechanism **113** have the same configuration as those in the second embodiment.

[0135] 4.2 Operation

[0136] The position of the nonlinear crystal **50** is adjusted with respect to the laser beam by driving the VZH stage **51a** and the θ stage **51b** provided in the position adjusting mechanism **51**. Driving the θ stage **51b** to rotate the crystal holder **50a** allows adjustment of the position of the nonlinear crystal **50** in the direction θ . Further, driving the VZH stage **51a** to move the θ stage **51b** and the first container **60** allows adjustment of the position of the nonlinear crystal **50** in the axis-V, axis-Z, and axis-H directions. The flexible introduction pipe **111a** and the flexible discharge pipe **112a** allow the rotation and movement of the first container **60**.

[0137] 4.3 Effects

[0138] According to the present embodiment, the contamination resulting from the outgas emitted from the position adjusting mechanism **51** is suppressed, whereby a decrease in transparency of the light incident window **63** and the light exiting window **64** due to contamination thereof can be suppressed as in the second embodiment. Further, according to the third embodiment, entry of water into the first container **60** is suppressed, whereby a decrease in the crystal life of the nonlinear crystal **50** is suppressed as in the second embodiment.

[0139] Further, in the present embodiment, in which the θ stage **51b** rotates the crystal holder **50a** in place of the first container **60**, the inertia force produced when the crystal holder **50a** is rotated is smaller than in the other embodiments, whereby the angle of the nonlinear crystal **50** is readily adjusted in the direction θ .

[0140] 4.4 Variation

[0141] A variation of the wavelength converter according to the third embodiment will next be shown. FIG. 7 shows the configuration of the wavelength converter according to the present variation. FIG. 8 is an enlarged view of the rotational shaft **50b** and therearound. The wavelength converter according to the present variation has the same configuration as that of the wavelength converter according to the third embodiment except the configurations of the rotational shaft **50b** and therearound.

[0142] In the present variation, an annular ring **121** is provided around the rotational shaft **50b** in place of the O ring **120**. The annular ring **121** is a resin ring made, for example, of Teflon (registered trademark) or rubber or a ceramic ring. In the present variation, the airtightness is low in the space between the rotational shaft **50b** and the inner wall of the through hole **61a** and the space between the annular ring **121** and the inner wall of the through hole **61a**, and an air gap is present in the spaces, as shown in FIG. 8.

[0143] It is preferable in the present variation that the first purge mechanism **110** adjusts the flow rate of the first purge gas with which the first container **60** is purged in such a way that the internal pressure in the first container **60** is maintained to be higher than the atmospheric pressure. The first purge gas thus flows from the interior of the first container **60** into the second container **100** via the air gaps described above. Entry of the outgas emitted from the position adjusting mechanism **51** into the first container **60** can thus be avoided.

[0144] In the present variation, in which the airtightness is low between the rotational shaft **50b** and the inner wall of

the through hole **61a** and between the annular ring **121** and the inner wall of the through hole **61a**, the resistance produced when the crystal holder **50a** is rotated is small, whereby the angle of the nonlinear crystal **50** is readily adjusted in the direction θ .

[0145] In the present variation, in which the gas discharging pipe **112** is connected to the first container **60**, the gas discharging pipe **112** may instead be connected to the recess **101a** of the second container **100**. The flow rate of the first purge gas flowing from the first container **60** into the second container **100** via the air gaps described above can therefore be increased.

5. Fourth Embodiment

[0146] A solid-state laser apparatus according to a fourth embodiment of the present disclosure has the same configuration as the configuration of the solid-state laser apparatus according to the first embodiment except that the wavelength converters in the two solid-state laser apparatuses have different configurations.

[0147] 5.1 Configuration

[0148] FIG. 9 shows the configuration of the wavelength converter according to the fourth embodiment. The wavelength converter according to the fourth embodiment includes two sets of the following components in a second container **200**: the crystal holder **50a**, which holds the nonlinear crystal **50**; the position adjusting mechanism **51**; the first container **60**; and the bellows **106**. The crystal holder **50a**, the position adjusting mechanism **51**, and the first container **60** have the same configuration as those in the second embodiment.

[0149] The second container **200** includes a container body **201**, a light incident window **203**, and a light exiting window **204**. The two nonlinear crystals **50** contained in the container body **201** are disposed along the optical path of the laser beam. The container body **201** has a light-incident-side opening **202a** so formed as to intersect the optical path along which the laser beam is incident. The container body **201** further has a light-exiting-side opening **202b** so formed as to intersect the optical path along which the laser beam exits. The light incident window **203** is so bonded to the container body **201** via an O ring **205a** as to close the light-incident-side opening **202a**. The light exiting window **204** is so bonded to the container body **201** via an O ring **205b** as to close the light-exiting-side opening **202b**. The second container **200** is disposed in an immobile manner.

[0150] Two recesses **201a** are formed in the bottom of the container body **201**. The position adjusting mechanism **51** is disposed in each of the recesses **201a**, and the first container **60** is disposed on each of the position adjusting mechanisms **51**. The wavelength converter according to the present embodiment includes two sets of first purge mechanisms **110**. The first purge mechanisms **110** each have the same configuration as that in the second embodiment and include the gas introducing pipe **111** and the gas discharging pipe **112**. The gas introducing pipe **111** and the gas discharging pipe **112** are connected to the first container **60**.

[0151] The wavelength converter according to the present embodiment further includes the second purge mechanism **113** for purging the interior of the second container **200**. The second purge mechanism **113** has the same configuration as that in the second embodiment and includes the gas introducing pipe **114** and the gas discharging pipe **115**. The gas

introducing pipe 114 and the gas discharging pipe 115 are connected to the second container 200.

[0152] Further, in the wavelength converter according to the present embodiment, an optical element is disposed in the optical path of the laser beam between the two first containers 60 in the second container 200. For example, the optical element is the first dichroic mirror 44 shown in FIG. 1. In this case, the nonlinear crystal 50 on the upstream of the first dichroic mirror 44 corresponds to the first CLBO crystal 40. The nonlinear crystal 50 on the downstream of the first dichroic mirror 44 corresponds to the second CLBO crystal 41. The optical element is not limited to the first dichroic mirror 44, and another optical element may be disposed in the second container 200.

[0153] 5.2 Effects

[0154] According to the present embodiment, in which a plurality of first containers 60 and optical elements are disposed in the second container 200, the size of the wavelength converter as a whole can be reduced.

[0155] In the present embodiment, the first containers 60 and the position adjusting mechanisms 51 each having the same configuration as that in the second embodiment are accommodated in the second container 200, and the configurations described above are changeable as appropriate. Further, the number of first containers 60 accommodated in the second container 200 is not limited to two and may be three or more.

6. Various Variations

[0156] Various variations of the embodiments described above will be described below. The light incident window 63 of the first container 60 is so bonded to the container body 61 via the O ring 65a as to close the light-incident-side opening 62a in the embodiments described above. FIG. 10 shows an example in which a shielding film 130 is formed on the light incident window 63 to prevent the O ring 65a from being irradiated with scattered light resulting from the laser beam. For example, the shielding film 130 is formed by evaporating aluminum onto the light incident window 63. The shielding film 130 is so formed in a donut shape as to correspond to the shape of the O ring 65a, as shown in FIG. 11.

[0157] As described above, forming the shielding film 130 on the light incident window 63 prevents the O ring 65a from being irradiated with the scattered light, whereby creation of organic substances produced when the O ring 65a is irradiated with the scattered light can be avoided. Contamination of the nonlinear crystal 50, the light incident window 63, and the light exiting window 64 can thus be suppressed.

[0158] The shielding film 130 is not necessarily provided only on the light incident window 63 and may further be provided on the light exiting window 64. The shielding film 130 may further be provided on the light incident window 103 and the light exiting window 104 of the second container 100 shown in FIGS. 5 to 7. Still further, the shielding film 130 may further be provided on the light incident window 203 and the light exiting window 204 of the second container 200 shown in FIG. 9.

[0159] In the embodiments described above, a fluorine-based resin tube made of Teflon (registered trademark) or the like is presented by way of example as the resin tube used as the flexible introduction pipe and the flexible discharge pipe connected to the first and second containers and located

therebetween. It is also preferable to use THV as the material of the resin tube. THV is a terpolymer formed from the following three fluorine monomers: tetrafluoroethylene (TFE); hexafluoropropylene (HFP); and vinylidene fluoride (VDF).

[0160] The flexible introduction pipe and the flexible discharge pipe connected to the first and second containers and located therebetween can instead be made of a metal material that allows no water penetration, such as SUS. In the case where the flexible introduction pipe and the flexible discharge pipe are made of a metal, however, the load required when the position adjusting mechanism moves the first container could undesirably increase, and it is therefore more preferable that the flexible introduction pipe and the flexible discharge pipe are made of a resin material.

[0161] In the embodiments described above, a CLBO crystal is used as the nonlinear crystal 50, and a KBBF ($\text{KBe}_2\text{BO}_3\text{F}_2$) crystal or a BBO ($\beta\text{-BaB}_2\text{O}_4$) crystal can be used in place of a CLBO crystal.

[0162] The above description is intended not to be limiting but merely to exemplary. It will therefore be apparent for a person skilled in the art that the embodiments of the present disclosure can be changed without departing from the accompanying claims.

[0163] The terms used in the entire specification and accompanying claims should each be construed as a “non-limiting” term. For example, the term “include” or “included” should be construed as “does not necessarily include only what is described.” The term “have” should be construed as “does not necessarily have only what is described.” Further, an indefinite article “a” described in the present specification and the accompanying claims should be construed as a term that means “at least one” or “one or more.”

[0164] The description above is intended to be illustrative and the present disclosure is not limited thereto. Therefore, it would be obvious to those skilled in the art that various modifications to the embodiments of the present disclosure would be possible without departing from the spirit and the scope of the appended claims. Further, it would be also obvious for those skilled in the art that embodiments of the present disclosure would be appropriately combined.

[0165] The terms used throughout the present specification and the appended claims should be interpreted as non-limiting terms. For example, terms such as “comprise”, “include”, “have”, and “contain” should not be interpreted to be exclusive of other structural elements. Further, indefinite articles “a/an” described in the present specification and the appended claims should be interpreted to mean “at least one” or “one or more.” Further, “at least one of A, B, and C” should be interpreted to mean any of A, B, C, A+B, A+C, B+C, and A+B+C as well as to include combinations of the any thereof and any other than A, B, and C.

What is claimed is:

1. A wavelength converter comprising:

- A. a crystal holder configured to hold a nonlinear crystal configured to convert a wavelength of a laser beam incident thereon and output the wavelength-converted laser beam;
- B. a first container configured to accommodate the crystal holder and include a light incident window so provided as to intersect an optical path of the laser beam incident on the nonlinear crystal and a light exiting window so

- provided as to intersect the optical path of the laser beam having exited out of the nonlinear crystal;
- C. a second container configured to accommodate the first container;
- D. a position adjusting mechanism configured to adjust at least a position of the first container; and
- E. an isolation mechanism configured to spatially isolate the light incident window and the light exiting window from the position adjusting mechanism.
2. The wavelength converter according to claim 1, further comprising:
- F. a first purge mechanism configured to purge an interior of the first container with a first purge gas; and
- G. a second purge mechanism configured to purge an interior of the second container with a second purge gas.
3. The wavelength converter according to claim 2, wherein the first purge mechanism includes
- a first gas introducing pipe configured to pass through the second container and be connected to the first container and configured to introduce the first purge gas into the first container, and
- a first gas discharging pipe configured to pass through the second container and be connected to the first container and configured to discharge the first purge gas from the first container.
4. The wavelength converter according to claim 3, wherein the first purge gas is argon gas, helium gas, neon gas, or hydrogen gas, and
- the second purge gas is nitrogen gas, argon gas, helium gas, or hydrogen gas.
5. The wavelength converter according to claim 3, wherein the second purge mechanism includes
- a second gas introducing pipe configured to introduce the second purge gas into the second container, and
- a second gas discharging pipe configured to discharge the second purge gas from the second container.
6. The wavelength converter according to claim 3, wherein the first gas introducing pipe includes a flexible introduction pipe connected to the first container and the second container and located therebetween, and
- the first gas discharging pipe includes a flexible discharge pipe connected to the first container and the second container and located therebetween.
7. The wavelength converter according to claim 6, wherein the flexible introduction pipe and the flexible discharge pipe are each a fluorine-based resin tube.
8. The wavelength converter according to claim 1, wherein the position adjusting mechanism includes a rotational driver configured to rotate the nonlinear crystal to change an angle of incidence of the laser beam incident on the nonlinear crystal and a linear driver configured to linearly move the nonlinear crystal.
9. The wavelength converter according to claim 8, wherein the first container is placed on the rotational driver, and the second container is placed on the linear driver.

10. The wavelength converter according to claim 9, wherein a recess configured to accommodate the rotational driver is formed in the first container, and the isolation mechanism is disposed between an upper end of the recess and the first container.
11. The wavelength converter according to claim 10, wherein the isolation mechanism includes an O ring.
12. The wavelength converter according to claim 8, wherein the second container is configured to accommodate the rotational driver and the linear driver, and the first container is placed on the rotational driver, and the rotational driver is placed on the linear driver.
13. The wavelength converter according to claim 12, wherein the isolation mechanism includes a bellows configured to cover a circumference of the position adjusting mechanism and disposed between the first container and the second container.
14. The wavelength converter according to claim 13, wherein the isolation mechanism includes an O ring disposed between the bellows and the first container.
15. The wavelength converter according to claim 8, wherein the first container is connected to the rotational driver via a through hole provided at a bottom of the first container,
- the rotational driver is held by a holder provided at the bottom of the first container, and
- the holder is placed on the linear driver accommodated in the second container.
16. The wavelength converter according to claim 15, wherein the isolation mechanism includes a bellows configured to cover a circumference of the position adjusting mechanism and disposed between the first container and the second container.
17. The wavelength converter according to claim 15, further comprising:
- F. a first purge mechanism configured to purge an interior of the first container with a first purge gas; and
- G. a second purge mechanism configured to purge an interior of the second container with a second purge gas,
- wherein the first purge mechanism holds internal pressure in the first container higher than an atmospheric pressure.
18. The wavelength converter according to claim 1, wherein the second container accommodates a plurality of sets of the crystal holder, the first container, the position adjusting mechanism, and the isolation mechanism.
19. The wavelength converter according to claim 1, wherein the light incident window is connected via an O ring to a light-incident-side opening provided in a body of the first container, and
- a shielding film configured to shield the O ring from scattered light resulting from the laser beam is formed on the light incident window.
20. The wavelength converter according to claim 1, wherein the nonlinear crystal is a CLBO crystal, a KBBF crystal, or a BBO crystal.

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