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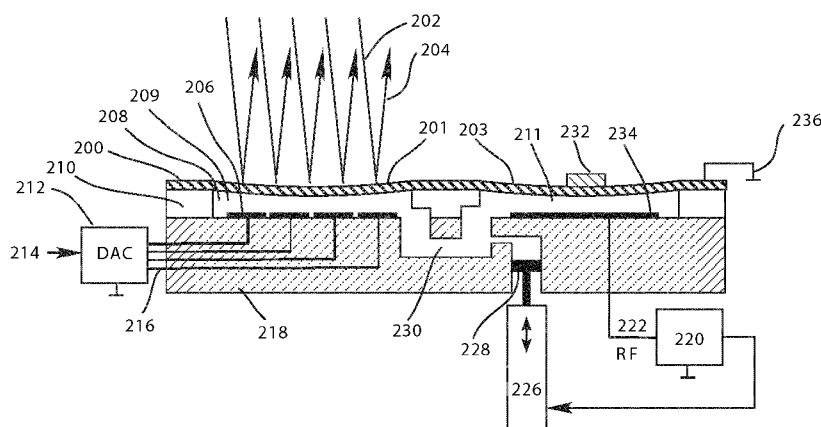


FIG. 2A

(57) Abstract: The present invention describes a method and adaptive optics device in form of an assembly comprising a first deformable mirror, or membrane (201), which is coupled to a first cavity (208) comprised in a hermetically closed cavity, and a second deformable mirror (203) or membrane coupled to a second cavity (211) of the same hermetically closed cavity, wherein the deformable membrane coupled to the second cavity is configured to be used in order to balance or compensate for a change of volume or pressure in the first cavity.

Adaptive optics device and method

Technical Field

[0001] The invention relates to the technical field of adaptive optics, and in particular to a method and an optical system using a deformable mirror assembly to control aberrations and focus.

Background Art

[0002] Adaptive optics in state of art solutions may use a deformable mirror to modify a so-called wave front of light, typically by recomposing an image that has become distorted. A deformable mirror is one of several means whereby aberrations can be dynamically controlled in an optical system. Two common applications are the correction of aberrations induced in astronomical telescopes by atmospheric turbulence and human vision (ophthalmology) where the, in optical terms, poor optical quality of the human eye blurs the image of the retina and prevents examination.

[0003] Looking to human vision, the human eye can be aided by an adaptive optic device that counteracts defects or deviations from optical perfection in a human eye, making it possible to accurately view the retina. Looking to the sky, an adaptive optic device can compensate for atmospheric turbulence. The deformable mirror is typically a low inertia device that can respond very quickly, see e.g. US Pat. No. 5,022,745. A variety of mirror configurations are depicted in US Pat. No. 7,190,500.

[0004] The technology of adaptive optics using a deformable mirror is today applied to a less degree in optical systems for lithography because of the high requirements lithographic system put on the optical quality of the surface figure of the deformable mirror. A few applications of adaptive optics to microlithography have been proposed, see e.g. US Pat. Nos. 7,184,124 to ASML and US Pat. Nos. 7,294,814 to Zeiss.

[0005] US Pat. No. 7,184,124 to ASML discloses a lithography system comprising a projection system including at least one active mirror, which is adjusted to compensate for errors found on a surface of the pattern generator, the substrate, and or an optical element in the lithography system.

[0006] In certain embodiments of US Pat. No. 7,184,124, the projection system comprises a first deformable mirror positioned to direct light from the pattern generator to a first reflection device and a second deformable mirror positioned to direct light from the pattern generator to a second reflection device.

[0007] US Pat. Nos. 7,294,814 to Zeiss discloses a catadioptric projection objective for microlithography having at least one curved mirror that is deformable and adjusting elements that can deform the deformable mirror. The adjusting elements are matched to given image errors and their correction. This catadioptric projection objective is suitably designed for astigmatism, fourfold wave front deformations due to lens heating, compaction, and the like.

Summary of invention

[0008] The present invention describes a method and a deformable mirror comprised in a closed cavity assembly where the deformable mirror is used for controlling aberrations and focus.

- [0009] In example embodiments of the invention, the deformable mirror assembly is used to dynamically control aberrations and/or focus in lithographic applications.
- [0010] According to certain embodiments of the invention, a deformable mirror assembly is comprising a first deformable mirror, or membrane, which is coupled to a first cavity comprised in a hermetically closed cavity, and a second deformable mirror or membrane coupled to a second cavity of the hermetically closed cavity, wherein the deformable membrane coupled to the second cavity is configured to be used in order to balance or compensate for a change of volume or pressure in the first cavity.
- [0011] According to certain embodiments of the invention, a deformable mirror assembly is comprising a first deformable mirror, or membrane, which is coupled to a first cavity comprised in a hermetically closed cavity, and a second deformable mirror or membrane coupled to a second cavity of the hermetically closed cavity, wherein the deformable membrane and further means for controlling the pressure and/or volume of the second cavity, e.g. a pressure regulator, are configured to be used in order to balance or compensate for a change of volume or pressure in the first cavity.
- [0012] According to certain embodiments of the invention, a deformable mirror assembly is comprising a first deformable mirror, or membrane, which is coupled to a first cavity comprised in a hermetically closed cavity, and a second deformable mirror or membrane coupled to a second cavity of the hermetically closed cavity, wherein the deformable membrane and further means for controlling the pressure and/or volume of the second cavity, e.g. a pressure regulator, are configured to be used in order to balance or compensate for a change of volume or pressure in the first cavity, wherein the deformable membrane of the second cavity is configured to be kept at an essentially fixed position by said means for controlling the pressure and/or volume of the second cavity.
- [0013] According to certain embodiments of the invention, a deformable mirror assembly is comprising a first deformable mirror, or membrane, which is coupled to a first cavity comprised in a hermetically closed cavity, and a second deformable mirror or membrane coupled to a second cavity of the hermetically closed cavity, wherein the deformable membrane and further means for controlling the pressure and/or volume of the second cavity, e.g. a pressure regulator, are configured to be used in order to balance or compensate for a change of volume or pressure in the first cavity, wherein the said deformable mirror of the first cavity is having a focus range of positions corresponding to a range of focus settings spanning at least plus/minus 5 wavelengths of phase, and wherein the deformable membrane of the second cavity is configured to be positioned to a sequence of selected positions in the focus range, or corresponding to the focus range, by said means for controlling the pressure and/or volume of the second cavity.
- [0014] The present invention further describes a method of using an adaptive optics device in an optical system in order to focus a reading or writing beam relayed to a workpiece, comprising the action of balancing, or compensating for, a change of volume or pressure caused by the displacement of the deformable mirror coupled to a first cavity comprised in a hermetically closed cavity by changing the volume or pressure of a

second cavity, also comprised in the same hermetically closed cavity as the first cavity in order to achieving at least one of:

keeping a deformable membrane, coupled to the second cavity, at an essentially fixed position; or

positioning a deformable membrane, coupled to the second cavity, to a sequence of selected positions in the focus range of the deformable mirror, or corresponding to the focus range of the deformable mirror.

[0015] According to certain embodiments of the invention, a first deformable mirror, or membrane, coupled to a first cavity of a twin cavity assembly, of the invention may together with a second deformable mirror or membrane coupled to a second cavity of the twin cavity be used as a pressure gauge in order to balance the effect of external acceleration along an optical axis associated with the first deformable mirror, or membrane.

[0016] According to embodiments of the invention, the displacement of a first deformable mirror, or membrane, coupled to a first cavity of a hermetically closed assembly or system is measured, balanced and/or compensated for by the provision of a second deformable mirror, or membrane, coupled to a second cavity of the hermetically closed system. Thus, the decrease in volume of the first cavity which is caused by the displacement of the first deformable mirror is balanced and/or at least partly compensated for by an increase in volume of the second cavity, or vice versa, the increase in volume of the first cavity may be balanced or at least partly compensated for by a decrease in volume of the second cavity.

[0017] In example embodiments, the displacement of the second deformable membrane and the change of volume in the second cavity of the hermetically closed cavity assembly or system may be used in lithographic applications to measure, balance and/or compensate for the effects of at least one of aberrations, focus adjustments, pressure changes or external accelerations, where the effects of all those may first introduce a change of pressure or volume of a first cavity comprising a deformable mirror used for adaptive optics, e.g. through a displacement of the deformable mirror.

[0018] According to more specific embodiments of the invention, the change of volume in the second cavity caused by the effects of at least one of aberrations, external accelerations, pressure changes or focus refocusing by the active displacement of the first deformable mirror coupled to the first cavity of the same hermetically closed system as the second cavity may be used for at least one of correcting for aberrations, passive and/or active compensation of external pressure changes or external accelerations, e.g. along an optical axis, measuring or controlling the focus position of an optical beam impinging on the first deformable mirror and/or active and fast refocusing of an optical beam impinging on the first deformable mirror.

[0019] According to example embodiments of the invention, a hermetically closed cavity assembly comprises a deformable mirror subassembly defining a first volume at least partially between the internal surface of the deformable mirror and an electrostatic element. In example embodiments, the hermetically closed cavity assembly may further comprise a second subassembly in form of a compensating assembly having a second housing and a deformable membrane mounted to the second housing, wherein a second volume is defined at least partially between the internal surface of the deformable membrane and the second housing.

- [0020] In yet another example embodiment of the invention, the closed cavity assembly comprises a first deformable mirror subassembly defining a first volume at least partially between the internal surface of a deformable mirror and an electrostatic element, and a second subassembly comprising a second volume filled with hydrogen, the second subassembly further having a second deformable membrane, or mirror, mounted to a housing.
- [0021] According to example embodiments of the invention, a first deformable mirror cavity of a twin cavity assembly may together with a second cavity be used as a pressure gauge in order to balance the effect of external acceleration along an optical axis. The second cavity may preferably also have a membrane, or mirror, that is subject to gravity and a pressure differential, but not to electrostatic forces that affect the first deformable mirror, so the curve of the second membrane is somewhat different than the curve of the first deformable mirror, or membrane.
- [0022] In certain embodiments, the second membrane may be configured to have stiff surfaces with electrodes that support differential measurement of capacitance. The electrodes may be positioned between the surface above the second membrane and the surface below it.
- [0023] Example embodiments of the invention provide a focusing system, or focus control system, including the closed cavity deformable mirror assembly for use in a pattern generator where the closed cavity deformable mirror assembly is introduced in order to make the pattern generator system less or significantly less sensitive to translations and/or rotations.
- [0024] In example embodiments, the deformable mirror assembly is configured to refocusing a laser image or beam in an optical system by dynamically adjusting the optical path length of a light beam in the optical system.
- [0025] In certain embodiments, the deformable mirror assembly of the invention is configured to dynamically adjust the optical path length of the light beam in an optical system of a pattern generator in response to the translations and/or rotations caused by various movements or accelerations associated with the pattern generator.
- [0026] Example embodiments of the invention provide a deformable mirror assembly which is configured to suppress external accelerations by the use of a closed twin cavity that mimics some mechanical properties of a deformable mirror membrane.
- [0027] According to at least some example embodiments, the deformable mirror assembly of the invention is comprised in a focusing system configured to change a nominal focus position according to a topography map of the workpiece and/or focus length variations between the plurality of sweeps, or scans, during and/or after a projection swap between the plurality of sweeps or scans.
- [0028] According to at least one example embodiment, the deformable mirror of the closed cavity deformable mirror assembly of the invention is configured to refocus a writing beam for projecting a laser image or beam.
- [0029] Example embodiments of the invention provide a deformable mirror assembly with a closed cavity configured to maintain a constant and very accurate over-pressure by providing a mechanical arrangement quite similar to the deformable mirror but where the deformable mirror has been

replaced by a substantially equally deformable metallic membrane. In certain embodiments of the invention, metallic plates on both sides of the metallic membrane are used to measure the differential capacitance of the membrane.

- [0030] According to example embodiments, metallic plates associated with the metallic membrane are configured to allow free flow of gas on both sides of the membrane so that membrane experiences the same pressure difference as the deformable mirror when they are made to share the same communicating gas volume which is hermetically sealed from the surroundings.
- [0031] In example embodiments of the invention, accurate relative deflection may be obtained for the membrane in the twin cavity by measuring the capacitances of the back and front plates.
- [0032] In certain embodiments of the invention, a constant pressure may be maintained in both communicating cavities of a twin cavity by controlling the gas volume using a pressure regulator coupled to the closed cavity.
- [0033] In example embodiments, the present invention provides the combination of a closed cavity deformable mirror assembly with the selection of gas to be one of hydrogen or air, both two choices of gases being identified to have the specific properties required for high irradiance and largest possible driving forces.
- [0034] In example embodiments, the present invention provides the combination of a minimal separation between the deformable mirror and electrostatic actuators with the use of hydrogen in a closed volume.
- [0035] In yet another embodiment, the invention proposes the use of capacitive sensing in order to keep the pressure constant while maintaining a small lag time.

Brief description of drawings

- [0036] FIG. 1 shows conceptually a deformable mirror module with a closed cavity and position feedback as known in prior art.
- [0037] FIG. 2A depicts conceptually an inventive deformable mirror with a second, auxiliary or twin cavity.
- [0038] FIG. 2B shows a method for how focus and aberrations can be controlled using the deformable mirror assembly illustrated in FIG. 2A
- [0039] FIG. 3 illustrates conceptually a deformable mirror with two auxiliary cavities, one for measurement and one for high-frequency focus control.
- [0040] FIG 4A shows the same deformable mirror as in FIG. 3, but with the electrostatic actuation replaced by piezoelectric actuation.
- [0041] FIG. 4B shows a deformable mirror unit with position measurement directly on the deformable mirror and an auxiliary cavity for changing the enclosed volume.
- [0042] FIG. 5 illustrates how the equivalent multi-cavity deformable mirrors can be built with the cavities either side-by-side and with forced cooling (FIG. 5A) or stacked on top of each other (FIG. 5B).
- [0043] FIG. 6A illustrates a deformable mirror configuration according to example embodiments of the present invention;
- [0044] FIG. 6B shows another deformable mirror configuration according to example embodiments of the present invention;

- [0045] FIG. 7 shows an example of an optical writing system (e.g. for lithography) using the inventive deformable mirror, in which system accurate correction of aberrations, fast refocusing, and high power durability is desirable.

Description of embodiments

- [0046] There are several methods whereby a thin mirror surface can be deformed. Those include deformation by piezoelectric crystals pushing along the surface normal of the mirror, piezoelectric crystals in the mirror plane applying a local torque to the deformable mirror, miniaturized coils moving in magnetic fields and forces due to electrostatic attraction between both plates of a capacitor. The present invention primarily addresses design aspects of deformable mirrors using electrostatic forces.
- [0047] As lithographic systems push toward shorter wavelengths to keep up with the requirements of resolution, the requirements on surface uniformity, which scales with the wavelength, is pushed towards smaller and smaller values. For a near-UV system, mirror surface uniformity requirements in the range of 3 to 10 nm can be expected. Since the thin plate or membrane of a deformable mirror can not be polished to optical specifications, a deformable mirror may instead use its actuators to reshape the front surface to the desired form. The piezoelectric systems can handle much thicker mirrors than systems based on magnetic or electrostatic forces. However, the print-through of the piezo actuators reduces this apparent advantage and piezo-based systems which are essentially operating on par, in term of surface uniformity, with magnetic or electrostatic systems.
- [0048] Since all deformable mirror technologies can only apply forces at specific and fixed mirror positions, the limit on the quality of the final surface, once full correction has been applied, is limited by the actuator density. Typical numbers of actuators on deformable mirrors may be as low as 7 and up to over 1000. The lithographic surface uniformity requirements of 3-10 nm will often be fulfilled by deformable mirrors with no less than 50 and up to 100 actuators, depending on the initial quality of the front surface of the deformable mirror membrane. This drives the cost of the system. Another cost driver for a deformable mirror system is the common requirement of having an auxiliary optical feedback monitoring the mirror in the case where the aberrations can not be practically measured during operation. Although measurement of aberrations is the heart of the astronomical telescope using adaptive optics, in lithography, the light source is never a constant reference point source such as a star, or laser guide star, and an additional point source is often required to maintain stability of the mirror over time and optical power levels of the lithographic system.
- [0049] A deformable mirror driven by electrostatic forces present several advantages with respect to actuator density and mirror surface figure control. The actuator density is essentially only limited by the cost of the electronic driver for each actuator while there are essentially no additional costs associated with mirror manufacturing. Also, the capacitance of each actuator can be quite accurately measured using moderate frequency AC voltage which will not interfere with the position of the mirror.
- [0050] The accuracy of such capacitance measurement decreases with the size of the gap between the mirror and the ground plane defining the actuator structure. In lithography, large strokes are not needed to the same extent

as would be the case in for instance astronomy or ophthalmology and the gap can be made quite small. This allows the absolute distance to be measured with nanometer repeatability. This repeatability can be used to design the deformable mirror system using an off-line calibration which can be made with a true interferometer providing greater accuracy than is possible with optical feedback based on a Shack-Hartmann sensor which is probably the only today viable wavefront sensor with sufficient speed, at least if sub second corrections are needed.

- [0051] Electro-statically actuated mirrors must operate with very small differential pressures since relative to the atmospheric pressure, electrostatic forces are minute. The gap between the deformable mirror membrane and the electrode plane can not be made arbitrarily small for both practical reasons and requirements on stroke magnitude.
- [0052] Electric field strengths are limited by the properties of the gas for large distances and field emission for small. The maximum voltage that can be applied between two electrodes separated by some distance is governed by the so called Paschen curve where the abscissa is given by pressure times gap distance and ordinate is the breakdown voltage. Paschen's law exhibits one minimum, typically between 10 to 20 microns at standard atmospheric pressure. Most deformable mirror designs will not be able to make use of the higher electrostatic forces available below the Paschen minimum but some will be able to come close where a significant increase in field strength can be obtained compared to the few MV/m available at large distances. By the introduction of a closed cavity solution as proposed by the present invention, the gas can be selected with the properties required for high irradiance and largest possible driving forces.
- [0053] The irradiance will result in some heating of the mirror. A consequence of this may be thermal expansion of the membrane and reduced tension. Change of tension times membrane curvature amounts to a change in pressure and this pressure change must be kept small relative the electrostatic pressure. This is one reason to allow largest possible electric fields. Air has a good Paschen minimum but poor heat conductivity. The quality factor to evaluate for various gases is the square of the breakdown voltage times the heat conductivity of the gas. Two gases have comparatively good heat conductivity, Helium and Hydrogen but only Hydrogen has an acceptable Paschen minimum. Hence, Hydrogen is the gas of preference for this application. The problem of having the same deformable mirror membrane being overloaded by the tasks of aberration control, focus control, measurement of capacity and cancellation of mechanical inertial forces in a closed cavity comprising an adaptive mirror may be solved by the present invention by the addition of a second cavity with a second membrane and a gas duct between the cavities to thereby off-loading some of the functions to the second cavity. In particular, the second cavity may be used to off-loading the change of volume needed for refocusing an optical beam impinging on the deformable mirror, whereby a large and rapid focus throw can be accomplished.
- [0054] Focus is one of the first terms in a series expansion of the phase of the wavefront of a light beam, here the light beam after the reflection in the deformable mirror. A shape of the deformable mirror which gives focus to a parallel (flat wavefront) incident beam is called the focus of the mirror

and is often specified as the phase at the centre of the reflected beam relative to that at the edge of the same beam.

[0055] FIG. 1 depicts a state of the art deformable mirror module with a closed cavity. The deformable mirror reflects incoming light beam 102 and adds to the reflected beam 104 a phase variation across the beam, this phase variation being controlled by the electronic system. The mirror is a thin stretched elastic membrane 100, e.g. made from glass, metal or silicon, and optionally made more reflective by a reflective coating and more conductive by a metal coating. The membrane 100 is placed above a substrate 118 with a pattern of electrodes 106 driven 116 by one or more digital to analogue converters (DACs) 112 controlled by input data 114. The distance or gap between the membrane 100 and the substrate 118 with electrodes 106 is determined by an isolating spacer 110 in which a cavity 108 is carved out. The cavity is closed and filled with a gas 109 with a pressure approximately the same as that on the outside of the membrane 100. The shape of the mirror is controlled by the potential on the electrodes relative to the potential on the membrane. If there is a large voltage, e.g. 200 V, between an electrode and the membrane a strong (relatively speaking) force pulls the opposing part of the membrane towards the electrodes creating a bending in the membrane. Where the voltage is low, e.g. 0 V, there is little electrostatic force and the membrane shape is controlled by its stiffness, weight and the differential air pressure across the membrane. It is not possible to create repulsive forces by electrostatics, so therefore the membrane will always bend inwards. To correct for aberrations one needs both negative and positive displacements of the mirror and the nominal state of the membrane corresponds to an intermediate voltage, e.g. 140 V. The nominal state corresponding to no correction has all electrodes at 140 V and there is a strong bow in the membrane. With a closed cavity it is possible to push the membrane flat in the nominal state by a slight over-pressure (order of 1 mbar) in the gas 109. This may be done by a piston 128 in a cylinder. The piston is pushed inwards until the mirror is flat in the nominal state (or has another desired bow). The flatness may be detected by optical means e.g. by a star test, a knife-edge test, an interferometer or a Hartman-Shack sensor, but it can also be locally controlled as shown in FIG. 1. The capacitance is measured between the membrane 100 and the electrodes by the capacitive position monitor 120 and corrective signals 124 are sent to the actuator 126 which pushes the piston 128 until the position of the membrane is as desired, e.g. flat. The capacitance measurement may be done at a high frequency, e.g. at an RF frequency which is too high to excite any movement or resonances in the membrane.

[0056] The prior art module in FIG. 1 has some short-comings for the intended use in a lithographic writer. First, correction of higher-order aberrations which has zero average displacement over the mirror do not change the volume of the closed cavity. They are therefore responsive on a timescale set by the resonance frequency of the membrane and the damping of it. However, if the mirror is used for refocusing the displacement has the same sign over the entire surface and the volume of the cavity changes. For higher volume-neutral corrections the electrostatic force only work against the stiffness of the membrane, but for focusing it also has to

- compress the gas, i.e. it works against a much stiffer spring. With reasonable volumes focusing is difficult to do, unless the volume change is compensated by a movement of the piston. The piston is much slower than the membrane and therefore refocusing with the piston is slow.
- [0057] Second, if there is a vibration the inertial forces on the membrane will cause it to bend unacceptably. The capacitive measurement will see the bending and correct it, but only slowly. Low frequencies will be compensated, but for high frequency vibrations there is no compensation.
- [0058] Third, if the gap is designed to be the smallest possible for a given desired deflection the maximum deflection will be up to a third of the gap and the capacitance will a non-linear function of both focus and higher-order corrections. Assuming we want a maximum deflection of 10 microns and 3 nm accuracy in the measurement, the gap will be 30-40 microns and the position measurement has to be accurate to 1/10000. This is difficult to achieve by measurement of the capacitance in the presence of aberrations.
- [0059] Note that the first and third issues above are created or at least aggravated by the use of the mirror for focusing. The first issue, the stiffness of the air volume, can be made smaller by using a larger gas volume, but then the second issue is made worse by a slower response of the gas volume to the piston.
- [0060] FIG. 2 shows an innovative deformable mirror where all three problems with the device in FIG. 1 are improved by the use of a second auxiliary or twin cavity with a second membrane. In FIG. 2 there are a membrane 200, a spacer layer 210, and a substrate 218 forming two cavities 208 and 211 communicating with a channel 230. The gas 209 has the same pressure everywhere in the two cavities. The cavities correspond to two movable membrane areas 201 and 203 where the left area 201 is used to act on the light beam 204, 202 and the right areas 203 act as a pressure sensor. The electrodes 206 with driving 216, 212, and 214 give to the left membrane, i.e. the deformable mirror, the desired shape. For aberrations the electrostatic force work against the stiffness of the membrane and for focusing it works against the stiffness in series with the air compression spring and the other membrane. It is possible to do refocusing by controlling the potential on the electrodes since the auxiliary membrane area 203 is more compliant than the air spring in FIG. 1. Since only the two membrane areas need to move for a focus shift, focus can be changed with a time constant which is determined by the resonance frequencies of the membranes, typically in the kilohertz range.
- [0061] The nominal state, e.g. with the deformable mirror flat, is set by creating an overpressure in the enclosed volume. This can be done by a piston 228 moved by an actuator 226, or by other means. The auxiliary cavity may be used for pressure measurement, e.g. by measuring the position of the membrane area 203 by capacitance measurement 222 or by optical or other electrical methods. The flat state of the deformable mirror 201 corresponds to a specific position of the second area 203 and the piston 228 (or equivalent pressure-controlling device) may be controlled by a control system 220 to find this state. The system needs to be calibrated at least once, e.g. by testing optical focus of the system the deformable mirror belongs to. Since no higher-order corrections are applied to the

auxiliary membrane area 203 the capacitance measurement is much simpler and it is also possible to make it differential by adding a capacitance electrode above the membrane. Other methods for measuring the pressure may be also be used, e.g. by using an integrated pressure sensor.

- [0062] The third problem with FIG. 1 may be reduced by passive cancellation of vibration effects as follows. If the cavities are identical and there is a vertical acceleration both membranes are affected by the same amount. This is equivalent to Fig. 1. However, if some weight 232 is added to the auxiliary membrane area 203 the acceleration causes a larger displacement and a higher pressure in the gas. The gas pressure pushes the deformable mirror 201 back, and with a suitably selected weight the deformable mirror will not react at all to the acceleration. FIG. 2 shows a mass added to the auxiliary membrane area 203, but other combinations of shape, size, and membrane thickness may give the same result without an added mass.
- [0063] FIG. 3 shows an embodiment with three communicating cavities, one with the deformable mirror 302, one for measuring the pressure 304, and one for changing the volume of the enclosed cavities 306. The volume-changing cavity 306 has partly the same function as the piston in FIG. 1 and FIG. 2, but is faster. An added mass 310 may fully or partially compensate for inertial forces on the membranes during vibration. The volume-changing cavity may use electrostatic actuation to change the volume by moving a membrane, or it may have another actuator.
- [0064] In FIG. 3 the volume actuator used for setting focus is electrostatic 322. The aberration correction 314 is input to the electrodes in the deformable mirror cavity and another input has the desired focus setting 316. The focus value is input to a controller 312 which adjusts the potential on the volume actuator 322. At the same time the pressure is measured in the measurement cavity 304 and the measured value 318 is sent to the same controller 312 which corrects the focus actuator 320 if needed. Not shown is FIG. 3 is a valve to adjust the amount of enclosed gas. This need only be done at long intervals, since volume changes during normal operation are controlled by the volume control cavity 306 and 322.
- [0065] FIG. 4A shows a piezoelectric bimorph 408 acting to change the enclosed volume, thereby establishing a slight overpressure and creating a flat (or other desired) nominal state for the deformable mirror. A piezoelectric actuator has high resonance frequency and high force, thereby creating a fast control loop for the bow in the deformable mirror. The circuit is essentially the same as in FIG. 3. The added mass 410 for passive compensation of mechanical accelerations may be place in the measurement cell 404. The deformable mirror 402 is controlled by the aberration correction inputs 414 and the air pressure created by the actuator in the volume change cavity 406 (in this example using a piezoelectric actuator 408). The pressure is measured in the measurement cavity 404 and the measurement 418 is combined with the focus input 416 in the controller 412 producing the control signal 420 to control the volume actuator 408.
- [0066] The devices in FIG 3 and FIG. 4A can be used in a slightly different operational mode. The electrodes under the deformable mirror are used to

- apply corrections to aberrations and the volume-changing actuator is used for changing focus. Since the aberrations are typically of the order of 1 lambda, where lambda is the wavelength of the light beam impinging on the deformable mirror, and the refocusing capacity needed is 10 lambda or more this relaxes the requirements on the electrostatic forces on the membrane or allows a thicker membrane to be used.
- [0067] In another embodiment the average deflection of the deformable mirror is measured on the deformable mirror itself, either by capacitance or by other electrical or optical methods, and a volume-changing actuator in an auxiliary cavity is used for changing focus. With a fast actuator fast feedback loops can be used and vibrations can be corrected by the feedback system up to kilohertz frequencies.
- [0068] FIG. 2B shows in block diagram form how the focus and aberrations can be set in the devices illustrated in FIG. 2, FIG. 3 and FIG. 4.
- [0069] In FIG. 5A an example embodiment with cavities side by side is shown. One good property is that the cavities can be made by the same process on a substrate of polymer, glass, ceramics, semiconductor, and/or metal. The deformable mirror 500 is placed side by side with the metrology cavity 506 where the pressure is measured. The optional third cavity 504 may be used for fast control of the volume and thereby focus. The figure also shows that the device has forced cooling. The example forced cooling in FIG. 5 is a cooler 508 mounted against the back side of the deformable mirror cavity and cooled by a flow 510, 512 of fluid (freon, water, air, hydrogen, or other suitable fluid). The cooler may also contain a Peltier element cooling the mirror to a lower temperature than the fluid temperature.
- [0070] In FIG. 5B the cavities are stacked, which makes a more compact device. Cooling may be from the back side, from the perimeter or by fluid passing through the stack.
- [0071] The closed cavity pressurized deformable mirror assembly according to the present invention is designed to suppress external accelerations by the use of a twin cavity that mimics some mechanical properties of a deformable mirror membrane.
- [0072] The closed cavity according to the invention must be made to maintain a constant and very accurate over-pressure. A suitable solution for this purpose according to example embodiments of the invention is a mechanical arrangement quite similar to the deformable mirror but where the deformable mirror has been replaced by a substantially equally deformable metallic membrane with metallic plates on both sides used to measure the differential capacitance to the membrane. The plates in this configuration must allow free flow of gas on both sides of the membrane so that the membrane experiences the same pressure difference as the deformable mirror when they are made to share the same communicating gas volume which is hermetically sealed from the surroundings. By differentially measuring the capacitances of the back and front plates, accurate relative deflection may be obtained for the membrane in the twin cavity and by controlling the gas volume so that this position is kept constant, a constant pressure may be maintained in both (communicating) cavities.

- [0073] External accelerations along the surface normal of the deformable mirror membrane will induce an additional pressure due to the inertia of the deformable mirror proportional to the acceleration times the density times the thickness. When the surface normals of the deformable mirror and the membrane in the twin cavity are co-aligned, the control system will react to the additional (inertial) pressure and restore the position of the membrane by increasing the pressure in the twin cavity and, since they are communicating, also in the deformable mirror cavity. To arrange for cancellation of external accelerations, it is sufficient to make the product density times height of the deformable mirror and the membrane in the twin cavity equal and align the surface normals. A good arrangement of both cavities would be to put the twin cavity in mechanical contact below the deformable mirror. They must not be arranged back-to-back because that would enhance the effect of external acceleration, not cancel it.
- [0074] A quality factor for the gas in the cavity beneath a high-power deformable mirror is the electro-static pressure limited by Paschens law and heat conductivity of the gas. When the mirror is deflected to obtain some amount of defocus, it has a spherical shape of constant curvature. Power absorbed by the mirror will cause a temperature change and a change in tension due to linear temperature expansion since the boundary and the rest of the non-illuminated parts of the mirror are at constant temperature. The curvature times the change in tension equals a pressure. This pressure will cause a change of deformation inversely proportional to the stiffness. For a given desired maximum deformation, if the gas allows us to create larger pressures, the membrane can be made stiffer and hence resist the relative changes of tension times curvature. For this reason, when selecting a gas, we want to consider the maximum voltage squared times heat conductivity to find the gas that will allow us to design the most resilient deformable mirror.
- [0075] Table 1 below shows gases and their Paschen minimum, heat conductivity and voltage squared x heat conductivity. C-318 and CF₄ are just two examples of Freons which also have good Paschen minimum breakdown voltages. However, as shown in Table 1, their thermal conductivities are rather poor in comparison with Hydrogen.

Table 1

Gas	Paschen minimum	Heat conductivity	Voltage squared x heat conductivity
H ₂	280	0.17	13.3k
Air	327	0.023	2459
He	180	0.15	4860
SF ₆	520	0.012	3244
C-318	420	0.011	1940
CF ₄	480	0.015	3456

- [0076] The elastic constant of the enclosed gas in the two-cavity arrangement is

$$\frac{dp}{dz} = -\gamma p_0 \left(\frac{A}{V_0} \right)^c$$

given by where c equals 2 for two communicating and substantially identical cavities. The factor γ is 7/5 for a diatomic gas and

5/3 for a mono-atomic gas. We can insert typical values. Gamma 5/2, $p_0 = 10^5$ and $V_0/A = 0.00003\text{ m}$. This gives a derivative for pressure vs deflection of 9×10^9 . The same derivative can be computed for a given mirror design where a change in electro-static pressure causes a deflection of the membrane. A theoretical expression for simply supported

$$\frac{dp}{dz} = \frac{64EH^3}{R^4(5+\nu)(1-\nu)}$$

circular membrane gives

[0077] We can evaluate this expression for a “typical” membrane with

$$\frac{dp}{dz} \approx 2 \times 10^6$$

$H=0.0001\text{m}$, $R=0.035\text{m}$, $E=170\text{GPa}$, and use the result to compare stiffness of the air column beneath the mirror with stiffness of the mirror. The resulting stiffness of the air column can be calculated to be on the order of 9×10^9 which is almost 5000 times stiffer than the top deformable membrane. For most applications, a $100\text{ }\mu\text{m}$ thick membrane is probably to be considered very thick. In practice, the relative stiffness of the air column is expected to be even larger than calculated above.

[0078] The deformable mirror cavity of the deformable mirror assembly of the invention may together with another cavity be used as a pressure gauge in order to balance the effect of external acceleration along an optical axis. The second cavity may also have a membrane that is subject to gravity and a pressure differential, but not to electrostatic forces that affect the upper membrane, so the curve of the second membrane is somewhat different than the curve of the first membrane. The second membrane may then be configured to have stiff surfaces with electrodes that support differential measurement of capacitance. The electrodes may be positioned between the surface above the bottom membrane and the surface below it. The stiff surfaces are permeable and not intended to restrict the flow of gas. In an alternative embodiment, capacitance measuring electrodes are placed at the top and bottom of the second cavity, depending on the cavity geometry. In the two cavity arrangement, the enclosed gas is rigid relative elasticity of the membranes.

[0079] A pressure regulator may effectively be used as a volume regulator. It is subject to the same influence as the membranes and can in principle be described by the same balanced approach. By choosing a regulator cross-section that is sufficiently smaller than the top and bottom membranes depicted, we can appropriately tune the swing of its movement so that its position can be easily measured. If a two-tier control, loop consisting of one outer control loop maintaining membrane position and one sufficiently faster inner control loop for the pressure regulator position, is made, vibrations affecting the pressure regulator can be cancelled out by its internal position control thus preventing this disturbance to propagate to the cavity.

[0080] Demanding aspects of microlithography include significant power handling at the deformable mirror surface, relying on passive cooling instead of active cooling, quick refocus capability responsive to height discontinuities as one rotating arm leaves off and the next takes up printing, and tight critical dimensions in images formed on a workpiece. In addition, vibration dampening is desired, as a deformable mirror with low inertia may be

- susceptible to a shock impulse that would be insignificant for ophthalmologic or astrophysical observations, but which might kill a critical electrical component on a substrate by relaying an unfocused patterning beam to the substrate for a non-trivial time.
- [0081] Yet another useful characteristic of the particular adaptive optics that we disclose is vibration or shock attenuation. FIG. 6A and 6B depict a dual cavity design that uses the stiffness of gas in a closed volume to dampen vibration by increasing the response time of the mirror membrane. In effect, the dual cavities act as a low pass filter, attenuating the effect fast transient vibrations or shocks on displacement of the mirror membrane. How this works is described in the attachments.
- [0082] The use of hydrogen as an enclosed gas is innovative. The combination of a minimal separation between the deformable mirror and electrostatic actuators with use of hydrogen in a closed volume appears to be new and inventive. The use of capacitive sensing to keep the pressure constant (with a small lag time) can further be useful.
- [0083] FIG. 6A shows a deformable mirror assembly with a first cavity (601) comprising a deformable mirror (603), or membrane, and a second cavity (602) which is used as a pressure gauge, e.g. to balance the effect of external acceleration along an optical axis. The second cavity (602) comprises a second membrane (604), or mirror, that is subject to gravity and a pressure differential, but not to electrostatic forces that affect the first deformable mirror, or membrane, so the curve of the second membrane is somewhat different than the curve of the first membrane.
- [0084] In the configuration shown in FIG. 6B, stiff surfaces (616, 617) with electrodes (619, 620), above and below the second membrane (614), may be used to support differential measurement of capacitance, between the surface above the second membrane and the surface below it. These stiff surfaces (616, 617) may preferably be permeable and not intended to restrict the flow of gas.
- [0085] Alternatively, as shown in FIG. 6B, the capacitance measuring electrodes (619, 620) could be positioned at the top and bottom of the second cavity (612), depending on the cavity geometry.
- [0086] In the configurations shown in FIG. 6A and FIG. 6B, a gas, preferably hydrogen but also air may be used, enclosed in a first volume of the first cavity (601, 611), is rigid relative elasticity of the two membranes, or mirrors. When the deformable mirror (603, 613) is deflected, e.g. to obtain some amount of defocus, it has a spherical shape of constant curvature. Power absorbed by the deformable mirror (603, 613) will then cause a temperature change and a change in tension due to linear temperature expansion since the boundary and the rest of the non-illuminated parts of the deformable mirror (603, 613) are at constant temperature. The curvature times the change in tension equals a pressure. This pressure will cause a change of deformation inversely proportional to the stiffness. For a given desired maximum deformation, if the gas in the first volume of the first cavity (601, 611) allows us to create larger pressures, the deformable mirror (603, 613) can be made stiffer and hence resist the relative changes of tension times curvature.
- [0087] The pressure regulator (605, 615) shown in FIG. 6A and FIG. 6B is effectively a volume regulator. The pressure regulator (605, 615) is subject

to the same influence as the membranes in the above description, and can in principle be described by the same balanced approach. By choosing a regulator cross-section that is sufficiently smaller than the first and second membranes depicted, it is possible to appropriately tune the swing of its movement so that its position can be easily measured. If a two-tier control, loop consisting of one outer control loop maintaining membrane position and one sufficiently faster inner control loop for the pressure regulator position, is made, vibrations affecting the pressure regulator can be cancelled out by its internal position control thus preventing this disturbance to propagate to the cavity.

- [0088] In example embodiments of the invention, the electrostatically actuated deformable mirror assembly of the invention is included in a focusing system, or focus control system, for refocusing a writer (or reader) beam during the patterning (or measuring) of a workpiece. The focusing system may then be provided with position information and/or workpiece topography information from a focus sensor and/or a focus sensor system.
- [0089] In example embodiments, the electrostatically actuated deformable mirror assembly of the invention is implemented and used in a focusing system, or focus control system, for refocusing a beam or image in a pattern generator system.
- [0090] Example embodiments of the invention provide a focusing system, or focus control system, comprising the deformable mirror assembly for use in a pattern generator system in order to make the pattern generator system less or significantly less sensitive to translations and/or rotations. The deformable mirror assembly may then be used as a focus control system that adaptively adjusts the optical path length in response to the translations and/or rotation in such a system.
- [0091] According to at least some example embodiments, the deformable mirror assembly of the invention is comprised in a focusing system configured to change a nominal focus position according to a topography map of the workpiece and/or focus length variations between the plurality of sweeps, or scans, during and/or after a projection swap between the plurality of sweeps or scans.
- [0092] According to at least one example embodiment, the deformable mirror assembly of the invention is configured to refocus a writing beam for projecting a laser image.
- [0093] A beam splitter configured to direct light reflected from the deformable mirror toward a plane to generate the pattern on the workpiece may also be coupled to the deformable mirror assembly.
- [0094] The pattern generation system comprising the deformable mirror assembly may further include a focus sensor or focus sensor system configured to provide position information to the focus motor.
- [0095] A focus sensor may provide "real-time" position information for dynamic refocusing during simultaneous scanning of an optical arm processing (e.g., imaging or measuring) the workpiece. Alternatively, a focus sensor may provide position information from a previous scan of the workpiece.
- [0096] The deformable mirror assembly configurations described in the example embodiments of the invention may be implemented as an adaptive optic device in a rotary lithography application using adaptive optics.

- [0097] The deformable mirror assembly of the invention may be implemented in an example optical writing system having a rotary scanning system as disclosed in pending applications by the same applicant. A one-dimensional image may then be formed by a one-dimensional or essentially one-dimensional SLM (having the length-wise dimension at least ten times longer than the cross-wise dimension). The optical system projects the image (formed on the SLM or projected from it) to an image on a workpiece. A scanning system scans the image along a trajectory which may be straight or curved such that a swath of sequential images are exposed and the swath can be patterned according to a bitmap or other description in a datapath of the system. The exemplary scanning is performed by a rotating prism and an optical relay with a mirror which directs the projected image onto the workpiece. When the prism has rotated a certain angle, a quarter of a full turn, a new facet of the prism intersects the beam and sends the image in a different radial direction. In one example embodiment, there are four directions and the optics has four scanning arms. As soon as one arm leaves the workpiece, the next one enters it from the opposite side. This gives very efficient scanning with little vibrations and little time lost between writing strokes. The system is an example of systems placing high requirements on both the optical quality and an accurate and nimble focus system. It is difficult to make all the arms optically identical in regard to focus plane and aberrations. A fast deformable mirror coupled to the deformable mirror assembly of the invention can be used adjust residual aberrations in the arms and make the focus plane follow the surface of a non-flat workpiece. It can also change the corrections of both aberrations and focus between the arms. The time available for setting new corrections and focus may be of the order of 10 ms. In order to track the surface of the workpiece with focus, the time constant of the focusing system is desired to be of the order of 1 ms. The four arms are located in a spinning rotor. It is advantageous to have the focus mechanism before the light enters the rotor, since only one focus actuator is then needed, and it can be easily supplied with electronic control signals, compressed air, etc. In example embodiments, the deformable mirror is used for focus and aberration control and it is placed before the light beam enters the rotor. The light beam carrying the image is reflected by the mirror to the deformable mirrors and reflected through the mirror (reflection can be controlled by polarisation or other means) and towards the prism or pyramid.
- [0098] The system places high requirements on the mirror's optical quality, since the lithographic performance depends on the wavefront quality of the beam. It also requires high power handling, since the laser beam may be 25 W or higher. The time constant needs to be 1 ms to track the workpiece surface or 10 ms to allow resetting between each arm. Deformable mirrors are commercially available, but the inventor has been unable to find devices with the combination of accurate wavefront control, high power handling and fast response. The inventive deformable mirror has therefore been developed. It is anticipated that other optical systems with similar requirements can benefit from the inventive deformable mirror, in particular for optical writers having high power and high throughput.

- [0099] In the rotary lithography application, the adaptive optic device of the invention may be positioned above a square footprint, pyramid-shaped mirror that relays the reading or writing beam successively to the four arms of the rotor (keeping in mind that a different shape of mirror and different number of arms could be used.)
- [00100] In one example embodiment of the rotary lithography application, the adaptive optic device may operate without optical wavefront feedback, as is common in astronomical applications. Instead, it may be calibrated in advance for mirror characteristics. Optionally, it is calibrated for the particular optics of the rotor machine. That is, less precise optics can be used for the rotor optical relays than might be used without an adaptive optics device, because the number of actuators that drive the device is sufficient to correct aberrations in the optical system as built. For instance, higher order Zernike polynomial terms can be fit and applied to correct a wide variety of typical optical defects. The required corrections can be determined once or periodically during the lifetime of the rotor machine and do not need to be revisited during operation.
- [00101] Another useful application of adaptive optics for a rotor machine is fast focus responsive to height discontinuities as one rotating arm leaves off and the next takes up printing. A height sensing mechanism determines the clearance between a rotor arm and a workpiece height. Since the workpieces typically are thin, even less than a millimetre in thickness, some variation in height is inevitable. So, the system is built to track the workpiece surface height. Across the width of the workpiece, this typically is a smoothly rolling topography. However, each time a new arm becomes active, there is a chance of an abrupt discontinuity, like a cliff to climb or drop off. The fast focus of an adaptive optic device can be useful in this new circumstance, which is unique to the focus requirements of a rotary microlithography system.
- [00102] At least one example embodiment provides a focusing system in a pattern generator or other tool including an optical system and a rotor. The optical system is configured to project a laser image onto an optical scanner. In certain embodiments, the rotor includes a plurality of optical arms arranged at a first angle relative to one another and the optical scanner. The laser image is then sequentially reflected by the optical scanner into each of the plurality of optical arms of the rotor to generate a pattern on a workpiece.
- [00103] In at least one other example embodiment, the focusing system may also include a focusing apparatus configured to change the nominal focus position according to a topography map of the workpiece and/or focus length variations between the plurality of optical arms during and/or after a projection swap between the plurality of optical arms; and a focus motor configured to drive the focusing apparatus.
- [00104] In example embodiments of the invention, a deformable mirror for refocusing is in a configuration with a beam splitter (e.g., polarization beam splitter) and possibly a wave plate that allows light beams to reflect at normal angles and that separates incoming and outgoing beams. The beam splitter directs light reflected from the deformable mirror toward a workpiece to generate an image.

- [00105] The beam splitter may be omitted, for example, by tilting the deformable mirror, thereby separating the incoming and outgoing beams. This may, however, limit the usable refocus range because sagittal and tangential rays have different focus positions for tilted rays reflected from a spherical mirror surface.
- [00106] In example embodiments, the (implied) astigmatism appears even on-axis and is proportional to the square of the tilt angle multiplied by the defocus.
- [00107] Skewed (tilted) rays are present even in the configuration with the polarization beam splitter and the wave plate, which limit the range of available refocus. However, this limitation is not severe because it is the mirror sag that determines the amount of refocus and the angle of the field point may be reduced by choosing a suitable focal length and corresponding mirror size.
- [00108] In example implementations, focus sensor(s) may be used to provide position information to the focusing system for refocusing (e.g., dynamic refocusing) and/or configured to provide a workpiece topography map prior to writing/reading on the workpiece.
- [00109] A focus sensor may include a plurality of (e.g., about 10) direction reflection sensors and a plurality of (e.g., about 25) diffuse reflection sensors. The focus sensor may be positioned under an alignment bridge (e.g., in the loading area) and/or just prior to the location of the rotor arms (e.g., in the writing/measuring area) in a pattern generation system.
- [00110] The focus sensor may be a topography sensor positioned at the alignment bridge (e.g., in the loading area). In an example embodiment, the focus sensor 606 is attached to one or more rotor arms (e.g., positioned in the writing/measuring area).
- [00111] Although the example embodiments in FIGS. 5 and 6 show focus sensors positioned in both the loading area and the writing/measuring area, according to example embodiments the focus sensors may be positioned in only one of the loading and measuring/writing areas.
- [00112] The pattern generator system may comprise an image generating device (not shown) as part of, or coupled to, the optical system 706, e.g. in form of at least one modulator such as a spatial light modulator (SLM), grating light valve (GLV) or acousto-optic modulator (AOM).
- [00113] According to at least some example embodiments, an image is printed on a substrate with a certain bow length at a specific position with one optical arm at a time. In this case, each of the plurality of optical arms prints an image scan with a certain bow length on the substrate.
- [00114] The laser image may be in the form of a static beam, and as mentioned above, a projection swap between the optical arms occurs when the static incoming beam reaches the edge of the optical scanner, which rotates together with the rest of the rotor at constant or substantially constant speed. Accordingly, each optical arm operates sequentially to print a corresponding image scan, and the time periods during which each optical arm prints the corresponding image scan do not overlap.
- [00115] As mentioned above, example embodiments may require a dynamic focus for various reasons. Dynamic focus may be provided by the focusing system.
- [00116] The focusing system may include a focusing apparatus and a focus motor. The focusing system may be configured to change the nominal focus

position according to at least one of a topography map of the workpiece and focus length variations between the plurality of optical arms during and/or after a projection swap between the plurality of optical arms. The focus motor may be configured to drive the focusing apparatus. Depending on configuration, the focusing system may be located at either end of the optical system. In the examples of a pattern generator system where an image generating device (not shown) is not part of the optical system, the focusing system may be located between the optical system and the image generator device, e.g. at the upper end of the optical system.

- [00117] In another example embodiment, the focusing apparatus may be configured to change the focus position of a writing beam for projecting the laser image based on position information from a focus sensor. The focus motor may be configured to drive the focusing apparatus. In this example, the focusing system may again be located at either end of the optical system.
- [00118] In yet another example, the focusing system may include a deformable mirror assembly according to any of the example embodiments and configurations described in this disclosure and which is configured to refocus a writing beam. In one example, the deformable mirror assembly of the invention may be located at the end of the optical system.
- [00119] The foregoing description of some example embodiments has been provided for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosure. Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. The same may also be varied in many ways. Such variations are not to be regarded as a departure from the disclosure, and all such modifications are intended to be included within the scope of the disclosure.

Claims

1. An electrostatically actuated deformable mirror assembly comprising:
 - a first cavity in form of a deformable mirror subassembly comprising a first housing, a deformable mirror coupled to the first cavity by being mounted to the first housing, and an electrostatic element carried by the first housing, the deformable mirror having an external, reflective surface and an internal surface, the deformable mirror subassembly defining a first cavity comprising a first volume at least partially between the internal surface of the deformable mirror and the electrostatic element;
 - a second cavity in form of a compensating assembly comprising a second housing and a deformable membrane coupled to the second cavity and mounted to the second housing, the deformable membrane having external and internal surfaces, the compensating assembly defining a second volume at least partially between the internal surface of the deformable membrane and the second housing; and
 - a pathway, or communication channel, fluidly coupling the first and second cavities, wherein the pathway, the first cavity and the second cavity are comprised in or defines a hermetically closed cavity configured to include a gas fluidly isolated from the ambient environment, wherein the deformable membrane coupled to the second cavity is configured to be used to balance or compensate for a change of volume or pressure in the first cavity.
2. The assembly of claim 1, further comprising means for controlling the pressure and/or volume of the second cavity, wherein said means is coupled to the hermetically closed cavity.
3. The assembly of claim 2, wherein the deformable membrane of the second cavity is configured to be kept at an essentially fixed position by said means for controlling the pressure and/or volume of the second cavity.
4. The assembly of claim 2, wherein the said deformable mirror of the first cavity is having a focus range of positions corresponding to a range of focus settings spanning at least plus/minus 5 wavelengths of phase, and wherein the deformable membrane of the second cavity is configured to be positioned to a sequence of selected positions in the focus range, or corresponding to the focus range, by said means for controlling the pressure and/or volume of the second cavity.
5. The assembly of any of claims 2 to 4, wherein said means for controlling the pressure and/or volume of the second cavity is a pressure regulator coupled to the second cavity.
6. The assembly according to any of claims 5, wherein outer and inner capacitance elements located opposite the outer and inner surfaces of the deformable membrane are positioned at distances suitable for being capacitively coupled to the deformable membrane of the second cavity, whereby movement of the deformable membrane can be sensed through the outer and inner capacitance elements so the pressure regulator can be operated in order to maintain a desired pressure within the second volume.
7. The assembly according to any of claims 1-6, wherein the hermetically closed cavity is filled with hydrogen.
8. The assembly according to any of claims 1-6, wherein the hermetically closed cavity is filled with a non-combustible hydrogen gas mixture.
9. The assembly according to any of claims 1-6, wherein the hermetically closed cavity is filled with air.

10. The assembly according to any of claims 5-9, wherein a desired pressure of the hermetically closed cavity is a constant pressure and the pressure regulator is further configured to keep the pressure of the hermetically closed cavity at a constant pressure.
11. The assembly according to any of claims 1-10, wherein the desired pressure of the hermetically closed cavity is a pressure above the ambient pressure.
12. The assembly according to any of claims 6-11, wherein the desired pressure is achieved using a closed loop controller operably coupled to the pressure regulator and the capacitance elements.
13. The assembly according to any of claims 1-12, wherein the deformable membrane has a thickness of less than 100 microns.
14. A method of balancing a change of volume or pressure induced by the displacement of a deformable mirror coupled to a first cavity comprised in a hermetically closed cavity by changing the volume or pressure of a second cavity, comprised in the same hermetically closed cavity as the first cavity, in order to achieve at least one of:
 - keeping a deformable membrane, coupled to the second cavity, at an essentially fixed position;
 - positioning a deformable membrane, coupled to the second cavity, to a sequence of selected positions in the focus range of the deformable mirror;
 - or
 - positioning a deformable membrane, coupled to the second cavity, to a sequence of selected positions corresponding to positions of the focus range of the deformable mirror.
15. The method of claim 14, further including focusing the adaptive optics device responsive to a sensing of height of the workpiece.
16. The method of any of claims 14-15, further including adapting the focusing of the adaptive optics device responsive to a capacitive sensor sensing deflection of a deformable mirror of the adaptive optics.
17. The method of any of claims 14-15, further including adapting the focusing of the adaptive optics device responsive to a capacitive sensor sensing deflection of the deformable membrane fluidly coupled to the deformable mirror of the adaptive optics.
18. The method of any of claims 14-16, further including passively cooling the deformable mirror of the adaptive optics.
19. The method of claim 18, wherein hydrogen in a closed volume behind the deformable mirror dissipates a majority of heat load on the deformable mirror.

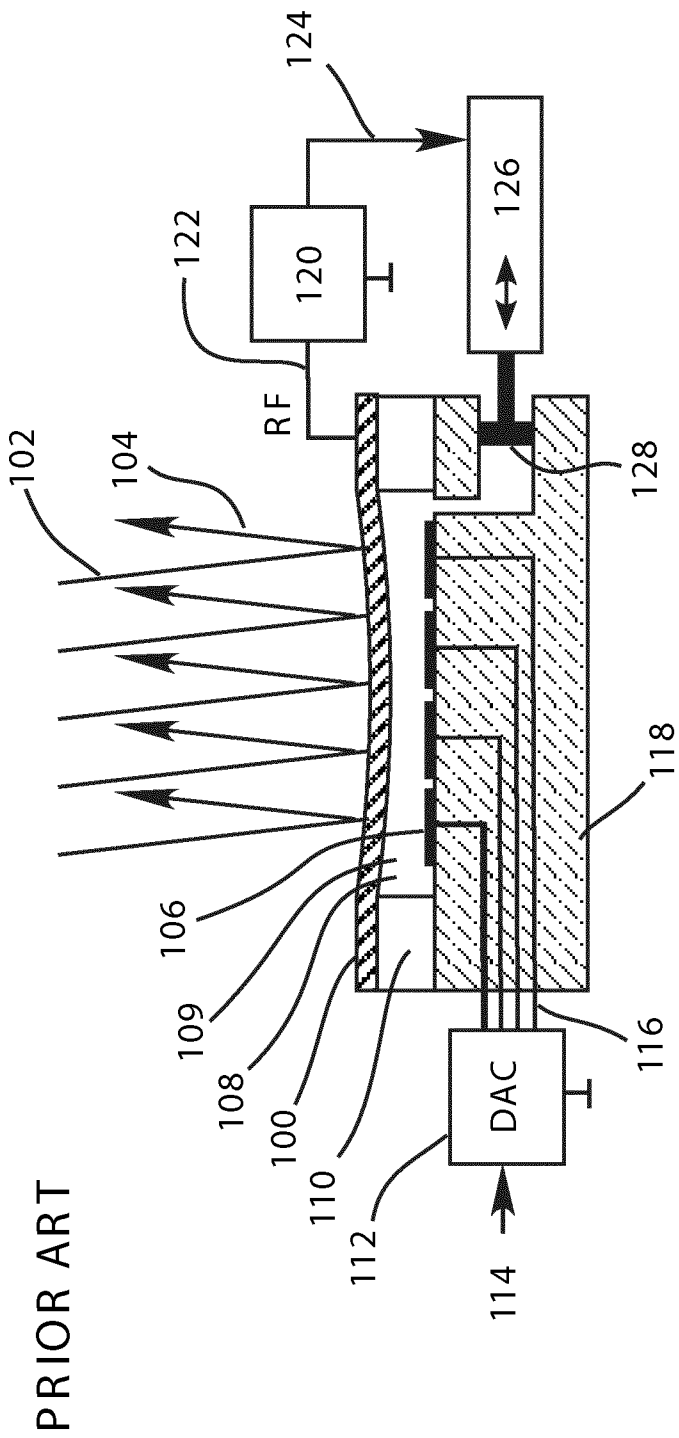


FIG. 1

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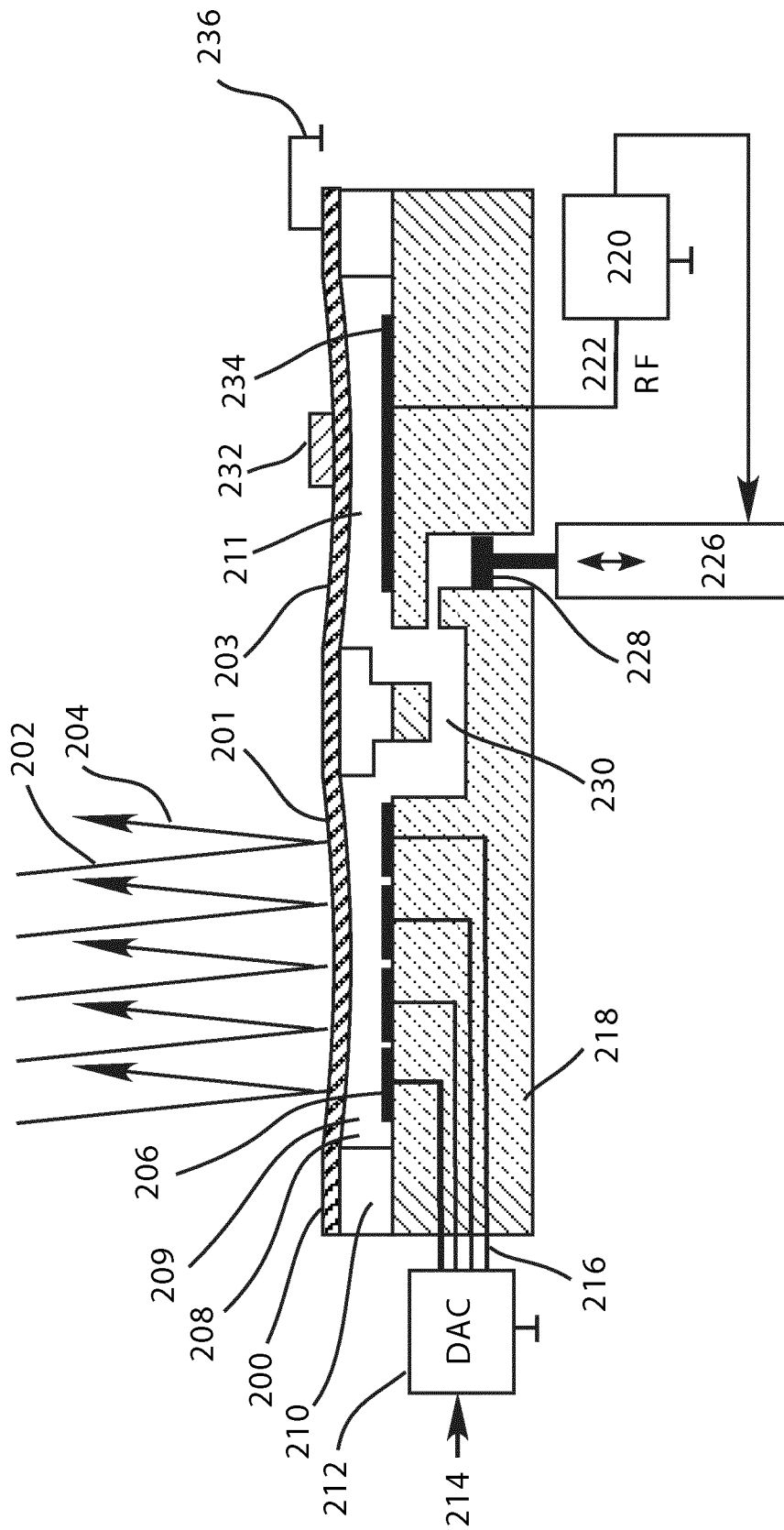


FIG. 2A

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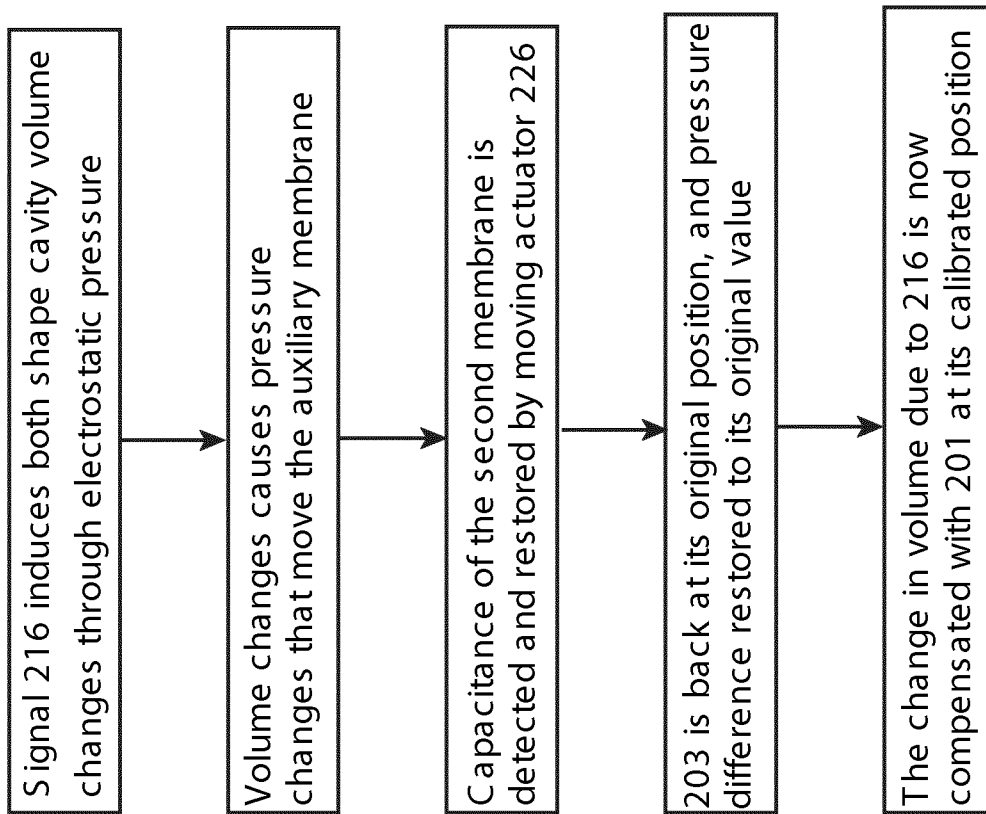


FIG. 2B

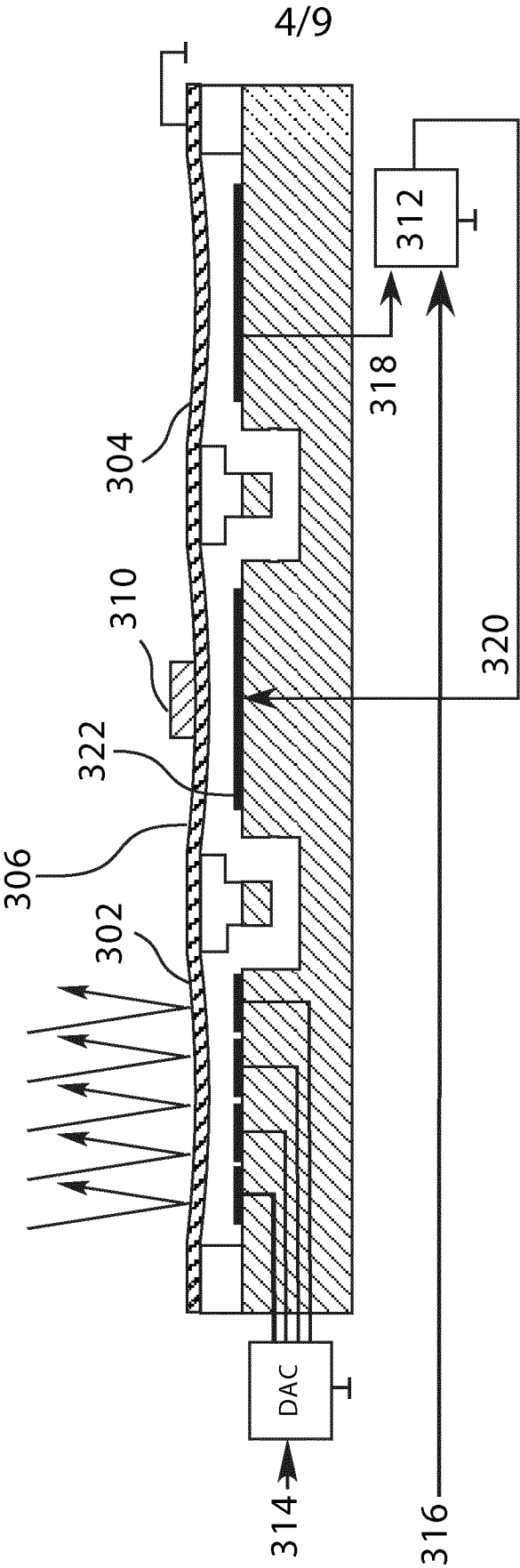


FIG. 3

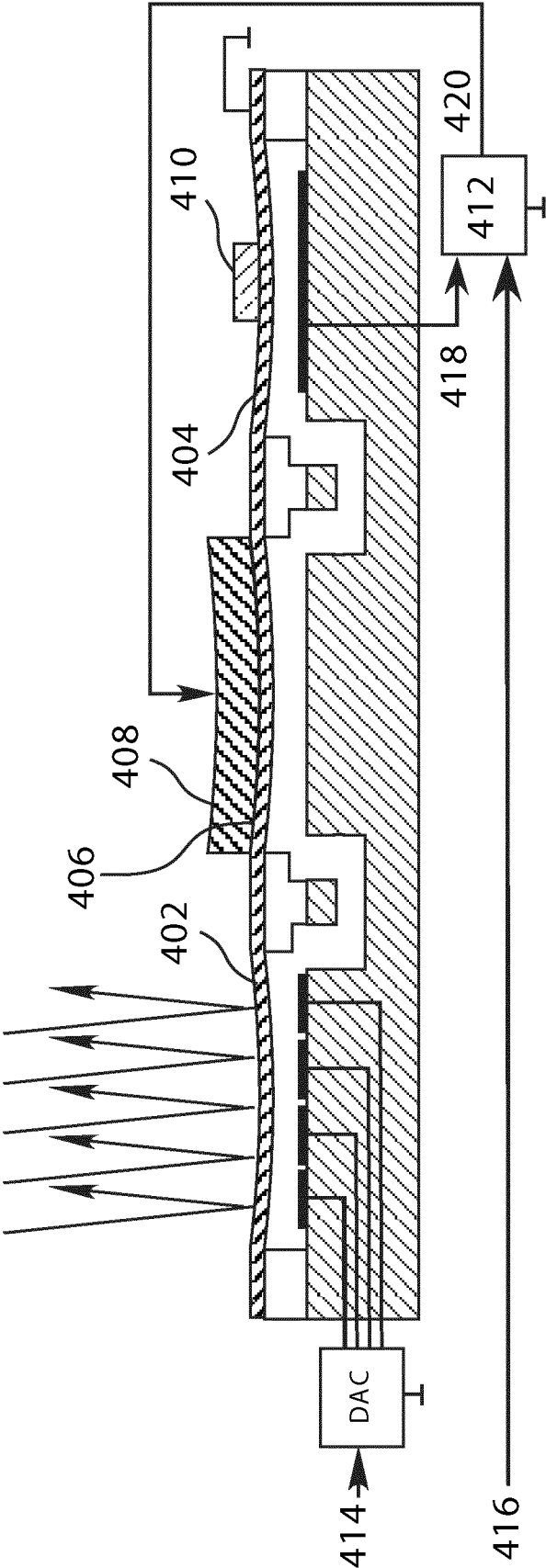


FIG. 4A

6/9

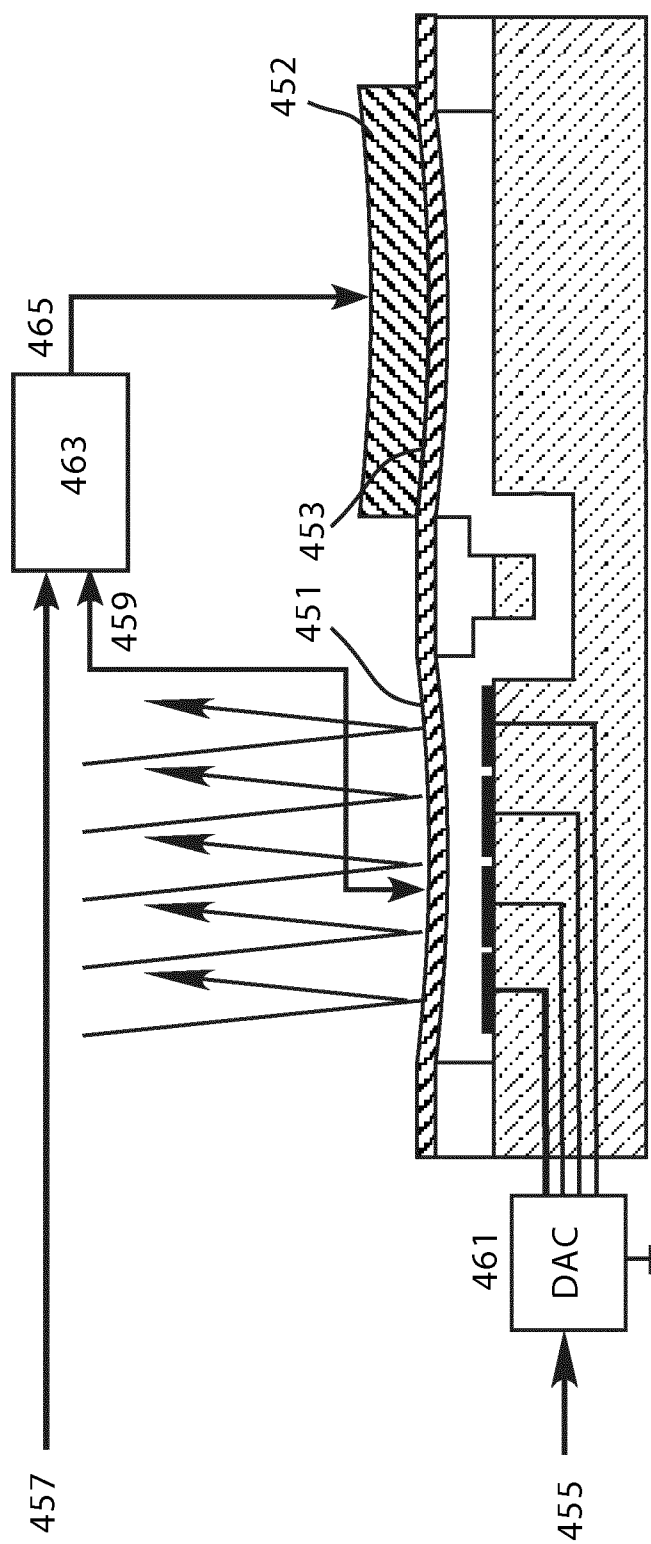


FIG. 4B

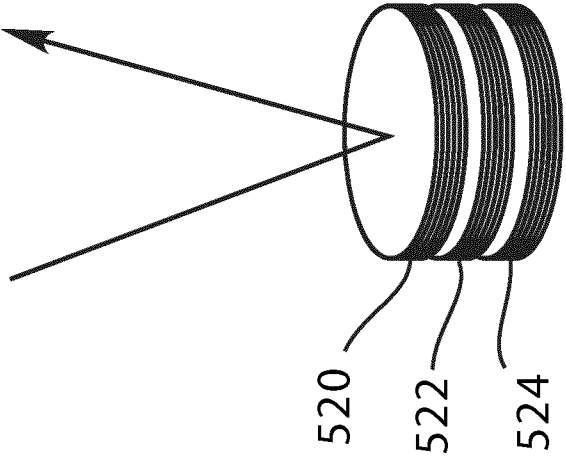


FIG. 5B

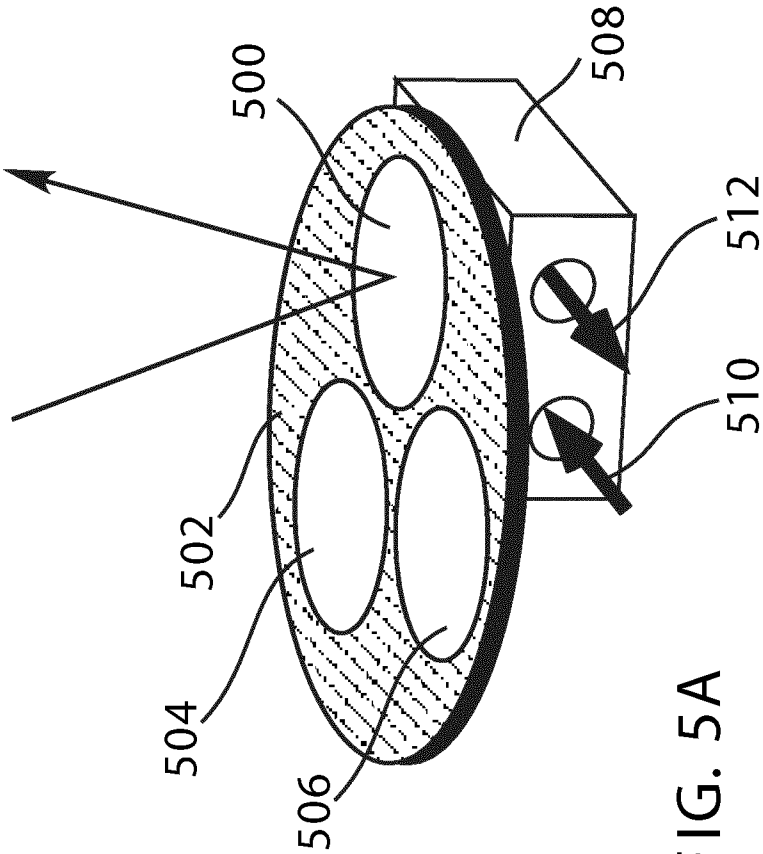


FIG. 5A

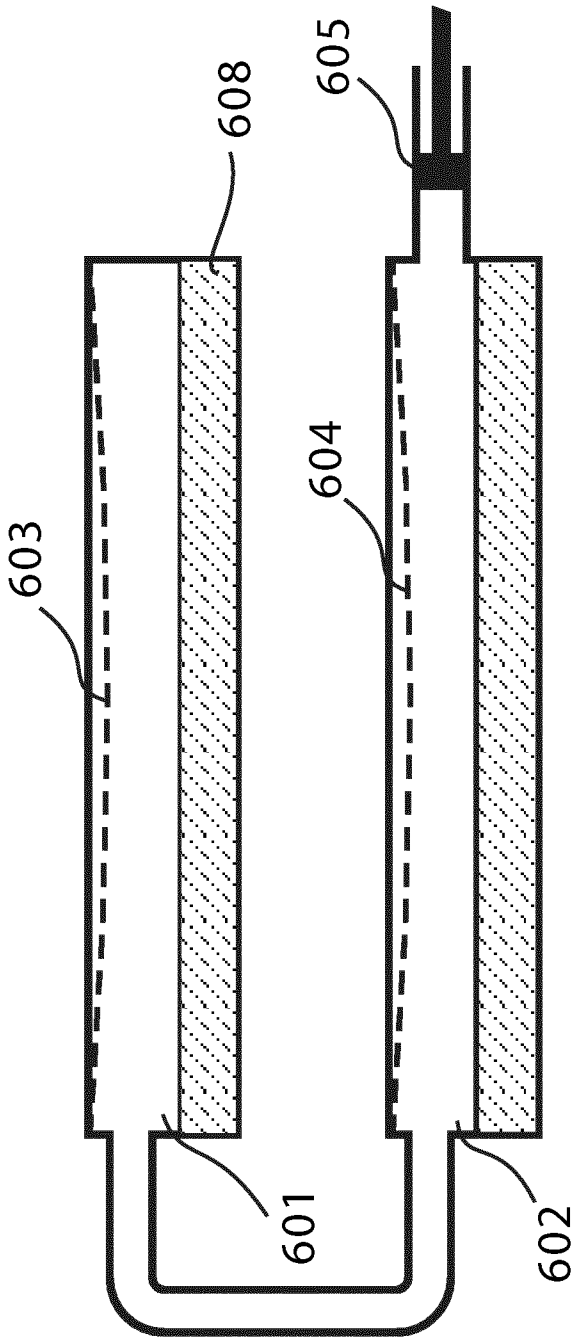


FIG. 6A

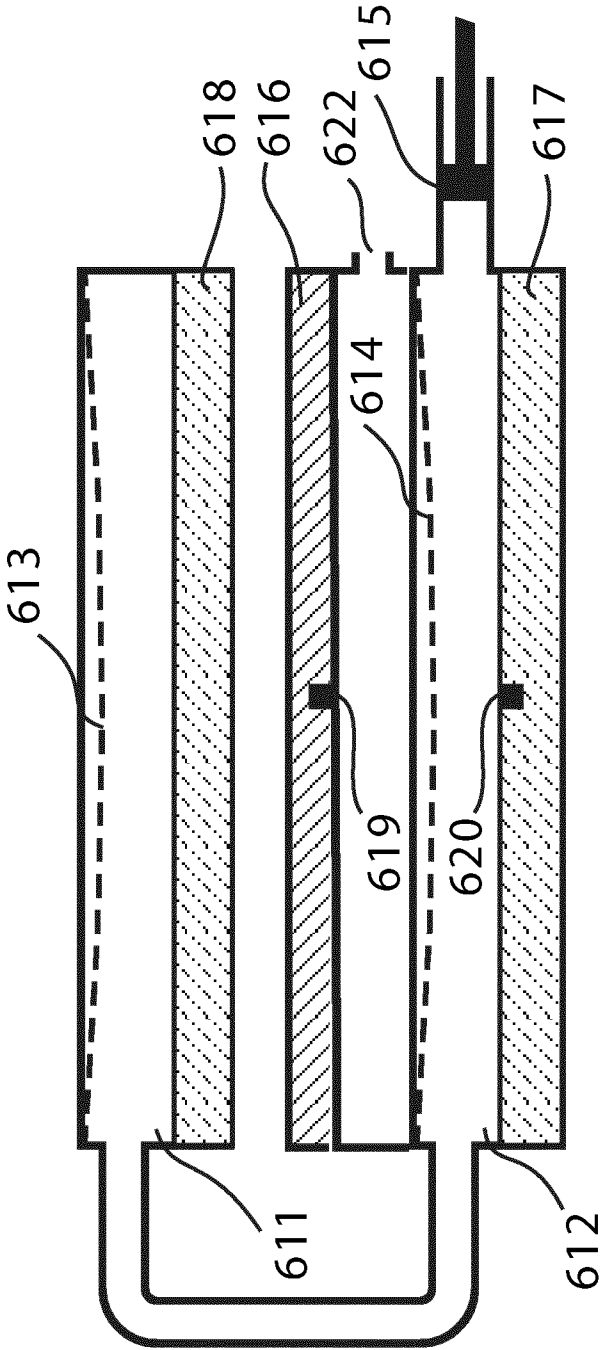


FIG. 6B

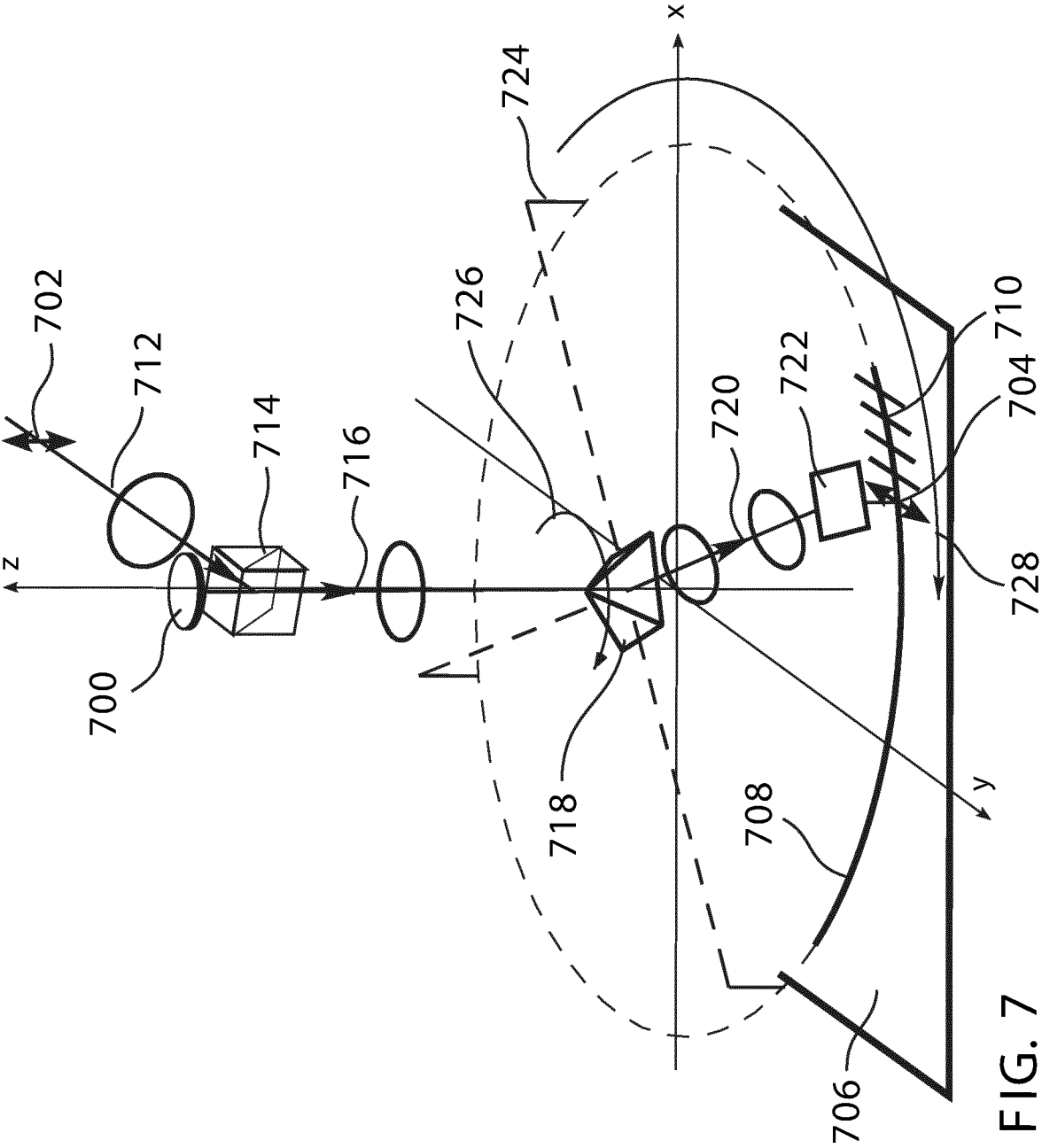


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/053377

A. CLASSIFICATION OF SUBJECT MATTER
 INV. G02B26/08
 ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 G02B

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/165312 A1 (AOKI SUNAO [JP] ET AL) 19 July 2007 (2007-07-19) the whole document	1,7-9, 11,13-19
A	US 2002/101646 A1 (IDE TAKAYUKI [JP] ET AL) 1 August 2002 (2002-08-01) paragraph [0174] - paragraph [0177]; figure 37	1-5,10, 12
A	US 2011/043937 A1 (JUNCKER DAVID [CA] ET AL) 24 February 2011 (2011-02-24) paragraph [0051] - paragraph [0064]; figures 2a,2b	1,14



Further documents are listed in the continuation of Box C.



See patent family annex.

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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