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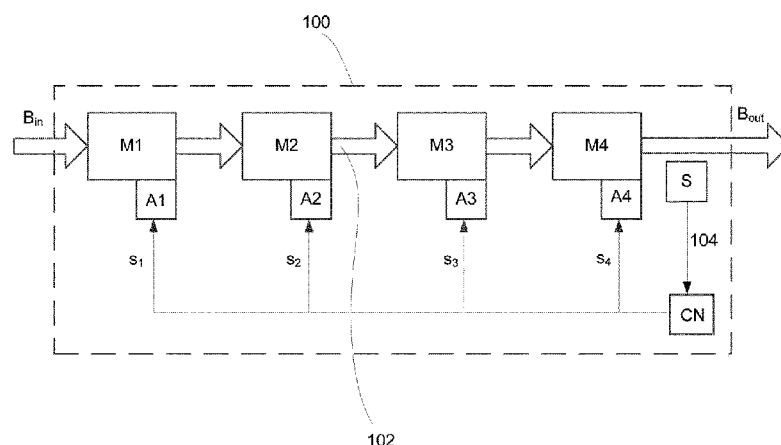


Fig. 4

(57) Abstract: A radiation beam expander comprises a diverging optic and a converging optic. The diverging optic comprises one or more mirrors for receiving a radiation beam and increasing a divergence of the radiation beam. The converging optic comprising one or more mirrors arranged to receive the radiation beam and to reduce the divergence of the radiation beam. At least one of the one or more mirrors of the diverging optic and/or the converging optic is provided with an actuator arranged to control a curvature of the mirror. This allows the optical power of the diverging optic and/or the converging optic to be controlled independently of the angle at which a radiation beam is incident on the mirrors of said diverging optic or the converging optic. This allows the radiation beam expander to control the divergence of the radiation beam after the diverging and converging optics independently of the orientations and relative positions of the mirrors of the diverging and converging optics.

Radiation Beam Expander

FIELD

5 [0001] This application claims priority of EP 15160280.2 which was filed on March 23, 2015 and EP 15168168.1 which was filed on May 19, 2015 and which are incorporated herein in its entirety by reference.

CROSS-REFERENCE TO RELATED APPLICATIONS

10 [0002] The present invention relates to radiation beam expander for receiving an input radiation beam, increasing its cross sectional area and outputting it as an output radiation beam. The radiation beam expander may, for example, form part of a lithographic system.

BACKGROUND

15 [0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may for example project a pattern from a patterning device (e.g. a mask) onto a layer of radiation-sensitive material (resist) provided on a substrate.

20 [0004] The wavelength of radiation used by a lithographic apparatus to project a pattern onto a substrate determines the minimum size of features which can be formed on that substrate. A lithographic apparatus which uses EUV radiation, being electromagnetic radiation having a wavelength within the range 4-20 nm, may be used to form smaller features on a substrate than a conventional lithographic apparatus (which may for example use electromagnetic radiation with a wavelength of 193 nm).

25 [0005] A lithographic system may comprise one or more radiation sources, a beam delivery system and one or more lithographic apparatus. The one or more radiation sources may comprise a free electron laser. It may be desirable to expand the cross sectional area of a radiation beam, for example so as to reduce a thermal load on one or more optical elements within a lithographic system.

30 [0006] It is an object of the present invention to obviate or mitigate at least one problem of prior art techniques.

SUMMARY

[0007] According to a first aspect of the invention there is provided a radiation beam expander comprising: a diverging optic for receiving a radiation beam and increasing a divergence of the

radiation beam, said diverging optic comprising one or more mirrors; and a converging optic arranged to receive the radiation beam and to reduce the divergence of the radiation beam, said converging optic comprising one or more mirrors; wherein at least one of the one or more mirrors of the diverging optic and/or the converging optic is provided with an actuator arranged to control a curvature of the mirror.

[0008] The first aspect of the invention allows the optical power of the diverging optic and/or the converging optic to be controlled independently of the angle at which a radiation beam is incident on the mirrors of said diverging optic or the converging optic. This allows the radiation beam expander to control the divergence of the radiation beam after the diverging and converging optics (which may be referred to as an output radiation beam) independently of the orientations and relative positions of the mirrors of the diverging and converging optics.

[0009] The radiation beam expander may further comprise: a sensor apparatus operable to determine the divergence of the radiation beam after the diverging and converging optics; and a controller operable to control the curvature of one or more of the mirrors of the diverging and/or converging optic in response to the divergence determined by the sensor apparatus.

[0010] With such an arrangement, the sensor apparatus, controller and the actuator of each of the one or more of the mirrors of the diverging and/or converging optic form a feedback loop than can automatically control the divergence of the output radiation beam.

[0011] The controller may be arranged to control the curvature of one or more of the mirrors of the diverging and/or converging optic so that after the diverging and converging optics the radiation beam is collimated.

[0012] One or more of the one or more mirrors of each of the diverging and converging optics may be provided with an actuator operable to rotate said mirror about one or more axes of rotation so as to control its orientation.

[0013] Such an arrangement allows the orientations of the mirrors to be controlled, which can be used to correct for position and/or pointing errors of an input radiation beam. A position error of an input radiation beam may be defined as the deviation of the position of that radiation beam from a nominal position at a given point along its optical path. A pointing error of an input radiation beam may be defined as the deviation of the direction of that radiation beam from a nominal direction at a given point along its optical path. Such an arrangement wherein the orientations and curvatures of the individual mirrors of the diverging and converging optics can be independently controlled is particularly advantageous, as now described.

[0014] A simple beam expander comprising mirrors with fixed curvatures can be used to produce a collimated radiation beam of increased cross section. However, since the optical

power of a grazing incidence mirror is dependent on both the curvature of the mirror and the grazing incidence angle of the incident radiation beam, rotation of the mirrors of the diverging and converging optics would introduce undesired divergence or convergence in the beam leaving the beam expander. Therefore, a simple beam expander comprising mirrors with fixed curvatures cannot be used to correct for pointing and/or position errors of a radiation beam. Radiation beam expanders according to embodiments of the invention allow simultaneous and independent control over the orientations and curvatures of the mirrors of the diverging and converging optics. This allows the divergence, position and direction of the radiation beam expander to be controlled by the radiation beam expander using a relatively small number of mirrors. This reduces the costs and the absorption losses of the radiation beam expander.

[0015] The sensor apparatus may be operable to determine the position and/or direction of the radiation beam after it leaves the converging optic. The controller may be operable to control an orientation of one or more of the mirrors of the diverging and converging optics in response to the position and/or direction determined by the sensor apparatus so as to control the position and/or direction of the radiation beam after it leaves the converging optic.

[0016] With such an arrangement, the sensor apparatus, controller and the actuator of each of the one or more of the mirrors of the diverging and/or converging optic form a feedback loop than can automatically control the position and direction of the output radiation beam.

[0017] In response to the divergence, position and/or direction determined by the sensor apparatus the controller may be arranged to simultaneously control: (i) the orientation of one or more of the mirrors of the diverging and/or converging optics; and (ii) the curvature of one or more of the mirrors of the diverging and/or converging optic.

[0018] This provides simultaneous control over the divergence, position and/or direction of the radiation beam after it leaves the converging optic.

[0019] More than one curvature of the one or more mirrors of the diverging optic may be controllable, such that the diverging optic is operable to independently control the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam.

[0020] Similarly, more than one curvature of the one or more mirrors of the converging optic may be controllable, such that the converging optic is operable to independently control the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam.

[0021] Independent adjustment of the more than one curvature of the mirrors of the diverging and converging optics allows the focal length of said optics to be independently varied in each

of the first and second directions. This provides control over the divergence of the output radiation beam without having to alter the orientations and/or relative positions of the mirrors of the diverging and converging optics. Such adjustment of the optical power of at least one of the diverging optic and the converging optic provides more accurate control over the divergence of the output radiation beam than would relative movement of the diverging optic and the converging optic. The first direction may be substantially perpendicular to the second direction.

[0022] The diverging optic increases the divergence of the radiation beam in both the first and second directions. Projected onto a plane defined by the propagation path of the radiation beam and the first direction, the radiation beam which leaves the diverging optic may appear to originate from a first virtual source. Projected onto a plane defined by the propagation path of the radiation beam and the second direction, the radiation beam which leaves the diverging optic may appear to originate from a second virtual source. The divergence of the output radiation beam in the first (second) direction may be dependent upon the relative position of the first (second) virtual source and a focal point of the converging optic in the first (second) direction.

[0023] The diverging optic may comprise: a first mirror for receiving the radiation beam and increasing the divergence of the radiation beam in the first direction; and a second mirror arranged to receive the radiation beam from the first mirror and to increase a divergence of the radiation beam in a second direction in a plane perpendicular to a propagation path of the radiation beam, wherein a curvature of each of the first and second mirrors is independently adjustable.

[0024] The first mirror may have a convex, cylindrical-like reflective surface with a first curvature in a first principal direction and a zero curvature in a second principal direction.

[0025] The second mirror may have a convex, cylindrical-like reflective surface with a second curvature in a first principal direction and a zero curvature in a second principal direction.

[0026] The converging optic may comprise a concave, toriodal-like mirror which has a third curvature in the first direction and a fourth curvature in the second direction.

[0027] The converging optic may comprise: a first concave, cylindrical-like mirror which has a third curvature in the first direction; and a second concave, cylindrical-like mirror which has a fourth curvature in the second direction.

[0028] According to a second aspect of the invention there is provided a radiation system for a lithographic system comprising: a radiation source operable to produce a radiation beam; and the beam expander according to the first aspect of the invention arranged to receive the

radiation beam from the radiation source and to increase its cross sectional area so as to provide an output beam.

[0029] The radiation source may be operable to produce an astigmatic radiation beam, having a different divergence in each of two mutually perpendicular directions in a plane perpendicular to a propagation path of the radiation beam.

[0030] The radiation beam may be elliptical in cross section, the cross section of the radiation beam having a major axis and a minor axis.

[0031] The radiation beam may have a first divergence in a direction of the major axis and a second divergence in a direction of the minor axis.

[0032] The radiation source and the radiation beam expander may be arranged such that the major axis of the radiation beam is aligned with one of the first and second directions and the major axis of the radiation beam is aligned with the other of the first and second directions.

[0033] According to a third aspect of the invention there is provided a lithographic system comprising: a radiation system according to the second aspect of the invention; one or more lithographic tools; and a beam delivery system arranged to deliver at least a portion of the expanded radiation beam to at least one of the one or more lithographic tools.

[0034] According to a fourth aspect of the invention there is provided a radiation beam expander comprising: a diverging optic for receiving a radiation beam and increasing a divergence of the radiation beam, the diverging optic being astigmatic such that it increases the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam by different amounts; a converging optic arranged to receive the radiation beam and to reduce the divergence of the radiation beam, the converging optic being astigmatic such that it decreases the divergence of the radiation beam in the first and second directions by different amounts; a sensor apparatus operable to determine the divergence of the radiation beam after the diverging and converging optics; and a controller; wherein at least one of the diverging optic and the converging optic is adjustable such that its optical power in each of the first and second directions is independently adjustable and wherein the controller is operable to control the optical power of that optic in the first and/or second directions in response to the divergence determined by the sensor apparatus.

[0035] By controlling the optical power of the diverging optic and/or the converging optic in the first and/or second directions in response to the divergence determined by the sensor apparatus the controller is able to control the divergence of the radiation beam after it leaves the converging optic.

[0036] The radiation beam after the diverging and converging optics may be output by the radiation beam expander and may be referred to as an output radiation beam. Independent adjustment of the optical power of at least one of the diverging optic and the converging optic in each of the first and second directions allows the focal length of that optic to be independently varied in those directions. This provides control over the divergence of the output radiation beam without having to move the diverging optic relative to the converging optic. Adjustment of the optical power of at least one of the diverging optic and the converging optic provides more accurate control over the divergence of the output radiation beam than relative movement of the diverging optic and the converging optic.

[0037] The diverging optic increases the divergence of the radiation beam in both the first and second directions. Projected onto a plane defined by the propagation path of the radiation beam and the first direction, the radiation beam which leaves the diverging optic may appear to originate from a first virtual source. Projected onto a plane defined by the propagation path of the radiation beam and the second direction, the radiation beam which leaves the diverging optic may appear to originate from a second virtual source. The divergence of the output radiation beam in the first (second) direction may be dependent upon the relative position of the first (second) virtual source and a focal point of the converging optic in the first (second) direction.

[0038] The first direction may be substantially perpendicular to the second direction.

[0039] The controller may be arranged to control the optical power of at least one of the diverging optic and the converging optic in the first and/or second directions so that after the diverging and converging optics the radiation beam is collimated.

[0040] It will be appreciated that a radiation beam being collimated means that the divergence of the radiation beam is substantially zero. This may be achieved by controlling the optical power of the diverging and/or converging optic such that: the first virtual source coincides with the focal point of the converging optic in the first direction; and the second virtual source coincides with the focal point of the converging optic in the second direction. In order for the first (second) virtual source to be considered to coincide with the focal point of the converging optic in the first (second) direction the divergence of the output radiation beam in the first (second) direction should be sufficiently small so that the output radiation beam can be considered to be collimated in that direction.

[0041] Each of the diverging and converging optics may be rotatable.

[0042] It will be appreciated that the diverging optic or converging optic may comprise a plurality of optical elements. To say that such an optic (comprising a plurality of optical

elements) is rotatable may mean that one or more of the plurality of optical elements is rotatable. Each of the plurality of optical elements may be independently rotatable so as to vary the angle of incidence of the radiation beam on that optical element.

[0043] The sensor apparatus may be operable to determine the position and/or direction of the radiation beam after it leaves the converging optic. The controller may be operable to control an orientation of one or more of the diverging and converging optics in response to the position and/or direction determined by the sensor apparatus so as to control the position and/or direction of the radiation beam after it leaves the converging optic.

[0044] This allows for correction of pointing and position errors of the radiation beam. For example, variation of the orientation of the diverging optic relative to the converging optic allows the direction of the radiation beam after it leaves the converging optic to be controlled. Further, variation of the orientation of the diverging optic and converging optic together allows the position of the radiation beam after it leaves the third optical element to be controlled.

[0045] Note that variation of the orientations of the diverging and/or converging optic will alter the angle of incidence of the radiation beam on the diverging and/or converging optic (or each of the optical elements which they comprise). In turn, this may vary the focal length of the diverging and/or converging optic. Therefore whenever the orientations of the diverging and/or converging optic are altered, the controller may be operable to independently alter the optical power of at least one of the diverging and/or converging optic, e.g. so as to ensure that the divergence of the radiation beam after it leaves the converging optic remains unchanged.

[0046] The controller may be arranged to simultaneously control: the orientation of the diverging and/or converging optics; and the optical power of at least one of the diverging and/or converging optic in the first and/or second directions; in response to the divergence, position and/or direction determined by the sensor apparatus so as to control the divergence, position and/or direction of the radiation beam after it leaves the converging optic.

[0047] The diverging optic may comprise: a first optical element for receiving the radiation beam and increasing the divergence of the radiation beam in the first direction; and a second optical element arranged to receive the radiation beam from the first optical element and to increase a divergence of the radiation beam in a second direction in a plane perpendicular to a propagation path of the radiation beam, wherein an optical power of each of the first and second optical elements is independently adjustable.

[0048] An advantage of using two different optical elements (the first and second optical elements) to increase the divergence of the beam in the two different directions (first and

second directions) is that it provides independent control over the divergence of the radiation beam that is output by the radiation beam expander in two different directions.

[0049] The first optical element may comprise a first convex mirror with a first curvature in the first direction.

5 **[0050]** The second optical element may comprise a second convex mirror with a second curvature in the second direction.

[0051] The converging optic may comprise one or more concave mirrors.

[0052] For example, the converging optic may comprise an astigmatic mirror, which has a third curvature in the first direction and a fourth curvature in the second direction. Such an arrangement is advantageous since a single mirror forms the converging mirror whilst the radiation beam expander provides control over the divergence of the radiation beam.

10 **[0053]** Alternatively, the converging optic may comprise: a first concave mirror which has a third curvature in the first direction; and a second concave mirror which has a fourth curvature in the second direction. Advantageously, such an arrangement provides a radiation beam expander that allows for control over the divergence and the diameter of the radiation beam.

[0054] According to a fifth aspect of the invention there is provided a radiation system for a lithographic system comprising: a radiation source operable to produce a radiation beam; and the beam expander according to the fourth aspect of the invention arranged to receive the radiation beam from the radiation source and to increase its cross sectional area so as to provide an output beam.

20 **[0055]** The radiation source may be operable to produce an astigmatic radiation beam, having a different divergence in each of two mutually perpendicular directions in a plane perpendicular to a propagation path of the radiation beam.

[0056] The radiation beam may be elliptical in cross section, the cross section of the radiation beam having a major axis and a minor axis.

25 **[0057]** The radiation beam may have a first divergence in a direction of the major axis and a second divergence in a direction of the minor axis.

[0058] The radiation source and the radiation beam expander may be arranged such that the major axis of the radiation beam is aligned with one of the first and second directions and the major axis of the radiation beam is aligned with the other of the first and second directions.

30 **[0059]** The radiation source may comprise a free electron laser.

[0060] According to a sixth aspect of the invention there is provided a lithographic system comprising: the radiation system of the fifth aspect of the invention; one or more lithographic

tools; and a beam delivery system arranged to deliver at least a portion of the expanded radiation beam to at least one of the one or more lithographic tools.

[0061] Various aspects and features of the invention set out above or below may be combined with various other aspects and features of the invention as will be readily apparent to the skilled person.

BRIEF DESCRIPTION OF THE DRAWINGS

[0062] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 is a schematic illustration of a lithographic system comprising a radiation beam expander according to an embodiment of the invention;
- Figure 2 is a schematic illustration of a lithographic apparatus that may form part of the lithographic system of Figure 1;
- Figure 3 is a schematic illustration of a free electron laser that may form part of the lithographic system of Figure 1;
- Figure 4 is a schematic illustration of the radiation beam expander that forms part of the lithographic system of Figure 1;
- Figure 5 is a first embodiment of the radiation beam expander of Figure 4;
- Figure 6a is a cross sectional view of a convex cylindrical-like mirror that may form part of the radiation beam expander of Figure 5 in a first plane;
- Figure 6a is a cross sectional view of a convex cylindrical-like mirror that may form part of the radiation beam expander of Figure 5 in a second plane;
- Figure 7 is a perspective view of concave toroidal-like mirror, which may form part of the radiation beam expander of Figure 5;
- Figure 8 illustrates the shape of a radiation beam as it propagates along a nominal path through the radiation beam expander of Figure 5;
- Figure 9 is a schematic illustration of a mechanism for rotating a mirror;
- Figure 10 is a schematic illustration of a mechanism for altering a curvature of a mirror;
- Figure 11 is a second embodiment of the radiation beam expander of Figure 4; and
- Figure 12 illustrates the shape of a radiation beam as it propagates along a nominal path through the radiation beam expander of Figure 11.

DETAILED DESCRIPTION

[0063] Figure 1 shows a lithographic system LS according to one embodiment of the invention. The lithographic system LS comprises a radiation source SO, a radiation beam expander 100, a beam delivery system BDS and a plurality of lithographic apparatus LA_a-LA_n (e.g. eight lithographic apparatus). The radiation source SO is configured to generate an extreme ultraviolet (EUV) radiation beam RB.

[0064] The radiation beam expander 100 is arranged to receive the radiation beam RB from the radiation source, increasing its cross sectional area and output it as an output radiation beam RB' (which may be referred to as a main beam).

[0065] Advantageously, this decreases the heat load on mirrors downstream of the radiation beam expander 100, including mirrors within the beam delivery system BDS and the lithographic apparatus LA_a-LA_n. This may allow the mirrors downstream of the radiation beam expander 100 to be of a lower specification, with less cooling, and therefore less expensive. Additionally or alternatively, it may allow the downstream mirrors to be nearer to normal incidence. For example, the radiation beam expander 100 may be operable to expand the radiation beam RB from a diameter of around 1 mm to a radiation beam RB' with a diameter of more than 1 cm.

[0066] Optionally, the radiation beam expander 100 may be operable to compensate for variations in the position and direction of the radiation beam RB output by the radiation source SO. That is, the radiation beam expander 100 may be operable to output a main beam RB' with a substantially constant position and direction, independent of variations in the position and direction of the radiation beam RB output by the radiation source SO. Whilst the radiation beam expander 100 may not be able to completely eliminate variations in the position and direction of the main beam RB', it may be operable to at least reduce such variations that arise due to variations in the position and direction of the radiation beam RB output by the radiation source SO.

[0067] Optionally, the radiation beam expander 100 may be operable to compensate for variations in the shape of the radiation beam RB output by the radiation source SO. That is, the radiation beam expander 100 may be operable to output a main beam RB' with a substantially constant shape, independent of variations in the shape of the radiation beam RB output by the radiation source SO. Whilst the radiation beam expander 100 may not be able to completely eliminate variations in the shape of the main beam RB', it may be operable to at least reduce such variations that arise due to variations in the shape of the radiation beam RB output by the radiation source SO.

[0068] The beam delivery system BDS comprises beam splitting optics and may optionally also comprise additional beam expanding optics and/or beam shaping optics. The main radiation beam RB' is split into a plurality of radiation beams B_a - B_n (which may be referred to as branch beams), each of which is directed to a different one of the lithographic apparatus LA_a - LA_n , by the beam delivery system BDS.

[0069] In an embodiment, the branch radiation beams B_a - B_n are each directed through a respective attenuator (not shown). Each attenuator may be arranged to adjust the intensity of a respective branch radiation beam B_a - B_n before the branch radiation beam B_a - B_n passes into its corresponding lithographic apparatus LA_a - LA_n .

[0070] The radiation source SO, radiation beam expander 100, beam delivery system BDS and lithographic apparatus LA_a - LA_n may all be constructed and arranged such that they can be isolated from the external environment. A vacuum may be provided in at least part of the radiation source SO, beam delivery system BDS and lithographic apparatuses LA_a - LA_n so as to minimise the absorption of EUV radiation. Different parts of the lithographic system LS may be provided with vacuums at different pressures (i.e. held at different pressures which are below atmospheric pressure).

[0071] Referring to Figure 2, a lithographic apparatus LA_a comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g. a mask), a projection system PS and a substrate table WT configured to support a substrate W. The illumination system IL is configured to condition the branch radiation beam B_a that is received by that lithographic apparatus LA_a before it is incident upon the patterning device MA. The projection system PS is configured to project the radiation beam B_a' (now patterned by the patterning device MA) onto the substrate W. The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus aligns the patterned radiation beam B_a' with a pattern previously formed on the substrate W.

[0072] The branch radiation beam B_a that is received by the lithographic apparatus LA_a passes into the illumination system IL from the beam delivery system BDS through an opening 8 in an enclosing structure of the illumination system IL. Optionally, the branch radiation beam B_a may be focused to form an intermediate focus at or near to the opening 8.

[0073] The illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 together provide the radiation beam B_a with a desired cross-sectional shape and a desired angular distribution. The radiation beam B_a passes from the illumination system IL and is incident upon the patterning device MA held by the support structure MT. The patterning device

MA reflects and patterns the radiation beam to form a patterned beam B_a' . The illumination system IL may include other mirrors or devices in addition to or instead of the faceted field mirror device 10 and faceted pupil mirror device 11. The illumination system IL may for example include an array of independently moveable mirrors. The independently moveable mirrors may for example measure less than 1mm across. The independently moveable mirrors may for example be microelectromechanical systems (MEMS) devices.

[0074] Following redirection (e.g. reflection) from the patterning device MA the patterned radiation beam B_a' enters the projection system PS. The projection system PS comprises a plurality of mirrors 13, 14 which are configured to project the radiation beam B_a' onto a substrate W held by the substrate table WT. The projection system PS may apply a reduction factor to the radiation beam, forming an image with features that are smaller than corresponding features on the patterning device MA. A reduction factor of 4 may for example be applied. Although the projection system PS has two mirrors in Figure 2, the projection system may include any number of mirrors (e.g. six mirrors).

[0075] The lithographic apparatus LA_a is operable to impart a radiation beam B_a with a pattern in its cross-section and project the patterned radiation beam onto a target portion of a substrate thereby exposing a target portion of the substrate to the patterned radiation. The lithographic apparatus LA_a may, for example, be used in a scan mode, wherein the support structure MT and the substrate table WT are scanned synchronously while a pattern imparted to the radiation beam B_a' is projected onto a substrate W (i.e. a dynamic exposure). The velocity and direction of the substrate table WT relative to the support structure MT may be determined by the demagnification and image reversal characteristics of the projection system PS. The patterned radiation beam B_a' which is incident upon the substrate W may comprise a band of radiation. The band of radiation may be referred to as an exposure slit. During a scanning exposure, the movement of the substrate table WT and the support structure MT are such that the exposure slit travels over a target portion of substrate W in a scan direction, thereby exposing the target portion of the substrate W to patterned radiation. It will be appreciated that a dose of radiation to which a given location within the target portion of the substrate W is exposed depends on the power of the radiation beam B_a' and the amount of time for which that location is exposed to radiation as the exposure slit is scanned over the location (the effect of the pattern is neglected in this instance). The term "target location" may be used to denote a location on the substrate which is exposed to radiation (and for which the dose of received radiation may be calculated).

[0076] Referring again to Figure 1, the radiation source SO is configured to generate an EUV radiation beam RB with sufficient power to supply each of the lithographic apparatus LA_a-LA_n. As noted above, the radiation source SO may comprise a free electron laser.

[0077] Figure 3 is a schematic depiction of a free electron laser FEL comprising an injector 21, a linear accelerator 22, a bunch compressor 23, an undulator 24, an electron decelerator 26 and a beam dump 27.

[0078] The injector 21 is arranged to produce a bunched electron beam E and comprises an electron source (for example a thermionic cathode or a photo-cathode) and an accelerating electric field. Electrons in the electron beam E are further accelerated by the linear accelerator 22. In an example, the linear accelerator 22 may comprise a plurality of radio frequency cavities, which are axially spaced along a common axis, and one or more radio frequency power sources, which are operable to control the electromagnetic fields along the common axis as bunches of electrons pass between them so as to accelerate each bunch of electrons. The cavities may be superconducting radio frequency cavities. Advantageously, this allows: relatively large electromagnetic fields to be applied at high duty cycles; larger beam apertures, resulting in fewer losses due to wakefields; and for the fraction of radio frequency energy that is transmitted to the beam (as opposed to dissipated through the cavity walls) to be increased. Alternatively, the cavities may be conventionally conducting (i.e. not superconducting), and may be formed from, for example, copper. Other types of linear accelerators may be used such as, for example, laser wake-field accelerators or inverse free electron laser accelerators.

[0079] Optionally, the electron beam E passes through a bunch compressor 23, disposed between the linear accelerator 22 and the undulator 24. The bunch compressor 23 is configured to spatially compress existing bunches of electrons in the electron beam E. One type of bunch compressor 23 comprises a radiation field directed transverse to the electron beam E. An electron in the electron beam E interacts with the radiation and bunches with other electrons nearby. Another type of bunch compressor 23 comprises a magnetic chicane, wherein the length of a path followed by an electron as it passes through the chicane is dependent upon its energy. This type of bunch compressor may be used to compress bunches of electrons which have been accelerated in a linear accelerator 22 by a plurality of resonant cavities.

[0080] The electron beam E then passes through the undulator 24. Generally, the undulator 24 comprises a plurality of modules. Each module comprises a periodic magnet structure, which is operable to produce a periodic magnetic field and is arranged so as to guide the relativistic electron beam E produced by the injector 21 and linear accelerator 22 along a

periodic path within that module. The periodic magnetic field produced by each undulator module causes the electrons to follow an oscillating path about a central axis. As a result, within each undulator module, the electrons radiate electromagnetic radiation generally in the direction of the central axis of that undulator module.

[0081] The path followed by the electrons may be sinusoidal and planar, with the electrons periodically traversing the central axis. Alternatively, the path may be helical, with the electrons rotating about the central axis. The type of oscillating path may affect the polarization of radiation emitted by the free electron laser. For example, a free electron laser which causes the electrons to propagate along a helical path may emit elliptically polarized radiation, which may be desirable for exposure of a substrate W by some lithographic apparatus.

[0082] As electrons move through each undulator module, they interact with the electric field of the radiation, exchanging energy with the radiation. In general the amount of energy exchanged between the electrons and the radiation will oscillate rapidly unless conditions are close to a resonance condition. Under resonance conditions, the interaction between the electrons and the radiation causes the electrons to bunch together into microbunches, modulated at the wavelength of radiation within the undulator, and coherent emission of radiation along the central axis is stimulated. The resonance condition may be given by:

$$\lambda_{em} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{A} \right), \quad (1)$$

where λ_{em} is the wavelength of the radiation, λ_u is the undulator period for the undulator module that the electrons are propagating through, γ is the Lorentz factor of the electrons and K is the undulator parameter. A is dependent upon the geometry of the undulator 24: for a helical undulator that produces circularly polarized radiation $A=1$, for a planar undulator $A=2$, and for a helical undulator which produces elliptically polarized radiation (that is neither circularly polarized nor linearly polarized) $1 < A < 2$. In practice, each bunch of electrons will have a spread of energies although this spread may be minimized as far as possible (by producing an electron beam E with low emittance). The undulator parameter K is typically approximately 1 and is given by:

$$K = \frac{q\lambda_u B_0}{2\pi mc}, \quad (2)$$

where q and m are, respectively, the electric charge and mass of the electrons, B_0 is the amplitude of the periodic magnetic field, and c is the speed of light.

[0083] The resonant wavelength λ_{em} is equal to the first harmonic wavelength spontaneously radiated by electrons moving through each undulator module. The free electron laser FEL may

operate in self-amplified spontaneous emission (SASE) mode. Operation in SASE mode may require a low energy spread of the electron bunches in the electron beam E before it enters each undulator module. Alternatively, the free electron laser FEL may comprise a seed radiation source, which may be amplified by stimulated emission within the undulator 24. The
5 free electron laser FEL may operate as a recirculating amplifier free electron laser (RAFEL), wherein a portion of the radiation generated by the free electron laser FEL is used to seed further generation of radiation.

[0084] Electrons moving through the undulator 24 may cause the amplitude of radiation to increase, i.e. the free electron laser FEL may have a non-zero gain. Maximum gain may be
10 achieved when the resonance condition is met or when conditions are close to but slightly off resonance.

[0085] An electron which meets the resonance condition as it enters the undulator 24 will lose (or gain) energy as it emits (or absorbs) radiation, so that the resonance condition is no longer satisfied. Therefore, in some embodiments the undulator 24 may be tapered. That is, the
15 amplitude of the periodic magnetic field and/or the undulator period λ_u may vary along the length of the undulator 24 in order to keep bunches of electrons at or close to resonance as they are guided through the undulator 24. The tapering may be achieved by varying the amplitude of the periodic magnetic field and/or the undulator period λ_u within each undulator module and/or from module to module. Additionally or alternatively tapering may be achieved by varying the helicity
20 of the undulator 24 (by varying the parameter A) within each undulator module and/or from module to module.

[0086] A region around the central axis of each undulator module may be considered to be a "good field region". The good field region may be a volume around the central axis wherein, for a given position along the central axis of the undulator module, the magnitude and direction of
25 the magnetic field within the volume are substantially constant. An electron bunch propagating within the good field region may satisfy the resonant condition of Eq. (1) and will therefore amplify radiation. Further, an electron beam E propagating within the good field region should not experience significant unexpected disruption due to uncompensated magnetic fields. That is, an electron propagating through the good field region should remain within the good field
30 region.

[0087] Each undulator module may have a range of acceptable initial trajectories. Electrons entering an undulator module with an initial trajectory within this range of acceptable initial trajectories may satisfy the resonant condition of Eq. (1) and interact with radiation in that undulator module to stimulate emission of coherent radiation. In contrast, electrons entering an

undulator module with other trajectories may not stimulate significant emission of coherent radiation.

[0088] For example, generally, for helical undulator modules the electron beam E should be substantially aligned with the central axis of the undulator module. A tilt or angle between the electron beam E and the central axis of the undulator module (in radians) should generally not exceed $\rho/10$, where ρ is the FEL Pierce parameter. Otherwise the conversion efficiency of the undulator module (i.e. the portion of the energy of the electron beam E which is converted to radiation in that module) may drop below a desired amount (or may drop almost to zero). In an embodiment, the FEL Pierce parameter of an EUV helical undulator module may be of the order of 0.001, indicating that the tilt of the electron beam E with respect to the central axis of the undulator module should be less than 100 μ rad.

[0089] For a planar undulator module, a greater range of initial trajectories may be acceptable. Provided the electron beam E remains substantially perpendicular to the magnetic field of a planar undulator module and remains within the good field region of the planar undulator module, coherent emission of radiation may be stimulated.

[0090] As electrons of the electron beam E move through a drift space between each undulator module, the electrons do not follow a periodic path. Therefore, in this drift space, although the electrons overlap spatially with the radiation, they do not exchange any significant energy with the radiation and are therefore effectively decoupled from the radiation. The bunched electron beam E has a finite emittance and will therefore increase in diameter unless refocused. Therefore, the undulator 24 may further comprise a mechanism for refocusing the electron beam E in between one or more pairs of adjacent undulator modules. For example, a quadrupole magnet may be provided between each pair of adjacent modules. The quadrupole magnets reduce the size of the electron bunches. This improves the coupling between the electrons and the radiation within the next undulator module, increasing the stimulation of emission of radiation.

[0091] The undulator 24 may further comprise an electron beam steering unit in between each adjacent pair of undulator modules which is arranged to provide fine adjustment of the electron beam E as it passes through the undulator 24. For example, each beam steering unit may be arranged to ensure that the electron beam remains within the good field region and enters the next undulator module with a trajectory from the range of acceptable initial trajectories for that undulator module.

[0092] Radiation produced within the undulator 24 is output as a radiation beam B_{FEL} (which may, for example, correspond to the radiation beam RB of Figure 1).

[0093] After leaving the undulator 24, the electron beam E is absorbed by a dump 27. The dump 27 may comprise a sufficient quantity of material to absorb the electron beam E. The material may have a threshold energy for induction of radioactivity. Electrons entering the dump 27 with an energy below the threshold energy may produce only gamma ray showers but will not induce any significant level of radioactivity. The material may have a high threshold energy for induction of radioactivity by electron impact. For example, the beam dump may comprise aluminium (Al), which has a threshold energy of around 17 MeV. It may be desirable to reduce the energy of electrons in the electron beam E before they enter the dump 27. This removes, or at least reduces, the need to remove and dispose of radioactive waste from the dump 27. This is advantageous since the removal of radioactive waste requires the free electron laser FEL to be shut down periodically and the disposal of radioactive waste can be costly and can have serious environmental implications.

[0094] The energy of electrons in the electron beam E may be reduced before they enter the dump 27 by directing the electron beam E through a decelerator 26 disposed between the undulator 24 and the beam dump 27.

[0095] In an embodiment the electron beam E which exits the undulator 24 may be decelerated by passing the electrons back through the linear accelerator 22 with a phase difference of 180 degrees relative to the electron beam produced by the injector 21. The RF fields in the linear accelerator therefore serve to decelerate the electrons which are output from the undulator 24 and to accelerate electrons output from the injector 21. As the electrons decelerate in the linear accelerator 22 some of their energy is transferred to the RF fields in the linear accelerator 22. Energy from the decelerating electrons is therefore recovered by the linear accelerator 22 and may be used to accelerate the electron beam E output from the injector 21. Such an arrangement is known as an energy recovery linear accelerator (ERL).

[0096] The radiation beam produced by a free electron laser typically has a relatively small etendue. In particular, the EUV radiation beam B_{FEL} provided by the free electron laser FEL has a significantly smaller etendue than an EUV radiation beam that would be generated by a laser produced plasma (LPP) source or a discharge produced plasma (DPP) source (both of which are known in the prior art). For example, the radiation beam B_{FEL} produced by the free electron laser FEL may have a divergence less than 500 μrad , for example less than 100 μrad , and may for example have a diameter of around 100 μm .

[0097] The output power of the free electron laser FEL may be of the order of tens of kilowatts, in order to support high throughput for one or more EUV lithographic apparatus. At these powers, since the initial diameter of the radiation beam RB' produced by the free electron

laser FEL is so small the power density will be significant. Therefore the radiation beam expander 100 may be located a sufficient distance from the undulator 24 to allow the beam to expand to a size with a more acceptable power density. Since the divergence of the radiation beam B_{FEL} produced by the free electron laser FEL is so small, a distance between the undulator 24 and the radiation beam expander 100 may be of the order of tens, or even hundreds of metres. After such a distance, the radiation beam B_{FEL} may have a diameter of the order of 1 mm.

[0098] Figure 4 is a schematic illustration of a radiation beam expander 100 according to an embodiment of the invention, which forms part of the lithographic system of Figure 1. Radiation beam expander 100 is suitable for receiving an input radiation beam B_{in} , increasing its cross sectional area and outputting it as an output radiation beam B_{out} . Radiation beam expander 100 comprises a plurality of mirrors M1, M2, M3, M4, which form part of an optical path through the radiation beam expander 100. Although four mirrors are shown in Figure 4, some embodiments of the radiation beam expander 100 may comprise fewer than four mirrors and some embodiments of the radiation beam expander 100 may comprise more than four mirrors. Two specific embodiments of radiation beam expanders 200, 250, which may form radiation beam expander 100 of Figures 1 and 4 are described further below with reference to Figures 5 and 10 respectively.

[0099] One or more of the plurality of mirrors M1, M2, M3, M4 forms a diverging optic and one or more of the plurality of mirrors M1, M2, M3, M4 forms a converging optic, as will be described further below. The diverging optic is arranged to increase a divergence of the input radiation beam B_{in} . The diverging optic is astigmatic such that it increases the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path 102 of the radiation beam by different amounts. The converging optic is arranged to reduce the divergence of the radiation beam in the first and second directions. The converging optic is astigmatic such that it decreases the divergence of the radiation beam in the first and second directions by different amounts. Unless stated otherwise, it will be appreciated that as used herein the divergence of a radiation beam in a given direction refers to the full angle of opening of the radiation beam in a plane containing the given direction and the propagation direction of the radiation beam.

[00100] The radiation beam expander 100 comprises a sensor apparatus S. Sensor apparatus S is operable to determine the divergence of the output radiation beam B_{out} , i.e. the radiation beam after the diverging and converging optics. The sensor apparatus S may be operable to determine the position and/or direction of the output radiation beam B_{out} . Sensor

apparatus S may comprise a plurality of radiation sensors. The sensing apparatus S may comprise separate sensors for determining each of the divergence, the position and the direction of the output radiation beam B_{out} .

[00101] In order to determine the divergence of the output radiation beam B_{out} , the sensor apparatus may comprise two sensors, each operable to determine a diameter of the output radiation beam B_{out} at a different point along its propagation path. The divergence of output radiation beam B_{out} may be determined from the difference in diameters determined by the two sensors and the distance between the two sensors. Each of the two sensors may be a gas monitor detector of the type comprising a chamber which contains a gas and through which the (pulsed) radiation beam propagates. As pulse of the radiation beam passes through the chamber, the radiation beam causes the gas within the chamber will emit secondary radiation (via fluorescence). Therefore, by detecting the distribution of secondary radiation emitted by the gas (e.g. using a camera), the position and/or diameter of the radiation beam at the chamber may be determined.

[00102] In order to determine the position of the output radiation beam B_{out} , the sensor apparatus may comprise one or more sensors, each operable to determine a position of the output radiation beam B_{out} at substantially the same point along its propagation path. In order to determine the direction (also referred to as the pointing) of the output radiation beam B_{out} , the sensor apparatus may comprise two sensors, each operable to determine a position of the output radiation beam B_{out} at a different point along its propagation path. The direction of output radiation beam B_{out} may be determined from the positions determined by the two sensors. Each of the sensors for determining the position and/or direction may be a gas monitor detector of the type comprising a chamber which contains a gas and through which the (pulsed) radiation beam propagates. As each pulse of the radiation beam passes through the chamber, the radiation beam causes ionization of the gas, resulting in the production of positively charged ions and free electrons. Therefore, by detecting the distribution of electrons caused by the ionization (e.g. using one or more electrodes) the position of the radiation beam within the chamber may be determined. An example of such a gas monitor detector is described in DE10244303.

[00103] Sensor apparatus S is operable to output a signal 104 indicative of one or more of the divergence, the position and the direction of the output radiation beam B_{out} .

[00104] Additionally or alternatively, the radiation beam expander 100 may comprise a sensor apparatus (not shown) which is operable to determine the divergence, position and/or direction of the input radiation beam B_{in} .

[00105] Each of the plurality of mirrors M1, M2, M3, M4 is provided with a corresponding actuator A1, A2, A3, A4. Each of the actuators A1, A2, A3, A4 is operable to simultaneously control a plurality of degrees of freedom of its corresponding mirror M1, M2, M3, M4. For example, each actuator A1, A2, A3, A4 may be operable to simultaneously control a curvature and an orientation of its corresponding mirror M1, M2, M3, M4. One or more of the mirrors M1, M2, M3, M4 forming the diverging optic and/or the converging optic is adjustable such that the optical power of the diverging optic and/or the converging optic in each of the first and second directions is independently adjustable. Therefore, one or more of the actuators A1, A2, A3, A4 may be operable to deform its corresponding mirror M1, M2, M3, M4 so as to control its optical power. Each actuator A1, A2, A3, A4 may be operable to rotate its corresponding mirror M1, M2, M3, M4 about one or more axes of rotation. Such rotation can be used to correct for so called position and pointing errors.

[00106] The radiation beam expander 100 comprises a controller CN. The controller CN is arranged to receive the signal 104 output by the sensor apparatus S. The controller CN is further operable to send a control signal s_1 , s_2 , s_3 , s_4 to the actuator A1, A2, A3, A4 associated with each mirror M1, M2, M3, M4. In response to the divergence determined by the sensor apparatus S, the controller CN is operable to control the optical power of one or more of the mirrors M1, M2, M3, M4 so as to control the optical power of the diverging optic and/or the converging optic in the first and/or second directions.

[00107] The controller may be operable to control an orientation of one or more of the mirrors M1, M2, M3, M4 in response to the position and/or direction determined by the sensor apparatus S. This may allow the sensor apparatus S and the controller CN to form a feed-back system that provided control over the position and/or direction of the output radiation beam B_{out} . This allows for correction of pointing and position errors of the input radiation beam B_{in} .

[00108] It will be appreciated that Figure 4 is a schematic representation of radiation beam expander 100 and the optical path 102 followed by the radiation beam has been represented linearly for clarity. However, it will be appreciated that the direction of radiation along the optical path 102 will change at each mirror M1, M2, M3, M4 and in general will comprise a three dimensional path. Figure 4 may be considered to be a schematic representation of the radiation beam expander 100 in a coordinate system that follows the radiation beam.

[00109] Embodiments of the invention relate to radiation beam expanders comprising a plurality of curved mirrors.

[00110] In general, a two dimensional surface (e.g. the surface of a curved mirror) may curve differently in different directions. In the following, it will be appreciated that "a curvature of a

surface in a given direction at a given point on said surface” means a curvature of the curve that is formed by the intersection of said surface and a plane containing the normal vector of the surface at that point and a vector in said given direction. The curvature of a curve is given by the inverse of the radius of curvature of that curve.

5 [00111] At a given point on a curved surface the principle directions of curvature and the principle curvatures are given by the eigenvectors and eigenvalues of the shape operator at that point respectively. For some two dimensional surfaces, the principle directions of curvature may be constant over the surface.

10 [00112] A two dimensional surface with non-zero curvature in a first principal direction a zero curvature in a second principal direction may be referred to as a cylindrical-like surface. The curvature of a cylindrical-like surface may be constant in the first principal direction and the surface may be cylindrical. Alternatively, the curvature of a cylindrical-like surface may vary in the first principal direction and the cylindrical-like surface may be an extruded parabola, an extruded hyperbola or an extruded ellipse. It will be appreciated that an extruded curve (where
15 the curve may, for example, be a portion of a parabola, a hyperbola or an ellipse) is a surface traced out by translating the curve in a direction perpendicular to the plane in which the curve lies.

[00113] A two dimensional surface with non-zero curvature in the first and second principal directions may be referred to as a toroidal-like surface. The curvature of a toroidal-like surface
20 may be constant in the first and second principal directions and the surface may be toroidal. Alternatively, the curvature of a toroidal-like surface may vary in the first principal direction and the toroidal-like surface may be a paraboloidal, hyperboloidal, or ellpoidal surfaces.

[00114] In the following description, unless stated otherwise, any reference to a curvature of a surface should be understood to be a curvature of that surface at the point of the surface
25 intersecting with the chief ray of a nominal radiation beam path.

[00115] The curved mirrors which form part of the radiation beam expanders according to embodiments of the invention may, for example, have a reflective surface with a shape described by a portion of a paraboloid, hyperboloid or ellipsoid. Additionally or alternatively, the curved mirrors may have a reflective surface with a shape described by an extruded parabola,
30 extruded hyperbola or extruded ellipse. Such paraboloid, hyperboloid, ellipsoid extruded parabolic, extruded hyperbolic or extruded elliptical curved mirrors may be suitable for focusing radiation beams with a Gaussian intensity distribution. Locally, a paraboloid, hyperboloid or ellipsoid surface may be approximated by a toroidal surface (i.e. the surface of a torus). Similarly, locally, the surface of an extruded parabola, extruded hyperbola or extruded ellipse

may be approximated by a cylindrical surface. Therefore some embodiments of the invention relate to radiation beam expanders comprising toroidal mirrors and/or cylindrical mirrors.

[00116] If the principal curvature of a mirror is not constant then deviation of a radiation beam that is incident upon that mirror from a nominal path may cause optical aberrations. In some
5 embodiments, the curved mirrors may each have a reflective surface which is cylindrical-like and which has a shape described by an extruded curve which differs from that of a parabola, a hyperbola or an ellipse such that optical aberrations caused by deviation of the radiation beam from a nominal path are reduced.

[00117] The approximation of paraboloid, hyperboloid or ellipsoid surfaces as toroidal surfaces
10 and the approximation of extruded parabolic, hyperbolic and elliptical surfaces as cylindrical surfaces is only valid in the limit that the diameters of radiation beams incident on those surfaces approaches zero. However, embodiments of the present invention may still use toroidal and cylindrical mirrors with an acceptably low level of aberrations provided that the parameters of incoming radiation beams do not deviate too much from a set of nominal values
15 for which the mirrors were designed. For larger radiation beam diameters embodiments of the invention may use mirrors with cylindrical-like and toroidal-like shaped surfaces such as, for example, extruded parabolas (curvature only in one direction) or paraboloids (curvature in two directions).

[00118] A toroidal mirror has a constant radius of curvature in each of its two mutually
20 perpendicular principal directions. Note that a cylindrical mirror may be considered to be a special case of a toroidal mirror, with a curvature of zero along one of its principal directions. Curved mirrors with a constant radius of curvature in two mutually perpendicular directions may be considered to have circular geometry and include cylindrical mirrors, spherical mirrors and toroidal mirrors. The curved mirrors are grazing incidence mirrors. The radiation beam is
25 incident upon each of the curved mirrors at a grazing incidence angle of β . Typical grazing incidence angles β are around 17 to 70 mrad (equivalent to 1° to 4°).

[00119] When a radiation beam is incident upon a mirror at a grazing incidence angle of β , then, in general, it will illuminate an elongate beam spot region on the reflective surface of the mirror, which is larger in one direction (which may define a major axis of the beam spot region)
30 than another perpendicular direction (which may define a minor axis of the beam spot region). The major axis of the beam spot region may lie in the plane of incidence and the minor axis of the beam spot region may be perpendicular to the plane of incidence. If the radiation beam is circular (or elliptical) in cross section and the mirror is flat then the beam spot region will be elliptical in shape. If the radiation beam is circular in cross section and the mirror is curved (e.g.

cylindrical or toroidal) then the curvature of the mirror will result in some deformation of the elliptical shape of the beam spot region.

[00120] The input radiation beam B_{in} may have a diameter of the order of 5 mm. The curved mirrors may have a short dimension and a long dimension. In use, the short dimension may be generally aligned with the minor axis of the beam spot region and may be larger than the diameter of the radiation beam incident upon it by a suitable amount so as to provide space for cooling and some tolerance for position errors of the radiation beam. In use, the long dimension may be generally aligned with the major axis of the beam spot region and may therefore be significantly larger than the diameter of the radiation beam incident upon it, for example of the order of 250 mm.

[00121] The curved mirrors may be astigmatic. In general, when a radiation beam is incident upon an astigmatic mirror the focal length in a plane containing each of the principal directions of curvature of the mirror may differ.

[00122] The curved mirrors (e.g. cylindrical-like and toroidal-like mirrors) which form part of the radiation beam expanders according to embodiments of the invention have well defined curvatures in their two mutually perpendicular directions of curvature. In use, the radiation beam is incident upon these curved mirrors such that one of the principal directions of curvature is substantially perpendicular to the plane of incidence (i.e. aligned with the major axis of the beam spot region) and the other principal direction of curvature is substantially parallel to the plane of incidence (i.e. aligned with the minor axis of the beam spot region). When the radiation beam is incident upon one of the curved mirrors (e.g. a cylindrical-like or toroidal-like mirror) the focal lengths in a plane containing each of the principal directions of the mirror are dependent upon: the principal curvatures of the mirror; and the angle at which the radiation beam is incident upon the mirror. Consider a circular radiation beam incident upon a curved mirror (e.g. a cylindrical-like or toroidal-like mirror) at a grazing incidence angle of β such that a first principal direction of curvature of the mirror is aligned with the major axis of the beam spot region and a second principal direction of curvature of the mirror is aligned with the minor axis of the beam spot region. The focal length f_1 in a plane containing the first principal direction of curvature is given by $f_1 = \beta / (2K_1)$, where K_1 is the curvature of the surface of the mirror in that the first principal direction. The focal length f_2 in a plane containing the second principal direction of curvature is given by $f_2 = 1 / (2\beta K_2)$, where K_2 is the curvature of the surface of the mirror in the second principal direction. The curvature K of the surface of the mirror in a given direction is given by the inverse of the radius of curvature R of the surface of the mirror in that direction.

[00123] Figure 5 shows a first embodiment of a radiation beam expander 200 according to an embodiment of the invention, which may form the radiation beam expander 100 of Figures 1 and 4. Note that for clarity the sensor apparatus S, actuators and controller CN have been omitted from Figure 5.

5 [00124] Radiation beam expander 200 comprises three curved mirrors M1, M2, M3. The first mirror M1 is arranged to receive and reflect an input radiation beam B_{in} . The input radiation beam B_{in} is reflected by each of the three mirrors M1, M2, M3 in turn such that the mirrors M1, M2, M3 form part of an optical path of the input radiation beam B_{in} . The grazing incidence angle of the radiation beam at each of the three curved mirrors M1, M2, M3 has been exaggerated in
10 Figure 5 so that it can be more clearly seen.

[00125] The first and second mirrors M1, M2 are convex cylindrical-like mirrors. The first and second mirrors M1, M2 may be extruded hyperbolas. Alternatively, the first and second mirrors M1, M2 may be cylindrical, or extruded parabolas or ellipses. Therefore the first and second mirrors M1, M2 have negative optical power and are arranged to increase a divergence of the
15 radiation beam as will be described below.

[00126] Figure 6 shows a cylindrical-like mirror 300, which may be used as either the first or second mirror M1, M2. Cylindrical-like mirror 300 is now described with reference to a right handed set of Cartesian axes, u, v, w. Figure 6a is a cross sectional view of the cylindrical-like mirror 300 in the v-w plane and Figure 6b is a cross sectional view of the cylindrical-like mirror
20 300 in the u-v plane. Cylindrical-like mirror 300 has two opposed surfaces: a reflective surface 302 for receiving and reflecting a radiation beam; and a rear surface 304. The reflective surface 302 is curved, as now described.

[00127] Note that since the reflective surface 302 is curved, the normal direction varies across the reflective surface 302. However, the normal to reflective surface 302 always lies in the v-w
25 plane (or a plane parallel thereto).

[00128] A curvature of the reflective surface 302 of the cylindrical-like mirror 300 in the w-direction may vary such that, for example, in the v-w plane the reflective surface 302 is hyperbolic, parabolic or elliptical. Alternatively, the reflective surface 302 of the cylindrical-like mirror 300 may have a constant curvature in the w-direction, i.e. the radius of curvature of the
30 reflective surface 302 in the w-direction may be constant such that in the v-w plane the reflective surface 302 is of the shape of a circular arc. The reflective surface 302 of the cylindrical-like mirror 300 has no curvature in the u-direction, i.e. in the u-v plane the reflective surface is flat. The two principal directions of the cylindrical-like mirror 300 are aligned with the u and w directions. The w-direction may be referred to as a curvature direction of the cylindrical-like

mirror 300 and the u-direction may be referred to as a flat direction of the cylindrical-like mirror 300. The focal length in each of the two perpendicular directions (u and w) is different. Therefore, the cylindrical-like mirror 300 will vary the divergence of a radiation beam that is incident upon the reflective surface 300 differently in two different (mutually perpendicular) directions in a plane perpendicular to a propagation path of the radiation beam, as now described. An optical element (e.g. cylindrical-like mirror 300) that is arranged to vary the divergence of an incident radiation beam differently in two different (mutually perpendicular) directions in a plane perpendicular to a propagation path of the radiation beam may be referred to as an astigmatic optical element.

[00129] It will be appreciated that as a radiation beam propagates through the radiation beam expander 200 its propagation direction will change. For example at each mirror M1, M2, M3 the direction of the radiation beam will change. For this reason it is convenient to define a coordinate system that follows the radiation beam through its optical path in a well-defined manner. The following convention will be used throughout this application.

[00130] A coordinate system that follows the radiation beam may be defined by a set of Cartesian axes x, y, z. By convention, the z direction is aligned with the propagation direction of the radiation beam and the x-y plane is the plane which is perpendicular to the direction of the radiation beam. Note that for a divergent radiation beam, in general, each ray of the beam may propagate in a different direction. For such divergent radiation beams the propagation direction of the radiation beam may be taken to be the central or chief ray of the radiation beam. At each reflective optical element the radiation beam is reflected and therefore its direction changes. At each reflective optical element the coordinate system that follows the radiation beam is rotated according to the following convention.

[00131] At a reflective optical element (e.g. cylindrical mirror 200) the plane of incidence may be defined as the plane which contains the chief ray and the normal to the surface of the optical element at the point that the chief ray is incident on. Suppose that the chief ray is incident upon the reflective surface at a grazing incidence angle of β . With such an arrangement, after the reflection of the radiation beam at the reflective surface the chief ray is rotated by an angle of 2β about an axis which is perpendicular to the plane of incidence and the coordinate system that follows the radiation beam is transformed in the following way. The coordinate system that follows the radiation beam is rotated by an angle of 2β about an axis (in the x-y plane) which is perpendicular to the plane of incidence and then reflected through a plane that contains both: the z axis and the axis (in the x-y plane) which is perpendicular to the plane of incidence. For example, suppose a radiation beam approaches a mirror at a grazing incidence angle of β such

that the x-axis lies in the plane of incidence and the y-axis is perpendicular to the plane of incidence, as shown in Figure 6a. After the reflection: the y-axis remains unchanged; the z axis has been rotated (about the y axis) by an angle of 2β ; and the x axis has been rotated (about the y axis) by an angle of 2β and then reflected through the y-z plane. Therefore, if the Cartesian axes x, y, z form a right-handed set immediately before reflection of the radiation beam then the axes x, y, z will form a left-handed set immediately after the reflection.

[00132] As explained above, when a radiation beam is incident upon a reflective optical element at a grazing incidence angle of β , then, in general, it will illuminate an elongate beam spot region on the reflective surface of the optical element. On the surface of the mirror, the x-y plane of the coordinate system that follows the radiation beam may be considered to be projected onto the reflective surface of the mirror (or a plane whose normal coincides with the normal to the surface of the optical element at the point that the chief ray is incident on). The direction of the major axis of the beam spot region corresponds to a direction in the x-y plane that is perpendicular to the plane of incidence. Similarly, the direction of the minor axis of the beam spot region corresponds to a direction in the x-y plane that is perpendicular to the plane of incidence. For example, suppose a radiation beam approaches a mirror at a grazing incidence angle of β such that the x-direction lies in the plane of incidence and the y-direction is perpendicular to the plane of incidence. On the surface of the mirror, the major axis of the beam spot region corresponds to the x-direction and the minor axis of the beam spot region corresponds to the y-direction. Therefore, the projection of the x-y plane onto the mirror corresponds to rotation of the coordinate system that follows the radiation beam by an angle of $(90^\circ - \beta)$ about the axis (in the x-y plane) which is perpendicular to the plane of incidence.

[00133] Since the cylindrical-like mirror 300 is astigmatic, when a radiation beam B_1 is incident on the reflective surface 302 its divergence is affected differently in two different (mutually perpendicular) directions in a plane perpendicular to a propagation path of the radiation beam (i.e. the x-y plane). In particular, cylindrical-like mirror 300 will increase the divergence of the radiation beam B_1 in a first direction in the x-y plane and will not alter the divergence of the radiation beam B_1 in a second, mutually perpendicular direction in the x-y plane. The first direction in the x-y plane is that which corresponds to the curvature direction of the mirror 300 (i.e. the w-direction) at the mirror. For example, consider a radiation beam B_1 which is incident upon the cylindrical-like mirror 300 such that the plane of incidence coincides with (or is parallel to) both the v-w plane and the x-z plane. Such an arrangement is shown in Figure 6a. At the cylindrical-like mirror, the x-y plane is projected onto the u-w plane such that the x-direction corresponds to the w-direction. Therefore, after the reflection, the divergence of the radiation beam in the x-

direction will be increased (due to the curvature of the reflective surface 302 in the w-direction) and the divergence of the radiation beam in the y-direction will remain unchanged.

[00134] Projected onto a plane defined by the propagation path of the radiation beam (i.e. the z-direction) and the first direction in the x-y plane (which corresponds to the curvature direction of the reflective surface, i.e. the w-direction) the radiation beam B_1 which leaves the cylindrical-like mirror 300 appears to originate from a virtual line source 306. Note that in the example illustrated in Figure 6a, the v-w plane and the x-z plane coincide (or are parallel). However, in general the curvature direction (e.g. the w-direction) of the reflective surface 302 may not lie in the plane of incidence.

[00135] As now described, the first and second mirrors M1, M2 are arranged such that they each increase the divergence of the radiation beam in a different direction in the plane perpendicular to a propagation path of the radiation beam (i.e. the x-y plane). In the following, with reference to Figure 5, the relative positions and orientations of the curved mirrors M1, M2, M3 will be described with reference to a right-handed set of Cartesian axes X, Y, Z.

[00136] The first mirror M1 is arranged such that its curvature direction is aligned with the Y-direction and its flat direction is aligned with the Z-direction. That is, for mirror M1, the Y-direction is equivalent to the w-direction of Figure 6 and the Z-direction is equivalent to the u-direction of Figure 6. The chief ray of an input radiation beam B_{in} is represented by line AB, which lies in the X-Y plane. Therefore, for the reflection at mirror M1, the plane of incidence is the X-Y plane, which is labelled as plane P1. Note that the mirror M1 is arranged relative to the input radiation beam B_{in} such that its curvature direction is generally aligned with the major axis of the beam spot region formed on the surface of mirror M1.

[00137] The first mirror M1 increases the divergence of the radiation beam in a first direction in the x-y plane. In the example shown in Figure 5, the radiation beam is incident on mirror M1 such that the plane of incidence coincides with (or is parallel to) the x-z plane. Therefore, after reflection from mirror M1, the first direction, in which the divergence of the radiation beam is increased, is the x-direction.

[00138] The plane of incidence for the reflection from the second mirror M2 is defined by the chief ray of the radiation beam which propagates between the first mirror M1 and the second mirror M2 (represented by line BC) and the normal to the second mirror M2.

[00139] Mirror M2 is arranged to receive the radiation beam reflected from the first mirror such that it increases the divergence of the radiation beam in a second direction in the x-y plane. The second direction may be perpendicular to the first direction. For example, in Figure 5 the second mirror M2 is arranged such that the radiation beam is incident upon it (from the first

mirror M1) such that curvature direction of the second mirror M2 corresponds to a direction in the x-y plane which is perpendicular to the first direction. It will be appreciated that the relative orientations of mirrors M1 and M2 which achieves this may depend on the orientation of the radiation beam that is incident upon the first mirror M1.

5 [00140] In the example shown in Figure 5, the second mirror M2 is orientated such that the plane of incidence P2 at mirror M2 is perpendicular to the plane of incidence P1 at mirror M1. The curvature direction of mirror M1 lies in plane P1 and the curvature direction of mirror M2 lies in plane P2. Such an arrangement ensures that each of the first and second mirrors M1, M2 increases the divergence of the radiation beam in a different direction in the plane perpendicular
10 to a propagation path of the radiation beam (i.e. the x-y plane). The first mirror M1 increases the divergence in the x-direction and the second mirror M2 increases the divergence in the y-direction. Therefore, after reflection from mirror M2, the divergence of the radiation beam has been increased in two directions in the x-y plane. It has been increased in a first direction by the first mirror M1 and in a second direction by the second mirror M2.

15 [00141] Note that the second mirror M2 is also arranged relative to the radiation beam such that its curvature direction is generally aligned with the major axis of the beam spot region formed on the surface of the second mirror M2.

[00142] Together, the first and second mirrors M1, M2 may be considered to be a diverging optic for receiving a radiation beam and increasing the divergence of the radiation beam. The
20 first mirror M1 may be considered to form a first optical element of the diverging optic for receiving the radiation beam and increasing the divergence of the radiation beam in a first direction. The second mirror M2 may be considered to form a second optical element of the diverging optic for receiving the radiation beam and increasing the divergence of the radiation beam in a second direction. In general the diverging optic (formed by mirrors M1, M2) is
25 astigmatic such that it decreases the divergence of the radiation beam in the first and second directions by different amounts.

[00143] The third mirror M3 is a concave toroidal-like mirror. The third mirror M3 may, for example, be paraboloidal, hyperboloidal, ellipsoidal or toroidal in this embodiment. Therefore the third mirror M3 has positive optical power and is arranged to decrease a divergence of the
30 radiation beam as will be described below. The third mirror M3 may be considered to be a converging optic for receiving a radiation beam and decreasing the divergence of the radiation beam

[00144] Figure 7 shows a concave toroidal-like mirror 350, which may be used as the third mirror M3. Toroidal-like mirror 350 is now described with reference to a right handed set of

Cartesian axes, u , v , w . Toroidal-like mirror 350 has a reflective surface 352 for receiving and reflecting a radiation beam. The reflective surface 352 is curved, such that it has a constant curvature K_1 in the u -direction and a constant curvature K_2 in the w -direction. The curvature of the reflective surface 302 is different in the two perpendicular directions (u and w).
 5 Furthermore, the cylindrical mirror 300 may be arranged to vary the divergence of a radiation beam that is incident upon the reflective surface 300 differently in two different (mutually perpendicular) directions in the plane perpendicular to a propagation path of the radiation beam (i.e. the x - y plane) such that the cylindrical mirror is astigmatic. The toroidal-like mirror 350 may have a first focal length in the u - v plane, which is related to the curvature of the reflective
 10 surface in the u -direction and the grazing incidence angle β of the radiation beam. The toroidal-like mirror 350 may have a second focal length in the w - v plane, which is related to the curvature of the reflective surface in the w -direction and the grazing incidence angle β of the radiation beam. The first focal length f_1 is given by $f_1 = \beta / (2K_1)$ and the second focal length f_2 is given by $f_2 = 1 / (2\beta K_2)$.

15 **[00145]** The third mirror M3 is arranged relative to the first and second mirrors M1, M2 such that one of its principal directions corresponds to the first direction in the x - y plane and the other one of its principal directions corresponds to the second direction in the x - y plane. The toroidal third mirror M3 will therefore decrease the divergence of the radiation beam in the first and second directions in the x - y plane by different amounts.

20 **[00146]** The divergence of the radiation beam as it leaves the third mirror M3 is dependent on: the divergence of the input radiation beam B_{in} ; the curvature of the three mirrors M1, M2, M3; the grazing incidence angle of the radiation beam at each of the three mirrors M1, M2, M3; and the relative positions of the mirrors, as now described. In particular, the divergence of the radiation beam in the first direction as it leaves the third mirror M3 is dependent on: the
 25 divergence of the input radiation beam B_{in} in the first direction; the curvature of the first mirror M1; the curvature K_2 of mirror M3 in the w -direction; and the relative positions of the first and third mirrors M1, M3. Similarly, the divergence of the radiation beam in the second direction as it leaves the third mirror M3 is dependent on: the divergence of the input radiation beam B_{in} in the second direction; the curvature of the second mirror M2; the curvature K_1 of mirror M3 in the
 30 u -direction; and the relative positions of the second and third mirrors M2, M3.

[00147] As discussed above, projected onto a plane defined by the propagation path of the radiation beam (i.e. the z -direction) and the first direction (in the x - y plane), the radiation beam which leaves the diverging optic may appear to originate from a first virtual source. Similarly, projected onto a plane defined by the propagation path of the radiation beam (i.e. the z -

direction) and the second direction (in the x-y plane), the radiation beam which leaves the diverging optic may appear to originate from a second virtual source. The divergence of the output radiation beam in the first (second) direction may be dependent upon the relative position of the first (second) virtual source and a focal point of the converging optic in a plane containing the first (second) direction.

[00148] It may be desirable for the radiation beam that leaves the third mirror M3 to be collimated. It will be appreciated that a radiation beam being collimated means that the divergence the radiation beam is negligible. This may be achieved by arranging the three mirrors M1, M2, M3 such that: the first virtual source coincides with the first focal point of the third mirror M3; and the second virtual source coincides with the second focal point of the third mirror M3. The curvatures of M1, M2, and M3 and the distances BC and CD are chosen such that the output radiation beam B_{out} leaving the third mirror M3 is collimated when the input radiation beam B_{in} enters the radiation beam expander 200 along the nominal input path AB.

[00149] As the radiation beam propagates through the radiation beam expander 200, the cross sectional area of the radiation beam is increased, as now described.

[00150] In general, the radiation beam produced by a free electron laser FEL may be an astigmatic radiation beam, having a different divergence in each of two mutually perpendicular directions in a plane perpendicular to a propagation path of the radiation beam. Further, the radiation beam produced by a free electron laser FEL may be elliptical in cross section, the cross section of the radiation beam having a major axis and a minor axis. The radiation beam produced by a free electron laser FEL may, for example, have a first divergence in a direction of the major axis and a second divergence in a direction of the minor axis. In use, the optical system of the radiation beam expander 200 may be orientated relative to the undulator 24 of a free electron laser FEL such that the major axis of the radiation beam is aligned with one of the first and second directions (which lie in the x-y plane) and the major axis of the radiation beam is aligned with the other of the first and second directions.

[00151] The radiation beam B_{FEL} output by a free electron laser has a two-dimensional Gaussian-like intensity distribution. In general, it may be described by 9 parameters. These parameters include: two position parameters, which define the position of the centre of the radiation beam at a point along its propagation path; and two angles, which define the direction of propagation away from said point. In general the radiation beam will be elliptical in cross section, the ellipse having mutually perpendicular major and minor axes. The parameters further comprise an angle which defines the orientation of the major and minor axes; two lengths, which define the size of the radiation beam (or, equivalently, the width of the Gaussian)

along each of the major and minor axes; and two angles, which define the divergence of the radiation beam along each of the major and minor axes.

[00152] The shape of the radiation beam as it propagates through the radiation beam expander 200 along the path illustrated in Figure 5 (which may be referred to as a nominal path) will now be described with reference to Figure 8.

[00153] At point A (see Figure 5), as the input radiation beam B_{in} enters the radiation beam expander 200 the cross sectional shape of the radiation beam is elliptical, as indicated by ellipse 212. The major and minor axes of the ellipse 212 are aligned with the y and x axes respectively. In practice this may, for example, be achieved by suitable orientation of the entire optical system of the radiation beam expander 200 relative to the undulator 24 of a free electron laser FEL.

[00154] In general, the input radiation beam may have a relatively small but non-zero divergence in along both the major and minor axes of ellipse 212. For example, the radiation beam B_{in} may be produced by a free electron laser FEL and may have a divergence of less than 500 μ rad. Therefore, at point B, the cross section of the radiation beam is increased in both the x and y directions, as indicated by ellipse 214. Such a small divergence will result in a small increase in both the x and y directions. It will be appreciated that this increase (as represented by the difference in the sizes of ellipses 212, 214) has been exaggerated so that it can be clearly illustrated in Figure 8.

[00155] The first mirror M1 increases the divergence of the radiation beam in the x-direction. Therefore, at point C, the cross section of the radiation beam is increased significantly in the x direction primarily due to the divergence introduced by mirror M1. In addition, there will also be a relatively small increase in the cross section of the radiation beam in both the x and y directions due to the initial divergence of the input radiation beam B_{in} . The cross section of the radiation beam at point C is represented by ellipse 216.

[00156] The second mirror M2 increases the divergence of the radiation beam in the y-direction. Therefore, at point D, the cross section of the radiation beam is increased significantly in the x direction primarily due to the divergence introduced by mirror M1 and is increased significantly in the y direction primarily due to the divergence introduced by mirror M2. In addition, there will also be a relatively small increase in the cross section of the radiation beam in both the x and y directions due to the initial divergence of the input radiation beam B_{in} . The cross section of the radiation beam at point D is represented by circle 218.

[00157] The third mirror M3 reduces the divergence of the radiation beam in both the x and y directions such that the radiation beam is collimated. Therefore, at point E the cross section of the radiation beam at point D is also represented by circle 218.

[00158] In use, the input radiation beam B_{in} may not be aligned with the nominal path AB. The radiation beam may be shifted relative to the nominal path AB. This may be referred to as a position error of the radiation beam. Additionally or alternatively, the radiation beam may be rotated relative to the nominal path AB. This may be referred to as a pointing error of the radiation beam. It may be desirable to ensure that the position and orientation of the radiation beam B_{out} which is output by the radiation beam expander 200 (i.e. the radiation beam that leaves the third mirror M3) remain fixed, independent of any variation in the position and orientation of the input radiation beam B_{in} .

[00159] Each of the three mirrors M1, M2, M3 is rotatable. Rotation of the mirrors M1, M2, M3 may be used to correct for position and/or pointing errors of the input radiation beam B_{in} . That is, rotation of the mirrors M1, M2, M3 may be used to ensure that the position and orientation of the radiation beam which is output by the radiation beam expander 200 remain fixed.

[00160] Each of the two convex mirrors M1, M2 is rotatable about an axis which is perpendicular to its direction of curvature (and aligned with its flat direction). The first mirror M1 is rotatable about a first axis R1 and the second mirror M2 is rotatable about a second axis R2. The first and second axes R1, R2 are perpendicular to planes P1, P2 respectively. The third mirror M3 is rotatable about two mutually perpendicular axes: a third axis R3 which is perpendicular to one of its principal directions; and a fourth axis R4 which is perpendicular to the other one of its principal directions.

[00161] Rotation of each of the mirrors M1, M2 about a single axis may be achieved by way of a shaft connected to the mirror and a drive mechanism (e.g. a motor) arranged to rotate the shaft.

[00162] Additionally or alternatively, rotation of any of the three mirrors M1, M2, M3 may be implemented by combining a pivot and one or more linear actuators, as shown in Figure 9. Figures 9a and 9b show a mirror 500 which is mounted on a pivot 502. The mirror 500 is provided with a linear actuator 504 which is offset from the pivot (in the w-direction in Figure 9) and is operable to move a point 506 on the mirror 500 in the v direction. Such linear motion of point 506 causes the mirror 500 to rotate about an axis passing through pivot 502.

[00163] As shown in Figure 9a, the pivot 502 may be located close to the centre of the mirror 500. With such an arrangement the rotation axis of the mirror 500 may be as close as possible to the axes R1-R8 as shown in Figures 5 and 10.

[00164] Alternatively, as shown in Figure 9b, the pivot 502 may be located proximate to an edge of the mirror 500. Such an arrangement may be mechanically more stable. However, the arrangement of Figure 9b will result in a mixing of pure rotation around the centre of the mirror 500 with a translation of the centre of the mirror 500. The configuration shown in Figure 9b is suitable for use with the embodiments shown in Figures 5 and 10. The translation of the centre of the mirror 500 will lead to an additional shift of the radiation beam but this additional shift can be compensated for by using the other available actuators.

[00165] For rotation of mirror M3 about two perpendicular axes R3, R4 two linear actuators may be used. For example a second linear actuator (not shown) may be provided which is offset from the pivot in direction perpendicular to the v-w plane and which is operable to move a second point (not shown) on the mirror 500 in the v direction. Such linear motion of point 506 causes the mirror 500 to rotate about a different axis passing through pivot 502.

[00166] If the point B on mirror M1 (which represents the point on the first mirror M1 upon which the chief ray is incident) is shifted and/or the direction of the path AB is changed then the first and second mirrors M1 and M2 are rotated about the first and second axes R1, R2 respectively such that the radiation beam hits mirror M3 at a nominal position in space (point D in Figure 5). In addition, the third mirror M3 is rotated about axes R3 and R4 such that the output radiation beam B_{out} is pointing in a nominal direction (line DE in Figure 5).

[00167] Note that when the input radiation beam B_{in} is not aligned with the nominal path AB, the path followed by the radiation beam within the radiation beam expander 200 will not be the nominal path shown in Figure 5. However, by rotating the three mirrors M1, M2, M3 it is possible to ensure that the output radiation beam B_{out} has a fixed position and direction (along line DE in Figure 5).

[00168] An optical power of each of the first and second mirrors M1, M2 is independently adjustable as now described. The optical power of each of the first and second mirrors M1, M2 is the degree to which it increases (or decreases) the divergence of a radiation beam.

[00169] The amount by which the divergence of the radiation beam is increased by the first or second mirror M1, M2 is dependent on: the curvature of the respective mirror M1, M2; and the grazing incidence angle of the radiation beam at the respective mirror M1, M2. The extent of the beam spot region formed on each mirror M1, M2 in its curvature direction is dependent on the orientation of the mirror M1, M2 relative to the incoming radiation beam (e.g. it is dependent upon the grazing incidence angle β).

[00170] The optical power of each of the first and second mirrors M1, M2 is independently adjustable by varying its curvature. A suitable mechanism for altering the curvature of the first

and second mirrors M1, M2 is now described with reference to Figure 10, which is a cross sectional view of a mirror 400.

[00171] Mirror 400 has opposed reflective and rear surfaces 402, 404 and two opposed sides 406, 408. The reflective surface 402 is a curved and convex. Reflective surface 402 is for receiving and reflecting a radiation beam.

[00172] The mirror 400 is provided with two actuators 412, 414 which each run along one of the two sides 406, 408 of the mirror 400. The actuators 412, 414 may for example be provided at least partially inside the mirror 400. The actuators 412, 414 are rotational and rotate to apply a torque to the reflector mirror as schematically indicated by arrows 420. Application of a torque using the actuators 412, 414 will tend to bend the reflective surface 402 and alter its curvature in the w-direction. An advantage of the mechanism shown in Figure 10 for altering a curvature of a mirror 400 is that it is relatively straightforward to implement.

[00173] The rear surface 404 may be generally flat when no torque is applied by actuators 412, 414. Alternatively, the rear surface 404 may be curved even in the absence of such an applied torque. For example, a thickness of the mirror 400 in the v-w plane may have a well-defined variation along the length of the mirror 400 (in the w-direction). With such an arrangement, a torque applied by actuators 412, 414 may result in a non-uniform change in the curvature of the mirror in the w-direction. For example, such an arrangement may allow a mirror 400 with a parabolic reflective surface in the v-w plane to remain parabolic when the actuators 412, 414 apply a torque.

[00174] Although the above described mirror 400 has a curved and convex reflective surface 402, it will be appreciated that a similar mechanism may be used for flat or concave curved mirrors.

[00175] Each of the first and second mirrors M1, M2 is provided with a mechanism as shown in Figure 10, or a similar mechanism, which allows the curvature of that mirror along its curvature directions to be controlled.

[00176] As discussed above, when a radiation beam is incident upon an optical element with circular geometry (e.g. a cylindrical or toroidal mirror) at a grazing incidence angle of β , if one of the principal axes of the optical element is aligned with the major axis of the beam spot region then the focal length f is given by $f = \beta / (2K)$, where K is the curvature of the surface of the mirror in direction of that principal axis. However, if one of the principal axes of the optical element is aligned with the minor axis of the beam spot region then the focal length f is given by $f = 1 / (2\beta K)$, where K is the curvature of the surface of the mirror in direction of that principal axis. Therefore, if the principal axis of the mirror is aligned with the major axis then the required curvature K (or

change in curvature) for a given focal length is smaller than the required curvature K (or change in curvature) when the principal axis of the mirror is aligned with the minor axis (by a factor of β^2). It is for this reason that the first and second mirrors $M1$, $M2$ are both arranged relative to the radiation beam such that their curvature directions are generally aligned with the major axis of the beam spot region formed on their surfaces.

[00177] Mirrors with an adjustable curvature in the perpendicular direction (i.e. the direction of the minor axis of the beam spot) would require higher torques (by a factor $1/\beta^2$) to achieve the same adjustment in optical power. However, such an arrangement could be used in principle. Similarly, in principle a mirror (e.g. a toroidal mirror) may be provided with actuators which are arranged to control its curvature in two mutually perpendicular principal axes. However, such an arrangement for actuating both curvature parameters may be difficult to achieve in practice.

[00178] The diverging optic comprises two separate mirrors $M1$, $M2$, each having an adjustable curvature, the curvature of each mirror $M1$, $M2$ resulting in an increase in the divergence of the radiation beam in a different direction. Such independent adjustment of the optical power of the diverging optic in each of the first and second directions allows the focal length of that optic to be independently varied in those directions. This provides control over the divergence of the output radiation beam B_{out} without having to move the diverging optic (i.e. mirrors $M1$, $M2$) relative to the converging optic (i.e. mirror $M3$). Adjustment of the curvature of the first and second mirrors $M1$, $M2$ provides more accurate control over the divergence of the output radiation beam B_{out} than movement of the diverging optic (i.e. mirrors $M1$, $M2$) relative to the converging optic (i.e. mirror $M3$).

[00179] As explained above, position and pointing errors of the input radiation beam B_{in} may be corrected for by rotating the three mirrors $M1$, $M2$, $M3$. However, such rotations of the three mirrors $M1$, $M2$, $M3$ will affect their focal lengths (since these are dependent on the grazing incidence angle of the beam on each mirror). As a result of this variation in the focal lengths of mirrors $M1$, $M2$, $M3$, when the input radiation beam B_{in} entering the radiation beam expander does not propagate along the nominal input path AB the first virtual source may not coincide with the first focal point of the third mirror $M3$; and the second virtual source may not coincide with the second focal point of the third mirror $M3$. With such an arrangement the output radiation beam B_{out} leaving the third mirror $M3$ will not be collimated.

[00180] A simple beam expander comprising a diverging optic and a converging optic can be used to produce a collimated radiation beam of increased cross section. However, it cannot be used to correct for pointing and/or position errors of a radiation beam, since rotation of the diverging and converging optics would introduce undesired divergence or convergence in the

beam leaving the beam expander. One solution to this problem would be to use a separate optical system to correct for pointing and position errors. For example, two flat (i.e. zero optical power), rotatable mirrors may be used upstream of the beam expander to correct for pointing and position. However, such an arrangement requires at least four mirrors (two flat mirrors and two with double curvature). Furthermore, such an arrangement may not be able to correct for time dependent variations in the initial divergence of the input radiation beam. As now described, the radiation beam expander 200 can achieve the same function (expanding and collimating the radiation beam and correcting for position and pointing errors) with just three mirrors M1, M2, M3.

[00181] In order to correct for variation in the focal lengths of the three mirrors M1, M2, M3 of radiation beam expander 200 caused by rotation of the mirrors M1, M2, M3, the curvature of the first and/or second mirror M1, M2 can be simultaneously varied to ensure that the first and second virtual sources do coincide with the first and second focal points of the third mirror M3 respectively. Therefore, the controller CN may be arranged to simultaneously control both: (a) the orientation of the mirrors M1, M2, M3; and (b) the curvatures of mirrors M1, M2.

[00182] Adjustment of the curvature of the mirrors M1, M2 may also be used to correct for variations in the divergence of the input radiation beam B_{in} .

[00183] The above described embodiment of a radiation beam expander 200 is advantageous since it provides a simple arrangement with only three mirrors which provides simultaneous control over the position, direction and divergence of the beam. Such a small number of mirrors reduces the cost of radiation beam expander 200 and absorption losses suffered by the radiation beam expander 200. The position of the radiation beam may be specified by two parameters (the position in the x and y directions) and therefore represents two degrees of freedom. The direction of the radiation beam may be specified by two parameters (two pointing angles) and therefore represents two degrees of freedom. In general the radiation beam will be elliptical in cross section, having a different divergence along each of the major and minor axes of its cross section. Therefore, the divergence of the radiation beam may be specified by two parameters (the divergence along each of the major and minor axes) and represents two degrees of freedom. Therefore, the simultaneous control over the position, direction and divergence of the beam allows six degrees of freedom in the parameters of an input radiation beam B_{in} to be controlled. Note that radiation beam expander 200 has six actuators (The first mirror M1 is rotatable about first axis R1; the second mirror M2 is rotatable about second axis R2; the curvatures of the first and second mirrors M1, M2 are adjustable; and the third mirror M3 is rotatable about the third and fourth axes R3, R4) and can compensate for variations in six

degrees of freedom in the parameters of an input radiation beam B_{in} . Therefore radiation beam expander 200 is not provided with any excess or redundant degrees of freedom in actuation. Radiation beam expander does not provide control over the overall diameter of the output radiation beam B_{out} . With this embodiment, the diameter of the output radiation beam B_{out} is dependent on the incoming diameter and divergence of the input radiation beam B_{in} .

[00184] Figure 11 shows a second embodiment of a radiation beam expander 250 according to an embodiment of the invention, which may form the radiation beam expander 100 of Figures 1 and 4. Note that for clarity the sensor apparatus S, actuators and controller CN have been omitted from Figure 11.

[00185] Radiation beam expander 250 comprises four curved mirrors M5, M6, M7, M8. The first mirror M5 is arranged to receive and reflect an input radiation beam B_{in} . The input radiation beam B_{in} is reflected by each of the four mirrors M5, M6, M7, M8 in turn such that the mirrors M5, M6, M7, M8 form part of an optical path of the input radiation beam B_{in} . The grazing incidence angle of the radiation beam at each of the four curved mirrors M5, M6, M7, M8 has been exaggerated in Figure 11 so that it can be more clearly seen.

[00186] The first and third mirrors M5, M7 are convex cylindrical-like mirrors. Therefore the first and third mirrors M5, M7 have negative optical power and are arranged to increase a divergence of the radiation beam. The second and fourth mirrors M6, M8 are concave cylindrical-like mirrors. Therefore the second and fourth mirrors M6, M8 have positive optical power and are arranged to decrease a divergence of the radiation beam. The curved mirrors M5, M6, M7, M8 may be cylindrical or, alternatively, they may have other shapes and may be, e.g., hyperbolic or parabolic in cross section. In one embodiment, the negative optical power mirrors M5, M7 may be extruded hyperbolic mirrors and the positive optical power mirrors M6, M8 may be extruded parabolic mirrors.

[00187] The first and third mirrors M5, M7 are arranged such that they each increase the divergence of the radiation beam in a different direction in the plane perpendicular to a propagation path of the radiation beam (i.e. the x-y plane). Similarly, the second and fourth mirrors M6, M8 are arranged such that they each decrease the divergence of the radiation beam in a different direction in the plane perpendicular to a propagation path of the radiation beam (i.e. the x-y plane). In the following, with reference to Figure 11, the relative positions and orientations of the curved mirrors M5, M6, M7, M8 will be described with reference to a right-handed set of Cartesian axes X, Y, Z.

[00188] The first mirror M5 is arranged such that its curvature direction is aligned with the Y-direction and its flat direction is aligned with the Z-direction. That is, for mirror M5, the Y-

direction is equivalent to the w-direction of Figure 6 and the Z-direction is equivalent to the u-direction of Figure 6. The chief ray of an input radiation beam B_{in} is represented by line FG, which lies in the X-Y plane. Therefore, for the reflection at mirror M5, the plane of incidence is the X-Y plane, which is labelled as plane P3. Note that the mirror M5 is arranged relative to the input radiation beam B_{in} such that its curvature direction is generally aligned with the major axis of the beam spot region formed on the surface of mirror M5.

[00189] The second mirror M6 is also arranged such that its curvature direction is aligned with the Y-direction and its flat direction is aligned with the Z-direction. The plane of incidence for the reflection from the second mirror M6 is defined by the chief ray of the radiation beam which propagates between the first mirror M5 and the second mirror M6 (represented by line GH) and the normal to the second mirror M5. Therefore, for the reflection at the second mirror M6, the plane of incidence is also plane P3. Note that the mirror M6 is arranged relative to the input radiation beam B_{in} such that its curvature direction is generally aligned with the major axis of the beam spot region formed on the surface of mirror M6.

[00190] The first mirror M5 increases the divergence of the radiation beam in a first direction in the x-y plane. In the example shown in Figure 11, the radiation beam is incident on mirror M5 such that the plane of incidence P3 coincides with (or is parallel to) the x-z plane. Therefore, after reflection from mirror M5, the first direction, in which the divergence of the radiation beam is increased, is the x-direction.

[00191] The second mirror M6 is arranged to decrease the divergence of the radiation beam in the first direction in the x-y plane. In the example shown in Figure 11, the radiation beam is incident on mirror M6 such that the plane of incidence P3 coincides with (or is parallel to) the x-z plane. Therefore, after reflection from mirror M6, the first direction, in which the divergence of the radiation beam is decreased, is the x-direction.

[00192] The divergence of the radiation beam in the first direction as it leaves the second mirror M6 is dependent on: the divergence of the input radiation beam B_{in} ; the curvature of the first and second mirrors M5, M6; the grazing incidence angle at each of the first and second mirrors M5, M6; and the relative positions of the mirrors M5, M6, as now described. Projected onto a plane defined by the propagation path of the radiation beam (i.e. the z-direction) and the first direction (in the x-y plane), the radiation beam which leaves the first mirror M5 may appear to originate from a first virtual point source. The divergence of the radiation beam in the first direction as it leaves the second mirror M6 may be dependent upon the relative position of the first virtual source and a focal point of the second mirror M6.

[00193] It may be desirable for the radiation beam that leaves the radiation beam expander 250 to be collimated. Collimation of the radiation beam in the first direction may be achieved by arranging the first and second mirrors M5, M6 such that: the first virtual source coincides with the focal point of the second mirror M6. The curvatures of the first and second mirrors M5, M6 and the distance GH are chosen such that the radiation beam leaving the second mirror M6 is collimated in the first direction when the input radiation beam B_{in} enters the radiation beam expander 250 along the nominal input path FG.

[00194] The third mirror M7 is arranged to receive the radiation beam reflected from the second mirror M6 such that it increases the divergence of the radiation beam in a second direction in the x-y plane. The second direction may be perpendicular to the first direction. For example, in Figure 11 the third mirror M7 is arranged such that the radiation beam is incident upon it (from the second mirror M6) such that the curvature direction of the third mirror M7 corresponds to a direction in the x-y plane which is perpendicular to the first direction. It will be appreciated that the relative orientations of the mirrors M5, M6, M7 which achieves this may depend on the orientation of the radiation beam that is incident upon the first mirror M5.

[00195] In the example shown in Figure 11, the third mirror M7 is orientated such that the plane of incidence at third mirror M7 is perpendicular to the plane of incidence P3 at the first and second mirrors M5, M6. The curvature direction of the first and second mirrors M5, M6 lies in plane P3 and the curvature direction of the third mirror M7 lies in plane P4. Such an arrangement ensures that each of the first and third mirrors M5, M7 increases the divergence of the radiation beam in a different direction in the plane perpendicular to a propagation path of the radiation beam (i.e. the x-y plane). The first mirror M5 increases the divergence in the x-direction and the third mirror M7 increases the divergence in the y-direction.

[00196] Note that the third mirror M7 is also arranged relative to the radiation beam such that its curvature direction is generally aligned with the major axis of the beam spot region formed on its surface.

[00197] The plane of incidence for the reflection from the fourth mirror M8 is defined by the chief ray of the radiation beam which propagates between the third mirror M7 and the fourth mirror M8 (represented by line IJ) and the normal to the fourth mirror M8. Therefore, for the reflection at the fourth mirror M8, the plane of incidence is also in plane P4. Note that the mirror M8 is arranged relative to the radiation beam such that its curvature direction is generally aligned with the major axis of the beam spot region formed on its surface.

[00198] The third mirror M7 increases the divergence of the radiation beam in a second direction in the x-y plane. In the example shown in Figure 11, the radiation beam is incident on

mirror M7 such that the plane of incidence P4 coincides with (or is parallel to) the y-z plane. Therefore, after reflection from mirror M7, the second direction, in which the divergence of the radiation beam is increased, is the y-direction.

[00199] The fourth mirror M8 is arranged to decrease the divergence of the radiation beam in the second direction in the x-y plane. In the example shown in Figure 11, the radiation beam is incident on mirror M8 such that the plane of incidence P4 coincides with (or is parallel to) the x-z plane. Therefore, after reflection from mirror M8, the second direction, in which the divergence of the radiation beam is decreased, is the y-direction.

[00200] The divergence of the radiation beam in the second direction as it leaves the fourth mirror M8 is dependent on: the divergence of the input radiation beam B_{in} ; the curvature of the third and fourth mirrors M7, M8; the grazing incidence angle at each of the third and fourth mirrors M7, M8; and the relative positions of the mirrors M7, M8, as now described. Projected onto a plane defined by the propagation path of the radiation beam (i.e. the z-direction) and the second direction (in the x-y plane), the radiation beam which leaves the third mirror M7 may appear to originate from a second virtual point source. The divergence of the radiation beam in the second direction as it leaves the fourth mirror M8 may be dependent upon the relative position of the second virtual source and a focal point of the fourth mirror M8.

[00201] It may be desirable for the radiation beam that leaves the radiation beam expander 250 to be collimated. Collimation of the radiation beam in the second direction may be achieved by arranging the third and fourth mirrors M7, M8 such that: the second virtual source coincides with the focal point of the fourth mirror M8. The curvatures of the third and fourth mirrors M7, M8 and the distance LJ are chosen such that the radiation beam leaving the fourth mirror M8 is collimated in the second direction when the input radiation beam B_{in} enters the radiation beam expander 250 along the nominal input path FG.

[00202] Together, the first and second mirrors M5, M6 act to expand and collimate the radiation beam in the first direction. Similarly, together the third and fourth mirrors M7, M8 act to expand and collimate the radiation beam in the second direction.

[00203] Together, the first and third mirrors M5, M7 may be considered to be a diverging optic for receiving a radiation beam and increasing the divergence of the radiation beam. The first mirror M5 may be considered to form a first optical element of the diverging optic for receiving the radiation beam and increasing the divergence of the radiation beam in a first direction. The third mirror M7 may be considered to form a second optical element of the diverging optic for receiving the radiation beam and increasing the divergence of the radiation beam in a second direction. In general the diverging optic (formed by mirrors M5, M7) may be astigmatic such that

it increases the divergence of the radiation beam in the first and second directions by different amounts.

[00204] Together, the second and fourth mirrors M6, M8 may be considered to be a converging optic for receiving a radiation beam and decreasing the divergence of the radiation beam. The second mirror M6 may be considered to form a first optical element of the converging optic for receiving the radiation beam and decreasing the divergence of the radiation beam in a first direction. The fourth mirror M8 may be considered to form a second optical element of the converging optic for receiving the radiation beam and decreasing the divergence of the radiation beam in a second direction. In general the converging optic (formed by mirrors M6, M8) may be astigmatic such that it decreases the divergence of the radiation beam in the first and second directions by different amounts.

[00205] As the radiation beam propagates through the radiation beam expander 250, the cross sectional area of the radiation beam is increased, as now described.

[00206] The shape of the radiation beam as it propagates through the radiation beam expander 250 along the path illustrated in Figure 11 (which may be referred to as a nominal path) will now be described with reference to Figure 12.

[00207] At point F (see Figure 11), as the input radiation beam B_{in} enters the radiation beam expander 250 the cross sectional shape of the radiation beam is elliptical, as indicated by ellipse 262. The major and minor axes of the ellipse 262 are aligned with the y and x axes respectively. In practice this may, for example, be achieved by suitable orientation of the entire optical system of the radiation beam expander 250 relative to the undulator 24 of a free electron laser FEL.

[00208] In general, the input radiation beam may have a relatively small but non-zero divergence in along both the major and minor axes of ellipse 262. For example, the radiation beam B_{in} may be produced by a free electron laser FEL and may have a divergence of less than 500 μ rad. Therefore, at point G, the cross section of the radiation beam is increased in both the x and y directions, as indicated by ellipse 264. Such a small divergence will result in a small increase in both the x and y directions. It will be appreciated that this increase (as represented by the difference in the sizes of ellipses 262, 264) has been exaggerated so that it can be clearly illustrated in Figure 12.

[00209] The first mirror M5 increases the divergence of the radiation beam in the x-direction. Therefore, at point H, the cross section of the radiation beam is increased significantly in the x direction primarily due to the divergence introduced by mirror M5. In addition, there will also be a relatively small increase in the cross section of the radiation beam in both the x and y

directions due to the initial divergence of the input radiation beam B_{in} . The cross section of the radiation beam at point H is represented by ellipse 266.

[00210] The second mirror M6 reduces the divergence of the radiation beam in the x direction such that the radiation beam is collimated in the x direction. In the y direction, the radiation beam will have the same (relatively small but non-zero) initial divergence as the input radiation beam. Therefore, at point I the cross section of the radiation beam is increased in the y direction but not the x direction and is represented by ellipse 268.

[00211] The third mirror M7 increases the divergence of the radiation beam in the y-direction. Therefore, at point J, the cross section of the radiation beam is increased significantly in the y direction primarily due to the divergence introduced by mirror M7. In addition, there will also be a relatively small increase in the cross section of the radiation beam in the y direction due to the initial divergence of the input radiation beam B_{in} . The cross section of the radiation beam at point J is represented by circle 270.

[00212] The fourth mirror M8 reduces the divergence of the radiation beam in the y direction such that the radiation beam is collimated in the y direction. Therefore, at point J the cross section of the radiation beam is also represented by circle 270.

[00213] In use, the input radiation beam B_{in} may not be aligned with the nominal path FG. The radiation beam may be shifted relative to the nominal path FG. This may be referred to as a position error of the radiation beam. Additionally or alternatively, the radiation beam may be rotated relative to the nominal path FG. This may be referred to as a pointing error of the radiation beam. It may be desirable to ensure that the position and orientation of the radiation beam B_{out} which is output by the radiation beam expander 250 (i.e. the radiation beam that leaves the fourth mirror M8) remain fixed, independent of any variation in the position and orientation of the input radiation beam B_{in} .

[00214] Each of the four mirrors M5, M6, M7, M8 is rotatable. Rotation of the mirrors M5, M6, M7, M8 may be used to correct for position and/or pointing errors of the input radiation beam B_{in} . That is, rotation of the mirrors M5, M6, M7, M8 may be used to ensure that the position and orientation of the radiation beam which is output by the radiation beam expander 250 remain fixed.

[00215] In particular each of the four mirrors M5, M6, M7, M8 is rotatable about an axis which is perpendicular to its direction of curvature (and aligned with its flat direction). The first mirror M5 is rotatable about a first axis R5; the second mirror M6 is rotatable about a second axis R6; the third mirror M7 is rotatable about a third axis R7; and the fourth mirror M8 is rotatable about

a fourth axis R8. The first and second axes R5, R6 are perpendicular to plane P3 and the third and fourth axes R7, R8 are perpendicular to plane P4.

[00216] If the point G on mirror M5 (which represents the point on the first mirror M5 upon which the chief ray is incident) is shifted and/or the direction of the path FG is changed then the mirrors M5, M6, M7, M8 are rotated about their respective axes R5, R6, R7, R8 such that the radiation beam hits the fourth mirror M8 at a nominal position in space (point J in Figure 11) and such that the output radiation beam B_{out} is pointing in a nominal direction (line JK in Figure 11).

[00217] Note that when the input radiation beam B_{in} is not aligned with the nominal path FG, the path followed by the radiation beam within the radiation beam expander 250 will not be the nominal path shown in Figure 11. However, by suitable orientation of the four mirrors M5, M6, M7, M8 it is possible to ensure that the output radiation beam B_{out} has a fixed position and direction (along line JK in Figure 11).

[00218] A curvature of each of the four mirrors M5, M6, M7, M8 is independently adjustable as now described. The optical power of each mirror is the degree to which it increases (or decreases) the divergence of a radiation beam. The optical power of each of the four mirrors M5, M6, M7, M8 is independently adjustable by varying its curvature. A suitable mechanism for altering the curvature of the mirrors M5, M6, M7, M8 is described above with reference to Figure 10. Each of the four mirrors M5, M6, M7, M8 is provided with a mechanism as shown in Figure 10, or a similar mechanism, which allows the curvature of that mirror along its curvature directions to be controlled.

[00219] As discussed above, when a radiation beam is incident upon an optical element with circular geometry (e.g. a cylindrical or toroidal mirror) at a grazing incidence angle of β , if one of the principal axes of the optical element is aligned with the major axis of the beam spot region then the focal length f is given by $f=\beta/(2K)$, where K is the curvature of the surface of the mirror in direction of that principal axis. However, if one of the principal axes of the optical element is aligned with the minor axis of the beam spot region then the focal length f is given by $f=1/(2\beta K)$, where K is the curvature of the surface of the mirror in direction of that principal axis. Therefore, if the principal axis of the mirror is aligned with the major axis then the required curvature K (or change in curvature) for a given focal length is smaller than the required curvature K (or change in curvature) when the principal axis of the mirror is aligned with the minor axis (by a factor of β^2). It is for this reason that each of the four mirrors M5, M6, M7, M8 is arranged relative to the radiation beam such that its curvature direction is generally aligned with the major axis of the beam spot region formed on its surfaces.

[00220] Since each of the four mirrors M5, M6, M7, M8 has an adjustable curvature the focal length of each mirror can be independently varied. This provides simultaneous control over the divergence and diameter of the output radiation beam B_{out} without having to move the diverging optic (i.e. mirrors M5, M7) relative to the converging optic (i.e. mirrors M6, M8), as described below.

[00221] As explained above, position and pointing errors of the input radiation beam B_{in} may be corrected for by rotating the four mirrors M5, M6, M7, M8. However, such rotations of the mirrors M5, M6, M7, M8 will affect their focal lengths (since these are dependent on the grazing incidence angle of the beam on each mirror). As a result of this variation in the focal lengths of mirrors M5, M6, M7, M8 when the input radiation beam B_{in} entering the radiation beam expander 250 does not propagate along the nominal input path FG the first virtual source may not coincide with the focal point of the second mirror M6; and the second virtual source may not coincide with the focal point of the fourth mirror M8. With such an arrangement the output radiation beam B_{out} leaving the fourth mirror M8 will not be collimated.

[00222] As explained above, one potential arrangement for expanding a radiation beam and correcting for position and pointing errors may use two separate optical systems: one to expand the beam and one to correct for pointing and position errors (for example, two flat, rotatable mirrors). Such an arrangement requires at least four mirrors (two flat mirrors and two with double curvature). Furthermore, such an arrangement with only four mirrors cannot for time dependent variations in the initial divergence of the input radiation beam and cannot provide control over the diameter of the output radiation beam. As now described, the radiation beam expander 250 can achieve the function of expanding and collimating the radiation beam and correcting for position and pointing errors with four mirrors M5, M6, M7, M8. Furthermore, radiation beam expander 250 can correct for time dependent variations in the initial divergence of the input radiation beam and provides control over the diameter of the output radiation beam.

[00223] In order to correct for variation in the focal lengths of the mirrors M5, M6, M7, M8 of radiation beam expander 250 caused by rotation of the mirrors M5, M6, M7, M8, the curvature of one or more of the mirrors M5, M6, M7, M8 can be simultaneously varied to ensure that the first and second virtual sources do coincide with the focal points of the second and fourth mirrors M6, M8 respectively. Therefore, the controller CN may be arranged to simultaneously control both: (a) the orientation of the mirrors M5, M6, M7, M8; (b) the curvatures of mirrors M5, M7; and (c) the curvature of mirrors M6, M8.

[00224] Adjustment of the curvature of the mirrors M5, M6, M7, M8 may also be used to correct for variations in the divergence of the input radiation beam B_{in} .

[00225] It is possible to ensure that the first virtual source coincides with the focal point of the second mirror M6 by only adjusting the curvature of one of the first and second mirrors M5, M6. However, with such an arrangement (which is similar to the radiation beam expander 200 of Figure 5) it is not possible to control the size of the output radiation beam in the first direction.

5 By providing control over the curvature of both the first and second mirrors M5, M6, the size of the output radiation beam in the first direction can be controlled. Similarly, it is possible to ensure that the second virtual source coincides with the focal point of the fourth mirror M8 by only adjusting the curvature of one of the third and fourth mirrors M7, M8. However, with such an arrangement (which is similar to the radiation beam expander 200 of Figure 5) it is not
10 possible to control the size of the output radiation beam in the second direction. By providing control over the curvature of both the third and fourth mirrors M7, M8, the size of the output radiation beam in the second direction can be controlled.

[00226] The above described embodiment of a radiation beam expander 250 is advantageous since it provides simultaneous control over the position, direction, divergence and diameter of
15 the beam. The position of the radiation beam may be specified by two parameters (the position in the x and y directions) and therefore represents two degrees of freedom. The direction of the radiation beam may be specified by two parameters (two pointing angles) and therefore represents two degrees of freedom. In general the radiation beam will be elliptical in cross section, having a different divergence along each of the major and minor axes of its cross
20 section. Therefore, the divergence of the radiation beam may be specified by two parameters (the divergence along each of the major and minor axes) and represents two degrees of freedom. The size of the radiation beam may be specified by two lengths, which each define the size of the radiation beam along each of its major and minor axes. Therefore, the simultaneous control over the position, direction, divergence and diameter of the beam allows
25 eight degrees of freedom in the parameters of an input radiation beam B_{in} to be controlled. Note that radiation beam expander 250 has eight actuators (each of the mirrors M5, M6, M7, M8 is rotatable about its axis R5, R6, R7, R8; and the curvature of each of the mirrors M5, M6, M7, M8 is adjustable) and can compensate for variations in eight degrees of freedom in the parameters of an input radiation beam B_{in} . Therefore radiation beam expander 250 is not
30 provided with any excess or redundant degrees of freedom in actuation.

[00227] In the above described embodiment radiation beam expander 250 the first and second mirrors M5, M6 act to expand and collimate the radiation beam in the first direction and the third and fourth mirrors M7, M8 act to expand and collimate the radiation beam in the second direction. However, in alternative embodiments, the mirrors may be arranged in a different

order. For example, the first and third mirrors may expand and collimate the radiation beam in the first direction while the second and fourth mirrors may expand and collimate the radiation beam in the second direction. Alternatively, the first and fourth mirrors may expand and collimate the radiation beam in the first direction while the second and third mirrors may expand and collimate the radiation beam in the second direction.

[00228] In the first embodiment of a radiation beam expander 200 described above, the diverging optic comprises two separate mirrors (M1, M2) which are each provided with an adjustable curvature in a different direction (in the x-y plane). The converging optic comprises a single mirror (M3) which is provided with curvature in two different directions. In a variant of this embodiment, the diverging optic may alternatively comprise a single mirror which is curved in two different directions and the converging optic may alternatively comprise two separate mirrors which are each provided with an adjustable curvature in a different direction (in the x-y plane).

[00229] The term “grazing incidence angle” refers to the angle between the propagation direction of an incident radiation beam and a tangent to the reflective surface at the point that it is incident upon. The term “angle of incidence” refers to the angle between the propagation direction of an incident radiation beam and a normal to the reflective surface at the point that it is incident upon. The grazing incidence angle is complementary to the angle of incidence, i.e. the sum of the grazing incidence angle and the angle of incidence is a right angle. It will be appreciated that for a divergent radiation beam, in general, each ray of the beam may propagate in a different direction. For such divergent radiation beams the propagation direction of the radiation beam may be taken to be the central or chief ray of the radiation beam.

[00230] The “optical power” of an optical element is the reciprocal of its focal length and is a measure of how much the optical element diverges or converges an incident radiation beam.

[00231] Whilst embodiments of a radiation source SO have been described and depicted as comprising a free electron laser FEL, it should be appreciated that a radiation source may comprise any number of free electron lasers FEL. For example, a radiation source may comprise more than one free electron laser FEL. For example, two free electron lasers may be arranged to provide EUV radiation to a plurality of lithographic apparatus. This is to allow for some redundancy. This may allow one free electron laser to be used when the other free electron laser is being repaired or undergoing maintenance.

[00232] Lithographic system LS may comprise any number of lithographic apparatus. The number of lithographic apparatus which form a lithographic system LS may, for example, depend on the amount of radiation which is output from a radiation source SO and on the

amount of radiation which is lost in a beam delivery system BDS. The number of lithographic apparatus which form a lithographic system LS may additionally or alternatively depend on the layout of a lithographic system LS and/or the layout of a plurality of lithographic systems LS.

[00233] Embodiments of a lithographic system LS may also include one or more mask inspection apparatus MIA and/or one or more Aerial Inspection Measurement Systems (AIMS). In some embodiments, the lithographic system LS may comprise a plurality of mask inspection apparatuses to allow for some redundancy. This may allow one mask inspection apparatus to be used when another mask inspection apparatus is being repaired or undergoing maintenance. Thus, one mask inspection apparatus is always available for use. A mask inspection apparatus may use a lower power radiation beam than a lithographic apparatus. Further, it will be appreciated that radiation generated using a free electron laser FEL of the type described herein may be used for applications other than lithography or lithography related applications.

[00234] The term “relativistic electrons” should be interpreted to mean electrons which have relativistic energies. An electron may be considered to have a relativistic energy when its kinetic energy is comparable to or greater than its rest mass energy (511 keV in natural units). In practice a particle accelerator which forms part of a free electron laser may accelerate electrons to energies which are much greater than its rest mass energy. For example a particle accelerator may accelerate electrons to energies of >10 MeV, >100 MeV, >1GeV or more.

[00235] Embodiments of the invention have been described in the context of a free electron laser FEL which outputs an EUV radiation beam. However a free electron laser FEL may be configured to output radiation having any wavelength. Some embodiments of the invention may therefore comprise a free electron which outputs a radiation beam which is not an EUV radiation beam.

[00236] The term “EUV radiation” may be considered to encompass electromagnetic radiation having a wavelength within the range of 4-20 nm, for example within the range of 13-14 nm. EUV radiation may have a wavelength of less than 10 nm, for example within the range of 4-10 nm such as 6.7 nm or 6.8 nm.

[00237] The lithographic apparatuses LA_a to LA_n may be used in the manufacture of ICs. Alternatively, the lithographic apparatuses LA_a to LA_n described herein may have other applications. Possible other applications include the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc.

[00238] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

[00239] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope
5 of the claims set out below.

CLAIMS:

1. A radiation beam expander comprising:

a diverging optic for receiving a radiation beam and increasing a divergence of the radiation beam, said diverging optic comprising one or more mirrors; and

a converging optic arranged to receive the radiation beam and to reduce the divergence of the radiation beam, said converging optic comprising one or more mirrors;

wherein at least one of the one or more mirrors of the diverging optic and/or the converging optic is provided with an actuator arranged to control a curvature of the mirror.

2. The radiation beam expander of any preceding claim, further comprising:

a sensor apparatus operable to determine the divergence of the radiation beam after the diverging and converging optics; and

a controller operable to control the curvature of one or more of the mirrors of the diverging and/or converging optic in response to the divergence determined by the sensor apparatus.

3. The radiation beam expander of claim 2, wherein the controller is arranged to control the curvature of one or more of the mirrors of the diverging and/or converging optic so that after the diverging and converging optics the radiation beam is collimated.

4. The radiation beam expander of any preceding claim, wherein one or more of the one or more mirrors of each of the diverging and converging optics is provided with an actuator operable to rotate said mirror about one or more axes of rotation so as to control its orientation.

5. The radiation beam expander of claim 4,

wherein the sensor apparatus is operable to determine the position and/or direction of the radiation beam after it leaves the converging optic; and

wherein the controller is operable to control an orientation of one or more of the mirrors of the diverging and converging optics in response to the position and/or direction determined by the sensor apparatus so as to control the position and/or direction of the radiation beam after it leaves the converging optic.

6. The radiation beam expander of claim 5, wherein in response to the divergence, position and/or direction determined by the sensor apparatus the controller is arranged to simultaneously control: (i) the orientation of one or more of the mirrors of the diverging and/or converging optics; and (ii) the curvature of one or more of the mirrors of the diverging and/or converging optic.

7. The radiation beam expander of any preceding claim, wherein more than one curvature of the one or more mirrors of the diverging optic is controllable, such that the diverging optic is operable to independently control the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam.

8. The radiation beam expander of any preceding claim, wherein more than one curvature of the one or more mirrors of the converging optic is controllable, such that the converging optic is operable to independently control the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam.

9. The radiation beam expander of claim 7 or claim 8, wherein the diverging optic comprises: a first mirror (M1, M5) for receiving the radiation beam and increasing the divergence of the radiation beam in the first direction; and a second mirror (M2, M7) arranged to receive the radiation beam from the first mirror and to increase a divergence of the radiation beam in a second direction in a plane perpendicular to a propagation path of the radiation beam, wherein a curvature of each of the first and second mirrors is independently adjustable.

10. The radiation beam expander of claim 9, wherein the first mirror (M1, M5) has a convex, cylindrical-like reflective surface with a first curvature in a first principal direction and a zero curvature in a second principal direction.

11. The radiation beam expander of claim 9 or claim 10, wherein the second mirror (M2, M7) has a convex, cylindrical-like reflective surface with a second curvature in a first principal direction and a zero curvature in a second principal direction.

12. The radiation beam expander of any one of claims 9 to 11, wherein the converging optic comprises a concave, toriodal-like mirror (M3) which has a third curvature in the first direction and a fourth curvature in the second direction.

13. The radiation beam expander of any one of claims 9 to 11, wherein the converging optic comprises: a first concave, cylindrical-like mirror (M6) which has a third curvature in the first direction; and a second concave, cylindrical-like mirror (M8) which has a fourth curvature in the second direction.

14. A radiation beam expander comprising:

a diverging optic for receiving a radiation beam and increasing a divergence of the radiation beam, the diverging optic being astigmatic such that it increases the divergence of the radiation beam in first and second directions in a plane perpendicular to a propagation path of the radiation beam by different amounts;

a converging optic arranged to receive the radiation beam and to reduce the divergence of the radiation beam, the converging optic being astigmatic such that it decreases the divergence of the radiation beam in the first and second directions by different amounts;

a sensor apparatus operable to determine the divergence of the radiation beam after the diverging and converging optics; and

a controller;

wherein at least one of the diverging optic and the converging optic is adjustable such that its optical power in each of the first and second directions is independently adjustable and wherein the controller is operable to control the optical power of that optic in the first and/or second directions in response to the divergence determined by the sensor apparatus.

15. A radiation system for a lithographic system comprising:

a radiation source operable to produce a radiation beam; and

the beam expander of any preceding claim arranged to receive the radiation beam from the radiation source and to increase its cross sectional area so as to provide an output beam.

16. The radiation system of claim 15, wherein the radiation source is operable to produce an astigmatic radiation beam, having a different divergence in each of two mutually perpendicular directions in a plane perpendicular to a propagation path of the radiation beam.

17. The radiation system of claim 16, wherein the radiation beam is elliptical in cross section, the cross section of the radiation beam having a major axis and a minor axis.

18. The radiation system of claim 17, wherein the radiation beam has a first divergence in a direction of the major axis and a second divergence in a direction of the minor axis.

5 19. The radiation system of claim 18 when dependent on any one of claims 7, 8 or 14, wherein the radiation source and the radiation beam expander are arranged such that the major axis of the radiation beam is aligned with one of the first and second directions and the major axis of the radiation beam is aligned with the other of the first and second directions.

10 20. A lithographic system comprising:
the radiation system of any one of claims 15 to 19;
one or more lithographic tools; and
a beam delivery system arranged to deliver at least a portion of the expanded radiation beam to at least one of the one or more lithographic tools.

1 / 8

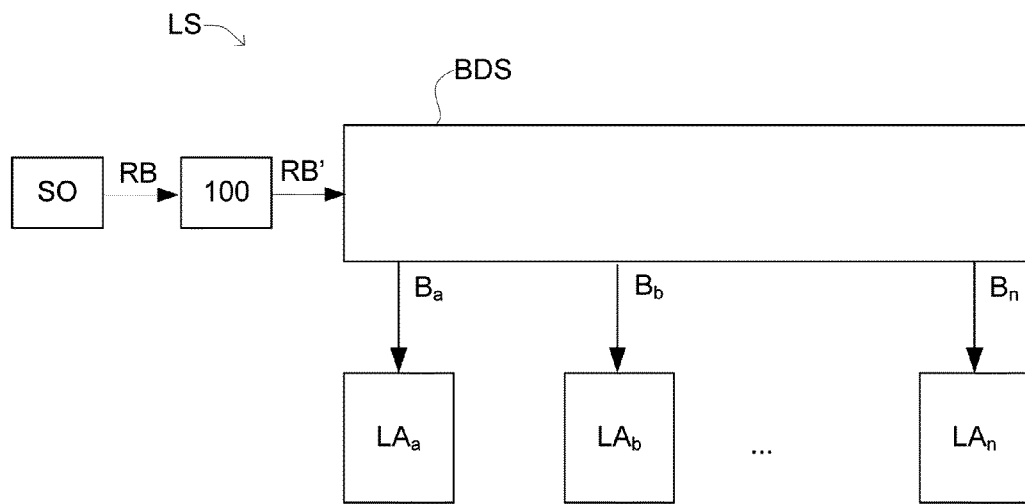


Fig. 1

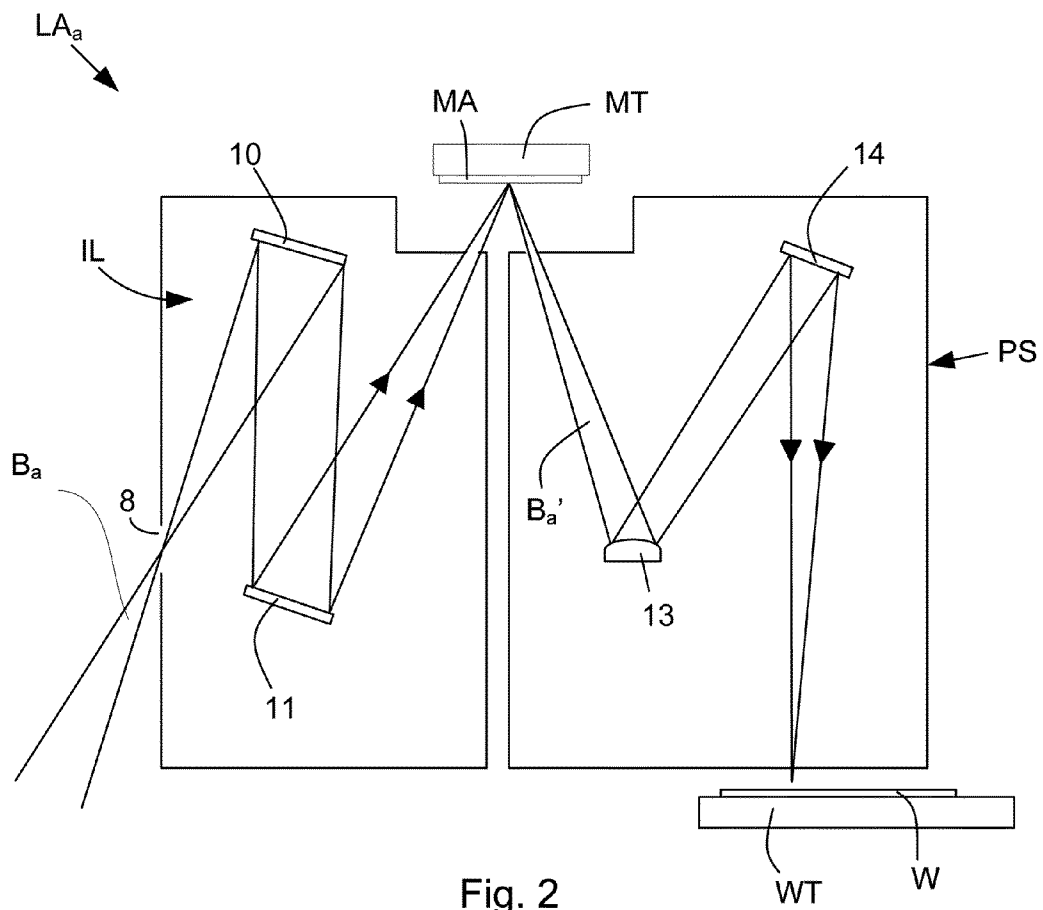


Fig. 2

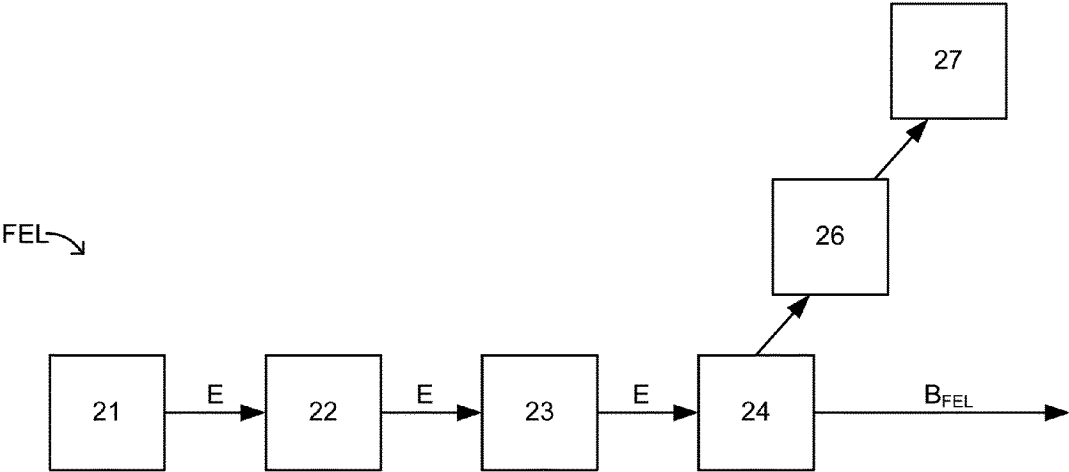


Fig. 3

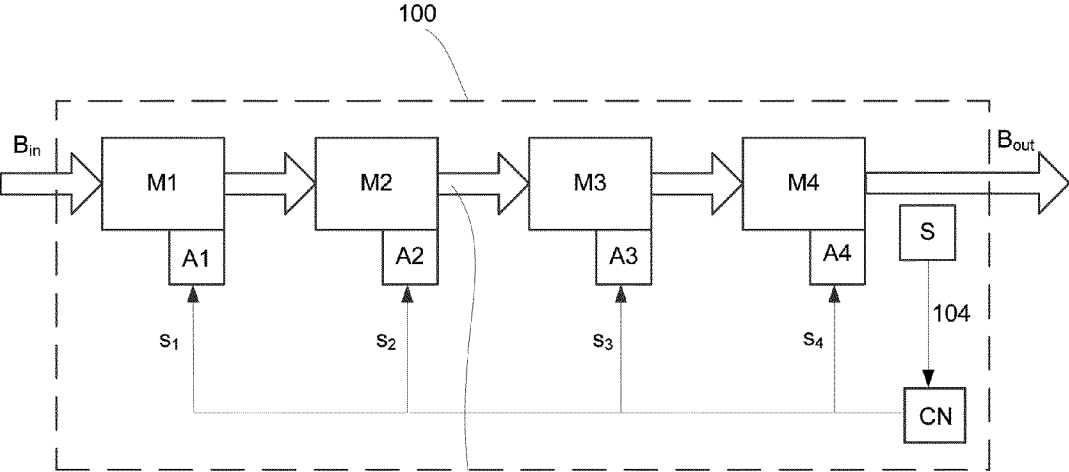


Fig. 4

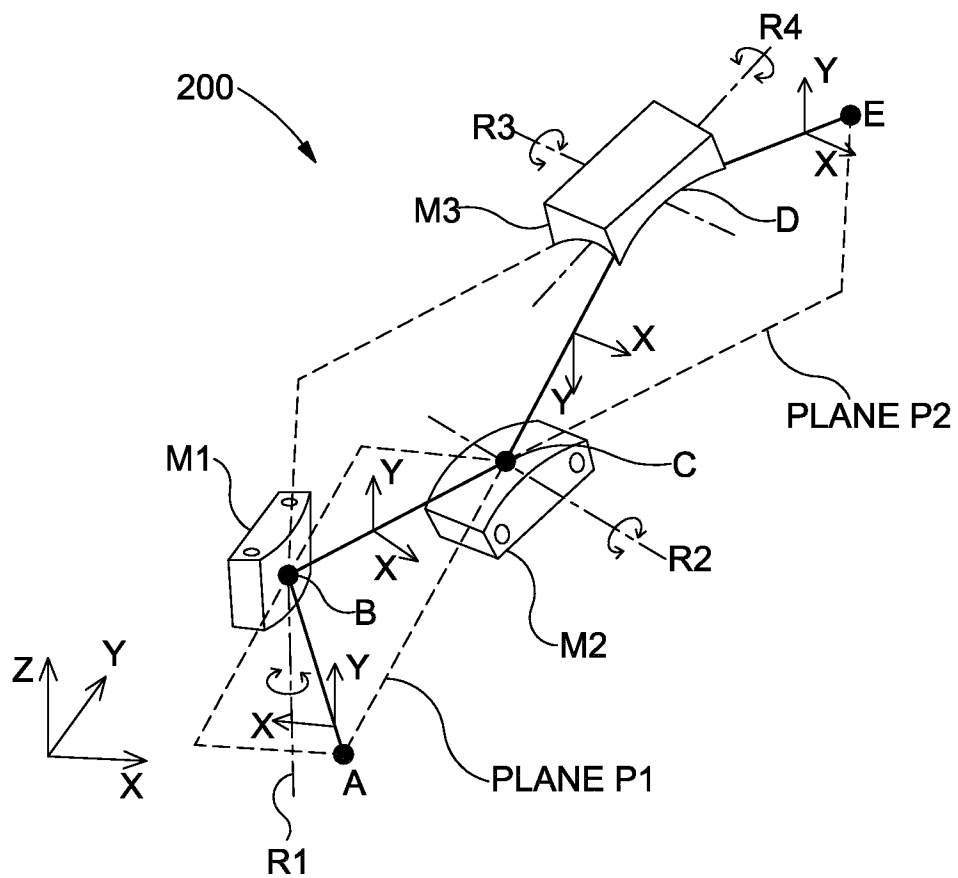


Fig. 5

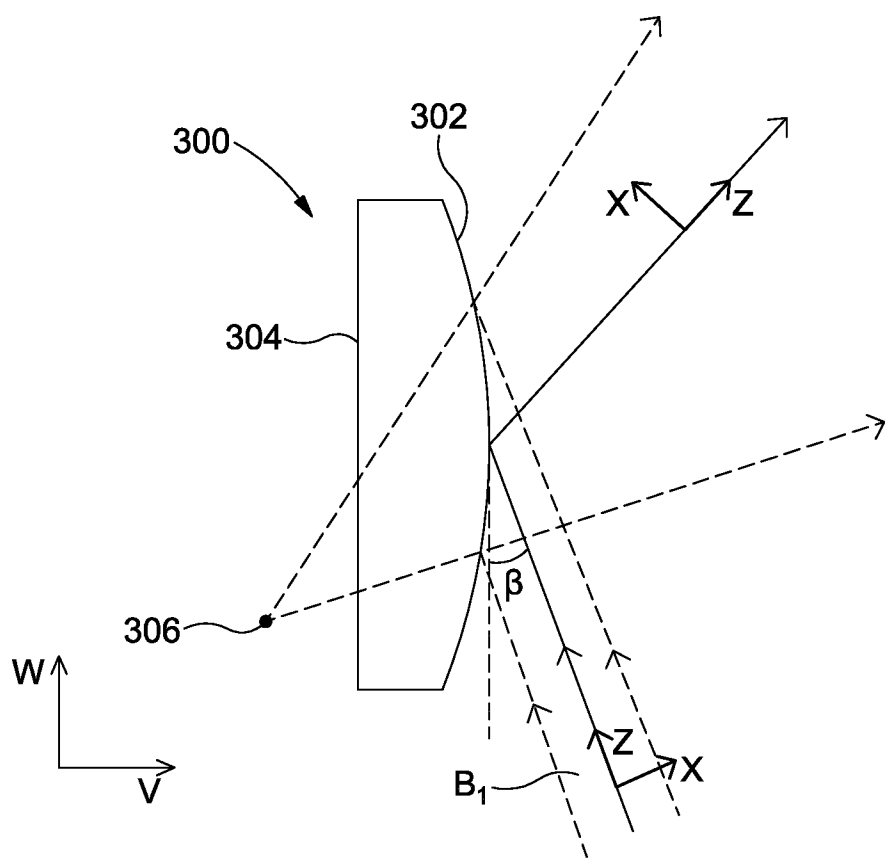


Fig. 6a

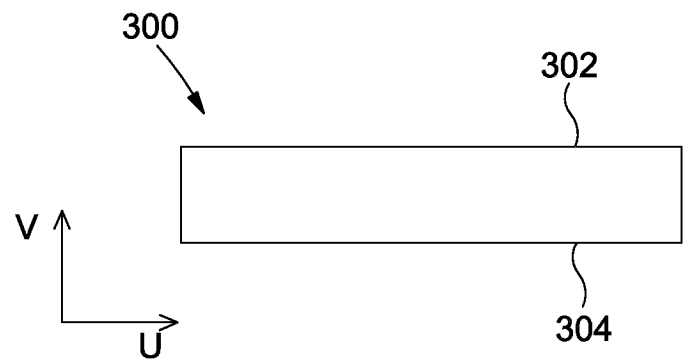


Fig. 6b

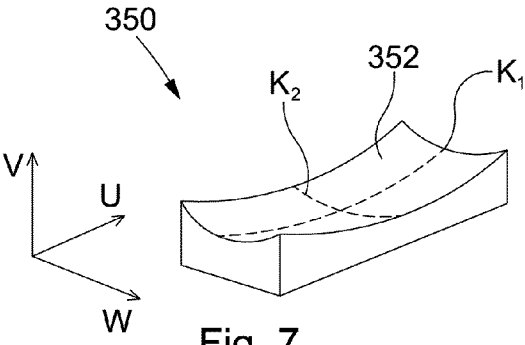


Fig. 7

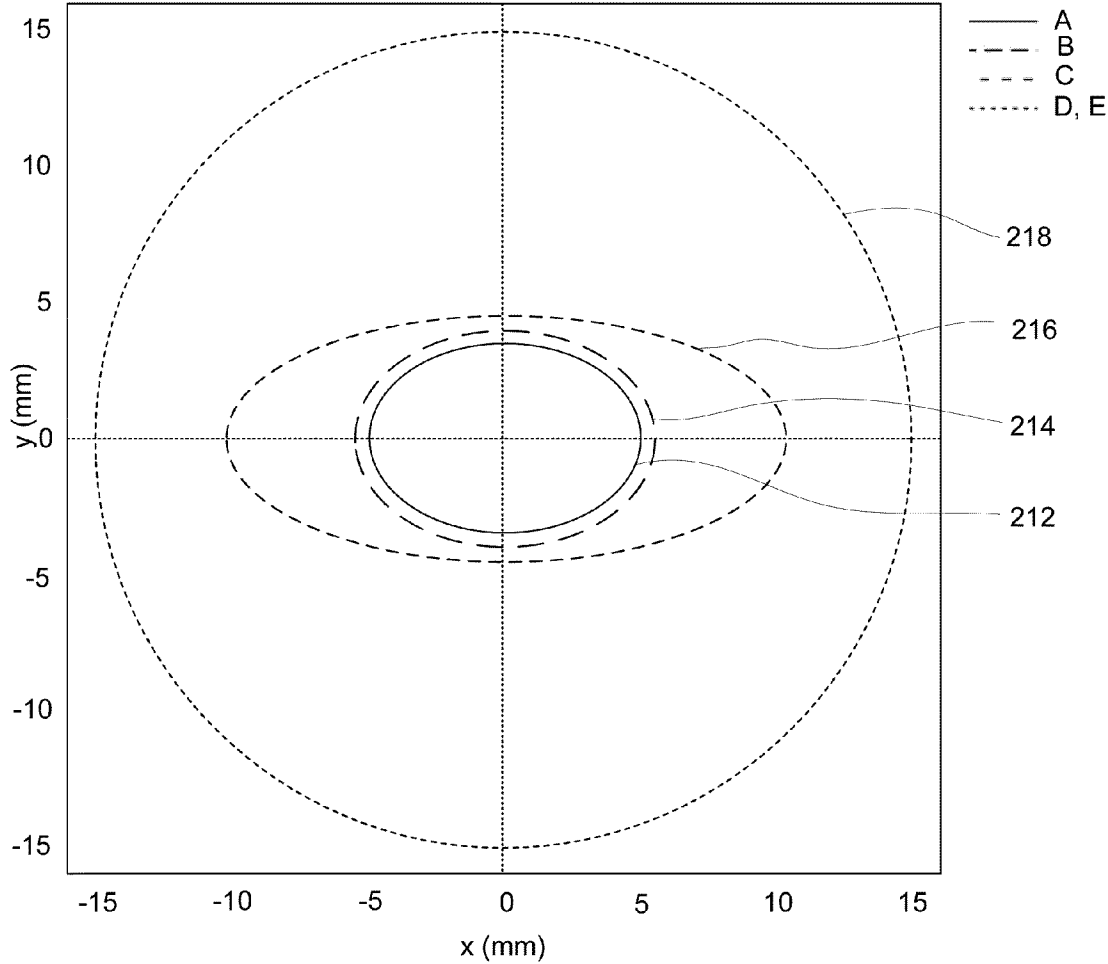
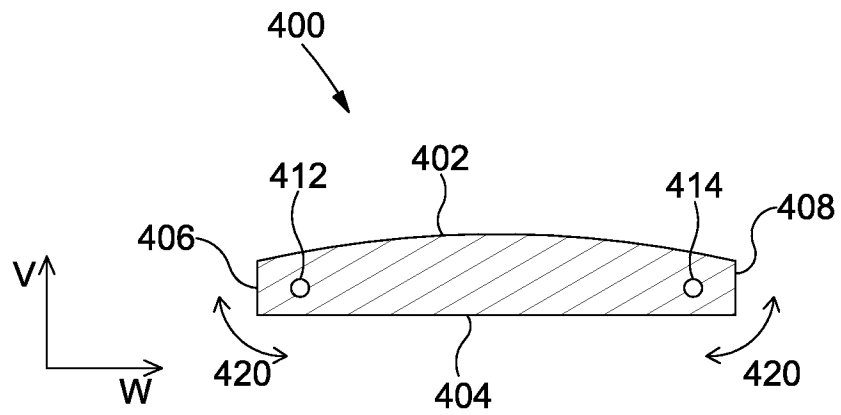
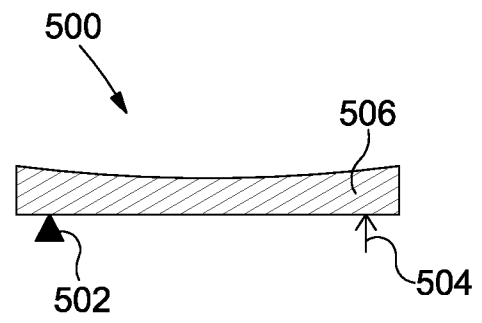
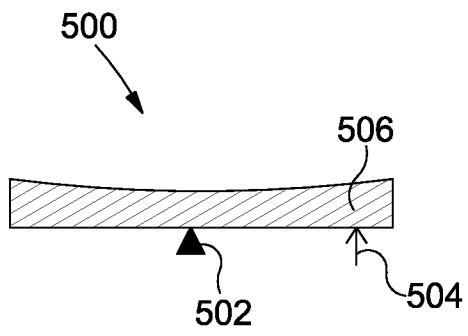


Fig. 8



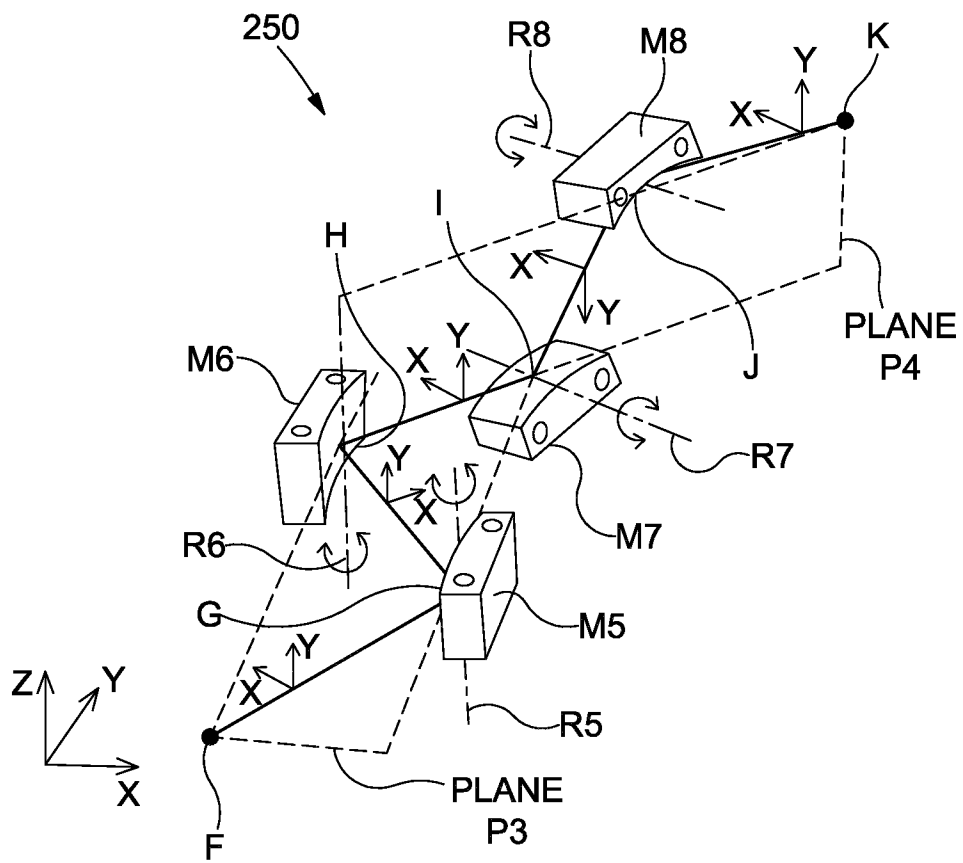


Fig. 11

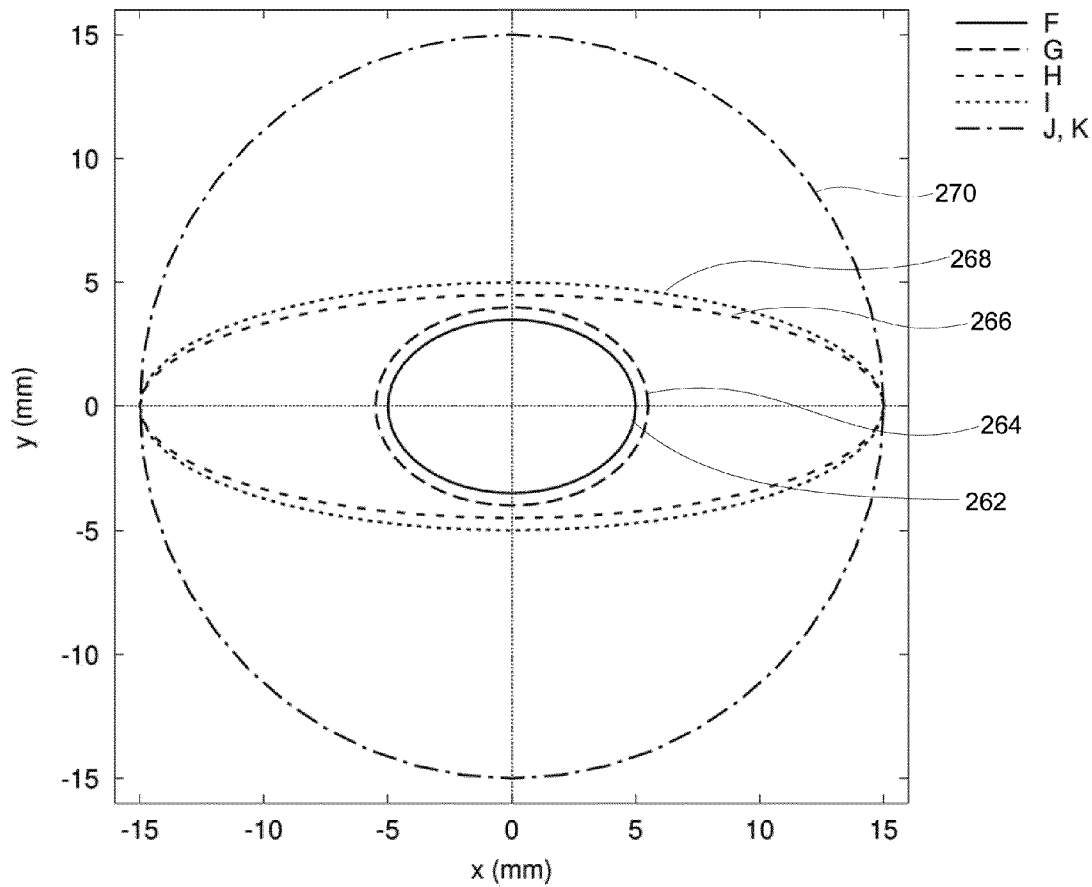


Fig. 12