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(54) Optical Element

(57) An optical element for receiving an input radiation beam and outputting an output radiation beam, the optical element comprises: a first member, a second member, a distortion mechanism and a controller. The first member has an optical surface for receiving the input radiation beam and a second surface opposite to the optical surface. The second member comprises a plurality of protrusions for contacting the second surface of the first member. The distortion mechanism is operable to locally alter a curvature of the optical surface in the vicinity of each protrusion. The controller is operable to control the curvature of the optical surface in the vicinity of each of the protrusions. The optical element provides an optical surface that can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions. This provides control over properties of the output radiation beam.

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Optical Element

FIELD

[0001] The present Invention relates to an optical element for receiving an input radiation beam and outputting an output radiation beam. In particular, the present invention may relate to such an optical element which is adjustable so as to provide some control over the angular distribution of the output radiation beam. The optical element may form part of a lithographic system.

BACKGROUND

[0002] 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.

[0003] 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).

[0004] 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. The beam delivery system may be arranged to deliver radiation from one or more of the radiation sources to each of the lithographic apparatus. It may be desirable to provide some control over properties of the radiation delivered to each lithographic apparatus. Such properties may include, for example, the intensity distribution and the size of a radiation beam delivered to the lithographic apparatus. In particular, it may be desirable to provide control over such properties of the radiation beam that can operate at relatively high bandwidths. For example, it may be desirable to control the properties of the radiation beam more quickly than a typical exposure time of the lithographic system.

[0005] It is an object of the present invention to obviate or mitigate at least one problem of prior art techniques.

SUMMARY

[0006] According to a first aspect of the invention there is provided an optical element for receiving an input radiation beam and outputting an output radiation beam, the optical element comprising: a first member having an optical surface for receiving the input radiation beam, and a second surface opposite to the optical surface; a second member comprising a plurality of protrusions for contacting the second surface of the first member; a distortion mechanism operable to locally alter a curvature of the optical surface in the vicinity of each protrusion; and a controller operable to control the curvature of the optical surface in the vicinity of each of the protrusions.

[0007] The first aspect of the invention provides an arrangement whereby the optical surface can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions. The topology of the optical element is therefore dependent on that of the plurality of protrusions. The plurality of protrusions provide some support for the first member and allow the optical surface to be distorted in a controlled way. The plurality of protrusions causes a modulation of the optical surface, causing it to be rippled or bumpy. A spacing, pitch or frequency of the modulation of the optical surface is determined by the spacing, pitch or frequency of the plurality of protrusions. The amplitude of the modulation of the optical surface can be controlled by the controller.

[0008] The angular distribution of the output radiation beam is dependent on the ratio of the pitch of the modulation to the amplitude of the modulation. Therefore, the first aspect provides some control over the angular distribution of the output radiation beam. In turn, this provides some control over the intensity distribution and diameter of the output radiation beam. Furthermore, the first aspect of the invention provides a simple arrangement that achieves this control. For example, control over the angular distribution of the output radiation beam may be achieved using an optical element comprising an array of independently moveable mirrors. The independently moveable mirrors may for example be microelectromechanical systems (MEMS) devices. However, such an arrangement is significantly more complicated than the arrangement provided by the first aspect of the invention. The optical element of the first aspect can therefore be operated at relatively high bandwidths. For example, the optical element may form part of a lithography system and the controller may be operable to control the curvature of the optical surface more quickly than a typical exposure time of the lithography system. This allows the optical element to be used for dose control and/or to at least partially reduce the effects of speckle on an image formed by the lithography system.

[0009] The first member may comprise a layer of piezoelectric material and the distortion mechanism may be operable to apply a voltage across the optical surface and an uneven surface of the second member formed by a base surface and the plurality of protrusions.

[0010] The protrusions effectively modulate the electric field within the layer of piezoelectric material. In turn, this modulates the stresses within the layer of piezoelectric material and causes a curvature of the optical surface in the vicinity of each protrusion. The piezoelectric material may, for example, comprise monocrystalline silicon or sapphire.

[0011] The distortion mechanism may be operable to urge the plurality of protrusions of the second member into contact with the second surface of the first member such that they exert a force on a region of the first member so as to locally alter a curvature of the optical surface in the vicinity of each protrusion.

[0012] As each protrusion exerts a force on a region of the first member it causes the optical surface in the vicinity of that protrusion to be distorted outwards, so as to form a generally convex portion of the optical surface. The regions of the optical surface in the vicinity of each protrusion form local high points of the optical surface. Regions of the optical surface between adjacent protrusions form local low points of the optical surface and are generally concave. In this way, the plurality of protrusions causes a modulation of the optical surface, causing it to be rippled or bumpy. An amplitude of the modulation of the optical surface is dependent on the force exerted on the first member by each of the protrusions.

[0013] The plurality of protrusions of the second member may be urged into contact with the second surface of the first member via an electrostatic force.

[0014] The distortion mechanism may be operable to apply a voltage across the second surface of the first member and a base of the second member from which the plurality of protrusions extend and wherein at least a portion of the plurality of protrusions comprises an insulating material. The insulating material ensures that the voltage across the second surface of the first member and a base of the second member can be maintained even when the plurality of protrusions is in contact with the second surface. The voltage results in an electrostatic attraction, which urges the plurality of protrusions of the second member into contact with the second surface of the first member.

[0015] The plurality of protrusions of the second member may be urged into contact with the second surface of the first member via a mechanical force.

[0016] The first member may comprise a supporting frame and a membrane, the optical surface may be provided on the membrane and the supporting frame may comprise a plurality of apertures, each aperture for receipt of one of the plurality of protrusions.

[0017] The mechanical force may be applied hydraulically.

[0018] The distortion mechanism may be operable to alter a curvature of the optical surface in the vicinity of each protrusion via an electrostatic repulsion between the plurality of protrusions and the first member.

[0019] Each of the plurality of protrusions may be maintained in fixed relationship to each of the other protrusions.

[0020] Such an arrangement is simple since it allows the curvature at each of the plurality of protrusions to be controlled using a single actuation. As a result, the optical element can be used at relatively high bandwidth.

[0021] Alternatively, the optical element may comprise a plurality of portions and the distortion mechanism may be operable to control a shape of the optical surface in each of the plurality of portions independently.

[0022] The second member may comprise a base from which each of the plurality of protrusions extends.

[0023] A profile of each of the plurality of protrusions in a plane of the second surface may be elongate.

[0024] The plurality of protrusions may be arranged as a one dimensional array. Such an arrangement may be used to control the angular distribution of the output radiation beam in a single direction.

[0025] Alternatively, the plurality of protrusions may be arranged as a two dimensional array. Such an arrangement may be used to control the angular distribution of the output radiation beam in two independent directions.

[0026] The arrangement of the plurality of protrusions may be such that an angular power distribution of the output radiation beam is generally flat.

[0027] It will be appreciated that a generally flat distribution may be of the form of a top hat distribution or, alternatively, a generally flat distribution may include distributions that comprise a generally flat central portion and which falls off on either side of the central portion. Such a flat angular power distribution is advantageous because it spreads the power of the radiation beam over a larger area and this can spread a heat load on a mirror which receives the output radiation beam over a larger area. This is especially beneficial for mirrors at, or close to, focal points of the radiation beam.

[0028] The arrangement of the plurality of protrusions may be such that an angular power distribution of the output radiation beam falls off towards the edge of the field.

[0029] The distortion mechanism may be operable to locally alter a curvature of the optical surface in the vicinity of each protrusion with a bandwidth of 1 kHz or higher.

[0030] The optical element may further comprise a mechanism for providing a flow of gas between the first member and the second member. The gas may, for example, comprise hydrogen. This mechanism may provide cooling to the optical element and may remove heat deposited by a radiation beam incident on the optical surface.

[0031] The optical element may comprise a grazing incidence mirror.

[0032] The optical element may be suitable for receiving an EUV radiation beam. For example, the optical surface of the element may be provided with a layer of material with a relatively high reflectance for EUV radiation. Suitable materials may include, for example, molybdenum and ruthenium.

[0033] According to a second aspect of the invention there is provided a lithographic apparatus comprising: an optical element according to any preceding clause; an illumination system configured to condition the output radiation beam of the optical element; a support structure constructed to support a patterning device, the patterning device being capable of imparting the output radiation beam with a pattern in its cross-section to form a patterned radiation beam; a substrate table constructed to hold a substrate; and a projection system configured to project the patterned radiation beam onto the substrate.

[0034] According to a third aspect of the invention there is provided a lithographic system comprising: a radiation source operable to produce a radiation beam; one or more lithographic apparatuses; and at least one optical element according to the first aspect of the invention, said optical element being arranged to receive at least a portion of the radiation beam produced by the radiation source and to provide the output radiation beam of the optical element to at least one of the one or more lithographic apparatuses.

[0035] The optical element may be arranged to receive the at least a portion of the radiation beam produced by the radiation source at a grazing incidence angle.

[0036] The grazing incidence angle may be less than 5 degrees.

[0037] The radiation beam may comprise EUV radiation.

[0038] According to a fourth aspect of the invention there is provided a method for forming an image, the method comprising: providing a radiation beam; reflecting the radiation beam using an optical element; imparting a pattern to the radiation beam; and projecting the patterned radiation beam onto a target portion of a substrate, each part of the target region being exposed for an exposure time; wherein a curvature of the optical element is varied through a range of different curvatures during exposure of the substrate, a frequency of the variation being such that the curvature varies through the entire range of different curvatures at least once during the exposure time.

[0039] Such an arrangement is beneficial because it can reduce the effect of speckle on the image formed on the target region of the substrate. The speckle caused by self-interference of the radiation beam after diffuse reflection from the optical element is dependent on the curvature of the optical element. By varying the curvature of the optical element the speckle varies with time. Since a frequency of the variation is such that the curvature varies through the entire range of different curvatures at least once during the exposure time, the speckle pattern should be at least partially smoothed out.

[0040] The frequency of the variation of the curvature of the optical element through the range of different curvatures may be such that the curvature varies through the entire range of different curvatures at least ten times during the exposure time.

[0041] The optical element may be the optical element of the first aspect of the invention.

[0042] The radiation beam may be reflected from the optical element at a grazing incidence angle of less than 5 degrees.

[0043] The radiation beam may comprise EUV radiation.

[0044] 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

[0045] 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 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 bending optics that are arranged to bend a branch radiation beam so as to change its direction from a generally horizontal to a generally vertical direction for delivery to a lithographic apparatus;
- Figure 4 is a schematic illustration of a free electron laser that may form part of the lithographic system of Figure 1;
- Figure 5 is a schematic illustration of a first embodiment of an adjustable optical element;

- Figure 6 is a schematic illustration of a second embodiment of an adjustable optical element;
- Figure 7 shows a plan view of part of a first embodiment of a second member of the optical element of either Figure 5 or Figure 6, showing protrusions and a base surface;
- Figure 8 shows a plan view of part of a second embodiment of a second member of the optical element of either Figure 5 or Figure 6, showing protrusions and a base surface;
- Figure 9A shows a first member of the optical element of Figure 9B;
- Figure 9B is a schematic illustration of a third embodiment of an adjustable optical element;
- Figure 10A shows a cross sectional view of a first embodiment of the first member of Figure 9A through the line A-A;
- Figure 10B shows a cross sectional view of a second embodiment of the first member of Figure 9A through the line A-A; and
- Figure 11 shows the angular power distribution of a radiation beam output by an optical element which comprises a modulated surface, for three different modulations of the optical surface.

DETAILED DESCRIPTION

[0046] Figure 1 shows a lithographic system LS according to one embodiment of the invention. The lithographic system LS comprises a radiation source SO, 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 (which may be referred to as a main beam).

[0047] 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.

[0048] The beam delivery system BDS may comprise beam expanding optics that are arranged to increase a cross section of the main radiation beam RB and/or the branch radiation beams B_a-B_n. Advantageously, this decreases the heat load on mirrors downstream of the beam expanding optics, for example mirrors within the lithographic apparatus LA_a-LA_n. This may allow these mirrors 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.

[0049] 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.

[0050] The radiation source SO, 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).

[0051] The radiation source SO may be arranged such that the main radiation beam RB propagates generally horizontally. The lithographic apparatus LA_a-LA_n may be arranged to accept a branch radiation beam B_a-B_n that propagates in a generally vertical direction. Therefore, the beam delivery system BDS may comprise bending optics that are arranged to bend each branch radiation beam B_a-B_n so as to change its direction from a generally horizontal to a generally vertical direction. The bending optics may comprise a plurality of grazing incidence mirrors that are collectively arranged to bend a branch radiation beam through an angle of around 90°.

[0052] Figure 2 shows a lithographic apparatus LA_a, which 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.

[0053] 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 though an opening 8 in an enclosing structure of the illumination system IL. The branch radiation beam B_a is focused to form an intermediate focus 9 at or near to the opening 8.

[0054] The illumination system IL may include a facetted field mirror device 10 and a facetted 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.

[0055] 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).

[0056] 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).

[0057] Figure 3 schematically shows bending optics that are arranged to bend branch radiation beam B_a so as to change its direction from a generally horizontal to a generally vertical direction. The branch radiation beam B_a propagates through a vacuum chamber defined by walls 19. The vacuum chamber can be isolated from the external environment and is arranged to support a vacuum so as to minimise the absorption of EUV radiation. For reference, a portion of a generally horizontal floor 15 is shown in Figure 3.

[0058] The bending optics comprises three grazing incidence mirrors 16, 17, 18 that are collectively arranged to bend a branch radiation beam B_a through an angle of around 90°. Two of the mirrors are shown here as generally flat grazing incidence mirrors 16, 17. The third mirror 18 is a grazing incidence collector, which is arranged to focus the branch radiation beam B_a at the intermediate focus 9. Although shown schematically as a single mirror, the third mirror 18 may comprise a plurality of curved mirrors. In cross section the one or more mirrors that form third mirror 18 may be conic sections, that is the cross sectional shape of the one or more mirrors may be parabolic, elliptical or hyperbolic.

[0059] It will be appreciated that a grazing incidence mirror is a mirror arranged to receive a radiation beam at a relatively small grazing incidence angle. For example, the grazing incidence angle may be less than 5 ° and may be less than 3° or less than 1°.

[0060] The lithographic apparatus LA_a may be arranged such that it can accept radiation from different radiation sources. In particular, the illuminator IL may be arranged such that it can receive radiation from a laser produced plasma (LPP) radiation source, for example from a near-normal incidence radiation collector. This provides a more versatile lithographic apparatus LA_a that can be used interchangeably with a plurality of different types of radiation source as required or desired.

[0061] 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.

[0062] Figure 4 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.

[0063] The injector 21 is arranged to produce a bunched electron beam E and may comprise an electron source and an electron beam chopper. The electron source may, for example, comprise a thermionic cathode or a photo-cathode arranged to emit electrons and an accelerating electric field arranged to accelerate said electrons so as to form an electron beam. An electron chopper that may form part of the injector 21 is discussed below with reference to Figure 4.

[0064] 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.

[0065] 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.

[0066] 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.

[0067] 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.

[0068] 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:

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

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:

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

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.

[0069] 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 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.

[0070] 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 achieved when the resonance condition is met or when conditions are close to but slightly off resonance.

[0071] 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 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 though 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 of the undulator 24 (by varying the parameter A) within each undulator module and/or from module to module.

[0072] 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 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 region.

[0073] 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.

[0074] 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 μrad.

[0075] 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.

[0076] 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.

[0077] 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. The beam steering unit may include a transverse beam position sensor.

[0078] 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).

[0079] 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.

[0080] 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.

[0081] 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 approximately 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).

[0082] 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.

[0083] The etendue of a radiation beam in free space (i.e. a medium with a refractive index of 1) at an infinitesimal surface element dS in an optical system is given by the product of the area of the surface dS, the solid angle dΩ subtended by radiation crossing (or emitted by) the surface element and the cosine of the angle between the normal to the surface element and the direction of the radiation crossing that point. In general, the etendue of a radiation beam at an extended surface S is given by integrating over the solid angle subtended by radiation crossing (or emitted by) each surface element (to account for the fact that light may cross each point on the surface at a range of angles) and integrating over the surface (to sum the contributions from all such surface elements). For a light source operable to produce a well collimated radiation beam, as is produced by a free electron laser FEL, the etendue of the light source may be estimated by the product of the area of the light source and the solid angle into which light is emitted. Further, for such a light source the solid angle into which light is emitted is given by (using small angle approximations) $\pi\theta^2$, where θ is the half divergence of the light source. Therefore the etendue of such a light source is given by $G=\pi A\theta^2$, where A is the area of the light source. A radiation beam which is emitted from a free electron laser FEL may, for example, have a divergence which is less than about 500 μrad (in some embodiments the divergence may be less than about 100 μrad) and may have a diameter of around 50 μm to 100 μm at its beam waist, as it leaves the undulator 24. In an embodiment in which the beam waist diameter is 50 μm and the beam divergence is 100 μrad the etendue of the radiation beam is around 1.5×10^{-11} mm^2.

[0084] In some embodiments a free electron laser FEL may emit a radiation beam which has a Gaussian-like intensity profile. The etendue of such a radiation beam having a Gaussian intensity profile is approximately equal to the wavelength of the radiation beam squared. In some embodiments a free electron laser FEL may emit an EUV radiation beam having a wavelength of approximately 13.5 nm and having a Gaussian intensity profile. In such an embodiment the etendue of the radiation beam is approximately 1.8×10^{-16} m^2. In practice the intensity profile of a radiation beam which is emitted from a free electron laser FEL may not be perfectly Gaussian. Consequently the etendue of a radiation beam which is emitted from a free electron laser FEL may in practice be approximately 2 or 3 times greater than the square of the wavelength of the radiation beam.

[0085] The etendue of a radiation beam cannot decrease as it propagates through an optical system. The etendue of a radiation beam may remain constant as it propagates through an optical system in free space and undergoes reflections and refractions. However, as a radiation beam propagates through an optical system which spreads out radiation, for example by scattering and/or diffraction, its etendue will increase. The higher the quality of the optical elements (for example mirrors and lenses) in the optical system, the smaller the increase in etendue will be.

[0086] 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 B_{FEL} produced by the free electron laser FEL is so small the power density will be significant. Therefore the beam delivery system BDS may comprise a radiation beam expander (not shown) that is arranged to increase the cross sectional area of the radiation beam B_{FEL} produced by the free electron laser FEL. The radiation beam expander 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 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.

[0087] For embodiments using a free electron laser FEL, the size of the branch radiation beam B_a at the intermediate focus 9 of the lithographic apparatus LA_a is expected to be almost diffraction limited, with a diameter of the order of 1-10 µm. By comparison, when an LPP source is used, a typical diameter of the branch radiation beam B_a at the intermediate focus 9 of the lithographic apparatus LA_a is or the order of 200-500 µm.

[0088] Providing a branch radiation beam B_a with a relatively small etendue to a lithographic apparatus (as may be the case for embodiments using a free electron laser FEL) can cause problems within the lithographic apparatus LA_a. For example, a radiation beam with a very small etendue may lead to imaging problems and to an unacceptable sensitivity to surface defects of mirrors in the lithographic apparatus LA_a. For a small etendue branch radiation beam B_a, radiation which is received at a given point on a substrate W may be considered to have originated from a discrete number N of point sources in an illumination pupil of the projection system PS. The N points in the illumination pupil translate to N discrete rays which illuminate the point on the substrate W from N different angles. A defect, such as a scratch on a mirror in the projection system PS may obscure one or more of the N rays of radiation and thus the point on the substrate will be illuminated from fewer than N different angles. Consequently the defect will deteriorate the imaging performance at some locations on the substrate W. Increasing the etendue of a branch radiation beam B_a may reduce this deterioration of the imaging performance.

[0089] The optical path of each branch radiation beams B_a-B_n may comprise an adjustable optic element according to an embodiment of the present invention. Each adjustable optic element may be of the form of an adjustable ripple plate. The adjustable optical element is disposed upstream of the intermediate focus 9. The adjustable optical element may be disposed either upstream or downstream of the focusing optics that focuses the branch radiation beam at the intermediate focus 9 (i.e. grazing incidence collector 18 in Figure 3). In some embodiments, the adjustable optical element may form part of the bending optics for the branch radiation beam B_a-B_n, e.g. it may replace one or more grazing incidence mirrors 16, 17 of the bending optics (see Figure 3). The adjustable optical element may be arranged to alter, and provide some measure of control over, properties of the branch radiation beams B_a-B_n delivered to each lithographic apparatus LA_a-LA_n. Such properties may include, for example, the intensity distribution and the diameter of a radiation beam delivered to the lithographic apparatus (for example, at the intermediate focus). For example, the adjustable optical element may be arranged to increase the divergence of the branch radiation beam B_a-B_n and/or to act as a diffuser, spreading out the branch radiation beam B_a-B_n and increasing its etendue before the branch radiation beam B_a-B_n passes into its corresponding lithographic apparatus LA_a-LA_n. The adjustable optical element may be arranged to control the angular power distribution of the branch radiation beam B_a-B_n. In turn, following focusing by suitable optics (e.g. grazing incidence collector 18 in Figure 3), this can provide control over the diameter and intensity profile of radiation at the intermediate focus 9.

[0090] Various embodiments of suitable adjustable optical elements that are suitable for receiving an input (branch) radiation beam and outputting an (branch) output radiation beam, are now described.

[0091] Figure 5 shows a first embodiment of an adjustable optical element 100. The adjustable optical element 100 comprises a first member 110 and a second member 120.

[0092] The first member 110 is formed form two adjacent layers: a layer of piezoelectric material 112 and a layer of reflective material 114. The layer of piezoelectric material may, for example, be formed from monocrystalline silicon or sapphire. It will be appreciated that in this context the layer of reflective material 114 is formed from a material with a relatively high reflectivity for radiation that the optical element 100 is to be used for. In addition, reflective material 114 is an electrical conductor. In one embodiment the optical element 100 is for use with EUV radiation and the reflective material 114 may comprise a layer of ruthenium (Ru).

[0093] The reflective layer 114 provides an optical surface 116 for receiving an input radiation beam (for example one of the branch radiation beams B_a-B_n upstream of its intermediate focus 9). The layer of piezoelectric material 112 provides a second surface 118 that is opposite to the optical surface 116 of the first member 110.

[0094] The second member 120 comprises a support 122, having an uneven surface which is provided with a coating layer 124 of an electrically conducting material. The support 122 comprises a base portion defining a generally flat surface 125. A plurality of protrusions or burls 126 extend from, and are integrally formed with, the base portion. Together, the surface 125 and the plurality of protrusions 126 may be considered to form an uneven surface of the support 122. The coating layer 124 of an electrically conducting material is provided over this entire uneven surface.

[0095] Each protrusion 126 of the support 122, together with a portion of the coating layer 124 of electrically conducting material provided over said support, forms a protrusion 128 of the second member 120. A portion of the coating layer 124 of electrically conducting material that is provided over the surface 125 of the support 122 (i.e. in between the protrusions 126) defines a base surface 127 of the second member 120.

[0096] The protrusions 128 of the second member 120 contact the second surface 118 of the first member 110. In this way, the first member 110 is supported by the second member 120.

[0097] The optical element 100 further comprises a distortion mechanism and a controller, as now described. The distortion mechanism is operable to locally alter a curvature of the optical surface 116 in the vicinity of each protrusion 128. To achieve this, the distortion mechanism is operable to apply a voltage across the layer of reflective material 114 and the coating 124 of electrically conducting material. In effect, the distortion mechanism is operable to apply a voltage across the optical surface 116 (provided by reflective material 114) and the uneven surface of the second member 120.

[0098] The protrusions 128 effectively modulate the electric field within the layer of piezoelectric material 116. In turn this modulates the stresses within the layer of piezoelectric material 116 and causes a curvature of the optical surface 116 in the vicinity of each protrusion 128.

[0099] A controller (not shown) is operable to control the curvature of the optical surface in the vicinity of each of the protrusions 128 of the second member 120. This is achieved by controlling the voltage applied across the layer of reflective material 114 and the coating 124 of electrically conducting material. The adjustable optical element 100 therefore provides an arrangement whereby the optical surface 116 can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions 128. The topology of the optical element 100 is therefore dependent on that of the plurality of protrusions 128. The plurality of protrusions 128 provide some support for the first member 110 and allow the optical surface 116 to be distorted in a controlled way. The plurality of protrusions 128 causes a modulation of the optical surface 116, causing it to be rippled or bumpy. A spacing, pitch or frequency of the modulation of the optical surface is determined by the spacing, pitch or frequency of the plurality of protrusions 128. The amplitude of the modulation of the optical surface can be controlled by the controller (by controlling the applied voltage).

[00100] Figure 6 shows a second embodiment of an adjustable optical element 200. The adjustable optical element 200 also comprises a first member 210 and a second member 220.

[00101] The first member 210 is formed form three adjacent layers: a layer of electrically conductive material 212, a support layer 213 and a layer of reflective material 214. The support layer 213 may, for example, be formed from polished monocrystalline silicon. It will be appreciated that in this context the layer of reflective material 214 is formed from a material with a relatively high reflectivity for radiation that the optical element 200 is to be used for. In one embodiment the optical element 200 is for use with EUV radiation and the reflective material 214 may comprise a layer of ruthenium (Ru), which may be applied to the support layer 213 as a coating.

[00102] The reflective layer 214 provides an optical surface 216 for receiving an input radiation beam (for example one of the branch radiation beams B_a-B_n upstream of its intermediate focus 9). The layer of electrically conductive material 212 provides a second surface 218 that is opposite to the optical surface 216 of the first member 210.

[00103] The second member 220 comprises a support plate 222, having a generally flat surface 223. A plurality of protrusions or burls 228 extend from the surface 223 of the support plate 222. The protrusions 228 are formed from a dielectric material. A layer 224 of an electrically conducting material is provided over the surface 223 of the support plate 222 in between the dielectric protrusions 228. The layer 224 of electrically conducting material provided over the surface 223 defines a base surface 227 of the second member 220.

[00104] The protrusions 228 of the second member 220 contact the second surface 218 of the first member 210. In this way, the first member 210 is supported by the second member 220.

[00105] The optical element 200 further comprises a distortion mechanism and a controller, as now described. The distortion mechanism operable to locally alter a curvature of the optical surface 216 in the vicinity of each protrusion 228. The distortion mechanism is operable to urge the plurality of protrusions 228 of the second member 220 into contact with the second surface 218 of the first member 210 such that they exert a force on a region of the first member 210 so as to locally alter a curvature of the optical surface 216 in the vicinity of each protrusion 228. The plurality of protrusions 228 of the second member 220 are urged into contact with the second surface 218 of the first member 210 via an electrostatic force.

[00106] To achieve this, the distortion mechanism is operable to apply a voltage across the second surface 218 of the first member 210 and the base surface 227 of the second member 220 from which the plurality of protrusions 228 extend. To achieve this, the distortion mechanism is operable to apply a voltage across the layer of electrically conductive material

212 on the first member and the layer 224 of electrically conducting material is provided over the surface 223 of the support plate 222.

[00107] Since protrusions 228 are formed from an insulating dielectric material the voltage across the second surface 218 of the first member 210 and a base surface 227 of the second member 220 can be maintained even when the plurality of protrusions 228 is in contact with the second surface 218. The voltage results in an electrostatic attraction, which urges the plurality of protrusions 228 of the second member 220 into contact with the second surface 218 of the first member 210.

[00108] In this embodiment, the protrusions 228 are formed entirely from an electrically insulating dielectric material. In variants of the present embodiment at least a portion of each of the plurality of protrusions 228 comprises an insulating material so as to electrically isolate the layer of electrically conductive material 212 of the first member 210 from the layer 224 of electrically conducting material is provided over the surface 223 of the support plate 222.

[00109] As each protrusion 228 exerts a force on a region of the first member 210 it causes the optical surface 216 in the vicinity of that protrusion 228 to be distorted outwards, so as to form a generally convex portion of the optical surface 216. The regions of the optical surface 216 in the vicinity of each protrusion 228 form local high points of the optical surface 216. Regions of the optical surface 216 between adjacent protrusions 228 form local low points of the optical surface 216 and are generally concave. In this way, the plurality of protrusions 228 causes a modulation of the optical surface 216, causing it to be rippled or bumpy. An amplitude of the modulation of the optical surface 216 is dependent on the force exerted on the first member 210 by each of the protrusions 228.

[00110] As with the optical element shown in Figure 5, a controller (not shown) is provided which is operable to control the curvature of the optical surface 216 in the vicinity of each of the protrusions 228 of the second member 220. This is achieved by controlling the voltage applied across across the layer of electrically conductive material 212 on the first member and the layer 224 of electrically conducting material is provided over the surface 223 of the support plate 222. The adjustable optical element 200 therefore provides an arrangement whereby the optical surface 216 can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions 228. The topology of the optical element 200 is therefore dependent on that of the plurality of protrusions 228. The plurality of protrusions 228 provide some support for the first member 210 and allow the optical surface 216 to be distorted in a controlled way. The plurality of protrusions 228 causes a modulation of the optical surface 216, causing it to be rippled or bumpy. A spacing, pitch or frequency of the modulation of the optical surface is determined by the spacing, pitch or frequency of the plurality of protrusions. The amplitude of the modulation of the optical surface can be controlled by the controller (by controlling the applied voltage).

[00111] As explained above, the distortion of the optical surfaces 116, 216 of the optical elements 100, 200 shown in Figures 5 and 6 is dependent on the topology of the protrusions 128, 228. Either embodiment of optical element 100, 200 may be used to alter characteristics of a radiation beam (for example size, divergence and angular distribution) in either one or two directions, as now described with reference to Figures 7 and 8. Figures 7 and 8 show a plan view of part of the second member 120, 220 of either optical element 100, 200, showing the protrusions 128, 228 and the base surface 127, 227.

[00112] As shown in Figure 7, a profile of each of the plurality of protrusions 128, 228 in plan view may be elongate, i.e. the protrusions 128, 228 may be of the form of elongate fins or ribs. For such embodiments, the plurality of protrusions 128, 228 may be arranged as either a one dimensional array or a two dimensional array. Embodiments wherein the plurality of protrusions 128, 228 are arranged as a one dimensional array may be used to control the divergence, diameter and/or angular distribution of the output radiation beam in a single direction. For such embodiments, two optical elements may be used in a sequence to alter characteristics of the radiation beam in two mutually perpendicular directions. For example two grazing incidence mirrors in the bending optics of a branch radiation beam may be replaced with such optical elements 100, 200. This allows control over the divergence of the radiation beam in the two mutually perpendicular directions, allowing the size of the intermediate focus 9 to be varied in two the directions.

[00113] As shown in Figure 8, the plurality of protrusions 128, 228 may be arranged as a two dimensional array. The protrusions 128, 228 are of the form of columns or cell-like structures. A profile of each of the plurality of protrusions 128, 228 in plan view may be generally circular (as shown in Figure 8) although it will be apparent to the skilled person that other profiles, for example square or hexagonal may alternatively be used. With such an arrangement, a single optical element 100, 200 may be used to control the divergence, diameter and/or angular distribution of a radiation beam in two independent directions.

[00114] The angular distribution of a radiation beam that has been scattered from optical element 100, 200 is dependent both on the shape of the surface and the orientation of the incident radiation beam with respect to the optical surface 116, 216. In particular, the angular distribution of the output radiation beam is dependent on the curvature of the optical surface 116, 216.

[00115] In general, a two dimensional surface 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.

[00116] The plane of incidence may be defined as the plane containing a vector pointing in the direction of the input radiation beam and a normal to the optical surface 116, 216. It will be appreciated that the vector pointing in the direction of the input radiation beam may be an average direction of the input radiation beam. The average direction of the input radiation beam is the general direction of the input radiation beam and may, for example, be defined by a chief ray of the input radiation beam. It will be appreciated that for an uneven optical surface 116, 216 the normal to the optical surface may be the normal to an average plane of the optical surface 116, 216.

[00117] A curvature of the optical surface 116, 216 in any direction will cause in increase in the angular spread of the output radiation beam. However, the angular spread caused by a curvature in a direction in the plane of incidence is different to that caused by the angular spread caused by a curvature in a direction perpendicular to the plane of incidence, as now discussed.

[00118] For perfect specular reflection of a collimated radiation beam from a perfectly flat optical element, one would expect the output radiation beam to be collimated and to propagate away from the optical element in a direction defined by the law of reflection. For example the input radiation beam may be incident on the optical element at a grazing incidence angle β of the order of 0.05 rad (approximately 2.9°) and the output radiation beam will be rotated relative to the input radiation beam within the plane of incidence by an angle of 2β.

[00119] If the optical element is curved in a direction in the plane of incidence then (ignoring diffraction effects) this effectively causes a local modulation of the grazing incidence angle. If the curvature of the optical surface causes a spread of grazing incidence angles of $\Delta\beta$ then the output radiation beam will have an angular spread of $2\Delta\beta$.

[00120] If the optical element is curved in a direction perpendicular to the plane of incidence then this curvature does not affect the grazing incidence angle. Therefore, each individual ray within the output radiation beam will still be rotated relative to the input radiation beam by an angle of 2β. However, the curvature of the optical surface causes a spreading out of the output radiation beam such that the individual rays extend along the surface of a cone centred on the direction of the input radiation beam. Under grazing incidence (e.g. with a grazing incidence angle β of the order of 0.05 rad), this cone is relatively small and therefore so too is the angular spread.

[00121] Therefore for a grazing incidence angle β of the order of 0.05 rad (approximately 2.9°) the angular spread caused by a curvature in a direction in the plane of incidence will be greater than the angular spread caused by a similar curvature in a direction perpendicular to the plane of incidence. Unless the plurality of protrusions 128, 228 is arranged such that a different curvature is provided in the directions parallel to and perpendicular to the plane of incidence, under grazing incidence the angular spread is mostly produced in the plane of incidence. In grazing incidence with a grazing incidence angle β, an embodiment as shown in Figure 8 with a two dimensional array of protrusions 128, 228 (with equal pitches in the X and Y directions) will generate an anisotropic angular distribution that has an aspect ratio of approximately β (the curvature in a direction perpendicular to the plane of incidence versus the curvature in a direction in the plane of incidence).

[00122] The curvature of the optical surface 116, 216 in each direction is dependent on the pitch of the modulation of the optical surface 116, 216 caused by the plurality of protrusions 128, 228 in that direction and the amplitude of the modulation of the optical surface 116, 216 caused by the plurality of protrusions 128, 228. For embodiments of the form shown in Figure 8, wherein the plurality of protrusions 128, 228 are arranged as a two dimensional array, the amplitude of the modulation is the same in both directions (parallel to and perpendicular to the plane of incidence). Therefore, in order to provide a different curvature in two mutually perpendicular directions, the two dimensional array of protrusions 128, 228 should be arranged such that their pitch in each of the two directions is different.

[00123] It may be desirable to provide an arrangement that produces approximately equal angular spread in the plane of incidence and perpendicular thereto. This could be achieved by an embodiment comprising a two dimensional array of protrusions 128, 228 wherein the pitch of the array in the plane of incidence and the pitch of the array perpendicular to the plane of incidence have a ratio of β (the grazing incidence angle). Such an embodiment may be provided with a two dimensional array of elongate protrusions. The profile of the protrusions may be chosen in dependence on a desired or required ratio of pitches.

[00124] Figures 9A and 9B show a third embodiment of an adjustable optical element 300. The adjustable optical element 300 also comprises a first member 310 and a second member 320.

[00125] The first member 310 comprises a supporting frame 313 over which is provided a flexible membrane 312. The supporting frame 313 is rigid and provides support for the flexible membrane 312.

[00126] The first member further comprises a layer of reflective material 314 adjacent to the flexible membrane 312. It will be appreciated that in this context the layer of reflective material 314 is formed from a material with a relatively high reflectivity for radiation that the optical element 300 is to be used for. In one embodiment the optical element 300 is for use with EUV radiation and the reflective material 314 may comprise a layer of ruthenium (Ru). The reflective layer 314 provides an optical surface 316 for receiving an input radiation beam (for example one of the branch radiation beams B_a-B_n upstream of its intermediate focus 9).

[00127] The flexible membrane 312 provides a second surface 318 that is opposite to the optical surface 316 of the first member 310.

[00128] The second member 320 comprises a support plate 322, having a generally flat base surface 327. A plurality of protrusions or burls 328 extend from, and are integrally formed with, the surface 327 of the support plate 322.

[00129] The supporting frame 313 of the first member 310 is provided with a plurality of apertures 315, each aperture 315 for receipt of one of the plurality of protrusions 328 of the second member 320. The protrusions 328 of the second member 320 are received within these apertures 315 and contact the second surface 318 of the first member 310. In this way, the first member 310 is supported by the second member 320.

[00130] The optical element 300 further comprises a distortion mechanism and a controller, as now described. The distortion mechanism operable to locally alter a curvature of the optical surface 316 in the vicinity of each protrusion 328. The distortion mechanism is operable to urge the plurality of protrusions 328 of the second member 320 into contact with the second surface 318 of the first member 310 such that they exert a force on a region of the first member 310 so as to locally alter a curvature of the optical surface 316 in the vicinity of each protrusion 328. The plurality of protrusions 328 of the second member 320 are urged into contact with the second surface 318 of the first member 310 via a mechanical force.

[00131] As each protrusion 328 exerts a force on a region of the first member 310 it causes the optical surface 316 in the vicinity of that protrusion 328 to be distorted outwards, so as to form a generally convex portion of the optical surface 316. The regions of the optical surface 316 in the vicinity of each protrusion 328 form local high points of the optical surface 316. Regions of the optical surface 316 between adjacent protrusions 328 form local low points of the optical surface 316 and are generally concave. In this way, the plurality of protrusions 328 causes a modulation of the optical surface 316, causing it to be rippled or bumpy. An amplitude of the modulation of the optical surface 316 is dependent on the force exerted on the first member 310 by each of the protrusions 328.

[00132] As with the optical elements 100, 200 shown in Figures 5 and 6, a controller (not shown) is provided which is operable to control the curvature of the optical surface 316 in the vicinity of each of the protrusions 328 of the second member 320. This is achieved by applying a mechanical force such that the protrusions 328 apply pressure to the flexible membrane 312. The mechanical force may for example be applied hydraulically.

[00133] The adjustable optical element 300 therefore provides an arrangement whereby the optical surface 316 can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions 328. The topology of the optical element 300 is therefore dependent on that of the plurality of protrusions 328. The plurality of protrusions 328 provide some support for the first member 310 and allow the optical surface 316 to be distorted in a controlled way. The plurality of protrusions 328 causes a modulation of the optical surface 316, causing it to be rippled or bumpy. A spacing, pitch or frequency of the modulation of the optical surface is determined by the spacing, pitch or frequency of the plurality of protrusions. The amplitude of the modulation of the optical surface can be controlled by the controller (by controlling the applied voltage).

[00134] As explained above, the distortion of the optical surface 316 of the optical element 300 shown in Figures 9A and 9B is dependent on the topology of the protrusions 328 (and apertures 315). The optical element 300 may be used to alter characteristics of a radiation beam (for example size, divergence and angular distribution) in either one or two directions, as now described with reference to Figures 10A and 10B. Figures 10A and 10B show a cross sectional view of the supporting frame 313 of the first member 310 of optical element 300 through the line A-A indicated in Figure 9A. Figures 10A and 10B therefore illustrate the cross sectional profile of the supporting frame 313 and the arrangement of apertures 315 provided therein (which substantially matched the arrangement of the protrusions 328).

[00135] As shown in Figure 10A, in cross section a profile of each of the apertures 315 (and therefore the plurality of protrusions 328) may be elongate. That is the protrusions 328 may be of the form of elongate fins or ribs. For such embodiments, the plurality of protrusions 328 may be arranged as a one dimensional array. Such an arrangement may be used to control the divergence, diameter and/or angular distribution of the output radiation beam in a single direction. For such embodiments, two optical elements may be used in a sequence to alter characteristics of the radiation beam in two mutually perpendicular directions. For example two grazing incidence mirrors in the bending optics of a branch radiation beam may be replaced with such optical elements 300. This allows control over the divergence of the radiation beam in the two mutually perpendicular directions, allowing the size of the intermediate focus 9 to be varied in two the directions.

[00136] Alternatively, as shown in Figure 10B, the apertures 315 (and therefore the plurality of protrusions 328) may be arranged as a two dimensional array. For such embodiments, the protrusions 328 are of the form of as columns or cell-like structures. A profile of each of the plurality of protrusions 328 in plan view may be of any suitable shape, including, for example, generally circular, square or hexagonal. With an arrangement as shown in Figure 10B, a single optical element 300 may be used to control the divergence, diameter and/or angular distribution of a radiation beam in two independent directions. An extent of each of the apertures 315 may be different in two different directions. For example, as shown in Figure 10B, each aperture 315 may have a first extent 315a in a first direction (the X-direction in Figure 10B) and may have a second extent 315b in a second direction (the Y-direction in Figure 10B). In general, the first and second extents 315a, 315b may be different. This may be used, for example, to provide a different pitch of modulation in the two directions. Furthermore, the pitch of the modulation may vary across the optical surface 316 in order to provide different curvatures and thus provide the desired power distribution in the intermediate focus 9. This variation in pitch of the modulation may be achieved by a corresponding variation in the extents 315a, 315b of the apertures 315.

[00137] Each of the adjustable optical elements 100, 200, 300 described above provides an arrangement whereby the optical surface 116, 216, 316 can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions 128, 228, 328. The topology of the optical surface 116, 216, 316 is therefore dependent on that of the plurality of protrusions 128, 228, 328. The plurality of protrusions 128, 228, 328 provide some support for the first member 110, 210, 310 and allow the optical surface 116, 216, 316 to be distorted in a controlled way.

[00138] The distortion mechanism causes the optical surface 116, 216, 316 in the vicinity of each protrusion 128, 228, 328 to be distorted outwards or inwards, so as to form a generally convex or concave portion of the optical surface 116, 216, 316. In some embodiments, the regions of the optical surface 116, 216, 316 in the vicinity of each protrusion 128, 228, 328 form local high points of the optical surface 116, 216, 316 (and are generally convex) and regions of the optical surface 116, 216, 316 between adjacent protrusions 128, 228, 328 form local low points of the optical surface 116, 216, 316 (and are generally concave). In other embodiments, the regions of the optical surface 116, 216, 316 in the vicinity of each protrusion 128, 228, 328 form local low points of the optical surface 116, 216, 316 (and are generally concave) and regions of the optical surface 116, 216, 316 between adjacent protrusions 128, 228, 328 form local high points of the optical surface 116, 216, 316 (and are generally convex). In this way, the plurality of protrusions 128, 228, 328 therefore causes a modulation of the optical surface 116, 216, 316, causing it to be rippled or bumpy. That is, the optical surface 116, 216, 316 becomes uneven.

[00139] As the radiation beam is incident on, and reflected by, the optical surface 116, 216, 316, the unevenness of the optical surface 116, 216, 316 has two effects on the radiation beam: (i) it increases the divergence of the radiation beam; and (ii) it alters the angular distribution (or, equivalently, the intensity profile) of the radiation beam. The increase in divergence results in a change in the diameter of the radiation beam at the intermediate focus 9.

[00140] The angular distribution of the radiation beam output by the optical element 100, 200, 300 is dependent on the modulation of the optical surface 116, 216, 316. In particular, the angular distribution of the output radiation beam is dependent on the ratio of the pitch of the modulation to the amplitude of the modulation, as now discussed with reference to Figure 11.

[00141] Figure 11 shows the angular power distribution of a radiation beam output by an optical element which comprises a modulated surface, for three different modulations of the optical surface. The angle α is the angle between a given portion of the radiation beam and an average direction of the radiation beam. The average direction of the radiation beam is the general direction of the radiation beam and may, for example, be defined by a chief ray of the radiation beam. The average direction of the radiation beam will in general be determined by the orientation of the optical element relative to the input radiation beam, i.e. the angle of incidence or, equivalently, the grazing incidence angle of the radiation beam. It will be appreciated that for a radiation beam incident upon an uneven optical surface, a grazing incidence angle may be defined, for example, as the angle between the incident radiation beam (or an average direction thereof) and an average plane of the optical surface. If the input radiation beam is generally collimated and is incident upon the optical element at a given grazing incidence angle (for example with respect to an average plane of the optical surface) then the average direction of the output radiation beam will be given by the law of reflection.

[00142] For perfect specular reflection of a collimated radiation beam from a perfectly flat optical element, one would expect the output radiation beam to be collimated and to propagate away from the optical element in a direction defined by the law of reflection. For such perfect specular reflection of a collimated radiation beam the angular power distribution of the output radiation beam would be a Dirac delta function centred at $\alpha=0$.

[00143] Figure 11 shows the angular power distributions 402, 404 of a radiation beam output from an optical element, which comprises an optical surface modulated by two different sinusoidal modulations 412, 414 respectively, when irradiated by a low divergence input radiation beam. The angular power distribution of the output radiation beam is dependent on the ratio of the pitch of the modulation to the amplitude of the modulation. The ratio of the pitch of the modulation to the amplitude of the modulation is larger for the first sinusoidal modulation 412 than for the second sinusoidal modulation 414. As a result, the first angular power distribution 402 has a smaller angular spread than the second angular power distribution 404.

[00144] Figure 11 also shows the angular power distribution 406 of a radiation beam output from an optical element, which comprises an optical surface modulated by a third modulation 416, when irradiated by a low divergence input radiation beam. The third modulation 416 is not a pure sinusoidal modulation but rather comprises a mixture of a plurality of sinusoidal modulations, the ratio of the pitch of the modulation to the amplitude of the modulation for each of the individual sinusoidal modulations being different. Such a modulation can be used to achieve a desired angular power distribution.

[00145] For example, the modulation 416 can be used to provide the angular power distribution 406 with a generally flat portion and which has a low power at and around $\alpha=0$. This is a close approximation of the angular distribution of radiation produced by an LPP radiation source. This may be advantageous since it may allow a lithographic apparatus LA_a to use LPP and FEL radiation sources interchangeably. In addition, such a flat angular power distribution 406 is advantageous because it spreads the power of the radiation beam over a larger area and this can spread a heat load on a mirror which receives the output radiation beam over a larger area. This is especially beneficial for mirrors at, or close to, focal points of the radiation beam.

[00146] Alternatively, another modulation (not shown) may be used to provide an angular power distribution (not shown) which falls off towards the edge of the field. For example, the intensity distribution may be Gaussian like. This may be advantageous since it may reduce loss of radiation within the illuminator IL. Note that the shape of the far field generated by the regular repeating modulation of the reflective surface 116, 216, 316 has the shape of the repeating unit cell of the modulation. It may be desirable for the entire first optical element (e.g. the facetted field mirror device 10) of the illumination system IL to be illuminated by the branch radiation beam B_a. Any radiation that does not illuminate the first optical element is lost. For embodiments wherein the periphery of the field has lower intensity than the center (as is the case for a Gaussian) this loss is reduced.

[00147] The optical elements 100, 200, 300 can therefore provide dynamic, real-time control over the radiation beam that is provided to a lithographic apparatus. The optical elements 100, 200, 300 can provide control over the instantaneous or averaged power distribution profile at the intermediate focus 9.

[00148] A spacing, pitch or frequency of the modulation of the optical surface 116, 216, 316 is determined by the spacing, pitch or frequency of the plurality of protrusions 128, 228, 328. Therefore, a desired spacing, pitch or frequency of the modulation of the optical surface 116, 216, 316 may be chosen and fixed at production (by manufacturing the optical element such that the plurality of protrusions 128, 228, 328 has the desired spacing, pitch or frequency). For each of the optical elements 100, 200, 300, an amplitude of the modulation of the optical surface 116, 216, 316 can be controlled by the controller. This may be achieved by controlling: (a) the voltage applied across the layer of reflective material 114 and the coating 124 (for optical element 100); (b) the voltage applied across the second surface 218 of the first member 210 and the base surface 227 of the second member 220 (for optical element 200); or (c) the mechanical force with which the plurality of protrusions 328 of the second member 320 are urged into contact with the second surface 318 of the first member 310 (for optical element 300).

[00149] The control over the amplitude of the modulation applied to the optical surface 116, 216, 316 provides some control control over the angular distribution of the output radiation beam. In turn, this provides some control over the intensity profile and diameter of the radiation beam at the intermediate focus 9.

[00150] Each of the plurality of protrusions 128, 228, 328 may be maintained in fixed relationship to each of the other protrusions 128, 228, 328. Such an arrangement is simple since it allows the curvature of the optical surface 116, 216, 316 at each of the plurality of protrusions 128, 228, 328 to be controlled using a single actuation. This may increase the bandwidth with which the optical elements 100, 200, 300 can be used relative to, for example, a more complicated arrangement wherein each of the plurality of protrusions 128, 228, 328 is independently actuable. The second member may comprise a base from which each of the plurality of protrusions 128, 228, 328 extends, which may allow the plurality of protrusions 128, 228, 328 to be maintained in fixed relationship to each other.

[00151] The control over the amplitude of the modulation applied to the optical surface 116, 216, 316 is dynamic and can be used to control the angular distribution of the output radiation beam in real time. In particular, for embodiments wherein the optical element 100, 200, 300 is used to control the angular distribution of a radiation beam provided to a lithographic apparatus (for example one of the branch radiation beams B_a-B_n of Figure 1), the controller may be operable to control the curvature of the optical surface 116, 216, 316 during exposure of a substrate W (i.e. while an image is being formed on the substrate W). For example, the controller may be operable to control the curvature of the optical surface 116, 216, 316 more quickly than a typical exposure time of the lithographic system. This may allow the optical element 100, 200, 300 to be used for dose control. Furthermore, this also allows the optical element 100, 200, 300 to be used to reduce the effect of speckle on an image formed on the substrate W, as now described.

[00152] In use, a curvature of the optical element 100, 200, 300 may be varied through a range of different curvatures during exposure of the substrate W. A frequency of this variation may be such that the curvature varies through the entire range of different curvatures at least once during the exposure time. Such an arrangement is beneficial because it can reduce the effect of speckle on the image formed on a target region of the substrate W. The speckle caused by self-interference of the radiation beam after diffuse reflection from the optical element is dependent on the curvature of the optical element. By varying the curvature of the optical element the speckle varies with time. Since a frequency of the variation is such that the curvature varies through the entire range of different curvatures at least once during the exposure time, the speckle pattern should be at least partially smoothed out. Preferably the frequency of variation of the curvature of the optical element 100, 200, 300 is such that the curvature varies through the entire range of different curvatures a plurality of times, for example at least ten times, during the exposure time. For example, the curvature of the optical element 100, 200, 300 may be altered at a frequency of 10 kHz or more and the typical exposure time may be or the order of 1 ms.

[00153] Another advantage of the frequency of the variation being such that the curvature varies through the entire range of different curvatures at least once during the exposure time is that the power of the radiation beam output by the optical element 100, 200, 300 may be dependent on the curvature of the optical element 100, 200, 300. Such power variations should be averaged out such that they do not cause variations in the radiation doses delivered to different parts of the substrate W.

[00154] The optical elements 100, 200, 300 according to embodiments of the invention provide a simple arrangement that provides control over the angular distribution of a radiation beam. For example, control over the angular distribution of the output radiation beam may alternatively be achieved using an optical element comprising an array of independently moveable mirrors. The independently moveable mirrors may for example be microelectromechanical systems

(MEMS) devices. However, such an arrangement is significantly more complicated that the arrangement provided by optical elements 100, 200, 300 according to embodiments of the invention. The optical elements 100, 200, 300 can therefore be operated at relatively high bandwidths. For example, the optical element may form part of a lithography system and the controller may be operable to control the curvature of the optical surface more quickly than a typical exposure time of the lithographic system, This allow the optical element to be used for dose control.

[00155] Optical elements according to embodiments of the invention may have a modulation with any convenient spacing, pitch or frequency. In some embodiments, the pitch of the modulation may be of the order of 0.1-10 mm. The optical surface 116, 216, 316 is provided on a flexible membrane, which may be any suitable thickness. In one embodiment, the flexible membrane may have a thickness of >0.1 µm. The protrusions 128, 228, 328 may be of any suitable dimension. In one embodiment, the protrusions 328 have a height (i.e. extent towards the first member 110, 210, 310) of between 10 nm and 1 mm. Processes developed for pellicle and wafer tables may be used for production of the optical elements 100, 200, 300.

[00156] Each of the optical elements 100, 200, 300 described above can be used to provide fine adjustment of the size of a branch radiation beam B_a at the intermediate focus 9 and to at least partially remove the effects of speckle.

[00157] It will be appreciated that in other embodiments of the invention the distortion mechanisms of any of the optical elements 100, 200, 300 described above can be combined. For example, a piezoelectric distortion mechanism as used by optical element 100 may be combined with an electrostatic distortion mechanism as used by optical element 200.

[00158] The electrostatic distortion mechanism used by optical element 200 described above involves the application of a voltage that results in an electrostatic attraction which causes distortion of the optical surface 216. In alternative embodiments, the distortion mechanism may be operable to apply a voltage that results in an electrostatic repulsion which causes distortion of the optical surface.

[00159] Any of the optical elements 100, 200, 300 described above may comprise a plurality of portions and the distortion mechanism may be operable to control the shape of the optical surface 116, 216, 316 within each portion independently.

[00160] Each of the optical elements 100, 200, 300 described above comprises a layer of reflective material, which may be formed form a material with a relatively high reflectivity for radiation that the optical element 100, 200, 300 is to be used for. The optical elements 100, 200, 300 may be for use with EUV radiation and the reflective material may comprise a layer of metal such as ruthenium (Ru) or molybdenum (Mo). Such an arrangement may be particularly suitable when the optical element 100, 200, 300 is used as a grazing incidence mirror. In alternative embodiments, each of the optical elements 100, 200, 300 may comprise a multi-layer stack (also known as a dielectric mirror or a Bragg mirror). Such embodiments may be particularly suitable when the optical element is used at relatively high grazing incidence angles, for example at near normal incidence.

[00161] In any of the optical elements 100, 200, 300 described above, a flow of hydrogen gas may be provided between first member 110, 210, 310 and second member 120, 220, 320. This may provide cooling to the optical element 100, 200, 300 and may remove heat deposited by a radiation beam incident on the optical surface 116, 216, 316.

[00162] A pitch of the modulation provided on the optical surface 116, 216, 316 of the optical elements 100, 200, 300 described above is dependent on the arrangement of the plurality of protrusions 128, 228, 328. The arrangement of the plurality of protrusions 128, 228, 328 may be such that a different pitch is provided in each of two different directions. Furthermore, the arrangement of the plurality of protrusions 128, 228, 328 may be such that the pitch of the modulation may vary across the optical surface 116, 216, 316.

[00163] It will be appreciated that the term “distortion mechanism” may include any combination of features that facilitates a local alteration in a curvature of the optical surface. The distortion mechanism may, for example, comprise one or more actuators that are operable upon receipt of a suitable control signal to control a curvature of the optical surface. It will be further appreciated that the term “controller” may include anything that is operable to control the curvature of the optical surface. The controller may be operable to generate a suitable control signal for the distortion mechanism and to send said control signal to the distortion mechanism. The distortion mechanism may receive one or more control signals from the controller.

[00164] 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.

[00165] 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.

[00166] 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.

[00167] It will be appreciated that term “grazing incidence angle” refers to the angle between the propagation direction of an incident radiation beam and a reflective surface that it is incident upon. This 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.

[00168] 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, >1 GeV or more.

[00169] 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.

[00170] 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.

[00171] 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.

[00172] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

[00173] 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 of the clauses set out below. Other aspects of the invention are set-out as in the following numbered clauses.

1. An optical element for receiving an input radiation beam and outputting an output radiation beam, the optical element comprising:

a first member having an optical surface for receiving the input radiation beam, and a second surface opposite to the optical surface;

a second member comprising a plurality of protrusions for contacting the second surface of the first member;

a distortion mechanism operable to locally alter a curvature of the optical surface in the vicinity of each protrusion; and

a controller operable to control the curvature of the optical surface in the vicinity of each of the protrusions.

2. The optical element of clause 1 wherein the first member comprises a layer of piezoelectric material and wherein the distortion mechanism is operable to apply a voltage across the optical surface and an uneven surface of the second member formed by a base surface and the plurality of protrusions.

3. The optical element of clause 1 or clause 2 wherein the distortion mechanism is operable to urge the plurality of protrusions of the second member into contact with the second surface of the first member such that they exert a force on a region of the first member so as to locally alter a curvature of the optical surface in the vicinity of each protrusion.

4. The optical element of clause 3 wherein the plurality of protrusions of the second member are urged into contact with the second surface of the first member via an electrostatic force.

5. The optical element of clause 4 wherein the distortion mechanism is operable to apply a voltage across the second surface of the first member and a base of the second member from which the plurality of protrusions extend and wherein at least a portion of the plurality of protrusions comprises an insulating material.

6. The optical element of clause 3 wherein the plurality of protrusions of the second member are urged into contact with the second surface of the first member via a mechanical force.

7. The optical element of clause 6 wherein the first member comprises a supporting frame and a membrane, the optical surface being provided on the membrane and the supporting frame comprising a plurality of apertures, each aperture for receipt of one of the plurality of protrusions.

8. The optical element of clause 6 or clause 7 wherein the mechanical force is applied hydraulically.

9. The optical element of any preceding clause wherein the distortion mechanism is operable to alter a curvature of the optical surface in the vicinity of each protrusion via an electrostatic repulsion between the plurality of protrusions and the first member.

10. The optical element of any preceding clause wherein each of the plurality of protrusions is maintained in fixed relationship to each of the other protrusions.

11. The optical element of any one of clauses 1 to 9 wherein the optical element comprises a plurality of portions and the distortion mechanism is operable to control a shape of the optical surface in each of the plurality of portions independently.

12. The optical element of any preceding clause wherein the second member comprises a base from which each of the plurality of protrusions extends.

13. The optical element of any preceding clause wherein a profile of each of the plurality of protrusions in a plane of the second surface is elongate.

14. The optical element of clause 13 wherein the plurality of protrusions is arranged as a one dimensional array.

15. The optical element of any one of clauses 1 to 13 wherein the plurality of protrusions is arranged as a two dimensional array.

16. The optical element of any preceding clause wherein the arrangement of the plurality of protrusions is such that an angular power distribution of the output radiation beam is generally flat.

17. The optical element of any preceding clause wherein the arrangement of the plurality of protrusions is such that an angular power distribution of the output radiation beam falls off towards the edge of the field.

18. The optical element of any preceding clause wherein the distortion mechanism is operable to locally alter a curvature of the optical surface in the vicinity of each protrusion with a bandwidth of 1 kHz or higher.

19. The optical element of any preceding clause further comprising a mechanism for providing a flow of gas between the first member and the second member.

20. A lithographic apparatus comprising:

an optical element according to any preceding clause;

an illumination system configured to condition the output radiation beam of the optical element;

a support structure constructed to support a patterning device, the patterning device being capable of imparting the output radiation beam with a pattern in its cross-section to form a patterned radiation beam;

a substrate table constructed to hold a substrate; and

a projection system configured to project the patterned radiation beam onto the substrate.

21. A lithographic system comprising:

a radiation source operable to produce a radiation beam;

one or more lithographic apparatuses; and

at least one optical element according to any one of clauses 1 to 19, said optical element being arranged to receive at least a portion of the radiation beam produced by the radiation source and to provide the output radiation beam of the optical element to at least one of the one or more lithographic apparatuses.

22. The lithographic system of clause 21 wherein the optical element is arranged to receive the at least a portion of the radiation beam produced by the radiation source at a grazing incidence angle.

23. The lithographic system of clause 22 wherein the grazing incidence angle is less than 5 degrees.

24. The lithographic system of any one of clauses 21 to 23 wherein the radiation beam comprises EUV radiation.

25. A method for forming an image, the method comprising:

providing a radiation beam;

reflecting the radiation beam using an optical element;

imparting a pattern to the radiation beam; and

projecting the patterned radiation beam onto a target portion of a substrate, each part of the target region being exposed for an exposure time;

wherein a curvature of the optical element is varied through a range of different curvatures during exposure of the substrate, a frequency of the variation being such that the curvature varies through the entire range of different curvatures at least once during the exposure time.

26. The method of clause 25 wherein the frequency of the variation of the curvature of the optical element through the range of different curvatures is such that the curvature varies through the entire range of different curvatures at least ten times during the exposure time.

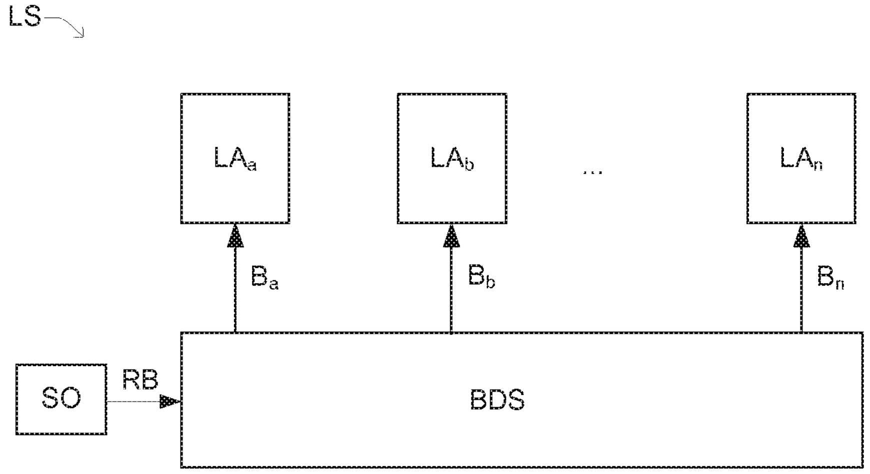
27. The method of clause 25 or clause 26 wherein the optical element is the optical element of any one of clauses 1 to 19.

28. The method of any one of clauses 25 to 27 wherein the radiation beam is reflected from the optical element at a grazing incidence angle of less than 5 degrees.

29. The method of any one of clauses 25 to 28 wherein the radiation beam comprises EUV radiation.

CONCLUSIE

1. Een lithografieinrichting omvattende:
een belichtinginrichting ingericht voor het leveren van een stralingsbundel;
een drager geconstrueerd voor het dragen van een patroneerinrichting, welke patroneerinrichting in staat is een patroon aan te brengen in een doorsnede van de stralingsbundel ter vorming van een gepatroneerde stralingsbundel;
een substraattafel geconstrueerd om een substraat te dragen; en
een projectieinrichting ingericht voor het projecteren van de gepatroneerde stralingsbundel op een doelgebied van het substraat, met het kenmerk, dat de substraattafel is ingericht voor het positioneren van het doelgebied van het substraat in een brandpuntsvlak van de projectieinrichting.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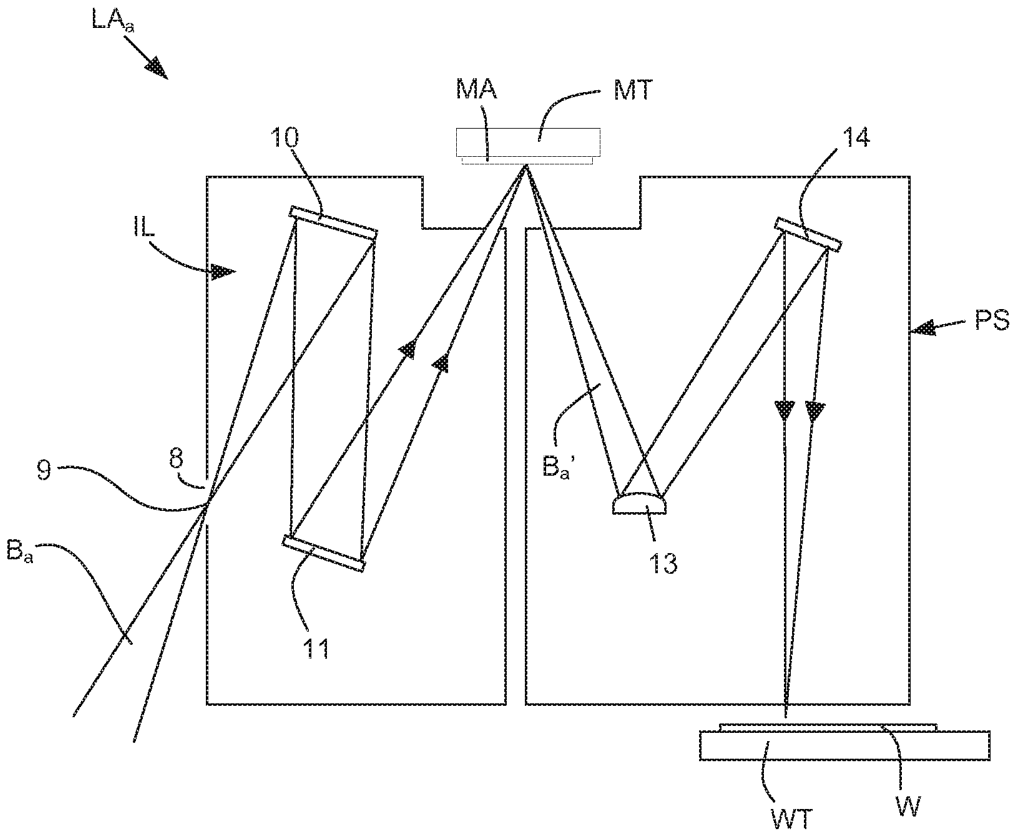
LA_a
LA_b
...
LA_n
B_a
B_b
B_n
SO
RB
BDS

Fig. 1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14
IL
PS
9
8
B_a'
B_a
13
11
WT
W

Fig. 2

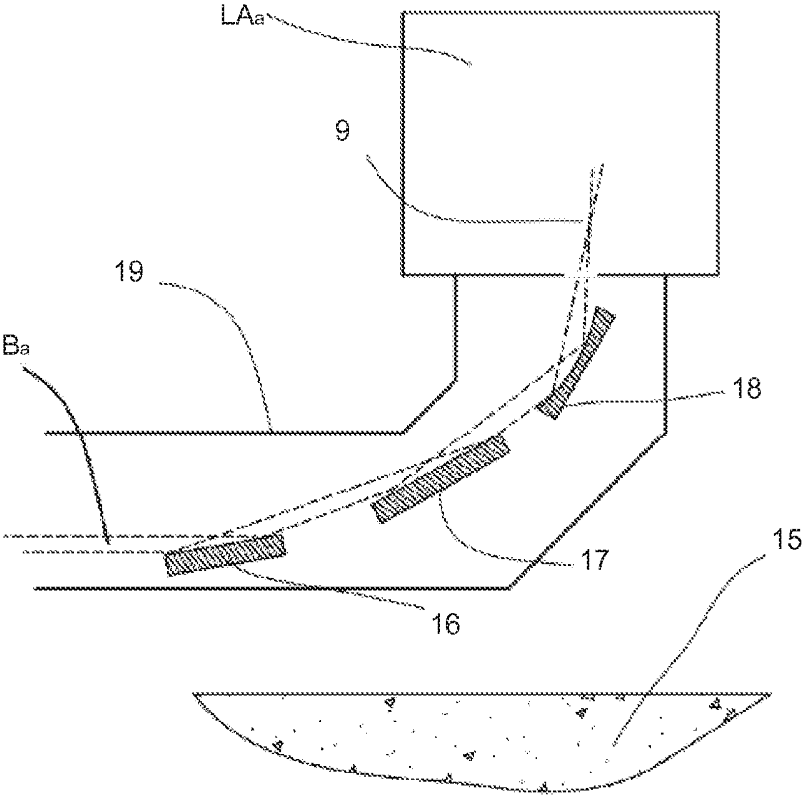


Fig. 3

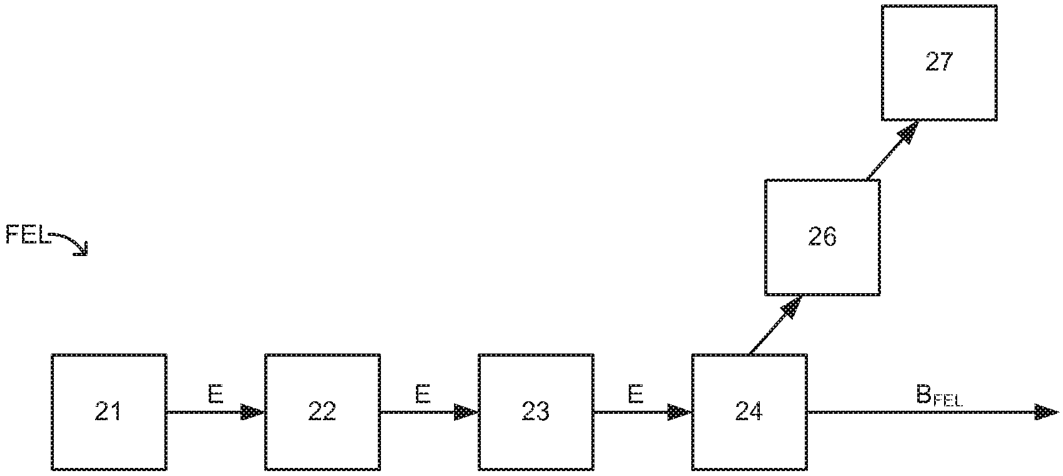
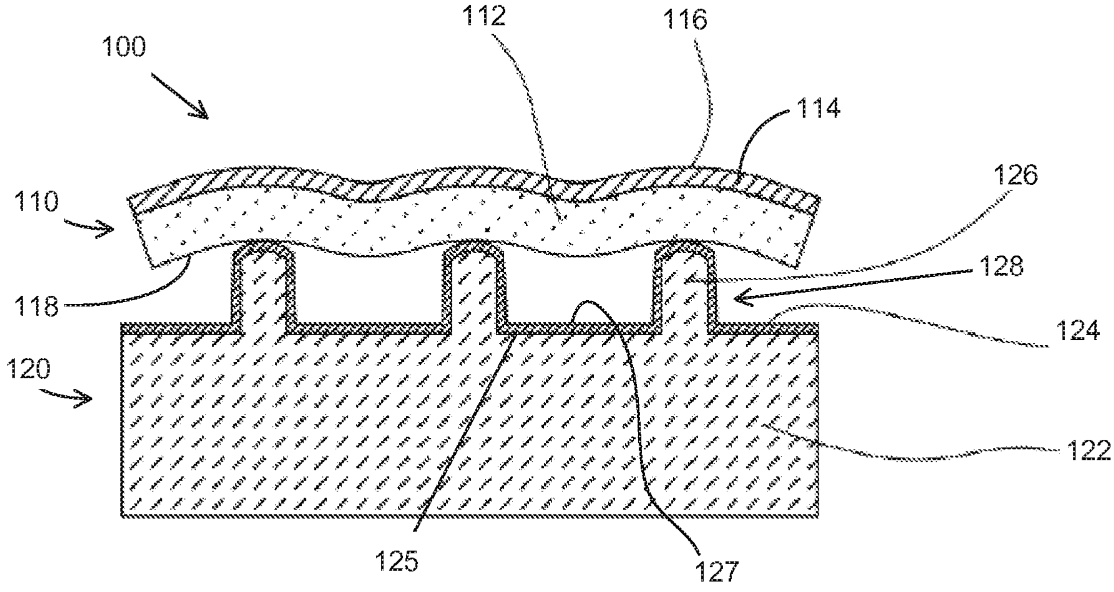


Fig. 4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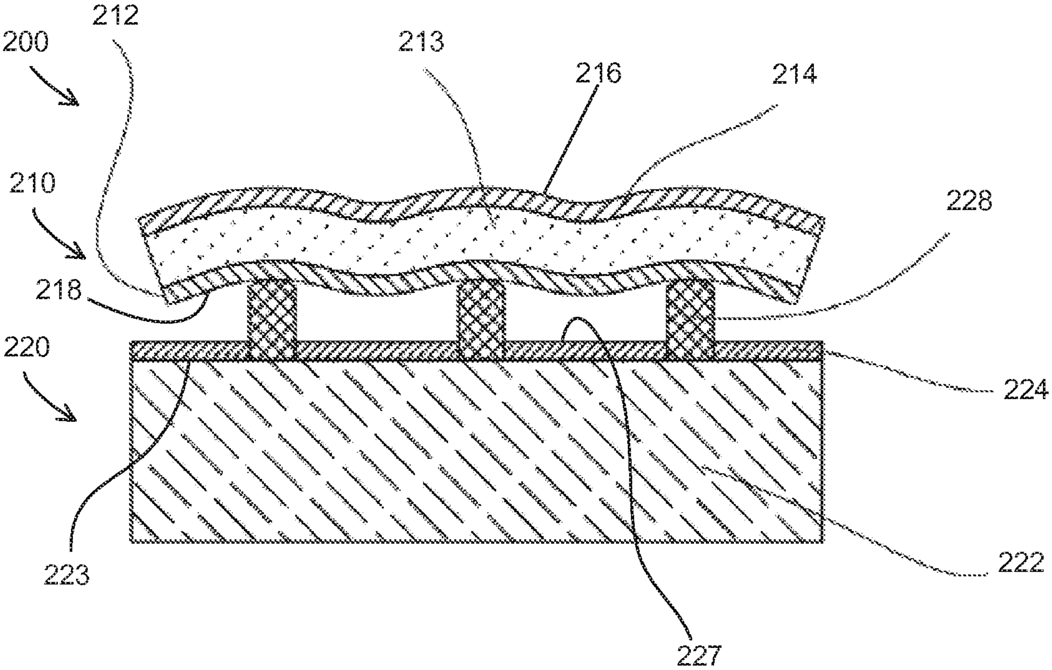
127

Fig. 5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227

Fig. 6

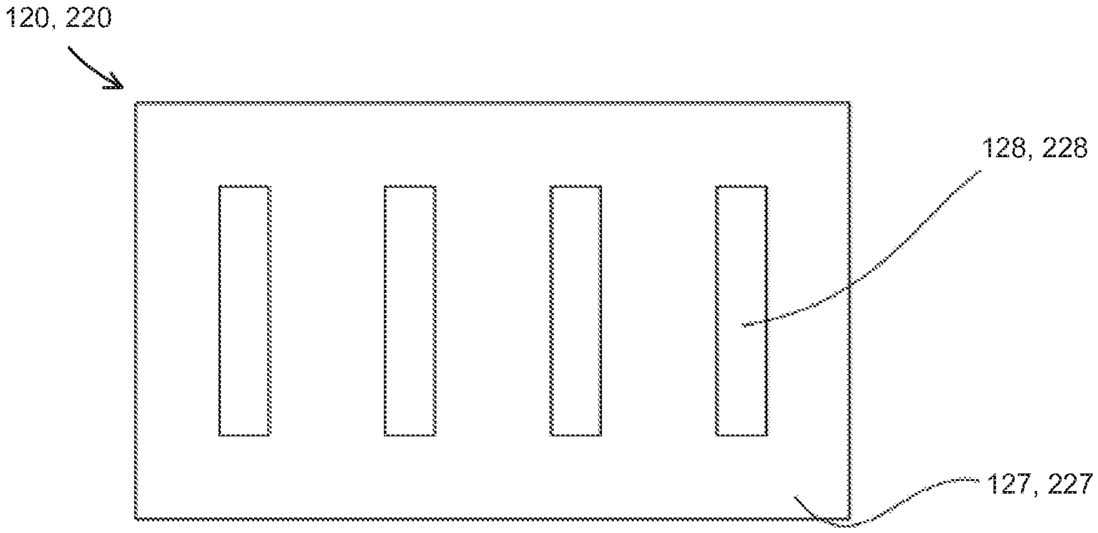


Fig. 7

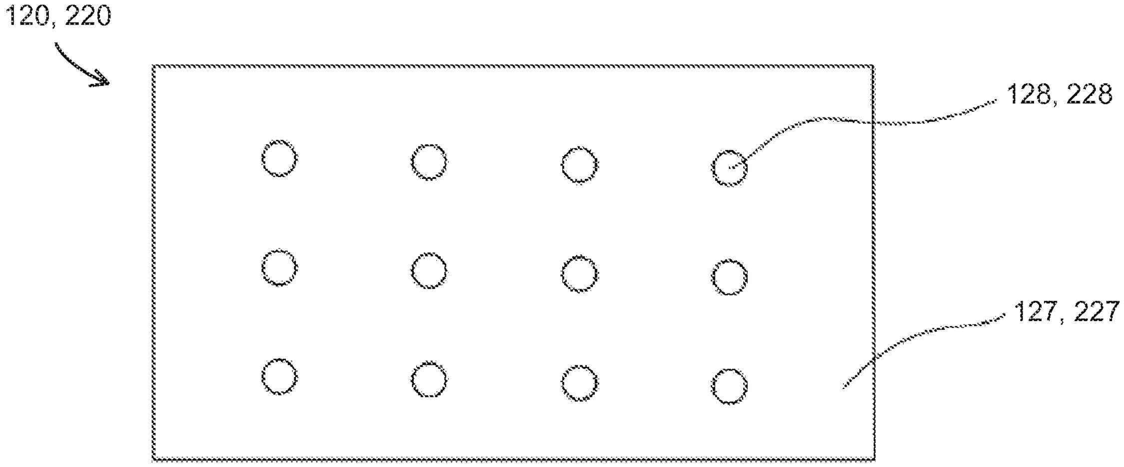
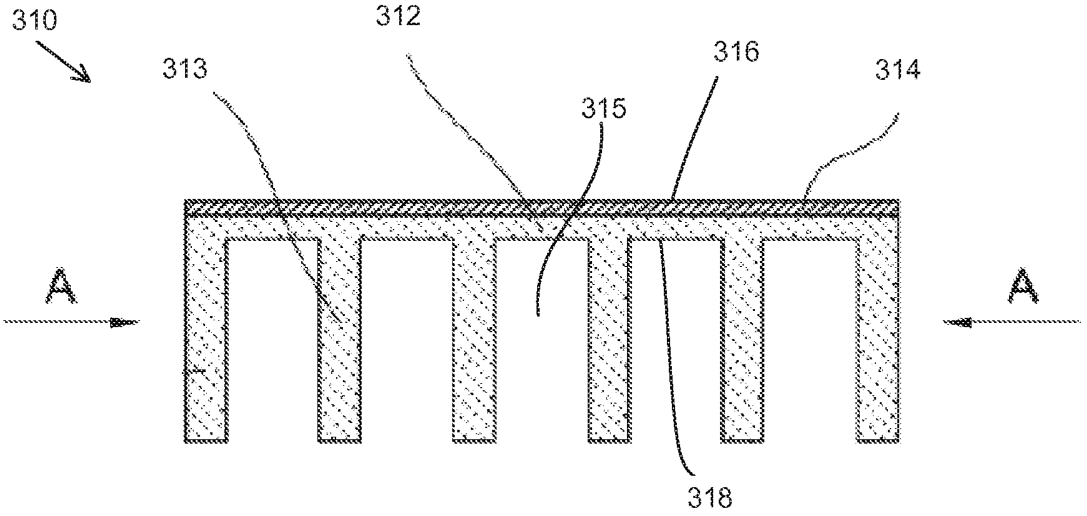


Fig. 8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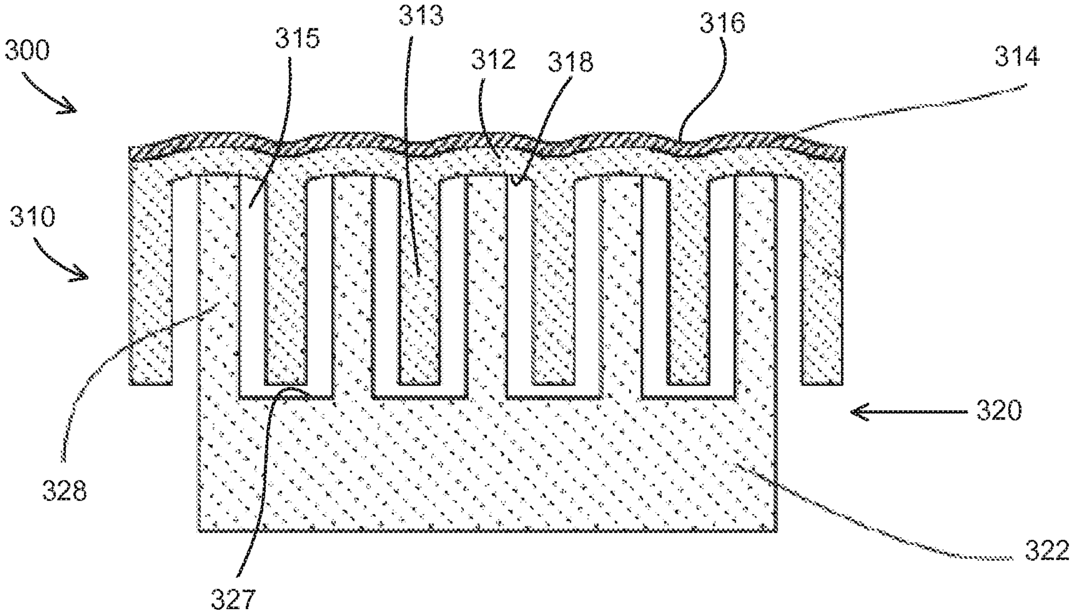
A
A
318

Fig. 9A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322
327

Fig. 9B

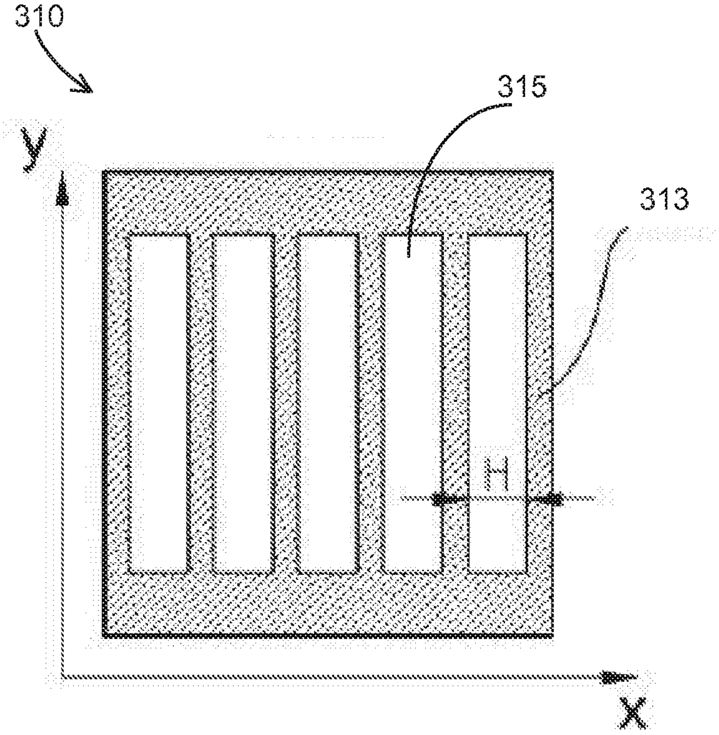

Fig. 10A

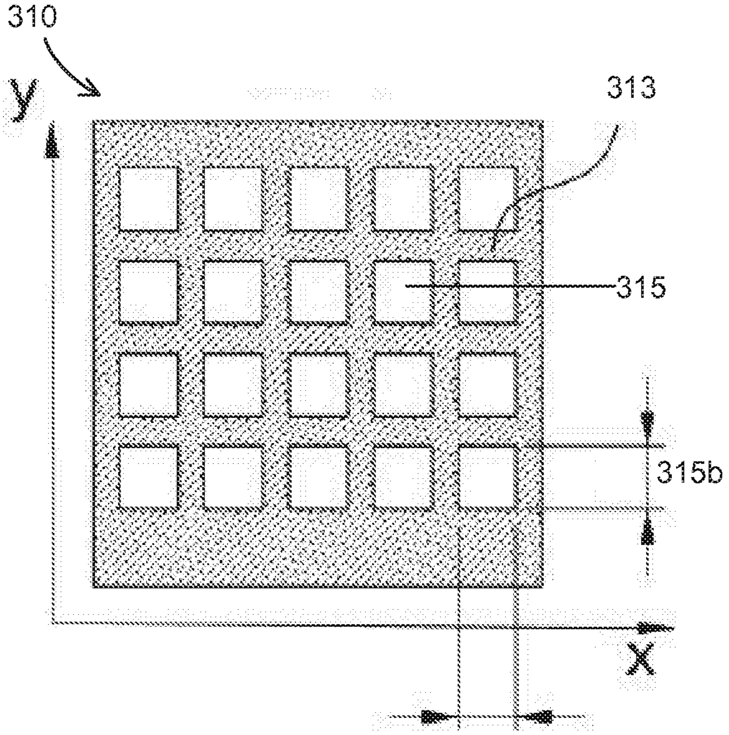

Fig. 10B

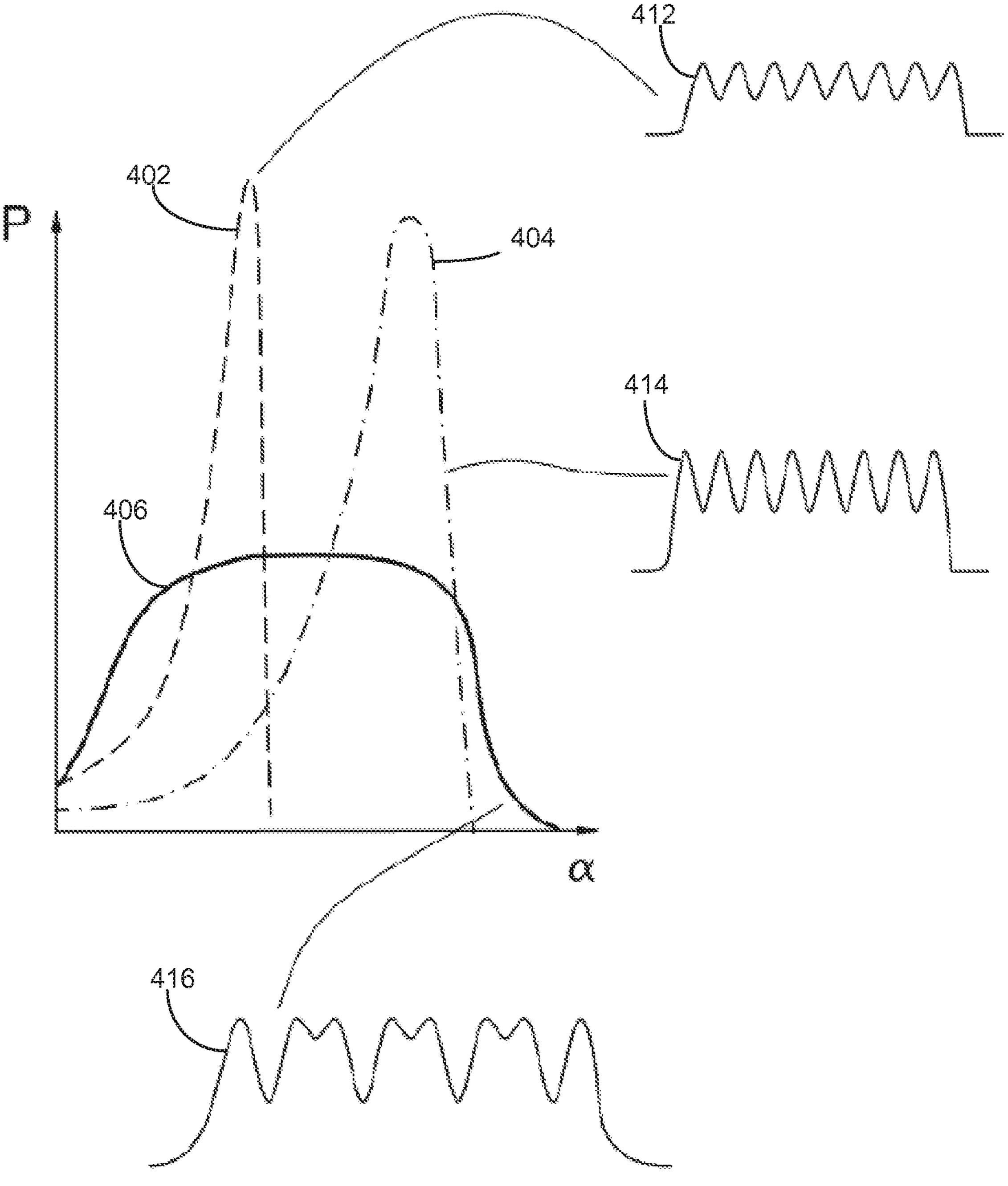

Fig. 11

ABSTRACT

An optical element for receiving an input radiation beam and outputting an output radiation beam, the optical element comprises: a first member, a second member, a distortion mechanism and a controller. The first member has an optical surface for receiving the input radiation beam and a second surface opposite to the optical surface. The second member comprises a plurality of protrusions for contacting the second surface of the first member. The distortion mechanism is operable to locally alter a curvature of the optical surface in the vicinity of each protrusion. The controller is operable to control the curvature of the optical surface in the vicinity of each of the protrusions. The optical element provides an optical surface that can be locally curved in a plurality of different regions, each in the vicinity of one of the plurality of protrusions. This provides control over properties of the output radiation beam.