



- (51) **International Patent Classification:**
G03F 7/20 (2006.01) *G02B 5/18* (2006.01)
- (21) **International Application Number:**
PCT/EP2016/051174
- (22) **International Filing Date:**
21 January 2016 (21.01.2016)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
15156662.7 26 February 2015 (26.02.2015) EP
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- (81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title:** RADIATION BEAM APPARATUS

(57) **Abstract:** An apparatus for receiving an input radiation beam at a beam receiving location and outputting from the beam receiving location one or more output radiation beams. The apparatus comprises: an optical element; and a movement mechanism. The optical element comprises a plurality of portions for receiving the input radiation beam. The movement mechanism is operable to move the plurality of portions so as to selectively position each of the plurality of portions at the beam receiving location. When one of the plurality of portions is disposed in the beam receiving location it is configured to receive the input radiation beam and to scatter the input radiation beam so as to form the one or more output radiation beams. A direction of each of the one or more output radiation beams formed by each of the plurality of portions is substantially the same as a direction of a corresponding output radiation beam formed by each of the other portions. One or more properties of each of the plurality of portions differs from that of the other portions such that a power of at least one of the one or more output radiation beams formed by each of the plurality of portions is different to that of the corresponding output radiation beam formed by at least one of the other portions.



Radiation Beam Apparatus

CROSS-REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims priority of EP application 15156662.7 which was filed on February 26, 2015 and which is incorporated herein in its entirety by reference.

FIELD

10 [0002] The present invention relates to radiation beam apparatus for receiving an input radiation beam at a beam receiving location and outputting from the beam receiving location one or more output radiation beams. The radiation beam apparatus may form a beam splitting apparatus or a radiation beam attenuator. In particular, but not exclusively, the radiation beam apparatus may form part of a lithographic system.

BACKGROUND

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

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

25 [0005] A lithographic system may comprise one or more radiation sources, a beam delivery system and one or more lithographic apparatus. The beam delivery system of a lithographic system may be arranged to direct radiation from the one or more radiation sources to the one or more lithographic apparatus. It may be desirable to control the power of one or more radiation beams that propagate through an optical system.

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

SUMMARY

[0007] According to a first aspect of the invention there is provided an apparatus for receiving an input radiation beam at a beam receiving location and outputting one or more output radiation beams from the beam receiving location, the apparatus comprising: an optical element with a plurality of portions for receiving the input radiation beam; a movement mechanism operable to move the plurality of portions so as to selectively position each of the plurality of portions at the beam receiving location; wherein when one of the plurality of portions is disposed in the beam receiving location it is configured to receive the input radiation beam and to scatter the input radiation beam so as to form the one or more output radiation beams; wherein a direction of at least one of the one or more output radiation beams formed by each of the plurality of portions is substantially the same as a direction of a corresponding output radiation beam formed by at least one of the other portions; and wherein one or more properties of each of the plurality of portions differs from that of the other portions such that a power of at least one of the one or more output radiation beams formed by each of the plurality of portions is different to that of the corresponding output radiation beam formed by at least one of the other portions.

[0008] The first aspect of the present invention provides an apparatus that can form part of an optical system for a radiation beam. For example, the apparatus may form part of a beam delivery system for a lithographic system, which may direct radiation from one or more radiation sources to one or more lithographic apparatus. It may be desirable to control the power of one or more radiation beams that propagate through an optical system. The first aspect allows for such control over the power of one or more radiation beams whilst maintaining the directions of the radiation beams. Advantageously, as a result other optical elements within the optical system do not need to move when a power of one or more of the radiation beams is altered.

[0009] The apparatus may split a single input radiation beam into a plurality of output radiation beams, i.e. it may form a beam splitting apparatus. For such embodiments, the apparatus may allow the relative power of each of the output radiation beams to be controlled.

[0010] Alternatively, the apparatus may form a single output radiation beam and may allow the power of the output radiation beam to be controlled, i.e. the apparatus may form an attenuator.

[0011] Each of the plurality of portions may be provided with a grating structure configured such that when the input radiation beam is incident upon that portion it is diffracted so as to form a plurality of output radiation beams.

[0012] That is, the apparatus may be a beam splitting apparatus, which is arranged to split a single input radiation beam into a plurality of output radiation beams.

[0013] The grating structure of each of the plurality of portions may be formed from a plurality of unit cells. A length of the plurality of unit cells of each of the plurality of portions may be substantially equal and a shape of the plurality of unit cells of each of the plurality of portions may differ from a shape of the plurality of unit cells of the other portions.

5 **[0014]** A shape of the plurality of unit cells of the grating structure of each of the plurality of portions may be considered to be a property of that portion which differs from that of the other portions.

[0015] The relative power of the diffraction orders of a diffraction grating is dependent upon the shape of the unit cell of that grating structure. For a given direction of the input radiation beam with respect to the grating structure and a given wavelength of the input radiation beam, the
10 direction of the diffraction orders of a diffraction grating is dependent on the pitch of the grating, i.e. the length of its unit cells, and is independent of the shape of the unit cells. Therefore, such an arrangement, wherein each of the plurality of portions is provided with unit cells of substantially equal length but different shape, provides a beam splitting apparatus wherein the
15 relative power of the output radiation beams may be controlled whilst their directions remain fixed.

[0016] The shape of the plurality of unit cells of the grating structure of at least one of the plurality of portions may vary within that portion. Such an arrangement may allow for a large (continuous) range of relative powers of the output radiation beams because the layout of the
20 grating structure may vary continuously over the reflective surface.

[0017] Alternatively, the shape of the plurality of unit cells of the grating structure of at least one of the plurality of portions may be substantially constant within that portion. Such an arrangement may allow the intensity profile of the output radiation beams to more closely match that of the input radiation beam.

25 **[0018]** Each of the plurality of portions may be provided with a reflective surface configured such that when the input radiation beam is incident upon that portion it is reflected so as to form a single output radiation beam.

[0019] The single output radiation beam may be formed from specular reflection from the reflective surface of the portion. The output radiation beam may comprise radiation propagating
30 in generally a single direction. It will be appreciated that although only a single output radiation beam is produced, a portion of the input radiation beam may be scattered from the reflective surface via diffuse reflection and another portion of the input radiation beam may be absorbed by the reflective surface.

[0020] A reflectivity of the reflective surface of at least one of the plurality of portions may be different to the reflectivity of the reflective surface of at least one of the other portions. A reflectivity of the reflective surface of each of the plurality of portions may be considered to be a property of that portions which differs from that of the other portions.

5 **[0021]** The reflective surfaces of two or more of the plurality of portions may have different surface roughness.

[0022] Additionally or alternatively, the reflective surfaces of two or more of the plurality of portions may be formed from different materials.

[0023] Two or more of the plurality of portions may overlap.

10 **[0024]** Additionally or alternatively, two or more of the plurality of portions may be spatially separated.

[0025] The movement mechanism may be operable to move the optical element linearly.

[0026] Additionally or alternatively, the movement mechanism may be operable to rotate the optical element.

15 **[0027]** According to a second aspect of the invention there is provided a radiation system comprising: a radiation source operable to produce a main radiation beam; and the apparatus of the first aspect of the invention arranged to receive the main radiation beam at the beam receiving location and to output one or more output radiation beams from the beam receiving location.

20 **[0028]** According to a third aspect of the invention there is provided a beam splitting apparatus for receiving an input radiation beam at a beam receiving location and outputting a plurality of output radiation beams from the beam receiving location, the beam splitting apparatus comprising: an optical element with a plurality of portions for receiving the input radiation beam; a movement mechanism operable to move the plurality of portions so as selectively position
25 each of the plurality of portions at the beam receiving location; wherein each of the plurality of portions is provided with a grating structure configured such that when that portion is disposed in the beam receiving location it receives the input radiation beam and diffracts the input radiation beam so as to form the one or more output radiation beams; wherein the grating structure of each of the plurality of portions is formed from a plurality of unit cells, wherein a
30 length of the plurality of unit cells of each of the plurality of portions is substantially equal and wherein a shape of the plurality of unit cells of each of the plurality of portions differs from a shape of the plurality of unit cells of the other portions.

[0029] The relative power of the diffraction orders of a diffraction grating is dependent upon the shape of the unit cell of that grating structure. For a given direction of the input radiation beam

with respect to the grating structure and a given wavelength of the input radiation beam, the direction of the diffraction orders of a diffraction grating is dependent on the pitch of the grating, i.e. the length of its unit cells, and is independent of the shape of the unit cells. Therefore, the third aspect of the invention provides a beam splitting apparatus wherein the relative power of the output radiation beams may be controlled whilst their directions remain fixed.

[0030] According to a fourth aspect of the invention there is provided an apparatus for receiving an input radiation beam at a beam receiving location and outputting an output radiation beam from the beam receiving location, the apparatus comprising: an optical element with a plurality of portions for receiving the input radiation beam; a movement mechanism operable to move the plurality of portions so as selectively position each of the plurality of portions at the beam receiving location; wherein each of the plurality of portions is provided with a reflective surface configured such that when that portion is disposed in the beam receiving location it is configured to reflect the input radiation beam so as to form the output radiation beam; and wherein a reflectivity of the reflective surface of at least one of the plurality of portions is different to the reflectivity of the reflective surface of at least one of the other portions.

[0031] The fourth aspect of the invention provides an optical element that may form part of an optical path of a radiation beam and which allows the power of the radiation beam to be controlled.

[0032] According to a fifth aspect of the invention there is provided a beam splitting apparatus for receiving an input radiation beam at a beam receiving location and outputting a plurality of output radiation beams from the beam receiving location, the beam splitting apparatus comprising an optical element with a plurality of regions; wherein each of the plurality of regions is arranged to receive a different portion of the input radiation beam and is provided with a periodic structure configured such that the portion of radiation received by that region is diffracted so as to form a plurality of radiation sub-beams, each of the plurality of radiation sub-beams forming part of a different one of the output radiation beams; and wherein the periodic structure of each of the plurality of regions has a different a pitch.

[0033] For a given direction of the input radiation beam with respect to a grating structure, the direction of the diffraction orders of a diffraction grating is dependent on the pitch of the grating and the wavelength of the input radiation beam. The fifth aspect of the invention provides a beam splitting apparatus wherein the pitch varies across the grating. This variation may be matched to a variation in wavelength of an input radiation beam across its cross section to ensure that the intensity profile of the output radiation beams substantially matches that of the input radiation beam.

[0034] The plurality of regions may be generally defined by a plurality of concentric ellipses, each of the plurality of concentric ellipses forming a boundary of at least one of the plurality of regions.

[0035] A boundary between two adjacent regions may be jagged. This may reduce the level of speckle introduced into the output radiation beams.

[0036] According to a sixth aspect of the invention there is provided a radiation system comprising: a radiation source operable to produce a main radiation beam; and the beam splitting apparatus of the fifth aspect of the invention arranged to receive the main radiation beam at the beam receiving location and to output from the beam receiving location a plurality of output radiation beams.

[0037] The pitch of the periodic structure of each of the plurality of regions may be dependent on the wavelength distribution of the main radiation beam that across its cross section.

[0038] The pitch of the periodic structure of each of the plurality of regions may be dependent on the wavelength of the portion of the main radiation beam that is received by that region

[0039] The pitch of the periodic structure of each of the plurality of regions may be proportional to the wavelength of the portion of the main radiation beam that is received by that region, averaged over that region.

[0040] According to a seventh aspect of the invention there is provided a reflective diffraction grating comprising: an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam; wherein the geometry of the grating structure is such that, when the input radiation beam comprises EUV radiation: there is at least one direction of the input radiation beam for which all of the plurality of output radiation beams has substantially equal power; and the at least one direction is such that when the input radiation beam propagates along it the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam is substantially zero.

[0041] Such a reflective diffraction grating can function as a beam splitting apparatus that can be used to split a single input radiation beam into a plurality of output radiation beams, each with substantially equal power. The reflective diffraction grating may, for example, form part of an optical system that distributes radiation from a single radiation source to a plurality of different targets. For example, the reflective diffraction grating may form part of a beam delivery system of a lithographic system that receives radiation from a single radiation source and distributes the radiation to a plurality of different lithographic apparatus.

[0042] Furthermore, the reflective diffraction grating according to the seventh aspect of the invention allows for such splitting of a single input radiation beam into a plurality of substantially equal power output radiation beams in such a way the power each of the output radiation beams is relatively insensitive to the initial direction of the input radiation beam. This is particularly advantageous if the reflective diffraction grating forms part of an optical system that distributes radiation from a single radiation source to a plurality of different targets to which it is desirable to deliver a substantially constant dose of radiation. For example, if the reflective diffraction grating forms part of a beam delivery system of a lithographic system that distributes radiation to a plurality of different lithographic apparatus, it may be particularly useful since variations in the dose of energy delivered to a lithographic apparatus may affect the imaging performance of the lithographic apparatus.

[0043] It will be appreciated that in addition to the plurality of output radiation beams output by the optical surface, one or more additional radiation beams may be output. That is, one or more additional radiation beams may be output, which have a power that is not substantially equal to the power of the plurality of output radiation beams. Furthermore, it may be that the differential of the power of each of the additional radiation beams with respect to the direction of the input radiation beam is not substantially zero when the input radiation beam propagates along the at least one direction. For example, the grating structure may be suitable for producing a plurality of diffraction orders and it may be that only some of those diffraction orders are considered to belong to the plurality of output radiation beams.

[0044] In general, the power of different diffraction orders output by a diffraction grating will vary as a function of both the wavelength and the direction of the input radiation beam. For example, as a function of either one of these parameters, the output power of different diffraction orders may oscillate between local minima and maxima. At these local minima and maxima, the differential of the output power of different diffraction orders with respect to these parameters is zero. In between these local minima and maxima, the magnitude of the differential of the output power of different diffraction orders with respect to these parameters is a local maximum.

[0045] It will be appreciated that for the differential of the power of an output radiation beam with respect to the direction of the input radiation beam to be “substantially zero”, the direction should be at or close to a local minimum or maximum. This ensures that variations in the direction of the input radiation beam will result in a relatively small change in the output powers of the output radiation beams. How close to a local minimum or maximum it should be may depend on the expected variation in direction of the input radiation beam and the magnitude of variation in output power can be tolerated.

[0046] The differential of the power of an output radiation beam with respect to the direction of the input radiation beam may be considered to be substantially zero if it is closer to a local minimum/maxima than the adjacent maxima in the magnitude of the differential of the output power with respect to these parameters.

5 [0047] It will be appreciated that the seventh aspect of the invention includes reflective diffraction gratings with any suitable geometry for which there is at least one direction of the input radiation beam for which all of the plurality of output radiation beams have substantially equal power and at which the power of all of the plurality of output radiation beams is relatively insensitive to changes in the direction of the input radiation beam. Furthermore, it will be appreciated that there may be a large number of possible geometries which achieve this.

10 [0048] The skilled person will appreciate that in order to assess whether a reflective diffraction grating has a geometry that falls within the scope of the seventh aspect of the invention, the following procedure may be followed. The diffraction grating is illuminated with an input radiation beam at a plurality of directions and the power of each of the output radiation beams is measured. This allows the power of each of the plurality of output radiation beams to be determined as a function of the direction of the input radiation beam. This may, for example, be plotted as a distribution, which may be a two dimensional distribution (e.g. in terms of the polar and azimuthal angles of the input radiation beam). Alternatively, two (or more) one dimensional curves may be plotted.

20 [0049] All points where all of the distributions are equal (i.e. the distributions cross or meet) should be determined. These represent all of the directions of the input radiation beam for which all of the plurality of output radiation beams have equal power. Finally, for each such point it should be determined whether or not the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam is substantially zero.

25 [0050] The grating structure may be periodic and may comprise a plurality of parallel and equally spaced grooves extending across the reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves.

30 [0051] That is, the grating structure may be formed from grooves that are generally V-shaped in cross section. The shape of a grating structure may be characterised by its unit cell, the unit cell being the profile shape of the optical surface in a plane perpendicular to the direction of the grooves. The unit cell may be considered to extend from one part of one of the plurality of grooves to a corresponding part of an adjacent groove. For example, the unit cell of the grating

structure may comprise the generally flat face between two grooves, and the two generally flat faces of one of the grooves.

[0052] The reflective surface may therefore be considered to comprise three groups of reflective faces. The faces within each group may be substantially mutually parallel and the faces are disposed at a non-zero angle to the faces from different groups. The generally flat faces between each pair of adjacent grooves may be considered to be a first group of faces and may define a plane. A first one of the two generally flat faces of each of the grooves may be considered to be a second group of reflective faces and a second one of the two generally flat faces of each of the grooves may be considered to be a third group of reflective faces.

[0053] The extent of the unit cell in the plane perpendicular to the direction of the grooves may be referred to as the pitch of the grating structure. The extent of the generally flat face between each pair of adjacent grooves in the plane perpendicular to the direction of the grooves may be referred to as the spacing between the pair of adjacent grooves. A ratio of the spacing between each pair of adjacent grooves to the pitch of the grating structure may be referred to as the duty cycle of the grating structure.

[0054] The diffraction grating may be formed from a crystalline material and each face of the reflective surface may correspond to a crystal plane within said crystalline material.

[0055] There may be three output radiation beams. The three output radiation beams may correspond to the 0th order and the $\pm 1^{\text{st}}$ order diffraction beams.

[0056] The grating structure may have a pitch of approximately 880 nm, the two generally flat converging faces of each of the grooves may be at an angle of approximately 70.5° and a depth of each groove may be approximately 542 nm. Such an arrangement may be suitable for use with an input radiation beam with a wavelength of 13.5 nm and at a grazing incidence angle of around 1° (i.e. an angle of incidence of around 89°).

[0057] There may be two output radiation beams. The two output radiation beams may correspond to the $\pm 1^{\text{st}}$ order diffraction beams. This may be achieved by suppression of the 0th order diffraction beam.

[0058] The grating structure may have a pitch of approximately 1240 nm, the two generally flat converging faces of each of the grooves may be at an angle of approximately 109.5° and a depth of each groove may be approximately 490 nm. Such an arrangement may be suitable for use with an input radiation beam with a wavelength of 13.5 nm and at a grazing incidence angle of around 1° (i.e. an angle of incidence of around 89°).

[0059] The at least one direction of the input radiation beam may correspond to an angle of incidence in range 85° to 90°.

[0060] When the input radiation beam propagates along the at least one direction the plane of incidence may be parallel to the direction along which the plurality of grooves extends.

[0061] The geometry of the grating structure may be such that the at least one direction exists when the input radiation beam comprises radiation with a wavelength around 13.5 nm.

5 **[0062]** According to an eighth aspect of the invention there is provided a reflective diffraction grating comprising: an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam; wherein the grating structure is
10 periodic and comprises a plurality of parallel and equally spaced grooves extending across the reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves; and wherein the grating structure has a pitch of approximately 880 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 70.5° and a depth of each groove is
15 approximately 542 nm.

[0063] Such an arrangement may be suitable for use with an input radiation beam with a wavelength of 13.5 nm and at a grazing incidence angle of around 1° (i.e. an angle of incidence of around 89°) to produce three output radiation beams.

[0064] According to a ninth aspect of the invention there is provided a reflective diffraction
20 grating comprising: an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam; wherein the grating structure is periodic and comprises a plurality of parallel and equally spaced grooves extending across the
25 reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves; and wherein the grating structure has a pitch of approximately 1240 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 109.5° and a depth of each groove is approximately 490 nm.

30 **[0065]** The reflective diffraction grating may be formed from a crystalline material and each face of the reflective surface may correspond to a crystal plane within said crystalline material.

[0066] The diffraction grating is provided with a reflective coating.

[0067] According to a tenth aspect of the invention there is provided a radiation system comprising: a radiation source operable to provide an input radiation beam; an optical element

having an optical surface for receiving the input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams; wherein the optical element and the input radiation beam are arranged such that the differential of the power of each of the plurality of output radiation beams with respect to a direction of the input radiation beam is substantially zero.

[0068] The radiation source may be operable to produce the input radiation beam and may, for example, comprise a free electron laser. Alternatively, the radiation source may comprise an optical element that is configured to direct the radiation beam towards the beam splitting apparatus. For example, the radiation source may comprise another beam splitting apparatus and the input radiation beam may be an output radiation beam output by said beam splitting apparatus.

[0069] The optical element and the input radiation beam may also be arranged such that all of the plurality of output radiation beams have substantially equal power.

[0070] The optical element may comprise the reflective diffraction grating of any one of the seventh, eighth or ninth aspects of the invention.

[0071] The input radiation beam may comprise EUV radiation. The input radiation beam may comprise radiation with a wavelength around 13.5 nm.

[0072] The optical element and the input radiation beam may be arranged such that the input radiation beam is incident upon the optical element at an angle of incidence in range 85° to 90°.

[0073] The optical element and the input radiation beam may be arranged such that the plane of incidence is parallel to the direction along which the plurality of grooves extends.

[0074] According to an eleventh aspect of the invention there is provided a method of designing a diffraction grating for receiving an input radiation beam and outputting a plurality of diffraction orders, the method comprising: selecting a general shape of the diffraction grating, the general shape having at least one parameter, the specific shape of the diffraction grating being dependent on said at least one parameter; for a given wavelength of the input radiation beam for which the diffraction grating may be used, determining a set of values for the at least one parameter for which the geometry of the grating structure is such that: there is at least one direction of the input radiation beam for which a plurality of the output diffraction orders has substantially equal power; and the at least one direction is such that when the input radiation beam propagates along it the differential of the power of each of the plurality of output diffraction orders with respect to the direction of the input radiation beam is substantially zero.

[0075] 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.

5 BRIEF DESCRIPTION OF THE DRAWINGS

[0076] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 is a schematic illustration of a lithographic system comprising a free electron laser according to an embodiment of the invention;
- 10 - Figure 2 is a schematic illustration of a lithographic apparatus that forms part of the lithographic system of Figure 1;
- Figure 3 is a schematic illustration of a free electron laser that forms part of the lithographic system of Figure 1;
- Figure 4 is a schematic illustration of a first apparatus according to an embodiment of
15 the invention, which may form part of a beam delivery system of the lithographic system of Figure 1;
- Figure 5 is a schematic illustration of a first embodiment of an optical element, which may form part of the apparatus of Figure 4.
- Figure 6 is a cross sectional view of a portion of a reflective surface of the optical
20 element of Figure 5 in the x-z plane;
- Figure 7A is a plan view of a first embodiment of a reflective surface of the optical element of Figure 5;
- Figure 7B is a plan view of a second embodiment of a reflective surface of the optical element of Figure 5;
- 25 - Figure 8 is a schematic illustration of a second embodiment of an optical element, which may form part of the apparatus of Figure 4.
- Figure 9A is a schematic illustration of a variant of the optical element shown in Figure 8;
- Figure 9B is a schematic illustration of another variant of the optical element shown in Figure 8;
- 30 - Figure 10 is a schematic illustration of a beam splitting apparatus according to an embodiment of the invention, which may form part of a beam delivery system of the lithographic system of Figure 1;
- Figure 11 is a plan view of a first embodiment of an optical element of the beam splitting apparatus of Figure 10;

- Figure 12 is a plan view of a second embodiment of an optical element of the beam splitting apparatus of Figure 10;

- Figure 13a is a schematic perspective view of an embodiment of an optical element, which may form part of a beam splitting apparatus;

5 - Figure 13b is a plan view of the optical element of Figure 13a;

- Figure 13c is a side view of the optical element of Figure 13a;

- Figure 14 is a cross sectional view of a portion of a reflective surface of the optical element of Figures 13a-13c in the x-z plane;

10 - Figure 15 shows, for a first embodiment of a grating geometry, the output power distribution for: the 0th order diffraction beam (dashed line), the $\pm 1^{\text{st}}$ order diffraction beams (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ (for an azimuthal angle $\varphi=90^\circ$);

15 - Figure 16 shows, for the same grating geometry used for Figure 15, the output power distribution for: the 0th order diffraction beam (dashed line), the +1st order diffraction beam (dot-dot-dashed line), the -1st order diffraction beam (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ for a deviation in azimuthal angle of 0.01° from the nominal value (90°); and

20 - Figure 17 shows, for a second embodiment of a grating geometry, the output power distribution for: the 0th order diffraction beam (dashed line), the $\pm 1^{\text{st}}$ order diffraction beams (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ (for an azimuthal angle $\varphi=90^\circ$).

25 DETAILED DESCRIPTION

[0077] 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 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 B (which may
30 be referred to as a main beam).

[0078] The beam delivery system BDS comprises beam splitting optics and may optionally also comprise beam expanding optics and/or beam shaping optics. The main radiation beam B 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.

[0079] The optional beam expanding optics (not shown) are arranged to increase the cross sectional area of the radiation beam B. Advantageously, this decreases the heat load on mirrors downstream of the beam expanding optics. This may allow the mirrors downstream of the beam expanding optics to be of a lower specification, with less cooling, and therefore less expensive. Additionally or alternatively, it may allow the downstream mirrors to be nearer to normal incidence. For example, the beam expanding optics may be operable to expand the main beam B from around 1 mm to more than 1 cm before the main beam B is split by the beam splitting optics.

[0080] 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 .

[0081] 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).

[0082] Referring to Figure 2, a lithographic apparatus LA_a comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g. a mask), a projection system PS and a substrate table WT configured to support a substrate W. The illumination system IL is configured to condition the branch radiation beam B_a that is received by that lithographic apparatus LA_a before it is incident upon the patterning device MA. The projection system PS is configured to project the radiation beam B_a' (now patterned by the patterning device MA) onto the substrate W. The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus aligns the patterned radiation beam B_a' with a pattern previously formed on the substrate W.

[0083] The branch radiation beam B_a that is received by the lithographic apparatus LA_a passes into the illumination system IL from the beam delivery system BDS through an opening 8 in an enclosing structure of the illumination system IL. Optionally, the branch radiation beam B_a may be focused to form an intermediate focus at or near to the opening 8.

[0084] The illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 together provide the radiation beam B_a with a desired cross-sectional shape and a desired angular distribution. The radiation beam B_a passes from the illumination system IL and is incident upon the patterning device MA held by the support structure MT. The patterning device MA reflects and patterns the radiation beam to form a patterned beam B_a' . The illumination system IL may include other mirrors or devices in addition to or instead of the faceted field mirror device 10 and faceted pupil mirror device 11. The illumination system IL may for example include an array of independently moveable mirrors. The independently moveable mirrors may for example measure less than 1mm across. The independently moveable mirrors may for example be microelectromechanical systems (MEMS) devices.

[0085] 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).

[0086] 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).

[0087] Referring again to Figure 1, the radiation source SO is configured to generate an EUV radiation beam B 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.

[0088] Figure 3 is a schematic depiction of a free electron laser FEL comprising an injector 21, a linear accelerator 22, a bunch compressor 23, an undulator 24, an electron decelerator 26 and a beam dump 100.

[0089] The injector 21 is arranged to produce a bunched electron beam E and comprises an electron source (for example a thermionic cathode or a photo-cathode) and an accelerating electric field. Electrons in the electron beam E are further accelerated by the linear accelerator 22. In an example, the linear accelerator 22 may comprise a plurality of radio frequency cavities, which are axially spaced along a common axis, and one or more radio frequency power sources, which are operable to control the electromagnetic fields along the common axis as bunches of electrons pass between them so as to accelerate each bunch of electrons. The cavities may be superconducting radio frequency cavities. Advantageously, this allows: relatively large electromagnetic fields to be applied at high duty cycles; larger beam apertures, resulting in fewer losses due to wakefields; and for the fraction of radio frequency energy that is transmitted to the beam (as opposed to dissipated through the cavity walls) to be increased. Alternatively, the cavities may be conventionally conducting (i.e. not superconducting), and may be formed from, for example, copper. Other types of linear accelerators may be used such as, for example, laser wake-field accelerators or inverse free electron laser accelerators.

[0090] 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.

[0091] 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.

[0092] 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.

[0093] As electrons move through each undulator module, they interact with the electric field of the radiation, exchanging energy with the radiation. In general the amount of energy exchanged between the electrons and the radiation will oscillate rapidly unless conditions are close to a resonance condition. Under resonance conditions, the interaction between the electrons and the radiation causes the electrons to bunch together into microbunches, modulated at the wavelength of radiation within the undulator, and coherent emission of radiation along the central axis is stimulated. The resonance condition may be given by:

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

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

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

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

[0094] 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.

[0095] 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.

[0096] 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 through the undulator 24. The tapering may be achieved by varying the amplitude of the periodic magnetic field and/or the undulator period λ_u within each undulator module and/or from module to module. Additionally or alternatively tapering may be achieved by varying the helicity of the undulator 24 (by varying the parameter A) within each undulator module and/or from module to module.

[0097] 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.

[0098] 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.

[0099] For example, generally, for helical undulator modules the electron beam E should be substantially aligned with the central axis of the undulator module. A tilt or angle between the electron beam E and the central axis of the undulator module (in radians) should generally not exceed $\rho/10$, where ρ is the FEL Pierce parameter. Otherwise the conversion efficiency of the undulator module (i.e. the portion of the energy of the electron beam E which is converted to radiation in that module) may drop below a desired amount (or may drop almost to zero). In an embodiment, the FEL Pierce parameter of an EUV helical undulator module may be of the order of 0.001, indicating that the tilt of the electron beam E with respect to the central axis of the undulator module should be less than 100 μ rad.

[00100] 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.

[00101] 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.

[00102] 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.

5 **[00103]** Radiation produced within the undulator 24 is output as a radiation beam B_{FEL} .

10 **[00104]** After leaving the undulator 24, the electron beam E is absorbed by a dump 100. The dump 100 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 100 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 100. This removes, or at least reduces, the need to remove and dispose of radioactive waste from the dump 100. 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.

15 **[00105]** The energy of electrons in the electron beam E may be reduced before they enter the dump 100 by directing the electron beam E through a decelerator 26 disposed between the undulator 24 and the beam dump 100.

20 **[00106]** In an embodiment the electron beam E which exits the undulator 24 may be decelerated by passing the electrons back through the linear accelerator 22 with a phase difference of 180 degrees relative to the electron beam produced by the injector 21. The RF fields in the linear accelerator therefore serve to decelerate the electrons which are output from the undulator 24 and to accelerate electrons output from the injector 21. As the electrons decelerate in the linear accelerator 22 some of their energy is transferred to the RF fields in the linear accelerator 22. Energy from the decelerating electrons is therefore recovered by the linear accelerator 22 and may be used to accelerate the electron beam E output from the injector 21. Such an arrangement is known as an energy recovery linear accelerator (ERL).

25 **[00107]** Figure 4 shows an apparatus 200 according to an embodiment of the invention. The apparatus 200 may for example form part of the beam delivery system BDS of Figure 1. The apparatus 200 comprises an optical element 205 and a movement mechanism 220. The movement mechanism 220 is operable to move the optical element 205 (as indicated by arrow

D₁) through a range of different positions (as indicated schematically by the two dashed boxes, each of which depicts a different position of the optical element 205).

[00108] A first embodiment of an optical element 210, which may be the optical element 205 of apparatus 200 is illustrated schematically in Figure 5. Optical element 210 comprises a reflective surface 212 and is suitable for receiving an input radiation beam B_{in}. The reflective surface 212 lies generally in a plane (x-y plane in Figure 5). In use, the optical element 210 is arranged to receive the input radiation beam B_{in} at a beam receiving location 230 and to output a plurality of radiation beams B₁, B₂, B₃ from the beam receiving location 230. Therefore, for embodiments wherein apparatus 200 comprises optical element 210, apparatus 200 forms a beam splitting apparatus. The input radiation beam B_{in} may, for example, comprise the radiation beam B_{FEL} output by the free electron laser FEL in Figure 3.

[00109] The input radiation beam B_{in} is incident upon the reflective surface at a grazing incidence angle β . The grazing incidence angle β is the angle between the input radiation beam B_{in} and the reflective surface. The grazing incidence angle β may, for example, be less than 5°, for example, around 2° or even less, for example around 1°. The input radiation beam B_{in} may be generally circular in cross section and may therefore irradiate a generally elliptical region of the reflective surface 212. This generally elliptical region may be referred to as a beam spot region. The beam spot region comprises a portion of the reflective surface 212 which is disposed in the beam receiving location 230. The dimensions of the beam spot region are determined by the diameter of the input radiation beam B_{in} and the grazing incidence angle β . The length of the minor axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} whereas the length of the major axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} divided by $\sin(\beta)$. The orientation of the beam spot region is dependent upon the direction of the input radiation beam B_{in}. In the example embodiment shown in Figure 5, the major axis of the beam spot region is aligned with the y-direction and the minor axis of the beam spot region is aligned with the x-direction.

[00110] The beam receiving location 230 may be defined by a nominal, expected or desired direction and position of the input radiation beam B_{in} relative to the plane of the reflective surface 212 (i.e. the x-y plane). For example, the beam receiving location 230 may be defined as the intersection between a nominal, expected or desired input radiation beam B_{in} and the x-y plane. This may comprise an elliptical region in the x-y plane. A portion of the optical element 210 (the beam spot region of reflective surface 212) is positioned in the beam receiving location 230.

[00111] The movement mechanism 220 is operable to move the optical element 210 relative to the beam receiving location 230. In particular, movement mechanism 220 is operable to move the optical element 210 linearly in the positive or negative x-direction, as indicated by arrow D_2 . The direction in which the movement mechanism 220 is operable to move the optical element 210 (i.e. the x-direction) may be referred to as the movement direction of the apparatus 200. As the movement mechanism 220 moves the optical element 210 the portion of the optical element 210 which is positioned in the beam receiving location 230 changes. Equivalently, as the movement mechanism 220 moves the optical element 210, the beam receiving location 230 may be considered to move over the reflective surface 212.

[00112] The optical element 210 may be considered to comprise a plurality of portions for receiving the input radiation beam. Each of the plurality of portions may be a region of the reflective surface that can receive the input radiation beam B_{in} . That is, each of the plurality of portions may comprise an elliptical region of the reflective surface 212, the dimensions of which match (or are larger than) those of the beam receiving location 230. Alternatively, each of the plurality of portions may comprise a rectangular region of the reflective surface 212, with a dimension in the movement direction (i.e. the x-direction) which matches, or is larger than, that of the minor axis of the beam receiving location 230 and a dimension in the orthogonal direction (i.e. the y-direction) which matches, or is larger than, that of the major axis of the beam spot region/the beam receiving location 230.

[00113] As the movement mechanism moves the optical element 210 the plurality of portions move so that each of the plurality of portions can be selectively positioned at the beam receiving location 230.

[00114] When one of the plurality of portions is disposed in the beam receiving location 230 it is configured to receive the input radiation beam B_{in} and to scatter the input radiation beam B_{in} so as to form the output radiation beams B_1 , B_2 , B_3 . In particular, when the input radiation beam B_{in} is incident on one of the plurality of portions it is diffracted such that, in the far field, the output radiation beams B_1 , B_2 , B_3 are spatially separated, as now described. To achieve this, the reflective surface 212 is not flat but rather is provided with a grating structure. That is, the reflective surface 212 does not lie solely in the x-y plane but has some modulation in a direction normal to the x-y plane. Therefore, each of the plurality of portions of the reflective surface 212 may be considered to be provided with a grating structure configured such that when the input radiation beam is incident upon that portion, it is diffracted so as to form a plurality of output radiation beams B_1 , B_2 , B_3 . In this embodiment output radiation beam B_2 corresponds to the 0th order diffraction beam and output radiation beams B_1 and B_3 correspond

to the $\pm 1^{\text{st}}$ order diffraction beams. In other embodiments, a different number of radiation beams B_1, B_2, B_3 may be output from the beam receiving location 230. For example, in one embodiment five radiation beams may be output from the beam receiving location 230 and the five output radiation beams may correspond to the $0^{\text{th}}, \pm 1^{\text{st}}, \pm 2^{\text{nd}}$ order diffraction beams.

5 **[00115]** The grating structure comprises a plurality of grooves 92 extending across reflective surface 212. The grooves 92 may be formed by any suitable process such as, for example, etching, stamping or electroforming. The grooves 92 may have any profile shape, i.e. the cross sectional shape of the grooves 92 in a plane perpendicular to the direction that they extend along may have any shape.

10 **[00116]** In one embodiment (as now described), the grooves 92 are formed from a plurality of generally flat faces. A cross section of a portion of the reflective surface 212 in the x-z plane for such an embodiment is shown in Figure 6.

15 **[00117]** The grooves 92 form a plurality of ridges 95, dividing the reflective surface 212 into three groups of reflective faces. Top faces of each ridge 95 form a first group of faces S_1 , left-hand sides of each ridge 95 form a second group of faces S_2 and right-hand sides of each ridge 95 form the third group of faces S_3 . The grooves 92 therefore divide the reflective surface 212 into a plurality of groups of reflective faces, wherein the faces within each group are substantially parallel, but at different angles with respect to the faces of each other group. That is, the faces within a particular group each have a particular orientation which is different to
20 faces in other groups.

[00118] It will be appreciated that other groove profiles may alternatively be used. For example, in an alternative embodiment, the profile of the grooves may comprise one or more curved sections.

25 **[00119]** The grating structure may be considered to be formed from a plurality of unit cells 96. The unit cell 96 may be the local profile shape of the grooves 92, i.e. the cross sectional shape of the grooves 92 in a plane perpendicular to the direction that they extend along at a given location on the reflective surface 212 (in the x-direction). Each unit cell 96 may extend from one part of a groove 92 or ridge 95 to a corresponding part of an adjacent groove 92 or ridge 95. For example, each unit cell 96 may comprise a top face S_1 of a ridge 95, a left-hand
30 face S_2 of a ridge 95 and a right hand face S_3 of a ridge 95 (the three faces being adjacent to each other).

[00120] A conventional diffraction grating comprises a uniform unit cell. That is, the size and shape of each unit cell across a conventional diffraction grating are uniform and, as a result,

the grating structure is periodic. The width of the unit cell of a conventional diffraction grating may be referred to as its pitch.

[00121] Embodiments of the invention comprise a modified grating structure wherein the unit cell 96 varies across the reflective surface 212 (in the x-direction). A width (in the x-direction) of each of the plurality of unit cells 96 is substantially uniform. The width w of the unit cell 96 of the grating structure may, for example, be of the order of around $1\text{ }\mu\text{m}$. However, a shape of the plurality of unit cells 96 of each portion of the reflective surface 212 differs from a shape of the plurality of unit cells of the other portions. This may be achieved by varying the width w_1 of the S_1 faces (in the x-direction) whilst the width w of the unit cell 96 of the grating structure remains fixed. The width w_1 of the S_1 faces may, for example, be in the range of $0.10\text{ }\mu\text{m}$ to $0.50\text{ }\mu\text{m}$.

[00122] The relative powers of the output radiation beams B_1 , B_2 , B_3 are dependent upon the shape of the unit cells 96 within the beam spot region (i.e. the portion of the reflective surface 212 disposed in the beam receiving location). For a given direction of the input radiation beam B_{in} with respect to the grating structure (i.e. grooves 92) and a given wavelength of the input radiation beam B_{in} , the direction of the diffraction orders of a diffraction grating is dependent on the pitch of the grating, i.e. the width w of its unit cells 96, and is independent of the shape of the unit cells. In particular, the ratios of intensities of the branch radiation beams are dependent on the ratio of the width w_1 of the S_1 faces (in the x-direction) to the width w of the unit cell 96 pitch of the grating structure. The percentage of the width of the unit cell 96 (in the x-direction) which is formed by the top face S_1 may be referred to as the "duty cycle" of the grating structure. As explained above, embodiments of the invention comprise grating structures with a duty cycle which changes over the reflective surface 212.

[00123] The range of powers of each of the output radiation beams B_1 , B_2 , B_3 is dependent upon the range of duty cycles across the grating structure and the grazing incidence angle β of the input radiation beam B_{in} . In one embodiment, the width w of the unit cell 96 of the grating structure is $1\text{ }\mu\text{m}$, the wavelength of the input radiation beam B_{in} is 13.5 nm and the grazing incidence angle β is 1.1° . For such an embodiment, a duty cycle of 26% may result in an even distribution of power between the output radiation beams B_1 , B_2 , B_3 (i.e. each beam receives 33% of the power output by the optical element 210). A duty cycle of 22% may result in the 0th order beam B_2 receiving 39% of the power and each of the $\pm 1^{\text{st}}$ order diffraction beams B_1 , B_3 receiving 29% of the power output by the optical element 210. That is, a 15% (relative) decrease in the duty cycle yields an 18% (relative) increase in the power of the 0th order beam B_2 and a 9% (relative) decrease of the power of each of the $\pm 1^{\text{st}}$ order beams B_1 , B_3 . From this,

one might expect that in order to control the power of the 0th order beam B_2 by $\pm 30\%$, the grating structure should vary by $\pm 25\%$ over the reflective surface 212. A duty cycle of 10% may result in the 0th order beam B_2 receiving 80% of the power and each of the $\pm 1^{\text{st}}$ order diffraction beams B_1, B_3 receiving 10% of the power output by the optical element 210.

5 [00124] Therefore, optical element 210, which comprises a plurality of portions, each provided with unit cells 96 of substantially equal length but different shape, provides a beam splitting apparatus 200 wherein the relative power of the output radiation beams B_1, B_2, B_3 may be controlled whilst their directions remain fixed. That is, a direction of each of the output radiation beams B_1, B_2, B_3 formed by each of the plurality of portions of reflective surface 212 is
10 substantially the same as a direction of a corresponding output radiation beam formed by each of the other portions of reflective surface 212.

[00125] The shape of the plurality of unit cells 96 of the grating structure of each of the plurality of portions may be considered to be a property of that portion which differs from that of the other portions. Further, this property of each of the plurality of portions differs from that of
15 the other portions such that a power of the output radiation beams B_1, B_2, B_3 formed by each of the plurality of portions is different to that of the corresponding output radiation beam B_1, B_2, B_3 formed by at least one of the other portions.

[00126] The reflective surface 212 may comprise any suitable number of grooves 92. The number of grooves 92 is determined by the width w of the unit cell 96 of the grating
20 structure and the dimension of the reflective surface 212 in the movement direction (i.e. the x -direction). In one example embodiment, the reflective surface 212 may comprise of the order of 1000 grooves 92 across the beam spot region.

[00127] The output radiation beams B_1, B_2, B_3 may have an intensity distribution in the far field (e.g. at a lithographic tool LA_1 - LA_n) that is substantially similar to the intensity distribution of
25 the input radiation beam B_{in} , which may be desirable.

[00128] In the described example embodiment the grooves 92 extend generally in the y -direction. That is, the grooves 92 are generally parallel to the plane of incidence of input radiation beam B_{in} (which is the plane containing the incoming radiation beam B_{in} and the normal to the reflective surface 212, i.e. the z direction). Since the direction perpendicular to the
30 grooves (i.e. the x -direction) is not in the plane of incidence of input radiation beam B_{in} , the grating results in conical diffraction, with the output radiation beams B_1, B_2, B_3 lying on a cone. In an alternative embodiment the grooves may extend generally perpendicular to the direction of propagation of the input radiation beam B_{in} such that the output radiation beams B_1, B_2, B_3 lie in a plane.

[00129] Apparatus 200 may form part of an optical system for a radiation beam. For example, the apparatus 200 may form part of a beam delivery system BDS for a lithographic system LS, which may direct radiation from one or more radiation sources SO to one or more lithographic apparatus LA₁-LA_n. Apparatus 200 allows for control over the power of one or more radiation beams (e.g. output radiation beams B₁, B₂, B₃) whilst maintaining the directions of the radiation beams. Advantageously, as a result other optical elements within the optical system do not need to move when a power of one or more of the radiation beams is altered.

[00130] The optical element 210 can be formed from silicon by, for example, anisotropic etching along crystal planes of a silicon wafer. For example, the top faces S₁ may be formed along the (100) crystallographic plane and the faces S₂, S₃ may be formed along the (111) and (-111) crystallographic planes. In this case, the angle 93 at the bottom of the grooves will be approximately 70.5° and the grooves 92 and ridges 95 will extend along the (01-1) direction. It will be appreciated that various layouts are possible depending on the (h k l) numbers describing the top faces S₁.

[00131] A grating in which the top faces S₁ are formed along the (100) crystallographic plane and the faces S₂, S₃ are formed along the (111) and (-111) crystallographic planes form the plurality of (e.g. three) output radiation beams. The number of output radiation beams is dependent upon the number of diffraction orders that are present. In turn, the number of diffraction orders present is dependent on the grazing incidence angle of the input radiation beam B_{in} since larger grazing incidence angles enable more diffraction orders.

[00132] The optical element 210 may be provided with a coating of a more reflective (less absorbing) material (for EUV radiation). For example, the mirror may be provided with a coating of ruthenium (Ru) or molybdenum (Mo). This may, for example, have a thickness of around 50 nm.

[00133] As explained above, optical element 210 comprises a plurality of portions for receiving the input radiation beam B_{in}, each portion being provided with a grating structure (i.e. grooves 92) wherein a shape of the unit cells 96 of the grating structure of each of the plurality of portions differs from that of the other portions.

[00134] In one embodiment, the plurality of unit cells 96 of the grating structure of the plurality of portions varies within one or more of the portions. For such embodiments, the plurality of portions of the optical element 210 may overlap each other. This is illustrated in Figure 7A, wherein three portions 214a-214c of the reflective surface 212 of optical element are shown. Two of the portions 214a, 214b overlap in extent in the movement direction (i.e. the x-direction) of the optical element 210. Although (for clarity) only three portions 214a-214c of the

reflective surface 212 of optical element 210 are shown in Figure 7A, it will be appreciated that such embodiments may comprise a significantly larger number of overlapping portions.

[00135] The shape of the unit cells 96 across may continuously vary across the reflective surface 212 as a function of the movement direction. That is, the cross sectional profile of the grating structure in a plane perpendicular to the direction of the grooves 92 (i.e. the x-z plane) gradually changes in the movement direction (i.e. the x direction). For example, the width w of the unit cell 96 of the grating structure may be constant and may, for example, be $1\text{ }\mu\text{m}$ and the width w_1 of the S_1 faces (in the x-direction) may vary from $0.10\text{ }\mu\text{m}$ at one side of the reflective surface 212 to $0.50\text{ }\mu\text{m}$ at an opposite side of the reflective surface 212.

[00136] An advantage of the embodiment shown in Figure 7A is that it offers a large (continuous) range of relative powers of the output radiation beams B_1 , B_2 , B_3 because the layout of the grating structure varies continuously over the reflective surface 212. For such embodiments, the grating structure varies over the beam spot region and therefore a small variation in the power distribution of each of the output radiation beams B_1 , B_2 , B_3 is also introduced over the cross section of each output radiation beam B_1 , B_2 , B_3 . In particular, for such embodiments, the beam profile of each of the output radiation beams B_1 , B_2 , B_3 will be given by the beam profile of the input radiation beam B_{in} multiplied with a tilt. For embodiments wherein the output radiation beams B_1 , B_2 , B_3 are supplied to lithographic apparatus LA_1 - LA_n , the illumination system IL of each lithographic tool LA_1 - LA_n may be operable to correct for such a tilt introduced in a branch radiation beam B_1 - B_n .

[00137] The magnitude of the tilt introduced in the beam profile of the output radiation beams B_1 , B_2 , B_3 scales with the rate of change of the grating layout in the movement direction. For a fixed dimension of the optical element 210 in the movement direction (i.e. the x-direction) the larger the total change in the grating layout across the reflective surface 212, the larger the range of relative powers of output radiation beams B_1 , B_2 , B_3 and the larger the tilt will be. For a given range of relative powers of output radiation beams B_1 , B_2 , B_3 the tilt can be minimized by maximising the dimension of the optical element 210 in the movement direction (i.e. the x-direction). That is, by increasing the length of the optical element 210 (in the x-direction) the tilt introduced in the beam profile of the output radiation beams B_1 , B_2 , B_3 is reduced (for a given range of relative powers of output radiation beams B_1 , B_2 , B_3). In one example embodiment, the dimension of the optical element 210 in the movement direction (i.e. the x-direction) is a factor of ten greater than the beam spot region in the movement direction. For example, in the movement direction the beam spot region may be of the order of 5 mm and the optical element may be of the order of 50 mm .

[00138] For embodiments wherein the output radiation beams B_1 , B_2 , B_3 are supplied to lithographic apparatus LA_1 - LA_n that are operable to be used in a scan mode, the tilt introduced by the apparatus 200 may not need to be corrected by the illumination system IL of the lithographic apparatus LA_1 - LA_n if the tilt is introduced in scanning direction of the lithographic apparatus LA_1 - LA_n . Such embodiments may achieve a relatively large range of relative powers of output radiation beams B_1 , B_2 , B_3 with a relatively small dimension of the optical element 210 in the movement direction. Whether or not the tilt is introduced in the scanning direction of the lithographic apparatus LA_1 - LA_n depends on the optical path between the optical element 210 and the entrance to the lithographic apparatus LA_1 - LA_n (i.e. opening 8 in Figure 2).

[00139] In an alternative embodiment, the plurality of unit cells 96 of the grating structure of the plurality of portions may be substantially constant within that portion. For such embodiments, the plurality of portions of the optical element 210 may be spatially separated from each other. Such an arrangement is illustrated in Figure 7B, wherein six discrete portions 214a-214e of the reflective surface 212 of optical element 210 are shown.

[00140] An advantage of the embodiment of Figure 7B (over the continuous layout of the embodiment shown in Figure 7A) is that no tilt is introduced in the output radiation beams B_1 , B_2 , B_3 . This embodiment allows one of a plurality of (discrete) relative powers of the output radiation beams B_1 , B_2 , B_3 to be selected by shifting the optical element 210 grating in discrete steps in the movement direction. For such embodiments, the grating structure of optical element 210 may comprise a plurality of separate gratings (which may form separate reflective surfaces), mounted on a common body that the movement mechanism 220 is operable to move. The body may, for example, comprise a generally flat substrate that can be moved linearly in a movement direction. Alternatively, the body may comprise a plurality of generally flat faces, each of the plurality of separate gratings being provided on a different one of the faces. For such embodiments, the movement mechanism 220 may be operable to vary the position and/or orientation of the body so as to selectively position each of the separate gratings in a beam receiving location. For example, the body may be generally of the form of a prism (i.e. a polyhedron with two opposed polygonal faces and a plurality of rectangular faces extending therebetween) and each of the plurality of separate gratings may be provided on a different face of the prism. For example, the prism may comprise two opposed hexagonal faces and six rectangular faces extending therebetween). Each of the plurality of separate gratings may be provided on a different one of the rectangular faces. The movement mechanism 220 may be operable to rotate the prism about its axis so as to index through the separate gratings so as to selectively position each of the separate gratings in a beam receiving location.

[00141] It will be appreciated that while the optical element 200 is arranged to split an input radiation beam B_{in} into three branch radiation beams, gratings may be provided which split a radiation beam into a different number of branch radiation beams. Generally, a grating may be provided which splits a radiation beam into two or more branch radiation beams.

5 **[00142]** A second embodiment of an optical element 310, which may be the optical element 205 of apparatus 200 is illustrated schematically in Figure 8. Optical element 310 comprises a reflective surface 312 and is suitable for receiving an input radiation beam B_{in} . The reflective surface 312 lies generally in a plane (x-y plane in Figure 8). In use, the optical element 310 is arranged to receive the input radiation beam B_{in} at a beam receiving location 330 and to output a single radiation beam B_{out} from the beam receiving location 330. The input radiation beam B_{in} may, for example, comprise one of the branch radiation beams B_a - B_n that is directed to a lithographic apparatus LA_a - LA_n . Optical element 310 may form part of an attenuator 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 .

15 **[00143]** The input radiation beam B_{in} is incident upon the reflective surface 312 at a grazing incidence angle β . The grazing incidence angle β is the angle between the input radiation beam B_{in} and the reflective surface 312. The grazing incidence angle β may, for example, be less than 5° , for example, around 2° or even less, for example around 1° . The input radiation beam B_{in} may be generally circular in cross section and may therefore irradiate a generally elliptical region of the reflective surface 312. This generally elliptical region may be referred to as a beam spot region. The beam spot region comprises a portion of the reflective surface 312 which is disposed in the beam receiving location 330. The dimensions of the beam spot region are determined by the diameter of the input radiation beam B_{in} and the grazing incidence angle β . The length of the minor axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} whereas the length of the major axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} divided by $\sin(\beta)$. The orientation of the beam spot region is dependent upon the direction of the input radiation beam B_{in} . In the example embodiment shown in Figure 8, the major axis of the beam spot region is aligned with the y-direction and the minor axis of the beam spot region is aligned with the x-direction.

25 **[00144]** The beam receiving location 330 may be defined by a nominal, expected or desired direction and position of the input radiation beam B_{in} relative to the plane of the reflective surface 312 (i.e. the x-y plane). For example, the beam receiving location 330 may be defined as the intersection between a nominal, expected or desired input radiation beam B_{in} and

the x-y plane. This may comprise an elliptical region in the x-y plane. A portion of the optical element 310 (the beam spot region of reflective surface 312) is positioned in the beam receiving location 330.

[00145] The movement mechanism 220 is operable to move the optical element 310 relative to the beam receiving location 330. In particular, movement mechanism 220 is operable to move the optical element 310 linearly in the positive or negative x-direction, as indicated by arrow D_3 . The direction in which the movement mechanism 220 is operable to move the optical element 310 (i.e. the x-direction) may be referred to as the movement direction of the apparatus 200. As the movement mechanism 220 moves the optical element 310 the portion of the optical element 310 which is positioned in the beam receiving location 230 changes. Equivalently, as the movement mechanism 220 moves the optical element 310, the beam receiving location 330 may be considered to move over the reflective surface 312.

[00146] The optical element 310 may be considered to comprise a plurality of portions for receiving the input radiation beam B_{in} . Each of the plurality of portions may be a region of the reflective surface that can receive the input radiation beam B_{in} . That is, each of the plurality of portions may comprise an elliptical region of the reflective surface 312, the dimensions of which match (or are larger than) those of the beam receiving location 330. Alternatively, each of the plurality of portions may comprise a rectangular region of the reflective surface 312, with a dimension in the movement direction (i.e. the x-direction) which matches, or is larger than, that of the minor axis of the beam receiving location 330 and a dimension in the orthogonal direction (i.e. the y-direction) which matches, or is larger than, that of the major axis of the beam spot region/the beam receiving location 330.

[00147] As the movement mechanism moves the optical element 310 the plurality of portions move so that each of the plurality of portions can be selectively positioned at the beam receiving location 330.

[00148] When one of the plurality of portions is disposed in the beam receiving location 330 it is configured to receive the input radiation beam B_{in} and to scatter the input radiation beam B_{in} so as to form output radiation beam B_{out} . In particular, the single output radiation beam B_{out} is formed from specular reflection from the reflective surface 312 of a portion of the optical element 310. The output radiation beam B_{out} comprises radiation propagating in generally a single direction. It will be appreciated that although only a single output radiation beam B_{out} is produced, a portion of the input radiation beam B_{in} may be scattered from the reflective surface 312 via diffuse reflection and another portion of the input radiation beam B_{in} may be absorbed by the reflective surface 312.

[00149] The optical element 310 comprises a plurality of portions the reflective surface 312 of each of the plurality of portions having a different reflectivity. A reflectivity of the reflective surface of each of the plurality of portions may be considered to be a property of that portion which differs from that of the other portions.

5 **[00150]** The optical element 310 can be formed from silicon. The optical element 310 may be provided with a coating of a more reflective (less absorbing) material (for EUV radiation). For example, the mirror may be provided with a coating of ruthenium (Ru) or molybdenum (Mo). This may, for example, have a thickness of around 50 nm.

10 **[00151]** The difference in reflectivities of the plurality of portions the reflective surface 312 may be achieved in any suitable way. For example, in one embodiment, two or more of the plurality of portions of optical element 310 are provided with different levels of surface roughness. For example, for some embodiment the optical element 310 comprises a mirror formed from silicon and provided with a coating of ruthenium with a thickness of around 50 nm.

15 **[00152]** In general, the reflectivity of a radiation beam from a surface is dependent upon the grazing incidence angle of the radiation beam. For embodiments wherein the (EUV) input radiation beam B_{in} is incident upon the reflective surface 312 at a grazing incidence angle β of around 2° , if the surface roughness R_a of the mirror is 2 nm then the reflectivity (for EUV radiation) is 0.973; if the surface roughness R_a of the mirror is 5 nm then the reflectivity (for EUV radiation) is 0.953; and the surface roughness R_a of the mirror is 10 nm then the reflectivity (for
20 EUV radiation) is 0.885.

[00153] Therefore by providing a variation in the surface roughness R_a in the range of 2 nm to 5 nm, an attenuation of the power of the input radiation beam B_{in} of the order of 2% may be achieved. Further, by providing a variation in the surface roughness R_a in the range of 2 nm to 10 nm, an attenuation of the power of the input radiation beam B_{in} of the order of 9% may be
25 achieved.

[00154] The surface roughness of a surface may be defined as a typical scale of local deviations of the surface from a smooth ideal surface. The typical scale of local deviations of the surface from the smooth ideal surface may be defined in various different ways. The surface roughness R_a of a surface may be defined as an arithmetic average of the absolute
30 value of the distance between the surface and the ideal surface averaged over a plurality of points on the surface.

[00155] Different levels of surface roughness R_a may be achieved by polishing a surface of optical element 310 by different amounts.

[00156] Additionally or alternatively, the reflective surfaces of two or more of the plurality of portions may be formed from different material. For example, in one embodiment, the optical element 310 is formed from silicon and two or more of the plurality of portions may be provided with coatings formed from different materials.

5 **[00157]** As with the optical element 210, the portions of optical element 310 may overlap or may be spatially separated.

[00158] Figures 9A and 9B shows two variants 310a, 310b of the optical element 310 shown in Figure 8. In contrast to optical element 310, which the movement mechanism is operable to move in a linear fashion, optical elements 310a, 310b are both arranged to be
10 rotated by the movement mechanism.

[00159] Optical element 310a shown in Figure 9A is generally cylindrical and is arranged to be rotated about an axis 340a. The reflective surface 312a of optical element 310a is provided on a curved surface of the cylindrical optical element 310a. The movement mechanism is operable to rotate optical element 310a about its axis 340a, as indicated by arrow
15 D₄.

[00160] Optical element 310b shown in Figure 9B is generally cylindrical and is arranged to be rotated about an axis 340b. The reflective surface 312b of optical element 310b is provided on a flat end surface of the cylindrical optical element 310b. The movement mechanism is operable to rotate optical element 310b about its axis 340b, as indicated by arrow
20 D₅.

[00161] The plurality of portions of the reflective surfaces 312, 312a, 312b may be arranged such that as the movement mechanism moves the optical element 310, 310a, 310b in one direction the reflectivity of the reflective surface 312, 312a, 312b either increases or decreases. Alternatively, the plurality of portions of the reflective surfaces 312, 312a, 312b may
25 be arranged such that as the movement mechanism moves the optical element 310, 310a, 310b in one direction the reflectivity of the reflective surface 312, 312a, 312b alternately increases and decreases. This alternating arrangement may be advantageous since the movement mechanism can always move the optical element 310, 310a, 310b in a single direction.

[00162] In the above described embodiments, the optical elements 210, 310, 310a, 310b
30 each comprise a plurality of portions that are connected (e.g. form different regions of a single reflective surface). For such embodiments, as described above, the movement mechanism 220 is operable move the entire optical element 205. In an alternative embodiment, the optical element 205 may comprise a plurality of separately movable portions (e.g. a plurality of

separate gratings or mirrors) and the movement mechanism 220 is operable move the each such portion.

[00163] A beam splitting apparatus according to an embodiment of the invention will now be described with reference to Figures 10, 11 and 12. The beam splitting apparatus may for example form part of the beam delivery system BDS of Figure 1. The beam splitting apparatus comprises an optical element 410. Optical element 410 comprises a reflective surface 412 and is suitable for receiving an input radiation beam B_{in} . The reflective surface 412 lies generally in a plane (x-y plane in Figure 10). In use, the optical element 410 is arranged to receive the input radiation beam B_{in} at a beam receiving location 430 and to output a plurality of radiation beams B_1, B_2, B_3 from the beam receiving location 430. The input radiation beam B_{in} may, for example, comprise the radiation beam B_{FEL} output by the free electron laser FEL in Figure 3.

[00164] The input radiation beam B_{in} is incident upon the reflective surface 412 at a grazing incidence angle β . The grazing incidence angle β is the angle between the input radiation beam B_{in} and the reflective surface 412. The grazing incidence angle β may, for example, be less than 5° , for example, around 2° or even less, for example around 1° . The input radiation beam B_{in} may be generally circular in cross section and may therefore irradiate a generally elliptical region of the reflective surface 412. This generally elliptical region may be referred to as a beam spot region. The beam spot region comprises a portion of the reflective surface 412 which is disposed in the beam receiving location 430. The dimensions of the beam spot region are determined by the diameter of the input radiation beam B_{in} and the grazing incidence angle β . The length of the minor axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} whereas the length of the major axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} divided by $\sin(\beta)$. The orientation of the beam spot region is dependent upon the direction of the input radiation beam B_{in} . In the example embodiment shown in Figures 10, 11 and 12, the major axis of the beam spot region is aligned with the y-direction and the minor axis of the beam spot region is aligned with the x-direction.

[00165] The beam receiving location 430 may be defined by a nominal, expected or desired direction and position of the input radiation beam B_{in} relative to the plane of the reflective surface 412 (i.e. the x-y plane). For example, the beam receiving location 430 may be defined as the intersection between a nominal, expected or desired input radiation beam B_{in} and the x-y plane. This may comprise an elliptical region in the x-y plane. A portion of the optical element 410 (the beam spot region of reflective surface 412) is positioned in the beam receiving location 430.

[00166] The optical element 410 may be considered to comprise a plurality of regions 412a, 412b for receiving a portion of the input radiation beam B_{in} . As shown in Figures 11 and 12, the regions 412a, 412b are generally defined by a plurality of concentric ellipses, each of the plurality of concentric ellipses forming a boundary of at least one of the plurality of regions 412a, 412b.

[00167] Each of the plurality of regions 412a, 412b is a sub-region of the beam spot region. Therefore, each of the plurality of regions 412a, 412b is arranged to receive a different portion of the input radiation beam B_{in} .

[00168] The reflective surface 412 is configured to receive the input radiation beam B_{in} and to scatter the input radiation beam B_{in} so as to form the output radiation beams B_1 , B_2 , B_3 . In particular, when the input radiation beam B_{in} is incident on one of the plurality of portions it is diffracted such that, in the far field, the output radiation beams B_1 , B_2 , B_3 are spatially separated, as now described. To achieve this, the reflective surface 412 is not flat but rather is provided with a grating structure. That is, the reflective surface 412 does not lie solely in the x-y plane but has some modulation in a direction normal to the x-y plane.

[00169] Each of the plurality of regions 412a, 412b of the reflective surface 412 may be considered to be provided with a grating structure configured such that when the input radiation beam is incident upon that portion, it is diffracted so as to form a plurality of radiation sub-beams. Each of the plurality of radiation sub-beams forms part of a different one of the output radiation beams B_1 , B_2 , B_3 .

[00170] The grating structure of each region 412a, 412b comprises a plurality of grooves 92 extending across reflective surface 412. The grooves 92 may be formed by any suitable process such as, for example, etching, stamping or electroforming. The grooves 92 may have any profile shape, i.e. the cross sectional shape of the grooves 92 in a plane perpendicular to the direction that they extend along may have any shape.

[00171] In one embodiment (as now described), the grooves 92 are formed from a plurality of generally flat faces. A cross section of a portion of the reflective surface 412 in the x-z plane for such an embodiment may be substantially the same as the cross section of a portion of the reflective surface 212 in the x-z plane shown in Figure 6.

[00172] The grooves 92 form a plurality of ridges 95, dividing each region 412a, 412b of the reflective surface 412 into three groups of reflective faces. Top faces of each ridge 95 form a first group of faces S_1 , left-hand sides of each ridge 95 form a second group of faces S_2 and right-hand sides of each ridge 95 form the third group of faces S_3 . The grooves 92 therefore divide the reflective surface 412 into a plurality of groups of reflective faces, wherein the faces

within each group are substantially parallel, but at different angles with respect to the faces of each other group. That is, the faces within a particular group each have a particular orientation which is different to faces in other groups.

[00173] It will be appreciated that other groove profiles may alternatively be used. For example, in an alternative embodiment, the profile of the grooves may comprise one or more curved sections.

[00174] The reflective surface 412 may comprise any suitable number of grooves 92 and may, in one example embodiment, comprise of the order of 1000 grooves 92.

[00175] The grating structure may be considered to be formed from a plurality of unit cells 96. The unit cell 96 may be the local profile shape of the grooves 92, i.e. the cross sectional shape of the grooves 92 in a plane perpendicular to the direction that they extend along at a given location on the reflective surface 412 (in the x-direction). Each unit cell 96 may extend from one part of a groove 92 or ridge 95 to a corresponding part of an adjacent groove 92 or ridge 95. For example, each unit cell 96 may comprise a top face S_1 of a ridge 95, a left-hand face S_2 of a ridge 95 and a right hand face S_3 of a ridge 95 (the three faces being adjacent to each other).

[00176] A conventional diffraction grating comprises a uniform unit cell. That is, the size and shape of each unit cell across a conventional diffraction grating are uniform and, as a result, the grating structure is periodic. The width of the unit cell of a conventional diffraction grating may be referred to as its pitch.

[00177] Embodiments of the invention comprise a modified grating structure wherein the unit cell 96 varies across the reflective surface 412 (in the x-direction). The grating structure of each of the regions 412a, 412b of reflective surface 412 is of the form of a conventional diffraction grating, with uniform unit cells. However, the width of the unit cells 96 (i.e. the pitch of the periodic structure) of each of the regions 412a, 412b is different. Within each region 412a, 412b a width w (in the x-direction) of each of the plurality of unit cells 96 may, for example, be of the order of around $1\text{ }\mu\text{m}$, with a small variation in the width w of the unit cells 96 between the different regions 412a, 412b. The ratio of the width w_1 of the S_1 faces (in the x-direction) to the width w of the unit cell 96 of the grating structure may remain fixed across the reflective surface 412. The width w_1 of the S_1 faces may, for example, be around $0.26\text{ }\mu\text{m}$.

[00178] For a given direction of the input radiation beam B_{in} with respect to a grating structure, the directions of the radiation sub-beam formed are dependent on the pitch of the grating and the wavelength of the input radiation beam B_{in} . A beam splitting apparatus comprising optical element 410 comprises a grating structure wherein the pitch varies across

the reflective surface 412 of the optical element 410. This variation may be matched to a variation in wavelength of an input radiation beam B_{in} across its cross section to ensure that the intensity profile of the output radiation beams B_1 , B_2 , B_3 substantially matches that of the input radiation beam.

5 **[00179]** That is, the pitch of the periodic structure of each of the plurality of regions 412a, 412b may be dependent on the wavelength distribution of the input radiation beam B_{in} that across its cross section. In particular, the pitch of the periodic structure of each of the plurality of regions 412a, 412b is dependent on the wavelength of the portion of the input radiation beam B_{in} that is received by that region 412a, 412b. For example, the pitch of the periodic structure of
10 each of the plurality of regions 412a, 412b may be proportional to the wavelength of the portion of the input radiation beam B_{in} that is received by that region 412a, 412b, averaged over that region 412a, 412b.

[00180] The beam splitting apparatus may be used to split radiation beams with a wavelength that varies over its cross section. For example, a radiation beam B_{FEL} output by a
15 free electron laser may have a wavelength that varies over its cross section. For example, a (radially) central part of the beam may have a slightly shorter wavelength compared to a (radially) outer part of the beam. The distribution of wavelengths over the cross section of the radiation beam may be substantially constant in time (e.g. averaged over a plurality of pulses produced by the free electron laser).

20 **[00181]** The directions of the diffracted radiation beams (except the 0th order beam) leaving a diffraction grating depend on the wavelength of the incoming radiation beam. Therefore, a variation in the wavelength of the incoming radiation beam results in a change in the divergence of the outgoing beams (except the 0th order beam) from a standard (i.e. constant pitch) diffraction grating. This will lead to a change of intensity distribution of the outgoing
25 radiation beams in the far field of the standard diffraction grating. That is, the intensity distributions of the outgoing radiation beams may not match that of the incoming radiation beam, which may be undesirable. Furthermore, optical elements that are downstream of the diffraction grating may be located such that the incoming radiation beam irradiates a nominal position on such optical elements. The location of these optical elements may be dependent
30 upon the location of the grating and the direction of the output radiation beams (which is dependent upon the wavelength of the incoming radiation beam). The location of optical elements that are downstream of the diffraction grating may be chosen based on a nominal wavelength of the incoming radiation beam. If a portion of the incoming radiation beam has a wavelength that differs from the nominal wavelength then a portion of the $\pm 1^{st}$ (and higher) order

beams leaving the diffraction grating may propagate in a different direction such that optical elements that are downstream of the diffraction grating are irradiated at a position which deviates from the nominal position of those optical elements, which may be undesirable.

[00182] The layout of the grating structure on optical element 410 may be chosen in the following manner. First the distribution of wavelengths over the cross section of the radiation beam may be established (e.g. by calculation or measurement) to produce a wavelength map. This is then converted into a grating pitch map over the reflective surface 412, the pitch of a given part of the reflective surface being calculated as being proportional to a wavelength of the radiation that is incident upon it. Next a grating structure is formed on the reflective surface 412 in conformity with the grating pitch map.

[00183] For example, an etch mask may be formed on the surface of a silicon wafer in conformity with the grating pitch map, for example, using lithography. The etch mask is a two-dimensional pattern of stripes wherein the width of the stripes and the distance between them varies over the surface of the wafer. The etch mask will contain some discontinuities between adjacent regions. The regions of the silicon wafer in between the stripes of the etch mask can then be etched away (along the crystal planes of the silicon wafer) to produce the grating structure.

[00184] In one embodiment, as shown in Figure 11 the regions 412a, 412b are defined by a plurality of concentric ellipses, each of the plurality of concentric ellipses forming a boundary of at least one of the plurality of regions 412a, 412b. The smooth (elliptical) curve of discontinuity locations at the boundary between two adjacent regions 412a, 412b may result in constructive and destructive interference in the far field of optical element. In turn, this may introduce speckle into the output radiation beams B_1 , B_2 , B_3 .

[00185] In another embodiment, as shown in Figure 12 the regions 412a, 412b are generally defined by a plurality of concentric ellipses, however each boundary between two adjacent regions 412a, 412b is jagged (rather than a smooth ellipse). This random repositioning of the discontinuity locations at the boundary between two adjacent regions 412a, 412b may result may reduce the level of speckle introduced into the output radiation beams B_1 , B_2 , B_3 .

[00186] In the described example embodiment the grooves 92 extend generally in the y-direction. That is, the grooves 92 are generally parallel to the plane of incidence of input radiation beam B_{in} (which is the plane containing the incoming radiation beam B_{in} and the normal to the reflective surface 412, i.e. the z direction). Since the direction perpendicular to the grooves (i.e. the x-direction) is not in the plane of incidence of input radiation beam B_{in} , the grating results in conical diffraction, with the output radiation beams B_1 , B_2 , B_3 lying on a cone.

In an alternative embodiment the grooves may extend generally perpendicular to the direction of propagation of the input radiation beam B_{in} such that the output radiation beams B_1 , B_2 , B_3 lie in a plane.

[00187] As explained above, the optical element 410 can be formed from silicon by, for example, anisotropic etching along crystal planes of a silicon wafer. For example, the top faces S_1 may be formed along the (100) crystallographic plane and the faces S_2 , S_3 may be formed along the (111) and (-111) crystallographic planes. In this case, the angle 93 at the bottom of the grooves will be approximately 70.5° and the grooves 92 and ridges 95 will extend along the (01-1) direction. It will be appreciated that various layouts are possible depending on the (h k l) direction of top the surface.

[00188] A grating in which the top faces S_1 are formed along the (100) crystallographic plane and the faces S_2 , S_3 are formed along the (111) and (-111) crystallographic planes may form three output radiation beams.

[00189] The optical element 410 may be provided with a coating of a more reflective (less absorbing) material (for EUV radiation). For example, the mirror may be provided with a coating of ruthenium (Ru) or molybdenum (Mo). This may, for example, have a thickness of around 50 nm.

[00190] It will be appreciated that while the optical element 410 is arranged to split an input radiation beam B_{in} into three branch radiation beams, gratings may be provided which split a radiation beam into a different number of branch radiation beams. Generally, a grating may be provided which splits a radiation beam into two or more branch radiation beams.

[00191] An advantage of using silicon for the optical elements 210, 310, 310a, 310b, 410 is that thermal expansion during operation may be limited by operating at approximately 123 K. At this temperature the heat conductivity of silicon is of the order of 600 W/m/K or more, which is a factor of 4 better than its heat conductivity at room temperature and around 50% better than the heat conductivity of copper (Cu). Therefore, even a relatively large heat load can be withstood, while keeping the temperature of the optical element in the range where expansion of the optical element is low and the optical element maintains its designed structural dimensions, despite significant heat load.

[00192] An optical element 510 according to an embodiment of the present invention is illustrated schematically in Figures 13a, 13b and 13c. Optical element 510 is a reflective diffraction grating, as now described, and may be used as a beam splitting apparatus. The optical element 510 may serve as a beam splitting apparatus that may form part of the beam delivery system BDS of the lithographic system LS illustrated in Figure 1.

[00193] Optical element 510 comprises a reflective surface 512 and is suitable for receiving an input radiation beam B_{in} and outputting a plurality of output radiation beams B_1 , B_2 , B_3 . The input radiation beam B_{in} may, for example, comprise the radiation beam B output by the radiation source SO in Figure 1 (which may, for example, be the radiation beam B_{FEL} output by the free electron laser FEL in Figure 3). Alternatively, the input radiation beam B_{in} may comprise a portion of the radiation beam B output by the radiation source SO the radiation beam B having previously been split into a plurality of sub-beams (each sub-beam comprising a portion of the radiation beam B). The beam delivery system BDS of the lithographic system LS may comprise a plurality of optical elements 510 that are arranged to split the radiation beam B output by the radiation source SO into a desired number of branch radiation beams B_a - B_n .

[00194] The reflective surface 512 lies generally in a plane (x - y plane in Figures 13a-13c). In use, when the input radiation beam B_{in} is incident on the reflective surface 512 it is diffracted such that, in the far field, the output radiation beams B_1 , B_2 , B_3 are spatially separated. To achieve this, the reflective surface 512 is not flat but rather is provided with a grating structure. That is, the reflective surface 512 does not lie solely in the x - y plane but has some modulation in a direction normal to the x - y plane.

[00195] The grating structure comprises a plurality of grooves extending across reflective surface 512. Although not shown in Figure 13a (to aid the clarity of the Figure), the grooves extend along the y -direction.

[00196] The input radiation beam B_{in} is incident upon the reflective 512 surface at a grazing incidence angle β . The grazing incidence angle β is the angle between the input radiation beam B_{in} and the reflective surface 512. The grazing incidence angle β may, for example, be less than 5° , for example, around 2° or even less, for example around 1° . The input radiation beam B_{in} may be generally circular in cross section and may therefore irradiate a generally elliptical region of the reflective surface 512. This generally elliptical region may be referred to as a beam spot region 514. The dimensions of the beam spot region 514 are determined by the diameter of the input radiation beam B_{in} and the grazing incidence angle β . The length of the minor axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} whereas the length of the major axis of the elliptical beam spot region is equal to the diameter of the input radiation beam B_{in} divided by $\sin(\beta)$. The orientation of the beam spot region is dependent upon the direction of the input radiation beam B_{in} .

[00197] The direction of the input radiation beam B_{in} may be specified by two angles of a spherical polar coordinate system, as now described. In the following, the direction of the input radiation beam B_{in} will be specified by a polar angle θ and an azimuthal angle ϕ , defined as

follows. The polar angle θ is the angle between the wave vector of the input radiation beam B_{in} and the normal to the reflective surface 512 (i.e. the z-axis in Figure 13a). The polar angle θ may also be referred to as the angle of incidence. This angle θ is complementary to the grazing incidence angle β , i.e. the sum of the angle of incidence θ and the grazing incidence angle β is a right angle. The azimuthal angle ϕ is the angle between the orthogonal projection of the wave vector of the input radiation beam B_{in} onto the plane of the reflective surface 512 (i.e. the x-y plane in Figure 13a) and the direction perpendicular to which the grooves extend (the x-direction in Figure 13a).

[00198] In this embodiment output radiation beam B_2 corresponds to the 0th order diffraction beam and output radiation beams B_1 and B_3 correspond to the $\pm 1^{st}$ order diffraction beams. It will be appreciated that in other embodiments, a different number of radiation beams may be output from the optical element 510. For example, in one embodiment five radiation beams may be output from the optical element 510 and the five output radiation beams may correspond to the 0th, $\pm 1^{st}$, $\pm 2^{nd}$ order diffraction beams. The number of diffraction orders present may be dependent on the grazing incidence angle β and the wavelength of the input radiation beam B_{in} . The number of visible diffraction orders present may increase by increasing grazing incidence angle β and/or lowering the wavelength of the input radiation beam B_{in} . Furthermore, the plurality of output radiation beams may not include all diffraction orders. For example, some of the diffraction orders may be suppressed and may not be output radiation beams of the optical element 510. Generally, a grating may be provided which splits a radiation beam into two or more branch radiation beams.

[00199] In the example embodiment shown in Figures 13a-13c, input radiation beam B_{in} has an azimuthal angle $\phi=90^\circ$. With such an arrangement, the major axis of the beam spot region 514 is aligned with the y-direction and the minor axis of the beam spot region is aligned with the x-direction.

[00200] The angle of incidence θ may be chosen to lie in the range 85° - 90° (equivalent to a grazing incidence angle β in the range 0° - 5°) as this yields the highest reflectance, and therefore the highest EUV power delivered to each lithographic apparatus LA_a - LA_n .

[00201] Since the grooves of the grating structure extend generally in the y-direction, the grooves are generally parallel to the plane of incidence of input radiation beam B_{in} (which is the plane containing the incoming radiation beam B_{in} and the normal to the reflective surface 512, i.e. the z direction). Since the direction perpendicular to the grooves (i.e. the x-direction) is not in the plane of incidence of input radiation beam B_{in} , the grating results in conical diffraction, with the output radiation beams B_1 , B_2 , B_3 lying on a cone. In an alternative embodiment the

grooves may extend generally perpendicular to the direction of propagation of the input radiation beam B_{in} such that the output radiation beams B_1 , B_2 , B_3 lie in a plane.

[00202] The reflective surface 512 of the optical element 510 may comprise any suitable number of grooves 515. The number of grooves 515 across the beam spot region 514 is determined by the pitch p of the grating structure (i.e. the width of the unit cell 517) and the length of the minor axis of the beam spot region 514. In one example embodiment, the reflective surface 512 may comprise of the order of 5000 grooves 515 across the beam spot region 514.

[00203] The output radiation beams B_1 , B_2 , B_3 may have an intensity distribution in the far field (e.g. at a lithographic tool LA_a - LA_n) that is substantially similar to the intensity distribution of the input radiation beam B_{in} , which may be desirable.

[00204] As described above, the reflective diffraction grating provided by optical element 510 can function as a beam splitting apparatus that can be used to split a single input radiation beam into a plurality of output radiation beams B_1 , B_2 , B_3 , each with a desired fraction of the power of the input radiation beam B_{in} . For example, in some embodiments, the optical element 510 may be arranged such that each of the the output radiation beams B_1 , B_2 , B_3 has substantially equal power.

[00205] Furthermore, in embodiments of the present invention, the optical element 510 and the input radiation beam B_{in} are arranged such that the differential of the power of each of the plurality of output radiation beams B_1 , B_2 , B_3 with respect to a direction of the input radiation beam B_{in} is substantially zero. This ensures that the power each of the output radiation beams B_1 , B_2 , B_3 is relatively insensitive to the initial direction of the input radiation beam B_{in} . This is particularly advantageous if the reflective diffraction grating provided by the optical element 510 forms part of an optical system that distributes radiation from a single radiation source to a plurality of different targets to which it is desirable to deliver a substantially constant dose of radiation. For example, this is particularly beneficial for embodiments where the optical element 510 forms part of the beam delivery system BDS of a lithographic system LS of the type illustrated in Figure 1 that distributes radiation to a plurality of different lithographic apparatus LA_a - LA_n . This is because variations in the dose of energy delivered to each lithographic apparatus LA_a - LA_n may affect the imaging performance of the lithographic apparatus LA_a - LA_n .

[00206] For a given direction of the input radiation beam B_{in} with respect to the grating structure and a given wavelength of the input radiation beam B_{in} , the direction of the output radiation beams B_1 , B_2 , B_3 is dependent on the pitch of the grating but is independent of the profile shape of the grating structure. However, the relative powers of the output radiation

beams B_1 , B_2 , B_3 are dependent upon the profile shape of the grating structure. The power of each of the output radiation beams B_1 , B_2 , B_3 is dependent upon the pitch and shape of the grating structure, the direction of the input radiation beam B_{in} (i.e. the polar angle θ and the azimuthal angle φ) and the wavelength of the input radiation beam B_{in} .

5 **[00207]** The grating structure for embodiments of the optical element 510 should be chosen in order to ensure that the differential of the power of each of the plurality of output radiation beams B_1 , B_2 , B_3 with respect to a direction of the input radiation beam B_{in} can be substantially zero. In particular, the geometry of the grating structure of embodiments of the optical element 510 is such that, for a desired wavelength of radiation of the input radiation beam B_{in} , there is at
10 least one direction of the input radiation beam for which each of the plurality of output radiation beams has a desired output power, the at least one direction being such that when the input radiation beam propagates along it the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam is substantially zero.

[00208] Various different grating geometries or topologies may be chosen that achieve
15 this result. The grooves may have any suitable profile shape, i.e. the cross sectional shape of the grooves in a plane perpendicular to the direction that they extend along (i.e. the x-z plane in Figure 13) may have any shape. Furthermore, the grooves of the grating structure may be formed by any suitable process such as, for example, etching, stamping or electroforming. Two specific embodiments of suitable grating structures are described below, by way of example
20 only, with reference to Figures 14 to 17.

[00209] Two specific embodiments of suitable grating structures for optical element 510 are now described, by way of example only, with reference to Figures 14 to 17. Figure 14 shows a cross section of a portion of the reflective surface 512 in the x-z plane for a family of grating structures with a particular general shape. The grating structure is periodic and
25 comprises a plurality of parallel and equally spaced grooves 515 extending across the reflective surface 512 (in the y-direction). Each of the grooves 515 is formed from two generally flat converging faces S_2 , S_3 . Furthermore, a generally flat face S_1 is provided between each pair of adjacent grooves 515. That is, the grating structure shown in Figure 14 is formed from a plurality of parallel and equally spaced grooves 515 that are generally V-shaped in cross
30 section.

[00210] The grooves 515 form a plurality of ridges 516, dividing the reflective surface 512 into three groups of reflective faces. Top faces of each ridge 516 form a first group of faces S_1 , left-hand sides of each ridge 516 form a second group of faces S_2 and right-hand sides of each ridge 516 form the third group of faces S_3 . The grooves 515 therefore divide the reflective

surface 512 into a plurality of groups of reflective faces, wherein the faces within each group are substantially parallel, but at different angles with respect to the faces of each other group. That is, the faces within a particular group each have a particular orientation which is different to faces in other groups.

5 **[00211]** The shape of a grating structure may be characterised by its unit cell 517. The unit cell 517 is a single period of the periodic structure of the optical surface 512. The shape of the unit cell 517 may be characterised by the profile shape of a single period of the periodic structure of the optical surface 512 in a plane perpendicular to the direction of the grooves 515 (i.e. in the z-x plane). The unit cell 517 may be considered to extend from one part of one of the
10 plurality of grooves 515 to a corresponding part of an adjacent groove 515. For example, the unit cell 517 of the grating structure may comprise the generally flat face S_1 between two grooves, and the two generally flat faces S_2 , S_3 of one of the grooves (the three faces being adjacent to each other).

[00212] The extent of the unit cell 517 in the direction perpendicular to the direction of the
15 grooves (i.e. the x direction) may be referred to as the pitch p of the grating structure. The extent w_1 of the generally flat face S_1 between each pair of adjacent grooves 515 in the direction perpendicular to the direction of the grooves 515 (i.e. the x direction) may be referred to as the spacing between the pair of adjacent grooves 515. The extent w_2 of each groove 515 in the direction perpendicular to the direction of the grooves 515 (i.e. the x direction) may be referred
20 to as the width of the grooves 515. A ratio of the spacing w_1 between each pair of adjacent grooves 515 to the pitch p of the grating structure may be referred to as the duty cycle of the grating structure. The extent d of each groove 515 in the direction perpendicular to the plane of the reflective surface 512 (i.e. the z direction) may be referred to as the depth d of the grooves 515.

25 **[00213]** The pitch p of the grating structure, the spacing w_1 between each pair of adjacent grooves 515, the width w_2 and depth d of each groove 515 and the angle 518 between the two generally flat converging faces S_2 , S_3 from which each of the grooves 515 is formed may all be considered to be parameters of the general shape of diffraction grating illustrated in Figure 14. The grating structure illustrated in Figure 14 may be considered to be a general shape for a
30 diffraction grating, and by specifying each of its parameters, a specific shape of diffraction grating may be specified.

[00214] It will be appreciated that not all of parameters listed above are independent of each other. For example, the pitch p of the grating structure is equal to the sum of the spacing w_1 between each pair of adjacent grooves 515 and the width w_2 and depth d of each groove

515. Furthermore, for a given angle 518 between the two generally flat converging faces S_2 , S_3 from which each of the grooves 515 is formed, and a given width w_2 of the grooves 515, the depth d of the grooves 515 is fixed. Therefore, not all of these parameters need to be specified in order to uniquely define a specific shape of diffraction grating. The specific shape of the diffraction grating can, for example, be fully described by the pitch p of the grating structure, the depth d of each groove 515 and the angle 518 between the two generally flat converging faces S_2 , S_3 from which each of the grooves 515 is formed. It will be appreciated that other equivalent sets of parameters may alternatively be used to define the specific shape of the grating.

[00215] The angle 518 between the two generally flat converging faces S_2 , S_3 from which each of the grooves 515 is formed may be dependent on a crystalline structure of a material from which the optical element 510 is formed, as now described.

[00216] An optical element 510 with the general grating structure as shown in Figure 14 may be formed from a crystalline material (for example silicon). For such embodiments, each face of the reflective surface corresponds to a different family of crystal planes within said crystalline material. Each such family of crystal planes may be specified by a set of Miller indices (hkl).

[00217] For such embodiments, the optical element 510 can be formed from a crystalline material (e.g. silicon) by, for example, anisotropic etching along crystal planes of a substrate formed from a crystal of the material. For example, a silicon wafer may be provided with an upper surface corresponding to a particular crystallographic plane (e.g. the (100) plane). An etch mask may be provided on the surface of a silicon wafer in conformity with a grating pitch map. The etch mask may, for example, be applied using lithography. The etch mask is a pattern of stripes with a pitch equal to a desired pitch of the grating structure and wherein the width of the stripes corresponds to a desired separation w_1 between the grooves 515. The regions of the silicon wafer in between the stripes of the etch mask can then be etched away (along the crystal planes of the silicon wafer) to produce the grating structure. For example, using a silicon wafer with an upper surface corresponding to the (100) plane, the top faces S_1 may be formed along the (100) crystallographic plane and the faces S_2 , S_3 may be formed along the (111) and (-111) crystallographic planes. In this case, the angle 518 at the bottom of the grooves 515 will be approximately 70.5° (70.529°). It will be appreciated that various layouts are possible depending on the ($h k l$) direction of top the surface. For such embodiments formed from a silicon wafer there are two possible values for the angle 518 at the bottom of the grooves 515: 70.529° or 109.471° .

[00218] The optical element 510 may be provided with a coating of a more reflective (less absorbing) material (for EUV radiation). For example, the mirror may be provided with a coating

of ruthenium (Ru) or molybdenum (Mo). This may, for example, have a thickness of the order of 50 nm. The reflectivity of the optical element may increase with increasing thickness of such a reflective coating up to a plateau thickness above which the reflectivity does not increase significantly. For a ruthenium coating on a flat silicon mirror the plateau thickness may be around 15 nm. Furthermore, the provision of a reflective coating over the grating structure formed in silicon may result in rounding of the edges between different faces of the grating structure. The thickness of reflective coating may be chosen such that it is: (a) thick enough that there is little reduction in reflectivity relative to an infinitely thick coating; and (b) thin enough that the level of rounding of the edges between different faces of the grating structure is acceptable. A nominal coating thickness of around 15 nm (i.e. the plateau thickness) may be preferred since this minimises the effects of rounding of edges whilst not significantly compromising on the reflectivity of the optical element 510. However, in practice it may be difficult to control the thickness control of such a thin coating.

[00219] Given a general grating structure shape, a specific shape of diffraction grating that is suitable for use as the optical element 510 may be determined as follows. For a given wavelength of the input radiation beam B_{in} (for which the diffraction grating may be used), a set of values for the parameters of the general grating structure is determined for which the geometry of the grating structure is such that: there is at least one direction of the input radiation beam for which each of the plurality of output radiation beams has a desired output power, the at least one direction being such that when the input radiation beam B_{in} propagates along it the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam is substantially zero. The desired output powers for all of the output radiation beams may, for example, be equal.

[00220] The determination of the set of values for the parameters may involve determining the power of each of the output radiation beams as a function of the direction of the input radiation beam B_{in} for a plurality of sets of values. For example, for each set of values, the power of each of the output radiation beams may be determined as a function of the polar angle θ and the azimuthal angle ϕ of the input radiation beam B_{in} . The power of each output radiation beam may be represented as a two-dimensional function of polar angle θ and azimuthal angle ϕ .

[00221] All points where the power of each of the output radiation beams is equal to its desired output power are determined. Each such point (for example in θ - ϕ space) represents a direction of the input radiation beam B_{in} for which each of the plurality of output radiation beams has its desired output power. For each such point, the differential of the power of each of the

plurality of output radiation beams with respect to the direction of the input radiation beam B_{in} is determined. If for at least one of the points the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam B_{in} is substantially zero then a grating with the specific shape as defined by the set of values is suitable for use with optical element 510.

[00222] If none of the sets of values yields a suitable grating structure then additional sets of values may be tried. The method may be iterative in that the additional sets of values may be chosen in dependence on the suitability of the previous sets of values. For example, if one previous set of values was more suitable than other previous sets of values then the additional sets of values may be chosen to be closer in value to that one previous set of values than other previous sets of values.

[00223] Two examples of specific grating structures having the general grating structure shown in Figure 14 and which is suitable for use as the optical element 510 for an input radiation beam B_{in} with a wavelength of 13.5 nm are now described with reference to Figures 15 to 17.

[00224] The first specific example has a pitch p of 880 nm, the angle 518 between the two generally flat converging faces S_1 , S_2 of each of the grooves 515 is 70.529° and a depth d of each groove is 542 nm. This grating structure (with an angle 518 between the two generally flat converging faces S_1 , S_2 of each of the grooves 515 of 70.529°) may be formed from a silicon wafer with an upper surface corresponding to the (100) plane of the crystal. The grating structure so formed is then provided with a coating layer of ruthenium (Ru), which has a high reflectivity for EUV radiation. Figure 15 shows, for this specific grating geometry, the output power distribution for: the 0^{th} order diffraction beam (dashed line), the $\pm 1^{st}$ order diffraction beams (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ (for an azimuthal angle $\phi=90^\circ$). Also shown for comparison is the power distribution of a plane mirror provided with a ruthenium (Ru) coating (solid line).

[00225] Corresponding power distributions of the p-polarisation (TM) components are similar and therefore only one set of the power distributions have been included here. Furthermore, the cross terms between the s-polarisation and p-polarisation components (i.e. the amount of p-polarisation radiation in each output radiation beam arising from the s-polarisation component of the input radiation beam B_{in} are small). Therefore, for this grating geometry, the power of the output beams is relatively insensitive to changes in the polarisation state of the input radiation beam B_{in} . Furthermore, the retardance of the optical element 510 is relatively small and,

therefore, the polarisation of the output radiation beams is relatively insensitive to changes in the polarisation state of the input radiation beam B_{in} .

[00226] In general, the power of different diffraction orders output by a diffraction grating (such as that provided by optical element 510) will vary as a function of both the wavelength and the direction of the input radiation beam B_{in} . For example, as a function of either one of these parameters (i.e. wavelength and the direction of the input radiation beam B_{in}), the output power of different diffraction orders may oscillate between local minima and maxima. At these local minima and maxima, the differential of the output power of different diffraction orders with respect to these parameters is zero. In between these local minima and maxima, the magnitude of the differential of the output power of different diffraction orders with respect to these parameters is a local maximum.

[00227] This oscillating behaviour as a function of angle of incidence θ can be seen from Figure 15. For example, the output power distribution 520 for the 0^{th} order diffraction beam (dashed line) oscillates between a series of local minima 521 and local maxima 522 as a function of angle of incidence θ (for an azimuthal angle $\phi=90^\circ$). At these local minima and maxima 521, 522, the differential of the output power of the 0^{th} order diffraction beam with respect to the angle of incidence θ is zero. In between these local minima and maxima, 521, 522 the magnitude of the differential of the output power of the output power of the 0^{th} order with respect to the angle of incidence θ is a local maximum.

[00228] Similarly, the output power distribution 523 for the $\pm 1^{st}$ order diffraction beams (dotted line) oscillates between a series of local minima 524 and local maxima 525 as a function of angle of incidence θ . At these local minima and maxima 524, 525, the differential of the output power of the $\pm 1^{st}$ order diffraction beams with respect to the angle of incidence θ is zero. In between these local minima and maxima, 524, 525 the magnitude of the differential of the output power of the $\pm 1^{st}$ order diffraction beams with respect to the angle of incidence θ is a local maximum.

[00229] As can be seen from Figure 15, there exists an angle of incidence 526 of approximately 89° at which the 0^{th} order diffraction beam and the $\pm 1^{st}$ order diffraction beams have substantially equal output powers. Furthermore, at this angle of incidence 526 of approximately 89° the output power distribution 520 for the 0^{th} order diffraction beam is at a local minimum 521 and the output power distribution 523 for the $\pm 1^{st}$ order diffraction beams is at a local maximum 525. Therefore, at this angle of incidence 526 of approximately 89° the differential of the output power distribution 520 for the 0^{th} order diffraction beam with respect to the angle of incidence θ is zero and the differential of the output power distribution 523 for the $\pm 1^{st}$ order diffraction beams with respect to the angle of incidence θ is zero.

[00230] Therefore this specific grating structure is suitable for use with the optical element 510. In use, the input radiation beam B_{in} and the optical element 510 should be arranged such that the input radiation beam B_{in} is incident on the reflective surface with a nominal azimuthal angle $\varphi=90^\circ$ and at a nominal angle of incidence 526 of approximately 89° .

5 **[00231]** An advantage of such an arrangement is that the output powers of the 0^{th} order and the $\pm 1^{st}$ order diffraction beams are relatively insensitive to small changes in the angle of incidence of the input radiation beam B_{in} (which may vary over time). Note that sensitivity for angle of incidence variations θ is directly related to the sensitivity for variations in the wavelength of the input radiation beam B_{in} . Therefore, at the above described nominal angle of incidence 526 (approximately 89°), where the sensitivity of the power of the output radiation beams to variations in the angle of incidence of the input radiation beam B_{in} is zero, the sensitivity of the power of the output radiation beams to variations in the wavelength of the input radiation beam B_{in} is also zero.

15 **[00232]** It will be appreciated that in order to benefit from the above-mentioned advantage the nominal angle of incidence 526 does not need to correspond precisely with a local minimum or maximum of the power curves of each of the output radiation beams B_1 , B_2 , B_3 with respect to the direction of the input radiation beam B_{in} . It is sufficient that it is close to such a local minimum or maximum. How close to a local minimum or maximum the nominal angle of incidence should be may depend on the expected variation in direction of the input radiation beam B_{in} and the magnitude of variation in output powers of the output radiation beams B_1 , B_2 , B_3 that can be tolerated (in turn, this may be dependent on the level of dose variations delivered to each lithographic apparatus LA_a - LA_n that can be tolerated).

20 **[00233]** For example, it may be desirable to ensure that the variation in the output power of each of the output radiation beams is less than 0.1%. With this first specific example of a grating structure (with power curves as shown in Figure 15) the angle of incidence may be within a range of $\pm 0.01^\circ$ of the nominal angle of incidence 526. Furthermore, with this first specific example of a grating structure (with power curves as shown in Figure 15) the wavelength of the input radiation beam B_{in} may be within a range of ± 0.12 nm of the nominal wavelength (i.e. 13.5 nm).

30 **[00234]** As can be seen in Figure 15, there exists another angle of incidence 527 at which the 0^{th} order diffraction beam and the $\pm 1^{st}$ order diffraction beams have substantially equal output powers. However, at this angle of incidence 527 the output power distribution 520 for the 0^{th} order diffraction beam is approximately midway between a local minimum 521 and a local maximum 522 and, similarly, the output power distribution 523 for the $\pm 1^{st}$ order diffraction

beams is approximately midway between a local maximum 525 and a local minimum 524. Therefore, at this angle of incidence 527 the (magnitude of the) differential of the output power distribution 520 for the 0th order diffraction beam with respect to the angle of incidence θ is at a (local) maximum value and the (magnitude of the) differential of the output power distribution 523 for the $\pm 1^{\text{st}}$ order diffraction beams with respect to the angle of incidence θ is at a (local maximum value).

[00235] The differential of the power of an output radiation beam B_1 , B_2 , B_3 with respect to the angle of incidence θ of the input radiation beam B_{in} may be considered to be substantially zero if it is closer a local minimum or maxima of the power curve than the midpoint between adjacent minima and maxima (at which the magnitude of the differential of the output power with respect to the angle of incidence θ of the input radiation beam B_{in} is maximum).

[00236] The nominal direction of the input radiation beam B_{in} may be chosen so as to reduce the sensitivity of the power of each of the output radiation beams to changes in the azimuthal angle of the input radiation beam B_{in} as far as possible, as now described. As explained above, Figure 15 shows the power of each of the diffraction order radiation beams as a function of the angle of incidence θ of the input radiation beam B_{in} at a nominal azimuthal angle $\varphi=90^\circ$. At this azimuthal angle, the $\pm 1^{\text{st}}$ order diffraction beams have the same the output power distribution 523. However, for deviations from the nominal azimuthal angle φ of 90° , the output power distribution of $+1^{\text{st}}$ order diffraction beam differs from that of the -1^{st} order diffraction beam.

[00237] Figure 16 shows, for the same specific grating geometry described above and used in Figure 15, the output power distribution for: the 0th order diffraction beam (dashed line), the $+1^{\text{st}}$ order diffraction beam (dot-dot-dashed line), the -1^{st} order diffraction beam (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ for a deviation in azimuthal angle of 0.01° from the nominal value (90°). Also shown for comparison is the power distribution of a plane mirror provided with a ruthenium (Ru) coating (solid line).

[00238] It can be seen from Figure 16 that when the azimuthal angle deviates from its nominal value the output power distribution 528 for the $+1^{\text{st}}$ order diffraction beam differs from the output power distribution 529 for the -1^{st} order diffraction beam. Furthermore, as can be seen from Figure 16, at the previously discussed nominal angle of incidence 526, there is a significant deviation between the output powers of the $+1^{\text{st}}$ order and -1^{st} order diffraction beams. However, at a reduced angle of incidence 530 the deviation between the output powers of the $+1^{\text{st}}$ order and -1^{st} order diffraction beams is significantly reduced. Therefore, in order to reduce the sensitivity of the power of each of the output radiation beams to changes in the azimuthal

angle of the input radiation beam B_{in} , the nominal angle of incidence may be reduced relatively to the optimum angle 526 for $\varphi=90^\circ$. It may, for example be reduced to the angle of incidence 530 shown in Figure 16 or, alternatively, an intermediate nominal value that lies between the two angles incidence 526, 530 may be used. This will reduce the sensitivity of the power of each of the output radiation beams to changes in the azimuthal angle of the input radiation beam B_{in} at the expense of increasing the sensitivity of the power of each of the output radiation beams to changes in the angle of incidence and the wavelength of the input radiation beam B_{in} .

[00239] The optimum nominal angle of incidence θ may depend on the expected magnitude of the variations in azimuthal angle φ , the angle of incidence θ and the wavelength of the input radiation beam B_{in} .

[00240] The second specific example has a pitch p of 1240 nm, the angle 518 between the two generally flat converging faces S_1 , S_2 of each of the grooves 515 is 109.471° and a depth d of each groove is 490 nm. This grating structure (with an angle 518 between the two generally flat converging faces S_1 , S_2 of each of the grooves 515 of 109.471°) may also be formed from a silicon wafer. The grating structure so formed may then be provided with a coating layer of ruthenium (Ru), which has a high reflectivity for EUV radiation. Figure 17 shows, for this specific grating geometry, the output power distribution for: the 0th order diffraction beam (dashed line), the $\pm 1^{st}$ order diffraction beams (dotted line) and the total of these three diffraction orders (dot-dashed line), for a wavelength of 13.5 nm and s-polarisation (TE) as a function of the angle of incidence θ (for an azimuthal angle $\varphi=90^\circ$). Also shown for comparison is the power distribution of a plane mirror provided with a ruthenium (Ru) coating (solid line).

[00241] Corresponding power distributions of the p-polarisation (TM) components are similar and therefore only one set of the power distributions have been included here. Furthermore, the cross terms between the s-polarisation and p-polarisation components (i.e. the amount of p-polarisation radiation in each output radiation beam arising from the s-polarisation component of the input radiation beam B_{in} are small). Therefore, for this grating geometry, the power of the output beams is relatively insensitive to changes in the polarisation state of the input radiation beam B_{in} . Furthermore, the retardance of the optical element 510 is relatively small and, therefore, the polarisation of the output radiation beams is relatively insensitive to changes in the polarisation state of the input radiation beam B_{in} .

[00242] As with the first example grating, the output power of each of the diffraction orders as a function of angle of incidence θ oscillates between local maxima and minima. In the range of angles of incidence θ shown in Figure 17, the output power distribution 531 for the 0th order

diffraction beam (dashed line) has a local minimum and the output power distribution 532 for the $\pm 1^{\text{st}}$ order diffraction beams (dotted line) has a local maximum.

[00243] As can be seen from Figure 15, there exists an angle of incidence 533 of approximately 89° at which the 0^{th} order diffraction beam is almost fully suppressed (it has a reflectance $R < 0.16\%$). That is, at this angle of incidence the power of the 0^{th} order diffraction beam is approximately zero. The $\pm 1^{\text{st}}$ order diffraction beams have substantially equal output powers for the nominal azimuthal angle $\varphi=90^\circ$. Therefore, this grating geometry, when used at the angle of incidence 533 of approximately 89° , can be used to split the input radiation beam B_{in} and to form two output radiation beams (corresponding to the $\pm 1^{\text{st}}$ order diffraction beams respectively). At this angle of incidence 533 of approximately 89° the reflectance of the $\pm 1^{\text{st}}$ order beams is $>49.15\%$.

[00244] Furthermore, at this angle of incidence 533 of approximately 89° the output power distribution 532 for the $\pm 1^{\text{st}}$ order diffraction beams is at a local maximum. Therefore, at this angle of incidence 533 of approximately 89° the differential of the output power distribution 532 for the $\pm 1^{\text{st}}$ order diffraction beams with respect to the angle of incidence θ is zero.

[00245] Therefore this specific grating structure is suitable for use with the optical element 510. In use, the input radiation beam B_{in} and the optical element 510 should be arranged such that the input radiation beam B_{in} is incident on the reflective surface with a nominal azimuthal angle $\varphi=90^\circ$ and at a nominal angle of incidence 533 of approximately 89° .

[00246] An advantage of such an arrangement is that the output powers of the output radiation beams (i.e. the $\pm 1^{\text{st}}$ order diffraction beams) are relatively insensitive to small changes in the angle of incidence of the input radiation beam B_{in} (which may vary over time). Note that sensitivity for angle of incidence variations θ is directly related to the sensitivity for variations in the wavelength of the input radiation beam B_{in} . Therefore, at the above described nominal angle of incidence 526 (approximately 89°), where the sensitivity of the power of the output radiation beams to variations in the angle of incidence of the input radiation beam B_{in} is zero, the sensitivity of the power of the output radiation beams to variations in the wavelength of the input radiation beam B_{in} is also zero.

[00247] Again, it will be appreciated that in order to benefit from the above-mentioned advantage the nominal angle of incidence 526 does not need to correspond precisely with a local minimum or maximum of the power curves of each of the output radiation beams B_1 , B_2 , B_3 with respect to the direction of the input radiation beam B_{in} . It is sufficient that it is close to such a local minimum or maximum. How close to a local minimum or maximum the nominal angle of incidence should be may depend on the expected variation in direction of the input radiation

beam B_{in} and the magnitude of variation in output powers of the output radiation beams B_1 , B_2 , B_3 that can be tolerated (in turn, this may be dependent on the level of dose variations delivered to each lithographic apparatus LA_a - LA_n that can be tolerated).

[00248] Both of the example grating structures described above can be used as part of a beam splitting apparatus and, with suitable choice of nominal direction of the input radiation beam B_{in} , this beam splitting apparatus can be arranged such that the sensitivity of the power of the output radiation beams to variations in the direction and/or the wavelength of the input radiation beam B_{in} is low. It will be appreciated that any such variations in direction and/or the wavelength of the input radiation beam B_{in} will also result in corresponding variations in the directions of the output radiation beams. However, with sufficiently large optical elements within the beam delivery system BDS such small variations in the directions of the output radiation beams can be tolerated.

[00249] Embodiments of the present invention provide optical elements 510 with an intrinsic insensitivity to variations in the direction and wavelength of the input radiation beam.

This is a relatively inexpensive solution to the problem and, by suitable design of the diffraction grating structure, more expensive and complex feed back systems can be avoided.

[00250] From the above, it will be apparent that optical elements which provide a reflective grating structure may be manufactured in any of a plurality of suitable ways. In one embodiment, gratings may be produced by processing a silicon wafer using a plurality of etchants in order to provide ridges with surfaces that are substantially atomically flat. Etchants such as potassium hydroxide (KOH), sodium hydroxide (NaOH) and ammonium fluoride (NH₄F), for example, may be used. A suitable grating may be manufactured as described above. The grating may then be copied using a process such as thermoplastic moulding in a metal glass, or by stamping, for example.

[00251] While it is described above that the etched surface may be silicon, it is to be understood that other materials may be used. Examples of other materials which may be anisotropically etched to provide a grating include germanium (Ge), gallium arsenide (GaAs), silicon-germanium (SiGe), indium phosphide (InP) and indium arsenide (InAs). Generally, however, any suitable (crystalline) material may be used.

[00252] A coating may be deposited on the above described optical elements 210, 310, 310a, 310b, 410, 510 (which may be formed from silicon) so as to increase grazing incidence reflection and decrease absorption of radiation having a desired wavelength (for example EUV radiation). For example, molybdenum (Mo) or ruthenium (Ru) which have a high grazing incidence reflectivity for radiation having wavelengths of 13.5 nm may be used. Other coatings

may be selected for other wavelengths of radiation. Generally, however, transparent materials with a sufficiently high electron density provide good grazing incidence reflection. Heavy element metals are examples of such materials. Additionally, materials may be selected for resistance to conditions likely to be present within the beam delivery system BDS, such as the generation of EUV radiation-induced plasma.

[00253] In some embodiments, an amorphous metal (or metal glass), such as a mix of Mo and Ru, may be deposited on the optical elements (flat or etched silicon) to provide a reflective coating. The amorphous structure of the metal glass may be used to provide smooth surfaces with high reflectivity for a desired wavelength.

[00254] It will be appreciated that any other appropriate materials such as zirconium (Zr), platinum (Pt), nickel (Ni), copper (Cu), silver (Ag), gold (Au) may be used.

[00255] Where a reflective coating is provided, a further coating may be applied to the reflective coating. For example, oxides, nitrides, carbides, etc, may be applied in order to increase the stability and resistance of the reflective coating to conditions likely to be present.

[00256] Where a reflective coating is provided, one or more interface layers may be provided between the etched material (e.g. Si) and the reflective coating to reduce surface roughness and increase thermal conductivity. For example, an interface layer of graphene may be provided.

[00257] While not depicted in the Figures, cooling channels may be provided on a reverse side of any or all of the optical elements described above (i.e. a side which does not receive the input radiation beam B_{in}). Such cooling channels may be arranged to receive a liquid coolant such as water, or a two-phase liquid/gas coolant.

[00258] It will be appreciated that herein when an object is described as being configured to receive a radiation beam and to scatter the radiation beam so as to form the one or more output radiation beams, the term "scatter" is intended to include reflection or diffraction (either reflective or transmissive).

[00259] 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.

[00260] 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.

[00261] 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.

[00262] It will be further appreciated that a free electron laser comprising an undulator as described above may be used as a radiation source for a number of uses, including, but not limited to, lithography.

[00263] The term "relativistic electrons" should be interpreted to mean electrons which have relativistic energies. An electron may be considered to have a relativistic energy when its kinetic energy is comparable to or greater than its rest mass energy (511 keV in natural units). In practice a particle accelerator which forms part of a free electron laser may accelerate electrons to energies which are much greater than its rest mass energy. For example a particle accelerator may accelerate electrons to energies of >10 MeV, >100 MeV, >1GeV or more.

[00264] 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.

[00265] 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.

[00266] 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.

[00267] Different embodiments may be combined with each other. Features of embodiments may be combined with features of other embodiments.

[00268] 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 claims set out below.

CLAIMS:

1. An apparatus for receiving an input radiation beam at a beam receiving location and outputting one or more output radiation beams from the beam receiving location, the apparatus
5 comprising:
 an optical element with a plurality of portions for receiving the input radiation beam;
 a movement mechanism operable to move the plurality of portions so as selectively position each of the plurality of portions at the beam receiving location;
 wherein when one of the plurality of portions is disposed in the beam receiving location it
10 is configured to receive the input radiation beam and to scatter the input radiation beam so as to form the one or more output radiation beams;
 wherein a direction of at least one of the one or more output radiation beams formed by each of the plurality of portions is substantially the same as a direction of a corresponding output radiation beam formed by at least one of the other portions; and
15 wherein one or more properties of each of the plurality of portions differs from that of the other portions such that a power of at least one of the one or more output radiation beams formed by each of the plurality of portions is different to that of the corresponding output radiation beam formed by at least one of the other portions.
- 20 2. The apparatus of claim 1, wherein each of the plurality of portions is provided with a grating structure configured such that when the input radiation beam is incident upon that portion, it is diffracted so as to form a plurality of output radiation beams.
- 25 3. The apparatus of claim 2, wherein the grating structure of each of the plurality of portions is formed from a plurality of unit cells, wherein a length of the plurality of unit cells of each of the plurality of portions is substantially equal and wherein a shape of the plurality of unit cells of each of the plurality of portions differs from a shape of the plurality of unit cells of the other portions.
- 30 4. The apparatus of claim 3, wherein the shape of the plurality of unit cells of the grating structure of at least one of the plurality of portions varies within that portion.
5. The apparatus of claim 3, wherein the shape of the plurality of unit cells of the grating structure of at least one of the plurality of portions is substantially constant within that portion.

6. The apparatus of claim 1, wherein each of the plurality of portions is provided with a reflective surface configured such that when the input radiation beam is incident upon that portion, it is reflected so as to form a single output radiation beam.

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7. The apparatus of claim 6 wherein a reflectivity of the reflective surface of at least one of the plurality of portions is different to the reflectivity of the reflective surface of at least one of the other portions.

10 8. The apparatus of claim 7, wherein the reflective surfaces of two or more of the plurality of portions have different surface roughness.

9. The apparatus of claim 7 or claim 8, wherein the reflective surfaces of two or more of the plurality of portions are formed from different materials.

15

10. The apparatus of any preceding claim, wherein two or more of the plurality of portions overlap.

11. The apparatus of any preceding claim, wherein two or more of the plurality of portions are spatially separated.

20

12. The apparatus of any preceding claim, wherein the movement mechanism is operable to move the optical element linearly.

25 13. The apparatus of any preceding claim, wherein the movement mechanism is operable to rotate the optical element.

14. A radiation system comprising:

a radiation source operable to produce a main radiation beam; and

30 the apparatus of any preceding claim arranged to receive the main radiation beam at the beam receiving location and to output one or more output radiation beams from the beam receiving location.

15. A beam splitting apparatus for receiving an input radiation beam at a beam receiving location and outputting a plurality of output radiation beams from the beam receiving location, the beam splitting apparatus comprising an optical element with a plurality of regions;

wherein each of the plurality of regions is arranged to receive a different portion of the input radiation beam and is provided with a periodic structure configured such that the portion of radiation received by that region is diffracted so as to form a plurality of radiation sub-beams, each of the plurality of radiation sub-beams forming part of a different one of the output radiation beams; and

wherein the periodic structure of each of the plurality of regions has a different a pitch.

16. The beam splitting apparatus of claim 15, wherein the plurality of regions are generally defined by a plurality of concentric ellipses, each of the plurality of concentric ellipses forming a boundary of at least one of the plurality of regions.

17. The beam splitting apparatus of claim 15 or claim 16, wherein a boundary between two adjacent regions is jagged.

18. A radiation system comprising:

a radiation source operable to produce a main radiation beam; and

the beam splitting apparatus of any one of claims 15 to 17 arranged to receive the main radiation beam at the beam receiving location and to output from the beam receiving location a plurality of output radiation beams.

19. The radiation system of claim 18, wherein the pitch of the periodic structure of each of the plurality of regions is dependent on the wavelength distribution of the main radiation beam that across its cross section.

20. The radiation system of claim 18 or claim 19, wherein the pitch of the periodic structure of each of the plurality of regions is dependent on the wavelength of the portion of the main radiation beam that is received by that region.

21. The radiation system of claim 20, wherein the pitch of the periodic structure of each of the plurality of regions is proportional to the wavelength of the portion of the main radiation beam that is received by that region, averaged over that region.

22. A reflective diffraction grating comprising:

an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam;

wherein the geometry of the grating structure is such that, when the input radiation beam comprises EUV radiation:

there is at least one direction of the input radiation beam for which all of the plurality of output radiation beams has substantially equal power; and

the at least one direction is such that when the input radiation beam propagates along it the differential of the power of each of the plurality of output radiation beams with respect to the direction of the input radiation beam is substantially zero.

23. The reflective diffraction grating of claim 22 wherein the grating structure is periodic and comprises a plurality of parallel and equally spaced grooves extending across the reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves.

24. The reflective diffraction grating of claim 22 or claim 23 wherein the diffraction grating is formed from a crystalline material and each face of the reflective surface corresponds to a crystal plane within said crystalline material.

25. The reflective diffraction grating of any one of claims 22 to 24 wherein there are three output radiation beams.

26. The reflective diffraction grating of claim 25 when dependent either directly or indirectly on claim 23 wherein the grating structure has a pitch of approximately 880 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 70.5° and a depth of each groove is approximately 542 nm.

27. The reflective diffraction grating of any one of claims 22 to 24 wherein there are two output radiation beams.

28. The reflective diffraction grating of claim 27 when dependent either directly or indirectly on claim 23 wherein the grating structure has a pitch of approximately 1240 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 109.5° and a depth of each groove is approximately 490 nm.

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29. The reflective diffraction grating of any one of claims 22 to 28 wherein the at least one direction of the input radiation beam corresponds to an angle of incidence in range 85° to 90°.

30. The reflective diffraction grating of any one of claims 22 to 29 wherein when the input radiation beam propagates along the at least one direction the plane of incidence is parallel to the direction along which the plurality of grooves extends.

31. The reflective diffraction grating of any one of claims 22 to 30 wherein the geometry of the grating structure is such that the at least one direction exists when the input radiation beam comprises radiation with a wavelength around 13.5 nm.

32. A reflective diffraction grating comprising:
an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam;

wherein the grating structure is periodic and comprises a plurality of parallel and equally spaced grooves extending across the reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves; and

wherein the grating structure has a pitch of approximately 880 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 70.5° and a depth of each groove is approximately 542 nm.

33. A reflective diffraction grating comprising:
an optical surface for receiving an input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam so as to form a plurality of output radiation beams, a power of each of the plurality of output radiation beams being dependent on a direction of the input radiation beam;

wherein the grating structure is periodic and comprises a plurality of parallel and equally spaced grooves extending across the reflective surface, each of the grooves being formed from two generally flat converging faces, a generally flat face being provided between each pair of adjacent grooves; and

5 wherein the grating structure has a pitch of approximately 1240 nm, the two generally flat converging faces of each of the grooves are at an angle of approximately 109.5° and a depth of each groove is approximately 490 nm.

10 34. The reflective diffraction grating of claim 32 or claim 33 wherein the diffraction grating is formed from a crystalline material and each face of the reflective surface corresponds to a crystal plane within said crystalline material.

35. The reflective diffraction grating of claim 32 or claim 33 wherein the diffraction grating is provided with a reflective coating.

15 36. A radiation system comprising:
a radiation source operable to provide an input radiation beam;
an optical element having an optical surface for receiving the input radiation beam, the optical surface having a grating structure that is configured to scatter the input radiation beam
20 so as to form a plurality of output radiation beams;
wherein the optical element and the input radiation beam are arranged such that the differential of the power of each of the plurality of output radiation beams with respect to a direction of the input radiation beam is substantially zero.

25 37. The radiation system of claim 36 wherein the optical element and the input radiation beam are also arranged such that all of the plurality of output radiation beams have substantially equal power.

30 38. The radiation system of claim 36 or claim 37 wherein the optical element comprises the reflective diffraction grating of any one of claims 22 to 35.

39. The radiation system of any one of claims 36 to 38 wherein the input radiation beam comprises EUV radiation.

40. The radiation system of claim 38 wherein the input radiation beam comprises radiation with a wavelength around 13.5 nm.

41. The radiation system of any one of claims 36 to 40 wherein the optical element and the input radiation beam are arranged such that the input radiation beam is incident upon the optical element at an angle of incidence in range 85° to 90°.

42. The radiation system of any one of claims 36 to 40 wherein the optical element and the input radiation beam are arranged such that the plane of incidence is parallel to the direction along which the plurality of grooves extends.

43. A method of designing a diffraction grating for receiving an input radiation beam and outputting a plurality of diffraction orders, the method comprising:

selecting a general shape of the diffraction grating, the general shape having at least one parameter, the specific shape of the diffraction grating being dependent on said at least one parameter;

for a given wavelength of the input radiation beam for which the diffraction grating may be used, determining a set of values for the at least one parameter for which the geometry of the grating structure is such that:

there is at least one direction of the input radiation beam for which a plurality of the output diffraction orders has substantially equal power; and

the at least one direction is such that when the input radiation beam propagates along it the differential of the power of each of the plurality of output diffraction orders with respect to the direction of the input radiation beam is substantially zero.

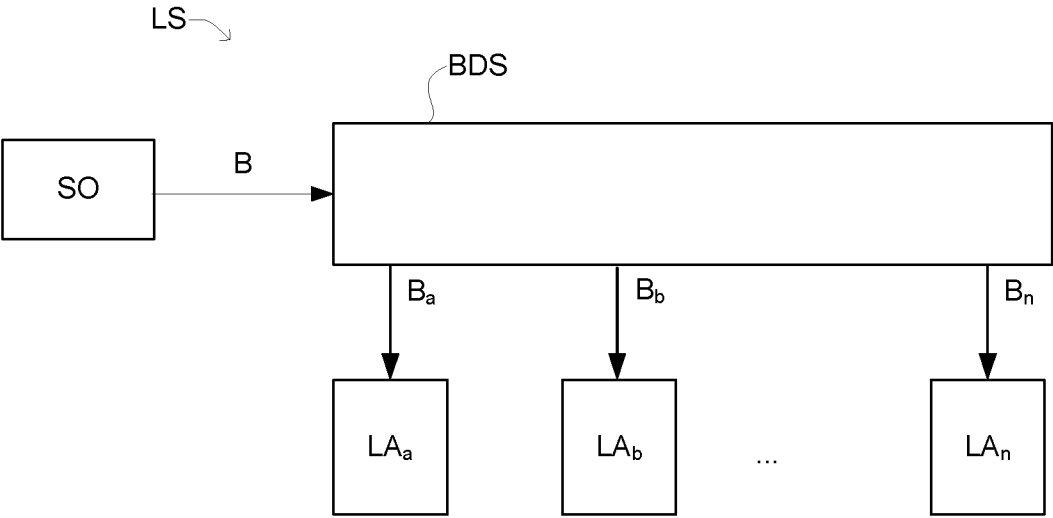


Fig. 1

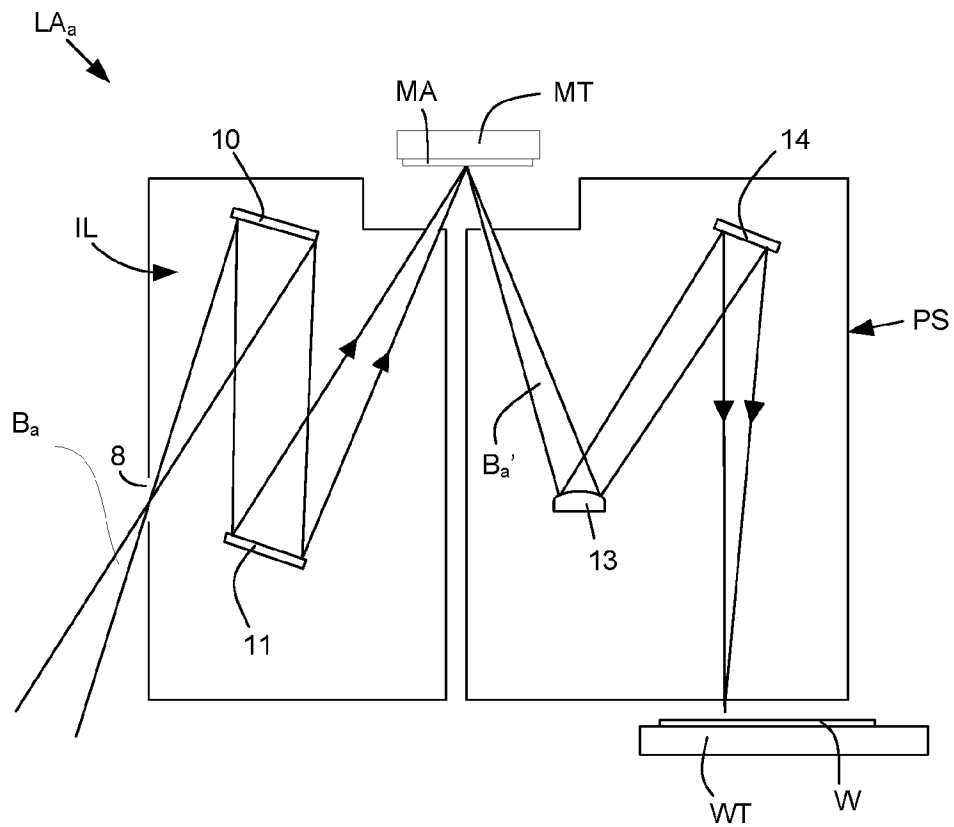


Fig. 2

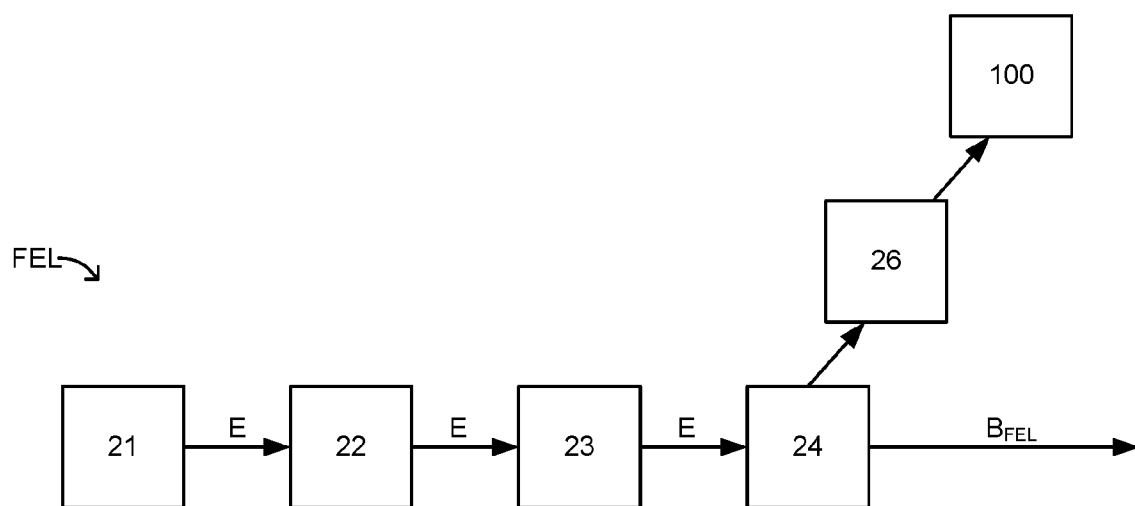


Fig. 3

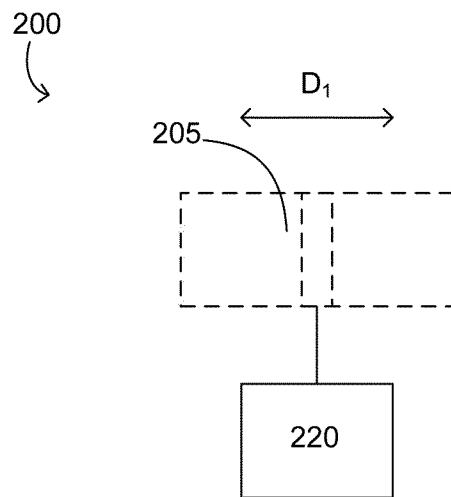


Fig. 4

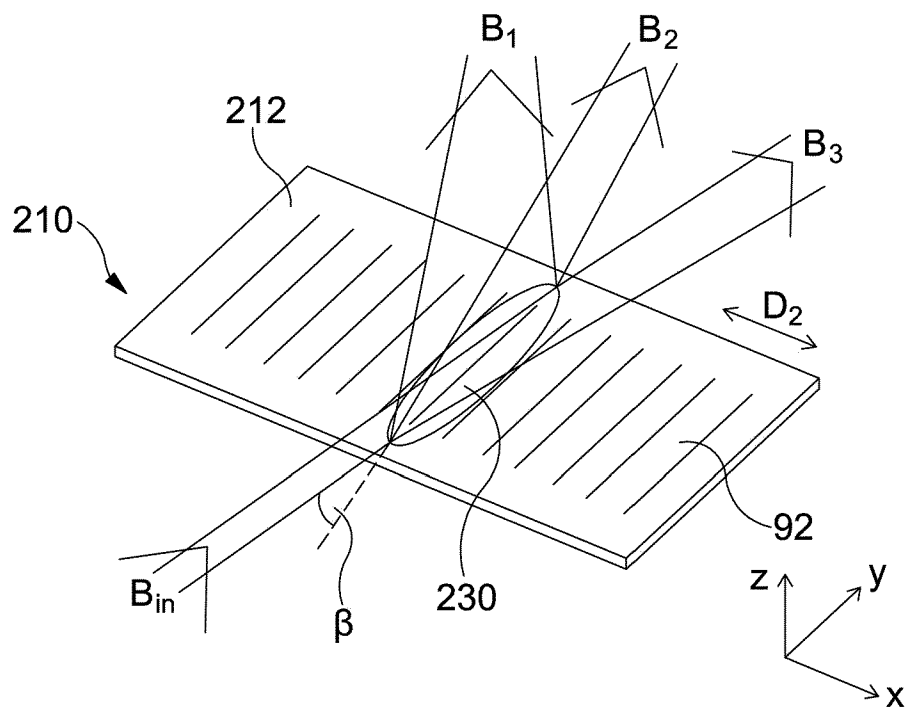


Fig. 5

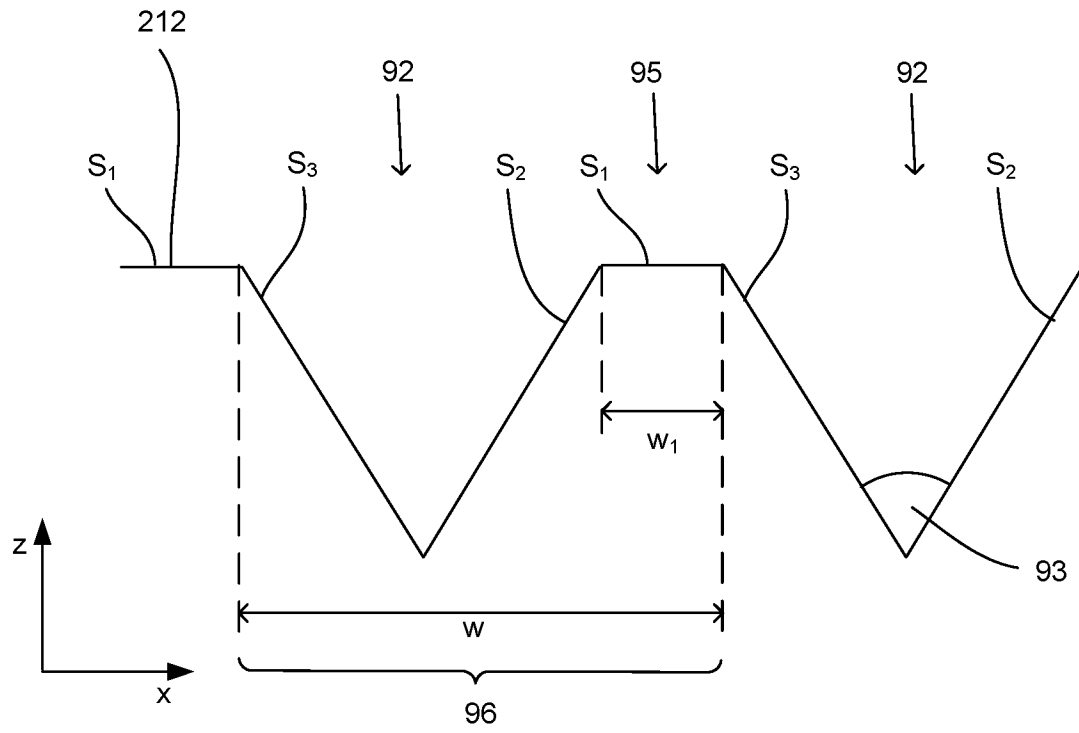


Fig. 6

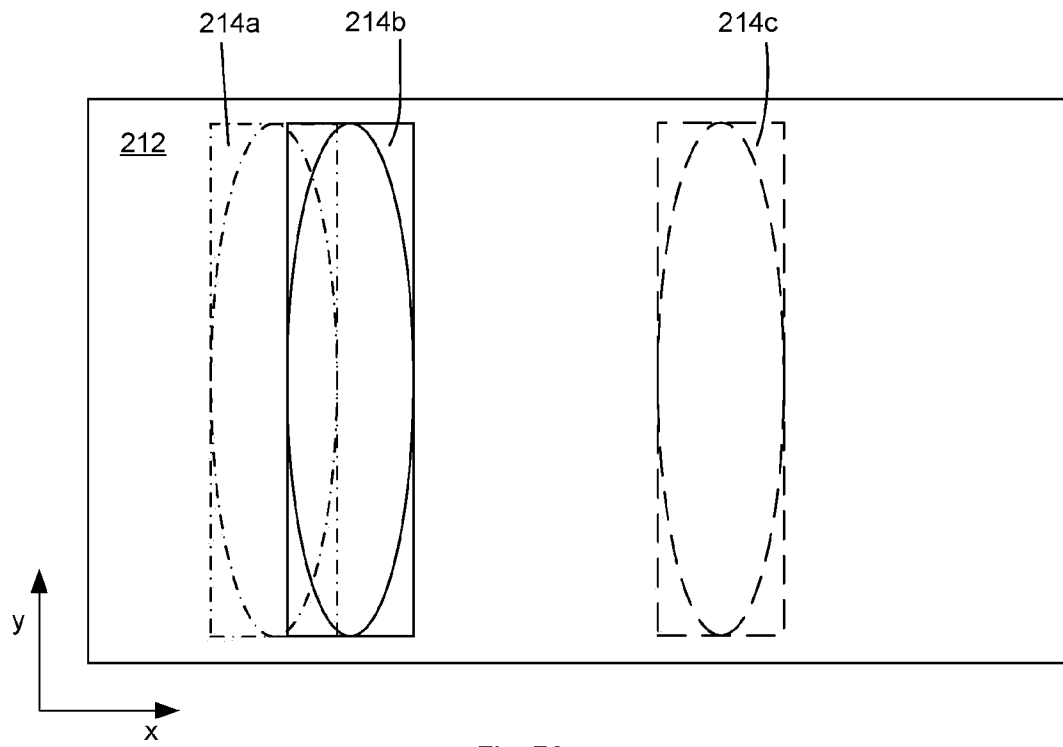


Fig. 7A

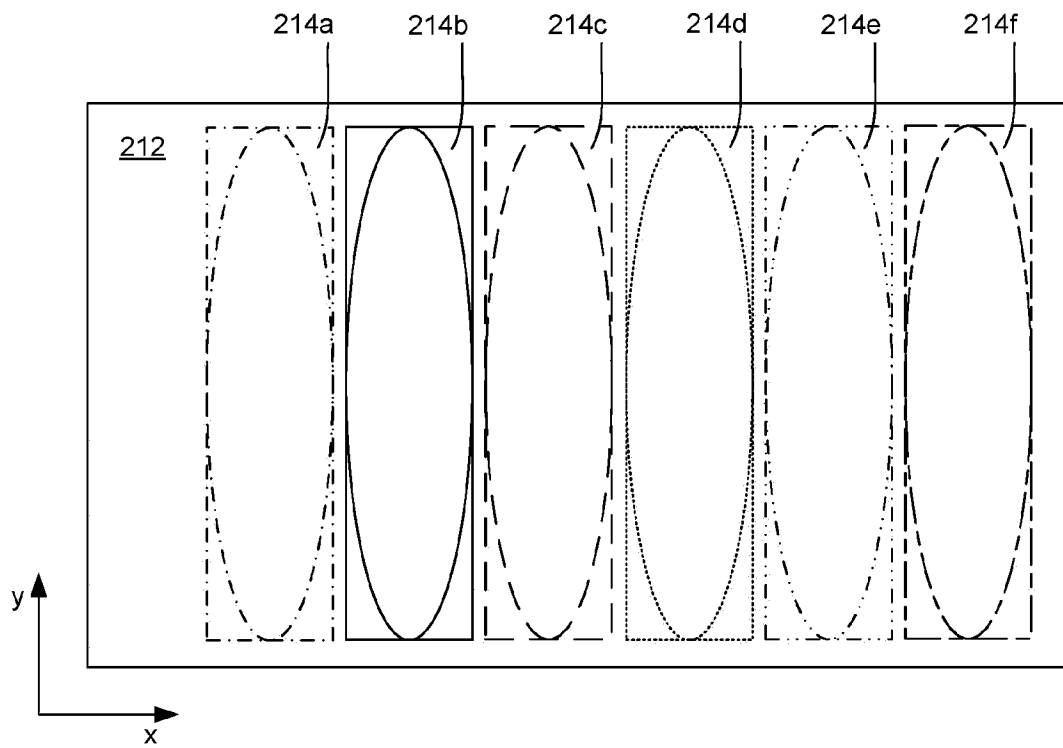


Fig. 7B

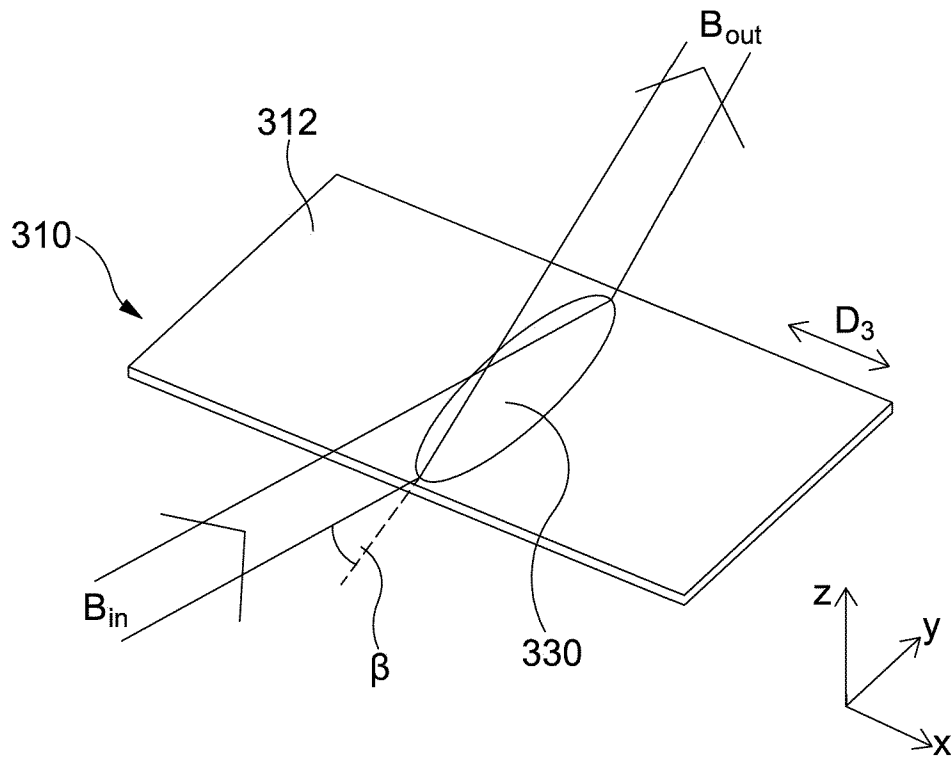


Fig. 8

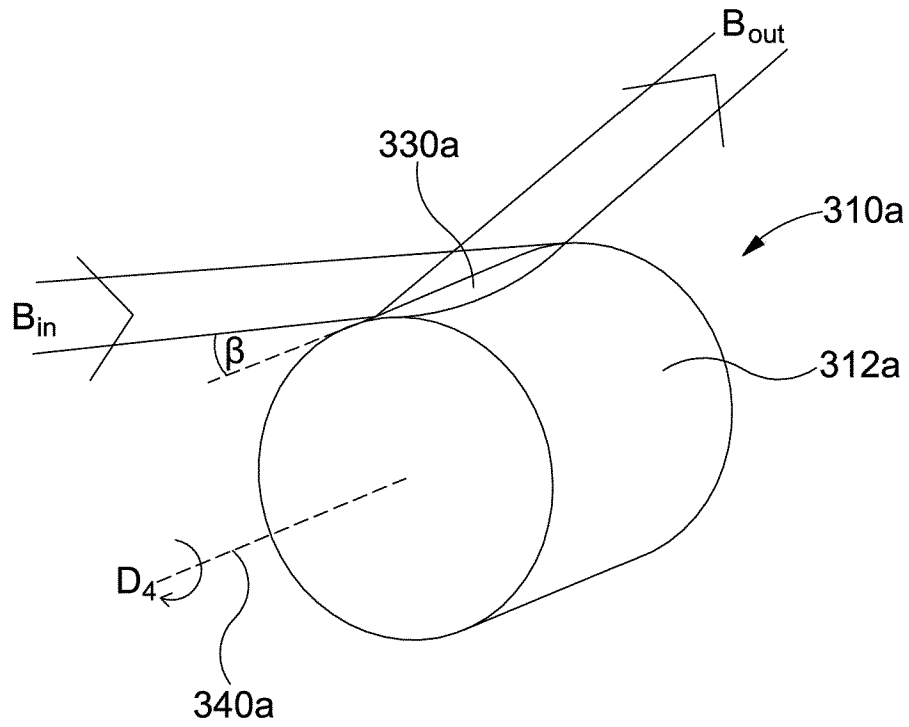


Fig. 9A

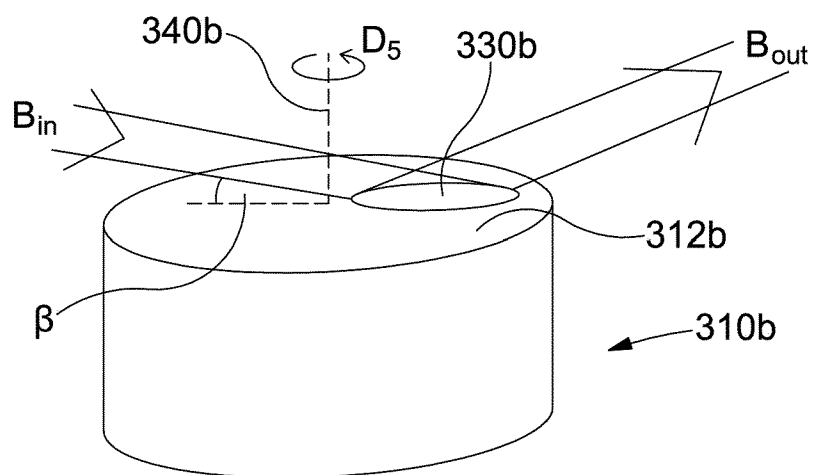


Fig. 9B

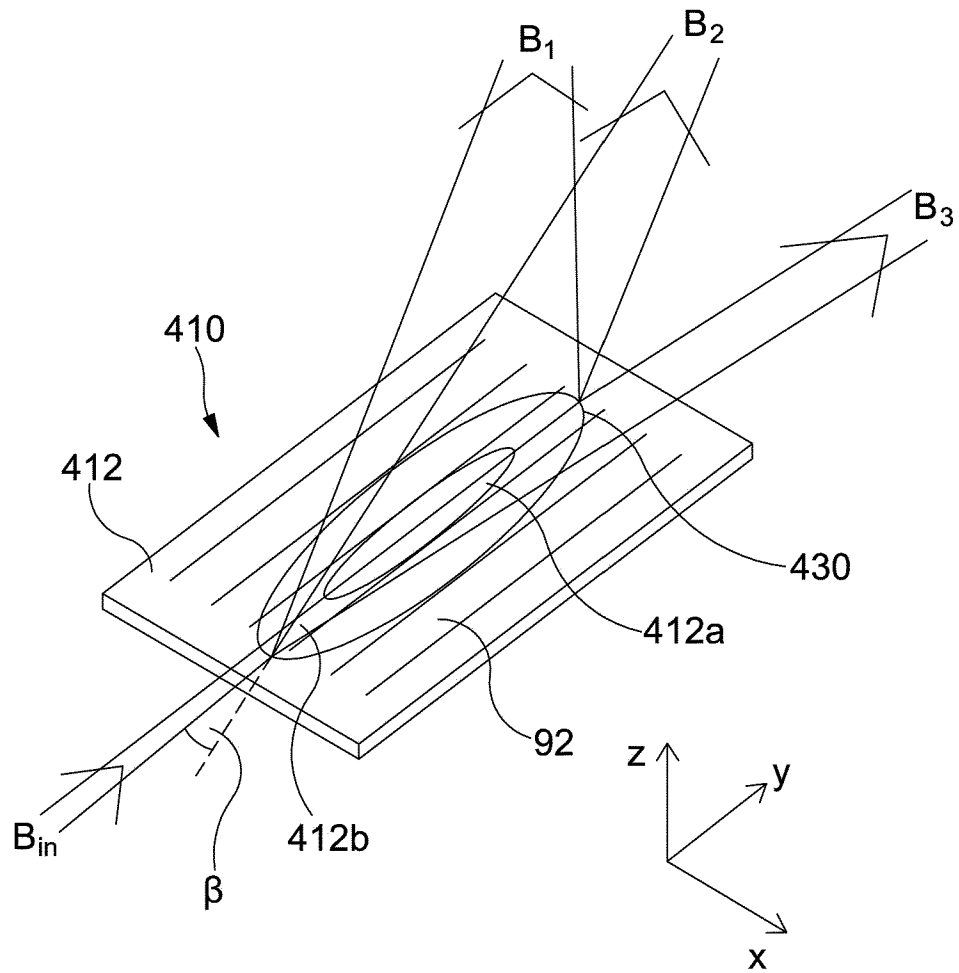


Fig. 10

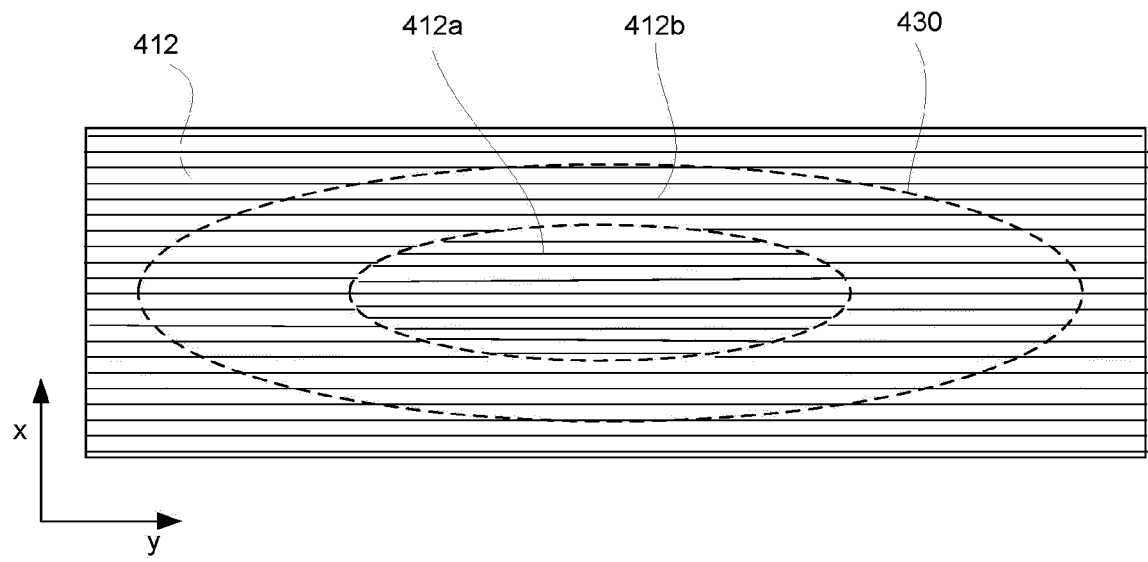


Fig. 11

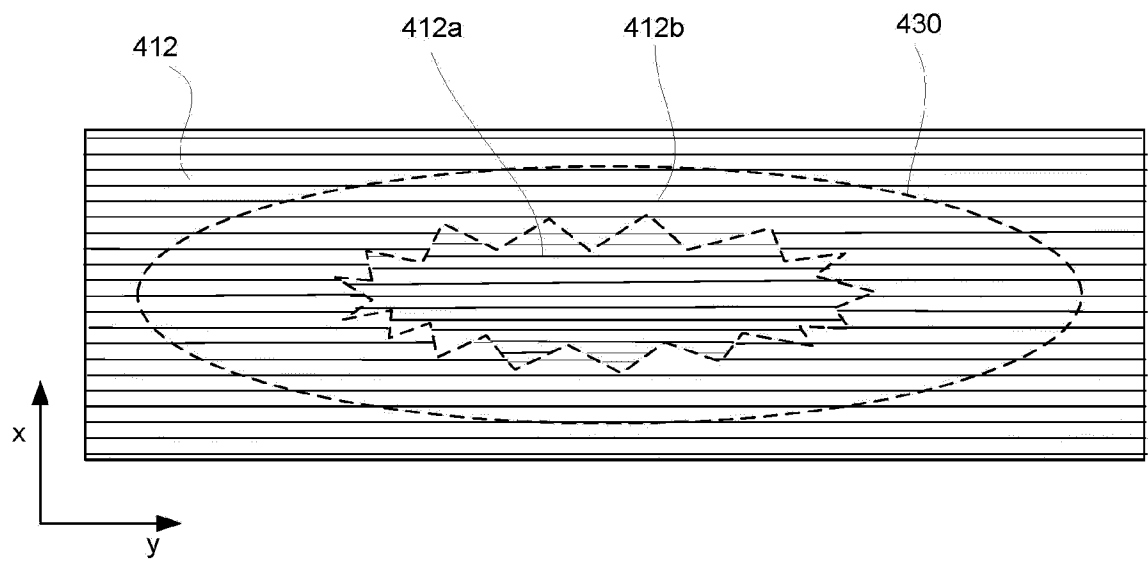


Fig. 12

10/13

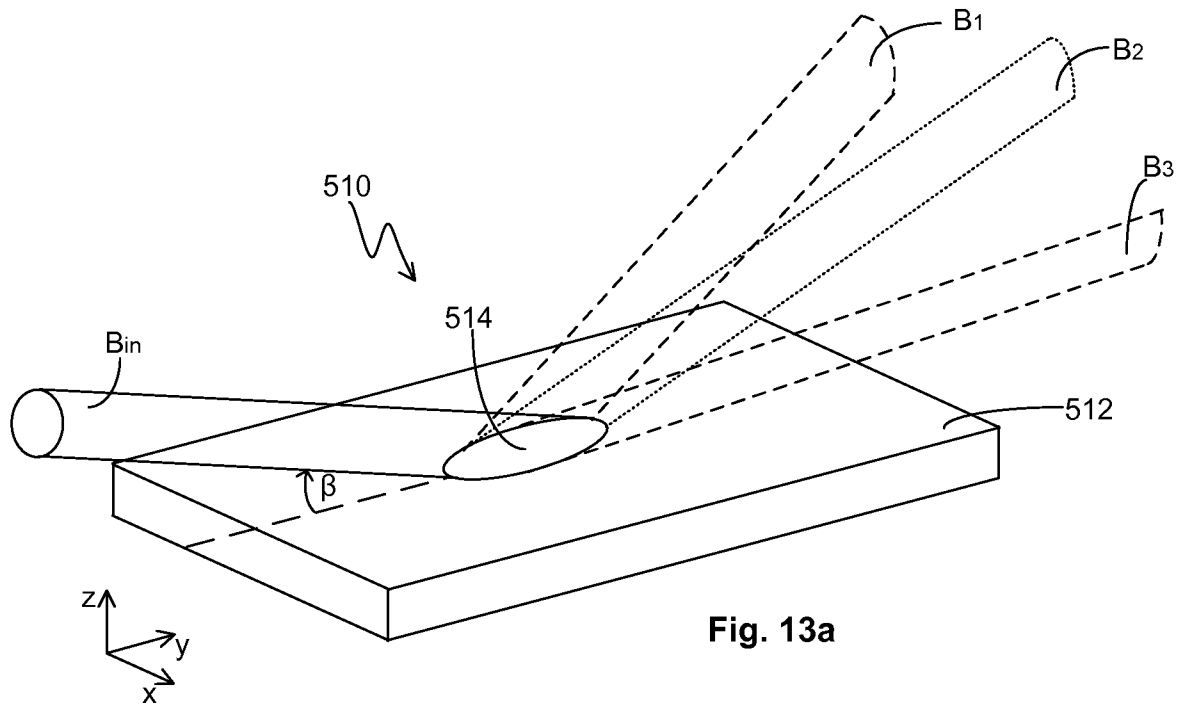


Fig. 13a

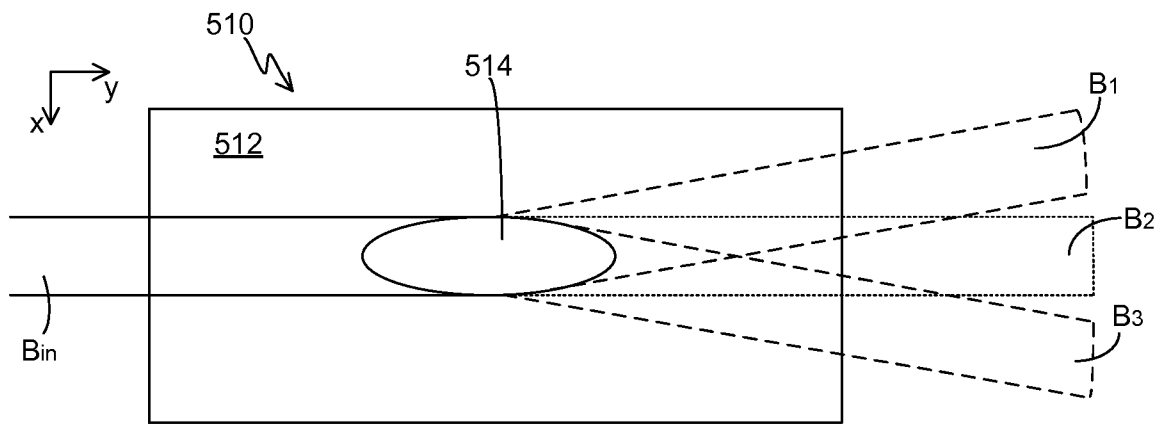


Fig. 13b

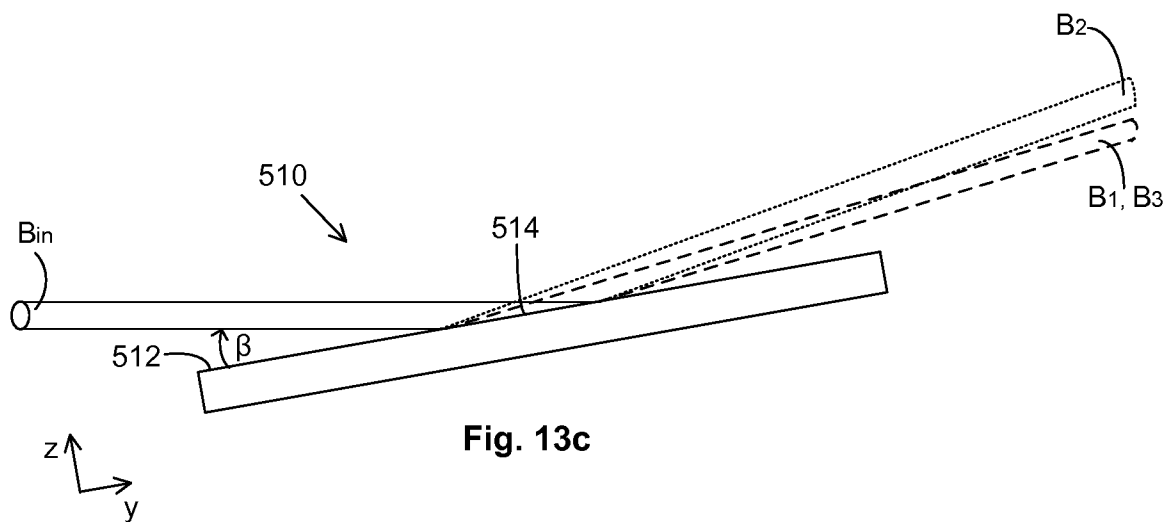


Fig. 13c

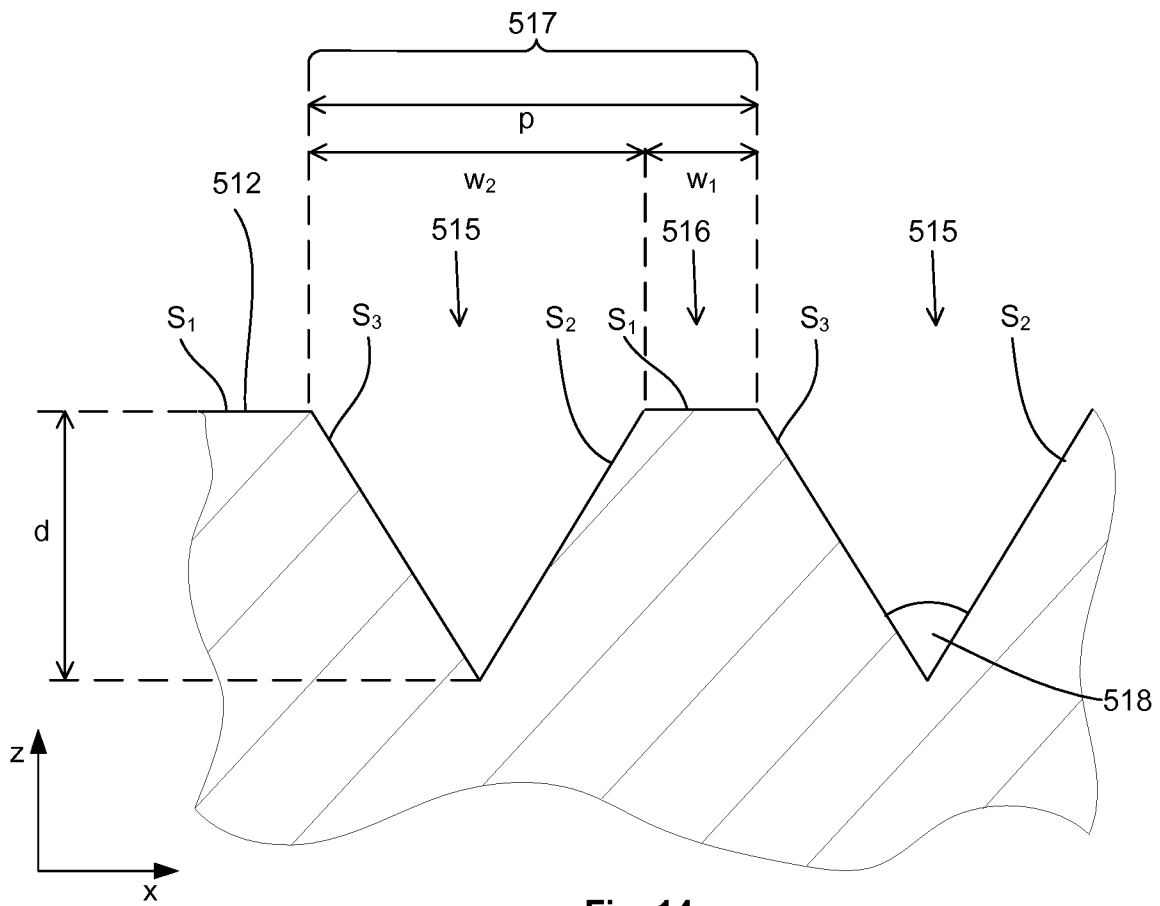


Fig. 14

12/13

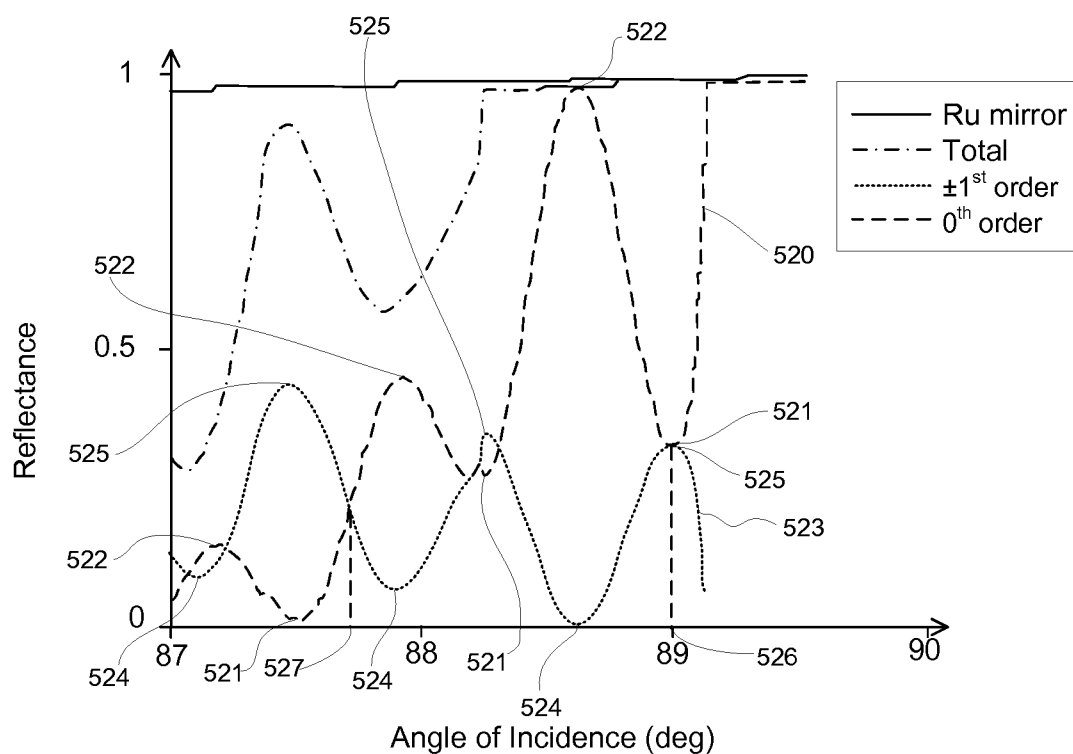


Fig. 15

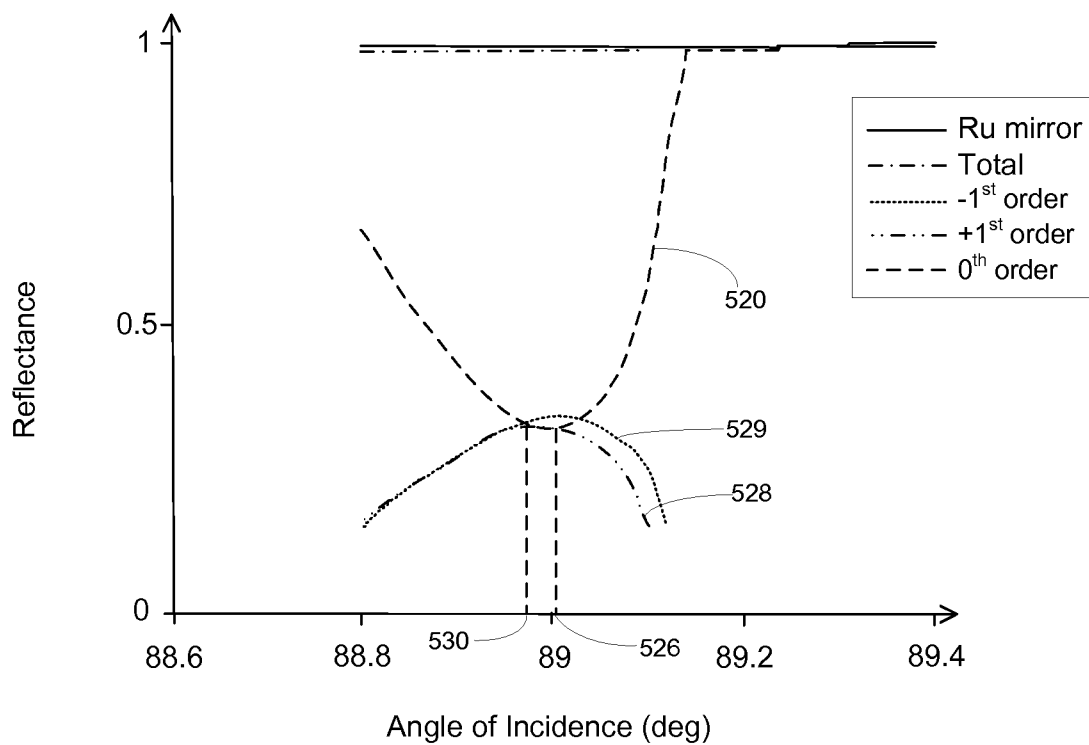


Fig. 16

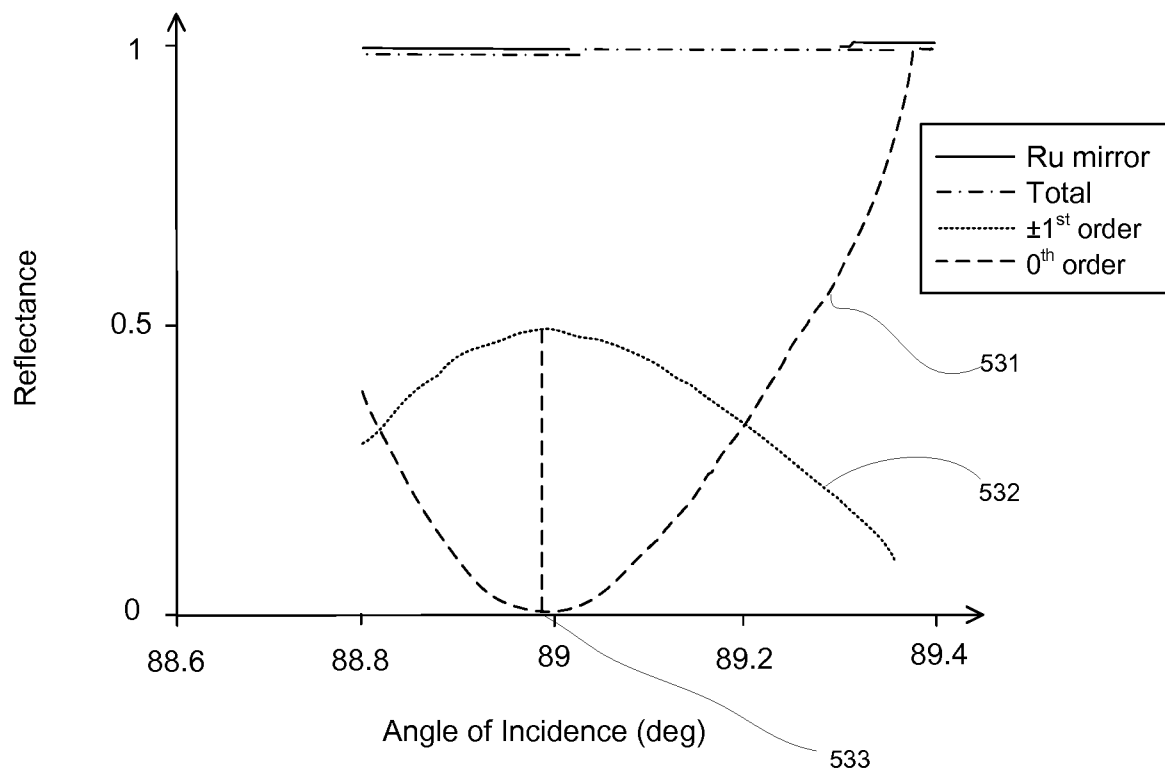


Fig. 17