

(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
30 April 2009 (30.04.2009)

PCT

(10) International Publication Number
WO 2009/053023 A2(51) International Patent Classification:
G02B 17/06 (2006.01) *G03F 7/20* (2006.01)

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BI, BR, BW, BY, BZ, CA, CH, 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, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(21) International Application Number:
PCT/EP2008/008886

(22) International Filing Date: 21 October 2008 (21.10.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10 2007 051 668.3 26 October 2007 (26.10.2007) DE

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(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

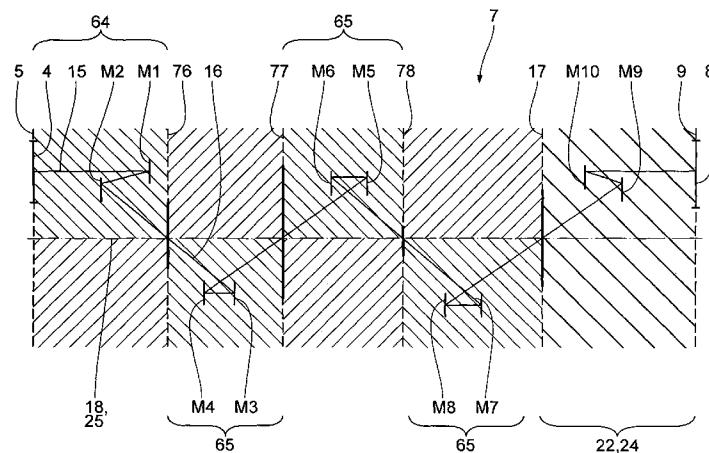
Declaration under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— without international search report and to be republished upon receipt of that report

(54) Title: IMAGING OPTICAL SYSTEM AND PROJECTION EXPOSURE APPARATUS FOR MICROLITHOGRAPHY COMPRISING AN IMAGING OPTICAL SYSTEM OF THIS TYPE



Imaging optical system and projection exposure apparatus for micro-lithography comprising an imaging optical system of this type

The invention relates to an imaging optical system with a plurality of mirrors, which image an object field in an object plane into an image field in an image plane,

- 5 - wherein imaging rays in the light path between non-obsured mirrors of the imaging optical system pass several times through at least one multiple pass-through region between spaced-apart planes which are
10 arranged parallel to the object plane and/or parallel to the image plane, and
- wherein the imaging optical system comprises at least one pupil plane.

The invention further relates to a catoptric imaging optical system with a plurality of mirrors which image an object field in an object plane into an image field in an image plane,

- 15 - wherein the object field has the shape of an arc field which is delimited by
- two graduated circles with the same radius which are displaced parallel to each other by a distance, and
20 - two boundary lines respectively connecting the two ends of both graduated circles.

Further, the invention relates to an imaging optical system with a plurality of mirrors, which image an object field in an object plane into an image field in an image plane,

- 25 - wherein the imaging optical system comprises an optical axis, and

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- wherein the imaging optical system comprises at least one non-
obscured mirror group which is spatially arranged between one of the
following types of boundary planes of the imaging optical system:
 - between a field plane and a pupil plane arranged directly down-
stream thereof, or
 - between a first pupil plane and a second pupil plane arranged di-
rectly downstream thereof.

Furthermore, the invention relates to a projection exposure apparatus comprising an imaging optical system of this type, to a method for the production of a microstructured component using a projection exposure apparatus of this type, and to a microstructured component produced by this method. Imaging optical systems of the type mentioned at the outset are known from US 6,750,948 B2, US 2006/0232867 A1, EP 0 267 766 A2, US 7,209,286 B2 and WO 2006/069 725 A1. WO 2005/098506 A1 discloses a catadioptric imaging optical system with a minimum ring field radius.

It is therefore an object of the present invention to develop an imaging optical system of the type mentioned at the outset in such a way as to facilitate the correction of image errors.

This object is achieved in accordance with the invention by an imaging optical system with a plurality of mirrors, which image an object field in an object plane into an image field in an image plane,

- wherein imaging rays in the light path between non-obscured mirrors of the imaging optical system pass several times through at least one multiple pass-through region between spaced-apart planes which are arranged parallel to the object plane and/or parallel to the image plane, and

- wherein the imaging optical system comprises at least one pupil plane, the imaging optical system being characterized in that all pupil planes are arranged outside the multiple pass-through regions between the non-obsured mirrors.

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By arranging the at least one pupil plane of the imaging optical system outside multiple pass-through regions in the light path between non-obsured mirrors, this enables the imaging optical system to be designed with an arc-shaped object field having a small field radius without causing vignetting

10 problems between the mirrors of the imaging optical system. The small field radius results in that for a given field size, the object field is arranged close to the optical axis of the imaging optical system. This facilitates the correction of image errors of the imaging optical system as higher aspheric orders, which are required for regions remote from the axis, as well as

15 higher asphericities can be dispensed with. The mirrors of the imaging optical system can therefore be designed such that the reflection surfaces thereof slightly deviate from spherical surfaces. For instance, it is conceivable to design the imaging optical system in a way that even for systems with a numerical aperture in the range of 0.5, the maximum deviation of

20 the reflection surfaces of a sphere which is best fitted to the reflection surfaces is less than 500 μm , in particular less than 200 μm . Furthermore, this facilitates the interferometric test as the diameter of the parent asphere is reduced. The parent diameter of a mirror is defined in the professional article "EUV Engineering Test Stand" by D. A. Tichenor et al., Lawrence Livermore National Laboratory, 14.02.2000, Fig. 6 (preprint UCRL-JC-137668). According to requirements, the imaging optical system in accordance with the invention enables in particular the non-obsured mirrors to be designed without vignetting despite the small field radii as the imaging ray bundles, which proceed from the arc-shaped object field and which are

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- correspondingly arc-shaped in a direction perpendicular to the optical axis, have arc shapes in planes which are perpendicular to the optical axis and which are passed through by imaging light several times, said arc shapes opening in the same direction. Arc-shaped bundles of this type can easily
- 5 be configured such that they lie next to each other at an approximately constant distance from each other; in a plane which is perpendicular to the optical axis and is passed through by imaging light several times, it is therefore possible to easily separate a reflected bundle from an arc-shaped bundle which is able to pass through. The at least one pupil plane is arranged
- 10 outside the multiple pass-through regions such that the pupil plane does not coincide with reflection surfaces delimiting the multiple pass-through regions. This ensures that there is no pupil plane in the light path of the multiple pass-through regions. The imaging optical system can be a purely catoptric optical system as well as, in principle, a catadioptric optical system.
- 15 If the imaging optical system according to the invention is equipped with more than one pupil plane, all these pupil planes are disposed in the light path between non-obsured mirrors outside multiple pass-through regions. All these pupil planes are then arranged outside the multiple pass-through regions such as to ensure that the pupil planes do not coincide with reflection surfaces which delimit multiple pass-through regions so that the edges thereof are still part of the multiple pass-through regions.
- 20

In the light path between obscured mirrors, the imaging rays can pass several times through at least another multiple pass-through region between

25 spaced-apart planes which are parallel to the object plane and/or parallel to the image plane, wherein at least one pupil plane and preferably all pupil planes are arranged outside those multiple pass-through regions between the non-obsured mirrors and those multiple pass-through regions between the obscured mirrors. This arrangement of the at least one pupil plane of

the imaging optical system according to the invention ensures accessibility of an illumination bundle in this pupil plane.

The object field can have the shape of an arc field which is delimited by

- 5 two graduated circles with the same radius, said graduated circles being displaced parallel to each other by a certain distance. The field is also delimited by two boundary lines respectively connecting the two ends of both graduated circles, wherein this arc field can have an azimuth angle of more than 75°. Arc field of this type have an advantageously low arc field radius
- 10 at a given field size. The azimuth angle can be greater than 80°, than 90°, than 100°, than 110°, than 120°, than 130°, than 140°, than 150°, than 160°, and even greater than 170°. At a given distance of the two graduated circles, which is referred to as scanning slot length in a scanning projection exposure apparatus, and a given width of the arc field, which is referred to
- 15 as scanning slot width in a scanning projection exposure apparatus, the azimuth angle can have a size of up to the theoretical maximum. In prior-art technology, corresponding arc fields can only be obtained using catadioptric designs, as it is described in WO 2005/098506 A1, for example. In a system of this type, dioptric elements can be used in sections of the imaging optical system in which vignetting problems occur, for instance near the object plane.
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Corresponding advantages are provided by an imaging optical system according to the invention with a plurality of mirrors which image an object

- 25 field in an object plane into an image field in an image plane,
 - wherein the imaging optical system has an optical axis,
 - wherein the imaging optical system has at least one group of non-obsured mirrors which is spatially arranged between one of the following types of boundary planes of the imaging optical system:

- 6 -

- between a field plane and a pupil plane arranged directly downstream thereof;
- between a first pupil plane and a second pupil plane arranged directly downstream thereof.

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- The field or pupil planes, respectively, delimiting at least one group of non-
obscured mirrors are in turn arranged outside this non-obscured mirror
group such that these delimiting field or pupil planes, respectively, do not
coincide with reflection surfaces which delimit an extension of the at least
10 one non-obscured mirror group along the optical axis. The field or pupil
planes, respectively, delimiting the at least one non-obscured mirror group
therefore lie at a distance from the at least one non-obscured mirror group
disposed therebetween.
- 15 The imaging optical system can be designed in a way that a principal ray,
which proceeds from a central object field point and passes through the
center of pupils in the pupil planes of the imaging optical system, proceeds
in the meridional section between mirrors of the at least one non-obscured
mirror group of the imaging optical system such that it does not pass
20 through a principal separation plane
 - in which lies the optical axis and
 - on which the normal from a central object field point to the optical axis
is perpendicular.
- 25 The imaging optical system can have a central pupil obscuration, in other
words an arrangement which does not allow imaging rays to pass through a
region of a pupil plane which is surrounded by another region in which a
passage of imaging rays is possible.

A pupil obscuration of this type can but need not necessarily be configured as a central pupil obscuration. It is sufficient to provide a region in a region of the pupil plane, which is otherwise passed through by imaging rays, which cannot be passed through by imaging rays.

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The object field and the image field can be arranged at a distance from the optical axis.

The imaging optical system according to the invention enables non-
10 obscured mirror groups to be provided on both sides of the principal separation plane without leading to the occurrence of vignetting problems as the separation by means of the pupil plane between the non-obscured mirror groups ensures a separation of the various arc-shaped imaging light bundles in planes which are perpendicular to the optical axis of the imaging
15 optical system and which are passed through by illumination light several times.

The imaging optical system can be designed in a way that

- imaging rays in the light path between non-obscured mirrors pass several times through at least one multiple pass-through region between spaced-apart planes which are arranged parallel to the object plane and/or parallel to the image plane,
20 - in the meridional section, the imaging rays between these planes delimiting the multiple pass-through region do not pass through the principal separation plane.
25

A design of this type enables imaging ray bundles to be separated particularly well in planes passed through by imaging light several times.

- The imaging optical system can have a plurality of mirrors which image an object field in an object plane into an image field in an image plane, wherein the imaging optical system has at least four mirrors of which at least two are non-obsured, and wherein the non-obsured mirror is de-
- 5 signed as a spherical mirror. In a design of this type, a spherical mirror can be used which is fabricable in a comparatively cost-effective way. It has been found that such an arrangement is possible in particular when using a small ring field radius.
- 10 The imaging optical system can have several non-obsured mirror groups between which in each case one pupil plane is arranged in the imaging light path. Such an arrangement ensures that the pupil plane separating the non-obsured systems is in any case disposed in a region of the imaging optical system which is passed through by imaging light only once, in other words
- 15 not in a multiple pass-through region.
- At least one obscured mirror with a through-opening for the penetration of imaging light facilitates the construction of the imaging optical system in terms of minimizing the maximum angle.
- 20 The imaging optical system can comprise exactly six mirrors of which at least three mirrors, preferably exactly four mirrors, are obscured. The imaging optical system can comprise exactly eight mirrors of which at least three mirrors, preferably exactly four mirrors, are obscured. The imaging
- 25 optical system can comprise exactly ten mirrors of which at least three mirrors, preferably exactly four mirrors, are obscured. Such designs proved to be particularly suitable for minimizing the ratio of the maximum angle of incidence and the image-side numerical aperture.

The imaging optical system according to the invention may also comprise the features discussed above in combinations other than those claimed.

The advantages of a projection exposure apparatus according to the invention correspond to those which were previously explained with reference to the imaging optical system according to the invention. The light source of the projection exposure apparatus may be configured so as to be broadband and may for example have a bandwidth which is greater than 1 nm, greater than 10 nm or greater than 100 nm. Additionally, the projection exposure apparatus may be configured so as to be able to be operated with light sources of different wavelengths. Light sources for other wavelengths, in particular those wavelengths used for microlithography, may also be used in combination with the imaging optical system according to the invention, for example light sources with wavelengths of 365 nm, 248 nm, 193 nm, 157 nm, 126 nm, 109 nm and, in particular, also with wavelengths which are less than 100 nm, for instance between 5 nm and 30 nm.

The light source of the projection exposure apparatus may be configured such as to generate illumination light with a wavelength of between 5 nm and 30 nm. A light source of this type requires reflective coatings on the mirrors, which have only a small acceptance bandwidth for the angle of incidence, in order to achieve minimum reflectivity. Together with the imaging optical system according to the invention, this requirement of a low acceptance bandwidth for the angle of incidence can be fulfilled.

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A production method according to the invention and the microstructured or component produced thereby have corresponding advantages.

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In the following, embodiments of the invention are described in greater detail by means of the drawings, in which:

- Fig. 1 is a schematic view of a projection exposure apparatus for
5 EUV microlithography;
- Fig. 2 is a meridional section of an embodiment of an imaging optical system of the projection exposure apparatus;
- 10 Fig. 3 is an enlarged view of an object field of the imaging optical system according to Fig. 2;
- Fig. 4 is a section through imaging rays of selected field points and through an optical axis of the imaging optical system
15 according to Fig. 2 in the region of an object plane thereof;
- Fig. 5 is a section through the imaging rays according to Fig. 4 through a plane V-V in Fig. 2;
- 20 Fig. 6 is a section through the imaging rays according to Fig. 4 through a plane VI-VI in Fig. 2;
- Fig. 7 shows a result of a partially coherent aerial image calculation of a structure image with the imaging optical system
25 according to Fig. 2, in the form of a diagram which shows a relative intensity of the imaging rays as a function of a displacement in the image field of the imaging optical system;

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- Fig. 8 is a view similar to Fig. 7 of the result of a partially coherent aerial image calculation of a structure image with a smaller structural width by comparison with Fig. 7;
- 5 Fig. 9 is a view similar to Fig. 2 of a further embodiment of an imaging optical system for the projection exposure apparatus according to Fig. 1;
- 10 Fig. 10 is a view similar to Fig. 4 of penetration points of imaging rays of selected field points of the imaging optical system according to Fig. 9;
- 15 Fig. 11 is a section through the imaging rays according to Fig. 10 through a plane XI-XI in Fig. 9;
- Fig. 12 is a section through the imaging rays according to Fig. 10 through a plane XII-XII in Fig. 9;
- 20 Fig. 13 is an illustration, similar to Fig. 2, of another embodiment of an imaging optical system for the projection exposure apparatus according to Fig. 1;
- 25 Fig. 14 is an illustration, similar to Fig. 2, of another embodiment of an imaging optical system for the projection exposure apparatus according to Fig. 1; and
- Figs. 15 and 16 are schematized imaging light paths through an imaging optical system which, compared to the embodiments

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shown above, are expanded by further mirror groups which are non-obsured on the object side.

A projection exposure apparatus 1 for microlithography has a light source 2 for illumination light or illumination radiation 3. The light source 2 is an EUV light source, which produces light in a wavelength range, for example, between 5 nm and 30 nm, in particular between 5 nm and 10 nm. The light source 2 may in particular be a light source with a wavelength of 6.9 nm. Other EUV wavelengths are also possible. In general, any desired wavelengths, for example visible wavelengths or even other wavelengths which may be used in microlithography and for which suitable laser light sources and/or LED light sources are available (for example 365 nm, 248 nm, 193 nm, 157 nm 129 nm, 109 nm), are possible for the illumination light 3 which is guided in the projection exposure apparatus 1. A light path 10 of the illumination light 3 is shown extremely schematically in Fig. 1. 15

An illumination optics 6 guides the illumination light 3 from the light source 2 to an object field 4 (cf. Fig. 3) in an object plane 5. The object field 4 is imaged into an image field 8 (cf. Fig. 2) in an image plane 9 at a predetermined reduction scale by a projection optical system or imaging optical system 7. One of the embodiments shown in Fig. 2 and the following may be used for the projection optical system 7. The projection optical system 7 according to Fig. 2 has a reduction factor of 8. Other reduction scales are also possible, for example 4x, 5x, or even reduction scales which are greater than 8x. For illumination light 3 with an EUV wavelength, an imaging scale of 8x is particularly suitable, because an object-side angle of incidence on a reflection mask 10 can thus remain small. Also, an imaging scale of 8x does not require the use of unnecessarily large masks. In the projection optical system 7 in the embodiments according to Fig 2 and the

following, the image plane 9 is arranged parallel to the object plane 5. In this way, a portion, coinciding with the object field 4, of the reflection mask 10 which is also referred to as a reticle is imaged.

- 5 The imaging performed by the projection optical system 7 takes places on the surface of a substrate 11 in the form of wafer which is supported by a substrate support 12. Fig. 1 schematically shows between the reticle 10 and the projection optical system 7 a light beam 13 of the illumination light 3 entering said projection optical system, and between the projection optical system and the substrate 11, a light beam 14 of the illumination light 3 exiting the projection optical system 7. The numerical aperture of the projection optical 7 on the image field side is 0.40 in accordance with Fig. 2. This is not shown to scale in Fig. 1.
- 10
- 15 In order to aid the description of the projection exposure apparatus 1 and the various embodiments of the projection optical system 7, an xyz system, which shows the respective locations of the components represented in the figures may be taken, is specified in the drawings. In Fig. 1, the x direction extends perpendicular to and into the drawing plane. The y direction extends to the right and the z direction extends downwards.
- 20

The projection exposure apparatus 1 is a scanner-type device. Both the reticle 10 and the substrate 11 are scanned in the y direction during the operation of the projection exposure apparatus 1. A stepper type device for the projection exposure apparatus 1, in which a stepwise displacement of the reticle 10 and of the substrate 11 in the y direction takes place between individual exposures of the substrate 11, is also possible.

Fig. 2 shows the optical construction of a first embodiment of the projection optical system 7. This shows the light path of each of three individual rays 15, which proceed in each case from two object field points, which are spaced from one another in the y direction in Fig. 2. The three individual rays 15, which belong to one of these two object field points, are each associated with three different illumination directions for the two object field points. Principal rays 16, which extend through the centre of a pupil in a pupil plane 17 of the projection optical system 7, are shown in Fig. 2 only for reasons of clarity, as these are not real imaging light paths of the projection optical system 7 due to the central pupil obscuration. Proceeding from the object plane 5, these principal rays 16 initially extend divergently. This is referred to in the following as a negative back focal length of an entrance pupil of the projection optical system 7. The entrance pupil of the projection optical system 7 according to Fig. 2 lies not inside the projection optical system 7, but before the object plane 5 in the light path. This makes it possible, for example, to arrange a pupil component of the illumination optics 6 in the entrance pupil of the projection optical system 7 before the projection optical system 7 in the light path, without further imaging optical components having to be present between this pupil component and the object plane 5. As an alternative, a positive back focal length of the entrance pupil, or an object-side telecentric light path as a further alternative, is also possible. The second alternative is used, for example, in relation to a reflection mask as a reticle 10 in the object plane 5 with the use of a ray divider element or in conjunction with a transmission mask as a reticle in the object plane 5.

The projection optical system 7 according to Fig. 2 has a total of six mirrors, which are numbered M1 to M6 in the sequence of the light path of the individual rays 15, starting from the object field 4. Fig. 2 shows merely the

- 15 -

calculated reflection surfaces of the mirrors M1 to M6. In general, the mirrors M1 to M6 are larger than the reflection surfaces which are actually used.

- 5 The optical data of the projection optical system 7 according to Fig. 2 are shown below by means of two tables. In the “radius” column, the first table shows the respective radii of curvature of the mirrors M1 to M6. The third column (thickness) describes the distance in each case to the following surface in the z direction starting from the object plane 5.

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The second table describes the precise surface shape of the reflection surfaces of the mirrors M1 to M6, where the constants K and A to E are to be used in the following equation for the sagittal height z:

$$15 \quad z(h) = \frac{ch^2}{1 + \text{SQRT}\{1 - (1 + K)c^2 h^2\}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12}$$

Here, h represents the distance of the projection optical system 7 from an optical axis 18. Therefore, $h^2 = x^2 + y^2$. The reciprocal of the radius is used for c.

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Surface	Radius (1/c)	Thickness	Operating mode
Object plane	INFINITY	348.222	
M1	-379.407	-157.578	REFL
M2	-202.767	1353.319	REFL
DIAPHRAGM	INFINITY	0.000	
M3	1127.182	-1195.630	REFL
M4	1374.690	1626.377	REFL
M5	-975.061	-330.747	REFL
M6	681.443	375.745	REFL
Image plane	INFINITY	0.000	

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Surface	K	A	B
M1	0.000000E+00	-6.780209E-11	-1.455553E-15
M2	0.000000E+00	2.307286E-09	2.337524E-14
M3	0.000000E+00	1.500225E-09	1.781600E-14
M4	0.000000E+00	-1.573831E-12	-8.140292E-19
M5	0.000000E+00	6.446612E-10	2.597249E-15
M6	0.000000E+00	3.799673E-10	1.680031E-15
Surface	C	D	E
M1	-3.423358E-21	0.000000E+00	0.000000E+00
M2	5.367802E-18	0.000000E+00	0.000000E+00
M3	-2.232896E-19	0.000000E+00	0.000000E+00
M4	-5.798511E-26	0.000000E+00	0.000000E+00
M5	4.409975E-20	1.865473E-25	-9.721913E-32
M6	5.791990E-21	0.000000E+00	0.000000E+00

The mirrors M1 and M2 of a first mirror group 19 are used in the shape of a ring segment and off-axis in relation to the optical axis 18. The used optical reflection surface of the mirrors M1 and M2 thus lies at a distance from the optical axis 18. The object field 4 and the image field 8 are arranged at a distance from the optical axis 18. The reflection surfaces of all the mirrors M1 to M6 are rotationally symmetrical about the optical axis 18 in accordance with the above equation for the sagittal height z.

10

The optically used regions of the mirrors M1 and M2 have no through-openings for the penetration of imaging light, i.e. are not obscured. The first mirror group 19 is thus a non-obscured mirror group. The reflection surfaces of the mirrors M1 and M2 face one another.

15

The mirrors M1, M4, M5 and M6 are concave mirrors. The mirrors M2 and M3 are convex mirrors.

- The individual rays 15 pass through a through-opening 20 in the mirror M4 between the mirrors M2 and M3 in the imaging light path. The mirror M4 is used around the through-opening 20. The mirror M4 is thus an obscured mirror. As well as the mirror M4, the mirrors M3, M5 and M6 are also obscured and likewise each comprise an approximately central through-opening 20. In total, two non-obscured mirrors, namely the mirrors M1 and M2, and then four obscured mirrors, namely the mirrors M3 to M6, are thus initially present in the projection optical system 7.
- 10 The pupil plane 17 lies in the light path in the projection optical system 7 in the region of the reflection of the individual rays 15 on the mirror M3.
- The mirrors M1 and M4 are arranged back-to-back as regards the orientation of the reflection surfaces thereof.
- 15 Between the mirrors M4 and M5 in the imaging light path lies an intermediate image plane 21 of the projection optical system 7. The individual rays 15 penetrate the intermediate image plane 21 directly after the individual rays 15 pass through the through-opening 20 of the mirror M3.
- 20 The mirrors M3 and M4 represent a first obscured mirror group 22 of the projection optical system 7 between the pupil plane 17 and the intermediate image plane 21, which is arranged after the non-obscured mirror group 19 in the imaging light path. The reflection surfaces of the mirrors M3 and M4 face one another.

The individual rays 15 penetrate the through-opening 20 in the mirror M6 between the intermediate image plane 21 and the mirror M5 in the light

path. A further pupil plane 23 of the projection optical system 7 is present in the region of the reflection of the individual rays 15 on the mirror M5.

The mirrors M5 and M6 represent a further obscured mirror group 24 of 5 the projection optical system 7 between the intermediate image plane 20 and the image plane 9, which is arranged after the obscured mirror group 22. The reflection surfaces of the mirrors M5 and M6 face one another.

After the reflection of individual rays 15 on the mirror M6, the individual 10 rays 15 pass through the through-opening 20 in the mirror M5 and reach the image field 8. The following table shows the maximum and minimum angles of incidence for the individual rays 15 in the meridional section according to Fig. 2. These are the respective maximum and minimum angles of incidence on the mirrors M1 to M6.

15

Mirror	Max. angle of incidence (meridional section) [°]	Min. angle of incidence (meridional section) [°]
M1	7.52	5.87
M2	12.35	9.16
M3	10.38	0.81
M4	2.35	0.42
M5	12.10	1.66
M6	10.41	2.19

The ratio of the maximum angle of incidence of imaging light onto the reflection surfaces of the mirrors M1 to M6 and the numerical aperture of the projection optical system 7 is thus specified by the maximum angle of incidence onto the mirror M2, which is 12.35°. The ratio of this maximum angle of incidence and the numerical aperture is thus 30.9° in the projection 20 optical system 7 according to Fig. 2.

The low maximum angle of incidence provides the possibility of using a reflection surface even for low EUV wavelengths, for example in the range of 6.9 nm, which have a comparatively large acceptance bandwidth for the angle of incidence because of the low maximum angle of incidence. This is

5 further explained below by means of Fig. 14. This acceptance bandwidth of the reflective layer for the angle of incidence increases as the maximum angle of incidence for which the reflective coating is constructed decreases.

Reflective coatings which are formed as a layer stack with a large number of, in particular, successively alternating layer materials with different re-

10 fractive indexes are also possible. When illumination light 3 with a wavelength of less than 10 nm is used, coatings of this type have a correspondingly low acceptance bandwidth for the angle of incidence. The projection optical system 7 can therefore be used with relatively low reflection losses by comparison with the state of the art and with smaller differences in the

15 reflectivity of the individual mirrors over the reflection surfaces thereof even at low wavelengths of this type.

The optical axis 18 is shown as a broken line in Fig. 2. This broken line simultaneously represents the line of intersection of a principal separation plane 25 (xz plane in Fig. 2) with the meridional plane (yz plane in Fig. 2) according to Fig. 2. This principal separation plane 25 is perpendicular to the drawing plane in Fig. 2. The optical axis 18 lies in the principal separation plane 25. Additionally, a normal 26 of a central object field point, lying in the meridional plane of Fig. 2, on the optical axis 18 is perpendicular

20 to the principal separation plane 25. This normal 26 also lies in the drawing plane of Fig. 2 and coincides with the line of intersection of the object plane 5 (xy plane in Fig. 2) with the meridional plane, i.e. the drawing plane in Fig. 2.

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- 20 -

- The imaging rays, extending in the meridional section, of the optical system do not pass through the principal separation plane 25 in the first, non-
obscured mirror group 19 of the projection optical system 7. The principal
separation plane 25 is first passed through by individual rays 15 after the
5 reflection on the mirror M2 between the mirrors M2 and M3 in the imaging
light path, i.e. at the transition between the mirror groups 19 and 22. The
principal separation plane 25 is first passed through by the principal rays
16 in the pupil plane 17.
- 10 Fig. 3 is an enlarged view of the object field 4 of the projection optical sys-
tem 7. The image field 8 has exactly the same shape except that it is re-
duced by a factor of 8. The field 4 is an arc-shaped field, which is delimited
by two graduated circles 27, 28 of the same radius R, which are displaced
parallel to one another in the y direction by a distance YS. The field 4 is
15 also delimited by two boundary lines 29, 30 respectively connecting the
two ends of the graduated circles 27, 28 and extending parallel to the nor-
mal 26. The two boundary lines 29, 30 are at a distance XS, the scanning
slot width, from one another. The principal separation plane 25 passes
through the centers of the two boundary lines 29, 30. The optical axis 18
20 therefore lies precisely between the centers of the two boundary lines 29,
30. Because of this arrangement of the optical axis 18 between the bound-
ary lines 29, 30, the field 4 is therefore a field with a minimum ring field
radius R. This is given by the following expression:
- 25
$$R = \text{SQRT} \left[\left(\frac{XS}{2} \right)^2 + \left(\frac{YS}{2} \right)^2 \right]$$

- 21 -

In the projection optical system 7 of Fig. 2, the object field 4 has dimensions of XS = 104 mm (scanning slot width) and YS = 8 mm (scanning slot length). This results in a ring field radius R of 52.154 mm for the object field 4.

5

Between the boundary lines 29, 30 and the graduated circle 28, which is shown at the top of Fig. 3, the field 4 has border transitions 31, 32, where the graduated circle 28 transitions into the boundary lines 29, 30 which extend in a straight line. Between the border transition 31, 32, a field radius

10 vector 33 covers an azimuth angle α , which is calculated using the following formula:

$$\alpha = 2 \arcsin(\frac{1}{2} XS/R)$$

15 This results in an azimuth angle α of 171.2° for the object field 4. The image field 8 has the same azimuth angle. This high azimuth angle means that the field 4 is arranged as close as possible to the optical axis 18 for a given XS extension. This facilitates an imaging error correction when imaging through the projection objective 7 between the object field 4 and the image field 8. In addition, the large azimuth angle leads to small parent diameters and to low asphericities of the mirrors M1 to M6. The parent diameter of a mirror is defined in the professional article "EUV Engineering Test Stand" 20 by D. A. Tichenor et al., Lawrence Livermore National Laboratory, 14.02.2000, Fig. 6 (preprint UCRL-JC-137668). With the large azimuth angle, it is also possible to keep the angles of incidence on the mirrors M1 25 to M6 low.

Fig. 4 to 6 show the path of light beams 34 to selected object field points within the non-obsured mirror group 19. The light beams 34 of all light

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beam groups which are discussed in the following in connection with Fig. 4 to 6 are each associated with the same 25 object field points. The light beams 34 of a total of five light beam groups 35, 36, 37, 38, 39 are shown. The light beam groups 35 to 39 are numbered from left to right in Fig. 4.

- 5 Each light beam group 35 to 39 has five light beams 34 which belong to object field points with the same x value and are spaced equidistantly from one another in the y direction. The central light beam group 37 in Fig. 4 belongs to the object field points lying in the meridional plane.
- 10 Fig. 4 shows the light beams 34 in the vicinity of the object plane 5 in such a way that the shape of the arc-shaped object field 4 can be seen. The two light beam groups 35 and 39 at the edges proceed from object field points lying on the boundary lines 29, 30. The view of Fig. 4 is compressed in the y direction in such a way that the arc field radius R appears smaller in the y direction than in the x direction.
- 15

The field radius sector R, which belongs to the central light beam group 37, appears at the top in Fig. 4. In Fig. 4, the light beam groups 35 to 39 form a downwardly open semicircle about the optical axis 18.

20

Fig. 5 shows the light beams 34 in a sectional plane V of Fig. 2, i.e. in the region of the mirror M1. Light beam groups 40 to 44 reflected on the mirror M1 lie on a ring segment and form, in Fig. 5, a downwardly open external semicircle about the optical axis 18.

25

Furthermore, the plane V is passed through by light beam groups 45 to 49, which extend between the mirrors M2 and M3 in the light path.

The light beam groups 45 to 49 also form a semicircle, which is downwardly open in Fig. 5, about the optical axis 18. The semicircle of the light beam groups 45 to 49 thus lies between the optical axis 18 and the semicircle which is formed by the light beam groups 40 to 44.

5

Due to the fact that the two semicircles of the light beam groups 40 to 44 on the one hand and 45 to 49 on the other hand are each open downwardly, a sufficiently large minimal distance may be achieved between the individual light beams 34 of the light beam groups 40 to 44 on the one hand and

- 10 45 to 49 on the other hand with a compact arrangement of the light beam groups 40 to 49. This distance is denoted by A in Fig. 5. The through-opening 20 in the mirror M4 may thus be delimited between the light beam groups 40 to 44 on the one hand and 45 to 49 on the other hand without further steps being taken, as is shown in Fig. 5 by a dotted and dashed line.
- 15 The distance A is necessary in practice because the mirrors M1 to M6 generally cannot be produced so as to be perfectly sharp-edged. The distance A also serves as a tolerance for assembling and adjusting the system. Conventionally, the distance A is a few millimeters.
- 20 Fig. 6 is a view similar to Fig. 5 of the light beams 34 to the 25 object field points in a plane VI, in the region of which the mirror M2 is arranged. Light beam groups 50, 51, 52, 53, 54 lie adjacent to the optical axis 18 at the place where the light beam 34 reflects on the mirror M2. The light beam groups 50 to 54 are arranged in a semicircle which is downwardly open in Fig. 6. This semicircle is surrounded by a likewise downwardly open semicircle of light beam groups 55 to 59, which pass through the plane VI between the object plane 5 and the mirror M1 in the imaging light path. Thus, the semicircle openings of the semicircles which are associated with the light beam groups 50 to 54 on the one hand and 55 to 59 on the

other hand are also open in the same direction in the plane VI, in such a way that a distance A is provided between these light beam groups 50 to 54 on the one hand and 55 to 59 on the other hand with a compact arrangement at the same time. In this case too, a delimitation 60 at the edges of the 5 mirror M2 is possible without vignetting the light beam groups 50 to 54 on the one hand and 55 to 59 on the other hand, as is indicated in dotted and dashed lines in Fig. 6.

Between the planes V and VI, the individual rays 15 thus pass through a 10 multiple pass-through region 61 (cf. Fig. 2). This multiple pass-through region 61 is passed through a total of three times, in particular, on the one hand by individual rays 15 between the object plane 5 and the mirror M1, on the other hand by individual rays 15 between the mirrors M1 and M2, and also by individual rays 15 between the mirrors M2 and M3. There is no 15 pupil plane of the projection optical system 7 in the multiple pass-through region 61. The pupil planes 17 and 23 are arranged outside the multiple pass-through region 61.

Fig. 7 shows the result of a partially coherent aerial image calculation of 20 the projection objective 7. A diagram is shown in which a relative intensity I is plotted upwards as a function of a position V, plotted to the right, in the image field 8. The diagram according to Fig. 7 shows the result of an imaging of a rectangular structure with a total of seven individual structures B with an image-side structure width of 10 nm and intermediate spaces C 25 with an image-side structure distance likewise of 10 nm. The object-side structure width results from the image-side structure width via the imaging scale and in the present case is $8 \times 10 \text{ nm} = 80 \text{ nm}$. This structure is arranged in the object field 4, i.e. on the reticle 10. The relative intensities at different y values during a scan through the image field 8 are plotted as

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approximately sinusoidal lines in the diagram of Fig. 7. The wavelength of the imaging light is 6.9 nm.

5 The relative intensities fluctuate between approximately 0.06 at the location of the 10 nm structures B and 0.62 in the centre of the 10 nm intermediate spaces C.

10 Due to the considerable variation in the relative intensity between the structure regions B and the structure intermediate spaces C, this 10 nm structure can be resolved in the image plane 9 without further steps being taken and can be used for the production of a corresponding structure in the image field 8 by exposure of a corresponding photoresist on the substrate 11.

15 Fig. 8 is a representation similar to Fig. 7 of the result of a partially coherent aerial image calculation of the projection objective 7 according to Fig. 2 in a structural resolution of structures B with structure intermediate spaces C with an extension of 6 nm in each case on the image side. A wavelength of 6.9 nm is also used in this case. In this case, the relative intensity likewise varies approximately sinusoidally from a value of approximately 0.2 in the middle of the structures B to approximately 0.37 in the centre of the intermediate space C between the structures B. Therefore, the 6 nm structures may also be imaged with sufficient intensity variation for a photoresist development.

20

25 A wavelength of 6.9 nm is also used in this case.

Fig. 9 shows a further embodiment of a projection optical system 7. Components and details which correspond to those which have already been

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explained with reference to Fig. 1 to 8 have the same reference numerals and will not be discussed in detail again.

The optical data of the projection optical system 7 according to Fig. 9 are
 5 reproduced in the following by means of two tables which correspond in layout to the tables for the projection optical system 7 according to Fig. 2.

Surface	Radius (1/c)	Thickness	Operating mode
Object plane	INFINITY	320.330	
M1	-393.803	-170.123	REFL
M2	-208.260	1326.985	REFL
STOP	INFINITY	0.000	
M3	3524.853	-1156.745	REFL
M4	1373.092	1633.832	REFL
M5	-2070.870	-417.088	REFL
M6	729.502	462.810	REFL
Image plane	INFINITY	0.000	

Surface	K	A	B
M1	0.000000E+00	-2.256168E-10	-1.464839E-15
M2	0.000000E+00	0.000000E+00	0.000000E+00
M3	0.000000E+00	1.686353E-09	1.384199E-14
M4	0.000000E+00	-1.141200E-12	-1.895182E-19
M5	0.000000E+00	3.648003E-10	9.829850E-16
M6	0.000000E+00	1.500658E-10	5.461440E-16
Surface	C	D	E
M1	-9.891998E-20	4.705529E-24	-1.095685E-28
M2	0.000000E+00	0.000000E+00	0.000000E+00
M3	4.803348E-20	6.493470E-24	-2.340102E-29
M4	1.242408E-24	-7.309532E-30	1.625546E-35
M5	1.150420E-20	-2.504098E-25	2.419328E-30
M6	1.394218E-21	6.518915E-27	1.785169E-32

10

The embodiment according to Fig. 9 has a numerical aperture of 0.50. The intermediate image plane 21 lies between the mirrors M4 and M5 in the light path, spatially in front of the mirror M3 and adjacent thereto. The mirror M2 is spherical. Otherwise, the construction of the projection optical

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system 7 according to Fig. 9 corresponds to that of the projection optical system 7 according to Fig. 2.

The following table summarizes the maximum angles of incidence for the 5 individual rays 15 on the mirrors M1 to M6. The third column additionally shows the maximum deviation of the reflection surfaces of the mirrors M1 to M6 from a spherical surface which is fitted to the reflection surface with a minimum error (best fit sphere). The maximum deviation is 180 μm . Thus, the asphericities of all of the mirrors M1 to M6 of the projection 10 optical system 7 according to Fig. 9 are small and the mirror M2 is actually spherical, and this simplifies the construction of the reflection surfaces thereof.

Mirror	Max. angle of incidence (meridional section) [$^{\circ}$]	Min. angle of incidence (meridional section) [$^{\circ}$]	Max. deviation of the surfaces from a best fit sphere [μm]
M1	6.95	4.61	5
M2	11.96	7.45	0
M3	9.75	0.47	160
M4	3.82	0.81	6
M5	15.34	2.27	104
M6	10.41	2.20	180

15 The ratio of the maximum angle of incidence of imaging light on the reflection surfaces of the mirrors M1 to M6 of the projection optical system 7 according to Fig. 9, in particular the angle of incidence 15.34 $^{\circ}$ on the mirror M5, and the numerical aperture of 0.5 is 30.68 $^{\circ}$ in the projection optical system 7 of Fig. 9.

20

The total constructional length of the projection objective 7 of Fig. 9 is 2,000 mm. The maximum central pupil obscuration in the surface is less than 7 per cent.

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Fig. 10 to 12 are a representation corresponding to that of Fig. 4 to 6 of the arrangement of the light beam groups 35 to 39 in the region of the object plane 5 (Fig. 10), of the light beam groups 40 to 44 and 45 to 49 in a plane XI in the region of the mirror M1 (Fig. 11) and of the light beam groups 50 to 54 and 55 to 59 in a plane XII in the region of mirror M2 (Fig. 12). The arrangement of the light beam groups is different in the projection objectives 7 of Fig. 2 and Fig. 9 in terms of the diameters of the light beams and of the distance of the light beams from one another, but not in terms of the semicircular arrangement of the light beam groups and of the respectively identically oriented downward openings of these semicircles which are at a distance from one another.

There is no pupil plane of the projection optical system 7 in the multiple pass-through region 61 of the projection objective 7 according to Fig. 9 between the planes XI and XII, as is also the case in the projection objective 7 of Fig. 2.

In the non-obsured mirror groups, the numerical aperture is in each case considerably lower than in the obscured mirror groups.

20

Fig. 13 is another embodiment of a projection optical system 7 to be installed in the projection exposure apparatus 1. Components and details which correspond to those explained above with reference to Figures 1 to 12 have the same reference numerals and are not discussed in detail again.

25

The optical data of the projection optical system 7 according to Fig. 13 are hereinafter listed in two tables whose structure corresponds to that of the tables according to Fig. 2.

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Surface	Radius (1/c)	Thickness	Operating Mode
Object plane	INFINITY	182,885	
M1	312,514	-135,045	REFL
M2	461,057	514,193	REFL
M3	-989,211	-295,490	REFL
M4	-210,779	875,015	REFL
M5	760,298	-545,015	REFL
M6	698,490	798,704	REFL
M7	-576,011	-19,744	REFL
DIAPHRAGM	INFINITY	-173,945	
M8	347,848	224,078	REFL
Image plane	INFINITY	0,000	

Surface	K	A	B	C
M1	0,000000E+00	2,054833E-08	-4,009641E-13	7,171735E-17
M2	0,000000E+00	3,334553E-10	-7,634038E-15	1,024823E-19
M3	0,000000E+00	-5,191038E-10	-4,805715E-16	1,117253E-19
M4	0,000000E+00	-8,530524E-08	-7,872800E-12	-8,643400E-16
M5	0,000000E+00	-9,493122E-10	-4,519746E-14	2,842871E-19
M6	0,000000E+00	1,067524E-10	3,344389E-16	8,381905E-22
M7	0,000000E+00	3,431647E-10	-3,006760E-15	1,681919E-19
M8	0,000000E+00	-5,212207E-09	-4,936095E-14	3,981107E-19
Surface	D	E	F	G
M1	-2,913353E-21	1,088107E-25	0,000000E+00	0,000000E+00
M2	-9,460244E-25	3,872599E-30	0,000000E+00	0,000000E+00
M3	-1,418804E-24	9,313360E-30	0,000000E+00	0,000000E+00
M4	-1,810090E-20	-3,582650E-23	0,000000E+00	0,000000E+00
M5	-9,298310E-24	-1,362975E-28	0,000000E+00	0,000000E+00
M6	2,378219E-27	2,644241E-33	3,062582E-38	0,000000E+00
M7	-1,186133E-24	2,512989E-29	0,000000E+00	0,000000E+00
M8	3,278180E-24	-3,575793E-29	0,000000E+00	0,000000E+00

The constants K and A to G indicated in the second table are to be used in the following equation for the sagittal height in order to describe the precise surface shape of the reflection surfaces of the mirrors M1 to M8:

$$\begin{aligned}
 z(h) = & \\
 = & \frac{ch^2}{1 + \text{SQRT}\{1 - (1 + K)c^2 h^2\}} + \\
 & + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12} + Fh^{14} + Gh^{16}
 \end{aligned}$$

The projection optical system 7 according to Fig. 13 has a total of 8 mirrors
 5 which are numbered M1 to M8 in the sequence of the light path, starting
 from the object field 4. Fig. 13 shows merely the calculated reflection sur-
 faces of the mirrors M1 to M8.

The mirrors M1, M4 and M5 are convex mirrors. The mirrors M2, M3 and
 10 M6 to M8 are concave mirrors. The reflection surfaces of the mirrors M1
 and M2 face each other. The reflection surfaces of the mirrors M2 and M3
 face each other. The reflection surfaces of the mirrors M1 and M4 are ar-
 ranged back-to-back. The reflection surfaces of the mirrors M4 and M5 as
 well as the reflection surfaces of the mirrors M7 and M8 face each other.
 15 The reflection surfaces of the mirrors M5 and M8 are arranged back-to-
 back.

The mirrors M1 to M4 form the first non-obsured mirror group 19 of the
 projection optical system 7 according to Fig. 13. The mirrors M1 to M4 are
 20 used in the shape of a ring segment and off-axis in relation to the optical
 axis 18.

In this embodiment, the ring segments of the used reflection surfaces of the
 mirrors M1 to M4 are also semicircular, wherein the semicircles are open
 25 when projected downwardly onto the xy-plane, in other words in the direc-
 tion of negative y-values.

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In the non-obsured mirror group 19 of the projection optical system 7 according to Fig. 13, the imaging rays extending in the meridional section do not pass through the principal separation plane 25.

- 5 In the projection optical system 7 according to Fig. 13, multiple pass-through regions 62, 63 are disposed between the mirrors M1 and M2 on the one hand and the mirrors M3 and M4 on the other hand, which multiple pass-through regions 62, 63 are delimited by planes which are indicated by dashed lines in Fig. 13 and extend parallel to the object plane 5 and the image plane 9 such as the planes V and VI in Fig. 2. The multiple pass-through regions 62, 63 are in each case passed through three times by the imaging rays. In the multiple pass-through region 62, the individual rays 15 extend on the one hand between the object field 4 and the mirror M1 and on the other hand between the mirror M1 and the mirror M2 as well as between the mirrors M2 and M3. In the multiple pass-through region 63, the individual rays 15 extend on the one hand in the light path between the mirrors M2 and M3 and on the other hand between the mirrors M3 and M4 as well as between the mirrors M4 and M5.
 - 10
 - 15
 - 20
 - 25
- There is no pupil plane of the projection optical system 7 according to Fig. 13 in the multiple pass-through regions 62, 63.

Likewise, in the projection optical system 7 according to Fig. 13, the object field 4 and the image field 8 have the shape described in relation to the description of Fig. 3 and the same dimensions XS and YS. Correspondingly, the fields 4, 8 also have an azimuth angle α of 171.2°.

In the projection optical system 7 according to Fig. 13, a first pupil plane 17 lies in the region of the reflection of the individual rays 15 on the mirror M5.

- 5 The mirrors M5 to M8 are obscured and have in each case a substantially central through-opening 20.

The mirrors M5 to M8 form two obscured mirror groups 22, 24 corresponding to the arrangement of the obscured mirrors M3 to M6 in the projection optical system 7 according to Fig. 2.

Like in the projection optical system 7 according to Fig. 2, the intermediate image plane 21 of the projection optical system 7 according to Fig. 13 lies between the non-obscured mirror groups 22 and 24.

15

The second pupil plane 23 as well as the aperture diaphragm are disposed near the reflection of the individual rays 15 on the mirror M7.

20 The projection optical system 7 according to Fig. 13 has a numerical aperture of 0.60.

25 Fig. 14 shows another embodiment of a projection optical system 7 to be used in the projection apparatus 1. Components and details which correspond to those explained above with reference to Figures 1 to 13 have the same reference numerals and are not discussed in detail again.

The optical data of the projection optical system 7 according to Fig. 13 are hereinafter listed in two tables whose structure corresponds to those of the tables according to Fig. 2.

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Surface	Radius (1/c)	Thickness	Operating Mode
Object plane	INFINITY	234,636	
M1	-287,951	-113,003	REFL
M2	-377,077	307,165	REFL
M3	448,125	-138,650	REFL
M4	454,548	458,111	REFL
M5	-589,208	-216,430	REFL
M6	-137,413	922,448	REFL
M7	3248,369	-656,018	REFL
M8	905,405	930,393	REFL
M9	-786,842	-34,144	REFL
DIAPHRAGM	INFINITY	-180,231	
M10	360,479	239,376	REFL
Image plane	INFINITY	0,000	

Surface	K	A	B
M1	0,000000E+00	-3,635133E-10	-1,272934E-13
M2	0,000000E+00	8,009620E-09	8,547440E-13
M3	0,000000E+00	-3,301069E-08	-3,864784E-13
M4	0,000000E+00	-2,379284E-09	-3,474204E-14
M5	0,000000E+00	-5,239687E-10	-3,534045E-14
M6	0,000000E+00	-1,393622E-07	-2,668110E-10
M7	0,000000E+00	3,133269E-10	-3,363547E-15
M8	0,000000E+00	5,440423E-11	6,900621E-17
M9	0,000000E+00	1,926841E-09	2,339942E-15
M10	0,000000E+00	-1,807405E-09	-9,306119E-15
Surface	C	D	E
M1	1,155813E-17	-4,826930E-22	7,023739E-27
M2	4,549328E-17	4,305677E-21	4,669221E-25
M3	8,526965E-17	-7,012381E-21	2,933090E-25
M4	-1,300936E-19	-5,982917E-24	-5,370645E-29
M5	9,162259E-19	-1,999188E-23	2,164273E-28
M6	2,736516E-13	-1,401026E-16	1,113816E-20
M7	20	-5,146768E-25	1,194508E-30
M8	9,097747E-23	6,493834E-29	4,098093E-34
M9	2,254061E-19	-2,921628E-24	4,530106E-29
M10	5,958825E-20	-3,478398E-25	7,219935E-30

The sagittal height equation used to describe the precise surface shape of the reflection surfaces of the mirrors M1 to M10 corresponds to that indi-

cated above in relation to the projection optical system 7 according to Fig. 2.

The projection optical system 7 according to Fig. 14 comprises a total of 10
5 mirrors which are numbered M1 to M10 in the sequence of the light path,
starting from the object field 4. Fig. 14 shows the calculated reflection sur-
faces of the mirrors M1 to M10.

The mirrors M1, M4, M5 and M8 to M10 are concave mirrors. The mirrors
10 M2, M3, M6, and M7 are convex mirrors.

The reflection surfaces of the mirrors M1 and M2 face each other. The re-
flection surfaces of the mirrors M2 and M3 face each other. The reflection sur-
faces of the mirrors M1 and M4 are arranged back-to-back. The reflec-
15 tion surfaces of the mirrors M3 and M4 as well as the reflection surfaces of
the mirrors M5 and M6 face each other. The reflection surfaces of the mir-
rors M3 and M6 are arranged back-to-back. The reflection surfaces of the
mirrors M7 and M8 as well as the reflection surfaces of the mirrors M9 and
M10 face each other. The reflection surfaces of the mirrors M5 and M8 as
20 well as the reflection surfaces of the mirrors M7 and M10 are arranged
back-to-back.

The mirrors M1 to M6 are used in the shape of a ring segment and off-axis
in relation to the optical axis 18. In analogy to the above description in re-
25 lation to the projection optical system 7 according to Fig. 2, these ring-
segment shaped reflection regions of the mirrors M1 and M2 are semicircu-
lar, wherein the semicircles of Fig. 14 open downwardly in other words in
the direction of negative y-values.

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Likewise, the mirrors M3 to M6 are provided with semicircular reflection surfaces as well which, however, open in the opposite direction, in other words towards positive y-values.

- 5 The mirrors M1 and M2 form a first non-obsured mirror group 64 of the projection optical system 7 according to Fig. 14. The mirrors M3 to M6 form a second non-obsured mirror group 65 of the projection optical system 7 according to Fig. 14. A first pupil plane 66 of the projection optical system 7 according to Fig. 14 is spatially arranged between the two mirror
- 10 groups 64 and 65, namely between the two mirrors M1 and M4 which are arranged back to back with respect to their reflection surfaces.

As the pupil plane 66 is arranged between the mirror groups 64 and 65, none of the individual rays 15 penetrates the principal separation plane 25 in the meridional plane when passing through the individual mirror groups 64, 65. This principal separation plane 25 is merely penetrated by the principal rays 16 between the non-obsured mirror groups 64, 65 but not, however, in the non-obsured mirror groups 64, 65. Outside the pupil planes, the principal rays 16 do not pass through the principal separation plane 25 in the non-obsured mirror groups 64, 65.

In the projection optical system 7 according to Fig. 14, a total of three multiple pass-through regions 67, 68 and 69 are present between the mirrors M1 and M2, between the mirrors M3 and M4 as well as between the mirrors M5 and M6. These multiple pass-through regions 67 to 69 are in each case delimited by planes which are arranged parallel to the object plane 4 and to the image plane 9 and are indicated by dashed lines in Fig. 14. The individual rays 15 in each case penetrate the multiple pass-through regions 67 to 69 three times, corresponding to the above description in relation to

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the multiple pass-through regions 61 to 63 of the embodiments according to Figures 2 and 13.

No pupil plane of the projection optical system 7 is arranged in the multiple 5 pass-through regions 67 to 69.

Groups of ray bundles in the shape of in each case two semicircles opening in the same direction pass through the two boundary planes of the multiple pass-through regions 67 to 69 several times, as explained above in relation 10 to the projection optical system 7 according to Fig. 2. Correspondingly, the requirements to a vignetting-free configuration of the edge-side boundaries of the mirrors M1, M2, M3, M4, M5 and M6 are relaxed.

The shape and size of the object field 4 and the image field 8 of the projection 15 optical system 7 according to Fig. 14 are equal to those of the embodiments described above. Likewise, the fields 4, 8 of the projection optical system 7 according to Fig. 14 therefore have an azimuth angle α of 171,2°.

20 In the projection optical system 7 according to Fig. 14, a first intermediate image plane 70 is arranged in the light path between the mirrors M5 and M6.

The arrangement of the mirrors M7 to M10 of the projection optical system 25 7 according to Fig. 14 corresponds to that of the mirrors M5 to M8 of the projection optical system 7 according to Fig. 13. The mirrors M7 to M10 are obscured and have in each case a substantially central through-opening 20.

The projection optical system 7 according to Fig. 14 has a numerical aperture of 0.60.

Figures 15 and 16 are a schematic illustration of the principal rays 16 passing through projection optical systems 7 which are an expansion to the projection optical systems 7 according to the embodiments of the Figures 2, 13 and 14 described above. Components and details which correspond to those explained above in relation to Figures 1 to 14 have the same reference numerals and are not discussed in detail again.

10

In contrast to the projection optical system 7 according to Fig. 14, the projection optical system 7 according to Figures 15 and 16 does not have two non-obsured mirror groups but a total of four non-obsured mirror groups 72, 73, 74, 75. The illustrations according to Figures 15 and 16 are different in that the illustration according to Fig. 16 additionally indicates folded light paths in the non-obsured mirror groups 72 to 75 as well as between the last pupil plane 17 and the image plane 9.

The first non-obsured mirror group 72 lies between the object plane 5 and a first pupil plane 76. The second non-obsured mirror groups 73 lies between the first pupil plane 76 and a second pupil plane 77. The third non-obsured pupil plane 74 lies between the second pupil plane 77 and a third pupil plane 78. The fourth non-obsured pupil plane 75 lies between the third pupil plane 78 and the pupil plane 17 at the transition to the obscured mirror groups 22, 24 which are indicated as a single obscured mirror group in the schematic illustration of the Figures 15 and 16. The non-obsured mirror groups 72 and 75 of the schematic illustrations according to Figures 15 and 16 correspond to the non-obsured mirror groups 64 and 65 of the embodiment according to Fig. 14. The schematic illustrations according to

Figures 15 and 16 may therefore be understood as an expansion of the embodiment according to Fig. 14 by two further non-obsured mirror groups, namely the mirror groups 73 and 74.

- 5 Figures 15 and 16 show that the principal separation plane 25 is in each case only penetrated between the non-obsured mirror groups 72 to 75 as well as in the light path behind the pupil plane 17 in the high-aperture region of the projection optical system 7, in other words in the region of the obscured mirror groups 22, 24. In the non-obsured mirror groups 72 to 75,
- 10 10 the principal rays 16 remain in each case on one side of the principal separation plane 25. This results in the effect described above, namely that in multiple pass-through regions of the non-obsured mirror groups 72 to 75, there are groups of ray bundles 35 in which the opening of the bundle path, which is arc-shaped in the direction perpendicular to the optical axis, is in
- 15 15 each case oriented in only one direction.

- In order to produce a microstructured or nanostructured component, the projection exposure apparatus 1 is used as follows: the reflection mask 10 or the reticle, respectively, and the substrate or the wafer 11, respectively,
- 20 20 are provided in a first step. Afterwards, a structure on the reticle, such as the structure B, C, is projected onto a light-sensitive layer of the wafer 11 by means of the projection exposure apparatus. The light-sensitive layer is then developed to create a microstructure or a nanostructure on the wafer 11 so as to obtain the microstructured component.

Claims

1. Imaging optical system (7) with a plurality of mirrors (M1 to M6; M1 to M8; M1 to M10), which image an object field (4) in an object plane (5) into an image field (8) in an image plane (9),
 - wherein imaging rays (15) in the light path between non-obsured mirrors (M1, M2; M1 to M4; M1 to M6) of the imaging optical system (7) pass several times through at least one multiple pass-through region (61; 62, 63; 67, 68, 69) between spaced-apart planes which are arranged parallel to the object plane (5) and/or parallel to the image plane (9),
 - wherein the imaging optical system (7) comprises at least one pupil plane (17, 23; 66, 17, 23; 76, 77, 78, 17),
characterized in that all pupil planes (17, 23; 66, 17, 23; 76, 77, 78, 17) are arranged outside the multiple pass-through regions (61; 62, 63; 67, 68, 69) between the non-obsured mirrors (M1, M2; M1 to M4; M1 to M6).
2. Imaging optical system according to claim 1, **characterized in that** the object field (4) has the shape of an arc field which is delimited by
 - two graduated circles (27, 28) with the same radius (R) which are displaced parallel to each other by a distance (YS);
 - two boundary lines (29, 30) respectively connecting the two ends of both graduated circles (27, 28);

wherein the arc field (4) has an azimuth angle (α) which is greater than 75°.

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3. Catoptric imaging optical system (7) with a plurality of mirrors (M1 to M6; M1 to M8; M1 to M10) which image an object field (4) in an object plane (5) into an image field (8) in an image plane (9),
 - wherein the object field (4) has the shape of an arc field which is delimited by
 - two graduated circles (27, 28) with the same radius (R) which are displaced parallel to each other by a distance (YS);
 - two boundary lines (29, 30) respectively connecting the two ends of both graduated circles (27, 28),
- 10 **characterized by** an azimuth angle (α) of the arc field (4) which is greater than 75° .
4. Imaging optical system (7) with a plurality of mirrors (M1 to M6; M1 to M8; M1 to M10), which image an object field (4) in an object plane (5) into an image field (8) in an image plane (9),
 - wherein the imaging optical system (7) comprises an optical axis (18);
 - wherein the imaging optical system (7) comprises at least one non-obsured mirror group (19; 64, 65; 72 to 75) which is spatially arranged between one of the following types of boundary planes of the imaging optical system:
 - between a field plane (5) and a pupil plane (17; 66) arranged directly downstream thereof;
 - between a first pupil plane (66) and a second pupil plane (17) arranged directly downstream thereof.
- 20 25 5. Imaging optical system according to claim 4, **characterized in that** a principal ray (16) which proceeds from a central object field point and passes through the center of pupils in the pupil planes (17; 66) of the

imaging optical system (7), proceeds in the meridional section between mirrors (M1, M2; M1 to M4; M1, M2, M3 to M6) of the at least one non-obsured mirror group (19; 64, 65; 72 to 75) of the imaging optical system (7) such that it does not penetrate a principal separation plane

5 (25)

- in which lies the optical axis (18) and
- on which a normal (26) from a central object field point to the optical axis (18) is perpendicular.

10 6. Imaging optical system according to claim 5, **characterized by** a central pupil obscuration, in other words an arrangement which does not allow imaging rays (15) to pass through a region of a pupil plane (17) which is surrounded by another region in which a passage of imaging rays (15) is possible.

15

7. Imaging optical system according to claim 5 or 6, **characterized in that** the object field (4) and the image field (8) are arranged at a distance from the optical axis (18).

20 8. Imaging optical system according to one of claims 5 to 7, **characterized in that**

- in the light path between non-obsured mirrors (M1, M2), imaging rays (15) pass several times through at least one multiple pass-through region (61) between spaced-apart planes which are arranged parallel to the object plane (5) and/or parallel to the image plane (9),
- in the meridional section, the imaging rays do not pass through the principal separation plane (25) between these planes delimiting the multiple pass-through region (61).

9. Imaging optical system according to one of claims 5 to 8, **characterized by** an azimuth angle (α) of the arc field (4) which is greater than 75°.

5

10. Imaging optical system with a plurality of mirrors (M1 to M6) which image an object field (4) in an object plane (5) into an image field (8) in an image plane (9), comprising at least four mirrors (M1 to M6) of which at least two (M1, M2) are non-obsured, **characterized in that** one of the non-obsured mirrors (M2) is a spherical mirror.

11. Imaging optical system according to claim 10, **characterized by** an azimuth angle (α) of the arc field (4) which is greater than 75°.

15 12. Imaging optical system according to one of claims 1 to 11, **characterized by** several non-obsured mirror groups (64, 65; 72 to 75) between which in each case one pupil plane (66; 76 to 78) is arranged in the imaging light path .

20 13. Imaging optical system according to one of claims 1 to 12, **characterized by** at least one obscured mirror (M3 to M6; M5 to M8; M7 to M10) with a through-opening (20) allowing imaging light (3) to pass through.

25 14. Imaging optical system according to claim 13, **characterized in that** the imaging optical system (7) comprises exactly six mirrors (M1 to M6) of which at least three mirrors, preferably exactly four mirrors (M3 to M6) are obscured.

15. Imaging optical system according to claim 14, **characterized in that** the imaging optical system (7) comprises exactly eight mirrors (M1 to M8) of which at least three mirrors, preferably exactly four mirrors (M5 to M8) are obscured.

5

16. Imaging optical system according to claim 14, **characterized in that** the imaging optical system (7) comprises exactly ten mirrors (M1 to M10) of which at least three mirrors, preferably exactly four mirrors (M7 to M10) are obscured.

10

17. Microlithographic projection exposure apparatus comprising

- an imaging optical system (17) according to one of claims 1 to 16;
- a light source (2) for the illumination and imaging light (3);
- an illumination optical system (6) for guiding the illumination light (3) to the object field (4) of the imaging optical system (7)

15

18. Projection exposure apparatus according to claim 17, **characterized in that** the light source (2) for producing illumination light (3) is configured with a wavelength of between 5 and 30 nm.

20

19. Method for the production of a microstructured component with the following method steps:

25

- providing a reticle (10) and a wafer (11),
- projecting a structure on the reticle (10) onto a light-sensitive layer of the wafer (11) by means of the projection exposure apparatus according to either claim 17 or claim 18,
- producing a microstructure on the wafer (11).

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20. Microstructured component produced by a method according to claim 19.

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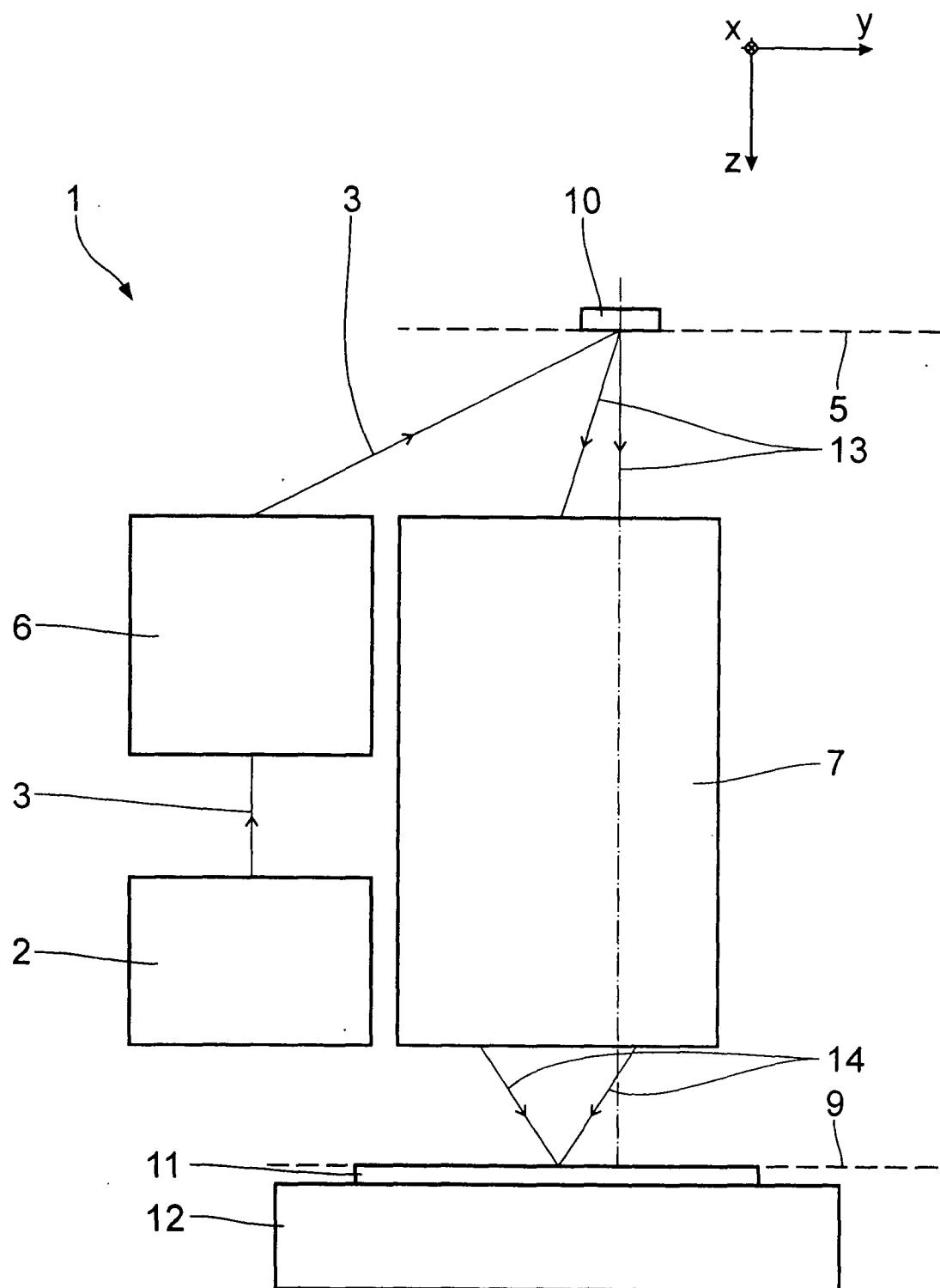


Fig. 1

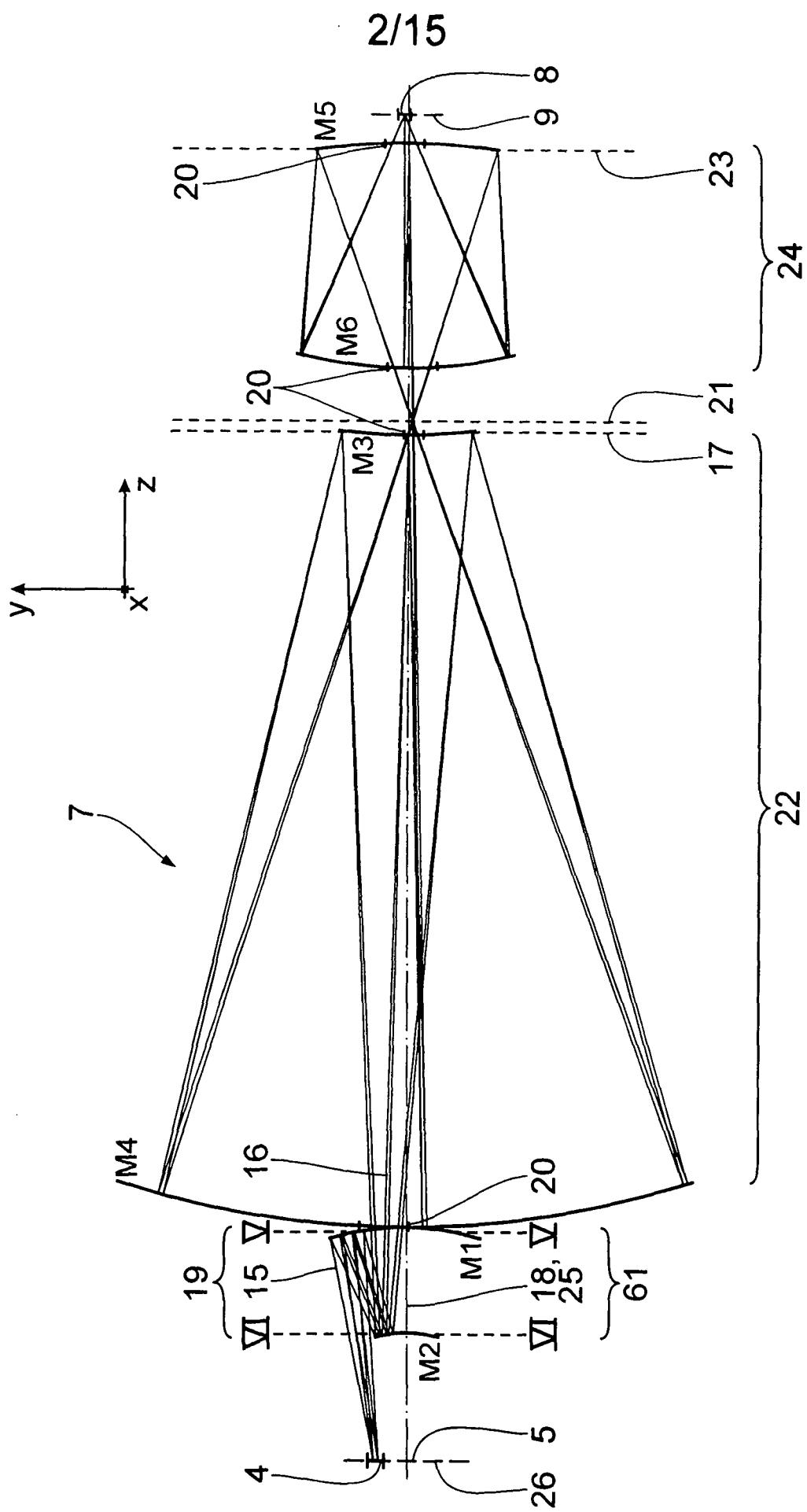


Fig. 2

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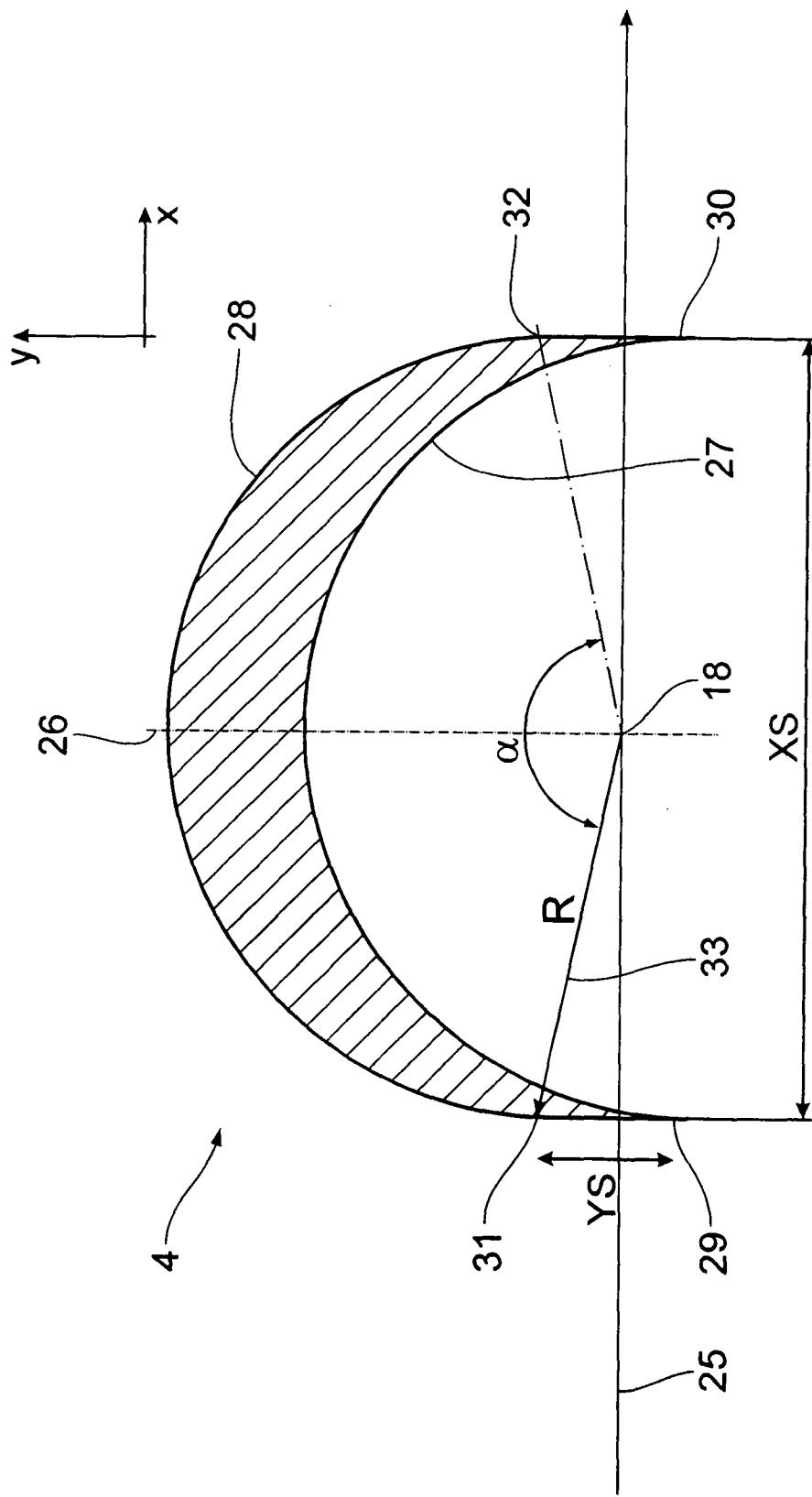


Fig. 3

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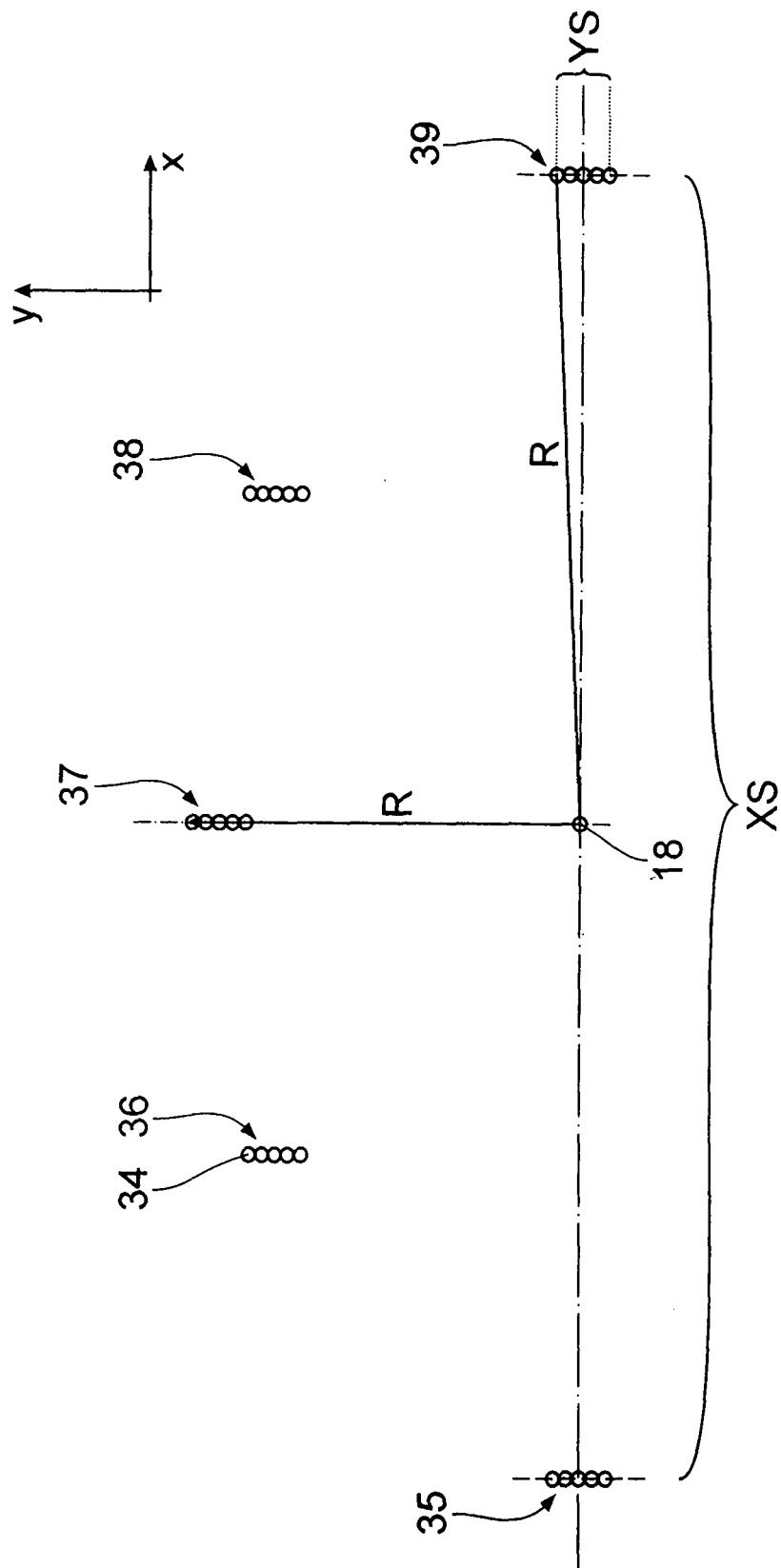


Fig. 4

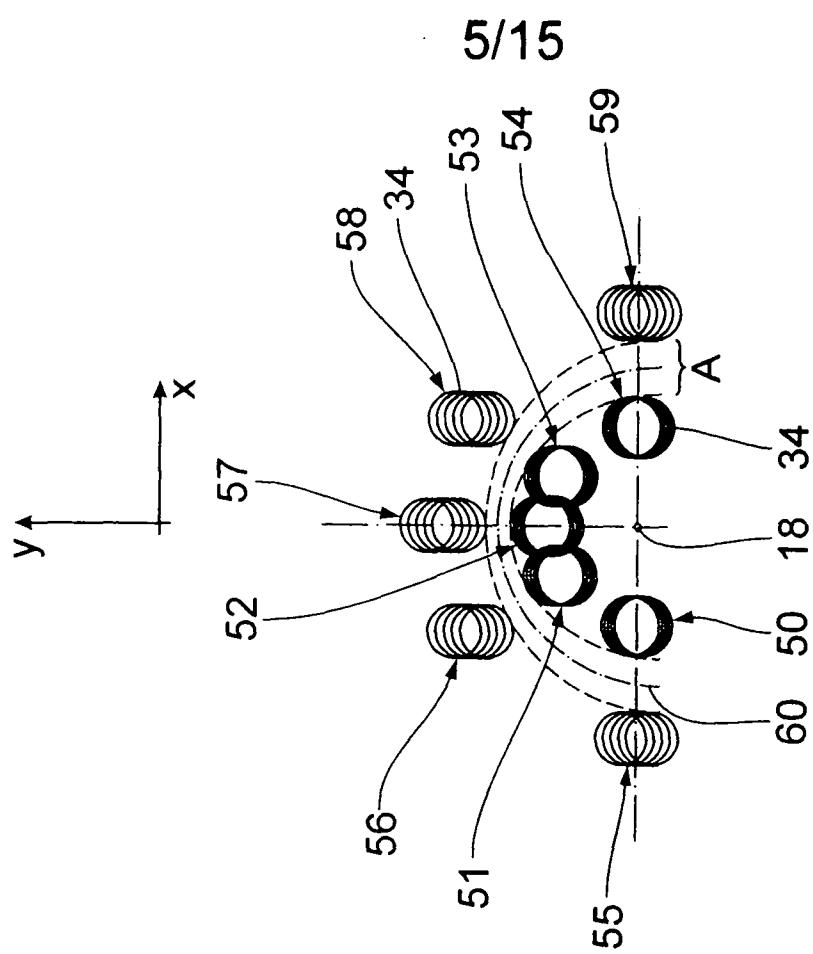


Fig. 6

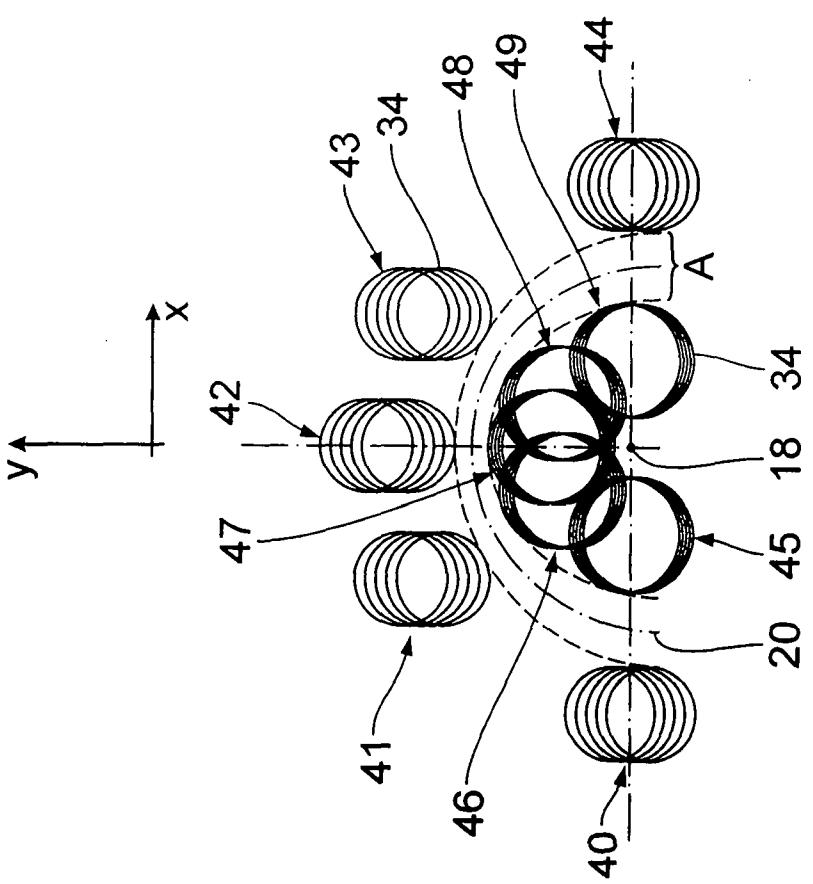


Fig. 5

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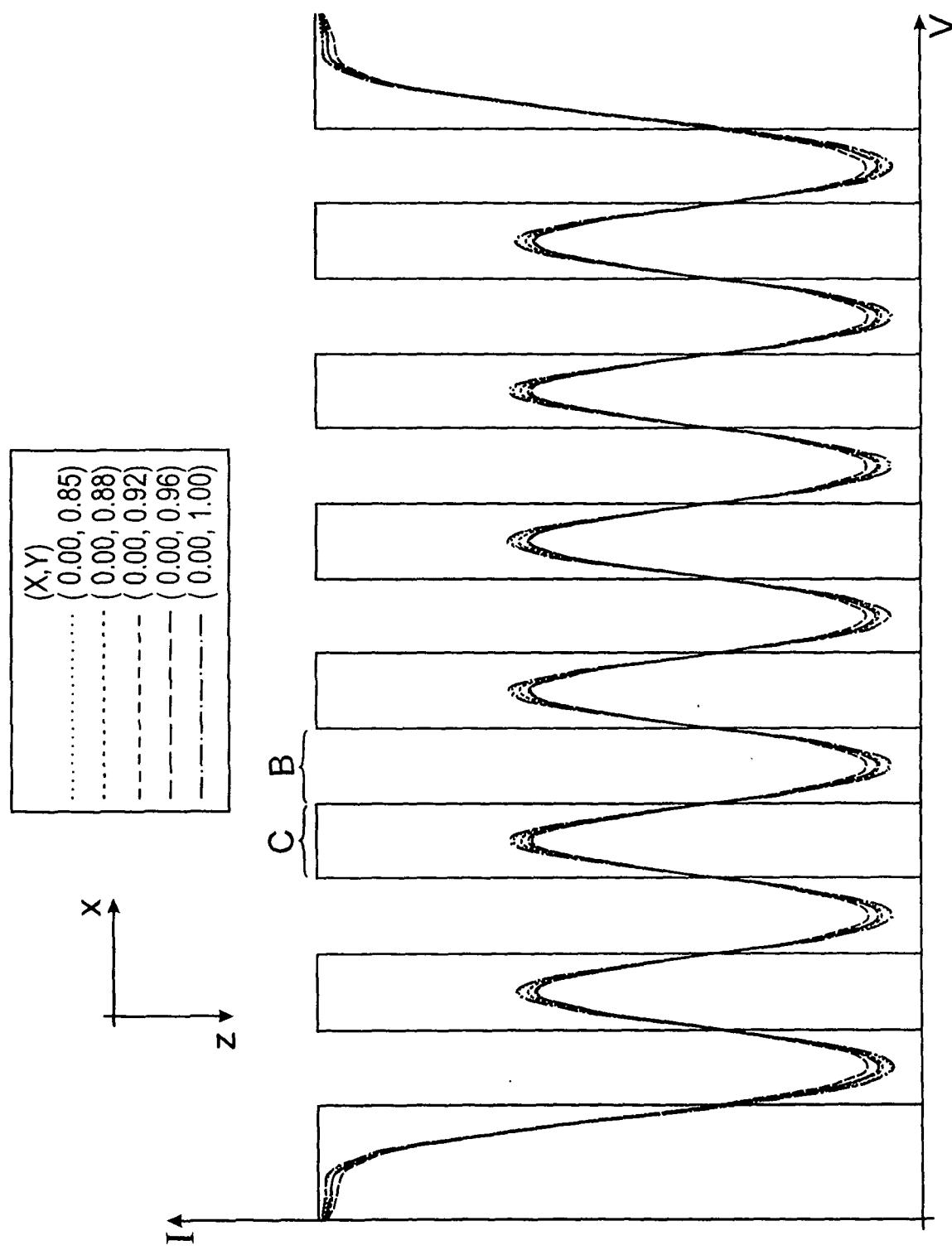


Fig. 7

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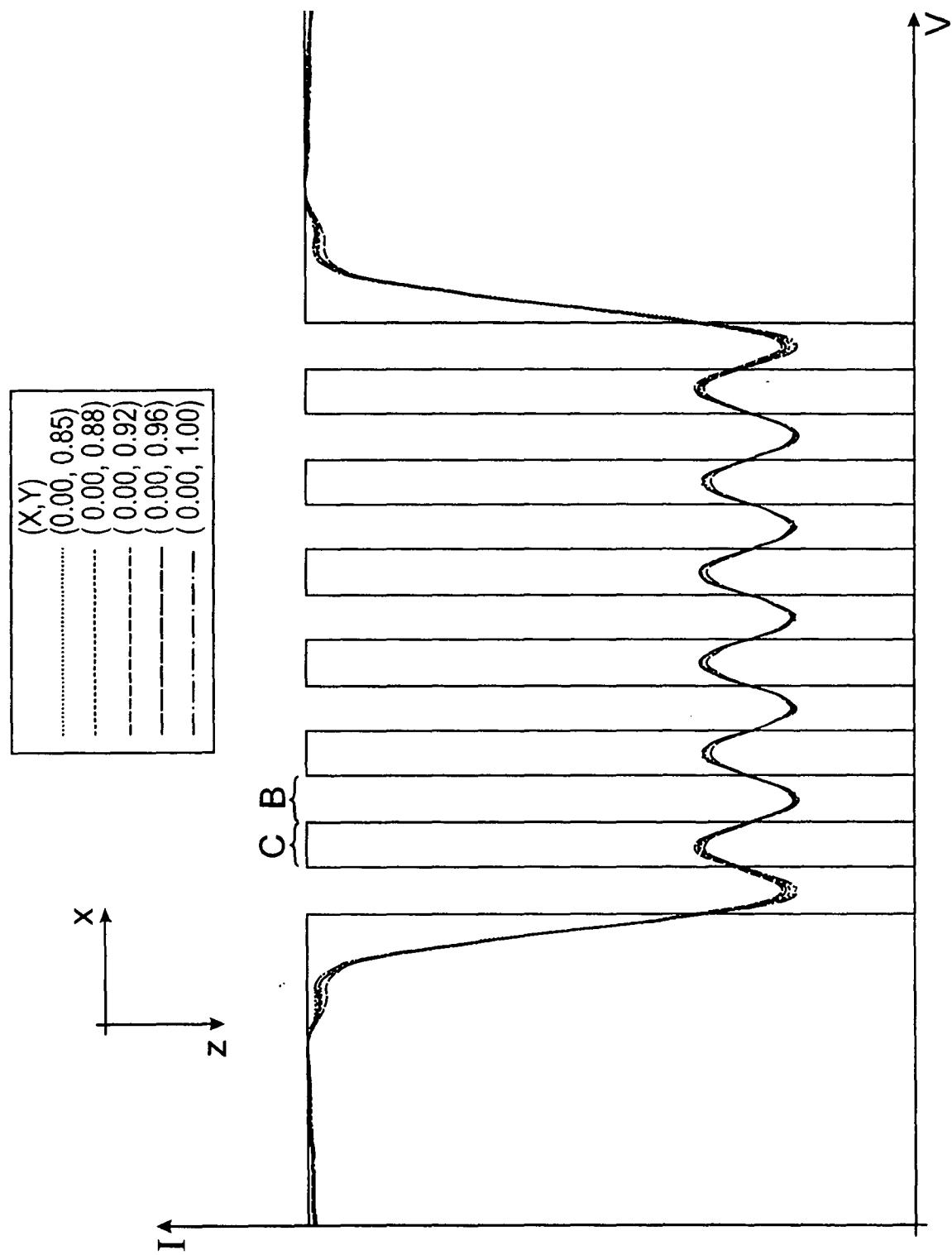


Fig. 8

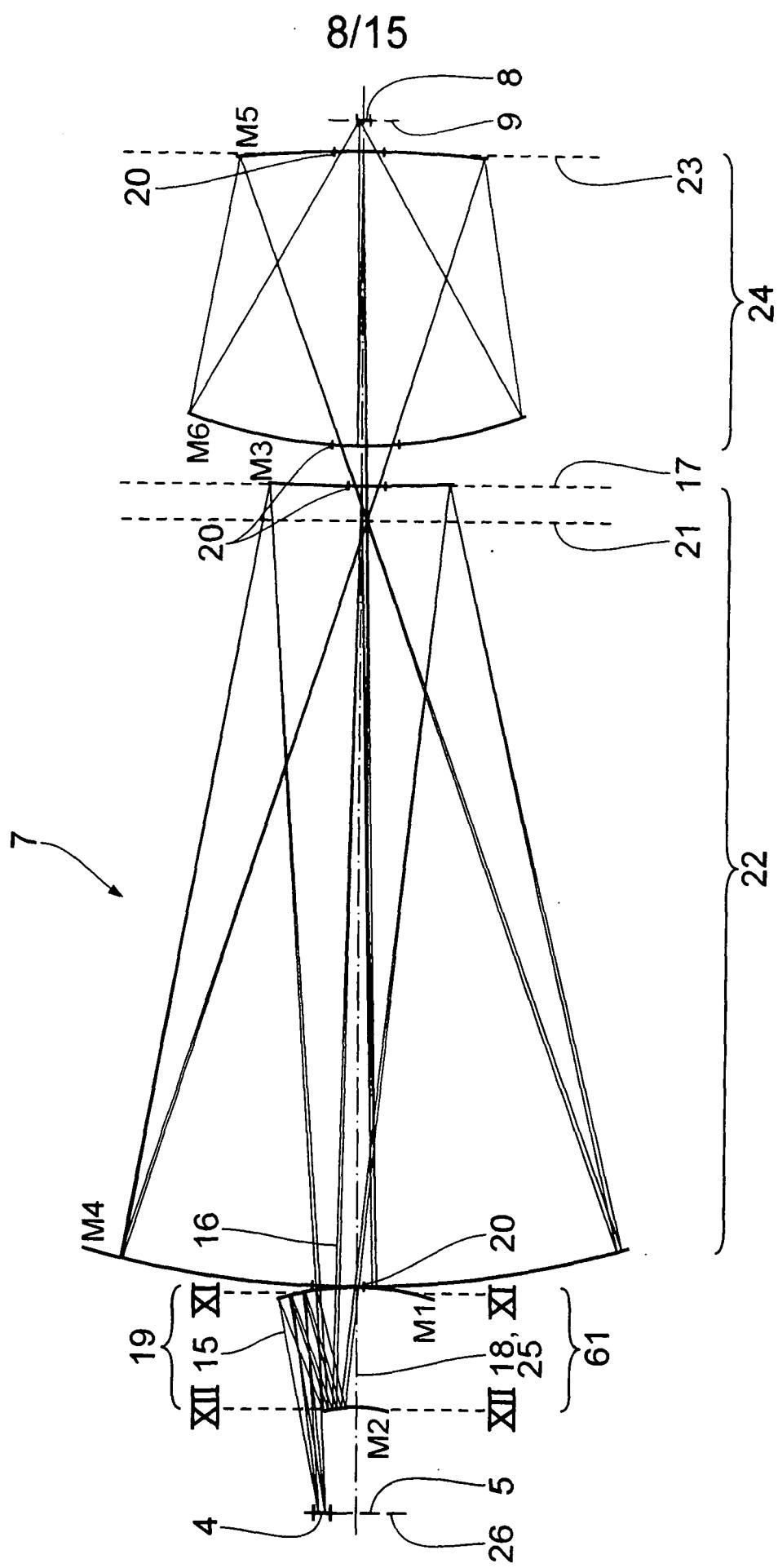


Fig. 9

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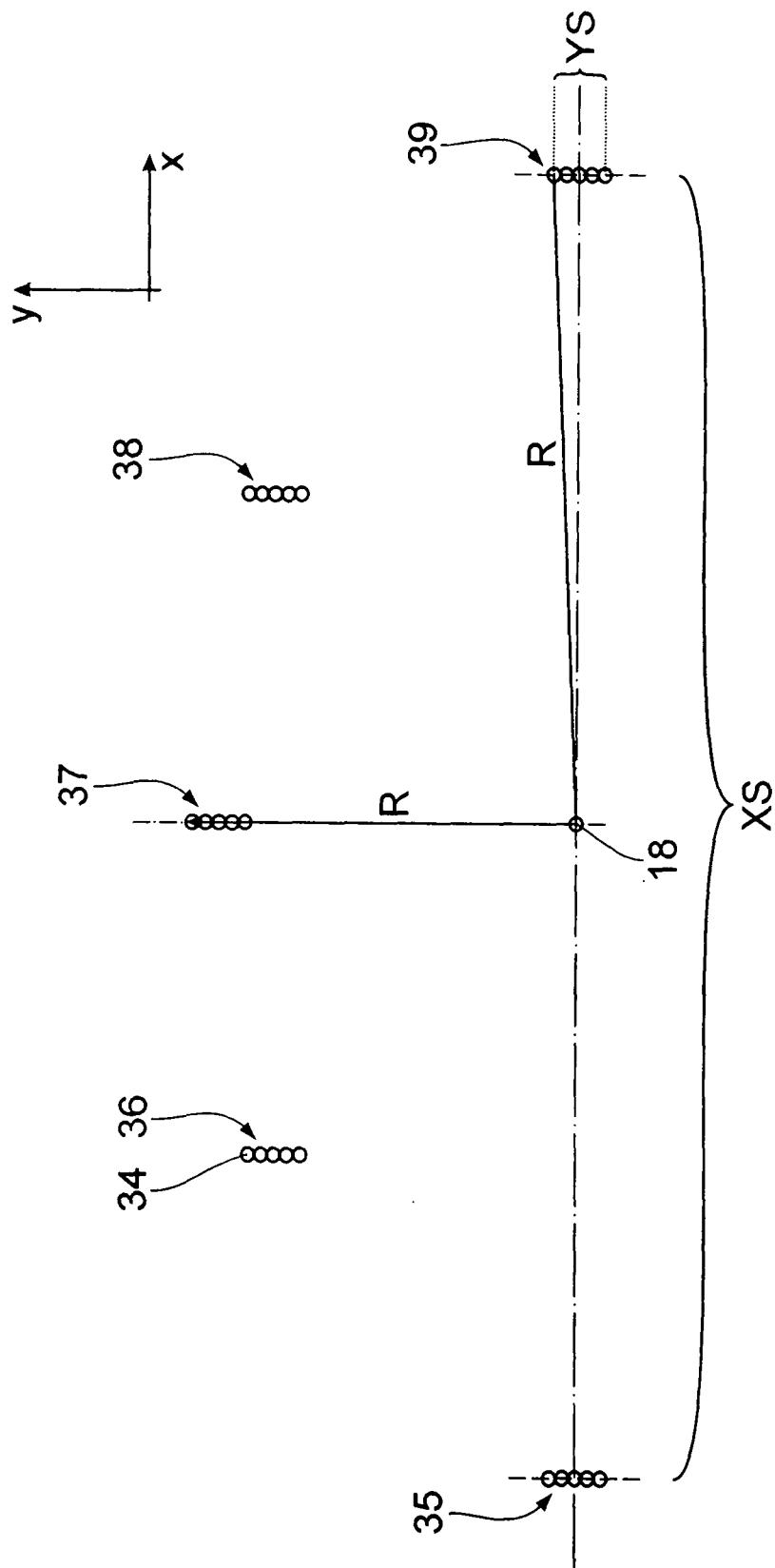


Fig. 10

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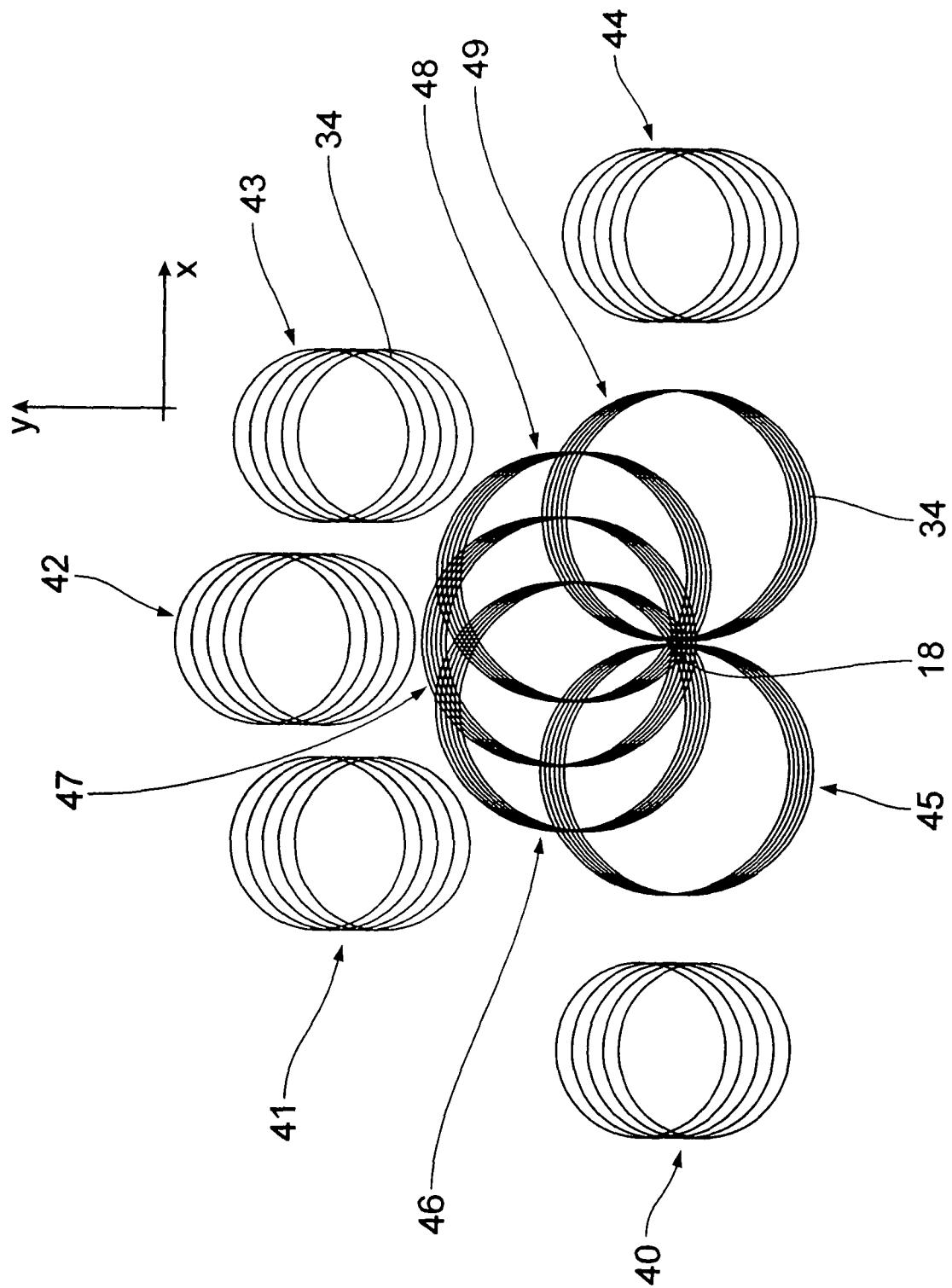


Fig. 11

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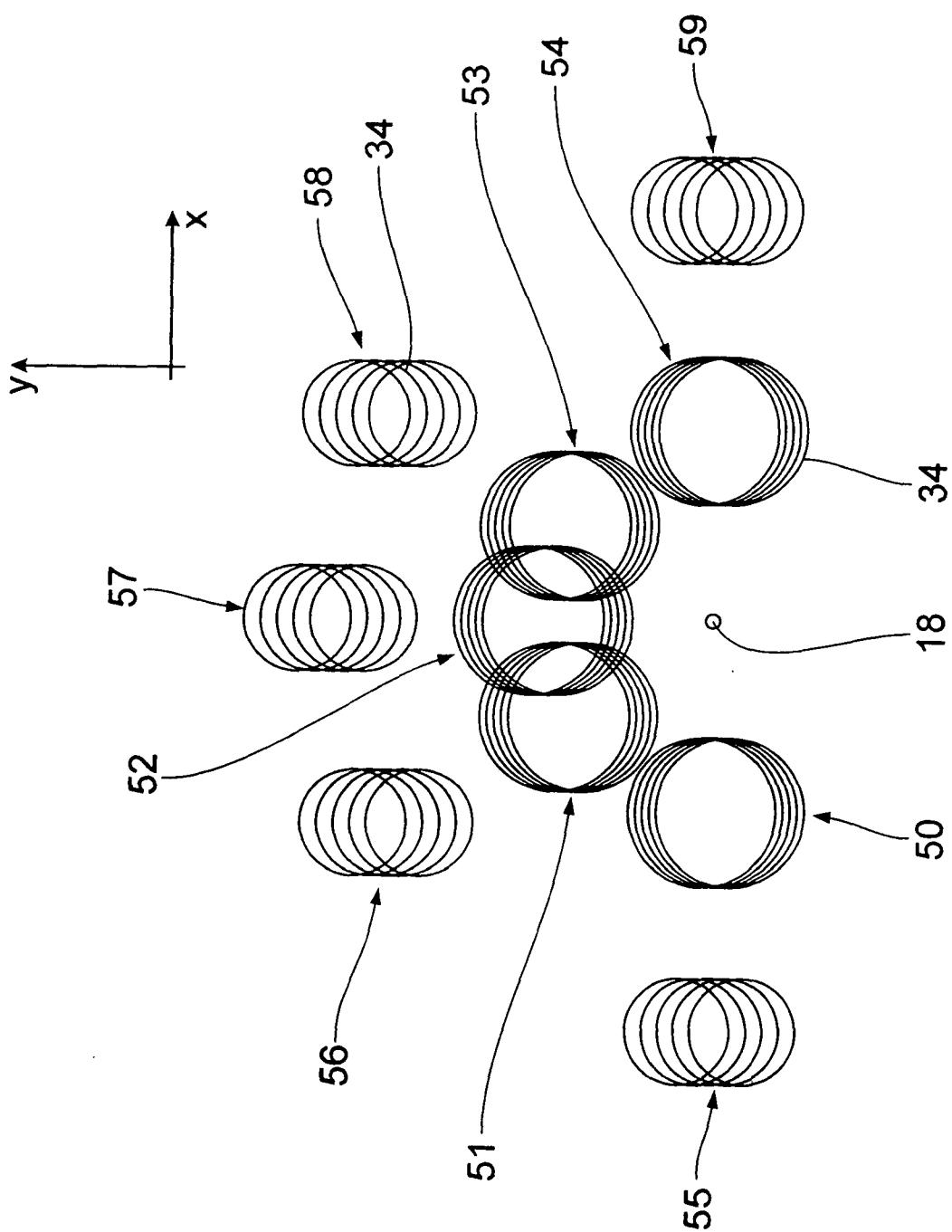


Fig. 12

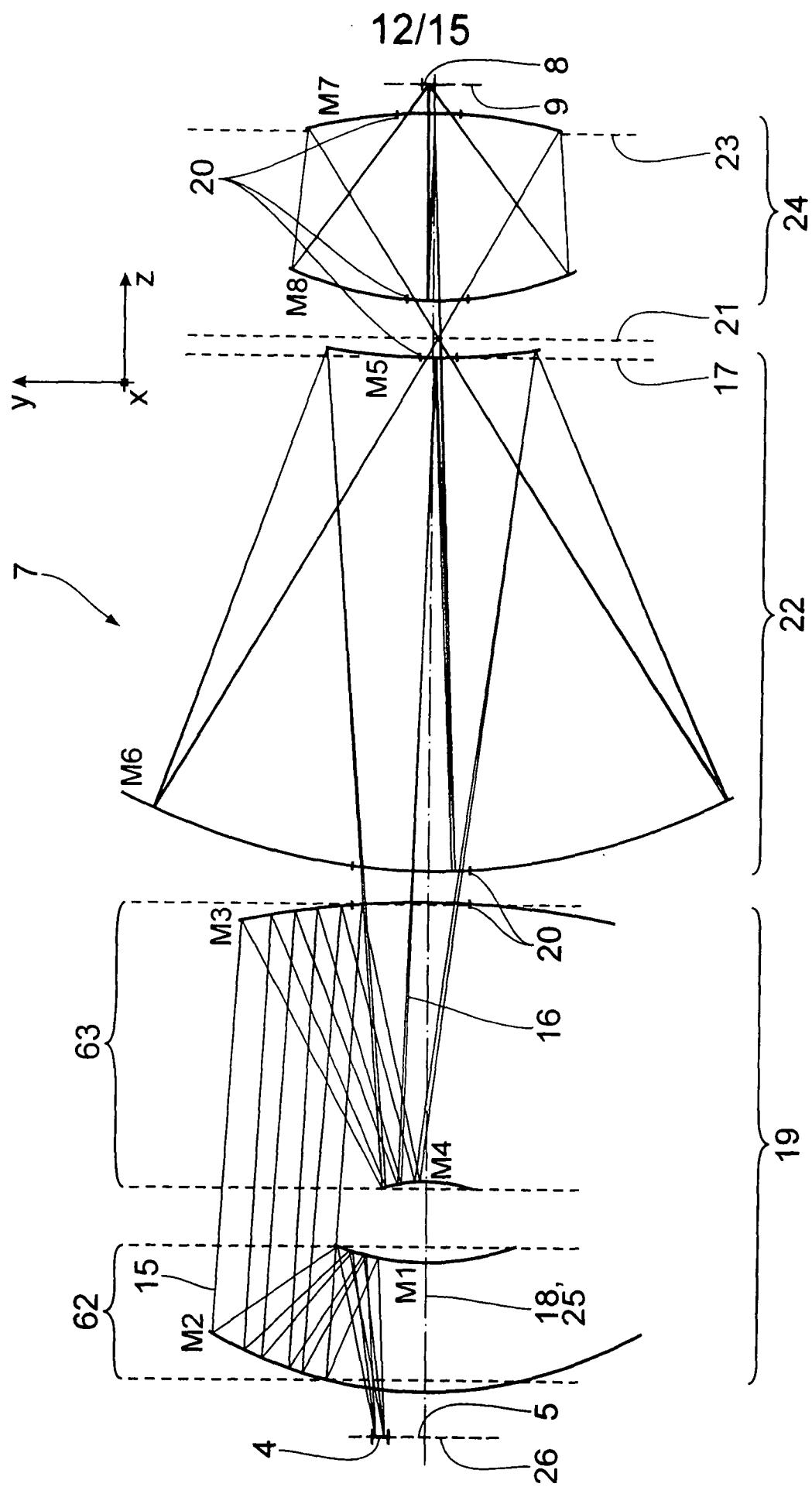


Fig. 13

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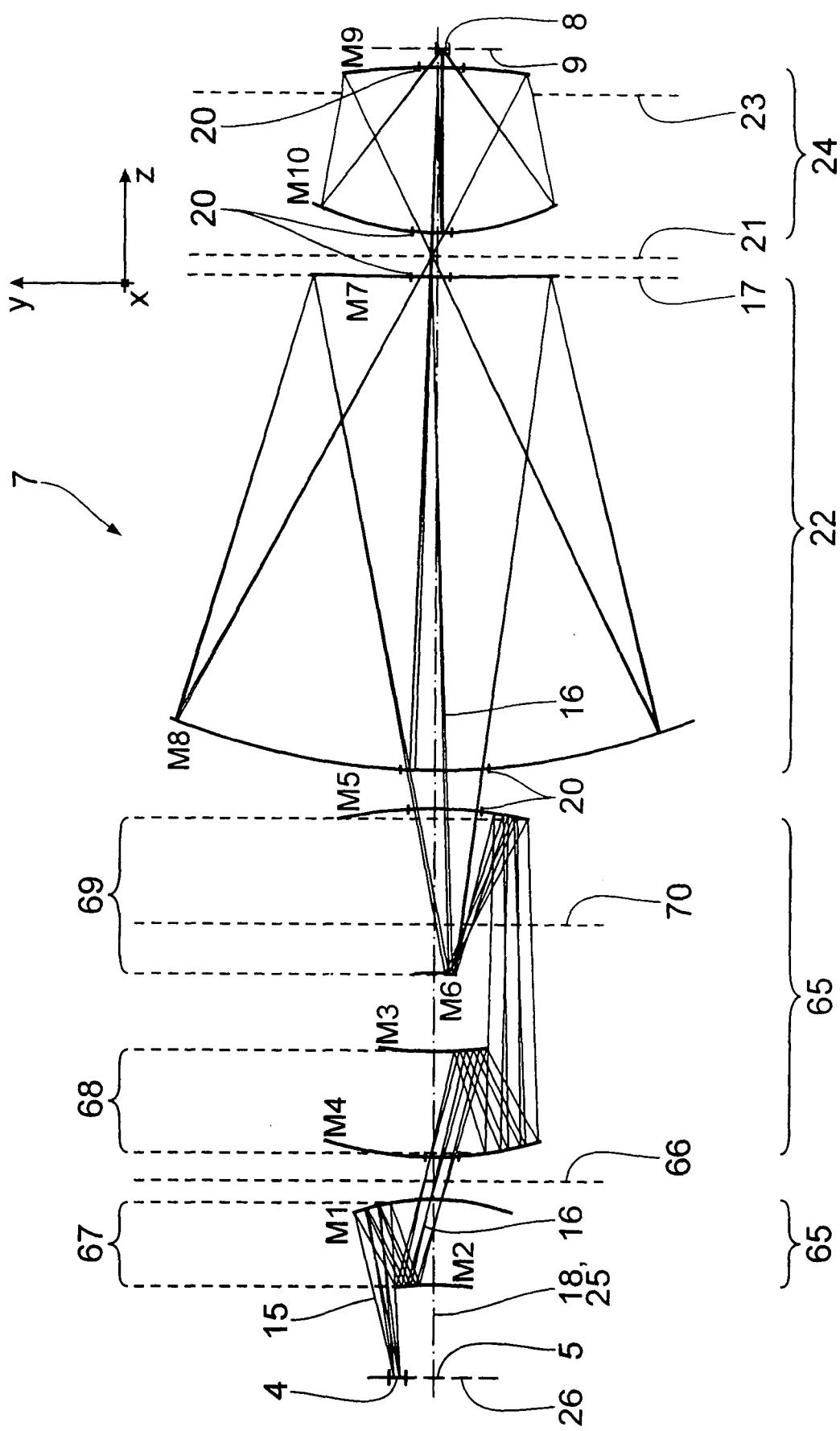


Fig. 14

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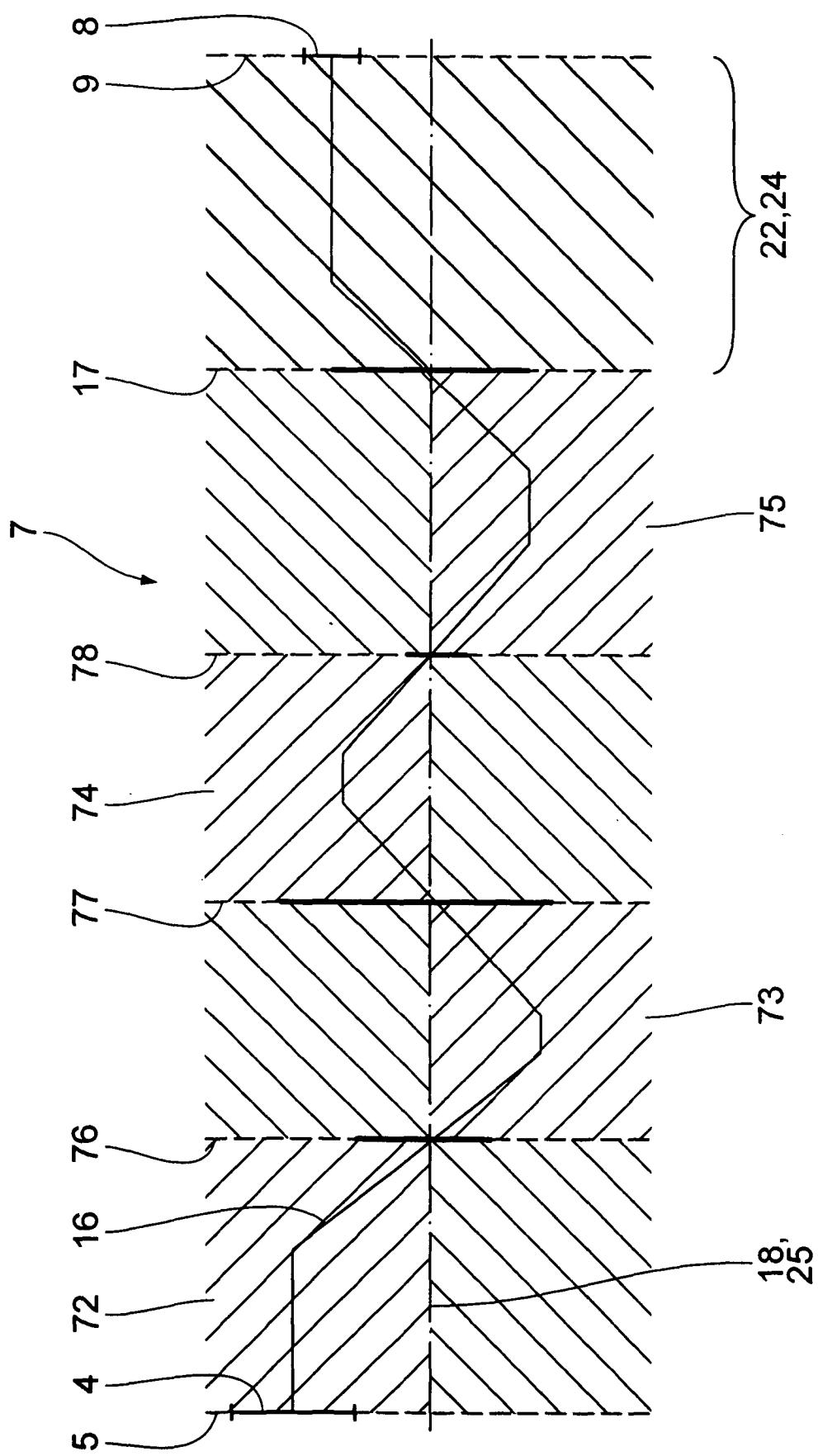


Fig. 15

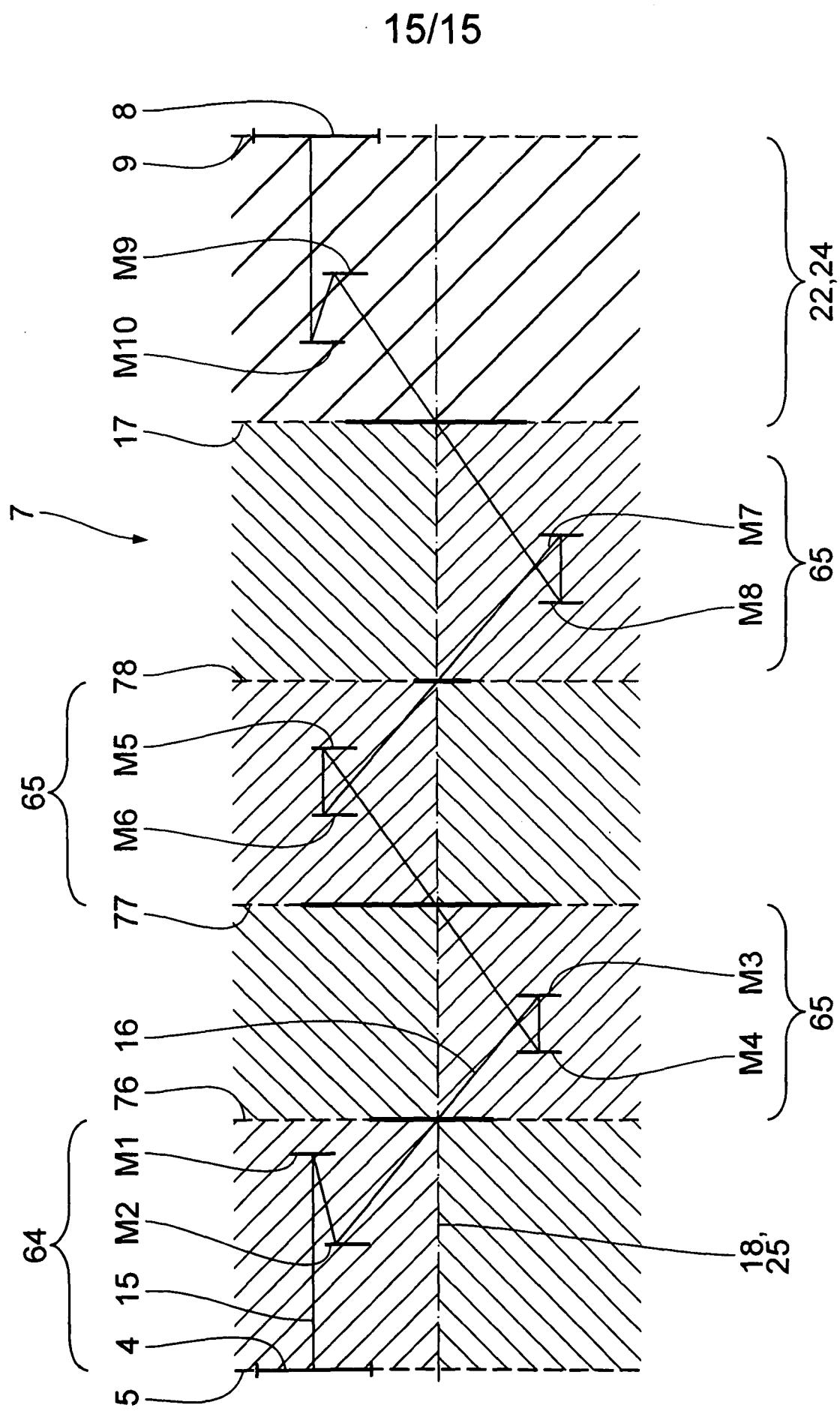


Fig. 16