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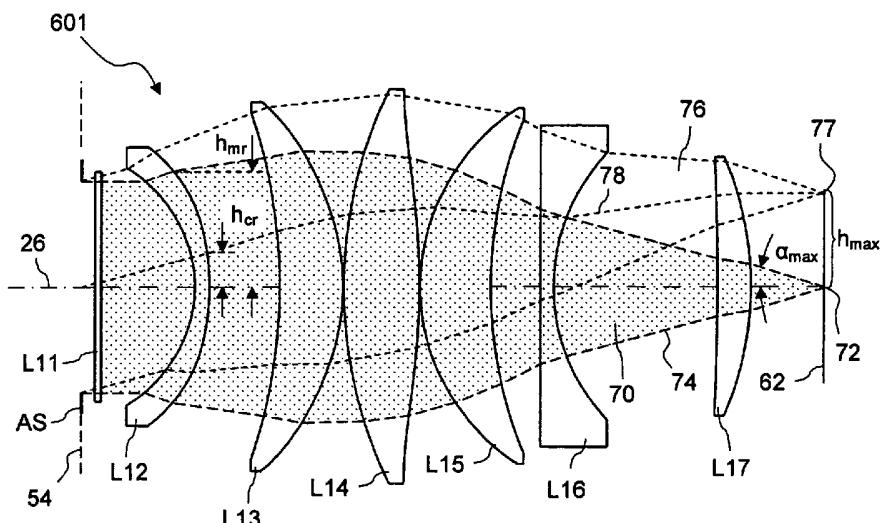
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(54) Title: ILLUMINATION SYSTEM FOR A MICROLITHOGRAPHIC EXPOSURE APPARATUS



WO 2006/114294 A2

(57) Abstract: An illumination system (12) of a microlithographic exposure apparatus (10) comprises a condenser (601; 602; 603; 604; 605; 606) for transforming a pupil plane (54) into a field plane (62). The condenser has a lens group (L14, L15, L16, L17; L24, L25, L26, L27, L28; L34, L35, L36, L37; L44, L45, L46; L53, L54, L55) that contains a plurality of consecutive lenses. These lenses are arranged such that a light bundle (70) focused by the condenser (601; 602; 603; 604; 605) on an on-axis field point (72) converges within each lens of the lens group. At least one lens (L15, L16, L17; L25, L26; L34, L44, L45; L54) of the lens group has a concave surface. The illumination system may further comprise a field stop objective (66; 666, 666') that at least partly corrects a residual pupil aberration of the condenser (601; 602; 603; 604; 605; 606).



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- 1 -

ILLUMINATION SYSTEM FOR A
MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit under 35 U.S.C 119(e)(1) of U.S. provisional Application No. 60/674,691 filed April 26, 2005.

BACKGROUND OF THE INVENTION

1. Field of the invention

The invention relates generally to an illumination system for a microlithographic projection exposure apparatus. Such apparatuses are used in the manufacture of integrated circuits and other microstructured devices. More 5 particularly, the invention relates to a condenser for such an illumination system that transforms a pupil plane into a field plane in which a field stop is arranged. The invention also relates to a field stop objective that images the field stop onto a mask plane.

10 2. Description of Related Art

Microlithography (also referred to as photolithography) is a technology for the fabrication of integrated circuits, liquid crystal displays and other microstructured devices. More particularly, the process of microlithogra-

phy, in conjunction with the process of etching, is used to pattern features in thin film stacks that have been formed on a substrate, for example a silicon wafer. At 5 each layer of the fabrication, the wafer is first coated with a photoresist which is a material that is sensitive to radiation, such as deep ultraviolet (DUV) light. Next, the wafer with the photoresist on top is exposed to projection light through a mask in a projection exposure apparatus. The mask contains a circuit pattern to be projected onto the photoresist. After the exposure, the 10 photoresist is developed to produce an image corresponding to the circuit pattern contained in the mask. Then an etch process transfers the circuit pattern into the thin film stacks on the wafer. Finally, the photoresist is removed. 15

A projection exposure apparatus typically includes an illumination system, a mask alignment stage, a projection objective and a wafer alignment stage. The illumination system illuminates a region of the mask that is to be 20 projected onto the photoresist.

Usually the illumination system contains a pupil plane in which an optical raster element is positioned. The optical raster element influences the geometry of the region that is illuminated on the mask. The light intensity distribution in the pupil plane determines the angular distribution of the projection light impinging on the mask. For modifying the intensity distribution in the pupil 25 plane, various optical elements, for example axicon ele-

ments or diffractive optical elements, may be used in the illumination system.

A condenser, which usually comprises a plurality of lenses, transforms the pupil plane into a field plane.

5 This means that the condenser images an object positioned at infinity on the field plane. Often a field stop comprising a plurality of adjustable blades is positioned in the field plane. The field stop ensures sharp edges of the region that is illuminated on the mask. To this end, 10 a field stop objective images the field stop onto the mask plane in which the mask is positioned.

The illumination system has to ensure a very uniform irradiance in the mask plane. The uniformity of the irradiance is often expressed in terms of the relative change 15 of the irradiance over 1 mm in an arbitrary direction. This gradient of the irradiance in the mask plane should not exceed a certain value that may be as low as 0.1 %/mm or even 0.015%/mm.

Furthermore, the illumination system should produce a 20 chief ray distribution in its exit pupil that matches the chief ray distribution of the subsequent projection objective. Usually it is desired that the chief rays are collimated, i.e. the exit pupil is positioned at infinity. In this case the illumination system is referred to 25 as being telecentric on the image side.

- 4 -

Another property of highly advanced illumination systems is a good pole balance. The pole balance denotes the ability of an illumination system to correctly transform an intensity distribution in the pupil plane into an angular distribution in the mask plane. For example, if only two poles are illuminated in the pupil plane with perfect symmetry, a perfect pole balance ($PB = 0$) means that the irradiance at an arbitrary point in the mask plane results from equal contributions from both poles.

If $PB \neq 0$ in the case of a dipole illumination, light rays impinging from one side on a field point are more intense than light rays impinging from the other side.

Another property, which has to be fulfilled by the condenser of the illumination system and which is closely related to the pole balance, is the extent to which the sine condition is fulfilled. According to the sine condition the distance from the optical axis in the pupil plane is proportional to the sine of the angle of incidence in the field plane. Ideally, the sine condition is perfectly fulfilled for all angles of incidence, and also for all field points.

These properties should be achieved with an illumination system having a short overall length, containing lenses with a small diameter and maintaining a certain minimum distance between the last lens and the mask plane.

Meeting these tight specifications has become more difficult in illumination systems that do not comprise a light

- 5 -

homogenization rod. Such a rod, which is known, for example, from US 6 285 443, is used to homogenize the illumination light bundle. Since the rod does not maintain the polarization state of the illumination light bundle, its 5 use is restricted to illumination systems without polarization control.

From US 6 583 937 B1 a condenser of a rod-less illumination system is known that comprises five lenses. The first surface of the condenser is aspherical.

10 US 2002/0171944 A1 discloses a condenser of a rod-less illumination system that comprises four lenses, namely a negative meniscus lens having an aspherical concave front surface, two bi-convex lenses and a flat convex lens having an aspherical convex rear surface.

15 US 6 680 803 B2 discloses a field stop objective for a rod-less illumination system comprising a totality of 9 lenses.

From DE 196 53 983 A1 another field stop objective is known comprising only 7 lenses with at least three 20 aspherical surfaces. In one embodiment, this objective ensures a telecentricity error of less than 0.3 mrad.

SUMMARY OF THE INVENTION

It is a first object of the present invention to provide an improved condenser for an illumination system for a microlithographic exposure apparatus.

5 This object is achieved by a condenser comprising a lens group that contains a plurality of consecutive lenses. These lenses are arranged such that a light bundle focused by the condenser on an on-axis field point converges within each lens of the lens group. At least one
10 lens of the lens group has a concave surface.

In the context of the present application the term "lens" shall denote a single refractive optical element that may have curved or planar surfaces.

The condenser according to the invention has a small
15 telecentricity error, a good pole balance, only very small deviations from the sine condition, a small gradient of the irradiance and a large optical geometrical flux of more than 15 mm.

Generally a small telecentricity error of the condenser
20 is advantageous if the field stop objective is telecentric at its object side, too. However, there may be cases in which this objective is significantly non-telecentric. The condenser may then be designed such that the directions of the chief rays in its exit pupil match as
25 closely as possible the directions of the chief rays in

the entrance pupil of the subsequent field stop objective. The deviations between these directions may be as small as 1 mrad.

It is a further object of the present invention to provide an improved illumination system for a microlithographic exposure apparatus comprising a condenser and a field stop objective.

This further object is achieved by an illumination system with a field stop objective that at least partly corrects a residual pupil aberration of the condenser.

When designing such an illumination system, it may be advantageous to optimize the design of the condenser and the field stop objective not separately for each component, but for the entire optical sub-system consisting of the condenser and the field stop objective. By suitably adjusting the optical properties of the condenser on the one hand and the field stop objective on the other hand, it is possible to allow deviations from certain optical properties in the field stop plane, in particular of the telecentricity error, from the optical properties required in the mask plane by a factor that may be as large as two or even four. Similar considerations apply to the spot diameter in the field stop plane and the mask plane. The spot is the illuminated region in a field plane if a preceding pupil plane is traversed by a parallel light bundle.

BRIEF DESCRIPTION OF THE DRAWINGS

Various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the 5 accompanying drawing in which:

FIG. 1 is a perspective and simplified view of a projection exposure apparatus comprising an illumination system and a projection objective;

10 FIG. 2 is a simplified meridional section through the illumination system shown in FIG. 1;

FIG. 3 is a meridional section through a condenser according to a first embodiment of the invention;

15 FIG. 4 is a meridional section through a condenser according to a second embodiment of the invention;

FIG. 5 is a meridional section through a condenser according to a third embodiment of the invention;

20 FIG. 6 is a meridional section through a condenser according to a fourth embodiment of the invention;

FIG. 7 is a meridional section through a condenser according to a fifth embodiment of the invention;

- 9 -

FIG. 8 is a meridional section through a condenser and a subsequent field stop objective;

5 FIG. 9 is a meridional section through an alternative embodiment for the field stop objective shown in FIG. 8;

10 FIG. 10 is a simplified meridional section through another embodiment of the illumination system shown in FIG. 1 comprising a diaphragm positioned at various alternative positions for shielding scattering light.

DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 shows a perspective and highly simplified view of a projection exposure apparatus 10 that comprises an illumination system 12 for producing a projection light bundle. The projection light bundle illuminates a field 14 on a mask 16 containing minute structures 18. In this embodiment, the illuminated field 14 has approximately the shape of a ring segment. However, other shapes of the illuminated field 14 are contemplated as well.

20 A projection objective 20 images the structures 18 within the illuminated field 14 onto a light sensitive layer 22, for example a photoresist, which is deposited on a substrate 24. The substrate 24, which is realized in this embodiment as a silicon wafer, is arranged on a wafer stage (not shown) such that a top surface of the light

- 10 -

sensitive layer 22 is precisely located in an image plane of the projection objective 20. The mask 16 is positioned by means of a mask stage (not shown) in an object plane of the projection objective 20. Since the latter has a 5 magnification of less than 1, a minified image 14' of the structures 18 within the illuminated field 14 is projected onto the light sensitive layer 22.

During the projection, the mask 16 and the substrate 24 move along a scan direction which coincides with the Y- 10 direction. Thus the illuminated field 14 scans over the mask 16 so that structured areas larger than the illuminated field 14' can be continuously projected. Such a type of projection exposure apparatus is often referred to as "step-and-scan tool" or simply a "scanner". The ratio between the velocities of the mask 16 and the substrate 24 15 is equal to the magnification of the projection objective 20. If the projection objective 20 inverts the image, the mask 16 and the substrate 24 move in opposite directions, as this is indicated in FIG. 1 by arrows A1 and A2. However, 20 the present invention may also be used in stepper tools in which the mask 16 and the substrate 24 do not move during projection.

In the embodiment shown, the illuminated field 14 is not centered with respect to an optical axis 26 of the projection objective 20. Such an off-axis illuminated field 14 may be necessary with certain types of projection objectives 20, for example objectives that contain one or 25 more truncated mirrors.

- 11 -

FIG. 2 is a more detailed meridional section through the illumination system 12 shown in FIG. 1. For the sake of clarity, the illustration of FIG. 2 is also considerably simplified and not to scale. This particularly implies 5 that different optical units are represented by very few optical elements only. In reality, these units may comprise significantly more lenses and other optical elements.

The illumination system 12 comprises a housing 28 and a 10 light source that is, in the embodiment shown, realized as an excimer laser 30. The excimer laser 30 emits projection light that has a wavelength of about 193 nm. Other wavelengths, for example 248 nm or 157 nm, are also contemplated.

15 The projection light emitted by the excimer laser 30 enters a beam expansion unit 32 in which the light bundle is expanded. After passing through the beam expansion unit 32, the projection light impinges on a first optical raster element 34. The first optical raster element 34 is 20 received in a first exchange holder 36 so that it can easily be replaced by other optical raster elements having different properties. The first optical raster element 34 comprises, in the embodiment shown, one or more diffraction gratings that deflect each incident ray such 25 that a divergence is introduced. This means that at each location on the optical raster element 34, light is diffracted within a certain range of angles. This range may extend, for example, from -3° to $+3^\circ$. In FIG. 2 this is schematically represented for an axial ray that is split

into two diverging rays 38, 40. The first optical raster element 34 thus modifies the angular distribution of the projection light and influences the local intensity distribution in a subsequent pupil plane. Other kinds of optical raster elements, for example micro-lens arrays, may 5 be used instead or additionally.

The first optical raster element 34 is positioned in an object plane 42 of an objective 44 that is indicated by a zoom lens group 46 and a pair 48 of axicon elements 50, 10 52 having opposing conical faces. If both axicon elements 50, 52 are in contact, the axicon pair 48 has the effect of a plate having parallel plane surfaces. If both elements 50, 52 are moved apart, the spacing between the axicon elements 50, 52 results in a shift of light energy 15 radially outward. Since axicon elements are known as such in the art, these will not be explained here in further detail.

Reference numeral 54 denotes an exit pupil plane of the objective 44. A second optical raster element 56 comprising 20 micro-lens arrays is received in a second exchange holder 58 that is positioned in or in close proximity to the exit pupil plane 54 of the objective 44. The second optical raster element 56, which preferably has a diameter of less than 150 mm, introduces a divergence for each 25 point and influences the geometry of the illuminated field 14 on the mask 16. The divergence introduced by the second optical raster element 56 is schematically represented in FIG. 2 by divergent rays 38a, 38b and 40a, 40b for the impinging rays 38 and 40. If the illuminated

- 13 -

field 14 has the shape of a curved slit as is shown in FIG. 1, the exit side numerical aperture of the second optical raster element 56 may be in the range from 0.28 to 0.35 in the X-direction and in the range from 0.07 to 5 0.09 in the Y-direction.

The diverging rays 38a, 38b and 40a, 40b emerging from the second optical raster element 56 enter a condenser 60 that is represented in FIG. 2 by a single lens element for the sake of simplicity. Various embodiments of the 10 condenser 60 will be explained in more detail below with reference to FIGS. 3 to 8.

The entrance pupil plane of the condenser 60 coincides with the exit pupil plane 54 of the objective 44. An image plane 62 of the condenser 60 is a field plane, close 15 to which a field stop 64 is positioned. A field stop objective 66 images the field stop 64 onto a mask plane 68 in which the mask 16 is positioned. The field stop 64 ensures sharp edges of the illuminated field 14 at least for the short lateral sides extending along the Y- 20 direction.

In the following various embodiments of the condenser 60 will be described with reference to FIGS. 3 to 8.

FIG. 3 shows a meridional section of a first embodiment of the condenser 60 that is denoted in its entirety by 25 601. An aperture stop AS arranged in the pupil plane 54 may be formed by the rim of the second optical raster

element 56. The pupil of the condenser 601 has a diameter of about 125 mm. The condenser 601 fourier-transforms the pupil to a field having a diameter of about 110 mm. The overall focal length of the condenser 601 is about 208 5 mm, and the image side numerical aperture is about 0.3. These values also apply to the other embodiments described further below.

Immediately behind the pupil plane 54 a first lens formed 10 as a thin planar plate L11 made of quartz glass is positioned. The thin plate L11 as such does not substantially contribute to the optical properties of the condenser 601. However, it may support various functional elements 15 such as a grey filter, a diffusing surface or a structure designed to selectively modify the state of polarization of traversing light rays. Depending upon the particular application, a plate L11 supporting a first functional element may be replaced by a plate L11' supporting another functional element. If no such functional element 20 is desired at all, the plate L11 may be completely dispensed with. This entails only minor modifications of the optical design shown in FIG. 3.

Behind the plate L11 a second lens L12 is arranged that is formed as a negative meniscus lens having an aspherical convex rear surface. A third lens L13 is a positive 25 meniscus lens having an aspherical convex rear surface. A fourth lens L14 is a bi-convex lens that also has an aspherical convex rear surface. A fifth lens L15 is a positive meniscus lens with a concave rear surface.

A sixth lens L16 is a planar concave lens. A seventh lens L17, which is the last lens of the condenser 601, is a positive meniscus lens with a slightly concave front surface.

5 In the embodiment shown, only the second lens L12 and the third lens L13 are made of CaF₂. All other lenses of the condenser 601 are made of quartz glass. This material selection is a good compromise in terms of costs and durability. Of course, other material could be envisaged as
10 well and would entail only minor changes of the design. For example, the second lens L12 and the third lens L13 may be made of another cubic crystalline material, for example BaF₂, SrF₂, LiF₂ or Ca_{1-x}Ba_xF₂, and the other lenses may be made of other glasses, or all lenses could
15 be made of CaF₂.

Table 1 contains the lens data of the condenser 601. The first column lists a surface number S# of all lenses of the condenser 601 in the order in which light propagates through the condenser 601 from the pupil plane 54 to the
20 field plane 62. The second column lists the radius of curvature (in mm) for each surface S#. The third column lists the spacing between successive surfaces (in mm) along the optical axis 26. The fourth column indicates the material of all media having an index of refraction
25 distinct from 1. The fifth column lists the $\frac{1}{2}$ diameter of the lenses, and the sixth column contains the indices of refraction of the materials listed in the fourth column at the exposure wavelength of $\lambda = 193.38$ nm.

Table 1: Lens data of embodiment #1

S#	RADIUS	THICKNESS	MATERIAL	% DIAMETER	n(193.38)
5	1	∞		62.54	1.000000
	2	∞	SiO2	64.74	1.560305
	3	∞		65.42	1.000000
	4	-81.16600	CAF2	69.70	1.501403
	5*	-164.05507	40.8166	79.53	1.000000
10	6	-324.09000	36.6603	102.45	1.501403
	7*	-131.96748	0.5000	106.03	1.000000
	8	269.95300	44.5830	113.39	1.560305
	9*	-451.38253	0.5000	112.38	1.000000
15	10	125.07200	41.5156	102.04	1.560305
	11	264.01000	28.8790	98.04	1.000000
	12	∞	SiO2	92.07	1.560305
	13	116.15500	95.5361	78.63	1.000000
	14	-1778.95000	19.6342	73.90	1.560305
20	15	-193.86600	42.8486	73.68	1.000000

Table 2: Aspherical constants of embodiment #1

S#	k	A	B	C	D
5	-0.71095E+00	-0.25034E-06	-0.11887E-10	0.37576E-15	
7	-0.18656E+01	-0.45117E-08	0.22449E-11	-0.81255E-15	0.24090E-19
9	0.00000E+00	-0.19790E-07	0.61213E-11	-0.16935E-15	

Aspherical surfaces are indicated in column 1 by an asterisk. Table 2 contains the values for the conical coefficient k and the aspherical coefficients A, B, C, and D for these surfaces. The height z of a surface point parallel to the optical axis 26 is given by

$$z = \frac{ch^2}{1 + \sqrt{1 - (1 + k)c^2h^2}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10}$$

with h being the radial distance from the optical axis 26 and c being the curvature of the respective surface.

The shaded area in FIG. 3 represents a coaxial light bun-

40 dle 70 that converges towards an on-axis image point 72

in the field plane 62. The shape of the coaxial light bundle 70 is determined by marginal rays 74 that are indicated by broken lines and pass the aperture stop AS parallel to the optical axis 26.

5 Another pair of broken lines indicates a marginal light bundle 76 that converges towards an image point 77 that has a maximum height (i.e. distance) h_{\max} from the optical axis 26. The centre of the marginal light bundle 76 is formed by a chief ray 78 that intersects the optical axis 10 26 in the pupil plane 54 and passes the field plane 62 at the marginal image point 77.

The lenses L14, L15, L16 and L17 form a group of consecutive lenses in which the coaxial light bundle 70 is converging. This group contains three concave surfaces, 15 namely the rear surfaces of lenses L15 and L16 and the front surface of lens L17. Apart from that, this group comprises a lens having a negative refractive power, namely the lens L16. This is a characteristic feature of the condenser 601 and contributes to the excellent optical properties that are discussed below with reference to 20 Table 3.

In condenser 601 shown in FIG. 3, the aspherical surfaces on the lenses L13 and L14 contribute to correcting pupil related aberrations. The first aspherical surface on lens 25 L12 is mainly used for correcting spherical aberration.

Table 3 contains a list of various quantities that characterize the optical quality of the various embodiments of the condenser 60 and are crucial for its use in an illumination system of a microlithographic exposure apparatus. Column 1 of Table 3 contains the values for these quantities for the condenser 601 that has been described above with reference to FIG. 3.

Table 3: Optical properties of embodiments #1 to #5

	Embody. #1	Embody. #2	Embody. #3	Embody. #4	Embody. #5
Image side numerical aperture NA_i	0.3	0.3	0.3	0.3	0.3
Geometrical optical flux [mm]	16.5	16.5	16.6	16.6	16.6
Telecentricity error [mrad]	0.1	0.2	0.3	0.2	1.7
Proximity P_{first} of first aspherical surface to pupil plane	3.5	7.5	7.5	7.5	0.66
Proximity P_{last} of last aspherical surface to field plane	0.6	1.9	1.6	1.5	2.0
Maximum deviation Δd from sine condition	± 0.004	± 0.004	± 0.005	± 0.007	± 0.035

In the following the various quantities listed in Table 3 will be briefly explained and discussed.

The image side numerical aperture NA_i listed in row 1 is defined as the product of the index of refraction of the medium between the condenser 601 and the field plane 62 on the one hand and the maximum aperture angle on the other hand. In FIG. 3 this angle is formed between the optical axis 26 and a marginal ray 74 when it passes through the field plane 62.

- 19 -

The geometrical optical flux, which is listed in row 2 of Table 3, is defined as the product of the image side numerical aperture NA_i and the maximum image height h_{max} . With growing geometrical optical fluxes it becomes more 5 and more difficult to obtain an optical system that meets the tight specifications that prevail in microlithographic exposure tools.

Row 3 of Table 3 lists the telecentricity error on the object side of the condensers according to the embodiment 10 1 to 5. The telecentricity error relates to the maximum angle formed between a chief ray, i.e. a ray that crosses the optical axis in the pupil plane 54 such as chief ray 78, and the optical axis 26 in the field plane 62. In an optical system that is perfectly telecentric on its object side, this angle equals 0° for all chief rays. This 15 means that the chief rays are collimated in the object plane.

Row 4 of Table 3 relates to the proximity P_{first} of the aspherical surface that is closest to the pupil plane 54. 20 This proximity P_{first} is a figure of merit, because the effect of an aspherical surface for correcting spherical aberration increases with decreasing distance from the pupil plane.

The proximity P_{first} is defined as the ratio of the height 25 h_{mr} of the marginal rays 74 of the coaxial light bundle 70 to the height h_{cr} of the chief ray 78 that impinges on the marginal image point 77. The heights h_{mr} and h_{cr} denote

- 20 -

the distances between the optical axis 26 and the point where the respective ray penetrates the aspherical surface that is closest to the pupil plane 54. In FIG. 3, this is the rear surface of the lens L12. The larger this 5 ratio P_{first} is, the closer is the aspherical surface positioned to the pupil plane 54.

Row 5 of Table 3 contains values for a quantity P_{last} that is characteristic of the proximity of the aspherical surface that is closest to the field plane 62. This proximity 10 P_{last} is also a figure of merit, because the effect of an aspherical surface for correcting pupil related aberrations increases with decreasing distance from the field plane.

The proximity P_{last} is defined as $1/P_{\text{first}} = h_{\text{cr}}/h_{\text{mr}}$. Thus a 15 large value for P_{last} indicates that the last aspherical surface is arranged in close proximity to the field plane 62.

Row 6 of Table 3 relates to the deviations Δd from the sine condition. The sine condition deviation Δd is defined by 20

$$\sin(\alpha) = p / ((1 + \Delta x) \cdot f) ,$$

where f is the focal length of the condenser 601, α is the angle of incidence of the light ray impinging on an arbitrary illuminated field point in the field plane 62, 25 and p is the distance between the optical axis 26 of the

condenser and a pupil point at which the light ray passes the pupil plane 54. For an axial point in the pupil plane 54, $p = 0$ which results in normal incidence. For a pupil point on the diameter of the pupil, $p = p_{\max}$ and α has its 5 maximum value α_{\max} , too (see FIG. 3). Ideally, the sine condition is perfectly fulfilled (i.e. $\Delta x = 0$) for all angles of incidence and also for all field points.

As can be seen from Table 3, the condenser 601 has excellent optical qualities, particularly as far as the 10 telecentricity error and the sine condition is concerned. Apart from that, the condenser 601 has a very good pole balance and a small gradient of the irradiance. A sine condition deviation $|\Delta x| = 0.004$ is an excellent value that has to be compared to conventional condensers having 15 sine condition deviations $\Delta x > 0.02$.

Apart from that, the condenser 601 has a good pole balance and a small gradient of the irradiance. More particularly, the condenser 601 produces in the field plane 62 a very uniform irradiance distribution $I(x)$ along the 20 X direction (cross-scan direction). This can be expressed by the ratio $\Delta I_{\max}/I(x)$, where ΔI_{\max} denotes the maximum fluctuations of the irradiance along the X direction. With the condenser 601, as well as with the other condensers described hereinafter, the ratio $\Delta I_{\max}/I(x)$ is 25 smaller than 0.5% irrespective of the selected illumination setting. Along the Y direction a non-uniform irradiance distribution may be deliberately produced for other reasons, for example in order to reduce the pulse quantization effect.

- 22 -

FIG. 4 shows a second embodiment of a condenser 60 which is denoted in its entirety by 602. The lens data and the aspherical constants are given in Table 4 and 5, respectively.

5 **Table 4: Lens data of embodiment #2**

	S#	RADIUS	THICKNESS	MATERIAL	1/2 Diameter	n(193.38)
10	1	∞	25.0000	CAF2	62.54	1.000000
	2	∞	4.0000		69.40	1.501484
	3	∞	2.5000		70.12	1.000000
	4*	172.07456	12.3100		74.95	1.501484
	5	222.75300	103.7810		75.53	1.000000
	6	-117.16460	35.0000		89.65	1.560293
	7	-118.84730	1.1540		101.02	1.000000
15	8	7987.00000	62.2400	SI02	109.90	1.560293
	9*	-161.38341	0.5000		112.21	1.000000
	10	126.36700	41.4500		93.52	1.560293
	11	298.55400	35.3040		87.00	1.000000
	12	-276.67400	11.0000		80.51	1.560293
	13*	111.64295	37.3149		71.13	1.000000
	14	∞	26.6900		70.80	1.560293
20	15	-168.13720	16.7565	SI02	70.66	1.000000
	16	∞	3.0500		60.45	1.560293
	17	∞	16.9500		59.85	1.000000

Table 5: Aspherical constants of embodiment #2

	S#	k	A	B	C	D
30	4	0.84843E+00	-0.57629E-07	-0.41326E-11	-0.41876E-15	-0.21243E-20
	9	-0.74026E+00	0.41420E-07	-0.18061E-11	0.66307E-16	-0.22252E-20
35	13	-0.99518E+00	-0.12832E-06	0.23043E-10	-0.22350E-14	0.81039E-19

The condenser 602 comprises two thin plates L21, L28, which have a similar function as the plate L11 of the 40 condenser 601 shown in FIG. 3, and a positive meniscus lens L22 having an aspherical front surface. The following lens L23 is a meniscus lens having surfaces with almost identical curvatures. Lens L24 is a positive lens with an almost planar front surface and an aspherical 45 rear surface. Lens L25 is again a meniscus lens having a positive refractive power. Lens L26 is a negative bi-

- 23 -

concave lens, and lens L27 is a planar convex lens. Reference numeral L28 denotes another flat plate that has a similar function as the plates L11 or L21 mentioned above, but with the difference that it is arranged very 5 close to the field plane 62. Thus the plate L28 may be used for manipulating those properties that should be modified in or in close proximity of a field plane.

The lenses L24 to L28 form a group of lenses in which the coaxial light bundle 702 converges. Within this group of 10 lenses, there are three concave surfaces and one negative lens, namely lens L26. As can be seen from Table 3, the optical properties of the condenser 602 are comparable to the optical properties of the condenser 601 shown in FIG. 3.

15 A further advantage of the condenser 602 is, compared to the condenser 601 or condensers known in the prior art, that (apart from the plate L21) there is only one lens, namely lens L22, that is arranged in close proximity to the aperture stop AS. To be more precise, the object side 20 vertex 86 of the front surface of the lens L23 is spaced apart by a distance from the pupil plane 54 being so large that the ratio h_{mr}/h_{cr} is smaller than 1.7.

This is advantageous for the following reason: If the pupil plane is not homogeneously illuminated, for example, 25 if a dipole setting is used, particularly high intensities may occur in those lenses that are arranged in the immediate vicinity of the pupil plane. Since quartz glass

- 24 -

or other conventional lens materials suffer from considerable deteriorations in the presence of such high intensities, it is often advantageous to use CaF₂ or a similar cubic crystal as lens material for these lenses, since

5 CaF₂ has a higher transmittance for DUV projection light and is less sensitive to degradations caused by high light intensities. On the other hand, CaF₂ is a very expensive material, and therefore its use should be restricted to those cases in which it is indispensable.

10 If there is only one lens arranged in close proximity to the pupil plane, here lens L22, it suffices to select CaF₂ as lens material only for this one lens. All other lenses L23 to L28 may be made of quartz glass or another comparatively cheap material, since they are relatively

15 far away from the pupil plane and are thus not subject to the aforementioned deteriorations.

In order to obtain optical properties that are comparable to the first embodiment, the condenser 602 requires not only three but four aspherical surfaces.

20 FIG. 5 shows a meridional section through a condenser 603 according to a third embodiment. The lens data and the aspherical constants are given in Tables 6 and 7, respectively.

25 The condenser 603 is, both in terms of optical design and optical properties (cf. Table 3), comparable to the condenser 602. However, the lenses L23 and L24 are combined

- 25 -

to form a single thick meniscus lens L33. Only the plate L31 and the first thin meniscus lens L32 are made of CaF₂ or a similar material. All other optical elements of the condenser 603 may be made of a conventional lens material
5 such as quartz glass.

Table 6: Lens data of embodiment #3

S#	RADIUS	THICKNESS	MATERIAL	% Diameter	n(193.38)
10	1	25.0000		64.86	1.000000
	2	4.0000	CAF2	71.72	1.501484
	3	2.5000		72.43	1.000000
	4*	200.04110	CAF2	77.08	1.501484
	5	233.03400	124.6858	77.77	1.000000
	6	-389.10600	60.0000	104.66	1.560293
15	7*	-114.20352	0.5000	110.58	1.000000
	8*	128.28959	62.8300	101.09	1.560293
	9	1000.17000	11.0902	92.72	1.000000
	10	-1778.96000	10.0000	90.56	1.560293
	11*	83.50000	43.1940	78.62	1.000000
	12	25.7000	SI02	78.38	1.560293
20	13	-198.36600	27.0000	78.24	1.000000
	14	3.0500	SI02	65.72	1.560293
	15	20.9500		65.16	1.000000
	16	0.0000		59.48	1.000000

Table 7: Aspherical constants of embodiment #3

S#	k	A	B	C	D
4	0.00000E+00	-0.41303E-08	-0.29279E-11	-0.71705E-15	0.83815E-19
35	-0.68105E+00	0.56622E-07	-0.16891E-11	-0.36668E-16	0.24541E-20
7	-0.58533E-01	-0.43568E-07	0.12312E-11	-0.28884E-15	
8	-0.83269E+00	-0.29382E-06	0.39629E-10	-0.42228E-14	0.19031E-18
11					

40

The vertex 88 of the front surface of the second curved lens, namely lens L33, is arranged at such a large distance from the aperture stop AS that the ratio h_{mr}/h_{cr} is smaller than 1.4. This means that the lens L33 is sufficiently far away from the pupil plane so that it can be made of quartz glass without taking the risk of incurring lifetime degradations due to high intensities in the vicinity of the pupil plane.

FIG. 6 shows a meridional section through a condenser 604 according to a fourth embodiment. The lens data and the aspherical constants are given in Tables 8 and 9, respectively.

5 **Table 8: Lens data of embodiment #4**

S#	RADIUS	THICKNESS	MATERIAL	% Diameter	n(193.38)
10	1	25.0000		58.39	1.000000
	2	4.0000	CAF2	65.70	1.501484
	3	2.5000		66.47	1.000000
	4*	123.94289	CAF2	73.72	1.501484
	5	136.47905	139.1226	73.44	1.000000
15	6	-272.90199	54.5413	105.44	1.560293
	7*	-112.50000	1.0000	111.00	1.000000
	8*	107.44500	78.1296	101.29	1.560293
	9*	84.84697	60.7565	76.60	1.000000
20	10	-166.37753	20.9500	75.96	1.560293
	11	-127.37113	13.0000	77.39	1.000000
	12	∞	3.0500	65.86	1.560293
	13	∞	20.9500	65.30	1.000000
	14	∞	0.0000	59.13	1.000000

25 **Table 9: Aspherical constants of embodiment #4**

S#	k	A	B	C	D
30	4	0.00000E+00	-0.14901E-07	-0.27484E-11	-0.24789E-14
	7	-0.94802E+00	0.25005E-08	-0.28140E-11	0.54836E-16
	8	-0.50760E+00	0.41660E-08	-0.24133E-12	0.17317E-15
35	9	-0.38355E+00	-0.14660E-06	0.19333E-10	-0.99009E-15

The condenser 604 is, both in terms of optical design and optical properties (cf. Table 3), comparable to the condensers 602 and 603 according to the embodiments 2 and 3, respectively. The thick meniscus lens L44 of the condenser 604 may be envisaged as a combination of the lenses L34 and L35 of the condenser 603. Thus the condenser 604 requires only eight curved surfaces, from which four surfaces are aspherical. The ratio h_{mr}/h_{cr} at the vertex 90 of the second curved lens (lens L43) is as low as about 1.3.

FIG. 7 shows a meridional section through a condenser 605 according to a fifth embodiment. The lens data and the aspherical constants are given in Tables 10 and 11, respectively.

5 **Table 10: Lens data of embodiment #5**

S#	RADIUS	THICKNESS	MATERIAL	% Diameter	n(193.38)
10	1	0.0000	CAF2	58.39	1.000000
	2	25.0000		58.39	1.000000
	3	4.0000		65.70	1.501484
	4	40.0000		66.47	1.000000
15	5	641.51121	CAF2	79.61	1.501484
	6	-824.68499	CAF2	81.64	1.000000
	7	175.43433	SI02	113.12	1.560293
	8*	-1808.45841	SI02	110.44	1.000000
20	9	220.27637	SI02	98.21	1.560293
	10*	280.26962	SI02	79.49	1.000000
	11	3.0500	SI02	64.99	1.560293
	12	16.9500	SI02	64.44	1.000000
	13	0.0000		59.68	1.000000

25 **Table 11: Aspherical constants of embodiment #5**

S#	k	A	B	C	D
8	-0.68105E+00	-0.73068E-07	0.73361E-11	-0.35149E-15	0.71240E-20
10	-0.83269E+00	0.16320E-06	0.11279E-10	-0.31948E-14	0.32841E-18

35 Apart from two flat plates L51, L55 the condenser 605 comprises only three lenses, namely a thin bi-convex lens L52, a thick bi-convex lens L53 and a thick negative meniscus lens L54. Only the rear surfaces of the lenses L53 and L54 are aspherical. The vertex of the front surface of the second lens is denoted by 92.

40 The lens L52 is made of CaF₂, whereas the other two lenses L53, L54 are made of quartz glass. Again, other materials are contemplated as well.

As can be seen from Table 3, the particularly simple design of the condenser 605 results in optical properties that are, in comparison to the embodiments 1 to 4, slightly inferior. However, in comparison to condensers 5 known in the prior art, the condenser 605 has still much better values for the gradient of irradiance.

FIG. 8 shows a meridional section through a condenser 606 and a field stop objective 666 according to a sixth embodiment. The lens data and the aspherical constants of 10 both optical subsystems are given in tables 12 and 13, respectively. Aspherical surfaces are indicated in column 1 by an asterisk.

The condenser 606 comprises two flat plates L61 and L66 having a similar function as the plate L11 of the condenser 601 shown in FIG. 3. The condenser 606 further comprises a thin positive meniscus lens L62 having an aspherical convex front surface, a thick positive meniscus lens L63 having an aspherical convex rear surface, a thick positive meniscus lens L64 having an aspherical 15 convex front surface, and a thick negative meniscus lens L65 having an aspherical convex front surface.

The first curved lens L62 of the condenser 606 is positioned in close proximity to the pupil plane 54. The proximity P_{first} of the first aspherical surface of the 20 condenser 606 to the pupil plane 54 is about 4.5. As a result, this surface is able to effectively correct spherical aberration. Due to the small spherical aberration.

tion, the condenser 606 focuses a parallel light bundle traversing the pupil plane 54 onto a spot in the field stop plane 62 having a spot diameter of less than 1.2 mm.

5 **Table 12: Lens data of embodiment #6**

	S#	RADIUS	THICKNESS	MATERIAL	% Diameter
10	1	∞	26.0000		68.01
	2	∞	8.5000	SiO2N2	75.98
	3	∞	0.0000		77.61
	4	∞	0.0000		77.61
	5	∞	18.8537		77.61
15	6*	129.50687	15.7952	CaF2N2	93.96
	7	167.44939	126.8379		93.31
	8	-216.15718	55.3914	SiO2N2	111.23
	9*	-141.69001	0.5000		120.81
	10*	143.92703	63.9518	SiO2N2	116.39
20	11	649.68828	1.0000		109.02
	12*	114.58152	44.8627	SiO2N2	91.94
	13	80.01238	49.5988		67.37
	14	∞	3.0500	SiO2N2	62.23
	15	∞	20.9500		61.49
25	16	∞	0.0000		53.80
	17	∞	53.4233		53.80
	18	-92.21665	7.0000	SiO2N2	64.65
	19	6178.26989	23.0715		84.54
	20*	-172.55434	68.1962	SiO2N2	94.41
30	21	-129.51211	7.9100		110.22
	22	∞	0.0000		138.32
	23	∞	0.0000		138.32
	24*	167.33230	81.0899	SiO2N2	161.97
	25	-4477.98704	472.1477		161.88
35	26	561.06993	44.9138	CaF2N2	148.26
	27*	-511.25943	74.9280		147.53
	28	∞	248.4590		120.96
	29	∞	248.4524		199.62
	30	1076.99100	38.1025	SiO2N2	147.25
40	31*	-502.36323	1.0000		147.13
	32	170.98764	44.7778	SiO2N2	131.69
	33	287.63431	2.0000		125.88
	34	200.11077	19.2090	SiO2N2	119.65
	35	128.37087	149.1988		102.22
45	36	∞	6.3000	SiO2N2	75.77
	37	∞	0.0000		75.20

50 As a result of the proximity of the lens L62 to the pupil plane 54, high projection light intensities may locally occur that could ultimately result in material degradations. In order to prevent such degradations, the lens L62 is, in the embodiment shown, made of CaF₂ or another optical material having a very high transmission for pro-

jection light wavelengths below 200 nm. However, it is also possible to position the lens L62 further away from the pupil plane 54. This reduces the maximum light intensities so that the lens L62 may be made of a material 5 having a higher absorption in the contemplated wavelength range. If the light source 30 of the illumination system 12 produces projection light with a wavelength above 200 nm, a conventional optical material such as SiO_2 may be used instead. Shifting the lens L62 away from the pupil 10 plane 52 implies only insignificant modifications of the design of the condenser 606, but may increase the spot diameter.

Table 13: Aspherical constants of embodiment #6

15	S#	k	A	B	C	D
20	6	-0.32913E+00	-0.21551E-07	-0.25629E-11	0.16252E-16	
	9	-0.74354E-01	0.24543E-07	-0.13570E-11	0.80765E-16	
	10	-0.50117E+00	0.12506E-07	-0.19246E-11	0.56157E-16	
	12	0.12133E-01	0.27417E-08	-0.24918E-12	0.12276E-15	0.93461E-20
	20	-0.54984E+01	0.13596E-06	-0.13388E-10	0.82432E-15	-0.20423E-19
	24	-0.42892E+01	0.16203E-07	-0.42640E-12	0.91798E-17	-0.10444E-21
	27	-0.22484E+02	-0.12014E-07	0.46833E-12	-0.65235E-17	
	31	-0.13984E-01	0.14072E-08	0.49095E-13	-0.15999E-18	

If the spot diameter in the field plane 62 is allowed to significantly exceed the value of 1.2 mm, the lens L62 may be completely dispensed with. In this case (not 30 shown) the condenser 606 comprises only the three thick meniscus lenses L63, L64 and L65 (apart from the plates L61 and L66).

The field stop objective 666 images the field stop 64 arranged in the field plane 62 onto the mask plane 68. In 35 the embodiment shown, the field stop objective 666 com-

prises a first negative bi-concave lens L661 with an only weakly curved rear surface. Behind the lens L661 a thick positive meniscus lens L662 having an aspherical concave front surface is arranged. The field stop objective 666

5 further comprises a bi-convex lens L663 having an aspherical front surface, a bi-convex lens L664 having an aspherical rear surface, a bi-convex lens L665 having an aspherical rear surface, a positive meniscus lens L666 and a negative meniscus lens L667.

10 The first four lenses L661 to L664 of the field stop objective 666 transform the field plane 62 into a pupil plane 67 of the field stop objective 666. The last three lenses L665, L666 and L667 transform the pupil plane 67 of the field stop objective 666 into the mask plane 68.

15 The curved optical surfaces that are positioned closest to the field stop plane 62, i.e. the rear surface of the lens L65 and the front surface of the lens L661, are both concave. More particularly, these surfaces are almost concentric with respect to an axial point on the field 20 plane 62. This means that the center of curvature of each concave surface coincides, at least to a certain degree, with this axial point in the field plane 62. For both surfaces the radius of curvature deviates from the axial distance of the respective surface from the field plane 25 62 by less than 1.75. Generally it is advantageous if this ratio does not exceed the value of 2.5. Further, the radii of curvature have similar magnitudes for both adjacent surfaces. In the embodiment shown, these magnitudes differ by less than 15%.

According to table 12 the axial distance between the field plane 62 and the lens L661 is 53.4233 mm. The radius of curvature should not exceed approximately 133 mm. This ensures small angles of incidence and thus less optical aberrations.

However, such a design may cause, at least for small conventional illumination settings, an increased double reflex ratio. The double reflex ratio relates to the amount of light that is reflected on the front surface of the mask 16, propagates back into the field stop objective 666 and is once again reflected at an optical surface such that it impinges on the mask 16, thereby disturbing the intensity uniformity on the mask 16. However, the double-reflected light is distributed over the entire pupil plane 67 of the field stop objective 666 so that it can be eliminated by a suitable diaphragm 69 positioned in the pupil plane 67. Such a diaphragm 69 makes it possible to reduce the intensity of the double-reflected light by about one or even two orders of magnitude. If the illumination setting is (also) adjusted by the diaphragm 69 in the pupil plane 67, the position of the diaphragm 69 and the diameter of its aperture should be determined by simulation.

In the embodiment shown in FIG. 8, the first lens L661 of the field stop objective 666 is bi-concave. However, it may also be formed by a concave-convex lens. This may be advantageous if the working distance between the field stop plane 62 and the field stop objective 666 shall be increased. The larger the working distance is, the more

may the radius of curvature of the front surface of the lens L661 approach its axial distance with regard to the field plane 62. A larger working distance, however, results also in an increased clear aperture of the first 5 three lenses L661, L662 and L663 positioned close to the field plane 62. This increases costs so that a reasonable trade-off has to be found between a large working distance on the one hand and costs on the other hand.

Due to the small height of the marginal rays at the first 10 lens L661 of the field stop objective 666, this lens introduces only a small amount of spherical aberration and coma.

The pupil plane 67 within the field stop objective 666 is corrected with regard to coma and oblique spherical aberration. A correction of astigmatism is not necessary. The 15 diaphragm 69 may be positioned in the tangential focal plane where the marginal ray and the coma ray intersect each other. In spite of a small spot diameter in the mask plane 68 of less than 0.4 mm, field dependent effects of 20 the telecentricity, the uniformity and the ellipticity may be observed if the diaphragm 69 stops a significant amount of light. For reducing these effects, the dia- phragm 69 may be axially shifted from its geometrical po- sition by up to +/-0.5 mm.

25 The diaphragm 69 in the pupil plane 67 is usually de- signed for the maximum numerical aperture NA of the illu- mination system 12. For reducing the numerical aperture

NA to smaller values, the aperture diameter of the dia-phragm 69 may be varied and/or the position of the dia-phragm 69 may be shifted along the optical axis 26.

The absolute value of the negative refractive power of
5 the last lens L667 of the field stop objective 666 is
larger than the value of the positive refractive power of
the preceding lens L666. This causes an over-correction
of the spherical pupil aberration. As a result of the
larger heights of the principal rays on the positive lens
10 L666, the overall refractive power of the combination of
the lens L666 and L667 is nevertheless positive.

FIG. 9 shows an alternative design for the field stop objective which is denoted in its entirety by 666'. The lens data and the aspherical constants of the field stop
15 objective 666' are given in tables 14 and 15, respectively. Aspherical surfaces are indicated in column 1 by an asterisk.

The main difference between the field stop objective 606' shown in FIG. 9 and the field stop objective 606 shown in
20 FIG. 8 is that the last three curved lenses L665 to L667 of the field stop objective 666 have been replaced by two lenses L665' and L666'. The lens L665' is a bi-convex lens having an aspherical rear surface. The positive refractive power of the lens L665' approximately equals the
25 combined optical power of the lenses L665 and L666 of the field stop objective 666 shown in FIG. 8. The last curved

lens L666' is a negative meniscus lens, similar to the lens L666 of the embodiment shown in FIG. 8.

Table 14: Lens data of embodiment #7

5	S#	RADIUS	THICKNESS	MATERIAL	% Diameter
10	1	∞	41.9861		54.50
	2	-95.03220	7.0000	SiO2HL	60.79
	3	1411.85000	18.8033		75.71
	4*	-133.33411	50.6593	SiO2HL	76.73
	5	-115.48230	4.4140		91.48
	6*	184.97857	56.4211	SiO2HL	127.28
	7	-600.22546	495.0160		128.29
	8	859.42677	46.1039	CAF2HL	140.03
	9*	-339.43972	121.7656		139.71
15	10	∞	205.9152		102.01
	11	∞	157.1883		178.83
	12	240.56900	68.0000	SiO2HL	131.65
	13*	-548.09685	27.1165		128.62
	14	124.10190	23.5076	SiO2HL	95.66
	15	99.29100	72.0520		81.95
	16	∞	5.0000	SiO2HL	72.89
	17	∞	51.4480		71.91
	18	∞	6.3000	SiO2HL	55.73
25	19	∞	0.0000		54.62

Table 15: Aspherical constants of embodiment #7

30	S#	k	A	B	C	D
	4	-0.38566E+01	0.13610E-06	-0.20627E-10	0.24693E-14	-0.11456E-18
	6	-0.75624E+01	0.15558E-07	-0.48560E-12	0.86199E-17	
35	9	0.16726E+01	0.15002E-07	0.97625E-15	0.47824E-17	
	13	-0.33526E+01	0.10256E-07	-0.45608E-13	-0.10392E-18	

The embodiments shown in FIGS. 8 and 9 generally differ from the embodiments previously described in that the 40 condenser 606 has a larger telecentricity error of up to 1.2 mrad. This value is significantly larger than the telecentricity errors of the condensers of the embodiments shown in FIGS. 3 to 6. This has the advantage that only four or, if a slightly larger spherical aberration 45 is acceptable, even three lenses with curved surfaces are

required, whereas the embodiments shown in FIGS. 3 to 5 require five or six curved lenses.

The slightly inferior optical properties of the condenser 606 are, however, fully compensated by the field stop objective 666 or 666'. To be more precise, the entire sub-system consisting of the condenser 606 and the field stop objective 666 or 666' has a telecentricity error of less than 0.3 mrad in the mask plane 68. This is a very low value for an optical sub-system having a geometrical optical flux of 16.4 mm. Thus even very tight specifications for telecentricity errors and also uniformity and ellipticity in the mask planes 68 may be fully met with the design shown in FIGS. 8 and 9.

Therefore it may be advantageous to optimize the design of the condenser and the field stop objective not separately for each component, but for the entire optical sub-system consisting of the condenser and the field stop objective. By suitably adjusting the optical properties of the condenser on the one hand and the field stop objective on the other hand, it is possible to allow deviations from certain optical properties required in the mask plane 68, in particular of the telecentricity error, by a factor that may be as large as two or even four. Similar considerations apply to the spot size in the field stop plane 62 and the mask plane 68. According to this new approach, residual pupil aberrations of the condenser are accepted, but fully corrected by the subsequent field stop objective.

The diaphragm 69 may not only shield double-reflected light, but also (or alternatively) scattering light produced in the preceding optical elements. Scattering light is mainly generated by minute defects in optical materials that scatter the projection light in arbitrary directions. The portion of the scattering light that is absorbed by lens mounts or the housing of the illumination system is usually of little concern. If, however, the scattered light propagates in such a direction that it eventually reaches the mask, it may cause inhomogeneities with respect to the intensity and angular distribution of the projection light impinging on the mask. In order to reduce the intensity of scattering light impinging on the mask, the aperture of the diaphragm 69 may be determined such that a large portion of the scattering light is effectively shielded by the diaphragm 69 and is therefore prevented from impinging on the mask.

If scattering light is shielded by the diaphragm 69 arranged in the field stop objective 666, it may be necessary to readjust the aperture of the diaphragm 69 each time the angular distribution (i.e. the illumination setting) of the projection light is changed.

In order to avoid such readjustments, it may be advantageous to arrange a diaphragm for shielding scattering at a position where it is not affected by changes of the illumination settings. Some of these possible positions are described below with reference to FIG. 10 that shows an illumination system 12' similar to the illumination system 12 shown in FIG. 2. Optical elements succeeding the

condenser 60 are not shown, whereas additional components arranged between the light source 30 and the first optical raster element 34 are schematically illustrated.

These additional components may comprise lenses 110, 112, 5 folding mirrors M1 to M4, a beam homogenizing unit 114 and a (de)polarizer unit 116. In the embodiment shown, the (de)polarizer unit 116 is configured such that a polarizer or a depolarizer may be inserted into an exchange holder.

- 10 One possible position for a diaphragm used for shielding scattering light is within a portion of the illumination system 12' that comprises the light source 30, the homogenizing unit 114 and all components in between. This portion is sometimes referred to as beam delivery module.
- 15 In the embodiment shown, a possible position for a diaphragm inside the homogenizing unit 114 is indicated by 69a.

The diaphragm 69a may be adjustable such that the diameter and/or the geometry of its aperture may be varied.

- 20 Instead of using a separate mechanical element, the diaphragm may generally be formed by a layer that is applied to a suitable surface of an optical element and is made of a material being opaque for the projection light. For changing the diameter and/or the geometry of the diaphragm aperture, an optical element supporting a different layer may be used instead. The preceding remarks apply generally to all diaphragms in the present context
- 25

and are therefore not restricted to the position within the beam delivery module.

Another possible position for a diaphragm used for shielding scattering light is the (de)polarizer unit 116.

5 Here a diaphragm 69b is represented by a layer applied to the front surface of the (de)polarizer unit 116.

A further possible position for a diaphragm used for shielding scattering light is the first optical raster element 34. Again, the diaphragm 69c is represented by a

10 layer applied to the first optical raster element 34.

A still further possible position for a diaphragm used for shielding scattering light is inside the objective 44 at a location preceding the first optical element which can be moved for changing the illumination setting. In

15 FIG. 10 this is illustrated by a diaphragm 69d arranged between a fixed lens 118 and a movable lens 120 of the zoom lens group 44. This position is perhaps the most advantageous one because it does not require adaptations if the illumination setting is changed, but the diaphragm 20 69d nevertheless shields scattering light produced in a large number of optical elements, namely all optical elements between the light source 30 and the diaphragm 69d.

It is to be understood that more than one diaphragm may be used for shielding scattering light in the illumination system 12'. On the other hand, it is obvious from 25 the foregoing that such a diaphragm may be advantageously

- 40 -

used at one or more of the positions discussed above in any other arbitrary illumination systems, i.e. independent from the condenser and field stop objective described further above.

- 5 The above description of the preferred embodiments has been given by way of example. From the disclosure given, those skilled in the art will not only understand the present invention and its attendant advantages, but will also find apparent various changes and modifications to
- 10 the structures and methods disclosed. The applicant seeks, therefore, to cover all such changes and modifications as fall within the spirit and scope of the invention, as defined by the appended claims, and equivalents thereof.

CLAIMS

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1. A condenser for an illumination system (12) of a microlithographic exposure apparatus (10), wherein the condenser transforms a pupil plane (54) into a field plane (62), in which a field stop (64) is arranged, and comprises a lens group (L14, L15, L16, L17; L24, L25, L26, L27, L28; L34, L35, L36, L37; L44, L45, L46; L53, L54, L55) that comprises a plurality of consecutive lenses, wherein
 - a) said lenses are arranged such that a light bundle (70) focused by the condenser (601; 602; 603; 604; 605) on an on-axis field point (72) converges within each lens of the lens group, and wherein
 - b) at least one lens (L15, L16, L17; L25, L26; L34, L44, L45; L54) of the lens group has a concave surface.
2. The condenser of claim 1, wherein the at least one lens (L16; L26; L35; L44) has a negative refractive power.
- 20 3. The condenser of claim 2, wherein the negative lens is a meniscus lens (L44).

4. The condenser of claim 1, wherein the at least one lens is a meniscus lens (L54) having positive refractive power.

5. The condenser of any of the preceding claims, wherein the at least one lens (L15, L16, L17; L25, L26; L34, L44, L45; L54) is contained in a subgroup of four curved lenses that are positioned closest to the field plane (62).

10 6. The condenser of claim 5, wherein the at least one lens (L15, L16, L17; L25, L26; L34, L44, L45; L54) is contained in a subgroup of three curved lenses that are positioned closest to the field plane (62).

15 7. The condenser of any of the preceding claims, wherein the lens group comprises a lens (L12, L13, L14; L22, L24, L26; L32, L33, L34, L35; L42, L43, L44; L53, L54) having an aspherical surface.

20 8. The condenser of claim 7, wherein the condenser (601; 602; 603; 604; 605) has an image side numerical aperture NA_i and a maximum image height h_{max} with $h_{max} \cdot NA_i > 15$ mm.

9. The condenser of any of the preceding claims, wherein the condenser (601; 602; 603; 604; 605) has an axial length of less than 450 mm.

10. A condenser for an illumination system (12) of a microlithographic exposure apparatus (10), wherein the condenser (601; 602; 603; 604; 605).

5 a) transforms a pupil plane (54) into a field plane (62), in which a field stop (64) is arranged,

10 b) has an optical axis (26), an image side numerical aperture NA_i , a maximum image height h_{max} with $h_{max} \cdot NA_i > 15$ mm and an image side telecentricity error with respect to an optical axis of less than 3 mrad.

11. The condenser of claim 10, having an image side telecentricity error of less than 0.5 mrad.

15 12. The condenser of claim 11, having an image side telecentricity error of less than 0.2 mrad.

20 13. The condenser of any of claims 10 to 12, comprising an aspherical surface with an image side vertex that is positioned at a distance from the field plane such that the ratio between the height (h_{cr}) of a chief ray (78) traversing the field plane (62) at maximum distance (h_{max}) from the optical axis (26) to the height (h_{mr}) of a marginal ray (74) traversing the field plane (62) on the optical axis (26) exceeds 1.5.

- 44 -

14. The condenser of claim 13, wherein said ratio exceeds 1.9.

15. An illumination system of a microlithographic exposure apparatus (10), comprising:

- 5 a) a pupil plane (54),
- b) a field plane (62),
- c) a field stop (64) arranged in the field plane (62),
- 10 d) a field stop objective (66) that images the field plane (62) to a mask plane (68) and has an entrance pupil with an object side distribution of chief rays,
- e) a condenser (601; 602; 603; 604; 605) that
 - 15 - transforms the pupil plane (54) into the field plane (62),
 - has an exit pupil with an image side distribution of chief rays,
 - has an optical axis (26), an image side numerical aperture NA_i and a maximum image height h_{max} with $h_{max} \cdot NA_i > 15 \text{ mm}$,

wherein directions of corresponding chief rays in the entrance pupil of the field stop objective (66) and the exit pupil of the condenser (601; 602; 603; 604; 605) differ by less than 1 mrad.

- 5 16. The illumination system of claim 15, wherein the directions of corresponding chief rays in the entrance pupil of the field stop objective (66) and the exit pupil of the condenser (601; 602; 603; 604; 605) differ by less than 0.5 mrad.
- 10 17. The illumination system of claim 16, wherein the directions of corresponding chief rays in the entrance pupil of the field stop objective (66) and the exit pupil of the condenser (601; 602; 603; 604; 605) differ by less than 0.2 mrad.
- 15 18. The illumination system of any of claims 15 to 17, comprising an aspherical surface with an image side vertex that is positioned at a distance from the field plane (62) such that the ratio between the height (h_{cr}) of a chief ray (78) traversing the field plane (62) at maximum distance (h_{max}) from the optical axis (26) to the height (h_{mr}) of a marginal ray (74) traversing the field plane (62) on the optical axis (26) exceeds 1.5.
20
- 25 19. The illumination system of claim 18, wherein said ratio exceeds 1.9.

20. A condenser for transforming a pupil plane (54) into a field plane (62), in which a field stop (64) is arranged, in an illumination system (12) of a microlithographic exposure apparatus (10), wherein
5 said condenser (601; 602; 603; 604; 605)

a) has an optical axis (26), an image side numerical aperture NA_i and a maximum image height h_{max} with $h_{max} \cdot NA_i > 15$ mm and

b) comprises, in order from the pupil plane (54), a curved first lens (L22; L32; L42; L52) and a curved second lens (L23, L33, L43; L53), said second lens having an object side vertex (86; 88; 90; 92) that is positioned at a distance from the pupil plane (54) such
10 that the ratio between the height (h_{mr}) of a marginal ray (749) traversing the field plane (62) on the optical axis (26) to the height (h_{cr}) of a chief ray (78) traversing the field plane (62) at maximum distance (h_{max})
15 from the optical axis (26) is smaller than
20 1.8.

21. The condenser of claim 20, wherein the ratio is smaller than 1.4.

22. The condenser of claim 21, wherein the ratio is
25 smaller than 1.2.

23. The condenser of any of claims 20 to 22, wherein the first lens (L22, L32, L42; L52) is made of a cubic crystal and the second lens (L23, L33, L43; L53) is made of quartz glass.

5 24. The condenser of any of claims 20 to 23, wherein 10 all lenses are made of a cubic crystal for which the ratio between the height (h_{mr}) of a marginal ray (749) traversing the field plane (62) on the optical axis (26) to the height (h_{cr}) of a chief ray (78) traversing the field plane (62) at maximum distance (h_{max}) from the optical axis (26) exceeds 2.

25. The condenser of claim 24, wherein the ratio exceeds 3.

15 26. A condenser for transforming a pupil plane (54) into a field plane (62), in which a field stop (64) is arranged, in an illumination system (12) of a microlithographic exposure apparatus (10), wherein the condition

$$20 \quad \sin(\alpha) = p / ((1 + \Delta x) \cdot f)$$

holds for any arbitrary light ray impinging on an arbitrary field point in the field plane (62), where f is the focal length of the condenser, α is the angle of incidence of the light ray impinging

on the field point, p is the distance between an optical axis of the condenser and a pupil point at which the light ray passes the pupil plane, and Δx is the deviation from the sin condition value having an absolute value $|\Delta x| \leq 0.018$.

- 5 27. The condenser of claim 26, wherein $|\Delta x| \leq 0.01$.
28. The condenser of claim 26, wherein $|\Delta x| \leq 0.005$.
- 10 29. A condenser for transforming a pupil plane (54) into a field plane (62), in which a field stop (64) is arranged, in an illumination system (12) of a microlithographic exposure apparatus (10), wherein said condenser (601; 602; 603; 604; 605) has
 - a) an image side numerical aperture $NA_i < 0.26$,
 - b) a focal length f with $f < 250$ mm,
 - 15 c) a pupil diameter $d_p > 120$ mm,
 - d) a field diameter $d_f > 100$ mm,
 - e) maximum fluctuations ΔI_{\max} of the irradiance $I(x)$ in the field plane (62) along an X direction, which is perpendicular to a scan direction of the exposure apparatus, wherein

$\Delta I_{\max}/I(x)$ is smaller than 1% irrespective of the illumination setting.

30. The condenser of claim 29, wherein $\Delta I_{\max}/I(x) < 0.5\%$.

5 31. An illumination system (10) of a microlithographic exposure apparatus (12), comprising the condenser (601; 602; 603; 604; 605) of any of claims 1 to 14 and 20 to 30.

10 32. The illumination system of claim 31, comprising an optical raster element (56) arranged in or in close proximity to the pupil plane (54), said optical raster element (56) having a diameter of less than 150 mm and an exit side numerical aperture between 0.28 to 0.35.

15 33. The illumination system of claim 31 or 32, comprising a field stop objective (66) that images the field plane (62) on a mask plane (68).

20 34. The illumination system of claim 33, wherein the field stop objective (66) at least partly corrects a residual pupil aberration of the condenser (601; 602; 603; 604; 605).

35. A microlithographic projection exposure apparatus, comprising the illumination system (12) of any of

claims 31 to 34 and a projection objective for imaging the mask plane onto a light sensitive layer.

36. The projection exposure apparatus of claim 35,
wherein

- 5 a) the projection objective (20) has an entrance pupil with an object side distribution of chief rays,
- 10 b) the condenser (601; 602; 603; 604; 605) has an exit pupil plane with an image side distribution of chief rays,
- c) the field stop objective (66) has an exit pupil with an image side distribution of chief rays, and wherein
- 15 d) the image side distribution of chief rays of the field stop objective matches the object side distribution of chief rays of the projection objective more closely than the image side distribution of chief rays of the condenser does.

20 37. An illumination system (12) for a microlithographic projection exposure apparatus (10), comprising:

- a) a pupil plane (54),

- b) a field plane (62),
- c) a condenser (606) that transforms the pupil plane (54) into the field plane,
- d) a field stop objective (666; 666') that images the field plane (62) onto a mask plane (68), wherein the field stop objective (666; 666') at least partly corrects a residual pupil aberration of the condenser (606).

38. The illumination system (12) of claim 37, wherein

- 10 a) the condenser (606) has a maximum telecentricity error angle α_c and
- b) the field stop objective (666; 666') has an image side maximum telecentricity error angle $\alpha_o < 0.8 \cdot \alpha_c$.

15 39. The illumination system of claim 38, wherein $\alpha_o < 0.5 \cdot \alpha_c$.

40. The illumination system of claim 39, wherein $\alpha_o < 0.3 \cdot \alpha_c$.

41. The illumination system of any of claims 38 to 40, 20 wherein $\alpha_o < 0.5$ mrad.

42. The illumination system of any of claims 37 to 41, wherein the field stop objective (666; 666') has an image side numerical aperture NA_i and a maximum image height h_{max} with $NA_i \cdot h_{max} > 15$ mm.

5 43. The illumination system of any of claims 37 to 42, wherein the condenser (606) comprises at least four meniscus lenses (L62, L63, L64, L65).

10 44. The illumination system of any of claims 37 to 43, comprising a diaphragm (69; 69a; 69b; 69c; 69d) for shielding double-reflected light and/or scattering light.

15 45. The illumination system of claim 44, wherein the diaphragm (69) is positioned in or in close proximity to a pupil plane (67) of the field stop objective (666; 666').

20 46. The illumination system of claim 44 or 45, wherein the diaphragm (69a; 69b; 69c) is positioned at a position before any optical element (118, 50, 52) that is adjustable for modifying the angular distribution of projection light, if seen in a propagation direction along which the projection light propagates.

47. The illumination system of claim 46, wherein the adjustable optical element (118, 50, 52) is movable along an optical axis (26).

48. The illumination system of claim 47, wherein the adjustable optical element is a lens (118) of a zoom objective (46).

49. The illumination system of any of claims 44 to 48, wherein the illumination system (12') comprises an optical raster element (34) which is the first optical element that increases the geometrical optical flux, and wherein the diaphragm (69c) is positioned in front of the optical raster element (34) if seen in a propagation direction along which the projection light propagates.

50. The illumination system of any of claims 44 to 49, wherein the illumination system comprises a (de)polarizer (116) for (de)polarizing projection light, and wherein the diaphragm (69a; 69b) is positioned in front of the (de)polarizer (116) if seen in a propagation direction along which the projection light propagates.

51. The illumination system of any of claims 44 to 50, wherein the diaphragm (69a; 69d) has a variable aperture.

52. The illumination system of claim 51, comprising an adjusting mechanism for varying the aperture of the diaphragm (69a; 69d).

5 53. The illumination system of any of claims 44 to 50, wherein the diaphragm (69b; 69c) is formed by a layer that is opaque for projection light and is applied to an optical element (116; 34) through which projection light propagates or is reflected from.

10 54. The illumination system of any of claims 37 to 53, wherein

15 a) the condenser (606) has a first concave optical surface positioned immediately adjacent the field plane (62) and having a radius of curvature r_1 and an axial distance d_1 from the field plane with $d_1 < r_1 < 2.5 \cdot d_1$, and

20 b) the field stop objective (666; 666') has a second concave optical surface being positioned immediately adjacent the field plane (62) and having a radius of curvature r_2 and an axial distance d_2 from the field plane with $d_2 < r_2 < 2.5 \cdot d_2$.

55. The illumination system of claim 54, wherein the working distance of the field stop objective (666,

666') from the field plane (62) is between 10 mm and 90 mm.

56. The illumination system of claim 54 or 55, wherein the radius of curvature r_1 is greater than 80 mm.

5 57. The illumination system of any of claims 54 to 56, wherein the radius of curvature r_2 is greater than 80 mm.

58. The illumination system of any of claims 37 to 57, wherein

10 a) the condenser (606) focuses a collimated light bundle entering the pupil plane (54) onto a spot in the field plane (62) having a spot diameter of less than 1.2 mm, and

15 b) the field stop objective (64) images a point in the field plane (62) on the mask (16) as a spot with a spot diameter of less than 0.4 mm.

20 59. A microlithographic projection exposure apparatus, comprising the illumination system (12) of any of claims 37 to 58.

60. A microlithographic method of fabricating a micro-structured device, comprising the following steps:

- 56 -

- a) providing a substrate (24) supporting a light sensitive layer (22);
- b) providing a mask (16) containing structures (18) to be imaged onto the light sensitive layer (22);
- c) providing a projection exposure apparatus (10) of claim 35 or 36 or claim 59;
- d) projecting at least a part of the mask (16) onto the light sensitive layer (22).

10 61. A microstructured device which is fabricated according to the method of claim 60.

1 / 8

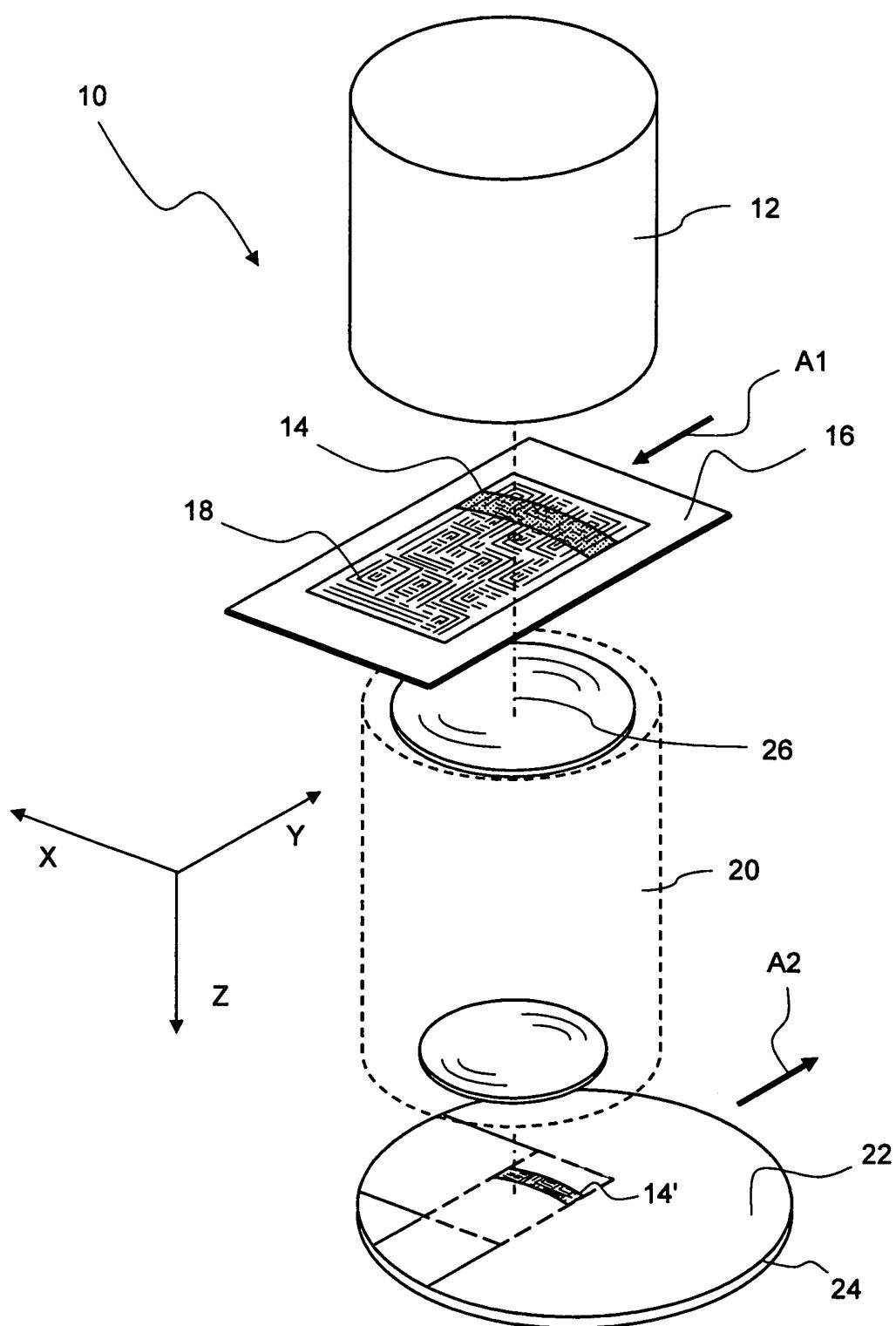


Fig. 1

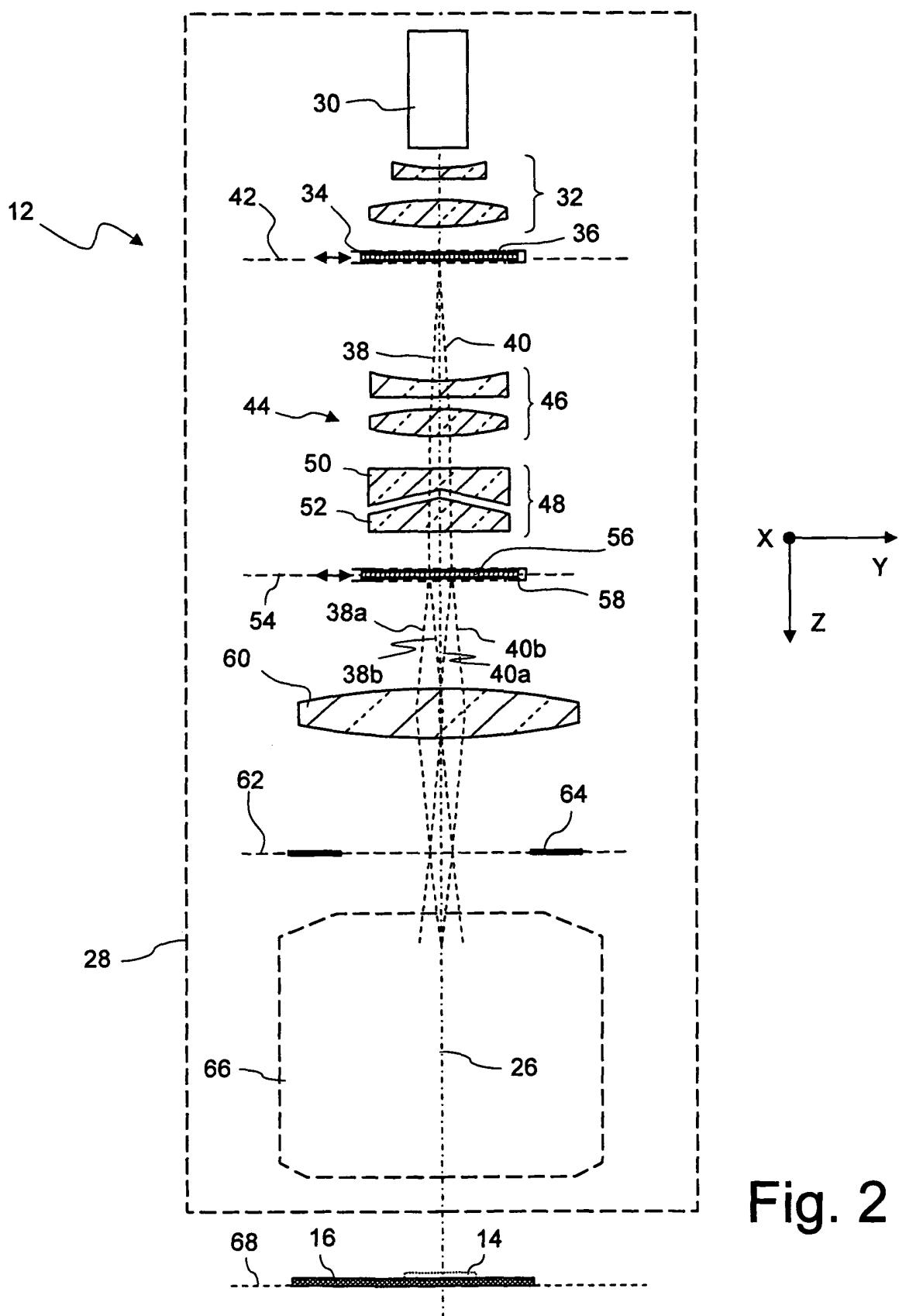


Fig. 2

3 / 8

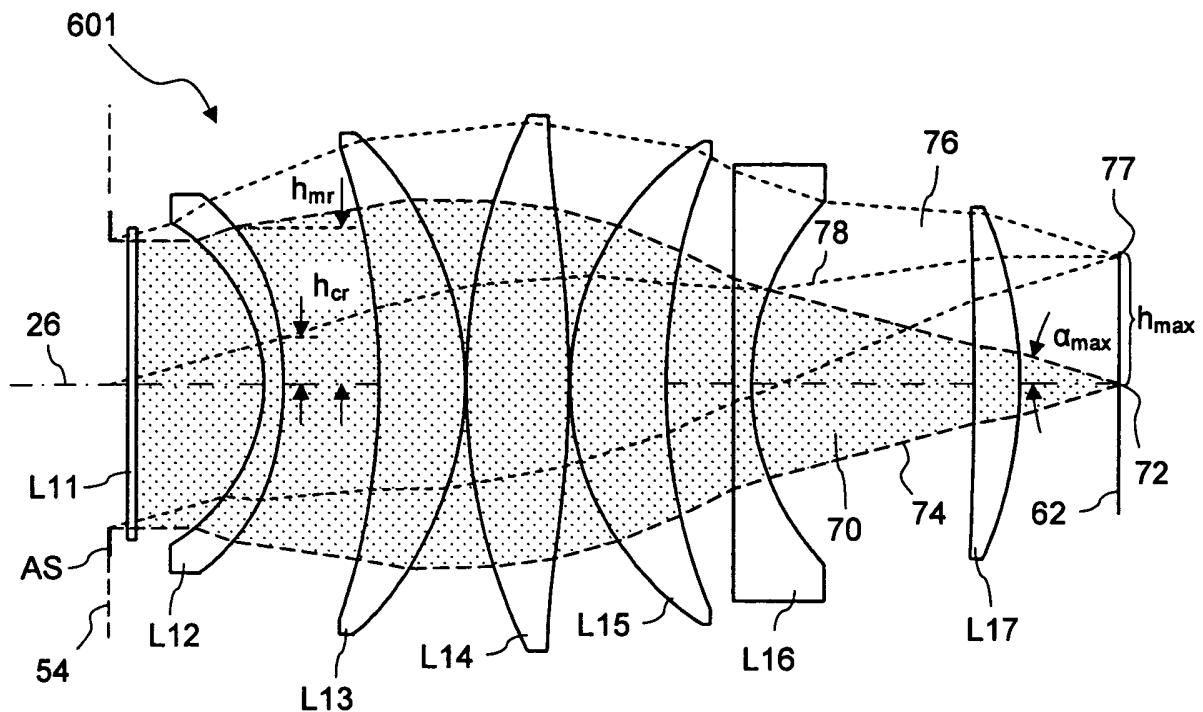


Fig. 3

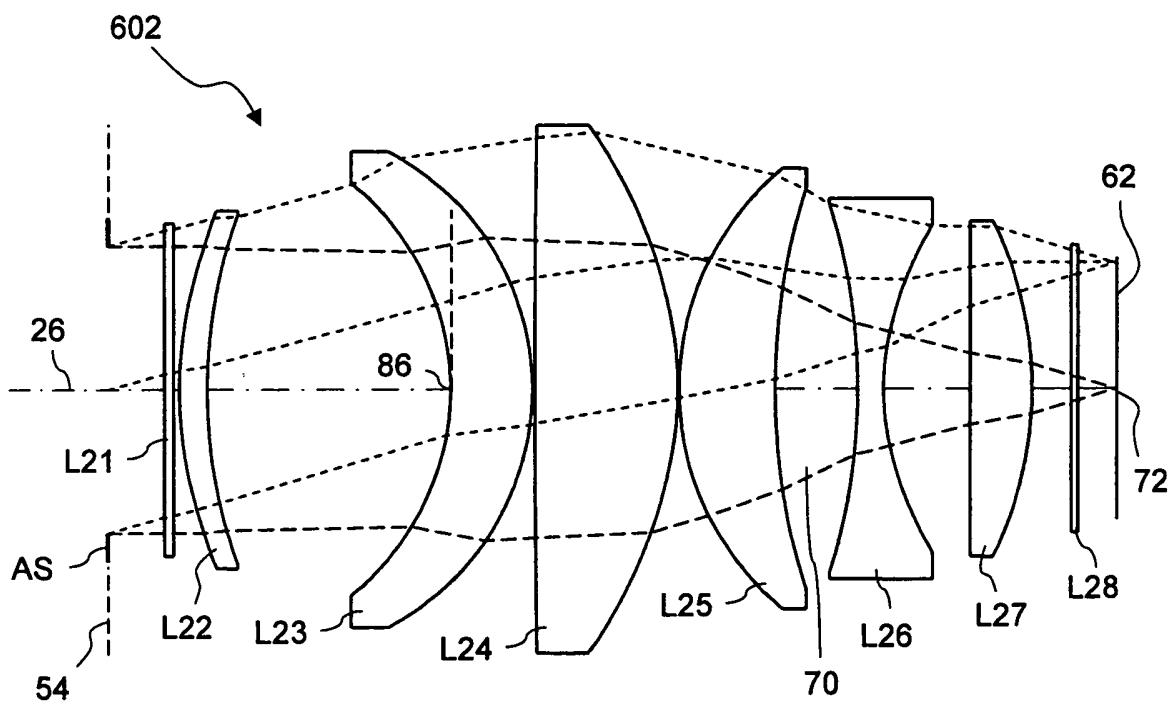


Fig. 4

4/8

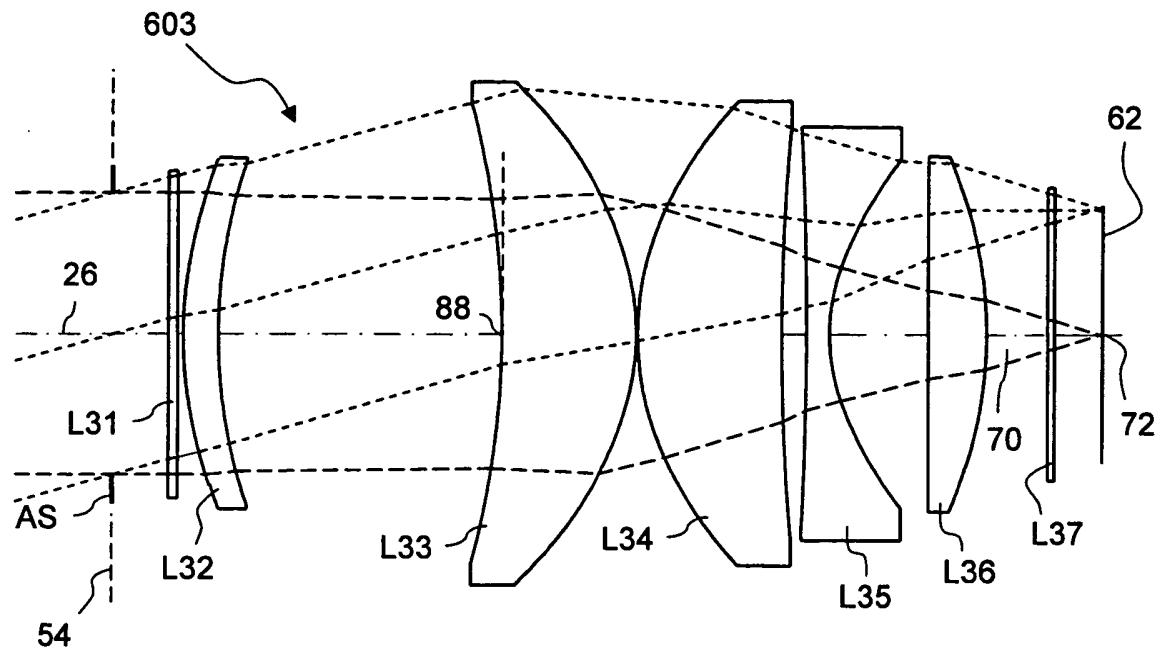


Fig. 5

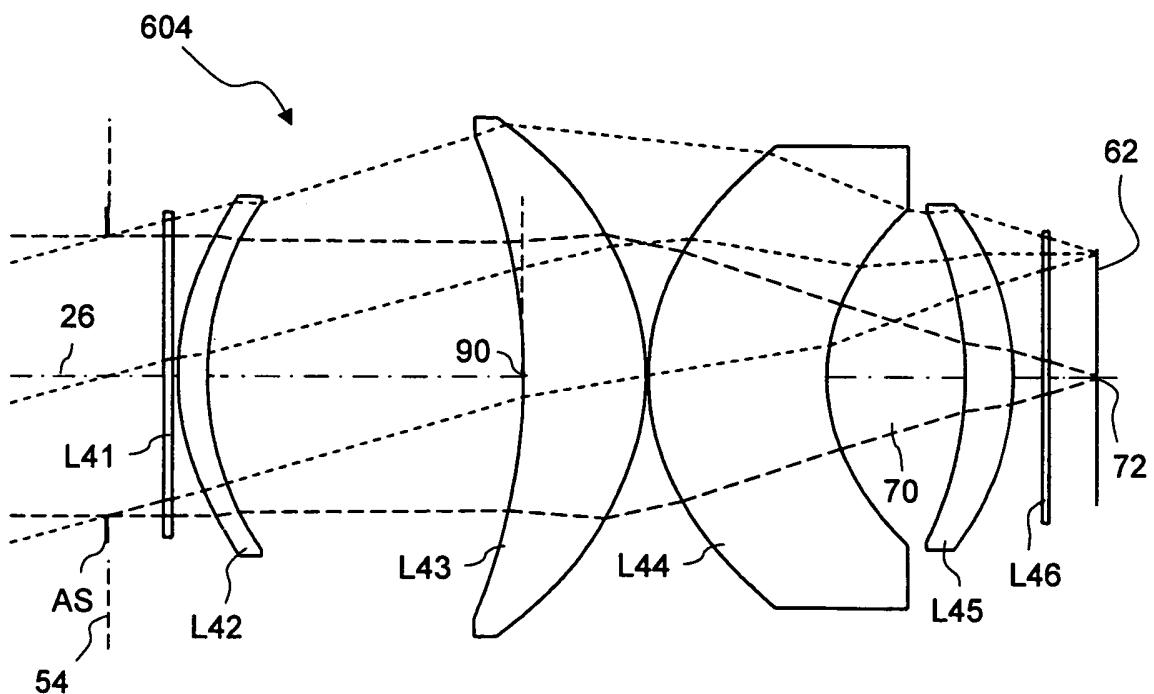


Fig. 6

5 / 8

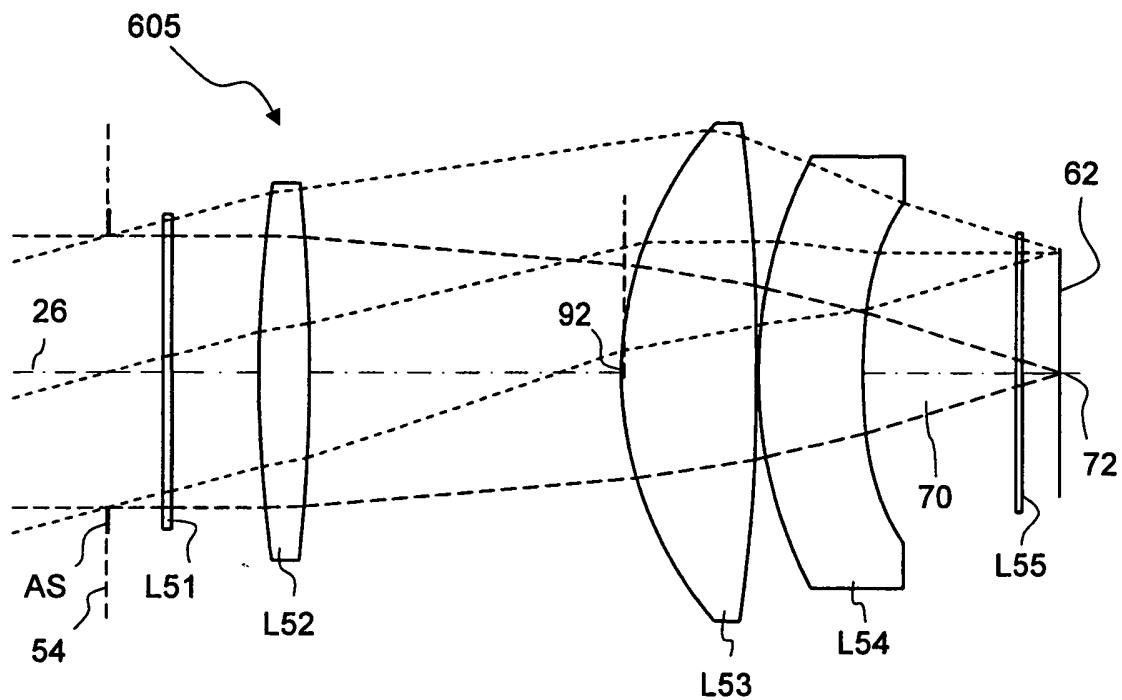


Fig. 7

6 / 8

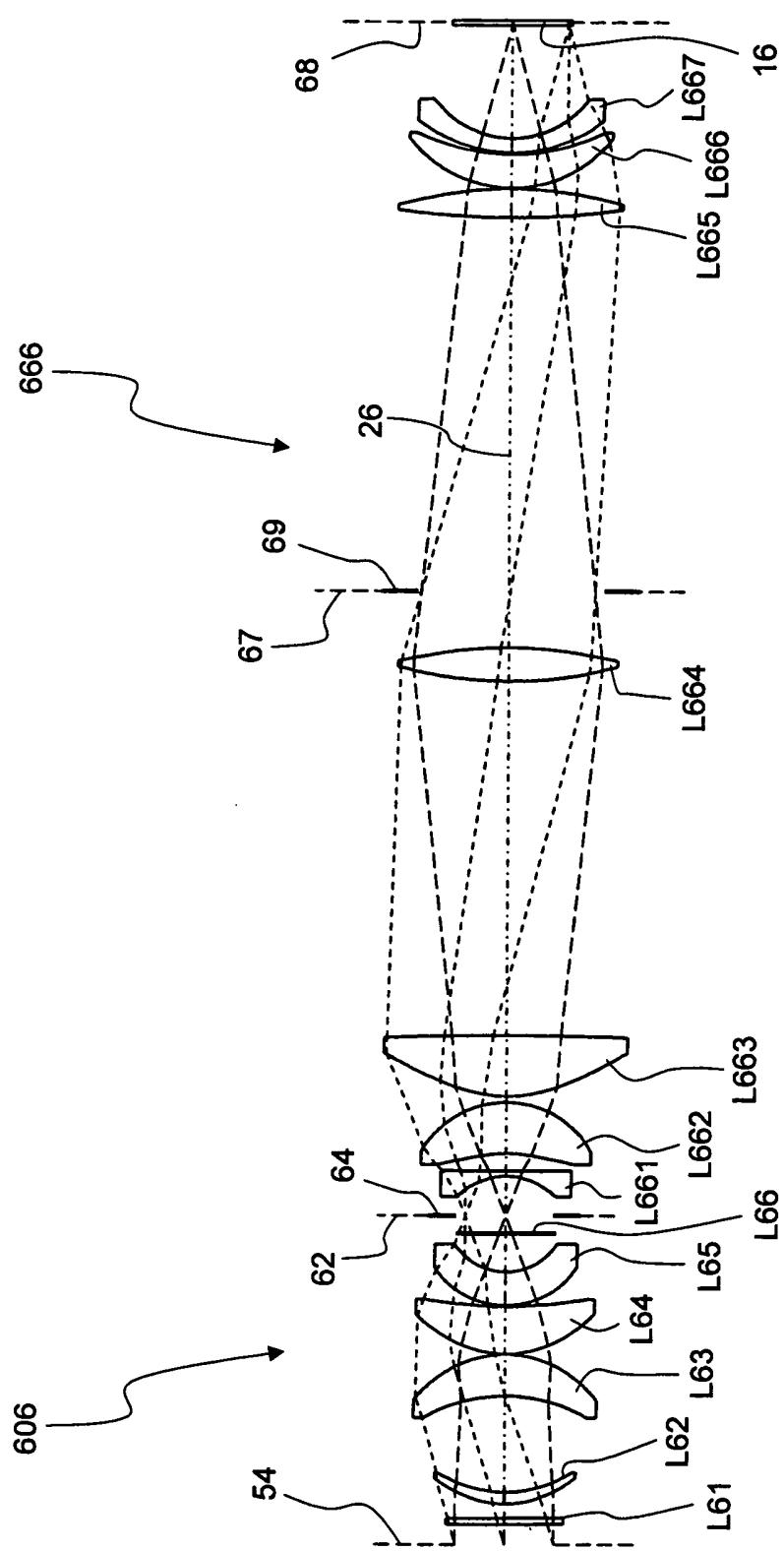


Fig. 8

7 / 8

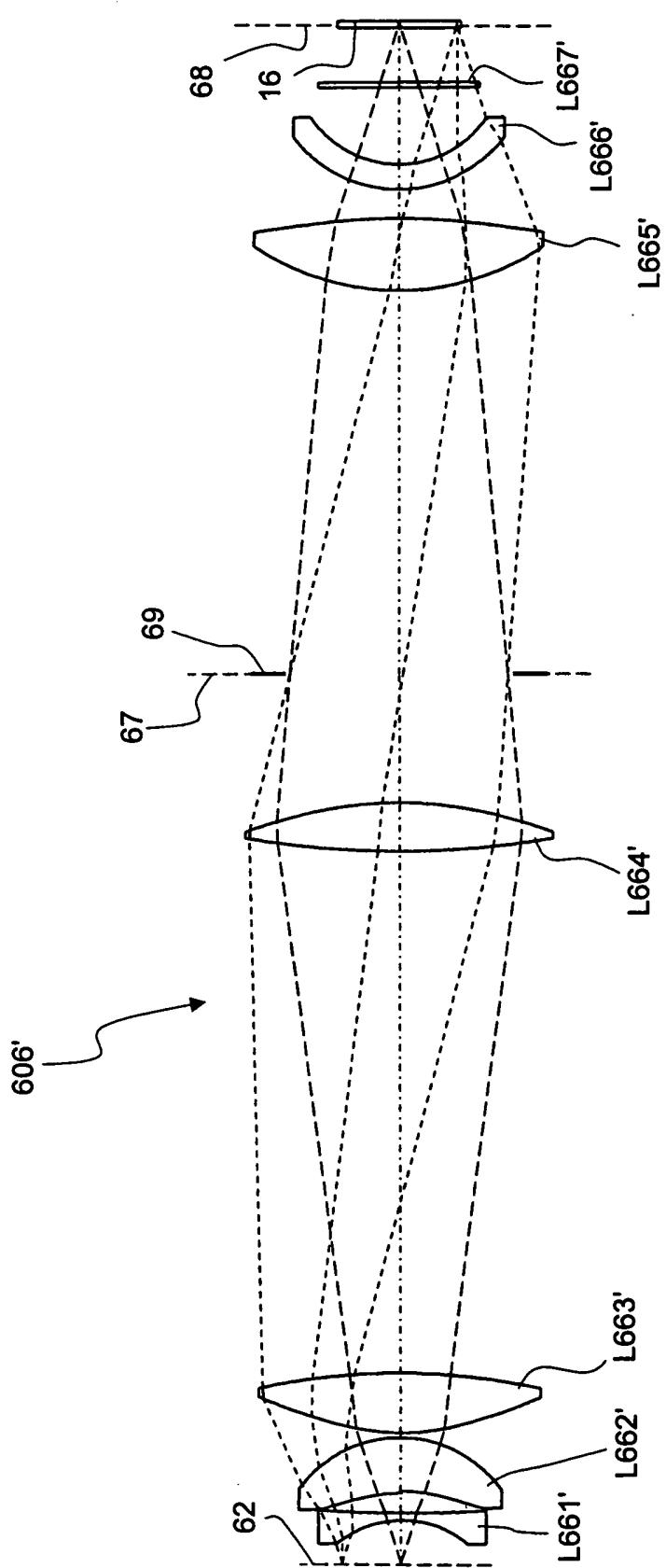


Fig. 9

8 / 8

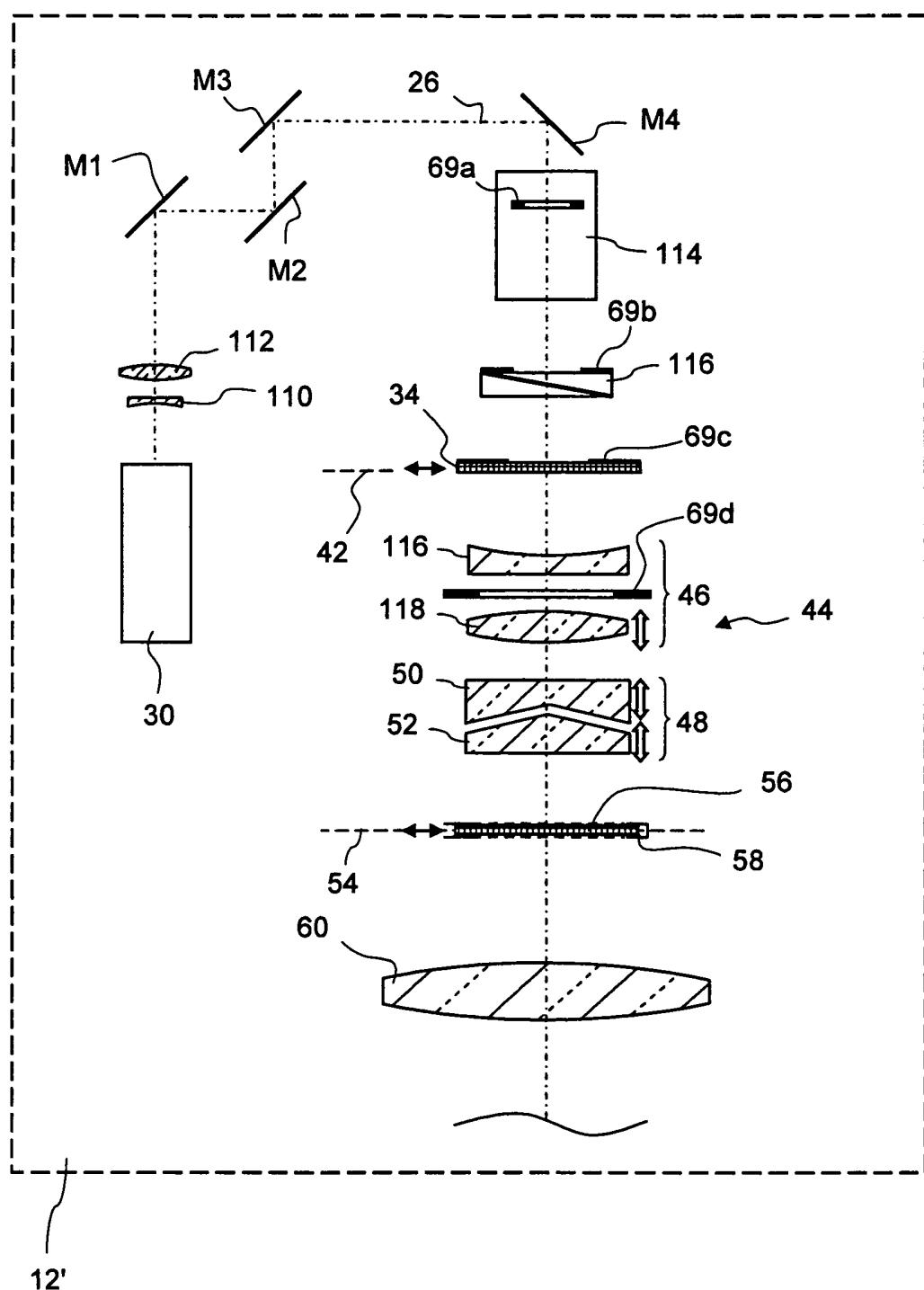


Fig. 10