(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 2 212 729 B9

(12) **CORRECTED EUROPEAN PATENT SPECIFICATION**

(15) Correction information:
Corrected version no 1 (W1 B1)
Corrections, see
Description Paragraph(s) 2, 37, 45, 46, 65, 82
Claims EN 4, 7, 15

(48) Corrigendum issued on:
21.12.2016 Bulletin 2016/51

(45) Date of publication and mention
of the grant of the patent:
18.05.2016 Bulletin 2016/20

(21) Application number: **08851993.9**

(22) Date of filing: **18.11.2008**

(51) Int Cl.:
G02B 5/30 $^{(2006.01)}$ ***G02B 1/08*** $^{(2006.01)}$
G03F 7/20 $^{(2006.01)}$

(86) International application number:
PCT/EP2008/065733

(87) International publication number:
WO 2009/065819 (28.05.2009 Gazette 2009/22)

(54) **Polarizer enabling the compensation of time-dependent distribution changes in the illumination**

Polarisator zur Kompensation von zeitabhänigen Polarisationsverteilung in der Beleuchtungseinheit

Polariseur permettant la compensation de fluctuations temporelles dans l’illumination

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MT NL NO PL PT RO SE SI SK TR

(30) Priority: **20.11.2007 DE 102007055567**
20.11.2007 US 989249 P

(43) Date of publication of application:
04.08.2010 Bulletin 2010/31

(73) Proprietor: **Carl Zeiss SMT GmbH**
73447 Oberkochen (DE)

(72) Inventors:
- **MÜLLER, Ralf**
  73430 Aalen (DE)
- **GRUNER, Toralf**
  73433 Aalen-Hofen (DE)

(74) Representative: **Frank, Hartmut et al**
Bonsmann Bonsmann Frank
Patentanwälte
Reichspräsidentenstraße 21-25
45470 Mülheim a. d. Ruhr (DE)

(56) References cited:
WO-A-03/023481 US-A- 4 643 534
US-A1- 2004 150 806

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

Printed by Jouve, 75001 PARIS (FR)

Description

BACKGROUND OF THE INVENTION

Field of the invention

[0001] The invention concerns an optical system, in particular an optical system of a microlithographic projection exposure apparatus.

State of the art

[0002] Microlithography is used for the production of microstructured components such as for example integrated circuits or LCDs. The microlithography process is carried out in what is referred to as a projection exposure apparatus having an illumination system and a projection objective. The image of a mask illuminated by means of the illumination system (= reticle) is in that case projected by means of the projection objective onto a substrate (for example a silicon wafer) which is coated with a light-sensitive layer (photoresist) and arranged in the image plane of the projection objective to transfer the mask structure onto the light-sensitive coating on the substrate.

[0003] Various approaches are known for specifically targetedly implementing adjustments or corrections in respect of polarization distribution in the illumination system or in the projection objective for optimizing the imaging contrast.

[0004] WO 2005/069081 A2 discloses inter alia a polarization-influencing optical element comprising an optically active crystal and a thickness profile which varies in the direction of the optical axis of the crystal.

[0005] It is known inter alia from US 2007/0146676 A1 to arrange in the illumination system a polarization manipulator for conversion of the polarization state, comprising a multiplicity of variable optical rotator elements by which the polarization direction of impinging linearly polarized light can be rotated with variably adjustable rotational angles.

[0006] WO 2005/031467 A2 discloses inter alia in a projection exposure apparatus, influencing the polarization distribution by means of one or more polarization manipulator devices which can also be arranged at a plurality of positions and which can be in the form of polarization-influencing optical elements which can be introduced into the beam path, wherein the effect of those polarization-influencing elements can be varied by altering the position, for example rotation, decentering or tilting of the elements.

[0007] US 6 252 712 B1 discloses inter alia a polarization compensator comprising two birefringent elements which are each provided with a free-form surface and which involve mutually rotated optical crystal axes.

[0008] It is known inter alia from US 6 104 472 to use optical elements of quartz glass or calcium fluoride for controlling axial astigmatism, which elements have mutually complementary aspheric surfaces and are arranged displaceably relative to each other in respect of their relative position. Publication US 4 643 534 A discloses a birefringent lens of particular interest. In practice however the problem which further arises is that changes in the polarization distribution can occur in dependence on time and possibly varying at high frequency, as is the case for example in regard to stress birefringence effects, which vary over the service life, in optical elements, or in the case of changes in the desired polarization distribution in the optical system as a consequence of a change in the illumination setting (for example from what is referred to as x-dipole-illumination setting to what is referred to as y-dipole-illumination setting). A further example is polarization-induced birefringence ("PBR") which increases in its amplitude in the course of time with illumination with the same illumination setting.

SUMMARY OF THE INVENTION

[0009] It is an object of the present invention to provide an optical system which permits effective compensation of disturbances which are variable in time in polarization distribution.

[0010] That object is attained by the features of independent claim 1.

[0011] An optical system which has an optical axis comprises

- at least one polarization manipulator having a first subelement which has a non-planar, optically effective surface and for light passing therethrough causes a change in the polarization state, wherein a maximum effective retardation introduced by the first subelement along the optical axis is less than a quarter of the working wavelength of the optical system, and a second subelement, wherein said first subelement and said second subelement have mutually facing surfaces which are mutually complementary; and

- a position manipulator for manipulation of the relative position of said first subelement and said second subelement.

[0012] The term retardation is used to denote the difference in the optical paths of two orthogonal (mutually perpendicular) polarization states. In addition the reference to an effective retardation which is introduced along the optical axis is used to denote the "modulo λ" retardation (that is to say instead of a retardation of for example a fifth of the working wavelength λ of the optical system, it is also possible to set a retardation $\lambda + 0.2^*\lambda$, $2\lambda + 0.2^*\lambda$ etc., which differs only by an integral multiple of the working wavelength λ). In addition, as is also stated in greater detail hereinafter, manipulation of the position of that subelement in relation to the optical axis can involve both any rotation and also displacement of the subelement as well as a combination of such movements.

[0013] By the manipulation in accordance with the invention of the position of the subelement, the amplitude of the retardation set by the subelement can be specifically targetedly manipulated and it is thus possible in particular to compensate for a disturbance, which varies in respect of time, in the polarization distribution. In that respect the position of the subelement is defined by the positional coordinates (x, y and z) as well as the rotary angles with respect to a coordinate system which contains the optical axis as the z-axis.

[0014] According to a further aspect, the invention also concerns an optical system which has an optical axis and comprises at least one polarization manipulator having at least one subelement which has a non-planar, optically effective surface and for light passing therethrough causes a change in the polarization state, wherein a maximum effective retardation introduced by the subelement along the optical axis is less than a quarter of the working wavelength of the optical system, and a position manipulator for manipulation of the position of that subelement.

[0015] In accordance with an embodiment the non-planar surface is an aspheric surface.

[0016] According to an embodiment the polarization manipulator in addition to the first subelement has at least one second subelement, wherein the position manipulator is adapted to change the relative position of the first and second subelements.

[0017] The invention makes use of the realization that, in the polarization manipulator according to the invention, upon a change in the relative position of the two mutually facing surfaces which in particular can both be aspheric and mutually complementary or mutually inverse, the polarization action on the light passing through the two subelements can be described as a good approximation by way of the derivative of a function describing the aspheric surface, in accordance with that relative movement, wherein the degree of the polarization manipulation implemented, within a certain linearity range, scales substantially linearly with the amplitude of the relative movement. Accordingly, the amplitude of a retardation set by the polarization manipulator can be manipulated and thus a disturbance, which varies in respect of time, in the polarization distribution can be specifically compensated, by relative displacement of the two subelements.

[0018] In accordance with an embodiment the mutually facing surfaces are both of an aspheric configuration. Furthermore preferably the mutually facing aspheric surfaces are mutually complementary. In particular the two subelements, when the other surfaces are in the form of plane surfaces, can supplement each other thereby to form an overall plane-parallel geometry.

[0019] In accordance with an embodiment of the invention at least one of said subelements causes a change in the polarization state by linear birefringence, circular birefringence and/or by transmission splitting between orthogonal polarization states (that is to say, by a change in the amplitude relationship of orthogonal polarization states in dependence on the orientations thereof).

[0020] In accordance with an embodiment the polarization manipulator is arranged in a plane in which the paraxial subaperture ratio is at least 0.8. In accordance with a further embodiment the polarization manipulator is arranged in a plane in which the paraxial subaperture ratio is at a maximum 0.2. In that respect the paraxial subaperture ratio S is defined as:

$$S = \frac{r}{|h| + |r|} \operatorname{sgn} h \qquad (1)$$

wherein r denotes the paraxial marginal ray height and h denotes the paraxial principal ray height. In the equation sgn(x) denotes what is referred to as the signum function, wherein by definition sgn(0) = 1 can be set.

[0021] The term principal ray is used to denote a ray which comes from an object point which in the object plane is at the greatest distance relative to the optical axis and which in the pupil plane intersects the optical axis. The term marginal ray is used to denote a ray from the point of intersection of the object field plane with the optical axis and which with maximum aperture opening passes through the edge of the aperture stop. In the case of extra-axial object fields this involves a notional ray which does not contribute to imaging of the object in the image space.

[0022] The paraxial subaperture ratio S represents a parameter that includes a sign, being a measurement in respect of the field or pupil proximity of a plane in the optical system. In that respect, in accordance with its definition, the subaperture ratio is standardized to values between -1 and +1, wherein a zero point of the paraxial subaperture ratio corresponds to each field plane and wherein a discontinuity point with a leap in the paraxial subaperture ratio from -1 to +1 or from +1 to -1 corresponds to each pupil plane. Accordingly planes with a paraxial subaperture ratio of at least 0.8 represent planes near the pupil whereas planes with a paraxial subaperture ratio of a maximum 0.2 represent planes near the field. In that case the sign of the paraxial subaperture ratio specifies the arrangement of the plane in front of or behind a reference plane. It is possible for example to involve the sign of the point of intersection of a coma ray in the plane in question, for definition purpose.

[0023] In accordance with an embodiment the optical system has at least two of the above-described polarization manipulators. That design configuration has the advantage that it is possible to limit the displacement travel of the respective individual polarization manipulators. In accordance with an embodiment the polarization manipulators are arranged in such a way that the paraxial subaperture ratios at the locations of those polarization manipulators differ from each other by at least 0.1 and preferably at least 0.15. Such a design configuration has the advantage that it is possible to influence both field-constant pupil effects and also field variations or to achieve compensation in that respect, by one of the polarization manipulators being arranged comparatively closer to the field than the other of the polarization manipulators.

[0024] In accordance with an embodiment the optical system further has a wave front compensator, that is to say an element for altering the wave front. That takes account of the fact that, besides the desired influence on the polarization state of the light passing therethrough, the polarization manipulator according to the invention additionally has a scalar action or a wave front contribution which is generally undesired and which can be compensated by the additional wave front compensator. The wave front compensator can be a conventional, so-called Alvarez manipulator, a deformable mirror, a deformable refractive element or an optical element which can be locally heated and/or cooled for example by means of a flow of liquid or gas, by means of irradiation of light of typically differing wavelength (for example infrared radiation) or by way of heating wires.

[0025] Preferably that additional wave front compensator is arranged at a position with a paraxial subaperture ratio which involves a sign and which is similar relative to the polarization manipulator (for example with a paraxial subaperture ratio differing by a maximum of 20%), whereby good wave front correction can be achieved. The inclusion of a wave front compensator is not limited to a wave front compensator which is variable in respect of time in its setting but it is also possible for a suitable interchangeable element to be appropriately aspherized as the wave front compensator and to be respectively interchanged upon adjustment of the polarization manipulator.

[0026] In accordance with an embodiment at least one of the mutually facing surfaces has a coating. Preferably at least one of those surfaces has a reflectivity of less than 2%, preferably less than 1%. In that way it is possible to reduce or minimize unwanted interference effects.

[0027] In accordance with an embodiment disposed between the first subelement and the second subelement is a gap which for example can be filled with air or another (for example inert) gas or also with a liquid medium. Preferably the gap is filled with a liquid medium which is adapted in respect of its refractive index, that is to say the liquid medium in the gap has a refractive index which, at a working wavelength of the optical system, differs by less than 0.2 and preferably less than 0.15 from a mean refractive index of the first and second subelements. Such a refractive index-adapted medium makes it possible to reduce or minimize any unwanted wave front action on the part of the polarization manipulator so that additional wave front compensators can be of a simple design in their structure or can even be entirely omitted.

[0028] In accordance with a configuration the optical system has an optical axis, wherein the position manipulator is adapted to effect one of the following changes in the relative position of the subelements or a combination of such changes:

- displacement of at least one of the subelements in a direction perpendicular to the optical axis;
- displacement of at least one of the subelements in a direction parallel to the optical axis;
- rotation of at least one of the subelements about an axis of rotation parallel to the optical axis; or
- rotation of at least one of the subelements about an axis of rotation which is not parallel to the optical axis.

[0029] The term optical axis of an optical system is used to denote that axis (or a succession of straight axis portions) which passes through the center points of the rotationally symmetrical optical components of the system. In that respect an axis of rotation which is parallel to the optical axis can coincide with or also be different from the optical axis of the system. Furthermore an axis of rotation which is not parallel to the optical axis of the system (that is to say an axis of rotation tilted relative to that optical axis) can extend through a center of one of the subelements or both subelements, or can also not extend through such a center. If the optical system is what is referred to as an extra-axial system the axis of rotation can in particular also pass through the center of the optically used region of the extra-axial system.

[0030] In accordance with an embodiment there can be provided a device for heating and/or cooling at least one of the subelements. That affords an additional degree of freedom for setting the mean refractive index of the subelements, and in particular it is possible to set a desired effect on the wave front and it is also possible to minimize a wave front action on the part of the polarization manipulator due to a change in temperature.

[0031] In accordance with an embodiment the spacing between the first subelement and the second subelement along the optical axis of the system is at a maximum 0.5 mm, preferably at a maximum 0.4 mm, further preferably at a maximum 0.3 mm.

[0032] In accordance with an embodiment provided between the first subelement and the second subelement is a gap which is at least partially filled with a fluid. In that case the fluid can be both a liquid fluid and also a (possibly high-refraction) gaseous fluid. In accordance with a preferred embodiment the fluid is a liquid medium.

[0033] In accordance with an embodiment the first subelement and the second subelement can be made from the same material.

[0034] In accordance with a further embodiment of the invention the first subelement and the second subelement can also be made from different materials. For example the first subelement can be made from magnesium fluoride (MgF_2) and the second subelement can be made from sapphire (Al_2O_3). In this example therefore the first and second subelements have different signs in their birefringence.

[0035] In particular the first subelement and the second subelement can be respectively made from a crystal material, in which case the orientation of a crystal axis of the first subelement can differ from the orientation of a crystal axis of the second subelement by an angle of more than 5°, preferably by an angle of more than 10°. Insofar as in that case different retardation distribution are mutually superposed, as a result it is possible to set a desired integral birefringence distribution, by suitable superpositioning.

[0036] In accordance with an embodiment the polarization manipulator in a predetermined starting position of the at least one subelement leaves unchanged the polarization state of light passing therethrough (in particular light incident in parallel relationship with the optical axis on the polarization manipulator).

[0037] The polarization manipulator can have both at least one subelement of positively birefringent crystal material and also at least one subelement of negatively birefringent crystal material. In that respect in the present case the term positively birefringent crystal material denotes a crystal material in which the extraordinary refractive index n_e is greater than the ordinary refractive index n_o, that is to say the value n_e-n_o is greater than zero (for example magnesium fluoride (MgF_2)). The term negatively birefringent crystal material denotes crystal material in which the extraordinary refractive index n_e is smaller than the ordinary refractive index n_o, that is to say the value n_e-n_o is smaller than zero (for example sapphire (Al_2O_3)).

[0038] In that case, a suitable choice of the total thicknesses of positively birefringent material on the one hand and negatively birefringent material on the other hand in the polarization manipulator in dependence on the respective refractive indices of the subelements, for example in a starting position of the polarization manipulator, makes it possible to achieve a behavior which overall is substantially polarization-neutral, wherein the variation according to the invention in the relative position of the two subelements leads to polarization influencing which can be adjusted in the desired manner.

[0039] In accordance with further embodiments which can be implemented in combination with the above-specified design configurations or alternatively thereto, the two subelements can be mechanically stressed to different or identical degrees, they can be doped in identical or different ways and/or they can be coated in identical or different ways. In particular such a coating can be an anti-reflection coating whereby it is possible to reduce or minimize unwanted interference effects.

[0040] In accordance with an embodiment the polarization manipulator can be arranged interchangeably, whereby optimum adaptation to the respective factors involved can be achieved under different conditions of use.

[0041] In accordance with an embodiment the polarization manipulator, in a predetermined starting position of said subelements, leaves the polarization state of light passing therethrough unchanged.

[0042] In accordance with an embodiment the polarization manipulator is configured such that a wave front for p-polarized light passing therethrough and a wave front for s-polarized light passing therethrough are manipulated by said polarization manipulator different from each other, wherein the manipulation of the mean value of the wave fronts for p-polarized light and for s-polarized light is different from zero.

[0043] The invention further concerns a polarization manipulator comprising a first subelement and at least one second subelement which respectively cause a change in the polarization state for light passing therethrough and have mutually complementary aspheric surfaces, wherein by manipulation of the relative position of the first and second subelements relative to each other it is possible to set a change in the polarization state, that varies with said manipulation, and wherein the polarization manipulator in a predetermined starting position of the first and second subelements leaves the polarization state of light passing therethrough unchanged (in particular of light incident parallel to an element axis of the polarization manipulator or relative to the optical system axis thereon).

[0044] In principle the system according to the invention can be any optical system, for example a mask testing device, an illumination system, or a respective subsystem thereof. In accordance with a preferred use the optical system is such an optical system of a microlithographic projection exposure apparatus, in particular a projection objective or an illumination system of the microlithographic projection exposure apparatus or a subsystem thereof.

[0045] In accordance with a further aspect the invention also concerns a polarization manipulator, wherein said polarization manipulator is configured such that a wave front for p-polarized light passing therethrough and a wave front for s-polarized light passing therethrough are manipulated by said polarization manipulator different from each other, wherein the manipulation of the mean value of the wave fronts for p-polarized light and for s-polarized light is different from zero.

[0046] According to this approach, the wave front for p-polarized light may in particular be manipulated in the optical system comprising the polarization manipulator independently and/or different (i.e. to another extent) compared to the wave front for s-polarized light. While the mean value of the two wave fronts for p- and s-polarized light represents what is usually referred to as the "wave front", the difference value of these two wave fronts represents what is usually referred to as birefringence or retardation of the system. Accordingly, the different manipulation of the wave front for p-polarized light, on the one hand, and of the wave front for s-polarized light, on the other hand, implies a change also in the mean value of the wave fronts for p- and s-polarized light. Furthermore, a change in the relative positions of the first and second subelement not only affects the birefringence, i.e. the difference between the wave fronts for p- and s-polarized light, but also affects the mean value of the wave fronts for p- and s-polarized light.

[0047] By deliberately exploiting a change also of the mean value of the wave fronts for p- and s-polarized light (i.e. not only a change of birefringence), the invention in the foregoing approach deviates from conventional approaches for polarization manipulators where only the birefringence is manipulated and where a modification of the mean value of the wave fronts for p- and s-polarized light is not desired and therefore avoided (since said mean value is usually manipulated by further, additional wave front manipulators).

[0048] According the above described approach, the invention in particular enables to account for effects such as degradation of material(s) in the optical components. Such degradations usually have effects to both the birefringence and the mean value of the wave fronts for p- and s-polarized light. The manipulator according to the invention may now be configured to account for, or correct, respectively, both of these properties/quantities. More specifically, a change in the relative positions of the first and second subelement may be realized such that undesired changes in both the mean value and the difference value of the wave fronts for p- and s-polarized light due to degradation of material(s) in the optical components are at least partially compensated. Such an approach is particularly advantageous in situations where the aforesaid degradation of material(s) in the optical components occur in a specific and application-dependent manner as a result of using specific illumination settings, specific mechanical stresses and accompanying compaction effects, or other specific operating conditions. Since these effects result in undesired changes of both the mean value and the difference value of the wave fronts for p- and s-polarized light, the inventive approach makes it possible to account for both of these values in a flexible manner adapted to the specific operating conditions.

[0049] Furthermore, the foregoing inventive approach makes it possible to e.g. dynamically enhance the correction amount concerning the mean value and the difference value of the wave fronts for p- and s-polarized light to account for an increasing degradation of material(s) in the optical components which may e.g. result from a continuing load in irradiation. If W_p denotes the wave front (or "phase surface") for p-polarized light and W_s denotes the wave front (or "phase surface") for s-polarized light, a relative displacement of the first and second subelement by e.g. 1 mm may be given as α*W_p + β*W_s, wherein the ratio of α and β is a specific ratio for the given manipulator. Further, a relative displacement of the first and second subelement by e.g. 2 mm may be given as 2α*W_p + 2β*W_s, etc.. Thereby, a dynamically increasing manipulation of W_p and W_s may be realized to e.g. account for an increasing degradation of material(s) in the optical components.

[0050] In accordance with a further aspect the invention concerns a microlithographic projection exposure apparatus having an illumination system and a projection objective, wherein the illumination system or the projection objective has an optical system having the above-described features.

[0051] In accordance with an embodiment the projection objective has a numerical aperture of more than 0.85, preferably more than 1.1. With numerical apertures of that kind an essential part in the microlithographic imaging process is attributed to the polarization effects which are correctable in accordance with the invention. The projection exposure apparatus can be designed in particular for immersion mode of operation. The term immersion mode is used to mean that an immersion liquid is disposed between the last surface of the projection objective and the layer to be exposed.

[0052] In accordance with an embodiment the exposure apparatus comprises a first disturbance of the mean value of the wave fronts for p- and s-polarized light and a second disturbance of the difference value of the wave fronts for p- and s-polarized light, wherein said first disturbance and said second disturbance are each at least partially compensated by said polarization manipulator.

[0053] The invention further concerns a process for the microlithographic production of microstructured components.

[0054] Further configurations of the invention are to be found in the description and the appendant claims.

[0055] The invention is described in greater detail hereinafter by means of embodiments by way of example illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0056] In the drawings:

Figure 1	shows a diagrammatic view of a polarization manipulator according to the invention in a first embodiment,
Figure 2	shows a diagrammatic view of a polarization manipulator according to the invention in a further embodiment,
Figures 3a-b	show a distribution by way of example of a retardation to be compensated (in nm) by virtue of polarization-induced birefringence and the associated orientation of the fast axis of said birefringence (Figure 3b),
Figure 4	shows a configuration, suitable for compensation of the retardation distribution in Figure 3a, in respect of the amplitude of the separation asphere in the polarization manipulator of Figure 2,
Figures 5a-b	show the distribution of the respective orientations of the fast axis of the birefringence for a predetermined disturbance to be compensated (Figure 5a) and for the polarization manipulator according to the invention as shown in Figure 2 (Figure 5b),
Figure 6	shows a structure in principle by way of example of a microlithographic projection exposure apparatus,
Figures 7-12	show by way of example embodiments of projection objectives in meridional section, and
Figures 13a-e	show diagrammatic views of embodiments by way of example of one or more subelements which can be used in an optical system according to the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0057] Reference is made to Figure 1 to firstly describe the structure in principle of a polarization manipulator 100 according to the invention. It has a first subelement 110 and a second subelement 120 which in the illustrated embodiment are each made from magnesium fluoride (MgF_2) and have mutually facing aspheric surfaces 110a and 120a respectively, those aspheric surfaces 110a and 120a being mutually complementary. As in this embodiment the other surfaces of the subelements 110 and 120 are each planar surfaces the two subelements 110 and 120 thus supplement each other to afford an overall plane-parallel geometry.

[0058] The relative position of the two subelements 110 and 120 of the polarization manipulator 100 is variable, wherein that variation, as shown in Figure 1, can be implemented in the x-direction in the illustrated coordinate system by way of an only diagrammatically illustrated position manipulator 150. In that respect it is assumed in Figure 1 that the optical axis of the optical system arid the light propagation direction extend in the z-direction so that the relative displacement of the optical elements 110 and 120 here occurs perpendicularly to that optical axis. The invention however is not limited thereto, in which respect the change in the relative position of the subelements 110 and 120 can alternatively or additionally also include displacement of at least one of the subelements 110, 120 in a direction along the optical axis (z-direction), rotation of at least one of the subelements 110, 120 abut an axis of rotation parallel to the optical axis or rotation of at least one of the subelements 110, 120 about an axis of rotation which is not parallel to the optical axis.

[0059] The orientation of the optical crystal axis in the crystal material of the subelements 110 and 120 in the illustrated embodiment extends in each case in the plane perpendicular to the optical axis of the optical system, for example in the y-direction, so that the retardation caused by the respective subelement is proportional to the thickness of that subelement. In that respect the orientation of the optical crystal axis of the first subelement 110 preferably differs from the orientation of the optical crystal axis of the second subelement 120 by an angle of more than 5°, preferably by an angle of more than 10°.

[0060] The invention is not limited to the configuration of the subelements of a crystal material with linear birefringence as shown in Figure 1. Rather one or both subelements in alternative embodiments can also be made from an optically active material involving circular birefringence (for example crystalline quartz with orientation of the optical crystal axis parallel to the light propagation direction) and/or a material which causes a change in the polarization state by transmission splitting between orthogonal polarization states, that is to say by a change in the amplitude relationship of orthogonal polarization states in dependence on the orientations thereof. Materials suitable for that purpose are those which, at the working wavelength of for example 193 nm, have natural dichroism (similar to turmalin), for example crystalline quartz, calcite ($CaCO_3$) or $Ba_3(B_3O_6)_2$(BBO).

[0061] Furthermore the possibly linear birefringence in one or both subelements 110, 120 can also be implemented using cubically crystalline material which can be put under compression or tensile stress (for example (CaF_2, BaF_2, $LiBaF_3$, $Lu_3Al_5O_{12}$, $Y_3Al_5O_{12}$ or $MgAl_2O_4$), by using amorphous material which can be put under compression or tensile stress (for example quartz glass (SiO_2)) or by using another optically uniaxial crystalline material than MgF_2 (for example LaF_3, Al_2O_3 or SiO_2 with a crystal axis which is not parallel to the light propagation direction).

[0062] Figures 13a - e diagrammatically show embodiments by way of example of a subelement which can be used in an optical system according to the invention, wherein the illustrated double-headed arrows respectively indicate the manipulation of the position of the subelement in relation to the optical axis OA of the optical system, which manipulation can be achieved by means of the position manipulator (not shown in Figures 13a through 13e).

[0063] In that respect the subelement can be for example a subelement 51 having an aspheric optical active surface (Figure 13a). Furthermore the subelement can also be a subelement having a non-planar but spherical optical active surface (Figure 13b). Figures 13c and 13d show arrangements 53 and 54 comprising two subelements 53a, 53b and 54a, 54b respectively having respectively mutually facing optical active surfaces which are complementary to each other and of a spherical configuration, wherein the change in the relative position of those subelements can be implemented both by displacement (Figure 13c, in which the displacement is effected only by way of example in a plane perpendicular to the optical axis OA) and also by rotation (Figure 13d in which the rotation is effected only by way of example about the optical axis OA). In that respect a respective maximum effective retardation introduced by the subelement along the optical axis is less than a quarter of the working wavelength of the optical system.

[0064] Figure 13e, in accordance with another also possible approach, shows an arrangement 55 comprising two subelements 55a and 55b in respect of which the birefringence distribution respectively varies within the subelements in a direction perpendicular to the optical axis OA, wherein that variation is here produced not by means of a thickness variation of the subelements but by means of a positional variation of the birefringence (for example a varying stress birefringence).

[0065] Figure 2 shows a further embodiment of a polarization manipulator 200 according to the invention. Firstly, in a structure similar to Figure 1, this polarization manipulator 200 includes two subelements 210 and 220 which are each made from magnesium fluoride (MgF_2) and have mutually facing aspheric and mutually complementary surfaces 210a and 220a respectively, a position manipulator 250 for changing the relative position and in addition a plane plate 230 which is made from sapphire (Al_2O_3) and which is arranged with its light entrance and light exit surfaces parallel to the light entrance and light exit surfaces respectively of the subelements 210 and 220. As magnesium fluoride (MgF_2) is an optically positive material (n_e-n_o= 0.0135 > 0) and sapphire (Al_2O_3) is a negatively birefringent material (n_e-n_o = -0.0133 < 0), a suitable choice of the (marginal) thicknesses d_1, d_2 and d_3 can provide that, in the starting position shown in Figure 2 of the polarization manipulator, for light which is propagated in the z-direction, there is not a resulting birefringent effect on the part of the overall arrangement. By way of example it is possible for that purpose to select the thicknesses $d_1 = d_2 = 2.5$ mm and $d_3 = 5.973$ mm. Then, as described hereinafter, polarization influencing can be adjusted in the desired fashion by way of a variation in the relative position of the two subelements.

[0066] In terms of the specific configuration of the aspheric surfaces 210a and 220a, the positional dependency of which is described by a function T(x,y) referred to hereinafter as the separation asphere, the basic starting point adopted hereinafter is a predetermined disturbance to be compensated in the optical system or a suitably selected thickness profile in the magnesium fluoride material, wherein the last-mentioned thickness profile can be described by a thickness function D(x,y). The aforementioned separation sphere T(x,y) is then given by the antiderivative or the integral of the desired thickness function D(x,y), that, is to say the following applies:

$$T(x,y) = \int_0^x D(x',y)dx' \qquad (2)$$

[0067] The amplitude of the retardation afforded by the polarization manipulator 100 or 200 respectively is now proportional to the relative displacement of the subelements 110, 120 and 210, 220 respectively and proportional to the amplitude of the separation asphere T(x,y).

[0068] Figure 3a shows the example of a retardation distribution (in nm) to be compensated, which is caused by polarization-induced birefringence in the optical system, wherein respectively standardized pupil coordinates are plotted on the axes of the diagram and also in the further diagrams in Figure 3b and Figures 5a - b. Figure 3b shows the associated orientation of the fast axis of that birefringence. Figure 4 shows a variation, which is suitable in accordance with equation (2) for compensation of the disturbance of Figure 3a, in the amplitude of the separation asphere T(x,y) in the polarization manipulator of Figure 2. As can be seen from a comparison of Figure 5a and 5b the respective orientations of the fast axis of the birefringence for a predetermined disturbance to be compensated (Figure 5a) and for the polarization manipulator according to the invention (Figure 5b) are mutually perpendicular.

[0069] The concrete calculation shows that, for the relative displacements of the two subelements 210 and 220 of up to 250 μm, the maximum amplitude of the separation asphere T(x,y) is at about ± 193 μm to afford a retardation of about 10 nm.

[0070] Figure 6 is an only diagrammatic view to illustrate the structure in principle of a microlithographic projection exposure apparatus in accordance with an embodiment of the invention. In this case the concept of the invention can be applied equally both in the illumination system and also in the projection objective. Positions by way of example, which are suitable for the arrangement of polarization manipulators according to the invention (namely positions near the pupil, near the image or near the intermediate image, or intermediate positions) are only diagrammatically indicated by arrows in Figure 6.

[0071] The microlithographic projection exposure apparatus has am illumination system 301 and a projection objective 302. The illumination system 301 serves for the illumination of a structure-bearing mask (reticle) 303 with light from a light source unit 304 which for example includes an ArF laser for a working wavelength of 193 nm and a beam-shaping optical means for producing a parallel light beam. The parallel light beam from the light source unit 304 is firstly incident on a diffractive optical element 305 which produces a desired intensity distribution (for example dipole or quadrupole distribution) in a pupil plane P1 by way of an angle beam radiation characteristic defined by the respective diffractive surface structure. Disposed downstream of the diffractive optical element 305 in the light propagation direction is an optical unit 306 having a zoom objective for producing a parallel light beam of variable diameter and an axicon lens. Different illumination configurations are produced in the pupil plane P1 depending on the respective zoom setting and position of the axicon elements, by means of the zoom objective in conjunction with the upstream-disposed diffractive optical element 305. The optical unit 306 in the illustrated embodiment further includes a deflection mirror 307. Disposed downstream of the pupil plane P1 in the beam path in the light propagation direction is a light mixing device 308 which for example in per se known manner can have an arrangement of microoptical elements, that is suitable for achieving a light mixing effect. The light mixing device 308 is followed in the light propagation direction by a lens group 309, downstream of which is disposed a field plane F1 with a reticle masking system (REMA) which is projected by an REMA objective 310 that follows in the light propagation direction onto the structure-bearing mask (reticle) 303 in the field plane F2, and thereby delimits the illuminated region on the reticle. The structure-bearing mask 303 is now projected onto a substrate 311 or wafer provided with a light-sensitive layer with the projection objective 302 which in the illustrated example has two pupil planes PP1 and PP2.

[0072] In addition Figures 7 through 12 show specific designs by way of example of projection objectives in which one or more polarization manipulators can be arranged as described hereinbefore.

[0073] Figure 7 shows a projection objective 400 in meridional section, which is disclosed in WO 2003/075096 A2 (see therein Figure 8 and Table 8). The projection objective 400 is of a purely refractive structure with a waist and a first positive lens group, a second negative lens group and a third positive lens group.

[0074] Figure 8 shows a projection objective 500 in meridional section, which is disclosed in WO 2004/019128 A2 (see therein Figure 19 and Tables 9 and 10). The projection objective 500 includes a first refractive subsystem 510, a second catadioptric subsystem 530 and a third refractive subsystem 540 and is therefore also referred to as an "RCR system". In that respect the term "subsystem" is always used to denote such an arrangement of optical elements, by which a real object is imaged as a real image or intermediate image. In other words, each subsystem, starting from a given object or intermediate image plane, always includes all optical elements to the next real image or intermediate image.

[0075] The first refractive subsystem 510 includes refractive lenses 511 through 520, after which a first intermediate image IMI1 is produced in the beam path. The second subsystem 530 includes a double-fold mirror with two mirror surfaces 531 and 532 arranged at an angle relative to each other, wherein light incident from the first subsystem 510 is firstly reflected at the mirror surface 531 in the direction towards the lenses 533 and 534 and a subsequent concave mirror 535. The concave mirror 535 in per se known manner permits effective compensation of the image field curvature produced by the subsystems 510 and 540. The light reflected at the concave mirror 535 is reflected after again passing through the lenses 534 and 533 at the second mirror surface 532 of the double-fold mirror so that as a result of the optical axis OA is folded twice through 90°. The second subsystem 530 produces a second intermediate image IMI2 and the light therefrom is incident on the third refractive subsystem 540 including refractive lenses 541 through 555. The second intermediate image IMI2 is projected onto the image plane IP by the third refractive subsystem 540.

[0076] Referring to Figure 9 shown therein is a projection objective 600 in meridional section, which is disclosed in WO 2005/069055 A2 (see therein Figure 32). The design data of that projection objective 400 are set out in Table 1. In that respect column 1 gives the number of the respective refractive or otherwise distinguished optical surface, column 2 gives the radius of that surface (in mm), column 3 optionally includes a reference to an asphere at that surface, column 4 gives the spacing, identified as thickness, of that surface relative to the following surface (in mm), column 5 gives the material following the respective surface and column 6 gives the optically useable free half diameter (in mm) of the optical component.

[0077] The aspheric constants are to be found in Table 2. The surfaces identified by thick dots in Figure 9 and specified in Tables 1 and 2 are aspherically curved, the curvature of those surfaces being given by the following asphere formula:

$$P(h) = \frac{(1/r)\cdot h^2}{1+\sqrt{1-(1+cc)(1/r)^2h^2}} + C_1h^4 + C_2h^6 + \ldots \qquad (3)$$

[0078] Therein P denotes the camber height of the surface in question parallel to the optical axis, h denotes the radial spacing from the optical axis, r denotes the radius of curvature of the surface in question, cc denotes the conical constant (identified by K in Table 7) and C_1, C_2, ... denote the asphere constants set forth in Table 2.

[0079] Referring to Figure 9 the projection objective 600 in a catadioptric structure has a first optical subsystem 610, a second optical subsystem 620 and a third optical subsystem 630. The first optical subsystem 610 includes an arrangement of refractive lenses 611 through 617 and projects the object plane "OP" into a first intermediate image IMI1, the approximate position of which is indicated by an arrow in Figure 9. That first intermediate image IMI1 is projected through the second optical subsystem 620 into a second intermediate image IMI2, the approximate position of which is also indicated by an arrow in Figure 9. The second optical subsystem 620 includes a first concave mirror 621 and a second concave mirror 622 which are each "cut off" in a direction perpendicular to the optical axis, in such a way that light propagation can respectively occur from the reflecting surfaces of the concave mirrors 621, 622 to the image plane IP. The second intermediate image IMI2 is projected into the image plane IP by the third optical subsystem 630. The third optical subsystem 630 includes an arrangement of refractive lenses 631 through 643.

[0080] Referring to Figure 10 shown therein is a further catadioptric projection objective 700 in meridional section, which is disclosed in WO 2005/069055 A2 (see therein Figure 39 and Tables 39, 39A) and which has a total of four mirrors. Referring to Figure 11 shown therein is a further catadioptric projection objective 800 in meridional section, which is disclosed in WO 2005/069055 A2 (see therein Figure 21 and Tables 21, 21A) and which has two mirrors with lenses disposed therebetween. Referring to Figure 12 shown therein is a further catadioptric projection objective 900 in meridional section which is disclosed in EP 1 480 065 A2 (see therein Figure 19) and which has telecentric deflection mirrors, such telecentry being afforded by a positive group between those deflection mirrors. Further designs for catadioptric projection objectives with an intermediate image are disclosed for example in US 6 665 126 B2.

[0081] Even if the invention has been described by reference to specific embodiments numerous variations and alternative embodiments will be apparent to the man skilled in the art, for example by combination and/or exchange of features of individual components. Accordingly it will be apparent to the man skilled in the art that such variations and alternative embodiments are also embraced by the present invention and the scope of the invention is limited only in the sense of the accompanying claims and equivalents thereof.

Table 1 (DESIGN DATA FOR Fig. 9):

Surface	Radius	Sphere	Thickness	Material	Half diameter
1	0.000000		-0.011620	LV193975	75.462
2	585.070331	AS	17.118596	SIO2V	76.447
3	-766.901651		0.890161	HEV19397	78.252
4	145.560665		45.675278	SIO2V	85.645
5	2818.543789	AS	40.269525	HEV19397	83.237
6	469.396236		29.972759	SIO2V	75.894
7	-193.297708	AS	21.997025	HEV19397	73.717
8	222 509238		27 666363	SIO2V	57.818
9	-274.231957		31.483375	HEV19397	52.595
10	0.000000		10.117766	SIO2V	44.115
11	0.000000		15.361487	HEV19397	47.050
12	26971.109897	AS	14.803554	SIO2V	54.127
13	-562.070426		45.416373	HEV19397	58.058
14	-510.104298	AS	35.926312	SIO2V	76.585

(continued)

Surface	Radius	Sphere	Thickness	Material	Half diameter
15	-118.683707		36.432152	HEV19397	80.636
16	0.000000		199.241665	HEV19397	86.561
17	-181.080772	AS	-199.241665	REFL	147.684.
18	153.434246	AS	199.241665	REFL	102.596
19	0.000000		36.432584	HEV19397	105.850
20	408.244008		54.279598	SIO2V	118.053
21	-296.362521		34.669451	HEV19397	118.398
22	-1378.452784		22.782283	SIO2V	106.566
23	-533.252331	AS	0.892985	HEV19397	105.292
24	247.380841		9.992727	SIO2V	92.481
25	103.088603		45.957039	HEV19397	80.536
26	-1832.351074		9.992069	SIO2V	80.563
27	151.452362		28.883857	HEV19397	81.238
28	693.739003		11.559320	SIO2V	86.714
29	303.301679		15.104783	HEV19397	91.779
30	1016.426625		30.905849	SIO2V	95:900
31	-258.080954	AS	10.647394	HEV19397	99.790
32	-1386.614747	AS	24.903261	SIO2V	108.140
33	-305.810572		14.249112	HEV19397	112.465
34	-11755.656826	AS	32.472684	SIO2V	124.O75
35	-359.229865		16.650084	HEV19397	126.831
36	1581.896158		51.095339	SIO2V	135.151
37	-290.829022		-5.686977	HEV19397	136.116
38	0.000000		0.000000	HEV19397	131.224
39	0.000000		28.354383	HEV19397	131.224
40	524.037274	AS	45.835992	SIO2V	130.144
41	-348.286331		0.878010	HEV19397	129.553
42	184.730622		45.614622	SIO2V	108.838
43	2501.302312	AS	0.854125	HEV19397	103.388
44	89.832394		38.416586	SIO2V	73.676
45	209.429378		0.697559	HEV19397	63.921
46	83.525032		37.916651	CAF2V193	50.040
47	0.000000		0.300000	SIO2V	21.480
48	0.000000		0.000000	SIO2V	21.116
49	0.000000		3.000000	H2OV193B	21.116
50	0.000000		0.000000	AIR	16.500

Table 2 (ASPHERIC CONSTANTS FOR Fig. 9):

	2	5	7	12	14
K	0	0	0	0	0
C1	-5.72E-02	-4.71E-02	1.75E-01	-8.29E-02	-4.35E-02
C2	-2.97E-07	7.04E-06	-1.17E-05	-1.87E-07	1.59E-06
C3	1.03E-12	1.09E-10	1.34E-09	-7.04E-10	-6.81E-11
C4	2.76E-14	-2.90E-14	-5.44E-14	6.65E-14	5.03E-15
C5	-1.51E-18	-1.55E-21	-1.82E-18	-1.33E-17	-1.68E-23
C6	-1.04E-24	5.61E-23	2.56E-22	2.46E-21	-2.36E-23
C7	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
C8	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
C9	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00

	17	18	23	31	32
K	-197.849	-204.054	0	0	0
C1	-2.94E-02	5.77E-02	-7.06E-02	3.41E-02	-4.85E-02
C2	2.63E-07	-5.00E-07	4.11E-06	4.07E-08	9.88E-07
C3	-6.11E-12	2.67E-11	-1.18E-10	8.10E-11	7.37E-11
~~C4~~	~~1.11E-16~~	~~-5.69E-16~~	~~2.92E-15~~	~~-4.34E-15~~	~~-6.56E-15~~
C5	-2.01E-21	1.89E-20	-3.23E-20	7.59E-19	6.53E-19
C6	2.08E-26	-1.49E-25	2.18E-25	-3.41E-23	-2.88E-23
C7	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
C8	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00
C9	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00

	34	40	43
K	0	0	0
C1	1.59E-02	-4.10E-02	-3.89E-02
C2	-1.51E-06	3.04E-07	4.76E-06
C3	6.62E-13	5.71E-11	-2.23E-10
C4	1.72E-15	-1.72E-15	8.89E-15
C5	-9.36E-20	-9.60E-22	-2.41E-19
C6	2.36E-24	3.81E-25	3.43E-24
C7	0.000000e+00	0.000000e+00	0.000000e+00
C8	0.000000e+00	0.000000e+00	0.000000e+00
C9	0.000000e+00	0.000000e+00	0.000000e+00

[0082] The present invention further comprises the aspects defined in the following clauses, which form part of the present description but are not claims, in accordance with decision J15/88 of the European Patent Office legal board of appeal.

1. An optical system which has an optical axis (OA), comprising

- at least one polarization manipulator (100, 200) having a first subelement, (110, 210) which has a non-planar, optically effective surface and for light passing therethrough causes a change in the polarization state, wherein a maximum effective retardation introduced by the first subelement along the optical axis (OA) is less than a quarter of the working wavelength of the optical system, and a second subelement (120, 220), wherein said first subelement and said second subelement have mutually facing surfaces (110a, 120a; 210a, 220a) which are mutually complementary; and
- a position manipulator (150, 250) for manipulation of the relative position of said first subelement (110, 210) and said second subelement (120, 220).

2. An optical system as set forth in clause 1, characterized in that at least one of said mutually facing surfaces (110a, 120a; 210a, 220a) is aspheric.

3. An optical system as set forth in clause 1 or 2, characterized that at least one subelement (110, 210, 120, 220) for light passing therethrough causes a change in the polarization state by linear birefringence, circular birefringence and/or by a change in the amplitude relationship of orthogonal polarization states in dependence on the orientations thereof.

4. An optical system as set forth in one of the clauses 1 through 3, characterized in that the polarization manipulator (100, 200) is arranged in a plane in which the paraxial subaperture ratio is at least 0.8.

5. An optical system as set forth in one of the clauses 1 through 3, characterized in that the polarization manipulator (100, 200) is arranged in a plane in which the paraxial subaperture ratio is at a maximum 0.2.

6. An optical system as set forth in one of the preceding clauses, characterized in that it has at least two such polarization manipulators.

7. An optical system as set forth in clause 6, characterized in that the polarization manipulators are arranged in such a way that the paraxial subaperture ratios at the locations of those polarization manipulators differ from each other by at least 0.1 and preferably at least 0.15.

8. An optical system as set forth in one of the preceding clauses, characterized in that it further has a wave front compensator for at least partial compensation of a change, caused by the polarization compensator (100, 200), in the wave front of light passing through the optical system.

9. An optical system as set forth in one of the preceding clauses, characterized in that at least one of the mutually facing surfaces has a coating.

10. An optical system as set forth in one of the preceding clauses, characterized in that at least one of the mutually facing surfaces has a reflectivity of less than 2%, preferably less than 1%.

11. An optical system as set forth in one of the preceding clauses, characterized in that at least one subelement is produced from a material selected from the group which contains:

- a cubically crystalline material which is put under compression or tensile stress,
- an amorphous material which is put under compression or tensile stress, or
- an optically uniaxial crystalline material.

12. An optical system as set forth in clause 11, characterized in that the cubically crystalline material which is put under compression or tensile stress is selected from the group which contains: calcium fluoride (CaF_2), barium fluoride (BaF_2), lithium barium fluoride ($LiBaF_3$), garnets, in particular lutetium aluminum garnet ($Lu_3Al_5O_{12}$) and yttrium aluminum garnet ($Y_3Al_5O_{12}$) and spinel, in particular magnesium spinel ($MgAl_2O_4$).

13. An optical system as set forth in clause 11 or clause 12, characterized in that the optically uniaxial crystalline material is selected from the group which contains: magnesium fluoride (MgF_2), lanthanum fluoride (LaF_3), sapphire (Al_2O_3) and crystalline quartz (SiO_2).

14. An optical system as set forth in one of the preceding clauses, characterized in that the position manipulator (150, 250) is adapted to effect one of the following changes in the position of at least one subelement (110, 120; 210, 220) or a combination of such changes:

- displacement of at least one subelement (110, 120; 210, 220) in a direction perpendicular to the optical axis;
- displacement of at least one subelement (110, 120; 210, 220) in a direction parallel to the optical axis; and
- rotation of at least one subelement (110, 120; 210, 220).

15. An optical system as set forth in clause 14, characterized in that the rotation is about an axis of rotation which is parallel to the optical axis.

16. An optical system as set forth in clause 14, characterized in that the rotation is about an axis of rotation which is not parallel to the optical axis.

17. An optical system as set forth in one of the preceding clauses, characterized in that the maximum spacing between the first subelement (110, 210) and the second subelement (120, 220) is at a maximum 0.5 mm, preferably at a maximum 0.4 mm, further preferably at a maximum 0.3 mm.

18. An optical system as set forth in one of the preceding clauses, characterized in that provided between the first subelement (110, 210) and the second subelement (120, 220) is a gap which is at least partially filled with a fluid.

19. An optical system as set forth in clause 18, characterized in that the fluid is a liquid medium.

20. An optical system as set forth in clause 19, characterized in that said liquid medium has a refractive index which at a working wavelength of the optical system differs by less than 0.2, preferably by less than 0.15, from a mean refractive index of the first and second subelements.

21. An optical system as set forth in one of the clauses 1 through 20, characterized in that the first subelement (110, 210) and the second subelement (120, 220) are made from the same material.

22. An optical system as set forth in one of the clauses 1 through 20, characterized in that the first subelement (110, 210) and the second subelement (120, 220) are made from different materials.

23. An optical system as set forth in clause 22, characterized in that the polarization manipulator has both positively birefringent crystal material and also negatively birefringent crystal material.

24. An optical system as set forth in one of the preceding clauses, characterized in that the first subelement (110, 210) and the second subelement (120, 220) are respectively made from an optically uniaxial crystal material, in which case the orientation of a crystal axis of the first subelement (110, 210) differs from the orientation of a crystal axis of the second subelement (120, 220) by an angle of more than 5°, preferably by an angle of more than 10°.

25. An optical system as set forth in one of the preceding clauses, characterized in that there is provided an interchange device for interchange of the polarization manipulator (100, 200).

26. An optical system as set forth in one of the preceding clauses, characterized in that the polarization manipulator in a predetermined starting position of the at least one subelement leaves the polarization state of light passing therethrough unchanged.

27. An optical system as set forth in one of the preceding clauses, characterized in that it is designed for a working wavelength of less than 400 nm, preferably less than 250 nm.

28. An optical system as set forth in one of the preceding clauses, characterized in that it is an optical system of a microlithographic projection exposure apparatus

29. An optical system as set forth in one of the preceding clauses, characterized in that the polarization manipulator is configured such that a wave front for p-polarized light passing therethrough and a wave front for s-polarized light passing therethrough are manipulated by said polarization manipulator different from each other, wherein the manipulation of the mean value of the wave fronts for p-polarized light and for s-polarized light is different from zero.

30. A polarization manipulator comprising:

- a first subelement and at least one second subelement which respectively cause a change in the polarization state for light passing therethrough and have mutually complementary aspheric surfaces,
- wherein by manipulation of the relative position of the first and second subelements relative to each other it is possible to set a change in the polarization state, that varies with said manipulation, and wherein the polarization manipulator in a predetermined starting position of the first and second subelements leaves the polarization state of light passing therethrough unchanged.

31. A polarization manipulator, wherein said polarization manipulator is configured such that a wave front for p-polarized light passing therethrough and a wave front for s-polarized light passing therethrough are manipulated by said polarization manipulator different from each other, wherein the manipulation of the mean value of the wave fronts for p-polarized light and for s-polarized light is different from zero.

32. A polarization manipulator as set forth in clause 31, comprising

- a first subelement and at least one second subelement which respectively cause a change in the polarization state for light passing therethrough and have mutually complementary surfaces,
- wherein by manipulation of the relative position of the first and second subelements relative to each other it is possible to set a change in the polarization state of light passing through said polarization manipulator, that varies with said manipulation.

33. A microlithographic projection exposure apparatus comprising an illumination system (301) and a projection objective (302), wherein the illumination system (301) and/or the projection objective (302) has an optical system as set forth in one of clauses 1 through 29 or a polarization manipulator as set forth in one of the clauses 30 through 32.

34. A microlithographic projection exposure apparatus as set forth in clause 33, characterized in that the projection objective (302) has a numerical aperture of more than 0.85, preferably more than 1.1.

35. A microlithographic projection exposure apparatus as set forth in clause 33 or 34, characterized in that it is adapted for an immersion mode of operation.

36. A microlithographic projection exposure apparatus as set forth in one of the clauses 33 through 35, characterized in that it comprises a first disturbance of the mean value of the wave fronts for p- and s-polarized light and a second disturbance of the difference value of the wave fronts for p- and s-polarized light, wherein said first disturbance and said second disturbance are each at least partially compensated by said polarization manipulator.

37. A process for the microlithographic production of microstructured components comprising the following steps:

- providing a substrate (311) to which a layer of a light-sensitive material is at least partially applied;
- providing a mask (303) having structures to be reproduced;
- providing a microlithographic projection exposure apparatus as set forth in one of clauses 33 through 36; and
- projecting at least a part of the mask (303) onto a region of the layer by means of the projection exposure apparatus.

Claims

1. An optical system which has an optical axis (OA), comprising

- at least one polarization manipulator (100, 200) having a first subelement (110, 210) which has a non-planar, optically effective surface and for light passing therethrough causes a change in the polarization state, wherein a maximum effective retardation introduced by the first subelement along the optical axis (OA) is less than a quarter of the working wavelength of the optical system, and a second subelement (120, 220), wherein said first subelement and said second subelement have mutually facing surfaces (110a, 120a; 210a, 220a) which are mutually complementary, and
- a position manipulator (150, 250) for manipulation of the relative position of said first subelement (110, 210) and said second subelement (120, 220); **characterized in that** the position manipulator (150, 250) is adapted to effect one of the following changes in the position of at least one subelement (110, 120; 210, 220) or a combination of such changes:
    - displacement of at least one of said subelelments (110, 120; 210, 220) in a direction perpendicular to the optical axis; and
    - rotation of at least one of said subelements (110, 120; 210, 220).

2. An optical system as set forth in claim 1, **characterized in that** at least one of said mutually facing surfaces (110a, 120a; 210a, 220a) is aspheric.

3. An optical system as set forth in claim 1 or 2, characterized that at least one of said subelements (110, 210, 120, 220) for light passing therethrough causes a change in the polarization state by linear birefringence, circular birefringence and/or by a change in the amplitude relationship of orthogonal polarization states in dependence on the orientations thereof.

4. An optical system as set forth in one of the preceding claims, **characterized in that** it has at least two such polarization manipulators, wherein the polarization manipulators are arranged in such a way that the paraxial subaperture ratios at the locations of those polarization manipulators differ from each other by at least 0.1 and preferably at least 0.15.

5. An optical system as set forth in one of the preceding claims, **characterized in that** it further has a wave front compensator for at least partial compensation of a change, caused by the polarization manipulator (100, 200), in the wave front of light passing through the optical system.

6. An optical system as set forth in one of the preceding claims, **characterized in that** at least one of said subelements is produced from a material selected from the group which contains:

   - a cubically crystalline material which is put under compression or tensile stress,
   - an amorphous material which is put under compression or tensile stress, or
   - an optically uniaxial crystalline material.

7. An optical system as set forth in one of the preceding claims, **characterized in that** the position manipulator (150, 250) is further adapted to effect the following change in the position of at least one subelement (110, 120; 210, 220):

   - displacement of at least one of said subelements (110, 120; 210, 220) in a direction parallel to the optical axis.

8. An optical system as set forth in one of the claims 1 through 7, **characterized in that** the rotation is about an axis of rotation which is parallel to the optical axis.

9. An optical system as set forth in one of the claims 1 through 7, **characterized in that** the rotation is about an axis of rotation which is not parallel to the optical axis.

10. An optical system as set forth in one of the preceding claims, **characterized in that** provided between the first subelement (110, 210) and the second subelement (120, 220) is a gap which is at least partially filled with a fluid.

11. An optical system as set forth in claim 10, **characterized in that** the fluid is a liquid medium, wherein said liquid medium has a refractive index which at a working wavelength of the optical system differs by less than 0.2, preferably by less than 0.15, from a mean refractive index of the first and second subelements.

12. An optical system as set forth in one of the claims 1 through 11, **characterized in that** the first subelement (110, 210) and the second subelement (120, 220) are made from the same material.

13. An optical system as set forth in one of the claims 1 through 11, **characterized in that** the first subelement (110, 210) and the second subelement (120, 220) are made from different materials, wherein the polarization manipulator has both positively birefringent crystal material and also negatively birefringent crystal material.

14. An optical system as set forth in one of the preceding claims, **characterized in that** the polarization manipulator in a predetermined starting position of the at least one subelement leaves the polarization state of light passing therethrough unchanged.

15. An optical system as set forth in one of the preceding claims, **characterized in that** the polarization manipulator is configured such that a wavefront for p-polarized light passing therethrough and a wavefront for s-polarized light passing therethrough, are manipulated by said polarization manipulator differently from each other, wherein the manipulation of the mean value of the wave fronts for p-polarized light and for s-polarized light is different from zero.

Patentansprüche

1. Optisches System, das eine optische Achse (OA) aufweist, aufweisend

   • mindestens einen Polarisationsmanipulator (100, 200) mit einem ersten Unterelement (110, 210), das eine nicht plane, optisch effektive Oberfläche aufweist und für Licht, das dort hindurchdringt, eine Änderung des

Polarisationszustands bewirkt, wobei eine maximale effektive Verzögerung, die durch das erste Unterelement entlang der optischen Achse (OA) eingeleitet ist, geringer als ein Viertel der Arbeitswellenlänge des optischen Systems ist, und mit einem zweiten Unterelement (120, 220), wobei das erste Unterelement und das zweite Unterelement einander zugekehrte Oberflächen (110a, 120a; 210a, 220a) aufweisen, die komplementär zueinander sind; und

- einen Positionsmanipulator (150, 250) zur Manipulation der relativen Position des ersten Unterelements (110, 210) und des zweiten Unterelements (120, 220); **dadurch gekennzeichnet, dass** der Positionsmanipulator (150, 250) dazu geeignet ist, eine der folgenden Änderungen der Position von mindestens einem Unterelement (110, 120; 210, 220) oder eine Kombination derartiger Änderungen auszuführen:

  - Verschiebung von mindestens einem der Unterelemente (110, 120; 210, 220) in einer senkrecht zur optischen Achse verlaufenden Richtung; und
  - Drehung von mindestens einem der Unterelemente (110, 120; 210, 220).

2. Optisches System nach Anspruch 1, **dadurch gekennzeichnet, dass** mindestens eine der einander zugekehrten Oberflächen (110a, 120a; 210a, 220a) asphärisch ist.

3. Optisches System nach einem der Ansprüche 1 oder 2, **dadurch gekennzeichnet, dass** mindestens eines der Unterelemente (110, 210, 120, 220) für Licht, das dort hindurchdringt, eine Änderung des Polarisationszustands durch lineare Doppelbrechung, kreisförmige Doppelbrechung und/oder durch eine Änderung der Amplitudenbeziehung von orthogonalen Polarisationszuständen in Abhängigkeit von Ausrichtungen derselben bewirkt.

4. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** es mindestens zwei derartige Polarisationsmanipulatoren aufweist, wobei die Polarisationsmanipulatoren derart angeordnet sind, dass die paraxialen Subaperturverhältnisse an den Standorten dieser Polarisationsmanipulatoren um mindestens 0,1 und bevorzugt mindestens 0,15 voneinander abweichen.

5. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** es ferner einen Wellenfrontkompensator zur mindestens Teilkompensation einer Änderung, die durch den Polarisationsmanipulator (100, 200) bewirkt ist, in der Wellenfront von Licht, das das optische System durchdringt, aufweist.

6. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** mindestens eines der Unterelemente aus einem Material erzeugt ist, das aus der Gruppe ausgewählt ist, die Folgendes enthält:

- ein kubisch kristallines Material, das unter Kompression oder Zugspannung gesetzt ist,
- ein amorphes Material, das unter Kompression oder Zugspannung gesetzt ist, oder
- ein optisch einachsiges kristallines Material.

7. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der Positionsmanipulator (150, 250) ferner zum Ausführen der folgenden Änderung der Position von mindestens einem Unterelement (110, 120; 210, 220) geeignet ist:

- Verschiebung von mindestens einem der Unterelemente (110, 120; 210, 220) in einer parallel zur optischen Achse verlaufenden Richtung.

8. Optisches System nach einem der Ansprüche 1 bis 7, **dadurch gekennzeichnet, dass** die Drehung um eine Drehachse verläuft, die parallel zur optischen Achse ist.

9. Optisches System nach einem der Ansprüche 1 bis 7, **dadurch gekennzeichnet, dass** die Drehung um eine Drehachse verläuft, die nicht parallel zur optischen Achse ist.

10. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** zwischen dem ersten Unterelement (110, 210) und dem zweiten Unterelement (120, 220) ein Spalt vorgesehen ist, der mindestens teilweise mit einem Fluid gefüllt ist.

11. Optisches System nach Anspruch 10, **dadurch gekennzeichnet, dass** das Fluid ein flüssiges Medium ist, wobei das flüssige Medium einen Brechungsindex aufweist, der bei einer Arbeitswellenlänge des optischen Systems um weniger als 0,2, bevorzugt um weniger als 0,15, von einem mittleren Brechungsindex des ersten und zweiten

Unterelements abweicht.

12. Optisches System nach einem der Ansprüche 1 bis 11, **dadurch gekennzeichnet, dass** das erste Unterelement (110, 210) und das zweite Unterelement (120, 220) aus demselben Material hergestellt sind.

13. Optisches System nach einem der Ansprüche 1 bis 11, **dadurch gekennzeichnet, dass** das erste Unterelement (110, 210) und das zweite Unterelement (120, 220) aus verschiedenen Materialien hergestellt sind, wobei der Polarisationsmanipulator sowohl positiv doppelbrechendes kristallines Material als auch negativ doppelbrechendes kristallines Material aufweist.

14. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der Polarisationsmanipulator in einer vorgegebenen Startposition des mindestens einen Unterelements den Polarisationszustand von Licht, das dort hindurchdringt, unverändert lässt.

15. Optisches System nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der Polarisationsmanipulator derart konfiguriert ist, dass eine Wellenfront für p-polarisiertes Licht, das dort hindurchdringt, und eine Wellenfront für s-polarisiertes Licht, das dort hindurchdringt, unterschiedlich voneinander durch den Polarisationsmanipulator manipuliert werden, wobei die Manipulation des Mittelwerts der Wellenfronten für p-polarisiertes Licht und für s-polarisiertes Licht von null abweicht.

Revendications

1. Système optique qui a un axe optique (OA), comprenant

- au moins un manipulateur de polarisation (100, 200) ayant un premier sous-élément (110, 210) qui a une surface non plane, optiquement efficace et pour faire traverser la lumière provoque un changement d'état de polarisation, un retard maximal effectif introduit par le premier sous-élément le long de l'axe optique (OA) étant inférieur à un quart de la longueur d'onde de travail du système optique, et un deuxième sous-élément (120, 220), ledit premier sous-élément et ledit deuxième sous-élément ayant des surfaces se faisant mutuellement face (110a, 120a ; 210a, 220a) qui sont mutuellement complémentaires ; et
- un manipulateur de position (150, 250) pour la manipulation de la position relative dudit premier sous-élément (110, 210) et dudit deuxième sous-élément (120, 220) ; **caractérisé en ce que** le manipulateur de position (150, 250) est adapté pour appliquer un des changements suivants dans la position d'au moins un sous-élément (110, 120 ; 210, 220) ou une combinaison de ces changements :
    - déplacement d'au moins un desdits sous-éléments (110, 120 ; 210, 220) dans une direction perpendiculaire à l'axe optique ; et
    - rotation d'au moins un desdits sous-éléments (110, 120 ; 210, 220).

2. Système optique selon la revendication 1, **caractérisé en ce qu'**au moins une desdites surfaces se faisant mutuellement face (110a, 120a ; 210a, 220a) est asphérique.

3. Système optique selon la revendication 1 ou 2, **caractérisé en ce qu'**au moins un desdits sous-éléments (110, 210, 120, 220), pour faire traverser la lumière, provoque un changement d'état de polarisation par biréfringence linéaire, biréfringence circulaire et/ou par un changement dans la relation d'amplitude d'états de polarisation orthogonaux dépendant des orientations de ceux-ci.

4. Système optique selon une des revendications précédentes, **caractérisé en ce qu'**il comporte au moins deux tels manipulateurs de polarisation, les manipulateurs de polarisation étant agencés de telle sorte que les facteurs de sous-ouverture paraxiale aux emplacements de ces manipulateurs de polarisation diffèrent l'un de l'autre d'au moins 0,1 et de préférence au moins 0,15.

5. Système optique selon une des revendications précédentes, **caractérisé en ce qu'**il comporte en outre un compensateur de front d'onde pour la compensation au moins partielle d'un changement, provoqué par le manipulateur de polarisation (100, 200), dans le front d'onde de la lumière traversant le système optique.

6. Système optique selon une des revendications précédentes, **caractérisé en ce qu'**au moins un desdits sous-éléments est produit à partir d'un matériau choisi dans le groupe qui contient :

- un matériau cristallin cubique qui est mis sous contrainte de compression ou de traction,
- un matériau amorphe qui est mis sous contrainte de compression ou de traction, ou
- un matériau cristallin optiquement uniaxial.

7. Système optique selon une des revendications précédentes, **caractérisé en ce que** le manipulateur de position (150, 250) est également adapté pour appliquer le changement suivant dans la position d'au moins un sous-élément (110, 120 ; 210, 220) :

- déplacement d'au moins un desdits sous-éléments (110, 120 ; 210, 220) dans une direction parallèle à l'axe optique.

8. Système optique selon une des revendications 1 à 7, **caractérisé en ce que** la rotation se fait autour d'un axe de rotation qui est parallèle à l'axe optique.

9. Système optique selon une des revendications 1 à 7, **caractérisé en ce que** la rotation se fait autour d'un axe de rotation qui n'est pas parallèle à l'axe optique.

10. Système optique selon une des revendications précédentes, **caractérisé en ce qu'**un espace qui est au moins partiellement rempli par un fluide est prévu entre le premier sous-élément (110, 210) et le deuxième sous-élément (120, 220).

11. Système optique selon la revendication 10, **caractérisé en ce que** le fluide est un milieu liquide, ledit milieu liquide ayant un indice de réfraction qui, à une longueur d'onde de travail du système optique, diffère de moins de 0,2, de préférence de moins de 0,15, d'un indice de réfraction moyen des premier et deuxième sous-éléments.

12. Système optique selon une des revendications 1 à 11, **caractérisé en ce que** le premier sous-élément (110, 210) et le deuxième sous-élément (120, 220) sont constitués du même matériau.

13. Système optique selon une des revendications 1 à 11, **caractérisé en ce que** le premier sous-élément (110, 210) et le deuxième sous-élément (120, 220) sont constitués de matériaux différents, le manipulateur de polarisation ayant à la fois un matériau cristallin à biréfringence positive et un matériau cristallin à biréfringence négative.

14. Système optique selon une des revendications précédentes, **caractérisé en ce que** le manipulateur de polarisation, dans une position de départ prédéterminée de l'au moins un sous-élément, laisse l'état de polarisation de la lumière le traversant inchangé.

15. Système optique selon une des revendications précédentes, **caractérisé en ce que** le manipulateur de polarisation est configuré de telle sorte qu'un front d'onde pour la lumière polarisée p le traversant et un front d'onde pour la lumière polarisée s le traversant sont manipulés par ledit manipulateur de polarisation différemment l'un de l'autre, la manipulation de la valeur moyenne des fronts d'onde pour la lumière polarisée p et la lumière polarisée s étant différente de zéro.

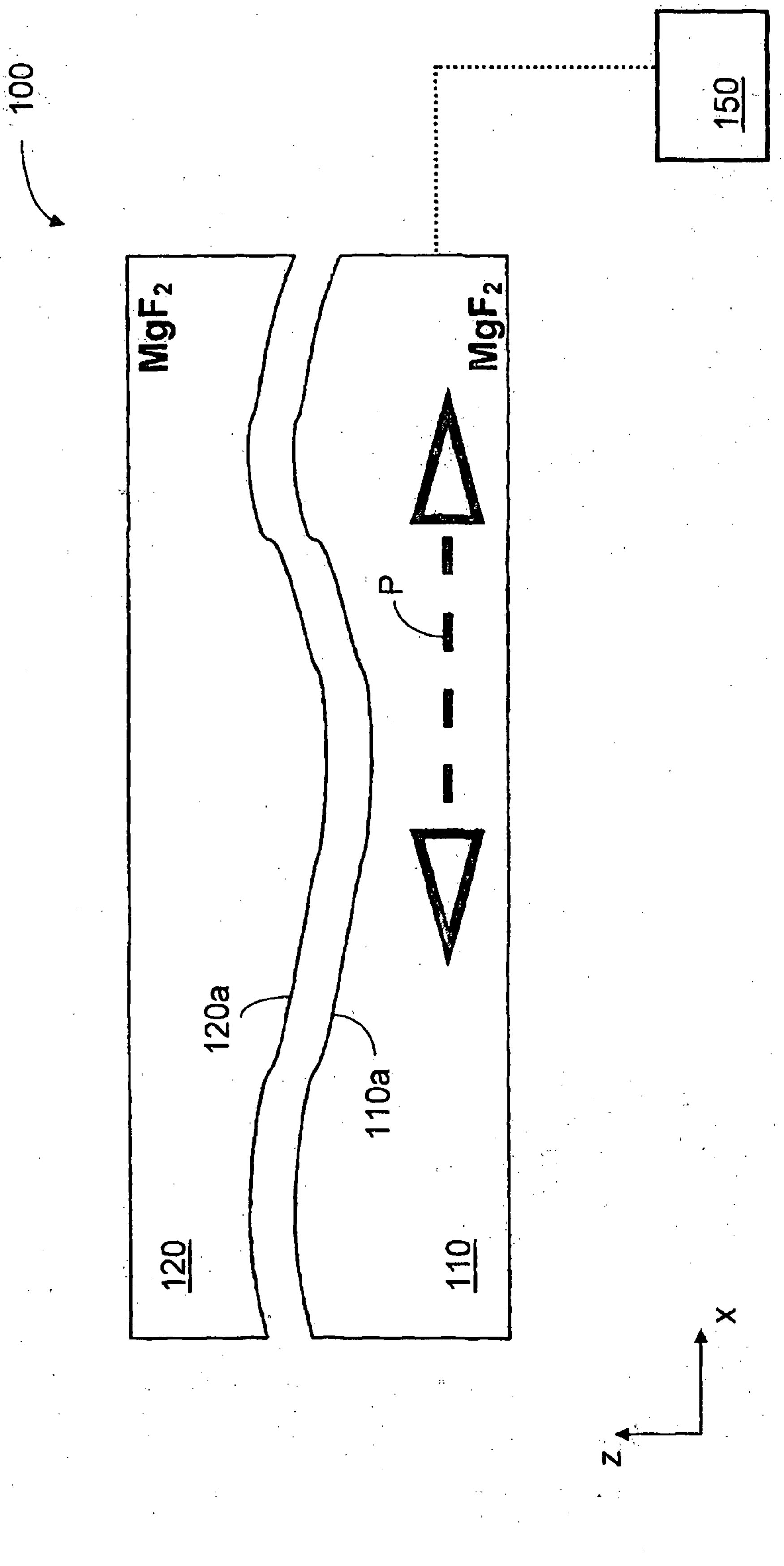


Fig. 1

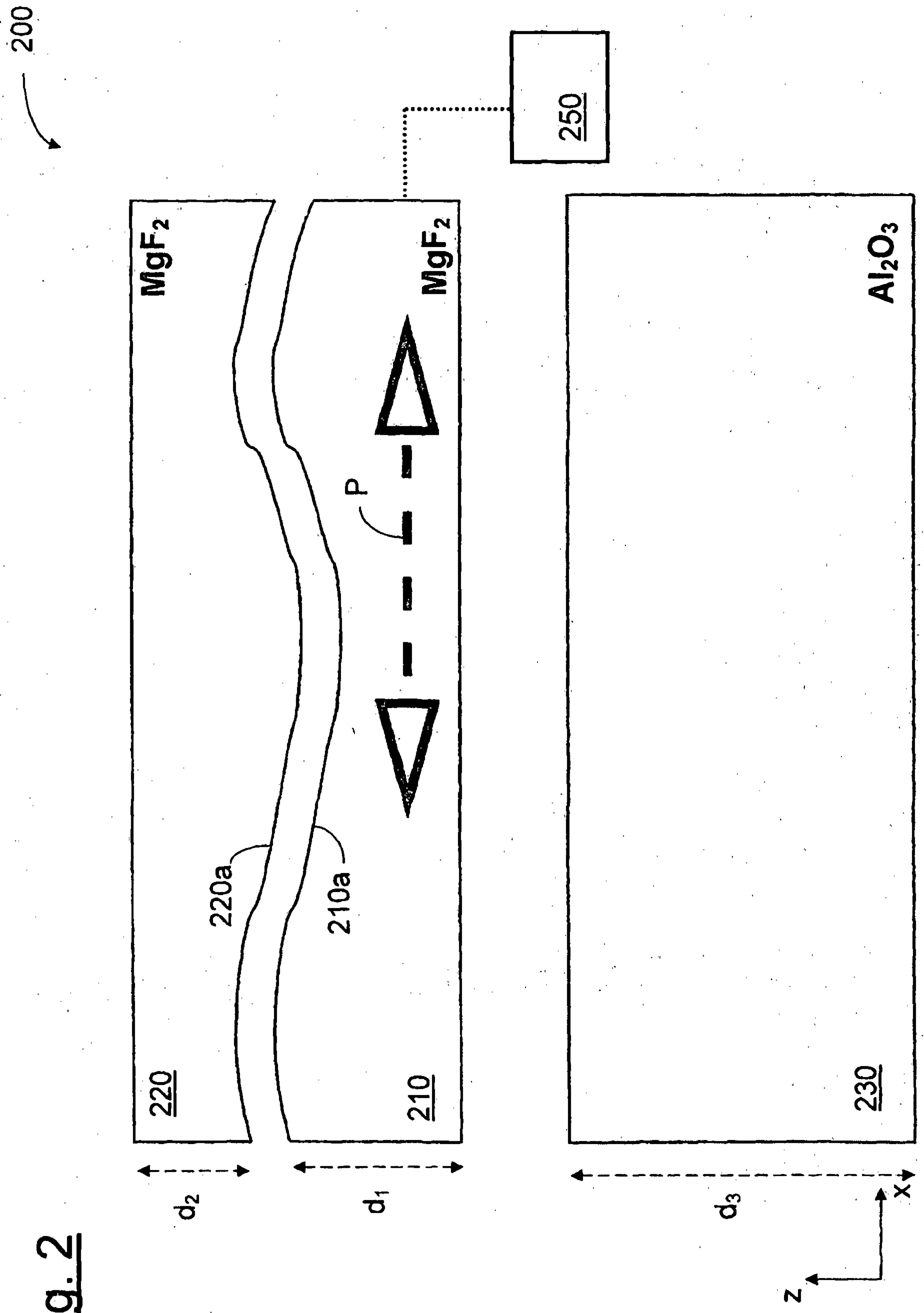


Fig. 2

Fig. 3a

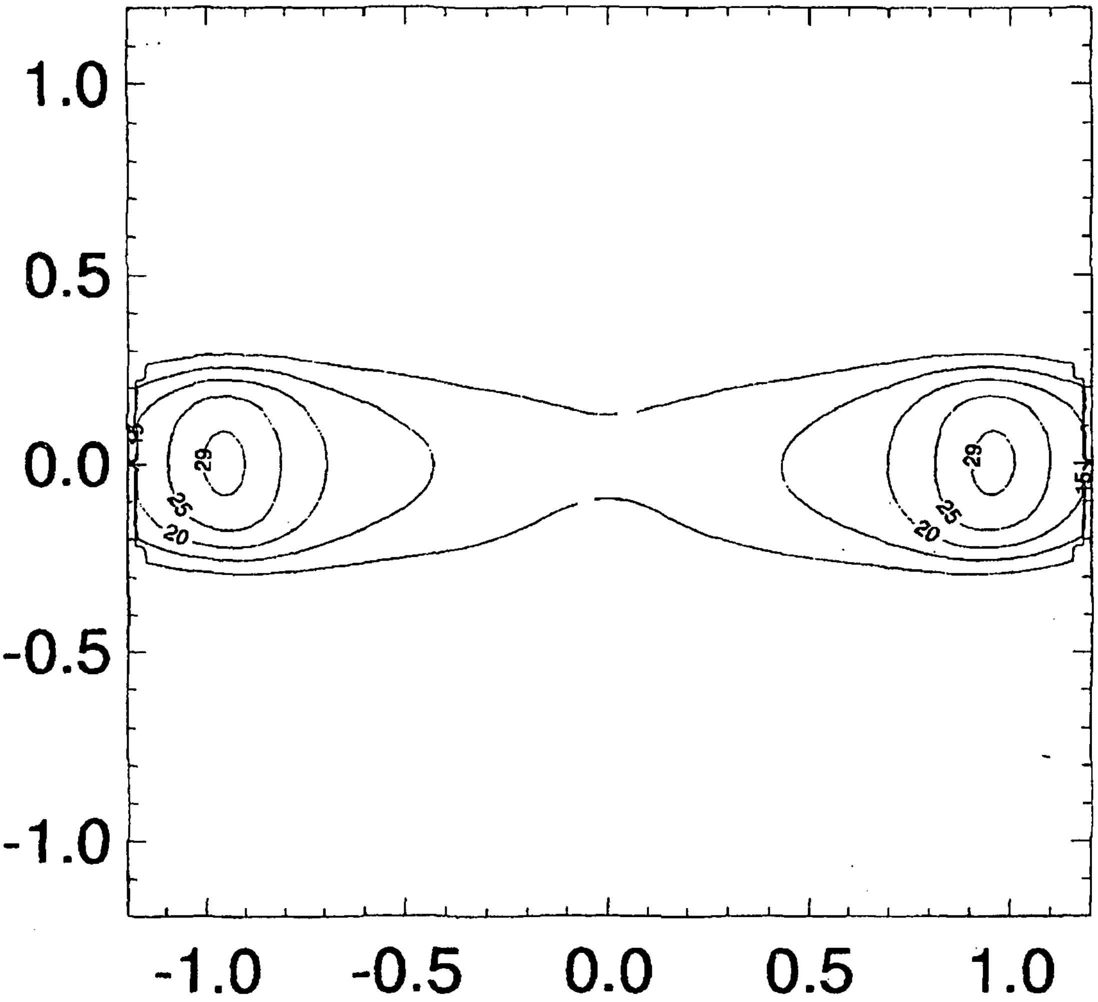


Fig. 3b

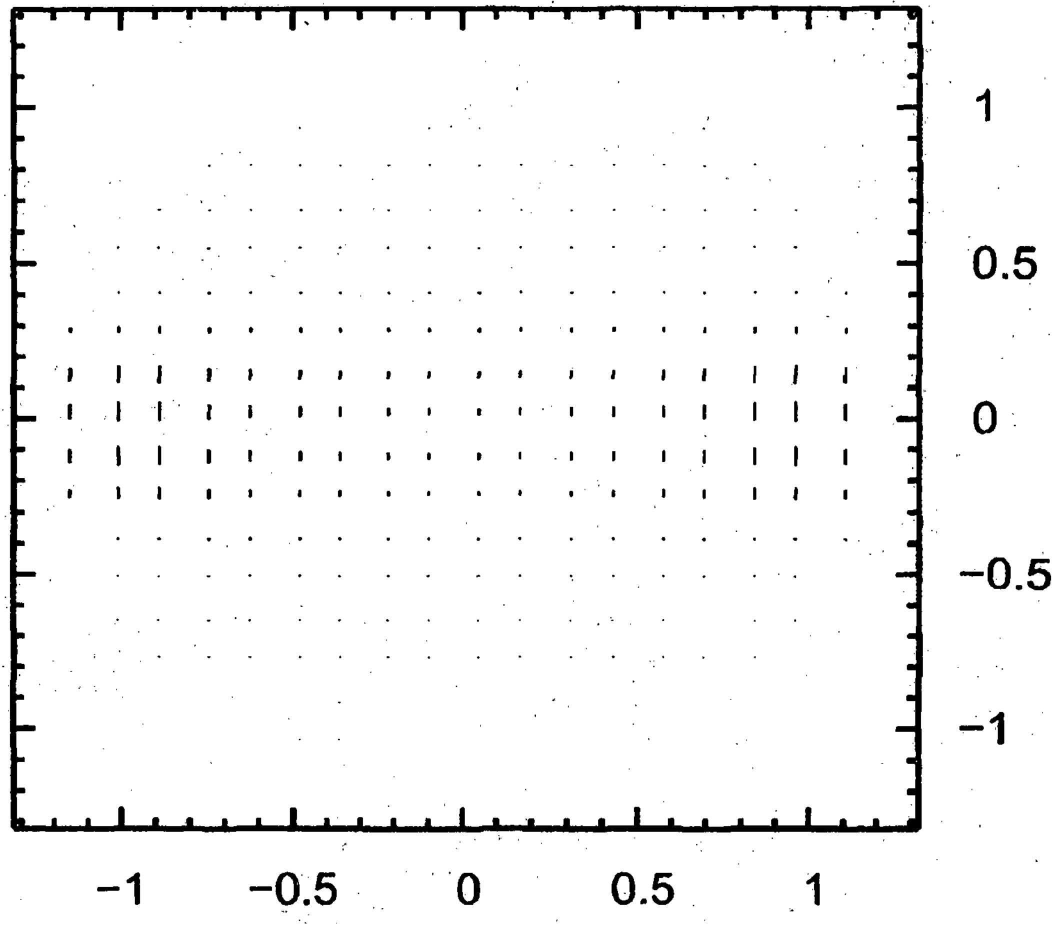


Fig. 4

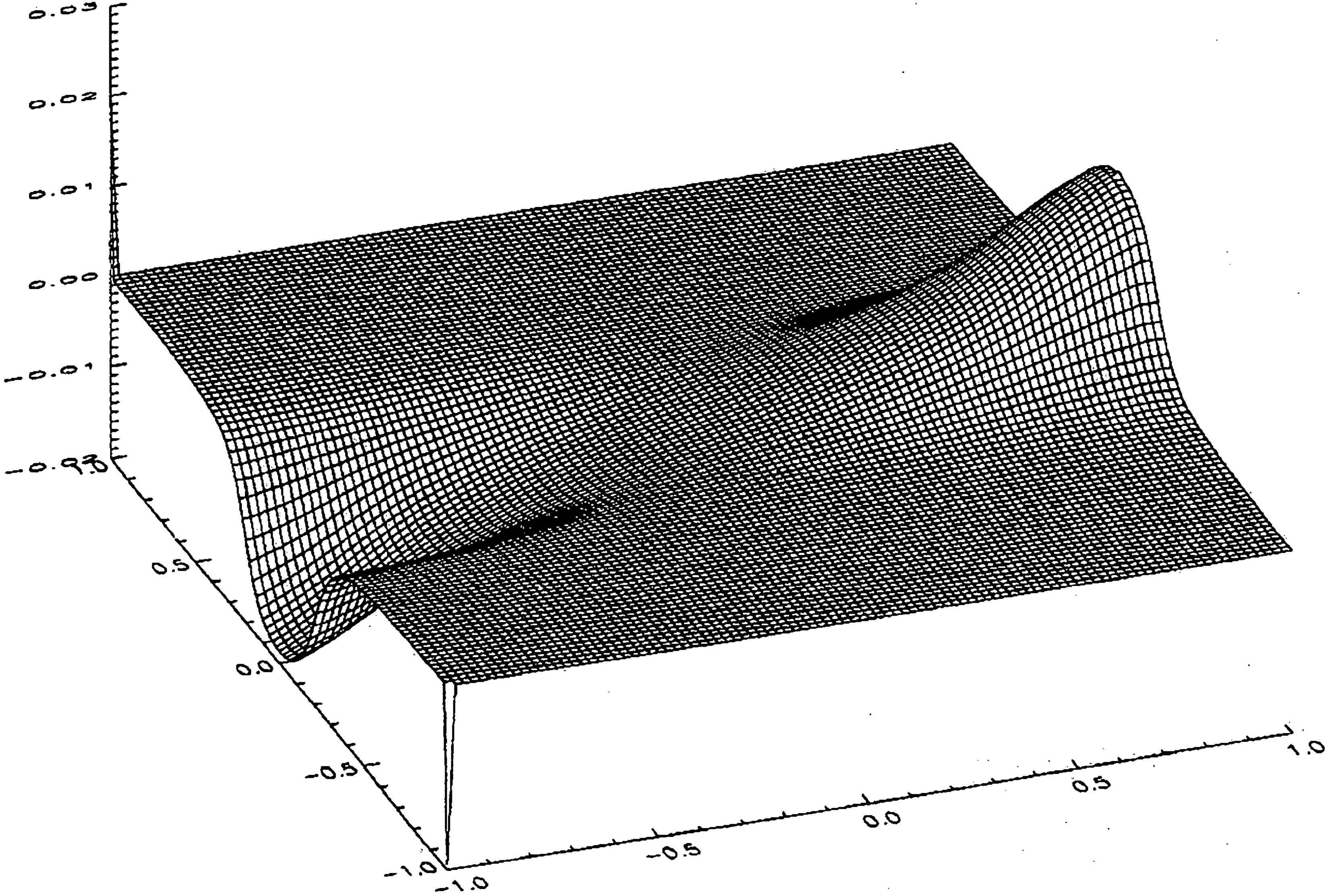


Fig. 5a

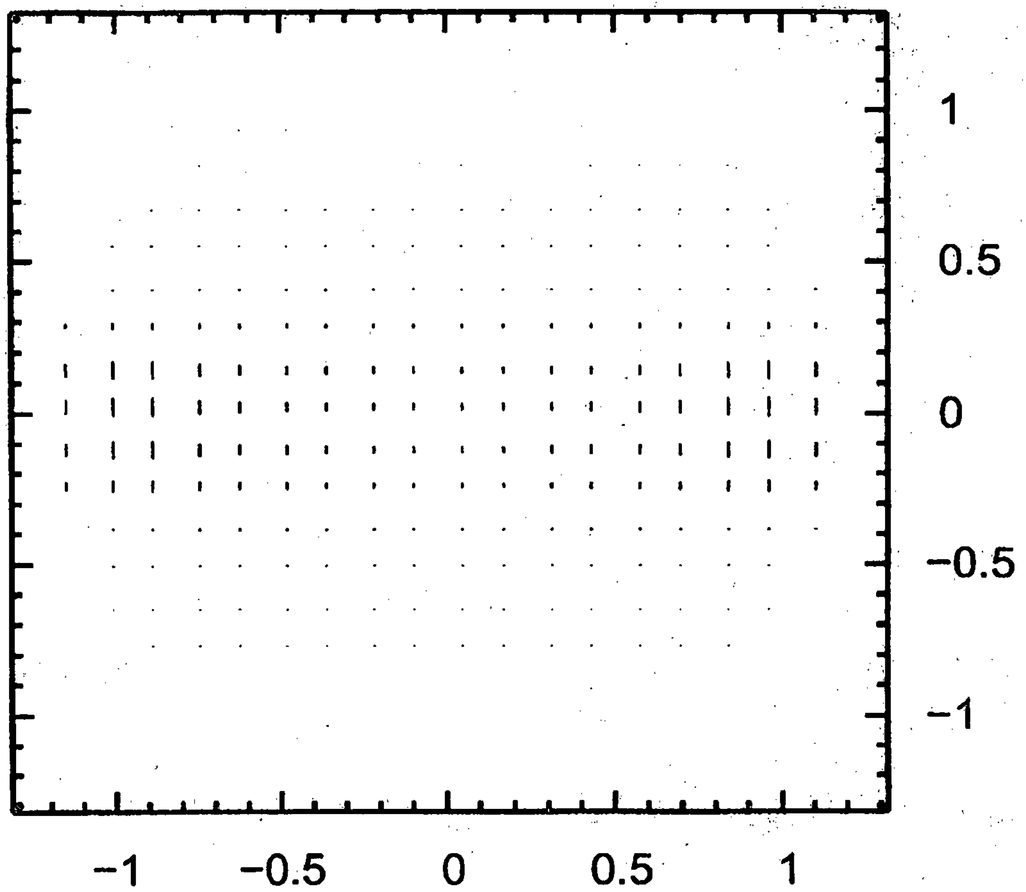
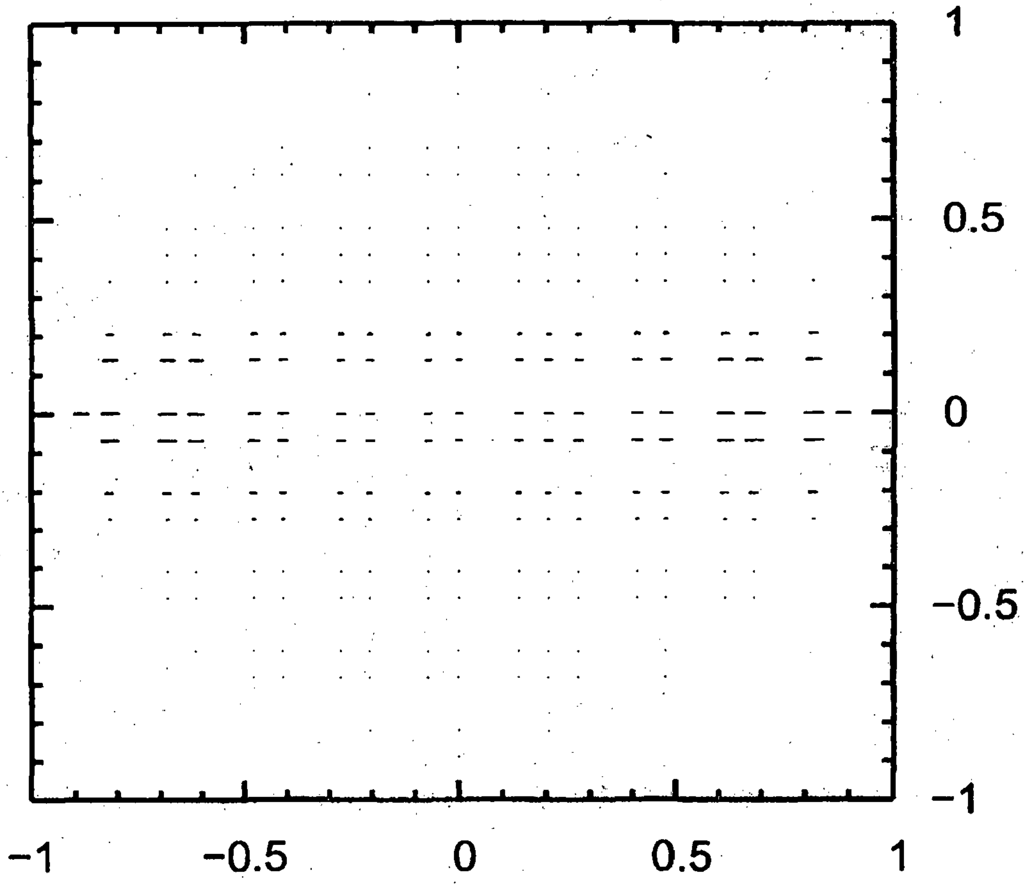


Fig. 5b



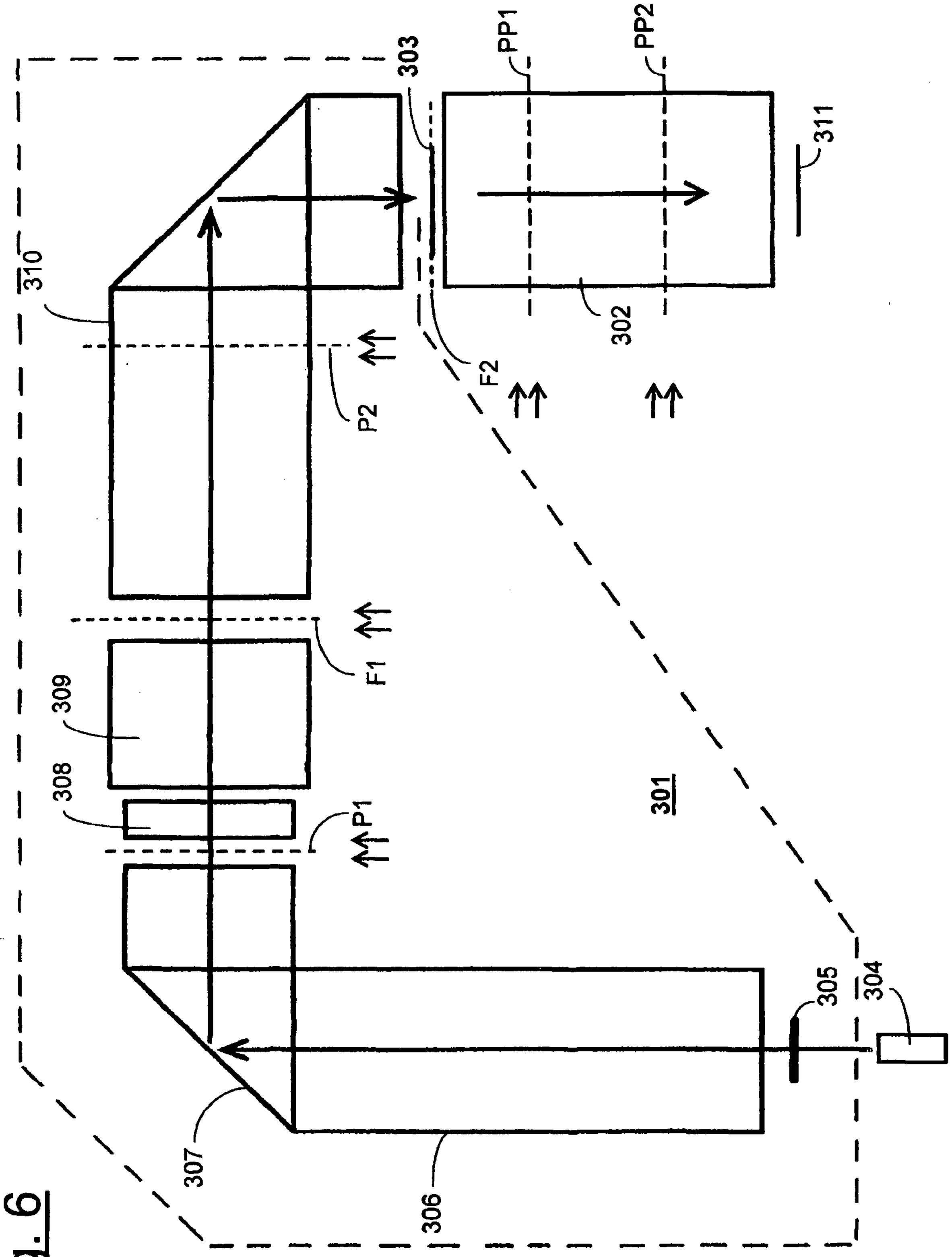


Fig. 6

]

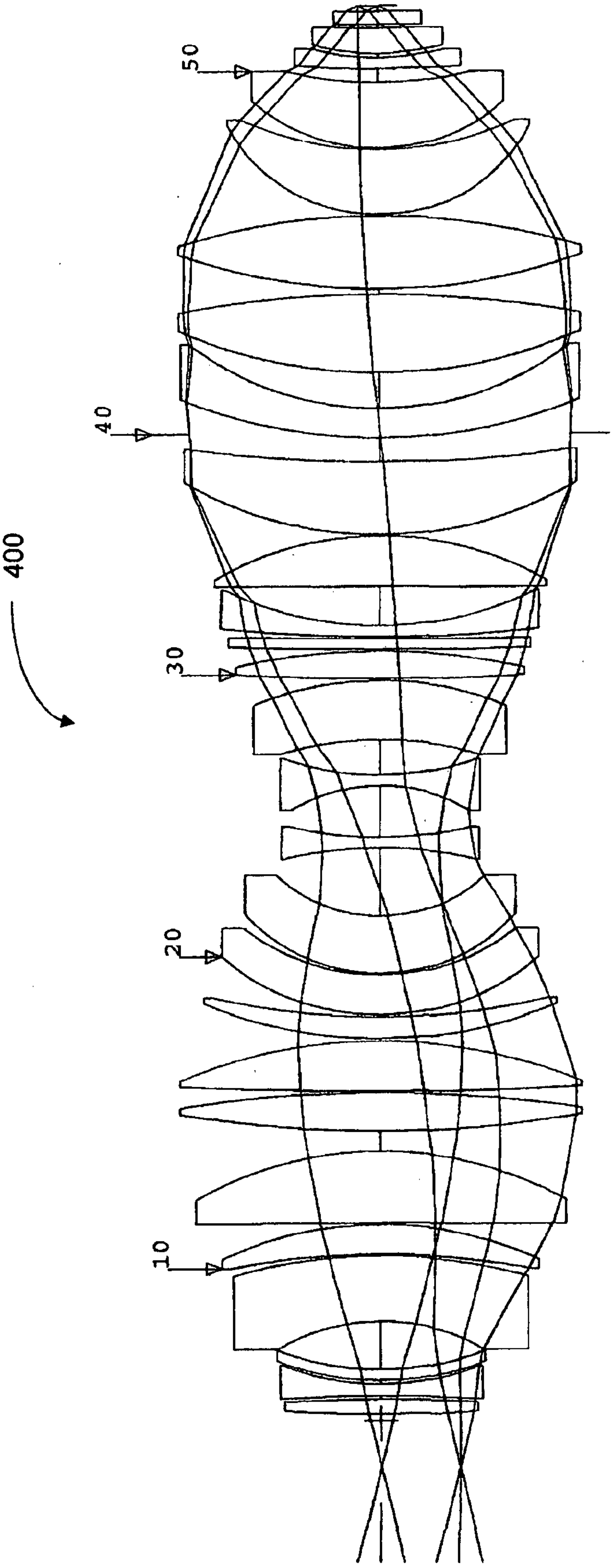


Fig. 7

Fig. 8

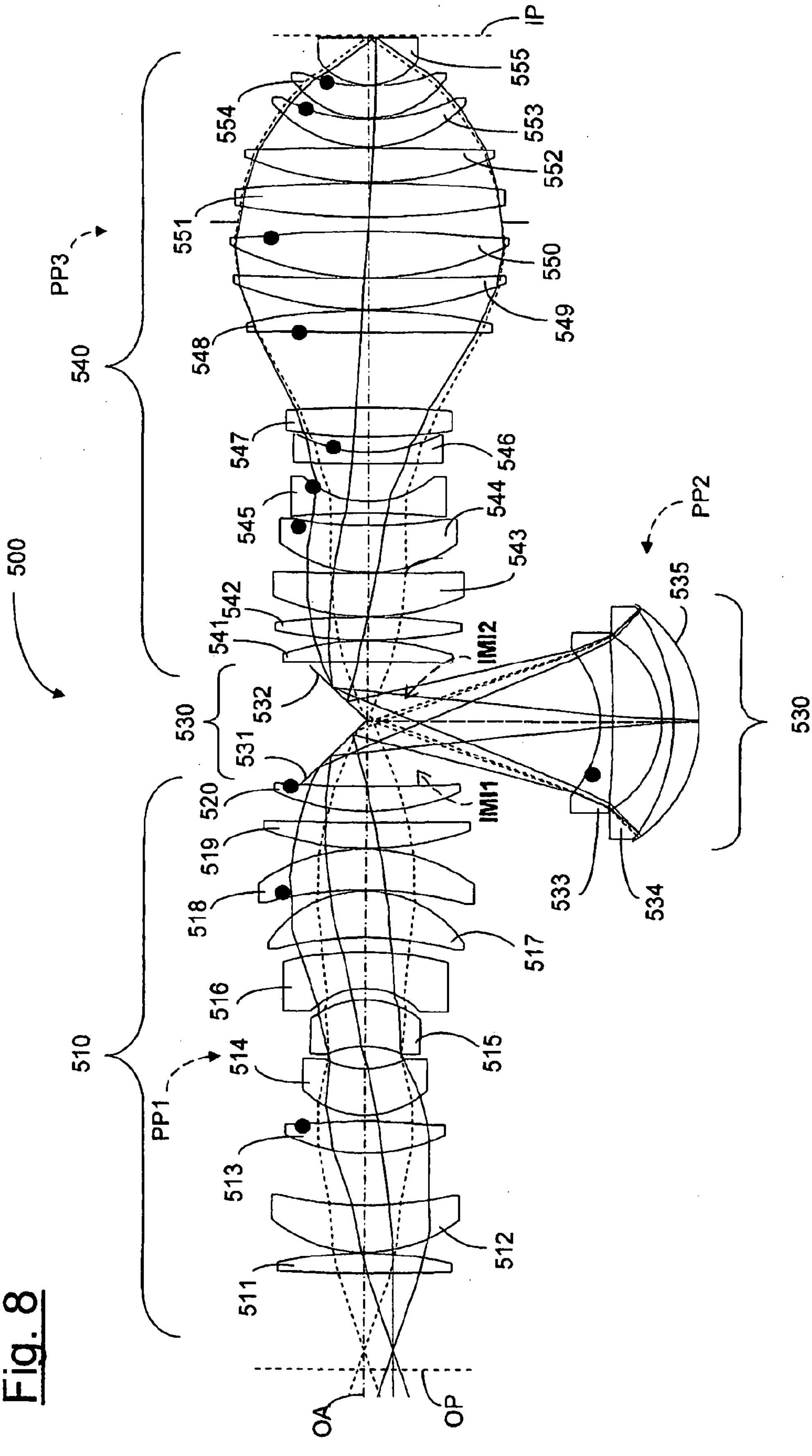
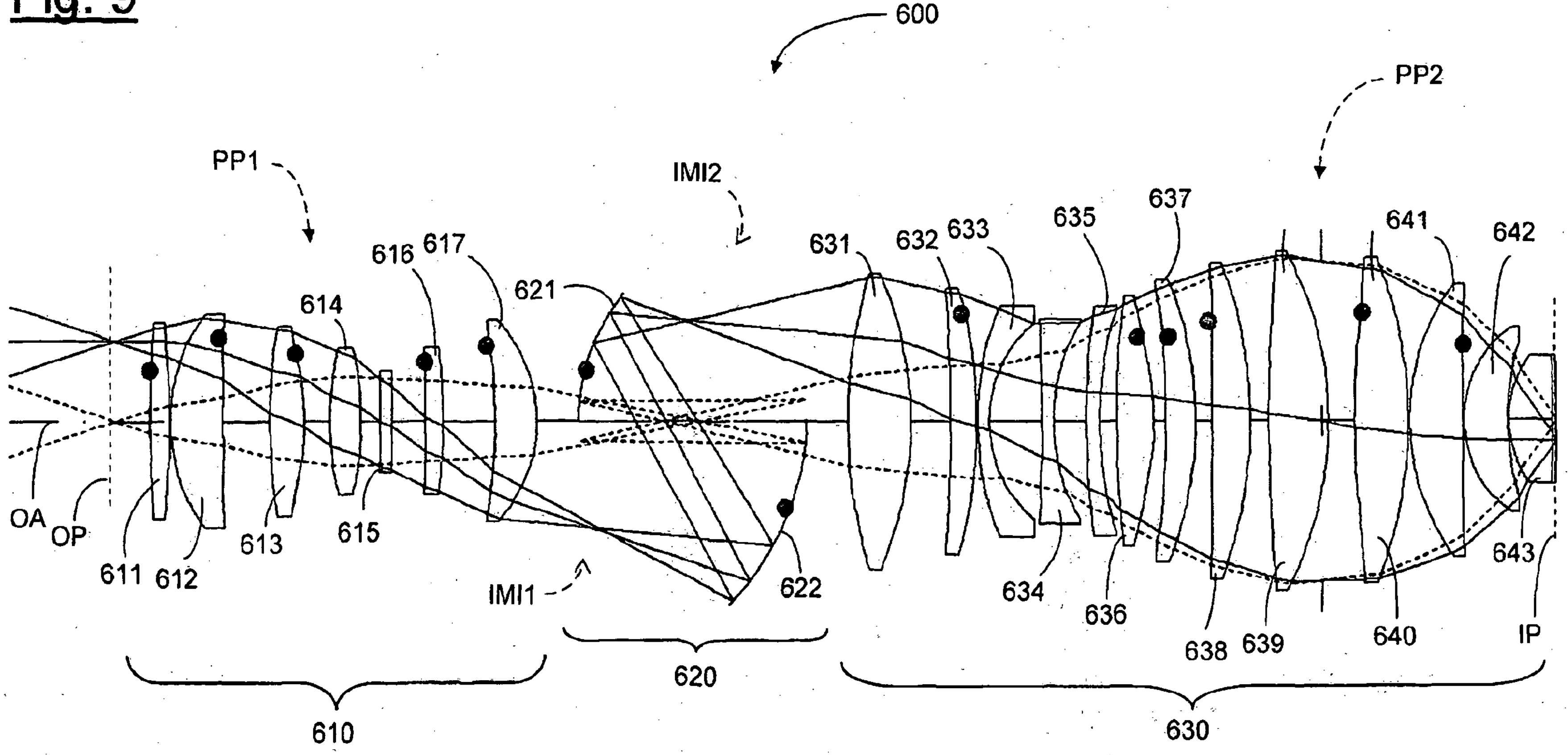

IP
555
554
553
552
551
550
549
548
540
PP3
547
546
545
544
543
542
541
500
IMI2
532
530
531
IMI1
520
519
518
517
516
515
514
510
PP1
513
512
511
OA
OP
PP2
535
530
533
534

Fig. 9


600
PP1
PP2
IMI2
IMI1
OA
OP
611
612
613
614
615
616
617
621
622
631
632
633
634
635
636
637
638
639
640
641
642
643
IP
610
620
630

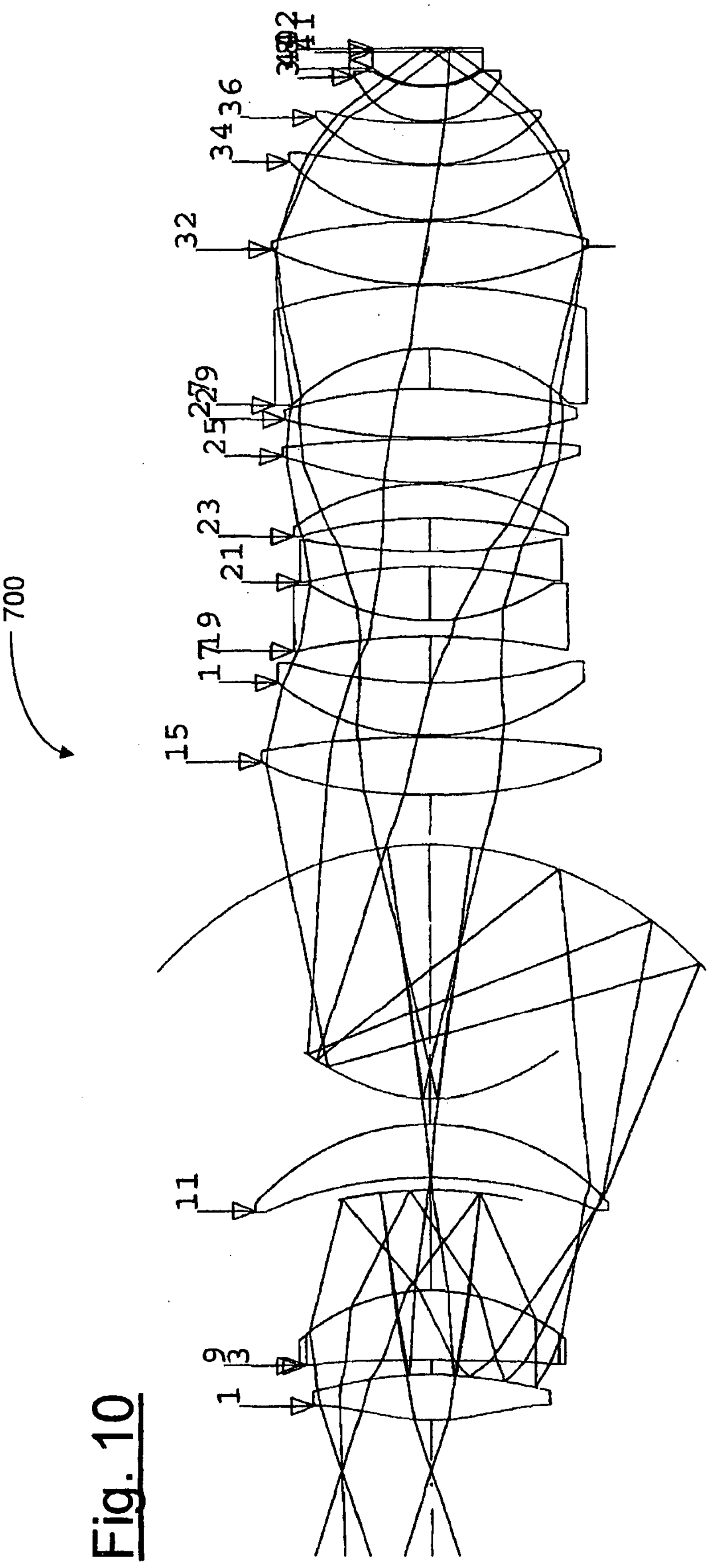


Fig. 10

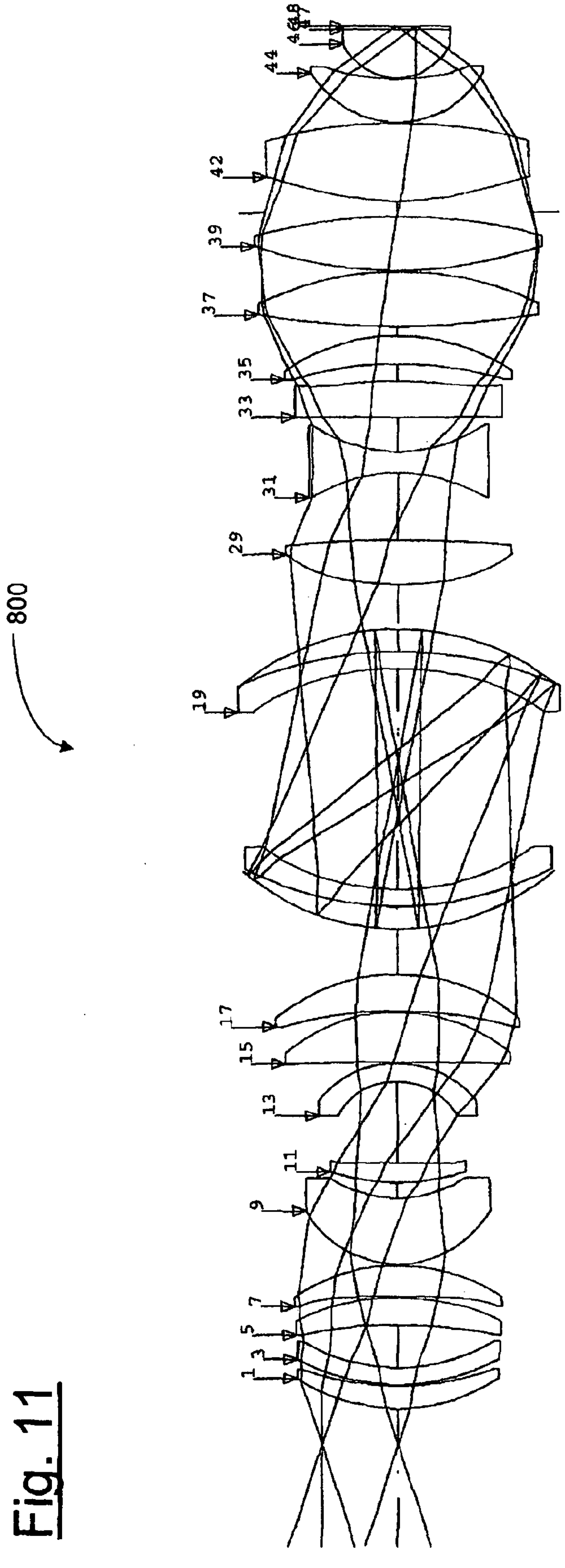


Fig. 11

Fig. 12

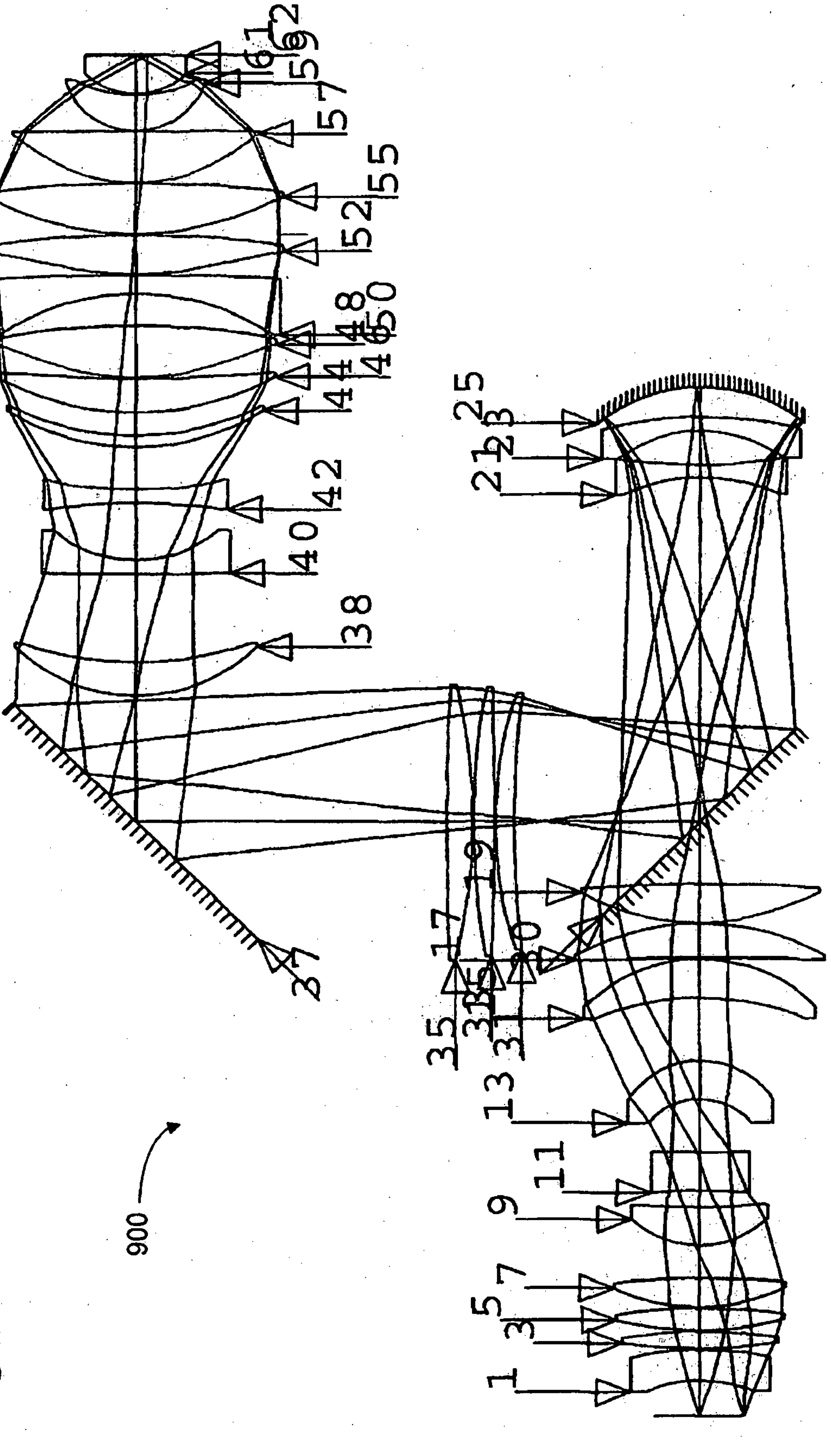

900
1
3
5
7
9
11
13
31
33
35
17
19
20
37
38
40
42
44
46
48
50
52
55
57
59
61
62
21
23
25

Fig. 13a

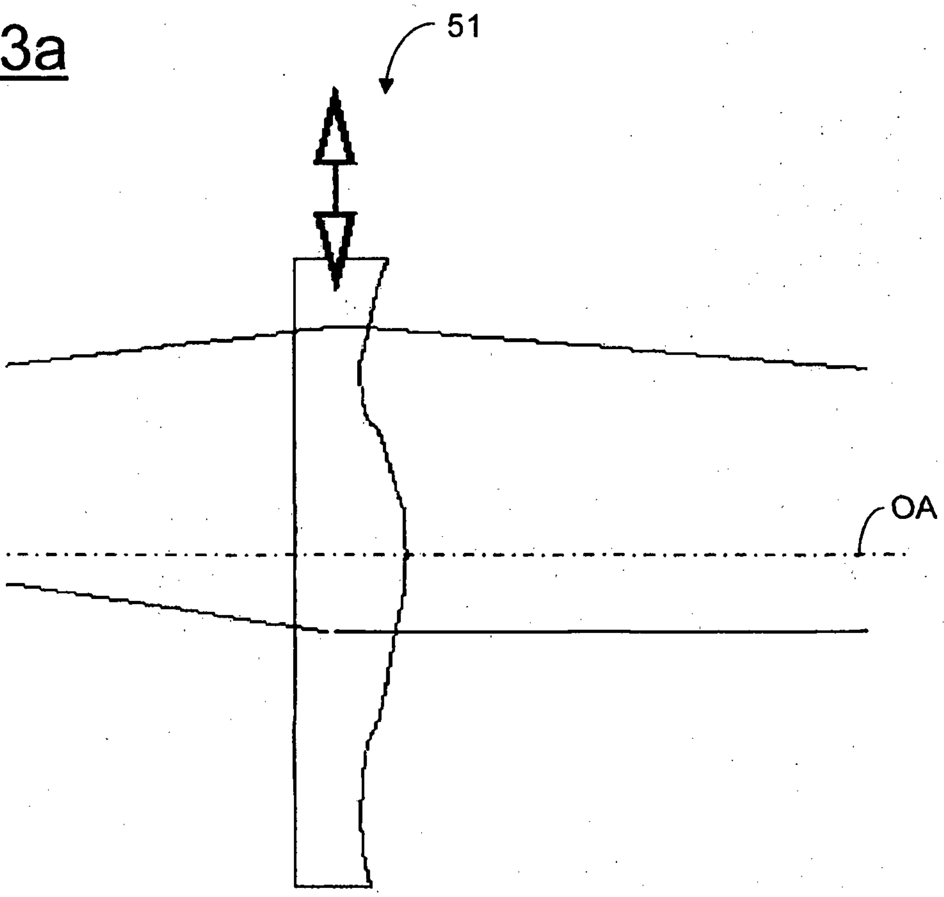


Fig. 13b

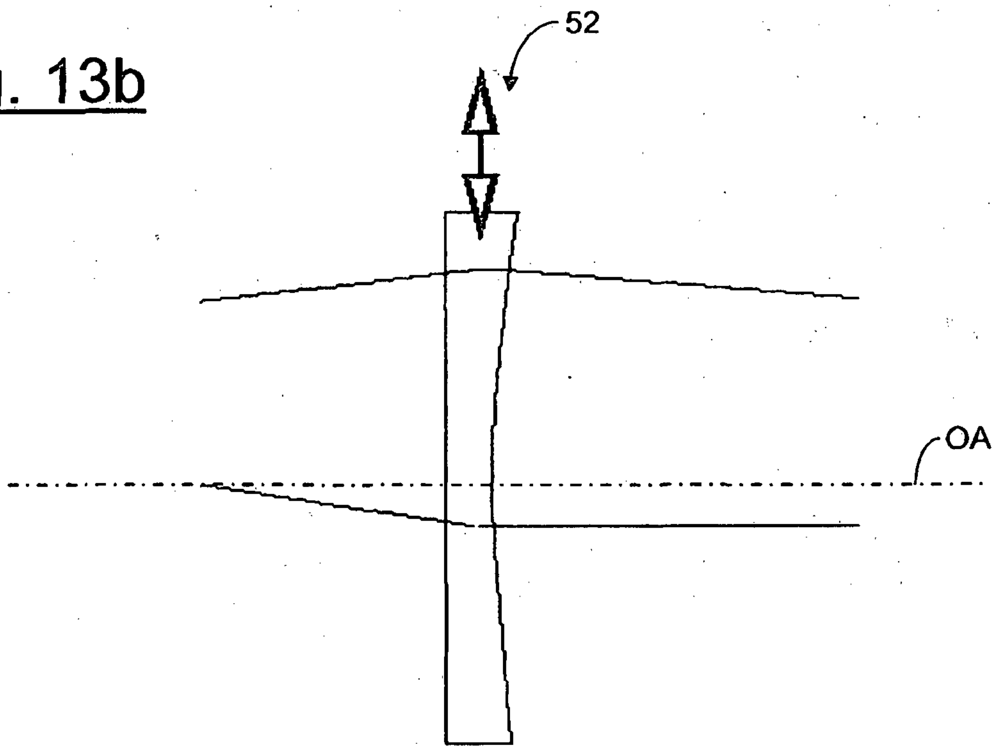


Fig. 13c

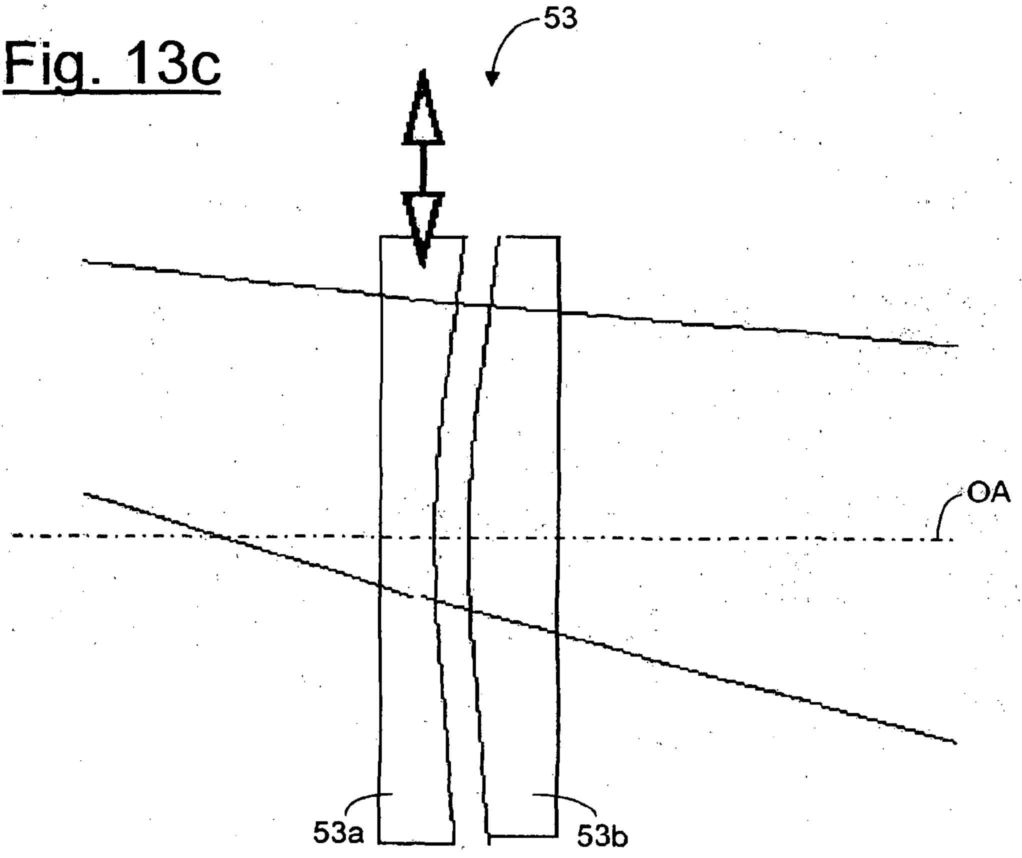


Fig. 13d

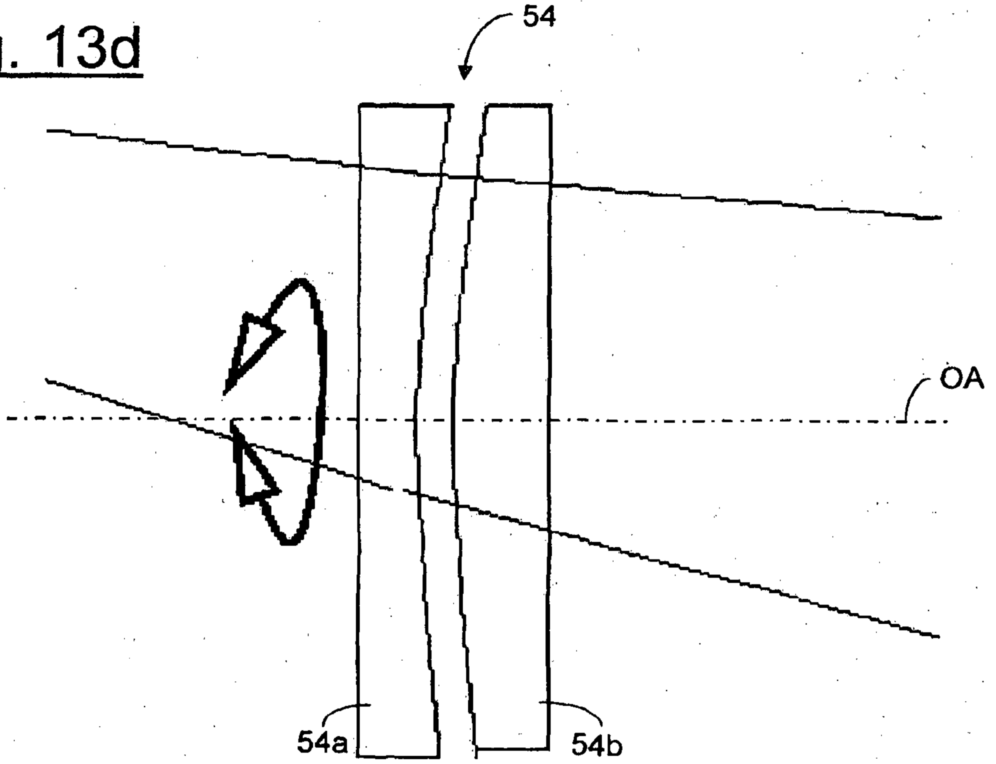
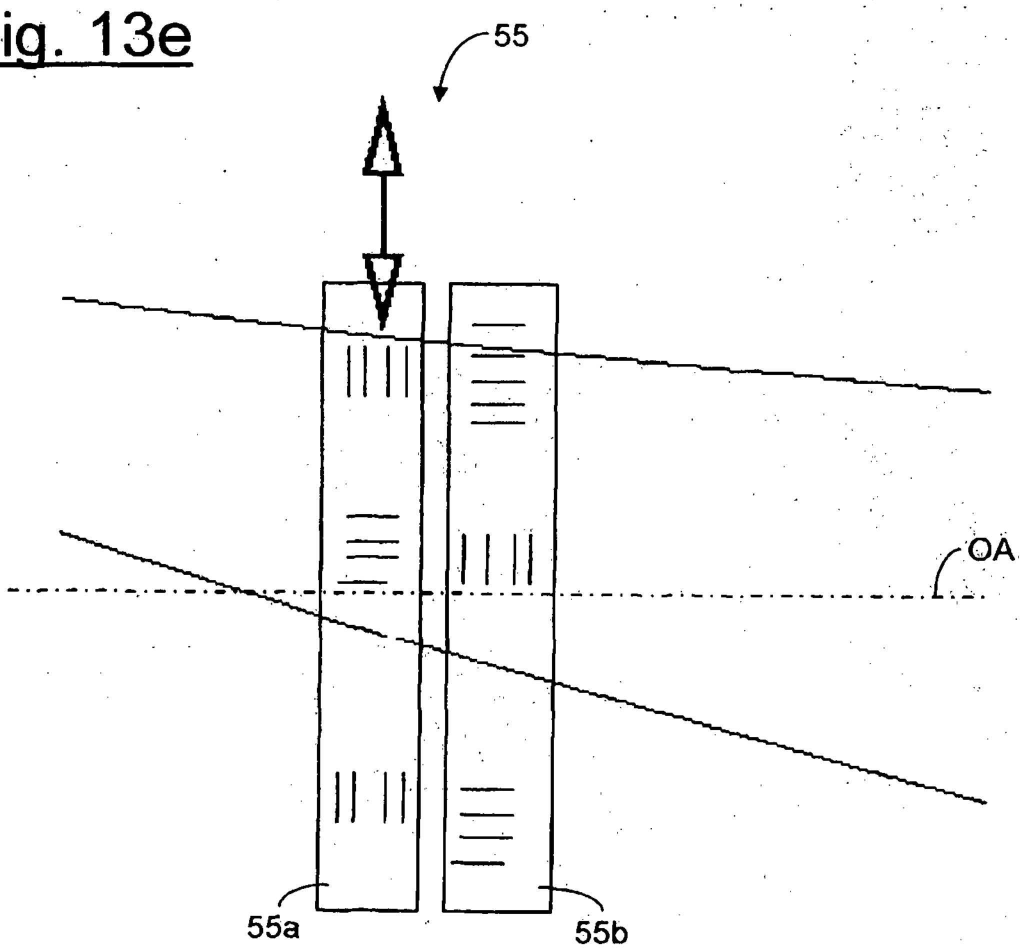


Fig. 13e



REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- WO 2005069081 A2 **[0004]**
- US 20070146676 A1 **[0005]**
- WO 2005031467 A2 **[0006]**
- US 6252712 B1 **[0007]**
- US 6104472 A **[0008]**
- US 4643534 A **[0008]**
- WO 2003075096 A2 **[0073]**
- WO 2004019128 A2 **[0074]**
- WO 2005069055 A2 **[0076]** **[0080]**
- EP 1480065 A2 **[0080]**
- US 6665126 B2 **[0080]**