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(54) Illumination system of a microlithographic projection exposure apparatus

Beleuchtungssystem eines mikrolithografischen Projektionsbelichtungsgerätes

Système d'illumination d'un appareil d'exposition de projection micro-lithographique

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Description

1. Field of the Invention

[0001] The invention generally relates to illumination systems for illuminating a mask in a microlithographic exposure apparatus, and in particular to such systems comprising an optical integrator configured to produce a plurality of secondary light sources in a pupil plane. The invention also relates to a method of operating such illumination systems and also to other optical systems in general.

2. Description of Related Art

[0002] Microlithography (also referred to as photolithography or simply lithography) is a technology for the fabrication of integrated circuits, liquid crystal displays and other microstructured devices. The process of microlithography, 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 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) or vacuum ultraviolet (VUV) light. Next, the wafer with the photoresist on top is exposed to projection light in a projection exposure apparatus. The apparatus projects a mask containing a pattern onto the photoresist so that the latter is only exposed at certain locations which are determined by the mask pattern. After the exposure the photoresist is developed to produce an image corresponding to the mask pattern. Then an etch process transfers the pattern into the thin film stacks on the wafer. Finally, the photoresist is removed. Repetition of this process with different masks results in a multi-layered microstructured component.

[0003] A projection exposure apparatus typically includes a light source, an illumination system that illuminates the mask with projection light produced by the light source, a mask stage for aligning the mask, a projection objective and a wafer alignment stage for aligning the wafer coated with the photoresist. The illumination system illuminates a field on the mask that may have the shape of a rectangular or curved slit, for example.

[0004] In current projection exposure apparatus a distinction can be made between two different types of apparatus. In one type each target portion on the wafer is irradiated by exposing the entire mask pattern onto the target portion in one go. Such an apparatus is commonly referred to as a wafer stepper. In the other type of apparatus, which is commonly referred to as a step-and-scan apparatus or scanner, each target portion is irradiated by progressively scanning the mask pattern under the projection beam along a scan direction while synchronously moving the substrate parallel or anti-parallel to this direction. The ratio of the velocity of the wafer and the velocity of the mask is equal to the magnification of the projection objective, which is usually smaller than 1, for example 1:4.

[0005] It is to be understood that the term "mask" (or reticle) is to be interpreted broadly as a patterning means. Commonly used masks contain opaque or reflective patterns and may be of the binary, alternating phase-shift, attenuated phase-shift or various hybrid mask type, for example. However, there are also active masks, e.g. masks realized as a programmable mirror array. Also programmable LCD arrays may be used as active masks.

[0006] As the technology for manufacturing microstructured devices advances, there are ever increasing demands also on the illumination system. Ideally, the illumination system illuminates each point of the illumination field on the mask with projection light having a well defined spatial and angular irradiance distribution. The term angular irradiance distribution describes how the total light energy of a light bundle, which converges towards a particular point in the mask plane, is distributed among the various directions of the rays that constitute the light bundle.

[0007] The angular irradiance distribution of the projection light impinging on the mask is usually adapted to the kind of pattern to be projected onto the photoresist. Often the angular irradiance distribution depends on the size, orientation and pitch of the features contained in the pattern. The most commonly used angular irradiance distributions of projection light are referred to as conventional, annular, dipole and quadrupole illumination settings. These terms refer to the irradiance distribution in a pupil plane of the illumination system. With an annular illumination setting, for example, only an annular region is illuminated in the pupil plane. Thus there is only a small range of angles present in the angular irradiance distribution of the projection light, and all light rays impinge obliquely with similar angles onto the mask.

[0008] Different means are known in the art to modify the angular irradiance distribution of the projection light in the mask plane so as to achieve the desired illumination setting. In the simplest case a stop (diaphragm) comprising one or more apertures is positioned in a pupil plane of the illumination system. Since locations in a pupil plane translate into angles in a Fourier related field plane such as the mask plane, the size, shape and location of the aperture(s) in the pupil plane determines the angular irradiance distributions in the mask plane. However, any change of the illumination setting requires a replacement of the stop. This makes it difficult to finely adjust the illumination setting, because this would require a very large number of stops that have aperture(s) with slightly different sizes, shapes or locations. Furthermore, the use of stops inevitably results in light losses and thus in a reduced throughput of the apparatus.

[0009] Many common illumination systems therefore comprise adjustable elements that make it possible, at least to a certain extent, to continuously vary the illumination of the pupil plane. Many illumination systems use an exchangeable diffractive optical element to produce

a desired spatial irradiance distribution in the pupil plane. If zoom optics and a pair of axicon elements are provided between the diffractive optical element and the pupil plane, it is possible to adjust this spatial irradiance distribution.

[0010] Recently it has been proposed to use mirror arrays that illuminate the pupil plane. In EP 1 262 836 A1 the mirror array is realized as a micro-electromechanical system (MEMS) comprising more than 1000 microscopic mirrors. Each of the mirrors can be tilted in two different planes perpendicular to each other. Thus radiation incident on such a mirror device can be reflected into (substantially) any desired direction of a hemisphere. A condenser lens arranged between the mirror array and the pupil plane translates the reflection angles produced by the mirrors into locations in the pupil plane. This known illumination system makes it possible to illuminate the pupil plane with a plurality of spots, wherein each spot is associated with one particular microscopic mirror and is freely movable across the pupil plane by tilting this mirror.

[0011] Similar illumination systems are known from US 2006/0087634 A1, US 7,061,582 B2, WO 2005/026843 A2 and WO 2010/006687 A1. US 2010/0157269 A1 discloses an illumination system in which an array of micromirrors is directly imaged on the mask.

[0012] As mentioned further above, it is usually desired to illuminate, at least after scan integration, all points on the mask with the same irradiance and angular irradiance distribution. If points on the mask are illuminated with different irradiances, this usually results in undesired variations of the critical dimension (CD) on wafer level. For example, in the presence of irradiance variations the image of a line having a uniform width on the light sensitive surface may also have irradiance variations along its length. Because of the fixed exposure threshold of the resist, such irradiance variations directly translate into widths variations of a structure that shall be defined by the image of the line.

[0013] If the angular irradiance distribution varies over the illumination field on the mask, this also has a negative impact on the quality of the image that is produced on the light sensitive surface. For example, if the angular irradiance distribution is not perfectly balanced, i. e. more light impinges from one side on a mask point than from the opposite side, the conjugate image point on the light sensitive surface will be laterally shifted if the light sensitive surface is not perfectly arranged in the focal plane of the projection objective.

[0014] For modifying the spatial irradiance distribution in the illumination field US 6,404,499 A and US 2006/0244941 A1 propose mechanical devices that comprise two opposing arrays of opaque finger-like stop elements that are arranged side by side and aligned parallel to the scan direction. Each pair of mutually opposing stop elements can be displaced along the scan direction so that the distance between the opposing ends of the stop elements is varied. If this device is arranged in a field plane of the illumination system that is imaged by an objective on the mask, it is possible to produce a slit-shaped illumination field whose width along the scan direction may vary along the cross-scan direction. Since the irradiance is integrated during each scan cycle, the integrated irradiance (sometimes also referred to as illumination dose) can be finely adjusted for a plurality of cross-scan positions in the illumination field.

[0015] However, these devices are mechanically very complex and expensive. This is also due to the fact that these devices have to be arranged in or very close to a field plane in which usually the blades of a movable field stop is arranged.

[0016] Adjusting the angular irradiance distribution in a field dependent manner is more difficult. This is mainly because the spatial irradiance distribution is only a function of the spatial coordinates x, y, whereas the angular irradiance distribution also depends on the direction of incidence given by a pair of angles α, β.

[0017] WO 2012/100791 A1 discloses an illumination system in which a first mirror array is used to produce a desired irradiance distribution in the pupil plane of the illumination system. In close proximity to the pupil plane an optical integrator is arranged that has a plurality of light entrance facets. Thus images of the light entrance facets are superimposed on the mask. The light spots produced by the mirror array have an area that is at least five times smaller than the total area of the light entrance facets. Thus it is possible to produce variable light patterns on the light entrance facets. In this manner different angular irradiance distributions can be produced on different portions of the illumination field. It is thus possible, for example, to produce an X dipole and a Y dipole illumination setting at a given time in the illumination field.

[0018] In order to ensure that the portions with different illumination settings are sharply delimited, it is proposed to use a second mirror array configured as a digital mirror device (DMD). This second mirror array is illuminated by the first mirror array and is imaged on the light entrance facets by an objective. By bringing larger groups of micromirrors of the second mirror array in an "off"-state, it is possible to produce irradiance distributions on the light entrance facets that have sharp boundaries.

[0019] However, it turned out that it is difficult to produce so many and so small freely movable light spots with the first mirror array. Furthermore, this prior art illumination system is mainly concerned with producing completely different illumination settings at different portions in the illumination field. For that reason the light entrance facets are usually not completely, but only partially illuminated.

[0020] Furthermore, it is difficult to provide a second mirror array having a sufficiently large number of micromirrors. If the number of light entrance facets on the optical integrator is large, the second mirror array needs more micromirrors than currently available digital mirror devices have.

[0021] US 6,515,734 B1 discloses a maskless exposure apparatus in which light patterns on a number of

digital mirror devices (DMD) are individually imaged on a wafer or another substrate so that the individual images of the light patterns partly overlap.US 5,517,279 discloses an exposure apparatus in which a mask is directly imaged on a wafer using a microlens array.

[0022] US 7,932,993 B2 discloses a maskless exposure apparatus in which a light pattern on a spatial light modulator is imaged by a field microlens array and an image microlens array on a wafer or another substrate. One field microlens and an associated image microlens commonly produce a reduced image of a certain object area of the spatial light modulator. The images on the wafer are therefore separated by gaps. By moving the wafer a contiguous exposure of the resist is accomplished.

[0023] US 8,334,935 B2 relates to a digital projection system to be used in cinematic theatres. In one embodiment the system comprises a plurality of DMD. Each DMD projects only a discrete portion of an entire image frame of a motion picture image on the target display surface.

[0024] WO 2010/006687 A1 discloses an illumination system that is similar to the one disclosed in WO 2012/100791 A1 that has been mentioned above. Here the variable light patterns on the light entrance facets are not used to modify a field dependence of the angular light distribution, but to take over the function of the movable blades of the adjustable field stop. However, also in this prior art illumination system very small light spots have to be produced on the light entrance facets. These spots are produced by a mirror array at positions that can be varied by changing a deflection angle produced by the mirrors.

SUMMARY OF THE INVENTION

[0025] It is an object of the present invention to provide an illumination system of a microlithographic projection exposure apparatus which is capable of adjusting both the spatial and the angular irradiance distribution in a field dependent manner. This means that it shall be possible to adjust the irradiance and angular irradiance distribution at different points in the illumination field differently.

[0026] In accordance with the present invention this object is achieved by an illumination system of a microlithographic projection exposure apparatus comprising a pupil plane and an optical integrator configured to produce a plurality of secondary light sources in the pupil plane. The optical integrator comprises a plurality of light entrance facets each being associated with one of the secondary light sources. A spatial light modulator has a light exit surface and is configured to transmit or to reflect impinging projection light in a spatially resolved manner. A pupil forming unit is configured to direct projection light on the spatial light modulator. An objective images the light exit surface of the spatial light modulator onto the light entrance facets of the optical integrator. A control unit is configured to control the pupil forming unit and the spatial light modulator. According to the invention the light exit surface of the optical light modulator comprises groups of object areas, wherein said groups are separated by areas that are not imaged on the light entrance facets. The objective is configured to combine images of the object areas so that the images of the object areas abut on the optical integrator.

[0027] The invention is based on the perception that instead of using a spatial light modulator only for producing sharp edges of an irradiance distribution on the light entrance facets, it may also be used to modify the irradiance distribution if the object area imaged on a light entrance facet is completely illuminated so that there would be no need for sharp edges.

[0028] Each group of object areas may be realized as a single and independent device, for example a digital mirror device (DMD). In accordance with the invention the objective combines the images of these devices on the optical integrator so that these images seamlessly abut. Thus the spatial resolution in each object area of the spatial light modulator can be extremely high, because the resolutions of all devices are added. In this manner it is possible to produce a total resolution which may be as high as 10^8 pixel.

[0029] With a spatial light modulator configured in this manner it is possible to dispense with mechanically complex devices that are used in prior art illumination systems to adjust the spatial irradiance distribution along the cross-scan direction, and simultaneously to flexibly adjust the angular irradiance distribution at mask level in a field dependent manner. Since the geometrical optical flux is small in front of the optical integrator, the objective that images the light exit surface of the spatial light modulator on the light entrance facets can be realized with very few and preferably spherical lenses.

[0030] In one embodiment light patterns on the light entrance facets of the optical integrator are imaged on the mask. By modifying these light patterns it is thus possible to vary the size of the illumination field on the mask. For modifying the light patterns the spatial light modulator is used. Thus the function of prior art instead of using adjustable field stops is taken over by a suitable control of the spatial light modulator. The macroscopic movements of the blades in prior art adjustable field stops is replaced, for example, by minute tilt movements of a huge number of digital micromirrors.

[0031] In this manner the mechanically complex and expensive adjustable field stop can be dispensed with. In accordance with the invention there is no need for a field plane (i.e. a plane that is optically conjugate to the mask) between the light entrance facets and the mask. Thus also the bulky and expensive objective that images the movable blades on the mask is not required.

[0032] In comparison to this bulky objective, the additional objective that images the light exit surface of the spatial light modulator on the light entrance facets of the optical integrator has a much smaller size and complex-

ity. This is because the light passing through this objective is usually almost parallel, which results in a small numerical aperture. Thus one of the two main quantities that have an impact on the size and complexity of objectives, namely numerical aperture and field size, is small as compared to objectives that image the blades on the mask. The objective that images the light exit surface of the spatial light modulator on the light entrance facets can therefore be realized with very few and preferably spherical lenses.

[0033] If compared to the prior art illumination system disclosed in WO 2010/006687 A1, the main benefit of the illumination system in accordance with the present invention is the use of a spatial light modulator having a light exit surface that is imaged on the light entrance facets. For that reason it is not necessary to move tiny spots to arbitrary positions on the light entrance facets, as this is the case in the prior art illumination system. Instead, the light modulator only needs to produce variable light patterns on its light exit surface. As will be explained below in further detail, this can be accomplished with relatively simple digital devices such as digital mirror devices (DMD) or LCD panels.

[0034] Since all components of the illumination system may be purely reflective, the invention can principally also be used in EUV illumination systems.

[0035] The objective may comprise a first array of first optical elements, wherein each first optical element forms a magnified image of one of the groups in an intermediate image plane. In principle the light entrance facets may be directly arranged in the intermediate image plane. Preferably, however, the objective comprises imaging optics that image the intermediate image plane on the light entrance facets of the optical integrator. This has the advantage that the size of the image field in the intermediate image plane can be adapted to the size of the optical integrator with the help of the imaging optics. Since the active area of the optical integrator often has a larger diameter than the image field in the intermediate image plane, the imaging optics preferably has a magnification M with $|M| > 1$.

[0036] In one embodiment the objective comprises a second array of second optical elements that is arranged in the intermediate image plane. These second optical elements may be used to ensure that light bundles emerging from the intermediate image plane have chief rays that extend parallel to the optical axis of the objective. Such a telecentric light path is often desirable for various reasons. In this context it is to be understood that the term "in the intermediate image plane" also encompasses cases in which the array is not arranged exactly in the intermediate image plane, but slightly displaced from it, as long as this can still be considered as being substantially optically equivalent, from a practical point of view, to an exact arrangement.

[0037] Preferably each second optical element is associated with one of the first optical elements in a one to one correspondence so that each second optical element receives projection light only from the associated one of the first optical elements.

[0038] The pupil forming unit may comprise a first beam deflection area of first reflective or transparent beam deflection elements. Each beam deflection element may be configured to illuminate a spot on the spatial light modulator at a position that is variable by changing a deflection angle produced by the beam deflection element. Then it is possible to quickly and variably change the irradiance distribution on the spatial light modulator and thus on the optical integrator. Alternatively or additionally, the pupil forming unit may comprise one or more diffractive optical elements that produce a desired angular light distribution.

[0039] The spatial light modulator may comprise a second beam deflection array of second reflective or transparent beam deflection elements. Each second beam deflection element may be capable to be in an "on" state, in which it directs impinging projection light towards the optical integrator, and in an "off" state, in which it directs impinging projection light elsewhere. Such digital beam deflection arrays may be realized as digital mirror devices (DMD) or as LCD panels, for example.

[0040] If the second beam deflection elements are mirrors, the projection light propagating from the pupil forming unit to the spatial light modulator preferably passes at least through a portion of the objective. This is particularly advantageous if the distance between the mirrors and the objective is small so that it is difficult to direct the projection light on the mirrors through the narrow gap between the mirrors and the objective.

[0041] In one embodiment projection light propagating from the pupil forming unit to the spatial light modulator impinges on the first array of first optical elements and also on the second array of second optical elements before it impinges on the mirror.

[0042] If the mirrors are planar mirrors having a mirror normal that forms, if the mirror in the in the "on" state, an angle $\alpha \neq 0°$ to a direction which is parallel to an optical axis of the objective, the latter may comprise a light tilting optical element that is configured to tilt impinging projection light rays by the angle α. Then the light tilting optical element compensates the tilt of the mirror. The advantage is that the objective may thus be configured in the same manner as if the mirrors were not tilted in the "on" state. In particular, the numerical aperture of the objective does not have to increase due to the tilted arrangement of the mirrors in the "on" state.

[0043] The light tilting element, which is preferably arranged between the mirrors and the first optical elements, may comprise a transparent refractive wedge. In one embodiment the wedge is formed as a Fresnel wedge comprising a plurality of individual wedge elements.

[0044] In another embodiment the pupil forming unit produces an angular light distribution in a pupil plane of the objective in an area such that projection light, after reflection from the mirrors, cannot pass through the area again irrespective of whether the mirrors are in the "on"

or "off" state. This exploits the fact that if the incoming projection light uses a different portion of the available numerical aperture NA as the modulated reflected projection light, the different angular distributions result in different portions in the pupil plane through which the incoming and the modulated reflected projection light pass. This can be used to couple the incoming projection light into the objective without disturbing the propagation of the modulated reflected projection light.

[0045] The area may be located on a beam deviating surface, for example a planar mirror or a deviating prism, that couples the projection light emerging from the pupil forming unit into a light path of the objective.

[0046] In another embodiment the objective contains an optical surface that reflects projection light propagating from the pupil forming unit towards the mirrors and transmits projection light after it has been reflected from the mirrors, but before it impinges on the light entrance facets, or vice versa. The different reflectance for the incoming projection light and the modulated projection light that has been reflected from the mirrors may be as result of a suitable polarization control, for example.

[0047] An easier approach is to use an optical surface that has an angle dependent reflectance. In the simplest case this is achieved by an optical surface, for example a prism surface, that reflects the projection light as a result of total internal reflection. Total internal reflection occurs only if the angle of incidence exceeds the critical angle. Therefore such an optical surface may be used to separate incoming projection light and modulated projection light using different portions of the available numerical aperture NA of the objective.

[0048] In one embodiment the control unit is configured to control the spatial light modulator such that along a scan direction a length of an image, which is formed on the mask from a light pattern in one of the object areas, gradually increases at the beginning of a scan cycle and gradually decreases at the end of the scan cycle. With such a control the movable blades that perform the same function in the prior art may be dispensed with.

[0049] The control unit may further be configured to control the spatial light modulator such that rows of adjacent second beam deflection elements are simultaneously brought from the "off" state into the "on" state, and vice versa, during the scan cycle.

[0050] If the function of prior art movable blades that are arranged in an intermediate field plane is taken over by the suitably controlled spatial light modulator, the intermediate field plane may be dispensed with. In other words, between the light entrance facets and the mask there will be no plane that is optically conjugate to the mask.

[0051] Subject of the present invention is also a method of operating an illumination system of a microlithographic projection exposure apparatus comprising the following steps:

a) providing a spatial light modulator having a light exit surface that comprises first areas that are separated by second areas;

b) imaging the first areas, but not the second areas, on a final image plane so that images of the first areas abut in the final image plane.

[0052] The final image plane may be arranged on an optical integrator that is configured to produce a plurality of secondary light sources in a pupil plane. The optical integrator may comprise a plurality of light entrance facets each being associated with one of these secondary light sources.

[0053] The light exit surface may be configured to transmit or to reflect impinging projection light in a spatially resolved manner.

[0054] A pupil forming unit may direct projection light on the spatial light modulator so that variable irradiance distributions can be obtained on the first areas.

[0055] The first areas may be imaged on a final image plane by an objective that comprises a first array of first optical elements. Each first optical element forms a magnified image of one of the first areas in an intermediate image plane. The intermediate image plane is then imaged on the final image plane.

[0056] Subject of the present invention is also an optical system comprising a final image plane and a spatial light modulator that has a light exit surface and is configured to modulate an optical property of light in a spatially resolved manner. The light exit surface of the optical light modulator comprises first areas and second areas, wherein the second areas separate the first areas and are not imaged on the final image plane. An objective images the light exit surface of the spatial light modulator on the final image plane, wherein the objective is configured to combine images of the first areas so that these images abut in the final image plane.

[0057] The optical property that is modulated by the spatial light modulator may be the amplitude, the phase or the state of polarization of light. For example, the spatial light modulator may be configured as a digital mirror device comprising a plurality of micromirrors that can be tilted about at least one axis, or as an LCD panel having a reflecting back surface. Such devices modulate the amplitude of impinging light. A spatial light modulator that modulates the phase of light may be realized as a digital mirror device in which the mirrors are not tilted, but axially displaced.

[0058] A spatial light modulator that modulates the state of polarization of impinging light may be realized as an LCD panel having a reflective back surface, but without an additional polarizing film.

[0059] If each first area of the spatial light modulator corresponds to a single light modulating device such as a DMD or an LCD panel, it is possible to obtain a continuous image in the final image plane which is seamlessly combined from the images of all first areas. Technical constraints that result from inevitable gaps between ad-

jacent devices that shall not be imaged on the final image plane are therefore removed. Instead, a light distribution is obtained in the final image plane that is equal to, or at least substantially similar to, the light distribution that would be obtained if the first areas seamlessly abutted in the object plane of the objective.

[0060] Preferably the objective comprises a first array of first optical elements each forming a magnified image of one of the first areas in an intermediate image plane. Imaging optics then image the intermediate image plane on the final image plane.

[0061] The objective may comprise a second array of second optical elements that is arranged in the intermediate image plane. Such second optical elements may be used to tilt light bundles such that a telecentric beam path is obtained.

[0062] Each second optical element may be associated with one of the first optical elements in a one to one correspondence so that each second optical element receives light only from the associated one of the first optical elements.

[0063] The spatial light modulator may comprise a beam deflection array of reflective or transparent beam deflection elements. Each second beam deflection element may be capable to be in an "on" state, in which it directs impinging light towards the final image plane, and in an "off" state, in which it directs impinging light elsewhere.

[0064] Particularly if the second beam deflection elements are mirrors, light directed on the spatial light modulator may pass at least through a portion of the objective. This is usually easier than directing light through a small gap formed between the spatial light modulator and the first optical elements. Light propagating to the spatial light modulator may not only impinge on the first array of first optical elements, but also on the second array of second optical elements before it impinges on the mirrors.

[0065] If the mirrors are planar mirrors having a mirror normal that forms, if the mirror is in the "on" state, an angle $\alpha \neq 0°$ to a direction which is parallel to an optical axis of the objective, the objective may comprise a light tilting optical element that is configured to tilt impinging projection light rays by an angle α.

[0066] The light tilting element may be arranged between the mirrors and the first optical element and may comprise a wedge. The latter may be formed as a Fresnel wedge comprising a plurality of individual wedge elements.

[0067] An angular light distribution may be produced in a pupil plane of the objective in an area such that light, after reflection from the mirrors, cannot pass through the array again irrespective of whether the mirrors are in the "on" or in the "off" state. The area may be located on a beam deviating surface that couples incoming projection light into a light path of the objective.

[0068] In another embodiment the objective contains an optical surface that reflects light on its way towards the mirrors and transmits light after it has been reflected from the mirrors, but before it impinges on the final image plane, or vice versa. The optical surface may reflect the light by total internal reflection and may be formed as a prism surface.

DEFINITIONS

[0069]

The term "light" is used herein to denote any electromagnetic radiation, in particular visible light, UV, DUV, VUV and EUV light and X-rays.

The term "light ray" is used herein to denote light whose path of propagation can be described by a line.

The term "light bundle" is used herein to denote a plurality of light rays that have a common origin in a field plane.

The term "light beam" is used herein to denote all light that passes through a particular lens or another optical element.

The term "position" is used herein to denote the location of a reference point of a body in the three-dimensional space. The position is usually indicated by a set of three Cartesian coordinates. The orientation and the position therefore fully describe the placement of a body in the three-dimensional space.

The term "surface" is used herein to denote any plane or curved surface in the three-dimensional space. The surface may be part of a body or may be completely separated therefrom, as it is usually the case with a field or a pupil plane.

The term "field plane" is used herein to denote the mask plane or any other plane that is optically conjugate to the mask plane.

The term "pupil plane" is a plane in which (at least approximately) a Fourier relationship is established to a field plane. Generally marginal rays passing through different points in the mask plane intersect in a pupil plane, and chief rays intersect the optical axis. As usual in the art, the term "pupil plane" is also used if it is in fact not a plane in the mathematical sense, but is slightly curved so that, in the strict sense, it should be referred to as pupil surface.

The term "uniform" is used herein to denote a property that does not depend on the position.

The term "optical raster element" is used herein to denote any optical element, for example a lens, a prism or a diffractive optical element, which is ar-

ranged, together with other identical or similar optical raster elements so that each optical raster element is associated with one of a plurality of adjacent optical channels.

The term "optical integrator" is used herein to denote an optical system that increases the product $NA \cdot a$, wherein NA is the numerical aperture and a is the illumination field area.

The term "condenser" is used herein to denote an optical element or an optical system that establishes (at least approximately) a Fourier relationship between two planes, for example a field plane and a pupil plane.

The term "conjugate plane" is used herein to denote planes between which an imaging relationship is established. More information relating to the concept of conjugate planes are described in an essay E. Delano entitled: "First-order Design and the y,y Diagram", Applied Optics, 1963, vol. 2, no. 12, pages 1251-1256.

The term "field dependence" is used herein to denote any functional dependence of a physical quantity from the position in a field plane.

The term "spatial irradiance distribution" is used herein to denote how the total irradiance varies over a real or imaginary surface on which light impinges. Usually the spatial irradiance distribution can be described by a function $I_s(x,y)$, with x, y being spatial coordinates of a point on the surface.

The term "angular irradiance distribution" is used herein to denote how the irradiance of a light bundle varies depending on the angles of the light rays that constitute the light bundle. Usually the angular irradiance distribution can be described by a function $I_a(\alpha,\beta)$, with α, β being angular coordinates describing the directions of the light rays. If the angular irradiance distribution has a field dependence, I_a will be also a function of field coordinates, i. e. $I_a = I_a(\alpha, \beta, x, y)$. The field dependence of the angular irradiance distribution may be described by a set of expansion coefficients a_{ij} of a Taylor (or another suitable) expansion of $I_a(\alpha, \beta, x, y)$ in x, y.

The term "scan cycle" is used herein to denote a scanning process during which a complete die on the wafer or another support is exposed to projection light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0070] 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 accompanying drawings in which:

FIG. 1 is a schematic perspective view of a projection exposure apparatus in accordance with one embodiment of the present invention;

FIG. 2 is an enlarged perspective view of the mask to be projected by the projection exposure apparatus shown in FIG. 1, illustrating various deficiencies of the angular irradiance distribution;

FIG. 3 is a meridional section through an illumination system being part of the apparatus shown in FIG. 1;

FIG. 4 is a perspective view of a first mirror array contained in the illumination system shown in FIG. 3;

FIG. 5 is a perspective view of a second mirror array contained in the illumination system shown in FIG. 3;

FIG. 6 is a perspective view of an optical integrator contained in the illumination system shown in FIG. 3;

FIG. 7 is a schematic meridional section through the first and the second mirror array shown in FIGS. 4 and 5;

FIG. 8 is a perspective view on the second mirror array shown in FIG. 5, but illuminated with two poles;

FIG. 9 is a perspective view of the optical integrator shown in FIG. 6, but illuminated with two poles;

FIG. 10 is a schematic meridional section through a portion of the illumination system in which only a mirror array, a condenser and an array of optical raster elements are shown;

FIGS. 11a and 11b are top views on the second mirror array and the optical integrator shown in FIG. 3;

FIG. 12 illustrates an irradiance distribution on a light entrance facet of the optical integrator;

FIG. 13 is a graph showing the scan inte-

grated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 12;

FIG. 14 illustrates another irradiance distribution on a light entrance facet of the optical integrator;

FIG. 15 is a graph showing the scan integrated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 14;

FIG. 16 is a top view on the second mirror array on which a plurality of light spots produce an irradiance distribution;

FIG. 17 shows the second mirror array of FIG. 16, but with several of the micromirrors in an "off"-state;

FIG. 18 is a top view on the irradiance distribution on a single light entrance facet for an alternative embodiment;

FIG. 19 is a graph showing the scan integrated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 18;

FIGS. 20a to 20c illustrate images of micromirrors on a light entrance facet and the corresponding irradiance distribution on the mask;

FIG. 21 is a graph showing the total irradiance distribution that is obtained by superimposing the irradiance distributions shown in FIGS. 20a to 20c;

FIG. 22 is a schematic meridional section through an objective, which is contained in the illumination system shown in FIG. 3, and an additional scattering plate;

FIG. 23 is a schematic perspective view on an object area on the second mirror array, an anamorphotic objective and an optical raster element of the optical integrator;

FIG. 24 shows on the left hand side a top view on a spatial light modulator comprising eight digital mirror devices on a single support, and on the right hand side images of the digital mirror devices on the optical integrator;

FIG. 25 is a meridional section through an objective that seamlessly stitches images of the digital mirror devices on the optical integrator according to one embodiment of the present invention;

FIG. 26 is a meridional section through an objective comprising field lenses according to another embodiment of the present invention;

FIG. 27 is a meridional section through an objective similar to the objective shown in FIG. 26;

FIG. 28 is a meridional section through an objective in which incoming projection light is coupled into the objective with the help of a prism at which total internal reflection occurs only for the incoming projection light;

FIG. 29 is a meridional section through an objective in which incoming projection light is coupled into the objective with the help of a mirror arranged in a pupil plane of the objective;

FIG. 30 is an enlarged meridional section through a micromirror that is tilted in its "on" state with respect to the optical axis of the objective;

FIG. 31 is a similar meridional section as shown in FIG. 30, but with an additional transparent wedge arranged in front of the mirror;

FIG. 32 is a meridional section through a plurality of mirrors and a Fresnel wedge arranged in front of it;

FIG. 33 is a meridional section through an illumination system according to another embodiment in which a diffractive optical element is used to define the irradiance distribution on an LCD panel used as spatial light modulator;

FIGS. 34a to 34h are top views on an object area of the spatial light modulator, on a light

entrance facet and on the mask at various stages of a scan cycle;

FIG. 35 is a flow diagram that illustrates important method steps of the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

I.

General Construction of Projection Exposure Apparatus

[0071] FIG. 1 is a perspective and highly simplified view of a projection exposure apparatus 10 in accordance with the present invention. The apparatus 10 comprises a light source 11 that may be realized as an excimer laser, for example. The light source 11 in this embodiment produces projection light having a center wavelength of 193 nm. Other wavelengths, for example 257 nm or 248 nm, are envisaged as well.

[0072] The apparatus 10 further comprises an illumination system 12 which conditions the projection light provided by the light source 11 in a manner that will be explained below in further detail. The projection light emerging from the illumination system 12 illuminates an illumination field 14 on a mask 16. The mask 16 contains a pattern 18 formed by a plurality of small features 19 that are schematically indicated in FIG. 1 as thin lines. In this embodiment the illumination field 14 has the shape of a rectangle. However, other shapes of the illumination field 14, for example a ring segment, are also contemplated.

[0073] A projection objective 20 comprising lenses L1 to L6 images the pattern 18 within the illumination field 14 onto a light sensitive layer 22, for example a photoresist, which is supported by a substrate 24. The substrate 24, which may be formed by a silicon wafer, is arranged on a wafer stage (not shown) such that a top surface of the light 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 magnification β with $|\beta| < 1$, a minified image 18' of the pattern 18 within the illumination field 14 is projected onto the light sensitive layer 22.

[0074] During the projection the mask 16 and the substrate 24 move along a scan direction which corresponds to the Y direction indicated in FIG. 1. The illumination field 14 then scans over the mask 16 so that patterned areas larger than the illumination field 14 can be continuously imaged. The ratio between the velocities of the substrate 24 and the mask 16 is equal to the magnification β of the projection objective 20. If the projection objective 20 does not invert the image ($\beta > 0$), the mask 16 and the substrate 24 move along the same direction, as this is indicated in FIG. 1 by arrows A1 and A2. However, the present invention may also be used in stepper tools in which the mask 16 and the substrate 24 do not move during projection of the mask.

II.

Field dependent angular irradiance distribution

[0075] FIG. 2 is an enlarged perspective view of the mask 16 containing another exemplary pattern 18. For the sake of simplicity it is assumed that the pattern 18 comprises only features 19 that extend along the Y direction. It is further assumed that the features 19 extending along the Y direction are best imaged on the light sensitive layer 22 with an X dipole illumination setting.

[0076] In FIG. 2 an exit pupil 26a associated with a light bundle is illustrated by a circle. The light bundle converges towards a field point that is located at a certain X position of the illumination field 14 at a first time during a scan cycle. In the exit pupil 26a two poles 27a, which are spaced apart along the X direction, represent directions from which projection light propagates towards this field point. The light energies concentrated in each pole 27a are assumed to be equal. Thus the projection light impinging from the +X direction has the same energy as the projection light impinging from the -X direction. Since the features 19 are assumed to be uniformly distributed over the pattern 18, this X dipole illumination setting should be produced at each field point on the mask 16.

[0077] Another exit pupil denoted by 26b is associated with a light bundle that converges towards a field point that is located at another X position of the illumination field 14 at a later time of the scan cycle. The light energies concentrated in each pole 27b are again equal. However, the light associated with the poles 27b are tilted compared to the light cones of light that are associated with the ideal pole 27a. This means that the field point receives the same amount of projection light, but the directions from which the projection light impinges on the field point are not ideal for imaging the features 19 on the light sensitive layer 22.

[0078] A further exit pupil denoted by 26c is associated with a point in the illumination field 14 that is located at still another X position. Here it is assumed that the directions from which the projection light impinges on the field point are again ideal for imaging the features 19. Therefore also the light cones associated with the poles 27c have the same cone angle and orientation as the cones associated with the ideal exit pupil 26a. However, the poles 27c are not balanced, i.e. the light energy concentrated in the poles 27c differs from one another. Thus the projection light impinging from the +X direction has less energy than the projection light impinging from the -X direction.

[0079] From the foregoing it becomes clear that the ideal angular irradiance distribution represented by the exit pupil 26a is not obtained at each X position in the illumination field 14. The angular irradiance distribution is therefore field-dependent, i.e. at different field points

the angular irradiance distribution is different.

[0080] A field dependence may not only occur along the X direction, but also along the Y direction within the illumination field 14. Then one point on the mask 16 experiences different angular irradiance distributions while it passes through the illumination field 14 during a scan cycle. If a field dependence along the Y direction (i.e. the scan direction) occurs, it has to be taken into account that the total effect for a particular field point is obtained by integrating the different angular irradiance distributions.

[0081] There is a wide variety of further field-dependent deviations of a real angular irradiance distribution from the ideal one. For example, the poles in the exit pupil associated with some field points may be deformed, blurred or may not have a desired non-uniform irradiance distribution.

[0082] If field dependent deviations from the ideal angular irradiance distribution occur, this generally has a negative impact on the quality of the pattern image that is formed on the light sensitive layer 22. In particular, the dimensions of the structures that are produced with the help of the apparatus 10 may vary inadvertently, and this may compromise the function of the devices containing these structures. Therefore it is generally desired to eliminate any field dependence of the illumination setting in the illumination field 14.

[0083] Sometimes, however, it is desirable to deliberately introduce a field dependence of the angular irradiance distribution. This may be expedient, for example, if the projection objective 20 or the mask 16 have field depending properties that affect the image of the pattern 18 on the light sensitive layer 22. Variations of the imaging properties of the projection objective 20 may occur as a result of manufacturing tolerances, aging phenomena or non-uniform temperature distributions, for example. A field dependence of the mask 16 often occurs as a result of features that have different orientations or dimensions, for example. Often field dependent adverse effects can be successfully reduced by selectively introducing a field dependence of the angular irradiance distribution. Since some of these effects change very rapidly, it is sometimes desired to change the field dependence of the angular irradiance distribution during a single scan cycle.

III.

General Construction of Illumination System

[0084] FIG. 3 is a meridional section through the illumination system 12 shown in FIG. 1. For the sake of clarity, the illustration of FIG. 3 is considerably simplified and not to scale. This particularly implies that different optical units are represented by one or very few optical elements only. In reality, these units may comprise significantly more lenses and other optical elements.

[0085] In the embodiment shown, the projection light emitted by the light source 11 enters a beam expansion unit 32 which outputs an expanded and almost collimated light beam 34. To this end the beam expansion unit 32 may comprise several lenses or may be realized as a mirror arrangement, for example.

[0086] The projection light beam 34 then enters a pupil forming unit 36 that is used to produce variable spatial irradiance distributions in a subsequent plane. To this end the pupil forming unit 36 comprises a first mirror array 38 of very small mirrors 40 that can be tilted individually about two orthogonal axes with the help of actuators. FIG. 4 is a perspective view of the first mirror array 38 illustrating how two parallel light beams 42, 44 are reflected into different directions depending on the tilting angles of the mirrors 40 on which the light beams 42, 44 impinge. In FIGS. 3 and 4 the first mirror array 38 comprises only 6x6 mirrors 40; in reality the first mirror array 38 may comprise several hundreds or even several thousands mirrors 40.

[0087] The pupil forming unit 36 further comprises a prism 46 having a first plane surface 48a and a second plane surface 48b that are both inclined with respect to an optical axis OA of the illumination system 12. At these inclined surfaces 48a, 48b impinging light is reflected by total internal reflection. The first surface 48a reflects the impinging light towards the mirrors 40 of the first mirror array 38, and the second surface 48b directs the light reflected from the mirrors 40 towards an exit surface 49 of the prism 46. The angular irradiance distribution of the light emerging from the exit surface 49 can thus be varied by individually tilting the mirrors 40 of the first mirror array 38. More details with regard to the pupil forming unit 36 can be gleaned from US 2009/0116093 A1.

[0088] The angular irradiance distribution produced by the pupil forming unit 36 is transformed into a spatial irradiance distribution with the help of a first condenser 50. The condenser 50, which may be dispensed with in other embodiments, directs the impinging light towards a digital spatial light modulator 52 that is configured to reflect impinging light in a spatially resolved manner. To this end the digital spatial light modulator 52 comprises a second mirror array 54 of micromirrors 56 that are arranged in a mirror plane 57 and can be seen best in the enlarged cut-out C of FIG. 3 and the enlarged cut-out C' of FIG. 5. In contrast to the mirrors 40 of the first mirror array 38, however, each micromirror 56 of the second mirror array 54 has only two stable operating states, namely an "on" state, in which it directs impinging light via a first objective 58 towards an optical integrator 60, and an "off" state, in which it directs impinging towards a light absorbing surface 62. The objective 58 is represented in FIG. 3 only schematically with two lenses. In section IV.8 it will be further explained how the objective 58 is configured in accordance with the present invention.

[0089] The second mirror array 54 may be realized as a digital mirror device (DMD), as they are commonly used in beamers, for example. Such devices may comprise up to several million micromirrors that can be switched be-

tween the two operating states many thousands times per second.

[0090] Similar to the pupil forming unit 36, the spatial light modulator 52 further comprises a prism 64 having an entrance surface 65 that is arranged perpendicular to the optical axis OA and a first plane surface 66a and a second plane surface 66b that are both inclined with respect to the optical axis OA of the illumination system 12. At these inclined surfaces 66a, 66b impinging light is reflected by total internal reflection. The first surface 66a reflects the impinging light towards the micromirrors 56 of the second mirror array 54, and the second surface 66b directs the light reflected from the micromirrors 56 towards a surface 68 of the prism 64.

[0091] If all micromirrors 56 of the second mirror array 54 are in their "on" state, the second mirror array 54 has substantially the effect of a plane beam folding mirror. However, if one or more micromirrors 56 are switched to their "off" state, the spatial irradiance distribution of the light emerging from the mirror plane 57 is modified. This can be used, in a manner that will be explained further below in more detail, to produce a field dependent modification of the angular light distribution on the mask 16.

[0092] As it already has been mentioned above, the light emerging from the prism 64 passes through the first objective 58 and impinges on the optical integrator 60. Since the light passing through the first objective 58 is almost collimated, the first objective 58 may have a very low numerical aperture (for example 0.01 or even below) and thus can be realized with a few small spherical lenses. The first objective 58 images the mirror plane 57 of the spatial light modulator 52 onto the optical integrator 60.

[0093] The optical integrator 60 comprises, in the embodiment shown, a first array 70 and a second array 72 of optical raster elements 74. FIG. 6 is a perspective view of the two arrays 70, 72. Each array 70, 72 comprises, on each side of a support plate, a parallel array of cylinder lenses extending along the X and the Y direction, respectively. The volumes where two cylinder lenses cross form optical raster elements 74. Thus each optical raster element 74 may be regarded as a microlens having cylindrically curved surfaces. The use of cylinder lenses is advantageous particularly in those cases in which the refractive power of the optical raster elements 74 shall be different along the X and the Y direction. A different refractive power is necessary if the square irradiance distribution on the optical integrator 60 shall be transformed into a slit-shaped illumination field 14, as this is usually the case. The surface of the optical raster elements 74 pointing towards the spatial light modulator 52 will be referred to in the following as light entrance facet 75.

[0094] The optical raster elements 74 of the first and second array 70, 72 respectively, are arranged one behind the other in such a way that one optical raster element 74 of the first array 70 is associated in a one to one correspondence with one optical raster element 74 of the second array 72. The two optical raster elements 74, which are associated with each other, are aligned along a common axis and define an optical channel. Within the optical integrator 60 a light beam which propagates in one optical channel does not cross or superimpose with light beams propagating in other optical channels. Thus the optical channels associated with the optical raster elements 74 are optically isolated from each other.

[0095] In this embodiment a pupil plane 76 of the illumination system 12 is located behind the second array 72; however, it may equally be arranged in front of it. A second condenser 78 establishes a Fourier relationship between the pupil plane 76 and a mask plane 88 in which the mask 16 moves along the scan direction Y during a scan cycle. Between the light entrance facets 75 of the optical integrator 60 and the mask 16 there is no field plane, i.e. no plane that is optically conjugate to the mask 16. This is a remarkable feature of the illumination system 12, because conventional illumination systems usually have an adjustable field stop that comprises movable blades and is arranged in a field plane between the optical integrator 60 and the mask 16. The movable blades ensure that the illumination field 14, synchronized with the mask movement, opens and closes along the scan direction Y at the beginning and the end of each scan cycle, respectively. As it will become apparent from section IV.10 below, this function is performed in the illumination system 12 by a suitable control of the spatial light modulator 52.

[0096] The mask plane 88 is thus optically conjugate to a raster field plane 84 which is located within or in close proximity to the light entrance facets 75 of the optical integrator 60. This means that an irradiance distribution on each light entrance facet 75 in the raster field plane 84 is imaged onto the mask plane 88 by the associated optical raster element 74 of the second array 72 and the second condenser 78. The images of the irradiance distributions (or light pattern) on the light entrance facet 75 within all optical channels superimpose in the mask plane 88, which results in a very uniform illumination of the mask 16.

[0097] Another way of describing the uniform illumination of the mask 16 is based on the irradiance distribution which is produced by each optical channel in the pupil plane 76. This irradiance distribution is often referred to as secondary light source. All secondary light sources commonly illuminate the mask plane 88 with projection light from different directions. If a secondary light source is "dark", no light impinges on the mask 16 from a (small) range of directions that is associated with this particular light source. Thus it is possible to set the desired angular light distribution on the mask 16 by simply switching on and off the secondary light sources formed in the pupil plane 76. This is accomplished by changing the irradiance distribution on the optical integrator 60 with the help of the pupil forming unit 36.

[0098] The pupil forming unit 36 and the spatial light modulator 52 are connected to a control unit 90 which is, in turn, connected to an overall system control 92 illus-

trated as a personal computer. The control unit 90 is configured to control the mirrors 40 of the pupil forming unit 36 and the micromirrors 56 of the spatial light modulator 52 in such a manner that the angular irradiance distribution in the mask plane 88 is uniform, or a desired field dependence angular irradiance distribution is obtained, and that the illumination field 14 opens and closes along the scan direction Y at the beginning and the end of the scan cycle.

[0099] In the following it will be described how this is accomplished.

IV.

Function and Control of the Illumination System

1. Pupil forming

[0100] FIG. 7 schematically illustrates how the pupil forming unit 36 produces an irradiance distribution on the micromirrors 56 of the spatial light modulator 52. For the sake of simplicity the prisms 46, 64 are not shown.

[0101] Each mirror 40 of the first mirror array 38 is configured to illuminate a spot 94 on the mirror plane 57 of the spatial light modulator 52 at a position that is variable by changing a deflection angle produced by the respective mirror 40. Thus the spots 94 can be freely moved over the mirror plane 57 by tilting the mirrors 40 around their tilt axes. In this way it is possible to produce a wide variety of different irradiance distributions on the mirror plane 57. The spots 94 may also partly or completely overlap, as this is shown at 95. Then also graded irradiance distributions may be produced.

[0102] FIG. 8 is a perspective view, similar to FIG. 5, on the second mirror array 54 contained in the spatial light modulator 52. Here it is assumed that the pupil forming unit 36 has produced an irradiance distribution on the second mirror array 54 that consists of two square poles 27 each extending exactly over 6x6 micromirrors 56. The poles 27 are arranged point-symmetrically along the X direction.

[0103] The objective 58 forms an image of this irradiance distribution on the light entrance facets 75 of the optical integrator 60, as this is shown in FIG. 9. Here it is assumed that all micromirrors 56 are in the "on"-state so that the irradiance distribution formed on the second mirror array 54 is identically reproduced (apart from a possible scaling due to a magnification of the objective 58) on the light entrance facets 75 of the optical integrator 60. For the sake of simplicity images of gaps that separate adjacent micromirrors 56 of the second mirror array 54 are disregarded. The regular grid shown on the light entrance facets 75 represent an image of the borderlines of the micromirrors 56, but this image does not appear outside the poles 27 and is shown only in FIG. 9 for illustrative reasons.

2. Field dependence

[0104] Since the light entrance facets 75 are located in the raster field plane 84, the irradiance distribution on the light entrance facets 75 is imaged, via the optical raster elements 74 of the second array 72 and the second condenser 78, on the mask plane 88.

[0105] This will now be explained with reference to FIG. 10 which is an enlarged and not to scale cut-out from FIG. 3. Here only two pairs of optical raster elements 74 of the optical integrator 60, the second condenser 78 and the mask plane 88 are shown schematically.

[0106] Two optical raster elements 74 that are associated with a single optical channel are referred to in the following as first microlens 101 and second microlens 102. The microlenses 101, 102 are sometimes referred to as field and pupil honeycomb lenses. Each pair of microlenses 101, 102 associated with a particular optical channel produces a secondary light source 106 in the pupil plane 76. In the upper half of FIG. 10 it is assumed that converging light bundles L1a, L2a and L3a illustrated with solid, dotted and broken lines, respectively, impinge on different points of the light entrance facet 75 of the first microlens 101. After having passed the two microlenses 101, 102 and the condenser 78, each light bundle L1a, L2a and L3a converges to a focal point F1, F2 and F3, respectively. From the upper half of FIG. 10 it becomes clear that points, where light rays impinge on the light entrance facet 75, and points where these light rays pass the mask plane 88 are optically conjugate.

[0107] The lower half of FIG. 10 illustrates the case when collimated light bundles L1b, L2b and L3b impinge on different regions of the light entrance facet 75 of the first microlens 101. This is the more realistic case because the light impinging on the optical integrator 60 is usually substantially collimated. The light bundles L1b, L2b and L3b are focused in a common focal point F located in the second microlens 102 and then pass, now collimated again, the mask plane 88. Again it can be seen that, as a result of the optical conjugation, the region where a light bundle L1b, L2b and L3b impinges on the light entrance facet 75 corresponds to a portion of the illumination field 14 in the mask plane 88. As a matter of course, these considerations apply separately for the X and the Y direction if the microlenses 101, 102 have refractive power both along the X and Y direction.

[0108] Therefore each point on a light entrance facet 75 directly corresponds to a conjugate point in the illumination field 14 in the mask plane 88. If it is possible to selectively influence the irradiance on a point on a light entrance facet 75, it is thus possible to influence the irradiance of a light ray that impinges on the conjugate point in the mask plane 88 from a direction that depends on the position of the light entrance facet 75 with respect to the optical axis OA of the illumination system. The larger the distance between a particular light entrance facet 75 from the optical axis OA is, the larger is the angle under which said light ray impinges on the point on the

mask 16.

3. Modifying irradiance on light entrance facets

[0109] In the illumination system 12 the spatial light modulator 52 is used to modify the irradiance on points on the light entrance facets 75. In FIG. 9 it can be seen that each pole 27 extends over a plurality of small areas that are images of the micromirrors 56. If a micromirror is brought into an "off" state, the conjugate area on the light entrance facet 75 will not be illuminated, and consequently no projection light will impinge on a conjugate area on the mask from the (small) range of directions that is associated with this particular light entrance facet 75.

[0110] This will be explained in more detail with reference to FIGS. 11a and 11b which are top views on the micromirrors 56 of the spatial light modulator 52 and on the light entrance facets 75 of the optical integrator 60, respectively.

[0111] The thick dotted lines on the second mirror array 54 divide its mirror plane 57 into a plurality of object areas 110 each comprising 3x3 micromirrors 56. The objective 58 forms an image of each object area 110 on the optical integrator 60. This image will be referred to in the following as image area 110'. Each image area 110' completely coincides with a light entrance facet 75, i. e. the image areas 110' have the same shape, size and orientation as the light entrance facets 75 and are completely superimposed on the latter. Since each object area 110 comprises 3x3 micromirrors 56, the image areas 110' also comprise 3x3 images 56' of micromirrors 56.

[0112] In FIG. 11a there are eight object areas 110 that are completely illuminated by the pupil forming unit 36 with projection light. These eight object areas 110 form the two poles 27. It can be seen that in some of the object areas 110 one, two or more micromirrors 56d represented as black squares have been controlled by the control unit 90 such that they are in an "off"-state in which impinging projection light is not directed towards the objective 58, but towards the absorber 62. By switching micromirrors between the "on" and the "off" state it is thus possible to variably prevent projection light from impinging on corresponding regions within the image areas 110' on the light entrance facets 75, as this is shown in FIG. 11b. These regions will be referred to in the following as dark spots 56d'.

[0113] As has been explained above with reference to FIG. 10, the irradiance distribution on the light entrance facets 75 is imaged on mask plane 88. If a light entrance facet 75 contains one or more dark spots 56d', as this is illustrated in the upper portion of FIG. 12, the irradiance distribution produced in the mask plane 88 by the associated optical channel will have dark spots at certain X positions, too. If a point on a mask passes through the illumination field 14, the total scan integrated irradiance will thus depend on the X position of the point in the illumination field 14, as this is shown in the graph of FIG. 13. Points in the middle of the illumination field 14 will experience the highest scan integrated irradiance, because they do not pass through dark spots, and points at the longitudinal ends of the illumination field 14 will receive total irradiances that are reduced to different extents. Thus the field dependence of the angular light distribution on the mask 16 can be modified by selectively bringing one or more micromirrors 56 of the spatial light modulator 52 from an "on"-state into the "off"-state.

[0114] In a foregoing it has to be assumed that each object area 110, which is imaged on one of the light entrance facets 75, contains only 3x3 micromirrors 56. Thus the resolution along the cross-scan direction X that can be used to modify the field dependence of the angular light distribution is relatively coarse. If the number of micromirrors 56 within each object area 110 is increased, this resolution can be improved.

[0115] FIG. 14 illustrates a top view on one of the light entrance facets 75 for an embodiment in which 20x20 micromirrors 56 are contained in each object area 110. Then more complicated scan integrated irradiance distributions along the X direction can be achieved on the mask 16, as this is illustrated in the graph shown in FIG. 15.

4. Clipping

[0116] In the foregoing it has been assumed that the pupil forming unit 36 illuminates poles 27 on the second mirror array 54 that exactly extend over four adjacent object areas 110. Generally, however, it will be difficult to produce such an irradiance distribution with sharp edges.

[0117] The spatial light modulator 52 may also be used to clip a blurred irradiance distribution in the mirror plane 57 by bringing those micromirrors 56 into the "off"-state that lie outside the object areas 110 that shall be illuminated.

[0118] This is illustrated in FIGS. 16 and 17 in which an irradiance distribution 96 on the second mirror array 54 are shown. Here it is assumed that the movable light spots 94 produced by the mirrors 40 of the pupil forming unit 36 are superimposed to form four poles. If all micromirrors 56 of the spatial light modulator 52 are in the "on" state as shown in FIG. 16, the blurred irradiance distribution 96 would be imaged on the light entrance facets 75. If those micromirrors 56 surrounding the desired object areas 110 are brought into the "off"-state as shown in FIG. 17, they form a frame that delimits the poles and thus produces sharp edges of the intensity distribution on the light entrance facets.

5. Relative rotation

[0119] In the embodiments described so far it has been assumed that the micromirrors 56 are aligned parallel to the borderlines of the object areas 110. The rectangular grid formed by the micromirrors 56 is then parallel to the rectangular grid which is formed by the light entrance

facets 75. This results in irradiance distributions as shown in FIGS. 13 and 15 in which the irradiance along one "column" of micromirrors 56 is always uniform. Thus only stepped irradiance distributions can be produced on the light entrance facets 75.

[0120] Sometimes it is desirable to produce irradiance distributions that are not stepped, but contain inclined portions. This can be achieved if the two rectangular grids are not arranged parallel to each other, but with an angle α, as this is shown in FIG. 18. Here the images 56' of the micromirrors 56 form a grid 114 which forms an angle α with the lateral sides of the light entrance facet 75. Then the centers of adjacent micromirrors 56 are aligned along a straight line having an image 116 that forms the same angle α to a boundary line of the light entrance facet 75. If this angle α is distinct from $m \cdot 45°$ with m = 0, 1, 2, 3,..., the irradiance distribution will not have the shape of stepped profiles as shown in FIGS. 13 and 15.

[0121] FIG. 19 is a graph that illustrates the scan integrated irradiance distribution along the X direction for the rotated arrangement shown in FIG. 18. Some particular X positions are indicated in FIG. 18 with broken lines. If the angle α is distinct from $m \cdot 45°$ with m = 0, 1, 2, 3,..., the degeneration is reduced so that a desired attenuation can be obtained at more different X positions. In other words, it is thus possible to effectively increase the resolution along the X direction that is available to modify the field dependence of the angular irradiance distribution.

6a. Gaps - lateral displacement

[0122] As mentioned further above, it is usually inevitable that small gaps are formed between adjacent micromirrors 56 of the second mirror array 38. Images of these gaps are formed on the light entrance facets 75 and also on the mask 16. If these images extend parallel to the cross-scan direction X, this is of little concern because of the integrating effect that results from the scan operation. However, dark lines extending parallel to the scan direction Y could not be compensated by the integrating effect.

[0123] FIG. 20a shows in the upper portion a top view on one of the light entrance facets 75 in which the images of the gaps are denoted by 118'. The graph in the lower portion of FIG. 20a illustrates the irradiance distribution along the cross-scan direction X that is produced by this particular light entrance facet 75 in the mask plane 88. If all light entrance facets 75 would produce dark lines 120 at the same X positions, no projection light would reach points on the mask 16 at these positions.

[0124] FIGS. 20b and 20c show other light entrance facets 75 in which the gap images 118' are laterally displaced along the cross-scan direction X to different degrees. Consequently also the dark lines 120 in the irradiance distributions shown in the lower portion of these figures are laterally displaced. Since the irradiance distributions produced by each optical channel are superimposed in the mask plane 88, the dark lines 120 are averaged out, as this is shown in FIG. 21. The larger the number of light entrance facets 75 is and the smaller the dark lines 120 are, the more approximates the irradiance distribution I(x) in the mask plane 88 a uniform distribution.

6b. Gaps - scattering plate

[0125] Alternatively or additionally, a scattering plate 122 may be arranged in an optical path between the optical light modulator 52 and the mask plane 88 in order to avoid dark lines on the mask plane 88 caused by gap images 118'. Suitable positions of the scattering plate 122 are between the optical light modulator 52 and the objective 58, between the objective 58 and the optical integrator 60, or in the vicinity of the mask plane 88.

[0126] FIG. 22 is a schematic meridional section showing several micromirrors 56 of the spatial light modulator 52, the objective 58 and the scattering plate 122 arranged in between. A gap 118 between two adjacent micromirrors 56 is assumed to have a width d, and the axial distance between the scattering plate 122 and the light exit surface 57 of the spatial light modulator 52 is denoted by b. If the characteristic scattering angle β of the scattering plate 122 is approximately d/b, the image of the gap 118 formed on the light entrance facet 75 is sufficiently blurred. If the scattering angle β is significantly larger than d/b, the desired spatial resolution for the field dependence of the irradiance and the angular irradiance distribution is reduced. If the scattering angle β is too small, the images of the gaps will still be prominent on the light entrance facets 75.

7. Rectangular object areas

[0127] In the embodiments described above it has been assumed that the number of micromirrors 56 along the scan direction Y and the cross-scan direction X is identical. Then a rectangular grid of square micromirrors 56 perfectly fits into a square light entrance facet 75 of the optical integrator 60.

[0128] The number N_X of micromirrors 56 along the cross-scan direction X determines the resolution that is available for adjusting the field dependence of the irradiance and the angular irradiance distribution. This number should be as high as possible.

[0129] The number N_Y of micromirrors 56 along the scan direction Y may be significantly smaller because of the integrating effect caused by the scan operation. Illustratively speaking, a plurality of optical channels adjacent along the scan direction Y may contribute to the reduction of the irradiance on a point on the mask 16 during a scan cycle. This does not apply to optical channels that are adjacent along the cross-scan direction X.

[0130] These requirements suggest that the object area 110 may well be rectangular, with the length along the cross-scan direction X being larger (for example two

times and preferably at least five times larger) than the length of the object area along the scan direction Y. Assuming micromirrors 56 having equal dimensions along the directions X and Y, this implies that the number N_X of micromirrors 56 along the cross-scan direction X is larger than the number N_Y along the scan direction Y.

[0131] If a rectangular object area 110 shall be imaged on a square light entrance facet 75, the objective 58 has to be anamorphotic. More specifically, the absolute value of the magnification M has to be smaller along the cross-scan direction X than along the scan direction Y, i.e. $|M_X|<|M_Y|$. This is illustrated in FIG. 23 in which two cylinder lenses 124, 126 of the objective 58 are arranged between a single rectangular object area 110 and the light entrance facet 75 of an optical raster element 74. If the length of the object area 110 along the cross-scan direction X is L_X and the length along the scan direction Y is L_Y, $|M_X/M_Y|$ should be equal to L_Y/L_X.

[0132] A similar result is achieved if not the objective 58, but the subsequent condenser 78 is anamorphotic so that its focal length f is different for the X and Y directions. If the objective 58 is rotational symmetric so that $M_X = M_Y$, the irradiance distributions on the light entrance facets 75 will be rectangular with the same aspect ratio L_X/L_Y as the object area 110. This rectangular irradiance distribution is then expanded by the anamorphotic condenser 78 so that a square irradiance distribution is obtained in the mask plane 88. This approach may require a redesign of the optical integrator 60 because the condenser's different focal lengths along the directions X, Y have to be compensated by the refractive power of the optical raster elements 74.

8. Grouping object areas

[0133] If the number of micromirrors 56 in each object area 110 and also the number of optical channels (and thus of the light entrance facets 75) shall be large, the total number of micromirrors 56 in the second mirror array 54 may become huge. Since it might be difficult to provide a second mirror array 54 that comprises such a huge number of micromirrors 56 in a single device, it is envisaged to split up the second mirror array 56 into several independent devices each containing a large number of object areas 110. The second mirror array 54 may then be considered as comprising several groups each comprising of large number of object areas. These groups are separated from each other by dark areas (i.e. an area from which no projection light emerges) that are not imaged on the light entrance facets. Each group may be realized as a single and independent device, for example a digital mirror device (DMD) or a LCD panel.

[0134] FIG. 24 shows on the left hand side a top view on the second mirror array 54 according to an embodiment in which eight groups 54-1 to 54-8 of object areas 110 are combined on a single support 170. Each group 54-1 to 54-8 is realized as a digital mirror device (DMD) in this embodiment. The areas 130 between adjacent groups 54-1 to 54-8 are not imaged on the optical integrator 60. Since they should not be illuminated by projection light, they will be referred to in the following as dark areas 130.

[0135] In this embodiment each group 54-1 to 54-8 comprises eight object areas 110 that are indicated for group 54-1 by thick lines. Each object area 110 is imaged on a corresponding light entrance facet 75 of the optical integrator 60 and comprises 5x5 micromirrors 56. As it is shown on the right hand side of FIG. 24, the images 54-1' to 54-8' of the groups 54-1 to 54-8 are stitched by the objective 58 so that they seamlessly abut on the optical integrator 60. Then also the images 110' of the object areas 110 seamlessly abut on the optical integrator 60 in such a way that each image 110' covers exactly one light entrance facet 75.

a) Stitching

[0136] FIG. 25 shows an objective 58 that is capable of seamlessly stitching the images 54-1' to 54-8' of the separated groups 54-1 to 54-8 on the optical integrator 60. The objective 58 comprises a first array of first optical elements 134. Each first optical element 134 forms a magnified image of one of the groups 54-1 to 54-8 in an intermediate image plane 132. The magnification by the first optical elements 132 is determined such that the images 54-1' to 54-8' of the groups 54-1 to 54-8 at least substantially seamlessly abut in the intermediate image plane 132. Imaging optics 138 images the intermediate image plane 132 on the light entrance facets 75 of the optical integrator 60. This objective 58 thus creates from a plurality of first areas separated by second areas a continuous image area in which the first areas at least substantially seamlessly abut.

[0137] In the embodiment shown in FIG. 25 the first optical elements 132 are formed by single lenses. However, it is also possible to use other imaging elements, for example diffractive optical elements, combinations of lenses or other optical elements to this end.

[0138] In principle it is also possible to dispense with the imaging optics 138. Then the first optical elements 132 image the groups 54-1 to 54-8 directly, i.e. without the intermediate image plane 132, on the optical integrator 60. Then, however, the size of the image field on the optical integrator 60 is exclusively determined by the number and size of and the distance between the groups 54-1 to 54-8, as this becomes clear from FIG. 25. Usually it is desired to adapt the size of the image field to the optical integrator 60, and not the optical integrator 60 to the size of the image field.

b) Field lenses

[0139] The size and complexity of the imaging optics 138 mainly depends on the size of the image field in the intermediate image plane 132, and also on the maximum light angles occurring in the intermediate image plane

132. As mentioned above, the size of the image field mainly depends on the number and size of and the distance between the groups 54-1 to 54-8, and usually these quantities cannot be freely chosen. However, the maximum angles occurring in the intermediate image plane 132 can be reduced by adding a second array of field lenses 136, as this is shown in FIG. 26. As can be seen by comparing the maximum angles in the intermediate image plane 132 in FIGS. 25 and 26, the field lenses 136 tilt the light bundles so that the objective 58 becomes telecentric on the image side, i.e. for all field points the light bundles emerge from the field lenses 136 with the same angle and with a chief ray that is parallel to the optical axis 180.

[0140] In the embodiment shown in FIG. 26 the circumferential rim of the field lenses 136 are positioned in the intermediate image plane 132. The rims (and any possible lens mounts) will thus be imaged on the optical integrator 60. If this shall be avoided, the field lenses 136 may be arranged slightly defocused with respect to the intermediate image plane 132, as this is shown in the bottom part of FIG. 26 for one of the field lenses 136. A residual tilt of certain light bundles (i.e. no perfect telecentricity) can usually be tolerated to some extent.

[0141] FIG. 27 is a schematic meridional section through the second mirror array 54 and the objective 58 according to a similar embodiment. Here it is assumed that the second mirror array 54 comprises two groups 54-1, 54-2 each realized as digital mirror device (DMD). Each group 54-1, 54-2 includes three object areas 110 that extend over a plurality of micromirrors 56. The two groups 54-1, 54-2 are separated by a dark area 130 which is absorptive and on which no projection light should be directed by the pupil forming unit 36.

[0142] The objective 58 is configured to combine the images 110' of the object areas 110 so that they abut at least substantially seamlessly on the optical integrator 60. There each image area 110' completely coincides with one of the light entrance facets 75. To this end the objective 58 produces magnified images of the object areas 110 in an intermediate image plane 132 with the help of a first array of lenses 134. The objective 58 further comprises an array of second lenses 136 that is arranged in the intermediate image plane 132. Common imaging optics 138 then image the intermediate image plane 134, in which the magnified images of the groups 54-1, 54-2 abut, on the light entrance facets 75 of the optical integrator 60. In this way the dark areas 130 between the groups 54-1, 54-2 are not imaged by the objective 58 on the optical integrator 60.

c) Separation of incoming and reflected light

[0143] For the sake of simplicity, the question has been disregarded in the foregoing explanations how the incoming projection light gets to the spatial light modulator 52. Due to geometric constraints it may not be possible to illuminate the spatial light modulator 52 shown in FIG. 24 obliquely, because the first array of first lenses 134 obstructs the light path. Therefore it will often be necessary to guide the incoming projection light at least through a portion of the objective 58. This makes it necessary to separate the reflected projection light from the incoming projection light. In principle it may be contemplated to use polarization control means such as retarders and polarization sensitive beam splitters to separate the modulated projection light from the incoming projection light.

[0144] However, it will often be easier to separate the incoming from the modulated projection light spatially. This means that the incoming and the modulated projection light beams propagate along different light paths that may intersect, but do not mix in the sense that incoming projection light may impinge on the optical integrator 60 without impinging on the spatial light modulator 52 before.

[0145] In the following an approach will be explained how the incoming and the modulated projection light can be guided through the objective 58 on separate light paths.

[0146] In FIG. 25 the numerical aperture NA is indicated for the lenses 134. All projection light that propagates towards the groups 54-1 to 54-8 and which is reflected from the micromirrors 56 has to be guided within the angle range that is determined by the numerical aperture NA. One approach is to split the available angle range such that a first angle range is used for the incoming projection light and a distinct second angle range is used for the modulated projection light. If no numerical aperture shall be "wasted", this requires that the two angle ranges should have equal sizes, and thus the numerical aperture NA of the lenses 134 should be twice as large as the divergence of the incoming projection light. If the objective 58 comprises not only the lenses 134, but also other optical elements such as the field lenses 136, it is the numerical aperture NA of the portion of the objective 58 through which the incoming projection light propagates, which matters in this context.

i) Total internal reflection

[0147] FIG. 28 shows an embodiment in which this approach is realized. The incoming projection light 34i, which is represented here only by two light bundles shown with a dark hatch and having a divergence δ, is directed from the pupil forming unit 36 (not shown in FIG. 28) towards a first and a second prism 172, 174 which are identical. The prisms 172, 174 have surfaces 176 and 178, respectively, that are inclined by an angle of 45° with respect to the optical axis 180 of the objective 58. The distance between the two surfaces 176, 178 should be at least as large as the wavelength of the projection light.

[0148] The direction of incidence of the incoming projection light 34i is chosen so that total internal reflection (TIR) occurs at the inclined surface 176 of the first prism 172. The reflected incoming projection light 34i then prop-

agates through the second lenses 136 and the first lenses 134. When it approaches the groups 54-1 to 54-3 of the spatial light modulator 52, it uses about one half of the available numerical aperture NA of the first and second lenses 134, 136. The modulated projection light 34m reflected from the spatial light modulator uses the other half of the available numerical aperture NA when it propagates, now in reverse order, through the first and second lenses 134, 136 towards the prism 172. Since the modulated projection light 34m propagates with different angles through the lenses 134, 136, it is not reflected at the inclined surface 176 of the first prism 172. Instead, it passes through the inclined surface 176 and also through the inclined surface 178 of the second prism 174. The second prism 174 thereby corrects the tilt of the light path produced by the inclined surface 176 of the first prism 172.

[0149] The same applies also to projection light bundles that are focused on other points on the spatial light modulator 52. The incoming projection light 34i always uses about one half of the available numerical aperture NA, and the modulated projection light the other half. Thus the angle range of the incoming and the modulated projection light is always different. The inclined surface 176 of the first prism 172 separates these different angle ranges by exploiting the effect of total internal reflection (TIR).

[0150] In many operating states the pupil forming unit 36 will illuminate, via the inclined surface 176, the second array of second lenses 136 not homogeneously, but only at certain portions in order to modify the angular light distribution at mask level (i.e. the illumination setting). Then only corresponding portions on the groups 54-1 to 54-3 are illuminated and - if the micromirrors 56 at these portions are in the "on" state - imaged in a "stitched" manner on the optical integrator 60.

ii) Mirror in pupil plane

[0151] FIG. 29 shows an alternative embodiment in which the separation of different angle ranges is not performed by an inclined surface at which total internal reflection may occur. Instead that fact is used that projection light emerging under different angles in a field plane passes a pupil plane at different locations.

[0152] The imaging optics 138 comprises a pupil plane 182 between lenses 184 and 186. In the pupil plane 182 a planar folding mirror 188 is arranged at an off-axis position so that a pupil portion centered at the optical axis 180 is kept clear. The pupil forming unit 36 produces an angular light distribution of incoming projection light 34i on the folding mirror 188 in the pupil plane 182 so that it is coupled into the light path of the imaging optics 138.

[0153] After reflection from the folding mirror 188, the incoming projection light 34i passes through the lens 184 of the imaging optics 138, the second lenses 136 and the first lenses 134 and finally impinges on the groups 54-1 to 54-3 of the spatial light modulator 52. There the incoming projection light 34i is modulated and - if the micromirrors 56 are in the "on" state - reflected back into the objective 58. However, similar to the embodiment shown in FIG. 28, the modulated and reflected projection light 34m propagates with another angle range through the objective 58. For that reason it does not impinge on the folding mirror 188, but through the center of the pupil plane 182 from which it further propagates through the lens 186 towards the optical integrator 60.

[0154] By modifying the angular distribution of the incoming projection light 34i in the pupil plane 182, the pupil forming unit 36 determines the spatial distribution of the incoming projection light 34i on the spatial light modulator 52 and thus on the optical integrator 60.

[0155] In the embodiment shown in FIG. 29 the modulated projection light 34m uses a telecentric light path from the spatial light modulator 52 through the objective 58. For that reason the chief rays of modulated projection light bundles intersect the optical axis 180 in the pupil plane 182. The radial distance between the optical axis 180 and the folding mirror 188 depends on the numerical aperture NA that is used by the modulated projection light 34m. The incoming projection light 34i uses a remaining portion of the available numerical aperture NA. This portion corresponds to a non-telecentric light path in which the incoming projection light 34i impinges on the spatial light modulator 52 with relatively large angles of incidence.

[0156] In this embodiment the imaging optics 138 has a magnification M with $|M| > 1$. Thus an enlarged and stitched image of the groups 54-1 to 54-3 is produced on the optical integrator 60. The imaging optics 138 is therefore used to adapt the size of the intermediate image, whose size cannot be modified, to the required field size in the final image plane.

d) Mirror tilt in "on" state

[0157] Often commercially available digital mirror devices, which may form the groups 54-1 to 54-8 of the spatial light modulator 52, comprise micromirrors 56 that are tilted in the "on" state at an angle α with respect to a surface normal of the support 170, and thus also with respect to the optical axis 180 of the objective 58. This is illustrated in FIG. 30 which is an enlarged meridional section through one of the micromirrors 56 and one of the first lenses 134. The tilt of the micromirror 56 by the angle α has the effect that a telecentric cone of impinging projection light 34i centered with respect to the optical axis is tilted by the angle 2α after reflection from the micromirror 56. The reflected light cone is denoted in FIG. 30 by 34m.

[0158] This tilt of the reflected light by the angle α is of no concern as long as the numerical aperture NA of the lens 134 is sufficiently large. In the embodiment shown in FIG. 30 this is not the case, and thus only a portion of the incoming projection light 34i may finally reach the optical integrator. This could be avoided by using a lens

134 with a larger numerical aperture NA. However, usually it is desired that the numerical aperture NA of the lens 134 shall be as small as possible, because a higher numerical aperture NA usually requires additional efforts to achieve the same imaging quality.

[0159] For achieving this goal it may be envisaged to use a light tilting optical element that tilts impinging incoming projection light rays by the angle α. Then the incoming projection light rays impinge on the micromirror 56 under the same angle as they would if the micromirror 56 was not tilted by the angle α in the "on" state. Consequently the numerical aperture NA is identical for the incoming projection light and the reflected projection light, as this is illustrated in FIG. 31. Here the light tiling element is a transparent wedge 190 that is arranged between the micromirror 56 and the lens 134. The wedge angle ε is determined such that light rays passing through the wedge are deviated by the angle α as a result of refraction at the inclined wedge surfaces.

[0160] Instead of arranging a single wedge in front of each micromirror 56, or a single wedge in front of the entire support 170, it is also possible to use a Fresnel wedge 192 comprising a plurality of individual wedge elements 194, as this is shown in FIG. 32. Such a Fresnel wedge 192 may be easily integrated into a transparent cover that protects the spatial light modulator and is attached to the support 170.

9. Diffractive optical element and LCD

[0161] FIG. 33 is a meridional section similar to FIG. 3 of an alternative embodiment of an illumination system 12. In this illumination system the pupil forming unit 52 is replaced by a diffractive optical element 142, zoom optics 144 and a pair of axicon elements 146, 148.

[0162] The spatial light modulator 52 in this embodiment is formed by an LCD panel comprising a two dimensional array of minute LCD cells whose optical activity can be controlled individually by the control unit 90. If the projection light produced by the light source 11 is not sufficiently polarized, an additional polarizer may be inserted in the light path in front of the spatial light modulator 52.

[0163] As a matter of course, the embodiments shown in FIGS 3 and 33 can also be combined in different ways so that, for example, a diffractive optical element 142 is used together with the second mirror array 54 as spatial light modulator 52.

10. Field stop blade function

[0164] In the illumination system 12 shown in FIG. 3 there is, as it has already been mentioned further above, no field plane between the light entrance facets 75 and the mask plane 88 (see also FIG. 10). In conventional illumination systems the opening and closing of the illumination field 14 at the beginning and the end of each scan cycle, respectively, is accomplished by movable blades of a field stop arranged in a field plane between the optical integrator 60 and the mask 16. In the illumination system 12 of the present invention this function is taken over by a suitable control of the second mirror array 54.

[0165] This will be explained in the following with reference to FIGS. 34a to 34h. These figures show, at different stages during a scan cycle, at the left hand side a schematic top view on one of the object areas 110 on the light exit surface 57 of the second mirror array 54. Here it is assumed that 9x9 digital micromirrors 56 are arranged within the object area 110.

[0166] Next to the object area 110 a corresponding image area 110' is schematically shown. Here it is assumed that the objective 58 images the object area 110 at a reduced scale on one of the light entrance facets 75 of the optical integrator 60. Since each light entrance facet 75 is optically conjugate to the mask plane 88, a light pattern in the image area 110' is reproduced in the mask plane 88. In the embodiment shown this image is compressed along the scan direction Y because the optical raster elements 74, 75 have different refractive power along the X and Y direction. For that reason the fully opened illumination field 14 is slit-shaped although the image fields 110' on the light entrance facets 75 are square.

[0167] In order to avoid gaps between adjacent micromirrors 56 causing dark stripes in the illumination field 14, different object areas 110 may be laterally displaced with respect to each other, as this has been explained above in section IV.6a, and/or a scattering plate may be provided, as this has been explained above in section IV.6b. For the sake of simplicity the effects of such gaps are neglected in the following.

[0168] At the right end side of each figure 34a to 34h the mask 16 is shown. The mask 16 is provided with an opaque rim 150 that surrounds a central area 142 containing the small features 19 to be imaged on the light sensitive surface 22. The opaque rim 150 comprises a front side 156 and a rear side 158 both extending along the cross-scan direction X, and two lateral sides 160 extending along the scan direction Y. The width of the front side 156 and the rear side 158 of the opaque rim 150 is denoted by w.

[0169] FIG. 34a illustrates the situation before a scan cycle begins. All micromirrors 56 of the second mirror array 54 are in the "off" state, and thus the corresponding image area 110' on the light entrance facet 75 is not illuminated.

[0170] Then a first row 162-1 of micromirrors 56 is brought into the "on" state, as this is shown in FIG. 34b. The light pattern formed on the light entrance facet 75 is a narrow stripe being an image of the first row 162-1. At the very moment when the first row 162-1 of micromirrors 56 is brought into the "on" state, the image of the narrow stripe, which now forms the illumination field 14, is positioned completely on the front side 156 of the opaque rim 150. Thus there are not yet any features 19 illuminated

with projection light; only the front side 156 of the opaque rim 150 is illuminated, and the projection light is completely absorbed by the opaque rim 150.

[0171] As the mask 16 moves further along the scan direction Y, the thin illumination field 14 evenly enters the central area 142 that is surrounded by the opaque rim 150. Now the imaging of the features 19 begins. If seen along the scan direction Y, the length of the light pattern formed on the light entrance facet 75, and thus also its image on the mask 16, increases continuously, while the length in the cross-scan direction X remains constant.

[0172] Then the next row 162-2 of micromirrors 56 is brought into the "on" state, as this is shown in FIG. 34c. As can be seen in the enlarged cutout, one half 164 of the illumination field 14 illuminates only the front side 156 of the opaque rim 150 where the projection light is absorbed, and the other half 166 of the illumination field 14 illuminates the features 19 in the central area 152 of the mask 16.

[0173] Then the next row of micromirrors 56 is brought into the "on" state, and so on. This process is continued until all micromirrors 56 are in the "on" state, as this is shown in FIG. 34d. Now the illumination field 14 has its full length along the scan direction Y. The fully opened illumination field 14 is positioned at this moment so that it abuts the front side 156 of the opaque rim 150.

[0174] As the mask 16 moves further along the scan direction Y, the illumination field 14 now having its full length along the scan direction Y continuously scans over the features 19 in the central area 152 of the mask 16, as this is shown in FIG. 34e. In this manner the mask 16 is scanned until the illumination field 14 abuts the rear side 158 of the opaque rim 150, as this is shown in FIG. 34f. Now the illumination field 14 begins to enter the rear side 158 of the opaque rim 150 where the projection light is absorbed. When the image of the row 162-1 of micromirrors 56 is arranged completely on the opaque rim 150, the micromirrors 56 of the first row 162-1 are brought into the "off" state. The length of the image of the light pattern on the light entrance facet 75, i.e. the illumination field 14, along the scan direction Y now decreases.

[0175] As soon as the image of the second row 162-2 is arranged completely on the rear side 158 of the opaque rim 150, the micromirrors 56 of the second row 162-2 are brought into the "off" state, and so on.

[0176] FIG. 34g illustrates a state in which the first five rows 162-1 to 162-5 have been brought into the "off" state. The length of the illumination field 14 along the scan direction Y has meanwhile decreased by more than one half.

[0177] When all micromirrors 56 are again in the "off" state, the illumination field 14 is completely closed, and no light reaches the mask 16, as this is shown in FIG. 34h.

V.

Important method steps

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[0178] Important method steps of the present invention will now be summarized with reference to the flow diagram shown in FIG. 35.

In a first step S1 a spatial light modulator having a light exit surface that comprises first areas that are separated by second areas is provided.

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In a second step S2 the first areas, but not the second areas, are imaged on a final image plane so that images of the first areas abut in the final image plane.

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Claims

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1. An illumination system of a microlithographic projection exposure apparatus (10), comprising

a) a pupil plane (76),
b) an optical integrator (60) configured to produce a plurality of secondary light sources (106) in the pupil plane (76), wherein the optical integrator (60) comprises a plurality of light entrance facets (75) each being associated with one of the secondary light sources (106),
c) a spatial light modulator (52) that has a light exit surface (57) and is configured to transmit or to reflect impinging projection light in a spatially resolved manner,
d) a pupil forming unit (36) that is configured to direct projection light on the spatial light modulator,
e) an objective (58) that images the light exit surface (57) of the spatial light modulator (52) onto the light entrance facets (75) of the optical integrator (60),
f) a control unit (90) configured to control the pupil forming unit (36) and the spatial light modulator (52),

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characterized in that
the light exit surface (57) of the optical light modulator (52) comprises groups (54-1 to 54-8) of object areas (110), said groups being separated by areas (130) that are not imaged on the light entrance facets (75), and wherein the objective (58) is configured to combine images (110') of the object areas (110) so that the images (110') of the object areas abut on the optical integrator (60).

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2. The illumination system of claim 1, wherein the objective (58) comprises

a) a first array of first optical elements (134),

wherein each first optical element forms a magnified image of one of the groups (54-1 to 54-8) in an intermediate image plane (132),
b) imaging optics (138) that image the intermediate image plane (132) on the light entrance facets (75).

3. The illumination system of claim 1 or 2, wherein the objective (58) comprises a second array of second optical elements (136) that is arranged in the intermediate image plane (132).

4. The illumination system of claim 3, wherein each second optical element (136) is associated with one of the first optical elements (134) in a one to one correspondence so that each second optical element receives projection light only from the associated one of the first optical elements.

5. The illumination system of any of the preceding claims, wherein the pupil forming unit (36) comprises a first beam deflection array (38) of first reflective or transparent beam deflection elements (40), and wherein each beam deflection element (40) is configured to illuminate a spot (94) on the spatial light modulator (52) at a position that is variable by changing a deflection angle produced by the beam deflection element (40).

6. The illumination system of any of the preceding claims, wherein the spatial light modulator (52) comprises a second beam deflection array (54) of second reflective or transparent beam deflection elements (56), and wherein each second beam deflection element (56) is capable to be in an "on" state, in which it directs impinging projection light towards the optical integrator (60), and in an "off" state, in which it directs impinging projection light elsewhere.

7. The illumination system of claim 6, wherein the second beam deflection elements are mirrors (56), and wherein projection light (34i) propagating from the pupil forming unit (36) to the spatial light modulator (52) passes at least through a portion of the objective (58).

8. The illumination system of 7 and of claims 3 or 4, wherein projection light (34i) propagating from the pupil forming unit (36) to the spatial light modulator (52) impinges on the first array of first optical elements (134) and on the second array of second optical elements (136) before it impinges on the mirrors (56).

9. The illumination system of claims 7 or 8, wherein the mirrors (56) are planar mirrors having a mirror normal that forms, if the mirror is in the "on" state, an angle $\alpha \neq 0°$ to a direction which is parallel to an optical axis (180) of the objective (58), and wherein the objective comprises a light tilting optical element (190, 192) that is configured to tilt impinging projection light rays by the angle α.

10. The illumination system of claim 9 and of claim 10, wherein the light tiling element is arranged between the mirrors (56) and the first optical elements (134).

11. The illumination system of claim 9 or 10, wherein the light tilting element comprises a transparent refractive wedge (190, 192).

12. The illumination system of claim 11, wherein the wedge is formed as a Fresnel wedge (192) comprising a plurality of individual wedge elements (194).

13. The illumination system of any of claims 7 to 12, wherein the objective (58) comprises a pupil plane (182), and wherein the pupil forming unit (36) produces an angular light distribution in the pupil plane in an area (188) such that projection light (34m), after reflection from the mirrors (56), cannot pass through the area again irrespective of whether the mirrors are in the "on" or in the "off" state.

14. The illumination system of claim 13, wherein the area is located on a beam deviating surface (188) that couples the projection light (36i) emerging from the pupil forming (36) unit into a light path of the objective (58).

15. The illumination system of any of claims 7 to 12, wherein the objective (58) contains an optical surface (176) that

a) reflects projection light (34i) propagating from the pupil forming unit (34) towards the mirrors (56) and
b) transmits projection light (34m) after it has been reflected from the mirrors (56), but before it impinges on the light entrance facets (75),

or vice versa.

16. The illumination system of claim 15, wherein the optical surface (176) reflects the projection light (34i, 34m) as a result of total internal reflection.

17. The illumination system of claim 16, wherein the optical surface (176) is a prism surface.

18. The illumination system of any of the preceding claims, wherein the control unit (90) is configured to control the spatial light modulator (52) such that along a scan direction (Y) a length of an image, which is formed on the mask (16) from a light pattern in one of the object areas (110), gradually increases at a

beginning of a scan cycle and gradually decreases at the end of the scan cycle.

19. The illumination system of claim 6 and of claim 18, wherein the control unit (90) is configured to control the spatial light modulator (52) such that rows of adjacent second beam deflection elements (56) are simultaneously brought from the "off" state into the "on" state, and vice versa, during the scan cycle.

20. A method of operating an illumination system of a microlithographic projection exposure apparatus (10), comprising the following steps:

a) providing a spatial light modulator (52) having a light exit surface (57) that comprises first areas (54-1 to 54-8) that are separated by second areas (130);

characterized by the step of

b) imaging the first areas (54-1 to 54-8), but not the second areas (130), on a final image plane (60) so that images (54-1' to 54-8') of the first areas abut in the final image plane.

21. The method of claim 20, wherein the final image plane is arranged on an optical integrator (60) configured to produce a plurality of secondary light sources (106) in a pupil plane (76), wherein the optical integrator (60) comprises a plurality of light entrance facets (75) each being associated with one of the secondary light sources (106).

22. The method of claim 20 or 21, wherein the light exit surface (57) is configured to transmit or to reflect impinging projection light in a spatially resolved manner.

23. The method of any of claims 20 to 22, wherein a pupil forming unit (36) directs projection light on the spatial light modulator (52) so that variable irradiance distributions can be obtained on the first areas (54-1 to 54-8).

24. The method of any of claims 20 to 23, wherein the first areas (54-1 to 54-8) are imaged on the final image plane (60) by an objective (58) that comprises a first array of first optical elements (134), wherein each first optical element forms a magnified image of one of the first areas in an intermediate image plane (132), and wherein the intermediate image plane (132) is imaged on the final image plane.

Patentansprüche

1. Beleuchtungssystem eines mikrolithografischen Projektionsbelichtungsgerätes (10), das umfasst:

a) eine Pupillenebene (76),
b) einen optischen Integrator (60), der so ausgeführt ist, dass er eine Vielzahl von sekundären Lichtquellen (106) in der Pupillenebene (76) erzeugt, wobei der optische Integrator (60) eine Vielzahl von Lichteintrittsfacetten (75) umfasst, die jeweils einer der sekundären Lichtquellen (106) zugeordnet sind,
c) einen räumlichen Lichtmodulator (52), der eine Lichtaustrittsfläche (57) aufweist und so ausgeführt ist, dass er einfallendes Projektionslicht räumlich aufgelöst durchlässt oder reflektiert,
d) eine Pupillenausbildungseinheit (36), die so ausgeführt ist, dass sie Projektionslicht auf den räumlichen Lichtmodulator leitet,
e) ein Objektiv (58), das die Lichtaustrittsfläche (57) des räumlichen Lichtmodulators (52) auf den Lichteintrittsfacetten (75) des optischen Integrators (60) abbildet,
f) eine Steuereinheit (90), die so ausgeführt ist, dass sie die Pupillenausbildungseinheit (36) und den räumlichen Lichtmodulator (52) steuert,

dadurch gekennzeichnet, dass
die Lichtaustrittsfläche (57) des optischen Lichtmodulators (52) Gruppen (54-1 bis 54-8) von Objektbereichen (110) umfasst, wobei die Gruppen durch Bereiche (130) voneinander getrennt sind, die nicht auf den Lichteintrittsfacetten (75) abgebildet sind, und wobei das Objektiv (58) so ausgeführt ist, dass es Bilder (110‘) der Objektbereiche (110) so kombiniert, dass die Bilder (110’) der Objektbereiche an den optischen Integrator (60) anstoßen.

2. Beleuchtungssystem nach Anspruch 1, wobei das Objektiv (58) umfasst:

a) ein erstes Array von ersten optischen Elementen (134), wobei jedes erste optische Element ein vergrößertes Bild einer der Gruppen (54-1 bis 54-8) in einer Zwischen-Bildebene (132) bildet,
b) Abbildungsoptiken (138), die die Zwischen-Bildebene (132) auf den Lichteintrittsfacetten (75) abbilden.

3. Beleuchtungssystem nach Anspruch 1 oder 2, wobei das Objektiv (58) ein zweites Array von zweiten optischen Elementen (136) umfasst, das in der ZwischenBildebene (132) angeordnet ist.

4. Beleuchtungssystem nach Anspruch 3, wobei jedes zweite optische Element (136) einem der ersten optischen Elemente (134) in einer Eins-zu-Eins-Entsprechung zugeordnet ist, so dass jedes zweite optische Element Projektionslicht nur aus dem zuge-

ordneten einen der ersten optischen Elemente empfängt.

5. Beleuchtungssystem nach einem der vorhergehenden Ansprüche, wobei die Pupillenausbildungseinheit (36) ein erstes Strahlablenkungsarray (38) von ersten reflektierenden oder transparenten Strahlablenkungselementen (40) umfasst und wobei jedes Strahlablenkungselement (40) so ausgeführt ist, dass es eine Stelle (94) auf dem räumlichen Lichtmodulator (52) an einer Position beleuchtet, die durch Verändern eines Ablenkungswinkels, der von dem Strahlablenkungselement (40) erzeugt wird, variierbar ist.

6. Beleuchtungssystem nach einem der vorhergehenden Ansprüche, wobei der räumliche Lichtmodulator (52) ein zweites Strahlablenkungsarray (54) von zweiten reflektierenden oder transparenten Strahlablenkungselementen (56) umfasst und wobei jedes zweite Strahlablenkungselement (56) in der Lage ist, sich in einem "Ein"-Zustand, in dem es einfallendes Projektionslicht in Richtung des optischen Integrators (60) leitet, und in einem "Aus"-Zustand zu befinden, in dem es einfallendes Projektionslicht zu einer anderen Stelle leitet.

7. Beleuchtungssystem nach Anspruch 6, wobei die zweiten Strahlablenkungselemente Spiegel (56) sind und wobei Projektionslicht (34i), das sich von der Pupillenausbildungseinheit (36) zu dem räumlichen Lichtmodulator (52) ausbreitet, zumindest durch einen Abschnitt des Objektivs (58) verläuft.

8. Beleuchtungssystem nach Anspruch 7 und nach Anspruch 3 oder 4, wobei Projektionslicht (34i), das sich von der Pupillenausbildungseinheit (36) zu dem räumlichen Lichtmodulator (52) ausbreitet, auf das erste Array von ersten optischen Elementen (134) und auf das zweite Array von zweiten optischen Elementen (136) einfällt, bevor es auf die Spiegel (56) einfällt.

9. Beleuchtungssystem nach Anspruch 7 oder 8, wobei die Spiegel (56) planare Spiegel mit einer Spiegelnormalen sind, die dann, wenn sich der Spiegel in einem "Ein"-Zustand befindet, einen Winkel $\alpha \neq 0°$ zu einer Richtung bildet, die parallel zu einer optischen Achse (180) des Objektivs (58) verläuft, und wobei das Objektiv ein Licht neigendes optisches Element (190, 192) umfasst, das so ausgeführt ist, dass es einfallende Projektionslichtstrahlen im Winkel α neigt.

10. Beleuchtungssystem nach Anspruch 9 und nach Anspruch 10, wobei das Licht neigende Element zwischen den Spiegeln (56) und den ersten optischen Elementen (134) angeordnet ist.

11. Beleuchtungssystem nach Anspruch 9 oder 10, wobei das Licht neigende Element einen transparenten Brechungskeil (190, 192) umfasst.

12. Beleuchtungssystem nach Anspruch 11, wobei der Keil als Fresnel-Keil (192) ausgebildet ist, der eine Vielzahl von einzelnen Keilelementen (194) umfasst.

13. Beleuchtungssystem nach einem der Ansprüche 7 bis 12, wobei das Objektiv (58) eine Pupillenebene (182) umfasst und wobei die Pupillenausbildungseinheit (36) eine winkelmäßige Lichtverteilung in der Pupillenebene in einem Bereich (188) so erzeugt, dass Projektionslicht (34m) nach der Reflexion von den Spiegeln (56) nicht wieder durch den Bereich verlaufen kann, unabhängig davon, ob sich die Spiegel im "Ein"- oder im "Aus"-Zustand befinden.

14. Beleuchtungssystem nach Anspruch 13, wobei sich der Bereich auf einer Strahlumlenkungsfläche (188) befindet, die das Projektionslicht (36i), das aus der Pupillenausbildungseinheit (36) austritt, in einen Lichtweg des Objektivs (58) einkoppelt.

15. Beleuchtungssystem nach einem der Ansprüche 7 bis 12, wobei das Objektiv (58) eine optische Fläche (176) enthält, die

a) Projektionslicht (34i), das sich von der Pupillenausbildungseinheit (34) in Richtung der Spiegel (56) ausbreitet, reflektiert, und
b) Projektionslicht (34m) durchlässt, nachdem es von den Spiegeln (56) reflektiert worden ist, jedoch bevor es auf die Lichteintrittsfacetten (75) einfällt,

oder umgekehrt.

16. Beleuchtungssystem nach Anspruch 15, wobei die optische Fläche (176) das Projektionslicht (34i, 34m) infolge einer internen Totalreflexion reflektiert.

17. Beleuchtungssystem nach Anspruch 16, wobei die optische Fläche (176) eine Prismenfläche ist.

18. Beleuchtungssystem nach einem der vorhergehenden Ansprüche, wobei die Steuereinheit (90) so ausgeführt ist, dass sie den räumlichen Lichtmodulator (52) so steuert, dass sich in einer Abtastrichtung (Y) eine Länge eines Bilds, das auf der Maske (16) aus einem Lichtmuster in einem der Objektbereiche (110) ausgebildet ist, zu Beginn eines Abtastzyklus graduell vergrößert und am Ende des Abtastzyklus graduell verkleinert.

19. Beleuchtungssystem nach Anspruch 6 und nach Anspruch 18, wobei die Steuereinheit (90) so ausgeführt ist, dass sie den räumlichen Lichtmodulator (52)

so steuert, dass Reihen von aneinander angrenzenden zweiten Strahlablenkungselementen (56) während des Abtastzyklus gleichzeitig aus dem "Aus"-Zustand in den "Ein"-Zustand und umgekehrt gebracht werden.

20. Verfahren zum Betreiben eines Beleuchtungssystems eines mikrolithografischen Projektionsbelichtungsgeräts (10), das die folgenden Schritte umfasst:

a) Bereitstellen eines räumlichen Lichtmodulators (52) mit einer Lichtaustrittsfläche (57), die erste Bereiche (54-1 bis 54-8) umfasst, welche durch zweite Bereiche (130) voneinander getrennt sind,

gekennzeichnet durch den Schritt des

b) Abbildens der ersten Bereiche (54-1 bis 54-8), jedoch nicht der zweiten Bereiche (130) auf einer finalen Bildebene (60) so, dass Bilder (54-1' bis 54-8') der ersten Bereiche in der finalen Bildebene aneinander anstoßen.

21. Verfahren nach Anspruch 20, wobei die finale Bildebene auf einem optischen Integrator (60) angeordnet ist, der so ausgebildet ist, dass er eine Vielzahl von sekundären Lichtquellen (106) in einer Pupillenebene (76) erzeugt, wobei der optische Integrator (60) eine Vielzahl von Lichteintrittsfacetten (75) umfasst, von denen jede einer der sekundären Lichtquellen (106) zugeordnet ist.

22. Verfahren nach Anspruch 20 oder 21, wobei die Lichtaustrittsfläche (57) so ausgeführt ist, dass sie einfallendes Projektionslicht räumlich aufgelöst durchlässt oder reflektiert.

23. Verfahren nach einem der Ansprüche 20 bis 22, wobei eine Pupillenausbildungseinheit (36) Projektionslicht so auf den räumlichen Lichtmodulator (52) leitet, dass variable Bestrahlungsstärkenverteilungen an den ersten Bereichen (54-1 bis 54-8) erhalten werden können.

24. Verfahren nach einem der Ansprüche 20 bis 23, wobei die ersten Bereiche (54-1 bis 54-8) auf der finalen Bildebene (60) mittels eines Objektivs (58) abgebildet werden, das ein erstes Array von ersten optischen Elementen (134) umfasst, wobei jedes erste optische Element ein vergrößertes Bild eines der ersten Bereiche in einer Zwischen-Bildebene (132) bildet und wobei die Zwischen-Bildebene (132) auf der finalen Bildebene abgebildet wird.

Revendications

1. Système d'illumination d'un appareil d'exposition par projection microlithographique (10), comprenant :

a) un plan de pupille (76),
b) un intégrateur optique (60) configuré pour produire une pluralité de sources de lumière secondaires (106) dans le plan de pupille (76), où l'intégrateur optique (60) comprend une pluralité de facettes d'entrée de lumière (75), chacune étant associée à l'une des sources de lumière secondaires (106),
c) un modulateur spatial de lumière (52) qui a une surface de sortie de lumière (57) et est configuré pour transmettre ou pour réfléchir une lumière de projection incidente de manière résolue spatialement,
d) une unité de formation de pupille (36) qui est configurée pour diriger une lumière de projection sur le modulateur spatial de lumière,
e) un objectif (58) qui image la surface de sortie de lumière (57) du modulateur spatial de lumière (52) sur les facettes d'entrée de lumière (75) de l'intégrateur optique (60),
f) une unité de commande (90) configurée pour commander l'unité de formation de pupille (36) et le modulateur spatial de lumière (52),

caractérisé en ce que
la surface de sortie de lumière (57) du modulateur de lumière optique (52) comprend des groupes (54-1 à 54-8) de zones d'objet (110), lesdits groupes étant séparés par des zones (130) qui ne sont pas représentées sur les facettes d'entrée de lumière (75), et où l'objectif (58) est configuré pour combiner des images (110') des zones d'objet (110) de sorte que les images (110') des zones d'objet se juxtaposent sur l'intégrateur optique (60) .

2. Système d'illumination selon la revendication 1, dans lequel l'objectif (58) comprend

a) un premier réseau de premiers éléments optiques (134), où chaque premier élément optique forme une image agrandie d'un des groupes (54-1 à 54-8) dans un plan d'image intermédiaire (132),
b) une optique d'imagerie (138) qui image le plan d'image intermédiaire (132) sur les facettes d'entrée de lumière (75).

3. Système d'illumination selon la revendication 1 ou la revendication 2, dans lequel l'objectif (58) comprend un second réseau de seconds éléments optiques (136) disposés dans le plan d'image intermédiaire (132).

4. Système d'illumination selon la revendication 3, dans lequel chaque second élément optique (136) est associé à l'un des premiers éléments optiques (134) dans une correspondance un à un, de sorte que chaque second élément optique reçoit une lumière de projection seulement du premier élément optique associé parmi les premiers éléments optiques.

5. Système d'illumination selon l'une quelconque des revendications précédentes, dans lequel l'unité de formation de pupille (36) comprend un premier réseau de déviation de faisceau (38) de premiers éléments de déviation de faisceau réfléchissants ou transparents (40), et dans lequel chaque élément de déviation de faisceau (40) est configuré pour éclairer un point (94) sur le modulateur spatial de lumière (52) dans une position qui est variable en modifiant un angle de déviation produit par l'élément de déviation de faisceau (40).

6. Système d'illumination selon l'une quelconque des revendications précédentes, dans lequel le modulateur spatial de lumière (52) comprend un second réseau de déviation de faisceau (54) de seconds éléments de déviation de faisceau réfléchissants ou transparents (56), et dans lequel chaque second élément de déviation de faisceau (56) est apte à être dans un état « activé », dans lequel il dirige l'incidence de la lumière de projection vers l'intégrateur optique (60), et dans un état « désactivé », dans lequel il dirige l'incidence de la lumière de projection ailleurs.

7. Système d'illumination selon la revendication 6, dans lequel les seconds éléments de déviation de faisceau sont des miroirs (56), et dans lequel la lumière de projection (34i) se propageant de l'unité de formation de pupille (36) au modulateur spatial de lumière (52) traverse au moins une partie de l'objectif (58).

8. Système d'illumination selon la revendication 7 et la revendication 3 ou la revendication 4, dans lequel la lumière de projection (34i) se propageant depuis l'unité de formation de pupille (36) vers le modulateur spatial de lumière (52) frappe le premier réseau de premiers éléments optiques (134) et le second réseau de seconds éléments optiques (136) avant de frapper les miroirs (56).

9. Système d'illumination selon la revendication 7 ou la revendication 8, dans lequel les miroirs (56) sont des miroirs plans ayant un miroir normal qui forme, si le miroir est dans l'état « activé », un angle $\alpha \neq 0°$ par rapport à une direction qui est parallèle à un axe optique (180) de l'objectif (58), et dans lequel l'objectif comprend un élément optique de déviation de lumière (190, 192) qui est configuré pour incliner les rayons lumineux de projection incidents de l'angle α.

10. Système d'illumination selon la revendication 9 et la revendication 10, dans lequel l'élément de déviation de lumière est agencé entre les miroirs (56) et les premiers éléments optiques (134).

11. Système d'illumination selon la revendication 9 ou la revendication 10, dans lequel l'élément de déviation de lumière comprend un coin de réfraction transparent (190, 192).

12. Système d'illumination selon la revendication 11, dans lequel le coin est formé comme un coin de Fresnel (192) comprenant une pluralité d'éléments de coins individuels (194).

13. Système d'illumination selon l'une quelconque des revendications 7 à 12, dans lequel l'objectif (58) comprend un plan de pupille (182), et dans lequel l'unité de formation de pupille (36) produit une distribution de lumière angulaire dans le plan de pupille dans une zone (188), de sorte que la lumière de projection (34m), après réflexion par les miroirs (56), ne peut pas traverser à nouveau la zone, indépendamment du fait que les miroirs sont dans l'état « activé » ou « désactivé ».

14. Système d'illumination selon la revendication 13, dans lequel la zone est située sur une surface de déviation de faisceau (188) qui couple la lumière de projection (36i) sortant de l'unité de formation de pupille (36) dans un trajet lumineux de l'objectif (58).

15. Système d'illumination selon l'une quelconque des revendications 7 à 12, dans lequel l'objectif (58) contient une surface optique (176) qui

a) réfléchit une lumière de projection (34i) se propageant depuis l'unité de formation de pupille (34) vers les miroirs (56) et
b) transmet une lumière de projection (34m) après qu'elle a été réfléchie par les miroirs (56), mais avant qu'elle ne frappe les facettes d'entrée de la lumière (75),

ou vice versa.

16. Système d'illumination selon la revendication 15, dans lequel la surface optique (176) réfléchit la lumière de projection (34i, 34m) à la suite d'une réflexion interne totale.

17. Système d'illumination selon la revendication 16, dans lequel la surface optique (176) est une surface de prisme.

18. Système d'illumination selon l'une quelconque des revendications précédentes, dans lequel l'unité de commande (90) est configurée pour commander le modulateur spatial de lumière (52) de telle sorte que, le long d'une direction de balayage (Y), une longueur d'une image, qui est formée sur le masque (16) à partir d'un motif lumineux dans l'une des zones d'objet (110), augmente progressivement au début d'un cycle de balayage et diminue progressivement à la fin du cycle de balayage.

19. Système d'illumination selon la revendication 6 et la revendication 18, dans lequel l'unité de commande (90) est configurée pour commander le modulateur spatial de lumière (52) de telle sorte que des rangées de seconds éléments de déviation de faisceau (56) adjacents sont amenées simultanément de l'état « désactivé » à l'état « activé », et vice versa, pendant le cycle de balayage.

20. Procédé de fonctionnement d'un système d'illumination d'un appareil d'exposition par projection microlithographique (10), comprenant les étapes suivantes :

a) fournir un modulateur spatial de lumière (52) ayant une surface de sortie de lumière (57) qui comprend des premières zones (54-1 à 54-8) qui sont séparées par des secondes zones (130);

caractérisé par l'étape consistant à

b) représenter les premières zones (54-1 à 54-8), mais pas les secondes zones (130), sur un plan d'image final (60) de sorte que les images (54-1' à 54-8') des premières zones se juxtaposent dans le plan d'image final.

21. Procédé selon la revendication 20, dans lequel le plan d'image final est agencé sur un intégrateur optique (60) configuré pour produire une pluralité de sources de lumière secondaires (106) dans un plan de pupille (76), où l'intégrateur optique (60) comprend une pluralité de facettes d'entrée de lumière (75) étant chacune associée à l'une des sources de lumière secondaires (106).

22. Procédé selon la revendication 20 ou la revendication 21, dans lequel la surface de sortie de lumière (57) est configurée pour transmettre ou réfléchir une lumière de projection incidente de manière résolue spatialement.

23. Procédé selon l'une quelconque des revendications 20 à 22, dans lequel une unité de formation de pupille (36) dirige une lumière de projection sur le modulateur spatial de lumière (52) de sorte que des distributions d'éclairements énergétiques variables puissent être obtenues sur les premières zones (54-1 à 54-8).

24. Procédé selon l'une quelconque des revendications 20 à 23, dans lequel les premières zones (54-1 à 54-8) sont imagées sur le plan d'image final (60) par un objectif (58) qui comprend un premier réseau de premiers éléments optiques (134), où chaque premier élément optique forme une image agrandie d'une des premières zones dans un plan d'image intermédiaire (132), et où le plan d'image intermédiaire (132) est représenté sur le plan d'image final.

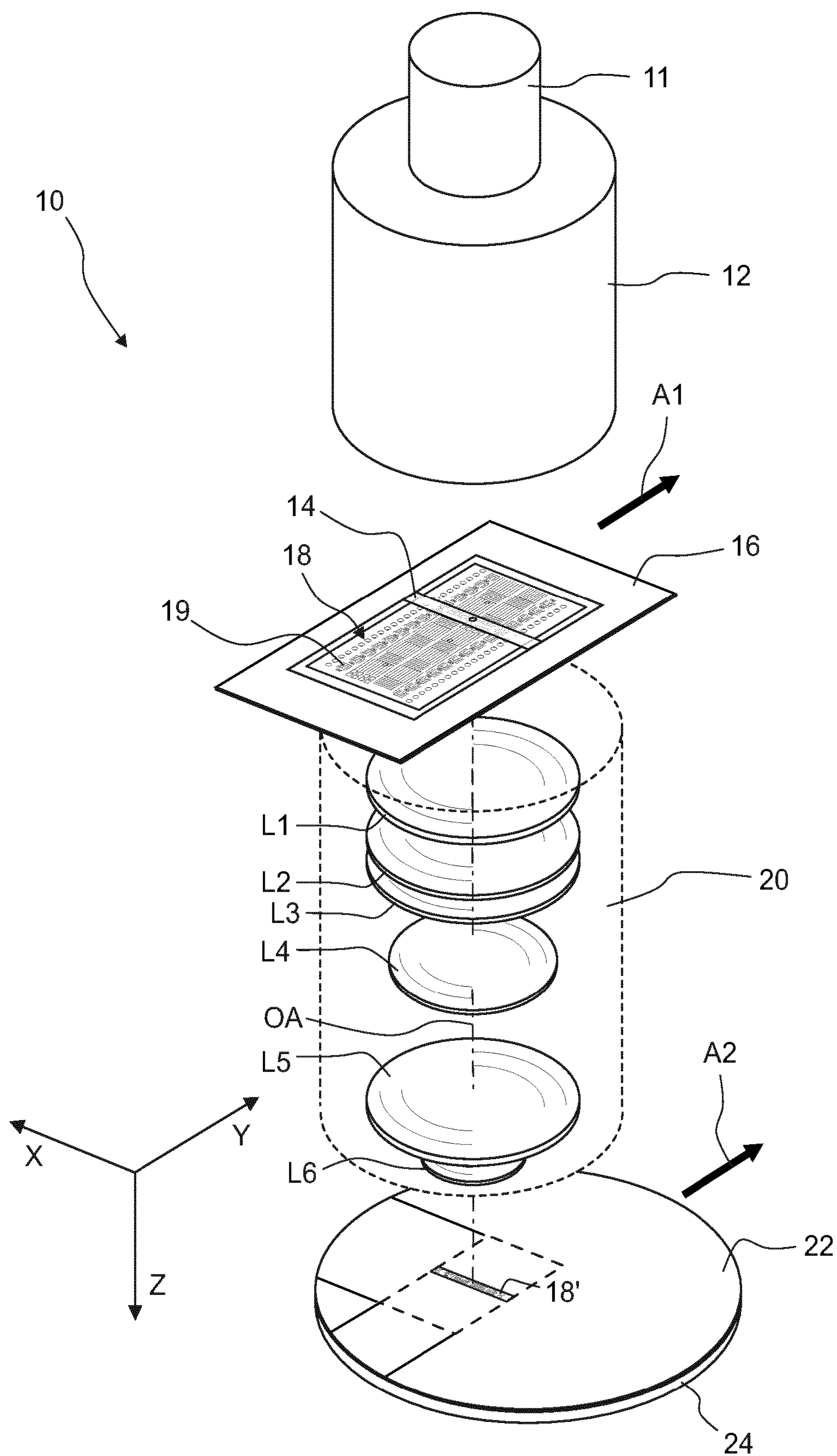
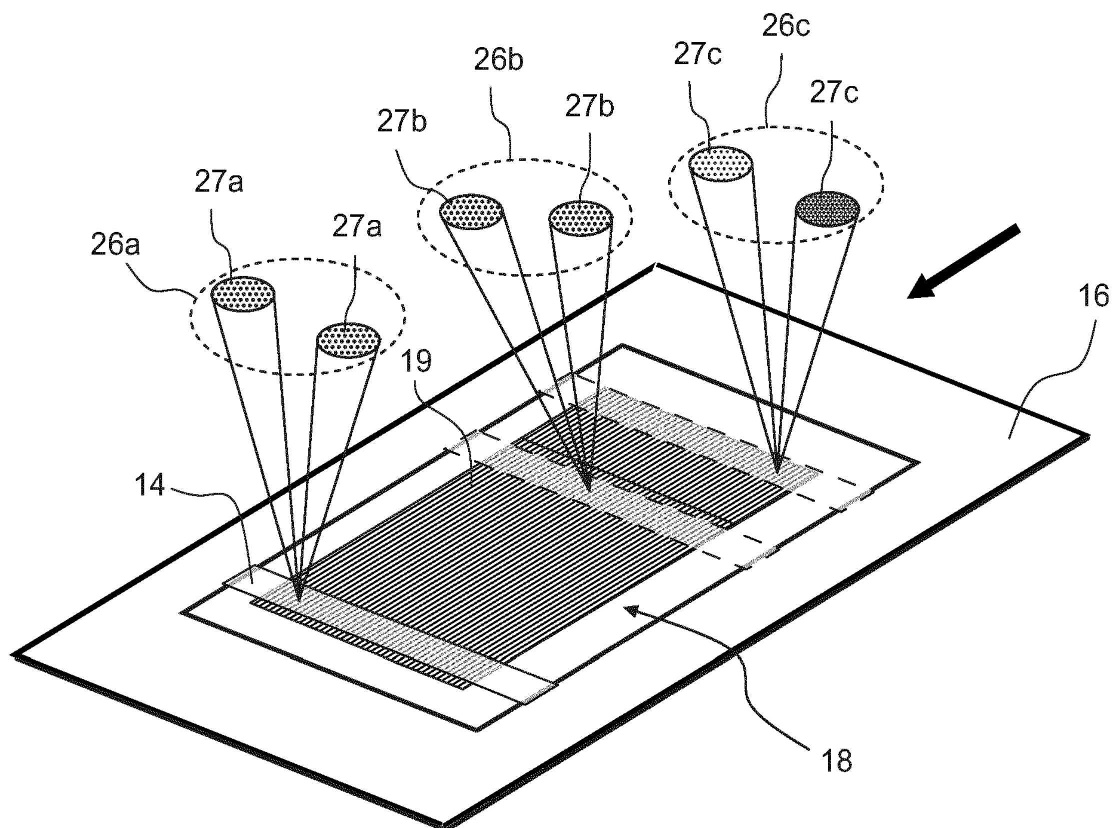


Fig.1



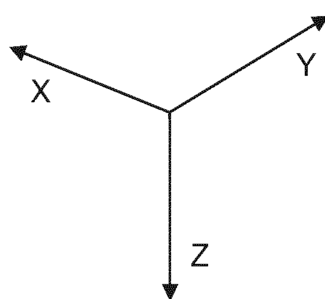


Fig. 2

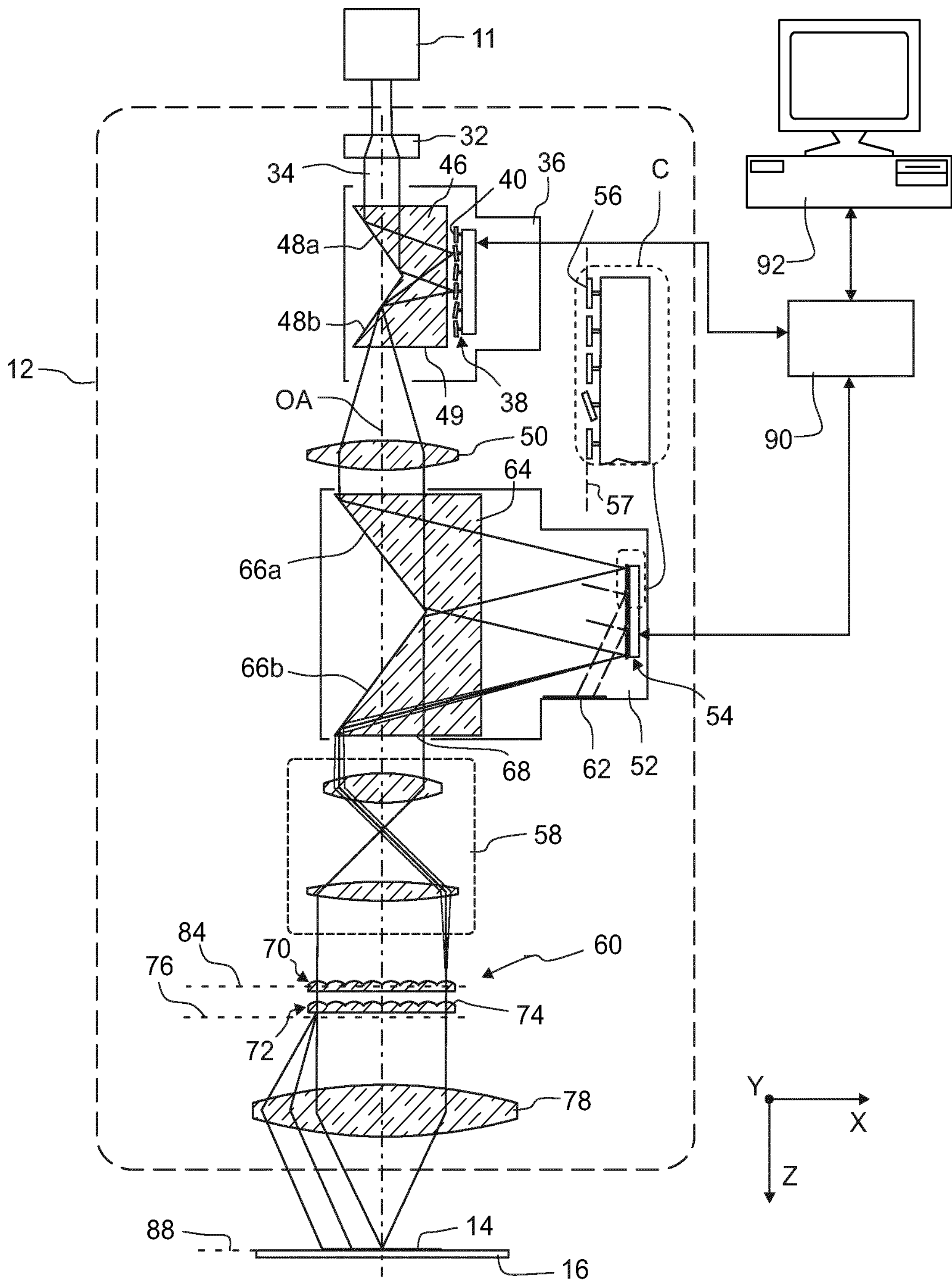


Fig. 3

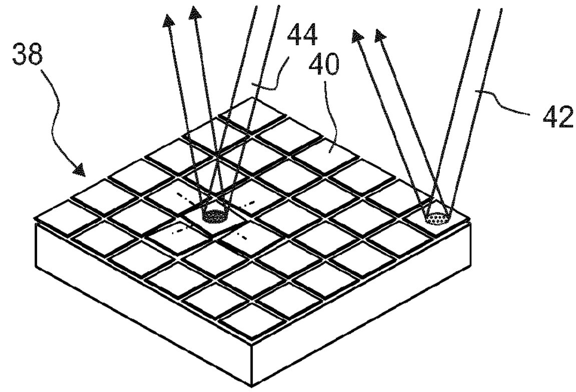


Fig. 4

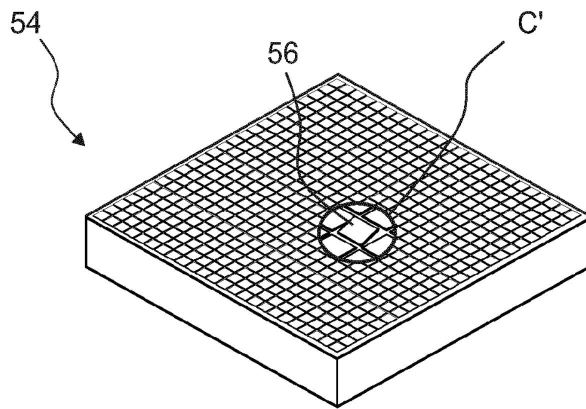


Fig. 5

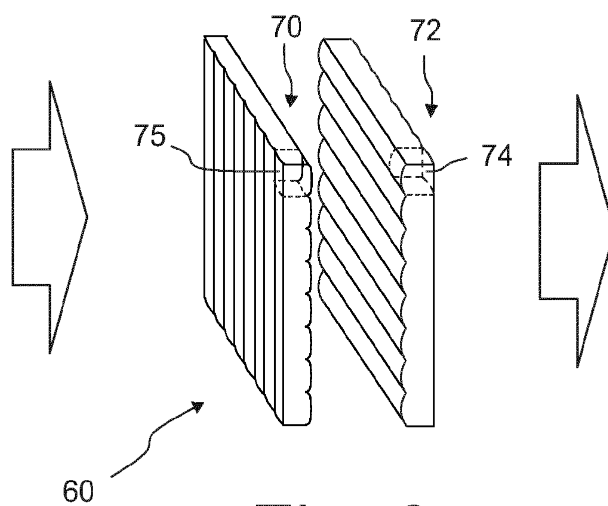


Fig. 6

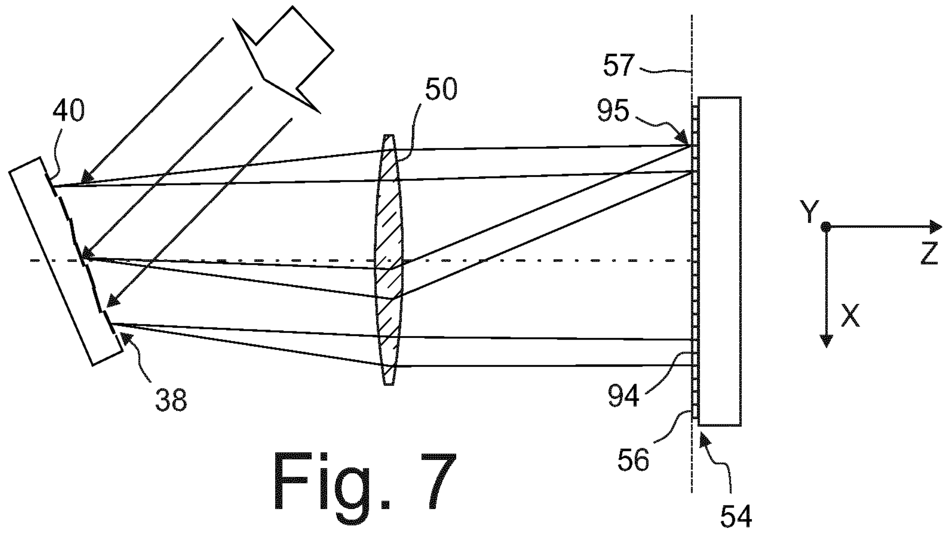


Fig. 7

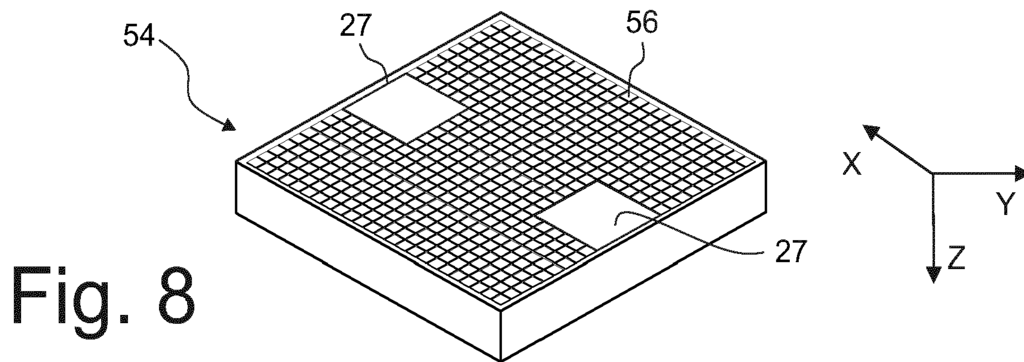


Fig. 8

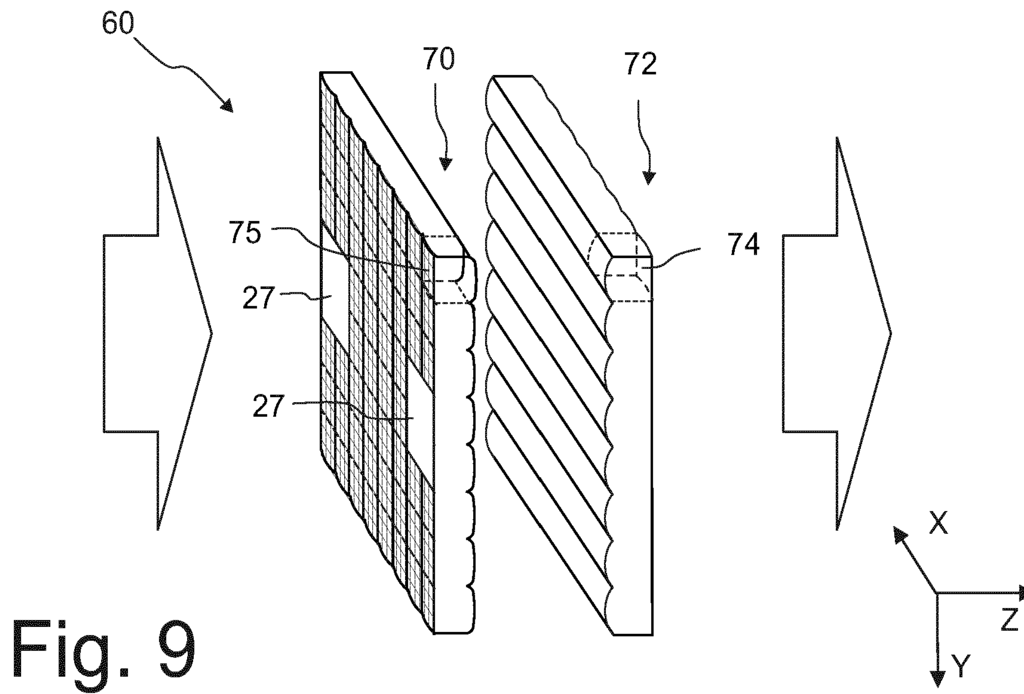


Fig. 9

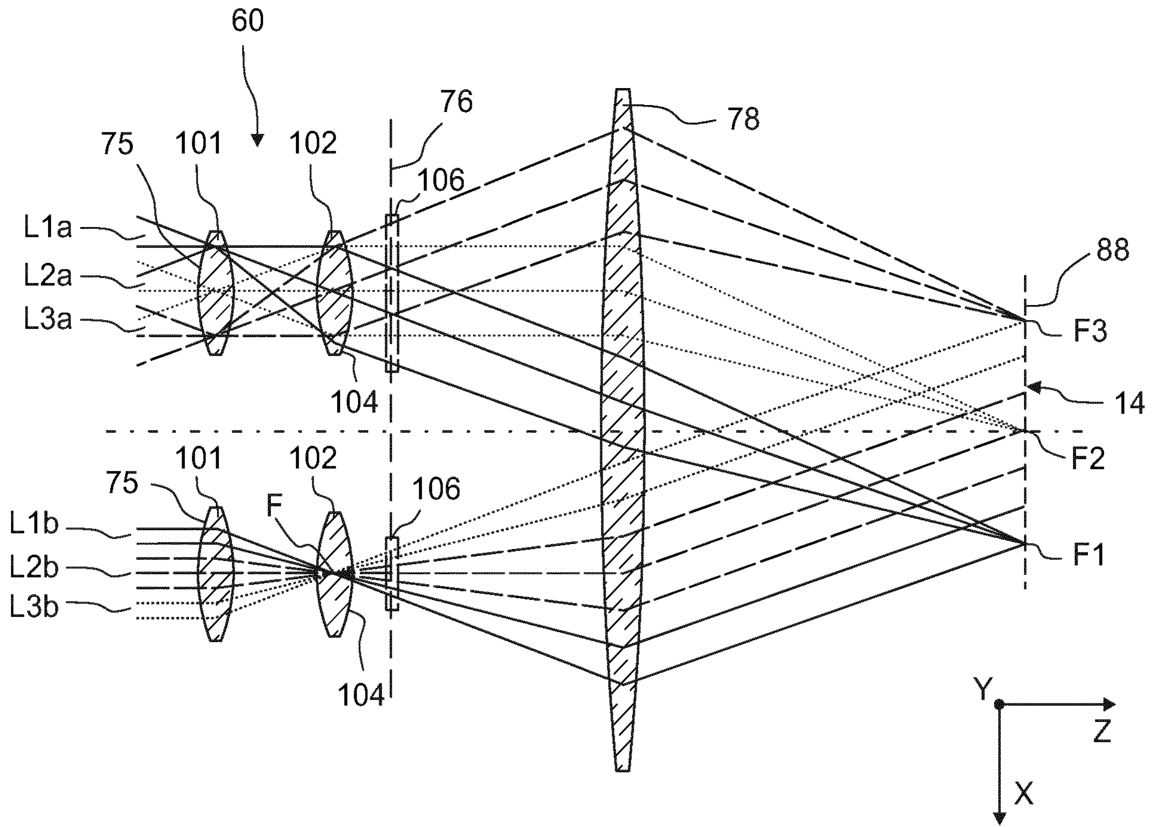


Fig. 10

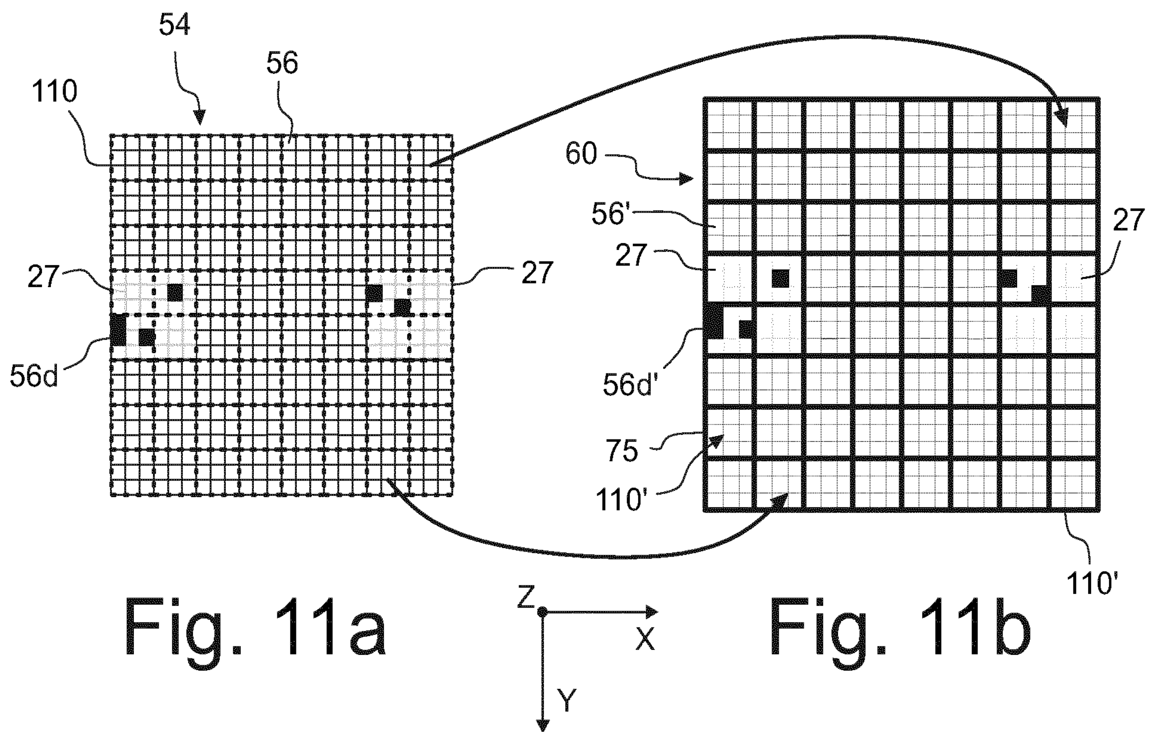


Fig. 11a

Fig. 11b

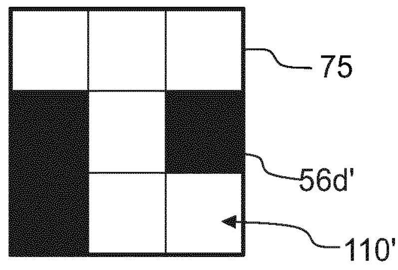


Fig. 12

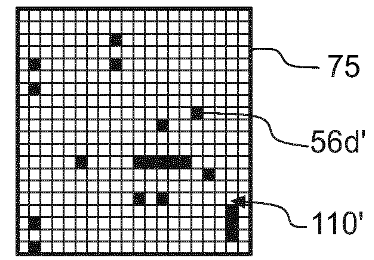


Fig. 14

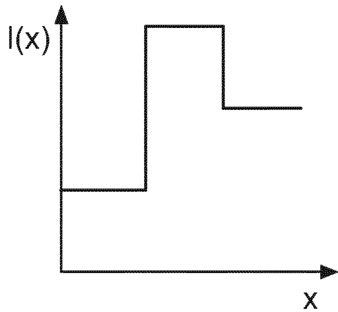


Fig. 13

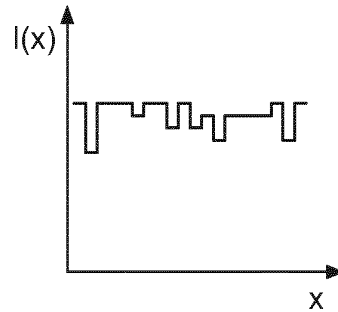


Fig. 15

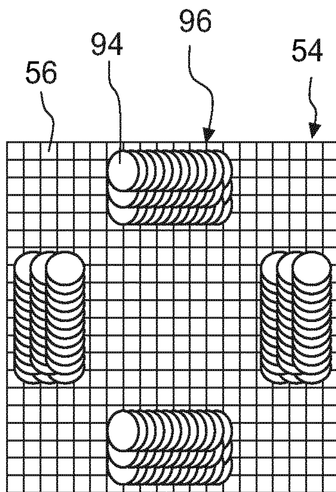
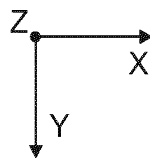
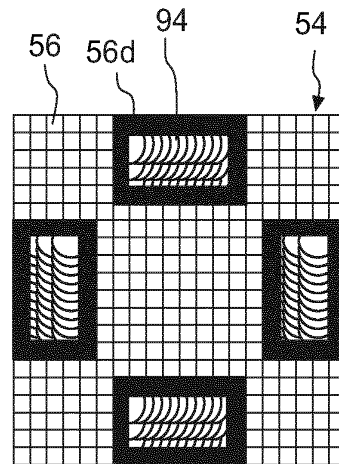


Fig. 16





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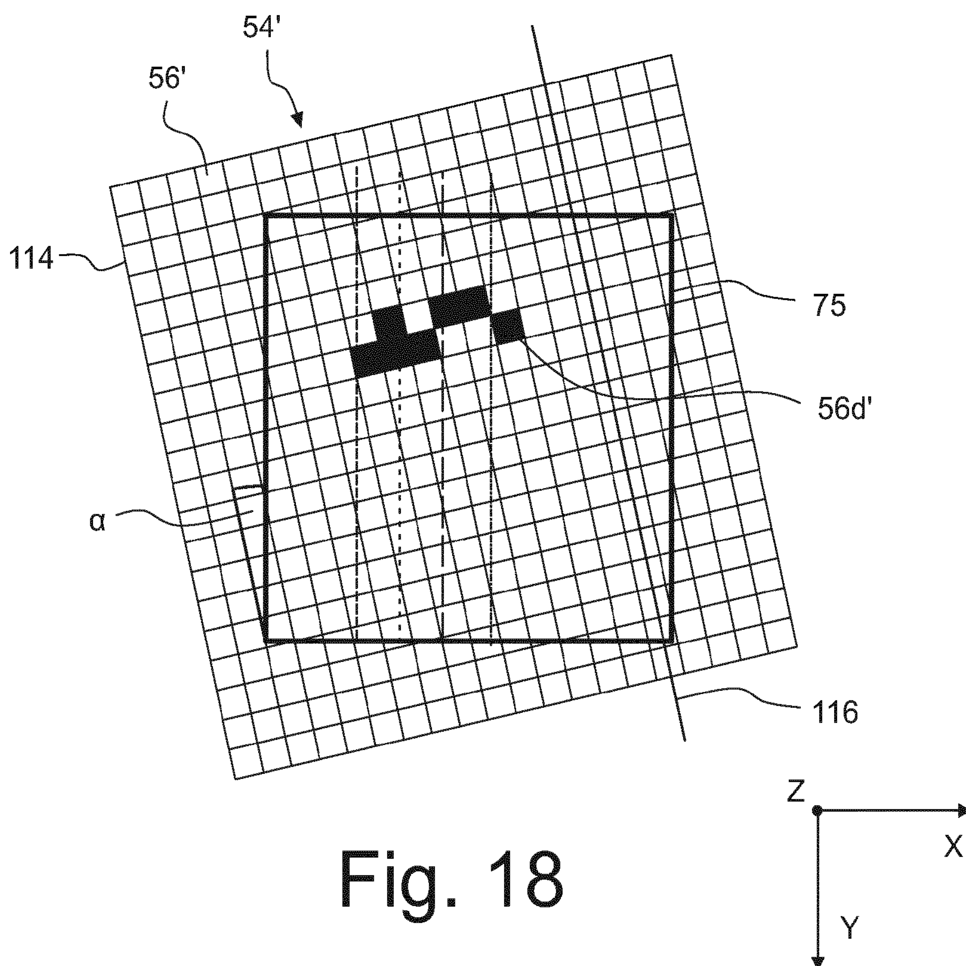

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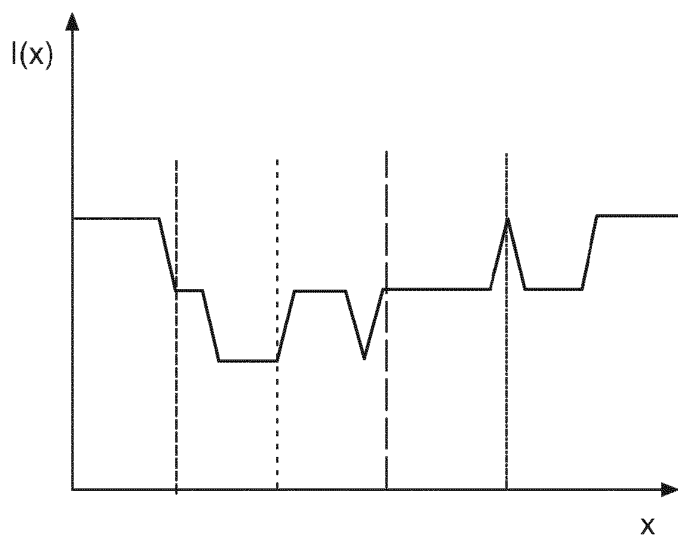

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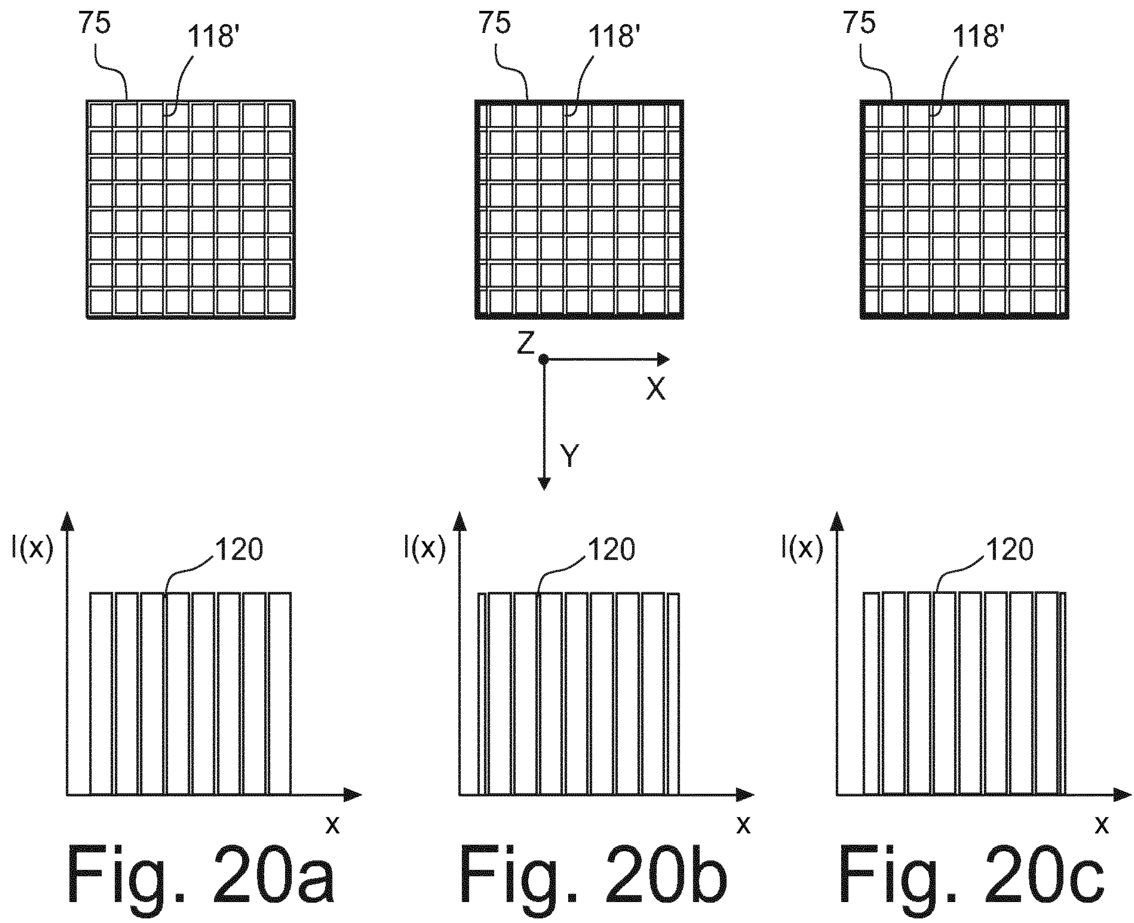


Fig. 20a Fig. 20b Fig. 20c

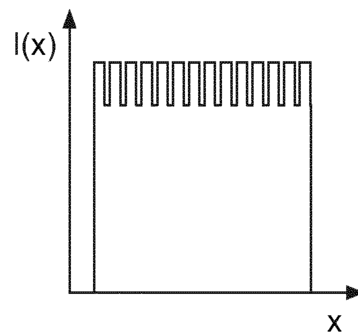


Fig. 21

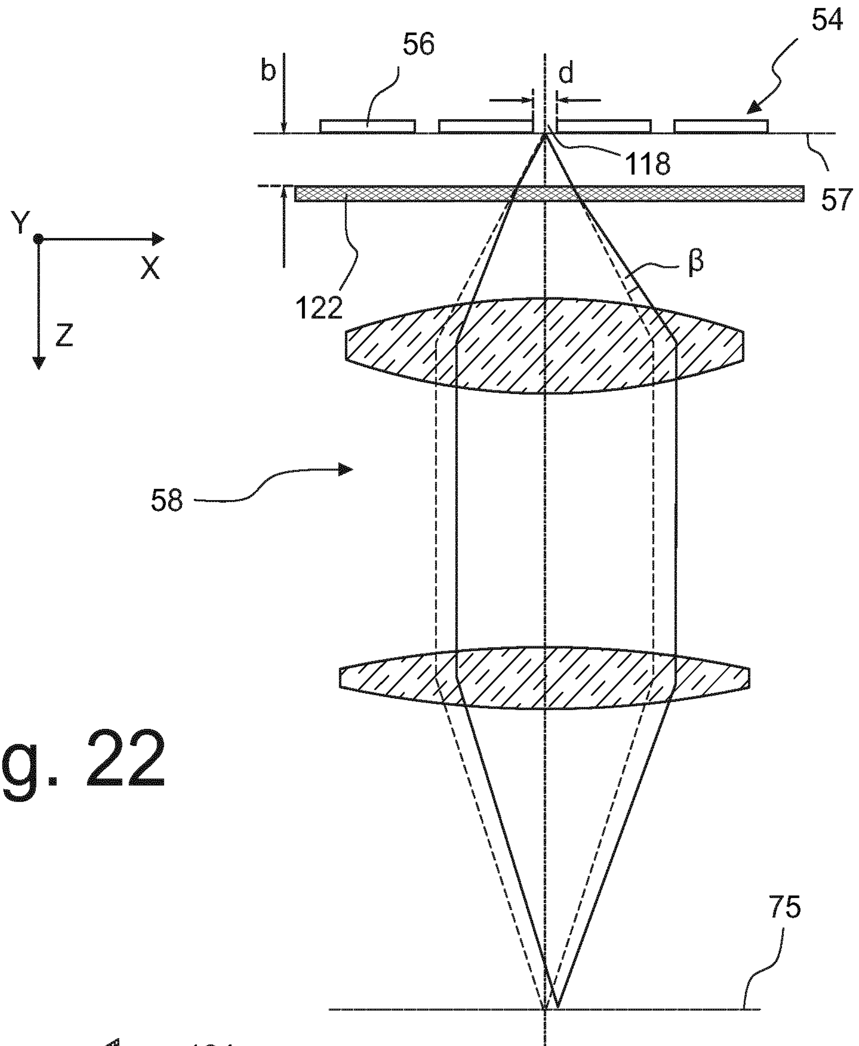


Fig. 22

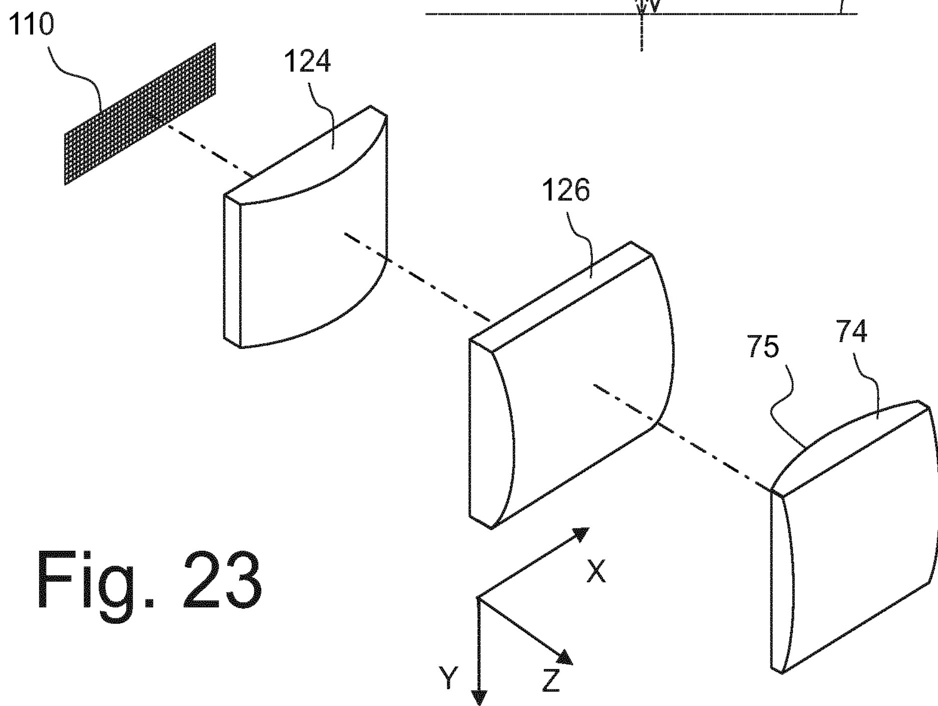


Fig. 23

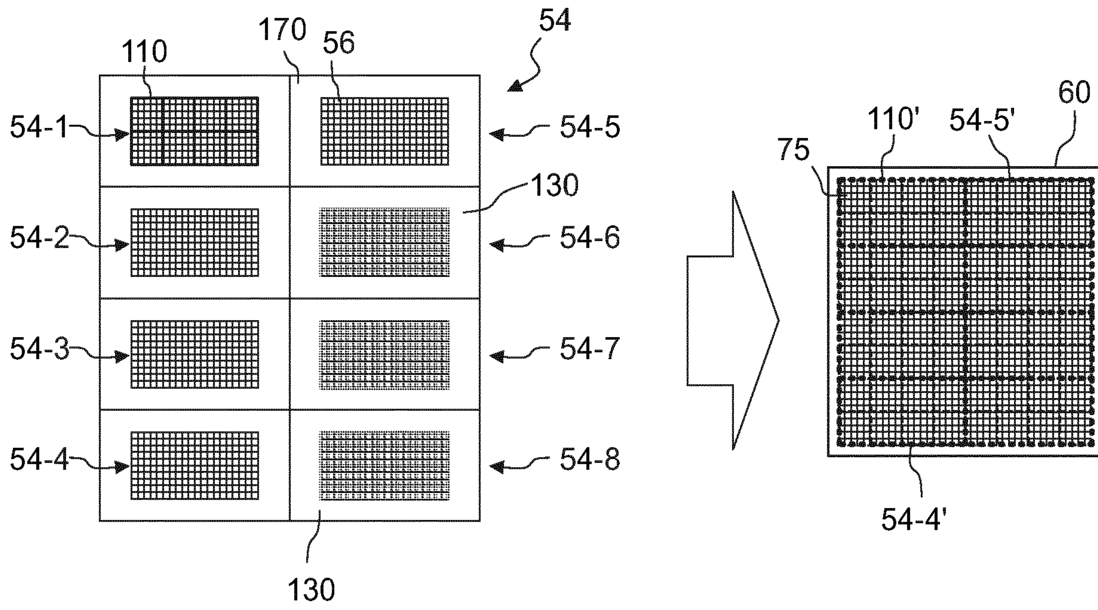


Fig. 24

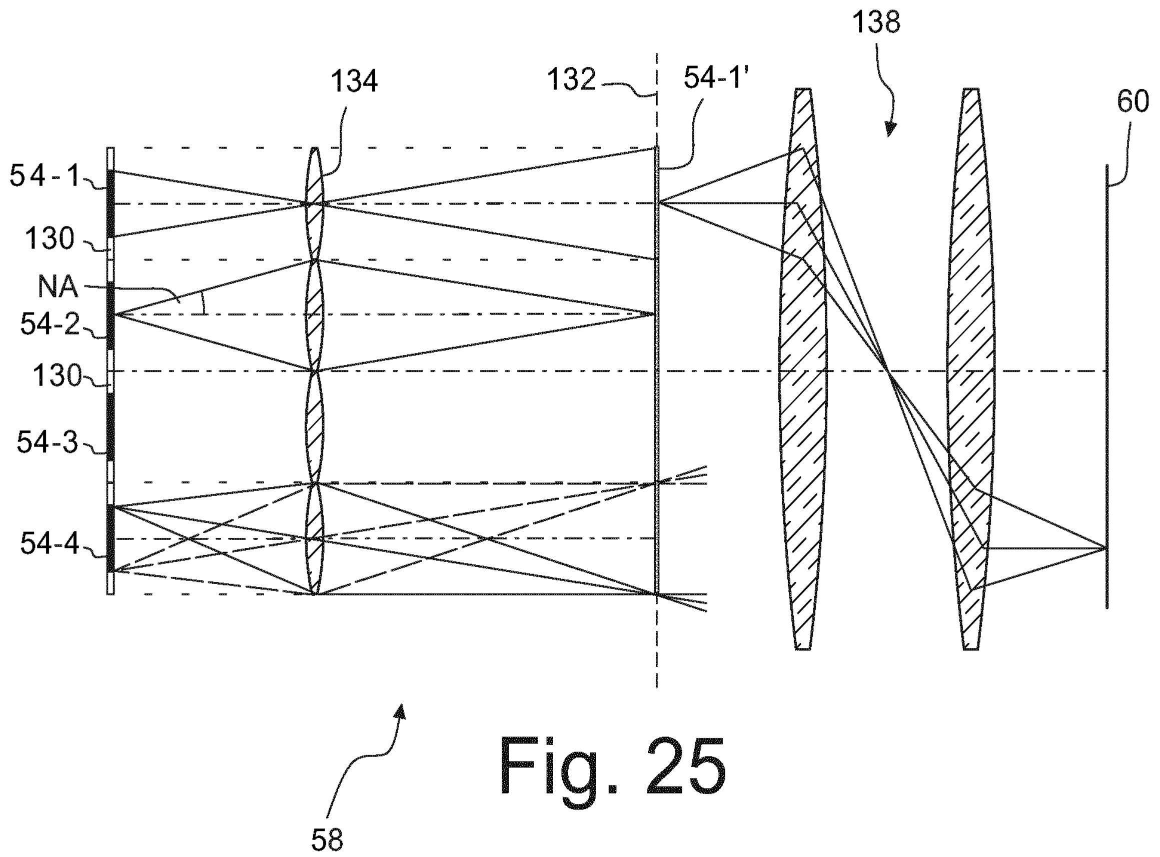


Fig. 25

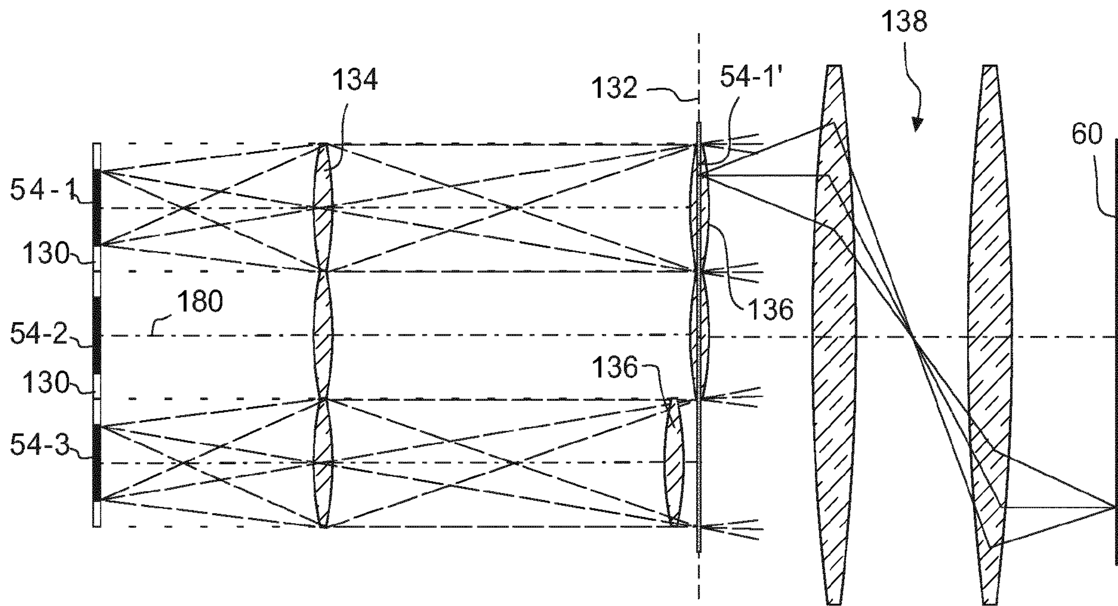


Fig. 26

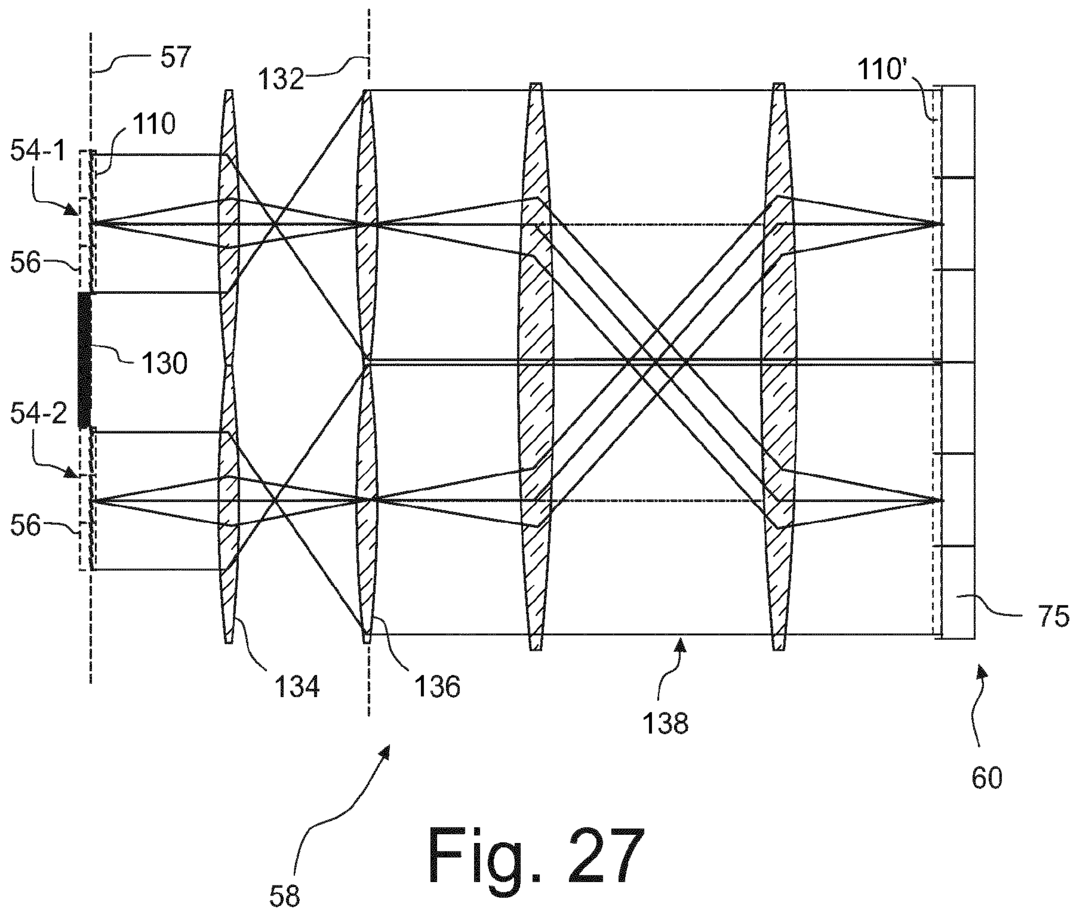


Fig. 27

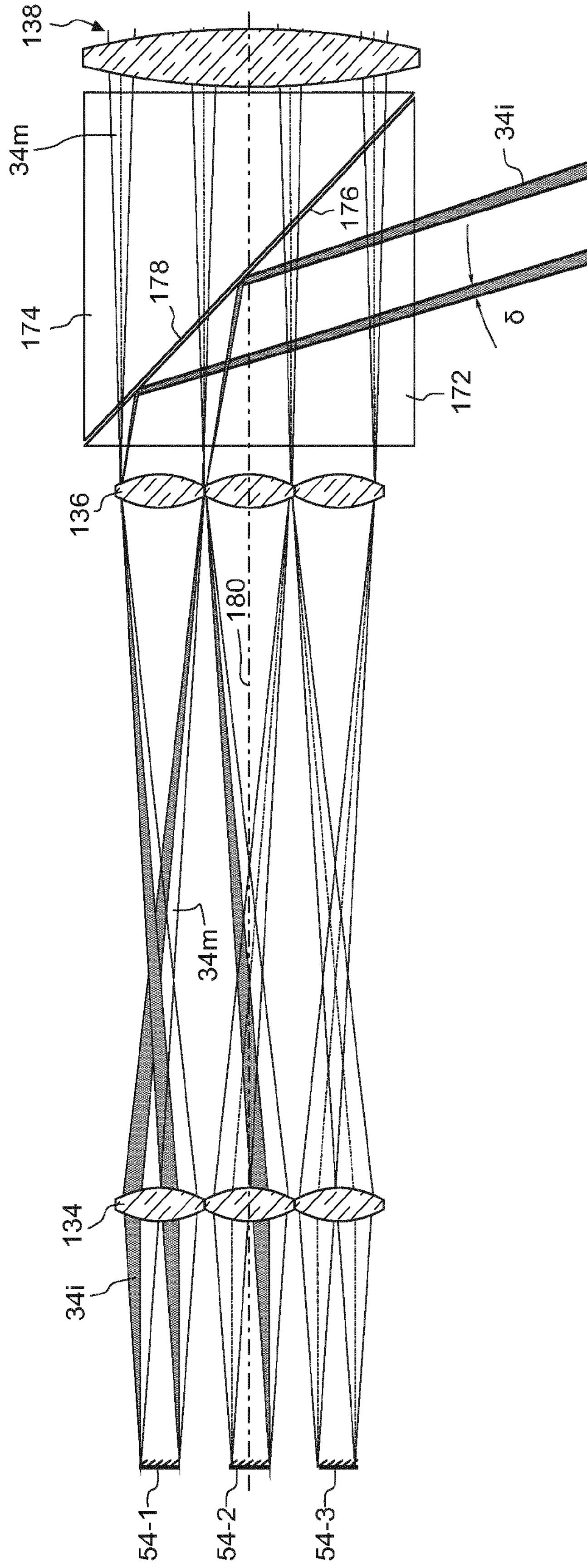


Fig. 28

60
180
186
36
188
182
184
138
34i
136
34i
34m
134
54-1
54-2
54-3

Fig. 29

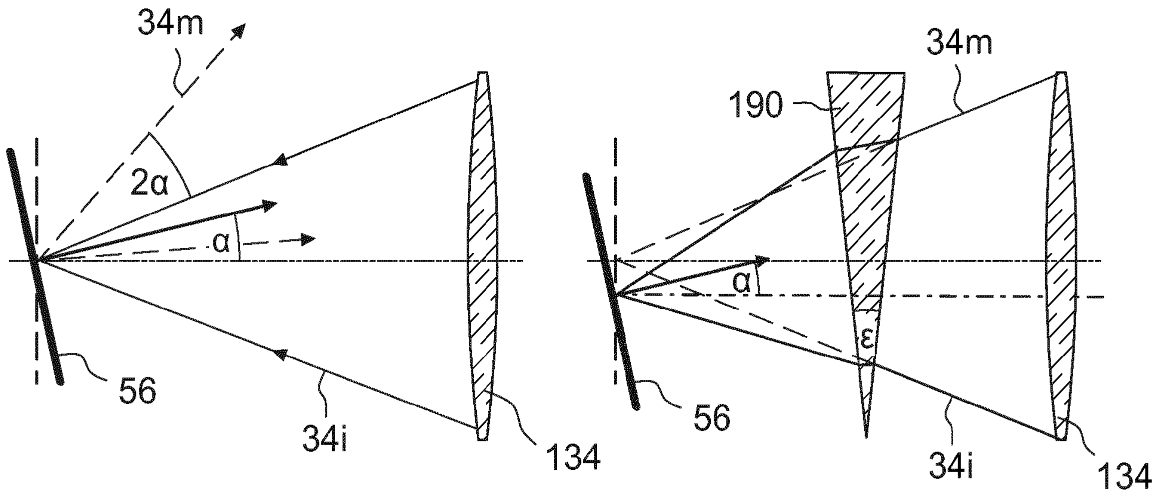


Fig. 30

Fig. 31

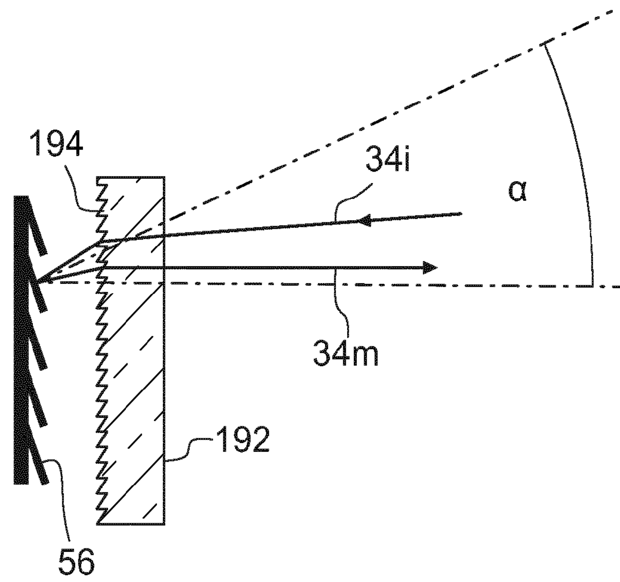


Fig. 32

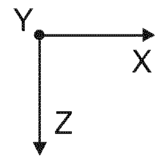


Fig. 33

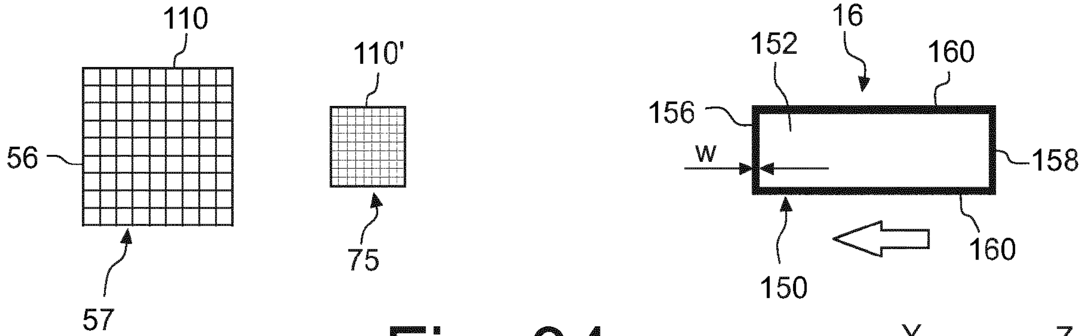


Fig. 34a

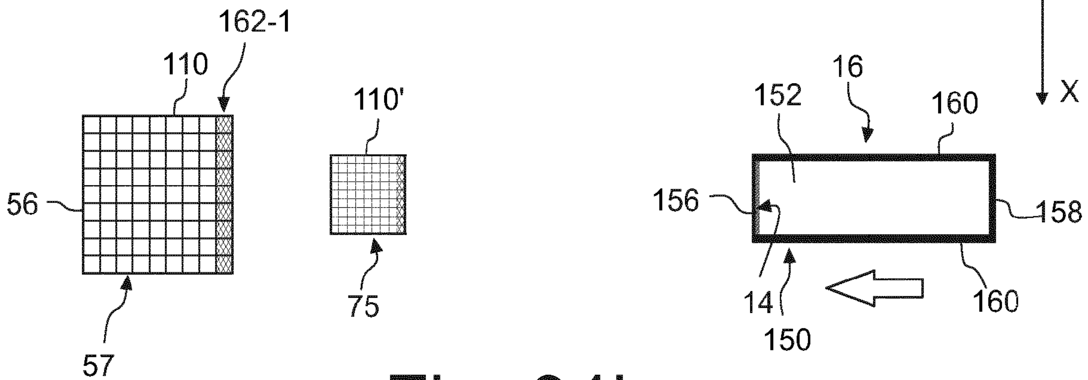


Fig. 34b

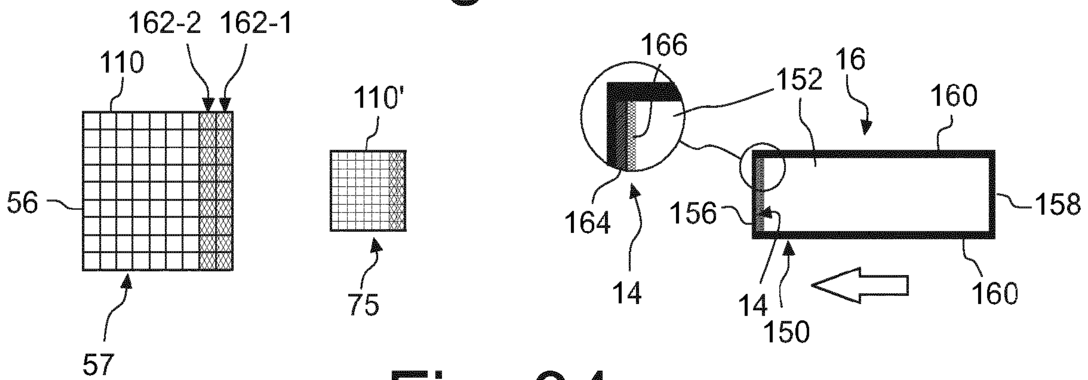


Fig. 34c

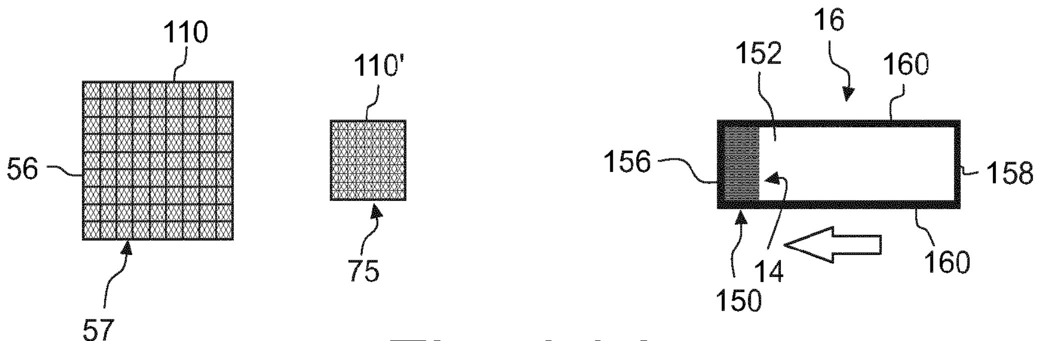
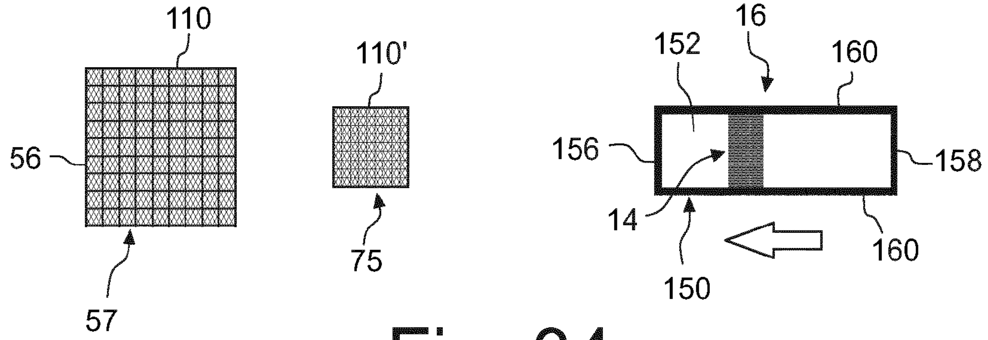


Fig. 34d



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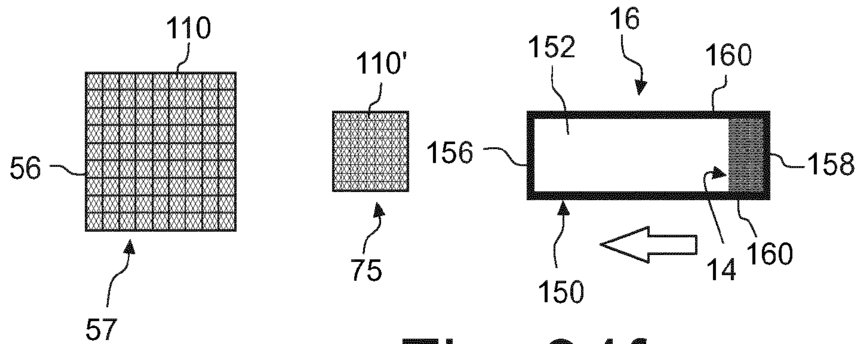

Fig. 34f

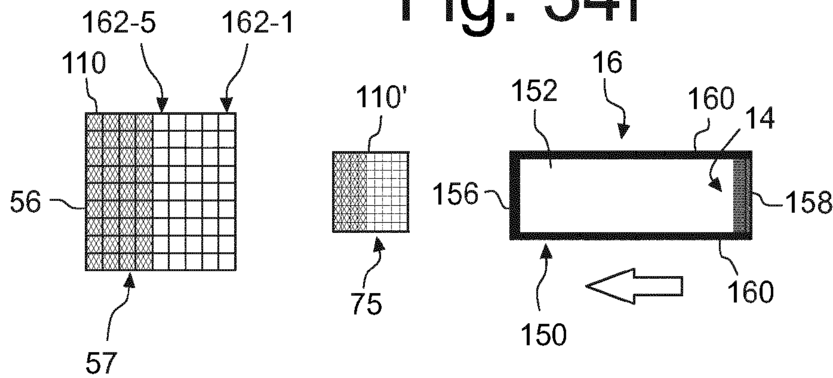

Fig. 34g

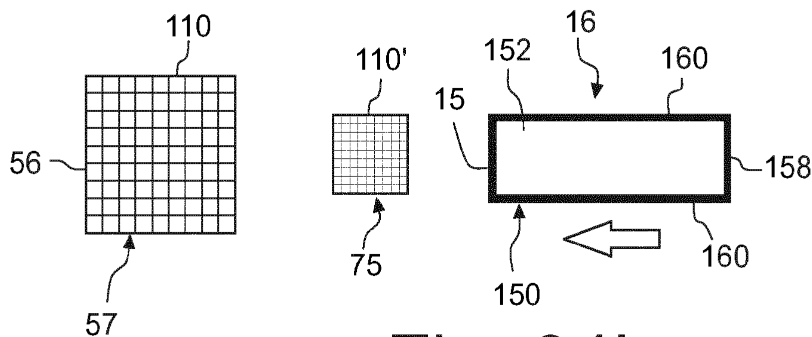

Fig. 34h

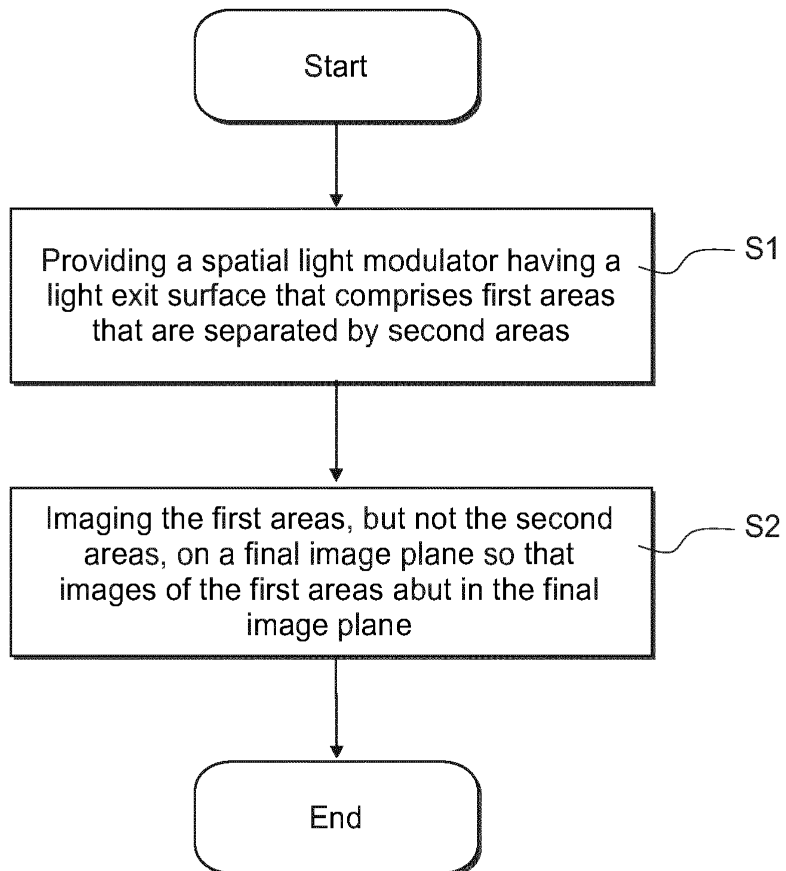

Fig. 35

REFERENCES CITED IN THE DESCRIPTION

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