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(54) Title: ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC APPARATUS

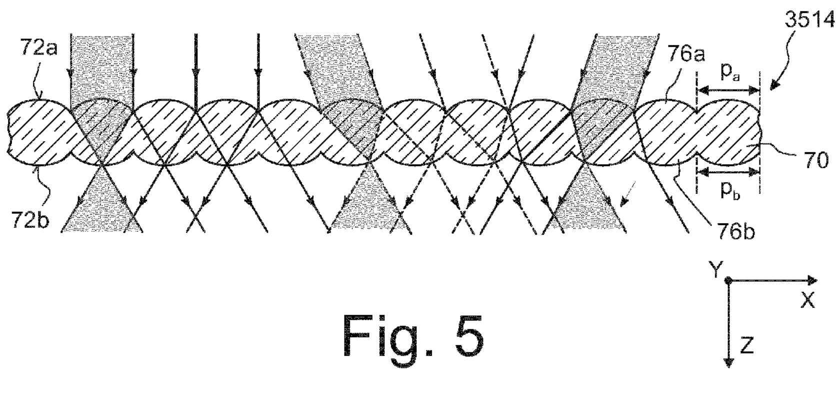


Fig. 5

(57) Abstract: An illumination system of a microlithographic apparatus has an optical axis (OA) and comprises an optical integrator (52) and a scattering structure (51). The scattering structure is arranged, along a light propagation direction of the system, in front of the optical integrator and comprises a first array of first optical raster elements (76a) and a second array of second optical raster elements (76b). The first array and the second array are spaced apart from each other along the optical axis (OA). This ensures that the light impinging on the optical integrator has an optimum divergence irrespective of the angular distribution of the light impinging on the scattering structure.

ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention generally relates to the field of microlithography, and more specifically to illumination systems used in projection exposure apparatus or mask inspection apparatus. The invention is particularly related to a scattering structure in such systems that improves the evenness of the illumination of a subsequent optical integrator.

2. Description of Related Art

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 light of a certain wavelength. Next, the wafer with the photoresist on top is exposed to projection light through a mask in a projection exposure apparatus. The mask contains a circuit pattern to be imaged onto the photoresist. After exposure the photoresist is developed to produce an image that corresponds to the circuit pattern contained in the mask. Then an etch process transfers the circuit pattern into the thin film stacks on the wafer. Finally, the photoresist is removed. Repetition of this process with different masks results in a multi-layered microstructured component.

A projection exposure apparatus includes a light source and an illumination system that directs the light produced by the light source on the mask. The apparatus further comprises a mask stage for aligning the mask, a projection objective (sometimes also referred to as 'the lens') that images the illuminated field on the mask onto the photoresist, and a wafer alignment stage for aligning the wafer coated with the photoresist.

In illumination systems designed for wavelengths below 200 nm, lasers are typically used as light sources. The projection light bundle emitted by a laser has a small cross section and a low divergence, and therefore also the geometrical optical flux is small. The geometrical optical flux, which is also referred to as the Lagrange invariant, is a quantity that is, at least for certain special configurations, proportional to the product of maximum light angle and size of the illuminated field. The small optical geometrical flux of laser light sources implies that - if only conventional lenses are used - it is possible to achieve either a large field illuminated with small illumination angles, or a small field illuminated with larger illumination angles, but not both.

For obtaining a large field that is illuminated with large illumination angles, most illumination systems contain an optical integrator that increases the light divergence and thus the geometrical optical flux. Former generations of illuminations systems contained a glass rod or a similar light mixing element that ensures a very good irradiance uniformity in the mask plane. However, these light mixing elements destroy the polarization state of the projection light. This is sometimes an undesired effect because it has been discovered that illuminating the mask with projection light having a carefully selected polarization state may significantly improve the imaging of the mask pattern onto the photoresist.

Current illumination systems often contain instead of a glass rod a "wabenkondensor" which is a synonym for a fly-eye optical integrator. Also the term "condenser" is sometimes used in this context instead of optical integrator.

US 6,583,937 B1 describes such a system in which a fly-eye optical integrator produces a plurality of secondary light sources that commonly illuminate a field plane. The fly-eye optical integrator comprises two arrays of cylindrical lenses extending along the X direction and two arrays of cylindrical lenses extending along the Y direction. The focal lengths of the microlenses determine the size and geometry of the field that is illuminated on the mask, and also determine how much the geometrical optical flux is increased. A scattering disc is arranged close to a field plane.

Fly-eye optical integrators using microlens arrays and other refractive optical elements produce a broad and continuous angular distribution. The main drawback of refractive optical elements, however, is the fact that the irradiance distribution generated in the far field and thus in the mask plane is not sufficiently uniform. Instead of being flat, the irradiance distribution is often characterized by a plurality of ripples that sometimes cannot be tolerated.

US 2007/0285978 A1 discloses an illumination system in which a scattering plate is arranged in immediate vicinity to a fly-eye optical integrator. The scattering plate increases the geometrical optical flux in a scan direction and perpendicular thereto and reduces ripples of the illumination distribution produced by the microlens array.

US 2004/0036977 A1 discloses an optical integrator for an illumination system comprising two integrator members that can be individually adjusted. To this end at least one integrator member may be moved along the optical axis (Z axis) or perpendicular to the scan direction (X axis), or it may be rotated around the Z axis, the X axis or the scan direction (Y axis) that is perpendicular to the Z and X axis. A corrective filter for reducing undesired irradiance fluctuations on the mask is arranged in front of each integrator member. The corrective filters each comprise random patterned stripes having a pitch that is identical to the pitch of cylinder lenses of the respective integrator member.

US 8,395,756 B2 discloses the combination of two scattering plates and a two-stage fly-eye optical integrator. One scattering plate is arranged, along the light propagation direction, in front of the optical integrator and has a scattering effect only in the cross-scan direction. The other scattering plate is arranged behind the optical integrator and scatters the light along two orthogonal directions. In some embodiments the first scattering plate comprises concave or convex cylindrical microlenses having different pitches and curvatures so that a certain degree of irregularity is achieved.

However, it turned out that even with such sophisticated scattering plates the desired irradiance distribution in the mask plane is sometimes not obtained with the accuracy which is required in high-end lithographic apparatus.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an illumination system which more reliably produces a desired irradiance distribution in the mask plane.

This object is achieved, in accordance with the present invention, by an illumination system of a microlithographic apparatus having an optical axis and comprising an optical integrator and a scattering structure. The scattering structure is arranged, along a light propagation direction of the system, in front of the optical integrator. It comprises a first array of first optical raster elements and a second array of second optical raster elements. The first array and the second array are spaced apart from each other along the optical axis.

A complete understanding of the invention requires some knowledge about fly-eye optical integrators that are used to produce, usually together with condenser optics, to produce a uniform irradiance distribution in a field plane. In an ideal fly-eye optical integrator, the far field irradiance distribution is perfectly flat for each optical channel. In real fly-eye optical integrators, however, manufacturing tolerances or material flaws result in far field irradiance distributions having ripples or other deviations from the ideal flat distribution. It turns out that these deviations are greatest if the incident light is perfectly parallel (i.e. the divergence is zero), and become smaller if the incident light is divergent. On the other hand, the deviations from the desired flat far field irradiance distribution increase again at large divergences become then channel cross-talk occurs, i.e. light from one optical channel of the optical integrator enters into an adjacent optical channel. Therefore there is an optimum divergence for the light which is incident on a fly-eye optical integrator. With light having this optimum divergence, deviations from the ideal flat far field irradiance distribution are as small as possible.

The invention is based on the perception that the laser light sources, which are typically used in microlithographic apparatus, produce a light beam which having a divergence (or geometrical optical flux or angular light distribution, which all denote basically the same) that is not perfectly stable, and which also varies to some extent between different specimens of the same type of laser source. Such variations may be caused by ageing or thermal effects, for example.

Another cause for a varying divergence are mirror arrays that are used in sophisticated illumination systems to determine the illumination setting by variably illuminating the optical integrator. Such a mirror array produces a large number of minute light spots on the optical integrator at arbitrary positions. If a light spot moves over the surface of the optical integrator, its direction, and thus the angular light distribution of the light that constitutes the light spot, varies considerably. Therefore the divergence of the light impinging on the optical integrator depends on which mirrors illuminate a given portion of the optical integrator.

The provision of a two-stage scattering structure in accordance with the present invention ensures that the illumination of the subsequent optical integrator is substantially independent of the divergence of the incident light. The two-stage scattering structure in accordance with the present invention can be designed such that it produces light having a target divergence which is – at least to a certain extent - independent from the divergence of incident light, and which is identical to the optimum divergence for which the deviations from the ideal flat far field irradiance distribution are minimum. Accordingly, the two-stage scattering structure ensures that variations of the divergence, as they may occur as a result of ageing or thermal effects or if a mirror array is used to illuminate the optical integrator, have no adverse effects on the irradiance distribution at mask level.

If a mirror array is used to illuminate the optical integrator, the use of the two-stage scattering structure makes it possible to dispense with a condenser that is typically arranged between the mirror array and the optical integrator. Such a condenser is used in order to reduce the divergence of the light impinging on the optical integrator. Since the two-stage scattering structure produces a target divergence which is – at least to a certain extent - independent from the divergence of the incident light, such a reduction of the divergence is not required any more.

Generally, it will be preferred to use a configuration in which the first optical raster elements extend in a first plane and the second optical raster elements extend in a second plane that is distinct from the first plane. In principle, however, the optical raster elements may also be arranged on a curved surface of a support plate.

In an embodiment the first plane is parallel to the second plane. However, it may also be envisaged to use a configuration in which the two planes form a small angle for adjusting certain properties, as this is described in the aforementioned US 2004/0036977 A1 for the two plates of a fly-eye optical integrator.

In an embodiment the first array is arranged, along the light propagation direction, in front of the second array. Pairs of a first optical raster element and a second optical raster element form light channels so that light, which enters the first optical raster element of a channel, passes exclusively through the second optical raster element of said channel. This ensures that no cross-talk between adjacent channels occur, and thus improves a uniform illumination of the subsequent optical integrator. If optical cross-talk occurs, ripples in the irradiance distribution behind the scattering structure may occur to some extent.

If the second plane is arranged in a rear focal plane of the first optical raster elements, and the first plane is arranged in a front focal plane of the second optical raster elements, this ensures that the divergence of the light incident on the subsequent optical integrator is completely independent of the divergence of the laser light which is incident on the scattering structure. As mentioned above, this makes it possible to illuminate the optical integrator with light having the optimum divergence. Sometimes, however, it may be prudent to arrange the optical raster elements at slightly defocused axial positions. Particularly if the laser light beam has a very low divergence, the light energy in the focal points in the second optical raster elements may be so high that material degradations or other damages may occur in the second optical raster elements.

In an embodiment the optical raster elements of one of the first and second arrays comprise a first kind of optical raster elements and a second kind of optical raster elements. The first and second kind of optical raster elements differ from each other with respect to the focal distance and/or the position of the optical raster elements along the optical axis. Such variations of the optical raster elements help to reduce the Talbot effect which occurs when perfectly regular raster elements are used.

When the illumination system is configured to produce an illumination field that is longer along an X direction than along an orthogonal Y direction, the directions X and Y being perpendicular to the optical axis, the scattering structure may scatter light only along the X direction which corresponds to the cross-scan direction in projection exposure apparatus of the scanner type. This is because along the scan direction, uniformity variations can be tolerated because of the time-integrating effect that is associated with the scanning movement.

An optical raster element in the context of the present invention is any optical element which can be placed, together with identical or similar other such elements, in a regular or in an irregular array on a common curved or planar surface. Usually the first and second optical raster elements will be cylindrical or rectangular microlenses, but the optical raster elements may also be formed by different regions of a diffractive optical element, for example.

The optical integrator may comprise at least one array of third optical raster elements. Then the first optical raster elements may have a first pitch along a reference direction that is perpendicular to an optical axis of the illumination system. The second optical raster elements may have a second pitch along the reference direction, and the third optical raster elements of the optical integrator may have third pitch along the reference direction, wherein the first and the second pitch is smaller than one half, and preferably between 1/5 and 1/20, of the third pitch. This configuration ensures that, for a given distance between the scattering structure and the optical integrator, the number of microlenses that contribute to the illumination of a third optical raster element of the optical integrator, is increased. The smaller the pitch of the first and second microlenses is compared to the pitch of the third microlenses, the more homogenous the illumination of the third microlenses is.

In one embodiment the illumination system comprises a spatial light modular comprising a beam deflection area of tiltable mirrors or other reflective or transparent beam deflection elements. Each beam deflection element is configured to deflect a light beam by a deflection angle that is variable in response to a control signal applied to the beam deflection element. In this manner the irradiance distribution on the scattering structure, and thus on the optical integrator, can be modified in almost any arbitrary way and very quickly.

The optical integrator may be configured to produce a plurality of light sources that commonly illuminate a field plane that is optically conjugate to a mask plane in which a mask can be arranged. To this end the illumination system may comprise a condenser having a front focal plane in which the secondary light sources are arranged. In the case of a fly-eye optical integrator, the latter may have a plurality of light entrance facets. The images of the light entrance facets are then superimposed in the field plane.

DEFINITIONS

The term "light" denotes any electromagnetic radiation, in particular visible light, UV, DUV and VUV light.

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 light that passes through a particular lens or another optical element.

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 illuminated field area.

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 "conjugated 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 Diagram", Applied Optics, 1963, vol. 2, no. 12, pages 1251-1256.

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 "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 "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 in the surface. If applied to a field plane, the spatial irradiance distribution necessarily integrates the irradiances produced by a plurality of light bundles.

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 dependency, I_a will be also a function of field coordinates, i. e. I_a= $I_a (\alpha, \beta, x, y)$.

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

The term "surface" is used herein to denote any planar 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.

BRIEF DESCRIPTION OF THE DRAWINGS

Various features and advantages of the present invention may be more readily understood with reference to the following detailed description taken in conjunction with the 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 a meridional section through an illumination system which is part of the apparatus shown in FIG. 1;

FIG. 3 is a perspective view of a mirror array contained in the illumination system shown in FIG. 2;

FIG. 4 is a perspective view of a field defining optical integrator contained in the illumination system shown in FIG. 2;

FIG. 5 is a cross section through a scattering plate, which may be used in the illumination system shown in FIG. 2, according to a first embodiment;

FIG. 6 is an enlarged cutout from the cross section shown in FIG. 5;

FIG. 7 is a graph illustrating the effects of the invention on the irradiance distribution in the mask plane;

FIG. 8 is a cross section through a scattering plate, which may be used in the illumination system shown in FIG. 2, according to a second embodiment;

FIG. 9 is a cross section through a scattering plate, which may be used in the illumination system shown in FIG. 2, according to a third embodiment.

DESCRIPTION OF PREFERRED EMBODIMENTS

I.
General Construction of Projection Exposure Apparatus

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 an illumination system 12 which produces a projection light beam. The latter illuminates a field 14 on a mask 16 containing a pattern 18 of fine features 19. In this embodiment the illuminated field 14 has the shape of a ring segment. However, other shapes of the illuminated field 14, for example rectangles, are contemplated as well.

A projection objective 20 having an optical axis OA and containing a plurality of lenses 21 images the pattern 18 within the illuminated 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 illuminated field 14 is projected onto the light sensitive layer 22.

During the projection the mask 16 and the substrate 24 move along a scan direction which corresponds to the Y direction indicated in FIG. 1. The illuminated field 14 then scans over the mask 16 so that patterned areas larger than the illuminated 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 inverts the image ($\beta < 0$), the mask 16 and the substrate 24 move in opposite directions; 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.

General Construction of Illumination System

FIG. 2 is a meridional section through the illumination system 12 shown in FIG. 1. For the sake of clarity, the illustration of FIG. 2 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.

The illumination system 12 includes a housing 29 and an entrance window 33 through which projection light, which has been produced by an external excimer laser or another light source 30, enters the illumination system 12. The light source 30 emits in this embodiment a beam 31 of projection light having a wavelength of about 193 nm. Other wavelengths, for example 248 nm or 157 nm, are also contemplated.

In the embodiment shown, the light beam 31 enters a beam expansion unit indicated at 32 in which the light beam 31 is expanded. To this end the beam expansion unit 32 may comprise several lenses or planar mirrors, for example. The expanded light beam 31 has a low divergence, i.e. it is almost collimated.

The light beam 31 then enters a beam homogenizing unit 34 which homogenizes the light beam 31 and stabilizes the angular distribution of the projection light at mask level. To this end the beam homogenizing unit 34 may comprise an optical integrator. Suitable designs for the beam homogenizing unit 34 are disclosed in WO 2009/080279 A1 and in US 2015/0185622 A1.

After homogenization the light beam 31 impinges on a beam dividing array 36. The latter divides the light beam 31 into a plurality of individual converging light beams from which only two denoted by LB1, LB2 are shown in FIG. 2. To this end the dividing array 36 comprises a plurality of small microlenses 37. Possible configurations of the dividing array 36 are disclosed in WO 2012/034571 A1, for example. Alternatively, the beam dividing array 36 may comprise an array of diffractive optical elements, as it is disclosed in WO 2005/026843 A2, or it may be completely dispensed with.

The converging light beams LB1, LB2 then propagate through a spatial light modulator 38 that is used to produce variable spatial irradiance distributions in a subsequent pupil plane. In this embodiment the spatial light modulator 38 comprises an array 40 of micromirrors 42 that can be tilted individually about two orthogonal axes with the help of actuators. The actuators are controlled by a control unit 43 which is connected to an overall system control 45.

FIG. 3 is a perspective view of the array 40 illustrating how the converging light beams LB1, LB2 are reflected into different directions depending on the tilting angles of the micromirrors 42 on which the light beams LB1, LB2 impinge. In FIGS. 2 and 3 the array 40 comprises only 6x6 micromirrors 42; in reality the array 40 may comprise several hundreds or even several thousands micromirrors 42.

Referring again to FIG. 2, the spatial light modulator 38 further comprises a prism 46 having a first planar surface 48a and a second planar surface 48b that are both inclined with respect to an optical axis 47 of the illumination system 12. At these inclined surfaces 48a, 48b the light beams LB are reflected by total internal reflection. The first surface 48a reflects the impinging light beams LB1, LB2 towards the micromirrors 42 of the array 40, and the second surface 48b directs the light beams LB1, LB2 reflected from the micromirrors 42 towards an exit surface 49 of the prism 46.

The directions of the light beams LB1, LB2, and thus the angular irradiance distribution of the light emerging from the exit surface 49 of the prism 46, can thus be varied by individually tilting the micromirrors 42 of the array 40. More details with regard to the spatial light modulator 38 can be gleaned from US 2009/0115990 A1, for example.

The angular irradiance distribution produced by the spatial light modulator 38 is transformed into a spatial irradiance distribution with the help of an optional first condenser 50 which directs the impinging light beams LB1, LB2 towards a scattering plate 51 that is arranged between the first condenser 50 and a field defining optical integrator 52. The scattering plate 51 will be discussed in more detail below in section III.

In this embodiment the field defining optical integrator 52 comprises two optical raster plates 53a, 53b each containing two orthogonal arrays of cylindrical microlenses 54a, 54a' and 54b, 54b' arranged with a pitch p, as this is shown in FIG. 4. The microlenses 54a, 54b extending along the cross-scan direction X are more strongly curved than the micro-lenses 54a', 54b' extending along the scan direction Y. Crossing microlenses on opposed surfaces of each raster plate 53a, 53b define anamorphotic raster elements 55 that have a stronger positive refractive power along the X direction than along the Y direction. Opposing raster elements 55 define an optical channel in the sense that light, which enters a raster element belonging to a channel, is confined to the other raster element of that channel.

The field defining optical integrator 52 produces a plurality of secondary light sources in a subsequent pupil plane 56 of the illumination system 12. A second condenser 58 establishes a Fourier relationship between the pupil plane 56 and a field stop plane 60 in which an adjustable field stop 62 is arranged. The second condenser 58 superimposes the light beams emerging from the secondary light sources in the field stop plane 60 so that the latter is illuminated very homogenously.

The field stop plane 60 is imaged by a field stop objective 64 onto a mask plane 66 in which the mask 16 supported on a mask stage (not shown) is arranged. Also the adjustable field stop 62 is thereby imaged on the mask plane 66 and defines at least the short lateral sides of the illuminated field 14 extending along the scan direction Y.

The spatial irradiance distribution in front of the field defining optical integrator 52 determines the spatial irradiance distribution in the pupil plane 56 and thus the angular irradiance distribution in the field stop plane 60 and the mask plane 66. By carefully setting the tilting angles of the micromirrors 42 of the array 40 with the help of the control unit 43, it is thus possible to quickly produce almost any arbitrary angular irradiance distribution in the mask plane

66. This, in turn, makes it possible to quickly adapt the angular irradiance distribution in the mask plane 66 to the pattern 18 contained in the mask 16. By using an angular irradiance distribution which is specifically tailored to the pattern 18, the latter can be imaged more accurately onto the light sensitive layer 22.

III.
Scattering Plate

FIG. 5 shows a cross section through a portion of the scattering plate 51. In this embodiment the scattering plate 51 comprises a substrate 70 having a first surface 72a and a second surface 72b that are substantially parallel to each other. On the first surface 72a an array of parallel first cylindrical microlenses 76a is arranged with a pitch p_a that have a positive refractive power along the cross-scan direction X and have no refractive power along the scan direction Y. Similarly, an array of parallel second cylindrical microlenses 76b is arranged, with an identical pitch $p_b = p_a$, on the second surface 72b. Also the second microlenses 76b have a positive refractive power only along the cross-scan direction X and no refractive power along the scan direction Y.

In this embodiment the first microlenses 76a and the second microlenses 76b are integrally formed with the substrate 70 and may be produced with the help of a fly-cut process, as it is described in US 7,880,969 B2, for example. However, it is to be understood that other manufacturing processes, for example grey scale lithography, may be used instead. The first and second microlenses 76a, 76b may also be manufactured as individual micro-optical elements that are attached to a separate support 70.

Directly opposing microlenses 76a, 76b form an optical channel so that light, which impinges on a first microlens 76a, is completely guided through the directly opposing microlens

76b on the second surface 74. The grey shadings shown in FIG. 5 illustrate that this property applies also to light bundles which impinge obliquely on the first microlenses 76a.

The pitches p_a, p_b of the first and second microlenses 76a, 76b is typically in a range between 1 and 1000 µm and is preferably much smaller than the pitch p of the microlenses of the optical integrator 52. Preferably $p_a, p_b < 1/2 \cdot p$, and more preferably $1/20 \cdot p < p_a, p_b < 1/5 \cdot p$. This ensures that a large number of optical channels of the scattering plate 51 contribute to the illumination of one optical channel of the field defining optical integrator 52.

It can further be seen in FIG. 5 that the divergence of the light bundles emerging from the scattering plate 51 is independent from the directions from which the light impinges on the scattering plate. In this manner the illumination of the field defining optical integrator 52 does not depend on the direction of the light which is reflected by the micromirrors 42 towards the scattering plate 51 via the first condenser 50.

This is also illustrated in FIG. 6 which shows at an enlarged scale two opposing microlenses 76a, 76b forming a single optical channel of the scattering plate 51. In this embodiment the curvatures of the microlenses 76a, 76b and the distances between the microlenses 76a, 76b are selected so that the rear focal plane 80a of the first microlens 76a is arranged in the plane in which the second microlens 76b extends. The same also applies to the second microlens 76b, i.e. its front focal plane 80b is arranged substantially in the plane in which the first microlens 76a extends. This arrangement of the microlenses in mutual focal planes is sometimes referred to as the fly-eye integrator condition.

From FIG. 6 it becomes clear that light bundles emerging from points 82, 82' in the front focal plane 80b leave the second microlens 76b as parallel light bundles 84 and 84', respectively. The direction of the light bundles 84, 84' only depends on the distance of the point 82, 82' from the optical axis 86 of this particular optical channel. However, the divergence or angular distribution of the light emerging from the points 82, 82' has no impact on the direction of the bundles 84, 84', but only influences the diameter of the light bundles 84, 84'.

The maximum angle, under which a light ray may emerge from this optical channel, depends on the pitch of the microlenses 76a, 76b. This is illustrated by a light ray 88 that impinges on the first microlens 76a at a point at its outer edge.

The advantageous effect of the scattering plate 51 on the irradiance distribution in the mask plane 66 will now be described in more detail.

In FIG. 2 a light ray 90 shown in broken lines emerges from a micro-mirror 42 of the array 40 which is situated on the optical axis OA of the illumination system 12. Since the array 40 is arranged in a front focal plane of the first condenser 50, light emerging from this on-axis point leaves the first condenser 50 parallel to the optical axis OA. However, light emerging from off-axis points in the front focal plane of the first condenser 50 emerges from the first condenser 50 in an angled manner with respect to the optical axis OA, as this is shown in figure 2 for two light rays drawn in solid lines. Therefore, most of the light emerging from the array 40 does not impinge parallel to the optical axis OA, but obliquely on the scattering plate 51. In embodiments in which the first condenser 50 is dispensed with, this effect is even stronger, i.e. the divergence of the light emerging from the array 40 is quite significant.

Because the divergence of the light emerging from the scattering plate 51 is independent from the angular distribution of the impinging light, the field defining optical integrator 52 will always be illuminated with light having the same divergence which is exclusively determined by the design of the scattering plate 51, and more specifically by the curvature, distance and pitch of its first and second microlenses 76a, 76b. In this manner it is possible to illuminate the optical integrator 52 with light having a divergence that is perfectly adapted to the optical integrator 52 and for which deviations of the far field irradiance distribution from the ideal flat top distribution become as small as possible.

FIG. 7 is a graph showing the irradiance distribution I(x) produced by a single channel of the field defining optical integrator 52 along the cross-scan direction X. Broken lines indicate the irradiance distribution that is produced if the optical integrator 52 is illuminated with light having an arbitrary divergence. It can be seen that the irradiance distribution deviates significantly from the desired flat top distribution, because it contains several ripples that often are particularly high at the field edges. If the optical integrator 52 is illuminated with light having an optimized divergence, as this is possible with the scattering plate 51, these ripples are significantly reduced or may even vanish, as this is represented in FIG. 7 by a solid line.

If all channels of the field defining optical integrator 52 produce a flat top irradiance distribution in the far field, the irradiance distribution in the mask plane 66 will also be almost perfectly uniform, because in the mask plane 66 (and also in the preceding field stop plane 60) the irradiance distributions of all optical channels are superimposed.

IV.
Alternative embodiments

FIG. 8 shows, in a representation similar to FIG. 5, a scattering plate 51 according to a second embodiment in which the curvatures of the first microlenses 76a are not identical, but differ between adjacent microlenses, while the curvatures of the second microlenses 76b are all equal. The different curvatures of the first microlenses 76a result in different focal lengths, and consequently the fly-eye integrator condition is only approximately fulfilled for some of the optical channels. But since the first microlenses 76a are still arranged in the front focal plane of the second microlenses 76b, the divergence of the light leaving the scattering plate 51 is still independent of the divergence of the incident light.

In FIG. 8 it can be seen that, due to the different curvatures of the first microlenses 76a, the focal positions 92a, 92b, 92c associated with adjacent optical channels are generally at different distances from the scattering plate 51 along the optical axis. This mitigates the Talbot effect that occurs if strictly periodic structures are illuminated by coherent or partially coherent light. In that case the periodic structures form exact images of themselves at so-called Talbot distances as a result of Fresnel diffraction. In addition, multiple phase-transformed Fresnel images are produced at fractional Talbot distances. Simply speaking, the Talbot phenomenon indicates that in any plane behind a periodic structure a certain periodicity of the irradiance distribution is observed.

By axially shifting the focal points 92a, 92b 92c to various extents, the Talbot effect is mitigated because there is not any more a strictly periodic structure or arrangement of focal points in a single plane.

FIG. 9 shows a scattering plate 51 according to a third embodiment in which basically the same effect is achieved. Here the axial displacement of the focal points 92a, 92b is achieved not by varying the curvatures of the first microlenses 76a, but by varying the distance between the micro-lenses 76a, 76b having identical refractive power.

CLAIMS

1. An illumination system of a microlithographic apparatus, having an optical axis (OA) and comprising an optical integrator (52) and a scattering structure (51), wherein the scattering structure

   - is arranged, along a light propagation direction of the system, in front of the optical integrator,

   - comprises a first array of first optical raster elements (76a) and a second array of second optical raster elements (76b), wherein the first array and the second array are spaced apart from each other along the optical axis (OA).

2. The illumination system of claim 1, wherein the first array is arranged, along the light propagation direction, in front of the second array, and wherein pairs of a first optical raster element (76a) and a second optical raster element (76b) form light channels so that light, which enters the first optical raster element of a channel, passes exclusively through the second optical raster element of said channel.

3. The illumination system of claim 1 or 2, wherein the first optical raster elements (76a) extend in a first plane, and wherein the second optical raster elements (76b) extend in a second plane that is distinct from the first plane.

4. The illumination system of claim 3, wherein the second plane is arranged in a rear focal plane (80a) of the first optical raster elements (76a), and wherein the

first plane is arranged in a front focal plane (80b) of the second optical raster elements (76b).

5. The illumination system of any of the preceding claims, wherein the optical raster elements (76a, 76b) of one of the first and second arrays comprise a first kind of optical raster elements and a second kind of optical raster elements, wherein the first and second kind of optical raster elements differ from each other with respect to the focal distance and/or the position of the optical raster elements along the optical axis.

6. The illumination system of any of the preceding claims, wherein the illumination system is configured to produce an illumination field (14) that is longer along an X direction than along an orthogonal Y direction, the directions X and Y being perpendicular to the optical axis (OA), and wherein the scattering structure (51) scatters light only along the X direction.

7. The illumination system of any of the preceding claims, wherein the first and second optical raster elements are microlenses (76a, 76b).

8. The illumination system of any of the preceding claims, wherein the optical integrator (52) comprises at least one array of third optical raster elements (54a, 54a', 54b, 54b'), and wherein

- the first optical raster elements (76a) have along a reference direction, which is perpendicular to the optical axis (OA) of the illumination system, a first pitch (p_a),

- the second optical raster elements (76b) have along the reference direction a second pitch (p_b),

- the third optical raster elements have along the reference direction a third pitch (p),

wherein the first and the second pitch is smaller than one half of the third pitch.

9. The illumination system of any of the preceding claims, wherein the optical integrator (52) is illuminated by a spatial light modulator (38) that is configured to vary a spatial irradiance distribution on the scattering structure (51).

10. The illumination system of claim 10, wherein the spatial light modulator comprises a beam deflection array (40) of reflective or transparent beam deflection elements (42), wherein each beam deflection element (42) is configured to deflect a light beam by a deflection angle that is variable in response to a control signal applied to the beam deflection element (42).

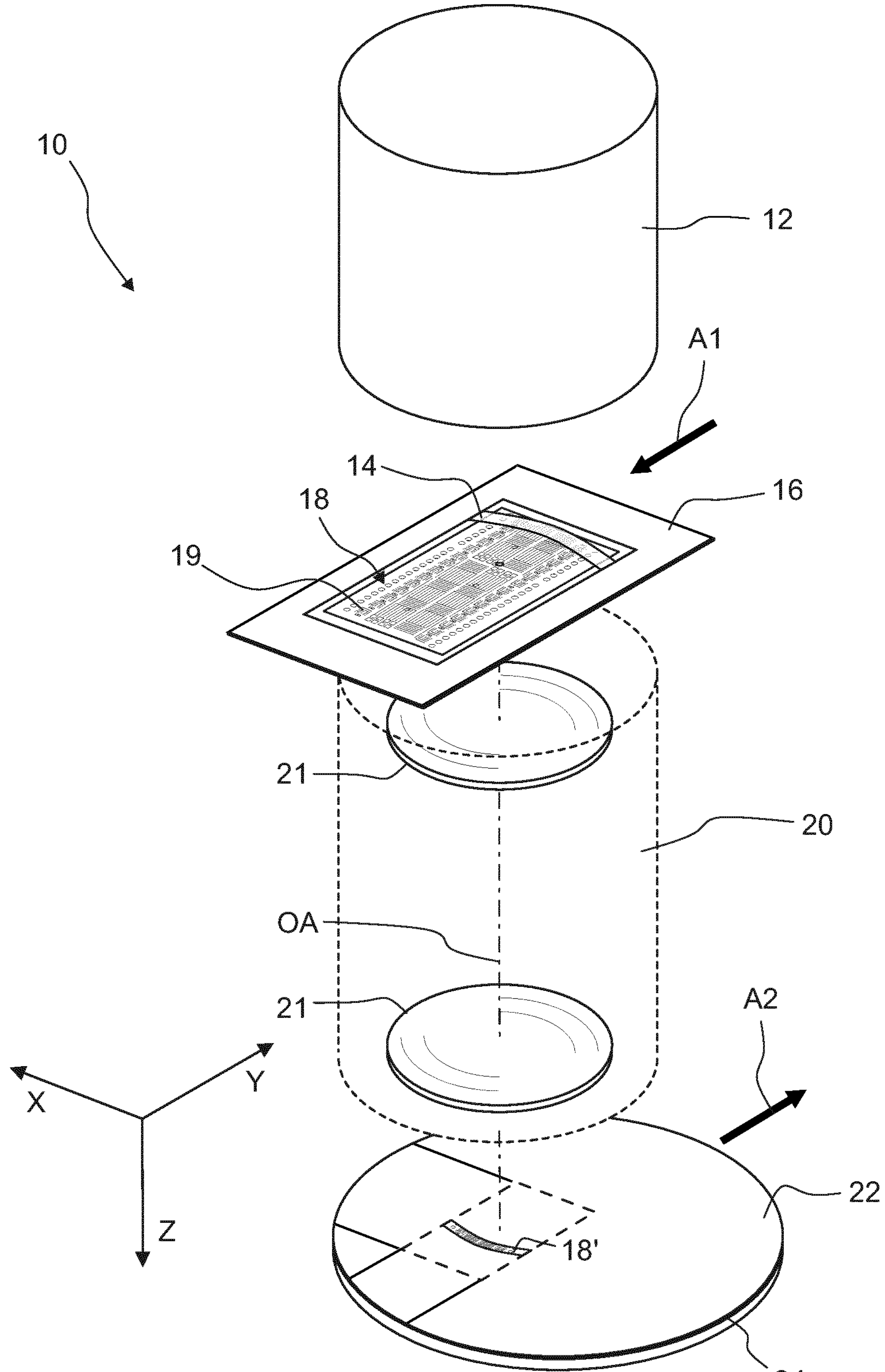
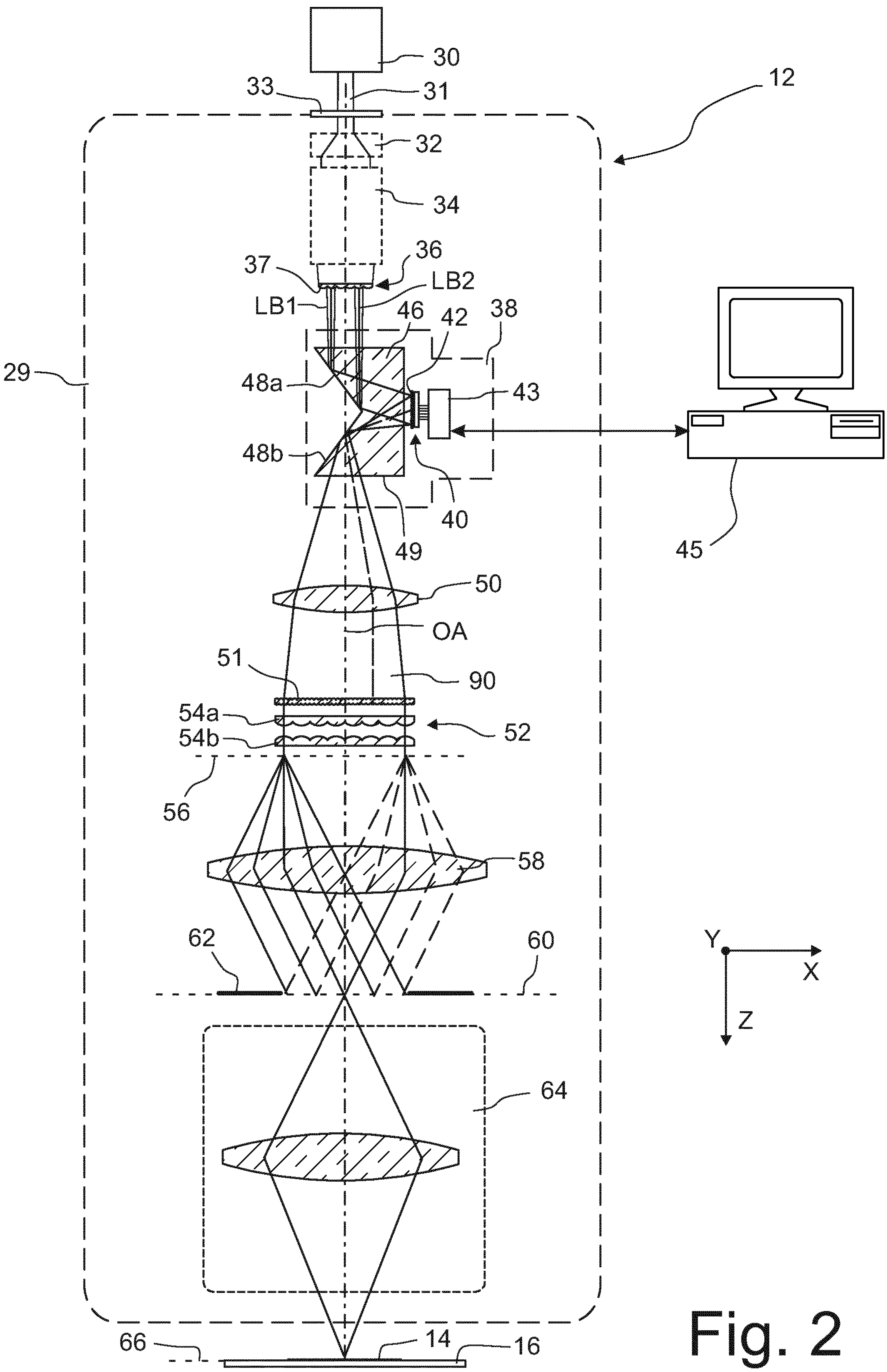


Fig.1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12
32
34
36
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LB2
LB1
46
42
38
48a
43
29
48b
40
49
45
50
OA
51
90
54a
52
54b
56
58
62
60
Y
X
Z
64
66
14
16

Fig. 2

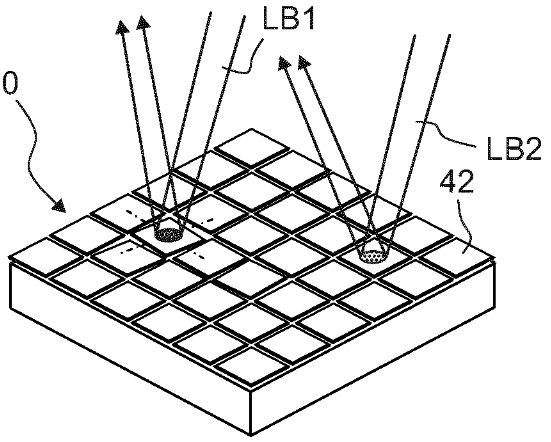


Fig. 3

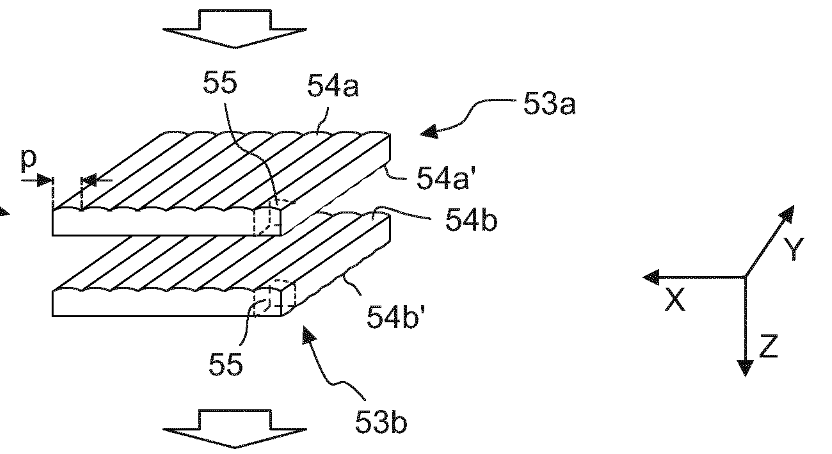


Fig. 4

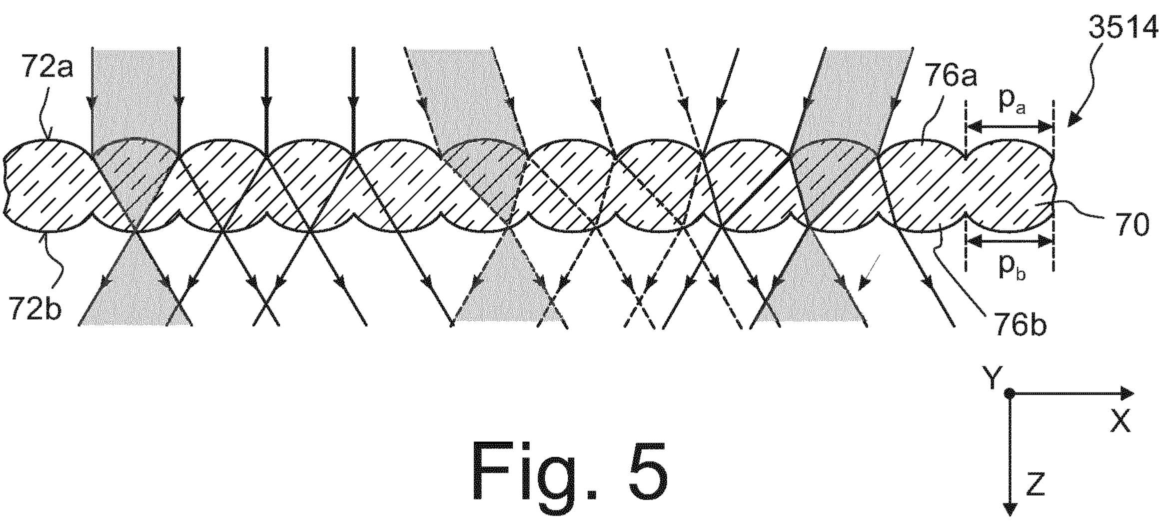


Fig. 5

Fig. 6

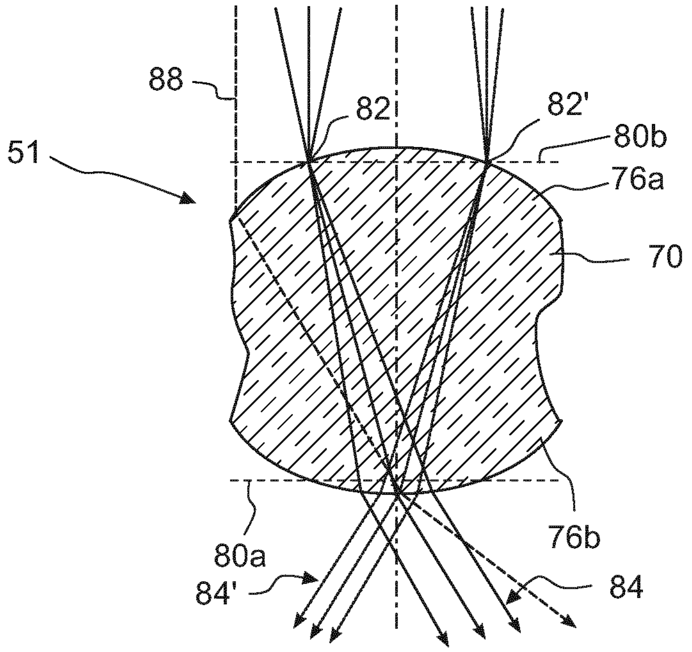


Fig. 7

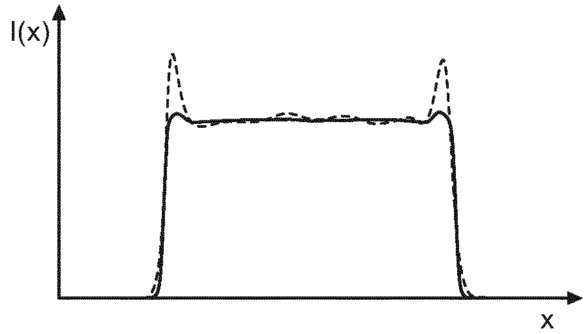


Fig. 8

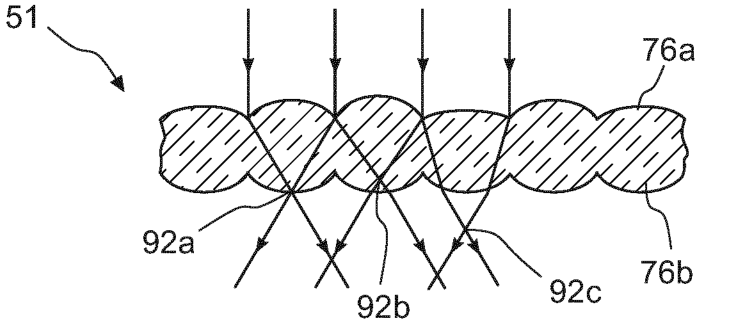
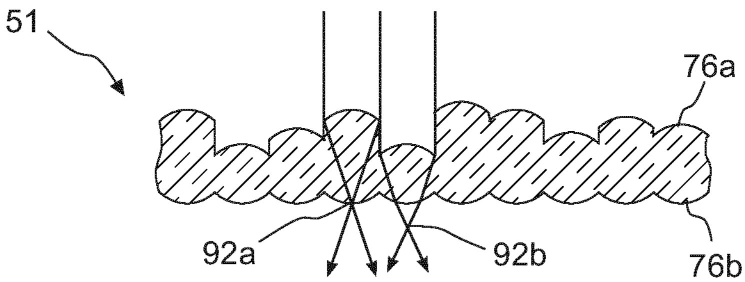


Fig. 9



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/080406

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 253 997 A2 (SUESS MICROTEC LITHOGRAPHY [DE]) 24 November 2010 (2010-11-24)	1-7
Y	paragraphs [0106] - [0109], [0113];	9,10
A	figures 1,6, 8	8
X	US 2003/043356 A1 (SHIRAISHI NAOMASA [JP]) 6 March 2003 (2003-03-06)	1-7
Y	paragraph [0294]; figure 20	9,10
Y	US 2015/146184 A1 (DEGUENTHER MARKUS [DE] ET AL) 28 May 2015 (2015-05-28) paragraph [0162]; figure 3	9,10
A	US 2011/285978 A1 (FIOLKA DAMIAN [DE] ET AL) 24 November 2011 (2011-11-24) paragraphs [0070] - [0078], [0111] - [0116]; figures 1, 19-21	1-10

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 March 2017	03/04/2017

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2

INTERNATIONAL SEARCH REPORT

Information on patent family members

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